Cleveland State University EngagedScholarship@CSU



ETD Archive

2011

A Systems Engineering Reference Model for Fuel Cell Power Systems Development

T. L. Blanchard *Cleveland State University*

Follow this and additional works at: https://engagedscholarship.csuohio.edu/etdarchive Part of the <u>Mechanical Engineering Commons</u> How does access to this work benefit you? Let us know!

Recommended Citation

Blanchard, T. L., "A Systems Engineering Reference Model for Fuel Cell Power Systems Development" (2011). *ETD Archive*. 535. https://engagedscholarship.csuohio.edu/etdarchive/535

This Thesis is brought to you for free and open access by EngagedScholarship@CSU. It has been accepted for inclusion in ETD Archive by an authorized administrator of EngagedScholarship@CSU. For more information, please contact library.es@csuohio.edu.

A SYSTEMS ENGINEERING REFERENCE MODEL FOR FUEL

CELL POWER SYSTEMS DEVELOPMENT

T. L. BLANCHARD

Bachelor of Arts in Physics

Cleveland State University

December, 1999

Submitted in Partial Fulfillment for the requirements for the degree

MASTER OF SCIENCE IN INDUSTRIAL AND MANUFACTURING ENGINEERING

at the

CLEVELAND STATE UNIVERSITY

November, 2011

© Copyright by T. L. Blanchard 2011

This Thesis has been approved

for the Department of Mechanical Engineering

And the college of Graduate Studies by

Chairperson, Professor L. Kenneth Keys
Mechanical Engineering Department

Date

Professor Paul P. Lin Mechanical Engineering Department

Professor Walter Kocher Civil & Environmental Engineering Department Date

Date

DEDICATION

This thesis is dedicated to the memory of my mother, who taught me the value of observation, examination and, the appreciation of the quest for answers. She taught me that even the greatest of obstacles could be surmounted and the greatest task could be accomplished if one, fueled by the desire to persevere, used three gifts: the knowledge of knowing what needs to be achieved, the willingness to do the diligence of working hard to accomplish and lastly, the ability to tolerate the (*sometimes, painful*) discomfort of personal growth.

ACKNOWLEDGEMENTS

This work would not have been possible without the help of numerous others. I have been blessed with good people who have been with me in good and bad times. They should share the pride I feel because they are a big part of what I have been able to accomplish. It is with immense gratitude that I acknowledge the support and help of my Professor, Dr. L. Kenneth Keys, for his sage advice, insightful criticisms, and patient encouragement in the writing of this thesis in innumerable ways. I would also like to thank Dr. Christopher Milliken, currently the Group Leader and the Production Manager at Technology Management Inc. whose steadfast support of this project was greatly needed and deeply appreciated. Much appreciation and gratitude to Benson Lee and Michael Petrik for giving me the opportunity to work in the fuel cell industry. This achievement would have been impossible to reach without the technical, business and entrepreneurial insights of Benison Lee and Dr. Robert Ruhl. I cannot find words to express my gratitude to Melinda Grigson for her help. Melinda's technical writing and computer skills are par excellent. Lastly, but not least, I owe my deepest gratitude to my father and the rest of my family for their undying support and love!

A SYSTEMS ENGINEERING REFERENCE MODEL FOR FUEL CELL POWER SYSTEMS DEVELOPMENT

T. L. BLANCHARD

ABSTRACT

This research was done because today the Fuel Cell (FC) Industry is still in its infancy in spite over one-hundred years of development has transpired. Although hundreds of fuel cell developers, globally have been spawned, in the last ten to twenty years, only a very few are left struggling with their New Product Development (NPD). The entrepreneurs of this type of disruptive technology, as a whole, do not have a systems engineering '*roadmap*', or template, which could guide FC technology based power system development efforts to address a more environmentally friendly power generation. Hence their probability of achieving successful commercialization is generally, quite low.

Three major problems plague the fuel cell industry preventing successful commercialization today. Because of the immaturity of FC technology and, the shortage of workers intimately knowledgeable in FC technology, and the lack of FC systems engineering, process developmental knowledge, the necessity for a commercialization process model becomes evident.

This thesis presents a six-phase systems engineering developmental reference model for new product development of a Solid Oxide Fuel Cell (SOFC) Power System. For this work, a stationary SOFC Power System, the subject of this study, was defined and decomposed into a subsystems hierarchy using a Part Centric Top-Down, integrated approach to give those who are familiar with SOFC Technology a chance to learn systems engineering practices. In turn, the examination of the SOFC mock-up could gave those unfamiliar with SOFC Technology a chance to learn the basic, technical fundamentals of fuel cell development and operations. A detailed description of the first two early phases of the systems engineering approach to design and development provides the baseline system engineering process details to create a template reference model for the remaining four phases. The NPD reference template model's systems engineering process, philosophy and design tools are presented in great detail. Lastly, the thesis draws an overall picture of the major commercialization challenges and barriers (both technical and non-technical) that SOFC developers' encounter.

LIST	OF TABLES		PAGEvi
LIST	OF FIGURES.		vii
CHA	PTER		
I	THE PURPO	SE AND THE OUTLINE OF THE THESIS	1
	1.1	Introduction	1
	1.2	The Thesis' Focus and Oranganization	2
	1.3	The Breakdown of the Thesis	3
II	INTRODUC	TION	5
	2.1	The History of Energy Sources and Technology Change.	5
	2.2	The Energy Technology S-Curve	6
	2.3	Non-renewable Energy Source – Wood	8
	2.4	Non-renewable Energy Source – Coal as Fuel	8
	2.5	Non-renewable Energy Source – Whale Oil	9
	1.6	Non-renewable Energy Source - Crude Oil	9
	2.7	Non-renewable Energy Source – Natural Gas	
	2.8	Non-renewable Energy Source – Nuclear Energy	11
	2.9	Renewable Energy Sources are Needed	12
	2.10	Types of Renewable Energy Sources	13
	2.11	Solar Power Systems	13
	2.12	Wind Farms	14
	2.13	Wind and Fuel Cell Technologies Combo	14
	2.14	Biofuels	15

TABLE OF CONTENTS

	2.15	Algaculture	17
	2.16	Hydrogen Production on the Spot	18
	2.17	A Few of the Accelerators of the SOFC Power System	19
	2.18	The Engineering Stages of a System (Product) Lifecycle	19
	2.19	The Proper Implementation of Systems Engineering	20
	2.20	A Total Life-cycle Approach	23
	2.21	The Reasons Products Fail and What Can Be Done About It.	24
III	THE HISTOI AND	RY OF FUEL CELLS, THEIR MATERIALS, THE GIRD THE NEGAWTT	31
	3.1	Introduction	31
	3.2	From Davy's Experiments	32
	3.3	Faraday, Hittorf and Others	32
	3.4	Cavendish	34
	3.5	Grove, Mond and Langer	35
	3.6	Ostwald's Predictions	37
	3.7	Nernst	38
	3.8	What were Helmholtz and Ostwald doing?	39
	3.9	The Search for the Dry Fuel Cells	41
	3.10	Temperature Ranges and Materials	41
	3.11	The Bacon Cell	41
	3.12	The Patents Mill	42
	3.13	Fuel Cells through the 1950s, the 1960s, and the 1970s	43
	3.14	Almost a Hit in the 1990s	44
	3.15	The Meaning of Success	44
	3.16	One in a Million?	45

	3.17	Bloom Energy
	3.18	One in a Large, Large Crowd
	3.19	Meeting the Needs of Power Hungry Cities
	3.20	Look there! We are grid locked!
	3.21	Improvements coming?
	3.22	Enter the Smart Grid54
	3.23	The Anatomy of the Grid and the Smart Grid's Function
	3.24	Governmental and Customer Support for the Smart Grid - A Future Vision
	3.25	Obstacles the Smart Grid58
	3.26	Up in Thin Air – Negawatt
	3.27	Typical Electric Power Supply Systems
	3.28	The Cost of Power
	3.29	Conclusion
THE I	NTROI MODI	DUCTION TO THE SIX PHASE LIFECYCLE REFERENCE EL FOR INNOVATIVE/DISRUPTIVE TECHNOLOGIES69
	4.1	Introduction
	4.2	Key's System Life Cycle Approach70
	4.3	The Learning Curve for SOFCs – Rivera-Tinoco (et al)77
	4.4	The General Learning Curve and Rivera-Tinoco's Model
	4.5	System Engineering, Cost and Life-Cycle Engineering - Key Approach
	4.6	The NIST/NSPE Reference Document Modified by Keys82
	4.7	The System View – From Keys' and Blanchard's Perspectives83
	4.8	Systems Configuration Management – From Keys' And Blanchard's Perspective

IV

	4.9	Quality Systems Engineering Management - From Keys' and Blanchard's Perspective
	4.10	Reliability Systems Engineering Management - From Keys' and Blanchard's Perspective
	4.11	Systems Testing Engineering - From Keys' and Blanchard's Perspective
	4.12	Concurrent Engineering – From Keys' and Blanchard's Perspective
	4.13	Conclusion – Playing the Game – The Players
V	THE INROD PLAN	UCTION TO THE CONCEPTUAL DESIGN AND ADVANCE INING PHASE – PHASE ONE
	5.1	Introduction
	5.2	The Conceptual Design & Advance Planning Phase95
	5.3	The Major Activities of the Conceptual Design & Advance Planning Phase
	5.4	In the Early Part of the Phase – The Major Focus
	5.5	The Middle Part of the Phase – The Major Focus
	5.6	The End of the Phase – The Major Focus
	5.7	Advance Planning
	5.8	The Milestones of the Conceptual Design and Advance Planning Phase consists of:
	5.9	The Need Identification Analysis103
	5.10	In what terms should the customer's problem be defined in?105
	5.11	What about the Electricity? – Defining the customer's Problem, what is it?106
	5.12	Who is the customer?
	5.13	The Power Requirements for the Typical Residential Household in Ohio109

5.	.14	Sizing a FC Power System for Residential Use 110
5.	.15	What about the Heat Requirement?
5.	.16	What about efficiency for a furnace?
5.	.17	Who sets the US Standards for heating?
5.	.18	The Fuel of Residential Choice – Natural Gas 114
5.	.19	The size of the average house in the United States – A potential SOFC Market
5.	.20	The Design Synthesis of System Design Alternatives117
5.	.21	The Algorithm for Evaluating Design Alternatives118
5.	.22	Which Type of FC should be selected? 120
5.	.23	For Power Production – Which Fuel Cell Power System is the best?
5.	.24	For Thermal Energy Production – Which Fuel Cell System is the best?
5.	.25	The Profile of a Solid Oxide Fuel Cell
5.	.26	Is an SOFC Power System as Commercialized Product, possible?
5.	.27	They were <i>not</i> the first
5.	.28	The Design of a System in the context of cost 133
5.	.29	Conclusion
THE TOI PI	P-DC HASI	WN HIERARCHY BREAKDOWN OF A SYSTEM – E ONE136
6.	.1	A Part Centric Top-Down Design Approach136
6.	.2	The SOFC Power System Structural Breakdown
6.	.3	The Cabinet Housing of the SOFC Power System 139
6.	.4	The Balance of Plant (BOP) 139

VI

6.5	A Brief Survey of the BOP142
6.6	A Brief Survey of the Cell Stack Package144
6.7	The Introduction to the Fuel Processing System
6.8	The Different Paths of Electricity Generation146
6.9	The Functions and Performance Requirements of the Fuel Processing System
6.10	The Functional Analysis – The Scenario of the Anode Leg of An SOFC Power System
6.11	The Fuel Condition Unit149
6.12	The Water Management System150
6.13	The Energy Production – The Anode Side of the Cell Stack 151
6.14	Systems Analysis
6.15	Noted Subsystem Interactions
6.16	Discussion
6.17	The Introduction to the Air and Waste Management Subsystems
6.18	The Functions and Performance Requirements of the Air and Waste Management Systems
6.19	The Functional Analysis – The Scenario of the Cathode Leg of An SOFC Power System
6.20	The Air Filtration Unit
6.21	The Energy Production – the Cathode Side of the Cell Stack And Temperature Conditioning Unit158
6.22	The Exhaust Section
6.23	The Waste Management Subsystem
6.24	Catalyst Management

6.25	The Nature of the Exhaust Gas from a SOFC Power System 162
6.26	Water Management 162
6.27	Desulphurization Management
6.28	Systems Analysis
6.29	Noted Subsystem Interactions 164
6.30	Discussion165
6.31	The Introduction to the Electrical System167
6.32	The Functions and Performance Requirements of the Electrical System
6.33	The Functional Analysis – The Scenario of the Output Leg of an SOFC Power System
6.34	The Power Conditioning Section of an SOFC Power System – The Functions of the Power Conditioning Unit171
6.35	The Electrical Controls and Energy Requirements of the Balance of Plant
6.36	The Data Acquisition Subsystem174
6.37	The End-User's Energy Requirements 176
6.38	System Analysis176
6.39	Discussion
6.40	The Basic Operation Scenario of the SOFC Model: 178
6.41	The Introduction to the Thermal Management System 179
6.42	The Functions and Performance Requirements of the Thermal Management System
6.43	Thermal Functional Analysis of the SOFC as a Whole System – Operational Modes
6.44	The Functional Analysis – The Concrete and Abstract Pathways of the Thermal Management System of a SOFC184

6.45	The Functional Analysis of the Cell Stack as a Heat Generator.	. 185
6.46	Functional Analysis of the Hot Assembly as a Thermal Shield.	185
6.47	Functional Analysis of the Heat Exchanger	186
6.48	System Analysis	.188
6.49	Noted Subsystem and Components Interactions of the Thermal Management System – Process Simulation Tools	. 189
6.50	Discussion – Introduction	189
6.51	Introduction – The Mechanical Subsystem and the Hot Assembly	191
6.52	The Functional and Performance Requirements of the Hot Assembly	.193
6.53	Functional Analysis of the Mechanical System	. 193
6.54	Compressors, Ejectors, Fans, Blowers, and Pumps	. 194
6.55	Compressors Efficiency	. 195
6.56	Compressor Power	. 197
6.57	Compressor Performance Charts	198
6.58	Ejector Circulators	.201
6.59	Fans and Blowers	. 202
6.60	The Introduction to the Unit Cell and the Cell Stack Package	204
6.61	Fuel Cell Operation	.206
6.62	The Functional Analysis – The Assumed Mechanisms of the Solid Oxide Fuel Cell.	.211
6.63	Anode Reaction Mechanism	. 213
6.64	Cathode Reaction Mechanism	213
6.65	System Analysis	.215

	6.6	5 Ohm's Law	216
	6.6	Fuel Cell Area Specific Resistance (ASR)	216
	6.6	3 Cell Efficiency	219
	6.6	9 Heat Production	219
	6.7) Conclusion	220
VII	TESTING PH	FOR THE CONCEPTUAL DESIGN AND ADVANCE PLANNI ASE – PHASE ONE	NG 221
	7.1	Introduction	221
	7.2	The Implementation of Testing Early On	221
	7.3	Bloom Energy – Quality Control and Reliability Problems	222
	7.4	The Test and Evaluation Master Plan	223
	7.5	Category of Tests in the Preliminary Design and Advance Planning Phase	225
	7.6	Testing Baseline Plans	228
	7.7	The Benefits of Testing	229
	7.8	The Type 1 Tests	230
	7.9	Computer Prototyping	231
	7.1	Examples of Fuel Cell Testing & Testing Equipment and Technique.	232
	7.1	Reliability	233
	7.1	2 Time	233
	7.1	B Environment	233
	7.1	Basic Reliability Function	234
	7.1	5 Redundancy	236
	7.1	5 Product Quality Feedback	238

	7.17	Maintenance Planning	242
	7.18	Quality Engineering	245
	7.19	Conclusion	247
VIII	THE OPERA FOR 7 SUBS PHAS	TIONAL REQUIRMENTS AND TECHNOLOGY BASELINI THE FUEL PROCESSING SUBSYSTEM, THE AIR YSTEM AND THE WASTE MANAGEMENT SYSTEMS – F ONE	ES 249
	8 1	Introduction	2/9
	8.2	Barriers to SOFC Power Systems	24)
	8.3	Rationale for the Requirement Analysis	250
	8.4	Types of Requirements	251
	8.5	Reasonable SOFC Power System Performance Assumptions.	252
	8.6	Packaging of the SOFC Power System's Enclosure and Interface Considerations	258
	8.7	The Fuel Processing System	258
	8.8	Internal Reforming	259
	8.9	External Reforming	261
	8.10	The Reformer of an External Reforming Design	262
	8.11	External Reforming Choices	263
	8.12	Steam-to-Carbon Ratio or Oxygen-to-Fuel Ratio	264
	8.13	Steam Reforming (SR)	265
	8.14	Coke (Carbon) Formations.	266
	8.15	How to prevent coking	267
	8.16	The Filtering of the Solid Particulates	269
	8.17	Sulfur Poisoning	270

8.18	Sulfur Poisoning of SOFC Anodes	. 270
8.19	Sulfur Reduction	. 272
8.20	Boiler (<i>Steam Generation Technology</i>) – The Water Management System	.274
8.21	After filtration has been performed	. 276
8.22	Corrosion	. 276
8.23	Carbon Dioxide Corrosion	. 277
8.24	Copper Complexing Corrosion	. 278
8.25	Mechanical and Chemical Deaeration	. 278
8.26	Tray-type Deaerating Heaters	.280
8.27	Why Some Corrosion in the Boiler is Necessary	280
8.28	Deposits/Sediments/Fouling – Mechanism of Deposition	. 281
8.29	Heat Transfer Losses	.283
8.30	Embrittlement	. 284
8.31	Caustic Embrittlement	. 284
8.32	Priming	286
8.33	Metallurgical Failures and Analysis	287
8.34	Fatigue Failures	.287
8.35	Corrosion failure occurs as pitting, thinning or gouging	. 287
8.36	The Element of Focus for a Fuel Processing Subsystem – How it works	.289
8.37	Packed Bed Fuel Processing System	292
8.38	Example of a reformer reactor (packed bed)	.294
8.39	A Fluidized Bed Condition – A Potential Problem for Packed Bed FC Reformers	. 296

	8.40	Important Catalyst Reformer Designs	298
	8.41	Ceramic Mats – A Possible Solution to the Fluidized Bed	300
	8.42	Alternatives to Pelletized SR Bed	302
	8.43	Catalysts and Sulfur	306
	8.44	Generalized Steam Reformer and Catalyst for SOFC System	309
	8.45	The Mechanical Subsystem and the Element of Focus for the Air Subsystem	e 312
	8.46	Conclusion	314
IX	OPERATIO FOF	ONAL REQUIREMENTS AND TECHNOLOGY BASELINES & THE ELECTRICAL SUBSYSTEM – PHASE ONE	315
	9.1	Introduction	315
	9.2	The Electrical System	315
	9.3	V6 Converter	317
	9.4	DC Regulation and Voltage Conversion – Cell Switching Circuitry	320
	9.5	Switching Regulators	323
	9.6	Linear Regulator	325
	9.7	The Buck Boost Regulator	327
	9.8	Inverters – Single Phase	331
	9.9	Inverters – Three Phase	337
	9.10	An Example of the Power Conditioning Unit with Line Frequency Transformer	340
	9.11	Summary of the Power Conditioning Unit with Line Frequer Transformer Example	юу 341
	9.12	The DC/DC boosted voltage is process via a Pulse Width Modulation PWM DC/AC inverter	344

	9.13	Problems with the Design:	.345
	9.14	Fuel Cell Ripple Current	346
	9.15	General comments about corrective measures for limiting fuel Cell ripple current	. 347
	9.16	Grid Electrical System Design Issues	. 348
	9.17	Fuel Cell/Battery or Capacitor Hybrid Systems	. 352
	9.18	Regulatory Issues and Tariffs	. 356
	9.19	Conclusion	359
Х	THE OPERA FOR T ASSE	FIONAL REQUIREMENTS AND TECHNOLOGY BASLINE THE THERMAL MANAGEMENT SYSTEM, THE HOT MBLY AND THE CELL STACK PACKAGE – PHASE ONE	S 360
	10.1	Introduction	360
	10.2	The Challenges of Thermal Management	.360
	10.3	Systems Engineering Modeling based on Thermodynamic And other Models	. 366
	10.4	Important Mathematical Fuel Cell Models	. 368
	10.5	Heat Recovery	. 371
	10.6	Heat Exchanger Design Considerations and Requirements	.373
	10.7	General Considerations	. 374
	10.8	Monitoring	375
	10.9	Fouling	376
	10.10	Cooling Water Fouling	377
	10.11	Maintenance	.377
	10.12	The Differences between HTHEs and low-temperature heat Exchangers (LTHE)	.379

10.13	General Design Considerations for High Temperature Heat Exchangers	. 380
10.14	Selection of Materials for HTHEs	.381
10.15	Ceramic Heat Exchangers	. 382
10.16	Ceramic Recuperators	.383
10.17	The Major Unsolved Problems in the use of the Ceramic Heat Exchangers	. 385
10.18	High Temperature Electrolysis	. 386
10.19	Ceramic monolith structures	. 390
10.20	The Hot Assembly Requirements	. 394
10.21	The Cell Stack – The Unit Cell	. 396
10.22	Cell and Stack Designs	. 396
10.23	The Materials of SOFCs	. 402
10.24	What is a Fluorite Structure	402
10.25	Yttria-Stabilized Zirconia (YSZ)	. 406
10.26	Ionic Conductivity of YSZ	. 408
10.27	Electronic Conductivity of YSZ	. 408
10.28	YSZ Characteristics	. 409
10.29	Grain Boundary Conduction	. 410
10.30	Mechanical Strength	. 411
10.31	Other Types of Electrolyte – Scandia-Stabilized Zirconia	. 411
10.32	Key Requirements for Electrolyte	. 412
10.33	The Specifications of the Ceramic Cathode Layer of the Electrolyte	.414

10.34	The Specifications of the Ceramic Anode Layer of the Electrolyte	415
10.35	Other Fluorite-Structure Materials	420
10.36	Perovskite-Structure Materials	422
10.37	Lanthanum Strontium Manganite (LSM)	423
10.38	Other Perovskite-Structure Materials	424
10.39	Other Conductive Oxides	424
10.40	The Interconnects or Separators	425
10.41	The Seals	430
10.42	Planar Challenges	430
10.43	(Mechanistically) Types of Seals	431
10.44	Thermal Expansion (CTE)	432
10.45	Rigid Seals Advantage	432
10.46	Rigid Seals – Approaches	433
10.47	Glass Seals	433
10.48	Glass Ceramics	434
10.49	Conclusion	437
THE EXPLO ANAI PHAS	RATORY/DEFINITION TECHNIQUES AND FEASIBILITY LYSIS OF SYSTEM DESIGN AND TECHNOLOGY BASES – E ONE	438
11.1	Introduction	438
11.2	The Evaluation of Conceptual System Design	439
11.3	The Design and Development Philosophy	439
11.4	The Process Design Approach	441
11.5	The IORC Process System	442

XI

11.6	Procedural Steps for using the IORC Process System443
11.7	From Figure 11-4 – Beginning of the Baseline Procedure - An Input – Which type of fuel preparation will the SOFC Power System use?
11.8	From Figure 11-4 – Beginning of the Baseline Procedure – How much oxidant does the Cell Stack Package require and what types of devices are available to deliver this demand?
11.9	From Figure 11-4 – Beginning of the Baseline Procedure – An Output – The Electrical Demands of the SOFC Power System and End Use
11.10	From Figure 11-4 – Beginning of the Baseline Procedure – Process Requirements - An Output - The Thermal Requirement of the SOFC Power System
11.11	What kind of Waste Management will the power system Incorporate?
11.12	The Modeling of the Power System
11.13	Why Use a Model
11.14	Feasibility and Sensitivity Analysis
11.15	Lisbona's SOFC Power System Model458
11.16	Lisbona's SOFC Power System's Performance Variables460
11.17	SOFC Power System's Performance Variables – Temperature and Pressure
11.18	SOFC Power System's Performance Variables – Reactant Utilization and Gas Composition464
11.19	SOFC Power System's Performance Variable –Current Density
11.20	Lisbona's SOFC Power System's Performance Input Variables
11.21	Lisbona's SOFC Power System's Nominal Operation473

	11.22	The Analysis of System Condition Variation – How to Determine which were the important ones?	475
	11.23	System without Anode Recirculation	487
	11.24	The Feasibility/Sensitivity Analysis of Uf with variable AR And Pre-Reforming	490
	11.25	Conclusion	494
XII	THE USE OF	F DESIGN SRUCTURE MATRIXING (DSM) – PHASE ONE	498
	12.1	Introduction	498
	12.2	The Use of Design Structure Matrixing (DSM)	498
	12.3	Why DSM Analysis?	499
	12.4	DSM Analysis of an SOFC Power System	500
	12.5	Analysis of the Overall Review of the SOFC Power System Mock-Up Model	503
	12.6	Examples of DSM Analysis on the Subsystem of an SOFC Power System.	504
	12.7	Fuel Utilization – Case 3	510
	12.8	Further Manipulation of DSM	513
	12.9	Multi-Type Element DMS Matrix	519
	12.10	Component Interaction of Systems and Subsystems	520
	12.11	Conclusion	524
XIII	THE PRELIN	/INARY SYSTEM DESIGN PHASE – PHASE TWO	525
	13.1	Introduction	525
	13.2	The Bottom-Up Design Approach	526
	13.3	Top-down Versus the Bottom-Up Design	527
	13.4	Prototyping used in Analysis	532

	13.5	The Need for Optimizing – System Evaluation	533
	13.6	Hawkes' Model – System Evaluation	535
	13.7	Model Structure: CODEGen	. 537
	13.8	SOFC High-Level Characterization	.538
	13.9	UK Residential Energy Demand & Other Input Parameters	.540
	13.10	Baseline Result	.541
	13.11	Sensitivity to Stack Capacity	. 542
	13.12	Sensitivity to Capital Costs	.544
	13.13	Sensitivity to Electrical Efficiency	550
	13.14	Sensitivity to Electrical Export Prices	553
	13.15	Conclusion	. 555
XIV	THE DESIGN	N DECISIONS FOR THE CELL STACK – PHASE TWO	558
	14.1	Introduction	559
	14.2	The Four Design criteria for the Cell Stack's Performance	. 556
	14.3	The Cell Stack Design and Integrity – Which unit cell and Cell stack configuration should be considered?	560
	14.4	How Many Stacks in the Cell Stack Package?	561
	14.5	Considering the operating temperature range, what material Options are there for the electrolyte?	.563
	14.6	Considering the electrolyte will be made from zirconia, what we Be the dopant percent?	ill .566
	14.7	Considering the Unit Cell design, which anode material should be selected?	566
	14.8	Which cathode material should be selected for a Fuel Cell design?	568
	14.9	Which Stack arrangement should be used?	569

14.10	Tubular	570
14.11	Which Cell configuration should be used?	573
14.12	How thick should the electrolyte be and which fabrication Techniques are available to obtain the desired thickness	574
14.13	Which Specific Model of a Cell Stack Package will be used?	.574
14.14	What about Gas Manifolding?	575
14.15	What are the Model's Assumptions?	577
14.16	What are the quantified losses which affect (decrease) the Unit Cell's voltage? Define the Electrochemical Model of the Unit Cell	578
14.17	What is the mass balance of the FC Power System?	580
14.18	Define a temperature profile of the SOFC	581
14.19	What will be the Pressure Losses of the Fuel and Air Channels.	.583
14.20	Conclusion	.585
XV DESIGN CH	ANGES – PHASE TWO	582
XV DESIGN CH 15.1	ANGES – PHASE TWO	582 .582
XV DESIGN CH 15.1 15.2	ANGES – PHASE TWO Introduction Change Propagation in Complex Designs	582 .582 582
XV DESIGN CH 15.1 15.2 15.3	ANGES – PHASE TWO Introduction Change Propagation in Complex Designs An Example of a Complex Design	582 582 582 585
XV DESIGN CH 15.1 15.2 15.3 15.4	ANGES – PHASE TWO Introduction Change Propagation in Complex Designs An Example of a Complex Design The Management of Change.	582 582 582 585 585
XV DESIGN CH 15.1 15.2 15.3 15.4 15.5	 ANGES – PHASE TWO. Introduction. Change Propagation in Complex Designs. An Example of a Complex Design. The Management of Change. A Partial Solution – Model based reasoning could be used for Complex design. 	582 582 582 585 591 592
XV DESIGN CH 15.1 15.2 15.3 15.4 15.5 15.6	 ANGES – PHASE TWO. Introduction. Change Propagation in Complex Designs. An Example of a Complex Design. The Management of Change. A Partial Solution – Model based reasoning could be used for Complex design. A Portrait of Change. 	582 582 582 585 591 592 592
XV DESIGN CH 15.1 15.2 15.3 15.4 15.5 15.6 15.7	 ANGES – PHASE TWO. Introduction. Change Propagation in Complex Designs. An Example of a Complex Design. The Management of Change. A Partial Solution – Model based reasoning could be used for Complex design. A Portrait of Change. Seeing the Big Picture. 	582 582 582 585 591 592 592 594
XV DESIGN CH 15.1 15.2 15.3 15.4 15.5 15.6 15.7 15.8	 ANGES – PHASE TWO Introduction. Change Propagation in Complex Designs. An Example of a Complex Design. The Management of Change. A Partial Solution – Model based reasoning could be used for Complex design. A Portrait of Change. Seeing the Big Picture. The Designers' Product Maturity? 	 582 582 582 585 591 592 594 595 596

	15.10	A Change Prediction Method	599
	15.11	The Initial Analysis	599
	15.12	Create a Product Model	599
	15.13	Complete Dependency and Predictive Matrices	600
	15.14	Product Risk Matrix	608
	15.15	The Case Analysis	609
	15.16	Identify Initiating Change – Step 1	609
	15.17	Identify Predicted Changes – Step 2	609
	15.18	Case Risk Plot – Step 3	610
	15.19	Redesign – Step 4	610
	15.20	Conclusion	611
XVI	ANALYTIC I	HIERARCHY PROCESS – PHASE TWO	612
	16.1	Introduction	612
	16.2	The Need for the Analytic Hierarchy Process	614
	16.3	APH used in the Fuel Cell Industry	616
	16.4	A Closer Look at APH	. 616
	16.5	An Example of APH – Pair Wise Comparisons	617
	16.6	Making a Comparison Matrix	619
	16.7	Determining the Priority Vectors	620
	16.8	Calculating the Consistency Index and Consistency Ratio	624
	16.9	Computing a Full Hierarchy – The Fuel Processing System	627
	16.10	An Alternative Choice – Steam Reforming	627
	16.11	An Alternative Choice – Autothermal Reforming	629

16.12	2 An Alternative Choice – Partial Oxidation	29
16.13	3 The Criteria	30
16.14	4 Details of the Analysis	31
16.1:	5 Paired Comparison Matrix (Level 2) with respect to Factor A: Efficiency	32
16.10	6 Paired Comparison Matrix (Level 2) with respect to Factor D: Coking	33
16.1	7 The Air System – Selection of a Condition Monitoring Method For an Air Blower for Desert Applications	35
16.1	8 Conclusion	41
XVII TESTING I PHA	N THE PRELIMINARY SYSTEMS DESIGN PHASE – SE TWO	42
17.1	Introduction	42
17.2	Responsibility to the End User6	42
17.3	Modeling Costs for Lifetime Warranty at System Level6	45
17.4	The Need for Reliability in Preliminary Engineering Designs of Innovative Products	48
17.5	Preparing for the 'Survival of the Fittest' by the Principle of Systems Engineering (including Reliability Analysis, Construction Feedback	54
17.6	The Barriers to Commercialization	59
17.7	Conclusion6	75
XVIII MODULAR	ITY – PHASE TWO6	76
18.1	Introduction	76
18.2	An Example of a Complex Design Synthesis6	77
18.3	What about the Cost?	79
18.4	Modularity – The Solution6	79

	18.5	Modularity for Manufacturing
	18.6	Example of Functional Dependency in relation to Manufacturing Design
	18.7	A Method for Modularizing an SOFC Power System
	18.8	The Pivotal Subsystem – The Cell Stack Module
	18.9	The Linking Subsystems – Bridge Modules
	18.10	The Identity Relational Module – the Modularity of the Thermal Management and Waste Management Subsystem of the SOFC Power System
	18.11	The Compliment Modules – the Air and Fuel Processing Systems
	18.12	The Housing Module
	18.13	Case Study Example of a Linking Subsystem – Examples of DFM
	18.14	Conclusion
XIX	DESIGN FOR MECH	R X, MATERIAL SELECTION FOR MANUFACTURING & IATRONICS – PHASE TWO708
	19.1	Introduction708
	19.2	The DFX Practices
	19.3	Systematic and Quantitative Methodologies for DFX Practices – Design for Assembly and Design for Manufacturing71
	19.4	Some of the Design and Development problems/decision that the Designer Manufacturers of fuel cell systems face:71
	19.5	The DFX Shell: A Generic Framework for Developing Design For X Tools
	19.6	Requirement Analysis717
	19.7	Functionality Requirements718

		19.8	Operability Requirements	. 719
		19.9	Focus and Flexibility Requirements	720
		19.10	Modeling for Product Analysis	.721
		19.11	Modeling for Process Analysis	. 722
		19.12	Flow Process Charts	723
		19.13	Operation Process Charts	.724
		19.14	Performance Measures	724
		19.15	Verification	. 725
		19.16	A Closer Look at DFM	. 727
		19.17	DFM Techniques	. 729
		19.18	Mechatronics	.732
		19.19	Conclusion	736
XX	MATE	RIAL S	SELECTION FOR MANUFACTURING – PHASE TWO	. 738
		20.1	Introduction	738
		20.2	What's the problem?	738
		20.3	What about the Energy Analysis?	740
		20.4	LCEA for Material Selection	742
		20.5	Comparison and Results of Energy Analysis Methods	.746
		20.6	LCEA for PV (Photo-Voltic) Modules – Example of the LCEA Practice	x 747
		20.7	Conclusion	747
XXI	STRAT	TEGIC	PARTNERSHIPS – PHASE TWO	. 748
		21.1	Introduction	. 748
		21.2	An Example of the Problems Fuel Cell Developers Face	.749

21.3	Design for Logistics	.751
21.4	Maybe there's another approach; maybe, they should try Strate Alliances?	gic 751
21.5	Conclusion	754
XXII THE OTHER	SIDE OF THE STORY – PHASE THREE AND BEYOND	. 755
22.1	Introduction	755
22.2	Uncertainty throughout and within the NPD Lifecycle – What can be done about it?	758
22.3	The Cross-Functional Teams working within the NPD Lifecycle	761
22.4	Lifecycle System Testing/Reliability/Quality Control/Maintenance Effort	762
22.5	The Manufacturable Prototype Summary	. 764
22.6	The Detail System Design & Development Phase	. 765
22.7	The Pilot (Pre-Production) Prove-in-Phase	. 767
22.8	Some more Considerations for the Pilot (Pre-Production) Prove-in-Phase	770
22.9	The Manufacturing & Distribution Phase	.772
22.10	The Operational Use & Logistic System Support Phase (Sustainability)	775
22.11	Conclusion	. 779
XXIII DISCUSSION	N AND CONCLUSION	. 782
23.1	Introduction	. 782
23.2	Discussion	. 783
23.3	The Aims	785
23.4	The Steps throughout the Research Process	. 786

	23.5	Future Work	791
BIBLIOGRA	РНҮ	· · · · · · · · · · · · · · · · · · ·	799
APPENDICES	S		840
	Appen	dix A	841
	Appen	dix B	845
	Appen	dix C	851

LIST OF TABLES

Table 2-1	The Comparative Expenditure On a New Product	24
Table 4-1	Examples of Experience Curves	79
Table 5-1	Need Identification Analysis	104
Table 5-2	DOE Technical Targets	106
Table 5-3	2009 Energy Needs for Three US States	108
Table 5-4	Examples of Analytical Tools for Need and System Requirements	109
Table 5-5	Daily Itemized Hypothetical Household's Energy Requirements	110
Table 5-6	Calculated Hypothetical Household's Energy Consumption Pattern	111
Table 5-7	The Base Model for Cost-Effectiveness of Furnace Performance	114
Table 5-8	Synthesis of Conceptual System Design Alternatives	117
Table 5-9	Weighting of Analysis Goals	120
Table 5-10	Types of Fuel Cells	121
Table 5-11	Three Types of Fuel Cells	126
Table 6-1	The Subdivision of the Fuel Processing Subsystem	152
Table 6-2	The Subdivision of the Air Subsystem of a SOFC Power System	164
Table 6-3	Measurement Items for a Data Acquisition System	175
Table 6-4	The Subdivision of the Electrical System	177
Table 6-5	The Elements of Focus for the Thermal Management System of a SOI Power System Related to the Individual Subsystems	FC 188
Table 6-6	The Legend for Figure 1's Solid-Oxide Hot Assembly	192
Table 6-7	The Electrochemical Reactions in Fuel Cells Adapted from The Fuel Cell Handbook	214
Table 6-8	The Ideal Voltage as a Function of Cell Temperature	215

Table 6-9	The Subdivision of the Unit Cell	. 216
Table 7-1	The Testing and Maintenance Baselines of an SOFC Power System's Subsystems	. 231
Table 7-2	Examples of Testing	. 232
Table 8-1	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	. 253
Table 8-2	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	254
Table 8-3	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	. 255
Table 8-4	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	. 256
Table 8-5	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	. 257
Table 8-6	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Fuel Processing System	. 288
Table 8-7	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Fuel Processing System.	. 289
Table 8-8	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Fuel Processing System	. 306
Table 8-9	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Fuel Processing System	. 311
Table 8-10	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	312
Table 8-11	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	313
Table 9-1	Maximum Permitted Harmonic Levels	334

Table 9-2	Power Conditioning Information Regarding PCE with Line Frequency Transformer	.5
Table 9-3	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	8
Table 9-4	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems	9
Table 10-1	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Thermal Management System	6
Table 10-2	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Heat Exchanger	'5
Table 10-3	The Maintenance Baselines of an SOFC Power System's Subsystems – The Heat Exchanger – Fouling	8'
Table 10-4	The Functional Requirements and the Testing and Maintenance Baselines Of an SOFC Power System's Subsystems – The Hot Assembly	•5
Table 10-5	The Functional Requirements of an SOFC Power System's Subsystems – The Cell Stack Package)1
Table 10-6	The Functional Requirements of an SOFC Power System's Subsystems – The Electrolyte	2
Table 10-7	Ionic Size	1
Table 10-8	The Functional Requirements of an SOFC Power System's Subsystems – The Ceramic Anode/Cathode Layer of the Electrolyte	:5
Table 10-9	The Functional Requirements of an SOFC Power System's Subsystems – The Interconnects (Separators)	:9
Table 10-10	The Functional Requirements of an SOFC Power System's Subsystems – The Seals	6
Table 11-1	Evaluation of Conceptual System Design 43	9
Table 11-2	The Lower Levels of the System	7
Table 11-3	Parameters Used for Stack Model	3
Table 11-4	Parameters Dealing with the SOFC Stack and with Global System	474
-------------	--	-----------
Table 11-5	System Inputs Parameters Related to Performance Requirements	496
Table 11-6	SOFC Stack Input Parameters	497
Table 11-7	SOFC Stack Input Parameters	497
Table 12-1	The 9 Subsystems of the SOFC Power System Mock-Up Model	500
Table 12-2	The Provisional Assumptions for the SOFC Power System	501
Table 12-3	The Provisional Assumptions for the SOFC Power System	502
Table 12-4	The DSM of the SOFC Power System Mock-Up Model	503
Table 12-5	The Ranking of Subsystem Dependency	503
Table 12-6	The Ranking of Subsystem Provisions	504
Table 12-7	Case 1 - The Provisional Assumptions for the Anodic Side of the Cell Stack.	506
Table 12-8	Case 1 - The Provisional Assumptions for the Anodic Side of the Cell Stack.	507
Table 12-9	Case 1 – The DSM Analysis of the Workings of the Anodic Side of the Cell Stack.	507
Table 12-10	Case 2 - The Provisional Assumptions for the Cathodic Side of the Cell Stack	508
Table 12-11	Case 2 - The Provisional Assumptions for the Cathodic Side of the Cell Stack	509
Table 12-12	Case 2 – The DSM Analysis of the Workings of the Cathodic Side of th Cell Stack	ne 510
Table 12-13	Case 3- The Provisional Assumptions for the Fuel Utilization	511
Table 12-14	Case 3- The Provisional Assumptions for the Fuel Utilization	512
Table 12-15	Case 3- The DSM Analysis for the Fuel Utilization Study	512
Table 12-16	The Subdivision of the Fuel Processing Subsystem	522

Table 12-17	DSM Analysis of the Fuel Processing Subsystem	523
Table 13-1	Grid-Boiler Baseline Results	541
Table 13-2	SOFC Micro-CHP Central Estimate Results	542
Table 14-1	Cell Configurations	573
Table 14-2	Different Cell Configurations External Supporting	573
Table 16-1	Number of Comparisons	619
Table 16-2	Random Consistency Index	626
Table 16-3	Paired Comparison Matrix of Fuel Processing Factors	631
Table 16-4	Paired Comparison Matrix (Level 1) with Respect to the Goal	632
Table 16-5	Paired Comparison Matriz (Level 2) with Respect to Factor A: Efficiency	632
Table 16-6	Factor A: Paired Comparison Matrix (Level 2) with Respect to the Efficiency of Hydrogen Production	633
Table 16-7	Factor D: Paired Comparison Matrix (Level 2) with Respect to Coking	633
Table 16-8	Factor D: Paired Comparison Matrix (Level 2) with Respect to Coking	634
Table 16-9	Overall Composite Weight of the Alternatives	634
Table 16-10	Pair-Wise Rating of Selection Criteria	637
Table 16-11	Normalized Pair-Wise Rating of Selection Criteria	.637
Table 16-12	Pair-Wise Rating of Alternative CM Method With Respect to Signal Usefulness	638
Table 16-13	Normalized Pair-Wise Rating of Alternatives With Respect to Signal Usefulness	639
Table 16-14	Average Normalized Rating of CM Methods With Respect to Each Criterion.	640
Table 16-15	Overall CM Method Rating	641
Table 18-1	The Ranking of Subsystem Functional Dependency	683

Table 18-2	The Grouping (Modulating) of the SOFC Power Systems' Subsystem Analysis (Bottom-Up Approach)
Table 18-3	Relational Characteristics of Each Subsystem
Table 18-4	Hot Assembly Bridge Module
Table 18-5	Fuel Processing/Air Module Components for Electricity Production 699
Table 19-1	An Examples of Design Guidelines728
Table 22-1	Quality/Testing Tools For NPD Stages (Examples)774
Appendix B	Residential Average Monthly Bill By Census Division, and State 2009 846
Appendix B	Residential Average Monthly Bill By Census Division, and State 2009 847
Appendix B	Residential Average Monthly Bill By Census Division, and State 2009 848
Appendix B	Residential Average Monthly Bill By Census Division, and State 2009 849
Appendix B	Residential Average Monthly Bill By Census Division, and State 2009 850
Appendix C	The Daily Itemized Hypothetical Household's Energy Requirements852
Appendix C	The Daily Itemized Hypothetical Household's Energy Requirements853
Appendix C	240 V AC Information

LIST OF FIGURES

Figure 2-1	The S-Curve Lifecycle Stages	7
Figure 2-2	The Energy Technology S-Curve	7
Figure 2-3	Dr. Joanne M. Belovich of Cleveland State University	17
Figure 2-4	After Adaption, Expansion and Modification of Blanchard's System Lifecycle Model	21
Figure 2-5	Examples of System Lifecycles	23
Figure 2-6	The NIST/NSPE Task Group's version of the 'Traditional Serial Commercialization Model'	25
Figure 2-7	The Modernized Commercialization Model <i>after</i> the NIST/NSPE Task Group.	26
Figure 2-8	The Formulation of Multi-Specialty Project Team Designed to Accomplish Concurrent Engineering in the Phases	28
Figure 2-9	Influence of Specialties on Stages	29
Figure 3-1	Faraday	33
Figure 3-2	Hittorf	34
Figure 3-3	Cavendish	35
Figure 3-4	William Grove	35
Figure 3-5	Ludwig Mond	36
Figure 3-6	Ostwald	37
Figure 3-7	Nernst	39
Figure 3-8	Helmholtz	40
Figure 3-9	Typical Electrical Power Supply Systems	60
Figure 3-10	US Transmission Grid	61
Figure 3-11	The Cascade Efficiency of Electric Power Distribution	65

Figure 3-12	US Historical Data for Electrical Power Transmission & Distribution Losses (kWh)	
Figure 4-1	Product Life Cycle Elements and Interactions	72
Figure 4-2	MTBM Versus Cost Tradeoff	73
Figure 4-3	Product Development and Organization Functions	74
Figure 4-4	Phases Effort Contribution to Reducing Ignorance	77
Figure 4-5	Learning Curve for R&D Stage of SOFC Production	81
Figure 4-6	The Systems View: the NPD System Engineering Process and Major Milestones.	84
Figure 5-1	Technology Adoption Life Cycle	98
Figure 5-2	Framework for Functional Configuration Identification (Main and 1 st Level)	101
Figure 5-3	Form Modest to McMansion (The Average Square Footage of a New Single-Family Home	116
Figure 5-4	The Average Size of a New Home by Region: 2005	116
Figure 5-5	Algorithm for Evaluation Design Alternatives	119
Figure 5-6	Decision Design Diagram Based on the Criteria of Power Production	125
Figure 5-7	Decision Design Diagram Based on the Criteria of Thermal Energy Production.	127
Figure 5-8	2kW SOFC Power System Simulation Model	129
Figure 5-9	Combustion Systems for Solid Fuels	132
Figure 5-10	CAD Drawing of Crankshaft and Pistons	132
Figure 5-11	A Stationary Boiler	133
Figure 6-1	The Top-Down Design	137
Figure 6-2	The First Level System Breakdown of a SOFC Power System	138
Figure 6-3	The Integration of Many Components	140

Figure 6-4	The System Breakdown of a SOFC Power System	141
Figure 6-5	Different Paths of Electricity Generation from Hydrocarbon-Based Solic Liquid, and Gaseous Fuels	d, 146
Figure 6-6	The Anode Leg of a SOFC Power System	148
Figure 6-7	The Desulphurization Unit	149
Figure 6-8	Water Management System	150
Figure 6-9	Gas Transfer to the Anode Side of the Cell Stack	151
Figure 6-10	The Hierarchical Structure of the Fuel Processing Subsystem	151
Figure 6-11	The Inputs/Outputs and Interactions of the Fuel Processing System	153
Figure 6-12	Representative Fuel Processing Steps & Temperatures	153
Figure 6-13	The Cathode Leg of a SOFC Power System	157
Figure 6-14	Filtration Section of the Air Subsystem	158
Figure 6-15	The Oxidant Producer for Cell Stack's Cathode Portion	158
Figure 6-16	The Return Section of the Air Subsystem	160
Figure 6-17	A Representation of Sustainability Showing How Both Economy and Society are Constrained by Environmental Limits (2003)	161
Figure 6-18	The Hierarchical Structure of the Air Subsystem	163
Figure 6-19	The Inputs/Outputs and Interactions of the Air Subsystem	165
Figure 6-20	The Different Types of Compressors	166
Figure 6-21	The Conceptual Output Leg of a SOFC Power System	168
Figure 6-22	A Concise Conceptual Block Diagram of a Fuel Cell Power System	169
Figure 6-23	The Electrical Pathways of the Generic SOFC Power System	170
Figure 6-24	Typical Fuel Cell Voltage/Current Characteristics	171
Figure 6-25	The Hierarchical Structure of the Electrical System	176

Figure 6-26	Concrete and Abstract Pathways of the Thermal Management System of a Generic SOFC Power System	. 184
Figure 6-27	A Flat Plate Heat Exchange	. 186
Figure 6-28	Halinen's SOFC Demonstration Unit	. 190
Figure 6-29	Schematic Cross-Section of the Solid-Oxide Fuel Cell Hot Assembly	. 192
Figure 6-30	Some Different Types of Compressors	. 194
Figure 6-31	Symbol Used for Compressors	. 195
Figure 6-32	Performance Chart for a Typical Lysholm or Screw Compressor	.200
Figure 6-33	Diagram of a Simple Ejector Circulation Pump	. 202
Figure 6-34	The Different Fuel Cell Types of Reactions	. 205
Figure 6-35	A Honeycomb-Type Cathode Supported SOFC	.205
Figure 6-36	The Chemical Reaction of an SOFC	207
Figure 6-37	The Cell Stack Configuration	. 209
Figure 6-38	(a) Schematic Diagram of a Fuel Cell; (b) Scheme of the Connection of Anode of a Single Fuel Cell to the Cathode of the Subsequent Single Fuel Cell, Constituting a SOFC Cell Stack.	.210
Figure 6-39	Shown in the Picture are the Interconnect (Center) with Seal (underneath) Of a Planar SOFC Stack	. 210
Figure 6-40	The SOFC Assumed Mechanisms	. 212
Figure 6-41	The Hierarchical Structure of the Cell Stack	. 215
Figure 6-42	The Cell Stack of an SOFC Power	. 220
Figure 7-1	The Basic System Requirements, Evaluation and Review Process	223
Figure 7-2	Stages of System Evaluation During the Life Cycle	. 227
Figure 7-3	Reliability and Maintainability Design	.236
Figure 7-4	The Systems Engineering Feedback Process	.238

Figure 7-5	A Hypothetical Maintenance Plan for an SOFC Developer	243
Figure 8-1	The Concepts and Steps for Fuel Processing of Gaseous, Liquid and Solid Fuels for High-Temperature and Low-Temperature Fuel Cell Applications	l 259
Figure 8-2	External Reforming and Internal Reforming MCFC System Comparison.	261
Figure 8-3	The Concept of an SOFC Power System Using an External Reformer	262
Figure 8-4	Carbon Deposition Mapping of Methane (CH4)	267
Figure 8-5	Carbon Deposition Mapping of Octane (C8H18)	. 267
Figure 8-6	Process Sensitivity of Stream/Carbon Ratios	. 269
Figure 8-7	Comparison of Impedance Spectra for an Electrolyte-Supported Cell	272
Figure 8-8	Diagram of a Tray-Type Boiler Feed Water Deaerator	279
Figure 8-9	A Diagram of an Embrittlement Detector	. 285
Figure 8-10	Generic Potential Energy Diagram Showing the Effect of a Catalyst	. 290
Figure 8-11	Raschig Rings One Inch (25mm) Ceramic	. 292
Figure 8-12	A Diagram of a Fluidized Bed	. 297
Figure 8-13	Fuel Gas Reformer Assemblage	. 299
Figure 8-14	Equilibrium Conversion of Methane Steam Reforming (H2O/CH4=3.0)	. 301
Figure 8-15	Energy Required for Steam Reforming of 1 Mol Methane When the Reformate Reaches Equilibrium at the Outlet Temperature	302
Figure 8-16	Examples of Catalyst Substrates	303
Figure 9-1	PCU Cost Per kW	316
Figure 9-2	The Block Diagram of the SOFC Power Plant featuring a SECA DC/DC Converter.	317
Figure 9-3	Circuit Diagram of the Proposed V6 Converter	. 318
Figure 9-4	Graph Summarizing Some Data from a 250-kW Fuel Cell Used to Power a Bus	319

Figure 9-5	Key Data for the Main Types of Electronic Switches Used in Modern Power Electronic Equipment	320
Figure 9-6	Two Power MOSFETs in the Surface-Mount Package D2PAK	321
Figure 9-7	Cross Section of a Typical IGBT Showing Internal Connection of MOSFET and Bipolar Device	321
Figure 9-8	Symbol Used for an Electronically Operated Switch	. 322
Figure 9-9	Circuit Diagram Showing the Operation of a Switch Mode Step-Down Regulator	323
Figure 9-10	Currents in the Step-Down Switch Mode Regulator Circuit	324
Figure 9-11	Linear Regulator Circuit	325
Figure 9-12	Circuit Diagram to Show the Operation of a Switch Mode Boost Regulator	326
Figure 9-13	Boost Converter Circuitry	. 328
Figure 9-14	Voltage Versus Current for a Fuel Cell With a Step-Up Chopper Circuit	. 330
Figure 9-15	Typical Fuel Cell, DC/DC Converter and Inverter Arrangement	. 330
Figure 9-16	H-Bridge Inverter Circuit for Producing Single-Phase Alternating Current	t. 331
Figure 9-17	Current/Time Graph for a Square-Wave Switched Single-Phased Inverter	332
Figure 9-18	Pulse-Width Modulation Switching Sequence for Producing an Approximately Sinusoidal Alternating Current from the Circuit of Figure 16	335
Figure 9-19	Typical Voltage/Time Graph for a Pulse-Modulated Inverter	336
Figure 9-20	Typical Voltage/Time Waveforms When Using the Tolerance Band Pulse Inverter Technique	e 336
Figure 9-21	Three-Phase Inverter Circuit	. 339
Figure 9-22	Switching Pattern to Generate Three-Phase Alternating Current	339
Figure 9-23	Current/Time Graphs for the Simple Three-Phase AC Generation System Shown in Figure 17, Assuming a Resistive Load	340

Figure 9-24	Power Conditioning Unit Circuit Topology	340
Figure 9-25	An Example of the I-V Characteristics of a Fuel Cell	342
Figure 9-26	The Fuel Cell Stack Voltage Under Loaded Condition as a Function Of Losses	342
Figure 9-27	I-V Characteristic Curve of a 2 Stack Fuel Cell	343
Figure 9-28	Voltage and Current Out of Phase	352
Figure 9-29	Power/Time Graphs for Two Different Systems Suite to a Hybrid Fuel Cell/Battery Power Supply	354
Figure 9-30	Simple Fuel Cell/Battery Hybrid System	355
Figure 10-1	The Generic SOFC Power System Model	363
Figure 10-2	A Co-Generative Brayton Cycle SOFC Power System	. 371
Figure 10-3	Heat Exchanger in a Steam Power Station Contaminated With Macrofouling.	373
Figure 10-4	The Three Major Configurations of Recuperators	383
Figure 10-5	Example of a Compact Plate-Fin Ceramic Recuperator (Allied Signal)	384
Figure 10-6	High-Temperature Electrolysis	386
Figure 10-7	Simplified Layout of an Atmospheric High Temperature Fuel Cell-Gas Turbine Hybrid System	388
Figure 10-8	Fuel Cell Efficiency, System Efficiency and Operating Temperatures Versus HTHE Effectiveness (atmospheric system)	390
Figure 10-9	Monolithic Honeycomb Regenerator and Dimensions of Solid Material and Flow Path	390
Figure 10-10	I-Type Manifold Assembly	393
Figure 10-11	A Tubular SOFC	397
Figure 10-12	A Planer SOFC	397
Figure 10-13	A Fluorite Structure Model	402

Figure 10-14	Fluorite Structure	. 404
Figure 10-15	Phase Diagram of YSZ	407
Figure 10-16	The Conductivity of YSZ	410
Figure 10-17	Thermal Expansion Behavior of Planar SOFC Components	413
Figure 10-18	A Tape Casting Set Up	416
Figure 10-19	Cerium (IV) Oxide (Powder)	418
Figure 10-20	Cerium (IV) Oxide Structure	419
Figure 10-21	Perovskite ABO ₃ CRYSTAL UNIT CELL	. 422
Figure 10-22	Hexis Fuel Cell Stack and Its Basic Principle	426
Figure 10-23	An SOFC Cell Stack	427
Figure 10-24	Distribution of Maximum In-Plane Principal Stress in Glass-Ceramic Sealants at RT.	430
Figure 11-1	The First Level System Breakdown of an SOFC Power System	442
Figure 11-2	The IORC Process	444
Figure 11-3	IORC Process of the Power System's Subsystems	. 445
Figure 11-4	Examples of the Primary Design Questions for the Unit Cell/Cell Stack Package and the BOP Subsystems Baselines	. 450
Figure 11-5	Why Use a Model?	454
Figure 11-6	From the General 0D Model of the FC Power system Five Specific Models Are Created	. 455
Figure 11-7	Block Diagram of a Combined Heat and Power SOFC System	459
Figure 11-8	The Theoretical Losses of Cell Performance	461
Figure 11-9	Cell Performance (Chemical Potential and Internal Losses)	462
Figure 11-10	Example of a Tafel Plot	464

Figure 11-11	The Electrical Potential of the Fuel Cell Depends on Fuel Type & Dilution	465
Figure 11-12	Fuel Utilizations as a Function of Cell Voltage and Operating Temperature.	466
Figure 11-13	The Relationship Between Power and Cell Voltage	466
Figure 11-14	Activation Over-Potentials	471
Figure 11-15	Anodic Gas Composition Varying Pre-Reforming Degree	480
Figure 11-16	Anodic Gas Composition Varying Anode Recirculation	481
Figure 11-17	S/C Varying Different Parameters	482
Figure 11-18	Current Density Trend vs. Different Parameters	483
Figure 11-19	Single Cell Voltage vs. Different Parameters	484
Figure 11-20	Cell Power vs. Different Parameters	485
Figure 11-21	Auxiliaries Consumption vs. Different Parameters	486
Figure 11-22	Electrical Efficiency vs. Different Parameters	486
Figure 11-23	Cathodic Flow Varying Different Parameters	487
Figure 11-24	Thermal Efficiency vs. Different Parameters	489
Figure 11-25	Global Efficiency vs. Different Parameters	490
Figure 11-26	Electrical Efficiency vs. Different Parameters	491
Figure 11-27	Electrical Efficiency vs. Uf for Different AR	492
Figure 11-28	Thermal Efficiency vs. Uf (Single Step) for Different AR	492
Figure 11-29	Electrical Efficiency vs. Uf for Different % Pre-Reforming	493
Figure 11-30	Thermal Efficiency vs. Uf for Different % Pre-Reforming	494
Figure 12-1	A DSM Example	499
Figure 12-2	DSM Taxonomy	513

Figure 12-3	Examples of Transfers Via Different Interconnections	514
Figure 12-4	DSM – Physical Connection	515
Figure 12-5	DSM – Examples of Physical Connection	515
Figure 12-6	DSM – Mass Flow	516
Figure 12-7	DSM – Energy Flow5	516
Figure 12-8	DSM – Energy Flow (Continue)	517
Figure 12-9	DSM – Information Flow	518
Figure 12-10	DSM – Information Flow	518
Figure 12-11	Block Diagram (left) and DSM (right) of a Simple System	519
Figure 12-12	Simple Taxonomy of System Elements Interactions5	520
Figure 12-13	Example of a Spatial Interaction Quantification Scheme5	520
Figure 12-14	The Anode Leg of the SOFC Power System	521
Figure 13-1	Concept and Technology Development	526
Figure 13-2	Sample Specification Tree (Partial) 5	529
Figure 13-3	The Bottom-Up Design Approach Cycle5	531
Figure 13-4	The Top-Down/Bottom-Up System Development Process	535
Figure 13-5	Hawke's Simplified SOFC CHP Power System5	536
Figure 13-6	Combined Stack and DC-AC Inverter Electrical Efficiency vs. Load Factor	538
Figure 13-7	Equivalent Annual Cost (EAC) of Meeting Energy Demand5	543
Figure 13-8	EAC of Meeting Energy Demands in a Small Dwelling	545
Figure 13-9	EAC of Meeting Energy Demands in a Average Dwelling	546
Figure 13-10	EAC of Meeting Energy Demands in a Average Dwelling Sensitivity of SOFC Lifetime	547

Figure 13-11	The Equivalent Annual Cost of Meeting Energy Demand in a Small Dwelling vs. Stack Capacity	549
Figure 13-12	The Equivalent Annual Cost of Meeting Energy Demand in a Small Dwelling vs. Installed SOFC Stack Capacity	549
Figure 13-13	EAC of Meeting Energy Demand in a Large Dwelling vs. Installed SOFC Stack Capacity	550
Figure 13-14	EAC of Meeting Energy Demand in a Small Dwelling vs. Installed SOFC Stack Capacity.	551
Figure 13-15	EAC of Meeting Energy Demand in an Average Dwelling vs. Installed SOFC Stack Capacity	552
Figure 13-16	EAC of Meeting Energy Demand in a Large Dwelling vs. Installed SOFC Stack Capacity	552
Figure 13-17	EAC of Meeting Energy Demand in a Small Dwelling vs. Installed SOFC Stack Capacity.	553
Figure 13-18	EAC of Meeting Energy Demand in an Average Dwelling vs. Installed SOFC Stack Capacity	554
Figure 13-19	EAC of Meeting Energy Demand in a Large Dwelling vs. Installed SOFC Stack Capacity	554
Figure 14-1	The Pontiac Fiero Design Concept: Excitement for the 1980's	558
Figure 14-2	Example of a Schematic Diagram of the Planar SOFC Design	561
Figure 14-3	Active Area of a Fuel Cell	562
Figure 14-4	The Effect of Cell Voltage on Cost of Electricity and System Efficiency	563
Figure 14-5	There is a Long and Expanding Set of Materials that are Being Developed For Fuel-Cell Applications	564
Figure 14-6	Types of Supported Unit Cell Configurations	570
Figure 14-7	Micrograph of a Planar Cell on Porous Metal Structure	.570
Figure 14-8	Tubular SOFC Design	571
Figure 14-9	Details of a Tubular Unit Cell	571

Figure 14-10	Cross-Section of a Tubular Unit Cell	571
Figure 14-11	The Flow Paths of a Tubular Design	572
Figure 14-12	Cell Geometry and Unit Element Configuration	575
Figure 14-13	SOFC Stack, the Air and Fuel Side Interconnectors	582
Figure 14-14	a) A Tube Showing the Imaginary Lamina, b) A Cross Section of the Tub Shows the Lamina Moving at Different Speeds	e 584
Figure 15-1	Analytical Planning is the Defender of a Reputation	. 588
Figure 15-2	Royal Air Force Merlin HC3, 2008	. 590
Figure 15-3	The Change Prediction Method	599
Figure 15-4	Design Structure Matrix for a Camera	601
Figure 15-5	Direct and Indirect Dependencies	. 604
Figure 15-6	And/Or Summation for a Propagation Tree	605
Figure 15-7	The Combining Impact, Weighted by Probability	606
Figure 15-8	The CPM Model	. 607
Figure 15-9	A Graphical Product Risk Matrix	608
Figure 15-10	Risk Graph	610
Figure 16-1	The Value of Information	. 613
Figure 16-2	Relative Scale to Compare Apples to Bananas	617
Figure 16-3	The Banana is Favored More than the Apple	. 618
Figure 16-4	Three Fruits Compared	618
Figure 16-5	Three Fruits Rated	619
Figure 16-6	A Generic Hierarchy Consisting of Two Levels	627
Figure 16-7	APH Example – The Selection of Fuel Processing Technology	. 631
Figure 16-8	An Air Blower	. 635

Figure 17-1	Warranty Policies Balance Between Protecting Manufacturers and the End Users	643
Figure 17-2	The Interrelationship of System Engineering Practices	. 645
Figure 17-3	Typical Project/Product Development Management Budget Cycle	650
Figure 17-4	A Typical Project/Product Development Management Budget Cycle	651
Figure 17-5	The Relationships of East of Design Change, Knowledge Building, and Costs Incurred.	656
Figure 17-6	Relationship Between Lifecycle Costs and Design and Development Feedback	659
Figure 17-7	Orson Wells Selling Gallo Wine	.663
Figure 17-8	A Glass of Fine White Wine	.663
Figure 17-9	Technology Validation or Lack of – It is a Barrier to Commercialization	. 665
Figure 17-10	The Integration of "Teamwork" Towards a Common Goal	669
Figure 17-11	Humorous Representation of System Engineering Dealing with a Difficult Situation and the Consequences in Pursuit for Quality, Reliability and Functionality in NPD.	. 672
Figure 18-1	Process Flow Chart	685
Figure 18-2	The Pictorial Representation of the Modular Groups of the SOFC Power System	691
Figure 18-3	The Elements of Focus for the Modules of the Thermal Management System	. 692
Figure 18-4	Modular Characteristic Attributes of the Thermal Management System	693
Figure 18-5	Block Diagram for DC-DC Converter Control (Gopinath's (et al) Design).	696
Figure 18-6	Schematic of the Gopinath's (et al) Fuel Cell Inverter System Design	698
Figure 18-7	Example of Schematics Ready for Schematic Capture Editor	698
Figure 18-8	Bill of Materials for DC/DC Converter, Bulk Capacitors and its Associated Control & Protection Circuitry	.700

Figure 18-9	Bill of Materials for DC/AC Inverter, Output Filter and its Associated Control & Protection Circuitry	701
Figure 18-10	Bill of Materials for Digital Signal Processor (DSP) Control Board	702
Figure 18-11	Photograph of the Packaged Gopinath's (et al) Fuel Cell Inverter	702
Figure 18-12	Experimental Results of the TAMU Fuel Cell Invert System	703
Figure 18-13	Cost Estimates for the DC-DC Converter Subsystem Costs	704
Figure 18-14	Cost Estimates for DC-AC Inverter Subsystem Costs	705
Figure 19-1	A Conceptual Relationship of "DF's"	709
Figure 19-2	Seven Steps for Developing a DFX Tool Using the DFX Shell	717
Figure 19-3	Product Bills of Materials	722
Figure 19-4	Sample Screen of Flow Process Charts	723
Figure 19-5	Sample Screen of Operation Process Charts	724
Figure 19-6	Integrating Manufacturing into the Design Process	730
Figure 19-7	Closing the Knowledge Information Design Loop	732
Figure 19-8	Mechatronic Environments	733
Figure 19-9	Mechatronic Systems	734
Figure 20-1	Lifecycle Energy Analysis (LEA)	740
Figure 22-1	NPD Planning is Very Much Like Playing (Strategizing) a Game of Chess.	755
Figure 22-2	The NPD System Engineering Process and Milestones - Revisited	757
Figure 22-3	Management Faced with Total Cost Visibility	758
Figure 22-4	The First Four Phases of NPD Lifecycle	760
Figure 22-5	Formulation of Multi-Specialty Project Teams for NPD	762
Figure 22-6	Testing Plan for the NPD Lifecycle	763

Figure 23-1	Concept of Heaven	.794
Figure A-1	Internal Combustion Engine vs. the Advantages of Fuel Cells	841
Figure A-2	The Cost Savings of a CHP	843

CHAPTER I

THE PURPOSE AND THE OUTLINE OF THE THESIS

1.1 Introduction

Since the beginning of mankind, all societies have harvested energy, depending on carbon based sources to meet their energy needs. In the last onehundred years many more energy sources have sprang up, progressing along their technology S-curves.

Modern non-renewal energy sources have contributed to more and more pollution and, in response have led to the appearance of renewal sources such as solar, wind power and fuel cell development, leading to economic, social, and technical changes.

One of the major, new sources of environmentally friendly energy production is the fuel cell which has been evolving over the last one-hundred years with its importance increasing over the last ten to twenty. Because of the fuel cell's newness and sophistication no extensive knowledge base reference model exists to offer competitive commercialization to entrepreneur's of fuel cell power systems who are struggling to get their product to the market place.

1.2 The Thesis' Focus and Organization

This thesis sets out to address building a reference model for guiding the commercialization process for fuel cell power systems. Because of the Fuel Cell (FC) Power System's complexity and product development immaturity, there exist three major problems plaguing the fuel cell industry, namely:

- Fuel cell developers lack a systems engineering approach to their New Product Development (NPD) effort.
- The Systems and other needed experienced engineers from other related technical disciplines and backgrounds lack the technical background and knowledge of the SOFC technologies in order to sufficiently, quickly aid FC developers with their new product developments.
- SOFC technology, being innovative, does not have an established, predictable lifecycle development 'game' model.

This thesis sets out to address these problems by:

 Providing the reader with an example of a Systems Hierarchy Model of an SOFC Power System. It's the subject of this study and will give those who are familiar with Solid Oxide Fuel Cell (SOFC) Technology a chance to learn systems engineering practices.

- Introducing a 6-phase New Product Development Lifecycle Reference Model and, to define the activities of the first two phase of an SOFC Power System's lifecycle.
- Drawing an overall picture of the technical, other challenges and barriers SOFC developers face so that the reader could understand what's involved in commercializing an SOFC Power System.
- 4. Introducing a set of systems engineering tools, and to demonstrate how they can aid the fuel cell development process by applying them to the first two phases.

1.3 The Breakdown of the Thesis

This thesis presents and details out a six-phase NDP Reference Model Template through and in the next twenty-two chapters. Chapter 2 presents the technology changes and the history of energy sources. Chapter 3 introduces the history of fuel cell technology development in the last one-hundred years to the present. Chapter 4 introduces the six-phase process and lifecycle model. In Chapter 5 to 12, the major activities of the Conceptual Design and Advance Planning Phase are covered. Chapter 5 gives the overview of the Conceptual Design and Advance Planning Phase.

Chapter 6 gives the description of the systems hierarchy architecture of a SOFC Power System. Chapter 7 introduces the topics of reliability, quality engineering, and maintenance. Chapters 8, 9, and 10 are dedicated to describing the Operational Requirements and Technology Baselines of the SOFC Power System. Chapter 11 covers feasibility analysis. Design Structure Matrix (DSM) is introduced in Chapter 12.

The Preliminary Systems Design Phase (the second phase) is addresses in detail in Chapters 13 to 21. Chapter 13 introduces the Preliminary Systems Design Phase.

The design decisions for the Unit Cell, the Cell Stack Package are contained in Chapter 14. Chapter 15 discusses Change manage in power system design. Chapter 16 covers the Analytical Hierarchy Process (AHP). Chapter 17 picks up the topics that were introduced in Chapter 7 and explains the important philosophical considerations involved in the reliability, quality engineering, and maintenance development of SOFC Power Systems. Chapter 18 discusses design modularity for power system designs. Chapter 19 covers the topic of Design for 'X' (DFX) practices. Chapter 20 introduces life-cycle energy analysis. Chapter 21 discusses strategic partnerships.

Chapter 22 defines the last four stages of the modernized NIST/NSPE Reference Model.

CHAPTER II

INTRODUCTION

2.1 The History of Energy Sources and Technology Change

The importance of this thesis has to do with the fact that over one-hundred years has passed since Sir Davy's first electrochemical experiments were performed, and roughly, fifty-one years has passed since Allis-Chalmers Manufacturing Company demonstrated a tractor driven by 15 kW_e, low-temperature, low-pressure hydrogen-oxygen fuel cells. It can be said that fuel cells hold immense promise in providing clean energy solutions, and with the untested successful commercialization of Bloom Energy Servers notwithstanding, the most current technologies are not yet ready for commercial use. Commercial readiness means that a system must be durable and have an operational lifetime that at least matches other power generation devices in the same power range. The sentiment regarding the fuel cell industry's inability to reach large scale success at commercialization was captured by Richard T. Stuebi of The Cleveland Foundation when he wrote on March 12, 2007:

'We all know that fuel cell technologies hold extraordinary promise for highlyefficient, low-emission energy production – far better than what many of today's power generation technologies can offer now or are likely to offer in the future. Alas, that promise is currently only that: a promise. The number of real-world installations of stationary fuel cells for power generation is very small. The basic reason for this is easy to understand: stationary fuel cells have yet to achieve the economic and proven performance thresholds that customers require. It does not mean that these thresholds cannot be attained; they just haven't been attained yet.'

2.2 The Energy Technology S-Curve

Energy is a quantity which defines '*work*'. There are many different forms of energy. All human societies need energy and energy use has a historical basis because human cultures are geared towards energy harvesting.

Before the topic of energy's history can be expanded upon, it must be mentioned that each source of energy has its own sub-S-Curve. In relation to technology management, the S-curve is represented as the variation of performance in function of the time or effort to develop a technology. The S-Curve illustrates the introduction, growth and maturation of innovations as well as the technological cycles that most industries experience, including the energy industries, as depicted in **Figure 2-1**.

In the early stage of the S-Curve, large amounts of money, effort and other resources are expended on the new technology, but small performance improvements are observed. Then, as the knowledge about the technology accumulates, progress becomes more rapid. As soon as major technical obstacles are overcome and the innovation reaches a certain adoption level, exponential growth will occur.



Figure 2-1: The S-Curve Lifecycle Stages [Keys, 2010]

During the mature phase, relatively small increments of effort and resources will result in large performance gains. Finally, as the technology starts to approach its physical limit, its decline and death are near, further pushing the performance becomes increasingly difficult.



Figure 2-2: The Energy Technology S-Curve [Keys, 2010]

Once a new technology is created, it creates a discontinuity for the old technology generation. As a result, a new innovation creates a new S-curve, which is shifted to the right of the original one; see new generation in **Figure 2-2**. As the history of energy is explored, arbitrary points in time will be selected in order to denote the beginnings and sometimes (if applicable) the ends of the S-Curves for the various energy technologies.

2.3 Non-renewable Energy Source – Wood

Mankind's first energy source was most likely wood. For example, timber was the energy source used by the ancient Roman Empire. At some point during the empire's life span, the supply of wood peaked and, then declined causing the Roman Empire to reach out into Northern Europe for wood. Unfortunately for the Roman Empire, it never succeeded in conquering the areas east of the Rhine and so it had to turn elsewhere for timber, in particular, the Mediterranean. The Rome Empire experienced the consequences of deforestation, which led to soil erosion. It's debatable, whether or not, the depletion of timber, without a main alternative energy source replacement, was one contributing factor which caused the Empire to fall.

2.4 Non-renewable Energy Source – Coal as a Fuel

In ancient China, wood shortages appeared in the 13th century. However, the Chinese technological S-Curve for the use of coal as a fuel began by the 4th century AD, but the extensive use and advances in coal technology did not occur until the eleventh century. Meanwhile in Western civilization, there is no evidence that coal was of great importance in Britain before the High Middle Ages, after about 10th century AD. In 1257-59 AD, Western Civilization's S-Curve for coal began when Newcastle coal was shipped to London for the smiths and lime-burners building of the Westminster Abbey. From that time on to modern times, the S-Curve for coal technology, for the West still continues. In 2006, the world's coal consumption was about 6,743,786,000 short tons, resulting in two unwanted byproducts of coal usage, strip mining erosion and carbon production pollution. The effects of soil erosion and pollution to our environment may produce a rapid discontinuity for this energy technology, especially if a renewable, inexpensive source is found or developed.

2.5 Non-renewable Energy Source – Whale Oil

Two energy sub-S-Curves can be measured in the production of whale oil and crude oil. Prior to the 18th century, few sperm whales were hunted for their oil. But after the 18th century whale oil was used for lamp oil, as well as a variety of commercial applications. Since oil from whales was becoming scarce as the giant mammals were hunted almost to extinction, oil producers began to look elsewhere to extract oil. By the 1850s, crude oil was still obtained by skimming it off the tops of ponds.

2.6 Non-renewable Energy Source – Crude Oil

The United States' S-Curve for crude petroleum began when the first oil well was drilled in 1859. By the 1920s, oil fields had been established in many countries including Canada, Poland, Sweden, Ukraine, the United States, and Venezuela. In 1922, commercial use of petroleum-based diesel fuels began with the development of a diesel injection pump. In 1947, the Superior Oil Company constructed the first offshore oil platform off the Gulf Coast of Louisiana and the petroleum industry took off. In the first quarter of the 20th century, the United States overtook Russia as the world's largest oil producer.

After World War II ended, the countries of the Middle East took the lead in oil production from the United States. In modern times, some petroleum industry operations have been responsible for water pollution through by-products of refining and oil spills.

The combustion of fossil fuels produces greenhouse gases and other air pollutants. These environmental problems have nations, environmental activist groups at odds with the petroleum industry. To make matters worse, petroleum is a non-renewable natural resource and the industry is faced with an inevitable eventual depletion of the world's oil supply. The petroleum sub-S-Curve may soon face a discontinuity.

The BP Statistical Review of World Energy 2007 lists the reserve/production ratio for proven resources worldwide. The study placed the prospective life span of proven oil reserves in the Middle East at 79.5 years, Latin America at 41.2 years and North America at only 12 years.

2.7 Non-renewable Energy Source – Natural Gas

The next energy source to be considered is natural gas. The history of natural gas production begins in antiquity. The first discoveries of natural gas seeps were made in Iran between BC 6000 and 2000 BC. In America it was known to the Indians, who observed it oozing from the ground in various places, chiefly along the western side of the Appalachian Highlands.

The technological S-Curve for natural gas, that is known today, began during World War II with the invention of a technology that converted stranded natural gas into synthetic gasoline, diesel or jet fuel through the Fischer-Tropsch process. Since World War II, the technological S-Curve for natural gas has matured from that turbulent time in human history. Notwithstanding delays or other commercial barriers, it only makes sense that the innovators of the world need to develop a new generation of technology before the world run out of natural gas and crude oil. In 2006, the world's largest proven natural gas reserves are located in Russia, with $4.757 \times 1013 \text{ m}^3$ (1.6 × 1015 cubic feet). Russia is also the world's largest natural gas producer, through the Gazprom Company. As with oil, natural gas supplies are not infinite. '*Peak Gas'* is the point in time at which the maximum global natural gas production rate is reached, after which the rate of production enters its terminal decline. US gas production reached its peak in 1973 at about 24.1 trillion cubic feet. Bentley (el al), who wrote in 2002's Energy Policy, predicted a world "*decline in conventional gas production from about 2020*".

2.8 Non-renewable Energy Source – Nuclear Energy

As the world sustains its energy needs with natural gas and crude oil, another S-Curve was being created. The pursuit of nuclear energy for electricity generation began soon after the discovery in the early 20th century that radioactive elements released immense amounts of energy, according to the principle of mass–energy equivalence.

In the United States, where Enrico Fermi, the Italian physicist and Leo Szilard, the Austro-Hungarian physicist had both emigrated, this led to the creation of the first man-made reactor, known as Chicago Pile-1, which achieved criticality on December 2, 1942. This work became part of the Manhattan Project, which built large reactors at the Hanford Site (formerly the town of Hanford, Washington) to develop plutonium for use in the first nuclear weapons, which were used on the cities of Hiroshima and Nagasaki.

Work in nuclear studies continued in the United States, United Kingdom, Canada, and USSR and preceded over the course of the late 1940s and early 1950s. Electricity

was generated for the first time by a nuclear reactor on December 20, 1951, at the EBR-I experimental station near Arco, Idaho, which initially produced about 100 kW. The world's first commercial nuclear power station, Calder Hall in Sellafield, England was opened in 1956 with an initial capacity of 50 MW (later 200 MW).

Nuclear waste is an enormously difficult political problem which to date no country has solved. It is, in a sense, the Achilles heel of the nuclear industry and, perhaps within this century, the S-Curve of nuclear power could be its discontinuity. Around 1970 and again in 1990, more than 50 GW of capacity was under construction (peaking at over 150 GW in the late 1970s and early 1980s — in 2005, around 25 GW of new capacity was planned. With all its advancement, nuclear power could be ahead of its time. Acording to a 2007 story broadcast on *60 Minutes*, France has stocked containers of waste because their scientists don't know how to reduce or eliminate the toxicity, but it is speculated that maybe in 100 years perhaps scientists will.

2.9 Renewable Energy Sources are needed

As was shown by these examples, the by-products of non-renewable energy sources have caused human societies environmental issues. The criteria for the solutions to the environmental problems must provide the means to clean up the legacies caused by the major non-renewable energy sources of the present -- coal, oil, natural gas and nuclear energy, promote the restoration of natural resources, and achieve the protection of human health. In addition, the solutions are future energy technologies that must allow for future growth, protect the environment, and maintain biodiversity. Perhaps the answers to environmental issues, the hopes of environment protection and, the

sustainable biodiversity are for different types of energy technologies; energy technologies that are renewable.

2.10 Types of Renewable Energy Sources

Renewable energy can be defined as energy which comes from natural resources, such as sunlight, wind, algaculture, and biomass, which are renewable (naturally replenished).

In 2008 about 19% of global final energy consumption came from renewables, with 13% coming from traditional biomass, which is mainly used for heating, and 3.2% from hydroelectricity. New renewables, small hydro, modern biomass, wind, solar, geothermal, and biofuel accounted for another 2.7% and are growing very rapidly. The share of renewables in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3% from new renewables. Solar thermal power stations operate in the United States (mostly in the west and southwest regions) and Spain. The largest solar thermal power station is the 354 megawatt (MW) SEGS power plant in the Mojave Desert.

2.11 Solar Power Systems

Solar water heating systems make an important contribution in many countries, most notably in China, which now has 70% of the global total (180 GWth). Most solar water heating systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50–60 million households in China. Worldwide, solar water heating systems meet a portion of the water heating needs of over 70 million households. Innovative research is being done to combine solar power and fuel cell technologies.

In a sense, the two distinct energy technologies S-Curves show promise in merging because when tied to solar power systems, fuel cells power systems use the hydrogen that is created when excess solar power is passed through an electrolyzer. The hydrogen can then be stored to power the fuel cell power system when the solar power platform is not generating enough energy to meet load demands.

2.12 Wind Farms

Areas where winds are stronger and more constant, such as offshore and at high altitude sites (the western prairies of the U.S.) are preferred locations for wind farms. Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand. However, this could require large amounts of land to be used for wind turbines, particularly in areas of higher wind resources in the U.S. Typically, wind turbines are found in the southwest and west. Offshore wind turbines experience mean wind speeds of ~90% greater than that of land, so offshore wind turbines could contribute substantially more energy.

2.13 Wind and Fuel Cell Technologies Combo

Fuel cell technologies are very flexible and adaptable in concert with wind power. In 2005, a study of coupling a wind-turbine with a fuel cell was conducted to improve the utilization of wind power in the non-interconnected Greek Archipelago Grid. A part of the energy produced by the wind-turbine was stored in the form of hydrogen and was then delivered to the consumption at constant power through a fuel cell power system. This decoupling between the wind potential and power delivery was necessary to increase the contribution of renewable energy sources to the small capacity grids of islands.

On the down side, electricity generated from wind power can be highly variable at several different timescales: from hour to hour, daily, and seasonally. Annual variation also exists, but is not as significant. Related to variability is the short-term (hourly or daily) predictability of wind plant output. Wind power forecasting methods are used, but predictability of wind plant output remains low for short-term operation making the coupling of a fuel cell/wind power hybrid system very desirable.

2.14 Biofuels

Biomass, a renewable energy source, is biological material from living, or recently living organisms, such as wood, waste, and alcohol fuels (ethanol, propanol, and butanol).

Although fossil fuels have their origin in ancient biomass, they are not considered biomass by the generally accepted definition because they contain carbon that has been "out" of the carbon cycle for a very long time.

There are a number of technological options available to make use of a wide variety of biomass types as a renewable energy source. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it to another form, such as liquid biofuel or combustible biogas. While for some classes of biomass resource there may be a number of usage options, for others there may be only one appropriate technology.

The Department of Energy's program National Renewable Energy Laboratory (NREL) sponsored a study to evaluate current gasifier technology for conversion of biomass to syngas. Many potential markets for biomass/biowaste fed fuel cell power systems appear attractive, the DOE-NREL reports stated.

First, it would be distributed power, where biomass is readily available. Examples are: logging operations, landfill gas, etc. The second would be auxiliary power using waste. Examples might be a large farm with confined animals, food processing waste or any waste process with a high value co-product. Solid feed (waste) to a gasifier followed by reformation and, then the fuel cell would be the most comprehensive technology to perform this function, since it could handle any feed. Coupling a digester to the front end to process biomass/biowaste slurries or biowaste would also be of great interest, the report concluded. Biomass, as an energy source, has remained a technology '*of great interest*' because the technology has been realized and the energy technology appears to be maturing readily.

The New Hope Power Partnership is the largest biomass power plant in North America. The 140 MW-facility uses sugar cane fiber (bagasse) and recycled urban wood as fuel to generate enough power for its large milling and refining operations as well as to supply renewable electricity for nearly 60,000 homes. The New Hope Power Partnership facility reduces dependence on oil by more than one million barrels per year. Also, by recycling sugar cane and wood waste, it preserves landfill space in the urban communities in Florida.

The down side to using a biomass energy source technology is that it produces air pollution in the form of carbon monoxide, nitrogen oxides, volatile organic compounds, particulates and other pollutants. In some cases the air pollution reaches levels above those found in traditional fuel sources such as coal or natural gas.

One possible solution to the air pollution caused by biomass may be the production of biochar, which is charcoal created by pyrolysis of biomass, and differs

from charcoal only in the sense that its primary use is not for fuel, but for biosequestration or atmospheric carbon capture and storage.

2.15 Algaculture

In a 1912 speech, Rudolf Diesel said, "the use of vegetable oils for engine fuels may seem insignificant today, but such oils may become, in the course of time, as important as petroleum and, the coal-tar products of the present time."

In his day and age, Rudolf Diesel could hardly imagine that common algae could become a fuel source, but today, fuel from algae holds promise. Algaculture is a form of aquaculture involving the farming of species of algae. Algae cost more per unit mass (as of 2010, food grade algae costs ~\$5000/tonne), due to high capital and operating costs, yet can theoretically yield between 10 and 100 times more energy per unit area than other second-generation biofuel crops.



Figure 2-3: Dr. Joanne M. Belovich of Cleveland State University [Belovich/Cleveland State University, 2010]

Dr. Joanne M. Belovich of Cleveland State University is doing research in this area. Her research of algae shows significant promise as a feedstock for biodiesel production, since up to 50% of the algae dry mass can be lipids, the precursor for biodiesel. Algae fuel yields have not yet been accurately determined, but DOE, is reported as saying that algae yield 30 times more energy per acre than land crops such as soybeans. Biodiesel could be an accelerant of the fuel cell industry. Fuel cells run off a hydrogen—and oxygen from the air, and can produce electricity as long as the hydrogen is flowing.

2.16 Hydrogen Production on the Spot

Patricia Irving, President, Chief Executive Officer and, Founder of Innovatek Inc. said, "Fuel cells operate differently than internal combustion engines and, therefore do not have those efficiency losses. Fueling the cells, however, remains problematic. Hydrogen must be stored at high pressure to be economical, and is explosive when released. Most hydrogen is also manufactured from natural gas, meaning that ultimately it's not a carbon-neutral fuel."

One way to solve the problem of transporting and storing hydrogen is to make it on the spot. The process for making hydrogen is fairly straightforward. A hydrocarbon is heated with steam at high pressure and temperature to form hydrogen and carbon dioxide, a process called steam reforming. Usually this is done in large production plants.

Innovatek has done just that by scaling a production plant down to something that is actually portable. Innovatek's device is called the InnovaGen fuel processor. It uses microscopic channels and proprietary catalysts to continuously produce hydrogen from a variety of hydrocarbon sources. "*Rather than natural gas, which is something we can also use, we have been focusing on liquid fuels,*" Irving says. "*That includes things like biodiesel, vegetable oil and other renewables.*"
2.17 A Few of the Accelerators of the SOFC Power System

From the works of Belovich and Irving, biodiesel could become the fuel of choice for fuel cell power systems. Fuel cell technology could change the world – many of its accelerators are in place (e.g. biodiesel, vegetable oil), but the innovative technology is still quiet few years away from commercialization on a large scale.

And, it is very difficult to tell which fuel cell developer(s) will enter and take the market, capturing the predominant market sector in the future. There are many problems to be solved in the SOFC Power System. If these challenges could be systematically solved or resolved, then SOFC will become the predominant fuel cell technology being developed in the future.

The use of systems engineering practices and principles could be the causation of this technology's bright future, its successful commercialization and its long product lifecycle.

2.18 The Engineering Stages of a System (Product) Lifecycle

One basic cycle that all organisms experience is the pattern of conception, birth, growth, maturity, senescence, and finally death [Blanchard, 2008]. Development of any manmade system (*such as a new product*) also follows a series of phases. A key feature of the systems approach is recognition of the logical order of thought and action that go into developing systems. The most logical general development of a system development cycle includes the phases of conception, definition, design and development, fabrication and testing, installation or launch, production, operation and maintenance, and, finally enhancement, replacement, or cancellation [Blanchard, 2008].

The definition of the stages of development for new products has been elucidated many times. Two decades ago, the National Institute of Standards and Technology and the National Society of Professional Engineers (NIST/NSPE) established a Task Group to provide a lifecycle phase model for new product development. The Task Group agreed early that engineering and business-related activities occur along parallel and often overlapping paths. Even though the group originally set out to define the engineering stages separate from business decisions, it became clear that attention must be given to certain business- related questions as the stages were defined.

There were various conceptions of the new product development process, none enjoying general acceptance and each varying in the activities included or emphasized. The lack of uniform, authoritative delineation and definition of the stages of new product development was seen as an impediment to communications in the industrial innovative process. The need assumed increasing importance as government and private efforts to accelerate the rate at which new technologies were applied in commercial products and processes were stepped up in order to help redress the loss of U.S. competitiveness. The definitions of engineering stages of development were intended to fulfill this need, insofar as providing engineering data and information are concerned.

The development status of a product weighs heavily in the assessment of its technical feasibility and commercial viability because uncertainty and risk vary as development advances. There is a clear need for criteria for establishing the stage of development and for a uniform standard describing the engineering work required to advance to the next stage. In addition, the ordering of the stages of development under well-defined formulations provides a basis for tracking the progress of projects and evaluating the

programs' effectiveness. The NIST/NSPE Task Group hoped that the definitions of the Engineering Stages of Development, therefore, would enable:

- Applicants to more effectively present data, facilitating evaluation of projects;
- Evaluators, project managers and consultants to better develop guidance on what engineering work needs to be done next;
- Reconstructing of the evaluation process to better consider risks and other criteria as they vary by stage of development;
- The investor, at the time a project is recommended, to document the project's stage of development in order to determine support requirements; and to better track the results of funding and other support of development efforts;
- The project leader to better support reporting and other management functions: statistics, outreach performance, etc.

2.19 The Proper Implementation of Systems Engineering

The NPD challenge is to be more effective and efficient in the development and acquisition of new systems (i.e., any time that there is a newly identified need and a new system requirement has been established), as well as in the operation and support of those systems already in use. This can be accomplished through the proper implementation of system engineering concepts, principles, and methods [Blanchard, 2008].



Figure 2-4: Adaption, Expansion and Modification of Blanchard's System Lifecycle Model [Blanchard, 2008]

As shown in **Figure 2-4**, the life cycle includes the entire spectrum of activity for a given system, commencing with the identification of need and extending through system design and development, production and/or construction, operational use and sustaining maintenance and support, and system retirement and material disposal. As the activities in each phase interact with the activities in other phases, it is essential to consider the overall life cycle in addressing system-level issues, particularly if one is to properly assess the risks associated with the decision-making process throughout [Blanchard, 2008].

Although the life-cycle phases conveyed in **Figure 2-4** reflect a more generic sequential approach, the specific activities (and the duration of each) may vary somewhat, depending on the nature, complexity, and purpose of the product's system. Needs may change, obsolescence may occur, and the levels of activity may be different, depending on the type of system and where it fits in the overall hierarchical structure of activities and events. In addition, the various phases of activity may overlap somewhat, as illustrated in the two examples presents in **Figure 2-5** [Blanchard, 2008].



Figure 2-5: Examples of System Lifecycles [Blanchard, 2008]

2.20 A Total Life-cycle Approach

A total life-cycle approach must be assumed in the decision-making process. The past is replete with examples in which major decision have been made in the early stages of system acquisition based on the "short-term" only. In other words, in the design and development of a new system, the consideration for production/construction, maintenance and support, and/or retirement and disposal for that system was inadequate [Blanchard, 2008]. These activities were considered later and, in many instances, the consequences of this "*after-the-fact*" approach were costly. Financial costs increase considerably as a product matures from concept to full-scale production. These increasing costs are suggested in **Table 2-1**.

Table 2-1						
THE COMPARATIVE EXPENDITURE ON A NEW PRODUCT						
[National Society of Professional Engineers, 1990]						
Stage of Development	Cost					
Conception	\$5,000					
	\$50,000					
Feasibility	(Depending on industry)					
Product/process development	20 x Cost of Feasibility					
Pilot production	20 x Cost of Development					
Full commercialization	Much More					

One of the main engineering challenges is to reduce technical risks as the product or process matures. New Product Development is a process of risk reduction. This is not to say that it is the sole function, but it is a necessary one. The new product matures from the Conceptual Stage with its concurrent high technical risk and small financial investment through to the large-scale production stage with reduced technical risk and a much larger financial requirement. **Table 2-1** makes it clear that identifying a new product as clearly as possible in its development can be critical to a financial investor, project-funding agency or a corporate manager.

2.21 The reasons Products fail and "what" can be done about it

Both serial and concurrent engineering approaches to new product development were addressed by the NIST/NSPE Task Group as the stages were defined. In either case the individual stages of development occur serially. In traditional product development, a serial approach is one in which both the engineering and business specialties contribute in a serial or linear fashion as illustrated in **Figure 2-6**. In fact, in many such instances the engineering specialist is brought on board at the proper time to complete only a single stage of development. His or her advice and consultation are often not called on either before or after that serial point in the stages of development. It is for this reason that many products fail.



Figure 2-6: The NIST/NSPE Task Group's version of the '*Traditional Serial Commercialization Model*' [National Society of Professional Engineers, 1990]

The dynamics of markets, technology, and competition have brought changes to virtually every market sector and have made new product development one of the most powerful business activities.

Being the first (the fastest) to get a robustly designed new product gains the leader the innovative edge in market sales, revenue, and profit growth and share. The monumental changes that constantly impact commerce have forced companies to innovate with increasing speed, efficiency, and quality. In turn, this has made new product development one of the most complex and difficult business functions (e.g. Apple and the iphone, ipod, etc).

The power of innovation is revealed in numerous studies, which show that companies leading their industries attribute about half of their revenues to products developed in the most recent five years. Product life cycles have become more complex hence the skills required for developing new products have increased in complexity. Therefore, fuel cell developers must embrace the view that the skills and expertise needed to develop their products are a much more persistent requirement for success. Instead of the mono-approach, in which technology or markets drive innovation, new product development now requires a convergence of technology, marketing, product design, engineering, and manufacturing capabilities wrapped into the systems engineering package of NPD. Speed, efficiency, and quality in product development are the challenges that new product development faces in today's intense competitive world as shown in **Figure 2-7**.



Figure 2-7: The Modernized Commercialization Model after the NIST/NSPE Task Group [Keys, 2010]

In the more modern simultaneous approach, the completion of each engineering stage of development is a composite of the achievements of several engineering and business specialties. For example, manufacturing and development/design might both be involved at the same time in completing the technical feasibility stage of development. This might be motivated by a desire for economy in the upcoming production stage of development. **Figure 2-8** is a more detailed representation of the interplay of several specialties toward the completion of a given stage and, eventually, through several stages, completion of the product itself.

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Conceptual	Technical Feasibility	Development	Commercial Validation & Production	Full Scale Production	Product/Logistics Support	Product Reuse/ Recycle- Death
Project Team	Project Team	Project Team	Preparation	Project Team	Project Team	Project Team
*Inventor Research engineer	*Research engineer Development engineer Marketing/ business Manufacturing engineer	*Development engineer Manufacturing engineer Test engineer Mktg/cost engineer	Project Team *Design engineer Test Engineer Manufaturing engineer Development engineer Buyer Q&A engineer Marketing	*Manufactur -ingengineer Q&A engineer Test engineer Construction engineer Process engineer Marketing Sales Product cost analyst Field service Buyer	*Customer service eng'r Marketing Sales Q&A Training Distributors Product extension /improvement Field service Supplies	*MFG Process Engineee Marketing Resale/Reuse Disposal Process Disassembly/ Scrap Reprocess into new product
				Supplies		

Figure 2-8: The Formulation of Multi-Specialty Project Team Designed to Accomplish Concurrent Engineering in the Phases [Keys, 2010]

The influence on the earlier stages may be made by scientific or engineering specialties, whereas in later stages more manufacturing and business specialties will be required Figure 2-9.





Figure 2-9: Influence of Specialties on Stages [Keys, 2010]

Today, it is common in larger companies to accomplish concurrent engineering by the formulation of a multi-specialty team. The smaller business or individual inventory should consider the need for independent consultant specialists even in the earlier stages. The NIST/NSPE Task Group recognized that the location of an affordable and qualified expert is often a challenge. Even though the NIST/NSPE Task Group recognized the simultaneous and possible overlap of activities in the stages, this does not detract from the logical serial ordering of the stages of development. It still holds that all activities should be addressed and satisfied before a stage is deemed to be complete. How an inventor weaves in and out of the stages and still satisfies their requirements is influenced to a great extent by the environment in which the development is carried out. The NIST/NSPE Task Group decided it was important and necessary at the beginning of each stage to describe the objective and resulting product of that stage and then proceed to

outline the engineering activities that need to be accomplished in order to complete a stage of development. At the end of each stage, the user should be able to check off significant engineering data and information required to satisfy completion of the stage.

It is readily accepted that fuel cell power systems performance and, customer requirements could be reached by the application of a systematic, modernized commercialization model of the NIST/NSPE Task Group, but only if fuel cell developers are willing to address performance and others issues (mostly systems engineering related) in a disciplined and time tested matter.

CHAPTER III

THE HISTORY OF FUEL CELLS, THEIR MATERIALS, THE GRID AND THE NEGAWATT

3.1 Introduction

The promise of fuel cell technology has captivated scientists for nearly two centuries. First as a fundamental materials concept, then as an enabling technology for manned space flight, and finally as a potential means of efficient energy conversion, fuel cells have held great promise but, have also faced mounting challenges. Large upfront capital requirements, uncertain cost of materials, lack of obvious market space, and regulatory hurdles have all conspired to inhibit development and adoption. However, given the ever increasing demands for electric power and the age and inherent inefficiencies of the existing generation and transmission systems, a future energy portfolio including fuel cells seems inevitable [Milliken, 2010].

3.2 From Davy's Experiments

More than 170 years of monumental, fuel cell research and development has transpired, yet, there has only been limited success at commercialization. Starting in 1800, Davy carried out many investigations into the electrolysis of water and aqueous solutions. Experiments using more and more concentrated solutions of alkali hydroxides led to melting flux electrolysis and in 1807 to the discovery of alkali metals. Davy observed that dried solid alkali compounds were nonconductors but became electrically conducting through just a little moisture. Needless to say, the principles of "electrolyte" were in the ways before the first fuel cell was invented [Mobius, 1997]

3.3 Faraday, Hittorf and Others

.

For Faraday it seemed to be an important law that many substances, electrically conducting in the liquid state, lost their conductivity during solidication [Mobius, 1997]



Figure 3-1: Faraday [Wikipedia, 2010] In his continuing investigations, Faraday introduced the basic terminology of electro-chemistry, and with the aid of many results concerning the concept "electrolyte" in 1834 he came to the classification of substances into first and second types of conductors [Mobius, 1997].

.



Figure 3-2: Hittorf [Wikipedia, 2010]

Hittorf (1851) devoted himself to this special problem and proved that Ag_2S is electrolytically decomposable. The generation of a counter voltage (polarization by chemical precipitation) during the passage of a current was recognized as a characteristic feature of electrolytic conductivity of solids and this led to the discovery of an increasing number of solid conductors of the second class [Mobius, 1997].

3.4 Cavendish

As early as 1774, Cavendish had observed an increase in the conductivity of glass on heating. The electrolytic nature of this conduction was discovered by Beetz and Buff in 1854. Using mercury, zinc amalgam, various solid metals, carbon, and pyrolusite (MnO₂) as electrodes, Buff demonstrated galvanic cells and batteries free of water "in which glass takes over the role of the moist conductor", and he investigated the associated voltage and polarizability [Mobius, 1997].



Figure 3-3: Cavendish [Wikipedia, 2010]

3.5 Grove, Mond and Langer

In 1839, William Grove combined hydrogen-oxygen and very diluted, sulfuric acid, creating the first fuel cell. Since fuels cells (FCs) have high theoretical thermal efficiencies, FC research and development has been aimed at commercial goals since the discovery of the hydrogen FC concept by Grove [Mobius, 1997].



Figure 3-4: William Grove [Wikipedia, 2010]

An important step forward in the development of fuel cell research is due to Mond and Langer. They constructed a fuel cell with a diaphragm from plaster of Paris, earthenware, asbestos pasteboard, impregnated with dilute sulfuric acid [Mobius, 1997].



Figure 3-5: Ludwig Mond [Wikipedia, 2010]

[Mobius, 1997] Mond and Langer designed the first fuel cell resembling its modern counterparts, though its performance was severely limited by available materials to only 3.5 mA/cm² at 0.73 V (on hydrogen and oxygen). They stated "*We prefer to work...with an e.m.f. o f about 0.73 V... which gives a useful effect of nearly 50% of the total energy of the hydrogen absorbed in the battery*". At that time, a steam engine was little better than 5% efficient. As a measure of one century of progress, today's protonexchange membrane FC (PEMFC) using a per fluorinated sulfuric acid polymer as the electrolyte can operate at a current density 300 times greater at the same cell voltage. Mond and Langer also showed that a water gas derived from coal would operate the fuel cell, even if only for short times.

3.6 Ostwald's Predictions

In 1894, Ostwald proposed that an electrochemical engine or fuel cell operating on clean fuel derived from coal would power the 20th century [Mobius, 1997].



Figure 3-6: Ostwald [Wikipedia, 2010]

[Mobius, 1997] In spite of his predictions, the FC remained a laboratory curiosity during the first half of the 20th century. Steam power produced a.c. electricity, and the spark-ignition Otto cycle engine began to dominate the private transportation energy economy.

Although restricted by the lack of sensitivity of the available measuring device (a leaf electroscope) so that small voltage differences could not be detected, Gaugain nevertheless found that, "*the new source of electricity possesses all the characteristic features of an aqueous-electric cell*", and thus he discovered in 1853 galvanic solid electrolyte gas cells. Towards the end of the 19th century the term "solid electrolyte" was in use, and many facts were known about the behavior of these materials. The 'Science of Electricity' by Wiedemann (1893/98) included the chapters 'Conductivity of Solid Salts' and 'Determination of the Electromyte' [Mobius, 1997].

However, in Ostwald's 'Treatise on Electrochemistry' (1885/1917) solid electrolytes are not mentioned; they were at that time a domain of the physicist. A technological interest in solid ion conductors arose in connection with the development of electric lighting devices. Early carbon lament lamps manufactured since about 1880 could not compete with the existing gas incandescent light [Mobius, 1997].

3.7 Nernst

In 1897, Nernst suggested in a patent that second-class conductors in the form of a thin rod could be made electrically conducting by means of an auxiliary heating appliance and then kept glowing by the passage of an electric current [Mobius, 1997].

Nernst mentioned only "lime, magnesia, and those sorts of substances" as appropriate conductors. Later investigations stimulated by experiences with gas mantles led to his observation "that the conductivity of pure oxides rises very slowly with temperature and remains relatively low, whereas mixtures possess an enormously much greater conductivity, a result in complete agreement with the known behavior of liquid electrolytes".



Figure 3-7: Nernst [Wikipedia, 2010]

Nernst pointed out that, for example, the conductivity of pure water and pure common salt is low but that of an aqueous salt solution is high [Mobius, 1997]. In a short time many of the mixed oxides which exhibit high conductivity at elevated temperatures, including the particularly favorable composition 85% zirconia and 15% yttria, the socalled Nernst mass, were identified.

3.8 What were Helmholtz and Ostwald doing?

Electrochemistry was given an important impetus by its connection with thermodynamics, discovered by Helmholtz in 1882 [Mobius, 1997].



Figure 3-8: Helmholtz [Wikipedia, 2010]

In 1894 Ostwald illustrated the advantages resulting when energy from coal is produced not with a steam engine but directly with a galvanic cell [Mobius, 1997]. The agreement between the voltages measured with galvanic solid electrolyte gas cells and calculated thermodynamically had already been verified by Haber and coworkers in 1905. From 330 to 570°C they used glass and from 800 to 1100°C porcelain as the electrolyte, and partly platinum, partly gold as the material for the electrodes in cells, first with C, CO, CO₂ and O₂, then in oxyhydrogen cells, and then in hydrogen and oxygen concentration cells. Typical phenomena such as the dependence of the voltage on the gas flux, deviations from zero (*'asymmetry voltages'*) and with decreasing temperature increasing sluggishness in the establishment of constant voltages were observed. Parallel to the publication of the results, Haber filed the first patent on fuel cells with a solid electrolyte. To compensate for alterations in the solid electrolyte of glass by the migration of ions caused by current, he proposed to exchange the gases in the electrode chambers as soon as disturbing alterations were noticed.

3.9 The Search for the Dry Fuel Cells

Only after many fruitless experiments with liquid electrolytes of different types did Baur 1937 come to the conclusion that fuel cells have to be made completely dry [Mobius, 1997]. But the extensive empirical search by Baur and other authors up to the 1950s for suitable solid electrolytes, covering glasses, porcelains, clays and a great variety of oxide mixtures, were unsuccessful.

In 1946, a new fuel cell was built, based on feed gases from cylinders, with double-porosity sintered nickel electrodes [Mobius, 1997]. Extensive work in the held of solid oxide fuel cells was done in the 1950's by Peters and Mobius.

3.10 Temperature Ranges and Materials

Up to 1950, the history of the FC was mostly in the area of extending the ranges of possible electrolytes and operating temperatures. Temperature ranges were largely determined by available materials. It was realized that only certain types of electrolytes would operate satisfactorily with a given fuel and oxidant, such as hydrogen and oxygen. The range of electrolytes was determined by those in which the major conducting ion was produced in one electrode reaction and consumed in the other, to avoid problems associated with ionic concentration gradients [Mobius, 1997].

3.11 The Bacon Cell

In the 1950's and 1960's, the cost of suitable stable materials for commercial fuel cells was always seen as a major issue. A fundamental problem in achieving high efficiency of solid electrolyte fuel cells was seen to be the possibility of internal short

circuit by electronic conduction of the electrolytes. This problem changed with the advent of the Bacon cell [Mobius, 1997].

[Mobius, 1997] By 1959 the Bacon cell was in a much more advanced state than other PC electrolyte technologies and it was licensed for space applications by a major manufacturer of aero-engines, the Pratt and Whitney Aircraft Division of United Aircraft Corporation (P&W). This company received the contract from NASA to develop the FC power supply for the Apollo Mission Service Module. This FC used a Bacon cell modified for zero-gravity applications, with a sealed (i.e., non-circulating) electrolyte operating at 4 atm pressure on pure hydrogen and oxygen. The pressure was reduced to save pressure vessel weight, and the performance was partially compensated by operation at about 260 ^oC. Under these conditions, cathode-side corrosion limited the Alkaline Fuel Cell's (AFC) life to the absolute requirements of the mission. It is no exaggeration to say that the FC technology, designated PC3A-2 (Power Cell Mark 3A-2) by P&W, was key element making the manned lunar missions possible. Other technologies form the Apollo Program, e.g. integrated circuits, have revolutionized the world. The FC has yet to do so.

3.12 The Patents Mill

[Mobius, 1997] After 1960, a rapidly increasing number of applications for patents were filed. In the USA, during a short period in 1961/62, patents were taken out by four companies on solid electrolyte fuel cells, partly with series connection. In the first British patent on the subject, filed in August 1963, it was intended to form fuel cells by depositing layers on a porous metallic carrier. In Japan, Takahashi, after investigations

with alkali carbonate electrolytes, published in 1964 his first results obtained on fuel cells with oxidic solid electrolytes.

3.13 Fuel Cells through the 1950s, the 1960s and the 1970s

In September 1959, Allis-Chalmers Manufacturing Co. demonstrated a tractor driven by 15 kW of low-temperature, low-pressure hydrogen-oxygen fuel cells, built up from a much larger number of 1,008 cells, than the Bacon 40-cell battery [Mobius, 1997]. In 1961, a new industrial firm, Energy Conversion, was formed in Great Britain to develop fuel cells commercially, with Bacon as a consultant.

This form joined forces with Pratt & Whitney in developing a battery for the Apollo space missions, yet, during the 1960's, no fuel cells were used on any form of large commercial bases. Westinghouse Electric Corporation continued to develop tubular solid oxide fuel cells, and in 1962 one of the first federal research contracts by the newlyformed Office of Coal Research in the Department of the Interior was granted to Westinghouse to study a fuel cell using zirconium and calcium oxide.

After the 1960's, a rapidly growing number of scientists worked on the different problems of SOFCs, and by 1970 the basis was established on which the broad technologically orientated development of SOFCs which proceeds today.

By 1976, the Energy Research and Development Administration--one of DOE's predecessor agencies--embarked upon an R&D program with Westinghouse to develop tubular solid oxide fuel cells. However, no market for fuel cell was in existence when in 1980 the effort was expanded with new fabrication techniques such as flame spraying the subsequent layers. Years later, a 5-kW, 24-cell stack was built, which after preheating could maintain its temperature of 10,000C. In Europe, SOFC research was mainly done

by Dornier Systems (Germany), starting from their experience in the Hot-Elly research and development program. Throughout the 1980s Westinghouse experimented with the design of tubular SOFCs.

3.14 Almost a Hit in the 1990s

[Mobius, 1997] Up to this time, the SOFC design closest to commercialization was thought to be the tubular Westinghouse system, which was technologically very advanced and showed excellent performance (approximately 0.7V at 0.25 A/cm² and 0.66 V at 0.35 A/cm² on real system gases at 85% fuel utilization, representing a polarization of only 40 and 80 mV, respectively, including internal resistance). The Westinghouse system cost approximately US\$100,000/kW in 1992-1993. New simplified approaches to tubular cell production or the further development of flat SOFC systems were thought of to reduce cost. During the 90's these were still in the laboratory stage in the USA, Japan, and Europe.

3.15 The Meaning of Success

[Appleby, 1995] There is no 'natural' market for fuel cells however over the years excuses for particular types of markets have been given. In all markets there will be competition. Fuel cell developers must know their competition's strengths and weaknesses, but also, and from a development standpoint, they must know their own technology and its limitations and create strategies for exploiting their product and at the same time, they must invent ways to eliminate or compensate for their product's weaknesses.

The benefits of the new technology must be exploited, and its inherent risks must be managed. However to spread the risks, government support is critical. For fuel cell developers the risks have always been financial, political, and technical.

3.16 One in a Million?

In this context, in the early 1990s, finally, one company commercialized - UTC Power was the first company to manufacture and commercialize a large, stationary fuel cell application for use as a co-generation power plant. Even so, unlike other fuel cell developers of the past and present, UTC is unique, for UTC had an established parent company which gave it two advantages: first, UTC fuel cell research was financed and funded from a well *established* parent organization, and secondly, UTC could draw upon its genitor's systems engineering knowledge and experience. These are two commodities which most fuel cell developers, somewhat, lack. UTC is one in a million.

3.17 Bloom Energy

Time went on and a new company entered the scene. In June, 2011, Bloom Energy vowed to build a manufacturing facility for its fuel-cell boxes at the former Chrysler site in Newark [Woody, 2011]. The company's board members include Colin Powell, and it has the backing of well-regarded venture capitalists. It also has some high-profile customers with "Bloom Boxes" onsite, like Google, eBay and Bank of America.

But as Bloom seeks changes to Delaware law and, a small monthly increase in Delmarva Power customer bills, observers say Bloom is facing the same old problems as other fuel cell developers have, namely, price and reliability problems. Bloom uses solid oxide fuel cells, and it avoids the need to use expensive materials like platinum. Bloom advertises the technology as cleaner and as more efficient than many existing energy production methods. "But it's challenging to produce a reliable fuel cell", said Shu Sun, an analyst with Bloomberg New Energy Finance. "To do so, a lot of effort needs to be put into perfecting the engineering design. Stationary fuel-cell companies existing today are just not making any profit", Sun said.

Bloom has been reported to be selling its system at about \$7,000-\$8,000 per kilowatt, which is high compared with fuel-cell systems from other companies, Sun said. To become competitive with combined cycle gas turbine power, the purchase cost needs to come down to about \$1,500 per kilowatt, he said. In regards to Bloom Energy's fuel cell stacks, the big challenge is thermal stress," said Tobin Fisher, who co-founded mobile fuel cell company Ardica Technologies out of Stanford University. "All of these different components heat up and expand at different rates. Over time, they can crack as a result." Generally, when a system like Bloom's is not working, it can result in a phenomenon called "gas short," quickly gaining in temperature and losing efficiency, according to Fisher.

3.18 One in a Large, Large Crowd

Five, ten or maybe twenty years from now, what will be the fates of Bloom Energy and other fuel cell developers? Since the late 1990's, many fuel cell developers have come into existence and are struggling to get to where UTC is at now. Many have not made it and, have gone or will go out of business. To show the magnitude of today's fuel cell industry, here are just a *few* developers. Note not all fuel cell developers are listed in this inventory:

Acumentrics Corporation, Massachusetts, USA (SOFC); Advanced

Measurements Inc., Alberta, CANADA (Fuel Cell Testing Systems); AFC Energy plc, Surrey, UK (AFC); Altergy Systems, California, USA (PEM); Apollo Energy Systems, Inc., Florida, USA (AFC); Arbin Instruments, Texas, USA (Fuel Cell Testing Systems); Argonne National Laboratory, Illinois, USA (PEM, MCFC and SOFC); Asia Pacific Fuel Cell Technologies, California, USA (PEM); Astris Energi, Mississauga, Ontario, CANADA (AFC); Ballard Power Systems, Inc., British Columbia, CANADA (PEM); BCS Technology, Inc., Texas, USA (PEM); Bloom Energy, California, USA (SOFC); Boyam Power System Co., Ltd., Taiwan (PEM); CellTech Power, Massachusetts, USA (SOFC); Ceramatec, Utah, USA (SOFC); Ceramic Fuel Cells Ltd., Victoria, AUSTRALIA (SOFC) ; ClearEdge Power, California, Oregon, USA (PEM); CMR Fuel Cells Limited, Cambridge, UK (DMFC); Diverse Energy, West Sussex, UK (PEM); EBARA Ballard Corporation, Tokyo, JAPAN (PEM); EBZ - Dresden, GERMANY (SOFC); Electric Power Research Institute, California, USA (PAFC and MCFC); Electrocell - Sao Paulo, BRAZIL; ElectroChem, Inc., Massachusetts, USA (PEM); Electro Power Systems, Palmero, ITALY (PEM); Element 1 Power Systems Inc., California, USA; Emprise Corporation, Georgia, USA; ENEOS (Nippon Oil Corporation), JAPAN (PEM); EnerFuel, Inc., Florida, USA (PEM); EnergyOr Technologies Inc., Quebec, CANADA (PEM) ;Energy Conversion Devices, Inc., Michigan, USA (RFC); Esoro AG, Faellanden, SWITZERLAND (PEM); eVionyx, New York, USA (AFC, Metal-Air FC); FEV Motorentechnik GmbH, GERMANY (PEM, SOFC); Forschungszentrum Julich, GERMANY (DMFC, SOFC & PEM); Franklin Advanced Materials, Pennsylvania, USA (SOFC); FuelCell Energy,

Connecticut, USA (DFC); Future E, Nürtingen, GERMANY (PEM); Gashub Technology, SINGAPORE (PEM); Heliocentris Energy Systems, CANADA; Hitachi Works, Ibaraki, JAPAN; MCFC); HTceramix - Lausanne, SWITZERLAND (SOFC); H-Tec - Wasserstoff-Energie-Systeme GmbH, Luebeck, GERMANY (PEM); Hydrogenics Corporation, Toronto, CANADA; IdaTech, Oregon, USA (PEM); Infintium Fuel Cell Systems, Texas, USA (PEM); Intelligent Energy, Leicestershire, UK (PEM); Jadoo Power - California, USA (PEM); Japan Automobile Research Institute, Inc., JAPAN (PEM); Lynntech, Inc., Texas, USA (PEM); Manhattan Scientifics Inc., New Mexico, USA (PEM); Medis Technologies, ISRAEL; Mesoscopic Devices, Colorado, USA (DMFC, SOFC); Microcell, North Carolina, USA (PEM); Mitsubishi Electric Corporation, JAPAN (PAFC); Mitsubishi Heavy Industries, Inc., New York, USA (PEM & SOFC); MTU Friedrichshafen GmbH, GERMANY (MCFC); myFC - Your Power Source, SWEDEN (micro fuel cells); NanoDynamics Energy Inc., New York, USA (SOFC); National Fuel Cell Research Center, California, USA; Neah Power Systems, Washington, USA; NedStack fuel cell technology BV - NETHERLANDS (PEM); NexTech Materials, Ltd., Ohio, USA (PEM & SOFC); NuVant Systems, Inc., Illinois, USA (PEM, DMFC); Nuvera Fuel Cells, Massachusetts, USA (PEM); Plug Power, LLC, New York, USA (PEM); Power Air Corporation, California, USA (ZAFC); Powerzinc Electric, Inc., California, USA (Zinc/Air); Precision Energy and Technology, Ohio, USA (PEM); Proton Energy Systems, Connecticut, USA (PEM, Electrolyzers); Protonex Technology Corporation, Massachusetts, USA (PEM); Proton Motor GmbH - Puchheim, GERMANY (PEM); ReliOn, Washington, USA (PEM); Risø National Laboratory, Roskilde, DENMARK

(SOFC); Schatz Energy Research Center (SERC), California, USA (PEM); Siemens
Westinghouse Power Corporation, Pennsylvania, USA (SOFC); Sulzer Hexis Ltd.,
SWITZERLAND (SOFC); Tekion, Burnaby, BC, CANADA and Champaign, IL
(Formira FC); Teledyne Energy Systems, Inc., Maryland, USA (PEM); Toshiba
Corporation, Yokohama, JAPAN (PAFC and PEM); Toyota Motor Corporation,
JAPAN (PEM); Trenergi, Massachusetts, USA (high temperature PEM); United States
Department of Energy (main), Washington D.C., USA (PAFC, PEM, MCFC and
SOFC); United States Department of Energy (Fuel Cells Technologies Program),
Washington D.C., USA (ALL); UTC Power, Connecticut, USA (PAFC and PEM); VTT
Technical Research Centre of Finland, FINLAND (PEM and SOFC); Wärtsilä
Corporation, Helsinki, FINLAND (SOFC); ZSW, Center for Solar Energy &
Hydrogen Research, Ulm, GERMANY (PEM, MCFC and SOFC); and Ztek

3.19 Meeting the Needs of Power Hungry Cities

Over the past 50 years, electricity networks have not kept pace with modern challenges, such as security threats from either energy suppliers; national goals to employ alternative power generation sources; conservation goals that seek to lessen peak demand surges during the day so that less energy is wasted in order to ensure adequate reserves; high demand for an electricity supply that is uninterruptible; digitally controlled devices that can alter the nature of the electrical load [Amin, 2005, Smartgridnews.com, 2009].

In modern times, to make more efficient use of energy, the United States needs more transmission lines that can transport power from one region to another and, connect energy-hungry cities with the remote areas where much of the United States renewable power is likely to be generated. The United States will also need far smarter controls throughout the distribution system--technologies that can store extra electricity from wind farms in the batteries of plug-in hybrid cars, for example, or remotely turn power-hungry appliances on and off as the energy supply rises and falls.

If these grid upgrades don't happen, new renewable-power projects could be stalled, because they would place unacceptable stresses on existing electrical systems. According to a recent study funded by the European Commission, growing electricity production from wind (new facilities slated for the North and Baltic Seas could add another 25,000 megawatts to Germany's grid by 2030) could at times cause massive overloads [Amin, 2005, Smartgridnews.com, 2009].

In the United States, the North American Electric Reliability Corporation, a nongovernmental organization set up to regulate the industry after a huge 1965 blackout, made a similar warning in November [Talbot, 2009]. "*We are already operating the system closer to the edge than in the past,*" says the group's president, Rick Sergel. "*We simply do not have the transmission capacity available to properly integrate new renewable resources.*"

The challenge facing the United States is particularly striking. Whereas Germany already gets 14 percent of its electricity from renewable sources, the United States gets only about 1 percent of its electricity from wind, solar, and geothermal power combined. But more than half the states have set ambitious goals for increasing the use of renewables, and president-elect Barack Obama wants 10 percent of the nation's electricity to come from renewable sources by the end of his first term, rising to 25 percent by 2025.

Yet unlike Germany, which has begun planning for new transmission lines and passing new laws meant to accelerate their construction, the United States has no national effort under way to modernize its system. "*A failure to improve our grid will be a significant burden for the development of new renewable technologies*," says Vinod Khosla, founder of Khosla Ventures, a venture capital firm in Menlo Park, CA, that has invested heavily in energy technologies [Talbot, 2009].

The major problem is that today's old grid is concentrated in historically located older industrial based large "*centers*", and do not facilitate shifting supply readily to where the power is needed – hence the recent past problematic *brownouts* [Talbot, 2009].

3.20 Look there! We are grid locked!

When its construction began in the late 19th century, the U.S. electrical grid was meant to bring the cheapest power to the most people. Over the past century, regional monopolies and government agencies have built power plants--mostly fossil-fueled--as close to population centers as possible. They've also built transmission and distribution networks designed to serve each region's electricity consumers. A patchwork system has developed, and what connections exist between local networks is meant mainly as backstops against power outages[Talbot, 2009].

Today, the United States ' grid encompasses ~164,000 miles of high-voltage transmission lines--those familiar rows of steel towers that carry electricity from power plants to substations--and more than 5,000 local distribution networks [Talbot, 2009]. But while its size and complexity have grown immensely, the grid's basic structure has changed little since Thomas Edison switched on a distribution system serving 59 customers in lower Manhattan in 1882. "*If Edison would wake up today, and he looked at*

the grid, he would say, 'that is where I left it," says Guido Bartels, general manager of the IBM Global Energy and Utilities Industry group.

While this structure has served remarkably well to deliver cheap power to a broad population, it's not particularly well suited to fluctuating power sources like solar and wind. First of all, the transmission lines aren't in the right places. The gusty plains of the Midwest and the sun-baked deserts of the Southwest--areas that could theoretically provide the entire nation with wind and solar power--are at tail ends of the grid, isolated from the fat arteries that supply power to, say, Chicago or Los Angeles. Second, the grid lacks the storage capacity to handle variability--to turn a source like solar power, which generates no energy at night and little during cloudy days, into a consistent source of electricity. And finally, the grid is, for the most part, a "dumb" one-way system. Consider that when power goes out on a customer's street, the utility probably won't know about it unless the customer or one of neighbors picks up the phone. That's not the kind of system that could monitor and manage the fluctuating output of rooftop solar panels or distributed wind turbines [Talbot, 2009].

The U.S. grid's regulatory structure is just as antiquated. While the Federal Energy Regulatory Commission (FERC) can approve utilities' requests for electricity rates and license transmission across state lines, individual states retain control over whether and where major transmission lines actually get built. In the 1990s, many states revised their regulations in an attempt to introduce competition into the energy marketplace. Utilities had to open up their transmission lines to other power producers. One effect of these regulatory moves was that companies had less incentive to invest in the grid than in new power plants, and no one had a clear responsibility for expanding the

transmission infrastructure. At the same time, the more open market meant that producers began trying to sell power to regions farther away, placing new burdens on existing connections between networks. The result has been a national transmission shortage [Talbot, 2009].

3.21 Improvements coming?

These problems may now be the biggest obstacle to wider use of renewable energy, which otherwise looks increasingly viable [Talbot, 2009]. Researchers at the National Renewable Energy Laboratory in Golden, CO, have concluded that there's no technical or economic reason why the United States couldn't get 20 percent of its electricity from wind turbines by 2030. The researchers calculate, however, that reaching this goal would require a \$60 billion investment in 12,650 miles of new transmission lines to plug wind farms into the grid and help balance their output with that of other electricity sources and with consumer demand. The inadequate grid infrastructure "*is by far the number one issue with regard to expanding wind*," says Steve Specker, president of the Electric Power Research Institute (EPRI) in Palo Alto, CA, the industry's research facility. "*It's already starting to restrict some of the potential growth of wind in some parts of the West.*"

The Midwest Independent Transmission System Operator, which manages the grid in a region covering portions of 15 states from Pennsylvania to Montana, has received hundreds of applications for grid connections from would-be energy developers whose proposed wind projects would collectively generate 67,000 megawatts of power. That's more than 14 times as much wind power as the region produces now, and much more than it could consume on its own; it would represent about 6 percent of total U.S.

electricity consumption. But the existing transmission system doesn't have the capacity to get that much electricity to the parts of the country that need it. In many of the states in the region, there's no particular urgency to move things along, since each has all the power it needs. So, most of the applications for grid connections are simply waiting in line, some stymied by the lack of infrastructure and others by bureaucratic and regulatory delays [Talbot, 2009].

3.22 Enter the Smart Grid

Yet a very important development in energy's history was the creation of the *Smart Grid*' and holds the promise of resolving electricity networks problems. The term *smart grid*' has been in use since at least 2005, when the article "Toward a Smart Grid", authored by S. Massoud Amin and Bruce F. Wollenberg appeared in the September/October issue of *IEEE P&E Magazine* (Vol. 3, No.5, pages 34-41).

3.23 The Anatomy of the Grid and the Smart Grid's Function

The electric grid delivers electricity from points of generation to consumers, and the electricity delivery network functions via two primary systems: the transmission system and the distribution system [Texas A&M, 2010].

The transmission system delivers electricity from power plants to distribution substations, while the distribution systems deliver electricity from distribution substations to consumers. The grid also will encompasses myriads of local area networks that use distributed energy resources to serve local loads and/or to meet specific application requirements for remote power, village or district power, premium power, and critical loads protection. The Smart National Grid is needed to be able to quickly shift or allocate supply peak energy from the evolving solar power centers of the United States
west and southwest; and wind turbine centers of the west and northwest to whatever region needs it in "*real time*".

The windowless laboratory at GE Global Research in Niskayuna, NY, is stocked with kitchen appliances and lined with wall screens like those in the control centers for an electrical grid. In the lab, Juan de Bedout, manager of the Electric Power and Propulsion Systems Laboratory, describes how a "smart grid" could help make renewables practical. Imagine he says, that the wind speed suddenly drops at a wind farm, or that a cloud bank moves over a photovoltaic installation. Existing transmission control systems--like those at Vattenfall--will detect the drop in supply and order increases in power production from other sources, particularly natural-gas plants, which can be fired up quickly[Talbot, 2009].

But in a smart grid, the controller could send a message down to a regional distribution system, seeking a reduction in demand. Instantly, a signal would go out to meters in the homes or offices of customers who had agreed, in exchange for rate reductions, to let the utility rig some of their appliances to cut power consumption during supply drop-offs. Within seconds, electric water heaters would shut off for a few minutes, and electronic thermostats would be automatically adjusted by two or three degrees. There would be no need to power up the natural-gas plant.

In one of the more advanced pilot projects testing such a system, the Minneapolisbased utility Xcel Energy and several vendors are investing \$100 million to install a smart-grid infrastructure in Boulder, CO. These days, a 115-person Xcel crew is out full time, installing two-way electric meters at 50,000 houses. Homeowners are getting software that lets them view and manage their energy consumption on the Web, and some

of their appliances are being fitted with switches that will let the utility shut them off remotely during periods of high demand.

Smart-grid technologies could reduce overall electricity consumption by 6 percent and peak demand by as much as 27 percent. The peak-demand reductions alone would save between \$175 billion and \$332 billion over 20 years, according to the Brattle Group, a consultancy in Cambridge, MA. Not only would a lower demand free up transmission capacity, but the capital investment that would otherwise be needed for new conventional power plants could be redirected to renewables. That's because smart-grid technologies would make small installations of wind turbines and photovoltaic panels much more practical. "*They will enable much larger amounts of renewables to be integrated on the grid and lower the effective overall system-wide cost of those renewables*," says the Brattle Group's Peter Fox-Penner.

3.24 Governmental and Customer Support for the Smart Grid – a Future Vision

The US Fuel Cell Council is now lobbying Congress for more than a billion dollar investment to accelerate America's manufacturing position around this important piece of the future energy sector. In 2009, the US smart grid industry was valued at about \$21.4 billion — by 2014, it is forecasted to exceed at least \$42.8 billion. Given the success of the smart grids in the U.S., the world market is expected to grow at a faster rate, forecasting to surge from \$69.3 billion in 2009 to \$171.4 billion by 2014 [Talbot, 2009] [Talbot, 2009].

For homeowners seeking true electrical grid independence, the invention of the Smart Grid coupled with SOFC power systems, for example, would take away the dependence and limitations of the electric distribution grid, in a remote stand-alone package that could also provide heat for the home [Grose, 2011].

As part of the American Recovery and Reinvestment Act, Vice President Biden said: 'By investing in updating the grid now, we will lower utility bills for American families and businesses, lessen our dependence on foreign oil and create good jobs that will drive our economic recovery – a strong return on our investment'.

[Grose, 2011] Few would argue against the need to transform America's aging and increasingly decrepit electric-power grid into a more robust Smart Grid, using digital technologies. But ultimately, consumers must buy in to the concept. And of that to happen, emerging technologies will have to be dead –simple to use, generate cost savings, improve efficiency, and "have a cool factor," says Alex Huang, a professor of electrical engineering at North Carolina State University. But, today's grid *is* a one-way system. Power companies generate and distribute electricity from large-and in the United States, mainly coal-fired-plants to businesses and households. Because the flow of electrons through the grid needs to remain uninterrupted, the grid's not good at accommodating power from renewable sources, like and wind and sunshine, because they're intermittent supplies. But using digital technologies and two-way communications to better control, manage, and balance demand and generation will make it easier to bring renewable online. Ultimately, a Smart Grid will also allow users to sell electricity back to utilities from, say, home solar panels or idling electric vehicles. Also for example, a superfast, solid-state, electronically controlled transformer will act as an *"energy routing device"* between the grid and consumers, the so-called last mile of an intelligent grid, says Huang, who is leading its development. Traditional copper and iron

transformers "can change voltage, and that's all." His semiconductor-based transformer will also change frequencies, and connect to both AC and DC devices, including electric vehicles, wind turbines, and solar panels. "*It's an enabling technology for a more actively controlled grid*," Huang adds. The transformers also will be smaller and lighter than today's and produce less heat [Grose, 2011].

3.25 Obstacles the Smart Grid

The evolution of the Smart Grid is not without many obstacles. There are concerns over regulatory environments that don't reward utilities for operational efficiency; consumer concerns over privacy; social concerns over "fair" availability of electricity; limited ability of utilities to rapidly transform their business and operational environments to take advantage of smart grid technologies; concerns over giving the government mechanisms to control the use of all power using activities. Regardless of all the obstacles that might delay the Smart Grid in coming to fruition- the evolution of the Smart Grid is in process and - the Smart Grid will be here to stay!

3.26 Up in Thin Air – Negawatt

[Guylas, 2008] Negawatt power is a theoretical unit of power representing an amount of energy (measured in watts) saved. The energy saved is a direct result of energy conservation or increased efficiency. The term was coined by the Chief Scientist of the Rocky Mountain Institute and environmentalist, Amory Lovins in 1989. The concept of Negawatt power is being re-implemented in several states in the United States and is emerging as an international strategy to reduce energy consumption. Electric companies motivated by various factors, including significant capital costs required to add new

capacity, have begun to inform customers on how to use energy more efficiently, resulting in a theoretical increase the amount of Negawatts.

The Negawatt market has gained some recognition on an international scale; however, the market is still a controversial proposal that has not yet fully developed. Events in the 1970s brought U.S. utilities to a crossroads. New power plants were larger, costlier, and less reliable, and the nuclear technology was unproven and frequently much more expensive than anticipated because of cost overruns. The economic and regulatory framework within which utilities operated also underwent significant changes. The oil embargo in 1973 and the Iranian Revolution in 1979 contributed to higher oil prices, high interest rates, and inflation. In 1978, the U.S. Congress obliged utilities to purchase at 'a *fair*' price privately generated electricity (produced by cogeneration plants in industry, for example) and to distribute it, thus effectively opening up electricity production to some competition. More important, these kinds of challenges stimulated some utilities to rethink their business. Edison's concept helped some of them return to basics by recognizing that their customers were not interested in electricity per se but in the services electricity provided. It opened up an entirely new horizon, as the focus of their business now shifted from supply to end use. Several utilities entered into what Amory Lovins (1992) had called the Negawatt revolution.

Negawatts, so they discovered, were almost always cheaper than megawatts, meaning that it was advantageous to negatively generate additional capacity by reducing demand through improving end-use efficiency rather than continuing to increase supply by means of building new power plants. By selling energy efficiency to customers, the saved electricity could be used to offset increasing demands.

3.27 Typical Electric Power Supply Systems

Electric power supply system in a country comprises of generating units that produce electricity; high voltage transmission lines that transport electricity over long distances; distribution lines that deliver the electricity to consumers; substations that connect the pieces to each other; and energy control centers to coordinate the operation of the components. The **Figure 3-9** shows a simple electric supply system with transmission and distribution network and linkages from electricity sources to end-users [Bureau of Efficiency, 2010].



Figure 3-9: Typical Electric Power Supply Systems [Bureau of Efficiency, 2010]

Electric power transmission or "*high voltage electric transmission*" is the bulk transfer of electrical energy, from generating power plants to substations located near to population centers. This is distinct from the local wiring between high voltage substations and customers, which is typically referred to as electricity distribution. Transmission lines, when interconnected with each other, become high voltage transmission networks. The power system network that weaves about the United States is by far the largest interconnection of a dynamic system in existence to date. Due to the size of the area that the power system serves, the majority of the system components are dedicated to power transmission. North America has three major grids: The Western Interconnection; The Eastern Interconnection and the Electric Reliability Council of Texas (or ERCOT) grid, see below figure which shows US Power Grid.



Figure 3-10: US Transmission Grid [Wikipedia, 2010]

Network structure of the transmission grid provides a number of alternative routes through which power can flow from a generator to a load, as determined by Kirchhoff's laws, given the nodal generation and demand vectors together with the pattern of network connections. Transmission loss in a line depends on power flow through it, and power flow in any line is additive over supplies from generators connected to the line. Thus, portion of the transmission loss attributed to a generator depends on the way its power flow shares the lines in the network with the supplies from the other generators. A load may be supplied by more than one generation. It is important to determine, how much power a load receives at the point of receipt, from a specific generation and through which transmission route. For determining the losses associated with a transaction sharing a transmission link with other transactions, it is also required to determine, how much power a generation has to produce at the sending end to meet a portion of the load through a specific transmission route.

The primary function of transmission and distribution equipment is to transfer power economically and reliably from one location to another. Conductors in the form of wires and cables strung on towers and poles carry the high-voltage, AC electric current. A large number of copper or aluminum conductors are used to form the transmission path. The resistance of the long-distance transmission conductors is to be minimized. Energy loss in transmission lines is wasted in the form of I²R losses. Capacitors are used to correct power factor by causing the current to lead the voltage. When the AC currents are kept in phase with the voltage, operating efficiency of the system is maintained at a high level. In general, losses are estimated from the discrepancy between energy produced (as reported by power plants) and energy sold to end customers; the difference between what is produced and what is consumed constitute transmission and distribution (T&D) losses.

Circuit-interrupting devices are switches, relays, circuit breakers, and fuses. Each of these devices is designed to carry and interrupt certain levels of current. Making and breaking the current carrying conductors in the transmission path with a minimum of arcing is one of the most important characteristics of this device. Relays sense abnormal voltages, currents, and frequency and operate to protect the system. Transformers are

placed at strategic locations throughout the system to minimize power losses in the T&D system. They are used to change the voltage level from low-to-high in step-up transformers and from high-to-low in step-down units. The power source to end user energy efficiency link is a key factor, which influences the energy input at the source of supply.

Energy losses in the transmission and distribution (T&D) systems must be replaced by additional generation resources. Two factors determine the cost of the system losses: the initial cost of energy used to generate what is eventually lost, and the cost of the added generation needed to replace that loss. The former is often referred to as the energy cost of losses, and the latter cost is often termed a demand cost. Both are expressed in \$/kW. The demand cost is the marginal cost of additional capacity in both generation and transmission/distribution facilities needed to provide for the system losses. The cost factors for power loss replacement are the same as those for the basic energy service-capital, fuel, and operations and maintenance components. Usually, transmission customers pay for losses on a system-wide or zonal-specific \$/MWh basis, depending on the system variable operating costs. Traders conducting wheeling transactions can either pay for the losses, or they can supply extra power to make up for these losses. Similar to transmission losses, the energy lost in the distribution system must be supplied by the generators at the system variable operating costs.

3.28 The Cost of Power

In 1996, Oak Ridge National Laboratory developed estimates of ancillary service costs using data, assumptions, and analyses from twelve U.S. electric utilities. The estimates show aggregate costs of ancillary services ranging from \$1.50 to \$6.80/MWh, with an average of \$4.15/MWh for the utilities sampled. The power loss replacement is the most expensive service, accounting for 30 percent of the total ancillary service costs. Thus, the energy losses in the T&D system had an average economic value of \$1.25/MWh in 1996 dollars.

According to the Energy Information Administration, two-thirds of transmissions losses occur in the more than 2.6 million miles of transmission and distribution lines that make up the national transmission system in the United States (155,000 of those miles being transmission lines of 230 kV and above) [Dale, 2002]. The remaining one-third of loss occurs in transformers. The losses in the transmission and distribution system as a whole account for about eight percent to 10 percent of the total net generation, with 55 percent occurring in the distribution system, and the remainder in the high voltage transmission system.

Public Utilities Reports [Dale, 2002] stated, 'the difference between the net generation and sales is often used as an indicator of the losses (or cascading efficiency) of the delivery system for the electric power: using this definition, the losses in the U.S. transmission and distribution system amount to about 379 billion kilowatt-hours annually, or 10 percent of the net generation. The 8.5 percent to 10.5 percent loss figure includes the real physical losses in the transmission and distribution systems, as well as

non-sampling errors and data collection frame differences. The actual physical losses associated with wires and equipment in the transmission and distribution systems are therefore somewhat smaller. Figures typically quoted for the physical losses in the transmission and distribution systems are 7.5 percent to eight percent of the total net generation from power plants'.

As an example, if the electricity flow from generation to the user in terms of cascade energy efficiency, typical cascade efficiency profile from generation to 11 - 33 kV user industry will be shown in the figure below [Bureau of Efficiency, 2010].



Figure 3-11: The Cascade Efficiency of Electric Power Distribution [Bureau of Efficiency, 2010]

Step 1:	The efficiency ranges $28 - 35$ % with respect to size of power plant, the
	age of plant and its capacity utilization.

- Step 2: Step-up to 400 / 800 kV to enable EHV transmission envisaged maximum losses 0.5 % or efficiency of 99.5 %.
- Step 3:EHV transmission and substations at 400 kV / 800 kV envisagedmaximum losses 1.0 % or efficiency of 99 %.
- Step 4: HV transmission & Substations for 220 / 400 kV envisaged maximum losses 2.5 % or efficiency of 97.5 %.
- Step 5: Sub-transmission at 66 / 132 kV envisaged maximum losses 4 % or efficiency of 96 %.
- Step 6: Step-down to a level of 11 / 33 kV envisaged losses 0.5 % or efficiency of 99.5 %.
- Step 7: Distribution is final link to end user at 11 / 33 kV envisaged losses maximum 5 % of efficiency of 95 %.

The End

User: Cascade efficiency from Generation to end user = $\eta 1 \ge x + \eta 2 \ge x + \eta 3 \ge x + \eta 4 \ge x + \eta 5 \ge x + \eta 6 \ge \eta 7$.

The cascade efficiency in the T&D system from output of the power plant to the end use is 87% (i.e. $0.995 \ge 0.995 \ge 0.975 \ge 0.965 \ge 0.995 \ge 0.955 \ge 0.955$

To iterate, electric power transmission and distribution losses include losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage. Below is a chart with historical data for electric power transmission and distribution losses (kWh) in the United States.



Figure 3-12: US Historical Data for Electric Power Transmission & Distribution losses (kWh) [Trading Economics, 2011]

It's no secret that the delivery of electricity from the generator plant to the end user causes energy losses in the power system. Since 1960, losses typically have ranged from 8.5 percent to 10.5 percent of total generation annually. If the national average retail price for electricity is used, these losses have a value of \$25 billion-a staggering sum that evaporates into thin air. Transmission and distribution losses in the USA were estimated at 6.6% in 1997 and 6.5% in 2007. For information about can some of the benefits of a Fuel Cell-Combined Heat and Power (FC-CHP) System with regards to power lose prevention, (see **Appendix A**).

3.29 Conclusion

The demand for electric power by modern society is clear. The limitations of the existing generation and transmission technology are equally evident. Fuel cells, based upon nearly two centuries of research and development, are poised to fill niche markets where high efficiency and distributed generation are at a premium. Many companies, including United Technologies, Bloom Energy, and a host of other public/private

partnerships are tackling the issues of cost, development, and performance. Buoyed by synergistic development in Smart Grid Technology, fuel cells seem very likely to move from the laboratory to the consumer over the next few decades, provided the developers themselves follow the tried and true axioms of process development.

CHAPTER IV

THE INTRODUCTION TO THE SIX PHASE LIFECYCLE REFERENCE MODEL FOR INNOVATIVE/DISRUPTIVE TECHNOLOGIES

4.1 Introduction

An investigation of the challenges of commercializing SOFC Power Systems and, the importance of achieving commercialization through the use of the systems engineering process will be the topics of this thesis.

The National Society of Professional Engineers (NIST/NSPE), twenty years ago, formulated a Engineering Stages of Development template. The NIST/NSPE task group was set up to serve the principal task of providing and defining the document's criteria for use in determining the development status of a new product and/or a process development project and, to provide a uniform language for use in describing the engineering work needed for each phase.

This thesis's vehicle for explaining and demonstrating systems engineering practices and showing the commercialization challenges Solid Oxide Fuel Cell

developers face will be within the framework of the modernized 20-year old, NIST/NSPE reference template. The document has been modernized by including the systems engineering lifecycle approaches from Ben S. Blanchard, L. Ken Keys and others. The technology background and challenges of developing an SOFC come from several sources: the author's knowledge of SOFCs, the knowledge and experience of other fuel cell developers, and, the fuel cell industry's and others' literature. The major activities of the first two phases will be examined to any great extent.

4.2 Key's System Life Cycle Approach

As with an increase in complexity, an increase in reliability is required to keep pace with NPD of innovative/disruptive technologies. This means increased engineering discipline is required to keep the final total system performance objectives of the new products in focus. At the same time, the product/system must be manufacturable, as required to meet or exceed the target manufacturing cost. Part of keeping the manufacturing cost under "control" is to perform good analyses of alternatives for the assembly processes involved. Should the product/system fail in the field, there must be adequate preparations made for effective field support [Keys, 1992, 1995, 2010].

In many cases, the general historical approach to engineering has just been to "start designing". Key's definition of 'foggy' serial approach to engineering consists of, '*the engineer or designer figures out how he is going to manufacture the product. Then the engineer or designer waits and sees how the product performs in the field*'. As a result and in response, Keys believes [1992, 1995, 2010], much more attention must be paid to the total engineering process, initiated by design, in response to the wants, needs of the customer (s) from a systems life-cycle perspective.

The Japanese automotive companies, Honda, for example, as an early leader, began to think about the design/development effort as a process to delivering a product. It was a group process, with a methodology, which under the name of Company Wide Quality Control (CWQC), represented a significant part of the Japanese high technology products business success [Keys 1991, 2010, Ishikawa, 1986].

Life-cycle engineering research, according to Keys, is challenging to the academic world because it is problem focused and requires a multidisciplinary approach. However, understanding the process and methodology of bringing every increasingly sophisticated products, systems, and structures into being, with dramatically increased reliability, maintainability, serviceability in shorter development time has to be in the critical path of U.S. companies and funding agencies.

The opportunity for helping the U.S. regain its competitive edge is much too important in today's global sources of competition. Money spent on making poorly designed military, industrial, and commercial systems work to specifications in the field, and with excessive maintenance, warranty, "field upgrade" expenses is not productive money. In fact, this effort is a double jeopardy effort, because fixing engineering effort not going into the engineering of more competitive new product/features/services. That is the essence of a significant part of the Japanese message of CWQC [Keys 1991].

Designing for the life-cycle, also called SYSTEM LIFE CYCLE Engineering, means considering from the early product concept, the complete projected life of the product, including the product/market research, design phases, manufacturing process, qualification, reliability issues, and customer service/maintainability/supportability issues. It means considering early in the product life-cycle appropriate failure modes,

spare parts availability, diagnostic tools and personnel, and logistic support needs for the fielded product. The interactions between these different activities are complex and at many levels of detail [Keys, 2010, Blanchard, 2008]. They are simply depicted in **Figure 4-1**.

Key's life-cycle approach recognizes the product development, i.e., the engineering process, involves various phases in the intellectualization process of transforming a product from concept to reality. These phases arise from the identification of a need. This need is identified (program office or marketing/planning) by characterization/description of the need in the form of functional requirements and documented.



Figure 4-1: Product life cycle elements and interactions [Keys, L. K. (el at), 1991]

The documentation which highlights key form, fit, function, aspects (and costs, volume, i.e., economics) is usually responded to, by design engineering, with a second

document, the product specification (conceptual, high-level, depicting key design performance parameters) [Blanchard, 2008, Keys, 2010].

The principle unique aspect of life-cycle engineering is that, again, the complete life-cycle of the product is kept in consideration and treated in each phase of the product development. This means that technical and economic consideration must continually be given throughout the life-cycle development phases, comparing the cost of the product design with a certain reliability level (warranted period, useful product life, expected product life) and support (or vendor) costs for some period of time after delivery to the customer for maintaining a certain performance level; by allowing for some level(s) of performance degradation, and/or providing appropriate level(s) of customer service support (maintenance, parts, logistic support), etc. **Figure 4-2** uses Mean Time Between Maintenance (MTBM) to depict an example of the typical cost trade off considerations.



Figure 4-2: MTBM versus Cost Tradeoff [Keys, L. K., 1990]

As the product evolves through these phases it is also being more quantitatively treated by each of the major key company functions as depicted in **Figure 4-3**. At each one of these phases there must exist- a definition of objectives, activities, and deliverables to/for the next phase. The latter provide the basis for design/product reviews and for the decision on whether or not to proceed to the next step, or phase, or repeat another interaction of the phase under review. At each one of the phases, all of the "issues/tradeoffs" of concern for the total life-cycle of the product are considered, but the unique business/function concerns of that specific phase are addressed the most quantitatively.



Figure 4-3: Product Development and Organization Functions [Keys, L. K., 1991]

Keys states, for example, during the conceptual model phase, various paper and/or simulation models of the product are generated, to begin to give marketing and engineering a more firm conceptual ground for engineering direction(s). At this time various ways of partitioning and fabricating these models will be considered consistent with the possible manufacturing, quality, reliability objectives, and customer service/support objectives (i.e., reliability/maintainability, logistic support tradeoffs). Types and extent of qualification/evaluation testing will be defined consistent with the expected life and use of the product technology.

According to Keys, from these conceptual models, requirements, specification, analyses will evolve decisions for breadboard/brass board models. These models are pure engineering "green wired" breadboard using the cheapest and quickest availability technologies to demonstrate possibility/feasibility of the product/concept. These physical models may be complemented by computer simulated ones for increase design insight and interaction sensitivities. At this phase, key components vendors will be identified along with preliminary assessments of company of others quality/reliability/delivery experiences and history with the vendor.

The next step in the process of the design transformation process is to begin to firm up the product/technology/implementation process, demonstrating the design for manufacture/assembly approach, how the product may be serviced (supported/maintained/repaired) in field. In this phase, the (Engineering) Prototype phase, more detailed component, product, vendor, qualification evaluations are done; detailed component specifications prepared; performance, reliability test evaluations are performed; and preliminary product testing (environmental, life, accelerated, etc.) is done. Preliminary in-house technology trails/ α -field trials may be run for short periods of time to audit technical performance and to get targeted in-house user feedback on product use performance. Second generation engineering prototypes could fully document the intended manufacturing process design; with all marketing, manufacturing, reliability, and customer service logistic support issues resolved with component vendors

and products fully qualified. The latter could be used for all final production process/equipment planning purchase and implementation. These prototypes may also be used for additional technology/field trials at selected customer sites and user feedback on overall product performance.

The pilot production quantities from the operating manufacturing line would then be audited by all the key business functions (marketing, engineering, quality/reliability, manufacturing, and customer service/logistics support) to confirm the product *as produced* meets all intents and needs. As a final performance confirmation some subset of this pilot production quantity may have detailed performance monitoring in field trials β - trials in selected customer sights for one to three months (depending on the product) before final product release approval, as a final acceptance step for release from engineering and marketing to production and sales.

In many cases for new products, and new technologies, few of these steps can be skipped; however, at each one of the (technical) phases, poor communication, inadequate definition of objectives, and documentation, produces *numerous extra sub phases*. The latter being the *less documented* but often more likely cause of extensive "unplanned work" and often delayed product development programs, with an associated increase in configuration control problems and costs.

Because this transformation process represents an aggregate company learning process (or *de-ignorance process*) it is quite interactive with feedback required of information by all team members on the results of evaluations and tests, at each phase, which may required redoing a phase, and feed forward of new information to the next phase. **Figure 4-4** depicts how these phases contribute to the "*de-ignorance*" (or

knowledge building) process, about the product/design during its life-cycle development process.



Figure 4-4: Phases Effort Contribution to Reducing Ignorance (Uncertainty) i.e. Learning Process (or) Building Knowledge Base [Keys, L. K., 1990]

To reiterate, the life-cycle of product or system evolves from the definition of the need (requirements) through conceptual design (evaluations); preliminary or breadboard designs, detailed or engineering prototypes designs, field trials, pilot production, shipment to customer, customer use, customer support (field service, maintenance), then to system enhancements and/or ultimate phase-out and disposal.

4.3 The Learning Curve for SOFCs - Rivera-Tinoco (et al)

Since the development of the first learning curve for the aircraft industry in 1936, many technologies have been subjected to learning curve studies, as a means to evaluate potential cost reductions based on realized progress in the past. The developed learning curves may apply to a large range of different types of technologies and to serve companies strategic purposes and as a tool for public policy making [Rivera-Tinoco, 2010].

A study done by Neij [Rivera-Tinoco, 2010] states that fuel-cell technology is immature and no experience curves have been developed. However, Neij believes that the fuel-cell technologies can be considered as modular and experience curves from other types of modular systems indicate learning rates of 15–30% (Neij, 1999a). Moreover, the bottom-up assessments of fuel cells indicate uncertain cost reductions in the future that may be based on radical changes or incremental changes. Proposing a "theoretical" experience curve for fuel cells is not easy.

The knowledge building process in regards to the fuel cell industry, Schoots (*et al*), presented an extensive analysis of learning phenomena for fuel cells in particular for proton exchange membrane fuel cells, phosphoric acid fuel cells and alkaline fuel cells. Rivera-Tinoco's (el al) work aimed at complementing this recent fuel cell learning curve study since so far no learning rates have been reported – or have been determined – for SOFCs. Only Krewitt and Schmid (2004) have attempted to determine a learning curve for SOFCs, but they found that insufficient information on produced SOFC capacity was available at the time to calculate a learning rate. Hence, their preliminary findings remained unpublished [Rivera-Tinoco, 2010].

According to Ferioli and van der Zwaan, [Rivera-Tinoco, 2010] however, learning curves often apply only up to and including the early phase of commercial deployment. In those cases, as they argue, learning curves usually reflect several types of

cost reductions, e.g. as associated with both learning-by-doing and learning-by-searching. Their observation, plus the asserted early-stage commercial production of SOFCs over recent years, motivated Rivera-Tinoco (el al) attempt to develop a learning curve for this technology. Learning curve analysis can provide valuable insight for strategic planning and policy making, and can help determining or shaping indicators like total investment requirements and needs for subsidies or deployment levels for new energy technologies such as SOFC systems.

Rivera-Tinoco (el al) found information for energy-related technologies (such as coal-burning power units, gas turbines, wind turbines and photovoltaic modules). Rivera-Tinoco (el al) reported, for the first time, a reliable learning curve for SOFCs. In 2010, Rivera-Tinoco (el al) found that for SOFC manufacturing there was a learning rate between 14% and 17%, and for total SOFC system fabrication between 16% and 19%. Rivera-Tinoco (el al) argued that the corresponding cost reductions result largely from learning-by-searching effects (R&D) rather than learning-by-doing. When considering a longer time frame that includes what Rivera-Tinoco defined as '*early commercial production stage*', learning rates were between 14% and 39%.

Table 4-1EXAMPLES OF LEARNING CURVES[NASA, 2010, http://cost.jsc.nasa.gov/learn.html]Aerospace 85%Shipbuilding 80-85%Complex machine tools for new models 75-85%Repetitive electronics manufacturing 90-95%Repetitive machining or punch-press operations 90-95%Repetitive electrical operations 75-85%Repetitive welding operations 90%

4.4 The General Learning Curve and Rivera-Tinoco's Model

A learning curve expresses graphically the cost decrease of a technology as function of cumulative production, and is usually represented by a power law (See Equation 1) [Rivera-Tinoco, 2010]. When cost and cumulative capacity data are plotted on a double-logarithmic scale, the power law of a learning curve becomes a downward sloping straight line. The slope of this line is called the learning index (α), which can be reformulated as the learning rate (*lr*) (see Equation 2). The latter expresses, usually in percentages, the relative cost reduction after each doubling of cumulatively produced items of a technology. In Rivera-Tinoco (el al) fuel cells case, the variables in Equation 1 are the costs of SOFCs at time *t* (*ci*), the costs of SOFCs in the first batch of production (the time of which is referred to as *t* = 0) (*c*₀), the cumulated production of SOFCs at time *t* (*Pt*) and the number of SOFCs in the first fabrication batch (hence at *t* = 0) (*P*₀). Rivera-Tinoco (el al) expressed values of *P* either in number of SOFCs (typically for fuel cells) or in terms of their capacity (hence in kW, for example when referring to SOFC systems).

$$c_t = c_0 \left(\frac{P_t}{P_0}\right)^{-\alpha} \tag{1}$$

$$lr = 1 - 2^{-\alpha}$$
 (2)

The learning rate summarizes how cost reductions materialize when a manufacturer accumulates production or, alternatively, when it contributes to cumulative production of a given technology thereby adding to the (global, regional or local) experience stock.

In practice it proves difficult to distinguish between different cost reduction sources, as in Rivera-Tinoco (el al) case with SOFC technology: the production process typically improves through several distinct ways, not only by the acquisition of experience based on manufacturing and deployment (learning-by-doing) but also via R&D efforts (learning-by-searching), and quite possibly from still other mechanisms.

In the case of SOFCs, as well as many other technologies, a learning curve typically captures various kinds of contributions to overall cost reductions. It is conventional wisdom, and common practice in most studies, that learning rates are determined for technologies that have matured sufficiently and have completely reached advanced stages of commercial deployment – presently not yet the case for SOFCs – so that they mostly capture the effect of learning-by-doing.

Rivera-Tinoco (el al) estimated the learning rate value for R&D stage at 16% (see **Figure 4-5**). Material and labor costs remain high and were not affected for the volume of fuel cells produced. They estimated cost values confirm the accuracy of their model, deviating at most 4% from literature data.



Figure 4-5: Learning curve for R&D stage of SOFC production. Data from HC Starck (former ECN-InDec) homogenized with Rivera-Tinoco's cost model [Rivera-Tinoco, 2010].

4.5 System Engineering, Cost and Life-Cycle Engineering – Keys' Approach

It has been identified [Blanchard, 2008, Keys 1992, 1995, 2010] that some 75 to 90 percent of opportunity to influence total life-cycle cost is gone by the time a design is released to production. This concept is which identifies the extent that gradual freezing of the product design influences the lifecycle cost.

The system engineering process, increasingly recognized as essential for the evolution of people-made systems, to support life-cycle engineering, involves the design and development efforts to achieve the following goals:

- Through the use of an iterative process of functional analysis, synthesis, optimization, definition, design, test, and evaluation, transform an operational need via a description of system performance parameters into a preferred system configuration.
- Consider related technical parameters and assure computability of physical, functional, and program interfaces in a manner that optimizes the total system definition and design.
- 3. Integrate performance, producibility, reliability, maintainability, manageability, supportability, etc., into the overall design process.

Thus by the assurance that this view of the systems engineering process is applied to the iterative design and development, a more complete product will evolve for the use phase (i.e., customer), with a life-cycle optimized product life.

4.6 The NIST/NSPE Reference Document modified by Keys

According to Keys, fuel cell power systems and customer requirements could be reached by the application of a systematic, modernized commercialization model of the NIST/NSPE Task Group, but only if fuel cell developers are willing to address performance and others issues (mostly systems engineering related) in a disciplined and time tested matter - the use of systems engineering practices.

Keys' modernized NIST/NSPE Reference Model provides such a means and it has five major milestones and the reference model itself is divided into six distinct phases, namely:

- 1. The Conceptual Design & Advance Planning Phase,
- 2. The Preliminary System Design Phase,
- 3. The Detail System Design & Development Phase,
- 4. The Pilot (Pre-Production) Prove in Phase,
- 5. The Manufacturing & Distribution Phase, and
- 6. The Operational Use & Logistic System Support Phase.

The development phasing and baselining of the reference model should describe the approach to phasing the engineering effort, including the tailoring of the basic processes and should provide a rationale for the activity. The key milestones should be in general keeping with the technical review process, but tailored as appropriate to support business management milestones and the project/program's development phasing.

4.7 The System View – From Keys' and Blanchard's Perspectives

In this thesis, certain designated activities need to be emphasized in a 'top-down' approach, because the whole systems engineering approach to NPD design must be viewed as a whole and an understanding of subsystems interactions must be known, quantified and controlled [Blanchard, 2008, Keys, 2010].



The NPD System Engineering Process and Major Milestones

Figure 4-6: Keys' Systems View: the NPD System Engineering Process and Major Milestones [Keys, 2010]

4.8 Systems Configuration Management – From Keys' and Blanchard's Perspectives

Configuration management focuses on establishing and maintaining consistency of a system's or product's performance and its functional and physical attributes with its requirements, design, and operational information throughout its life [Blanchard, 2008, Keys, 2010]. Its purpose is to provide a complete trail of design decisions and system modifications. This thesis will demonstrate some of the tasks (top-down parts centric approach to the system, the bottom-up approach to system design, discussions regarding feasibility studies, rework/redesign, the introduction of analytical process hierarchy, and design structure matrix analysis) in creating a configuration management system of a NPD.

The designated activities of each phase must be lifecycle oriented, in other words, addressed within and throughout the entire NPD lifecycle. As part of the systems engineering plan, as part of the configuration management plan, a complementary system test engineering plan needs to be created to support the quality, reliability, and product development testing in the various phase (stages) as presented.

4.9 Quality Systems Engineering Management – From Keys' and Blanchard's Perspectives

Quality Management is an approach which must be achieved throughout the entire lifecycle of an SOFC Power system, at each level in its overall system hierarchy [Blanchard, 2008, Keys, 2010]. A '*before-the-fact*' orientation to quality must be the approach taken in this NPD effort. A discussion about quality management topics will be included in this thesis with two objectives in mind: to show how complex and involved quality issues are in the development of an SOFC Power System and to promote a quality system necessary for the convergence of the conceptual product design into one which can be manufactured, as well as, the on-going maintenance of the product throughout its lifecycle.

4.10 Reliability Systems Engineering Management – From Keys' and Blanchard's Perspectives

Reliability engineering for fuel cell power system must be used to design a realistic and affordable test program that provides enough evidence that the system meets its requirements [Blanchard, 2008, Keys, 2010]. However, testing for the reliability requirements for a fuel cell power system is problematic for several reasons. One or two tests could be insufficient to generate enough statistical data. Secondly, multiple tests or long-duration tests are very expensive. Finally, some tests for certain components are simply impractical and/or impossible [Milliken, 2010]. This thesis will briefly discuss reliability practices with an emphasis on reliability system engineering management philosophy pertaining to SOFC development and lifecycle issues.

4.11 Systems Testing Engineering – From Keys' and Blanchard's Perspectives

Using Blanchard's and Key's philosophy that as the system design and development activities of an SOFC power system progresses, there needs to be an ongoing measurement and evaluation effort [Blanchard, 2008, Keys, 2010]. A complete evaluation of the power system, in terms of meeting its specified requirements, cannot be accomplished until an early system (demo) is produced and functioning in an operational environment.

An evaluation system must start at the beginning of the design process. The objective of any testing system is to acquire a high degree of performance as intended. Acquiring that confidence, through the accomplishment of successful test evaluation of lifecycle phase activities is the key.

Although not exhaustive, for demonstrative purposes, this thesis will start to create action lists listing some of the component/subsystem testing requirements, and system testing issues SOFC developers must address.

4.12 Concurrent Engineering – From Keys' and Blanchard's Perspectives

Concurrent engineering (CE) [Keys, 2010, Blanchard, 2008, Prasad, 2002, Xu (et al), 2007, Zhang, 2003] can be defined to be a systematic approach to the integrated simultaneous design of a product and the related processes, including manufacturing and the other support functions. This approach requires the formation of multifunction teams of specialists representing all organizational activities. CE requires that product, process, facilities, customer service, maintenance, and vendors become involved with the project at the earliest phases. It increasingly includes involving the customers(s) in the product requirements' definition and that all stakeholders actively participate in the development of the product.

CE will require that companies which have been following the usual sequential design process will need to make substantial changes in their management approaches to product development. The CE process and product development methodology will require that the marketing, design, manufacturing, quality, service, personnel etc. involved will all have to work simultaneously toward meeting/delivering a common goal.

While there have been many success stories of the benefits of this approach, there are still many challenges which remain: understanding, implementing, and continually evolving CE use.

As the products and processes increased in complexity and sophistication, the complex element of designing, developing, manufacturing, maintenance and service, etc., were subdivided into smaller more manageable pieces. Over time, a conceptual model of the product/process development process evolved consisting of stages or phases. This led to many product release delays, extra engineering, changes, poor quality, budget and product cost over-runs', and high maintenance costs. Increasingly, new products also involved the interfacing and integration of a number of technologies.

It was the aid of systems analysis, life cycle thinking, coupled with project management principles and discipline which began to bring improvement to the product/process development cycle problem [Keys, 2010, Milliken, 2010]. A systems approach to the project management product/process development process means viewing the entire process from concept, through implementation, to successfully maintained operation, as a system or entity, not just a string of activities. It means recognizing the interplay, interface, trade-off, and integration, among the elements or activities, as important parts of this life-cycle perspective.

Keys states that once the project is treated as a system, with elements and activities preliminarily defined, the next significant project must be managed by a project team representing all the significant element/organization participants identified by the system approach. These are the people who lead the detailed planning, organizing, and controlling of the project.

These two basic concepts, system analysis and team project management, provide the basis for simultaneous product/process development leading to successful CE, or what some researchers have called a dynamic systems engineering process (DSP) [Blanchard, 2008].

The status of CE practice was documented by an Institute for Defense Analysis (IDA) team report, which provided a basic definition, a description of the practice, reported benefits and a framework for further evolution [Keys, 2006]. The IDA report defined CE as:

"Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements."

Keys believes that this management engineering and business approach integrates the design of a product and its manufacturing and support processes. Its implementation takes a variety of forms and uses different methods and techniques; however, there are generic elements:

1. Reliance on multifunction teams to integrate the designs of a product and its manufacturing and support processes;

- Use of computer-aided design, engineering, and manufacturing methods (CAD/CAE/CAM) to support design integration through shared product and process models and data bases;
- Use of a variety of analytical methods to optimize a product's design and its manufacturing and support processes.

The IDA study team observed industry using CE on products ranging from digital communication switches to mainframe computers to mobile missile launch vehicles, which included some of the industries evaluated by Keys and others.

- 1. Improving the quality of designs which resulted in dramatic reductions of engineering change orders (greater than 50%) in early production;
- 2. Product development cycle time reduced by as much as 40-60% through the concurrent, rather than sequential, design of product and processes;
- Manufacturing costs reduced by as much as 30-40% by having multifunction teams integrate product and process design;
- 4. Scrap and rework reduced by as much as 75% through product and process design optimization;
- Reduced maintainability/serviceability efforts and warranty costs (i.e., life cycle cost savings).

Keys' principle findings of the report were the following:

- 1. Companies that have implemented CE report that they are producing higher products at lower cost and in less time than they were able to previously.
- Significant cultural and management changes underlay the successful implementation of CE. As a consequence, considerable time (2-4 years or more) is often needed before benefits are realized from CE. Up to ten years may be required to provide all the benefits possible.
- 3. CE requires top-down leadership and involvement to succeed with continual reinforcement through training, backing, interest, and dialogue throughout the product/system development process.
- 4. While the understanding of CE is continuing to emerge, and its boundaries are not yet fully defined, many of the methods and technologies to implement its central elements exist today.
- 5. Significant differences exist between the commercial marketplace and the Department of Defense (DOD) domain. Despite these differences, case studies of the implementation of CE by several defense contractors suggest the CE can be successfully applied in the DOD environment.
- 6. There are DOD policies, management procedures, contracting, methods, and regulations that could inhibit the successful implementation of CE within DOD. For example, one of the major problems is often separation of the contract phases and contract organizations in the DOD domain leading to different companies being involved in the concept, engineering, development, manufacturing, procurement, and logistic support phases. This can produce the segmented philosophy and segmented thinking that is counter to the CE philosophy.

One of the most important aspects of concurrent engineering, which is often overlooked and is also an important part of TQM, is the need for activity-based (or process-based) casting or activity-based management. Keys used activity-based costing in the early 1970's to obtain true costs for printed circuit board and assembly manufacturing and hybrid microelectronics operations. This process costing method forces the costing of non-value added drop-out, rework, and process change costs. True costing is required to have a good real cost rational for sound economic decisions. More research is needed to improve the application of this approach to modern manufacturing industries.

4.13 Conclusion - Playing the Game – The Players

To Keys, the importance of defining a mission, objectives, strategies, goals, and implementing these through a stream of projects/programs has been emphasized by others, Cleveland and Kind (1983), Croft and Ledbetter (1988c), (1988b). The advantages of project/program team involvement from beginning to end are also being increasingly recognized as a major element of success, Edsomwan (1988), Keys (1988).

The participating functions and technical skills for NPD advancement need to be identified. The new product development needs to be mapped into the organization, from conception thru configuration management and product support and maintenance. Communication and control processes and mechanisms need to be established. Checkpoints need also to be defined and set-up. Documentation and decision approval criteria, processes, and procedures must be determined. The various development phases of the program must be identified. Appropriate practices and procedures must be identified and taken into account in the planning and implementation process. All of these activities should fall under the umbrella of the modernized NIST/NSPE Reference Model

A fuel cell developer's organizational culture must also exist which allows the mistake making, correction, implementation, and learning process to expediently occur.

The experience, training, and personality of the program/project manager selected are also of critical importance [Keys, 2010, Milliken, 2010].

The formation and implementation of fuel cell development should be related to the organizing and playing of football [Keys, 2010]. In this context the simultaneous engineering, concurrent designing process is treated from a systems life cycle or holistic methodology. This approach involves built-in instability, phases, shared multidiscipline knowledge building, subtle control, and organizational knowledge (learning process) transfer. In order for an effective power system development and implementation process to occur, a number of things must be in place, or be put in place. The game must be defined. That is a development process (life cycle) must be established by the fuel cell developer. Roles and responsibilities of the various players must be defined for both the line organization and product functional needs to facilitate the transfer/development process. Elements of the program planning and control process need to be defined and accepted. These activities allow binding the project and organization together towards one common goal.

The program control processes need to be established: i.e. reviews, meetings, follow-up activities etc. At the various progress check points (milestones), the transferable (documents, drawings, models, etc.) must be built into the process to support knowledge building, knowledge, information, and technology transfer. It must be recognized, just like with any dynamic game, proficiency, efficiency, and improvements in the process, along with the experience of the players/participants/team member only comes from playing the game; i.e., being involved with successive project/programs (training or practice).

Lastly, just like in football, rugby, soccer, etc.; Keys believes that the rules of the game, infractions, errors, players, positions, etc. must be understood, practiced, "ruled", and played. However, too much structure, rules, second guessing by management/side-line, etc. can distort or destroy the game.

The next chapter will introduce the Conceptual Design and Advance Planning Phase.

CHAPTER V

THE INTRODUCTION TO THE CONCEPTUAL DESIGN AND ADVANCE PLANNING PHASE – PHASE ONE

5.1 Introduction

The conceptual phase of engineering development is that period during which a concept is proven scientifically valid or is shown to be potentially valid by the application of the test-of-principle models. The objective of this phase is to demonstrate through testing or analysis the performance and implementation potential of a concept. This chapter will outline some of the major activities of the Conceptual Design and Advance Planning Phase.

5.2 The Conceptual Design & Advance Planning Phase

The proof-of-concept analysis related to the SOFC seems to go back to the 60's where researchers at Westinghouse experimented with a cell using zirconium oxide and calcium oxide in 1962. More recently, climbing energy prices and advances in materials technology have reinvigorated work on SOFCs, and a recent report noted about 40

companies working on these fuel cells. So, as far as proof-of-concept goes, SOFC technology has a very sound, well established foundation.

Moving forward, within the Conceptual Design and Advance Planning Phase, besides developing a fully articulated technology concept, the confirmation of critical assumptions upon which the SOFC's performance is founded upon must be validated, as well as, identifying and accessing the critical manufacturing and market barriers are insofar as possible. Reiterating the objectives of the Conceptual Design and Advance Planning Phase are to:

- Demonstrate through test or analyses the performance and implementation potential of a design concept that will meet the customer's needs or solve a problem, effectively and efficiently.
- 2. Once a design shows potential promise, begin to define preliminary system effectiveness (in areas of performance, reliability, maintainability, supportability).

5.3 The Major Activities of the Conceptual Design & Advance Planning Phase

The engineering activities common to this stage are those necessary to describe an innovation, identify its potential utility and demonstrate its potential for achieving performance and implementation. The major activities in the Conceptual Design and Advance Planning Phase are the following:

Market Analysis (Finding the preliminary market entry point of the product).
Conceptual Design (Physical View of a Part Centric Top-Down Approach)
Testing & Maintenance Concept (What is most likely to fault and how will it be serviced).

Operational Requirements (*'Functional View' is 'How' the system will operate*).

System Feasibility Analysis (*"How" well does the system satisfy the requirements identified in the needs/ operational requirements analysis by way of testing*).

Evaluation of Technology Applications (*is a survey of the current technology*).

5.4 In the Early Part of the Phase – The Major Focus

For innovative technologies, the conceptual stage of engineering development is that period during which, in the early phase, the need identification occurs. The end user's needs or problems are defined. The preliminary market entry point of the product is defined so that the early tech trials have a goal to work towards.

The adopters of new products, especially early adopters of disruptive or innovative products, must be determined. The early adopters of the innovative products are usually the technology enthusiasts and visionaries and the early majority (the pragmatists). According to Moore, the marketer should focus on one group of customers at a time, using each group as a base for marketing to the next group.



Figure 5-1: Technology Adoption Life Cycle [Wikipedia, 2010]

Other major activities of the early part of this phase are:

- The Conceptual Design of the System The conceptual design for the innovative technology are laid out.
- *Technology Survey* A state-of-the-art survey of competing technologies is conducted.
- The beginning of the Potential Barriers Survey A preliminary identification and discussion of the potential barriers to development of the pure science and engineering of the technology and the marketing of the new product.

5.5 The Middle Part of the Phase – The Major Focus

The major activities of the middle part of this phase are:

- Product Development Philosophy The design and development philosophy of the product development is formed.
- *System Synthesis* The synthesis of conceptual system design is engineered.
- Testing Management Plan- A system and subsystem testing and risk analysis baselines are started.

- Maintenance Concept- begins at the component level and is define for higher subsystem levels.
- Design Alternatives Evaluation The evaluation of conceptual system design alternatives is considered.
- *The Potential Barriers Survey* A preliminary identification and discussion of the potential barriers to development of the applied science and engineering of the technology, and marketing of a new product.

5.6 The End of the Phase – The Major Focus

The major activities of the last part of this phase are:

- *Product Statement* A statement of how the concept will be used as a new product(s).
- Performance Specifications A target set of performance specifications or achievement goals for the concept. (A description of the concept including sketches, drawings and/or model(s)).
- *Testing and Risk Analysis* The tentative plan for testing and risk analysis must be started.
- Potential Barriers Survey A preliminary identification and discussion of the potential barriers to pure/applied science and engineering development, manufacturing and marketing of a new product.
- Advanced Program Planning The start of the system feasibility analysis which will be continued into the next phase is included in a review of all the activities in the phase and a strategy plan for engineering and development of the next phase, which is the preliminary design towards the manufacturable design of the product.

Information generated from the Conceptual Design & Advance Planning Phase:

- The Product Statement.
- A description of the concept including sketches, drawings and/or model(s).
- A target set of performance specifications or achievement goals for the concept.
- Crude test models of the subsystems and/or the system (as a whole).
- A presentation of test results or data for the subsystem and/or system performance.
- A preliminary identification and discussion of the potential barriers to development, manufacturing and marketing of a new product.

5.7 Advanced Planning

During the beginning of the Conceptual Design and Advance Planning Phase, the skeleton or framework for the functional configuration identification is initiated. At the main and lower levels of system are broken down. The conceptual designs for the system as a whole and for the subsystems are defined. As the Conceptual Design and Advance Planning Phase continue, performance specifications, related to subsystem functionality, are created, tested and refined.



Figure 5-2: Framework for Functional Configuration Identification (Main and 1st Level)

Design questions regarding system reliability and maintainability baselines are formulated; research, development and testing methods are developed in order to discover the performance capabilities of the subsystems, the components, the materials needed, etc.

In conjunction with these activities, cost analysis is performed in order to obtain a cost baseline for the system as a new product.

An evolutionary advance planning must clearly define how the system's subsystems will be structured, including:

- A clear description of an operationally suitable core system technology including identification of subsystems and components.
- Establishment of a process for obtaining, evaluating and integrating operational feedback, technology limits and tolerances via a testing plan.

- A baseline for developing a description of the technical constraints associated with the technical design of each subsystem.
- A testing and maintenance plan
- Risk analysis of the developmental design and functionality approach of the product as a unified system of systems.

5.8 The Milestones of the Conceptual Design and Advance Planning Phase consists of:

- PMP The Program Management Plan is initiated with the definition of program requirements which in turn, leads to the identification of system engineering requirements and, the preparation of a detailed System Engineering Management Plan (SEMP).
- SEMP The System Engineering Management Plan describes the activities, processes, and tools that will be used by the design and development teams to support the design and construction of the SOFC Power System. The objective of the Systems Engineering effort is to assure successful development of the power system primarily by defining clear and accurate system requirements and verifying compliance of the power system to those requirements.
- TEMP the Testing and Evaluation Master Plan is a document which includes the requirements for test and evaluation, the categories of test, the procedures for accomplishing testing, the resources required, and the associated planning information (i.e., tasks, schedules, organizational responsibilities, and cost).

- Conceptual Design Review The Conceptual Design Review is usually scheduled towards the end of the Conceptual Design and Advanced Planning Phase prior to entering into the Preliminary System Design Phase. The objective is to review and evaluate the functional baseline for the system, and the material to be covered through this review should include the following:
 - Feasibility Analysis.
 - System Operational Requirements.
 - System Maintenance Concept.
 - Reliability Factors.
 - Technical performance measures (TPMs).
 - System Specification (Type A).
 - System Engineering Management Plan
 - o Test and Evaluation Master Plan
 - System design documentation (layout drawings, sketches, parts lists, selected suppliers components data) – description of the system architecture.

In the next section, the activities of the early part of this phase will be explored, namely a very simple market analysis and, alternatives of a power system's conceptual design which might meet the customer's requirements.

5.9 The Need Identification Analysis

Gause and Weinberg characterize a "problem" as "the difference between things as perceived and things as desired." [Sidky, 2002]

Table 5-1 NEED IDENTIFICATION ANALYSIS				
[Blan	nchard, 2008, Keys, 2010, Sidky	y, 2002]		
Required Inputs	Expected Outcome	Resources		
 Customer surveys Marketing inputs Market niche studies Competitive product research 	 A specific qualitative and quantitative needs statement responding to a current deficiency. 	 Benchmarking, statistical analyses of data. 		

Problem analysis, therefore, can be viewed as the process of understanding the customer's real problem, and then translating that understanding into a set of needs. One of the easiest ways of specifying problems is by reference to a set of objectives.

The two concepts, objectives and problems, are two sides of the same coin. A fuel cell developer can start either with objectives or problems and come to the same conclusions. Objective analysis of problems requires the adoption of an appropriate set of indicators and targets. A system is only as good as the requirements from which it is developed. It is crucial, therefore, that fuel cell developers gain a firm understanding of the customer's stated as well as implied needs. The Conceptual and Advance Design Phase of an innovative NPD begins with developing a clear conception of the customer's need or problem by answering basic questions:

- *How did the problem or need arise?*
- Who believes it to be a problem or feels there is a need?
- In what terms should the customer's problem be defined in?
- Who is the customer?
- Why is a solution important? How much money (time, etc.) will it save, in other words, what are the benefits to the solution's use?

- What is the value of the system?
- *How important is the need?*
- What are the end user's needs or requirements?

5.10 In what terms should the customer's problem be defined in?

"*Electricity*", a form of energy now indispensable in our daily lives, is generated in large-scale atomic, thermal, or hydroelectric power stations and transmitted along power lines to individual homes.

To accommodate more renewable energy, the future electricity system will look significantly different from now. In an earlier chapter the problems of modern energy production were noted, the problems current energy sources were covered and, the need for renewal energy explained. Because of these and other problems, the United States Department of Energy (DOE) strongly believes that stationary fuel cells can save energy, reduce emissions, and offer increased reliability compared to traditional technologies.

DOE is a cabinet-level department of the United States government concerned with the United States' policies regarding energy and safety in handling nuclear material. Its responsibilities include energy conservation, energy-related research, and domestic energy production. DOE also sponsors more basic and applied scientific research than any other US federal agency; most of this is funded through the United States Department of Energy National Laboratories.

DOE helps the development of high-efficiency fuel cell systems for distributed and stationary uses as an alternative power source to grid-based electricity for buildings, which account for approximately 36% of the primary energy consumption and 30% to 40% of airborne emissions in the United States.

Table 5-2					
DOE TECHNICAL TARGETS					
[US Depart	ment of Ene	ergy, 2011]			
Year	2008	2012	2015	2020	
Electrical Efficiency at rated	34%	40%	42.5%	45%	
power ²					
CHP energy efficiency ³	80%	85%	87.5%	90%	
	\$750/kW	\$650/kW	\$550/k	\$450/kW	
Factory Cost ⁴			W		
Transient response (10%-90%	5 min	4 min	3 min	2 min	
rated power)					
Start-up time from 20 ^o C ambient	60 min	45 min	30 min	20 min	
temperature					
	<2%/100	0.7%/100	0.5%/1	0.3%/10	
Degradation with cycling ⁵	0 h	0 h	000 h	00 h	
Operating lifetime ⁶	6,000 h	30,000 h	40,000	60,000 h	
			h		
System availability	System availability 97%				
¹ Standard utility natural gas delivered at	¹ Standard utility natural gas delivered at typical residential distribution line pressures.				
² <i>Regulated AC net/lower heating value of fuel</i>					
⁴ Cost includes materials and labor costs to produce stack plus any balance of plant necessary					
for stack operation. Cost defined at 50.000-unit/year production (250MW in 5-kW modules).					
⁵ Based on operating cycle to be released in	⁵ Based on operating cycle to be released in 2010.				
⁶ <i>Time until</i> >20% <i>net power degradation</i>					

With regards to the end user's needs or requirements, a full articulation of the concept of the needs analysis and system requirements definitions should be performed. From a designer's standpoint, a type of fuel cell power system must be selected which is based on how well it fits the customer's requirements which is electricity for household power consumption.

5.11 What about the Electricity? - Defining the customer's problem, what is it?

The kilowatt hour (\mathbf{k} ·**Wh**) is most commonly known as a billing unit for energy delivered to residential consumers by electric utilities. The kilowatt hour is a unit of energy equal to 1000 watt hours or 3.6 megajoules. For constant power, energy in watt hours is the multiplication of power in watts and time in hours.

Examples:

- A heater rated at 1000 watts (1 kilowatt), operating for one hour uses one kilowatt hour (equivalent to 3,600 kilojoules) of energy.
- Using a 60 watt light bulb for one hour consumes 0.06 kilowatt hours of electricity.
- Using a 60 watt light bulb for one thousand hours consumes 60 kilowatt hours of electricity.

5.12 Who is the Customer?

The Residential Energy Consumption Survey (RECS) [US Energy Information Administration (EIA), 2011] is a national area-probability sample survey, given out by the U.S. Energy Information Administration that collects energy-related data for occupied primary housing units. RECS data come from three sources:

- 45-minute in-person interviews with householders of sampled housing units.
- Mail questionnaires from or in-person or telephone interviews with rental agents for sampled rental units where some or all energy costs were included in the rent.
- Mail questionnaires from energy suppliers who provide actual energy consumption and expenditure data for the sampled housing unit.

The RECS provides information on the use of energy in residential housing units in the United States. This information includes:

- The physical characteristics of the housing units,
- The appliances utilized including space heating and cooling equipment,

- Demographic characteristics of the household,
- And, the types of fuels used and other information that relates to energy use.

The RECS also provides energy consumption and expenditures data for:

- Natural gas,
- Electricity,
- Fuel oil,
- Liquefied petroleum gas (LPG), and,
- Kerosene

RECS data are tabulated for the United States four census regions, the nine census divisions, and for the four most populous States--California, Florida, New York, and Texas. In 2009, the average annual electricity consumption for an U.S. residential utility customer was **11,040 k·Wh**, an average of **920 kilowatt-hours (k·Wh) per month**. Tennessee had the highest annual consumption at **15,624 k·Wh** (per year) and Maine the lowest at **6,252 k·Wh**. The latest RECS was conducted in 2009, see **APPENDIX B** for details. Below is a table showing the 2009 energy need of Maine, Ohio and Tennessee tabulated monthly energy consumptions.

Table 5-3					
2009 ENERC	2009 ENERGY NEEDS FOR THREE US STATES				
[US Energy In	[US Energy Information Administration (EIA), 2010]				
	k-Wh per Month SOFC Power System Size				
State	_	k∙W			
Maine	521	0.72			
Ohio	878	1.22			
Tennessee	1,248	1.73			

5.13	The Power Rec	quirements for	r the Typical	Residential H	Household in Ohio
		1	~ 1		

Table 5-4EXAMPLES OF ANALYTICAL TOOLS FOR NEED AND SYSTEM REQUIREMENTS[Blanchard, 2008, Keys, 2010, Sidky, 2002]			
Required Inputs	Expected Outcome	Resources	
A specific qualitative and quantitative needs statement expressed in functional terms.	Qualitative and quantitative factors pertaining to system performance levels, expected utilization profiles, operational lifecycle, effectiveness requirements, the levels of maintenance and support, logistic support, and so on.	Quality function deployment; input-output matrix, checklists; value engineering; statistical data analysis; trend analysis; parametric analysis; various categories of analytical models and tools for simulation studies, trade off, etc.	

By using hypothetical examples, in this phase, fuel cell developers can aid systems engineers in developing strategic, flexible long-term plans for their NPD. For demonstration purposes of this design practice, a hypothetical household was created for determining the electrical needs of a (typical) residential customer living in Northeastern Ohio (**See Appendix C**).

Table 5-5 DAILY ITEMIZED HYPOTHETICAL HOUSEHOLD'S ENERGY REQUIREMENTS (See Appendix C)				
Description of Household Appliances	Quantity	Watts consumed		
Incandescent Lamp A	1	60		
Incandescent Lamp B	1	60		
Incandescent Lamp C	1	30		
Incandescent Lamp D	1	10		
Microwave Oven	1	400		
Electric Stove	1	100		
Garbage Disposal	1	50		
Dishwasher	1	200		
Coffee Maker	1	50		
Fan & Vent	1	35		
Clocks	2	2		
Televisions	1	100		
DVD Player	1	10		
Refrigerator	1	400		
Central Air Unit	1	1500		

5.14 Sizing a FC Power System for Residential Use

From the hypothetical example, the FC Power System must satisfy two criterions:

- First, it must be able to deliver the 'peak amperage' that may be desired, which turned out to be 21-Amps.
- Second, the FC system must provide the average power consumed over the day, which turned out to be 3.50 k·Watt·hours. Note the power output has been round up in order to account for efficiency and other losses.

For this example, a system that could provide **3.50-** kW peak power and **0.7 k·Watt** base capacity is needed. A summary of energy requirements (not counting the BOP energy requirements) is listed in the table below.

Table 5-6CALCULATED HYPOTHETICAL					
HOUSEHOLD'S ENE	HOUSEHOLD'S ENERGY CONSUMPTION				
Max Peak Watts	Max Peak Watts 3.34 k·Wp				
Continuous Power	16.263	kW∙hr			
Base Capacity	0.68	k·Watt			
Max Peak Current	21	Amps.			

5.15 What about the Heat Requirement?

The household furnace, a major appliance, is permanently installed in a residential home to provide heat to an interior space through intermediary fluid movement, which may be air, steam, or hot water. The most common fuel source for modern furnaces in the United States is natural gas; other common fuel sources include LPG (liquefied petroleum gas), fuel oil, coal or wood. In some cases electrical resistance heating is used as the source of heat, especially where the cost of electricity is low.

The furnace system can be divided into three major subsystems:

- 1. A Thermal System comprising: the burners, heat exchanger, draft inducer, and venting.
- 2. An Electrical System comprising: the controls and safety devices.
- 3. A Mechanical System comprising: the blower and air movement.

Combustion furnaces are always vented to the outside. Traditionally, ventilation was through a chimney which tended to expel heat along with the exhaust. Modern "high-efficiency" furnaces can be 98% efficient and operate without a chimney. The small amount of waste gas and heat are mechanically ventilated through a small tube through the side or roof of the house. Modern household furnaces are classified as condensing or non-condensing based on their efficiency in extracting heat from the exhaust gases.

Furnaces with efficiencies greater than approximately 89% extract so much heat from the exhaust that water vapor in the exhaust condenses; they are referred to as condensing furnaces. Such furnaces must be designed to avoid the corrosion that this highly acidic condensate might cause and may need to include a condensate pump to remove the accumulated water.

5.16 What about Efficiency for a Furnace?

The Annual Fuel Utilization Efficiency (AFUE) is a thermal efficiency measure of combustion equipment like furnaces, boilers, and water heaters. The AFUE differs from the true 'thermal efficiency' in that it is not a steady-state, peak measure of conversion efficiency, but instead attempts to represent the actual, season-long, average efficiency of that piece of equipment, including the operating transients [ASHRAE Handbook].

The method for determining the AFUE for residential furnaces is the subject of ASHRAE Standard 103. A furnace with a thermal efficiency (η_{th}) of 78% may yield an AFUE of only 64% or so, for example, under the Standard's test conditions [ASHRAE Handbook]. When estimating annual or seasonal energy used by combustion devices, the AFUE is the better efficiency measure to use in the calculations. But for an instantaneous fuel consumption rate, the thermal efficiency may be better.

5.17 Who sets the US standards for Heating?

Federal agencies are required by the National Energy Conservation Policy Act (P.L. 95-619), Executive Order 13423 and Federal Acquisition Regulations (FAR) Subpart 23.2 and 53.223 to specify and buy ENERGY STAR®-qualified products or, in categories not included in the ENERGY STAR program, FEMP-designated products which are among the highest 25 percent of equivalent products for energy efficiency. This specification applies to residential furnaces that operate on propane or natural gas and have heat input rates less than 225,000 British Thermal Units per hour (Btu·h).

Annual energy use in the below example is based on the standard DOE test procedure for a non-weatherized furnace configured with an upward airflow and heating capacity of 72,000 Btu·h. Operating hours are assumed to be 2,080 hours per year. The assumed price for natural gas is \$1.00 per "*Therm*" and electricity is \$8¢ per kilowatt-hour, the average rates for federal facilities throughout the United States. A "*Therm*" is a non-SI unit of heat energy equal to 100,000 British thermal units (BTU). It is approximately the energy equivalent of burning 100 cubic feet (often referred to as 1 Ccf) of natural gas.

Table 5-7 THE BASE MODEL FOR COST-EFFECTIVENESS OF FURNACE PERFORMANCE

[U.S. Department of Energy, Federal Program Federal Energy Management Program, 2009]

	Raca Madal	Doquirod	Bost Availabla^B		
Performance	Dase Wilder	Requireu	Dest Available		
Annual Fuel Utilization Efficiency ^A	80%	90%	95%		
Annual Natural Gas Use	750 therms	660 therms	635 therms		
Annual Natural Gas Cost	\$750	\$660	\$635		
Annual Electricity Use	1,200 kWh	990 kWh	225 kWh		
Annual Natural Electricity Cost	\$96	\$80	\$18		
Lifetime Energy Cost ^C \$11,730 \$10,230 \$9,030					
Lifetime Energy Cost Savings	-	\$1,500	\$2,700		
A. From GAMA's Consumer's Directory of Certified Efficiency Ratings for Heating and Water Heating Equipment.					
B. More efficient products may have been introduced to the market since this Specification was published.					
C. Lifetime Energy Cost is the sum of the discounted value of annual energy costs based on average usage and an assumed furnace life of 20 years. Future natural gas and electricity price trends and a discount rate of 3.0% are based on federal guidelines (effective from April 2008 to March 2009).					

The efficiency of the above model meets current US DOE appliance standards,

efficiency standards and is equipped with a standard fan motor. The Best Available

represents the most efficient product on the market for this size class that also meets the

CEE/GAMA annual electricity use (EAE) criterion.

5.18 The Fuel of Residential Choice– Natural Gas

Many residential customers in the United States use natural gas as an energy

source. Many fuel cell systems can operate on natural gas. During a Needs Analysis, the

designer of a fuel cell system must determine which fuel his system can operate on.

Natural gas is supplied to homes where it is used for such purposes as cooking in gas-powered ranges and ovens, gas-heated clothes dryers, heating/cooling and central heating.

Home or other building heating may include boilers, furnaces, and water heaters. Compressed Natural Gas (CNG) is used in rural homes without connections to piped-in public utility services, or with portable grills.

Natural gas is also supplied by independent natural gas suppliers through Natural Gas Choice programs throughout the United States. However, due to CNG being less economical than LPG, LPG (propane) is the dominant source of rural gas.

In 2007, Ohio had 3,273,791 residential, 272,548 commercial, and 6,865 industrial customers. They consumed approximately 300, 159, and 295 billion cubic feet of natural gas, respectively. Currently, Ohio has 35 natural gas suppliers certified to participate in Natural Gas Choice programs including IGS Energy, M Xenergy and Spark Energy.

5.19 The Size of the "Average" House in the United States – a Potential SOFC Market

According to a 2006 report, the average American house size has more than doubled since the 1950s; it now stands at 2,349 square feet [Alder, 2006].





Figure 5-3: Form Modest to McMansion (the average square footage of a new single-family home). [Alder, 2006]

Figure 5-4: The average size of a new home by region: 2005. [Alder, 2006]

The BTUs required that could heat a 2, 349 square feet home was calculated to be 69,925 BTUs. How the 69,925 BTUs were derived was by following the below procedure:

1. The area of the house is 2,349 square feet. Multiply the square footage by 25. For a 2,349 -square-foot area, 2,349 x 25 = 58,725.

2. The number of windows this hypothetical house has is ten (10); therefore,

multiply the number of windows in the area by $1,000, 10 \ge 10,000$.

3. A count of the individuals who live in the house are needed and multiply by 400. For this example, three individuals live in the house, so $3 \ge 400 = 1,200$,

multiplied the number of individuals.

4. Sum the results from Steps 1, 2 and 3.

Therefore: (58,725+10,000 + 1,200) BTUs = 69,925 BTUs.

Converted to kilowatts, the heat requirement of the hypothetical household was found to be **20.5** \mathbf{k} ·W. In order to compete with the modern furnace an SOFC Power System must be able to supply the '*average*' household with this amount of heat.

Table 5-8SYNTHESIS OF CONCEPTUAL SYSTEM DESIGN ALTERNATIVES[Blanchard, 2008, Keys, 2010, Sidky, 2002]			
Required Inputs	Expected Outcome	Resources	
Results from needs analysis and requirements definition process; technology research studies; supplier information. Candidate conceptual solutions and technologies; results from the needs analysis and requirements definition process.	Identification and description of candidate conceptual system design alternatives and technology applications. Approximation of the "goodness" of each feasible conceptual solution relative to the pertinent parameters, both direct and indirect. This goodness may be expressed as a numeric rating, probabilistic measure, or fuzzy measure.	Pugh's concept generation approach; brainstorming; checklists. TRIZ, Design Structure Matrix. Indirect system experimentation (e.g., mathematical modeling and simulation); parametric analyses; risk analysis.	

5.20 The Design Synthesis of System Design Alternatives

From the needs analysis, once the requirements are specified a systematic

approach for designing the product needs to be in place. The analysis goals of the system design are fashioned from the requirements of the customer with a 2, 349 square feet home which were:

- Lifespan the same as a furnace or hot water heater.
- System availability of 97%.
- Annual Fuel Utilization Efficiency of 95%
- Must produce ~4.0 k·W (electricity).
- Must produce ~21k·W (thermal heat).
- The ability to run off natural gas.

Suppose that further market analysis and system design considerations dictate that inexpensive materials must be used in order to keep the overall cost of the system down, this requirement should be added to the analysis goals checklist.

5.21 The Algorithm for Evaluating Design Alternatives

Although the SOFC power system is the topic of this paper, a method for selecting a particular fuel cell power system design based on the analysis goals should be touched upon briefly. When the alternative solutions are narrowed down, and it becomes apparent that an innovative technology is favored, inventiveness is needed to provide a range of strategies and tools for fueling product development. The below figure shows an algorithm systems engineers use to make macroscopic design choices and decisions. The advantage of this approach to decision making is that subjective opinions about one alternative versus another can be made more objective. It can be used also for decision making once the design concept has been frozen and system/subsystem/component development is underway. Another advantage of this method is that sensitivity studies can be performed. An example of this might be to see how much a design opinion would have to change in order for a lower ranked alternative to out rank a competing alternative.



Figure 5-5: Algorithm for Evaluating Design Alternatives [Blanchard, 2008]

The analysis goals have already been listed. A weighting scale should be assign to each criterion.

Table 5-9
WEIGHTING OF ANALYSIS GOALS
Most important criteria:
Produce $\sim 4.0 \text{ k} \cdot \text{W}$ (electricity).
Produce $\sim 21 \text{k} \cdot \text{W}$ (thermal heat).
Fabricated using inexpensive materials
Criteria which needs further development
after choice (type of fuel cell) is made:
System availability of 97%.
Annual Fuel Utilization Efficiency of
95%
Lifespan the same as a furnace or hot
water heater.

5.22 Which Type of FC should be selected?

Three types of low temperature fuel cells are the DMFCs, the AFCs and the PEMs. Direct-methanol fuel cells or DMFCs are a subcategory of proton-exchange fuel cells in which methanol is used as the fuel. Their main advantages are the ease of transport of methanol, an energy-dense yet reasonably stable liquid at all environmental conditions, and the lack of complex steam reforming (used to generate hydrogen from fossil fuels) operations. Efficiency is presently quite low for these cells, so they are targeted especially to portable applications, where energy and power density are more important than efficiency.

Table 5-10						
	TYPES OF FUEL CELLS					
	L L	U.S. Depar	tment of Energy,	2010]		1
Name	Electrolyte	Power Output (W)	Operating Temperature (C°)	Efficiency Cell	Efficiency System	(\$US /W)
Alkaline Fuel Cell (AFC)	Aqueous Alkaline Solution	10 – 100 kW	< 80	60–70%	62%	N/A
Direct- methanol fuel cells or DMFCs	Polymer Membrane (ionomer)	100- mW – 1 kW	90–120	20–30%	10–20%	125
Proton Exchange Membrane Fuel Cell (PEMFCs)	Polymer Membrane (Ionomer)	100 W - 500 kW	50–120 (Nafion) 125–220 (PBI)	50–70%	30–50%	30– 35
Phosphoric Acid Fuel Cells (PAFC)	Phosphoric Acid	< 10 MW	150-200	55%	40% Co-Gen: 90%	4– 4.50
Solid Oxide Fuel Cell (SOFC)	O ²⁻ - conducting ceramic oxide	< 100 MW	500-1100	60–65%	55-60%	N/A

The alkaline fuel cell (AFCs), also known as the Bacon fuel cell after its British inventor, is one of the most developed fuel cell technologies and is the cell that flew man to the Moon. NASA has used alkaline fuel cells since the mid-1960s, in Apollo-series missions and on the Space Shuttle. AFCs consume hydrogen and pure oxygen producing potable water, heat, and electricity. They are among the most efficient fuel cells, having the potential to reach 70%. Alkaline fuel cells use an electrolyte that is an aqueous (water-based) solution of potassium hydroxide (KOH) retained in a porous stabilized matrix. The concentration of KOH can be varied with the fuel cell operating temperature, which ranges from 65°C to 220°C. The charge carrier for an AFC is the hydroxyl ion (OH-) that migrates from the cathode to the anode where they react with hydrogen to

produce water and electrons. Water formed at the anode migrates back to the cathode to regenerate hydroxyl ions. Therefore, the chemical reactions at the anode and cathode in an AFC are shown below. This set of reactions in the fuel cell produces electricity and by-product heat.

Polymer electrolyte membrane (PEMFCs) fuel cells—also called proton exchange membrane fuel cells-deliver high-power density and offer the advantages of low weight and volume, compared with other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. A decomposition of the membrane takes place if different grade fuels are used. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO. Typically fueled with pure hydrogen supplied from storage tanks or on-board reformers. Polymer electrolyte membrane fuel cells operate at relatively low temperatures, around 80° C (176°F). Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel.

The PEMFCs requires heavy accessories. Operating compressors, pumps and other apparatus consumes 30% of the energy generated. The PEMFC stack has an

estimated service life of 4000 hours. The relatively short life span is caused by intermittent operation. Start and stop conditions induce drying and wetting, which contributes to membrane stress. If run continuously, the stationary stack is estimated at 40,000 hours. Stack replacement is a major expense. There is little tolerance for contaminates such as sulfur compounds or carbon monoxide. Carbon monoxide can poison the system. The complexity of repairing a fuel cell stack becomes apparent when considering that a typical 150V, 50 kW stack contains about 250 cells.

Being a mid-temperature range fuel cell, PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEM cells, which are easily "poisoned" by carbon monoxide because carbon monoxide binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. They are 85% efficient when used for the co-generation of electricity and heat but less efficient at generating electricity alone (37%–42%). This is only slightly more efficient than combustion-based power plants, which typically operate at 33%–35% efficiency. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. Like PEM fuel cells, PAFCs require an expensive platinum catalyst, which raises the cost of the fuel cell.

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte. Because the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. SOFCs are expected to be around 50%–60% efficient at converting fuel to electricity. In applications designed to

capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 80%–85%.

A general comparison of fuel cell technology, a significant advantage of the SOFC is its leniency to fuel. Carbon monoxide, a contaminant in the PEM systems, is a fuel for the SOFC. In addition, the SOFC system offers a fuel efficiency of 60 percent, one of the highest among fuel cells. The limitations of the PEM system are high manufacturing costs and complex water management issues. The stack contains hydrogen, oxygen and water. If dry, the input resistance is high and water must be added to get the system going. Too much water causes flooding. The low efficiency of the PAFC coupled with its limited service life and expensive catalyst makes the PAFC a poor choice for cost effective residential use.

Based on power output, all of the fuel cells, except for the AFCs seem able to provide the end user with power in the requirement range.

5.23 For Power Production – Which Fuel Cell Power System is the best?

In order to select a type of fuel cell, the electrical requirements for the hypothetical household was evaluated.





For demonstrating the simplified design process and decision making of systems engineering, three types of the fuel cells have been selected based on their power output which could meet the electrical requirements of the hypothetical household. Note, the household's thermal requirements are not considered when making this selection. The tables below depict three different types of fuel cell systems, namely the PEMFCs, the SOFCs and the PAFCs and it provides a summary of the major advantages and disadvantages of each type.

Table 5-11				
THREE TYPES OF FUEL CELLS				
	. Department of Energy, 2010	DAEC.		
PEMIFCS	SUFCS	PAFCS		
Power Output Range is 100 W – 500 kW.	Power Output Range is < 100 MW.	Power Output Range is < 10 MW.		
 Advantages Solid electrolyte reduces corrosion & electrolyte management problems Low temperature Quick start-up 	 Advantages: High efficiency Fuel flexibility Can use a variety of catalysts Solid electrolyte Suitable for CHP & CHHP Hybrid/G T cycle 	 Advantages: Higher temperature enables CHP Increased tolerance to fuel impurities 		
Disadvantages:		Disadvantages:		
 Expensive catalysts Sensitive to fuel impurities Low temperature waste heat 	 Disadvantages: High temperature corrosion and breakdown of cell components High temperature operation requires long start up time 	 Pt catalyst Long start up time Low current and power		
5.24 For Thermal Energy Production – Which Fuel Cell Power System is the

best?



Figure 5-7: Decision design diagram based on the criteria of thermal energy production

The SOFCs appear to be the most promising type of fuel cell for residential use base on the facts that SOFCs can provide electricity (high voltage and current if needed) and high quality heat, operate on many types of fuels and, if designed correctly, could possibly be the least expensive type of fuel cell of the three, although currently, the PAFCs appear to be the '*least expensive*' based solely on initial price. Unlike PAFCs and PEMFCs which require precious metal catalyst to operation, SOFCs' catalysts can be made of common (cheap) metals.

5.25 The Profile of a Solid Oxide Fuel Cell

Solid oxide fuel cells operate at very high temperatures—around 1,000°C (1,830°F). To make efficient use of energy, the "*waste heat*" produced by an SOFC Power System must be used purposefully. Traditionally, since it is practical to transport electricity, but not always practical, to transport waste heat, an energy efficient power system must generate electricity near locations where the waste heat can be put to good use.

The space heating thermal requirement of a household can often be ten times greater than the electrical load. It can thus be seen that the use of residential fuel cell power systems to serve space-heating loads is difficult to achieve without other system concepts. In contrast, the domestic hot water demand illustrates a better match between the magnitudes of thermal energy available from the SOFC Power System and the thermal energy required. The thermal capacity factor of the fuel cell, defined as, *'the kWh recovered from the exhaust gas divided by the kWh that could have been supplied had the exhaust gases been reduced to the water main temperature'*, is a useful measure in discussing such heating applications.

Some other advantages SOFCs have with regards to residential use, hightemperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally if needed, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more of sulfur than other cell types. In addition, they are not poisoned by

carbon monoxide (CO), which can even be used as fuel. This property allows SOFCs to use gases made from coal.

5.26 Is an SOFC Power System, as a commercialized product, possible?

It has been shown in a 2001 study by the Energy Center of Wisconsin, that 81% thermal capacity factor was achieved by a 2kW SOFC Power System simulation model. In cogeneration mode it displaced 4,800 kWh of thermal energy that otherwise would have been provided by a residual hot water heater. This high degree of waste heat recovery was possible due to the use of a 2-tank thermal storage configuration, see the below figure. Using thermal storage applications, such as this, would effectively increase fuel cell electric and thermal capacity factors.



Figure 5-8: 2kW SOFC Power System Simulation Model [Energy Center of Wisconsin, 2001]

The conceptual system was designed for electric load following and buffering of non-steady electrical demands by the grid. The two-tank hot water storage configuration allows for thermal buffering, that is, heat recovery during zero hot water 'draws' situations. Cold water from the main entered the first hot water tank at 10°C. Depending on the amount of heat recovery and the tank temperature, the cold water was heated from 10° to about 65°C. If the heated water left the first tank at a temperature lower than 60°C, a burner in the second tank accomplished supplementary heating to the delivery temperature. At rated power conditions, fuel cell waste heat gases enter the first hot water tank at 385°C where 1.6 kW of heat was recovered before the gases exhaust the system at about 95°C. The corresponding steady-state thermal-to-electric power ratio was found to be 0.8:1 at rated power conditions, meaning that for every 1kW of electricity was produce, 0.8 kW of heat was produced.

5.27 They were *not* the First...

SOFCs were not the World's first high temperature devices. To give the reader a relative sense of the kind of temperatures, reliability and safety issues involved with high temperature devices, four examples that Society has live with, in the past and present, will follow.

Wood gas is a syngas, also known as producer gas, which is produced by thermal gasification of biomass or other carbon-containing materials such as coal in a gasifier or wood gas generator. It is the result of two high-temperature reactions (above 700 °C (1,292 °F)): an exothermic reaction where carbon burns to CO_2 but is then reduced partially back to CO (endothermic); and an endothermic reaction where carbon reacts with steam, producing carbon monoxide (CO), molecular hydrogen (H₂), and carbon dioxide (CO₂). A wood gasifier takes wood chips, sawdust, charcoal, coal, rubber or similar materials as fuel and burns these incompletely in a fire box, producing solid ashes and soot (which have to be removed periodically from the gasifier) and wood gas. The

wood gas can then be filtered for tars and soot/ash particles, cooled and directed to an engine or fuel cell.

The first wood gasifier was apparently built by Bischof in 1839. The first vehicle powered by wood gas was built by Thomas Hugh Parker in 1901. Around 1900, many cities delivered wood gas (centrally produced, typically from coal) to residences. Natural gas began to be used only in 1930. Wood gas vehicles were used during World War II in countries such as Sweden and Finland.

Fluidized bed combustion (FBC), another example of a high temperature device, is a combustion technology used in power plants. Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer.

FBC plants are more flexible than conventional plants in that they can be fired on coal and biomass, among other fuels. Fluidized-bed combustion evolved from efforts to find a combustion process able to control pollutant emissions without external emission controls (such as scrubbers-flue gas desulfurization). The technology burns fuel at temperatures of 1,400 to 1,700 °F (750-900 °C). FBC boilers can burn fuels other than coal. Wood gasifiers are still manufactured in Singapore, China and Russia for automobiles and as power generators for industrial applications.



Figure 5-9: Combustion systems for solid fuels [Wikipedia, 2010]

A third example, a piston is a component of reciprocating engines, reciprocating pumps, gas compressors and pneumatic cylinders, among other similar mechanisms. A piston's typical temperature range is around 500° to 600° F.



Figure 5-10: CAD drawing of crankshaft and pistons [Wikipedia, 2010] Lastly, a boiler is a closed vessel in which water or other fluid is heated. The heated or vaporized fluid exits the boiler for use in various processes or heating applications. Most boilers produce steam to be used at saturation temperature; that is,

saturated steam. The steam piping is directed through the flue gas path in the boiler furnace. The temperature in this area is typically between 1,300-1,600 degrees Celsius (2,372-2,912 °F).



Figure 5-11: A Stationary Boiler [Wikipedia, 2010]

5.28 The Design of a System in the context of cost

In the design of systems it is important to view all decisions in the context of total cost if one is to properly assess the risks associated with the decisions in question. In addressing the aspect of economics, one often wonders if there is a lack of total cost visibility linked with fuel cell development. Where as the Cell Stack has received the greatest amount of research and development because it is the "*heart*" of the fuel cell power system; i.e., the electrochemical process, the Balance-of-Plant (BOP) and Cabinet have received the least amount of attention since a basic tenet of the of fuel cell manufacturers is that the assemblies within the BOP and the Cabinet components can be manufactured from existing technology.

On the other hand, the BOP represents up to 50% of the overall cost of commercialized fuel cell power systems. Ongoing research and, development indicates a need for specialized BOP components, particularly in areas of compressors and expanders. Very little, if nothing is said about the design, development and testing of the Enclosure's components and the Enclosure's costs.

5.29 Conclusion

Every developer of fuel cell power systems has at one time or, other, during the Conceptual Design and Advance Planning Phase has completed the following activities: performed a needs analysis in order to target a market for the new product; create hypothetical models for analyzing customer's requirements; and started design synthesis for a conceptual system design.

All activities of NPD are done with cost in mind. As the lifecycle of the NPD of a fuel cell system continues, the market that was first selected might remain the target market or, the selection might change to another group.

If the market group of early adopters must change, the fuel cell developer would be wise to select a group, whose requirements for the power system are very close to the original group's needs. The reasons for this will be explained later in this paper.

Hypothetical models are used to analyze simple concepts, which later, might because the bases for simulation modeling, which in turn might be the foundation upon which systems models are based. Besides helping the designer select the best design which best satisfies the customer's needs, any design synthesis for a conceptual system must take into consideration, *will the customer consider the product to be a safe one* or does the potential customer base has any previous dealings with a product which has characteristics very similar to the NDP.

In the next chapter, a subsystem, top-down design "*description*" of an SOFC power system will follow, as well as, a physical and functionality descriptions of each subsystem of the BOP and the Cell Stack Package.

Besides the activity of performing a market analysis, in the Conceptional and Advance Design Phase of new product development, the proper utilization of the engineering and technology management innovation process with the end result directed at addressing the aspect of economics in all design and development decisions made in the context of total system cost is the motivation for a Top-Down Hierarchy Breakdown of a System.

The evaluation of technology applications, the system's conceptional design, its operational requirements, makes way for the creating of a system feasibility analysis, a maintenance concept baseline, and advance program planning.

CHAPTER VI THE TOP-DOWN HIERARCHY BREAKDOWN OF A SYSTEM – PHASE ONE

6.1 A Part Centric Top-Down Design Approach

In the Conceptual Design and Advance Planning Phase a description of the system concept will include sketches, drawings and/or model(s). A good initial overview of a fuel cell power system's hierarchy architecture is to provide an understanding about the needs, the requirements, the complexities, and the challenges fuel cell developers have in their endeavour to create a marketable product. A Top-Down Design approach is essential for breaking down a fuel cell system in order to gain insight into its compositional sub-systems.

In a Top-Down Design Approach, an overview of the fuel cell system is first formulated, specifying, but not detailing any first-level subsystems. Each subsystem of the whole system is then refined in yet greater detail, sometimes in many additional subsystem levels, until the entire specification is reduced to base elements.



Figure 6-1: The Top-Down Design [Wikipedia, 2010]

The Top-Down Design Approach is preferred because, at the beginning of an analysis and design cycle, it is usually not possible to know the lower level design details. A top-down model is often specified with the assistance of "*black boxes*", the black boxes make it easier to manipulate the design of the system. However, the drawback associated with "*black boxes*" is that it may fail to elucidate elementary mechanisms or be detailed enough too realistically, validate the model. A Part-Centric Top-down design eliminates many of the risks associated with a general Top-Down Design Approach.

Depending on the complexity of the fuel cell system, a number of levels of the system will be created until the basic definition of components and their functions can be identified. The structures of fuel cell systems are in deed very complex and are made up of many smaller sub-systems which interact with one another. The interaction effects between the different fuel cell sub-systems within a higher-level system of systems (SOS) configuration, often leads to added complexities making it necessary to design fuel cell systems so that changes can be incorporated quickly, efficiently, and without causing a significant impact on the overall configuration of the system. Systems engineering practices and methods can be the means by which design modifications are structured.

In characterizing a SOFC Power System's design needs, requirements and challenges by way of providing a *'functional view'* which focuses on *'WHAT'* the system must do to produce the required operational behavior, the functional requirements, in combination with the physical breakdown are the primary sources for the system's and its subsystem specifications. By providing a physical view (breakdown) of the system will later lead to baselining for defining, for example:

- The System's Handicaps (special operating environments).
- The Technical and/or Design Constraints.
- The System's Physical Limitations (*capacity, power, size, weight*).
- Its technology limitations (*range, precision, data rates, frequency*).
- The need for Commercial-Off-the-Shelf (COTS), Non-developmental Item (NDI), and reusability requirements.
- The evaluation for necessary or directed standards.

6.2 The SOFC Power System Structural Breakdown



Figure 6-2: The First Level System Breakdown of a SOFC Power System

A SOFC power system is built from three main subsystems:

- 1. The Cabinet Housing,
- 2. The Balance-of-Plant (BOP)
- 3. And, lastly, The Cell Stack Package

6.3 The Cabinet Housing of the SOFC Power System

The Cabinet (Enclosure) is the housing for the Balance of Plant Subsystems and the Cell Stack Package. It is the main part (*subsystem*) of the SOFC Power System which interacts with the end user. The Enclosure is one of the most evolutionary subsystems of the SOFC Power System. The Enclosure is highly dependent on the designs and structure of the Cell Stack configuration, the Hot Assembly, the Fuel Processing Subsystem, etc. As these and their components develop, the Enclosure of the SOFC Power System design changes in order to accommodate the requirements of the Balance of Plant, the Cell Stack Package, and the End User(s).

6.4 The Balance of Plant (BOP)

A fuel cell power system requires the integration of many components, for its Cell Stack will produce only dc power and utilizes only certain processed fuel. To name a few other functions, besides various system components are incorporated into a power system to allow operation with conventional fuels, it must also be able to tie into the AC power grid, and often, to utilize rejected heat to achieve high efficiency.



Figure 6-3: The Integration of Many Components [Fuel Cell Handbook, 2004]

As shown in latter sections of this chapter, a combination of a variety of sophisticated devices, the subsystems of the BOP are required to keep the Cell Stack Package operating. Not only that, but most SOFC Power Systems need forced air to boost the amount of oxygen into the Cell Stack Package for the electrochemical reaction to take place. Efficient compressors are required. However, when air is compressed it heats therefore an intercooler might be needed to reduce temperatures. In addition, filters must be included to keep the air, gaseous fuel, and water streams clean, as well as, flow and recirculation devices to keep the gases and fluids moving. Various energy recovery devices must be used to retain heat for the reforming process. The Power System requires monitoring, conditioning and diagnostic equipment.



Figure 6-4: The System Breakdown of a SOFC Power System

The Cabinet (Enclosure), The BOP and, the Cell Stack Package can be further divided into smaller subsystems. The BOP can be divided into seven main subsystems:

- 1. The Electrical Subsystem.
- 2. The Mechanical Subsystem.
- 3. The Hot Assembly.
- 4. The Thermal Management Subsystem.
- 5. The Air Subsystem.
- 6. The Waste Management Subsystem.
- 7. The Fuel Processing Subsystem.

The Cell Stack Package is comprised of Unit Cells. A Unit Cell can be divided into four main components: the Electrolyte, the Ceramic Electrodes, the Interconnects, and the Seals.

The configuration of the Enclosure and its functions are highly dependent on the BOP and the Cell Stack Package configuration requirements. Note as the SOFC Power System progresses through its lifecycle, the Enclosure design will evolve to meet the needs of the BOP, the Cell Stack Package and the end user.

6.5 A Brief Survey of the BOP

Two BOP systems control the regulation of the reactants going into the Cell Stack Package: the Fuel Processing System and the Air System.

The Air System serves three purposes. First, it provides oxidant for the hydrogen/oxygen chemical reaction, which takes place at the interfaces of the fuel cell, which is the principle driving force of the production of electricity. Second, it is part of the thermal management system for temperature control. Lastly, the Air System is linked to the Waste Management Subsystem for it is the means by which the Cell Stack Package is rid of exhaust gases.

The Fuel Processing System converts fuel into a form useable by the fuel cell. Fuel processing is the conversion of a commercially available gas, liquid, or solid-fuel to a fuel gas reformate suitable for the fuel cell anode reaction. Fuel Processing encompasses the cleaning and removal of harmful species in the fuel, the conversion of the fuel to the fuel gas reformate, and downstream processing to alter the fuel gas reformate according to specific fuel cell requirements.

The Waste Management System, as said earlier, manages the collection of gases, which are left over from the hydrogen/oxygen chemical reaction. The Waste Management System collects the gases, cools and vents the waste from the fuel cell

power system. Although fuel cells are not heat engines, heat is still produced and must be removed.

The Thermal Management System encompasses the power system's insulation packaging and to some extent the Air System to maintain thermal equilibrium and control. Currently, fuel cell power systems are not primarily used to generate heat.

However, this excess energy can be used to produce steam or hot water or to be converted to electricity via a gas turbine or other technologies. These methods increase the overall energy efficiency of the system. Depending upon the size of the system, the temperature of the available heat, and the requirements of the particular site, thermal energy can be either rejected, used to produce steam or hot water, or converted to electricity via a gas turbine or steam bottoming cycle or some combination thereof. Because significant amounts of heat are generated by some fuel cell systems—especially those that operate at high temperatures, such as solid oxide and molten carbonate systems—a means to control the thermal environment of the unit is imperative to the functionality of the power system.

The Mechanical System and the Hot Assembly constitutes the loading system, the mounting of the Cell Stack Package within the system, itself, packaging and all auxiliary mechanical components necessary for the fuel cell power system to function and operate.

The Electrical Subsystem is designed to control and condition the electricity produced by the Cell Stack Package. It controls the other BOP subsystems electronics, provides the BOP with power, as well as, provides power to the end user. In addition, the Electrical System supplies power and controls the data acquisition system, if one exists and, is attached to the power system. The Power Conditioning Unit of the Electrical

System converts DC electrical power generated by a fuel cell into usable AC power. Depending on the type of fuel cell power system and the overall design, the configuration of the power conditioning will vary from one type to another.

6.6 A Brief Survey of the Cell Stack Package

Fuel cells are characterized by their electrolyte material. For example, the phosphoric acid fuel cells (PAFC) are a type of fuel cell that uses liquid phosphoric acid as an electrolyte. The electrodes are made of carbon paper coated with a finely dispersed platinum catalyst, which make them expensive to manufacture.

Another example is the Polymer Electrolyte Membrane (PEM) fuel cells (PEMFC), is a type of fuel cell being developed for transport applications, stationary fuel cell applications and portable fuel cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special polymer electrolyte membrane.

A Solid Oxide Fuel Cell (*SOFC*) is a high temperature electrochemical conversion device. Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, and low emissions. A SOFC is made up of four layers, three of which are ceramic oxides (*hence the name*). A single cell consisting of these four layers stacked together is typically only a few millimeters thick.

Hundreds of these cells are then connected in series to form what most people refer to as a "*Cell Stack Package*". The ceramics used in SOFCs do not become electrically and, ironically active until they reach very high temperatures and as a consequence the stacks have to run at temperatures ranging from 500 to 1,000 °C.

Reduction of oxygen into oxygen ions occurs at the cathode. These ions can then diffuse through the solid oxide electrolyte to the anode where they can electrochemically oxidize the fuel. In this reaction, a water byproduct is given off as well as two electrons. These electrons then flow through an external circuit where they can do work. The cycle then repeats as those electrons enter the cathode material again.

6.7 The Introduction to the Fuel Processing System

A fuel cell is similar to a typical battery in many ways, although it differs in several respects. Namely, a battery is an energy storage device in which all the energy available is stored within the battery itself (*at least the reductant*). Also, the battery will cease to produce electrical energy when the chemical reactants are consumed (*i.e.*, *discharged*). A fuel cell, on the other hand, is an energy conversion device in which fuel and oxidant are supplied continuously. In principle, the fuel cell produces power for as long as fuel is supplied.

By properly designing of a fuel processing system, a wide variety of fuels may be converted into suitable reformates. Once the fuel is transformed into reformate it then can be used to promote internal reforming for high temperature fuel cell systems. For each type of fuel cell, optimum operating parameters such as temperature, steam-to-carbon ratio, and catalyst must be established. It is increasingly recognized that the fuel processing subsystem can have a major impact on overall fuel cell system costs particularly, as ongoing research and development efforts result in reduction of the basic cost structure of the Cell Stack Package which currently dominate system costs.

6.8 The Different Paths of Electricity Generation

Figure 6-5 illustrates the different paths of electricity generation from hydrocarbon-based solids, liquids and gaseous fuels by both conventional and new technologies based on fuel cells.



Figure 6-5: Different paths of electricity generation from hydrocarbon-based solid, liquid and gaseous fuels [Song, 2002]

The most versatile fuel sources are the boiler and, the fuel cell (*when the fuel cell is equipped with a fuel processing unit*). Except when pure fuels (*such as pure hydrogen*) are used, some fuel preparation is required, usually involving the removal of impurities and, thermal conditioning. Because most fuel cells are powered by hydrogen, one major issue is the way hydrogen is generated. The best way to generate hydrogen is by extracting it from available fuels or hydrocarbon fuels such as natural gas, methanol, gasoline or ethanol by a process known as '*reforming*'. Reforming is a chemical process in which hydrogen containing fuels react with steam, oxygen or both to produce a hydrogen-rich gas stream. Fossil fuel reforming is a method of producing hydrogen or other useful products from fossil fuels such as natural gas. There are two kinds of reforming processes to choice from: external reforming, which is performed before the fuel reaches the fuel cell; and internal reforming, which occurs within the fuel cell anode (*the ceramic electrode portion of the Unit Cell*). In addition, there are three principal

pathways that reforming can take; they are steam reforming, partial oxidation, and autothermal reforming.

6.9 The Functions and Performance Requirements of the Fuel Processing System

The three main functions of the Fuel Processing System of a SOFC Power System are:

- Fuel-to-gas reformate conversion.
- Cleaning and removal of harmful compounds (e.g. *sulfur*) in the fuel.
- The filtering of the solid particulates from the fuel.

The three main subsystem requirements of the Fuel Processing System of a SOFC Power System are:

- Fuel (free of particulate and its sulfur levels within a certain tolerance range).
- Water (free of particulate and contaminants).
- Heat Production.

6.10 The Functional Analysis – The Scenario of the Anode Leg of an SOFC Power System

In the following example, a generic model of the fuel processing system will be shown. Because the fuel processing system's end product (fuel) will be supplied to the anode side of the Cell Stack Package, the fuel processing subsystem is referred to as the 'anode leg' of a SOFC Power System. Natural gas will be the system's fuel source. It will be equipped with external reforming technology. The subsystem's hydrogen production will be performed by steam reforming via a process called '*cracking*'.

'Cracking' is the process whereby complex organic molecules such as kerogens or heavy hydrocarbons are broken down into simpler molecules such as light hydrocarbons, by the breaking of carbon-carbon bonds in the precursors. The rate of cracking and the end products are strongly dependent on the temperature and presence of catalysts.



Figure 6-6: The Anode Leg of a SOFC Power System (The Fuel Processing Subsystem)

Figure 6-6 above shows the structural diagram model of the Anode Leg of the generic SOFC Power System. Each section of the fuel processing subsystem will be explained in the following sections.

6.11 The Fuel Condition Unit



Figure 6-7: The Desulphurization Unit

Fuel is stored in a tank, which could be an external source or an on-board container. The fuel leaves the fuel tank via fuel pump and passes through a filter before entering the plant where the fuel is preheated prior to desulphurization. Sulfurous components (*left over from desulphurization*) exit the system as waste products. From the desulphurizer, the gaseous fuel enters the steam reformer.

6.12 The Water Management System



Figure 6-8: Water Management System

Water leaves the external source via a recirculation pump and the water filter purifies the steam before it enters the steam generator, where the water is turned into steam. The pure steam is a transparent gas. Steam leaving the generator enters into the steam reformer where the steam and gaseous fuel are mixed turning into '*syngas*' (*from synthetic gas*), syngas is a gas mixture that contains varying amounts of carbon monoxide, hydrogen and carbon dioxide.



6.13 The Energy Production – The Anode Side of the Cell Stack

Figure 6-9: Gas Transfer to the Anode Side of the Cell Stack

The goal of the Steam Reformer is to remove as much of the hydrogen as possible from the syngas. The extracted hydrogen and other gases leave the Steam Reformer and pass to the anode side of the Cell Stack Package. Once in the Cell Stack Package the hydrogen is used to produce electricity and heat.



6.14 Systems Analysis

Figure 6-10: The Hierarchical Structure of the Fuel Processing Subsystem

Table 6-1		
THE SUBDIVISION OF THE FUEL PROCESSING SUBSYSTEM		
		The Fuel Tank
		The Fuel Filter
		The Fuel Pump
The Fuel Conditioning Unit	-	The Desulphurizer
The Thermal Connection of	•	The Pre-heater
the Fuel Processing Unit	•	The Heat Exchanger
The Subsystem's Element of	•	The Steam Generator
Focus	-	The Catalysis/the Steam Reformer
The Power Generation		
Component of the Fuel		
Processing Subsystem	•	The Unit Cell (Anode)
The Water Management		The External Water Source
Subsystem of the Fuel	•	The Recirculation Pump
Processing Subsystem	•	The Water Condenser

6.15 Noted Subsystem Interactions

The Fuel Processing Subsystem has direct interactions with the Thermal and Waste

Management Subsystems and, it is controlled and, monitored by the Electrical Subsystem

as depicted in Figure 6-11.



Figure 6-11: The Inputs/Outputs and Interactions of the Fuel Processing System

6.16 Discussion



Figure 6-12: Representative Fuel Processing Steps & Temperatures [Fuel Cell Handbook, 2004]

Figure 6-12 depicts the processing steps needed for different fuel cells. A fuel

processor is an integrated unit consisting of one or more of the above processes as needed

for the fuel cell requirements. Fuel processing design considerations may include high

thermal efficiency, high hydrogen yield (*for some fuel cells hydrogen plus carbon monoxide yield*), multi-cycling, compactness, low weight, and quick starting capability, depending on the application. Most fuel processors make use of the chemical and heat energy left in the fuel cell effluent to provide heat for fuel processing thus enhancing system efficiency.

Historically, steam reforming has been the most popular method of converting light hydrocarbons into hydrogen. The fuel is heated and vaporized, then injected with superheated steam into the reaction vessel. Steam reforming is endothermic, thus favored by high temperatures; hence, it is well suited for pipeline gas and light distillate stationary fuel cell power generation. Hydrogen can be reformed from natural gas and steam in the presence of a catalyst starting at a temperature of ~760°C.

Catalyst materials modify and increase the rate of chemical reactions without being consumed in the process. Specifically, a physical catalyst is a substance which alters the reaction rate of a chemical reaction without appearing in the end product. Some reactions can be speeded up or controlled by the presence of substances which themselves appear to remain unchanged after the reaction has ended. By increasing the velocity of a desired reaction relative to unwanted reactions, the formation of a desired product can be maximized compared with unwanted by-products.

Known physical catalysts go through a cycle in which they are used and regenerated so that they can be used again and again. The exact mechanisms of catalytic actions are unknown. The catalytic act has historically been represented by five essential steps originally postulated by Ostwald around the late 1800's:

- 1. Diffusion to the catalytic site (*reactant*);
- 2. Bond formation at the catalytic site (*reactant*);
- 3. Reaction of the catalyst-reactant complex;
- 4. Bond rupture at the catalytic site (*product*); and
- 5. Diffusion away from the catalytic site (*product*).

Note the sulfur compounds in hydrocarbon fuels poison the catalysts in fuel cell processors.

The second and third objectives of the Fuel Processing Subsystem are the cleaning (*filtration of particulates from the fuel and water*) and, the removal of harmful compounds (e.g. *sulfur*) from the fuel.

Desulfurization is a catalytic chemical process widely used to remove sulfur (*S*) from natural gas and from refined petroleum products such as gasoline or petrol, jet fuel, kerosene, diesel fuel, and fuel oils. Filtration is the mechanical or physical operation which is used for the separation of solids from fluids (*liquids or gases*) by interposing a medium through which only the fluid can pass.

6.17 The Introduction to the Air and Waste Management Subsystems

The Cathode Leg of the SOFC Power System contributes to the combustion process of producing electricity. It is referred to as the '*cathode leg*' of the SOFC Power System because its end product (oxidant) ends up on the cathode side of the Cell Stack Package. The Air System is actually composed of two subsystems because its part of the Waste Management System. Both of these subsystems are very parasitic to the overall energy efficiency of the power system as far as energy consumption is concerned.

6.18 The Functions and Performance Requirements of the Air and Waste

Management Systems

The two main functions of the Cathode Leg of a SOFC Power System are:

- To provide clean oxidant at operational temperature to the cathode side of the cell stack.
- When the Cell Stack Package's temperature exceeds standard operating temperature, to provide a means by which the Cell Stack Package and the Hot Assembly can expel excess heat.

The three main subsystem requirements of the Air System of a SOFC Power System are:

- Oxidant.
- Electricity.
- Filtration Materials.

The Waste Management System eliminates the waste products from the SOFC Power

System. The sources of waste products are:

- Produced when excess fuel left over from the combustion process must be decomposed into safe elements.
- Pollutants in the excess water that the system generates.
- Sulfurous solids extracted from the fuel.

6.19 The Functional Analysis - The Scenario of the Cathode Leg of an SOFC Power System

Figure 6-13 below shows the structural diagram model of the Cathode Leg of the

generic SOFC Power System.



Figure 6-13: The Cathode Leg of a SOFC Power System (the Air Subsystem)

6.20 The Air Filtration Unit



Figure 6-14: Filtration Section of the Air Subsystem

The Air Compressor pushes fresh air into the system where the air is passed through a particulate filter before being moved via a fan into the Air Preheater.

6.21 The Energy Production – the Cathode Side of the Cell Stack and





Figure 6-15: The Oxidant Producer for Cell Stack's Cathode Portion

The goal of the Air Pre-heater is to heat the air to operational temperature.

Preheating is performed in order to prevent thermal shock. Thermal shock is the name given to cracking as a result of rapid temperature change.

Glass and ceramics are particularly vulnerable to this form of failure due to their low toughness, low thermal conductivity, and high thermal expansion coefficients. However, they are used in many high temperature applications due to their high melting point. The solid oxide electrolyte used in Power Systems is a type of ceramic which enables oxygen ion conduction while blocking electronic conduction. For example, in order to achieve sufficient ion conduction, a SOFC with an YSZ electrolyte must be operated at high temperatures (800°C-1000°C). Therefore the air must be heated to operating temperature before reaching the Cell Stack Package.

Thermal shock also occurs when a thermal gradient causes different parts of an object to expand by different amounts. This differential expansion can be understood in terms of stress or of strain. At some point this stress overcomes the strength of the material causing a crack to form. If nothing stops cracks from propagating through the material, it will cause the object's structure to fail. Thermal shock can be prevented by:

- 1. Reducing the thermal gradient seen by the object, by:
 - Changing its temperature more slowly.
 - Increasing the material's thermal conductivity.
- 2. Reducing the material's coefficient of thermal expansion.
- 3. Increasing its strength.
- 4. Decreasing its Young's modulus.
- 5. Increasing its toughness, by:
 - Crack tip blunting, i.e., plasticity or phase transformation.

• Crack deflection.

Once in the Cell Stack Package, the air is used to produce electricity and heat.



6.22 The Exhaust Section

Figure 6-16: The Return Section of the Air Subsystem

Exhaust gas, excess heat and water leave the Cell Stack and travel to the heat exchanger (*a combination of a fan and a condenser*). When heat transfer occurs water is collected from the gas, and the excess water exits the system and is stored in the external water source. The hot gas is then vented out into the environment.

6.23 The Waste Management Subsystem

Waste management is the collection, transport, processing, recycling or disposal, and monitoring of waste materials. Education and awareness in the area of waste and waste management is increasingly important from a global perspective of resource management. The Talloires Declaration is a declaration for sustainability concerned about the unprecedented scale and speed of environmental pollution and degradation, and the depletion of natural resources. Since the 1980s *sustainability* has been used more in the sense of human sustainability on planet Earth and this has resulted in the most widely quoted definition of sustainability and sustainable development. The Brundtland Commission of the United Nations on March 20, 1987 stated: "*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*."



The management of waste is a key component in a business' ability in maintaining ISO14001 accreditation. Companies are encouraged to improve their environmental efficiencies each year. Integrated waste management uses Life Cycle Analysis (LCA) in attempts to offer the most benign options for waste management.

6.24 Catalyst Management

From a life-cycle system engineering approach, a plan for catalyst management needs to be included into the design and development of a SOFC Power System. The reasons why are as follows:

- The development and redesign of Cell Stack Package components, namely the anode, will prompt new catalyst development and specification changes.
- Quality control guidelines need to be defined for reformer construction, fabrication and operations.
- Over time and with use the catalyst material will be depleted. Therefore a system must be in place in order to handle this waste product.
- Because catalyst has a finite life span of useful service, reliability studies must be done in order to determine when catalyst materials should be replaced.

6.25 The Nature of the Exhaust Gas from a SOFC Power System

The efficiency of the Cell Stack Package to use fuel determines the composition of the gas exiting the system. From a life-cycle system engineering approach, efficiency standards, a safety plan, and emission standards will need to be defined.

6.26 Water Management

The content of the water used and made by a Power System must be regulated under some safety guidelines, a safety plan and emission standards need to be defined.
6.27 Desulphurization Management

Desulphurizing fuel is not without expense. Because the filters of the unit must be serviced from time to time, from a life-cycle system engineering approach, a management plan needs to be in place for this process, in addition to a safety plan.



6.28 Systems Analysis

Figure 6-18: The Hierarchical Structure of the Air Subsystem

Table 6-2						
THE SUBDIVISION OF THE AIR SUBSYSTEM OF A SOFC POWER SYSTEM						
	The Air Filter					
The Filtration Unit	The Air Compressor					
The Element of Focus	• The Fan					
The Thermal connection of the Filtration	The Preheater					
Unit	The Heat Exchanger					
The Power Generation Component of						
the Air System	• The Unit Cell (<i>Cathode</i>)					
	The Water Condenser					
The Anode Leg of the Air System	The External Water Storage Source					

6.29 Noted Subsystem Interactions

The Air System has direct interactions with the Thermal and Waste Management Subsystems and, it is controlled and, monitored by the Electrical Subsystem as depicted in **Figure 6-19**.



Figure 6-19: The Inputs/Outputs and Interactions of the Air Subsystem

6.30 Discussion

The Element of Focus is the Cathode Air Compressor. A gas compressor is a mechanical device that increases the pressure of a gas by reducing its volume. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. The main types of gas compressors are illustrated and discussed below.



Figure 6-20: The Different Types of Compressors [Wikipedia, 2010]

To describe how the compressor and motor drive is situated in relation to the gas or vapor being compressed, compressors are often classified as being, open, hermetic, or semi-hermetic. An open compressor has a motive drive which is outside of the system and provides drive to the compressor by means of an input shaft with suitable gland seals. Open compressors are driven by an input shaft and can be powered by an electric motor, internal combustion engine, turbine, or any other engine. In hermetic and most semihermetic compressors, the compressor and motor are integrated and operate within the system. The motor is designed to operate and be cooled by the gas or vapor being compressed.

One disadvantage of hermetic compressors is that the motor drive cannot be maintained in situ, and the entire compressor must be removed if a motor fails. Another disadvantage is that burnt out windings can contaminate whole systems.

A Condenser is a device used to condense a substance from its gaseous to its liquid state, by cooling it. In so doing, the latent heat is given up by the substance, and

will transfer to the condenser coolant. Condensers are typically heat exchangers which have various designs and come in many sizes ranging from rather small (*hand-held*) to very large industrial-scale units used in plant processes.

For example, a refrigerator uses a condenser to get rid of heat extracted from the interior of the unit to the outside air. Condensers are used in air conditioning, industrial chemical processes such as distillation, steam power plants and other heat-exchange systems. Use of cooling water or surrounding air as the coolant is common in many condensers.

6.31 The Introduction to the Electrical System

This section will create the conceptual baseline of the Electrical Subsystem of a generic SOFC Power System and will explain its functions. It must be noted that many different DC–DC converter topologies have been proposed for power conditioning units in fuel cell systems without a single winning topology.

6.32 The Functions and Performance Requirements of the Electrical System

The Electrical System has one requirement - a DC Power Source which is produced by the Cell Stack Package. The Electrical Subsystem has seven main functions. The first three involve its Elements of Focus. The Electrical Subsystem:

- 1. Is responsible for drawing power from the Cell Stack Package.
- Has a means to boost or decrease the Cell Stack's DC power output in order to generate a regulated DC voltage.
- 3. Has a means, in which, to respond to dynamic loads when operation conditions or load requirement change via an Energy Storage Device.

4. Has a means to convert direct current (*DC*) of the Cell Stack Package to alternating current (*AC*) for the end user's use.



Figure 6-21: The Conceptual Output Leg of a SOFC Power System (*The Elements of Focus shown*)

- Has a means to satisfy the electrical requirements of the Balance of Plant Subsystems.
- 6. May be equipped with an Energy Storage Device. It has a means to replenish the device's energy reserves.
- 7. Has a Data Acquisition System, which records the power system's vitals (*fuel and oxidant flow rates, pressures, voltage and current settings e.g.*).

6.33 The Functional Analysis – The Scenario of the Output Leg of an SOFC



Power System

Figure 6-22: A Concise Conceptual Block Diagram of a Fuel Cell Power System [Fuel Cell Handbook, 2004]

The Electrical System of a SOFC Power System consists of the following primary

components:

- The Cell Stack Package (*the power generator*)
- The Power Conditioning Unit (*PCU*)
- The Electrical Distribution System (*EDS*) provides safe means to

distribute service power to the auxiliary circuit of the BOP Subsystems.

The Data Acquisition Subsystem



Figure 6-23: The Electrical Pathways of the Generic SOFC Power System

In the above figure, assuming 100% efficiency, the SOFC Power System produces 4,000 Watts of electricity. At 40V @ 100 Amps, the electrical pathway branches into two paths. The pathway leading to the DC/DC Converter provides power to the Balance of Plant (BOP) subsystems, and provides recharge power to its battery bank. The other pathway, the one leaving the DC/DC Converter headed towards the DC/AC Converter provides power (*after it has been changed from DC to AC*) to the end user. In this scenario a step down (*Buck*) DC/DC Converter was used. The output voltage is lower than the input voltage and of the same polarity. A linear regulator could have been used, however, upon operation the linear regulator bleeds off excess energy as heat.

6.34 The Power Conditioning Section of an SOFC Power System - The Functions of the Power Conditioning Unit

Various power conversion "*building*" blocks, DC-DC Converters and DC-AC Inverters are employed, in fuel cell power conditioning systems.

 DC/DC Power Conversion: the output voltage from the Cell Stack Package can be either boosted up or down via a DC–DC converter. A DC-DC converter is responsible for drawing power from the fuel cell. The DC-DC converter should not introduce any negative current into the fuel cell. If the boost converter is operated in current control mode, rather than, voltage control mode, it becomes ideally suited for interfacing the inverter system with the Cell Stack Package. Based on the load conditions, the boost stage can be commanded to draw a specific amount of current from the fuel cell with a ripple well defined by the frequency, size of the inductor, and duty ratio. Figure 6-24 shows variations in the output voltage of the Cell Stack Package. The Cell Stack Package is responding to changes in load current. Fuel cell output DC voltage exhibits nearly 2:1 voltage range.



Figure 6-24: Typical Fuel Cell Voltage/Current Characteristics [Fuel Cell Handbook, 2004]

For a hypothetical design, for instance, if the number of cells in the Cell Stack Package is few, the DC voltage generated by a fuel cell stack will vary widely and will be low in magnitude. <50V for a 5 to 10kW system, <350V for a 300kW system, a step up DC-DC converter would be essential to generate a regulated higher voltage DC (400V typical for 120/240V AC output).

- 2. DC/AC Power Conversion: The DC electricity is converted to AC via some type of an Inverter. Most standard appliances are designed to accept only AC (alternating current) voltages because that's how electricity is supplied from the grid. To run an electronic device from a DC (direct current) voltage source the electricity needs to be transformed from DC into AC voltage. A power inverter is a device that converts electrical energy from DC form to AC form using electronic circuits. Its typical application is to convert a 12V voltage into conventional household voltage. The inverter with filter will supply a single phase or three phases to the load. A DC-AC inverter is essential to provide the DC to useful AC power at 60Hz or 50Hz frequency. An output filter connected to the inverter filters the switching frequency harmonics and generates a high quality sinusoidal AC waveform suitable for the load. Output from the power conversion unit is expected to be high quality power with less than 5 percent total harmonic distortion (THD). For domestic loads, a 5:1 or better peak to average power capability for tripping breakers and starting motors is desired.
- 3. The load for DC/DC Power Conversion and the Energy Storage Device (*together*) behave more like a constant power load than a resistive load. The DC- AC inverter needs to respond to dynamic load conditions. However, the chemistry of the fuel cell cannot respond instantaneously to these load dynamics. The function of the energy

172

storage device is to provide momentary ride through capability while the fuel cell adjusts to the new operating point.

Electrical energy storage enables more high-efficiency base load operation strategies for the SOFC. Such high efficiency operation may be necessary to offset the inefficiencies of power conditioning and electrical storage requirements of systems that include batteries. On average, the state of charge (SOC) for the energy storage device of a battery bank for example, has no net change: any energy supplied to the load by the battery during a transient must be replenished from the fuel cell once the chemistry has reached steady state condition. Therefore, the current command for the boost converter must include the average load current as well as the battery charging current:

I(command) = I(load) + I(battery)

The energy storage device, such as a battery bank or super capacitor with appropriate interfacing circuits can be either voltage switching (ZVS), or zero circuit switching (ZCS). The introduction of a digital signal processor (DSP)-based controller makes this goal easier to achieve.

4. Utility Synchronization. If grid connected, a step-up transformer may be needed to further boost up the AC -voltage in order to match the grid's value.

6.35 The Electrical Controls and Energy Requirements of the Balance of Plant

The SOFC Power System controls are divided into three main areas: the master control; the power control and back-up control. Programmable logic control (*PLC*) equipment functions as a master control unit which controls the overall system. In order

to control the operation of the subsystems and keep the subsystems within their operational window, several basic parameters need to be adjusted. Below are listed just a few:

- A means, which will determine the fuel flow to the stacks.
- A means, which will control the amount of air fed to the system, thus controlling stack temperature.
- A means to control the air flow to cathodic side of the Cell Stack Package.
- Power control for steering the stack voltage.

6.36 The Data Acquisition Subsystem

Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems (abbreviated with the acronym DAS or DAQ) typically convert analog waveforms into digital values for processing. The components of data acquisition systems include:

- Sensors that convert physical parameters to electrical signals.
- Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values.
- Analog-to-digital converters, which convert conditioned sensor signals to digital values.

Data acquisition begins with the physical phenomenon or physical property to be measured. For a SOFC Power System the following table shows the physical properties of the SOFC Power System's subsystems which must be measured and recorded.

Table 6-3 MEASUREMENT ITEMS FOR A DATA ACOUISITION SYSTEM			
THE SUBSYSTEM	THE COMPONENT(S) OF THE SUBSYSTEM	THE PHYSICAL PROPERTY	
The Fuel Processing System	Reformer: The Catalyst	The Temperature	
The Fuel Processing System	The Gas Supply The Air System	The Pressure The Temperature The Flow Rate	
The Fuel Processing System (The Water Management System)	The Water	The Flow Rate	
The Fuel Processing System The Air System	The Fuel The Air	The Pressure The Temperature The Humidity The Flow rate	
The Electrical System	The Cell Stack	The Voltage The Current The Temperature The Gas Flow Rate	
The Electrical System	The Inverter System	The Temperature The Cooling Flow Rate	
The Thermal Management System	The Waste Heat	The Pressure The Temperature The Flow Rate	

Regardless of the type of physical property to be measured, the physical state that is to be measured must first be transformed into a unified form that can be sampled by a data acquisition system. The task of performing such transformations relies on devices called *sensors*. The ability of a data acquisition system to measure differing properties depends on having sensors that are suited to detect the various properties to be measured. There are specific sensors for many different applications. DAQ systems also employ various signal conditioning techniques to adequately modify various different electrical signals into voltage that can then be digitized using an analog-to-digital converter.

6.37 The End-User's Energy Requirements

The System Power output to the End User equals, 'what's left over from system losses

and is directly based on inverter efficiency'.

A = The Cell Stack's (DC) Power OutB = Parasitic Power Requirements of the BOP (DC)C = (Inverter Efficiency)

SYSTEM POWER = $(A - B) \times C$

Example: Let: A = 1.3 kW; B = 0.2 kW; and C = 0.90System Power = the End User's Power = 1 kW

6.38 System Analysis



Figure 6-25: The Hierarchical Structure of the Electrical System

Table 6-4				
THE SUBDIVISION OF THE ELECTRICAL SYSTEM				
The Power Source	The Cell Stack			
The Monitoring and				
Testing Subsystem	The Data Acquisition System			
	DC-DC Converter			
	DC-AC Inverter			
The Elements of Focus	The Energy Storage Source			
The Electrical Distribution				
System	The BOP Electrical Systems			
The Load	The Electrical Needs of a Residential			
	Household			

6.39 Discussion

Today every application ranging from those used at home, small offices, hospitals, banks and huge call centers are dependent on electricity. Any power disturbance such as power outage or voltage sag/swell can result in malfunctioning of the equipment; loss in productivity and data and in the case of health care, loss of lives is also possible. Hence, power quality and continuity are important factors that need to be ensured for critical applications.

There exists an intrinsic relationship between the load performance and the electric power quality. Power outages and other power disturbances cannot be avoided but a system can be developed to ensure that the load (end user) does not see these power disturbances.

As a result, the generic SOFC Power System model of this paper will be for distributed generation (DG) and combined heat and power (CHP) applications. It will be capable of producing continuous reliable electric power while generating useable waste

177

heat. This heat can be used for space heating, hot water applications, and for driving an absorption chiller to provide cooling. It can provide backup power when the electric utility service fails. The model will be designed for residential use and the fuel of choice will be natural gas. It will be connected to the electrical grid and will be supplied with an arsenal of batteries. The reasons for this type of system configuration are:

- When the SOFC Power System produces excess electricity, during these times the electricity will be sold to the household's utility company.
- When there are times that the electrical grid experiences a power outage, the household will use the SOFC Power System as its sole source of electricity.
- When there are times that the customer's electricity needs supersede the power system's energy production, the household will use the utility company's service.

6.40 The Basic Operation Scenario of the SOFC Model:

- 1. Natural gas is first converted to hydrogen in the fuel processing system (*FPS*) through a process known as catalytic steam reformation.
- 2. Hydrogen and air are then supplied to the Cell Stack Package.
- 3. The hydrogen and oxygen combine electrochemically to produce direct current (DC) electricity, heat, and water.
- 4. Alternating current (*AC*) electricity is produced through an on-board DC to AC inverter.
- Heat generated in the fuel cell process generates steam, which is returned to the Fuel Processing Subsystem for use in the steam reformation process.

6. Useable heat is delivered to a customer-supplied water source through heat recovery heat exchangers.

6.41 The Introduction to the Thermal Management System

Containing and controlling the thermal energy associated with a SOFC Power System will ensure possible commercialization for all Fuel Cell Power Systems require careful management of their Cell Stack Package's temperature. In general, the Cell Stack Package energy balance states that the enthalpy flow of the reactants entering the Cell Stack Package will equal the enthalpy flow of the products leaving the Cell Stack plus the sum of three terms:

- The net heat generated by physical and chemical processes within the cell.
- The dc power output from the cell
- The heat loss from the cell to its surroundings.

Unlike conventional power devices, i.e., steam turbines, gas turbines and internal combustion engines, which are based on certain thermal cycles, the maximum efficiency of fuel cells is not limited by the Carnot cycle principle. The heat generated in a Cell Stack Package may be dumped into the atmosphere, but often it is used in other system components requiring heat. In some cases the heat is used to run a thermodynamic cycle for additional power generation.

SOFC Power Systems provide high quality waste heat suitable for Brayton or Rankine combined cycle to boost system efficiency. For example, a fuel cell operating at 1.0 kW with 50% efficiency generates 1.0 kW of waste heat. This heat may be dissipated by convection, conduction, radiation or phase change. Specific fuel cell power systems' engineering designs for thermal management are needed to manage and control heat transfer through all fundamental modes of heat transfer, when applicable:

- Conduction or diffusion The transfer of energy between objects that are in physical contact.
- Convection The transfer of energy between an object and its environment due to fluid motion.
- 3. Radiation -The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation.
- 4. Mass transfer- The transfer of energy from one location to another as a side effect of physically moving an object containing that energy.
- 5. Phase Change- The transformation of a thermodynamic system from one phase or state of matter to another, a phase of a thermodynamic system and the states of matter have uniform physical properties. During a phase transition of a given medium certain properties of the medium change, often discontinuously, as a result of some external condition, such as temperature, pressure, and others. For example, a liquid may become gas upon heating to the boiling point, resulting in an abrupt change in volume.

With regard to the other balance of plant subsystems, the air flow rate required to maintain the Cell Stack Package at the desired constant temperature will depend chiefly upon its temperature, stack electrochemical efficiency, heat losses to the environment, fuel composition, air and fuel feed temperatures, air humidity, etc. One of the specialized purposes of the Hot Assembly is thermal management of the Cell Stack Package and the protection of the BOP subsystems. The ceramic materials of the Cell Stack Package of a SOFC Power System cannot withstand steep temperature gradients. To obtain a uniform temperature distribution in the cell a higher air-flow rate than that required for fuel cell oxidation must be fed to the cell at high temperature.

6.42 The Functions and Performance Requirements of the Thermal Management System

The Thermal Management System has three main functions:

- 1. To ensure the Cell Stack Package's operation within the specific temperature range.
- 2. For optimal thermal management for effective use of the power system's byproduct, heat, leading to substantial increases in overall system efficiency.
- 3. It involves the conservation and management of the heat loss from the Cell Stack Package and power system to its surroundings. It conserves and prevents heat loss to the Cell Stack Package's surroundings via insulation packages which, prevents the BOP subsystems and the Cabinet from overheating.

The three main requirements of the Thermal Management System are:

- Electricity
- Water
- Heat

With regards to development and design of SOFC Thermal Management Systems, designers must consider the following:

- Fundamentals of heat transfer
- Radiative equilibrium
- Surface properties

- Non-ideal effects
- Internal power generation
- Environmental temperatures
- Conduction
- Thermal system components

High temperature materials are needed to possess (high temperature strength, creep resistance, corrosion resistance, etc.) and the active mechanisms in a temperature range of 400 to 1800 °C under extreme service conditions.

6.43 Thermal Functional Analysis of the SOFC as a Whole System - Operational Modes

Containing and controlling the thermal energy from the SOFC system is critical to the operation of the system. The thermal energy emitted from a power system must be controlled for warm-up and cool-down periods, as well as during operation. A SOFC Power System has four modes of operation. The start-up conditions, operational conditions, idling mode, and cool down mode.

In start-up mode the SOFC Power System is heated from room temperature to operational temperature. This mode can take a several hours. When the SOFC Power System reaches operational temperature the cell stack loading may increase, the fuel and air gases are turned on and allowed to flow to the Cell Stack Package.

The SOFC stack and other system components operate at temperatures of about 600° C. up to about 1,000° C. At these temperatures the components are glowing orange to white hot requiring radiation shielding and insulation to reduce energy loss and protect

the surrounding subsystems surfaces. In operational mode the SOFC Power System is capable of exporting power to an external source. During a typical operating cycle, the power load on the fuel cell power system will vary over time. As the load demands on the Cell Stack Package increases the amount of waste heat generated also increases, while at the same time more fuel is also required in the anode side of the Cell Stack Package to maintain high reaction rates. After initial transients the thermal transfer process will reach a steady state condition where the quantity of heat transferred is passively regulated by the external power load.

Idle mode occurs when gas flows to the Cell Stack Package are shut off, yet all other system operations remain unchanged. Maintenance activities can take place when the system is in idle.

Cool down mode occurs when the SOFC Power is disengaged from providing power to the external circuitry. The gas flows and heaters have been shutoff and the system is allowed to cool back down to room temperature. 6.44 The Functional Analysis – The Concrete and Abstract Pathways of the Thermal Management System of a SOFC



Figure 6-26: Concrete and Abstract Pathways of the Thermal Management System of a generic SOFC Power System

The Thermal Management Subsystem is partially a '*concrete*' and partially an '*abstract*' subsystem. It is considered '*abstract*' because many of its components are not connected together in one continuous component-part linkage or pathway, like for example the way the Fuel Processing Subsystem's components are linked.

A model of the SOFC Power System in the above figure shows the Thermal Management System's pathways and components. The insulation package of the Hot Assembly, a structure which maintains the Cell Stack Package's temperature, as well as, protects the BOP and Cabinet from the extreme temperature of the Cell Stack Package, is not shown. The following is a brief summary of the main components (the Elements of Focus) which comprise the Thermal Management System of this paper's model.

6.45 The Functional Analysis of the Cell Stack as a Heat Generator

For optimum fuel cell operation, the distribution of temperature has to be substantially uniform across the Cell Stack Package's anode and cathode portions and should not exceed a maximum value.

A portion of the energy from the reaction of fuel and oxidant within the Cell Stack Package is released as heat, which in turn increases its operating temperature. The Waste Management System, through the Air Subsystem provides the means for the Cell Stack Package to rid itself of excess heat.

The amount of heat generated can be different at different locations on the Cell Stack Package.

6.46 Functional Analysis of the Hot Assembly as a Thermal Shield

The Hot Assembly which houses the Cell Stack Package is the chief source of heat for the power system. The Hot Assembly controls the temperature of the balance of plant subsystems that surrounds the hot assembly. It keeps the Cell Stack Package at operating temperature, while cools the inside of the cabinet interior to sufficiently keep the environment of the BOP systems at about 45° C. or less. The insulation of the Hot Assembly comprises of passive insulation which acts as a vacuum gap between its inner and outer surface with a substance preferably disposed in the vacuum space to shield the transfer of heat from the interior to the exterior of the Hot Assembly. These methods can be used alone or in combination.

6.47 Functional Analysis of the Heat Exchanger

A Heat Exchanger is a device built for efficient heat transfer from one medium to another. The media may be separated by a solid wall, so that they never mix, or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment.

The Heat Exchanger for a SOFC Power System will provide the means for heat transfer for the Fuel Processing Subsystem and the Air Subsystem. Heat can be transferred from the Heat Exchanger to heat the Steam Generator and the steam reformer, if needed. On the return trip from the Cell Stack Package, exhaust gas loses its excess heat to the Heat Exchanger where upon water is distilled from the gas, before the gas is expelled from the system. In some designs, the Heat Exchanger could provide heat to the desulphurizer.



Figure 6-27: A Flat Plate Heat Exchange [Wikipedia, 2010]

There are two primary classifications of heat exchangers according to their flow arrangement. In *parallel-flow* heat exchangers, the two fluids enter the exchanger at the same end and travel in parallel to one another to the other side. In *counter-flow* heat

exchangers the fluids enter the exchanger from opposite ends. The counter current design is most efficient, because it can transfer the most heat from the heat (*transfer*) medium. In a *cross-flow* heat exchanger the fluids travel roughly perpendicular to one another through the exchanger.

For efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids while minimizing resistance to fluid flow through the exchanger. The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence. The driving temperature across the heat transfer surface varies with position, but an appropriate, mean temperature can be defined. In most simple systems this is the "*log mean temperature difference*" (LMTD).

Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but, much iteration is needed. As such, heat exchangers are most often selected via computer programs or by system designers who are engineers, or by equipment vendors. In order to select an appropriate heat exchanger, the system designers (*or equipment vendors*) would firstly consider the design limitations for each heat exchanger type.

Although cost is often the first criterion evaluated, there are several other important selection criteria which include: high or low pressure limits; thermal performance; temperature ranges; product mix (liquid/liquid, particulates or high-solids liquid); pressure drops across the exchanger; fluid flow capacity; cleanability,

187

maintenance and repair; materials required for construction; ability and ease of future expansion.

6.48 System Analysis

The Elements of Focus for the Thermal Management System for each of the BOP subsystems are listed in the table below. Conventional methods of containing and controlling thermal energy from the SOFC system require the use of expensive insulation and heat pipes, which are be bulky and heavy.

Current technology can successfully regulate the temperature of the hot assembly to keep it within acceptable limits, however, in doing so there is an expense to overall system performance. It would be advancement in the improvement of fuel cell systems to have a thermal management system that uses inherent thermal behavior and synergy within the system to regulate its operating conditions. It would obviate the need for additional components such as separator plates, coolant plates, pumps, fans, valves, etc.

Table 6-5				
THE ELEMENTS OF FOCUS FOR THE THERMAL MANAGEMENT SYSTEM				
OF A SOFC POWER SYSTEM RELATED TO THE INDIVIDUAL				
SUBSYSTEMS				
The Power Generation System	•	The Cell Stack Pack		
	•	The Pre-Heaters		
The Fuel Processing	•	The Steam Generator		
Subsystem	•	The Steam Reformer		
The Hot Assembly	•	The Hot Assembly Fixture		
	•	The Preheaters		
The Air, Mechanical and the	•	The Compressors		
Waste Management Systems	•	Fans, Pumps, Blowers		
The Electrical System	•	The heat producing electronic		

6.49 Noted Subsystems and Components Interactions of the Thermal Management System – Process Simulation Tools

The heat transfer required in the fuel cell system is determined by the thermodynamic principles of the chemical and electrochemical conversion of the fuel to a hydrogen rich gas and a subsequent conversion of the hydrogen into electricity in the fuel cell. A thermodynamic system analysis is usually done for a SOFC with a suitable process simulation tool like AspenPlus or Hysis. Using these simulators the thermodynamic, electrical and physical properties of the systems and interactions are calculated. Based on these calculations the heat transfer network between the fuel cell power system's components and, subsystems can be evaluated, forecasted and designed.

6.50 Discussion - Introduction

The Thermodynamic models of SOFC Power Systems are very complex and challenging. Many fuel cell developers shy away from including the thermodynamics into their system models, when thermodynamic modeling is not necessary, because of the complications involved. An example of a generic SOFC Power System model without thermodynamic interactions of its subsystems was Halinen's research, which was the basics of his paper entitled, *"Experimental Analysis on Performance and Durability of a SOFC Demonstration Unit"*, which appeared in a 2009 issue of Fuel Cell. The rationale behind Halinen's SOFC Demonstration unit's configuration was to simplify the thermodynamic interactions which occur in real SOFC Power Systems. His generic SOFC Power System was simplified in the following ways:

- The unit was not designed to be thermally self-sufficient.
- A non-integrated design was applied to obtain characteristic measurement data from its individual components. To reduce the effect of surface-to-surface heat transfer between components and to make modifications and replacements of different components easy, a non-integrated design will be necessary.
- Components and piping that was operated above the room temperature was insulated with insulation sleeves.
- The heat loss in the pipelines between the heat exchangers, the reformer unit and the stack was compensated with electric trace heating elements.
- The SOFC stack was placed in a furnace. The furnace acted as a hot assembly.
 The furnace was used for start-up and to influence the temperature of the Cell
 Stack Package during system operation.



Figure 6-28: Halinen's SOFC Demonstration Unit

6.51 Introduction - The Mechanical Subsystem and the Hot Assembly

The Mechanical System of a SOFC Power System consists of the components which promotes '*physical work or mass in motion*', such as the transfer of water or gas from one section of the system to another, via fans, compressors, tubing, pumps, and/or mass flow meters, and compressors, to name a few examples. It is classified as an '*abstract*' system because many of its parts are scattered throughout the SOFC Power System.

The Hot Sub-Assembly is a specially designed platform mount and enclosed structure for the power system's Cell Stack Package. A Hot Assembly can be very simple or it can be complex.

Halinen used a very simple hot assembly. A 5 kW power class planar SOFC stack from Research Centre Jülich was assembled to a demo unit and a long-term experiment was conducted to assess the characteristic performance and durability of different components of the unit (*e.g. the SOFC stack, the fuel pre-reformer and air heat exchangers*). Halinen's SOFC Cell Stack Package, used in the unit, was designed manufactured and assembled by Forschungzentrum Jülich (FZJ). The 5 kW class stack used in the experiments consisted of 50 rectangular unit cells with an active area of 361 cm². The Cell Stack Package rested on top of ceramic bricks inside a furnace. The inner dimensions of the furnace were 1,100 mm × 1,100 mm, the inner height was 640 mm and the thickness of the insulation layer was 150 mm. The heating elements of the furnace were situated on two opposite sides of the furnace. Current was collected from the end plates of the Cell Stack Package with steel bars that were led through the bottom of the furnace. Gas pipelines were, likewise, led through the bottom of the furnace.

191

A more complex hot assembly was patented in 2002, by Technology Management Inc. (TMI), a SOFC developer, who created an invention known as the solid-oxide fuel cell hot assembly. TMI's electrochemical apparatus incorporated a thermally integrated vaporizer and fuel steam reformer with a solid oxide fuel cell stack package.



Figure 6-29: Schematic Cross-Section of the Solid-Oxide Fuel Cell Hot Assembly [Technology Management Inc., 2002]

Table 6-6				
THE LEGEND FOR FIGURE 1'S SOLID-OXIDE HOT ASSEMBLY				
Item				
Number	Description	Subsystem Category		
12	The Fuel Cell Stack	Cell Stack		
14	The Assembly Enclosure (a cylindrical body)	Hot Assembly		
	Electrical Connection	Electrical System		
22	Vaporizer	Fuel Processing System		
23	Insulation	Thermal Management System		
24	Steam Reformer	Fuel Processing System		
26, 28	Fuel and Water Tubes	Fuel Processing System		
30	Start up Heaters	Thermal Management System		
32	Annular Passage (exhaust gas exit, provides			
	source of heat for the vaporizer and reformer)	Exhaust System		
34	Mixing Orifice (on top of vaporizer)	Fuel Processing System		
38	Catalyst Chamber	Fuel Processing System		
40	Catalyst Beads	Fuel Processing System		
48	Electrical Conductive Plate	Electrical System		
50	Electrical Conductive Plate	Electrical System		
52	Air Orifices	Air System		
56	Insulation Package	Thermal Management System		
62	Hot Air Inlet	Air System		
66	Exhaust Vent	Air System		
68	Exhaust Vent	Air System		
74	Cool Air Plenum	Thermal Management System		
80	The reactant depleted fuel & air eventually exit at	Exhaust System		
	the stack surface			

6.52 The Functional and Performance Requirements of the Hot Assembly

The five main functions of the Hot Assembly System are to:

- Provide structural support for the Cell Stack Package's mount.
- Maintain the Cell Stack Package's temperature via its insulation package and temperature monitoring devices.
- Provide the Cell Stack Package with a manifold, which supplies the Cell Stack with reactants to generate electricity.
- Provide the housing, which surrounds the Cell Stack Package and contains the exhaust gases after the gases have exited the Cell Stack Package's chamber.
- Physically connected to the power-conditioning unit (*including the data acquisition system*).

The two main functions of the Mechanical System are to:

- Provide the means by which gases travels to and from the Cell Stack Package and throughout the system.
- Transport gas and other material throughout the Power System.

6.53 Functional Analysis of the Mechanical System

Both gas and liquid flow can be measured in volumetric or mass flow rates, such as liters per second or kilograms per second. These measurements can be converted between one another if the material's density is known.

The density for a liquid is almost independent of the liquid conditions. However, this is not the case for gas. The density of the gas depends greatly upon pressure, temperature and to a lesser extent to its composition. When gases or liquids are transported (for energy harvesting and utilization), such as the sale of natural gas, the flow rate may also be expressed in terms of energy flow, such as GJ/hour or BTU/day.

The energy flow rate is the volume flow rate multiplied by the energy content per unit volume or mass flow rate multiplied by the energy content per unit mass. Where accurate energy comes to the time of the legit flow rate is desired, most flow meters will be used to calculate the volume or mass flow rate which is then adjusted to the energy flow rate by the use of a flow computer.

6.54 Compressors, Ejectors, Fans, Blowers, and Pumps

Air needs to be moved around fuel cell systems for cooling and to provide oxygen to the cathode. Fuel gas has to be pumped around the anode side of the fuel cell. Therefore, pumps, fans, compressors and blowers have to be used.

In addition, the energy of exhaust gases from a fuel cell can sometimes be harnessed using a turbine, making use of what would otherwise go to waste. The technology for such equipment is very mature, having already been developed for other applications.

The types of compressors used in fuel cell systems are the same as those used in other engines, especially diesel engines.



Figure 6-30: Some different types of compressors [Larminie & Dicks, 2003]

6.55 Compressor Efficiency



Figure 6-31: Symbol used for compressors. [Larminie & Dicks, 2003]

Compressor efficiency is not easy to define. Whenever a gas is compressed, work is done on the gas, and so its temperature will rise, unless the compression is done very slowly or there is a lot of cooling. In a reversible process, which is also adiabatic (no heat loss), it can readily be shown that if the pressure changes from P1 to P2, then the temperature will change from T1 to T2, where:

$$\frac{T_2'}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

This formula gives the constant entropy, or isentropic temperature change, as is indicated by the 'on T'_2 . γ is the ratio of the specific heat capacities of the gas, C_p/C_v .

In practice, the temperature change will be higher than this. Some of the motion of the moving blades and vanes serves only to raise the temperature of the gas. Also, some of the gas might 'churn' around the compressor, doing little but getting hotter. We call the actual new temperature T_2 . To derive the efficiency, we use the ratio between the following two quantities:

- 1. The actual work done to raise the pressure from P1 to P2
- The work that would have been done if the process had been reversible or isentropic– the isentropic work.

To find these two figures we make some assumptions that are generally valid:

- The heat flow from the compressor is negligible.
- The kinetic energy of the gas as it flows into and out of the compressor is negligible, or at least the change is negligible.
- The gas is a '*perfect gas*', and so the specific heat at constant pressure, *CP*, is constant.

With these assumptions, the work done is simply the change in enthalpy of the gas:

$$W = c_p (T_2 - T_1) m$$

Where, m is the mass of gas compressed. The isentropic work done is:

$$W' = c_p (T_2 - T_1) m$$

The isentropic efficiency is the ratio of these two quantities. Note that the name *'isentropic'* does not mean we are saying the process *is* isentropic; rather we are *comparing it with* an isentropic process.

$$\eta = \frac{isentropic \ work}{real \ work} = \frac{cp(T'2 - T\mathbf{1})m}{cp(T2 - T\mathbf{1})m}$$

And, so:

$$\eta_c = \frac{T'\mathbf{2} - T\mathbf{1}}{T\mathbf{2} - T\mathbf{1}}$$

It is useful to rearrange the equation to give the change in temperature:

$$\Delta T = T_2 - T_1 = \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right)$$

This definition of efficiency does not consider the work done on the shaft driving the compressor. To bring this in we should also consider the mechanical efficiency η_{m} , which takes into account the friction in the bearings, or between the rotors and the outer casing (if any). In the case of centrifugal and axial compressors, this is very high, almost certainly over 98%. We can then say that:

$$\eta_T = \eta_m \cdot \eta_d$$

However, it is the isentropic efficiency η_c that is the most useful, because it tells us how much the temperature rises. The rise in temperature can be quite high. For example, using air at 20°C (293 K) for which $\gamma = 1.4$, a doubling of the pressure, and using a typical value for n_c of 0.6, the below equation becomes:

$$\Delta T = T_2 - T_1 = \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right)$$

$$\Delta T = \frac{293}{0.6} (2^{0.286} - 1)$$

= 170 K

For some fuel cells, the rise in temperature is useful as it preheats the reactants. On the other hand, for low-temperature fuel cells it means that the compressed gas needs cooling.

6.56 Compressor Power

The power needed to drive a compressor can be readily found from the change in temperature. If unit time is given, then clearly:

Power =
$$\dot{W} = c_p \cdot \Delta T \cdot \dot{m}$$

Where \dot{m} is the rate of flow of gas in kg s⁻¹. *T* is given in the below equation, and so:

$$\Delta T = T_2 - T_1 = \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right)$$

Power = $c_p \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \cdot \dot{m}$

In the case of an air compressor which is a feature of many fuel cell systems, the use of the values for air:

$$c_p = 1004 \, \text{J kg}^{-1} \, \text{K}^{-1}$$

and

$$\gamma = 1.4$$

So power = $1004 \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1} \right)^{0.286} - 1 \right) \dot{m} W$

The isentropic efficiency η_c can be found, or at least estimated, from charts.

6.57 Compressor Performance Charts

The efficiency and performance of a compressor will depend on many factors that include the following:

- Inlet pressure, P_1
- Outlet pressure, P_2
- Gas flowrate, *m*[·]
- Inlet temperature, T_1
- Compressor rotor speed, N
- Gas density, ρ
- Gas viscosity, μ.
Attempting to tabulate or draw on some kind of map for compressor performance is not advised because of the complexity of the variables involved. It is necessary to eliminate or group together these variables. This is often done in the following way:

- The inlet and outlet pressures are combined into one variable, the pressure ratio P_2/P_1 .
- Since, for any gas, density ρ = P/RT, and P and T are being considered, the density can be ignored. It is considered via the inclusion of pressure and temperature.
- It turns out that the viscosity of the gas, bearing in mind the limited range of gases normally used, can be ignored.

Further simplification is done by a process of dimensional analysis. The result is to group together variables in 'non-dimensional' groups. They are not really nondimensional, but that is because various constants, with dimensions, have been eliminated from the analysis.

The two groups are
$$\frac{\dot{m}\sqrt{T_1}}{P_1}$$
 and $\frac{N}{\sqrt{T_1}}$

These are called the *mass flow factor* and the *rotational speed factor*, respectively. Charts are then plotted of the efficiency, for different pressure ratios and mass flow factors. Lines are plotted on these charts of constant rotational speed factor. The chart for a typical screw compressor (Lysholm) is shown in **Figure 6-32**. The lines of constant efficiency are like the contours of a map. Instead of indicating hills, they indicate areas of higher operating efficiency.



Figure 6-32: Performance chart for a typical Lysholm or screw compressor. A mass flow factor of 5 corresponds to the air needs of a fuel cell of power of about 250 kW. [Larminie & Dicks, 2003]

The unit generally used for *P*1 is the bar, and for temperature we use Kelvin. The mass flow factor can be related to the power of a fuel cell reasonably simply. If it is assumed of typical fuel cell operating conditions, (i.e. the air stoichiometry = 2 and the average fuel cell voltage = 0.6V), then, the flow rate of the air for a 250-kW fuel cell is:

$$\frac{3.57 \times 10^{-7} \times 2 \times 250\,000}{0.6} = 0.3\,\mathrm{kg\,s^{-1}}$$

If it is assumed standard conditions for the air (i.e. P1 = 1bar, T = 298 K), the mass flow factor is:

$$\frac{0.3 \times \sqrt{298}}{1.0} = 5.18 \approx 5 \text{ kg s}^{-1} \text{ K}^{\frac{1}{2}} \text{ bar}^{-1}$$

Therefore, the horizontal *x*-axis of **Figure 6-32** corresponds to the airflow needs of fuel cells of power approximately 0 to 250 kW. Similarly, if the rotor speed factor is 1000, this will correspond to a speed of about 17,000 rpm. (Note these units have to run fast, the centrifugal compressors considered in the next section have to turn even faster!).

Generally speaking, such charts will give satisfactory results – except in the case of multistage compressors. When gas has been compressed through the first stage, its temperature and pressure would obviously have changed markedly, and so the mass flow factor will be quite different, even though the actual mass flow rate is unchanged.

6.58 Ejector Circulators

The ejector is the simplest of all types of pumps. It has no moving parts. They are widely used in hydrogen fuel cells where the hydrogen is stored at pressure. In some Siemens Westinghouse SOFCs, they were used to recirculate the fuel gas. They harness the stored mechanical energy in the gas to circulate the fuel around the cell.

A simple ejector is shown in **Figure 6-33**. A gas or liquid passes through the narrow pipe A into the venturi B. It acquires a high velocity at B and hence produces suction in pipe C. The fluid coming through at A thus entrains with it the fluid from C and sends it out at D. For this to work, the fluid from A must be at a higher pressure than that in C/B/D, otherwise it would not eject from pipe A at high velocity.

The fluid entering at A does not have to be the same as that in pipe C/B/D. The most common use of the ejector is in steam systems with the steam being the fluid passing through the narrow pipe and jet A. Ejectors are used to pump air to maintain vacuum in the condensers of steam turbines. They are also used to pump water into boilers, and since the steam mixes with the pumped water it also preheats it. The steam is also used to circulate lower pressure steam in steam heating systems. In this application it is closest to its normal use in fuel cell systems.

In terms of converting the mechanical energy stored in the compressed gas into kinetic energy of the circulating gas, the ejector circulator is very inefficient. However,

since the mechanical energy of the stored gas is not at all convenient to harness, it is essentially '*free*' and so as long as the circulation is sufficient, the inefficiency does not matter. The internal diameter of Pipe A and the mixing region B, and C/D, have to be chosen bearing in mind the pressure differences and the flow rates. Tables and graphs for these can be found in chemical engineering reference books such as Perry (1984).



Figure 6-33: Diagram of a simple ejector circulation pump [Larminie & Dicks, 2003]

6.59 Fans and Blowers

For straightforward cooling purposes, fans and blowers are available in a huge range of sizes. The normal axial fan, such as we see cooling all types of electronic equipment, is an excellent device for moving air, but only against very small pressures. A small fan, such as is commonly used in electronic equipment, might move air at the rate of about 0.1kg s–1, which is equivalent to 85 L s^{-1} at standard conditions. However, this flow rate will drop to zero if the back pressure even rises to 50 Pa. These pressures are so low that they are often converted to centimeters of water and this helps us visualize how low they are – in this case just 0.5 cm of water. This is a typical maximum back pressure for such a fan. The result is that they can only be used when the air movement is in a very open area, such as equipment cabinets, and in a few very open designs of PEM fuel cells.

With these fans and blowers the concept of efficiency is a difficult one. The input power is simply the electrical power used to run the motor. The purpose of the blower could be said to move the air, and so the output power is the rate of change of kinetic energy of the air. Using this measure, fans and blowers usually have very low efficiencies, which fall even lower as the back pressure against the airflow rises. However, this is not really a very helpful measure, since we do not actually want kinetic energy in the air. We usually want something else, for example, the removal of heat. Let us take as an example a small 120-mm axial fan such as is often used to cool electronic equipment. Such a fan might move air at 0.084 kg s–1 and consume 15W of electric power. If the air it blows rises in temperature by just 10°C, then the rate of removal of heat energy will be:

Power = $C_p \times \Delta T \times \dot{m} = 1004 \times 10 \times 0.084 = 843W$

That is, 843W of heat removed for just 15W of electrical power. Is that efficient? It may be. But it is not, if more of that heat could be removed by natural convection and radiation, and we are using a larger fan than is necessary. The point is, that the efficiency of the heat removal system depends more on the design of the airflow path, and how much temperature the air can pick up as it goes through, than on the performance of the motor. Rather than the efficiency of such a cooling system, it is more useful to define *effectiveness* as:

 $Cooling system effectiveness = \frac{rate of heat removal}{electrical power consumed}$

In this case, that would give a figure of 843/15 = 56. The effectiveness of this system is thus 26, somewhat lower than in the previous case. This is because the rate of movement of air with a centrifugal blower is less than that with an axial fan?

On the other hand, the more compact systems should be able to achieve a greater temperature change in the air as it goes through. Generally, fuel cell system designers should obtain effectiveness figures of between 20 and 30 fairly readily. There is always a balance in cooling systems between flow rate of air and electrical power consumed. Higher flow rates improve heat transfer, but at the expense of fan power consumption.

6.60 The Introduction to the Unit Cell and the Cell Stack Package

This section will describe the components, technology parts of the Unit Cell of the SOFC Cell Stack. Appleby and Foulkes noticed that, in theory, any substance that was capable of chemical oxidation could be supplied continuously and be burned galvanically as fuel at the anode of a fuel cell. Similarly, the oxidant can be any substance that can be reduced at a sufficient rate. In addition, chemically combining the molecules of a fuel and oxidizer without burning, fuel cells have dispensed with the inefficiencies and pollution of traditional combustion. Classified according to the choice of electrolyte and fuel, these traits determine the electrode reactions and, the type of ions that carry the current across the electrolyte.

From a systems engineering perspective, just as a pivotal subsystem exists for a system, an element of focus exists for a particular subsystem. In the Cell Stack Package configuration the electrolyte and its ceramic electrodes that are the elements of focus, for they are the subsystem's essential components and their outputs are electricity and heat.



Figure 6-34: The Different Fuel Cell Types of Reactions [Fuel Cell Today, 2010]

The Cell Stack Package's basic physical structure is called the 'Unit Cell' which consists of an electrolyte in contact with an anode layer and a cathode layer on either of its sides. The electrolyte of a SOFC is a dense layer of ceramic that conducts oxygen ions. The high operating temperatures of SOFCs allow the kinetics of oxygen ion transport to be sufficient for good performance. SOFCs have an electrolyte that is a solid, non-porous metal oxide, usually Y_2O_3 -stablilized ZrO₂. The cell operates at 600-1000 C where ionic conduction by oxygen ions takes place.



Figure 6-35: A honeycomb-type cathode supported SOFC. [Advance Industrial Science and Technology, 2006]

Ceramic anode and cathode layers are very porous and are attached (sintered) on either side of the solid ceramic electrolyte to create a tri-layered, cell package or Unit Cell as shown in **Figure 6-35**. The ceramic anode and cathode layers must be very porous to allow the fuel and air to flow towards the ceramic electrode/electrolyte's interfaces. On either side of the Unit Cell are Interconnects or "*Separators*" which serve as current collectors and gas separators.

The high operating temperatures can lead to extremely stringent requirements for materials. The thermal expansion coefficients for cell components must be closely matched to reduce thermal stress arising from differential expansion between components. Chemical compatibility of the stack components with gases in the high oxidizing and reducing environments is also of primary concern.

6.61 Fuel Cell Operation

The mechanisms of solid-oxide fuel cell operation are not completely understood and involve a number of unproven postulates. The mechanisms may differ in some details based upon cell design. Most treatments of the subject have been oversimplified and have attempted to transfer experience from low-temperature, liquid-electrolyte cells which are not relevant with high temperature SOFCs.

In theory, the complete combustion process of producing electricity may be divided into three stages. Two of these stages involve the chemical reactions at the ceramic electrode layers. The next is the ion conduction through the electrolyte. A schematic representation of a Unit Cell with the reactant and product gases and the ion conduction flow directions through the cell are shown in **Figure 6-36** and the chemical reactions of the SOFC are shown below.





Figure 6-36: The Chemical Reaction of an SOFC [US Department of Energy, 2010]

For the fuel cell to produce electricity, hydrogen and oxygen must be combined to form water through a free radical mechanism. Useful energy obtained from the thermal heat of this reaction through an internal combustion engine with an upper efficiency of 60% (*for compression ratio of 10 and specific heat ratio of 1.4*) based on the Otto thermodynamic cycle. It is also possible to combine the hydrogen and oxygen through redox mechanism as in the case of a fuel cell. In this process, the reaction is broken into two half-reactions which occur at separate electrodes. In this situation the reactant's energy is directly converted to electricity.

Hydrogen gas is fed to the anode side of the Unit Cell where ionization occurs along with the release of electrons and H^+ ions. The hydrogen arrives as a diatomic gas $2H^2$ where each adsorbed hydrogen molecule ionizes into four hydrogen protons (H+) and four electrons (e-). The rate of this process can be increased with the help of a catalyst. Because the chemical reaction at this electrode produces positive ions, it can be thought of as the '*positive*' electrode. The negatively charged electrons are then forced to flow from the ceramic anode to the bulk anode electrode to an interconnect until the electrons finally enter an external load before re-entering the cathode side of the unit cell (*i.e. electrons will diffuse naturally from high concentration to low concentration of electrons*). However, the hydrogen ions are not conducted through the electrolyte. The hydrogen ions temporarily remain at the anode in a receptive state.

The ceramic cathode or '*air electrode*' is a thin, porous layer on the opposite side of the electrolyte where its catalytic surface facilitates the separation of the adsorbed oxygen molecules (oxygen bonds are broken) into oxygen atoms, which are held momentarily into a "*receptive*" state on the active catalyst. The cathode processes the electrons and oxygen atoms to form oxygen ions $2O^{-2}$. The free moving oxygen ions then are conducted through the electrolyte and, combine with the hydrogen ions waiting at the anode to form water molecules $2H_2O$.

In a typical SOFC fuel cell, fuel is fed continuously to the ceramic anode electrode. An oxidant (*often oxygen from air*) is fed continuously to the ceramic cathode electrode of the unit cell. The electrochemical reactions take place at the ceramic electrodes to produce an electric current through the electrolyte, while driving a complementary electric current that performs work on the end load. If the fuel is a light hydrocarbon, such as methane, another function of the ceramic anode is to act as a catalyst for steam reforming the fuel into hydrogen. This provides another operational benefit to the fuel cell because the reforming reaction is endothermic, which cools the unit cell internally. To produce enough power for a particular application, Unit Cells are

'stacked' together on top of each other in series, repeatedly, to create a Cell Stack Package, as shown in **Figure 6-37**.



Figure 6-37: The Cell Stack Configuration [NETL, 2010]

The Interconnect or '*Separator*' can be either a metallic or ceramic layer that sits between each individual cell. The interconnects serve as current collectors. "*Current collector*" means a plate or device which can conduct electrons produced by, for example, an oxidation reaction at an anode. These devices are typically plates that also may incorporate a flow field and are thus made from materials that are typically relatively impervious to reactants and/or reaction products under the process conditions of the cell reaction system. The separator's purpose is to connect each cell in series so that the electricity each cell generates can be combined.



Figure 6-38: (a) Schematic diagram of a fuel cell; (b) scheme of the connection of the anode of a single fuel cell to the cathode of the subsequent single fuel cell, constituting a SOFC Cell Stack [Furtado, 2008]

Another function of the Interconnect is to separate the fuel and oxygen gases.

Because the Interconnect is exposed to the oxidizing and reducing environments at high

temperatures it must be extremely stable. For this reason, ceramics have been more

successful in the long term than metals as interconnect materials. However, these ceramic

interconnect materials are very expensive as compared to base metals.



Figure 6-39: Shown in the picture are the interconnect (center) with seal (underneath) of a planar SOFC stack.

In an ordinary design, the sealant separates air and fuel in an SOFC cell and/or cell stack. It must be stable in both oxidizing and reducing environments. It should adhere to and be mechanically and chemically compatible with other components of the fuel cell. It is also expected to reduce thermal stress during high temperature operation and be able to withstand thermal cycling due to shutdown and/or start up conditions. In addition, it may serve as a structural component in some SOFC designs.

Seal development and application are key barriers for the high efficiency and long-term integrity of fuel cell operations. Compared to tubular designs, planar SOFCs can provide a higher power density, but requires high temperature sealants that may not be necessary in tubular SOFCs.

It is essential for the seal to be gas-tight or have a negligible leak rate, since even small leaks in seals can affect the cell and stack potential and degrade performance. Various sealants have been developed and to name a few: there are compressive seal, ceramic fiber seal, glass seal, glass-ceramic seal, and hybrid seal.

6.62 The Functional Analysis – The Assumed Mechanisms of the Solid Oxide Fuel Cell

In the example treatment presented, the functionality of a particular type of SOFC will be discussed and the following basic assumptions are made:

- The fuel is hydrogen and the oxidizer is air. The uses of reformed natural gas, coal gas, or other mixed gases are believed to exhibit no essential differences in the actual fuel cell reactions.
- 2. The cathode is porous LSM, which is a mixed conductor or equivalent.
- 3. The zirconia has a mixed-conducting surface layer on the fuel side.
- 4. The anode is porous nickel cermet plus ZrO_2 or equivalent.
- The 'Separator' is an oxidized FeNiCr alloy having an adherent nonporous oxide skin.

The SOFC Assumed Mechanisms figure shows a simplified schematic diagram of the assumed solid-oxide fuel cell electrochemical mechanism. The separators in the diagram sandwich the Unit Cell are covered on both of their sides with oxide layers. Due to the different reducing or oxidizing environments that each side is exposed to, the oxide layers of each have different thicknesses, compositions, and resistivities. They are labeled 1 and 2.



Figure 6-40: The SOFC Assumed Mechanisms [Milliken, 2010]

Sometimes bulk electrodes are used in SOFC designs. For this example treatment,

bulk electrodes were not included. Sandwiching the Unit Cell the bulk electrodes partially restrict gas flow of the air and fuel. The restriction promotes maximum gas exposure of the Unit Cell's ceramic electrode layers/electrolyte interface, which promotes the efficiency of the electrochemical reactions. Also bulk electrodes act as current collectors for they provide electrical conductive pathways because the electrons to travel away from the Unit Cell.

6.63 Anode Reaction Mechanism

The anode-side surface of the zirconia electrolyte exhibits a mixed conductivity which is enhanced by the value of oxygen potential in the adjacent fuel gas mixture. Hydrogen gas molecules (H_2) are adsorbed on the electrolyte surface and undergo the following reaction:

$$H_2 (ads) + O^= \rightarrow H_2O (ads) + 2e^-$$

The H2O molecule is then desorbed into the surrounding flowing gas stream and is carried away by convection and diffusion. The electrons flow near the electrolyte surface to the nearest anode contact and flow through the anode to the next cell. Since the electrolyte anode surface area is orders of magnitude greater than the tiny areas adjacent to the anode-electrolyte-fuel gas the "triple phase boundaries". The boundaries will not play an important role compared with the mixed-conductivity mechanism: a situation related to the cathode mechanism, but with differing geometry and resistivities.

6.64 Cathode Reaction Mechanism

Oxygen gas molecules (O_2) arrive at the cathode surface by combined forced convection plus diffusion through the remaining air present. Oxygen molecules are then adsorbed onto the cathode surface. Electrons are conducted through the bulk cathode material and also arrive at the cathode surface. Each O2 molecule then acquires 4 electrons to form 2 oxygen ions:

$$O_2 (ads) + 4e^- \rightarrow 20^=$$

(*This reaction probably proceeds via 2 or more steps, but the net overall reaction is of principal interest here*). The ions then flow through the mixed-conducting cathode towards the electrolyte interface.

Since the cathode total surface area is orders of magnitude greater than the tiny areas adjacent to *the cathode-electrolyte-air* the "*triple phase boundaries*", the mechanism will dominate even though the cathode ionic conductivity is relatively low. The cathode reaction will occur preferentially to the surfaces nearest the electrolyte. The oxygen ions will flow from the cathode surface reaction sites to the anode reaction sites via the electrolyte as shown in the SOFC Assumed Mechanisms figure.

The overall reactions for various types of fuel cells are present in the table below.

Table 6-7 THE ELECTROCHEMICAL REACTIONS IN FUEL CELLS				
Adapted from The Fuel Cell Handbook				
Fuel Cell	Anode Reaction	Cathode Reaction		
Polymer Electrolyte & Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2}O_2 + 2H^+ + 2e^-$ $\rightarrow H_2O$		
Alkaline	$\mathrm{H}_{2} + 2(\mathrm{OH})^{-} \rightarrow 2\mathrm{H}_{2}\mathrm{O} + 2\mathrm{e}^{-}$	$\begin{array}{c} \frac{1}{2} O_2 + H_2 O + 2e^- \\ \rightarrow 2(H_2 O) \end{array}$		
Molten Carbonate	$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^{-}$ $CO + CO_3^{=} \rightarrow 2CO_2 + 2e^{-}$	$\frac{1/2}{2} O_2 + CO_2 + 2e^-$ $\rightarrow CO_3^-$		
Solid Oxide	$H_{2} + O^{=} \rightarrow H_{2}O + 2e^{-}$ $CO + O^{=} \rightarrow CO_{2} + 2e^{-}$ $CH_{4} + 4O^{=} \rightarrow 2H_{2}O +$ $CO_{2} + 8e^{-}$	$\frac{1}{2}$ O ₂ +2e ⁻ \rightarrow O ⁼		
CO - Carbon Monoxide $CO_2 - Carbon Dioxide$ $CO_3^{=} - Carbonate ion$	e^{-} - electron H ⁺ - Hydrogen ion H ₂ - Hydrogen	H_2O – water O_2 – oxygen OH^- - Hydroxyl ion		

The total potential or open circuit voltage created in a fuel cell is the sum of the voltages created by each of the half-reactions. The oxidation half-reaction at the anode produces a certain voltage potential and the reduction half-reaction at the cathode produces another voltage potential. These two voltage potentials can be summed to obtain the total voltage of the fuel cell.

Table 6-8 THE IDEAL VOLTAGE AS A FUNCTION OF CELL TEMPERATURE Adapted from The Fuel Cell Handbook							
Temperature	25°C	80°C	100°C	205°C	650°C	800°C	1100°C
	(298K)	(353K)	(373K)	(478K)	(923K)	(1073K)	(1373K)
Cell Type		PEFC	AFC	PAFC	MCFC	ITSOFC	TSOFC
Ideal Voltage	1.18	1.17	1.16	1.14	1.03	0.99	1.091

6.65 System Analysis



Figure 6-41: The Hierarchical Structure of the Cell Stack

Table 6-9		
THE SUBDIVISION OF THE UNIT CELL		
Fast Ionic Conductor		
The Element of Focus	The Electrolyte	
Gas Resistor/Current Collectors	Bulk Electrodes	
Anions		
The Element of Focus	Ceramic Anode	
Cations		
The Element of Focus	Ceramic Cathode	
Gas Separators	The Seals	
Gas Separators/Current Collectors	The Interconnects	

6.66 Ohm's Law

Ohm's Law V = I R

$$O_2 (ads) + 4e^- \rightarrow 20^=$$

Where:

V = Voltage I = Current R = Resistance

Current is the movement of electrical charges in a conductor (e.g., electrons moving in an electronic conductor and ions moving in an ionic conductor). Electrochemistry uses almost exclusively direct current. Unless mentioned otherwise, the use of the term "current" is typically in connection with direct currents. The typical unit of a current is an ampere.

6.67 Fuel Cell Area Specific Resistance (ASR)

The area specific resistance (ASR) of a fuel cell is its resistance normalized by its area. Fuel cell resistance is basically the sum of all the series ASRs implied by the SOFC. Such a sum must include:

- 1. All bulk resistances (ASR = ρ t)
- 2. All interfacial resistances (ASR = $r/f (\rho_{\downarrow} 1 + \rho_{\downarrow} 2)$): (except where f=1, such as at the separator/oxide interface, for example)
- 3. Any influences from gas flows on ASR

The separator plus both oxide layers may be added without internal interfaces (*since here* f=1). This ASR is believed to be quite low. All contact resistances should be computed using ρ values for the dense materials in contact, where as the bulk resistance of the porous electrodes should use the measured value for the porous material having that structure.

The cathode and the electrolyte anodic surface require special treatment. On the cathode, the ionic conductivity is probably 10^2 to 10^3 lower than the electronic conductivity. Therefore, the average t for path 3 may be taken as the cathode thickness, t_c , while the weighted-average t value for path 4 is much lower, but not known. A first approximation of its value might be to use the mean pore size (or power particle diameter) of the cathode material in contact with the electrolyte. The cathode electronic and its ionic resistivity depend upon the adjacent oxygen pressure, as noted earlier.

For the electrolyte anodic surface (*see the SOFC Assumed Mechanisms Figure*, *flow 7*) where the charge transfer occurs, the following equation may be derived:

$$ASR = \frac{\rho m^{2r^2}}{2\pi t} \ln (m/2)$$

Where: $r = average \ contact \ radius, \ cm$
 $m = average \ contact \ spacing, \ as \ a \ multiple \ of \ the \ radius$
 $\rho = \ electronic \ resistivity \ of \ surface \ layer$
 $t = \ thickness \ of \ surface \ layer, \ cm$

The value of $\boldsymbol{\rho}$ can be as low as about 10^{-2} ohm-cm under strongly reducing conditions. If no reduced layer exists, $\boldsymbol{\rho}$ may be between 10^3 and 10^4 ohm-cm at 1000 C, but in that case t would be the entire electrolyte thickness. The value of ASR is often a significant portion of the total ASR. Since this value can vary as the oxygen potential varies, it follows that the fuel cell ASR should be observed to decrease as the fuel flow increases and vice versa, with some time lags.

The electrical power and energy output are easily calculated from the well known formulas:

Power = VI and Energy = V/t Where: V = Voltage I = Current (Amperage) T = TimeHowever, the energy of the chemical input and output of a fuel cell is not so

easily characterized. The problem is that chemical energy' is not simply defined – and terms such as enthalpy, Helmholtz function, and Gibbs free energy are used. The Gibbs free energy is the *maximum* amount of non-expansion work that can be extracted from a closed system. This maximum can be attained only in a completely reversible process. When a system changes from a well-defined initial state to a well-defined final state, the Gibbs free energy ΔG equals the work exchanged by the system with its surroundings, minus the work of the pressure forces, during a reversible transformation of the system from the same initial state to the same final state.

In the ideal case of an electrochemical converter the change in Gibbs free energy the change in G, of the reaction is available as useful electric energy at the temperature of the conversion. In thermodynamics, the Gibbs free energy is a thermodynamic potential that measures the "useful" or process-initiating work obtainable from an isothermal, isobaric thermodynamic system. Just as in mechanics, where potential energy is defined as capacity to do work, similarly different potentials have different meanings. Gibbs energy is the capacity of a system to do non-mechanical work and ΔG measures the nonmechanical work done on it.

6.68 Cell Efficiency

The thermal efficiency of a fuel conversion device is defined as the amount of useful energy produced relative to the change in enthalpy, change in H, between the product and feed streams.

Conventionally, chemical (fuel) energy is first converted to heat, which is then converted to mechanical energy, which can then be converted to electrical energy. For the thermal to mechanical conversion, a heat engine is conventionally used. Carnot showed that the maximum efficiency of such an engine is limited by the ratio of the absolute temperatures at which heat is rejected and absorbed, respectively.

6.69 Heat Production

Heat is produced when a fuel cell operates. All of the enthalpy of reaction of a hydrogen fuel cell was converted into electrical energy then the output voltage would be:

- 1.48V (if the water product was in liquid form)
- Or 1.25V (if the water product was in vapor form)

It clearly follows that the difference between the actual cell voltage and this voltage represents the energy that is not converted into electricity – that is, the energy that is converted into heat instead. The cases in which water finally ends in liquid form are so few and far between that they are not worth considering. So we will restrict ourselves to the vapor case. However, please note that this means we have taken into account the

cooling effect of water evaporation. It also means that energy is leaving the fuel cell in three forms: as electricity, as ordinary 'sensible' heat, and as the latent heat of water vapor. For a stack of n cells at current I, the heat generated is thus:

Heating rate =
$$nI(1.25 - Vc)$$
 W

Figure 6-42 is a pictorial representation of the Unit Cell is shown below and has been used, when applicable, in this paper to represent the Cell Stack Package.



Figure 6-42: The Cell Stack of An SOFC Power

6.70 Conclusion

An elephant, no matter how large, can be eaten if broken down into smaller pieces. The workings of a SOFC Power System can be understood if the whole system is decomposed down into lower level subsystems and components. The beauty of the Topdown Design Approach is it gives designers the capability to understand fundamental subsystem interactions as they realize that each system depends and provides for other systems. From this knowledge, system feasibility studies, operational requirements, evaluation of technology applications, and advanced planning can be scheduled and executed.

Some components, such as blowers, fans, tanks, and heaters might be very familiar to the reader. Depending on the reader's technical background the principles of catalytic activity, and the electro-chemical mechanism of the unit cell can be understood.

CHAPTER VII

TESTING FOR THE CONCEPTUAL DESIGN AND ADVANCE PLANNING PHASE – PHASE ONE

7.1 Introduction

Increasing customer awareness of quality control and reliability and its influence on lifetime costs and safety, together with increasing complexity of industrial plants and equipment has resulted in an escalating need for systematic methods of accounting for reliability in design and manufacturing [Blanchard, 2008].

Traditionally, the use of such methods has essentially been limited to aviation, space and nuclear applications. In the Conceptual Design and Advance Planning Phase, part of system engineering methodology is to set up a testing plan which includes a quality control, reliability and maintenance plan that should begin early in the phase and, is continually be updated as the system matures.

7.2 The Implementation of Testing Early On

Even though testing cannot begin until the system has reached a reasonable level of sophistication and, enough capabilities are present to ensure that this will be an effective effort, it is necessary to begin the implementation of component/subsystem testing and

maintenance planning as early as possible. Besides allowing time to be fully prepared for the first test effort, the test and maintenance plan should have time to become fully integrated into the power systems lifecycle early on [Blanchard, 2008].

7.3 Bloom Energy – Quality Control and Reliability Problems

A large, fuel cell developer in February 24[,] 2010, unveiled its technology at a launch event at eBay's campus in Silicon Valley, attended by a number of luminaries, including former Secretary of State Colin Powell and the governor of California, Arnold Schwarzenegger. Bloom Energy touted that its fuel-cell technology was a cheap, reliable source of electricity, with a much more stable source of electricity than solar, wind, or geothermal power.

Yet Bloom Energy is not without quality control and reliability problems. For example, one of its fundamental challenges is to make its electrolyte reliable.

The Bloom Energy's power system uses thousands of fuel cells, each using ceramic squares coated with Bloom's proprietary "ink". The individual cells can fail, CEO Sridhar acknowledged, but would not disclose the failure rate of individual cells. It's extremely thin and operates at a wide range of temperatures. The big challenge is thermal stress," said Tobin Fisher, who co-founded mobile fuel cell company Ardica Technologies out of Stanford University. "All of these different components heat up and expand at different rates. One of the challenges with the technology is reliability and temperature volatility. Thermal stress is a big factor. Apparently all of the components heat up, expanding at different rates causing the electrolyte to crack as a result. Fisher indicates that Bloom Energy would have to conduct longer term stress-testing experiments to study the reliability of boxes loosing efficiency over time. It seems like Bloom Energy may not be completely out of the woods fighting reliability issues. The

company, with about 500 employees, has 50 systems deployed and expects to have double that number working by the end of the year, said Sridhar, who wants to be producing far more boxes to meet what he calls "robust" demand. "I'm not patient by nature," Sridhar said. "Getting all the ducks lined up so that we can be making a lot more than one box a day, that's what I worry about." Sridhar's worry might be misplaced; rather than focusing on 'quantity', perhaps better quality and reliability methods and practices would aid Sridhar and Bloom Energy in getting "all their ducks lined up". Special emphasis should be placed on quality control, testing and reliability analysis of, not only the cell stacks, all subsystems of an SOFC power system. All developers, not only Bloom Energy, need a method for assessing system wide reliability and critical failure predictability requirements.







In determining the need for test and evaluation, fuel cell developers should commence with the initial specification of system requirements in the conceptual design. As specific technical performance measures are established, it is necessary to determine the methods by which compliance with these factors will be verified. How will these tests be measured, and what resources will be necessary to accomplish this?

Responses to this question may entail using simulation and related analytical methods, using an engineering model for test and evaluation purposes, testing a production model, evaluating an operational configuration in the end user's environment, or a combination of these.

In essence, fuel cell developers need to review the requirements for the system, determine the methods that can be used in the evaluation effort and the anticipated effectiveness of subsystem processes, and develop a comprehensive plan for an overall integrated test and evaluation effort.

The Test and Evaluation Master Plan (TEMP) is the major plan that coordinates the entire test and evaluation effort of a power system, including system and subsystem test management [Blanchard, 2008].

. The Test and Evaluation Master Plan is drafted during the Conceptual and Advance Design Phase of a NPD's Lifecycle and approved by the end of the Preliminary System Design Phase. The Plan should be reviewed at each formal review to ensure that any design changes are reflected in the testing program.

While the contents related to subsystems will vary from one fuel cell design to another, the Test and Evaluation Master Plan outline contents should include [Blanchard, 2008].:

- A brief description of the system,
- System subsystems and components;
- The test and evaluation program summary including test and evaluation responsibilities and schedule;
- An outline of the test and evaluation delineation between operational parameters
- And the technical issues and problems of the system, of its subsystems and of the subsystems' components;
- The development; acceptance,
- Reference testing to compare the results of future tests;
- The details of future testing, test and evaluation resource summary, including personnel, test equipment, facilities, training and so on;
- And lastly, appendices providing relevant documentation, test procedures and test reports.

7.5 Category of Tests in the Preliminary Design and Advance Planning Phase

In **Figure 7-2** [Blanchard, 2008] the first category is entitled "Analytical Type 1 Testing," which pertains to certain design evaluations that can be conducted early in the system life cycle using computerized techniques such as CAD, CAM, CAS, simulation, rapid prototyping, and related approaches [Blanchard, 2008].

. With the availability of a wide variety of models, three-dimensional databases, and so on, the design engineer is now able to simulate human—equipment interfaces, equipment packaging schemes, the hierarchical structures of systems, and activity/task sequences. In addition, through the utilization of these technologies, the fuel cell design

engineer is able to do a better job of predicting, forecasting, and accomplishing sensitivity/contingency analyze with the objective of reducing future risks. In other words, a great deal can be now accomplished in system evaluation that, in the past, could not be realized until equipment became available in the latter phases of detail design and development [Blanchard, 2008].

•



7.6 Testing Baseline Plans

The objectives of testing and maintenance baseline plans are to verify the status of development, verify that design risks can be minimized, demonstrate that all technical and performance requirements specified in the systems requirements are met, and as the baselines are developed certify the commercial readiness of the power system [Blanchard, 2008, Key, 2010].

Throughout the lifecycle of NPD, testing and maintenance baseline plans are structural in nature and will consist of Unit, Integration, and System Testing.

In the Conceptual Design Phase, testing and maintenance planning considers the basic level of 'unit' testing that focuses on the components and/or subsystem designs separately. Each subsystem/component requirement should be analyzed to determine its functionality and performance limits. The four verification methods used during the design development process should include the following [Blanchard, 2008]:

- Subsystem or component testing is executed under specified conditions, the results are observed or recorded, and an evaluation is made of some aspect or function of the test subject.
- Demonstration is a dynamic analysis technique that relies on observation of system or component behavior during execution, without need for post-execution analysis, to detect errors, violations of development standards, and other problems.
- 3. Process Analysis evaluates a system or component based on its form, structure, content, or manufacturer's documentation.
- 4. Inspection is a static analysis technique that relies on varies forms of examination to detect errors, violations of development standards, and other problems.

During the Conceptual Design Phase, subsystem testing strategy should be created in order to address or determine which tests should be performed and the most efficient approaches to accomplish these tests. The test approach should include the following steps:

- Learning and understanding the environment and functions that the subsystem/components will to perform relative to overall system performance.
- 2. Learning and understanding the subsystem itself.
- 3. Analyzing requirement traceability.
- 4. Identifying risks associated with subsystem operation and malfunction and technical challenges.
- 5. Determining the type of testing that should be performed.
- 6. Determining when testing should occur.
- 7. Developing tests.
- 8. Executing tests.
- 9. Reporting on test results.

After design modifications, re-executing tests should be performed to determine if problems/issues have been corrected and to reexamine reliability and/or quality control requirements.

7.7 The Benefits of Testing

Testing is the earliest phase of system evaluation and, it is the most cost-effective method for removing defects. Testing permits the testing and debugging of component parts and subsystems, thereby providing a better way to manage the integration of the components and subsystems into larger units. The detailed unit design is used as a basis to compare 'how' and 'what' the component or subsystem is able to perform [Blanchard, 2008].

7.8 The Type 1 Tests

Type I testing refers primarily to the evaluation of system components in the laboratory using engineering breadboards, bench test models, service test models, rapid prototyping, and the likes. These tests are designed primarily with the intent of verifying certain performance and physical characteristics and are developmental by nature [Blanchard, 2008].

. The test models used operate functionally, but do not by any means represent production models. Such testing is usually performed in the fuel cell developer's laboratory facility by engineering technicians using "jury-rigged" test fixtures and engineering notes for procedures. It is during this initial phase of testing that design concepts and technology applications are validated and changes can be initiated on a minimum-cost basis.

In the Conceptual Design and Advanced Planning Phase, challenging Type 1 Test application can require new combinations of test measurements that are not addressed by fundamental instrumentation because fuel cell test systems must accurately monitor and control hundreds of measurements, for example, including the flow, temperature, pressure, and power of the Cell Stack.

Realistically, a complete evaluation of the power system, in terms of meeting initial performance specification and requirements cannot be accomplished until the system is produced and functioning in some sort of an operational environment. However, if problems occur and system modifications are necessary, the accomplishment of such an evaluation so far downstream in its life cycle may turn out to be quite costly [Blanchard, 2008]. In essence, the earlier problems are detected and corrected; the better

off the fuel-cell designer is in terms of both incorporating the required changes and the associated costs of the modifications. Type 1 tests are done for these reasons.

In addressing the subject of evaluation, the objective is to acquire a high degree of confidence, as early in the life cycle as possible, that the power system will ultimately perform as intended. Acquiring this confidence, through the accomplishment of laboratory and field testing involving a physical replica of the system (and/or its subsystems), can be quite expensive. The resources required for testing are often quite extensive, and the necessary facilities, test equipment, personnel, and so on, may be difficult to schedule.

Table 7-1			
THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS			
		Maintenance	
	Testing Plan	Plan	
Subsystem	Needed	Needed	
The Enclosure	Yes	Yes	
The Cell Stack	Yes	Yes	
The BOP:	Yes	Yes	
The Electrical Subsystem	Yes	Yes	
The Mechanical Subsystem	Yes	Yes	
The Hot Assembly	Yes	Yes	
The Thermal Management			
Subsystem	Yes	Yes	
The Air Subsystem	Yes	Yes	
The Waste Management Subsystems	Yes	Yes	
The Fuel Processing Subsystem	Yes	Yes	

7.9 Computer Prototyping

However, with a more comprehensive analysis effort and the use of prototyping, it may be possible to verify certain design concepts during the early stages of conception and preliminary and detail design. With the advent of three-dimensional databases and the application of simulation techniques, the designer can now accomplish a great deal relative to the evaluation of system layouts, component relationships and interferences, human—machine interfaces, and so on. There are many functions that can now be accomplished with computerized simulation that formerly required a physical mock-up of the system, a preproduction prototype model, or both. The availability of computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided support (CAS) methods, and related technologies has made it possible to accomplish much in the area of system evaluation relatively early in the system life cycle, when the incorporation of changes can be accomplished with minimum cost [Blanchard, 2008].

Table 7-2 EXAMPLES OF TESTING		
Subsystem	Testing	
The Enclosure	Structural Integrity	
The Cell Stack Package	Output voltage and response to various load conditions.	
The BOP Subsystems:		
The Electrical Subsystem	Step Load, Transient Response and Transient Overload testing	
The Mechanical Subsystem	Loading capability, verification of gas flow rates and pressures tolerance.	
The Hot Assembly	Thermal properties of the material; functionality of the subsystem connections.	
The Thermal Management Subsystem	Heat Transfer	
The Fuel Processing Subsystem	The amount of hydrogen produced	
The Air Subsystem	Verification of gas flow rates and pressures.	
The Waste Management Subsystems	Levels of sulfur	

7.10 Examples of Fuel Cell Testing & Testing Equipment and Technique

7.11 Reliability

Reliability, in a generic sense, can be defined as "the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions." The *probability* factor relates to the number of times, that one can expect an event to occur in a total number of trials. A probability of 95%, for example, means that (on average) a system will perform properly 95 out of 100 times, or that 95 of 100 items will perform properly [Blanchard, 2008].

The aspect of *satisfactory performance* relates to the system's ability to perform its mission. A combination of qualitative and quantitative factors defining the functions that a system is to accomplish is usually presented in the context of the System Specifications [Blanchard, 2008].

7.12 Time

The element of *time* is most significant because it represents the measure against which the degree of performance can be rated. A system may be designed to perform under certain conditions, but for how long? Of particular interest is the ability to predict the probability of a system surviving for a designated period of time without failure. Other time-related measures are mean time between failure (MTBF), mean time to failure (MTTF), mean cycles between failure (MCBF), and failure rate (λ) [Blanchard, 2008].

7.13 Environment

The forth key element in the reliability definition *specified operating conditions* pertains to the environment in which the system will operate. Environmental requirements are based on the anticipated mission scenarios (or profiles), and appropriate considerations for reliability must include temperature cycling, humidity, vibration and

shock, sand and dust, salt spray, and so on. Such considerations must also address the conditions of the system during the accomplishment of maintenance activities, when the system (or components thereof) is being transported from one location to another, and/or when the system is in the storage mode [Blanchard, 2008].

Experience indicates that the transportation, handling, maintenance, and storage modes are often more critical from a reliability standpoint than the environmental conditions during the periods of actual system utilization [Blanchard, 2008].

7.14 Basic Reliability Function

In applying reliability requirements to a specific system, one needs to relate these requirements in terms of some quantitative measure (or a combination of several figures of merit). The basic reliability function, R(t), may be stated as [Blanchard, 2008]:

$$\mathbf{R}(\mathbf{t}) = 1 - \mathbf{F}(\mathbf{t})$$

Where R (t) is the probability of success and F(t) is the probability that the system will fail by time t. F(t) represents the failure distribution function. When dealing with failure distributions, one often assumes average failure rates and attempts to predict the expected (or average) number of failures in a given period of time. To assist in the prediction, the Poisson distribution (which is somewhat analogous to the binomial distribution) can be applied. This distribution is generally expressed as:

$$P(x, t) = \frac{(\lambda t)^{x} e^{-\lambda t}}{x!}$$
Where λ represents the average failure rate, *t* is the operating time, and *x* is the observed number of failures. This distribution states that if an average failure rate (λ) for an item is known, then it is possible to calculate the probability, P(x, t), of observing 0,1,2,3,..., *n* number of failures when the item is operating for a designated period of time, *t*. Thus, the Poisson expression may be broken down into a number of terms:

$$1 = e^{-\lambda t} + (\lambda t)e^{-\lambda t} + \frac{(\lambda t)^{2\mathbb{E}}e^{-\lambda t}}{2!} + \frac{(\lambda t)^{3\mathbb{E}}e^{-\lambda t}}{3!} + \dots + \frac{(\lambda t)^{n\mathbb{E}}e^{-\lambda t}}{n!}$$

Where $e^{-\lambda t}$ represents the probability of zero failures occurring in time *t*, $(\lambda t)e^{-\lambda t}$ is the probability that one (1) failure will occur, and so on.

In addressing the reliability objective, dealing with the probability of success, the first term in the Poisson expression is of significance. This term, representing the "exponential" distribution, is often assumed as the basis for specifying, predicting, and later measuring the reliability of a system. In other words,

$$\mathbf{R} = \mathrm{e}^{-\lambda t} = \mathrm{e}^{-t/M}$$

Where M is the MTBF. if an item has a constant failure rate, the reliability of that item at its mean life is approximately 0.37, or there is a 37% chance that the item will survive its mean life without failure.

7.15 Redundancy

In engineering, redundancy is the duplication of critical components of a system with the intention of increasing reliability of the system, usually in the case of a backup or fail-safe[Blanchard, 2008]. Redundancy can be applied in design at different hierarchical indenture levels of the system. At the subsystem level, it may be appropriate to incorporate parallel functional capabilities, so that the system will continue to operate if one path fails to function properly. The flight control capability (incorporating electronic, digital, and mechanical alternatives) in an aircraft is an example where there are alternate paths in case of a failure in any one. At the detailed piece-part level, redundancy may be incorporated to improve the reliability of critical functions, particularly in areas where the accomplishment of maintenance is not feasible. For example, in the design of many electronic circuit boards, redundancy is often built in for the purpose of improving reliability when the accomplishment of maintenance is not practical.



Figure 7-3: Reliability and Maintainability Design [Sidhu, 2006]

The application of redundancy in design is a key area for evaluation. Although redundancy per se does improve reliability, the incorporation of extra components in a design requires additional space, and the costs are higher. This leads to a number of questions: Is redundancy really required in terms of criticality relative to system operation and the accomplishment of the mission? At what level should redundancy be incorporated? What type of redundancy should be considered (active or standby)? Should maintainability provisions be considered? Are there any alternative methods for improving reliability (e.g., improved part selection, part de-rating)? In essence, there are many interesting and related concerns that require further investigation. [Sidhu, 2006, Chatopadhyay, 2008]

With modern times the challenge is to design in quality and reliability early in the development lifecycle. As quality and reliability are design into products at their earliest stages of development, the early and consistent use of essential feedback in the design process allows the engineer to design out failures and produce reliable, safe, and customer stable functioning products. Constructive feedback design analysis amplifies possibilities of divergences (design changes and iterations); setting up the right conditions to develop a reliable product.



Figure 7-4: The Systems Engineering Feedback Process [Blanchard, 2008]

7.16 Product Quality Feedback

Product quality feedback also captures historical information for use in future product improvement. Feedback loops and methodologies, especially Failure Modes and Effects Analysis (FEMA) in the design process assist the engineer improve the quality and reliability of products. Among, others, these benefits include [Blanchard, 2008]:

- Improve product/process reliability and quality.
- Increase customer satisfaction.
- Early identification and elimination of potential product/process failure modes.
- Prioritize product/process deficiencies.

- Capture engineering/organization knowledge.
- Emphasizes problem prevention.
- Documents risk and actions taken to reduce risk.
- Provide focus for improved testing and development.
- Minimizes late changes and associated cost.
- Catalyst for teamwork and idea exchange between functions.

A general familiarization of the subject area is necessary, as well as an understanding of some of the activities that are usually undertaken in the performance of a typical reliability program [Blanchard, 2008]:

 Reliability program plan. Although the requirements for a reliability program may specify a separate and dependent effort, it is essential that the program plan be developed as part of, or in conjunction with, the SEMP. Organizational interfaces, task inputsoutputs, schedules, and so on, must be directly supportive of system engineering activities. In addition, reliability activities must be closely integrated with maintainability and logistic support functions and must be included in the respective plans for these program areas (which also should be tied directly into the SEMP).
 Reliability modeling. This task, along with several others (e.g., allocation, prediction, stress/strength analysis, tolerance analysis), depends on the development of a good reliability block diagram. The block diagram should evolve directly from, and support, the system functional analysis and associated functional flow, and support, the system functional analysis and associated functional flow diagrams. Further, the reliability block diagram is used for analyses and predictions, the results of which are provided as a major input to maintainability, human factors, logistics, and safety analyses. The reliability block diagram represents a major link in a long series of events and must be developed in conjunction with these other activities.

3. *Failure mode, effect, and criticality analysis* (FMECA). The FMECA is a tool that has many different applications. Not only is it an excellent design tool for determining cause-and-effect relationships and identifying weak links, but it is useful in maintainability for the development of diagnostic routines. It is also required in the accomplishment of supportability analysis (SA) relative to the identification of both corrective and preventive maintenance requirements. The FMECA constitutes a major input to the reliability-centered maintenance (RCM) program. It is used to supplement both the fault-tree analysis and the hazard analysis accomplished in a system safety program. The FMECA is critical activity, must be accomplished in a timely manner (started during the Conceptual Design Phase and carried into the Preliminary System Design Phase and subsequently updated on an iterative basis), and must be directly tied into these other activities.

4. *Fault-Tree analysis* (FTA). The FTA is a deductive approach involving the graphical enumeration and analysis of different ways in which a particular system failure can occur and the probability of its occurrence. A separate fault tree may be developed for every critical failure mode or undesired top-level event. Attention is focused on this top-level event and the first-tier causes associated with it. Each of these causes is next investigated for its causes, and goes on. The FTA is narrower in focus than the FMECA and does not require as much input data.

5. *Reliability-centered maintenance* (RCM) analysis. The RCM analysis includes an evaluation of the system/process, in terms of the life cycle, to determine the best overall

program for preventive (scheduled) maintenance. Emphasis is on the establishment of a cost-effective preventive maintenance program based on reliability in formation derived from the FMECA (i.e., failure modes, effects, frequency, criticality, and compensation through preventive maintenance).

6. *Failure reporting, analysis, and corrective-action system* (FRACAS). Although this is indentified as a reliability program task designed to address recommendations for corrective action as result of catastrophic failures, the overall task objective relates closely to the system engineering feedback and control loop. Often, as problems arise and corrective action is initiated, the events that take place and the results are not adequately documented. Although it is important to respond to the short-terms needs (i.e., correct outstanding problems in an expeditious manner), it is also important to provide some long-term memory through good reporting and documentation. This task should be tied directly with the system engineering reporting, feedback, and control process.

7. *Reliability, qualification testing.* This task, usually accomplished as part of type 2 testing, should be defined in the context of the *total* system test and evaluation effort. The specific requirements will depend on the system complexity, the degree of design definition, the nature of the mission that the system is expected to accomplish, and the TPMs (and their priorities) established for the system. In addition, for this and any other individual test, there are certain expectations and opportunities for gathering information. For instance, the objectives of environmental qualification testing are to determine whether the system will perform in a specified environment. In performing this test, it may be possible to gather some reliability information by observing system operating

times, failures, and so on. This, in turn, may permit a reduction in subsequent reliability testing. A second example pertains to the gathering of maintainability data during the performance of formal reliability testing. As failures occur during the test, maintenance actions can be evaluated in terms of elapsed times and resource requirements. This, in turn, may allow for some reductions in both maintainability and supportability test and evaluation efforts. In other words, there are numerous possibilities for reducing costs (while still gathering the necessary information) through the accomplishment of an integrated testing approach. Thus, reliability test must be viewed in the context of the overall system test effort, and the requirements for this must be covered in the TEMP.

7.17 Maintenance Planning

Creating a maintenance plan is generally not difficult to do. But creating a comprehensive maintenance program of an SOFC Power System, that is effective, poses some interesting challenges. It would be difficult to appreciate the subtleties of what makes a fuel cell power system's maintenance plan effective without understanding how the plan forms part of the total maintenance environment .

Maintenance practitioners across many industries use many maintenance terms to mean different things. It is necessary to explain the way in which a few of these terms have been utilized in this section to ensure common understanding by all who read it. It must be emphasized, however, that this is the author's preferred interpretation of these terms, and should not necessarily be taken as gospel truth. In sporting parlance, the maintenance policy defines the "rules of the game", whereas the maintenance strategy defines the "game plan" for that game or season [Porrill-Reliable Plant, 2010].

- Maintenance Plan Highest-level document, typically applies to the entire power system.
- Maintenance Strategy Next level down for the maintenance plan, typically reviewed and updated every time a component/subsystem or whole system undergoes a design change or rework and is part of the Configuration Management of the System's design.
- Subsystem Maintenance Plan Applies to a particular subsystem or group of subsystems, describes the total package of all maintenance requirements to care for that group or subsystem.
- Maintenance Checklist List of maintenance tasks (preventive or predictive) typically derived through some form of analysis, generated automatically as work orders at a predetermined frequency.
- Short-term maintenance plan (sometimes called a "schedule of work") Selection
 of checklists and other ad-hoc work orders grouped together to be issued to a
 development team for completion during a defined maintenance period.



Figure 7-5: A Hypothetical Maintenance Plan for an SOFC Developer[Porrill-Reliable Plant,

2010].

The large square block indicates the steps that take place within a hypothetical fuel cell developer's laboratory. It is good practice to conduct some form of analysis to identify the appropriate maintenance tasks. The analysis will result in a list of tasks that need to be sorted and grouped into sensible chunks, which each form the content of a checklist. Sometimes it may be necessary to do some smoothing and streamlining of these groups of tasks in an iterative manner.

The most obvious next step is to schedule the work orders generated by the system into a plan of work for the development teams.

Less common, however, is to use this checklist data to create a long-range plan of forecasted maintenance work. This plan serves two purposes:

- 1. The results can be used to determine future design and development requirements, and
- 2. They later will be feed into the preliminary design production plan.

The schedule of planned systems tasks is issued to the team and the work is completed. Feedback from these work orders, together with details of any systems failures, is captured in the Maintenance Strategy for historical reporting purposes.

A logical response to this systems engineering feedback is that the content of the checklists should be refined to improve the quality of the preventive maintenance, especially to prevent the recurrence of system or component failures. Implicit in this approach is the need to have a robust analysis system in which the content of the analysis can be captured and updated easily. All the information that gets captured into the Maintenance Strategy and eventually the Maintenance Plan must be put to good use otherwise it is a waste of time.

7.18 Quality Engineering

Basically, quality pertains to meeting or exceeding the requirements, expectations, and needs of the consumer (customer of the SOFC Power System). The prime motivator is that of "survival" in a highly competitive industry.

In the past, in other, older industries the fulfillment of quality objectives has primarily been accomplished in the production and/or construction phase of product lifecycle through the implementation of formal quality control (QC) or quality assurance (QA) programs. Statistical process control (SPC) techniques, incoming and in-process inspection activities, closely monitored supplier control programs, periodic audits, and selective problem solving methods have been implemented with the objective of attaining a designated level of system quality. In addition, the advent of such techniques as Six Sigma, applying Baldridge criteria for the purposes of evaluation, and the ever-increasing application and strengthening of ISO standards have aided in the maintenance of highquality programs in many firms [Blanchard, 2008].

However, within the fuel cell industry, these efforts (although very effective in their application else where) have, for the most part been neglected and the overall results have been an adverse effort towards freezing a workable, reliability, maintainable, high quality design which could be given to a manufacturer for scale-up and productions.

The solution to the fuel cell industry's quality problem would be to view the aspect of quality from a top-down life-cycle perspective, and to develop its own concept of total quality management (TQM) which describes as a total integrated management approach that addresses system/product quality during all phases of the lifecycle and at each level in the overall system hierarchy structure, where quality is sorely needed. It

should provide a before-the-fact orientation to quality, and it focuses on system design and development activities, as well as production, manufacturing, assembly and test, construction, product support, and related functions.

TQM is a unification mechanism linking human capabilities to engineering, production, and support processes. It provides a balance between the "technical system" and the "social system". Specific characteristics of TQM include the following [Blanchard, 2008]:

- Total customer satisfaction is the primary objective, as compared with the practice of accomplishing as little as possible in conforming to the minimum requirements. The customer orientation is important versus the "what can I get away with" approach.
- Emphasis is placed on the iterative practice of "continuous improvement" as applied to engineering and developmental functions and the like. The objective is to seek improvement on a day-to-day basis, as compared with the often-imposed last-minute single thrust initiated to force compliance with some standard.
- Quality in design and development emphasizes a direction towards design simplicity, flexibility, standardization, and so on.

Taguchi's general approach to "robust design" is to provide a design that is insensitive to the variations normally encountered in production and/or operational use. The more robust a design is the less the support requirements are, the lower the lifecycle costs are, and the higher the degree of effectiveness. Overall design improvement is anticipated through a combination of careful component evaluation and selection, the

appropriate use of statistical process control methods, and application of experimental testing approaches, applied on a continuous basis.

7.19 Conclusion

In closing, the material presented in this chapter is obviously not intended to be a comprehensive text on the subject of reliability, quality engineering, and maintenance of SOFC Power Systems and FC developers, but enough information is included to provide the reader with some overall knowledge of key terms, definitions, and the prime objectives associated with the disciplines. Basically, these subjects are being presented as some of the many disciplines requiring consideration within the overall context of system engineering of an innovative technology.

The nature of the quality engineering, reliability, and maintenance are highly dependent on the overall objectives of the test and evaluation effort. SOFC Power Systems require a great deal of testing at all system levels. Whatever the requirements (under testing and reliability and quality control studies) may dictate, these considerations are important to the successful completion of the power system's overall design objectives.

The problem with Bloom Energy's Bloom Box stationary fuel cell is that, despite 60 MINUTES' assertion that it might be the "holy grail" to free Americans shackled to a coal-fired grid, the product has unresolved reliability issues which points to a need for a better total quality management plan.

When involved in testing SOFC Power Systems (which in regards to quality, reliability and maintenance) five questions usually must be answered:

- 1. How well did the system/subsystem/component actually perform, and did it accomplish its mission objective?
- 2. What is the *true* effectiveness of the system/subsystem/component?
- 3. What is the *true* effectiveness of the system/subsystem/component support capability?
- 4. Does the system/subsystem/component meet all of the requirements as covered through the specified technical performance measures?
- 5. Does the system/subsystem/component meet all of the expected output requirements?

CHAPTER VIII

THE OPERATIONAL REQUIREMENTS AND TECHNOLOGY BASELINES FOR THE FUEL PROCESSING SUBSYSTEM, THE AIR SUBSYSTEM AND THE WASTE MANAGEMENT SYSTEMS – PHASE ONE

8.1 Introduction

During the Conceptual Design and Advance Planning Phase, operational requirements analysis in systems engineering encompasses those tasks that go into determining the needs or conditions to meet for a new or altered product, taking account of the possibly conflicting requirements of system design. In designing a fuel cell power system an engineer accounts for the physical performance and limitations of equipments and components to be utilized in the system. In addition, a survey of the potential technical barriers must be considered in system design.

This chapter defines the operational requirements for and the technology baselines of the Fuel Processing Subsystem, The Air and Waste Management Subsystems of the SOFC Power System and in addition, to provide the reader with technical information

which is necessary in order to understand what is needed by way of operational and functional requirements of the subsystems.

8.2 Barriers to SOFC Power Systems

Of the many barriers facing SOFC developers, cost and durability present two of the most significant challenges. While addressing cost and durability, fuel cell performance must meet or exceed that of competing technologies. For example, durability of fuel cell stacks, which must include tolerance to impurities and mechanical integrity, has not been established. Tolerance to air, fuel and system-derived impurities (including the storage system) needs to be established. Stationary fuel cells must achieve greater than 40,000 hours durability (*in the long run*) to compete against other distributed power generation systems. Sulfur-tolerant catalysts are required to achieve this durability target in the fuel processor, respectively. State-of-the-art systems need to be benchmarked. Materials and manufacturing costs are too high for catalysts, electrolyte, electrodes and other components. Balance-of-plant (BOP) components specifically designed for use in fuel cell systems need development in order to achieve cost targets. Low-cost, high-volume manufacturing processes are also necessary.

8.3 Rationale for the Requirement Analysis

To manage this tall order of requirements and technical challenges of SOFC Power System design, requirements analysis is critical to the success of its New Product Development. Requirements must be documented, actionable, measurable, testable, related to identified engineering and business needs or advantages, and defined to a level of detail sufficient for good system design. The design, optimization, and integration procedure of a fuel cell power system is very complex because of the number of required

systems, components and functions. Many possible design options and trade-offs exist that ultimately affect unit capital cost, operating cost, efficiency, parasitic power consumption, complexity, reliability, availability, fuel cell life, and operational flexibility.

For example, practical heat exchangers are limited in how close the temperature of the cold fluid or gas can come to the temperature of the hot fluid or gas at any point in the heat exchanger. This minimum temperature difference is known as the "*approach*." For a gas to gas heat exchanger, a reasonable approach design value is 100⁰F. An engineer who employs a gas to gas heat exchanger with only a 50⁰F approach will have implied the use of a very large and expensive heat exchanger, and is likely to find the cycle is not practical.

8.4 Types of Requirements

Although a detailed discussion of fuel cell design requirements and integration is not within the scope of this thesis, a few of the most common system requirements will be explored. Generally, requirements can be architectural, structural, behavioral, functional, and non-functional. Behavioral requirements describe all the cases where the system uses the functional requirements are captured in case studies. Functional requirements are supported by non-functional requirements (also known as *quality requirements*), which impose constraints on the design or implementation (such as performance requirements or reliability). In **Chapter 6**, the architectural requirements of an SOFC Power System were looked at. In this chapter the functional requirements of the Power System will be defined. Generally, functional requirements are expressed in the form "*the system shall do*", while non-functional requirements are expressed in the form

"*the system shall be*". A non-functional requirement is a requirement that specifies criteria that can be used to judge the operation of a system, rather than specific behaviors. This should be contrasted with functional requirements that define specific behavior or functions. The plan for implementing *functional* requirements is detailed in the system *design* where as the plan for implementing *non-functional* requirements is detailed in the system *architecture*.

8.5 Reasonable SOFC Power System Performance Assumptions

This chapter documents reasonable performance assumptions of an SOFC Power system design that can be used in a first pass conceptual design effort. The reader should be aware that the development of such a list includes many assumptions and simplifications that may not be suitable for detailed design. The documentation of equipment guidelines at a significant level of detail is the subject for entire books. The list presented here simply illustrates the more important equipment performance considerations and their common performance ranges, which may be useful to the novice system designer for incorporating a level of realism. Detailed conceptual design efforts need to address many factors that are addressed by the list below which is an example of system requirements of a hypothetical SOFC Power System. Such requirements are the effects of flow rates, temperatures, pressures, corrosive elements, the impact of the equipment on the cycle itself, and, of course, the specific performance of the actual equipment. The tables below show an outline of the operational and functional requirements of the Cabinet/Enclosure, one of the three major subsystems of the SOFC Power System. The two additional columns serve as checklists denoting possible system/subsystem/component testing and maintenance planning.

Table 8-1 THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS

The Functional Requirements of the SOFC Power System are:

Requirements	Testing Plan	Maintenance Plan
	Needed	Needed
1. To produce AC electricity.	Yes	Yes
2. To produce heat for water and home.	Yes	Yes
3. To provide the means by which	Yes	Yes
power could be given to the Grid.		
Subsystem	n Level-1	
The End User's requirements for the Cabinet:		
	Testing Plan	Maintenance Plan
	Needed	Needed
The outer surface of the Cabinet must not		
exceed a certain tolerance level for		
temperature.	Yes	Yes
The Cabinet's structure must support and		
protect the BOP and Cell Stack from		
elements of the outside environment.	Yes	Yes
The Cabinet of the SOFC must provide		
safety.	Yes	Yes
Other product requirements the customer		
might have are:	Safety	Yes
	Quiet operation	Yes
	Small and compact	
	enough to be a	Yes
	home appliance.	
	Easy to service and	Yes
	maintain	
	Dependable, and	Yes
	reliability	

Table 8-2		
THE FUNCTIONAL	L REQUIREMENTS AND T	HE TESTING AND
MAINTENANCE BASELIN	NES OF AN SOFC POWER	SYSTEM'S SUBSYSTEMS
The Cabinet/Enclosure's	Subsystem Level -1	Fuel Processing System).
The Cabinet/ Eliciosure s	Requirements (retated to the I	Maintenance Plan
	Testing Plan Needed	Needed
The Englacy report he	NI/A	NI/A
large enough to house the	IN/A	IN/A
Fuel Processing System		
Tuer Trocessing System.		
If needed, the Enclosure		
must provide a means by		
which the water tank can be	To be determined	Yes
cleaned or decanted.		
The Enclosure could		
provide the means to install		
and unifisian the fuel and	To be determined	Vac
water inters when needed.	10 be determined	Tes
The Cabinet/ Encl	osure's Requirements (related a	to the Air System):
The Enclosure must provide		
the means to allow air to		
reach the compressor(s) or		
be expelled from the		
system. In order words, the	To be determined	Yes
system must have a vent.		
The Enclosure could		
provide the means to install		N/
and uninstall the air filters	To be determined	Yes
The Engloque must provide		
a means to hold the filter		
assembly	To be determined	Yes
asseniory.		100

THE FUNCTIONA MAINTENANCE BASELI	Table 8-3 L REQUIREMENTS AND T NES OF AN SOFC POWER S	HE TESTING AND SYSTEM'S SUBSYSTEMS
	Subsystem Level -1	
The	Cabinet/ Enclosure's Requirem	nents
(related	to the Waste Management Sub	system)
	Testing Plan Needed	Maintenance Plan Needed
The design goal should be to include a catalyst which has as long a service life as the Power System itself. Therefore, if applicable, the enclosure must provide a means by which the catalyst can be change out	To be determined	Yes
The enclosure must provide a means to expel exhaust gases (e.g. CO_2) into the outside environment	Yes	Yes
If applicable, the enclosure must provide a means to replace the filters of the desulfurizing unit.	Yes	Yes
If applicable, the enclosure must provide a means to replace water and refill the water tank.	Yes	Yes
The	Cabinet/ Enclosure's Requirem	nent
(related to the Thermal Management Subsystem)		
	Testing Plan Needed	Maintenance Plan Needed
If applicable, the Enclosure must provide a means to expel heat to the outside environment.	Yes	Yes
The Enclosure must provide a means to provide high quality heat to the customer.	Yes	Yes

Table 8-4 THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS

	Subsystem Level -1	
The C	abinet/ Enclosure's Require	ment
(related to the T	hermal Management Subsyst	tem continued)
	Testing Plan	Maintenance Plan
The Cabinet/Enclosure must		
provide a means to allow		
the Heat Exchanges to be	Yes	Yes
easy cleaned.		
If applicable, the		
Cabinet/Enclosure must		
provide a support structure	Yes	Yes
for the thermal insulation		
packages.		
The Cabinet/Enclosure must		
provide a means by which		
the fans or blowers can be	Yes	Yes
easy serviced.		
The C	abinet/ Enclosure's Require	ment
(re	lated to the Electrical System	n)
The Cabinet/Enclosure could		
provide a display which would		
provide the end user with real-t	ime Yes	Yes
data (e.g. efficiency, fuel		
consumption, etc.)		
The Cabinet/Enclosure must		
provide a means by which the H	BOP	
system's controls can be service	ed. Yes	Yes
The Cabinet/Enclosure must		
provide a means by which the		
system can connect to the end	Yes	Yes
user's load panel or the grid.		
The Cabinet/Enclosure must		
provide a place to store the batt	ery	
bank.	N/A	N/A
If applicable, the enclosure mus	st	
have to capability to cool the		
battery bank to a certain	Yes	Yes
temperature which extends the		
batteries life span.		

THE FUNCTIONAL RE	Table 8-5 OUIREMENTS AND '	THE TESTING AND	
MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S			
	Subsystem Level -1		
The Cabi	net/ Enclosure's Require	ement	
(related to t	he Electrical System con	ntinued)	
	Testing Plan Needed	Maintenance Plan Needed	
Certain types of batteries			
produce hydrogen gas. The			
Cabinet/Enclosure's battery	Yes	Yes	
shelter must be equipped with			
ventilation to the outdoors.			
The Cabinet/Enclosure must			
provide housing for power			
conditioning unit.	N/A	N/A	
If applicable, the			
Cabinet/Enclosure must provide			
a means by which the inverter	Yes	Yes	
can connect to the end user's			
utility grid.			
The Cabinet/Enclosure must			
protect the end user from			
electrical shock, burns and other	Yes	Yes	
harms.			
The Cabi	net/ Enclosure's Require	ement	
(related to the Mecha	anical Subsystem and the	e Hot Assembly)	
The Cabinet/Enclosure must			
provide a stable structural			
mount for the Hot Assembly	Yes	Yes	
and its insulation packages.			
The Cabinet/Enclosure must			
provide a stable structural			
support for the pipe networks.	Yes	Yes	

8.6 Packaging of the SOFC Power System's Enclosure and Interface Considerations

Packaging for the SOFC Power System's subsystems is usually designed on an ad-hoc basis depending on which evolutionary path is taken by the balance-of-plant, even within the same overall system. The proliferated system design throughout the NPD lifecycle of the system increases the expense and complexity of later manufacturing of the system.

Interfaces to the system may differ for different customers. Moreover, different customers of the same system--or the same customers at different times--require subsystems of the same type which are customized to their particular needs. For example, one customer may want grid connection capabilities, another customer might not, regardless of any other consideration. Another may need more power, while still another customer might want less. One customer may not require a permanent, uninterruptible power, but may need enough emergency power.

8.7 The Fuel Processing System

The main functions of the Fuel Processing System of an SOFC Power System were reformate conversion and fuel cleaning. This section will expand on these topics and will also include technology bases and system requirements of the steam generator (boiler) and the element of focus, the catalyst of the fuel processor.

For a conventional combustion system, a wide range of gaseous, liquid and solid fuels may be used, while hydrogen, reformate, and methanol are the primary fuels available for current fuel cells. Reforming is a chemical process in which hydrogen

containing fuels react with steam, oxygen, or both to produce a hydrogen-rich gas stream. Reformate (*syngas and other components such as steam and carbon dioxide*) can be used as the fuel for high-temperature SOFCs, for which the solid or liquid or gaseous fuels need to be reformulated. **Figure 8-1** illustrates the general concepts of processing gaseous, liquid, and solid fuels for fuel cell applications. For SOFCs, only desulfurization is required for reforming of liquid fuels and natural gas.



Figure 8-1: The concepts and steps for fuel processing of gaseous, liquid and solid fuels for hightemperature and low-temperature fuel cell applications. [Song, 2008]

When selecting a fuel processing design the designer has one of two fuel processing mechanism for hydrogen production and they are internal reforming or external reforming. In SOFC Power Systems, reforming can take one of two paths.

8.8 Internal Reforming

Internal Reforming is performed inside the Cell Stack, namely on the anode side of the electrolyte. The internal reforming reaction is driven by the decrease in hydrogen as the Cell Stack Package produces power. Internal reforming can be beneficial to system efficiency because there is an effective transfer of heat from the exothermic cell reaction to satisfy the endothermic reformer reaction. A reforming catalyst is needed adjacent to the anode gas chamber for the reaction to occur. The cost of an external reformer is eliminated and system efficiency is improved, but at the expense of a more complex cell configuration and increased maintenance issues.

Reformation of carbon-containing fuels is necessary to prevent solid carbon deposition, "*coking*", at the high solid-oxide stack operating temperatures and to minimize local stack temperature variations. The required heat input for vaporization and reforming may be obtained from the surplus heat from the fuel cell stack operation and/or using burners or partial oxidation of the fuel stream. MCFC and SOFC operating temperatures are high enough for internal reforming to occur. **Figure 8-2** shows a comparison of internal reforming and external reforming MCFCs.





8.9 External Reforming

External Reforming is performed outside the cell stack and is carried out in a specialized subsystem of the BOP. The advantage of external reforming is its flexibility of design. In the case of using liquid fuels (*gasoline, diesel, and jet fuel*) and gaseous fuels (*natural gas, propane gas*) a catalytic reformer needs to be placed adjacent to the anode gas chamber. In a fuel cell design with external reformer the reformer can be operated at elevated pressures although the fuel cell stack may be operated under atmospheric pressure.

Because external reforming is the most widely used system design external reforming will be selected for the SOFC Power System model of this paper.



Figure 8-3: The concept of an SOFC Power System using an external reformer [Song, 2008]

8.10 The Reformer of an External Reforming Design

In most cases, a reformer must be preceded by a vaporizer or steam generator to vaporize water and liquid fuel *if used*. Then the process is followed by mixing the steam with the fuel gas and/or vapor.

Besides heat transfer, the reformer and the fuel cell do not have a direct physical effect on each other. This is an advantage because external reforming design eliminates the problem of deactivation of electrode catalyst due to carbon formation by way of fuel decomposition.

A desirable reformer design is compact, low in cost, requires infrequent cleaning or maintenance, and produces a fuel gas mixture containing low methane levels (*leakage*). The output fuel gas "*syngas*" from a reformer intended for a solid-oxide fuel cell will preferably comprise chiefly hydrogen, steam, carbon monoxide, carbon dioxide, (*optional*) nitrogen, and contain less than about 5 percent of methane. Many of the known reformers can produce syngas having high methane leakage, leading to large temperature variations in the fuel cell stack. Cold spots occur when high-methane syngas contacts cells tending to reduce both stack power and cell stack operating life.

Thermal "*cracking*" in over-heated preheaters and manifolds can easily form carbon. If the fuel conversion reactor is not properly designed or operated, coking is likely to occur.

Adding steam generator and reformation steps to the energy conversion process adds to the cost and size of the fuel processing system. Yet many different types of vaporizers and reformers exist with current technology. However each design contains its own disadvantages.

8.11 External Reforming Choices

There are three principle types of external reforming:

- Steam reforming (SR) provides the highest concentration of hydrogen and, can obtain conversion efficiency.
- Partial oxidation (POX) is a fast process, good for starting, fast response, and a small reactor size. Non-catalytic POX operates at temperatures of approximately 1,400 °C, but adding a catalyst (catalytic POX or CPOX) can reduce this temperature to as low as 870 °C.
- Combining steam reforming closely with CPOX is termed autothermal reforming (ATR).

Since steam reforming generates more hydrogen per mole of methane fed than the other reactions, SR reactors are the standard approach used in industrial hydrogen generation plants. External steam reforming, the most widely used technology in the fuel cell industry, has been selected as the hydrogen production processing for the SOFC Power System model of this paper.

8.12 Steam-to-Carbon Ratio or Oxygen-to-Fuel Ratio

There are two major fuels that SOFCs use: pure hydrogen and fuel composed of hydrogen linked to carbon. Steam-to-carbon ratio and oxygen-to-fuel are interchangeable terms meaning the ratio of oxygen to either carbon or the ratio of oxygen to hydrogen *linked* carbon.

An elegant, general equation was written Argonne National Laboratory (ANL) which describes generic fuel conversion. Autothermal reforming also falls within this spectrum so that the equation encompasses processes of interest to many fuel cells. The equation does not apply to complete combustion, but that conversion process is not relevant to fuel cells. The general, idealized equation is:

 $C_nH_mO_p + x(O_2 + 3.76N_2) + (2n - 2x - p)H_2O = nCO_2 + (2n - 2x - p + m/2)H_2 + 3.76xN_2$ Where, x is the molar ratio of oxygen-to-fuel. This ratio is very important because it determines:

- The minimum amount of water that is required to completely convert the carbon in the fuel to carbon dioxide (2n 2x p). Excess water is used in practice to ensure the conversion, resulting in water in the reformate (*right side of the equation*). Typically, one or two moles of water for every mole of oxygen are used.
- The maximum hydrogen yield (2n 2x p + m/2).
- The maximum concentration (percentage) of hydrogen in the reformate:
 - {[2n 2x p + m/2]/[n + (2n 2x p + m/2) + 3.76x] all times 100}

• The heat of reaction { $\Delta H_r = n(\Delta H_{f,CO2}) - (2n - 2x - p)\Delta H_{f,H2O} - \Delta H_{f,fuel}$ }.

Decreasing the oxygen-to-fuel ratio, x, results in increasing demand for water (*water-to-fuel ratio*), with commensurate increases in the yield and concentration of hydrogen in the reformate gas. When x = 0, the equation reduces to the strongly endothermic steam reforming reaction. The reaction becomes less endothermic with increasing oxygen. It becomes thermoneutral at $x = x_0$ (0.44 for methane). Above this point, the reaction becomes increasingly exothermic. At x = 1 with methane, the pure POX reaction, the feed contains sufficient oxygen to convert all of the carbon in the fuel to CO₂. No water needs to be added. The equation is a mix of the steam reforming reaction and the POX reaction at values of x between 0 and n.

Beyond x = [n - (p/2)] = n (when p = 0), where water is a product, the heat of reaction is determined by the phase of the product water. At still higher values, the excess oxygen oxidizes the hydrogen to produce water. Finally, at stoichiometric combustion, all carbon and hydrogen are converted to carbon dioxide and water. Here, x = Xc = [n - (p/2) + (m/4)]. The value of x reduces to 2 with CH₄ as the fuel.

8.13 Steam Reforming (SR)

The steam reformer is widely used in industry to make hydrogen. Small-scale steam reforming units to supply fuel cells are currently the subject of research and development, typically involving the reforming of methanol or natural gas but other fuels are also being considered such as propane, gasoline, autogas, diesel fuel, and ethanol.

Hydrogen can be reformed from natural gas and steam in the presence of a catalyst starting at a temperature of \sim 760°C. The reaction is endothermic. The CH₄ in the natural gas is usually converted to H₂ and CO in a SR reactor. Steam reforming reactors

yield the highest percentage of hydrogen of any reformer type. The basic SR reactions for methane and a generic hydrocarbon are:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$C_nH_m + nH_2O \rightarrow nCO + (m/2 + n) H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

Fuels are typically reformed at temperatures of 760 to 980 °C (1,400 to 1,800 °F).

8.14 Coke (Carbon) Formations

The processing of hydrocarbons always has the potential to form coke (*carbon*). If the fuel processor is not properly designed or operated, coking is likely to occur. Carbon deposition not only represents a loss of carbon for the reaction, but more importantly results in deactivation of catalysts in the processor and the fuel cell due to deposition at the active sites of the unit cell. Thermodynamic equilibrium provides a first approximation of the potential for coke (carbon) formation. The governing equations are:

$C + CO2 \leftrightarrow 2CO$	(Boudouard Equation)	
$C + 2H2 \leftrightarrow CH4$	(Carbon-Hydrogen Equation)	
$C + H2O \leftrightarrow CO + H2$	(Carbon-Steam or Gasification Equation)	

The possible formation of carbon using a particular fuel can be determined by the simultaneous solution of the above equations using their equilibrium coefficients. No solid graphitic carbon exists at low temperatures (~600 °C) in binary mixtures containing at least 2 atoms of oxygen or 4 atoms of hydrogen per atom of carbon. At these conditions, all carbon is present as CO_2 or CH_4 . Free carbon in hydrocarbon fuels forms according to the three equations, (*Boudouard Equation*), (*Carbon-Hydrogen Equation*),

and (*Carbon-Steam or Gasification Equation*). **Figures 8-4 and 8-5** show the effect of increasing steam on carbon deposition for methane and octane, respectively.



Figure 8-4: Carbon Deposition Mapping of Methane (CH4) (Carbon-Free Region to the Right of Curve) [Fuel Cell handbook, 2004]



(Carbon-Free Region to the Right and Above the Curve) [Fuel Cell handbook, 2004]

8.15 How to prevent Coking

Coking can be avoided by operating at high temperatures and at high steam-tocarbon ratios, where the ratio is based on the total atoms of oxygen contained in the steam and air feeds. For a given (s/c) ratio in the feed, it is preferable that the oxygen comes from water. Thus, for a given (s/c), steam reforming is preferred over ATR, which is preferred over POX; "preferred" meaning that coke formation can be avoided while still operating at a lower temperature. Reformer inlet steam-to-carbon (s/c) ratio is also an important factor in reformer design. The literature advises the maintenance of a relatively high s/c ratio to prevent mechanical as well as economic problems during the life of a power system. Higher s/c ratios are more effective for a number of reasons.

First, because a high s/c ratio favors the products in the reforming reaction equilibrium, it lowers the amount of unreacted methane and increases the production of hydrogen.

Second, a high s/c ratio inhibits the occurrence of carbon-forming side reactions in a reformer that result in carbon deposits on the catalyst. Carbon deposition increases the resistance to gas flow in the reformer tubes and may impair catalyst activity. This impairment lowers the rate of the reforming reaction and can cause local overheating or "*hot bands*" in reformer tubing all the way up to the cell stack itself resulting in premature tube wall failure and system shut down. Finally, a high (s/c) ratio provides the necessary steam for the shift conversion of carbon monoxide and reduces the risk of carburization damage to the fuel processing system's material.

In the below figure, an example of a Stream-to-Carbon Ratio Process Sensitivity Analysis is shown. A 3.0/1.0 s/c ratio was found to be the most optimum ratio. The below sensitivity runs showed that 4.0/1.0 s/c ratio requires a larger heat duty than a 3.0/1.0 ratio. This increases cost as more heat has to be applied to the reforming process. Increasing steam/carbon ratios for the reforming could reduce carbon formation, but higher steam/carbon ratios also result in lower energy efficiency, because vaporization and heating of water consume significant amount of energy.

Process Sensitivity to Steam/Carbon Ratio		
Methane Leak (%)	Net H ₂ O Production (kmol/hr)	
.66%	4117.62	
.35%	4189.86	
.12%	4243.83	
3	Sensitivity to Steam/Carb Methane Leak (%) .66% .35% .12%	

Figure 8-6: Process Sensitivity of Stream/Carbon Ratios [Strait, 2010]

In industrial steam reforming, steam/carbon ratios of around 3 are used, but much lower ratios would be desirable for fuel cell processors. Yet current technology shows that lowering the s/c ratio to 2.5/1.0 was found to increase methane leakage significantly, decreasing the amount of hydrogen produced. However, in practice, a slight excess of steam to carbon may be necessary to allow for the fluctuations in pressure needed for load changes and to allow for gas composition fluctuations.

8.16 The Filtering of the Solid Particulates

AN SOFC Power System's fuel tank should be a safe container for flammable fluids. A generic fuel filter is a filter in the fuel line that screens out dirt and rust particles from the fuel, normally made into cartridges containing a filter paper. They are found in most internal combustion engines. Fuel filters serve a vital function in SOFC Power System's tight-tolerance fuel processing systems. Unfiltered fuel may contain several kinds of contamination, for example rust and dirt that has been knocked into the fuel tank while filling, or rust caused by moisture in a steel tank. If these substances are not removed before the fuel enters the system, they will cause rapid wear and failure of the fuel pump, due to the abrasive action of the particles on the high-precision components used in modern injection systems. Fuel filters also improve performance, as the fewer contaminants present in the fuel, the more efficiently the fuel can be burnt.

8.17 Sulfur Poisoning

Besides their basic fuel reforming function fuel processors require the removal of impurities that degrade the fuel processor or fuel cell performance. Sulfur is the major contaminant encountered. The SOFC is the most tolerant of any fuel cell type to sulfur. It can tolerate several orders of magnitude more sulfur than other fuel cells. Hydrogen Sulfide (H₂S) levels of 1ppm result in an immediate performance drop, but this loss soon stabilizes into a normal linear degradation. Sulfur in the H₂S form has been found in fuel used for an external reforming SOFC Power Systems operating at 1,000 °C. SOFC - <1 ppm sulfur as H₂S, poisoning is reversible for the tubular SOFC. Tests show that high temperature planar SOFCs with all-ceramic components can tolerate up to 3,000 ppm of sulfur.

However, developers want to reduce the cell temperature to allow less expensive metal components, primarily interconnect, and improve cycle efficiency. There is a requirement to lower sulfur significantly if metal parts are used in an SOFC. For planar SOFCs, claims for sulfur tolerance vary among the developers. The range of sulfur has been published as 10 to 35 ppm.

8.18 Sulfur Poisoning of SOFC Anodes

The sulfur poisoning of SOFC anodes has been investigated extensively. Most studies show that the initial sulfur poisoning of SOFC anodes is a very fast process. A few studies also suggest that sulfur poisoning effect may continue to develop for tens to hundreds of hours. Most previous studies also indicate that the extent of sulfur poisoning
increases as the hydrogen sulfide (H_2S) concentration increases or the cell temperature decreases.

The degree of sulfur poisoning of ceramic anode electrode layers of Unit Cells is most accurately described by the increase in cell anode polarization resistance due to sulfur poisoning. The Cell Stack's current drops as the anode is poisoned by sulfur, leading to an increase in cathode polarization resistance but a decrease in cathode over potential. It was found that the relative increase in cell internal resistance, caused by sulfur poisoning, is smaller when current is increased or the cell-terminal voltage is lowered under either potentiostatic or galvanostatic conditions. Thus, the increase in anode polarization resistance, not the drop in cell power output, should be used to describe the degree of sulfur poisoning in order to avoid any confusion.

In one study, while the detrimental effect of hydrogen sulfide in the fuel stream for SOFCs is well known a complete understanding of the sulfur poisoning behavior of a nickel- yttria stabilized zirconia (Ni-YSZ) anode in a high-performance anode-supported SOFC under typical operating conditions is yet to be determined. None the less, many previous studies indicate that sulfur poisoning behavior is characterized by two stages. Since bulk sulfide would not be formed under the operating conditions it is well accepted that the rapid drop in power output upon initial exposure to several ppm H₂S is caused by the dissociative adsorption of sulfur species around three-phase boundaries (*the active sites for electrochemical oxidation of the fuel*), leading to an increase in anodic polarization. However, the mechanism of the slow degradation in performance during continuous exposure to H₂S over a long period of time (*hundreds to even thousands of hours*) as observed in some studies is still not clear. One hypothesis is that the continuous sulfur exposure leads to surface reconstruction of nickel. Another hypothesis is that H_2S results in migration of nickel in the anode, thereby degrading the distribution of the percolating Ni phase in the anode.



Figure 8-7: Comparison of impedance spectra for an electrolyte-supported cell operated at a constant current density of 0, 44, 129, 258, and 391mA-cm² before and after 10 ppm H₂S was introduced into a fuel flow at 800 °C. [Virkar, 2003]

8.19 Sulfur Reduction

There are high temperatures and low temperature methods to remove sulfur from a fuel reformate. Low temperature cleanup, such as hydro-desulfurizing limited to fuels with boiling end points below 205 °C is less difficult and lower in cost so should be used where possible, certainly with low temperature fuel cells. Sulfur species in the fuel are converted to H₂S, if necessary, and then the H₂S is trapped on zinc oxide. A minimum bed volume of the zinc oxide reactor is achieved at temperatures of 350 to 400 °C. At least one developer has a liquid-phase fuel desulfurizer cartridge that will be used to remove sulfur prior to fuel vaporization. Other developers remove the sulfur immediately after vaporization and prior to reforming. Hydrogen must be re-circulated to the removal device to convert the sulfur species to H₂S so that it can be entrapped on zinc oxide. Zinc oxide beds are limited to operation at temperatures below 430 °C to minimize thermal cracking of hydrocarbons that can lead to coke formation. Thermodynamics also favor lower temperatures.

At higher temperatures, the H_2S cannot be reduced to levels low enough for shift catalyst or to reach fuel cell limits. For sulfur removal in the reformer, the presence of significant concentrations of steam in the fuel gas has a negative impact on the reaction equilibrium, leading to a higher concentration of H_2S than could be achieved with a dry fuel gas.

Thermodynamic and economic analyses show that it is appropriate to use high temperature cleanup with high temperature fuel cells by removing the sulfur in the reforming reactor at high temperature, or by incorporating sulfur resistant catalysts.

There is a vast difference between removing sulfur from a gaseous fuel and a liquid fuel. The sulfur in a liquid fuel is usually removed after it is converted to a gas. Sulfur resistant catalysts are being developed, but none are mature enough for present use. The Argonne National Laboratory (ANL) in 2003 was developing catalysts to reform gasoline, and have demonstrated that their catalyst can tolerate sulfur. The ANL catalyst

has been shown to tolerate 100s of hours sulfur present in natural gas in an engineering scale reformer.

8.20 Boiler (Steam Generation Technology) – The Water Management System

A boiler or steam generator is a device used to create steam by applying heat energy to water. Although the definitions are somewhat flexible, it can be said that older steam generators were commonly termed boilers and worked at low to medium pressure (1–300 psi/0.069–20.684 bar; 6.895–2,068.427 kPa) but, at pressures above this, it is more usual to speak of a steam generator.

The boiler of an SOFC Power system should be designed to generate high quality steam. It must be designed to absorb the maximum amount of heat released in the process of combustion. This heat is transferred to the boiler water through radiation, conduction and convection. The relative percentage of each is dependent upon the type of boiler, the designed heat transfer surface and the power source.

Water introduces appreciable amounts of oxygen into the fuel processing system. Oxygen can enter the feed water system from the condensate return. Possible return line sources are direct air-leakage on the suction side of pumps, systems under vacuum, the breathing action of closed condensate receiving tanks, open condensate receiving tanks and leakage of nondeaerated water used for condensate pump seal and/or quench water. With all of these sources, good housekeeping is an essential part of the preventive maintenance program.

The water required for steam generator feed purposes i.e. for steam generation should be of very high quality and thus requires a lot of treatment. Untreated water, containing impurities may lead to the following problems in steam boilers:

- 1. Boiler Corrosion.
- 2. Scale and sludge formation.
- 3. Caustic Embrittlement.
- 4. Priming and foaming.

External treatment, as the term is applied to water prepared for use as boiler feed water, usually refers to the chemical and mechanical treatment of the water source. The goal is to improve the quality of this source prior to its use as boiler feed water, external to the operating boiler itself. Such external treatment normally includes:

- 1. Clarification
- 2. Filtration
- 3. Softening
- 4. Dealkalization
- 5. Demineralization
- 6. Deaeration
- 7. Heating

Any or all of these approaches can be used in feed water or boiler water preparation. Even after the best and most appropriate external treatment of the water source, boiler feed water including return condensate still contains impurities that could adversely affect boiler operation. Internal boiler water treatment is then applied to minimize the potential problems and to avoid any catastrophic failure, regardless of external treatment malfunction.

8.21 After filtration has been performed

Once feed water quality has been optimized with regard to soluble and particulate contaminants, the next problem is corrosive gases. Dissolved oxygen and dissolved carbon dioxide are among the principal causes of corrosion in the boiler and pre-boiler systems. The most common source of corrosion in boiler systems is dissolved gas: oxygen, carbon dioxide and ammonia. Of these, oxygen is the most aggressive.

The importance of eliminating oxygen as a source of pitting and iron deposition cannot be over-emphasized. Even small concentrations of this gas can cause serious corrosion problems.

8.22 Corrosion

One of the most serious aspects of oxygen corrosion is that it occurs as pitting. This type of corrosion can produce failures even though only a relatively small amount of metal has been lost and the overall corrosion rate is relatively low. The degree of oxygen attack depends on the concentration of dissolved oxygen, the pH and the temperature of the water. The influence of temperature on the corrosivity of dissolved oxygen is particularly important in closed heaters and economizers where the water temperature increases rapidly. Elevated temperature in itself does not cause corrosion. Small concentrations of oxygen at elevated temperatures do cause severe problems. This temperature rise provides the driving force that accelerates the reaction so that even small quantities of dissolved oxygen can cause serious corrosion.

The deposition of corrosive oxides in the boiler is frequently more troublesome than the actual damage caused by the gases. Deposition is not only harmful in itself, but it offers an opening for further corrosion mechanisms as well. Contaminant products in the feed water cycle up and concentrate in the boiler. As a result, deposition takes place on internal surfaces, particularly in high heat transfer areas, where it can be least tolerated. Metallic deposits act as insulators, which can cause local overheating and failure. Deposits can also restrict boiler water circulation. Reduced circulation can contribute to overheating, film boiling and accelerated deposition. The best way to start to control preboiler corrosion and ultimate deposition in the boiler is to eliminate the contaminants from the feed water.

8.23 Carbon Dioxide Corrosion

Carbon dioxide can enter a condensate system as a dissolved gas or it can be chemically combined in the bicarbonate or carbonate alkalinity of the feed water. Generally dissolved carbon dioxide is removed in the deaerating heater. The following reactions show the breakdown of naturally occurring bicarbonate and carbonate alkalinity to carbon dioxide.

Reaction 1: NaHCO2 + heat ± NaOH + CO2

Reaction 2: Na2CO3 + H2O + heat ± 2 NaOH + CO2

Reaction #1 proceeds to completion. Reaction #2 is only about 80% complete.

The manifestation of carbon dioxide corrosion is generalized loss of metal, typified by grooving of the pipe walls at the bottom of the pipe: attack occurs at the threaded or stressed areas. This is the most common form of condensate system attack.

Mechanical deaeration is the first step in eliminating oxygen and other corrosive gases from the feed water. Free carbon dioxide is also removed by deaeration, while combined carbon dioxide is released with the steam in the boiler and subsequently dissolves in the condensate. This can cause additional corrosion problems.

8.24 Copper Complexing Corrosion

The most commonly found copper complexing agent in condensate systems is ammonia. This can be present in low concentrations due to the decomposition of organic contaminants, hydrazine or amine type treatment chemicals. A good understanding of the levels of ammonia is necessary in the event the condensate system contains copperbearing alloys.

8.25 Mechanical and Chemical Deaeration

Mechanical and chemical deaeration is an integral part of modern boiler water protection and control. Deaeration is the process of removing dissolved gasses from solutions. Some of the benefits of Deaerating heaters are:

- 1. Violent scrubbing action occurring in the deaerator scrubber section ensures complete heating and deaerating.
- 2. Maximum deaerating efficiency because the water is preheated to near steam temperature in the pre-heater section.

Deaeration, coupled with other aspects of external treatment provides the best and highest quality feed water for boiler use. Simply speaking, the purposes of deaeration are:

- To remove oxygen, carbon dioxide and other noncondensable gases from feed water
- 2. To heat the incoming makeup water
- 3. Minimizing solubility of the undesirable gases
- 4. Providing the highest temperature water for injection to the boiler

Because dissolved oxygen is a constant threat to boiler tube integrity, deaeration will be aimed at reducing the oxygen content of the feed water. The two major types of deaerators are the tray type and the spray type. In both cases, the major portion of gas removal is accomplished by spraying cold makeup water into a steam environment.



Figure 8-8: Diagram of a tray-type boiler feed water deaerator (with vertical, domed aeration section and horizontal water storage section) [Wikipedia, 2010]

8.26 Tray-type Deaerating Heaters

Tray-type deaerating heaters release dissolved gases in the incoming water by reducing it to a fine spray as it cascades over several rows of trays. The steam that makes intimate contact with the water droplets then scrubs the dissolved gases by its counter-current flow. The steam heats the water to within 3-5 ° F of the steam saturation temperature and it removes all but the very last traces of oxygen. The deaerated water then falls to the storage space below, where a steam blanket protects it from recontamination. Nozzles and trays should be inspected regularly to insure that they are free of deposits and are in their proper position.

8.27 Why Some Corrosion in the Boiler is Necessary

Water will rapidly corrode mild steel; as the temperature increases, the reaction accelerates. The following reaction is typical of iron corrosion in a boiler:

$3 \ Fe + 4H_20 \gg Fe_3O_4 + 4H_2$

Iron + Water/Steam » Magnetite + Hydrogen gas

The magnetite produced is black iron oxide. Under normal operating conditions, this is the typical product of corrosion. However, it is also this reaction that inhibits excessive corrosion in steaming boilers. In a new or clean boiler, the initial corrosion process produces this magnetite film as a tenacious layer at the steel surface. This magnetite layer prevents any further contact with the steel or water surface. Consequently, the corrosion reaction is self-inhibiting.

This magnetite layer grows to an approximate thickness of 0.0004-0.001 inches at which point any further corrosion process ceases. Periodic weakening or damaging of this protective shell does occur and proper internal boiler water treatment can repair this layer. The normal corrosion in a clean boiler system progresses at approximately 1 mm per year. The appropriate pH levels for maintenance of the magnetite layer are approximately 8.5-12.7, with most systems operating at a pH level of 10.5-11.5.

In summary, corrosive components, especially O_2 and CO_2 have to be removed, usually by use of a deaerator. Remnants can be removed chemically, by use of oxygen scavenger. Furthermore feedwater has to be alkalized to a pH of 9 or higher, to reduce oxidation and to support the forming of a stable layer of magnetite on the water-side surface of the boiler, protecting the material underneath from further corrosion. This is usually done by dosing alkalic agents into the feedwater, like sodium hydroxide (*caustic soda*) or volatile ammonia. Inlet water should be virtually free of suspended solids that could clog spray valves and ports of the inlet distributor and the deaerator trays. In addition, spray valves, ports and deaerator trays may become plugged with scale that forms when the water being deaerated has high hardness and alkalinity levels. In this case, routine cleaning and inspection of the deaerator is very important. Minimization of these contaminants prior to the feed water train is the most successful way of dealing with this problem.

8.28 Deposits / Sediments / Fouling - Mechanism of Deposition

In any steaming boiler, three basic conditions exist:

 A circulation pattern is developed in the boiler due to steam bubbles, which alter the density of the boiler water. The hottest area of the boiler where nucleate boiling occurs is where the steam-boiler water mixture is the least dense. A rolling circulation pattern is developed as the steam proceeds through the boiler to its outlet for further plant use.

- 2. Based on convective, conductive and radiant heat transfer, thermal gradients are experienced throughout the steaming boiler. The hottest areas become primary deposition points due to high heat flux.
- Flow patterns, velocities and concentrations of contaminants also follow the laws of gravity. Thus, any area of the boiler considered to be low flow may exhibit significant deposition.

A good understanding of scale-forming tendencies and the resultant problems is necessary. The principal scaling and fouling ions are calcium, magnesium, iron and bicarbonate and carbonate alkalinity. Silica is also a potential foulant. Migratory iron, migratory copper and other contaminants such as calcium, magnesium and silica must be conditioned within the boiler itself. Excursions of calcium, magnesium and silica can create deposition problems within the feed water train. Scale formation is a function of two criteria:

- 1. The concentration and solubility limits of the dissolved salt
- 2. The retrograde solubility inversely proportional to temperature characteristic of some salts

In a steaming boiler, both of these conditions are met. While the boiler water is raised to a high temperature, the concentration of the dissolved salts is also increased. As steam is produced, dissolved salts remain in the boiler and continue to concentrate. Some salts may be soluble in the bulk boiler water. However, the boiler water immediately at the

tube surface is considerably hotter than the bulk boiler water. As steam bubbles form near the wall, the soluble salts remain with the boiler water. This creates a localized high concentration of salts, even though the bulk boiler water may be well below saturation levels. The precipitation normally formed under these conditions has a crystalline structure and is relatively homogeneous. In actuality, the crystallization of salts is a relatively slow process. A well-defined crystal is formed and often results in a dense and highly insulating deposit. From a chemical equilibrium standpoint, reversibility of this reaction is quite low.

Deposits reduce the heat transfer in the boiler, reduce the flow rate and eventually block boiler tubes. Any non-volatile salts and minerals that would remain in soluted form when the feedwater is evaporated have to be removed, because these would be concentrated in the liquid phase and require excessive "blow-down" (draining) to avoid that the liquid eventually becomes saturated and solid crystals fall out. Even worse are minerals that form limescale. Therefore, the make-up water added to replace any losses of feedwater has to be demineralized/deionized water.

8.29 Heat Transfer Losses

If the process of deposition starts and is allowed to continue, whether it is caused by poor external treatment or internal treatment, a slow and continuous loss of heat transfer and thermal efficiency occurs. As a result, there are two significant reasons for maintaining the proper external and internal control: safe, reliable operation and efficient, cost-effective operation. Thermal efficiency calculations can be made. However, they are time consuming and they generally do not change dramatically over a short period of time.

8.30 Embrittlement

Embrittlement of boiler metal is normally referred to as caustic embrittlement or intercrystalline cracking. Failure of a boiler due to caustic embrittlement is normally undetectable during operating conditions; it generally occurs suddenly, with catastrophic results. Three major factors must be present to cause intercrystalline cracking in boiler metal:

- 1. Leakage of boiler water must occur so as to permit the escape of steam and subsequent concentration of boiler water.
- 2. Attack of the boiler metal by concentrated caustic soda occurs from the concentrated boiler water.
- 3. There is high metal stress in the area of caustic concentration and leakage. In the past, caustic embrittlement failures have normally been associated with riveted seams in boiler drums. Modern welding techniques have eliminated this particular factor in today's boilers.

The actual phenomenon of caustic embrittlement is through high caustic concentrations traversing the grain boundaries within the crystalline structure of the metal. The caustic does not attack the crystals themselves, but rather travels between the crystals.

8.31 Caustic Embrittlement

Caustic embrittlement is a form of stress corrosion cracking that occurs in mild and low alloy steel due to the conjugant action of an enduring tensile stress and concentrated solution of sodium hydroxide. The stress may be residual from welding or

prior cold work or applied. Metallographic examination shows continuous, branched, intergranular cracking.

An embrittlement detector was patented by the United States Bureau of Mines and is covered by U. S. patents 2,283954 and 2,283955. **Figure 8-9** shows a typical embrittlement detector.



Figure 8-9: A Diagram of an Embrittlement Detector [www.gc3.com, 2010]

The normal installation area for an embrittlement detector is in the continuous blow down line, providing the blow down is approximately at boiler water temperature. Tests of 30, 60 or 90 days are run with the embrittlement detector, and the test bar is then submitted to bending tests. For fuel cell application a similar device or technology should be used.

8.32 Priming

Priming is the carryover of varying amounts of droplets of water in the steam foam and mist which lowers the energy efficiency of the steam and leads to the deposit of salt crystals on the super heaters and in the turbines. Priming may be caused by improper construction of boiler, excessive ratings, or sudden fluctuations in steam demand. Priming is sometimes aggravated by impurities in the boiler-water. Some mechanical entertainment of minute drops of boiler water in the steam always occurs. When this boiler water carryover is excessive, steam-carried solids produce turbine blade deposits. The accumulations have a composition similar to that of the dissolved solids in the boiler water. Priming is common cause of high levels of boiler water carryover. These conditions often lead to super heater tube failures as well. Priming is related to the viscosity of the water and its tendency to foam. These properties are governed by alkalinity, the presence of certain organic substances and by total salinity or TDS. The degree of priming also depends on the design of the boiler and its steaming rate.

The most common measure to prevent foaming and priming is to maintain the concentration of solids in the boiler water at reasonably low levels. Avoiding high water levels, excessive boiler loads, and sudden load changes also helps. Very often contaminated condensate returned to the boiler system causes carry-over problems. In these cases the condensate should be temporarily wasted until the source of contamination is found and eliminated. The use of chemical anti-foaming and anti-priming agents, mixtures of surface-active agents that modify the surface tension of a liquid, remove foam and prevent the carry-over of fine water particles in the stream,

can be very effective in preventing carry-over due to high concentrations of impurities in the boiler-water.

8.33 Metallurgical Failures and Analysis

Temperature failure can occur through rapid overheating or long-term overheating. Rapid overheating is characterized by thin-lipped ruptures and complete microstructural transformation due to overheating to above 1333 °F. It is typically caused by starvation of a tube due to a blockage or rapid start-ups

8.34 Fatigue Failures

Fatigue cracking is caused by cyclic stresses. Typical causes are:

- 1. Vibration failure usually occurs near an unyielding restraint.
- 2. Thermal expansion /contraction of boiler tubing cracking can occur along entire tube length.

Metallographic examination of the cracking will reveal transcrystalline, unbranched cracks.

8.35 Corrosion failure occurs as pitting, thinning or gouging.

Pitting corrosion can occur due to the presence of free oxygen entering the boiler with the feed water as a result of incomplete deaeration and/or chemical scavenging. Oxygen pitting can also occur during downtime due to improper storage procedures. Plating of copper metal onto a boiler tube side during acid-cleaning can also result in pitting due to dissimilar metal corrosion. General corrosion or thinning can occur due to:

- 1. Acid attack
- 2. Chelant attack
- 3. Steam blanketing (localized to the hot side of the tubing)

Caustic gouging typically occurs under deposits due to the concentration of sodium

hydroxide via evaporation of the boiler water. Caustic attack can also occur in

conjunction with steam blanketing.

Table 8-6						
THE FUNCTIONAL	REQUIREMENTS AND THE TESTING AND					
MAINTENANCE BA	MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S					
SUBSYSTEM	G SYSTEM					
Requirements	Testing Plan Needed	Maintenance Plan				
The amount of hydrogen	Yes: Gas Composition	Yes: To be determined				
the fuel processing	Analysis	and related to the fuel				
system produces must be		processing design				
verified.						
The reformer inlet steam-	Yes: Temperature studies	Yes: To be determined				
to-carbon (s/c) ratio	and carbon-to-steam ratio	and related to the fuel				
which prevents coking	sensitivity analysis or	processing design.				
must be chosen.	water-to-fuel ratio. Gas	Example: inspection of				
	(back) pressure analysis.	catalysis for coke				
	Energy efficiency modeling	deposition and tubing				
	of fuel processing system.	for 'hot bands'.				
The filters must be able	Yes: Visual inspection	Yes: The fuel pump				
to filter out harmful		should be inspected for				
particles which would		particles.				
contaminate the fuel and						
water.	N C V	XZ · · · · · ·				
What amount of sulfur	Yes: Gas composition	Yes: inspection of				
and hydrogen sulfide	analysis: anode exposure to	sulfur remover.				
(H_2S) content can the fuel	sulfur. Cell anode	Inspection of the Cell				
processing system	polarization resistance	Stack's anode.				
handle?	testing. Gas composition to					
	power output study.	Very Telle determined				
Size and configuration	Yes: performance study of	Yes: To be determined				
should the zinc bed have?	sunur remover.	Dy				
Steem Deiler's	Vasi Cananatan shauld ba	Nanufacturer/designer.				
Steam Boller S	tested for	rest the Generator				
containinates should be at	Reiler Correction	should be checked for.				
a certain tolerance range	Scale and sludge formation					
Certain tolerance range.	Caustic Embrittlement					
	Driming and feaming					
	Finning and toanning					

Table 8-7							
THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND							
MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS							
- THE FUEL PROCESSING SYSTEM							
Requirements	Testing Plan Needed	Maintenance Plan					
Boiler Feed Water							
Deaerator: should one be	To be determined.	To be determined.					
used?							
Feed Water should be free	Yes: should be tested for:	Yes: should be tested for:					
of contaminates within a	Clarification	Clarification					
certain tolerance range.	Filtration	Filtration					
	Softening	Softening					
	Dealkalization	Dealkalization					
	Demineralization	Demineralization					
	Deaeration	Deaeration					
	Heating	Heating					
Feed Water should have a	Test: oxygen and carbon	Yes: To be determined by					
certain level of dissolved	dioxide in water.	designer/manufacturer.					
oxygen/carbon dioxide	Oxygen/carbon dioxide	Pitting inspection					
content.	content in water vs.						
	temperature.						
Feed Water should have a	Test: for metals in feed	Yes: Inspect for metallic					
certain level of metallic	water.	deposits					
content.							
Feed Water should have a	Test: levels of ammonia	Yes: if copper material is					
certain level of ammonia		used.					
content							
Heat Transfer of the	Yes: subsystem modeling	Yes					
Generator should be in a	and heat transfer study.						
certain range.							

8.36 The Element of Focus for a Fuel Processing Subsystem - How it works

Catalysts work by providing an alternative mechanism involving a different transition state and lower activation energy. Consequently, more molecular collisions have the energy needed to reach the transition state. Hence, catalysts can enable reactions that would otherwise be blocked or slowed by a kinetic barrier. The catalyst may increase reaction rate or selectivity, or enable the reaction at lower temperatures. This effect can be illustrated with a Boltzmann distribution and energy profile diagram.

Figure 8-10: Generic potential energy diagram showing the effect of a catalyst [Wikipedia, 2010]





the equilibrium is a consequence of the second law of thermodynamics. Suppose there was such a catalyst that shifted equilibrium. Introducing the catalyst to the system would result in reaction to move to the new equilibrium, producing energy. Production of energy is a necessary result since reactions are spontaneous if and only if Gibbs free energy is produced, and if there is no energy barrier, there is no need for a catalyst. Then, removing the catalyst would also result in reaction, producing energy; i.e. the addition and its reverse process, removal, would both produce energy. Thus, a catalyst that could change the equilibrium would be a perpetual motion machine, a contradiction to the laws of thermodynamics. Catalysts generally react with one or more reactants to form intermediates that subsequently give the final reaction product, in the process regenerating the catalyst. The following is a typical reaction scheme, where *C* represents the catalyst, X and Y are reactants, and Z is the product of the reaction of X and Y:

$X + C \rightarrow XC$	(1)
$\mathbf{Y} + \mathbf{X}\boldsymbol{C} \to \mathbf{X}\mathbf{Y}\boldsymbol{C}$	(2)
$XYC \rightarrow CZ$	(3)
$CZ \rightarrow C + Z$	(4)

Although the catalyst is consumed by reaction (1), it is subsequently produced by reaction (4), so for the overall reaction:

$$X + Y \rightarrow Z$$

As a catalyst is regenerated in a reaction, often only small amounts are needed to increase the rate of the reaction. In practice, however, catalysts are sometimes consumed in secondary processes.

The chemical nature of catalysts is as diverse as catalysis itself, although some generalizations can be made. Proton acids are probably the most widely used catalysts, especially for the many reactions involving water, including hydrolysis and its reverse. Multifunctional solids often are catalytically active, e.g. zeolites, alumina, higher-order oxides, graphitic carbon, nanoparticles, nanodots, and facets of bulk materials. Transition metals are often used to catalyze redox reactions (oxidation, hydrogenation). Many catalytic processes, especially those used in organic synthesis, require so called "*late transition metals*", which include palladium, platinum, gold, ruthenium, rhodium, and iridium.

An electrocatalyst is a catalyst that participates in electrochemical reaction. The electrocatalyst assists in transferring electrons between the electrodes and reactants, and/or facilitates an intermediate chemical transformation described by overall half-reactions. In the context of electrochemistry, specifically in fuel cell engineering, various metal-containing catalysts are used to enhance the rates of the half reactions that comprise the fuel cell. One common type of fuel cell electrocatalyst is based upon nanoparticles of platinum that are supported on slightly larger carbon particles. When in

contact with one of the electrodes in a fuel cell, this platinum increases the rate of oxygen reduction to water, either to hydroxide or hydrogen peroxide.

8.37 Packed Bed Fuel Processing System

In fuel cell applications, catalyst is often placed in a "packed bed". A packed bed is a hollow vessel that is filled with a packing material. The packing can be randomly filled with small objects like Raschig rings or else it can be a specifically designed structured packing. Raschig rings are pieces of tube (approximately equal in length and diameter) used in large numbers as a packed bed within columns for distillations and other chemical engineering processes. They are usually ceramic or metal and provide a large surface area within the volume of the column for interaction between liquid and gas or vapor.



Figure 8-11: Raschig Rings one inch (25 mm) ceramic [Wikipedia, 2010]

The purpose of a packed bed is typically to improve contact between two phases in a chemical or similar process [Subramanian,2010]. According to Keith (2010), the chemical reaction takes place on the

surface of the catalyst. The advantage of using a packed bed reactor is the higher conversion per weight of catalyst than other catalytic reactors. The reaction rate is based on the amount of the solid catalyst rather than the volume of the reactor. The Ergun equation can be used to predict the pressure drop along the length of a packed bed. The differential form of the pressure drop in a packed bed reactor is given by the Ergun equation [Keith, 2010]:

$$\frac{dP}{dz} = -\frac{G}{\rho g_c D_p} \left(\frac{1-\phi}{\phi^3}\right) \left(\frac{150(1-\phi)\mu}{D_p} + 1.75G\right)$$

In this equation, the following notation and units are used:

- *P*, pressure (lb_f/ft^2)
- ϕ , porosity (dimensionless)

 g_c , 4.17 x 10⁸ (lb_m-ft)/(h²-lb_f)

 D_p , diameter of particle in the bed (ft)

- μ , viscosity of gas, lb_m/(ft-h)
- z, length down packed bed (ft)
- *u*, superficial velocity (ft/h)
- ρ , gas density (lb_m/ft³)
- $G = \rho u$, superficial mass velocity (lb_m/(ft²-h))

Fogler proceeds to account for the fact that the gas density is a function of the number of moles in the system, temperature, and pressure. For the water-gas shift reaction, the number of moles does not change. If the reactor is operated isothermally, then we have that:

$$\rho = \rho_o \frac{P}{P_o}$$

Where ρ_o is the density and P_o is the feed pressure. It is also noted that the weight of catalyst W (lb_m) can be written as:

 $W = (1 - \phi) A_c z \rho_c$

 A_c , cross sectional area (ft²)

 ρ_c , solid catalyst density (lb_m/ft³)

Defining $y = P/P_0$, yields:

$$\frac{dy}{dW} = -\frac{\alpha}{2y}$$

Where α and β_0 are constants and are given by:

$$\alpha = \frac{2\beta_o}{A_c(1-\phi)\rho_c P_o}$$

And:

$$\beta_{o} = \frac{G(1-\phi)}{\rho_{o}g_{c}D_{p}\phi^{3}} \left[\frac{150(1-\phi)\mu}{D_{p}} + 1.75G \right]$$

The first term in the brackets is dominant for laminar flow and the second term is dominant for turbulent flow.

$$\frac{P}{P_o} = (1 - \alpha W)^{1/2}$$

Thus, for an isothermal reaction with no change in moles, the pressure drop can be described.

8.38 Example of a reformer reactor (packed bed)

Consider a reformer reactor in a tubular packed bed of 1 cm diameter with 7.5 g catalyst. If the feed is at 5 atm and 800 K, determine the pressure drop in this reactor. The following parameters are available **[Keith, 2010]**:

G, 565 lb_m/(ft²-h)

 ρ_o , 0.086 lb_m/ft³

φ, 0.5 μ, 0.91 lb_m/(ft-h) D_p , 0.1 cm $ρ_c$, 76 lb_m/ft³

Example Problem Solution:

Step 1) First the value of β_o is determined. All of the terms in the problem statement are in the appropriate units except for the particle diameter:

$$D_{p} = \frac{0.1 \text{cm}}{30.48 \text{ cm}} = 3.3 \times 10^{-3} \text{ ft}$$

$$\beta_{o} = \frac{G(1-\phi)}{\rho_{o} g_{c} D_{p} \phi^{3}} \left[\frac{150(1-\phi)\mu}{D_{p}} + 1.75G \right]$$

$$\beta_{o} = \frac{565 \frac{\text{lb}_{m}}{\text{ft}^{2} - \text{h}} (1-0.5)}{0.086 \frac{\text{lb}_{m}}{\text{ft}^{3}} 4.17 \times 10^{8} \frac{\text{lb}_{m} - \text{ft}}{\text{h}^{2} - \text{lb}_{f}} 3.3 \times 10^{-3} \text{ft} (0.5)^{3} \left[\frac{150(1-0.5)0.91 \frac{\text{lb}_{m}}{\text{ft} - \text{h}}}{3.3 \times 10^{-3} \text{ft}} + 1.75(565 \frac{\text{lb}_{m}}{\text{ft}^{2} - \text{h}}) \right]$$

$$\beta_{o} = 414 \frac{\text{lb}_{f}}{\text{ft}^{3}}$$

Step 2) Determine the value of αW which is needed in the formula for the pressure drop. First, the cross-sectional area, feed pressure, and catalyst weight in the appropriate units is needed. The cross-sectional area is:

$$A_{c} = \pi \frac{D_{reactor}^{2}}{4} = \frac{\pi}{4} \left(\frac{1 \text{ cm}}{30.48 \frac{\text{ cm}}{\text{ ft}}} \right)^{2} = 8.5 \times 10^{-4} \text{ ft}^{2}$$

The feed pressure in lb_f/ft^2 is:

$$P_{o} = \frac{5 \operatorname{atm}}{\left(\frac{14.696 \frac{\operatorname{lb}_{f}}{\operatorname{in}^{2}}}{1 \operatorname{atm}}\right)} \left(\frac{144 \operatorname{in}^{2}}{\operatorname{ft}^{2}}\right) = 10600 \frac{\operatorname{lb}_{f}}{\operatorname{ft}^{2}}$$

The catalyst weight in lb_m is:

$$W = \frac{7.5\,\mathrm{g}}{454\,\mathrm{g}} = 0.017\,\mathrm{lb}_{\mathrm{m}}$$

Thus,

$$\alpha W = \frac{2\beta_o W}{A_c (1-\phi)\rho_c P_o} = \frac{2(414 \frac{\mathbf{b}_f}{\mathbf{ft}^3})(0.017 \,\mathbf{b}_m)}{8.5 \times 10^{-4} \,\mathrm{ft}^2 (0.5)76 \frac{\mathbf{b}_m}{\mathbf{ft}^3} 10600 \frac{\mathbf{b}_f}{\mathbf{ft}^2}} = 4.0 \times 10^{-2}$$

The exit pressure can be determined as:

$$\frac{P}{P_o} = (1 - \alpha W)^{1/2} = 0.98$$

Analysis

Since $P_0 = 5$ atm, the exit pressure *P* is equal to 4.9 atm. Thus, the pressure drop is about 0.1 atm (1.5 psi) in the reformer reactor. This is relatively negligible.

8.39 A Fluidized Bed Condition– A Potential Problem for Packed Bed FC Reformers

A 'fluidized' bed is formed when a quantity of a solid particulate substance usually present in a holding vessel is placed under appropriate conditions to cause the solid/fluid mixture to behave as a fluid or gas. This is usually achieved by the introduction of pressurized fluid through the particulate medium. This results in the medium then having many properties and characteristics of normal fluids or gases; such as the ability to free-flow under gravity, or to be pumped using fluid or gas type technologies.



Figure 8-12: A diagram of a fluidized bed [Wikipedia, 2011]

Fluidized beds are used as a technical process which has the ability to promote high levels of contact between gases and solids. In a fluidized bed a characteristic set of basic properties can be utilized, indispensable to modern process and chemical engineering, these properties include:

- Extremely high surface area contact between fluid and solid per unit bed volume
- High relative velocities between the fluid and the dispersed solid phase.
- High levels of intermixing of the particulate phase.
- Frequent particle-particle and particle-wall collisions.

Fluidized bed tunnels are typically used on small food products like peas, shrimp or sliced vegetables, and may use cryogenic or vapor-compression refrigeration. Fluidized

beds are used to catalyze chemical reactions and also to improve the rate of reaction, such as fuel processing of SOFC Power Systems.

When the packed bed has a gas passed over it, the pressure drop of the gas is approximately proportional to the gas's superficial velocity. In order to transition from a packed bed to a fluidized condition, the gas velocity is continually raised. For a freestanding bed there will exist a point, known as the minimum or incipient fluidization point, whereby the bed's mass is suspended directly by the flow of the gas stream. The corresponding gas velocity, known as the "*minimum fluidization velocity*", is u_{mf} .

Beyond the minimum fluidization velocity ($u \ge u_{mf}$), the bed material will be suspended by the gas-stream and further increases in the velocity will have a reduced effect on the pressure, owing to sufficient percolation of the gas flow. Thus the pressure drop from for $u > u_{mf}$ is relatively constant.

At the base of the vessel the apparent pressure drop multiplied by the cross-section area of the bed can be equated to the force of the weight of the solid particles less the buoyancy of the solid in the fluid or gas:

$$\Delta p_w = H_w(1 - \varepsilon_w)(\rho_s - \rho_f)g$$

8.40 Important Catalyst Reformer Designs

Important properties to consider when designing catalyst reformers are in the areas of entrance flow velocity distribution, reaction monitoring, and reactor construction.

Entrance flow distribution is an important consideration when designing reforming reactors. The flow pattern reaching the inlet face of the supported catalyst structure should be uniform, both in terms of velocity and composition, to take best advantage of the coated catalyst performance.



Figure 8-13: Fuel gas reformer assemblage [Nielsen, 2009]

Another consequence of the segmented nature of the catalyst reactor affects how analysis and monitoring of the reaction is done. A thermocouple inserted within one channel of a catalyst bed may not offer a reading that is representative of all channels. A gas sample collected too close to the catalyst face may also not be representative of a well-mixed outlet gas composition. This is no worse than the results of non-uniform flow distribution or hot spots occurring in a packed pellet bed though.

Particulate catalysts under the pressure of the weight of a packed bed, or in motion in a fluidized bed, or in the presence of an aggressive chemical environment such as high temperature and partial pressure of hydrogen and steam, and rapid temperature changes during transient operation can weaken particulates causing attrition, and blockage, thereby decreasing activity and increasing pressure drop.

Attrition is a broad term denoting the unwanted break down or abrasion of particles when in a process. Generally, there is the 'break-up' of big particles into smaller particles, as well as the abrasion at the edge of particles which creates more 'fines'. The greater the number of 'fines' the more likelihood of blockage of downstream filters. The attrition of moving particulate material is determined by the properties of the catalyst particles (strength, size, shape, composition, etc) and by the properties of the environment (temperature, time, dispersion medium, viscosity, hydrodynamics (turbulence), mechanical impact, equipment designed, etc). Currently, there is no standard for measuring attrition.

8.41 Ceramic Mats – A Possible Solution to the Fluidized Bed

Catalysts used in SOFC applications, properly canning to hold the catalyst inside a reactor shell is important. For this, a ceramic mat material is used in the gap between the catalyst and the reactor shell. The mat material provides the gripping force to hold the catalyst inside the reactor shell during heating and cooling cycles and forces all gas to pass through the catalyst without flowing through the gap (i.e., flow bypass). One popular ceramic mat used in auto exhaust catalytic converters is InteramTM by 3MTM. This intumescent mat material expands and secures the catalyst tightly within the reactor shell upon heating. Millions of commercial exhaust catalysts have been canned successfully this way each year since 1975.



Figure 8-14: Equilibrium conversion of methane steam reforming (H2O/CH4 = 3.0) [Liu, 2006]

However, these mat materials can degrade gradually upon constant exposure to temperatures over 800 C. They can lose their gripping force and increased bypass can be observed. Therefore, similar to the catalytic converters for utility engines, other hightemperature ceramic fiber material must be used for fuel cell reformers where temperatures over 800 C are expected. Several mat materials from various companies are available for high-temperature canning applications, and can be used satisfactorily in a fuel cell reformer. For example, the non-intumescent CC-Max1 from Unifrax Corporation uses this type of catalyst during catalyst aging and evaluation experiments.

A heavy duty in heat supply is required for a steam reforming reactor even when the feed is preheated to a very high temperature. For instance, at an inlet temperature of 800 C with a feed of $H_2O/CH_4 = 3$, the energy required to reach equilibrium at 800 C is 213 kJ/mol CH₄ in the feed.

In industrial-scale H_2 production, the SR of hydrocarbons takes place inside hundreds of chromium–nickel alloy reactor tubes of 70–130 mm inner diameter and 10– 13 m long containing pelletized Ni-based catalyst. The tubes are located inside a large direct-fired chamber. In the primary reformer, the outlet temperature is typically required to be from 800 to 900 C, which requires the flue gas in the combustion chamber to be in excess of 1000 C exiting the fired section. The severe reaction condition is extremely damaging to the steel reactor. Gas hourly space velocity for steam reforming is typically on order of 5000–8000 h⁻¹ on a wet feed basis. This means that a large volume of catalyst is required. To reduce the pressure drop across such a large catalyst bed, the pellet size used is relatively large, which results in low effectiveness of the catalyst.



Figure 8-15: Energy required for steam reforming of 1 mol methane when the reformate reaches equilibrium at the outlet temperature (H2O/CH4 = 3.0, P = 1 bar)) [Liu, 2006]

8.42 Alternatives to Pelletized SR Bed

Alternatives to a large pelletized catalyst bed for steam reforming must overcome the aforementioned difficulties, especially for smaller-scale applications, such as on-site H₂ generation and fuel processing for fuel cells, where rapid responses to transient operation is required. Use of monolithic steam reforming catalyst was discussed by Voecks for hexane steam reforming and comparable performance to pelletized SR catalyst with 20 wt. % NiO loading was achieved with a straight channel 300 cpsi monolith with 10% NiO loading. Because of the endothermic nature of the reaction, the SR process is often heat transfer limited. Fast heat transfer to the catalyst, therefore, is critical to accelerate the reaction process. Engelhard Corporation reported that by depositing a precious metal catalyst onto a metal monolithic substrate that facilitates faster heat conduction, a higher temperature was obtained in the catalyst reactor, resulting in higher CH_4 conversion than with the same catalyst on ceramic particulates.

There are recent reports of new steam reformer reactor designs that supply heat to the SR catalyst more effectively, utilize the catalyst more efficiently, and increase the volumetric efficiency. A common feature in these designs is to integrate catalytic combustion of hydrogen-containing exhaust gas and/or methane with steam reforming into a heat exchanging unit where heat transfer takes place from the combustion side to the steam reforming side through the conductive metallic substrate.



Figure 8-16: Examples of catalyst substrates (clockwise from upper left): ceramic monolith, corrugated metal foil sheet, small metal monolith, fine metal foam, coarse ceramic foam, large metal monolith. [Giroux, 2004]

The substrate material of construction affects the coating and adhesion of the catalyst layer. Ceramic monoliths made from cordierite have been proven for more than 30 years as capable catalyst substrates with few compatibility issues. Precious metals usually do not migrate into the cordierite monolith support and components of cordierite do not migrate into the wash coat. This is true even at high steam content, in a reducing atmosphere, and in the presence of sulfur, etc. The porosity of the cordierite material ensures good bonding with the wash coat material. When supporting catalysts on metal structures, care must be taken that the metal and supported catalyst are compatible. Metals that are routinely coated with catalyst wash coat layers are aluminum, Fecralloy and similar alloys, and stainless steels. Many metals or alloys have components that may be mobile in the reducing atmosphere and elevated temperature and steam of operation.

These metals can potentially migrate into the catalytic wash coat and poison the catalyst after a short time of operation. The problem of metal contamination is of particular concern when catalysts are supported on brazed metal parts. In general, it is advisable to finish all brazing operations first and thoroughly wash the part before coating it with catalyst. Brazing compounds often contain heavy metals like Cd, Sn, etc., which are known catalyst poisons. Residues of the flux can usually be removed by washing. Adhesion problems can occur if the thermal expansion coefficient of the metal is incompatible with that of the wash coat material and the part is put through thermal cycles. The compatibility of wash coat and substrate may have to be individually evaluated before a part is manufactured.

The substrate material of construction can affect the pressure drop across a monolith metal monoliths can be made with very thin walls compared to ceramic monoliths. This additional open face surface areas at a given cell density means that pressure drop across metal monoliths can be lower than across a ceramic monolith. Regardless of the material of construction, the pressure drop across a coated heat

exchanger or monolithic catalyst reactor is significantly lower than that across a packed bed reactor.

Heck and Farrauto discuss the calculation of pressure drop across a monolith. Farrauto and Bartholomew calculate the pressure drop across a given pellet bed and the pressure drop across a 400 cells per square inch (cpsi) monolith of comparable volume at a gas hourly space velocity (GHSVor SV) of 100,000 h_1 to be 0.32 MPa for the pellet bed versus only 2670 Pa for the monolith.

In the comparison of pellet bed and monolith space velocities, an important distinction must be made. The convention is to calculate space velocities of monolithic catalyst reactions using the total gross volume occupied by the monolith substrate. Thus, for the purpose of space velocity calculations, a rectangular monolith catalyst that is 5 cm wide, 5 cm high and 40 cm long is considered to be 1 L of catalyst regardless of the cell density, catalyst loading, wash coat thickness, etc. This is not a rigorous description of the catalyst concentration, but this is the convention found in the literature.

In some instances, monolithic reactors can be operated at significantly higher space velocities than pellet bed reactors. This reduction in reactor size saves both cost and weight, which has the secondary benefit of having a smaller reactor to heat so that there can be rapid thermal responses to transient behavior. Whether the application is a load-following stationary fuel cell or an on-site hydrogen generator stepping up from standby mode to full operation, the reactors need to be able to respond quickly to changes in temperatures and flow rates. A monolithic reactor or a catalyzed heat exchanger can withstand such transients.

Table 8-8					
THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S					
Requirements	Testing Plan	Maintenance Plan			
Should a packed bed be used?	Yes: for the design	Yes: to be determined.			
-	criteria for the bed:				
	pressure drop;				
	amount of catalysis				
	required; cross-				
	sectional area of bed;				
	feed pressure;				
	catalyst weight, etc.				
Determine to criteria to prevent	Yes: for the design	Yes: to be determined.			
fluidized bed conditions from	criteria of the				
happening.	condition.				
Catalyst Reformer Design	Yes: areas of	Yes: to be determined.			
Criteria	entrance flow				
	velocity distribution;				
	reaction monitoring;				
	and reactor				
	construction				
A uniform flow distribution of	Yes: for the design	Yes: to be determined.			
gas and prevention of 'hot	criteria of the bed.				
spots'.					
Mechanical and chemical	Yes: for the design	Yes: to be determined.			
integrity of the catalyst.	criteria of the				
	catalyst.				
Should a catalyst mat be used?	Yes	Yes			
Should monolithic steam	Yes	Yes			
reforming catalyst be used?					
Determine the possible catalyst	Yes	Yes			
poison that would most likely					
occur and at what conditions?					
For waste management	Yes	Yes			
purposes, if precious metal-					
based catalysts are used, can the					
metals be easily reclaimed?					

8.43 Catalysts and Sulfur

The major constituents of pipeline gas are methane, ethane, propane, CO₂, and, in some cases, N₂. Sulfur-containing odorants (mercaptans, disulfides, or commercial odorants) are added for leak detection. The sulfur compounds in hydrocarbon fuels
poison the catalysts in fuel processor can be generated from reforming. Because neither fuel cells nor commercial reformer catalysts are sulfur tolerant, the sulfur must be removed. This is usually accomplished with a zinc oxide sulfur polisher and the possible use of a hydrodesulfurizer, if required.

The zinc oxide polisher is able to remove the mercaptans and disulfides. However, some commercial odorants, such as Pennwalt's Pennodorant 1013 or 1063, contain THT (tetrahydrothiophene), more commonly known as thiophane, and require the addition of a hydrodesulfurizer before the zinc oxide sorbant bed. The hydrodesulfurizer will, in the presence of hydrogen, convert the thiophane into H₂S that is easily removed by the zinc oxide polisher. The required hydrogen is supplied by recycling a small amount of the natural gas reformed product. Although a zinc oxide reactor can operate over a wide range of temperatures, a minimum bed volume is achieved at temperatures of 350 to 400 °C (660 to 750 °F).

In summary, from a systems engineering perspective, a management plan for the catalyst (if catalyst is used) and reformer design, is in order if a lifecycle approach should be undertaken for, not only new production development efforts but to overcome some very challenging problems.

There are a number of issues involved with known industrial catalysts: firstly, catalysts can not only lose their efficiency but also their selectivity, which can occur due to, for example, overheating or contamination of the catalyst; secondly, many fuel cell catalysts include costly metals such as platinum or silver and have only a limited life span, some are difficult to rejuvenate, and the precious metals may not be easily reclaimed.

307

Platinum was the transition metal used in the first generation of fuel cell catalyst. Because of concerns over the cost associated with using a precious metal-based catalyst, work has begun on reducing the cost of the catalyst either by replacing Pt with a less expensive non-noble metal or by using a combination of a noble metal, at a considerably lower metal loading, and with a base metal without sacrificing performance.

There are numerous physical limitations associated with reforming catalysts which render them less than ideal participants in many reactions. Performance targets for the fuel processor for fuel cell systems will require that the reforming catalysts used in these processors exhibit a higher activity and better thermal and mechanical stability than reforming catalysts currently used in the production of H₂ for large-scale manufacturing processes. To meet these targets, reforming catalysts will have to process the feed at a space velocity of 200,000/hr (based on the volumetric flow of the feed in the gaseous state at 25 °C and 1 atm) with a fuel conversion of >99 percent and a H₂ selectivity of >80 percent (moles of H₂ in product/moles of H₂ "extractable" from the feed), and have a lifetime of 5,000 hr.

Another issue is that coke formation will be problematic with higher hydrocarbons, especially diesel. Most industrial reforming catalysts are operated steamrich to minimize coke formation. However, this increases the size of the reformer as well as the energy needed to vaporize the water. This option may not be viable for reformers used with fuel cells. Finally, <20 ppb of S is the target for use with nickel steam reforming catalyst.

308

Most fuels being considered contain either sulfur at the ppm level, such as gasoline, or added as and odorant for safety reasons, such as to natural gas. The ability of the catalyst to process fuels containing ppm levels of sulfur would be beneficial.

There are discrepancies in the tolerance for harmful species specified by fuel cell developers, even for similar type fuel cells. These discrepancies are probably due to electrode design, microstructure differences, or in the way developers establish tolerance. In some cases, the presence of certain harmful species causes immediate performance deterioration. More often, the degradation occurs over a long period of time, depending on the developer's permissible exposure to the specific harmful species.

8.44 Generalized Steam Reformer and Catalyst for SOFC System

- 1. Coke-free operation on target fuel(s).
- 2. High Catalyst activity \rightarrow moderate costs, size and weight.
- 3. Long useful life (up to 40,000 hr. for residential applications).
- 4. Moderate pressure drop.
- 5. No dusting to contaminate synags (reformate).

Based on the studies reported in literature and conducted in our laboratory, some key issues can be summarized for fuel processing for fuel cells. Based on a preliminary analysis of current situations, it appears necessary for further research to develop:

- 1. Choice of commercially available fuels suitable for specific applications.
- 2. More energy-efficient and compact processors.

- 3. Vaporization of heavy hydrocarbons. Heavy hydrocarbons, such as diesel, require vaporization temperatures much in excess of 350 to 400 °C, at which temperature some of the heavier fuels pyrolyze.
- 4. High-performance catalysts with lower costs or lower loading of precious metals.
- 5. The size of the catalyst bed.
- 6. Highly selective and active catalysts for preferential oxidation of CO to enable maximum production of H₂.
- Effective ways for ultra-deep removal of sulfur from hydrocarbon fuels before reforming.
- 8. Maintaining a good temperature distribution in the catalyst bed.
- 9. There is a need to investigate improved and simplified fuel processor designs. Examples are combining the reformer and the desulfurizer in a single stage to reduce weight and volume, producing an integrated vaporizer design, and designing for a wide variation of fuel vaporization temperatures to allow fuel flexible operation.

Table 8-9 THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS

Functional Requirements

The overall object of the Fuel Processing System is to, at all ranges of operations, convert hydrocarbon fuel into syngas and to prevent carbon formation.

The Fuel Conditioning Unit					
The Fuel Tank	Storage of fuel: the SOFC Power System must contain a				
If applicable	given quantity of fuel and must avoid leakage and limit				
	evaporative emissions.				
	Filling the fuel tank must be filled in a secure way,				
	without sparks.				
	Provide a method for determining level of fuel in tank,				
	Gauging (the remaining quantity of fuel in the tank:				
	must be measured or evaluated).				
	Venting (if over-pressure is not allowed, the fuel vapors must be managed through valves).				
	Must be equipped so as to provide feeding of the power				
	system (through a pump).				
	Anticipate potentials for damage and provide safe				
	survival potential.				
The Fuel Filter	Must provide clean, particle-free, liquid fuel.				
The Fuel Pump	Must maintain stable fuel pressure, no surges.				
	Smooth idling.				
	Meets performance specifications.				
	Does not spluttering at high engine rpm.				
	Starts easy.				
	Smooth engine running.				
	Quiet (usually associated with contaminate free fuel).				
	Low current draw.				
The	Sulfur removal to very low levels.				
Desulphurizer	Adsorption of simple organic sulfur.				
1	High crushing strength and low pressure drop.				
	Reliable performance and long predictable lives.				
	High sulfur capacity and effective cost.				
	Desulphurization by reaction with zinc oxide.				

Table 8-10THE FUNCTIONAL REQUIREMENTS AND THE TESTING ANDMAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS

The Thermal Connection of the Fuel Processing Unit						
The Steam Generator	Feed water for boilers needs to be as pure					
	as possible with a minimum of suspended					
	solids and dissolved impurities which cause					
	corrosion, foaming and water carryover					
The Steam Reformer	Must be able to intake a superheated					
	gaseous mixture of water and fuel into the					
	catalytic reactor to form hydrogen by an					
	endothermic reaction of water and fuel over					
	the catalyst bed.					
	Must be able to pass a high quality,					
	continuous supply of (operational					
	temperature) hydrogen rich gas to the					
	anode portion of the Cell Unit.					
	High temperature resistant.					
	Low level of carbon dioxide (CO ₂).					
	Corrosion Resistant Material					
The Water Condenser	Must condense water from exhaust gas					
	Corrosion resistance material					

Functional Requirements

8.45 The Mechanical Subsystem and the Element of Focus for the Air Subsystem

Like the Cabinet and Hot Assembly the components and design requirements of the Mechanical Subsystem and the Waste Management System will depend directly on the evolution of the other BOP subsystems as well as the Cell Stack's design.

The element of focus for systems design of the Air Subsystem is the means by which the Air Subsystem '*moves the oxidant into the Cell Stack*'. Most of the time, the oxidant will be fresh air and most of the time compressors will be used. Most compressors available for use with internal combustion engines have pressure ratios in the range 1.4 to around 3. However, such units are produced only for comparatively large petrol engines. In terms of fuel cell applications, this is quite a high power.

Obtaining an off-the-shelf compressor for fuel cells of a power range less than 50kW is

very difficult. The same problem applies to the higher-pressure ratios, of above 1.6 up to

3, which corresponds to 0.6 to 2 bar gauge, or about 9 to 30 psig. In this pressure range,

the screw compressor or Lysholm would be the first choice for efficiency and flexibility.

Such screw compressors are known commercially in the motor trade as

'WhippleChargers', and the majority are manufactured by a company called *Autorotor* in Sweden.

Table 8-11 THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS					
The Air System					
Requirements	Testing Plan	Maintenance Plan			
Pump Efficiency	Yes: to be determined.	Yes: to be			
Air Blower Efficiency		determined.			
Compressor Efficiency	Yes: to be determined.	Yes: to be			
		determined.			
Compressor Inter-cooling	Yes: to be determined.	Yes: to be			
		determined.			

8.46 Conclusion

During the Conceptual Design and Advance Planning Phase, operational requirements analysis determines the needs or conditions of system design. This chapter defined the operational requirements for and the technology baselines of the Fuel Processing Subsystem, The Air and Waste Management Subsystems of the SOFC Power System and in addition, to provide the reader with technical information which is necessary in order to understand what is needed by way of operational and functional requirements of the subsystems. Of the many barriers facing SOFC developers, cost and durability present two of the most significant challenges. In the next chapter, the operational requirements for and the technology baselines of the Electrical Subsystem of the SOFC Power System will be discussed.

CHAPTER IX

OPERATIONAL REQUIREMENTS AND TECHNOLOGY BASELINES FOR THE ELECTRICAL SUBSYSTEM – PHASE ONE

9.1 Introduction

This chapter defines the operational requirements for and the technology baselines of the Electrical Subsystem of the SOFC Power System and in addition, to provide the reader with technical information which is necessary in order to understand what is needed by way of operational and functional requirements of the subsystem.

9.2 The Electrical System

The purpose of this section is to provide a preliminary identification and discussion of the technology and development of the electrical system. **Figure 9-1** shows a representative cost per kW of the power conditioning unit, as the voltage and current values are varied for a certain power level. The figure below is comparison between the DC Voltage (power) fuel cell stacks produce, the power the fuel cell system outputs in k·Watts and cost/ k·Watt.



Figure 9-1: PCU cost per kW [Fuel cell handbook, 2004]

The electrical power delivered can be expressed as:

$$P(t) = I(t) \cdot V(t)$$

Where:

- P(t) is the power, measured in watts (joules per second).
- V(t) is the potential difference (or voltage drop) across the component, measured in volts.
- I(t) is the current through it, measured in amperes.

Translating power into a function of voltage and current, it is clear from the above figure that the extremes of voltage at low power and high current at high power levels do not result in an optimum design. In general, higher voltage levels are required at higher power outputs to minimize the cost of power conditioning hardware. The other issue is power density and size of power conditioning units. Using higher a switching frequency for the power conversion *should* result in smaller size. However, the losses due to switching are higher and a design compromise becomes necessary.

Employing power semiconductor devices with lower losses combined with active cooling methods should yield an optimum size. Power integrated circuits can also be considered for further size reduction and become viable, if the fuel cell systems are produced in medium or high volume.

9.3 V6 Converter

Another application of advance technology is the work done by Dr. Jih-Sheng (Jason) Lai of the Virginia Polytechnic Institute and State University who studied the static and dynamic performances of a new V6 Converter.



Figure 9-2: The Block Diagram of the SOFC Power Plant featuring a SECA DC/DC Converter [Lai, 2004]

Motivation for Dr. Lai's work came from Don Collins, who quoted that a 1% increase in efficiency is worth \$75/kWe given a \$6.50/mbtu gas cost for an SOFC power plant of the size about 150kW – A motivation to create a high-efficiency power converter design.



Figure 9-3: Circuit Diagram of the Proposed V6 Converter [Lai, 2004]

The key features of Dr. Lai's V6 Converter were:

- 1. Double output voltage \rightarrow reduce turns ratio and associated leakage inductance.
- 2. No overshoot and ringing on primary side device voltage.
- 3. DC link inductor current ripple elimination \rightarrow cost and size reduction on inductor
- Secondary voltage overshoot reduction →cost and size reduction with elimination of voltage clamping
- 5. Significant EMI reduction \rightarrow cost reduction on EMI filter
- 6. Soft switching over a wide load range
- 7. High efficiency ~97%
- 8. Low device temperature \rightarrow High reliability

Fuel cells bring a few special problems, but by and large standard or modified equipment and methods can be employed. In other words, unlike many aspects of fuel cell systems, the electrical problems can generally be solved using more-or-less standard technologies. There are two technologies that which particularly need to address.

- The electrical output power of a fuel cell will often not be at a suitable voltage, and certainly that voltage will not be constant. Increasing the current causes the voltage to fall in all electrical power generators, but in fuel cells the fall is much greater. Voltage regulators, DC/DC converters, and chopper circuits are used to control and shift the fuel cell voltage to a fixed value, which can be higher or lower than the operating voltage of the Cell Stack Package.
- Fuel cells generate their electricity as direct current, DC. The voltage from all sources of electrical power varies with time, temperature, and many other factors, especially current. However, fuel cells are particularly badly regulated. For example, Figure 9-4 summarizes some data from a real 250-kW fuel cell used to drive a bus.



Figure 9-4: Graph summarizing some data from a 250-kW fuel cell used to power a bus [Larminie & Dicks, 2003]

The voltage varies from about 400 to over 750 V, but also the voltage can have different values at the same current. This is because, as well as current, the voltage also depends on temperature, air pressure, and on whether its compressors have got to speed, among other factors.

9.4 DC Regulation and Voltage Conversion - Cell Switching Circuitry

Most electronic and electrical equipment require a fairly constant voltage. This can be achieved by dropping the voltage down to a fixed value below the operating range of the fuel cell, or boosting it up to a fixed value. This is done using '*switching*' or '*chopping*' *circuits*'.

Туре	Thyristor	MOSFET	IGBT	
Symbol	_‡	g d s	alt	
Max. voltage (V)	4500	1000	1700	
Max. current (A)	4000	50	600	
Switching time (us)	10 - 25	0.3-0.5	1 - 4	

Figure 9-5: Key data for the main types of electronic switches used in modern power electronic equipment [Larminie & Dicks, 2003]

The metal oxide semiconductor field effect transistor (MOSFET) is turned on by

applying a voltage, usually between 5 and 10V, to the gate.



Figure 9-6: Two power MOSFETs in the surface-mount package D2PAK [Larminie & Dicks, 2003]

When 'on' the resistance between the drain (d) and source (s) is very low. The power required to ensure a very low resistance is small, as the current into the gate is low. However, the gate does have a considerable capacitance, so special drive circuits are usually used. The current path behaves like a resistor, whose ON value is R_{DSON} . The value of R_{DSON} for a MOSFET used in voltage regulation circuits can be as low as about 0.01 ohms. However, such low values are only possible with devices that can switch low voltages, in the region of 50V. Devices that can switch higher voltages have values of R_{DSON} of about 0.1 ohms, which causes higher losses. MOSFETs are widely used in low-voltage systems of power less than about 1-kW.



Figure 9-7: Cross section of a typical IGBT showing internal connection of MOSFET and Bipolar Device [Larminie & Dicks, 2003]

The insulated gate bipolar transistor, IGBT, is essentially an integrated circuit combining a conventional bipolar transistor and a MOSFET, and has the advantages of both. The voltage does not raise much above 0.6V at all currents within the rating of the device. This makes it the preferred choice for systems in which the current is greater than about 50 A. They can also be made to withstand higher voltages. The IGBT is now almost universally the electronic switch of choice in systems from 1kW up to several hundred kW, with the 'upper' limit rising each year.

The thyristor has been the electronic switch most commonly used in power electronics. Unlike the MOSFET and IGBT, the thyristor can only be used as an electronic switch – it has no other applications. The only advantage of the thyristor (in its various forms) for DC switching is that higher currents and voltages can be switched.



Figure 9-8: Symbol used for an electronically operated switch [Larminie & Dicks, 2003] Ultimately, the component used for the electronic switch is not of great importance. As a result, the circuit symbol used is often the '*device independent*' symbol shown in Figure 9-8. No energy is dissipated in the switch while it is in open circuit, and only very little energy is lost when it is fully on; it is while the transition is taking place that the product of voltage and current is non-zero and that power is lost.

9.5 Switching Regulators

The 'step-down' or 'buck' switching regulator (or chopper) is shown in **Figure 9-**9.



Figure 9-9: Circuit diagram showing the operation of a switch mode step-down regulator [Larminie & Dicks, 2003]

The essential components are an electronic switch with an associated drive circuit, a diode, and an inductor. In **Figure 9-9a** the switch is on, and the current flows through the inductor and the load. The inductor produces a back electromotive force (emf), making the current gradually rise. The switch is then turned off. The stored energy in the inductor keeps the current flowing through the load using the diode, as in **Figure 9-9b**. The different currents flowing during each part of this on–off cycle are shown in **Figure 9-10** (below). The voltage across the load can be further smoothed using capacitors if needed.



Figure 9-10: Currents in the step-down switch mode regulator circuit [Larminie & Dicks, 2003]

If V_1 is the supply voltage, and the 'on' and 'off' times for the electronic switch are ^{*t*}ON and ^{*t*}OFF, then it can be shown that the output voltage V_2 is given by:

$$V_2 = \frac{t_{\rm ON}}{t_{\rm ON} + t_{\rm OFF}} V_1$$

It is also clear that the ripple depends on the frequency – at higher frequency, the ripple is less. However, each turn-on and turn-off involves the loss of some energy, so the frequency should not be too high. A control circuit is needed to adjust ^{*t*}ON to achieve the desired output voltage – such circuits are readily available from many manufacturers. The main energy losses in the step-down chopper circuit are:

- Switching losses in the electronic switch,
- Power lost in the switch while it is turned on $(0.6 \times I \text{ for an IGBT or } R_{\text{DSON}} \times I^2$ for a MOSFET),
- Power lost because of the resistance of the inductor,
- Losses in the diode, $0.6 \times I$.

In practice all these can be made very low. The efficiency of such a step-down chopper circuit should be over 90%. In higher voltage systems, of about 100V or more, efficiencies, as high as 98%, are possible.

9.6 Linear Regulator



Figure 9-11: Linear regulator circuit [Larminie & Dicks, 2003]

The principle is shown in **Figure 9-11**. A transistor is used again, but this time it is not switched fully on or fully off. Rather, the gate voltage is adjusted so that its resistance is at the correct value to drop the voltage to the desired value. This resistance will vary continuously depending on the load current and the supply voltage. This type of circuit is widely used in electronic systems, but should *never* be used with fuel cells. Simply converting the surplus voltage into heat does reduce the voltage, but wastes energy. Fuel cells will always be used where efficiency is of paramount importance, and linear regulators have no place in such systems.

Because fuel cells are essentially low-voltage devices, it is often desirable to step up or boost the voltage. This can also be done, quite simply and efficiently, using switching circuits. The circuit of **Figure 9-12** is the basis usually used.



Figure 9-12: Circuit diagram to show the operation of a switch mode boost regulator [Larminie & Dicks, 2003]

Assuming some charge is in the capacitor, in **Figure 9-12a** the switch is on, and an electric current is building up in the inductor. The load is supplied by the discharging of the capacitor. The diode prevents the charge from the capacitor from flowing back through the switch. In **Figure 9-12b** the switch is off. The inductor voltage rises sharply because the current is falling. As soon as the voltage rises above that of the capacitor (plus about 0.6V for the diode), the current will flow through the diode, charge up the capacitor, and flow through the load. This will continue as long as there is still energy in the inductor. The switch is then closed again, as in **Figure 9-12a**, and the inductor reenergized while the capacitor supplies the load. Higher voltages are achieved by having the switch off for a short time. It can be shown that for an ideal converter with no losses:

$$V_2 = \frac{t_{\rm ON} + t_{\rm OFF}}{t_{\rm OFF}} V_1$$

In practice, however, the output voltage is somewhat less than this. As with the step-down (*buck*) switcher, control circuits for such boost or step-up switching regulators are readily available from many manufacturers.

The losses in this circuit come from the same sources as for the step-down regulator. However, because the currents through the inductor and switch are higher than the output current, the losses are higher. Also, all the charge passes through the diode this time, and so is subject to the 0.6-V drop and hence energy loss. The result is that the efficiency of these boost regulators is somewhat less than that for the buck. Nevertheless, over 80% efficiency should normally be obtained, and in systems in which the initial voltage is higher (over 100 V); efficiencies of 95% or more are possible.

9.7 The Buck Boost Regulator

A third possibility is to use a buck-boost regulator. In this case the final output is set somewhere within the operating range of the fuel cell. While such circuits are technically possible, their efficiency tends to be rather poor, certainly no better than the boost chopper, and often worse. The consequence is that this is not a good approach.



Figure 9-13: Boost Converter Circuitry [Wikipedia, 2010]

The boost converter is a high efficiency step-up DC/DC switching converter. The converter uses a transistor switch, typically a MOSFET, to pulse width modulate the voltage into an inductor. Rectangular pulses of voltage into an inductor result in a triangular current waveform. For this discussion it is assumed that the converter is in the continuous mode, meaning that the inductor's current never goes to zero.

The main question when designing a converter is what sort of inductor should be used. In most designs the input voltage, output voltage and load current are all dictated by the requirements of the design, whereas, the inductance and ripple current are the only free parameters. The inductance is inversely proportional to the ripple current, so if a *'small'* ripple is desired, then a 'large' inductor must be used. There are tradeoffs with low and high ripple current. Large ripple current means that the peak current is i_{pk} greater, and the greater likelihood of saturation of the inductor, and more stress on the transistor. To prevent this, the saturation current of the inductor is greater than i_{pk} . Likewise, the transistor should be able to handle peak current greater than i_{pk} . The inductor should also be chosen such that it can handle the appropriate rms current. It should be noted that when there is a light load the circuit can slip into discontinuous mode, where the inductor becomes fully discharged of its current each cycle. When a

328

load is reapplied the inductor needs to recharge, and so the transistor's duty cycle increases pulling the inductor towards ground and because of the increased duty cycle V_{out} decreases when in actuality it is desirable for it to increase. This causes an instability, which is well known for boost converters, and not a problem with buck converters.

One way to combat this instability is to choose a large enough inductor so that the ripple current is greater than twice the minimum load current. When this condition is met then the inductor is always in continuous mode, this can be expressed as follows:

$$L = \frac{(V_{out} - V_{in} + V_D)(1 - D)}{\min(i_{load})f}$$

For higher efficiency the diode should be an ultra fast recovery diode.

An exception to the above possibility is in cases in which a small variation in output voltage can be tolerated, and an up-chopper circuit is used at *higher currents only*. This is illustrated in **Figure 9-14**. At lower currents the voltage is not regulated. The circuit of **Figure 9-12** is used, with the switch permanently off. However, the converter starts operating when the fuel cell voltage falls below a set value. Since the voltage shift is quite small, the efficiency would be higher.



Figure 9-14 graph of voltage against current for a fuel cell with a step-up chopper circuit that regulates to a voltage a little less than the maximum stack voltage.



Figure 9-15: Typical fuel cell, DC–DC converter and inverter arrangement [Larminie & Dicks, 2003]

It should be pointed out that, of course, the current 'out' from a step-up converter is less than the current 'in'. In **Figure 9-14**, if the fuel cell is operating at point A', the system output will be at point A - a higher voltage but a lower current. Also, the system is not entirely 'loss free' while the converter is not working. The current would all flow through the inductor and the diode, resulting in some loss of energy.

These step-up and step-down switching or chopper circuits are called DC - DC *converters*. The symbol usually used in diagrams is shown in **Figure 9-15**. Complete

units, ready-made and ruggedly packaged, are available in a very wide range of powers, and with input and output voltages. In the cases in which the requirements cannot be met by an off-the-shelf unit, we have seen that the units are essentially quite simple and not hard to design. Standard control integrated circuits can nearly always be used to provide the switching signals.

9.8 Inverters - Single Phase

In small domestic systems, the electricity will be converted to a single AC voltage. In larger industrial systems, the fuel cell will be linked to a three-phase supply.

The arrangement of the key components of a single-phase inverter is shown in **Figure 9-16.** There are four electronic switches, labeled A, B, C, and D, connected in what is called an *H-bridge*. Across each switch is a diode, whose purpose will become clear later. A resistor and an inductor represent the load through which the AC is to be driven.



Figure 9-16: H-bridge inverter circuit for producing single-phase alternating current [Larminie & Dicks, 2003]

The basic operation of the inverter is quite simple. First switches A and D are turned on and a current flows to the right through the load. These two switches are then turned off; at this point we see the need for the diodes. The load will probably have some inductance, and so the current will not be able to stop immediately, but will continue to flow in the same direction, through the diodes across switches B and C, back into the supply. The switches B and C are then turned on, and a current flows in the opposite direction, to the left. When these switches turn off, the current 'free wheels' on through the diodes in parallel with switches A and D. The resulting current waveform is shown in **Figure 9-17**. In some cases, though increasingly few, this waveform will be adequate. The fact that it is very far from a sine wave will be a problem in almost all circumstances in which there is a connection to the mains grid.



Figure 9-17: Current/time graph for a square-wave switched single-phase inverter [Larminie & Dicks, 2003]

The difference between a pure sine wave and any other waveform is expressed using the idea of 'harmonics'. These are sinusoidal oscillations of voltage or current whose frequency, *f*v, is a whole number multiple of the fundamental oscillation frequency. It can be shown that *any* periodic waveform of *any* shape can be represented by the addition of harmonics to a fundamental sine wave. The process of finding these harmonics is known as the Fourier analysis. For example, it can be shown that a square wave of frequency f can be expressed by the equation:

$$\begin{aligned} v &= \sin(\omega t) - \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) - \frac{1}{7}\sin(7\omega t) \\ &+ \frac{1}{9}\sin(9\omega t)\dots\text{ etc.} \end{aligned}$$

where $\omega &= 2\pi f$

So, the difference between a voltage or current waveform and a pure sine wave may be expressed in terms of higher-frequency harmonics imposed on the fundamental frequency.

The problem is that these higher-frequency harmonics can have harmful effects on other equipment connected to the grid and on cables and switchgear owing to high harmonic currents. Among the most serious effects are possible damage to protective equipment and disturbance of control systems. For this reason, there are now regulations concerning the 'purity' of the waveform of an AC current supplied to the grid.

Unfortunately, these standards vary in different countries and circumstances. However, they are all expressed in terms of the amplitude of each harmonic relative to the amplitude of the fundamental frequency. One widely accepted standard is **IEC 1000-2-2.** The maximum percentage of each harmonic, up to the 50th, for this standard is given in **Table 9-1.**

As can be seen from the above equation, a square wave exceeds the limits on the third harmonic by a factor of over 6, as well as others. So, how can a purer sinusoidal voltage and current waveform be generated? Two approaches are used, pulse-width modulation and the more modern tolerance-band pulse-inverter technique.

The principle of pulse-width modulation is shown in **Figure 9-18**. The same circuit as shown in **Figure 9-12** is used. In the positive cycle, only switch D is on all the

333

time, and switch A is on intermittently. When A is on, current builds up in the load. When A is off, the current continues to flow, because of the load inductance, through switch D and the 'free-wheeling' diode in parallel with switch C, around the bottom right loop of the circuit.

In the negative cycle a similar process occurs, except that switch B is on all the time, and switch C is 'pulsed'. When C is on, current builds in the load, and when off it continues to flow – though declining – through the upper loop in the circuit, and through the diode in parallel with switch A.

v		2	3	4	5	6	7	8	9	10
%		2.0	5.0	1.0	6.0	5.0	5.0	0.5	1.5	0.5
v	11	12	13	14	15	16	17	18	19	20
%	3.5	0.2	3.0	0.2	0.3	0.2	2.0	0.2	1.5	0.2
v	21	22	23	24	25	26	27	28	29	30
%	0.2	0.2	1.5	0.2	1.5	0.2	0.2	0.2	0.63	0.2
v	31	32	33	34	35	36	37	38	39	40
%	0.6	0.2	0.2	0.2	0.55	0.2	0.53	0.2	0.2	0.2
v	41	42	43	44	45	46	47	48	49	50
%	0.5	0.2	0.49	0.2	0.2	0.2	0.46	0.2	0.45	0.2

Table 9-1: Maximum permitted harmonic levels as a percentage of the fundamental in the low voltage grid up to the harmonic number 50 according to IEC 1000-2-2. (Reproduced by kind permission from Heier S. (1998) Grid Integration of Wind Energy Conversion Systems, John Wiley & Sons, Chichester.) [Larminie & Dicks, 2003]



Figure 9-18: Pulse-width modulation switching sequence for producing an approximately sinusoidal alternating current from the circuit of Figure 16. [Larminie & Dicks, 2003]

The precise shape of the waveform will depend on the nature (resistance, inductance, and capacitance) of the load, but a typical half cycle is shown in **Figure 9-19**. The waveform is still not a sine wave, but is a lot closer than that of **Figure 9-13**. Clearly, the more pulses there are in each cycle, the closer will be the wave to a pure sine wave and the weaker will be the harmonics. A commonly used standard is 12 pulses per cycle, and generally this gives satisfactory results.

In modern systems, the switching pulses are generated by microprocessor circuits. This has led to the adoption of a more 'intelligent' approach to the switching of inverters called the *tolerance band pulse* method. This method is illustrated in **Figure 9-20**. The output voltage is continuously monitored, and compared with an internal 'upper limit' and 'lower limit', which are sinusoidal functions of time. In the positive cycle, switch D (**in Figure 9-12**) is on all the time. Switch A is turned on, and the current through the load rises. When it reaches the upper limit A is turned off, and the current flows on, though declining, through the diode in parallel with C, as before. When the lower limit is

reached, switch A is turned on again, and the current begins to build up again. This process is continuously repeated, with the voltage rising and falling between the tolerance bands.



Figure 9-19: Typical voltage/time graph for a pulse-modulated inverter [Larminie & Dicks, 2003]



Figure 9-20: Typical voltage/time waveforms when using the tolerance band pulse inverter technique [Larminie & Dicks, 2003]

In **Figure 9-20**, the on/off cycle is shown in (a) for a wide tolerance band and in (b) for a narrow tolerance band. It should also be appreciated that the resistance and inductance of the load will also affect the waveform, and hence the frequency at which switching occurs. This is thus an adaptive system that always keeps the deviation from a sine wave, and hence the unwanted harmonics, below fixed levels.

The only significant disadvantage of the '*tolerance band*' regulation method is that it is possible for the pulsing frequency to become very high. Because most of the losses in the system occur at the time of switching, while the transistors move from off to on and on to off, this can lead to lower efficiency. The well-tried pulse-width modulation method is still widely used, but the tolerance band technique is becoming more widespread, especially for mains-connected inverters, where the nature of the load will not vary as much as in some other cases.

9.9 Inverters - Three Phases

In almost all parts of the world, electricity is generated and distributed using three parallel circuits, the voltage in each one being out of phase with the next by 120°. While most homes are supplied with just one phase, most industrial establishments have all three phases available. So, for industrial CHP systems, the DC from the fuel cell will need to be converted to three-phase AC.

This is only a little more complicated than the single phase. The basic circuit is shown in **Figure 9-21**. Six switches, with freewheeling diodes, are connected to the three-phase transformer on the right. The way in which these switches are used to generate three similar but out-of-phase voltages is shown in **Figure 9-22**. Each cycle can be divided into six steps. The graphs of **Figure 9-23** show how the current in each of the three phases changes with time using this simple arrangement. These curves are obviously far from being sine waves. In practice, the very simple switching sequence of **Figure 9-22** is modified, using pulse-width modulation or tolerance band methods, in the same way as for the single-phase inverters described above.

337

The modern three-phase inverter is built along similar lines whether it is for high or low power, and whether it is 'line-commutated' (i.e. the timing signals are derived from the grid to which it is connected) or 'self-commutated' (i.e. independent of the grid). Indeed, the same basic circuit is used whatever modulation method is used (pulse-width or tolerance band). The basic circuit is shown in **Figure 9-21**. The signals used to turn the switches on and off are taken from the microprocessor. Voltage and current sense signals may be taken from the three phases, the input, each switch, or other places. Digital signals from other sensors may be used. Also, instructions and information may be sent to and received from other parts of the system. The use of this information may be different in every case, but the *hardware* will essentially be the same – the circuit of **Figure 9-21**. Inverter units have thus become like many other electronic systems – a standard piece of equipment.



Figure 9-21: Three-phase inverter circuit [Larminie & Dicks, 2003]



Figure 9-22: Switching pattern to generate three-phase alternating current [Larminie & Dicks, 2003]



Figure 9-23: Current/time graphs for the simple three-phase AC generation system shown in Figure 17, assuming a resistive load [Larminie & Dicks, 2003]

One complete cycle for each phase is shown above. Current flowing *out* from the common point is taken as *positive*. The switches would vary depending on the power requirements, but the same controller could be suitable for a large range of powers. The same inverter hardware, differently programmed, would thus be suitable for fuel cells, solar panels, wind-driven generators, Stirling cycle engines, and any other distributed-electricity generator. Inverters thus follow the trend seen throughout electronic engineering – lower prices, less electronics circuit design, and more programming.

9.10 An Example of the Power Conditioning Unit with Line Frequency Transformer



Figure 9-24: Power Conditioning Unit Circuit Topology [Fuel Cell Handbook, 2004]

In Figure 9-24, the fuel cell output DC (say 29V to 39V) is converted to a regulated DC output (say 50V) by means of a simple DC-DC boost converter. The output of the DC-DC converter is processed via a pulse width modulation (PWM) DC-AC inverter to generate a low voltage sinusoidal AC of ± 35 V AC (rms), a line frequency isolation transformer with a turns ratio of 1:3.5 is then employed to generate 120V/240VAC output as shown above. A 42 to 48V battery is connected to the output terminals of the DC-DC converter to provide additional power at the output terminals for motor startups, etc. During steady state, the DC-DC converter regulates its output to 50V and the battery operates in a float mode. The fuel cell and the DC-DC converter are rated for steady state power (say 10kW), while the DC-AC inverter section is rated to supply the motor-starting VA. Assuming a motor-starting current of 3 to 5 times the rated value, the DC-AC inverter rating will be in the 15kVA to 25kVA range. The DC-DC boost converter is operated in current mode control. During a motor startup operation, the current mode control goes into saturation and limits the maximum current supplied from the cell. During this time, the additional energy from the battery is utilized. During steady state operation, the fuel cell energy is used to charge the battery when the output load is low.

9.11 Summary of the Power Conditioning Unit with Line Frequency Transformer Example

Fuel Cell Output DC = (29V to 39V)

This is a typical value range for many fuel cell developers.

The DC/DC Converter Output DC = 50V



Figure 9-25: An Example of the I-V Characteristics of a Fuel Cell [Fuel Cell Handbook, 2004]

The electrical efficiency of the fuel cell depends on the activation & concentration loss apart from natural Ohmic loss. The fuel cell stack voltage under loaded condition $(V_{dc\;stack})$ is a function of activation loss (V_{Act}) , concentration loss

 (V_{Con}) , and ohmic loss (V_{ohmic}) and is given by Nernst equation (Ideal Voltage).



 $\mathbf{V}_{dc \ stack} = \mathbf{V}_{open} - \mathbf{V}_{ohmic} - \mathbf{V}_{Act} - \mathbf{V}_{Con}$

Figure 9-26: The Fuel Cell Stack Voltage under Loaded Conditions as a Function of Losses [Fuel Cell Handbook, 2004]
It can be seen that at low current level, the ohmic loss becomes less significant and, the increase in output voltage is mainly due to activity of slowness of chemical reactions. So this region is also called *active* polarization. At very high current density the voltage falls down significantly because of the reduction of gas exchange efficiency. This region is called *concentration* polarization. Intermediate between the active region and concentrations region there is a linear slope which is mainly due to internal resistance offered by various components of the fuel cell. This region is generally called as *ohmic* region.



Figure 9-27: I-V Characteristic Curve of a 2 Stack Fuel Cell [Fuel Cell Handbook, 2004]

Figure 9-27 shows the I-V characteristics of a hypothetical fuel cell. The hypothetical fuel cell power system can, be safely operated in the linear range of voltages from 40V to 71V as compared to its operation from 26V to 36V (for single stack) with almost double power for same current as compared to single stack operation. Therefore for this example, a simple DC/DC boost converter is used to boost the output voltage of the fuel cell system due to its superiority of higher efficiency and simplicity in control.

Looking into the drooping characteristics curve, the unregulated terminal voltage cannot be directly interfaced to the DC bus or by using DC/AC inverters for residential/grid applications. Therefore for converter design, a linear region operation (*due to resistance offered by internal components*) of the fuel cell stack is only taken into account. Beyond the linear region, the fuel cells can not be operated as the electrolyte of the cell may get damaged.

The main advantages of the boost converter are higher efficiency & reduced component count and it converts the unregulated voltage into desired regulated voltage by varying the duty cycle at high switching frequency lowering the size and cost of energy storage components. The selection of components like boost inductor value and capacitor value is very important to reduce the ripple generation for a given switching frequency. However large inductance tends to increase the start-up time slightly while small inductance allow the coil current to ramp up to higher levels before the switch turns off .The size of the reactive elements of boost converters can be determined from the rated voltage, current ripple, voltage ripple and switching frequency of the converter.

9.12 The DC/DC boosted voltage is process via a Pulse Width Modulation PWM DC/AC inverter.

PWM allows control and regulation of the total output voltage. This approach is also employed in applications involving alternating current, including high-efficiency dcac power converters (inverters and power amplifiers), ac-ac power converters, and some ac-dc power converters (low-harmonic rectifiers).

Energy Storage Device = 42 to 48V battery

Table 9-2 POWER CONDITIONING INFORMATION REGARDING PCU WITH LINE FREQUENCY TRANSFORMER			
Component	Ratings	Additional Information	
Fuel cell	Steady State (fuel cell (only) is supplying power)	When fuel cell is in steady state, the battery is in float mode.	
DC-DC Converter	Steady State (fuel cell (only) is supplying power)	Operated in current mode	
DC-AC Inverter	Motor stating (VA)	The motor-starting current is 3 to 5 times the rated value.	

Efficiency calculation (approximate)

DC-DC converter efficiency = μ_1

DC-AC inverter efficiency = μ_2

Line frequency isolation transformer efficiency = μ_3

The overall conversion efficiency of the power conditioning unit $\mu = \mu_1 * \mu_2 * \mu_3$

Assuming:

 $\mu_1 = 0.95 (95 \text{ percent})$

 $\mu_2 = 0.95 (95 \text{ percent})$

 $\mu_3 = 0.98 (98 \text{ percent})$

Therefore: $\boldsymbol{\mu} = 0.88$ (88 percent).

9.13 **Problems with the Design:**

• The main limitation of this system is the low voltage of the entire power conditioning unit, which results in higher current and lower overall efficiency.

 Another disadvantage is the presence of a line frequency isolation transformer, which is large in size and weight, hence added cost.

9.14 Fuel Cell Ripple Current

Since the fuel cell produces DC electricity, a power conditioning unit is essential to produce commercial AC power (120/240V, 60Hz). A typical fuel cell PCU employs switch-mode dc-dc and dc-ac converters. Important variables for the design of the PCU are:

- 1. Variation of fuel cell terminal voltage from no-load to full load
- 2. The amount of ripple current the fuel cell can tolerate.

The effect of the ripple current on the performance of a fuel cell stack has not been investigated thoroughly and so far remains uncertain. A clear understanding of various factors including additional losses (if any) due to ripple current can contribute to better design of next generation fuel cell power systems.

From the research that has been done, an important variable in the design of the power conditioner for a fuel cell is the amount of ripple current the fuel cell can withstand. Since reactant utilization is known to impact the mechanical nature of a fuel cell, it is suggested that the varying reactant conditions surrounding the cell (*due to ripple current*) govern, at least in part, the lifetime of the cells. Both the magnitude and frequency of the ripple current is important.

For fuel cells powering single phase loads (60Hz), the ripple current of concern is twice the output frequency, i.e. 120Hz. A limit of 0.15 per unit (i.e. 15 percent of its rated current) from 10 to 100 percent load is specified. Further, the magnitude of the low frequency ripple current drawn from the fuel cell by the DC-DC converter is largely

dependent on the voltage loop response characteristics. Also, the dc-link capacitor size determines the 120Hz-voltage ripple on the dclink, which, in turn has an impact on the input current drawn from the fuel cell. It should be noted that switching frequency components in the DC-DC converter can be easily filtered via a small high frequency capacitive filter. For balanced three phase AC loads at the inverter output, the possibility of low frequency components in the fuel cell input current is low.

Experimental results have indicated that ripple current can contribute up to 10% reduction in the available output power. A large variation in fuel cell terminal voltage from no-load to full load, results in larger volt-amp rating of the PCU. Also, for fuel cells powering single-phase loads (60Hz), the ripple current is twice the output frequency i.e. 120Hz. It was shown experimentally that PCU ripple current (120 Hz) can contribute to a reduction in the fuel cell available output power and increased distortion of the terminal voltage. Limiting the low frequency (120 Hz) fuel cell ripple current to between 30% and 40% has been shown to result in less than 0.5-1.5% reduction in fuel cell output power, and therefore, may be acceptable. Restricting the ripple current below these values will require a more robust input *L*–*C* filter within the PCU. Additional losses within the PCU's *L*–*C* filter then become a concern and contribute to a lower PCU efficiency.

9.15 General comments about corrective measures for limiting fuel cell ripple current

The following corrective measures are suggested for limiting the fuel cell ripple current (especially for power conditioners with single phase AC output):

- Install an input filter to filter the 120Hz component of the ripple current to 0.15 per unit: however, this approach contributes to additional size, weight, and cost of the unit.
- Increase the size of the dc-link capacitor in the DC-AC inverter: size, weight, and cost are of concern.
- Reduce the response time of the voltage loop of the DC-DC converter: this will affect the regulation of the dc-link and impact the quality of inverter AC output, and possibly increase the size of the output AC filter.

9.16 Grid Electrical System Design Issues

An electrical subsystem that has the capability to deliver the real power (watts) and reactive power (VARS) to a facility's internal power distribution system or to a utility's grid is a major requirement. The power conditioning electrical equipment included in a fuel cell power system has two main purposes. The first is providing power to the fuel cell system auxiliaries and controls. The second is adaption the fuel cell output to suit the electrical requirements at the point of power delivery.

The conversion of the direct current produced by the fuel cell into three-phase alternating current required by a facility or utility is accomplished by solid state inverters and if required, voltage transformers. Inverters are constructed to minimize both system harmonics and radiated noise. Controls should provided regulation of the real power output by controlling both, the fuel rate and the electrical output. The system electrical protection should provided such that the supplied facility or a utility grid disturbance will not damage the fuel cell power system while connected to the power distribution system which in turn is protected by conventional equipment isolation in case of an over-current malfunction.

When a fuel cell power system is used for electric utility applications, the inverter is the interface equipment between the fuel cells and the electrical network. The inverter acts as the voltage and frequency adjusters to the final load. The grid provides a "*signal*" for a grid-tied inverter to follow, creating an AC waveform from the DC SOFC Power System's output.

Once the signal disappears or goes too far out of voltage or frequency specifications, the inverter stops operating. During a utility outage, the inverter switches to converting DC from the battery bank to AC for the back-up loads panel. The means of feeding the grid during grid-tied mode is disconnected when the grid is down, and all loads in the main panel are de-energized. Once the gird power returns, the inverter will wait five minutes to make sure the grid is stable and then switch the back-up loads panel from inverter power to grid power and start recharging the battery bank.

When the grid is out-of-spec but not out, the inverter will disconnect from the utility and send power to the backup panel. The loads inside the main panel will continue to run as long as the loads are getting enough voltage from the grid. Inverters have a very tight spec and may disconnect from the utility even when there is not a major problem. In this scenario, the inverter would not be able to send power back to the grid if the SOFC Power System was producing excess power. The interface conditions require the following characteristics for the inverters:

- Ability to synchronize to the network.
- Inverter output voltage regulation typically 480 volts plus or minus 2%, threephase. Network voltage unbalance will not be concern while the fuel cell is connected to the grid.
- Inverter output frequency regulation typically plus or minus 0.5%.
- Supply of necessary reactive power to the network within the capabilities of the inverter, adjustable between 0.8 lagging and 1.0 power factor depending on the type of inverter used and without impacting maximum kW output.
- Protection against system faults
- Suppression of the ripple voltage fed back to the fuel cells
- Suppression of harmonics such that the power quality is within the IEEE 519 harmonic limits requirements.
- High efficiency, high reliability, and stable operation.

Some limitations of the inverters used are:

- Transient current capability for such conditions as motor or other inrush currents.
- Transient current capability to operate over current devices to clear equipment or cable faults.

The response of the fuel cell to system disturbances or load swings also must be considered whether it is connected to a dedicated load of the utility's grid. Demonstrated fuel cell power conditioning responses are:

- No transient overload capability beyond the kW rating of the fuel cell.
- A load ramp rate of 10 kW/second when connected to the utility grid.

- A load ramp rate of 0 to 100% in once cycle when operated independently of the utility grid.
- A load ramp rate of 80 kW/second when operated independently of the utility grid and following the initial ramp up to full power.

A major advantage of distributed generators of electricity, especially those with higher power, is the ability to correct the power factor of a customer, or even a small district. The problem of power factors arises when the current consumed is not exactly in phase with the voltage. For example, the current might lag behind the voltage, as in Figure 9-28. The current can be split into two components, an in-phase component and a 90° out-of phase component. This 90° out-of-phase component consumes no power, and is known as *reactive* power. Although it consumes no power locally, it does increase the power dissipated in the resistive electric cables distributing the electricity. This reactive power is, in a sense, 'free' to generate but not free to distribute. For this reason, it is particularly advantageous if it can be generated locally. Inverters fed from DC supplies are particularly suitable for this. The switching pulses in the pulse width modulation (PWM) or tolerance band inverter circuits are driven so that the current produced is deliberately out of phase with the line voltage. It is a particular feature of fuel cell CHP (combined heat and power) systems, as they will always be very close to the point of usage of electricity.



distributed power systems such as fuel cells. [Larminie & Dicks, 2003]

9.17 Fuel Cell/Battery or Capacitor Hybrid Systems

AN SOFC Power System is a constant-current energy source- it does not have the ability to cut back or increase the energy available depending upon how much the end user needs at any moment. When connected to the grid, an SOFC Power System has the grid available to make up for any deficiencies, like during appliance start-up surges. The grid also provides a place to go for any excess energy produced by the SOFC Power System.

By its very nature, without a battery bank, the grid-tied SOFC Power System will not operate if the grid goes down. The decision of whether to go for a hybrid system (fuel cell power system/battery bank), is influenced by two opposing characteristics of fuel cells. The main driving force in favor is that fuel cells are very expensive 'per watt', and so it makes sense to have them working at their full-rated power for as much time as possible, to get the maximum possible value from the investment.

On the other hand, one of the advantages of fuel cells over most other fuel energy converters is that at part load their voltage, and thus their efficiency, increases. Thus we should rate the fuel cell at the maximum required power, and if it operates at only part load for much of the time, so much the better: the efficiency will have improved. It is fair to say that at the time of writing, the question of cost weighs more heavily in the balance. The fuel cell power is sufficient most of the time, but the battery can '*lop-the-peaks*' off the power requirement and can substantially reduce the required fuel cell capacity. During times when the fuel cell power exceeds the power demand, the battery is recharged, as before.

Including a battery in the system adds a source of energy that can vary according to the needs of the end user. A battery-based grid interactive system for an SOFC Power System requires a specialized inverter. Most of the time, the inverter operates in its grid-tied function, converting DC energy into grid-quality AC energy that can be consumed on-site or – if the loads do not use all the energy- exported to the grid.

The inverter's second function is as a backup power supply, which handles battery charging when the grid is available and seamlessly switches to battery backup mode when grid power drops out. Special battery-based, grid-tied inverters are designed to disconnect from the grid, instantaneously switching internally to draw needed energy from the battery instead of the grid. These inverters still disconnect themselves from the grid when the grid goes down, so that they do not inadvertently energize the grid while utility workers are working on it – a potentially dangerous hazard.

The easiest SOFC Power System (*with a battery bank*) to design are those in which the electrical power requirements are highly variable, yet also predictable. Such a situation is illustrated in **Figure 9-29a**, and can occur with certain data-logging equipment, with data transmitters, certain types of telecommunications equipment, and with land- or buoy-based navigation equipment. For fairly long periods the device is in

'standby' mode, and the fuel cell will be recharging the battery. During the *'transmit'* periods, the battery supplies most of the power. The fuel cell power system operates more-or-less continuously at the average power, and is thus simple to specify. The battery requirements are also clear; they must provide sufficient power and hold enough energy for just one *'high-power pulse'*, and must be able to be recharged in the period between high-power pulses.

In many more cases the electrical power requirements are not only highly variable but also unpredictable. A good example is the mobile telephone. Such a situation is shown in **Figure 9-29b**. The higher power pulses can be more frequent and longer lasting or less frequent and shorter lasting. It would still be possible to have a fuel cell running at the long-term average power, but the battery would need to be considerably larger, since it might need to provide several high-power pulses without any time to recharge. It might also be advantageous to increase the power of the fuel cell above the long-term average power, so that the battery recharges more quickly.



Figure 9-29: Power/time graphs for two different systems suited to a hybrid fuel cell/battery power supply [Larminie & Dicks, 2003]

In such systems the two main variables are thus the fuel cell power and the battery or capacitor capacity. In the case of a mobile telephone, these would be chosen on the basis of the following:

- The standby power.
- The '*on-call*' power.
- The probability of receiving a call.
- The probable length of a call.
- The acceptable probability of system failure.

Notice that the only way to bring this last factor to zero is to have the fuel cell power equal to the '*on-call*' power and to abandon the hybrid concept altogether. Most likely, the system would be modeled on a computer. In essence, such systems can be said to be using the fuel cell as a battery charger. The concept is shown in **Figure 9-30**. A controller of some sort is needed to prevent overcharging.



Figure 9-30: Simple fuel cell/battery hybrid system [Larminie & Dicks, 2003]

The benefits of adding a battery bank to an SOFC Power System is not without costs particularly increase maintenance costs and responsibilities. Flooded lead-acid batteries – still the most common energy-storage medium- require checking electrolyte levels periodically to see if distilled water must be added. Sealed batteries require no electrolyte checks, but still have connections and terminal posts that must be periodically inspected and cleaned of corrosion, as is the case with any battery. In addition, there are battery inefficiencies. A lead-acid battery is about 80% efficient, with 20% of the energy wasted as heat during the battery's chemical reactions. Better efficiency can be had by charging and discharging a battery slowly; quick charging and discharging means lower efficiency.

Once the battery is full, almost all the energy from the inverter is directed to the grid or loads, although a little energy will be used to keep the battery at float level (full). With the inverter sending energy to the grid, the main efficiency difference between battery-based and batteryless systems is how well the inverter processes energy from a renewable source and delivers it to a load.

When the grid is down, the battery efficiency comes into play during the cycle of charging and discharging the battery to power the backed-up loads. A consequence of adding batteries to a grid-tied system is a drop in overall efficiency. A batteryless grid-tied inverter will be from 90% to 97% efficient at turning the available Power System's output power into grid-quality output – the bulk of most tested inverters hover around 95% efficient. Introducing batteries drops the inverter efficiency to about 92%.

With batteries also come with environmental issues that must be considered but will not be included in this paper.

9.18 **Regulatory Issues and Tariffs**

It is not sufficient simply to generate AC electricity and connect the SOFC Power System to the grid. Quite properly, any private system has to conform to certain standards

before it can be allowed to supply electricity. One of the most important of these is the level of the harmonics. There must also be protection systems to protect the fuel cell, the inverter, and the grid from faults such as short circuits and lightning strikes.

The SOFC Power System connected to the grid will have two metres – one measuring the electricity consumed and the other the electricity provided. The charges paid will sometimes vary according to time. It is generally more expensive to generate and supply electricity during periods of high demand. Peaks of demand occur daily and vary according to the types of clients a utility has, on the climate, and on weather conditions.

In the United States, the Public Utilities Regulatory Policies Act (PURPA) of 1978 requires electric utilities to purchase electricity generated by small-power producers (SPPs) who run CHP systems. Furthermore, the price of this electricity is fixed by a body independent of the electric utilities, a state utility regulatory agency, which operates under federal guidelines. The concept of *'avoided cost'* is used as the basis for the utility power purchase rates. This is the rate that it costs the utility to generate the electricity itself. However, those rates will naturally be lower than the *'retail'* rate at which they sell power.

Table 9-3					
THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE PASELINES OF AN SOLC DOWED SYSTEM'S					
MAINTENANCE BASELINES OF AN SOFU POWER SYSTEM'S SUBSYSTEMS					
Subsystem Level -1					
The Electrical System					
Maintenance Pla					
	Testing Plan Needed	Needed			
What voltage level should the	Yes: to be determined.	Yes: to be			
power conditioning unit output?		determined.			
What should be the size of the	Yes: to be determined.	Yes: to be			
power conditioning unit?		determined.			
Turns ratio	Yes: to be determined.	Yes: to be			
		determined.			
Overshoot and ringing on	Yes: to be determined.	Yes: to be			
primary side device voltage		determined.			
Current ripple	Yes: to be determined.	Yes: to be			
		determined.			
Secondary voltage overshoot	Yes: to be determined.	Yes: to be			
reduction		determined.			
EMI reduction	Yes: to be determined.	Yes: to be			
		determined.			
Switching over a wide load	Yes: to be determined.	Yes: to be			
range		determined.			

Table 9-4				
THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND				
MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S				
	SUBSYSTEMS			
Efficiency	Yes: to be determined.	Yes: to be		
		determined.		
Device temperature	Yes: to be determined.	Yes: to be		
		determined.		
Voltage Switching Method	Yes: to be determined.	Yes: to be		
		determined.		
Determine the type of DC/AC	Yes: to be determined.	Yes: to be		
Converter the system needs.		determined.		
Determine the type of DC/DC	Yes: to be determined.	Yes: to be		
inverter the system needs		determined.		
higher-frequency harmonics	Yes: to be determined.	Yes: to be		
tolerance		determined.		
Will the inverter connect the	Yes: to be determined.	Yes: to be		
power system to the Grid?		determined.		
Design of the Battery Bank	Yes: to be determined.	Yes: to be		
		determined.		
Battery Bank, Inverter, Power	Yes: to be determined.	Yes: to be		
System interface		determined.		

9.19 Conclusion

This chapter created the conceptual operational and requirements baseline of the

Electrical Subsystem of a generic SOFC Power System. The Elements of Focus for the

Electrical Subsystem of the SOFC Power System mock-up model were the DC-DC

Converter, the DC-AC Inverter and the Energy Storage Source.

CHAPTER X

THE OPERATIONAL REQUIREMENTS AND TECHNOLOGY BASELINES FOR THE THERMAL MANAGEMENT SYSTEM, THE HOT ASSEMBLY AND THE CELL STACK PACKAGE – PHASE ONE

10.1 Introduction

This chapter is a continuation of the last chapter which will define the requirements of the Thermal Management System, the Hot Assembly and the Cell Stack Package (the Unit Cell) subsystems of the SOFC Power System and in addition, to provide the reader with technical information which is necessary in order to understand what is needed by way of operational and functional requirements of theses subsystems and their components.

10.2 The Challenges of Thermal Management

Numerous technical challenges exist in fuel cell technology development related to the issues and challenges of thermal management of fuel cell technology. The high operating temperature imposes stringent requirements both on SOFC design and on

defining operating conditions. The key to thermal management of SOFC stacks is to satisfy the high temperature reaction requirement of the Cell Stack but, avoid steep temperature gradients.

A better understanding of thermal management issues of fuel cell systems will enable the system's designer to select suitable reactor designs, to estimate the size of the auxiliary equipment (pumps, compressor, heat exchangers, etc.), and to estimate the optimal set of stack operating conditions for a higher efficiency and long-term operation.

Thermal management issues are closely related to the fuel cell operating temperature. For example, low temperature fuel cells (e.g., PEMFC and DMFC) usually operate below 100° C, whereas solid oxide fuel cells (SOFC) operate near 1000 °C. Therefore, heat transfer problems could be dramatically different in low temperature fuel cells and SOFCs. Operating temperature affects the maximum theoretical voltage at which a fuel cell can operate. Higher temperatures correspond to lower theoretical maximum voltages and lower theoretical efficiency. However, higher temperature at the electrodes increases electrochemical activity, which in turn increases efficiency. Operating at a higher temperature also improves the quality of the waste heat. It should be noted that there is a moderate temperature range within which a specific type of fuel cell can operate well and with reliability. The main purpose of thermal management in fuel cell systems is to ensure stack operation within the specific temperature range.

The two principal types of SOFCs are tubular and planar. In the tubular configuration, bundles of tubes are arranged in parallel. For a closed-end tubular design air is introduced to the inside of each tube while fuel flows over the outside of the cells. In a typical planar SOFC's high operating temperature the thermal expansion coefficients

for cell components must be closely matched to reduce thermal stress arising from differential expansion between components. Chemical compatibility of the stack components with gases in the high oxidizing and reducing environments is also of primary concern.

A key requirement in all fuel cell systems is the need for heat removal from the Cell Stack Package. The heat released by fuel oxidation is always significantly greater than the electric power which may be extracted from the fuel cell stack. Known fuel cell systems prefer to operate at nearly isothermal conditions in order to minimize internal thermal stresses and to achieve a good balance between stack life and performance. Optimal thermal management also allows for effective use of the fuel cell system's byproduct, heat, leading to substantial increases in overall system efficiency. For example, a fuel cell operating at 1.0 kW and 50% efficiency generates 1.0 kW of waste heat. This heat may be dissipated by convection, conduction, radiation or phase change. The excess heat generated in a fuel cell stack may be dumped to the atmosphere, but often it is used in other system components requiring heat. In some cases the heat is used to run a thermodynamic cycle for additional power generation or maybe funneled from the system entirely to provide the end user with high quality heat for hot water or residential and/or commercial heating.

As shown by the generic SOFC Power System model, see below figure, the dominant cooling mechanism for heat removal from the Cell Stack was convective heat transfer using air as the cooling fluid. In this scheme, cold air is forced through the system using a blower or compressor. The air is partially heated in a heat exchanger by hot air and/or exhaust. The preheated air (at a temperature around the stack operating

temperature) is then introduced to the Cell Stack Package. The air flows through the Cell Stack Package, interacting chemically to provide oxygen to the electrochemical reaction while absorbing heat from the internal stack surfaces. The oxygen-depleted hot air is then released from the stack and redirected through the heat exchanger outside of the stack to preheat new incoming air.



Figure 10-1: The generic SOFC Power System model

There are several issues that must be considered in this scheme. First, to minimize the thermal stress to the Cell Stack Package, the incoming air is preheated to a temperature not too far below the desired operating temperature. However, preheating the air limits its ability to absorb more heat from the Cell Stack Package (*essentially, the heat capacity and change in temperature dictate the amount of heat that can be removed*). To compensate, considerable more air must be driven through the Cell Stack Package than is required for satisfactory electrochemical operating. The amount of air necessary for completing the chemical reaction is called the stoichiometric ratio, or stoic. Typical planar fuel cells require 6-10 stoics of air to maintain thermal control.

The size and weight of the required heat exchanger for air preheating is proportional to this quantity of air, and further depends upon its heat duty, stream flow rates, temperature approach, and allowable pressure drops. Preheating air to the temperatures required for solid oxide fuel cells in particular requires heat exchangers made of expensive high temperature materials. To accommodate the bulk and cost of the heat exchanger, known solid oxide fuel cell systems are generally limited to producing at least 10 kW of power. These systems are thus impracticable for smaller, lower cost applications. Additionally, these systems, because of their size and cost, are impractical for portable or mobile applications where weight and size are critical issue. Matsumura U.S. Patent No. 5,426,002 and Elangovan 5,480,738 describe examples of fuel cells that use conductive cooling to control the temperature in a fuel cell. Hsu's U.S. Pat. No. 5,338,622 also describes a conductive method of controlling fuel cell temperature. Hsu, however, uses a working fluid instead of the oxidant air to conduct heat from the fuel cell. While using the working fluid reduces the amount of air used, the working fluid is disadvantageous because it adds expense and requires additional components for providing it to the heat exchanger. Thus, it is desirable to utilize a thermal control mechanism that requires less air to control fuel cell temperature. It is further desirable to reduce the size and expense of the heat exchanging equipment and thus reduce the size of the balance of systems to provide for smaller fuel cell systems, such as for residential or portable use.

It has been shown that a relatively small sized solid oxide fuel cells power system using conduction and radiation heat rejection as the primary thermal control mode for its Cell Stack presents significant improvements over other known methods. These include

a significant reduction in the air flow required to cool the stack, leading to more compact stacks and smaller, lighter, and less expensive balance of system equipment.

In summary, material properties and prediction capability local reaction rates of the Cell Stack are highly dependent upon local temperatures. The local temperature distributions are established primarily by both surface and volumetric radiation transfer and conduction. Very little is known about the spectral radiation heat transfer properties of the layered, semi-transparent ceramic structures that constitute the cathode/anode/electrolytic structure within which the electrochemical reactions occur. Even if these properties were known, computational methods and models must be created to predict the performance in order to create an intelligent design for the entire stack of these materials. The unknown radiation and electrochemical properties affected by the methods by which these ceramics are produced must also be better defined. Then the question, 'how are the coupled, multi-mode heat transfer effects coupled to the electrochemical reaction rates' must be satisfactory answered to generate an optimal design of such ceramic materials and layers. These thermal management issues as well as a great many others which were not covered in this section must be addressed and dealt with throughout the NPD lifecycle of SOFC Power Systems.

Table 10-1THE FUNCTIONAL REQUIREMENTS AND THE TESTING ANDMAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS- THE THERMAL MANAGEMENT SYSTEM

Demission	Testing Plan	Maintenance Plan
Requirements	Needed	Needed
the (Anode Side) Unit Cells of the Cell	Ves	N/A
Stack Package	105	1 4/ 7 x
~		
Satisfy the high temperature requirement of		
the (Cathode Side) Unit Cells of the Cell	Yes	N/A
Stack Package		
When needed, remove excess heat from the		
Cell Stack Package	Yes	Yes
The size and shape of the BOP component		
related to thermal management requirements	Yes	Yes
The size and share of the Englement eleted		
to thermal management requirements	Vac	Vac
to thermal management requirements	res	res
The design and development of the heat		
recover process (e.g. bottom cycling).	Yes	Yes

10.3 Systems Engineering Modeling based on Thermodynamic and other Models

Systems engineering focuses on how complex engineered systems should be designed and managed over the life cycle of a system. Central to systems engineering are the concepts of *system* requirements and *system* surroundings, where as central to thermodynamics are the concepts of *system* and *surroundings*.

A thermodynamic system is a macroscopic physical object, explicitly specified in terms of macroscopic physical and chemical variables which describe its macroscopic properties. The macroscopic variables of thermodynamics have been recognized in the course of empirical work in physics, chemistry and product development. Thermodynamics describes how systems change when they interact with one another or with their surroundings. Modeling plays important and diverse roles in systems engineering. A model can be defined in several ways, including:

- An abstraction of reality designed to answer specific questions about the real world.
- An imitation, analogue, or representation of a real world process or structure; or
- A conceptual, mathematical, or physical tool to assist a decision maker.

The recent intensive increase in interest in SOFCs has been accompanied by an increase in the use of mathematical modeling as a tool for interpreting experimental results and providing insight on how to improve SOFC design and performance. Various mathematical models provided by investigators concern the theoretical fundamentals and practical operation of an SOFC. Arthur D. Little Inc. specialized in environmental, risk and management consulting. It also specialized in technology and product development and carried out cost structure studies for a variety of fuel cell technologies for a wide range of applications. Because phenomena at many levels of abstraction have a significant impact on performance and cost, Little developed a multi-level system performance and cost modeling approach. At the most elementary level, the Little model included fundamental chemical reaction/reactor models for the fuel processor and fuel cell as one-dimensional systems. Each detailed sub-model was fed into a thermodynamic system model which provided sizing information directly for use in the conceptual design. The thermodynamic system model provided a technical hub for the multi-level

approach. It provided inputs on the required flow rates and heat duties in the system. The fundamental models concern is the ideal efficiency of SOFC combined cycle plants. Chan et al. developed a thermodynamic model for simple SOFC power systems (only waste heat recovery used for pre-heating the fuel and air) fed by hydrogen and methane, respectively. Winkler and Lorenz estimate that simple combined SOFC and gas turbine cycle efficiency is between 60% and 70%. They proposed a RH–SOFC–GT–ST (ReHeat–SOFC–Gas Turbine–Steam Turbine) cycle, which has an efficiency of more than 80% and confirms predictions of the theoretical thermodynamic model.

10.4 Important Mathematical Fuel Cell Models

Mathematical models are critical for fuel cell scientists and developers as they can help elucidate the processes within the cells, allow optimization of materials, cells, stacks, and systems, and support control systems. Mathematical models are perhaps more important for fuel cell development than for many other power technologies because of the complexity of fuel cells and fuel cell systems, and because of the difficulty in experimentally characterizing the inner workings of fuel cells. Some of the most important uses of mathematical fuel cell models are:

- To help understand the internal physics and chemistry of fuel cells. Because experimental characterization is often difficult (because of physical access limitations and difficulty in controlling test parameters independently), models can help understand the critical processes in cells.
- To focus experimental development efforts. Mathematical models can be used to guide experiments and to improve interpolations and extrapolations of data. The

rigor of modeling often forces the explicit position of a scientific hypothesis and provides a framework for testing the hypothesis.

- To support system design and optimization. Fuel cell systems have so many unit operations and components that system models are critical for effective system design.
- To support or form the basis of control algorithms. Because of the complexity of fuel cell systems, several developers have used fully dynamic models of fuel cell systems as the basis for their control algorithms.
- To evaluate the technical and economic suitability of fuel cells in applications.
 Models can be used to determine whether a fuel cell's unique characteristics will match the requirements of a given application and evaluate its cost-effectiveness.

Models intended to improve understanding of complex physical and chemical phenomena or to optimize cell geometries, flow patterns and to analysis the thermodynamics of the Cell Stack, the balance-of-plant or the system as a whole. Proving to be necessary but very sophisticated intensive computational requirements, analyzing the thermodynamics of fuel cell systems would be severely hindered, if impossible without the use of such tools. For example, to determine the potential impacts of fuel cells on future distribution systems, a dynamic model for computing low-order linear system models of SOFCs from the time domain was created by Jurado. This model uses the Box-Jenkins algorithm for calculating the transfer function of a linear system from samples of its input and output. It is capable of modulating real and reactive power in response to voltage and frequency changes on the grid. Van herle et al. performed the energy balance analysis on an SOFC fed by biogas combined with a small gas engine and heat system. Petruzzi (et al) developed a numerical model for SOFC. This SOFC is being developed as an auxiliary power unit (APU) for luxury car conveniences. The model simulated the thermal-electrochemical behavior in all conditions that may occur during operation. Padulle´s (et al) created a simulation model of an SOFC-based power plant for use in a particularly well-known commercial power system simulation package. Fuel cell system models have been developed to help understand the interactions between various unit operations within a fuel cell system.

Most fuel cell system models are based on thermodynamic process flow simulators used by the process industry (power industry, petroleum industry, or chemical industry) such as Aspen Plus, HYSIS, and ChemCAD. Most of these codes are commercially distributed, and over the past years they have offered specific unit operations to assist modeling fuel cell stacks (or at least a guide for putting together existing unit operations to represent a fuel cell stack) and reformers. Others have developed more models to help with dynamic or quasi-dynamic simulations. The balance of plant components usually can be readily modeled using existing unit operations included in the packages. These types of models are used routinely by fuel cell developers, and have become an indispensable tool for system engineers. The accuracy of the basic thermodynamic models is quite good, but because the fuel cell sub-models are typically lumped parameter models or simply look-up tables, their accuracy depends heavily on model parameters that have been developed and validated for relevant situations. Aspen Plus is described below as an example, followed by a description of GCTools; an Argonne National Laboratory modeling set that offers an alternative to codes from the commercial software industry.

10.5 Heat Recovery

The ability to combine an SOFC with a bottoming cycle has been known in concept for many years. A general thermodynamic model has shown that combined fuel cell/heat engine systems may reach an energy conversion efficiency of more than 80%. **Figure 10-2** shows a cogenerative Brayton cycle SOFC power system. The hot air and fuel streams leave the stack and enter the combustor where they mix and the residual fuel burns. The combustion product enters the expander to generate additional power and to drive the compressor, which is connected to the expander. The compressor is used to compress the air flow to the stack. The flow then passes through a pre-heater to recover heat from the combustion product gases leaving the expander.





The exhaust from the turbine in a cogenerative Brayton cycle SOFC power system could be used to heat fuel and air that enter the anode and cathode. There are at least two purposes for this pre-heating process: to recover waste heat and to prevent the SOFC stack from undergoing thermal shock. To obtain a uniform temperature distribution in the cell, a higher air-flow rate than that required for fuel cell oxidation must be fed to the cell at high temperature. As a consequence, the air pre-heater and the air blower become bulky and expensive. Costamagna proposed an integrated air pre-heater for a planar SOFC, which will dramatically reduce the size of a conventional preheater.

Another, parametric study of an SOFC Power System design was conducted with the intention of determining the thermodynamically based design space constrained by modern material and operating limits. The analysis was performed using a thermodynamic model of a generalized an SOFC Power System where the sizing of all components, except the fuel cell, was allowed to vary. Effects of parameters such as pressure ratio, fuel utilization, oxygen utilization, and current density were examined. Operational limits were discussed in terms of maximum combustor exit temperature, maximum heat exchanger effectiveness, limiting current density, maximum hydrogen utilization, and fuel cell temperature rise.

It showed that the maximum hydrogen utilization and combustor exit temperature were the most significant constraints on the system design space.

The design space included the use of cathode flow recycling and air preheating via a heat exchanger. The effect on system efficiency of exhaust gas recirculation using an ejector versus using a blower was also touched upon, while both were compared with the base case of using a heat exchanger only. It was found that use of an ejector for exhaust gas recirculation caused the highest efficiency loss, and the base case was found to exhibit the highest overall system efficiency. The use of a cathode recycle blower allowed

the largest downsizing of the heat exchanger, although avoiding cathode recycling altogether achieved the highest efficiency. Efficiencies in the range of 50–75% were found for variations in pressure ratio, fuel utilization, oxygen utilization, and current density. The best performing system that fell within all design constraints were those that used a heat exchanger only to preheat air, moderate pressure ratios, low oxygen utilizations, and high fuel utilizations.

10.6 Heat Exchanger Design Considerations and Requirements

Heat exchangers are used in many commercial applications and numerous types can be purchased from a large number of manufacturers. In recent years two important factors have contributed to the growing need for high temperature heat exchangers (HTHEs):

- 1. The global trend towards more efficient power and propulsion systems that require higher operating temperatures.
- 2. High temperature thermal pollution control processes (such as thermal oxidation) and heat recovery applications. Research to date has focused primarily on the mechanical design of these heat exchangers and has neglected thermal-hydraulic design. Ohadi and Buckley suggested that compact heat exchangers that utilize state-of- the-art augmentation technologies for reduced surface requirements are needed to facilitate cost-effective developments of HTHEs. They viewed various passive and active heat transfer augmentation technologies provided. Ahuja and Green described a novel and simple process whereby Hz boiloff can be used to continuously sublime and remove CO₂ from air, prior to the purified air and hydrogen being supplied to an alkaline fuel cell. The process depended on very high effectiveness heat exchangers.

10.7 General Considerations

Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but much iteration is typically needed. As such, heat exchangers are most often selected via computer programs, either by system designers, who are typically engineers, or by equipment vendors. In order to select an appropriate heat exchanger, the system designers (or equipment vendors) would firstly consider the design limitations for each heat exchanger type. Although cost is often the first criterion evaluated, there are several other important selection criteria which are included in the below table (See Requirements for a Heat Exchanger).

Table 10-2 THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS - THE HEAT EXCHANGER

Requirements	Testing Plan Needed	Maintenance Plan Needed
High/ Low pressure limits	Yes	N/A
Thermal Performance	Yes	N/A
Temperature ranges	Yes	N/A
Best Product Mix (liquid/liquid, particulates or high- solids liquid)	Yes	N/A
Pressure drops across the exchanger	Yes	N/A
Fluid flow capacity	Yes	Yes
Cleanability	Yes	Yes
Materials required for construction	Yes	Yes

10.8 Monitoring

Monitoring of commercial heat exchangers is done by tracking the overall heat transfer coefficient. The overall heat transfer coefficient tends to decline over time due to fouling.

$$U=Q/A\Delta T_{lm}$$

By periodically calculating the overall heat transfer coefficient from exchanger flow rates and temperatures, the owner of the heat exchanger can estimate when cleaning the heat exchanger will be economically attractive. Integrity inspection of plate and tubular heat exchanger can be tested in situ by the conductivity or helium gas methods. These methods confirm the integrity of the plates or tubes to prevent any cross contamination and the condition of the gaskets. Mechanical integrity monitoring of heat exchanger tubes may be conducted through nondestructive methods such as eddy current testing.

10.9 Fouling



Figure 10-3: Heat exchanger in a steam power station contaminated with macrofouling [www.gc3.com, 2010]

Fouling occurs when impurities deposit on the heat exchange's surface. Deposition of these impurities can be caused by:

- Low wall shear stress
- Low fluid velocities
- High fluid velocities
- Reaction product solid precipitation

Precipitation of dissolved impurities due to elevated wall temperatures

The rate of heat exchanger fouling is determined by the rate of particle deposition less re-entrainment/suppression.

10.10 Cooling Water Fouling

Cooling water systems are susceptible to fouling. Cooling water typically has high total dissolved solids content and suspended colloidal solids. Localized precipitation of dissolved solids occurs at the heat exchange surface due to wall temperatures higher than bulk fluid temperature. Low fluid velocities allow suspended solids to settle on the heat exchange surface. Cooling water is typically on the tube side of a shell and tube exchanger because it's easy to clean. To prevent fouling designers typically ensure that cooling water velocity is greater than 3 ft/s and bulk fluid temperature is maintained less than 140F. Other approaches to control fouling control combine the "blind" application of biocides and anti-scale chemicals with periodic lab testing.

10.11 Maintenance

Plate heat exchangers need to be disassembled and cleaned periodically. Tubular heat exchangers can be cleaned by such methods as acid cleaning, sandblasting, highpressure water jet, bullet cleaning, or drill rods.

Table 10-3 THE MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S SUBSYSTEMS - THE HEAT EXCHANGER- FOULING

Requirements	Testing Plan Needed	Maintenance Plan Needed
Monitoring of commercial heat exchangers. The overall heat transfer coefficient tends to decline over time due to fouling.	Yes	Yes
Integrity inspection	Yes	Yes
Test for fouling: Low wall shear stress	Yes	Yes
Test for fouling: Low fluid velocities	Yes	Yes
Test for fouling: High fluid velocities	Yes	Yes
Test for fouling: Reaction product solid precipitation	Yes	Yes
Test for fouling: Precipitation of dissolved impurities due to elevated wall temperatures	Yes	Yes

In large-scale cooling water systems for heat exchangers, water treatment such as purification, addition of chemicals, and testing, is used to minimize fouling of the heat exchange equipment. Other water treatment is also used in steam systems for power plants, etc. to minimize fouling and corrosion of the heat exchange and other equipment.
A variety of companies have started using water borne oscillations technology to prevent biofouling. Without the use of chemicals, this type of technology has helped in providing a low-pressure drop in heat exchangers.

10.12 The Differences between HTHEs and low-temperature heat exchangers (LTHE)

- Radiation heat transfer may have a significant role in the high temperature units.
- Tube diameters and pitch should be larger in high-temperature units so that the pressure drop is kept low. The cost of adding a fan or blower to work at high temperatures might be prohibitive.
- Even though the gases have low heat transfer coefficient, fins are generally not used in high-temperature units because (Scaccia and Theolitus, 1980) (a) the gaseous stream usually carries suspended dirt particles that will foul or fill up the space between the fins and make a finned tube worse than a plain and (b) the gas velocity is low anyway, due to low available pressure drop, hence the advantage of fins is negligible.
- The materials for construction are different in the two cases. In high temperature units, one uses ceramics, or high alloy and costly tubing, while low alloy tubings are usually used in the low-temperature units.
- The selection of materials and their thickness and the mechanical design are governed by the thermal stresses in the high-temperature units. Other factors to be considered are: the extent of oxidation of the material, thermal shock bearing capability, and erosion due to suspended dirt particles. Fouling and corrosion due

to metallic salts, sulfates, etc., also have to be considered. Stress analysis has to be carried out for a safe and reliable design.

- A variety of designs are used in high-temperature units. These are exemplified (a) stationary regenerators made of refractory brickwork where cyclic gas flows and more than one unit is used, (b) rotary regenerators or recuperators made of compact metal surfaces, (c) shell-and-tube heat exchangers made of metals and ceramics, and (d) compact ceramic units.
- Differential expansion is an important factor in high temperature units and should be accounted for either by using expansion bellows or by using bayonet-type units. Floating tube-sheets cannot generally be used, because sealing gasket or packing materials do not work effectively at such high temperatures.
- Heat losses from the outside surfaces to the environment have to be considered in the mechanical design of the unit and the design of the foundation.
- For high-temperature heat transfer, gases, air, or liquid metals and the molten salts are preferred over steam because the latter requires very thick shell and tubes to contain its high pressure.

10.13 General Design Considerations for High Temperature Heat Exchangers

- For high temperature heat exchangers, the thermal stresses during the startup, shutdown and load fluctuations can be significant. Heat exchanger must be designed accordingly for reliability and long life.
- The thermal capacitance ("thermal mass") should be reduced for high temperature heat exchangers for shorter startup time.

 High temperature heat exchangers require costly materials contributing to the high cost of balance of power plant. Heat exchanger cost increases significantly with temperature above about 675°C.

10.14 Selection of Materials for HTHEs

Three major classes of high-temperature materials are promising candidates for different applications:

- High-temperature nickel-based alloys (e.g., Hastelloy): Good material compatibility potential for helium and molten salts up to temperatures in the range of 750°C. Also a candidate material for sulfuric acid thermal decomposition. Limited capability under fusion neutron irradiation.
- 2. High-temperature ferritic steels (particularly oxidedispersion ferritic steels). Good performance under fusion and fission neutron irradiation, to temperatures around 750 °C. Good potential for compatibility with lead/bismuth under appropriate chemistry control. Demonstrated compatibility with molten salts would have substantial value for the fusion application. Silica bearing steels provide a candidate material for sulfuric acid thermal decomposition.
- 3. Advanced carbon and silicon carbide composites, with excellent mechanical strength to temperatures exceeding 1000°C, these are now used for high temperature rocket nozzles to eliminate the need for nozzle cooling and for thermal protection of the space shuttle nose and wing leading edges. Many options are available that trade fabrication flexibility and cost, neutron irradiation performance, and coolant compatibility. These materials can

potentially be used with helium and molten salt coolants. Silicon carbide is also compatible with sulfur-iodine thermochemical hydrogen production. Major opportunities and research challenges exist to apply these materials to high-temperature heat transport applications.

The best material available seems to be a SiCp/Al₂O₃, (particles reinforcing phase-based material), from a US manufacturer; no European manufacturer could supply Ceramic Matrix Composites (CMC) bayonet tubes. However, it should be noted that such material is still under development and that, as often happens, the numerical values of the properties are indicative and much more characterization work is required.

10.15 Ceramic Heat Exchangers

The key properties for the selection of heat exchanger ceramics include: thermal shock resistance, high temperature capability, corrosion resistance and in some cases thermal conductivity. There are three prime candidate industrial areas for ceramic heat exchangers: process heat exchange, power generation heat exchange, and industrial waste heat recovery.

For chemical process heat exchange, the primary use of ceramic heat exchanger would be for liquid-to-liquid or liquid to-vapor heat exchange. This would employ the ceramic heat exchanger in a medium-to-low temperature (<100 °C) range where it would have no advantage over metallic heat exchangers with respect to temperature. However, many process streams are highly corrosive; requiring at least that the metal heat exchanger has protective coating.

For power generation, such as in SOFC Power Systems such heat exchange, the primary use of the ceramic heat exchanger would be the transfer of heat to a working

fluid. This use would employ the ceramic heat exchanger in a medium-to-high temperature (between 100-400 °C) range, where it would have advantages over the metallic heat exchangers with respective to temperature. Additionally, depending on the nature of the working fluid and on the heat source, the environment could be too corrosive for a metallic heat exchanger. The major drawback to use ceramic heat exchangers for power generation heat exchange is the lack of high-pressure seals.

10.16 Ceramic Recuperators

A recuperator is a special purpose counter-flow energy recovery heat exchanger positioned within the supply and exhaust air streams of an air handling system or in the exhaust gases of an industrial process, in order to recover the waste heat . The image below shows the three major configurations.

Principle			www.paul-lueftung.de
Profile			
Counter current Heat exchanger	Vertical flat plate	Horizontal flat plate	Cellular
Efficiency	50 - 70 %	70 - 80 %	85 - 99 %

Figure 10-4: The three major configurations of recuperators [Wikipedia, 2010]

The recuperators in current engines are fabricated mainly from stainless steel. The gas-inlet temperature typically varies from 593°C (1100°F) at full power to perhaps as high as 816°C (1500°F) at part power. The latter temperature represents an upper value for the capability of stainless steels. For operation at higher temperatures, use could be made of super alloys, such as Inconel 625, Inconel 617 or Haynes 230, but their cost would be prohibitively high for most applications. It is generally agreed, particularly for military applications, such as an advanced battle-tank engine recuperator (McDonald), that ultimately ceramic heat exchangers will be necessary. In the case of the small hybrid automobile gas turbine, cost considerations mandate the use of ceramic heat exchangers. In support of various high-temperature systems, development work on ceramic heat exchangers have been in progress for more than 25 years (Allied Signal). An excellent example of a compact ceramic recuperator module developed by Allied Signal in the late 1980s for a cruise missile application (Parker and Coombs) is shown in **Figure 10-5**. Ceramic heat exchangers that have been fabricated and tested include platefin, prime-surface and tubular geometries.



Figure 10-5: Example of a compact plate-fin ceramic recuperator [Allied Signal, 2010].

10.17 The Major Unsolved Problems in the use of the Ceramic Heat Exchangers

According to Tennery the following problems are unsolved for ceramic heat exchangers:

- High cost of the ceramic tubes.
- Long tubes of uniform properties are difficult to produce by the currently available methods. These may produce fracture. Hence, the ceramic tube production techniques need improvement.
- Tube-to-tube sheet joints cannot yet be made completely leak tight, because the differential thermal expansion of the tubes has to be accommodated.
- Durability of ceramic tubes in an environment of highly contaminated hot process gases has to be confirmed.
- The coefficient of thermal expansion may change with time due to reaction with some of the species present in the flue gases. This may result in unforeseen stresses and cracking of the tubes.
- Most of the mechanical properties known have been evaluated using small bars. The exact behavior of the same material in the form of long, hollow tubes is not known out.
- Flue gases from coal or residual oil result, after long time, in corrosion
 reactions with silconized and sintered alpha silicon carbide, changing their
 fact fracture strength. The exact reason for this and also the preventive steps
 need to be worked out.
- Ceramic-metal composites are also being considered, but fabrication would pose greater problems.

10.18 High Temperature Electrolysis



Figure 10-6: High-temperature electrolysis [Wikipedia, 2010]

High-temperature electrolysis (HTE) uses the technology of solid oxide fuel cells to split steam into hydrogen and oxygen. The cells operate at 700-850 °C and have the electrical potential reversed from that of the fuel cell mode. A schematic diagram of an HTE plan is shown above. The materials challenges in the development of hightemperature electrolysis are divided into categories: those within the cells themselves and those in the surrounding plant.

The concept of HTE builds on the technology of Solid-Oxide Fuel Cells (SOFCs), using the same materials, but producing hydrogen and oxygen rather than electricity. DOEFE and commercial interests have had very significant programs for the last two decades to develop SOFCs, particularly for use with coal gasification. The service conditions for such coal-based SOFCs are severe, with temperature above 1000 °C and fuel gas containing the full range of products characteristic of the partial oxidation of coal, including CO2, CO, H₂, SO₂ and various nitrogen oxides. In comparison, the severe conditions of solid oxide electrolytic cell is more benign, operating at lower temperatures (750 to 900 °C) with the inlet and outlet gases consisting of only steam and hydrogen in different proportions. The anode of the electrolytic cell contains the only instance of more severe conditions than an SOFC, since pure O_2 may be present if no diluents are used.

Heat exchangers play a critical role in many fuel cell systems. In fact, fuel cells thermal management is particularly critical for ensuring both the proper feeding conditions for air/oxygen and fuel, and for keeping the operating temperature under control. Magistri (et al) discussed the types of heat exchangers used in fuel cell systems, the related design issues and performance requirements. Several options in terms of cycle layout and heat exchanger technology are also discussed from the on design, off-design and control perspectives. The impact of heat exchangers on the performance of PEMFC systems and SOFC-MCFC gas turbine hybrid systems has been investigated.

Waste heat recovery from the exhaust gases of high temperature fuel cells or from the reformed fuel in a low temperature fuel cell is essential to increase the overall system efficiency. This will require high temperature heat exchangers. The design requirement may dictate to take care of considerable thermal stresses during the startup, shutdown and load fluctuations. The cost of high temperature materials could be prohibitive when the balance of power plant in a fuel cell system dictates the major cost.

Fuel preheating and reforming, both internal and external; involve extensive use of heat exchangers to drive the reforming reactions, which are endothermic overall. Internal reforming usually ensures higher efficiencies to be achieved, compared to the external reforming configuration, which on the other hand can rely on existing reforming reactors. The choice between them is driven by technical, cost and risk considerations.

The experience and know-how today exists for heat exchangers (a developed technology) at inlet temperature below 650°C, where stainless steel alloys can be used.

Higher temperatures involve advanced materials which are very costly or ceramics having durability issues, which still need to be addressed for achieving reliable products at reasonable capital cost. In this respect, analytical approaches and detailed performance models are required for design optimization and cost reduction.

High temperature heat exchangers, operating in the inlet temperature range of 750-1100°C, require the use of advanced materials, such as nickel-based alloys, cobalt based alloys and ceramics, which still represent a cost and reliability issue. Moreover, previous experiences on externally fired gas turbine cycles (Jolly et al., Traverso et al.) showed that pressure drops of ceramic heat exchangers can significantly affect the performance of the cycle, because even if high turbulent flows can enhance the heat exchange coefficients, pressure drops over 10% (loss relative to inlet pressure) become unacceptable for achieving good cycle performance.



Figure 10-7: Simplified layout of an atmospheric high temperature fuel cell-gas turbine hybrid system [Sunden, 2005]

As shown in **Figure 10-7**, another high temperature heat exchanger is also present. This component, called "Ceramic HX" in the same figure, is less critical than the previous one because it preheats the air flow entering the fuel cell. In this case, a low effectiveness is however acceptable (less than 50%), without affecting the performance of the plant. Moreover, **Figure 10-7** shows the "Ceramic HX" as a separate unit for sake of clarity. Normally, this component is fully integrated in the fuel cell stack and it is not a proper ceramic heat exchanger.

Figure 10-8 shows the performance of an atmospheric hybrid system with an SOFC, but similar conclusions could be drawn for an MCFC system. The size of the system is about 500 kW and the efficiency is 55%. The Fuel Cell power is around 400 kW and the gas turbine is 100 kW. Presently, the system size more suitable for combined HTFC-GT is around 1 MW, where about 80 % of the power comes from the fuel cell and the remaining part derives from the gas turbine. As a consequence, technical characteristics of the compressor, expander and especially heat exchangers come directly from the Microturbine Technology (McDonald) and are similar for Hybrid Systems with MCFC or SOFC. **Figure 10-8** represents also the influence of the effectiveness of the high temperature heat exchanger on the efficiency of the Fuel Cell and overall plant.



Figure 10-8: Fuel cell efficiency, system efficiency and operating temperatures versus HTHE effectiveness (atmospheric system) [Sunden, 2005]

10.19 Ceramic monolith structures

Ceramic monolith structures are used in the industry today and they are produced in large numbers by use of the extrusion technique. They are uni-body structures composed of interconnected repeating cells or channels.



Figure 10-9: Monolithic honeycomb regenerator and dimensions of solid material and flow path. A dashed line bound one symmetrical cell [Sunden, 2005]

They are increasingly under development and evaluation for many new reactor applications (Selimovic, et al. and Heck and Gulati), e.g., chemical process and refining industries, catalytic combustion, low emission power plants, etc. However, monoliths are mainly used where only one fluid flows through all the channels. An example is the monolithic exhaust structure in automotive applications. In endothermic and slow reactions such as steam reforming of hydrocarbons, large amount of heat are needed to maintain reaction rates. If the catalysts were deposited on tubes then usage of monoliths would be more efficient, leading to greater reaction rates and a smaller reactor (Williams). Additionally, there would be a great improvement in mechanical integrity. Especially it would be advantageous if two fluids in monolithic channels can exchange heat and/or mass. The reason why monoliths are not widely used in these applications is because of complex technique for feeding and distributing the two fluids in and out of the channels.

Selimovic (et al) focused on the compact ceramic heat exchanger where two fluids are fed and distributed into individual channels in a multi-channels structure. Their study show three different approaches of modeling: analytical, experimental and numerical modeling. The exchanger is of monolithic shape where heat and mass is transferred in rectangular channels. Usually, for the pressure drop calculations of standard channel shapes, different available correlations can be applied. However, when these channels are manifolded and connected to other components complex geometries are involved and then modeling with correlation parameters may be unsuccessful. Similar to plate heat exchangers, the pressure drop as well as thermal performance depends on distribution of fluid. Therefore it is important to investigate how good the flow distribution is from the main port pipe into the channels. The analytical investigation made here includes both U- and Z-type configurations. Monolithic "honeycomb"

structure has been manifolded by two stage manifolds where either U-type or Z-type manifold can be used to distribute the flow rate uniformly through each branch. This stage manifold can be compared to the manifolding of plate heat exchangers (PHE). The main difference compared to PHE's is that each branch will further divide the flow to the monolithic structure with specified channel arrangement. This stage manifolding is called I-type manifold here. More detailed picture of I-type manifold can be observed in **Figure 10-10**. Concerning the monolithic channels, two different gas distributions (channel arrangements) are investigated: the checkerboard and linear, **Figure 10-10**. The important physical characteristics are then the size of the channel through which the gaseous reactants and products traverse wall thickness, and the total monolith's compactness. Rafidi and Blasiak developed a two dimensional simulation model to find out the temperature distribution of the solid storing material and flowing gases and other thermal and flow parameters for this regenerator and compared computed results with experiments.





Because of geometric symmetry of the honeycomb structure, mathematical analysis was made on one honeycomb cell, or matrix, that formed a small part of the regenerator cross-section along the flow path. The regenerator is composed of two different materials along the heat exchangers, one is 0.2 m long alumina and the other is 0.1 m long cordierite. The honeycomb compact heat regenerator has relatively high effectiveness of about 88% and recovers 72% of energy contained in combustion flue gases at nominal operating conditions. Consequently, the energy storage and the pressure drop were calculated and the thermal performance of the honeycomb heat regenerator was evaluated at different switching times and loading. The model took into account the thermal conductivity parallel and perpendicular to flow direction of solid and flowing gases. It considers the variation of all thermal properties of solid material and gases with temperature. Moreover, the radiation from combustion flue gases to the storage materials was considered in the analysis.

10.20 The Hot Assembly Requirements

Besides the Enclosure or Cabinet, the Hot Assembly is another unique subsystem of the SOFC Power System because it requires direct critical interaction with all other BOP subsystems and the Cell Stack. Its design evolution is directly dependent upon the Cell Stack's design evolution and the Cell Stack's requirements of the BOP subsystems. Because the Hot Assembly is the platform which bridges the BOP subsystems to the Cell Stack its design is a very important factor because it must be able to withstand the Cell Stack's operational temperature throughout the power system's lifespan without functional, structural, mechanical or material failure.

Table 10-4				
THE FUNCTIONAL REQUIREMENTS AND THE TESTING AND				
MAINTENANCE BASELINES OF AN SOFC POWER SYSTEM'S				
SUBSYSTEMS - THE	E HOT ASSEMBLY			
		Maintenance		
Requirements	Testing Plan	Plan Needed		
The Freed Drug and the Constants The Had	Needed	Needed		
A samply must provide a means by				
which the Call Stock receives clean				
operational temperature reformate to	Vac	Vac		
the anode portion of the Cell Stack	105	105		
the anode portion of the Cell Stack.				
The Air System: The Hot Assembly				
must provide a means by which the Cell				
Stack receives clean, operational	Yes	Yes		
temperature oxidant to the cathode				
portion of the Cell Stack.				
The Waste Management Subsystem:				
The Hot Assembly must be connected				
to the Waste Management Subsystem in				
such a manner as to provide a means to	Yes	Yes		
expel exhaust gases (e.g. CO_2) into the				
outside environment.				
The Thermal Management Systems				
The Hot Assembly must have the				
means to:				
1 Monitor the temperature of the Cell	Ves	Ves		
Stack	105	105		
2. To maintain the temperature of the				
Cell Stack.				
To expel excess heat from the Cell				
Stack when needed.				
The Electrical System: The Hot				
Assembly must have the means to				
connect the Cell Stack to the Electrical				
System so that:	Yes	Yes		
1. DC power can be drawn from the				
Cell Stack.				
2. The Cell Stack's operational current				
and voltage can be controlled.				

Г

10.21 The Cell Stack – The Unit Cell

System design depends strongly on fuel type, application, and required capacity, but the cell stack has several important impacts on the system design and configuration:

- The cell stack operating temperature range, degree of internal reforming, operating voltage, and fuel utilization determine the air cooling flow required, as well as level of recuperation required. This determines specifications for the blower or compressors and the thermal management system.
- The cell stack geometry and sealing arrangement typically determine cell stack pressure drop and maximum operating pressure, which can influence the system design.
- The cell stack's sulfur tolerance determines the specifications of the desulfurization system.
- The degree of internal reforming that the cell stack can accept influences the choice and design of the reformer.

10.22 Cell and Stack Designs

In terms of stack design, most development has focused on planar and tubular design cells, each of these designs having a number of interesting variants; for example, the planar SOFC may be in the form of a circular disk fed with fuel from the central axis, or it may be in the form of a square plate fed from the edges. Stacks of planar solid oxide fuel cells (SOFC) are believed to offer the potential for higher cost efficiency and power density per unit volume when compared to, for example tubular designs. The tubular SOFC may be of a large diameter (>15 mm), or of much smaller diameter (<5 mm), the so-called micro-tubular cells. Also, the tubes may be flat and joined together to give higher power density and easily printable surfaces for depositing the electrode layers. The single biggest advantage of tubular cells over planar cells is that they do not require any high temperature seals to isolate oxidant from the fuel, and this makes performance of tubular cell stacks very stable over long periods of times (several years). However, their areal power density is much lower (*about 0.2 W/cm²*) compared to planar cells (*up to 2 W/cm² for single cells and at least 0.5 W/cm² for stacks*) and manufacturing costs higher.

Planar SOFCs are becoming more popular because they are easier to fabricate, operate at a lower temperature, and offer a higher power density relative to the tubular type of SOFC. A typical unit cell in a planar SOFC stack is composed of a positive electrode–electrolyte–negative electrode (PEN) assembly, a porous nickel mesh, two endinterconnect plates, and gas seals.



Fuel Cell Repeat Unit

Figure 10-12: A Planar SOFC[Fuel Cell Today, 2010]

Figure 10-11: A Tubular SOFC [Fuel Cell

Today, 2010]

The structural support for the cell stack's Unit Cell assembly consists of:

- Electrolyte-supported. Early planar cells were mostly electrolyte-supported. This requires a relatively thick electrolyte (>100 but typically around 200 µm, with both electrodes at about 50 µm) which leads to high resistance, requiring high-temperature operation.
- Cathode-supported. This allows for a thinner electrolyte than electrolytesupported cells, but mass transport limitations (*high concentration polarization*) and manufacturing challenges (*it is difficult to achieve full density in an YSZ electrolyte without over sintering an LSM cathode*) make this approach inferior to anode-supported thin-electrolyte cells.
- Anode-Supported. Advances in manufacturing techniques have allowed the production of anode-supported cells (*supporting anode of 0.5 to 1 mm thick*) with thin electrolytes.
- Metal interconnect-supported. Metal-supported cells to minimize mass transfer resistance and the use of (*expensive*) ceramic materials. In such cells, the electrodes are typically 50 µm thick and the electrolyte around 5 to 15 µm. While the benefits are obvious, the challenges are to find a materials combination and manufacturing process that avoids corrosion and deformation of the metal and interfacial reactions during manufacturing as well as operation.

Shape of the cell stack:

- Rectangular, with gases flowing in co-flow, counter-flow, or cross-flow.
- Circular, typically with gases flowing out from the center in co-flow, and mixing and burning at the edge of the cells. Spiral flow arrangements and counter-flow arrangements have also been proposed.

Method for creating flow-channels:

- Flat ceramic cell with channels in interconnect or flow-plate.
- Corrugated ceramic with flat interconnects.

Manifolding arrangement:

- External manifolding.
- Internal manifolding, through the electrolyte.
- Internal manifolding through the interconnect, but not through the electrolyte.

Interconnect material:

- Ceramic (lanthanum or yttrium chromite) suitable for high-temperature operation (900 to 1000 °C). These materials, while chemically stable and compatible with the MEA from a chemical and thermal expansion perspective, are mechanically weak and costly.
- Cr-based or Ni-based superalloy for intermediate-high temperature operation (800 to 900 °C). These materials are chemically stable at 900 °C, but they require additional coatings to prevent Cr-poisoning of the electrodes. In addition, they are expensive and difficult to form.
- Ferritic steel (coated or uncoated) for intermediate temperature operation (650 to 800 °C). While uncoated steels are chemically unstable, especially during thermal

cycling, coated steels provide corrosion resistance as well as acceptable conductivity when new. However, thermal cycling performance still requires improvement.

In practical applications of SOFCs, multiple cells are assembled to form a stack and make a serial connection in the electric loop to generate a high voltage and power. The high-temperature operation, however, gives rise to significant thermal stresses due to mismatch of coefficient of thermal expansion (CTE) between components and temperature gradients in the SOFC system. Such thermal stresses can cause delamination and micro-cracking in the critical layers of the PEN and degrade the SOFC performance. Operation of SOFCs requires individual cell components that are thermally compatible so that stable interfaces are established at 1,000 °C, i.e., CTEs for cell components must be closely matched to reduce thermal stress arising from differential expansion between components (*i.e.*, ~10^s cm/cm °C from room temperature to 1,000 °C). Therefore, a comprehensive thermal stress analysis of the SOFC stack is necessary for the success in design and operation of an SOFC system.

Table 10-5			
THE FUNCTIONAL REQUIREMENTS OF AN SOFC POWER SYSTEM'S SUBSYSTEMS - THE CELL STACK PACKAGE			
Requirements	Testing Plan Needed	Maintenance Plan Needed	
The Cell Stack Operational Temperature	Yes	N/A	
The degree of internal reforming capacity	Yes	Yes	
Operating voltage	Yes	N/A	
Fuel utilization	Yes	Yes	
The amount of air cooling flow required	Yes	N/A	
Cell stack geometry	Yes	N/A	
Sealing arrangement	Yes	Yes	
The cell stack's sulfur tolerance	Yes	Yes	
The structural support for the cell stack's electrolyte assembly	Yes	Yes	
Method for creating flow-channels	Yes	Yes	
Manifolding arrangement	Yes	Yes	
Interconnect Material Integrity	Yes	Yes	

10.23 The Materials of SOFCs

At the present time, two major types of electrically conductive ceramics are used in solid-oxide fuel cells:

- 1. Those having the fluorite structure (*especially Yttria-stabilized Zirconia*)
- 2. Those having Perovskite structure (*including Lanthanum Strontium Manganite*). A few other oxides are also of interest.

10.24 What's a Fluorite Structure?



Figure 10-13: A Fluorite Structure Model [Milliken, 2010]

Oxides based on the fluorite structure are important as electrolytes in solid oxide fuel cells, thermal barrier coatings, gate dielectrics, catalysts, and nuclear materials. Though the parent fluorite structure is simple, the substitution of trivalent for tetravalent cations, coupled with the presence of charge-balancing oxygen vacancies, leads to a wealth of short-range and long-range ordered structures and complex thermodynamic properties. The location of vacancies and the nature of clusters affect the energetics of mixing in rare earth doped zirconia, hafnia, ceria, urania, and thoria, with systematic trends in energetics as a function of cation radius. Fluorite oxides are the most common and classical oxygen ion conducting materials. The crystal structure consists of a cubic oxygen lattice with alternate body centers occupied by eight coordinated cations. The cations are arranged into a face centered cubic structure with the anions occupying the tetrahedral sites. Fluorite structure (*known as the C1 structure, with the prototype being* CaF_2) is cubic, with a unit cell formula A₄B₈ and an edge length called a₀. The A sites contain the smaller metal ions (cations) and the B sites contain the larger anions, such as F^{-} or $O^{=}$.

This leaves a rather open structure with large octahedral interstitial void. The general formula has the form AO_2 , where A is usually a big tetravalent cation, e.g. U, Th, Ce. Since Zr^{4+} is too small to sustain the fluorite structure at low temperatures, it has to be partly substituted with a larger cation, called dopant. Doping involves usually substituting lower valence cations into the lattice. In order to maintain charge neutrality oxygen vacancies have to be introduced, which allow oxygen ion migration.



Figure 10-14: Fluorite structure [Milliken, 2010]

The metal ions form a face-centered cubic sublattice with a lattice parameter equal to a_0 . The anions form a simple cubic sublattice with a cube edge equal to $a_0/2$. Thus the fractional coordinates of the 4 A ions are:

0	0	0	
1/2	1/2	0	
1/2	0	1/2	
0	1/2	1/2	

While the fractional coordinates of the 8 B ions are:

1⁄4	1/4	1/4	1⁄4	3⁄4	3⁄4
1⁄4	1/4	3⁄4	3/4	1⁄4	3/4
1⁄4	3⁄4	1⁄4	3/4	3⁄4	1⁄4
3⁄4	1⁄4	1/4	3/4	3⁄4	3/4

Each A cation is coordinated by the following nearest neighbors:

8 B at
$$\frac{\sqrt{3}}{4}$$
 a₀ = 0.433 a₀

12 B at
$$\frac{\sqrt{2}}{2}$$
 a₀ = 0.707 a₀

Each B anion is coordinated by the following nearest neighbors:

$$4 \text{ A at} \frac{\sqrt{3}}{4} a_0 = 0.433 a_0$$

Very careful x-ray measurements have revealed that very small disappointments of some of these ions from their ideal sites exist, but they are not significant for this discussion.

In ordinary polycrystalline materials, the unit cells are stacked in 3 dimensions into crystallites (having various occasional flows in their stacking). These crystallites, or sub-grains, are separated from one another by narrow regions of relative disorder called subgrain boundaries and grain boundaries to form the polycrystalline solid, which also invariably contains a small percentage of porosity.

A number of ceramic oxides posses the C1 structure over certain composition ranges. Many of these exhibit significantly high values of ionic conductivity for oxygen ions (O^x), combined with low electronic solid-oxide fuel cells. At present, the material of choice for electrolytes is yttria-stabilized zirconia (YSZ), which will be discussed first in detail, followed by a brief discussion of other C1 – structure materials of potential interest. Compositions having 100% cubic phase are called fully stabilized zirconia, whereas compositions having a mixture of cubic and another phase are called partially stabilized zirconia.

10.25 Yttria-Stabilized Zirconia (YSZ)

The figure shows is the phase diagram of the zirconia-yttria system. The cubic C1 phase (labeled F_{ss}) in equilibrium at 1000 C extends from 9 to 36 mole percent Y_2O_3 , with a tetragonal phase occurring from 0 to about 3 mole percent Y_2O_3 . There is considerable disagreement amongst various authors about many of the details of this phase diagram. In particular, the lower limit of the C1 phase field at 1000 C has been variously reported to lie anywhere from 6 to 10 mole percent. The diagram in the ZrO_2 - Y_2O_3 Phase Diagram is believed to be the most accurate.

At low temperatures, the phase transformations are very slow and thus the accurate determination of that portion of the diagram is very difficult. Two-phase (*i.e. partially-stabilized, tetragonal plus cubic*) YSZ materials are usually stronger and tougher than 100% cubic (fully-stabilized) compositions, with the strength increasing as the yttria level is reduced.



Figure 10-15: Phase Diagram of YSZ [Milliken, 2010]

An YSZ composition having 8.0 mole percent Y_2O_3 has its sites in the C1 lattice occupied as follows:

The ionic radii of the above ions are: $Zr^{+4} = 0.79$ A, $Y^{+3} = 0.89$ A, and $o^{=}$ about 1.4 A. It is believed that, due to these sizes, there is a tendency for partial clustering (short-range ordering) of vacancies near to the Y^{+3} ions. This ordering increases as the percentage of Y_2O_3 increases with the C1 phase field.

10.26 Ionic Conductivity of YSZ

Pure ZrO_2 is an electrical insulator at both high and low temperatures. The tetragonal phase of YSZ has an ionic conductivity, which is up to an order of magnitude lower than the cubic C1 phase.

Cubic YSZ is very good ionic conductor (for O^{-}) with its maximum value of ionic conductivity occurring at or just above the lower phase boundary (i.e. about 8 to 10 mole % Y₂O₃). The corresponding minimum value of resistivity has been reported in the literature to lie anywhere from about 6 to 10 ohm-cm at 1000 C. The activation energy for ionic conduction is reported to be anywhere from about 0.7 to 1.05 eV.

Partially-stabilized YSZ has a lower conductivity which is roughly proportional to the volume fraction of C1 phase. Thus a composition with 50% C1 phase has perhaps twice the resistivity of the fully-stabilized material at 8-10 mole percent. Compositions richer in Y_2O_3 beyond about 10 mole percent exhibit an increased ionic resistivity, due apparently to the above-mentioned ordering phenomenon.

10.27 Electronic Conductivity of YSZ

Measurements of the electronic conductivity of fully-stabilized YSZ in air at 1000 C show its value to be on the order of 500 times lower than the ionic conductivity, which makes YSZ a very good electrolyte material in this regard. (*i.e. the ionic transference number is about 0.998 here*).

At very low oxygen pressures (in the vicinity of roughly 10⁻¹⁸ atm and below), however, a very significant change in high-temperature electronic conductivity occurs. The YSZ can be chemically partially reduced to a sub oxide, whose composition differs very little from the original YSZ, but which contains so-called F-centers. The F-centers cause the color of the material to change from white to grey and give rise to a small concentration of highly mobile electrons which can produce an electronic conductivity as large as 10^3 times higher than the ionic conductivity (which is itself believed to change little when this occurs): an increase of up to 5×10^5 times its equilibrium value in air. The sub oxide is sometimes designated ZrO_{2-x} , with X believed to lie between 10^{-2} and 10^{-3} . However, as seen above, YSZ already has an oxygen deficiency of some 3.7%, and thus the value of X is actually relative to the base composition.

This partial reduction, sometimes called blackening, is both slow (requires minutes to hours at 1000 C, depending upon thickness and das composition) and reversible. It has been demonstrated using 3 different means of reduction at high temperatures: chemical (noted above), electrical (*using about 3.5 volts applied potential per wafer*), or high vacuum.

If the sample is exposed to the reducing gas on both sides, the blackening will eventually penetrate the entire sample thickness. In a fuel cell, however, the blackening will be confined to a thin layer on the anode side, whose equilibrium or steady-state thickness depends upon the adjacent value of oxygen potential, reaching a zero thickness above a value somewhere around 10^{-18} atm.

10.28 YSZ Characteristics

The most common solid electrolyte material used in solid oxide fuel cells is yttriastabilized zirconia (YSZ). Yttria is added to stabilize the conductive cubic fluorite phase, as well as to increase the concentration of oxygen vacancies, and thus increase the ionic conductivity. **Figure 10-16** shows that the conductivity of YSZ increases for yttria additions of up to about 8-mole% and then decreases for higher yttria contents. The

decrease at higher dopant contents is due to association of point defects, which leads to a reduction in defect mobility and thus conductivity.



Figure 10-16: The Conductivity of YSZ [Han, 2007]

10.29 Grain Boundary Conduction

A grain boundary is the interface between two grains, or crystallites, in a polycrystalline material. Grain boundaries are defects in the crystal structure, and tend to decrease the electrical and thermal conductivity of the material. The high interfacial energy and relatively weak bonding in most grain boundaries often makes them preferred sites for the onset of corrosion and for the precipitation of new phases from the solid. They are also important to many of the mechanisms of creep. On the other hand, grain boundaries disrupt the motion of dislocations through a material, so reducing crystallite size is a common way to improve strength, as described by the Hall-Petch relationship. Grain boundary conduction is also important in YSZ, and since the grain boundary contribution increases with decreasing temperature.

For example, for YSZ materials produced by several different methods, the fraction of the total resistance due to grain boundary resistance is negligible at 900 °C, but increases to \sim 0–40% at 700 °C, and then further to \sim 10–65% at 500 °C.

Grain boundary transport becomes especially important for nano-structured materials due to their high proportion of grain boundary area. For example, YSZ to produce grain sizes less than 10 nm resulted in conductivities which were 50% higher than those of materials with larger grain sizes.

10.30 Mechanical Strength

Although the strength of an electrolyte in an SOFC is of secondary importance as compared to electrochemical properties, it is important for the production of reliable long-life SOFCs. The mechanical properties of ScSZ are similar or better than those of YSZ. Although the strength of an electrolyte in an SOFC is of secondary importance as compared to electrochemical properties, it is important for the production of reliable long-life SOFCs. The strength and toughness can be improved with the addition of oxide dispersants, such as alumina or niobates. However, such additions typically reduce conductivity, so the benefits in improved strength must be balanced with any resulting increases in cell impedance.

10.31 Other Types of Electrolyte - Scandia-Stabilized Zirconia

Toho Gas has developed Scandia-stabilized zirconia (ScSZ), which has a higher ionic conductivity than yttria-stabilized zirconia (YSZ), and is one of the candidates for use in making high-performance SOFCs. The electrochemical performance of planar type single cells with a ScSZ electrolyte has already been demonstrated, and an extremely high power density of 2 W/cm² has been achieved.

In addition, Sc-TZP (Scandia doped tetragonal zirconia polycrystal) electrolytes have been developed that have high mechanical strength and great resistance to fractures. Toho Gas's electrolyte technologies have been transferred to DKKK (Daiichi Kigenso

Kagaku Kogyo, the largest zirconia supplier in Japan). ScSZ and Sc-TZP materials are now available for mass production. Many SOFC developers are interested in these electrolytes.

Table 10-6 THE FUNCTIONAL REQUIREMENTS OF AN SOFC POWER SYSTEM'S SUBSYSTEM - THE ELECTROLYTE			
Dense and leak tight	Yes	N/A	
Stable in reducing and oxidizing environments	Yes	N/A	
A good ionic conductor at operating temperatures	Yes	N/A	
Non-electron conductor	Yes	N/A	
Thin to reduce ionic resistance	Yes	N/A	
Extended in area for maximum current capacity	Yes	N/A	
Thermal shock resistant	Yes	Yes	
Economically processable	Yes	Yes	

10.32 Key Requirements for Electrolyte

The SOFC-type fuel cell is wherein by a plate-like structure and a solid oxide ceramic electrolyte. Different oxide ceramic electrolytes, for example doped zirconium oxide (zirconia) or cerium oxide (ceria), are used depending on the working temperature selected for the cell in the range between 500° and 1000° C. In actual fact, nowadays

plate-like fuel cell arrangements with a surface area of up to 1000 cm^2 , wherein the thickness of the electrodes and of the solid electrolyte is regularly much less than 100µm, are used. The lowest possible electrolyte thickness, which is important for the efficiency of the cell, is between 5 and 30 µm.





The electrolyte material must also be chemically and mechanically (*e.g.* thermal expansion) compatible with other fuel cell components. This compatibility extends to fabrication processes, since some processes may need to be performed with multiple components present, which limit the range of parameters (*e.g.* temperature or pressure) to those acceptable for all components.

10.33 The Specifications of the Ceramic Cathode Layer of the Electrolyte

Most cathode materials used in SOFC today are lanthanum-based perovskite materials (structure ABO₃). During early development, platinum and other noble metals, and even magnetite, were used as cathode materials for SOFC. They are no longer pursued actively because of chemical and physical instability, incompatibility with most electrolytes, and, in the case of platinum, cost. Currently, most cathodes are based on doped lanthanum manganites. In high temperature SOFC (operating temperature ~1000 °C), strontium-doped LaMnO₃ (LSM) is used.

The choice of this material is a compromise between a number of factors:

- Chemical stability and relatively low interactions with electrolyte. With YSZ electrodes, many La-based compounds form the insulating La₂Zr₂O₇. With ceria-based electrolytes, this issue is not a concern and other cathode materials are considered (e.g. (La,Sr)(Co,Fe)O₃ or LSCF).
- Adequate electronic and ionic conductivity. Though the conductivities are adequate, the ionic conductivity of LSM is significantly lower than YSZ, and its electronic conductivity is a fraction of any of the metals or even of lanthanum chromite. Consequently, ionic and electronic resistance can become a significant factor, especially in cell designs that incorporate long current paths through the cathode. For lower-temperature cells, conductivity of LSM is inadequate, and other materials, such as strontium-doped lanthanum ferrite (LSF) are considered.
- Relatively high activity.
- Manageable interactions with ceramic interconnect (notably lanthanum chromite). Though some interdiffusion occurs, this does not represent a major problem.
- Thermal expansion coefficients that closely match those of YSZ.

10.34 The Specifications of the Ceramic Anode Layer of the Electrolyte

The anode (*the fuel electrode*) must meet most of the same requirements as the cathode for electrical conductivity, thermal expansion compatibility and porosity, and must function in a reducing atmosphere. The reducing conditions combined with electrical conductivity requirements make metals attractive candidate materials.

Most development has focused on nickel owing to its abundance and affordability. However, its thermal expansion ($13.3 \times 10^{-6}/C$ compared with $10 \times 10^{-6}/C$ for YSZ) is too high to pair it in pure form with YSZ; moreover, it tends to sinter and close off its porosity at operation temperatures. These problems have been solved by making the anode out of a Ni-YSZ composite. The YSZ provides structural support for separated Ni particles, preventing them from sintering together while matching the thermal expansions. Adhesion of the anode to the electrolyte is also improved.

Anodes are applied to the fuel cell through powder technology processes. Either a slurry of Ni is applied over the cell and then YSZ is deposited by electrochemical vapor deposition, or a Ni-YSZ slurry is applied and sintered. More recently NiO-YSZ slurries have been used, the NiO being reduced to particulate Ni in the firing process. In order to maintain porosity, pore formers such as starch, carbon, or thermosetting resins are added. These burn out during firing and leave pores behind.

There are problems with this approach. First, the process tends to form tortuous porosity pathways that reduce the transport efficiency of reacting gasses through the anode. Second, there is an increased likelihood of cracking on firing because of the thinness of the interior solid structure left behind. Third, there are environmental issues associated with the burning of the pore formers.

Many companies in the solid oxide fuel cell industry are in the process of developing anode tape formulations and manufacturing methods. There are, however, few options except to look to other more mature industries for processing equipment.

Tape casting is a fabrication technique where a slurry of the metal or ceramic powder suspended in an organic matrix is metered onto a moving carrier film (*in this case silicone-coated Mylar*) using a tool called a doctor blade. The silicone coating on the Mylar film provides the necessary release characteristics so that the cast layer does not release prematurely during, or after, drying.



Figure 10-18: A Tape Casting Set up [Belko, 2008]

However, it can be stripped when it is completely dry. The release coating has been developed to provide the best of these characteristics. Most have made the decision to use tape casting for their sheet forming needs. It is well known to people familiar with the tape casting process that it can be difficult and laborious to keep the process in control. It is also difficult to produce many small test batches. The most difficult aspect of tape casting for fuel cell anode tapes is to disperse fugitive pore formers.

Screen printing, one of the first--but best--deposition methods, is unique among the many printing, coating and image--placement processes. While many methods can print fine, detailed images, they deposit extremely thin layers of material. Screen printing can resolve fine feature sizes while printing relatively thick deposits of almost any fluid or paste. This ability to control thickness makes screen printing one of the few printing processes used to apply coating and to actually build three-dimensional (3-D) structures. The capability to precisely apply thick coatings of ceramic and metal-filled conductive pastes makes screen printing a popular process for fuel cell applications.

Other choices of material are under investigation as well. Although Ni-YSZ is currently the anode material of choice and screen printing solves most of the associated problems, nickel still has a disadvantage: it catalyzes the formation of graphite from hydrocarbons. The deposition of graphite residues on the interior surfaces of the anode reduces its usefulness by destroying one of the main advantages of SOFCs, namely their ability to use unreformed fuel sources.

Cerium(IV) oxide is used in ceramics, to sensitize photosensitive glass, as a catalyst and as a catalyst support, to polish glass and stones, in lapidary as an alternative to "jeweler's rouge".



Figure 10-19: Cerium(IV) oxide (powder) [Wikipedia, 2010]

It is also known as "optician's rouge". In the doped form (it comes from cerium and oxygen), ceria is of interest as a material for solid oxide fuel cells or SOFCs because of its relatively high oxygen ion conductivity (i.e. oxygen atoms readily move through it) at intermediate temperatures (500-800 °C). Undoped and doped ceria also exhibit high electronic conductivity at low partial pressures of oxygen due to the formation of small polarons.

A polaron is a quasiparticle composed of a charge and its accompanying polarization field. A slow moving electron in a dielectric crystal, interacting with lattice ions through long-range forces will permanently be surrounded by a region of lattice polarization and deformation caused by the moving electron. Moving through the crystal, the electron carries the lattice distortion with it, thus one speaks of a cloud of phonons accompanying the electron.

The resulting lattice polarization acts as a potential well that hinders the movements of the charge, thus decreasing its mobility. Polarons have spin, though two close-by polarons are spinless. The latter is called a bipolaron.

In materials science and chemistry, a polaron is formed when a charge within a molecular chain influences the local nuclear geometry, causing an attenuation (or even reversal) of nearby bond alternation amplitudes. This "excited state" possesses an energy level between the lower and upper bands.



Figure 10-20: Cerium(IV) oxide structure [Wikipedia, 2010]

However, doped ceria has an extended electrolytic region (area of predominant ionic conductivity), over that of ceria, that allows its use as an electrolyte in SOFCs. Substituting a fraction of the ceria with gadolinium or samarium will introduce oxygen vacancies in the crystal without adding electronic charge carriers. This increases the ionic conductivity and results in a better electrolyte.

Under reducing conditions, those experienced on the anode side of the fuel cell, a large amount of oxygen vacancies within the ceria electrolyte can be formed. Some of the cerium(IV) oxide is also reduced to cerium(III) oxide under these conditions which consequently increases the electronic conductivity of the material. The constant of ceria lattice increases under 'reducing' conditions, as well as, with decreasing nanocrystal size in nanocrystalline ceria, as a result of reduction of the cerium cation from a 4+ to a 3+ state in order to charge compensate for oxygen vacancy formation. In the most stable

fluorite phase of ceria, it exhibits several defects depending on partial pressure of oxygen. The primary defects of concern are oxygen vacancies and small polarons (electrons localized on cerium cations) because these two are located in the "useful" range of ceria. In the case of oxygen defects, the increased diffusion rate of oxygen in the lattice causes increased catalytic activity as well as an increase in ionic conductivity, making ceria interesting as a fuel cell electrolyte in solid-oxide fuel cells.

Cu (copper)-cerium oxide anodes are being studied as a possible alternative. Copper is an excellent electrical conductor but a poor catalyst of hydrocarbons; cerium oxide is used as the matrix in part because of its high activity of hydrocarbon oxidation. A composite of the two thus has the advantage of being compatible with cerium oxide electrolyte fuel cells. Initial results using a wide range of hydrocarbon fuels are promising.

The composition of the anode material, the particle sizes of the anode powdered form, and anode manufacturing method are key to achieving high electrical conductivity, adequate ionic conductivity, and high activity for electrochemical reactions and reforming and shift reactions.

10.35 Other Fluorite-Structure Materials

Although several doped CeO_2 ceramics have been used as solid electrolytes, systems based on ZrO_2 so far have shown the greatest ionic conductivity and other attractive properties.

Binary ZrO₂ ceramics containing CaO or MgO form the C1 phase only at temperatures above about 1140 C (CaO) or 1400 C (MgO). Both systems are

inexpensive and the zirconia-calcia system especially has structural uses, but neither can compare with YSZ for good electrical properties.

The C1 zirconia phases containing Sc_2O_3 or Yb_2O_3 have been shown to have ionic conductivity superior to YSZ (roughly 2.0 and 1.5 times the YSZ value, respectively, at 1000 C). This may be related to the ionic sizes, as follows:

Table 10-7 IONIC SIZE		
Ion	Approx. Ionic Radius, A	
Zr+4	0.79	
Y+3	0.893	
Sc+3	0.73	
Yb+3	0.858	

The substitution of Y^{+3} for Zr^{+4} causes a size distortion of the C1 lattice due to its larger radius. The Yb⁺³ and Sc⁺³ cause less distortion and hence higher conductivity. Unfortunately, both of these oxides are much more expensive than Y₂O₃. Other potential oxide choices have the wrong radius, the wrong valence, too little solubility in ZrO₂, or other disadvantages. However, of lower-cost Sc₂O₃ later became available, this could be of considerable interest (*it could become competitive with Y₂O₃ even at a considerably higher price per kg*).

Other C1 materials of potential interest are ternary compositions which exhibit mixed conductivity for application as electrode components. The system $ZrO_2-Y_2O_3$ -TiO₂ has been shown to exhibit mixed conductivity over a very wide range of oxygen pressures. The system $ZrO_2-Y_2O_3$ -CeO₂ shows dramatic darkening with mixed conductivity under strongly reducing conditions and may be useful in anodes. The system $ZrO_2-Y_2O_3-V_2O_5$ has been suggested for study of possible mixed conductivity.

10.36 Perovskite-Structure Materials

A perovskite structure is any material with the same type of crystal structure as calcium titanium oxide (CaTiO₃), known as the *perovskite structure*, or $^{XII}A^{2+VI}B^{4+}X^{2-}_{3}$ with the oxygen in the face centers.



Figure 10-21: Perovskite ABO3 CRYSTAL UNIT CELL [Milliken, 2010]

The perovskite structure is possessed by many hundreds of mixed oxides and other compounds, with the idealized formula ABO_3 (although the anion need not be oxygen, it will be for all of our cases) and the idealized unit cell shown below. The ideal cubic-symmetry structure has the B cation in 6-fold coordination, surrounded by an octahedron of anions, and the A cation in 12-fold cuboctahedral coordination. The relative ion size requirements for stability of the cubic structure are quite stringent, so slight buckling and distortion can produce several lower-symmetry distorted versions, in which the coordination numbers of A cations, B cations or both are reduced. The A

cations are relatively large and occupy the corners of the unit cells (coordinate 0,0,0). The B cations are relatively small and occupy the centers of the unit cells (coordinate $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$). The anions (here oxygen) occupy the center of the 6 cube faces, with fractional coordinates:

1/2	1/2	0	1⁄2	1/2	1
1/2	0	1/2	1/2	1	1.2
0	1/2	1/2	1	1/2	1/2

10.37 Lanthanum Strontium Manganite (LSM)

Lanthanum manganite, LaMnO, exhibits electronic conductivity at high temperatures. However, this can be enhanced (and the materials cost reduced) by the substitution of Sr for some of the La. Compositions up to $La_{0.5}$ Sr_{0.5} have good conductivity, but those near $La_{0.9}$ Sr_{0.1} (or slightly higher up to $La_{0.8}$ Sr_{0.2}) are apparently best. Since residual La_2O_3 may be quite detrimental to conductivity at 1000 C of approximately 100 ohm⁻¹CM⁻¹ (a resistivity of 0.01 ohm-cm) in air. The material is jet black in color and its x-ray pattern reveals a nearly cubic (tetragonal) pattern with some notable peak splitting.

If exposed to reducing conditions, the material changes to a brown color, its resistivity increases by many orders of magnitude, and it undergoes volume changes, which make it unusable for separators of as an anode component. One theory of conductivity predicts that LSM electronic conductivity should be p type and may be proportional to (oxygen partial pressure) thus increasing with higher oxygen pressures.

The great majority of the LSM high conductivity is electronic. However, it also apparently has a small, but potentially significant oxygen ionic conductivity. Indeed, the existence of this mixed conductivity may help explain the superior cathode performance of LSM versus metals such s Pt, which have no ionic conductivity. The value of ionic resistivity in LSM is not reported, but may be in fact comparable to the value of YSZ resistivity (e.g. 6-10 ohm-cm).

10.38 Other Perovskite-Structure Materials

Lanthanum strontium cobaltite, with a composition $La_{0.3}Sr_{0.7}CoO_3$, has been reported to have a total conductivity superior to LSM together with increased ionic conductivity versus LSM. It has been reported to have been used as a cathode material in solid-oxide fuel cells.

Lanthanum chromite, LaCrO₃, doped with Sr, Mg or other cations, has been used as a ceramic interconnect material. Its total conductivity is considerably lower than LSM, but it is degraded less by exposure to fuel mixtures than is LSM. Compositions combining La, Sr, Mn, and Co might have advantageous properties as cathodes. It may also be worthwhile testing perovskites with partial substitution of Ni, Cr, or Fe into LSM.

10.39 Other Conductive Oxides

Nickel oxide, NiO, is a semiconductor with significant conductivity at high temperatures². Nb-doped Tio₂ is reported to have high conductivity. Mixed oxides containing Fe, Ni, and Cr are normally semiconducting.

Table 10-8			
THE FUNCTIONAL REQUIREMENTS OF AN SOFC POWER			
SYSTEM'S SUBSYSTEMS			
THE CERAMIC ANODE/CATHODE LAYER OF THE ELECTROLYTE			
		Maintenance Plan	
Requirements	Testing Plan Needed	Needed	
Chemical stability and			
relatively low interactions with			
electrolyte	Yes	N/A	
Adequate electronic and ionic			
conductivity	Yes	N/A	
Relatively high activity	Yes	N/A	
Manageable interactions with			
ceramic interconnects	Yes	N/A	
Thermal expansion			
coefficients that closely match			
those of the electrolyte	Yes	N/A	

10.40 The Interconnects or Separators

The cell voltage of an individual fuel cell of an SOFC is approximately 1 volt, and therefore it is always necessary for a multiplicity of individual cells with surface dimensions which are as large as possible to be stacked and electrically connected in series in order to achieve electrical voltages and power outputs that are technically useful. Plate-like individual unit cells stacked on top of one another are separated from one another by interconnectors, or "*separators*".



Figure 10-22: Hexis Fuel cell stack and its basic principle [Volker Nerlich, Hexis GmbH, 2010]

To be satisfactorily useable over the entire fuel cell service life, which has to be sufficiently long from an economic viewpoint, the separators have to meet high demands imposed on a wide range of mechanical, physical and chemical material properties and at the same time it must be possible to manufacture the separators at relatively low cost. The material costs alone must not make the overall fuel cells system commercially unattractive. It is therefore quite understandable that the development of suitable separators has in recent years been the subject of considerable attention, both with regard to the selection of material and with regard to economic fabrication. Desirable requirements for separators include:

- High mechanical strength, in particular high rigidity of even thin separators over the wide temperature range between room temperature and approx.
 1000° C.
- Optimum matching of the coefficient of thermal expansion to that of the solid electrolyte: this match must be equally present at any temperature in the entire range between room temperature and operating temperature.

- High thermal and electrical conductivity, low electrical surface contact resistance, including maintaining these values throughout the entire service life of a fuel cell power system.
- High corrosion resistance of the material with respect to the fuel gas and exhaust gas atmospheres in the cell, which on the anode side are substantially hydrogen and H₂O vapor, CO and CO₂, and on the cathode side are substantially oxygen and air.



Figure 10-23: AN SOFC Cell Stack [MSRI News, 2009]

The development of suitable materials for separators was initially concentrated on chromium alloys. In recent years, the development concentration has shifted to ferritic iron alloys with significant levels of chromium. During the efforts to further refine the proposed ferritic alloys for separators in SOFC-type fuel cell units, it has been important to suppress the formation of volatile chromium compounds and the vaporization of these compounds from the separators' surfaces as far as possible. By way of example, one countermeasure proposed has been the addition of suitable quantities of titanium and manganese.

Even with the ferritic materials, which are known to be resistant to corrosion, it has been impossible to completely avoid superficial growth of oxide. To reduce the oxide growth rate, but at the same time also to increase the mechanical strength, it has been proposed to add small quantities of the elements yttrium, cerium, lanthanum, zirconium and/or hafnium. With materials developments of this type, the person skilled in the art has been relying on the theoretical and empirical knowledge of the action of individual metallic and nonmetallic components. Known ferritic iron-based materials with a multiplicity of additions which have by now been described, in view of the state which has been reached in the demands for matching a wide range of extremely divergent materials properties, make a prediction about measures aimed at further matching of properties impossible or at least rather dubious.

A material that is characterized in this way for current collectors has no guiding significance in the context of this description with regard to matching of properties. Even with regard to the coefficients of thermal expansion, nowadays more refined criteria apply, for example in connection with the design and material of the solid electrolyte used in each case.

Alloys containing more than 18% by weight of chromium are considered to be difficult to process. The report refers to layers which are formed on the material as a result of corrosion and which flake off. Despite tests using the Cr and W contents over the entire range covered by the scope of protection of the alloy, it was impossible for the coefficient of thermal expansion of the alloy to be satisfactorily matched to the coefficient for yttrium-stabilized ZrO $_2$ solid electrolytes.

According to new measurements, in the temperature range between 20° and 1000° C. this material constant varies continuously between 11.7, 10.8 and back to 11.7×10^{-6} K⁻¹. The resistance to oxidation, in particular under the hot H ₂/H ₂O vapor atmosphere

which is present on the anode side when the cell is operating was recorded to be unsatisfactory.

Table 10-9			
THE FUNCTIONAL REQUIREMENTS OF AN SOFC POWER SYSTEM'S SUBSYSTEMS THE INTERCONNECTS (SEPARATORS)			
High mechanical strength	Yes	N/A	
Optimum matching of the coefficient of thermal expansion to that of the solid electrolyte	Yes	N/A	
High thermal and electrical conductivity	Yes	N/A	
Low electrical surface contact resistance	Yes	N/A	
High corrosion resistance of the material	Yes	N/A	
ASR for a high quality separator < 0.1 ohm-cm ²	Yes	N/A	

10.41 The Seals



Figure 10-24: Distribution of maximum in-plane principal stress in glass-ceramic sealants at RT for: (a) edge-support, (b) plane-support, and (c) point-support [Singh, 2005]

10.42 Planar Challenges

However, the high-temperature sealing concept in planar design is one of the crucial challenges of this power conversion technology. The occurrence of leakage during long-term operation of a stack may contribute to the degradation of the electrical stack performance. In particular, local sealing failure must be strictly prevented because the severe exothermal reaction between fuel and oxidant significantly increases the temperature. As an extreme, the '*so-called*' hot spots can cause a catastrophic loss of electrical performance during stack operation.

10.43 (Mechanistically) Types of Seals

Mechanistically, there are two types of seals: compressive seals and rigid seals. Compressive Seals

Compressive seals, as the name implies, involve the use of materials (such as metals or mica based composites) under compressive loads to ensure gas tight sealing as opposed to rigid seals which rely on effective bonding of the seal to the sealing surfaces. Compressive seals with a metal-mica arrangement provide a high potential for SOFC application avoiding the inherent drawbacks of glass-ceramics. For that purpose metallic seals, mica paper and combined arrangements of these materials were investigated under SOFC operating conditions.

Corrugated metallic seals achieving a leak rate of $<1 \times 10-4$ mbar l/mm at an adequate compression force of 16 N/mm seem to be promising for SOFC requirements. The insufficient spring-back effect of <0.2% and their strong susceptibility to creep require the use of appropriate filler materials. Plain mica paper exhibits the highest elastic recovery of about 5.8%, but a detectable improvement in gas tightness does not take place before a very high level of compression load of more than 50 N/mm (15MPa) is applied. Mica paper is less stable under high temperature conditions after the binder has been burnt off due to the flake-like structure of the material. This disadvantage is compensated by the use of commercial mica paper with a thin metallic inlay, which improves the durability during long-term operation.

A sandwich arrangement of mica sheet embedded between embossed metallic profiles was found to be the most suitable combination. At a compression load of 2.7 N/mm (0.7MPa) the flow rate dropped below the detection limit of the testing device.

However, it has to be considered that this seal is not suitable for sealing the manifolds between adjacent interconnects due to the occurrence of short circuits.

Compressive Metal Seals

Currently, the most popular type of sealants used is compression metal seals. These types of seals are radically different from those mentioned above since bonding is not required. Sufficient compressive load is applied to deform the metal gaskets and therefore prevent gas leakage. The combination of elastic and plastic deformation of the metal seals leads to an increased tolerance of the SOFC stack of thermal expansion mismatch as well as thermal cycling and vibrations. Since the ceramic cell and the metallic interconnect are not rigidly bonded to each other (as in the case of glass–ceramic seals), residual stresses do not develop or are substantially reduced. Research in the area of compressive metal seals for SOFCs is still relatively new and very little data is available. It is possible to purchase metallic O-ring seals commercially. These vary in shape, material and cost and certain types are already being used by fuel cell manufacturers.

10.44 Thermal Expansion (CTE)

Therefore, in the case of rigid seals, physical properties such as the coefficient of thermal expansion (CTE) become critical since it is required that the CTE mismatch across the sealing interface be minimal.

10.45 Rigid Seals Advantage

Rigid seals offer significant advantages over compressive seals which suffer from problems of oxide scaling and chemical stability under highly reactive environments in addition to the disadvantages of incorporating an externally applied load.

10.46 Rigid Seals – Approaches

Among the rigid seals there are three separate approaches to sealing—glass seals, glass-ceramic seals and metal brazes. Among the glass seals, one area of significant interest is in the development of innovative self-healing glasses.

10.47 Glass Seals

Glass is the most preferred candidate as planar solid oxide fuel and electrolyzer cell seals. To be used as a seal, one of the most important and challenging criteria is thermal stability at solid oxide cell operating temperature for a long time ~50,000-hours (5.7 years). Chemical interaction of the sealing glass with the interconnect steel may deteriorate the corrosion resistance of both chromia-forming as well as alumina-forming alloys. The inherent brittleness of glass ceramics and the rigid bonding of the stack components limit the compensation of mechanical and thermal stresses and promotes growth of defects or cracks at the interconnect/glass-ceramic interface. Due to the stiff stack assembly, the reduction of mechanical or thermal stresses by elastic or plastic deformation or by free expansion and contraction of stack components is hampered. Furthermore, a non-destructive dismantling of stacks to replace malfunctioning components is impossible.

The self-healing glass sealant also exhibits much shorter relaxation times due to its high creep rate, thereby indicating that the self-healing glass has the potential to be a simple yet effective sealing material from a seal stress management perspective. However, Govindaraju noted that the self-healing glass seal will experience continuing creep deformation under the operating temperature of the SOFC therefore resulting in

possible overflow of the sealing material. Therefore, a stopper material may need to be added to maintain its geometric stability during operation.

10.48 Glass Ceramics

Currently glass-ceramics are the preferred materials in many rigid sealing concepts of SOFC stacks. They combine moderate sealing loads with few restrictions in stack design and provide sufficient gas tightness for mid-term stack operation (several 1000 h). The thermal expansion coefficient (CTE) of glass-ceramics can be adapted to other stack components by controlling the phase content of the partially crystallized glass and enables thermal cycles during stack operation with moderate heating and cooling rates. However, glass-ceramics are disadvantageous for long-term stack operation. Govindaraju's carried out stack level simulation to evaluate the time-dependent stress and strain behaviors in the Positive electrode-Electrolyte-Negative electrode (PEN) seal fabricated using a glass-ceramic and a self-healing glass. Govindaraju's simulations utilize coupled electrochemical, fluid flow, heat transfer and thermomechanical analyses. The results of this study indicate that for both the materials the dominant effects on the resultant stresses and strains at the operating temperature of the SOFC are due to mismatch of CTE of the different stack components. Further, it was found that the stresses at the operating temperature in the case of the self-healing glass were significantly lower as compared to the glass-ceramic seal, due to its much lower modulus at the operating temperature of SOFC.

One of the major drawbacks of the SOFC is the need for gas-tight sealing around the edge of the cell. In case of a significant gas leak, the resulting combustion would create a hot spot leading to failure by local reaction/melting. Sealing the stack remains an

unsolved problem with SOFCs. Several sealing techniques have been developed over the years, although standards have yet to be set. From a materials standpoint, the seal must satisfy several criteria; among many technical hurdles hindering the advancement of solid oxide fuel cells (SOFC), a durable stack sealant or sealants is at or near the top on the list.

- The seal must have long-term stability.
- The seal must not cause degradation of the materials with which it is in contact (e.g. stabilized zirconia, interconnect and electrodes) at the elevated temperatures and harsh environments typical of SOFCs during operation.
- The seal has to survive many thermal cycles during routine operation.
- Depending on the design, geometrical limitation of the sealing components, e.g. corners and junctions, have to be taken into account. Adequate sealing should also sufficiently compensate the mechanical and thermal mismatch of the stack components. In the case of metallic seals, the creep behavior and the elastic recovery are important.

Seals in SOFC stacks have to fulfill a variety of requirements. Primarily, long-term stable separation of oxidant and fuel gases, even under thermal cycling operation, has to be achieved. The sealant needs to be not only thermally and chemically stable in the dual oxidizing and reducing environment, but also to be electrical insulating and mechanically strong for long-term operation of over 40,000-hours. The problem becomes more challenging when thermal cycle stability is also required for planar stacks in which dissimilar SOFC components are sealed together. The sealants have to survive hundreds to several thousands of thermal cycles during life service. The issue of thermal cycling is

critical for materials which have different coefficients of thermal expansion, especially for SOFCs with metallic interconnects.

Table 10-10 THE FUNCTIONAL REQUIREMENTS OF AN SOFC POWER SVSTEM'S SUBSYSTEMS - THE SEALS		
Requirements	Testing Plan Needed	Maintenance Plan Needed
Long-term stability	Yes	N/A
Seal material must not cause degradation of the materials	Yes	N/A
Survive many thermal cycles	Yes	N/A
Geometrical limitation of the sealing components	Yes	N/A
Adequate sealing should also sufficiently compensate the mechanical and thermal mismatch of the stack components.	Yes	N/A
Electrochemical-insulating to avoid shorting	Yes	N/A
Lowest possible thermo- mechanical stresses upon processing, during heat up, cool down, and in steady state/transient operations	Yes	N/A
Lowest possible thermo- mechanical stresses upon processing, during heat up, cool down, and in steady state/transient operations	Yes	N/A
Long life (5,000-40,000 h) under electrochemical and oxidizing/reducing environments at high temperatures ~600-850C	Yes	N/A

10.49 Conclusion

After studying the major components of each subsystem of the SOFC Power System, the reader should understand the major technical baselines and the design and development challenges for each subsystem and their major components.

CHAPTER XI

THE EXPLORATORY/DEFINITION TECHNIQUES AND FEASIBILITY ANALYSIS OF SYSTEM DESIGN AND TECHNOLOGY BASES – PHASE ONE

11.1 Introduction

This chapter will describe some of the practical working methodologies used in the engineering development which includes a brief introduction the TRIZ methods for problem solving. The objectives of the process design approach are to assess the optimal BOP design, lay-out or components sizing and of the related performances in terms of efficiency and power output

The procedural steps for defining the initial definition knowledge baselines using the Input-Output-Resource-Constraints (IORC) Process System will be detailed, and an overview of the levels of Fuel Cell models will be reviewed.

A general parameter-based feasibility/sensitivity analysis, an example of the types of studies/models fuel cell developers use is presented. Through this case study, important operational parameters and variables will be defined.

11.2 The Evaluation of Conceptual System Design

During the Conceptual Design & Advance Planning Phase of New Product

Development of an innovative technology, engineering development must have or create

a practical working systems engineering methodology which includes:

- A Technical Knowledge Base (examples which were presented in Chapters 4, 5, 7 and 8).
- A protocol for verification, validation and for the iteration of the later designs (methodology which were presented in Chapter 6 and further developed in Chapter 16).
- Baselining Techniques (encompassing, but not limited to a systematic design and development philosophy, a systems engineering design process, modeling techniques, and feasibility analysis, examples which are presented in this chapter).

Table 11-1			
EVALUATION OF CONCEPTUAL SYSTEM DESIGN			
[Blanchard, 2008, Keys, 2010, Sidky, 2002]			
Required Inputs	Expected Outcome	Resources	
Results from the analysis	A specific qualitative and	Design-dependent	
task in the form of a set of	quantitative needs statement	parameter approach;	
feasible conceptual design	responding to a current	generation of hybrid	
alternatives.	deficiency.	numbers to represent	
		candidate solution	
		"goodness"; conceptual	
		system design evaluation	
		display.	

11.3 The Design and Development Philosophy

In order to bring an innovative technology to the market place quicker and with less cost, intelligential power and drive becomes very important and will be constantly challenged with very complex problems. During design development, baselining, modeling and early prototyping of NPD, technical challenges will arise. In order to meet these challenges, engineering and development and design needs direction. The author of this paper has used Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ) methods and believes that the technical problems that an SOFC developer faces can be overcome by using Altshuller's methods of problem solving.

TRIZ is "a problem-solving, analysis and forecasting tool derived from the study of patterns of invention in the global patent literature." It was developed by the Soviet inventor Genrich Altshuller and his colleagues, beginning in 1946.

One of the earliest findings of the massive research on which the theory is based is that the vast majority of problems that require inventive solutions typically reflect a need to overcome a dilemma or a trade-off between two contradictory elements. The central purpose of TRIZ-based analysis is to systematically apply the strategies and tools to find superior solutions that overcome the need for a compromise or trade-off between the two elements.

TRIZ presents a systematic approach for analyzing the kind of challenging problems where inventiveness is needed and provides a range of strategies and tools for finding inventive solutions. TRIZ science expands approaches developed in systems engineering and provides powerful tools and systemic methods for use in problem formulation, system analysis, failure analysis, and patterns of system evolution (both "asis" and "could be"). TRIZ, in contrast to techniques such as brainstorming (which is

based on random idea generation), aims to create an algorithmic approach to the invention new systems, and the refinement of old systems.

11.4 The Process Design Approach

A simplified process design approach will be used in hopes of maintaining an acceptable accuracy in the overall power system feasibility performances assessment. The one described in this paper is based on assumptions, parameters and information provided in literature. The objectives of this kind of analyses could be the assessment of optimal power system design, lay-out or components sizing and of the related performances in terms of efficiency and power output.

The fundamental component/subsystem levels of the Physical Hierarchy Architecture of the SOFC are:

- Cell Stack Packages, in which individual cells (Unit Cells) are modularly combined by electrically connecting the cells to form units with the desired output capacity.
- Balance-of-plant which comprises components that provide feed stream conditioning (including a fuel processor if needed), thermal management, and electric power conditioning among other ancillary and interface functions.

The Enclosure which houses the Cell Stack Package and the BOP subsystems.
In the Conceptual and early design stages of power system development, the system

is created from the inside out in a top-down approach. The precise arrangement of, the balance-of-plant depends heavily on the fuel cell type, the fuel choice, and the application.



Figure 11-1: The First Level System Breakdown of an SOFC Power System. The Cabinet Housing enclosed the Cell Stack and the BOP

In addition, specific operating conditions and requirements of individual cell and stack designs determine the characteristics of the balance-of-plant. These and other requirements will determine which requirements and functions the Enclosure will later satisfied.

11.5 The IORC Process System

Technology conceptual baselines of new product development are usually performed during the conceptual stage of an innovative technology. Whereas the Conceptual Stage of NPD is a period during which a concept is proven *scientifically valid* or is shown to be potentially valid by the application of a *test-of-principle model(s)*. The objective of the NPD Conceptual and Advance Design Phase is to demonstrate through test or analysis the performance and implementation potential of a concept.

However, before the conceptual stage of NPD ends, a full articulation of the new product (as an IORC Process System) must be completed. To commercialize an innovative technology, a type of Input-Output-Resources-Constraint (IORC) Process System analytical method is required for a better and more complete effort to relate the initial identification of customer requirements to specific design goals, and the development of appropriate design criteria. Inherent within the systems engineering process is an ongoing analytical effort, an effort which is directed to this end.

11.6 Procedural Steps for using the IORC Process System

Step 1: The overall mission of the new product should be stated.

A statement of how the end user will use the product should be declared. The requirement for identifying the customer of the product (as a starting point) in the new product development effort is self-evident and logical, for a system to be deterministic. Hence, the SOFC Power System must be developed for a particular market and with an end user in mind. The SOFC Power System's primary, basic functions are defined below:

- The SOFC Power System produces DC power.
- The SOFC Power System produces heat.

From a new product development effort, a logical, cost effective, efficient method is desired to transform SOFC Power System's primary, basic functions into customer fulfillment.

In order to meet the first and second needs of the customer, the Power System requires a means by which to convert its DC Power output to AC, and connect to the Grid. Also the Power System needs to be constructed in such a manner that it is capable of producing enough heat to meet part or all of the customer's heating requirements. *Step 2: Using literature relative to the industry of the product, a theoretical break down of the mock up system model should be performed.*

Chapter 6 presented a mock-up model (a top-down hierarchy breakdown of an SOFC Power System) which, quite possibly, upon its development completion, could meet the customer's needs and requirements. The mockup model did not delve into

subsystem interactions, but it provided a general sense of how the system should be divided and listed the subsystems' inputs and outputs.



Figure 11-2: The IORC Process.

Step 3: After the diagrams of the subsystems were defined, the subsystems were treated as implicit processes and defined in such a way as to list the parameters necessary for the processes.

A multitude of technology bases made up the subsystems of the SOFC Power System. Their technology bases and some of their technical constraints were mentioned and defined in earlier chapters. The testing and maintenance plans for the subsystems/components were started.

Continuing on with the IORC System Process, the subsystems themselves will be treated as individual processes which affect one another. As was shown in pervious chapters, each process had inputs, outputs, and technical constraints (which must be overcome).



Figure11-3: IORC Process of the Power System's Subsystems

Step 4: Exploratory questions should be asked in order to find the pivotal subsystem.

First, the author of this paper theorized that an SOFC Power System is a deterministic system in which no randomness is involved in the systems engineering design and development of its future states of development. It is assumed that each subsystem of the SOFC Power System process model is a system in which the later states of its development follow from, or are determined by, the earlier ones.

Since the new product development effort of a system could and most definitely will change with time, in a logical, systematic manner, the system's primary functional purpose must be defined and explored from the system's conception. The transitions probabilities, associated with various states of design and development iterations can be limited if a pivotal point of the system is defined (the pivotal subsystem(s)).

With disruptive technologies which possess exotic technology bases, it is imperative that the pivotal subsystem(s) are identified and defined early on in their NPD lifecycle. Fuel Cell technology is in its early childhood, as best, and the design techniques and development to bring this innovative technology into existence is of a revolutionary nature. Unknown variables for a design can be so numerous that only a tried and true method for categorization is needed to start the design process. In order to categorize the subsystems into defined groups which have significant design and development value, the pivotal subsystem of the SOFC Power System must be found. This subsystem must, as closely as possible, be the embodiment of the power system's primary functional purposes. In determining the pivotal subsystem, the following questions must be answered:

- Which subsystems/component requires most of the system inputs relative to others subsystems/components?
- Which subsystems/components (along with their support components) produce all, or most of the outputs of the system?
- With regards to the system's primary (overall) functional purpose, which subsystem/component is the crucial, irreplaceable element? In other words, if this component were removed from the system, would the system still function or perform its intended purpose(s)?

In checking to determine if the pivotal subsystem(s) have been correctly identified, an attempt to further break-down analysis should be performed in order to explain most, if not all, of the needed subsystem interaction (inputs and outputs).

Step 5: The element of focus for each subsystem should be determined and their functional interactions should be noted.

An element of focus is the component of a subsystem that embodies and directly performs the functional purpose of that subsystem. Other components in a subsystem are defined in terms of their supportive functions and interactions with the element of focus of the subsystem.

The Air Subsystem has two purposes: to supply oxidant to the cathode side of the Cell Stack Package and, provides as a means to rid the power system of excess heat. The Air Subsystem as a subsystem has one element of focus, a compressor.

Systems can have more than one pivotal element, for example, the Fuel Processing Subsystem provides reformate gas to the anode side of the Cell Stack Package. It has three elements of focus, namely the Steam Reformer, the Catalysis and the Steam Generator that work together to perform this function.

As shown in these two examples, the Cell Stack Package (the pivotal subsystem) is the beneficiary of the services of the Fuel Processing System and the Air System.

Step 6: Continue the system analysis by asking exploratory questions to define system/subsystem baselines. From the baselines, using models, determination of the system/subsystem interaction should be studied.

Defining the working of a complex system starts with conceptual baselining. From the systems engineering perspective, The BOP and the Cell Stack, (which are

surrounded by the Cabinet Housing of the SOFC) shown in **Figure 11-1**, can be thought of as the mechanics of an electrochemical, thermodynamic system process, a process which needs inputs and resources, produces outputs and is limited by constraints of its constituents. As said before, the same concept of this '*process mechanics model of a system*' can be used repeatedly for system development, thus, this excogitation has many instantiations.

A separate analysis of each subsystem would not yield useful system-to-system interaction information because when the product is broken down into subsystem levels, one or more of the levels might interact with one another in such a way (worst case scenario) as to negate the overall mission of the product. Once the pivotal subsystem(s) has been determined, its relationship with the other subsystems must be determined. Concentration of design and study efforts on the elements of focus should not only be viewed as the means by which to predict and prevent most possible system failures. But, it should be looked upon as a systematic practice, a special type of functional/interaction analysis tree in which the state of a system is analyzed by combining a series of lowerlevel functions/interactions (of the components to the elements of focus) to mid-level functions/interactions (of the elements of focus to the pivotal subsystem) then to highlevel ones (of the whole system) in such a way as to eventually model/determine the functionality of the entire system as a sum and the performance of its parts.

In order to do evaluation and feasibility analysis, baselining is needed to determine the initial performance parameters of the subsystem components, the subsystems' processes and the entire system as a whole. To start conceptual baselining for the

subsystem processes, questions regarding the subsystems' inputs, outputs and process parameters must be answered, see **Figure 11-4**.

After baselining has occurred, there are many tools available to designers which could aid in the process of notating subsystem-to-subsystem interaction. For this task, Design Structure Matrix (DSM) and Sensitivity Analysis are two of the tools which should be considered. DSM will be covered in **Chapter 12**.



Figure 11-4: Examples of the Primary Design Questions for the Unit Cell/Cell Stack Package and the BOP Subsystems Baselines
11.7 From Figure 11-4 – Beginning of the Baseline Procedure - An Input - Which type of fuel preparation will the SOFC Power System use?

Except when pure fuels (such as pure hydrogen) are used, some fuel preparation is required, usually involving the removal of impurities and thermal conditioning. In addition, many fuel cells that use fuels other than pure hydrogen require some fuel processing, such as reforming, in which the fuel is reacted with some oxidant (usually steam or air) to form a hydrogen-rich anode feed mixture.

11.8 From Figure 11-4 – Beginning of the Baseline Procedure - How much oxidant does the Cell Stack Package require and what types of devices are available to deliver this demand?

In order to deliver the oxidant, the Cell Stack Package will need an air supply of a certain pureness and temperature. In most practical fuel cell systems, this includes air compressors or blowers as well as air filters.

11.9 From Figure 11-4 – Beginning of the Baseline Procedure - An Output - The Electrical Demands of the SOFC Power System and End User

Since fuel cell stacks provide a variable DC voltage output that is typically not directly usable for the load, electric power conditioning is typically required. The design of the SOFC Power System's power capacity will, in a general sense, depend of the answers to the three below questions:

- What are the electrical demands of the electric power conditioning equipment?
- What are the electrical demands of the balance-of-plant?
- What are the electrical demands of the end users?

11.10 From Figure 11-4 – Beginning of the Baseline Procedure - Process

Requirements - An Output - The Thermal Requirement of the SOFC Power System

In answering the below questions, first and for most SOFC systems require careful management of the fuel cell stack temperature.

- What are the thermal demands of the power system?
- What are the thermal requirements of the end user?
- What are the thermal management issues of the power system and what types of materials and equipment could resolve these issues?

Since fuel cell stacks are heat generators requiring a certain amount of heat to operate, in addition, many of the fuel cell's balance-of-plant components require heat to function, and of course considering the end user's thermal requirement, the fuel cell developers must incorporate all these considerations into the system analysis.

11.11 What kind of Waste Management will the power system incorporate?

A large portion of waste is generated by industry. Innovative/Disruptive NPD must take into consideration the recycling and waste management of the new product. The focus of many recycling programs done by industry is the cost-effectiveness of recycling. The Cradle-to-Cradle Framework posits a new way of designing human systems that ultimately can solve rather than alleviate the human-created conflicts between economic growth and environmental health that result from poor design and market structure. Within this principled framework, which is based on the manifested rules of nature and re-defines the problem at hand, eco-efficient strategies can serve a larger purpose. The Cradle-to-Cradle Framework does not reach for sustainability as it is typically defined. Discussed at length in various papers, books and other venues,

452

environmental sustainability in the industrial sector is popularly understood as a strategy of "doing more with less" or "reducing the human footprint" to minimize troubling symptoms of environmental decline. From an engineering perspective, conventional sustainability too often suggests retrofitting the machines of industry with cleaner, more efficient "engines" to secure ongoing economic growth. But this is not an adequate longterm goal.

While being eco-efficient may indeed reduces resource consumption and pollution in the short-term, it does not address the deep design flaws of contemporary industry. Rather, it addresses problems without addressing their source, setting goals and employing practices that sustain a fundamentally flawed system.

The Cradle to Cradle model can be viewed as a framework that considers systems as a whole or holistically. Developed and successfully applied over the past decade, the Cradle-to-Cradle Framework is a science- and values-based vision of sustainability that enunciates a positive, long-term goal for engineers: the design of a commercially productive, socially beneficial and ecologically intelligent industrial system.

Fuel cell developers should consider the use of a Cradle to Cradle model because it lowers the financial cost of system design and development. It can be applied to many aspects of human society, and is related to Life cycle assessment (LCA).

11.12 The Modeling of the Power System

In beginning system design, defining the initial overall operational expectations of a FC power system is done by way of conceptual system design models. The below figure depicts several types of these models.



Figure 11-5: Overview of the Levels of Fuel Cell Models

Very simple design models, 0-D and/or 1-D models are usually created initially so that the information gained for them can be used in the creation of higher order, more advanced models (e.g. advance models could be: designed for the study of system's/subsystems' thermodynamics, or designed for the analysis of the power system's structural makeup).

11.13 Why use a Model?

There are a lot of uncertainties about the best layout of the SOFC system in terms of feasibility, performance, economics and controllability. Therefore, the development and evaluation of building SOFC power systems require experimental setups or detailed models on cell, stack and system levels.

Black-box fuel cell stack models are the simplest types of models, in which their geometries are reduced to points and spatial averaging is performed for every dimension. These models are used to assess the impact of fuel composition, oxidant or fuel utilization and over-potential on the macroscopic performance of SOFC in terms of

efficiency and characteristic curve.



Figure 11-6: From the general 0D Model of the FC Power System five specific models are created.

They should be used where attention is not focused on the Cell Stack Package itself but on how the Cell Stack Package affects the performances of the whole system.

In general, 0-D models have been developed as thermodynamic models for the numerical analysis of energy systems based on fuel cells where single elements of the system are simulated through independent models. For example, Zink (et al) developed a black-box SOFC model to assess an integrated system for district heating and cooling applications. The fuel cell model consisted of heat and mass macroscopic balances, simplifying the electrochemical model through the definition of empirical input parameters such as fuel utilization. Another example, Costamagna (et al) developed a 0D model of an SOFC/micro gas turbine (MGT) hybrid system to analyze a hybrid system under variable fuel cell and MGT operating conditions. The fuel cell is modeled through macroscopic equations that express the balance between inlet and outlet conditions.

These simplified approaches can be used by the designer to save computational time while maintaining an acceptable accuracy in the overall plant performances

455

assessment. As a result, performances of the energy system under part-load and offdesign conditions can be assessed.

Fuel cell 0-D models, as the ones described here, are usually based on assumptions, parameters and information provided in literature or taken from experiments.

Parametric studies of SOFC-based energy systems can be performed in a relatively short time for defining and hopefully, optimizing the performances of operational parameters of the Cell Stack and balance-of-plant subsystems, and their system components, and predicting subsystem and component relationships and interactions, especially interactions which involve a power system's elements of focus such as the ones listed in **Table 11-2**.

Table 11-2	
THE LOWER LEVELS OF THE SYSTEM	
The Subsystem	The Elements of Focus
	DC-DC Converter
	DC-AC Inverter
The Electrical Subsystem	The Energy Storage Source
The Mechanical Subsystem	The equipment which moves matter (fluids, gases, etc) and the 'moving' parts of the Power System
The Hot Assembly	The Hot Assembly Fixture
The Thermal Management Subsystem	The Cell Stack The pre-heaters The steam generator The steam reformer The Hot Assembly Fixture The Heaters Insulation
The Air Subsystem	The Air Compressor
The Waste Management	The consumables and intermediates of the system
The Fuel Processing Subsystem	The Steam Generator The Catalysis/the Steam Reformer
The Power Generation System	The Unit Cell/The Cell Stack Package

11.14 Feasibility and Sensitivity Analysis

Feasibility and Sensitivity Analysis are the studies of how the variation (uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of the model. Put another way, it is a technique for systematically changing parameters in a model to determine the effects of such changes. In more general terms feasibility, uncertainty and sensitivity analysis investigate the robustness of a study when the study includes some form of mathematical

modeling. These analyses can be useful to fuel cell developers for a range of purposes, including:

- Support decision making or the development of recommendations for decision makers (e.g. testing the robustness of a result);
- Enhancing communication from modelers to decision makers (e.g. by making recommendations more credible, understandable, compelling or persuasive);
- Increased understanding or quantification of the system (e.g. understanding relationships between input and output variable parameters); and
- Model development (e.g. searching for errors in the power system).

11.15 Lisbona's SOFC Power System Model

To demonstrate how fuel cell developers determine ideal and theoretical performance baselines for SOFC Power Systems, a model previously developed by Lisbona at the University of Perugia will be the topic of this and following sections.

Lisbona's SOFC Power System's Cell Stack was simulated as a black-box, i.e. a zero-dimensional stationary model. The basic concept of this SOFC system is represented as a block diagram in **Figure 11-7**.





The analyzed system is an SOFC-based heat and power generator of 1 kWe of nominal power operated on natural gas (assumed 100% CH₄). It is designed to cover the parasitic electrical consumptions in the system, except for the start-up stage when it requires electricity from a back-up battery or from the grid to operate fans and electrical heaters. The flow of natural gas is preheated in the system to reach the required temperature (200–300 °C) for the desulphurization stage in which H₂S content is reduced by the action of an activated carbon bed. The clean fuel is then mixed with the anode offgas recycle and heated in a second heat exchanger. Prior to enter the Cell Stack Package, the fuel is pre-reformed (methane is partially converted into hydrogen and carbon monoxide). The recycled anode off-gas flow adds the steam demand to sustain the reforming reaction. Air is supplied by a blower and preheated prior to enter the SOFC stack. Non-recycled gases are sent to the after-burner where the remaining fuel is burnt with part of the excess air. Internal demand of electricity and heat is self supported by the system.

11.16 Lisbona's SOFC Power System's Performance Variables

The performance of fuel cells is affected by operating variables, to name the major ones:

- Temperature
- Pressure
- Gas composition
- Reactant utilization
- Current density
- Cell design
- And other factors (impurities, cell life, delamination rate of the ceramic anode/cathode electrode layers of the unit cell's electrolyte)

11.17 SOFC Power System's Performance Variables - Temperature and Pressure

The effect of temperature and pressure on the ideal potential (E) of a fuel cell can be analyzed on the basis of changes in the Gibbs free energy with temperature and pressure:

$$\left(\frac{\partial E}{\partial T}\right)_{p} = \frac{\Delta S}{nF}$$

Or

$$\left(\frac{\partial \mathbf{E}}{\partial \mathbf{P}}\right)_{\mathrm{T}} = \frac{-\Delta \mathbf{V}}{\mathbf{n}F}$$



Figure 11-8: The Theoretical Losses of Cell Performance [Fuel Cell Handbook, 2004] Because the entropy change for the H2/O2 reaction is negative, the reversible potential of the H2/O2 fuel cell decreases with an increase in temperature (by 0.84 mV/°C, assuming reaction product is liquid water). For the same reaction, the volume change is negative; therefore, the reversible potential increases with an increase in pressure (with the square root of the pressure, assuming pressure is equal on both electrodes).

However, temperature has a strong impact on a number of other factors:

- Electrode reaction rates. Typically, electrode reactions follow Arrhenius
 behavior. As a consequence, these losses decline exponentially with increasing
 temperature, usually more than off-setting the reduction in ideal potential. The
 higher the activation energy (*and hence usually the losses*) the greater the impact
 of temperature. The impact of total pressure depends on the pressure dependence
 of rate-limiting reaction steps.
- Ohmic losses. The impact of temperature on cell resistance is different for different materials. For metals, the resistance usually increases with temperature, while for electronically and ionically, conductive ceramics it decreases

461

exponentially (Arrhenius-form). As a rule of thumb, for high-temperature fuel

cells, the net effect is a significant reduction in resistance.



Activation Losses. Activation losses are caused by sluggish electrode kinetics.

Figure 11-9: Cell Performance (chemical potential and internal losses) [Kee, 2004]

There is a close similarity between electrochemical and chemical reactions in that both involve an activation energy that must be overcome by the reacting species. In reality, activation losses are the result of complex surface electrochemical reaction steps, each of which, have their own reaction rate and activation energy. Usually, the rate parameters and activation energy of one or more rate limiting reaction steps controls the voltage drop caused by activation losses on a particular electrode under specific conditions. However, in the case of electrochemical reactions with $|_{act} > 50-100$ mV, it is possible to approximate the voltage drop due to activation polarization by a semi-empirical equation, called the Tafel equation. The equation for activation polarization is shown by this equation:

$$\Delta V = A \times \ln\left(\frac{i}{i_0}\right)$$

Where:

- ΔV is the over-potential, V
- A is the so called "Tafel slope", V
- i is the current density, A/m² and
- i_0 is the so called "exchange current density", A/m².

In can be written:

$$i = nFk \exp\left(\pm \alpha F \frac{\Delta V}{RT}\right)$$

Where

- the plus sign under the exponent refers to an anodic reaction, and a minus sign to a cathodic reaction,
- n is the number of electrons involved in the electrode reaction
- k is the rate constant for the electrode reaction,
- R is the universal gas constant,
- F is the Faraday constant



Figure 11-10: Example of a Tafel Plot [Fuel Cell Handbook, 2004]

• Mass transport processes are not strongly affected by temperature changes within the typical operating temperature and pressure ranges of most fuel cell types. An increase in operating pressure has several beneficial effects on fuel cell performance because the reactant partial pressure, gas solubility, and mass transfer rates are higher. In addition, electrolyte loss by evaporation is reduced at higher operating pressures. Increased pressure also tends to increase system efficiencies. However, there are compromises such as thicker piping and additional expense for pressurization. The benefits of increased pressure must be balanced against hardware and materials problems, as well as parasitic power costs.

11.18 SOFC Power System's Performance Variables -Reactant Utilization and Gas Composition

Reactant utilization and gas composition have major impacts on fuel cell efficiency.



Figure 11-11: The Electrical Potential of the Fuel Cell Depends on Fuel Type & Dilution [Kee, 2004]

Utilization (Uf) refers to the fraction of the total fuel or oxidant introduced into a fuel cell that reacts electrochemically.

$$Uf = (H_{in} - H_{out})/(H_{in}) = H_{consumed}/H_{in}$$

Where, H_{in} and H_{out} are the flow rates of H₂ at the inlet and outlet of the fuel cell, respectively. However, hydrogen can be consumed by various other pathways, such as by chemical reaction (i.e., with O₂ and cell components) and loss via leakage out of the cell. These pathways increase the apparent utilization of hydrogen without contributing to the electrical energy produced by the fuel cell. A similar type of calculation is used to determine the oxidant utilization.



Figure 11-12: Fuel Utilization as a function of Cell Voltage and Operating Temperature [Fuel Cell Handbook, 2004

11.19 SOFC Power System's Performance Variable - Current Density

Figure 11-13 presents the most important trade-off in choice of the operating

point. It would seem logical to design the cell to operate at the maximum power density





Figure 11-13: The Relationship between Power and Cell Voltage [modified: Fuel Cell Handbook, 2004]

However, operation at the higher power densities will mean operation at lower cell voltages or lower cell efficiency. Setting operation near the peak power density can cause instability in control because the system will have a tendency to oscillate between higher and lower current densities around the peak. It is usual practice to operate the cell to the left side of the power density peak and at a point that yields a compromise between low operating cost (high cell efficiency that occurs at high voltage/low current density) and low capital cost (less cell area that occurs at low voltage/high current density). In reality, the precise choice of the operating point depends on complex system trade-offs, usually aided by system studies that allow the designer to take into account effects of operating voltage and current density on parasitic power consumption, sizing of balance of plant components, heat rejection requirements, and other system design considerations.

It is interesting to observe that the resulting characteristic provides the fuel cell with a benefit that is unique among other energy conversion technologies: the fuel cell efficiency increases at part load conditions. Even though other components within the fuel cell system operate at lower component efficiencies as the system's load is reduced, the combination of increased fuel cell efficiency and lower supporting component efficiencies can result in a rather flat trace of total system efficiency as the load is reduced. This is in contrast with many heat engine-based energy conversion technologies that typically experience a significant drop-off in efficiency at part-load. This gives the fuel cell system a fuel cost advantage for applications where a significant amount of partload operation is required.

467

11.20 Lisbona's SOFC Power System's Performance Input Variables

Lisbona's SOFC Power System model's assumptions imply that the Cell Stack Package has a uniform temperature and that gases leave the anode and cathode sides at the same temperature. To determine the cell voltage and temperature, the following inputs were used:

- Gas composition, flow rate, temperature and pressure of the cathode and the anode inlet stream;
- Fuel utilization, *Uf*;
- Cell (active) Area.

The reactions occurring in the cell were: steam reforming (i), water-shift reaction (ii) and overall electrochemical reaction (iii):

$$CH_4 + H_2O \leftarrow \xi \rightarrow CO + 3H_2 \tag{i}$$

$$CO + H_2O \leftarrow \psi \rightarrow CO_2 + H_2$$
 (ii)

$$H_2 + 1/2O_2 \leftarrow \zeta \rightarrow CO + 3H_2$$
 (iii)

It was assumed that methane present in the channels cannot be electrochemically oxidized but only reformed to H₂, CO and CO₂. It was also assumed that CO is not oxidized but converted by shift reaction into H₂. The fuel utilization is the fuel fraction which is oxidized through reaction (iii) and considering that 4 mol of hydrogen could be theoretically produced by reactions (i) + (ii) and 1 mol of H₂ could be generated by (ii) from CO provided by the inlet, ζ is given by:

$$\zeta = UF(4CH_4^{i} + CO^{i} + H_2^{i}) \tag{1}$$

Therefore, ζ is the number of H₂ moles oxidized inside the cell and superscript i indicates *"inlet fuel flow."* Due to the high operational temperature it was assumed also

that all the methane was reformed according to reaction (i), thus $\xi = CH_4^{i}$. The water–gas shift reaction was supposed to reach equilibrium conditions. The expression of the equilibrium constant of (ii) as function of the gas species concentrations allows to determine the number of the converted moles of CO (ψ). Therefore, ζ was the number of H₂ moles oxidized inside the cell and superscript i indicated *"inlet fuel flow."* Due to the high SOFC temperature it was assumed also that all the methane is reformed according to reaction (i), thus $\xi = CH_4$. The water–gas shift reaction was supposed to reach equilibrium conditions. The expression of the equilibrium constant of (ii) as the function of the gas species concentrations allowed for determining the number of the converted moles of CO (ψ).

$$K_{\rm s}(T) = \frac{\left[{\rm CO}_2^{\,\rm i} + \psi\right] \left[{\rm H}_2^{\,\rm i} + 3\xi + \psi - \zeta\right]}{\left[{\rm CO}^{\rm i} + \xi - \psi\right] \left[{\rm H}_2{\rm O}^{\rm i} - \xi - \psi + \zeta\right]}$$
(2)

Where *K*s depends only on the SOFC temperature:

$$K_{\rm s}(T) = 0.0126 \exp\left(\frac{4639}{T}\right) \tag{3}$$

With ψ and ζ it is possible to determine the gas composition at the anode and cathode outlet and the electric current density generated by the single cell:

$$i = 2\zeta F \tag{4}$$

The single cell voltage is determined as:

$$V = OCV - \eta_{act} - \eta_{ohm} - \eta_{con}$$
⁽⁵⁾

Where OCV is the open circuit voltage and η indicates the voltage loss due respectively to, activation polarization, ohmic resistance and concentration polarization. OCV was given by the Nernst equation:

$$E = E_0 + \frac{RT}{2F} \ln \frac{p_{\rm H_2} p_{\rm O_2}^{0.5}}{p_{\rm H_2O} p_{\rm atm}^{0.5}}$$
(6)

Where:

$$E_0 = 1.2723 - 2.7645 \times 10^{-4} T \tag{7}$$

Previous work has shown that the OCV given by Nernst equation usually differs from experimental values, thus an empirical coefficient θ was introduced for taking into account the effect of OCV deviation from Nernst's equation.

$$\theta = \frac{OCV_{exp}}{OCV_{Nernst}}$$
(8)

The activation polarization, η_{act} , was expressed by the Butler–Volmer equation:

$$i = i_0 \left[\exp\left(\alpha \frac{nF}{RT} \eta_{\text{act}}\right) - \exp\left(-(1-\alpha) \frac{nF}{RT} \eta_{\text{act}}\right) \right]$$
(9)



Figure 11-14: Activation Over-potentials [Kee, 2004]

Where α was the apparent charge transfer coefficient and i_0 was the exchange current density, given by the following equation respectively for, the anode and the cathode:

$$i_{0,c} = \gamma_{\rm C} \left(\frac{p_{\rm O_2}}{p_{\rm atm}}\right)^{0.25} \exp\left(-\frac{E_{\rm act,c}}{RT}\right)$$
(10)
$$i_{0,a} = \gamma_{\rm a} \left(\frac{p_{\rm H_2}}{p_{\rm atm}}\right) \left(\frac{p_{\rm H_2O}}{p_{\rm atm}}\right) \exp\left(-\frac{E_{\rm act,a}}{RT}\right)$$
(11)

Where the assumption of $\alpha = 0.5$ led to a simplified expression for the activation polarization:

$$i = 2i_0 \sinh\left(\frac{nF}{2RT}\eta_{\rm act}\right) \tag{12}$$

The ohmic losses η_{ohm} were calculated considering the dependence of resistivity from the temperature:

$$\rho_j = A_j \exp\left(\frac{B_j}{T}\right) \tag{13}$$

$$\eta_{\rm ohm} = i \sum \rho_j \delta_j \tag{14}$$

The concentration polarization η_{con} was determined as:

$$\eta_{\rm con} = \frac{RT}{nF} \ln \left(1 - \frac{i}{i_{\rm L}} \right) \tag{15}$$

Where $i_{\rm L}$ was the limiting current density.

Finally, the thermal behavior of the Lisbona's Cell Stack Package was evaluated through the thermo-chemical balance of the system assuming one representative temperature for each reactant gas and the Cell Stack Package:

$$H_{\rm IN} = H_{\rm OUT} + Q_{\rm LOSS} + V(T)I$$
(16)

Where, *H*IN represented the enthalpy flow of the gases at anode and cathode inlet. It did not depend on the cell temperature, but only from the entering gas temperature. It included Δ^H REACT (*T*), the global heat of the reactions (i)–(iii) occurring inside the cell. It was weakly affected by the SOFC temperature. ^{*H*}OUT (*T*) was the enthalpy flow of the outlet streams, which, of course, was a function of SOFC temperature. ^{*Q*}LOSS was the heat loss by the single cell. *V*(*T*)*I* was the electric power produced by the single cell, which was deeply influenced by its temperature.

Gas constants for the determination of enthalpy flows and heat of reaction were taken from "*NIST-JANAF Thermochemical Tables*." In Lisbona's model, the equilibrium temperature which satisfied Equation (16) was determined through an iterative calculation. In the model, SOFC operates at fixed inlet and outlet temperature. Therefore, the desired temperature was achieved by varying the airflow rate. The model was validated with the experimental data relative to an anode supported SOFC tested at the University of Perugia.

After the electrochemical reaction has taken place, anode off-gas exiting the Cell Stack Package which was not recycled and mixed with the fresh fuel was fed into the afterburner where it burnt with the non-recycled part of the oxidant flow. The combustion reactions carried out in this adiabatic reactor of the system were:

 $\begin{array}{l} H_2 + 1/2O_2 {\rightarrow} H_2O \quad (iv) \\ \\ CO + 1/2O_2 {\rightarrow} CO_2 \left(v \right) \end{array}$

It was assumed that (iv) consumes 95% of the remaining hydrogen and (v) consumes 95% of the CO present in the flow.

11.21 Lisbona's SOFC Power System's Nominal Operation

A number of relevant parameters that control the system performance were set to define the reference condition of operation. These parameters dealing with the SOFC stack and with global system are gathered in **Tables 11-3 and 11-4**.

Table 11-3	
PARAMETERS USED FOR STACK	
MODEL	
[Lisbona, 2007]	
Activation Polarization Coefficients	
For the Ceramic (Anode) Electrode	
For the Ceramic (Cathode) Electrode	
The "limiting" Electric Current Density	
(at a particular temperature)	
(A/cm2)	
The Amount of current leakage	
(Leakage Coefficient) θ	

Table 11-4		
PARAMETERS DEALING WITH THE		
SOFC STACK AND WITH GLOBAL		
SYSTEM		
[Lisbona, 2007]		
Nominal Operations for the SOFC Cell		
Stack		
Number of Cells		
Active Cell Area (cm2)		
Pressure (bar)		
Fuel temperature at stack inlet (°C)		
Air temperature at stack inlet (°C)		
Fuel Cell temperature (°C)		
Fuel Utilization (%)		
Thermal Losses (%)		
Nominal Operations for the Balance-of-		
Plant		
Anode Recycle (%)		
Degree of pre-reforming (%)		
DC/AC Inverter Efficiency (%)		

Electrical and thermal efficiencies in the system were defined as:

$$\eta_{\rm el} = \frac{P_{\rm DC}\eta_{\rm inverter} - P_{\rm aux}}{m_{\rm fuel}\rm LHV_{\rm fuel}}$$
(17)

$$\eta_{\rm th} = \frac{Q_{\rm HEX04} - Q_{\rm HEX03} - Q_{\rm HEX02} - Q_{\rm HEX01}}{m_{\rm fuel} \rm LHV_{\rm fuel}}$$
(18)

Where *PDC*, *DC* power generated by the stack; P_{aux} , power consumed by

blowers; m_{fuel} , inlet fuel mass flow; LHV_{fuel}, lower heating value of the fuel.

Three heat exchangers (HEX01, HEX02, HEX03 and HEX04), were used in

Lisbona's SOFC Power System. They were required to preheat fuel and air flows.

Fuel had to be preheated up to 250 °C (HEX01) prior entering the

desulphurization stage (optimal temperature for this adsorption process). Considering the

heat demand of the endothermic pre-reforming reaction, another heater (HEX02)

increasing clean fuel flow temperature was located prior the pre-reforming block. The reached temperature ensured the optimal conditions to carry out the pre-reforming reaction in the established extent and the desired stack inlet temperature. A third heat exchanger (*HEX03*) was used to preheat SOFC stack inlet air up to required temperature. In the system layout, a fourth "virtual" heat exchanger (*HEX04*) which cools exhaust gases down to 50 °C was located downstream the after-burner to assess the maximum theoretical recoverable heat. Recovered heat from the exhaust gases (*HEX04*) was reused in the different points of the system where heat was demanded and the remaining heat was utilized for cogeneration applications.

11.22 The Analysis of System Condition Variation – How to determine which were the important ones?

In general, electricity generation systems for residential applications work for long periods under off-design operation due to continuous fluctuations in the demand.

An independent analysis of single parameters is not enough to understand the behavior of the whole system because all these parameters are related, affecting the others. Because of these reasons, a study of load demand behavior should be carried out.

The information given by a load demand behavior assessment may be useful to determine which parameters are the relevant or key parameters (and when the parameters are important), may be used to understand which operational scenarios present '*too poor*' efficiencies or give critical values for relevant parameters.

475

Consideration 1: The designer must find the main parameters describing the SOFC system performance presented under nominal operational conditions.

The Nominal Operational Conditions represent the reference scenario to compare results to other conditions. In this way, a tool to assess the relative effect of the variation of any parameter during nominal operation is determined, defined and documented.

Consideration 2: What are the important input parameters of system's operations?

Important Power System Parameters used for the model were:

- The composition of the Anodic Gas.
- Fuel Utilization.
- Oxidant Utilization.
- Cell Stack Temperature (°C).
- Cell Active Area (cm²)

The Parameters used for the Cell Stack Model are:

- Ohmic Loss of the Electrolyte = E
- Ohmic Loss of the Ceramic (Anode) Electrode = CAE
- Ohmic Loss of the Ceramic (Cathode) Electrode = CCE
- Total Ohmic Losses = E + CAE + CCE

Consideration 3: What are the subsystems which directly affect nominal operations?

A number of relevant parameters that control the system performance must be set

to define the reference condition of operation.

Electrical efficiency is defined as the ratio between the power output of the Cell Stack Package adjusted for (Electrical System) inverter efficiency with the power losses attributed to the balance-of-plant (BOP) systems subtracted and compared with the quality of output of the Fuel Processing System.

The quantity known as lower heating value (LHV) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. This treats any H_2O formed as a vapor. The energy required to vaporize the water therefore is not realized as heat. LHV calculations assume that the water component of a combustion process is in vapor state at the end of combustion, as opposed to the higher heating value (HHV) (a.k.a. *gross calorific value* or *gross CV*) which that assumes all of the water in a combustion process is in a liquid state after a combustion process.

The LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered. It is useful in comparing fuels where condensation of the combustion products is impractical, or heat at a temperature below 150 °C cannot be put to use.

The difference between the two heating values (higher heat value and lower heat value) depends on the chemical composition of the fuel. In the case of pure carbon or carbon monoxide, both heating values are almost identical, the difference being the sensible heat content of carbon dioxide between 150°C and 25°C.

In contrast, latent heat is added or subtracted for phase changes at constant temperature. Examples: heat of vaporization or heat of fusion). For hydrogen the difference is much more significant as it includes the sensible heat of water vapor between 150°C and 100°C, the latent heat of condensation at 100°C and the sensible heat

477

of the condensed water between 100°C and 25°C. All in all, the higher heating value of hydrogen is 18.2% above its lower heating value (142 MJ/kg vs. 120 MJ/kg). For hydrocarbons the difference depends on the hydrogen content of the fuel. For gasoline and diesel the higher heating value exceeds the lower heating value by about 10% and 7%, respectively, for natural gas about 11%. A common method of relating HHV to LHV is:

HHV = LHV +
$$h_v x (n_{H2O,out}/n_{fuel,in})$$

Where h_{ν} is the heat of vaporization of water, $n_{H2O,out}$ is the moles of water vaporized and $n_{fuel,in}$ is the number of moles of fuel combusted.

Most SOFC applications which burn fuel produce water vapor which is not used and thus wasting its heat content. In such applications, the lower heating value is the applicable measure. This is particularly relevant for natural gas, whose high hydrogen content produces much water. The gross energy value is relevant for gas burnt in condensing boilers and power plants with flue gas condensation which condense the water vapor produced by combustion, recovering heat which would otherwise be wasted.

Consideration 4: What are the Anodic Gas Composition and S/C Ratio

Parameters?

Input parameters differ from one SOFC thermodynamic model to another. For the study mentioned here, external reforming degree and anode off-gas recirculation ratio in the total system, and fuel utilization and temperature spring (difference between stack inlet and stack operation temperature) in the fuel cell stack are considered input data.

The extension of the external reforming reaction (utilization of methane during steam reforming prior entering the Cell Stack Package), referred as the degree of prereforming, affects the concentration of H_2 and CO in the anodic gas which has an important influence in carbon deposition existence. It also has a great influence in heat management within the Cell Stack Package.

Recirculation of anode off-gas represents a common practice for every fuel cell system design. Benefits linked to the selection of this layout configuration are the selfstanding steam generation (retro-feed of steam from electrochemical reaction), the increase of the global fuel utilization and the reduction of heat demand prior prereforming. However, high recirculation ratios increase the system's complexity, which is undesirable.

Consideration 5: What will the Fuel Utilization of the Power System be?

Fuel utilization is one of the most important operating parameters for fuel cell power system and has significant effects on the cell voltage and efficiency. It also affects thermal efficiency through the unburned fuel concentration in the exhaust of the fuel channel. These parameters have been chosen in order to carry out a series of feasibility/sensitivity analysis.

Consideration 6: For external steam reforming, determine the safe zone – in other words, what are the minimum operating conditions where coke formation will not take place?

An example of the effect of input parameters on anode inlet gas composition and S/C ratio is shown in the below figure which presents four gas compositions.

479





It is known that increasing the degree of pre-reforming, H_2 concentration becomes higher whereas H_2O decreases in the inlet flow. Therefore, cell voltage is enhanced by means of increasing OCV according to Nernst's Eq. (6). Unlike pre-reforming degree, increasing fuel utilization leads to a high concentration of H_2O (and poor H_2) in the anode off-gas. This effect is consequently manifested in the anodic inlet gas through anodic recirculation stream. The recirculation ratio may also adjust the S/C ratio entering the anode section. The gain in H_2O fraction is much more significant when anode recirculation (AR) grows.



Figure 11-16: Anodic gas composition varying anode recirculation. [Lisbona, 2007]

Consideration 8: What is the relationship between inlet temperature and gas composition?

The effect of inlet temperature variation is not reported as no significant variation of gas composition occurs. Actually, the temperature at cell inlet is the same of shift reactor, therefore a decrease of this parameter results in a high conversion of $CO-CO_2$, since the reaction is exothermal and consequently enhanced at low temperature. However, in the considered temperature range, the variation of gas concentrations is below 2 points %.



Figure 11-17: S/C varying different parameters [Lisbona, 2007]

Figure 11-17 shows an example of a trend of S/C for the different parameters analyzed. This ratio follows a similar trend to that of steam concentration at anode inlet flow. Steam to carbon ratio exponentially grows with anode recirculation. This behavior is explained based on the synergetic effects produced by large recirculation ratios. As anodic off-gas content becomes richer in steam and, simultaneously, the "global" fuel utilization increases leading to a lower concentration of oxidable carbon in the flow.

If the minimum S/C which ensures no carbon deposition in the system is 2.5, from **Figure 11-17** the limiting operating conditions are found. In this example, a minimum Uf of 60% (70% anode recycle) and a minimum AR of 68% (75% fuel utilization) will avoid solid carbon formation in the inlet manifold to the stack.

Consideration 9: How does the Anodic Gas Composition and S/C ratio Parameters affect Electric Power?

To better understand how the studied parameters affect the generated power, current density and single cell voltage have been plotted in **Figs. 11-18** and **11-19**.



Figure 11-18: Current density trend vs. different parameters [Lisbona, 2007]

The current density is independent of the degree of reforming and the temperature of inlet streams into the fuel cell, remaining constant all along the studied range of operation.

On the contrary, current increases when increasing the anode recirculation (AR) or the utilization factor (Uf). Actuation on both parameters leads to the same eventual effect: higher amount of reacted hydrogen in the inlet stream to the Cell Stack Package. High recirculation ratios produce this effect through an increase of fuel flow entering the Cell Stack Package, high fuel utilizations through a better utilization of the same fuel flow.



Figure 11-19: Single cell voltage trend vs. different parameters [Lisbona, 2007]

Due to the assumption of the 0-D model, the single cell voltage (see Figure 11-19) is constant at the various inlet temperatures, since electrochemical model is evaluated at the fixed outlet temperature.

The single cell voltage slightly increases when a relevant percentage of methane is reformed prior entering the fuel cell, due to the higher hydrogen content and the lower steam content in the anodic gas when the extent of external reforming is increased. This enhances the cell voltage by means of OCV according to Nernst's equation.

However, a dramatic drop in cell voltage is observed when raising AR and Uf. Two facts justify this trend: Firstly and following the polarization curve, low values of cell voltage correspond to the high current density generated under these conditions. Secondly, the well-known effect of decreases in H_2/H_2O ratio in the anodic gas which lead to a detriment of cell voltage by means of OCV.

Since the reactant concentrations in fuel cells drop as the Uf rises and since cell voltage cannot be higher than the lowest local potential in the cell, Uf considerations limit the cell voltage. Even if anode inlet flow is enriched with hydrogen as AR rises, there is a still higher steam enrichment of this flow. Therefore a drop in voltage due to the increase of steam partial pressure is observed. Also, the increase of the total molar flow entering the fuel cell (with a constant inlet flow of natural gas) produces an extreme drop of hydrogen molar fraction in the fuel cell anode inlet flow.



Figure 11-20: Cell power vs. different parameters [Lisbona, 2007] Since the power is the electric current multiplied by the voltage, the power is constant with inlet temperature and increases monotonically with the degree of prereforming (Figure 11-20). Due to the simultaneous effect of increasing current density and decreasing cell voltage, the power has a peak for Uf ~80% and AR ~65%.



Consideration 10: Why about Auxiliaries Consumptions?

Figure 11-21: Auxiliaries consumption vs. different parameters [Lisbona, 2007]

In Lisbona's model, the effect of the studied input parameters on auxiliary's consumption is illustrated on **Figure 11-21**.



Figure 11-22: Electrical efficiency vs. different parameters [Lisbona, 2007]
The electrical consumption is increased by all the parameters considered, thus decreasing the electrical efficiency of the whole system (**Figure 11-22**). The reason can be found in the evolution of flow rate of cathodic air and the consequent higher consumption for air blower. Therefore, the peak of η_{el} is obtained for AR equal to 50–60% and a Uf 75%.

11.23 System without Anode Recirculation

In the Lisbona's model system, an increase of Uf means also a variation of the stack inlet flow composition which produces an opposite effect mitigating the expected increase of electrical efficiency.

However, within an SOFC system *without* anode recirculation in which inlet composition entering the Cell Stack Package remains constant, an increase of fuel utilization has a directly proportional response in electrical efficiency of the Cell Stack Package.

Consideration 11: How do the studied parameters affect airflow rate and heat output?



Figure 11-23 shows the effect of the investigated parameters on the airflow rate.

Figure 11-23: Cathodic flow varying different parameters [Lisbona, 2007]

It is worth noting in this example that the airflow rate is not fixed, but it is varied in order to maintain heat balance of the fuel cell and the operating temperature at 800 °C.

Therefore, in general a higher air flow rate is required when more heat is produced by the Cell Stack Package. The increase of pre-reforming degree results in an increased airflow-rate because the extent of internal reforming reactions (endothermic) is lower, thus the heat to be evacuated from the Cell Stack Package grows. Similarly, when the inlet temperature is increased, a higher airflow-rate will be required to maintain the Cell Stack Package at the fixed temperature of 800 °C because extra heat is being added with inlet flow.

The cathodic flow is directly proportional to Uf - the higher the extent of the electrochemical reaction, the higher heat released within the stack and the higher demand of cathodic flow to cool down the Cell Stack Package. Due to the high value of the heat of the electrochemical reaction small variations of Uf produces dramatic increases of the cathodic flow. When the percentage of anode off-gas re-circulated increases two opposite trends balance the required cathodic flow to fulfill the energetic balance. Firstly, the increase of fuel content in inlet flow leads to a higher extent of the reaction in the Cell Stack Package. And, secondly, it is a synergetic effect of an increase of the total anodic inlet flow and a variation in its composition (higher concentrations of steam and CO₂). In this way, the higher recirculation flow, the higher capacity of anodic flow to remove heat by convection.

Oxidant utilization is inversely proportional to the cathodic flow for all the parameters. As seen in **Figure 11-23** when AR is over 70%, airflow decreases, raising

488

*U*ox. Thus, the effect of *U*ox on heat output: a lower *U*ox (or equivalently a higher air flow rate) results in a lower heat output and thus in a lower thermal efficiency (**Figure 11-24**).



Figure 11-24: Thermal efficiency vs. different parameters [Lisbona, 2007]

This trend is observed for each studied parameter but for an AR higher than 70%. The global efficiency (**Figure 11-25**) follows the global trend of thermal efficiency.



Figure 11-25: Global efficiency vs. different parameters [Lisbona, 2007]

11.24 The Feasibility/Sensitivity Analysis on Uf with variable AR and Pre-Reforming

As illustrated in **Figure 11-26**, the electrical efficiency presents a sharp peak when varying Uf while all the other parameters remained constant.



Figure 11-26: Electrical efficiency vs. different parameters [Lisbona, 2007]

A further investigation has been carried out, to determine the trend of Uf at different values of AR and degree of pre-reforming. The results in terms of electrical and thermal efficiency are plotted on **Figures 11-27** and **11-28**.



Figure 11-27: Electrical efficiency vs. Uf for different AR [Lisbona, 2007]

Figure 11-27 shows that the maximum electrical efficiency moves along with AR: for the lowest AR (40%) the electrical efficiency increases monotonically with Uf, while for the highest AR (90%) the trend is monotonically decreasing.



Figure 11-28: Thermal efficiency vs. Uf (single step) for different AR [Lisbona, 2007]

The intermediate values investigated (60–70%) confirm this general rule: when AR increases the peak of electrical efficiency is shifted towards higher value of Uf. As seen before increasing the pre-reforming degree has a positive effect on the electrical efficiency.



Figure 11-29: Electrical efficiency vs. Uf for different % pre-reforming [Lisbona, 2007]

However, Figure 11-29 shows that this effect is very low for Uf lower than 70%.



Figure 11-30: Thermal efficiency vs. Uf for different % pre-reforming [Lisbona, 2007]

Also in this case, the electrical efficiency presents a maximum and the peak moves towards higher values of Uf if pre-reforming is increased. **Figure 11-28** and 11-**30** show that the thermal efficiency decreases when Uf is raised. This occurs for any value of pre-reforming degree and AR, except for AR= 90%. The analysis has confirmed that the increase of pre-reforming degree causes a drop of η th. When increasing AR instead, the η th has not a monotonic trend: for Uf lower than 65% η th is always decreasing, but for Uf higher than 65% η th shows a minimum in function of AR (as just seen in the previous analysis). For Uf = 95% the trend is even reversed: the increase of AR enhances thermal efficiency.

11.25 Conclusion

During the Conceptual Design & Advance Planning Phase of New Product Development a technical knowledge base, a design tool sets, and modeling technology are needed in developing a product concept. A protocol for verification, validation and iteration must also be set up and developed further for later lifecycle phases. Intelligential power and drive is very important and will be constantly challenged throughout the NPD's lifecycle. A systematic approach for analyzing technical challenge is needed for finding inventive solutions.

There are a lot of uncertainties about the best layout of the SOFC system in terms of feasibility, performance, economics and controllability. Therefore, experimental setups or detailed models, on cell, stack and system levels, are needed to determine (which are) the most important operational parameters. The below tables summarize some of the important operational parameters of a generic SOFC Power System (which includes parameters from Lisbona's case study).

Table 11-5						
SYSTEM INPUTS PARAMETERS RELATED TO						
PERFORMANCE REQUIREMENTS						
[Lisbona, 2007]						
Subsystem Involvement	Process or Characteristic					
The Hot Assembly Configuration	Anode recycling ratio (%)					
The Cell Stack Configuration	Cathode recycling ratio (%)					
The BOP Configuration						
The Fuel Processing Subsystem	Extent of methane reforming					
The Cell Stack	(percent of external					
	reforming)					
	Steam to carbon ratio to cells					
	and reformer					
The Air Celescot and	Air feed to the systems					
The Air Subsystem	Air feed					
	Compressor efficiency (%)					
	compressor enterency (70)					
	Air excess ratio					
The Hot Assembly	Air and fuel inlet					
The Mechanical Subsystem	temperatures to the Cell					
The Thermal Management Subsystem	Stack Package (°C)					
	Fuel and air input					
	temperature to system (°C)					
	Inlat process (Ba)					
The Fuel Processing & the Air	Plower officiancy (%)					
Subsystem	Blower enticiency (%)					
The Exhaust Subsystem	Whole system temperature					
The Enclosure	range					
The Mechanical Subsystem	exhaust gas temperature (°C)					
The Thermal Management Subsystem						
The Electrical Subsystem	DC/AC convertor efficiency					
	(%)					
The Thermal Management Subsystem	System heat losses (W)					

Table 11-6 SOFC STACK INPUT PARAMETERS

[Lisbona, 2007]

The cell stack configuration Number of cells Average current density (A/ cm²)

Anode thickness *Usually in (µm)*

Cathode thickness Usually in (µm)

Electrolyte thickness Usually in (µm)

Interconnector thickness Usually in (µm)

Cell active area (width x height)

Table 11-7 SOFC STACK INPUT PARAMETERS

[Lisbona, 2007]

Max. positive electrode/electrolyte/negative electrode (PEN) allowable temperature increase

> Number of channels, (fuel and air sides)

Channel height (fuel and air sides)

Channel width (fuel and air sides)

Fuel utilization (%) Oxidant utilization (%)

Cell electrochemical and thermal properties

CHAPTER XII

THE USE OF DESIGN STRUCTURE MATRIXING (DSM) – PHASE ONE

12.1 Introduction

Systems engineering of products, processes, and organizations require tools and techniques for system decomposition and integration. A Design Structure Matrix (DSM) provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems of systems design. A DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format. This chapter takes the SOFC Power System (Top-Down) mock-up model and analyzes a few of its subsystem-to-subsystem interactions via DSM.

12.2 The Use of Design Structure Matrixing (DSM)

A DSM is a square matrix with identical row and column labels. In the below example, DSM elements are represented by the shaded elements along the diagonal. An off-diagonal mark signifies the dependency of one element on another. Reading across a row reveals what other elements the element in that row provides to; scanning down a column reveals what other elements the element in that column depends on. That is, reading down a column reveals input sources, while reading across a row indicates output sinks. Thus, in **Figure 12-1**, element B provides something to elements A, C, D, F, H, and I, and it depends on something from elements C, D, F, and H.



Figure 12-1: A DSM Example [Browning, 2001]

12.3 Why DSM Analysis?

DSM techniques in fuel cell development have two main strengths. First, it can represent a large number of power system's subsystems and components and their relationships in a compact way that highlights important patterns in the data (such as feedback loops and modules). Second, it is amenable to matrix-based analysis techniques, which can be used to improve the structure of the system. DSM analysis provides insights into how to manage complex systems or projects, highlighting information flows, task sequences and iteration. It can help teams to streamline their processes based on the optimal flow of information between different interdependent activities. DSM analysis can also be used to manage the effects of change. For example, if the specification for a component of Lisbona's model system (as seem in the last chapter) had to be changed, it would be possible to quickly identify all processes or activities which had been dependent on that specification, reducing the risk that work continues based on out-of-date information.

12.4 DSM Analysis of an SOFC Power System

Table 12-1
THE 9 SUBSYSTEMS OF THE SOFC
POWER SYSTEM MOCK-UP MODEL
The Enclosure
The Cell Stack Package
The Electrical Subsystem
The Mechanical Subsystem
The Hot Assembly
The Thermal Management Subsystem
The Air Subsystem
The Waste Management Subsystem
The Fuel Processing Subsystem

The SOFC Power System Mock-up Model had nine subsystems:

From a systems engineering perspective, the rationale behind and the reasons for grouping the subsystems of the SOFC Power System into this formation were:

- To define significant subsystem definitions at a basic level, which can provide complete but flexible, stable, yet controllable baselines for higher level development throughout and for the entire lifecycle of the system (as a whole, as well as, the partitioned section of the subsystems).
- For the preparatory activity of phasing development that the controls design process and for providing the subsystem baselines that would coordinate design

efforts of present, as well as, the foreseen and unforeseen future modification that

might affect design requirements.

• To provide a structure for solving design problems and tracking requirement flow

through the design effort.

The functions of each subsystem are listed in Tables 12-2 and 12-3. These

provisional assumptions have been placed in the DSM Matrix below, see Table 12-4.

Table 12-2						
THE PROVISIONAL ASSUMPTIONS FOR THE SOFC POWER SYSTEM						
The Cell Stack Package	The Cell Stack's generates:					
(A)	DC Electricity (which the Electrical Subsystem					
	exports).					
	Heat (which the Thermal Management System					
	regulates).					
The Electrical Subsystem	The Electrical Subsystem's purposes are to:					
(B)	Import DC power from the Cell Stack Package					
	To distribute power to all the other subsystems, as					
	well as convert DC power to AC for the end user.					
	Part of the Electrical Subsystem monitors and					
	controls the BOP subsystems.					
The Fuel Processing	The Fuel Processing Subsystem's purpose is to provide					
Subsystem (C)	the Cell Stack with clean hydrogen rich fuel.					
The Thermal	The Thermal Management System's purposes are:					
Management System (D)	To maintain the operational temperatures of the					
	Cell Stack Package.					
	To heat the fuel and oxidant to operational					
	temperature.					
	To another the most action to the DOD					
	To provide thermal protection to the BOP					
The Air Subgrater (E)	The Air Subaystem's sum age is to:					
The Air Subsystem (E)	The Air Subsystem's purpose is to: Drovide the esthede side of the Cell Steek					
	Provide the cathode side of the Cell Stack					
	To remove excess heat from the Cell Stack					
	Package.					

Table 12-3						
THE PROVISIONAL ASSUMPTIONS FOR THE SOFC POWER SYSTEM						
The Hot Assembly (F)	The Hot Assembly's purpose is to provide:					
	A structural support for the Cell Stack.					
	A structural which houses the insulation packages					
	and other structural elements of the Thermal					
	Management System.					
	A connection between the Cell Stack and the					
	Electrical System.					
	A means by which the Fuel Processing System					
	and Air System can deliver their gases.					
	A magne by which the Call Steak can rid its waste					
	gases (via the Exhaust System)					
The Waste Management	The Exhaust System's nurnoses are to provide a means to					
System (G)	rid the Cell Stack Package, Fuel Processing System and					
	the Air System of waste products.					
The Mechanical	The Mechanical Subsystem's purpose is to provide serve					
Subsystem (H)	to:					
	The Cell Stack Package via providing stable					
	loading.					
	To provide the Fuel Processing System and the					
	Air System with the means by which gases are					
	transported.					
The Enclosure (En)	The Enclosure houses the BOP Systems and the Hot					
	Assembly, which contains the Cell Stack.					

In the below tables, reading across a row reveals what other subsystem the subsystem in that row provides to, namely what services does it provides; scanning down a column reveals what other subsystems the subsystem's functionality in that column depends on.

Table 12-4											
THE DSM OF THE SOFC POWER SYSTEM MOCK-UP MODEL											
										Е	
The Subsystems		Α	В	С	D	Е	F	G	Η	n	Provisions
Cell Stack	Α	А	х		Х						2
Electrical System	В	Х	В	Х	х	Х	х	х	х	Х	8
Fuel Processing System	С	Х		С							1
Thermal Management											
System	D	Χ	Х	Х	D	Х	Х	Х	Х	Х	8
Air System	E	Х				Е		Х			2
Hot Assembly	F	Х	Х	Х	Х	Х	F	Х	х		7
Waste Management											
System	G	Χ		Χ		Х	Х	G			4
Mechanical System	Н	Х		Х		Х			Н		3
	E									Е	
The Enclosure	n		Х	Х	Х	Х	Х	Х	Х	Ν	7
Dependents		7	4	6	4	6	4	5	4	2	

12.5 Analysis of the Overall Review of the SOFC Power System Mock-up Model

From the stated provisional assumptions of the subsystems listed in **Tables 12-2** and **12-3**, A DSM Matrix was created (**Table 12-4**) from which two inferences can be drawn (**Tables 12-5** and **12-6**).

Table 12-5 THE RANKING OF SUBSYSTEM DEPENDENCY					
The Subsystems	# of Dependents				
The Cell Stack Package	7				
The Fuel Processing System	6				
The Thermal Management System	5				
The Air System	5				
The Electrical System	4				
The Hot Assembly	4				
The Waste Management System	4				
The Mechanical System	4				
The Enclosure	2				

 Table 12-5 reveals which subsystem is the pivotal one (the subsystem with the greatest number of dependencies).

Table 12-6					
THE RANKING OF SUBSYSTEM PROVISIONS					
	# of				
The Subsystems	Provisions				
The Electrical System	8				
The Thermal Management System	8				
The Hot Assembly	7				
The Enclosure	7				
The Waste Management System	4				
The Mechanical System	3				
The Cell Stack	2				
The Air System	2				
The Fuel Processing System	1				

Scanning down the columns of the **Table 12-5** reveals that the Cell Stack Package is the most dependent subsystem of the Power System. So, in order for the Cell Stack to perform a proper operation, the Cell Stack Package requires the services of the other subsystems of the balance of plant (BOP). Because of its functions (to produce electricity and heat), because of its dependency on the other subsystems the Cell Stack Package is the pivotal subsystem of the SOFC Power System.

 Table 12-6 reveals that the most provisional subsystem is the Electrical System

 followed by the Thermal Management System and the Hot Assembly, respectively.

12.6 Examples of DSM Analysis on the Subsystems of an SOFC Power System

From Lisbona's model in the last chapter, the characteristics that were studied, directly related to the Power System's outputs (of DC voltage and heat), were:

- 1. On the anodic side of the Cell Stack Package (Case 1):
 - The gas composition.
 - The gas flow rate.
 - The temperature and pressure of the anode inlet stream.
- 2. On the cathodic side of the Cell Stack Package (Case 2):
 - The gas composition of the oxidant.
 - The air flow rate.
 - Temperature and pressure of the cathode inlet stream.
- 3. Fuel utilization (**Case 3**).

Table 12-7 CASE 1					
THE PROVISIONAL ASSU	MPTIONS FOR THE ANODIC SIDE OF THE CELL STACK				
The Cell Stack Package (A)	The Cell Stack is NOT directly involved in the activity				
	OI: Creating the gas composition of the fuel.				
	Creating the gas flow rate.				
	Managing the temperature of the anode inlet stream.				
	Managing the pressure of the anode inlet stream.				
The Electrical Subsystem (B)	The Electrical System provides power to: The components of the Fuel Processing System (responsible for the gas composition).				
	The components of the Mechanical System (responsible for the gas flow and pressure).				
	The components of the Thermal Management Systems (responsible for the temperature control of the gas composition).				
The Fuel Processing	The Fuel Processing System:				
Subsystem (C)	Creates the gas composition of the fuel used by the Cell Stack Package to produce electricity.				
	Does not creating the gas flow rate or gas pressure.				
	Does not managing the temperature of the anode inlet stream.				
	Does not managing the pressure of the anode inlet stream.				

	Table 12-8					
CASE 1						
THE PROVISIONAL ASSUMPTIONS FOR THE ANODIC SIDE OF THE CELL						
	STACK					
The Thermal Management System (D)	The Thermal Management System:					
	Does not create the gas composition of the fuel.					
	Does not creating the gas flow rate.					
	Does manage the temperature of the anode inlet					
	stream.					
The Air System (E)	The Air system is not involved in these activities.					
The Hot Assembly (F)	The Hot Assembly provides the means by which the fuel					
	can enter the cell stack chamber.					
The Waste Management	The Exhaust System is not involved with this activity					
System (G)						
The Mechanical System (H)	The Mechanical System:					
	Does not create the gas composition of the fuel.					
	Do control the gas flow rate.					
	Do not manage the temperature of the anode inlet					
	stream.					
The Enclosure (EN)	The Enclosure is not involved with these activities.					

Table 12-9											
CASE 1 - THE DSM ANALYSIS OF THE WORKINGS OF THE ANODIC SIDE											
OF THE CELL STACK											
The Subsystems		А	В	С	D	Е	F	G	Η	En	Provisions
The Cell Stack Package	Α	А									0
The Electrical System	В		В	Х	Х				Χ		3
The Fuel Processing System	С	Х		С							1
The Thermal Management											
System	D			Χ	D						1
The Air System	Е					Е					0
The Hot Assembly	F			Х			F				1
The Exhaust System	G							G			0
The Mechanical System	Η			Х					Н		1
The Enclosure	En									EN	0
Dependents		1	0	4	1	0	0	0	1	0	

From a systems engineering design perspective, for the anodic gas characteristics of the SOFC Power System, the Electrical System is the most provisional subsystem. The Fuel Processing System is the most dependent subsystem during the delivery of the fuel to the Cell Stack Package. If design changes must be made to either one, the other will most like need some sort of redesign.

Table 12-10					
CASE 2					
THE PROVISIONAL ASSUMPTIONS FOR THE CATHODIC SIDE OF THE					
	CELL STACK				
The Cell Stack Package (A)	The Cell Stack is NOT directly involved in the activity of :				
	Creating the gas composition of the air.				
	Creating the gas flow rate.				
	Managing the temperature of the cathode inlet stream.				
	Managing the pressure of the cathode inlet stream.				
The Electrical Subsystem (B)	The Electrical System provides power to: The components of the Air System (responsible for the gas composition).				
	The components of the Mechanical System (responsible for the gas flow and pressure).				
	The components of the Thermal Management Systems (responsible for the temperature control of the gas composition).				
The Fuel Processing	The Fuel Processing System is not involved with these				
Subsystem (C)	activities.				

Table 12-11CASE 2THE PROVISIONAL ASSUMPTIONS FOR THE CATHODIC SIDE OF THE							
CELL STACK							
The Thermal Management System (D)	The Thermal Management System:						
System (D)	Is not involved with the gas composition of the oxidant.						
	Is not involved with the air flow rate.						
	Is involved with the temperature.						
	Is not involved with the pressure of the cathode inlet stream.						
The Air System (E)	The Air system is involved with the gas composition.						
The Hot Assembly (F)	The Hot Assembly provides the means by which the air can enter the cell stack chamber.						
The Waste Management System (G)	The Exhaust System is not involved in these activities.						
The Mechanical System (H)	The Mechanical System						
	Is not involved in the gas composition of the						
	oxidant.						
	Is involved in the air flow rate.						
	Is not involved in the temperature control.						
	Is involved pressure of the cathode inlet stream						
The Enclosure (EN)	The Enclosure is not involved with these activities.						

Table 12-12											
CASE 2 - THE DSM ANALYSIS OF THE WORKINGS OF THE CATHODIC SIDE OF THE CELL STACK											
									Provisi		
The Subsystems		Α	В	С	D	Е	F	G	Η	En	ons
The Cell Stack Package	Α	А									0
The Electrical System	В		В		Χ	Х			Χ		3
The Fuel Processing System				С							0
The Thermal Management											
System	D				D	Χ					1
The Air System	Е	Χ				Е					1
The Hot Assembly	F					Χ	F				1
The Exhaust System	G							G			0
The Mechanical System	Н					Χ			Н		1
The Enclosure	En									EN	0
Dependents		1	0	0	1	4	0	0	1	0	

From a systems engineering design perspective, for the cathodic gas characteristics of the SOFC Power System, again the Electrical System is the most provisional subsystem. The Air System is the most dependent subsystem during the delivery of the oxidant to the Cell Stack Package. If design changes must be made to either one, the other will most like need some sort of redesign.

12.7 Fuel Utilization – Case 3

Utilization is the ratio (*often expressed in percentage*) of hydrogen consumption to the net available hydrogen in the anode. Fuel Utilization can be written as:

$$FU\% = \frac{T^* MV^* (number of cells) * operating current (Amps.)}{2 * F * (H2 flow sccm)}$$

Where:

T = 60 seconds

MV = the molar volume of any ideal gas = $22.414 \text{ m}^3/\text{kmol}$ at 0 degrees C at 101.324 kPaF = Faraday's Constant = $96,485 \text{ C mol}^{-1}$ The above equation assumes that the power system is operating at normal

operating conditions and it links the operations of the Electrical System to that of the Fuel

Processing Subsystem and, so a DSM analysis can be preformed for Fuel Utilization.

	Table 12-13					
	CASE 3					
THE PROVISIONAL ASSUMPTIONS FOR THE FUEL UTILIZATION						
The Cell Stack Package (A)	The # Unit Cell's directly influences this activity by					
	providing an active area in which the fuel is utilized.					
The Electrical Subsystem (B)	The Electrical System is controlling the utilization which					
	is taking place at any given time at the active areas of the Unit Cells.					
	The Electrical System also provides power to:					
	The components of the Fuel Processing System					
	(responsible for the fuel composition).					
	The components of the Air System (responsible					
	for the oxidant composition).					
	The components of the Mechanical System					
	(responsible for the gas flows and pressures).					
	The components of the Thermal Management					
	Systems (responsible for the temperature control					
	of the gas compositions).					
The Fuel Processing	The Fuel Processing System is involved in providing the					
Subsystem (C)	material for the electrochemical activity.					

Table 12-14						
CASE 3						
THE PROVISIONAL ASS	UMPTIONS FOR THE FUEL UTILIZATION					
The Thermal Management	The Thermal Management System provides the					
System (D)	Cell Stack, the Fuel Processing and Air Systems					
	and the Hot Assembly with heat management					
	services.					
The Air System (E)	The Air system provides the Cell Stack Package					
	with oxidant for the electrochemical reaction.					
The Hot Assembly (F)	The Hot Assembly provides the means by which					
	the gas and enter and leave the cell stack					
	chamber					
The Waste Management	The Exhaust System is connected to the Hot					
System (G)	Assembly.					
	The Waste Management System handles the					
	wastes of the Air and Fuel Processing Systems					
	along with the wastes of the Thermal					
	Management System.					
The Mechanical System (H)	The Mechanical System provides services to the					
	Air and Fuel Processing Systems.					
The Enclosure (EN)	The Enclosure is not involved in this function.					

Table 12-15 CASE 2 THE DSM ANALYSIS FOR THE FUEL LITH LZATION											
CASE 5 - THE DSM ANALYSIS FOR THE FUEL UTILIZATION STUDY											
									Provis		
The Subsystems		А	В	С	D	Ε	F	G	Η	En	ions
The Cell Stack Pack	Α	А		Х							1
The Electrical System	В	Х	В	Х	Х	Х	х	Х	Х		7
The Fuel Processing											
System	С	Χ		С							1
The Thermal											
Management System	D	Χ		Χ	D	Х	Х				4
The Air System	Е	Х				Е					1
The Hot Assembly	F	Х	Х	Х	Х	Х	F	Х			6
The Waste Management											
System	G	Х		Χ	Χ	Х		G			4
The Mechanical System	Н			Х		Х			Н		2
The Enclosure	En									EN	0
Dependents		6	1	6	3	6	2	2	1		

The most provisional subsystem involved with the power system's activity of fuel utilization is the Electrical System followed by the Hot Assembly. The most dependent subsystems are the Cell Stack Package, the Fuel Processing System and the Air System.

12.8 Further Manipulation of DSM

Products, processes, and organizations are each a kind of complex system. The classic approach to increasing understanding about a complex system is to model it, typically by:

- Decomposing it into subsystems about which we know relatively more;
- Noting the relationships between (the integration of) the subsystems that give rise to the system's behavior;
- Noting the external inputs and outputs and their impact on the system.

With a reasonable model, it becomes possible to explore innovative approaches to system decomposition and integration. The design structure matrix (DSM) is becoming a popular representation and analysis tool for system modeling, especially for purposes of decomposition and integration.



Figure 12-2: DSM Taxonomy [Browning, 2001]

As shown, a DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format.



Figure 12-3: Examples of transfers via different interconnections [De Weck, 2009]

DSM can be used to analyze many different types of system interconnections. Examples and a brief explanation of several of the connections (in the above figure) will follow.



Figure 12-4: DSM – Physical Connection [De Weck, 2009]

Physical connections show how elements within the system are physically connected, either by welding, bolted joints, or other means.



Figure 12-5: DSM – Examples of Physical Connection [De Weck, 2009]



Figure 12-6: DSM – Mass Flow [De Weck, 2009]

Mass Flow Connection: In the air and fuel processing systems, there can be two

or three different types of mass flows.



Figure 12-7: DSM – Energy Flow [De Weck, 2009]

Energy Flow Connection: Energy flow includes all flows related to power and energy transfer, including mechanical, heat and electrical energy. Energy flow is shown here as vertical line patterned cells. Similar to the mass flow connection, energy flow can be one way or circulating. In the below figure, paper printing is used as an example.



Figure 12-8: DSM – Energy Flow (continue) [De Weck, 2009]



Figure 12-9: DSM – Information Flow [De Weck, 2009]

Information Flow Connection: Information flow includes any information

exchange between elements. The paper printing example is continued in the below figure.



Figure 12-10: DSM - Information Flow (continuous) [De Weck, 2009]

12.9 Multi-Type Element DMS Matrix

A DSM technique developed by Smaling and de Weck is used, which can represent physical connections, as well as mass flows, power flows, and information flows, all in one matrix. An example system (DSM) shows the main elements or subsystems as the rows and columns of a matrix. The connections between the elements are shown as the off-diagonal elements. **Figure 12-11** shows how to read a highly simplified DSM matrix for a simple system composed of three components *A*, *B*, and *C*.



Figure 12-11: Block diagram (left) and DSM (right) of a simple system. [Browning, 2001]

In this example component A physically connects to B which in turn is connected to C. A mass flow occurs from B to C, while energy is supplied from A to B and C, respectively. Such a DSM forms the basic information upon which the subsequent analysis can be built. In the DSM, four types of interconnections between components and/or subsystems are modeled: physical connections, mass flow connections, power flow connections, and information flow connections.

Fuel cell developers could use Smaling and de Weck DSM Analysis to model the physical, mass transfer, energy, information connections of power systems and/or power system's subsystems.

12.10 Component Interactions of Systems and Subsystems

An organized taxonomy can help differentiate types of interactions. Pimmler and Eppinger suggest four types (Spatial, Energy, Information, and Material), as shown in **Figure 12-12**.

Spatial	associations of physical space and alignme	int needs for adjacency
	or orientation between two elements	
Energy	needs for energy transfer/exchange betwee	in two elements (e.g.,
	nower supply)	
	Power suppry	
Information	needs for data or signal exchange between	two elements
Material	needs for material exchange between two	elements
	4	

Figure 12-12: Simple Taxonomy of System Elements Interactions [Browning, 2001]

The important types of interactions will vary from product to product, and

others—such as vibrational or electrical—could also be included.

A quantification scheme facilitates weighting interactions relative to each other.

Off-diagonal square marks in the DSM are replaced by a number (coupling coefficient)—

e.g., an integer, 0, 1, or 2 (Figure 12-13).

Required	+2	Physical adjacency is necessary for functionality.
Desired	+1	Physical adjacency is beneficial, but not necessary for functionality
Indifferent	0	Physical adjacency does not affect functionality.
Undesired	-1	Physical adjacency causes negative effects but does not prevent functionality.
Detrimental	•2	Physical adjacency must be prevented to achieve functionality

Figure 12-13: Example of a Spatial Interaction Quantification Scheme [Browning, 2001]

Alternatively, the weighting scheme could be exponential instead of linear.

Weighting information can be obtained by reviewing architectural diagrams and system schematics. Further clarification comes from interviewing engineers and developmental domain experts.

Integration analysis—via the clustering of off-diagonal elements by reordering the rows and columns of the DSM—can provide new insights into system decomposition and integration. Clustering requires several considerations. The foremost objective is to maximize interactions between elements within clusters (chunks) while minimizing interactions between clusters.

Using A component-based DSM method, the Fuel Processing Subsystem of the SOFC Power System was analyzed. The subsystem's sections are shown in **Table 12-16**. The physical hierarchy structure of the Fuel Processing System is shown in the below figure.



Figure 12-14: The Anode Leg of the SOFC Power System (The Fuel Processing System)

Table 12-16						
THE SUBDIVISION OF THE FUEL PROCESSING SUBSYSTEM						
	•	The Fuel Tank				
	•	The Fuel Filter				
	•	The Fuel Pump				
The Fuel Conditioning Unit	•	The Desulphurizer				
The Thermal Connection of	•	The Pre-heater				
the Fuel Processing Unit	•	The Heat Exchanger				
The Subsystem's Element of	•	The Steam Generator				
Focus	•	The Catalyst/the Steam Reformer				
The Power Generation						
Component of the Fuel						
Processing Subsystem	•	The Unit Cell (Anode)				
The Water Management		The External Water Source				
Subsystem of the Fuel	•	The Recirculation Pump				
Processing Subsystem		The Water Condenser				

Table 12-17 shows the materials interaction perspective for the Fuel Processing

Subsystem. Using special DSM software this table could be cluster to show the physical

interactions of the fuel processing subsystem's components.
DMS ANALVSIS OF THE FUEL	PR	റ	₽	SS	SI	N	2.0	311	RS	v	S	ГF	м	r			
(Material Interactio	ns -	In	ita	lS	'et-	Uj))	50	DE	, Т	ю.		IVI	e.			
		A	B	C	D	E	F	G	H	Ι	J	K	\mathbf{L}	Μ	Ν	0	I
Piping from the Desulphurizer to the Steam														Γ			Γ
Reformer	Α	А	117 14 -														
Piping from the Stream Reform to the										Γ		Γ					Γ
Anodic Inlet	B		В														
The Desulphurizer	C			C													
The Unit Cell (Anode)	D				D										0		-
The Steam Reformer	E				201 1	Е											
The Heat Exchanger	F		Ĩ				F										Γ
The Fuel Tank	G							G									
The Pre-heater	Η	1						5	Η						9 v		
The Steam Generator	Ι			Γ						I							Γ
														Γ			
Anodic Inlet to Cell Stack Package Chamber	J		17		27	4					J	5					
Controls of the Recirculation Pump	K		ξe.						5.5.	Γ		K					
Controls of the Desulphurizer	L												L				
Controls of the Fuel Pump	Μ		- -							Γ				M			
Controls of the Steam Generator	Ν	5						·				Č.			Ν		
The Fuel Filter	0					<					2					0	
The Fuel Pump	P														\square		P

Table 12-17: DMS Analysis of the Fuel Processing Subsystem

12.11 Conclusion

The Design Structure Matrix (DSM) is a simple tool to perform both the analysis and the management of complex systems. It enables the user to model, visualize, and analyze the dependencies among the entities of any system and derive suggestions for the improvement or synthesis of a system. As a tool for system analysis, DSM provides a compact and clear representation of a complex system and a capture method for the interactions/interdependencies/ interfaces between system elements (i.e. sub-systems and modules).

The use of DSM techniques in fuel cell development has two main strengths. First, it can represent a large number of power system subsystems, their subsystems' components and their relationships in a compact way that highlights important patterns in the data (such as feedback loops and modules). Second, it is amenable to matrix-based analysis techniques, which can be used to improve the structure of the system. DSM analysis provides insights into how to manage complex systems or projects, highlighting information flows, task sequences and iteration.

CHAPTER XIII

THE PRELIMINARY SYSTEM DESIGN PHASE - PHASE TWO

13.1 Introduction

The Preliminary System Design Phase of new product engineering development is that period during which it is proven possible within the technological state of the art to design (create) a new product from the concept by building a physically advanced prototype.

The objective of this stage is to confirm the target performance of the new product through experimentation and/or accepted engineering analysis and to ascertain that there are major technical or economic barriers to implementation that cannot be expected to be overcome by development.

The usual product of this stage is a bench or breadboard model. Where it is not realistic to produce an entire model, feasibility must be demonstrated through an appropriate combination of tests of materials, full or partial product or process models or by other acceptable engineering techniques (e.g., computer simulations). It is largely desirable to build an advance prototype by the end of this phase.

During this phase at least the following activities must be completed:

- A Functional Analysis
- Requirements Allocation
- Synthesis and the evaluation of design alternatives.
- The Creation and Documentation of a Preliminary Design.
- Criterion for Testing and Evaluating the System's Design Concepts.
- Creation of an advance engineered demonstrative prototype.



Figure 13-1: Concept and Technology Development

This chapter will serve as the journey's start from the Conceptual Design and Advance Planning Phase to the Preliminary System Design Phase of the SOFC Power System that was created in the last three chapters. The major objective of this phase is to create a Function Configuration Identification (System Specifications) corroborate by physical components/system engineering of an advance prototype.

13.2 The Bottom-Up Design Approach

Traditionally, two alternative design approaches have been available to engineers: The Top-down and the Bottom-up. In the top-down approach, the design process starts with specifying the global system state and assuming that each component has global knowledge of the system, as in a centralized approach.

In the bottom-up approach, the design starts with specifying requirements and capabilities of individual components, and the global behavior is said to emerge out of interactions among constituent components and between components and the environment. A bottom-up approach is the piecing together of systems to give rise to grander systems, thus making the original systems sub-systems of the emergent system. In a bottom-up approach the individual base elements of the system are first specified in great detail. These elements are then linked together to form larger subsystems, which then in turn are linked, sometimes in many levels, until a complete top-level system is formed. This strategy often resembles a "seed" model, whereby the beginnings are small but eventually grow in complexity and completeness.

Bottom-up design approach tends to focus on the capabilities of available realworld physical technology, implementing those solutions which this technology is most suited to. The risk of bottom-up design is that it very efficiently provides solutions to low-value problems. The focus of Bottom-Up design is "*what can we most efficiently do with this technology*?" rather than the focus of Top-Down which is "What is the most valuable thing to do?"

13.3 Top-down versus the Bottom-up Design Approach

The bottom-up approach starts with the conceptual design of the power system through a set of system specifications (Type A):

- 1. System Operational Requirements.
- 2. Maintenance Concept.

- 3. Technical Performance Measures (TPMs).
- 4. Functional Analysis (System Level).
- 5. Allocation of Requirements.
- 6. Functional Interfaces.
- 7. Subsystem Environmental Requirements.
- System Characteristics:
 - 1. Performance Characteristics
 - 2. Physical Characteristics
 - 3. Effectiveness Requirements
 - 4. Reliability
 - 5. Maintainability
 - 6. Usability (Human Factors)
 - 7. Supportability
 - 8. Producibility
 - 9. Disposability (The Waste Management Plan)
- Design and Construction:
 - 1. CAD/CAM/CAS Requirements
 - 2. Material, Processes, and Parts
 - 3. Hardware/software
 - 4. Interchangeability
 - 5. Flexibility/Robustness
 - 6. Safety
- Design Data and Database Requirements

- Logistics:
 - 1. Supply Chain Requirements
 - 2. Spares, Repair Parts, and Inventory Requirements
 - 3. Test and Support Systems/Subsystems
 - 4. Technical Data/Information
- Quality Assurance
- Maintenance and Support (Life cycle)



Figure 13-2: Sample Specification Tree (partial)

Note that the global system requirements can be delegated to individual components. For some tasks this might not be straightforward. Interaction is important in both the approaches but its impact is completely different if not opposite. In the top-down case a form of explicit interaction synchronicity is a requirement implied by the necessity, in the pivotal subsystem's case, for example, to access remote resources (fuel, oxidant), and to output deliverables (electricity, heat) according to the global design.

In the Bottom-Up Design Approach, on the component level of the subsystem design, component interaction is important in so far as the impact of component-tocomponent effect propagation throughout the system.

As a consequence, the performance of top-down systems, although optimal in ideal conditions, is expected to be very sensitive to component/subsystem interactive *"noise"* and malfunction. It is then necessary to analyze the parameter of each subsystem to define how accurately individual components operate. In extreme situations caused typically by intolerable levels of interaction, the Bottom-Up Approach seems to represent the only viable solution.

Both approaches are similar in their reliance on model simulations to analyze global system properties. However, the Top-Down Approach usually utilizes systems engineering tools such as System Feasibility Analysis, Proof of Concept Techniques, Global Performance Testing, Global Reliability Testing, and Parameter Estimation.



Figure 13-3: The Bottom-up Design Approach Cycle

The Bottom-Up Design Approach relies heavily on Local Performance, Local Reliability Testing, Design Synthesis Principles, Optimization Theory, and Systems Analysis Methods etc. Hence, in the Top-down Approach it is possible to establish stringent bounds on the system behavior and make performance guarantees within its range of applicability as it relies on well established systems engineering methods.

The Top-Down procedure identifies relationships between product requirements and design parameters and specifies an acceptable range of design parameters (called a design range) from product specifications and tolerances.

The analysis tools in the Bottom-Up Approach, on the other hand, can be extremely efficient in describing the system performance in terms of subsystem/component monetary and design expenditures towards tailoring the product towards becoming manufacturable. Within the design range, the bottom-up procedure optimizes design specifications and tolerances in order to minimize a product cost. A product cost is defined as a sum of component costs, each of which is a function of design specifications and tolerances.

13.4 Prototyping used in Analysis

In the Bottom-up Design Approach the designer/developers translates the conceptual design mock-up into a prototyping design. The conditions for a bottom-up approach are:

1. A conceptual design possessing potential significant improvement.

- 2. There is a minimal change in the technology.
- 3. The customers' needs must not conflict with the product specification.

Technically, a prototype is the first thing of its kind. But "prototype" has come to mean many different things in the context of fuel cell product development.

For the lucky developer of the Enclosure Subsystem, the prototype might be the final product. At the other extreme, the development of a new Fuel Processing Subsystem or Unit Cell design may involve more than 10 prototypes before the design is finalized. Some fuel cell prototypes are used for thermal studies, some are used to perform life testing, and some are used to verify power output.

Other words frequently used to describe the function of a prototype include breadboard, model, and mock up. Each is an example of a prototype; each emphasizes a different aspect of what a prototype does. In this paper the definition of a prototype used includes both the electronic and physical representations of the part, subsystem or final product (the power system).

In most cases prototypes are built to answer questions. In the engineering context, a prototype proves a technology or its application. In the marketing context, the prototype is a vehicle through which the marketer simulates customer response or finalizes design requirements. In the manufacturing context, a prototype proves a process or procedure.

Effective prototyping requires understanding which questions to ask, when to ask them, and how to answer them.

Different types of prototypes are used in many different ways to address different types of questions. For example, electronic prototypes are often used for simulation. They may be subjected to finite element analysis, mass properties calculations, tolerance analysis, assembly analysis, or motion analysis. Some prototypes are used for verification; often analysis and simulation have been used to make many design decisions, and the prototype is used to detect unanticipated problems. Some prototypes are used to perform tests; they may be used for functional testing, customer perception testing, life testing, assembly planning, etc. Other prototypes serve as *crystal balls* to anticipate future problems; they may be used to prepare for tooling design, or to compare the evolving product with customer needs.

Prototyping is one of the most critical activities in new product development. Fuel cell developers are constantly confronted with a variety of difficult issues in their prototyping activities of the Preliminary Systems Design Phase. Some of these issues are tactical: For a given part, how can a choice among fabrication technologies be made? Some of the issues are strategic: How can their technologies be evaluated?

13.5 The Need for Optimizing – System Evaluation

To start the Bottom-up Design Approach, fuel cell design and development requires that engineers and developers consider trade-offs between power system attributes in the cost areas of system functionality, system's manufacturability, and quality. The "optimum" design is in fact usually one in which compromises are acceptable, but understanding the impact of design decisions on all relevant attributes is

tremendously difficult. Fuel cell developers are faced with the difficult challenge of determining how to arrive at the best overall design, making the right compromises, and not sacrificing in critical attributes like safety.

The case presented in this chapter, is a model created by Hawkes (el al) to identify cost of the "optimum" SOFC stack capacity (kWe) and supplementary boiler capacity (kWth), to meet a given energy demand profile. The economic/technical factors analyzed in Hawkes' studies were of the pivotal subsystem: stack capacity, stack capital cost, stack lifetime, and the Cell Stack Package's electrical efficiency. Also included in Hawkes' study were electricity export price, and energy import prices. Hawkes' work is presented here in order to demonstrate the types of analysis fuel cell developers must perform before finalized components/parts selection are made and before scale-up to small quantities of production models transpire.



Figure 13-4: The Top-down/Bottom-up System Development Process [Blanchard, 2008]

13.6 Hawkes' Model – System Evaluation

The purpose of Hawkes' model was to identify the minimum equivalent annual cost and corresponding "optimum" SOFC stack capacity (kWe) and supplementary boiler capacity, to meet a given energy demand profile. Equivalent annual cost of meeting energy demand is defined as the equivalent cost per year of owning the micro-CHP/boiler system over their entire lives, plus the cost per year of providing whatever fuel and electricity is necessary meet energy demands in the dwelling. It was necessary to use equivalent annual cost in this study rather than net present value as the CHP unit and supplementary boiler can have different lifetimes.



Figure 13-5: Hawkes' simplified SOFC CHP Power System [Hawkes, 2005]

The Equivalent Annual Cost (EAC) is the cost per year of owning and operating an asset over its entire lifespan. EAC is often used as a decision making tool in capital budgeting when comparing investment projects of unequal life spans. For example, if project A has an expected lifetime of 7 years, and project B has an expected lifetime of 11 years it would be improper to simply compare the net present values (NPVs) of the two projects, unless neither project could be repeated. The NPV of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows. In the case when all future cash flows are incoming (such as coupons and principal of a bond) and the only outflow of cash is the purchase price, the NPV is simply the PV of future cash flows minus the purchase price (which is its own PV). NPV is a central tool in discounted cash flow (DCF) analysis, and is a standard method for using the time value of money to appraise long-term projects.

The technical CHP system modeled was an anode supported intermediate temperature direct internal reforming solid oxide fuel cell micro-CHP system operating in

parallel with the electrical grid. Electricity was bought from and sold to a supplier, and natural gas was imported from the piped network. An additional boiler was also included in the micro-CHP system to provide any supplementary heat required, and met any rapidly fluctuating heat loads that the fuel cell was unable to respond to. This system, including a basic depiction of BOP, is represented diagrammatically in **Figure 13-5**.

13.7 Model Structure: CODEGen

The model developed used a sparse sequential quadratic programming optimization method to minimize the equivalent annual cost of meeting the given heat and power demand. The programming language employed was object-oriented C++ in conjunction with the E04UGC routine from the NAGC Library Mark 7. Quadratic programming (QP) is a special type of mathematical optimization problem. It is the problem of optimizing (minimizing or maximizing) a quadratic function of several variables subject to linear constraints on these variables.

The CODEGen model, for the cost optimization of decentralized energy generation, was developed to analyze the FC model system. The system had six cost drivers:

- 1. The cost of fuel to run the fuel cell;
- 2. The operation and maintenance of the fuel cell;
- 3. The cost of fuel to run the additional boiler;
- 4. The operation and maintenance of the boiler;
- 5. The cost of imported electricity, and
- 6. The revenue from any electricity sold to the Grid.
- 7.

The objective function is subject to constraints:

- Overall, the given power and heat demands must be satisfied. The heat demand may be exceeded by a specified amount, limited by the technical constraint for heat dump from the system.
- Neither SOFC nor boiler output can exceed their rated capacities. One may
 explicitly limit the stack and boiler capacities, or allow the optimizer to choose
 these capacities.
- Thermal stresses within the SOFC prevent rapid changes in power output, so power output in each time period is limited to be within a specified range of the power output for the previous time period.



13.8 SOFC High-Level Characterization

As apparent from **Figure 13-6**, the electrical output from the SOFC Cell Stack was directed through a DC–AC inverter. In order to obtain a high-level characterization of the system, the electrical efficiencies of the stack and inverter were combined.

The electrical efficiency profile of the SOFC, given by Equation (2), was generated from an SOFC model developed by Imperial College London Chemical Engineering department and exhibits typical high part-load efficiency:

$$Electrical_{eff} = -0.0607r^3 + 0.253r^2 - 0.453r + 0.6593,$$

(2)

Where *r* is the load factor

The dc–ac inverter typically incorporates approximately 7% losses at low load factors, and 3% losses at rated capacity. When the stack and dc–ac inverter efficiency profiles were combined, the resulting system electrical efficiency is shown in **Figure 13-6**. In addition to the system electrical efficiency profile, it is assumed overall efficiency (heat + power) of the stack is similar to competing boiler technology (circa 90%) and is given by Eq. (3).

$$Overall_{eff} = 0.05r + 0.9, where r is the load factor$$
(3)

This implied that the system has good heat recovery characteristics, with 90% overall efficiency at minimum load, and 95% overall efficiency at maximum load. Note that balance of plant consideration relating to the electrical and overall efficiency profile was simplified in this analysis, being reduced to four basic measures to conservatively account for these loads. These are:

- An additional heat load proportional to stack output—to account for fuel and air pre-heating, and pre-reformer loads (set to 10% in this study).
- An additional electrical load proportional to stack output—to account for blower loads (set to 5% in this study).

- An additional constant electrical load—to account for control system load (set to 50W in this study, designed to combine with the boiler control system load already present in the investigated electricity demand profile).
- System is limited to operate above a load factor of 0.2. Below this level, BOP loads and thermal balancing issues are significant, and our efficiency profile inapplicable.

13.9 UK Residential Energy Demand & Other Input Parameters

From the point of view of a stack manufacturer, in order to obtain an accurate picture of the optimum stack capacity, it is necessary to first obtain a representative picture of the range of electricity and heat demand profiles of potential customers. Other input parameters of interest, with their central estimates, are:

- Stack capital cost—£333 for any stack above zero kWe plus £333kWe-1 installed.
- Boiler capital cost—£1000 for any boiler, plus £50 kWth⁻¹ installed, based on installed cost of a variety of advertised systems.
- 3. Stack lifetime—5 years.
- 4. Boiler lifetime—10 years.
- 5. Discount rate—12%, a basic commercial discount rate.
- Natural gas cost—2.309 p kWh⁻¹ for the first 1143 kWh per quarter, 1.453 p kWh⁻¹ thereafter, based on London Electricity prices at May 1st 2003.
- Electricity import cost—10.79 p kWh⁻¹ for the first 225 kWh per quarter, 6.38 p kWh⁻¹ thereafter, based on London Electricity prices at May 1st 2003.

- 8. Electricity export price—3 p kWh⁻¹, near the UK average wholesale electricity price.
- 9. Maintenance— \pounds 45/year for the boiler, \pounds 20/year for the stack.
- 10. Maximum heat dump—0.5 kWth, through a fan-assisted flue.
- 11. Stack minimum output level—0.2 load factor.
- 12. Boiler minimum capacity—5 kWth, to meet domestic hot water load variations.

This approach avoids introducing potentially confounding factors to the analysis by attempting projections of other input parameters—for example the future trajectories of gas and power prices. Sensitivity analysis is used to indicate the relative importance of the key input assumptions.

13.10 Baseline Result

The baseline result in this study is the case where all electricity demands are met by the grid, and all heat demands are met by importing natural gas for use in a 90% efficient condensing boiler. Results for this analysis are presented in **Table 13-1**, and are used as a check for other results, in that a viable micro-CHP system must yield a result with either equal or lower equivalent annual cost than this baseline.

Grid-boiler baseline result							
Dwelling	EAC (£)	Boiler capacity (kWth)					
Small	791	11.97					
Average	987	14.82					
Large	1361	22.47					

Table 13-1: Grid-Boiler Baseline Results [Hawkes, 2005]

The central estimates of each input variable and demand profiles are input to the CODEGen model, and the stack and supplementary boiler capacities that result in

minimum equivalent annual cost are identified. The optimization results for these input data are presented **Table 13-2**.

Dwelling	EAC (£)	Optimum stack capacity (kWe)	Optimum boiler capacity (kWth)				
Small	791	0	11.97				
Average	987	0	14.82				
Large	1347	1.25	20.58				

Table 13-2: SOFC Micro-CHP Central Estimate Results [Hawkes, 2005]

From **Table 13-2** it is apparent that the central estimate input variables results in only the dwelling with large demand choosing to install an SOFC micro-CHP system. However, decision is marginal as the cost saving between this system and the baseline result (**Table 13-1**) is only £16 per year. Given the large number of assumptions in the central estimates, and significant uncertainty in many of them, this single point solution is of limited value.

13.11 Sensitivity to Stack Capacity

It is of interest to examine how important the optimum stack capacity (i.e. stack capacity that results in minimum equivalent annual cost of meeting energy demand) is in terms of economic benefit to the energy user. If the equivalent annual cost of meeting energy demand across a variety of stack capacities maintains a relatively stable value, one could conclude that manufacturing an optimum capacity stack is relatively unimportant. Alternatively, if the EAC across a variety of stack capacities exhibits a steep gradient then it is more important to determine the optimum stack capacity.



corresponding baseline EAC vs. installed SOFC stack capacity for small, average, and large dwellings. [Hawkes, 2005]

Figure 13-7 plots EAC of meeting energy demand divided by the corresponding baseline EAC, against installed SOFC capacity on the *x*-axis, for each of the three energy consumption profiles and central estimate input parameters.

Figure 13-7 exhibits the typical characteristics of cost versus installed capacity curves. At zero installed CHP capacity, the EAC of meeting energy demand is equal to the baseline cost. As a small amount of CHP capacity is added to the system (i.e. moving a short way right on the *x*-axis), the EAC rapidly increases, consistent with the significant additional cost of having any stack in the system and its associated balance of plant. However, as further CHP capacity is added to the system the benefits obtained from operating the additional CHP capacity begin to outweigh the additional capital cost, and the EAC decreases. Finally, as more CHP capacity is added to the system, and less electricity and heat demand can be served by that capacity, and EAC of meeting energy demand increases (i.e. extra CHP capacity is installed but there is no load for it to serve, thus increasing the capital cost with no operating cost benefit). These tensions between capital and operating costs result in the "tick" shape of all EAC versus capacity curves —

a sharp initial spike, falling to a minimum, and then rising. There is an important difference in the shape of the curves for the three dwellings analyzed. The small dwelling EAC is relatively sensitive to stack capacity (i.e. the "small dwelling" curve is steeper than the other two), whilst the average and large dwellings show relatively less variation in EAC in the 0–5kWe stack capacity range (i.e. their curves have a shallower gradient than the "small dwelling" curve). This means that it is more important to choose the correct stack capacity for dwellings with smaller energy demand. The large dwelling is the only case with a minimum EAC below that of the grid/boiler baseline (represented by the horizontal line on the figure). It also offers relatively little variation in EAC between approximately 0.75 and 2.75kWe stack capacity, implying that a manufacturer could choose a capacity anywhere in this range with little effect upon an investors incentive to purchase the technology. For the small and average dwellings, at the 0.75kWe level, "next-best" stack capacity (i.e. where EAC is lowest, but micro-CHP stack capacity is above zero) is apparent, although it is noted that this system is still inferior to the grid/boiler baseline.

13.12 Sensitivity to Capital Costs

Sensitivity to capital cost is now explored. The estimates of capital costs are used as a guide to obtain **Figures 13-8 to 13-10**, which plot equivalent annual cost against stack capacity for each demand profile under a number of "cost per kWe" scenarios. The fixed cost to include any stack in the system is £333 (US\$600) which is considered to be a basic system cost, and variable costs (per kWe installed) used are £167 (US\$300), £250 (US\$450), £333 (US\$600), £500 (US\$900) and £833 (US\$1500). When the £333 fixed cost is incorporated, these estimates are on average slightly higher because it is perceived

that there is some loss of economies of scale in the 0–5kWe range we are investigating, resulting in higher prices per kWe in this study.

Figures 13-8 and 13-9 show that both the small and average dwellings should only install a fuel cell once the stack cost drops below $\pounds 250 \text{kWe}^{-1}$ plus the $\pounds 333$ basic cost, because the $\pounds 250 \text{kWe}^{-1}$ curves almost touch the horizontal line in the figures which correspond to the grid/boiler baseline. For the large dwelling, this figure is approximately $\pounds 400 \text{kWe}^{-1}$ plus the $\pounds 333$ basic cost.



Figure 13-8: EAC of Meeting Energy Demands in a Small Dwelling [Hawkes, 2005]

Another important result is the rate at which the optimum stack capacity decreases with respect to increasing capital cost. The optimum stack capacity—where EAC reaches a minimum—for the $\pounds 167$ kWe⁻¹ curves (plus $\pounds 333$ basic cost) is at approximately 2, 3, and 5 kWe stack capacity for the small (**Figure 13-8**), average (**Figure 13-9**) and large (**Figure 13-10**) dwellings, respectively. Optimum stack capacity then falls rapidly with increasing stack capital cost in all cases—for the average dwelling to approximately 1

kWe at 250kWe⁻¹ and then zero at £333kWe⁻¹, implying that relatively small changes in the total capital cost of the stack translate to large changes in optimum stack capacity.



Figure 13-9: EAC of Meeting Energy Demands in an Average Dwelling [Hawkes, 2005]

Finally, the lower the capital cost per kWe installed, the less sensitive the EAC is to stack capacity (all curves exhibit a shallower gradient at lower capital cost per kWe). Therefore, if capital costs are low, then precise sizing of the SOFC generator capacity is less important.



Figure 13-10: EAC of Meeting Energy Demands in an Average Dwelling Sensitivity to SOFC Lifetime [Hawkes, 2005]

Stack lifetime estimates suggested that lifetimes of 40,000 h with acceptable voltage degradation are currently achievable for large-scale tubular SOFC technology. As the technology under analysis here is embryonic, a range of lifetimes around this value will be investigated. 3, 5 and 7 years were chosen as the input lifetime values to give an indication of the relevance of this parameter to model outcomes. Industry expectations are for a stack lifetime of 10 years (or boiler-equivalent lifetime), and technology developers are working towards this target. Therefore, the upper limit used here is conservative. The lifetime of the stack does not affect how it is dispatched, but does change the equivalent annual capital cost of the system. Therefore, this section simply observes the effect of changing the annuity factor on the equivalent annual capital cost of the stack.

In **Figures 13-11** to **13-13** stack lifetime clearly has a significant influence on optimum stack size and on system economics generally, although the influence across the

range of lifetimes chosen is less than the influence of capital cost. In all cases the 3-year lifetime stack is not an attractive investment. For 5-year lifetime the large dwelling optimum stack capacity is 1.25kWe, but this investor would choose not to invest for small and average dwellings. For 7-year lifetime, the small and average dwellings become an attractive investment with a 0.75 and 1 kWe stack respectively, and optimum stack capacity for the large dwelling increases to nearly 2 kWe.

Note that the EAC curves become steeper as stack lifetime becomes shorter, implying that a shorter-lived stack owner has more to gain from purchase of a system with an accurate optimum stack capacity. Another interesting result here is that the small energy demand profile appears to benefit more from the increase in lifetime than the average profile (the optimum "average" case EAC just equals the grid/boiler baseline result, whilst the "small" case dips well below that line). An explanation for this lies in the specifics of the energy demand profiles—the small energy demand profile may have more coincidence of electricity and heat demand, or a larger portion of the energy demand within the capacity of stack (i.e. a larger percentage of total electricity demand at lower than the 0.75kWe stack capacity).



Figure 13-11: The Equivalent Annual Cost of Meeting Energy Demand in a Small Dwelling vs. Stack Capacity [Hawkes, 2005]



Figure 13-12: The EAC of Meeting Energy Demand in an Average Dwelling vs. Installed SOFC Stack Capacity [Hawkes, 2005]



Figure 13-13: EAC of Meeting Energy Demand in a Large Dwelling vs. Installed SOFC Stack Capacity [Hawkes, 2005]

13.13 Sensitivity to Electrical Efficiency

The electrical efficiency used in this simulation ranges from roughly 40% at maximum load up to 54% at minimum load (minimum load in this study is load factor of 0.2). It is possible that a manufacturer would be able to develop an SOFC stack with lower electrical efficiency than this for lower cost, without significant loss in overall efficiency (heat + power) of the micro-CHP system. In order to investigate the benefit obtained by the energy user as a result of lower efficiency we subtract a constant 10 and 20% from the electrical efficiency profile, whilst maintaining the overall efficiency (heat + power) of the system. The capital cost for these analyses is fixed at £333 basic cost for any stack plus £333 per kWe of installed capacity.

The first point to note about **Figures 13-14** to **13-16** is that the minimum boiler capacity (5 kWth) begins to play an increasing role in the economics of the system. For example, in **Figure 13-14**, for–20% electrical efficiency, the EAC versus capacity curve

exhibits a discontinuity at 2 kWe stack capacity where EAC begins to increase more rapidly. This is the point where a trade-off between increased stack capacity and reduced boiler capacity can no longer be achieved because minimum boiler capacity has been reached. This trend is evident to a greater or lesser degree in each of **Figures 13-14** to **13-16**.



Figure 13-14: EAC of Meeting Energy demand in a Small Dwelling vs. Installed SOFC Stack capacity [Hawkes, 2005]

Another point regarding electrical efficiency is that the most drastically reduced stack electrical efficiency of -20% results in a larger "next-best" stack capacity (i.e. if the grid/boiler baseline is ignored represented by the horizontal lines in the figures, and take the "next-best" stack capacity based on lowest EAC) in all three cases. From a manufacturers point of view this is interesting because the larger stack may generate higher revenue for the manufacturer from its sale and may be cheaper to manufacture because it is less electrically efficient, but can still provide the customer with close to the best EAC outcome. However, this conclusion would require further analysis, as the

"-20%" case is not competitive with the grid/boiler baseline result in any of the dwellings.



Figure 13-15: EAC of Meeting Energy demand in an Average Dwelling vs. Installed SOFC Stack Capacity [Hawkes, 2005]



Figure 13-16: EAC of meeting energy demand in a large dwelling vs. installed SOFC stack capacity (sensitivity over a range of stack electrical efficiencies) [Hawkes, 2005]

13.14 Sensitivity to Electrical Export Prices

The prevailing spark-spread is an important factor when considering investment in CHP. For residential premises that wish to sell electricity generated, the price difference between the sell price and the cost to generate power does not need to be positive for the generator to be dispatched. This is because the cost to meet onsite heat demand may be lower using the CHP unit (and gaining some small revenue from any incidental electricity export) than using the additional boiler, or it may be economically efficient to dump excess heat (limited to 0.5 kWth dump in Hawkes' study) and gain revenue from the exported power. This tension between natural gas price and electricity export price is important in choosing optimum stack capacity, and is investigated through a sensitivity analysis to electricity export prices. Export prices used are 0, 2, and 4 p kWh⁻¹. All other input variables are identical to the central estimates.



Figure 13-17: EAC of Meeting Energy Demand in a Small Dwelling versus Installed SOFC Stack Capacity [Hawkes, 2005]



Figure 13-18: EAC of Meeting Energy demand in an Average Dwelling versus Installed SOFC Stack Capacity [Hawkes, 2005]



Figure 13-19: EAC of Meeting Energy demand in a large dwelling versus installed SOFC Stack Capacity [Hawkes, 2005]

The results in **Figures 13-17** to **13-19** show the importance of revenue from electricity export for stack economics. High electricity export prices, of the order of 4 p kWh⁻¹, indicate much improved EAC, and push the optimum stack capacity to the 1 kWe

vicinity for the small and average dwelling cases, and to above 2 kWe for the large dwelling case.

On the other hand, low export prices suggest much poorer economics at high stack capacities, and relatively unchanged outcomes at low stack capacities where the system is operating in the base load of the dwelling and therefore electricity export is less important as all electricity is being used onsite.

There is clearly a critical point between 2 and 4 p kWh⁻¹ electricity export price where EAC improves significantly and the curve flattens over the range of stack capacities. This is because the revenue gained from export begins to outweigh the increased capital cost of the stack, making it justified to follow a larger portion of the heat load and therefore export more power. However, a number of complex interactions are at work here such as the high part-load efficiency (which can make it economically efficient to generate at low load factors, but not at high load factors), tensions between the fuel/electricity import prices and export prices, and the trade-off between the cost of increased stack capacity or increased boiler capacity to meet heat demands.

13.15 Conclusion

The focus of Bottom-Up design is "*what can we most efficiently do with this technology*?" rather than the focus of Top-Down which is "*What is the most valuable thing to do*?"

Fuel cell design and development requires that engineers and developers consider trade-offs between power system attributes in the areas of cost, weight, manufacturability, quality, and performance.

Using the Bottom-Up design approach, to determine the "optimum" design is in fact usually one in which compromises are acceptable, but understanding the impact of design decisions on all relevant attributes is tremendously difficult.

Hawkes' study showed that the optimum energy delivery system was zero stack capacity (i.e. grid/boiler only system) for small and average UK residential dwellings using central estimates of input parameters. A large dwelling demand profile yielded an optimum stack capacity of 1.25kWe, indicating that under current conditions this application is likely to be the first target market. However, due to a great deal of uncertainty regarding these parameters, a sensitivity analysis was then performed on key economic drivers. Variation in stack capital cost per kWe, electricity export prices, and energy import prices were found to be the most important of the investigated factors, where small changes in these parameters translated to large changes in optimum stack capacity, equivalent annual cost and the sensitivity of economic performance to system sizing. A change in capital cost from \pounds 333 to \pounds 250kWe⁻¹ (plus a basic system capital cost of £333), or a change in electricity export price from 3 to 4 p kWh⁻¹, or a positive movement in energy import prices improved the annual cost for the small and average dwellings to the point where they represent a reasonable investment with a stack capacity of the order of 1 kWe.

The other two sensitivity analyses performed were for stack lifetime and stack electrical efficiency. Stack lifetime is also an important factor, although less so than stack capital cost over the range of investigated values. Increasing the lifetime to 7 years from the 5 year central estimate resulted in all demand cases becoming viable with small stack

capacities. This result is intuitive as it relates to the longer period of operation of the equipment, resulting in an increased period over which the initial investment is spread.

The stack electrical efficiency sensitivity analysis illustrated the relative unimportance of extremely electrically efficient technology for residential applications with significant heat demand. Provided the overall efficiency (heat + power) of the system is maintained at high levels, an optimally dispatched system will achieve similar cost savings regardless of electrical efficiency.

CHAPTER XIV

THE DESIGN DECISIONS FOR THE CELL STACK- PHASE TWO

14.1 Introduction

The typical automobile or commercial vehicle such as a truck is constructed from the ground up (and out).





Likewise, a fuel cell system is designed from the 'engine' out (and around). While there are multiple components and systems in an automobile that have to function as designed, they must also work in harmony with the complete automobile. Likewise, the balance-of-plant (BOP) subsystems must work in harmony and unison with each other to
provide the system's 'engine', the Cell Stack, with the requirements it needs to function. Before the balance-of-plant subsystems are designed the Cell Stack configuration must be laid out.

14.2 The Four Design Criteria for the Cell Stack's Performance

1. Electrical performance:

- Minimize ohmic losses thus the current path in the components (especially those having low electrical conductivity) must be designed to be as short as possible;
- There must be good electrical contact and sufficient contact area between the components;
- The current collector must also be designed to facilitate current distribution and flow in the Cell Stack Package.

2. Electrochemical performance:

- Design must provide for full open circuit voltage and minimal polarization losses thus significant gas leakage or cross-leakage and electrical short must be avoided;
- Fuel and oxidant must be distributed uniformly not only across the area of each cell but also to each cell of the Cell Stack Package;
- The gases must be able to quickly reach the reaction sites to reduce potential for mass transport limitations.

3. Thermal management:

- Means for stack cooling and more uniform temperature distribution during operation.
- The design must permit the highest possible temperature gradient across the Cell Stack Package.

4. Mechanical/structural integrity:

 Adequate mechanical strength for assembly and handling. Mechanical and thermal stresses must be kept to minimum to prevent cracking, delamination or detachment of the components under the variety of operating conditions the stack can experience.

14.3 The Cell Stack Design and Integrity - Which unit cell and cell stack

configuration should be considered?

For most practical fuel cell applications, unit cells must be combined in a modular fashion into a cell stack to achieve the voltage and power output level required for the application. Generally, the stacking involves connecting multiple unit cells in series via electrically conductive interconnects. Different stacking arrangements have been developed, which are described below.



Figure 14-2: Example of a schematic diagram of the planar SOFC design [http://www.spice.or.jp/~fisher/sofc.html#descript]

14.4 How Many Stacks in the Cell Stack Package?

Power as a function of Voltage and Current is represented by the equation:

W(V, I) = V * I

Where: V = Voltage(V)

I = Current (Amps.)

Ideally, high voltage and low ampere is preferred due to higher efficiency and lower cost of wire.

Let Voltage Output = 80 V DC and Current = 50 Amps.

Given, a DC/AC converter's efficiency is 93% the desired output of the SOFC

Power System is $3,763W_{DC}$. When using the desired operating point of 700 mV and 300 mA/cm² @ 85% fuel utilization, and the active cell area to be 400 cm². According to current industry experience, cells with an active area of 400 cm² can be manufactured.



Figure 14-3: Active Area of a Fuel Cell [http://thefraserdomain.typepad.com/energy/2006/10/effficient_fuel.html]

Note from a 2001 study, it was shown that the cell performance for a fixed stack size was investigated for a fuel utilization of 85%. The effect of varying operating cell voltage on the cost of electricity (COE) and system electric efficiency is shown in the below figure. At 650 mV operation, the reference COE is 6.3ϕ /kWh. The unit system capital cost (not including installation, transportation or contingency fees) associated with an average 650mV cell voltage was 1100 \$/kW. As the operating voltage increased (increasing fuel conversion efficiency), the cell-stack costs began to increase at a rate greater than operating costs because lower current densities result and therefore larger cell areas were required. Continued increases in fuel efficiency could not pay for increases in capital costs, which were dominated by the fuel cell stack, and the selling price of electricity had to be raised to compensate. The minimum cost occurred at a cell voltage of 700 mV with a corresponding system efficiency of 52%.





Power is the product of voltage and current, first determine the total current for the fuel cell as:

$$I = P/V = (3,763 \cdot W_{DC} / 0.700 \text{ V}) * (1 \text{VA} / 1 \text{ W}_{DC}) = 5.38 \text{ kA}$$

Because each individual cell will operate at 400 mA/cm², determine the total area as:

AREA = 1/CURRENT DENSITY =

$$= (5.38 \text{ kA}/(300 \text{ mA}/\text{ cm}^2))*(1,000 \text{ mA}/1\text{A})*(1,000 \text{ A}/1\text{kA}) = 17,933.3 \text{ cm}^2$$

The number of cells required is:

NUMBER OF CELLS = 17,933.3-cm²*(1 cell/400 cm²) = 44.8 or 45 Cells

The number of stacks required is:

45 Cells per Stack = 1 Stack

14.5 Considering the operating temperature range, what material options are there for the electrolyte?

When selecting a raw material for electrolyte three physical characteristics are important: increased surface area, finer average particle size, and a narrower particle size distribution. These characteristics make for an excellent choice for enhancing triple-phase boundary areas in composite electrodes, reducing process temperatures, for developing new process technologies. Below are some examples of materials which can be used as electrolyte raw material.



Figure 14-5: There is a long and expanding set of materials that are being developed for fuel-cell applications [Kee, 2004]

• Yttria-Stabilized Zirconia 8 mole% TC Grade (YSZ8-TC)

Fully stabilized powder suitable for tape casting, ink manufacture, pellet pressing

and other non-aqueous manufacturing processes.

Specifications:

Formulation: (Y2O3)_{0.08} (ZrO2)_{0.92}

Surface Area: 6-9 m²/g

Particle Size (d50): 0.5 to 0.7 μ m.

• Gadolinium Doped Ceria (10% Gd) TC Grade (GDC10-TC)

Powder suitable for tape casting, ink manufacture, pellet pressing and other non-

aqueous manufacturing processes.

Specifications:

Formulation: Gd_{0.10} Ce_{0.90} O₂₋

Surface Area: 5-8 m²/g

Particle Size (d50): 0.3 to 0.5 µm.

• Samarium Doped Ceria (15% Sm) TC Grade (SDC15-TC)

Powder suitable for tape casting, ink manufacture, pellet pressing and other non-

aqueous manufacturing processes.

Specifications:

Formulation: Sm_{0.15} Ce_{0.85} O₂₋

Surface area: $5-8 \text{ m}^2/\text{g}$

Particle Size (d50): 0.3 to 0.5 µm

• Scandium Ceria Stabilized Zirconia (10Sc1CeSZ)

Powder suitable for tape casting, ink manufacture, pellet pressing and other non-

aqueous manufacturing processes.

Specifications:

 $(Sc_2O_3)_{0.1}(CeO_2)_{0.01}(ZrO_2)_{0.89}$

Surface Area: 10-12 m²/g

Particle Size (d50): 0.5 to 0.7 μ m.

14.6 Considering the electrolyte will be made from zirconia, what will be the dopant percent?

Zirconia doped with 8 to 10 mole % yttria (yttria-stabilized zirconia (YSZ) is still the most effective electrolyte for the high temperature SOFC (but others such as Bi^2O^3 , CeO^2 and Ta^2O^5 have been also investigated with mixed success). Above the temperature of 800°C zirconia becomes a conductor of oxygen ions (O=) and typically the state of the art zirconia based SOFC operates between 800 and 1100°C.

Advantages:

Zirconia is highly stable in both the reducing and oxidizing environments that are experienced at the anode and cathode, respectively; the ability to conduct O=ions is brought about by the fluorite crystal structure of zirconia in which some of the Zr^{4+} ions are replaced by Y^{3+} ions. When ion exchange occurs, a number of oxide-ion sites become vacant because of three O=ions replacing four O= ions. Oxide-ion transport occurs between vacancies located at tetrahedral sites in the perovskite lattice. The ionic conductivity of YSZ (0.02 Scm⁻¹at 800°C and 0.1 Scm⁻¹at 1000°C) is comparable with that of liquid electrolytes and it can be made very thin (25-50 μ m) ensuring that the ohmic loss in the SOFC is comparable with other fuel cell types.

14.7 Considering the Unit Cell design, which anode material should be selected?

Nickel Oxide-GDC Anode Powder for Coating Applications (NiGDC-P)
 Material has complex composition optimized for creating thin, highly catalytic layers. Can be used with ceria- or zirconia-based electrolytes. A current anode

layer is recommended. Firing temperatures are on the order of 1200-1350°C. Adhesion tests are recommended.

Specifications:

Composition: 60% NiO - 40% GDC10 by weight

Surface Area: $4-8 \text{ m}^2/\text{g}$

Nickel Oxide-SDC Anode Powder for Coating Applications (NiGDC-P)

Material has complex composition optimized for creating thin, highly catalytic layers. Can be used with ceria- or zirconia-based electrolytes. A current collecting anode layer is recommended. Firing temperatures are on the order of 1200-

1350°C. Adhesion tests are recommended.

Specifications:

Composition: 60% NiO - 40% SDC20 by weight

Surface Area: 4-8 m²/g

Nickel Oxide-YSZ Anode Powder for Coating Applications (NiYSZ-P)

Material has simple composition optimized for creating conducting layers. The powder is designed to be processed by tape casting. Most often used in conjunction with a catalytic anode layer and is recommended to be used with our NiO-GDC. Firing temperatures are on the order of 1350-1400°C. Adhesion tests are recommended.

Specifications:

Composition: 66% NiO - 34% YSZ8 by weight

Surface Area: 4-8 m²/g

The anode is usually a zirconia cermet (an intimate mixture of ceramic and metal). The metallic component is usually Ni (nickel chosen amongst other things because of its high electronic conductivity and stability under chemically reducing and part reducing conditions; it can also be used as catalyst for direct internal reforming on the anode).

14.8 Which cathode material should be selected for a fuel cell design?

Lanthanum Strontium Manganite (20%) Cathode Powder (LSM20-P)

LSM is readily formulated into an ink for coating onto electrolyte substrates. Tape casting is possible as well. LSM works well at higher temperatures and is normally used with zirconia-based electrolytes. Slightly A-site deficient (non-stoichiometric).

Specifications:

Formulation: La_{0.80} Sr_{0.20} Mn O₃₋

Surface area: $4-8 \text{ m}^2/\text{g}$

Particle Size (d50): 0.3 to 0.6 µm

Lanthanum Strontium Cobalt Iron Oxide (LSCF-P) Cathode Powder

LSCF is readily formulated into an ink for coating onto electrolyte substrates. Tape casting is possible as well. LSCF works well at lower temperatures and is normally used with ceria-based or lanthanum gallate electrolytes. Slightly A-site deficient (non-stoichiometric).

Specifications:

Formulation: La_{0.60} Sr_{0.40} Co_{0.20} Fe_{0.80} O₃₋

Surface area: $4-8 \text{ m}^2/\text{g}$

Particle Size (d50): 0.3 to 0.6 µm

Manganese Cobalt Oxide Premium Spinel Powder (MCOA-HP)
 Specifications:
 Formulation: Mn_{1.5} Co_{1.5} O₄.

Surface Area: $12.0 + - 2.0 \text{ m}^2/\text{g}$ Particle Size: $0.30 + - 0.20 \text{ }\mu\text{m}$.

Cathodes proved to be difficult from the point of view of choosing the right material (initially noble metals were used but proved too expensive for mass production). At present, most cathodes are made from electronically conducting oxides or mixed electronically conducting and ion-conducting ceramics. The most common cathode material of the latter type is strontium-doped-lanthanum manganite (SLM).

14.9 Which Stack arrangement should be used?

In the Planar SOFC design, cell components are configured as flat plates which are connected in electrical series:

- SOFC Short stack planar (Julich)
- Integrated Planar (Rolls Royce)



Figure 14-6: Types of Supported Unit Cell Configurations



Figure 14-7: Micrograph of a planar cell on porous metal structure

14.10 Tubular

- SOFC Siemens Westinghouse (relatively large diameter >15 mm)
- Microtubular SOFC (Adelan) (diameter < 5 mm)

Two general types are being pursued:

- Large diameter (> 15 mm) (Siemens Westinghouse Power Corporation)
- Very small diameter (< 5 mm) (Adelan, UK; Adaptive Materials Inc., USA).



Figure 14-8: Tubular SOFC Design







Figure 14-10: Cross-section of a Tubular Unit Cell

The cell components are deposited in the form of thin layers on a cylindrical tube. In the earlier designs the tube was made of calcia-stabilized zirconia; this porous support tube (PST) acted both as a structural member onto which the active cell components were fabricated and as a functional member to allow the passage of air to the cathode during cell operation. This porous support tube was fabricated by extrusion followed by sintering at an elevated temperature (problems with air flow); the porous support tube was eliminated and replaced by a doped LaMnO₃tube (air electrode-supported cell, AES) leading to significant improvements in performance (see next figure).



Figure 14-11: The Flow Paths of a Tubular Design

Table 14-1 CELL CONFIGURATIONS [Fuel Cell Handbook, 2004]			
Cell configuration	Advantage	Disadvantage	
Self-supporting			
Electrolyte supported	Relatively strong structural support from dense electrolyte Less susceptible to failure due to anode re-oxidation	Higher resistance due to lower electrolyte conductivity Higher operating temperatures required to minimize ohmic loses	
Anode supported	Highly conductive anode Lower operating temperature via use of thin electrolyte	Potential anode re-oxidation Mass transport limitations due to thick anodes	
Cathode supported	No oxidation issues Lower operating temperature via use of thin electrolyte	Lower conductivity Mass transport limitation due to thick cathodes	

14.11 Which cell configuration should be used?

Table 14-2 DIFFERENT CELL CONFIGURATIONS EXTERNAL SUPPORTING [Fuel Cell Handbook, 2004]			
Interconnect supported	Thin cell components for lower operating temperature Stronger structures from metallic interconnects	Interconnect oxidation Flow field design limitations due to cell support requirement	
Porous substrate	Thin cell components for lower operating temperature Potential for use of non-cell material for support to improve properties	Increased complexity due to addition of new materials Potential electrical shorts with porous metallic substrate due to uneven surface	

14.12 How thick should the electrolyte be and which fabrication techniques are available to obtain the desired thickness?

Based on deposition approach a wide range of techniques have been used focusing on the aim of making thin (5-20 μ m) YSZ electrolytes:

- Sputtering-involving electrical discharge in argon/nitrogen mixtures to deposit YSZ;
- Dip coating -porous substrates are immersed in YSZ slurries of colloidal size particles. Deposited films are then dried and fired;
- Spin coating-YSZ films are produced on a dense or porous substrate by spin coating a sol-gel precursor followed by heat treatment at relatively low temperatures;
- Spray pyrolysis-a solution consisting of powder precursor and /or particles of the final composition is sprayed onto a hot substrate followed by a sintering step to densify the deposited layer;
- Other methods-electrophoretic deposition, slip casting, plasma spraying, electrostatic assisted vapor deposition, vacuum evaporation, laser spraying, transfer printing, sedimentation method, and plasma metal organic chemical vapor deposition.

14.13 Which Specific Model of a Cell Stack Package will be used?

Many current stack designs in the range of the application used in this research (1–4 kW_e) are moving towards planar designs the considered geometry for the SOFC cells is therefore planar type with internal fuel and air manifolding. A detailed quasi-2D SOFC channel model based on electrochemical, mass and energy balances was developed

and extrapolated for the entire cell–stack. A schematic of the cell model is shown in **Figure 14-12**. As can be seen, the planar SOFC channel is divided into series of piped-type volumes (cells), where the number and dimensions can be defined by the user. The finite volume method is used to discretize the governing equations on each cell.



Figure 14-12: Cell geometry and unit element configuration [Recknagle, 2010]

14.14 What about Gas Manifolding

The choice of gas-flow arrangement depends on the type of fuel cell, the application, and other considerations. Finally, the manifolding of gas streams to the cells in bipolar stacks can be achieved in various ways:

- 1. Internal: the manifolds run through the unit cells.
- 2. Integrated: the manifolds do not penetrate the unit cells but are integrated in the interconnects.
- 3. External: the manifold is completely external to the cell, much like a wind-box.

The most common fuel cell stack design is the so-called planar-bipolar arrangement.

Individual Unit Cells are electrically connected with interconnects. Because of the

configuration of a flat plate cell, the interconnect becomes a separator plate with two functions:

- To provide an electrical series connection between adjacent cells, specifically for flat plate cells, and
- 2. To provide a gas barrier that separates the fuel and oxidant of adjacent cells.

The most important design feature of the Planar SOFC relates to gas flow configuration and gas manifolding which can be arranged in several ways. Fuel and oxidants flows can be arranged as cross-flows, co-flows or counter-flow with potentially significant effects on temperature and current distribution within the stack depending on the stack precise configuration. In many planar-bipolar designs, the interconnect also includes channels that distribute the gas flow over the cells. The planar-bipolar design is electrically simple and leads to short electronic current paths (which helps to minimize cell resistance). Planar-bipolar stacks can be further characterized according to arrangement of the gas flow:

- 1. Cross-flow. Air and fuel flow perpendicular to each other
- 2. Co-flow. Air and fuel flow parallel and in the same direction. In the case of circular cells, this means the gases flow radially outward
- 3. Counter-flow. Air and fuel flow parallel but in opposite directions. Again, in the case of circular cells this means radial flow
- 4. Serpentine flow. Air or fuel follow a zig-zag path
- 5. Spiral flow. Applies to circular cells

14.15 What are the Model's Assumptions?

The main assumptions of the model are:

- uniform distribution of feed gases to each individual cell in the stack and among the channels;
- 2. steady-state condition;
- 3. 1D cell representation along the stream wise direction;
- each of the gas channels in the unit cell acts as continuously stirred tank reactors (CSTR);
- 5. lumped temperature of the solid cell structure:
- due to the high conduction electrodes and current collector acts as isopotential surfaces;
- 7. A constant Nusselt number is assumed. In heat transfer at a boundary (surface) within a fluid (or gas), the Nusselt number is the ratio of convective to conductive heat transfer across (normal to) the boundary. Named after Wilhelm Nusselt, it is a dimensionless number. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. A Nusselt number close to unity, namely convection and conduction of similar magnitude, is characteristic of "slug flow" or laminar flow. A larger Nusselt number corresponds to more active convection, with turbulent flow typically in the 100–1000 range.

Any combination of H_2 , CO, CO₂, H_2O , CH₄ and N_2 is allowed as fuel composition, and the oxygen fraction in the cathode gas can be set to any value.

14.16 What are the quantified losses which affect (decrease) the Unit Cell's voltage? Define the Electrochemical model of the Unit Cell.

The Nernst equation, for hydrogen, (considering the complete calculation of activation, ohmic and diffusion losses equations (1) and (2)) are used for modeling the electrochemical performance of the SOFC:

$$V_{op} = V_{Nernst} - \left(\eta_{ohm} + \eta_{act} + \eta_{diff}\right)$$
(1)

$$V_{\text{Nernst}} = E^{0} + \frac{RT_{\text{PEN}}}{n_{e}F} \ln\left(\frac{X_{\text{H}_{2},b}(X_{\text{O}_{2},b})^{0.5}}{X_{\text{H}_{2}\text{O},b}}\right) + \frac{RT_{\text{PEN}}}{2n_{e}F} \ln\left(\frac{P_{\text{Ca}}}{P^{0}}\right)$$
(2)

The calculation of the ohmic voltage losses follows Ohm's law:

$$\eta_{\rm ohm} = i R_{\rm eq,ohm} \tag{3}$$

In the equations a method is presented for the calculation of the ohmic equivalent resistance. In this method it is assumed that the current flow path is directed perpendicularly to the cell plane. Then the resistance of the cell, estimated by subdividing the cell into three parts, namely air channel interconnector, solid structure of anode, electrolyte and cathode layers (PEN), and fuel channel interconnector, all of which act as series of resistances.

The Butler–Volmer equation is one of the most fundamental relationships in electrochemistry. It describes how the electrical current on an electrode depends on the electrode potential, considering that both a cathodic and an anodic reaction occur on the same electrode. The activation losses are due to the energy barrier to be overcome in order for the electrochemical reaction to occur, and can be characterized by the Butler– Volmer equation:

$$J = J_0 \left\{ \exp\left(\beta \frac{n_e F \eta_{act}}{RT_{PEN}}\right) - \exp\left[-(1-\beta) \frac{n_e F \eta_{act}}{RT_{PEN}}\right] \right\}$$
(4)

The complete form of Eq. (4) with b ¹/₄ 0.5 is considered in the present model. The diffusion polarization can be described in a variety of ways. Two levels of diffusion phenomena between the bulk gas phase to the electrode surface and between electrode surface and triple phase boundary (TPB) have been applied in the model as follows:

$$\eta_{\rm diff,Ca} = \frac{RT_{\rm PEN}}{4F} \ln\left(\frac{X_{\rm O_2,b}}{X_{\rm O_2,TPB}}\right)$$
(5)

$$\eta_{\text{diff},\text{An}} = \frac{RT_{\text{PEN}}}{2F} \ln\left(\frac{X_{\text{H}_2\text{b}}X_{\text{H}_2\text{O},\text{TPB}}}{X_{\text{H}_2\text{O},\text{b}}X_{\text{H}_2,\text{TPB}}}\right)$$
(6)

In the electrochemical model, binary diffusion is considered to calculate the gas concentrations in the electrode surfaces. Both ordinary diffusion and Knudsen diffusion may occur simultaneously in the porous media and the effect of these can be considered with the effective diffusion coefficient.

Knudsen diffusion is a means of diffusion that occurs in a long pore with a narrow diameter (2–50nm) because molecules frequently collide with the pore wall. In the Knudsen diffusion regime, the molecules do not interact with one another, so that they move in straight lines between points on the pore channel surface. Self-diffusivity is a measure of the translational mobility of individual molecules. Under conditions of thermodynamic equilibrium, a molecule is tagged and its trajectory followed over a long time. If the motion is diffusive, and in a medium without long-range correlations, the

squared displacement of the molecule from its original position will eventually grow linearly with time (Einstein's equation). Therefore, the diffusion between the surfaces and TPB is calculated considering the effective diffusion coefficient.

14.17 What is the mass balance of the FC Power System?

A mass balance (also called a material balance) is an application of conservation of mass to the analysis of physical systems. By accounting for material entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure without this technique. The exact conservation law used in the analysis of the system depends on the context of the problem but all revolve around mass conservation, i.e. that matter cannot disappear or be created spontaneously.

Mathematically the mass balance for a system without a chemical reaction is as follows:

Input = Output + Accumulation

Strictly speaking the above equation holds also for power systems with chemical reactions if the terms in the balance equation are taken to refer to total mass i.e. the sum of all the chemical species of the system. In the absence of a chemical reaction the amount of any chemical species flowing in and out will be the same. This gives rise to an equation for each species in the system. However if this is not the case then the mass balance equation must be amended to allow for the generation or depletion (consumption) of each chemical species. Some use one term in this equation to account for chemical reactions, which will be negative for depletion and positive for generation. However, the

conventional form of this equation is written to account for both a positive generation term (i.e. product of reaction) and a negative consumption term (the reactants used to produce the products). Although overall one term will account for the total balance on the system, if this balance equation is to be applied to an individual species and then the entire process, both terms are necessary. This modified equation can be used not only for reactive systems, but for population balances such as occur in particle mechanics problems. The amended equation is given below; Note that it simplifies to the earlier equation in the case that the generation term is zero.

Input + Generation = Output + Accumulation + Consumption

Mass balance models must be created and calculated to determine the compositions in the fuel and air channels due to the electrochemical reactions, water–gas-shift reactions, and mass transfer of the chemical species.

As the chemical reaction rate depends on temperature it is often necessary to make both an energy balance (often a heat balance rather than a full fledged energy balance) as well as mass balances to fully describe the system. Different reactor models might be needed for the energy balance: A system that is closed with respect to mass might be open with respect to energy e.g. since heat may enter the system through conduction.

14.18 Define a temperature profile of the SOFC.

In the SOFC energy analysis, the different temperature layers can be used to calculate the temperature profiles in the SOFC. Different approaches with one to five temperature layers are presented in the literature. However, there are no guidelines available how to

properly select temperature layers. To improve the accuracy of the specific model, five temperature layers have been considered:

- 1. The PEN
- 2. The air channel
- 3. The fuel channel
- 4. The air interconnector
- 5. The fuel interconnector

In the middle of a planar SOFC stack, the air and fuel side interconnectors of adjacent cells could be considered as one temperature layer, but a separate temperature layer is used here for future investigations of the cells at the boundaries of the stack.





A schematic of the energy flow for a unit element is shown in Figure 14-13. In

Figure 14-13, *ERea*, *EPro* are the energies related to the mass transfer of reaction products and to the reactants between bulk gases and PEN or vice versa. *q Rad PEN*, *Ic* is the radiation heat exchange between PEN and interconnector.

14.19 What will be the Pressure Losses of the Fuel and Air Channels?

In the SOFC channels, the gas flow is not isothermal, but the flow can be assumed to be laminar and fully developed due to the small size of the channels. The fully developed laminar flow solutions of the Navier–Stokes equations or steady Hagen– Poiseuille analysis can be used for the calculation of the pressure losses.

The Navier–Stokes equations describe the motion of fluid or gaseous substances. These equations arise from applying Newton's second law to fluid (gas) motion, together with the assumption that the fluid stress is the sum of a diffusing viscous term (proportional to the gradient of velocity), plus a pressure term. The Navier–Stokes equations dictate not position but rather velocity. A solution of the Navier–Stokes equations is called a velocity field or flow field, which is a description of the velocity of the fluid at a given point in space and time.

In fluid dynamics, the Hagen–Poiseuille equation is a physical law that gives the pressure drop in a fluid flowing through a long cylindrical pipe. The assumptions of the equation are that the flow is laminar viscous and incompressible and the flow is through a constant circular cross-section that is substantially longer than its diameter. The fluid flow will be turbulent for velocities and pipe diameters above a threshold, leading to larger pressure drops than would be expected according to the Hagen–Poiseuille equation.



Figure 14-14: a) A tube showing the imaginary lamina. b) A cross section of the tube shows the lamina moving at different speeds. Those closest to the edge of the tube are moving slowly while those near the center are moving quickly [Recknagle, 2010]

Considering the definition of the hydraulic diameter and the related Reynolds number, the mass-flow rate in the channel, in function of the net pressure difference from the channel inlet to the outlet, is calculated as:

$$\dot{m} = \left(\frac{1}{\text{Ref}} \frac{D_{h}A_{Ch}}{2L_{Ch}} \frac{\rho}{\mu}\right) (P_{In} - P_{Out}) = K_{c}(P_{In} - P_{Out})$$
(12)

Where, 'm' is the dynamic viscosity of the fluid. The constant K_c , flow conductance, characterizes the proportionality between the mass-flow rate in a channel and the net pressure difference from inlet to outlet. In the present model, the flow conductance Kc is constructed based on the viscous effects in the channels.

$$K_{c} = \left(\frac{1}{\text{Ref}} \frac{D_{h} A_{Ch}}{2L_{Ch}} \frac{\rho}{\mu}\right)$$
(13)

14.20 Conclusion

Before the balance-of-plant (BOP) subsystems are designed the Cell Stack configuration must be laid out. The four design criteria for the Cell Stack's performance are: electrical performance, electrochemical performance, thermal management, and mechanical/structural integrity.

CHAPTER XV

DESIGN CHANGES – PHASE TWO

15.1 Introduction

In the Preliminary System Design Phase, fuel cell power system designs are continuously modified and changed until a working breadboard design is frozen. As a result, most power system development involves the steady evolution of an initial design. This is necessary, both to eliminate mistakes that have been made during the initial design and development process, and to adapt the design to new requirements and/or different requirements depending on if the customer (end user) changes. Regardless of the causes of these changes, the challenges involved in implementing them are the same.

15.2 Change Propagation in Complex Designs

The degree to which change propagates through a product depends on the complexity of the product itself. Simon defines the complexity of a product in terms of the connections between its parts, and calls engineering products "*almost decomposable*

systems" where connections between parts of a system can never be fully avoided. Suh advocates an axiomatic approach to design, where the functional structure of a product is well organized and its information content minimized, thus clarifying the functional role of each part of the product. Such an approach can reduce complexity and the propagation of change.

However, few products are designed with these principles in mind. This is unfortunate because all parts of a design are connected to at least one part; design changes can also be connected. If part A is changed then part B might need changing. A change to part B leads to a change in C, which in turn might be connected to part D. A single design change may set off a series of others, transforming the initial modification into a flow of change that propagates, often unexpectedly, through large sections of the design.

During the Preliminary System Design Phase of development, because how funding sources are set up, the customer requirements for an SOFC Power System might change many times before a working breadboard design is acceptable and frozen. For example, if the initial customer selected is the agricultural industry, and that market requires that the power system must operate on bio-fuel, the power system's design will be tailored to operate on this type of fuel. If agricultural funding decreases or is curtailed, or if these monies were the developers' sole source of the company's '*bread and butter*', then the fuel cell developers will seek funds elsewhere. If the developers' new '*paying*' customer is in the transportation sector and the power system is required to operate on diesel fuel and be fitted to operate on a truck APU, then the design might need to be changed and rework will occur. If the funding source changes once more, with the

military being the third customer requiring the power system to operate on military fuel, and the system must be fitted for an airplane and/or submarine, then the design might go through another change.

Depending on the limited resources that a fuel cell company has, a vicious fundseeking/system-redesign cycle (the redesign trap of death) might be created, which quite possibly will see the product's death before its market entry because the power system will never reach its second phase of development and beyond.

The developer's motives might be questioned. An undesirable reputation and image as a corporate welfare recipient, whom sole business plan (*scam*) is to '*devour*' developmental funding, might be attributed to the developer. Needless to say, to avoid these consequences and ill side-effects, a method for speedy, thorough redesign and rework is needed if fuel cell systems are to continue on in their lifecycle.



Figure 15-1: Analytical Planning is the Defender of a Reputation [http://www.reputation.com]

On the other hand, the honest innovative developers, the ones who have every intention of commercializing, those who are making every effort towards this aim, have invested in the project with their own blood, sweat and tears, must use a systematically organized design effort to escape, what the author calls '*the redesign death trap*'.

If redesign and rework are unavoidable, for whatever reasons, many industries, such as the automotive industry, are developing methodologies for rework and redesign. During redesign and design for customization, a change to one part of the product will, in most cases, result in changes to other parts. The prediction of such change provides a significant challenge in the management of redesign and customization of complex products such as fuel cell power systems, where many change propagation paths may be possible.

As a system engineering example, this chapter will report on an analysis of change behavior based on a case study in Westland Helicopters of rotorcraft design; the development of mathematical models to predict the risk of change propagation in terms of likelihood and impact of change; and the development of a prototype computer support tool to calculate such information for a specific product. With knowledge of likely change propagation paths and their impact on the delivery of the product, design effort can be directed towards avoiding change to "*expensive*" sub-systems and, where possible, allowing change where it is easier to implement while still achieving the overall changes required. The author of this paper believes that the work of Clarkson (et al) and his systems engineering methodology could greatly aid and direct the fuel cell industry closer towards commercialization so it is included in this paper.

15.3 An Example of a Complex Design

The AgustaWestland AW101 (rebranded from EH101 in June 2007) is a mediumlift helicopter for military applications but also marketed for civil use. The helicopter was developed as a joint venture between Westland Helicopters in the UK and Agusta in Italy (now merged as AgustaWestland). The aircraft is manufactured at the AgustaWestland

factories in <u>Yeovil</u>, England and <u>Vergiate</u>, Italy. The first group of production EH101s for the RAF began arriving in 1997. In 2002 Westland made an unsolicited and unsuccessful offer to provide the MoD with an enhanced version of the Merlin to meet the UK's demand for lift capability. Westland and Agusta merged together to form AgustaWestland International Limited in July 2000, closing down EHI as a separate entity shortly afterwards. Consequently in June 2007 the EH101 was re-branded as the AW101.

The systems of a helicopter are highly interconnected through functional parameters such as balance and vibration, while being minimized for weight. In comparison to other products, and like fuel cell systems, military helicopters are produced in very low volumes. Often fewer then 30 identical sub-systems are required which in turn have to be supported throughout the entire 30-year life span of the craft. Over the past 15 years, Westland Helicopters have been developing the EH101, a civil and military sea rescue and attack helicopter (**Figure 15-2**).



Figure 15-2: Royal Air Force Merlin HC3, 2008 [Wikipedia, 2010]

Westland Helicopters described the EH101 as a "new concept"—"Based on a common airframe and core systems, the EH101 is configured to meet the multi-role requirements of many diverse customers around the world. It is uniquely capable of mastering the requirements of any role using the same airframe and core systems." Thus, the basic design is partially redesigned for each new customer. However, even with this philosophy a fully modular helicopter design could not be achieved at reasonable cost and each new version requires considerable development effort.

15.4 The Management of Change

The scale and cost of product redesign depends strongly on the particular changes that are required. Hence, a company's ability to undertake and manage change can be influenced greatly by their understanding of the links that exist between different parts of the product and the impact that these will have on the propagation of change. It is also important to identify the need for change early in the design process, since the later a change or the impact of a change is detected the more expensive it becomes to undertake. The work discussed in this chapter is concerned with the prediction and management of changes to an existing product resulting from faults or new requirements. This is very different from the traditional meaning of the term "*change management*," which is concerned with managing the change of business processes in any kind of enterprise. It is also different from the business process of configuration management that refers to the tracking and control of design changes during product design and manufacturing.

15.5 A Partial Solution - Model based reasoning could be used for complex design

Model-based reasoning has been used to generate and evaluate redesign plans, within which design modifications and accompanying side effects can be explored. This approach focuses on the physical quantities that describe the performance of the design and the causal relationships between them, utilizing a qualitative measure to describe changes. The plans proposed are rather abstract; however, they do focus the designer's attention of the relevant parts of the design. The following is a summary of some more popular model based reasoning tools that are able to predict change. However, none alone are suited to products of the scale and complexity of a helicopter or a fuel cell power system.

In the field of computer-aided mechanical design, the C-FAR system aims to trace and predict change propagation. A product is broken down into elements that are then considered in terms of their attributes. The attribute interactions are recorded in semi C-FAR matrices that are analyzed to predict the effect ("high," "medium" or "low") of one attribute on another. C-FAR's computational complexity makes it appropriate for small or relatively simple products.

State of the art solid modelers, such as Catia or Dymola, begin to provide analysis of the designs that are generated in them. If a change is undertaken in them, then they show where the new version of the design is no longer technically correct. Catia mainly checks for geometric coherence, whilst Dymola can check for functional connections. In addition, mathematical analysis can identify problems related to structural properties through techniques such as finite element analysis. However, the major drawback with

such approaches is that they can generally only identify the immediate implications of a change, rather than the consequences that propagate through a product.

CATIA (Computer Aided Three-dimensional Interactive Application) is a multiplatform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systemes. Written in the C++ programming language, CATIA is the cornerstone of the Dassault Systemes product lifecycle management software suite. CATIA competes in the CAD/CAM/CAE market with Siemens NX, Pro/ENGINEER, Autodesk Inventor, and <u>SolidEdge</u> as well as many others. Commonly referred to as a 3D Product Lifecycle Management software suite, CATIA supports multiple stages of product development (CAx), from conceptualization, design (CAD), manufacturing (CAM), and engineering (CAE). CATIA facilitates collaborative engineering across disciplines, including surfacing & shape design, mechanical engineering, equipment and systems engineering.

Surfacing & Shape Design

CATIA provides a suite of surfacing, reverse engineering, and visualization solutions to create, modify, and validate complex innovative shapes. From subdivision, styling, and Class A surfaces to mechanical functional surfaces.

Mechanical Engineering

CATIA enables the creation of 3D parts, from 3D sketches, sheet metal, composites, molded, forged or tooling parts up to the definition of mechanical assemblies. It provides tools to complete product definition, including functional tolerances, as well as kinematics definition.

• Equipment Design

CATIA facilitates the design of electronic, electrical as well as distributed systems such as fluid and HVAC systems, all the way to the production of documentation for manufacturing.

Systems Engineering

CATIA offers a solution to model complex and intelligent products through the systems engineering approach. It covers the requirements definition, the systems architecture, the behavior modeling and the virtual product or embedded software generation. CATIA can be customized via application programming interfaces (API). CATIA V5 & V6 can be adapted using Visual Basic and C++ programming languages via CAA (Component Application Architecture); a component object model (COM)-like interface.

Although later versions of CATIA V4 implemented NURBS, V4 principally used piecewise polynomial surfaces. CATIA V4 uses a non-manifold solid engine.

Catia V5 features a parametric solid/surface-based package which uses NURBS as the core surface representation and has several workbenches that provide KBE support.

15.6 A Portrait of Change

Simply put, Clarkson's change prediction model is composed of three parts: an initial analysis, a case study and redesign. The activities done before the initial analysis are: conduct interviews, and determine the product development experience of the design team. The activities of the initial analysis are: create a product model, complete dependency matrices, and compute a product risk matrix. A case study consists of: identify initiating change, identify predicted changes, and case risk plots.
15.7 Seeing the Big Picture

Clarkson (et al) first conducted interviews. Four were conducted with chief engineers or deputy chief engineers, who were responsible for the development of a particular product version and all the changes associated with it, and a fifth with a manager responsible for producing tendering estimates for new projects. These interviews focused on all the changes involved in generating a new version of a helicopter and were loosely structured to cover the following topics:

- The interviewee's position and experience;
- The creation of new product requirements;
- The identification of the version in which they were involved, including its new requirements;
- The time scale of the version redesign process;
- The changes involved and how the changes and redesign process were executed; their conception of the nature of change;
- Their level of interest in a change prediction system.

Clarkson (et al) found that the four chief engineers made several consistent points

about changes affecting the entire craft:

- The designers frequently fail to realize how their section of the helicopter will affect others;
- Retrofit customer requirements frequently create the most difficult and costly redesign projects;
- The possibility of being *unable* to create a functional design solution *does* exist;

- Change flow does occur, resulting in changes propagating up to four steps (components/systems) from the initial change;
- Currently, not all changes are predicted—the interviewee estimates of the percentage of unexpected changes ranged from 5% to 50%.

Overall, the relationship of change to cost was highly evident and the commercial importance of effective change management is seen in these comments from the interviews. Only the remarks relative to the fuel cell industry are listed below:

- 10-15% of the redesign cost occurs before a contract is signed, spent on planning solutions and predicting changes;
- Retrofit design changes (from a late requirement or from a delayed problem realization) cost about five times more than an early design change and contracts may have to be renegotiated for them;
- Individual unexpected changes can be immensely costly—for example, an unexpected change to the helicopter's wheels in one project cost or the order of \$80,000.

15.8 The Designers' Product Maturity?

Another key fact that emerged from these interviews was the importance of developers' product maturity. Customer change requirements are likely to be ones previously encountered and the designers' experience would guide the changes required. Three out of four of the chief engineers interviewed and most of the senior engineers had worked on versions of the EH101. In addition, most interviewees had been in Westland Helicopters for over 20 years and had therefore had exposure to other projects. The fourth chief engineer worked on the Lynx, which is a much more mature product, having been in service for about 30 years. For redesign work on the Lynx, designers are able to rely very heavily on past work.

It emerged from all the interviews that nobody had a complete, detailed overview of the entire helicopter. The chief engineer in charge of a specific helicopter, such as the EH101 had a broad understanding of the complete product, but knew little about design details. The deputy chief engineers in charge of a version, like the ones interviewed in this study had probably the greatest understanding of the overall design. However, their view was that they only really understood about half of the design. In addition, their understanding was typically biased by their previous role. For example, a deputy chief engineer who was formerly a structural engineer had a more detailed understanding of structures, then say of avionics.

The system heads, at the level of the senior engineers interviewed in the first phase of the interviews, understood their own field in detail and those of their colleagues with whom they collaborated regularly. They knew much less about fields with no direct impact on their own work and again were biased by their own career path. A stress engineer, who had previously worked in "loads" would know the implication of changes to loads on stress.

In summary, the points above highlight the need for a means to capture knowledge of the interactions within a product that influence change propagation. Such knowledge should not be influenced by the knowledge of a particular individual rather it should be governed by the collective knowledge of the design team.

15.9 Meetings

Most, if not all fuel cell developers schedule and attend review meetings. However, the work Clarkson's team performed for Westland Helicopters should be a model for fuel cell developers attempting to enter the Preliminary Design Phase because of two reasons. First, a holistic, systems engineering lifecycle view must be taken when conducting review meetings which means each member of the team, must understand the workings of the *complete* system. Secondly, a review of the team's technical base, technical skills and disciplines should be evaluated in case the team might need additional engineers, scientists, designers and/or other disciplines.

Design meeting should be regularly held and should loosely be structured to cover the following topics:

- The team's design and development experience and skills;
- The product requirements;
- The time scale of the design process;

What each member of the design and development team should realize:

- How his subsystem or section of the product will affect others parts of the system;
- That retrofitting customer requirements will create costly redesign;
- There is a possibility of being *unable* to create a functional design solution *which* exists;
- Change flow does occur, resulting in changes propagating up to four steps;
 (components/systems) from the initial change;
- Expect the unknown; there will be a large percentage of unexpected;

15.10 A Change Prediction Method

The change prediction method, a procedure which Clarkson used is illustrated in **Figure15-3**, and will be explained in the sections that follow.



Figure 15-3: the change Prediction Method [Clarkson, 2004]

15.11 The Initial Analysis

This first stage of the change prediction method (CPM) uses product data and a model of change propagation to allow preliminary examination of component relationships. It consists of three steps: create a product model, complete dependency matrices, and complete the predictive matrices.

15.12 Create a Product Model

Creating the product model; before a product can be analyzed it must first be broken down into sub-systems, allowing the product to be viewed as a collection of parts whose designs affect one another. A *sub-system* is a part of the overall product and its delineation can be based on location, function, sourcing or any other relevant distinction. Designers and managers familiar with the original product's design can advise on how it may be broken down into an appropriate number of sub-systems. This requires a careful balance between the level of detail required and the subsequent cost of populating the model. A model with fewer than 50 components is recommended.

Experience with the Westland Helicopters case study, and other subsequent studies, suggests that the creation of the product model is not as difficult as it sounds. This is particularly true if all the sub-systems are described at a similar level of detail. The Westland Helicopters model, comprising of 19 components, took a little over 20 hours to construct. An appreciably more complex model, comprising 41 components, took a total of 50 hours, while another of 20 components took 26 hours.

Models can describe the whole of a product in terms of key sub-systems or describe a particular sub-system with reference to individual components. Yet models that attempt to describe change propagation between individual components and subsystems are more problematic. Where such range of detail is required it is better to define separate models, where those at the component level provide input to those at the subsystem level.

15.13 Complete Dependency and Predictive Matrices

Completing the dependency matrices and computing the predictive matrices. Design Structure Matrices (DSMs) can provide an indication as to how change may propagate through a product. They provide a well-established technique for identifying the parts of a product or design tasks, and the parametric or precedence relationships

between them. Each cell in the matrix may contain a numerical or binary representation of the link between one part/task (the column heading) and another (the row heading). This is illustrated in **Figure 15-4** by a DSM that describes the tasks required to design a camera.

	Α	В	С	D	Ε	F	G	Η
A Set specifications	Х							
B Design concept	Х	Х						
C Design shutter mechanism		Х	Х	Х	Х	Х		
D Design viewfinder		Х	Х	Х	Х	Х		
E Design camera body		Х	Х	Х	Х	Х		
F Design film mechanism		Х	Х	Х	Х	Х		
G Design lens optics		Х					Х	Х
H Design lens housing		Х					Х	

Figure 15-4: Design structure matrix for a camera [Clarkson, 2004]

DSMs can show difficulties that may be encountered in redesign work. The high levels of connectivity frequently found between design-tasks suggest that high levels of interdependence will also exist between the resulting product components. For example, since the design of parts C, D, E and F are dependent upon the design of part B one would expect that these tasks will be affected by a change to the conceptual design task, B.

The DSM provides no direct indication as to the likelihood or scale of any such redesign. However, it may be used as the basis of a process simulation that includes consideration of rework, allowing the identification of critical process features that impact cost and schedule risk. Such an approach can be used, where the underlying process is known, to analyze the impact of planned design changes.

The component breakdown allows interconnectivity within the product design to be presented in a DSM. In particular, it allows the capture of the *change* relationships

between product sub-systems, where change is defined as any alteration to a sub-system's design. Within the DSM the column headings show *instigating* sub-systems and the row headings the *affected* sub-systems, whose designs change as a result of change to the instigating sub-systems.

The scale of change propagation predicted between subsystems is measured as a probabilistic impact, or *risk*, where risk is defined as the product of the *likelihood* of the change occurring and the *impact* of the subsequent change. This terminology is borrowed from risk management, which was first developed as a tool for use in safety management, for example by the UK Ministry of Defense.

Change relationships may be presented as a combination of likelihood and impact, rather than a single composite measure of risk. In this context likelihood is defined as the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface. Likewise, impact is defined as the average proportion of the design work that will need to be redone if the change propagates. Both these quantities are assigned values between 0 and 1 and refer to the total change experienced during the redesign process.

These likelihood (*l*) and impact (*i*) matrices may be derived from a history of previous design changes and from the views of experienced product designers. They capture a view of the average change experienced during a complete redesign process. As such, the views of a group of designers would be preferable to the views of an individual, whilst still giving more weight to the views of a designer in their own area of expertise. Above all a consensus view is desirable.

These dependencies should represent the *direct* risk (r) of a change in one subsystem resulting in a change to its neighbor by propagation across their common interface. The risk of propagation of these changes to other sub-systems can then be predicted from this data.

Defining impact as the "*average proportion of the design that will need to be redone if the change propagates*" simplifies the analysis that follows. In practice, a number of levels of impact may be possible depending upon the nature of the changes propagating through the design.

Further work by Clarkson's team has shown that Monte-Carlo simulation can be used in place of the simpler analysis described, enabling risk to be computed as a function of the type of change mechanism. For example, likelihood and impact data can be elicited separately for change propagation by mechanical, thermal and electrical means or by some combination of these. The effect of changes propagating along each path can then be summed.

The cost of any subsequent redesign, in terms of time or money, can be estimated by multiplying the impact for each sub-system by the corresponding design costs. This may be done at any stage of the analysis. However, for the purpose of this paper, costs were not calculated since the necessary data remains commercially sensitive.

The basic structure of the model is an amalgamation of DSM and risk management techniques. Products are modeled as linked components, where links consist of separate likelihood and impact terms.

Change propagation is contingent upon two processes: first, the flow of change from one sub-system to another; and second, the combination of changes from a number

of sources to effect change within a particular sub-system. A predictive model must allow for both these behaviors and calculate a *combined* risk of propagation from its *direct* and *indirect* components.

omponent	Dependency	a	b	с	d	e	f	Direct
one	a power supply	-	х	х				dependency:
du	b motor	Х	-		Х	×	Х	a → b
S	c heating unit	х			х	х	х	Indirect
ted	d fan	Х	x	x	-		х	dependencies:
ffec	e control system			x	x		х	a d b
A	f casing	X	x	x	х	х	-	a→f→b

Figure 15-5: Direct and indirect dependencies [Clarkson, 2004]

Change flow may be modeled as a sequence of links created by the direct subsystem dependencies, where a *direct* dependency refers to the propagation of change between adjacent sub-systems, for example the power supply **a** and motor **b** of **Figure15-5**. By contrast, an *indirect* dependency would require the involvement of at least one intermediate sub-system for a change in **a** to affect a change in **b**. For example, changes to **b** via changes to **d** and **f** are indirect. These links combine to create a change propagation network, based on the dependency matrix of **Figure 15-5**. A *propagation tree*, for routes between sub-systems **a** and **b**, can be derived from the network, where for clarity routes returning to previously visited sub-systems are not shown.

Propagation trees allow consideration of the combination of *direct* and *indirect* effects. A *combined* effect is then defined as the change in **b** caused by a change in **a**, via both direct and indirect links. The initial likelihood and impact matrices contain only the direct dependency values and are thus referred to as the direct likelihood (l) and direct impact (i) matrices, which combine to provide the direct risk (r) matrix. These three matrices have their parallels in the combined likelihood (L), impact (I) and risk (R) matrices.



Figure 15-6: And/Or summation for a Propagation Tree [Clarkson, 2004]

Combined likelihood is the probability that the end effect will arise, regardless of the path. Combined impact is the total impact to the affected sub-system, which is expected to appear with probability *L*. The combined likelihood algorithm views propagation trees as logic trees, such as the one illustrated in **Figure 15-6**. Vertical lines are mathematically represented by ϕ (*And*), while horizontal lines are represented by \cap For each tree, the *And/Or* summation begins at the bottom, farthest from the instigating subsystem. Through a combination of *And /Or* evaluations, a single combined likelihood value can be computed at the top of the tree. Since the events are not mutually exclusive the summations take the form:

$$l_{b,u} \cup l_{b,v} = l_{b,u} \times l_{b,v}$$
(1)
$$l_{b,u} \cap l_{b,v} = l_{b,u} + l_{b,v} - (l_{b,u} \times l_{b,v}) = 1 - ((1 - l_{b,u}) \times (1 - l_{b,v}))$$
(2)

Where Eq. (1) represents the *And* function as a product of probabilities and Eq. (2) represents the *Or* function as a sum of probabilities minus the product term ~the inverse of the product of inverse probabilities. This form of the *Or* evaluation is not dependent on the individual terms being small and ensures that the combined likelihood (*L*) will always be less than unity. This contrasts the approach taken in where independence is assumed.

Defining likelihood as the "average probability that a change in the design of one sub-system will lead to a design change in another" makes no assumption about the scale of the initiating and subsequent changes. Hence Equations (1) and (2) make no reference to impact values. This in turn simplifies the calculation of combined risk (R) and combined impact (I).

There are a number of possible algorithms for computing the combined risk, each involving a number of assumptions. The one used in this paper may be summarized as follows. Rb,a is the combined risk of change propagating to **b** from **a**, where:

$$R_{b,a} = 1 - \prod (1 - \rho_{b,u}) \tag{3}$$

For all links from the penultimate sub-system **u** in the chain from **a** to **b**, and:

$$\rho_{b,u} = \sigma_{u,a} l_{b,u} i_{b,u} \tag{4}$$

Where $r_{b,u}$ is the risk of change propagating from **u** to **b**, $_{su,a}$ is the likelihood of change reaching sub-system **u** from **a**, $l_{b,u}$ is the direct likelihood of change propagating from **u** to **b** and $l_{b,u}$ is the direct impact of such a propagation.



Figure 15-7: The Combining Impact, weighted by Probability [Clarkson, 2004]

The execution of this algorithm is illustrated in **Figure 15-7**. The likelihoods ($s_{u,a}$) of change reaching the penultimate subsystems **d** and **f** are $l_{d,a}$ and $l_{f,a}$ respectively, while the direct likelihoods of change propagating from **d** and **f** to **b** are $l_{b,d}$ and $l_{b,f}$, with corresponding direct impacts of $i_{b,d}$ and $i_{b,f}$. Note that the direction of the evaluation is now reversed from that of the combined likelihood. Finally, combined impact can be easily determined from the combined likelihood and risk using the simple equation:



$$I_{b,a} = R_{b,a} / L_{b,a} \tag{5}$$

Figure 15-8: The CPM Model [Clarkson, 2004]

The complete product and propagation model is summarized in **Figure 15-8.** The transformation of this model into executable steps requires an analysis of step limits (path truncation), the creation of a computer program and an appropriate format for presenting results.

15.14 Product Risk Matrix

Once the combined matrices have been derived, the resultant risk data may be presented in a single matrix, as shown on the right of **Figure 15-9.** Each rectangle shows the combined risk of change propagation between the subsystem represented by the column heading and that represented by the row. Its width indicates the likelihood L, its height the impact I and its area the risk R.



Figure 15-9: A Graphical Product Risk Matrix [Clarkson, 2004]

The graphical product risk matrix is the main output of the initial analysis. It allows the change characteristics of a product to be inspected and is appropriate for use with both large and small matrices. In general, a matrix with a lot of large rectangles represents a product that will exhibit a significant amount of change propagation, while a sparse matrix will limit change.

The concentration of large rectangles, i.e. significant area, with respect to particular columns or rows reflects the *influence* on and *susceptibility* to change. Clustering algorithms could also be employed to identify groups of components that are particularly coupled, or indeed uncoupled. Note, that given the fact that the order of the rows and columns need not be the same, many of the normal ordering algorithms used for DSM are not relevant.

15.15 The Case Analysis

A case-by-case analysis consisting of the identification of prospective changes and the presentation of predicted changes is required is a case analysis study.

15.16 Identify Initiating Change – Step 1

The first step is the identification of the instigating sub-system, which consists of two parts: deciding on the new product requirement and associating this requirement with one of the product sub-systems. Often the link will be obvious, but sometimes the identity of the instigating sub-system may not be clear. For this reason, the initial product model must be clearly defined and documented, particularly for highly complex products.

15.17 Identify Predicted Changes – Step 2

The identification of predicted changes is straightforward following completion of the initial case analysis. The likelihood, impact and risk data for the specific case need only be extracted from the complete change propagation data. It is convenient to rank the changes in order of descending risk as a means of prioritizing the possible changes. In addition, more notice should be taken of those changes predicted with higher likelihood for comparable risk. Note that the list of predicted changes should act as a prompt for discussion within the planning team rather that an absolute indication of the changes that will take place. Indeed, there may be sub-systems for which change should be avoided, since it would not be commercially attractive.

15.18 Case Risk Plot – Step 3

The *L* and *I* values for the given instigating sub-system(s) are mapped to a 0 1 log scale and plotted (*I* vs *L* for each affected sub-system) on a risk scatter graph of the form shown in **Figure 15-10**. This re-scaling of the results has the advantage that lines of equal risk are straight, allowing immediate comparison of data.



Figure 15-10: Risk Graph [Clarkson, 2004]

15.19 Redesign – Step 4

Hopefully, by this stage, designers and managers will know which sub-systems should be assigned additional resources to respond to likely changes. Hence with combined risk data as a guide, project teams can create cost-efficient project plans, and ultimately design solutions, more quickly.

A necessary and final step of the redesign process is to return to the initial analysis in order to update the product model and direct dependency matrices for use in later projects. The greater the accuracy of the direct data and the greater care used in selecting change requirements the better the resulting redesign will be, both in terms of functionality and efficiency.

15.20 Conclusion

During the Preliminary System Design Phase of development, because how funding sources are set up, distributed and end, the customer requirements for an SOFC Power System might change many times before a working breadboard design is acceptable and frozen. If redesign and rework are unavoidable, for whatever reasons, many industries, such as the automotive industry, are developing methodologies for rework and redesign. Clarkson (el al) study offers one such method and the results suggest the following:

- The change prediction method gives a good indication of future change likelihood without the need for detailed knowledge of the product development process;
- 2. The granularity of the product model and availability of change data critically influence the prediction results.
- Change' Loops could be included in the analysis to allow the prediction of additional changes to the initiating systems.

CHAPTER XVI

ANALYTIC HIERARCHY PROCESS – PHASE TWO

16.1 Introduction

How are most engineers taught about decision-making? Probably the engineer-intraining learned that if the answer matched the one in a text book- it was the right answer. Matching the right answer makes decision-making easy. Yet, when fuel cell developers design a power system there are no right answers.

In fact, most fuel cell design issues have multiple, alternative, trade-off solutions. These options evolve as the developer works through the problem. As more is learned about the particular issues, the criteria used to evaluate these potential solutions evolve. The bigger the technical problems, many more developers are involved in making the decisions, and the harder it is to manage the alternatives, criteria and evaluation.



Figure 16-1: The Value of Information [Ullman, Robust Decisions Inc, 2010]

Not all types of information are of equal value in solving a problem. In **Figure 16-1**, four classes of information are shown. The most basic form of information is raw "data." Raw data is numbers, textual clauses or other descriptive information about some object or idea. One step above "data," a model is a form of information that represents the relationships between data. This relationship may be: a math equation, full sentence or paragraph, or graphic images that relate basic data resulting in a richer form. Models are static relationships among the data and are vital to evaluation.

During engineering evaluations, if an engineer finds that an alternative does not meet a criterion, this discovery itself does not tell the engineer how to change the alternative to better fit the need. To gain knowledge necessary to make an informed change, the behavior of models must be understood and interpreted. It is the knowledge gained during evaluation that developers depend on to refine the alternatives and criteria.

Finally, when knowledge is sufficient, decisions using a judgment based on this knowledge can be made. Thus, according to this argument, the most valuable type of information is a decision, as it is based on all the less valuable information types. In other

words, decision making support requires the management of data, models and knowledge, and the associated judgment on which decisions are based.

16.2 The Need for the Analytic Hierarchy Process

One of the key skills required of an engineer is the ability to produce systems that satisfy users' requirements by the correct selection, configuration, integration, operation and control of proprietary building blocks. These component parts can be physical entities such as computers and manufacturing machinery -the "*hard*" system components.

However, they can also be nonphysical entities such as software, algorithms, control strategies and methods-the "*soft*" systems components. If the wrong components are selected then the users' requirements will not be satisfied. If sub-optimal components are selected then the system solution will be sub-optimal. Clearly, selection is a critical element of the engineering process. Therefore, it is essential that it is systematic, formalized and accountable, so that it is amenable to detailed analysis for the purposes of verification and optimization.

The Analytic Hierarchy Process (AHP) is a structured technique for dealing with complex decisions. Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem—it is a process of organizing decisions that designers are already dealing with, but trying to do in their heads.

Based on mathematics and psychology, the AHP was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. It provides a comprehensive and rational framework for structuring a decision problem, for

representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem—tangible or intangible, carefully measured or roughly estimated, well or poorly understood anything at all that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations. Decision situations in relations to the fuel cell industry to which the AHP can be applied include:

- Choice The selection of one design alternative from a given set of design alternatives, usually where there are multiple decision criteria involved.
- Ranking Putting a set of alternatives in order from most to least desirable
- Prioritization Determining the relative merit of members of a set of alternatives, as opposed to selecting a single one or merely ranking them
- Resource allocation Apportioning resources among a set of alternatives

- Benchmarking Comparing the processes in one's own organization with those of other best-of-breed organizations
- Quality management Dealing with the multidimensional aspects of quality and quality improvement

16.3 APH used in the Fuel Cell Industry

APH has been used before in the fuel cell industry. In 2005, Hua-Kai Chiou et al research focused on the optimal development strategy of fuel cell industry in Taiwan. Chiou and his team employed fuzzy AHP to establish an evaluation system, which composed of thirteen developments strategies with respect to nineteen evaluated criteria for fuel cell development by analyzing these strategies using a multiple criteria decision making approach. It was found that the first five important criteria for fuel cell development, according the Chiou (et al) were: technology enhancement, R&D investment, explicit government policy, reducing production cost, and R&D manpower. Choiu's study indicated that technology enhancement and R&D investment, how to make an explicit policy was very important especially in the fuel cell industry. In addition, most of the participated experts in Choiu's study agreed that how to reduce production cost and how to recruit and manage the R&D manpower also were the critical factors for getting into such new applied field.

16.4 A Closer Look at APH

AHP, in short, is a method to derive ratio scales from paired comparisons. The input can be obtained from actual measurement such as price, weight etc., or from subjective opinion such as satisfaction feelings and preference. AHP allows some small

inconsistency in judgment because humans are not always consistent. The ratio scales are derived from the principal Eigen vectors and the consistency index is derived from the principal Eigen value. The prefix "Eigen" is adopted from the German word "Eigen" for "own" in the sense of a characteristically description.

The Eigen vectors of a square matrix are the non-zero vectors that, after being multiplied by the matrix, remain proportional to the original vector (i.e., change only in magnitude, not in direction). For each eigenvector, the corresponding Eigen value is the factor by which the eigenvector changes when multiplied by the matrix. The eigenvectors are, sometimes also called proper vectors, or characteristic vectors. Similarly, the Eigen values are also known as proper values, or characteristic values.

16.5 An Example of APH - Pair Wise Comparisons

Two fruits (Apple and Banana) will be compared. A relative scale was created to measure how much the author like the fruit on the left (Apple) compared to the fruit on the right (Banana) [Teknomo, 2006].



Figure 16-2: Relative Scale to compare Apples to Bananas [Teknomo, 2006].

If the author likes the apple better than banana, the author will place a mark between number 1 and 9 on the left side, however, if the author favors a banana more than an apple, then the author will place a mark on the right side of the scale. The author strongly favor banana to apple [Teknomo, 2006].



Figure 16-3: The banana is favored more than the apple [Teknomo, 2006].

Now suppose there are three choices of fruits. Then the pair wise comparison goes as the following:



Figure 16-4: Three Fruits compared [Teknomo, 2006].

The number of observations (comparisons) is a combination of the number of things to be compared. Since there are 3 objects (Apple, Banana and Cherry), 3 comparisons are made. **Table 16-1** below shows the number of comparisons[Teknomo, 2006].

		Fable	16-1					
NU	MBER (OF C	OMP	ARIS	SONS			
	[Tel	knom	0, 200	06]	_	_	_	
Number of things	1	2	3	4	5	6	7	n n(n-1)
number of comparisons	0	1	3	6	10	15	21	2

The scaling does not necessarily have to be 1 to 9, but for qualitative data such as preference, ranking and subjective opinions, it is suggested to use scale 1 to 9.

16.6 Making a Comparison Matrix

Example: John has 3 kinds of fruits to be compared and he made subjective judgment on which fruit he likes best, like the following [Teknomo, 2006]:



Figure 16-5: Three Fruits rated [Teknomo, 2006]

A matrix is made from the 3 comparisons above. Because there are three comparisons, a 3 by 3 matrix is created. The diagonal elements of the matrix are always 'one'. To complete the matrix, what is needed is to fill up the upper triangular matrix. The following rules apply to filling up the upper triangular matrix:

- 1. If the judgment value is on the *left* side of 1, we put the *actual judgment* value.
- 2. If the judgment value is on the **right** side of 1, we put the **reciprocal** value.

Comparing apple and banana, John slightly favor banana, thus a $\frac{1}{3}$ is placed in the row 1, column 2 of the matrix. Comparing Apple and Cherry, John strongly likes apple, and so the actual judgment 5 is placed on the first row, last column of the matrix. Comparing banana and cherry, banana is dominant. Thus his actual judgment is placed on the second row, last column of the matrix. Then based on his preference values above, the reciprocal matrix is:

	apple	banana	сетту
A _ apple	[1	<u>1</u> 3	5
h = banana		1	7
сетту	L		1

To fill the lower triangular matrix, the reciprocal values of the upper diagonal are used. If \vec{a}_{j} is the element of row \vec{i} column \vec{j} of the matrix, then the lower diagonal is filled using this formula:

$$a_{j\bar{i}} = \frac{1}{a_{j\bar{i}}}$$

The complete comparison matrix is:

$$\mathbf{A} = \frac{apple}{banana} \begin{bmatrix} 1 & \frac{1}{3} & 5\\ 3 & 1 & 7\\ \frac{1}{5} & \frac{1}{7} & 1 \end{bmatrix}$$

-

Notice that all the element in the comparison matrix are positive, or $a_{ij} > 0$.

16.7 Determining the Priority Vectors

Once a comparison matrix has been created, a priority vector must be computed, which is the normalized Eigen vector of the matrix. The method shown is only an approximation of Eigen vector (and Eigen value) of a reciprocal matrix. This approximation is actually worked well for small matrix $\pi \leq 3$ and there is no guarantee that the rank will not reverse because of the approximation error. Nevertheless it is easy to compute because all that is needed is just to normalize each column of the matrix. At the end, the error of this approximation will be shown.

Suppose a 3 by 3 reciprocal matrix was created from paired comparison:

	apple	banana	сетту
A_ apple	[1	<u>1</u> 3	5
hanana banana	3	1	7
сетту	15	17	1

Each column of the reciprocal matrix is summed:

	app	le bana	ы сетту
A _ apple	1	13	5
h= banan	a 3	1	7
сетту	_ <u></u>	17	1
sum	<u>7</u> 5	<u>1 31</u> 21	13

Then each element of the matrix is divided with the sum of its column, normalized by relative weight. The sum of each column is 1.



The normalized principal Eigen vector is also called a "*priority vector*." Since it is normalized, the sum of all elements in a priority vector is 1. A priority vector shows the relative weights among the things that are compared. In this example, apple is 28.28%, banana is 64.34% and cherry is 7.38%. John's most preferable fruit is a banana, followed by an apple and a cherry. In this case, ranking can be considered. In fact, the relative weight is a ratio scale can be divided among them. For example, John likes a banana 2.27 (=64.34/28.28) times more than apple and he also like banana so much 8.72 (=64.34/7.38) times more than a cherry.

Aside from the relative weight, the consistency of John's answer can be checked. To do that, what is need is the '*Principal Eigen*' value. The Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

$\lambda_{\text{max}} = \frac{21}{5} (0.2828) + \frac{31}{21} (0.6434) + 13 (0.0738) = 3.0967$

As a note, the comparison matrix was placed into Matlab to see how different is the result of numerical computation of Eigen value and Eigen vector compared to the approximation above.

$$\mathbf{A} = \begin{bmatrix} 1 & \frac{1}{3} & 5 \\ 3 & 1 & 7 \\ \frac{1}{5} & \frac{1}{7} & 1 \end{bmatrix}$$
$$[\mathbf{W}, \boldsymbol{\lambda}] = eig(\mathbf{A})$$

Three Eigen vectors concatenated into 3 columns of matrix W

$$\mathbf{W} = \begin{bmatrix} 0.3928 & -0.1964 + 0.3402i & -0.1964 - 0.3402i \\ 0.9140 & 0.9140 & 0.9140 \\ 0.1013 & -0.0506 - 0.0877i & -0.0506 + 0.0877i \end{bmatrix}$$

The corresponding Eigen values are the diagonal of matrix $\boldsymbol{\lambda}$:

$$\lambda = \begin{bmatrix} 3.0649 & 0 & 0 \\ 0 & -0.0324 + 0.4448i & 0 \\ 0 & 0 & -0.0324 - 0.4448i \end{bmatrix}$$

The largest Eigen value is called the Principal Eigen value, that is $\lambda_{m\pi} = 3.0649$ which is very close to our approximation $\lambda_{m\pi} = 3.0967$ (about 1% error). The principal Eigen vector is the Eigen vector that corresponds to the highest Eigen value:

$$\overline{\mathbf{v}} = \begin{bmatrix} 0.3928 \\ 0.9140 \\ 0.1013 \end{bmatrix}$$

The sum is 1.4081 and the normalized principal Eigen vector is:

w^{*} =
$$\begin{bmatrix} 0.2790 \\ 0.6491 \\ 0.0719 \end{bmatrix}$$

This result is also very close to our approximation:



Thus the approximation is quite good.

Thus the sum of Eigen vector is not one. When normalizing an Eigen vector, the result is a priority vector. The sum of priority vector is one.

16.8 Calculating the Consistency Index and Consistency Ratio

How can the consistency of subjective judgment be measured?

Is John's judgment consistent or not?



First he prefers Banana to Apple. Thus for John, Banana has greater value than Apple. We write it as $B \succ A$.

Next, he prefers Apple to Cherry. For him, Apple has greater value than Cherry. Therefore $\mathbf{A} \succ \mathbf{C}$. Since $B \succ A$ and $A \succ C$, logically, $B \succ C$ or Banana must be preferable than Cherry. This logic of preference is called transitive property. If John answers in the last comparison is transitive (that he like Banana more than Cherry), then his judgment is consistent. On the contrary, if John prefers Cherry to Banana then his answer is inconsistent. Thus consistency is closely related to the transitive property.

A comparison matrix **A** is said to be consistent if $a_{ij} a_{jk} = a_{k}$ for all i, j and k. However, consistency should not be forced. For example, $B \succ A$ has value $3 \succ 1$ and $A \succ C$ has value $5 \succ 1$, however what is not consistent to insist that $B \succ C$ must have value $15 \succ 1$. This too much consistency is undesirable when dealing with human judgment. To be called consistent, the rank can be transitive but the values of judgment are not necessarily forced to multiplication formula $a_{ij} a_{jk} = a_{k}$.

Prof. Saaty proved that for consistent reciprocal matrix, the largest Eigen value is equal to the number of comparisons, or $\lambda_{mn} = \pi$. Then he gave a measure of consistency, called Consistency Index as deviation or degree of consistency using the following formula:

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$

Thus from the example, $\lambda_{max} = 3_0967$ and three comparisons, or n = 3, thus the consistency index is:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{3.0967 - 3}{2} = 0.0484$$

Knowing the Consistency Index, the next question is how to use this index? Again, Prof. Saaty proposed that a way to use this index by comparing it with the appropriate one. The appropriate Consistency index is called Random Consistency Index (\mathbf{RI}).

He randomly generated reciprocal matrix using scale $\frac{1}{9}$, $\frac{1}{8}$, ..., 1, ..., 8, 9 (similar to the idea of Bootstrap) and get the random consistency index to see if it is about 10% or less. The average random consistency index of sample size 500 matrices is shown in the table 2 below:

Table 16-2														
RANDOM CONSISTENCY INDEX (N)														
[Teknomo, 2006]														
	n	1	2	3	4	5	6	7	8	9	10			
	RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49			

Then, he proposed what is called Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index, or in formula:

$$CR = \frac{CI}{RI}$$

If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, the subjective judgment needs to be revised.

For the example,
$$CI = 0.0484$$
 and RI for $n = 3$ is 0.58, then
 $CR = \frac{CI}{RI} = \frac{0.0484}{0.58} = 8.3\% < 10\%$

Thus, John's subjective evaluation about his fruit preference is consistent.

16.9 Computing a Full Hierarchy – The Fuel Processing System



The structure of hierarchy in this example can be drawn as the following:

Figure 16-6: A Generic Hierarchy consisting of two levels [Wikipedia, 2010]

For this example, a fuel processing technology will be selected for an SOFC Power System. Level 0 is the goal of the analysis. Level 1 is multi-criteria that consist of several factors. The factors chosen are: efficiency; cost; design simplicity and coke production/or lack of. The last level (level 2 in **Figure 16-6**) is the alternative choices. As shown below, the fuel processing alternative choices are: Steam Reforming, Autothermal Reforming and Partial Oxidation (POX).

16.10 An Alternative Choice – Steam Reforming

Steam reforming involves the reaction of steam with the fuel in the presence of a catalyst to produce H2 and CO, as illustrated in Eq. (1) for methane, CH₄, and isooctane, C8H18 (2,2,4-trimethylpentane, which is used as a surrogate for gasoline).

$$CH_{4} + H_{2}O \rightleftharpoons CO + 3H_{2},$$

$$\Delta H_{298}^{\circ} = +206.2 \text{ kJ mol}^{-1}$$

$$C_{8}H_{18} + 8H_{2}O \rightleftharpoons 8CO + 17H_{2},$$

$$\Delta H_{298}^{\circ} = +1273.2 \text{ kJ mol}^{-1}$$
(1)

$$CO + H_2 \rightleftharpoons CO_2 + H_2O$$
 (2)

In addition to H2+CO, the fuel gas contains some CO₂ produced via the water– gas shift reaction (Eq. (2)) SR of light hydrocarbons, especially methane, is used for many large-scale manufacturing processes that require H₂, such as ammonia synthesis. Coke produced by thermal cracking of hydrocarbons (Eq. (3)) or by the Bouduard reaction (Eq. (4)) leads to catalyst deactivation. These processes are problematic when the steam-to-carbon ratios are low, i.e. close to the stoichiometric ratio as defined in Eq. (1).

$$CH_4 \rightleftharpoons C + 2H_2, \qquad (CH_2)' \rightleftharpoons C + 2H_2 \qquad (3)$$

 $2CO \rightleftharpoons C + CO_2 \qquad (4)$

To minimize coke formation excess steam is used to ensure that any carbon formed is gasified (Eq. (5)).

$$C + H_2 O \rightleftharpoons CO + H_2 \tag{5}$$

For methane, a steam-to-carbon ratio of ~2.5 is sufficient to avoid coking. For higher hydrocarbons, a steam-to-carbon ratio of 6–10 is not uncommon. Commercial catalysts consist of nickel supported on alumina, calcium aluminate or magnesia. Rhodium

catalysts are more active and less susceptible to coking than nickel catalysts but are more expensive.

16.11 An Alternative Choice – Autothermal Reforming

Autothermal reforming involves the reaction of oxygen, steam, and fuel to produce H_2 and CO_2 (Eq. (7)).

$$CH_{4} + 0.5O_{2} + H_{2}O \rightleftharpoons CO_{2} + 3H_{2},$$

$$\Delta H_{298}^{\circ} = -18.4 \text{ kJ mol}^{-1}$$

$$C_{8}H_{18} + 4O_{2} + 8H_{2}O \rightleftharpoons 8CO_{2} + 17H_{2},$$

$$\Delta H_{298}^{\circ} = -236.7 \text{ kJ mol}^{-1}$$
(7)

In essence, this process can be viewed as a combination of PO and SR. The fuel gas contains a mixture H_2 , CO_2 , and CO, with the relative concentration being determined by the water–gas shift reaction (Eq. (2)) if thermodynamic equilibrium is achieved. No external heating source is required, because the exothermic oxidation reaction provides the heat necessary for the endothermic SR reaction. The oxidation reaction can be conducted with or without a catalyst, as previously discussed for PO, but most recent work has focused on catalytic oxidation.

16.12 An Alternative Choice – Partial Oxidation

Partial oxidation involves the reaction of oxygen with fuel to produce H2 and CO when the oxygen-to-fuel ratio is less than that required for total combustion, i.e. complete conversion to CO_2 and H_2O (Eq. (6)).

$$CH_{4} + 0.5O_{2} \rightleftharpoons CO + 2H_{2},$$

$$\Delta H_{298}^{\circ} = -35.7 \text{ kJ mol}^{-1}$$

$$C_{8}H_{18} + 4O_{2} \rightleftharpoons 8CO + 9H_{2},$$

$$\Delta H_{298}^{\circ} = -158.1 \text{ kJ mol}^{-1}$$
(6)

The use of PO to generate H_2 (in particular synthesis gas $[H_2 + CO]$) for largescale commercial applications has received some attention recently; however, such processes have not been extensively commercialized. The reaction can be conducted with a catalyst (catalytic PO) or without a catalyst (non-catalytic PO). The reaction rates are much higher for PO than for SR, but the H_2 yield per carbon in the fuel is lower. For non-catalytic PO, reaction temperatures above 1000 °C are required to achieve rapid reaction rates. Although the reaction is exothermic, some of the fuel must be combusted, because the amount of heat generated by the reaction is not sufficient to preheat the feed to achieve optimal rates. Recently, there has been an interest in catalytic PO, because it operates at a lower temperature than the non-catalytic route, thus providing better control over the reaction, minimizing coke formation, and allowing for a wider choice of materials of construction for the reactor. Catalysts are typically group VIII metals, such as rhodium, platinum, palladium, ruthenium, cobalt, nickel, and iridium, which are either supported on oxide substrates or used unsupported, as metal wires and gauzes.

16.13 The Criteria

For level 1, a one comparison (4x4) matrix corresponding to pair-wise comparisons between the 4 factors with respect to the goal will be created. Because each choice is connected to each factor (3 choices and 4 factors), at level 2, four (3x3) comparison matrices will be created.


Figure 16-7: APH Example – the Selection

Of Fuel Processing Technology

Based on a questionnaire survey given to a number of fuel cell developers, the

four factors were ranked in the following order: 9 being the most important and 1 being the least important).

Table 16-3 PAIRED COMPARISON MATRIX OF FUEL PROCESSING FACTORS							
	Efficiency Cost Simplicity Coking						
Efficiency	1.00	8.50	9.00	4.50			
Cost	0.12	1.00	1.00	1.00			
Simplicity	0.11	1.00	1.00	1.00			
Coking	0.22	1.00	1.00	1.00			
Sum	1.45	11.50	12.00	7.50			

16.14 Details of the Analysis

The efficiency at which a particular design processes fuel into hydrogen is very important. The cost and simplicity of the design must be taken into consideration when hopes of manufacturing the design come into play. Coking will cause the subsystem to malfunction and will limit or prevent the production of hydrogen. The entire criterion is listed in the table below.

Table 16-4PAIRED COMPARISON MATRIX (LEVEL 1) WITH RESPECTTO THE GOAL							
	Efficiency Cost Simplicity Coking Vector						
Efficiency	0.689	0.739	0.750	0.600	69.46%		
Cost	0.081	0.087	0.083	0.133	9.62%		
Simplicity	0.077	0.087	0.083	0.133	9.50%		
Coking	0.153	0.087	0.083	0.133	11.42%		
Sum	1.00	1.00	1.00	1.00	100.00%		

According to the fuel cell developers, efficiency has the greatest priority (69.46%)

followed by the fuel processing system's ability to prevent coking (11.42%).

16.15 Paired Comparison Matrix (Level 2) with respect to Factor A: Efficiency

Three designs were selected for fuel process reforming and tests were conducted to determine the efficiency of the hydrogen production of each of the three types of reforming. From the data, the results are shown below.

Table 16-5PAIRED COMPARISON MATRIX (LEVEL 2)WITH RESPECT TO FACTOR A: EFFICIENCY						
	Stream Autothermal Reforming Reforming POX					
Stream Reforming	1.00	5.00	9.00			
Autothermal Reforming	0.20	1.00	3.50			
POX Sum	0.11 1.31	0.29 6.29	1.00 13.50			

Table 16-6 FACTOR A: PAIRED COMPARISON MATRIX (LEVEL 2) WITH RESPECT TO THE EFFICIENCY OF HYDROGEN PRODUCTION							
	StreamAutothermalPriorityReformingReformingPOXVector						
Stream Reforming	0.76	0.80	0.67	74 16%			
Autothermal 0.76 0.80 0.67 74.16							
Reforming	0.15	0.16	0.26	19.03%			
POX	0.08	0.05	0.07	6.81%			
Sum	1.00	1.00	1.00	100.00%			

The Stream Reforming design appears to be the most efficient followed by the

Autothermal Reforming design.

A = 3.087, CI = 0.043, CR = 7.58% < 10% (acceptable)

16.16 Paired Comparison Matrix (Level 2) with respect to Factor D: Coking

Three designs were selected for the three types of fuel process reforming and tests were conducted to determine the amount of coking of each of the three types of reforming.

Table 16-7 FACTOR D: PAIRED COMPARISON MATRIX							
(LEVEL 2)	WITH RESPI	ECT TO COKI	NG				
	Stream Autothermal Reforming Reforming POX						
Stream	8	g					
Reforming	1.00	4.50	8.00				
Autothermal	Autothermal						
Reforming	0.22	1.00	2.60				
POX	0.13	0.38	1.00				
Sum	1.35	5.88	11.60				

Table 16-8 FACTOR D: PAIRED COMPARISON MATRIX (LEVEL 2) WITH RESPECT TO COKING						
	StreamAutothermalPriorityReformingReformingPOXVector					
Stream						
Reforming	0.74	0.76	0.69	73.22%		
Autothermal						
Reforming	0.16	0.17	0.22	18.63%		
POX	0.09	0.07	0.09	8.14%		
Sum	1.00	1.00	1.00	100.00%		

The paired comparison with respect to Factor B and C could also be calculated. However, the weight of factor B and C are very small. Their effect can be assumed negligible. Their two weights can be set to zero. In this case, the weight of factor A and D must be adjusted so that the sum is still 100%

- Adjusted weight for factor A: 69.46%/(69.46% + 11.42%) = 0.8588
- Adjusted weight for factor D: 11.42%/(69.46% + 11.42%) = 0.1412

The overall composite weight of each alternative choice based on the weight of level 1 and level 2 must be computed. The overall weight is just normalization of linear combination of multiplication between weight and priority vector.

Table 16-9 OVERALL COMPOSITE WEIGHT OF THE ALTERNATIVES							
	Composite Distribution						
	Factor A	Factor D	weight				
(Adjusted)							
Weight	0.8588	0.1412					
Stream							
Reforming	74.16	73.22	74.03				
Autothermal	Autothermal						
Reforming	Reforming 19.03 18.63 18.97						
POX	6.81	8.14	7.00				

16.17 The Air System - Selection of a Condition Monitoring Method for an Air Blower for Desert Applications

The connections of the Fuel Processing and Air System to the manifolds of the Hot Assembly are based on the Hot Assembly design which in turn is dependent upon the design of the Cell Stack Package. In the Preliminary Systems Design Phase, specifications for the gas (output) flow rates for the Air and Fuel subsystems will be benchmarked leaving sufficient degrees of freedom for the Cell Stack Package design. The limits and tolerances of the gas flow rates will be tested and documented for possible system design considerations and modifications.

In this example, AHP will be used to select of a monitoring device which controls a air blower, the element of focus for the Air Subsystem of a particular SOFC Power System.



Figure 16-8: An Air Blower [Wikipedia, 2010]

Presented in detail here is the application of the AHP to the selection of a condition monitoring method for the air blower that operates within an Air Subsystem of an SOFC Power System.

Four condition monitoring methods were assessed in a laboratory:

- The blower's outlet pressure
- Vibration
- Blower motor current and,
- Acoustic emission.

Four selection criteria were considered to be relevant to this particular application:

- Signal usefulness in terms of condition monitoring;
- Ease of maintenance of the associated hardware;
- Ruggedness of the associated hardware with respect to harsh external environments (example: desert environments);
- Ease of mounting of sensors.

The fuel cell power system, in this example, was intended for a location in the United States where the climate that receives an extremely low amount of precipitation and was plagued by many sand storms.

Having defined the selection criteria, the next step in the AHP is the pair-wise comparison of the importance of the criteria. This is done by assigning a weight between 1 (equal importance) and 9 (absolutely more important) to the more important criterion, and the reciprocal of this value is then assigned to the other criterion in the pair. The results of this operation are presented in **Table 16-10** which shows that, for example, signal usefulness is much more important than ease of mounting.

Table 16-10						
PAIR	-WISE RATIN	G OF SELECT	TION CRITER	RIA		
	Signal Ease of Ease of					
	Usefulness	Maintenance	Ruggedness	Mounting		
Signal						
Usefulness	1.00	3.00	5.00	6.00		
Ease of						
Maintenance	0.33	1.00	3.00	5.00		
Ruggedness	0.20	0.33	1.00	4.00		
Ease of						
Mounting	0.17	0.20	0.25	1.00		
Sum	1.70	4.53	9.25	16.00		

The weightings in **Table 16-10** are then normalized, by dividing each entry in a column by the sum of all the entries in that column, so that they add up to one. Following normalization, the weights are averaged across the rows to give an average weight for each criterion as shown in **Table 16-11**.

Table 16-11 NORMALIZED PAIR-WISE RATING OF SELECTION CRITERIA						
	Signal Ease of Ease of Priori					
	Usefulness	Maintenance	Ruggedness	Mounting	Vector	
Signal						
Usefulness	0.588	0.662	0.541	0.375	54.14%	
Ease of						
Maintenance	0.196	0.221	0.324	0.313	26.34%	
Ruggedness	0.118	0.074	0.108	0.250	13.73%	
Ease of						
Mounting	0.098	0.044	0.027	0.063	5.79%	
Sum	1.00	1.00	1.00	1.00	100.00%	

The final column of **Table 16-11** reflects the developer's view that the most important signal selection criterion is "usefulness." The weight given to this criterion is such that it effectively eliminates condition monitoring methods that are rated lowly under this criterion. This is intuitively correct since it is pointless acquiring a "useless" signal. Ease of maintenance was given a high weighting. Further discussion with the designer on this point, prompted by the AHP results, revealed that he wanted to seek solutions that would enable on-line maintenance and thereby avoid increased downtime.

 Table 16-11 also verifies that the designer was aware that his particular target

 monitoring environment was a very harsh environment.

The next step is the pair-wise comparison of the CM methods to quantify how well they satisfy each of the criteria. For each pairing within each criterion, the better method is awarded a rating on a scale between 1 (equally good) and 9 (absolutely better), whilst the other method in the pairing is awarded a rating equal to the reciprocal of this value. The results for the `signal usefulness' criterion are given in **Table 16-12**.

Table 16-12 PAIR-WISE RATING OF ALTERNATIVE CM METHOD WITH RESPECT TO SIGNAL USEFULNESS								
	Blower Output Motor Acoustic							
	Pressure	Current	Vibration	Emission				
Blower								
Output								
Pressure	1.00	4.00	2.00	5.00				
Motor								
Current	0.25	1.00	0.50	3.00				
Vibration	0.50	2.00	1.00	3.00				
Acoustic								
Emission	0.20	0.33	0.33	1.00				
Sum	1.95	7.33	3.83	12.00				

Table 16-12 reveals how the student interprets his experimental results to reach the conclusion that blower outlet pressure is the most useful signal. His experiments show that the blower outlet pressure is sensitive to the fault conditions to be detected whilst being insensitive to the noise that is present. Conversely, acoustic emission is found in his experiments to be the least useful signal. In contrast, the acoustic emission sensor is highly rated under the categories of `ease of maintenance' and `ease of mounting', as it is attached to the outside of the blower which is located in the BOP of the power system.

Each entry in this matrix records how well the method corresponding to its row meets the 'signal usefulness' criterion when compared to the method corresponding to its column. For example, the blower outlet pressure is found to be a far more useful CM signal than acoustic emission. The ratings in these comparison matrices are normalized as before and averaged across the rows to give an average normalized rating by criterion for each CM method, as illustrated in **Table 16-13** for 'signal usefulness'.

Table 16-13 NORMALIZED PAIR-WISE RATING OF ALTERNATIVES WITH RESPECT TO SIGNAL USEFULNESS							
	Blower OutputMotorAcousticPriorityPressureCurrentVibrationEmissionVector						
Blower							
Output							
Pressure	0.513	0.545	0.522	0.417	49.92%		
Motor							
Current	0.128	0.136	0.130	0.250	16.13%		
Vibration	0.256	0.273	0.261	0.250	26.00%		
Acoustic							
Emission	0.103	0.045	0.087	0.083	7.96%		
Sum	1.00	1.00	1.00	1.00	100.00%		

 Table 16-14 summarizes the average normalized ratings with respect to each of the selection criteria.

Table 16-14 AVERACE NORMALIZED RATING OF CM METHODS WITH							
AVEKAGI	L NORMALIZ	ED KATING U TO EACH CR	F CM METHU	JDS WITH			
	Signal Eage of Eage of						
	Usefulness	Maintenance	Ruggedness	Mounting			
Blower							
Outlet							
Pressure	0.499	0.137	0.074	0.17			
Motor							
Current	0.161	0.067	0.284	0.069			
Vibration	0.260	0.515	0.471	0.455			
Acoustic							
Emission	0.080	0.280	0.171	0.306			

The final step in the AHP is to combine the average normalized CM method ratings (**Table 16-13**) with the average normalized criterion weights (**Table 16-14**), to produce an overall rating for each CM method, i.e. the extent to which the methods satisfy the criteria is weighted according to the relative importance of the criteria.

This is done as follows: $A_i = \sum (W_i * K_{ij})$

Where:

 A_j = overall relative rating of the CM method j.

 W_i = average normalized weight of criterion i.

 $K_{jj} = \mbox{average}$ normalized rating for CM method j with respect to criterion i.

Table 16-15 gives the results of this final step. These results show clearly that vibration

 analysis and blower outlet pressure are the preferred CM methods.

Table 16-15OVERALL CM METHOD RATING	
CM Method	$\mathbf{A_{j}}$
Blower Outlet Pressure	0.326
Motor Current	0.148
Vibration	0.367
Acoustic Emission	0.158

16.18 Conclusion

This chapter has been an effort to describe Analytic Hierarchy Process (AHP). AHP is a structured technique for dealing with complex decisions. Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem—it is a process of organizing decisions that people are already dealing with, but trying to do in their heads.

The general procedure for using the AHP can be summarized as:

- 1. Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives.
- 2. Establish priorities among the elements of the hierarchy by making a series of judgments based on pair-wise comparisons of the elements.
- 3. Synthesize these judgments to yield a set of overall priorities for the hierarchy.
- 4. Check the consistency of the judgments.
- 5. Come to a final decision based on the results of this process.

CHAPTER XVII

TESTING IN THE PRELIMINARY SYSTEMS DESIGN PHASE – PHASE TWO

17.1 Introduction

This chapter involves the NPD activities which link developers/manufacturer's responsibility to their end users.

17.2 Responsibility to the End User

Warranty policies balance between protecting Manufacturers and the End Users as symbolically shown in **Figure 17-1**. Warranty is a legal obligation of the manufacturer or dealer in connection with the sale of the product. Warranties define the responsibility of the manufacturer/dealer in the event of product failure.

To the customers, longer warranty terms signal higher reliability and a peace of mind. It plays a protective role for the customer by acting as an insurance against failure of an item due to design, manufacturing or quality assurance problems. Reliability and the prevailing warranty have been the major reasons for Honda's and Toyota's succeed in the past 10 years in keeping their competitive edge over U.S and other automobile manufacturers as observed by annual consumer report issues.



A major reason for Honda's sales was its warranty coverage. [Honda trademark]



Figure 17-1: Warranty Policies balance between protecting Manufacturers and the End Users



A major reason for Toyota's sales was its warranty coverage. [Toyota trademark]

On the other hand, to the manufacturer, the expected warranty cost generally increases with the increase of duration of warranty coverage. Moreover, the longer the coverage period the greater is the risk due to uncertainty of failure mechanisms and costs. Due to the fierce competition in the market and the customer demand, the warranty period offered by the manufacturer of modern products has been progressively increasing since the beginning of the 21st Century.

In addition, warranty coverage plays the promotional role to signal the quality of products to the potential customers. Warranty coverage also acts as a powerful advertising tool for a manufacturer to compete effectively in the market place and it also protects the manufacturer against any damage/failure of the product due to misuse or abuse by the customer.

Under the contractual agreement, a manufacturer of FC power systems would be obliged to rectify defects or failure of power systems due to design, manufacturing and quality assurance.

There is a need to develop a framework for studies of system lifetime and reliability issues for the fuel cell industries, and to develop models for predicting failures and estimating costs for such systems. Modeling power system failures over the NPD's lifetime and estimation of their costs for limited and lifetime warranty is complex due to the uncertainties of usage and level of maintenance during uncertain periods of the NPD's lifecycle (*demonstration, pilot testing and field service*), and the prediction of costs due to limited failure. However, warranties would also act as a source of information about FC Power System's quality and reliability.

Product warranty has received huge attention from researchers from many different disciplines dealing with a diverse range of issues. These include historical, legal and legislative, economic, behavioral, consumerist and engineering issues. Other areas include stochastic statistical modeling and analysis, operations research, accounting, marketing, management, societal and many others.

Yet, fuel cell literature shows that only a very few researchers have worked in the area of warranty. There is huge scope for future research in this area. This includes modeling failures and costs for different types of cost sharing and trade in lifetime warranty policies, modeling failures and costs for two-dimensional policies, expected life cycle costs (LCC) for complex system with repairable and non-repairable components and provision of second-hand components used in servicing warranty claims. Other areas

for future research could be modeling effects of various servicing strategies such as overhauling and preventive maintenance on the long-term warranty costs.

17.3 Modeling Costs for Lifetime Warranty at System Level

Availability, reliability and maintainability are key considerations in most product development. With recognition that in-service failure cost can far exceed initial purchase cost, companies are required to pay as much attention to reliability as to performance.

Performance is optimized by integrating reliability into product development from its earliest stages and by considering the appropriate trade off. According to Turban et al. (2002), "*Customer service is a series of activities designed to enhance the level of customer satisfaction – that is, the feeling that a product or service has met the customer expectation*." In later phases, through its access to engineering design and analysis skills, fueled by data collected from customer service, only by these measures can fuel cell developers bring practical understanding to their product reliability and maintainability approaches of their first generation products.



Figure 17-2: The Interrelationship of System Engineering Practices [Chatopadhyay, 2008]

After a product (*viewed as a system*) is produced, reliability engineering monitors, assesses, and corrects deficiencies. Monitoring includes electronic and visual surveillance of critical parameters identified during the fault tree analysis design stage. The data are constantly analyzed using statistical techniques, such as Weibull analysis and linear regression, to ensure the system reliability meets requirements.

During the scale-up and manufacturing phases of the FC Power System's lifecycle, reliability data and estimates will be key inputs for system logistics. Production logistics ensures, for example, that each machine and workstation is being fed with the right product in the right quantity and quality at the right time. The concern is not the transportation itself, but to streamline and control the flow through value-adding processes and eliminate non–value-adding ones.

Reliability data collection is highly dependent on the nature of the system. Most large organizations have quality control groups that collect failure data on product volume, equipment, and machinery. Consumer product failures are often tracked by the number of returns. Track and tracing is an essential part of production logistics—due to product safety and product reliability issues. Product reliability definition may be defined in several ways:

- The idea that a product (as a system or collection of subsystems) is capable of performing a function with respect to time;
- The capacity of a system or (the collections of the system of systems) to perform as designed;

- The resistance to failure of a system or (the collections of the system of systems);
- The ability of a system or (the collections of the system of systems) to perform a required function under stated conditions for a specified period of time;
- The probability that a functional unit will perform its required function for a specified interval under stated conditions.
- The ability of a product to "fail well" (fail without catastrophic consequences).

Most real life, commercialized products are treated as a system comprising number of components and failures are modeled at the system or sub-system level. Cumulative failure distribution of the product is assumed and modeled as F(t) with density function f(t) = dF(t)/dt and the product failure intensity function is modeled as:

$$\Lambda(t) = \frac{f(t)}{(1 - F(t))}.$$

Assumptions:

- Item failures are statistically independent.
- Item failure, in a probabilistic sense, is only a function of its age.
- The time to carry out a rectification action by repair or replacement is negligible compared to the mean time between failures and this time is ignored.

17.4 The Need for Reliability in Preliminary Engineering Designs of Innovative Products

For any system, one of the first tasks of reliability engineering is to adequately specify the reliability requirements. Reliability requirements address the system itself, test and assessment requirements, and associated tasks and documentation. Reliability requirements are included in the appropriate system/subsystem requirements specifications, test plans, and contract statements of any product.

Reliability is a measure of the frequency of product, systems, subsystem, and equipment failures as a function of time and it has a major impact on maintenance, rework, redesign and repair costs and on the continuity of product service and customer satisfaction. There are those who would argue that the costs of reliability activities associated with developing new products have little payoff.

However, reliability driven NDP is one of the most important principles in systems engineering design of innovative products. Key stated the importance of these principles when he stated "that the development process methodology of having welldefined phases, with activities, documentation, deliverables, responsibilities, and participation by representatives of all company lines functions for each phase assures that each has a well-defined plan. The scheduling of regular program progress reviews and major decision (design, program) reviews to document completion of phase(s) and preparedness for next phase, assures effect continuous quantitative program/product quality assurance. The participation and approval requirement by all of the subprogram project/product managers and their sub-teams members also assures a total quality control process. This team participation approach also has a total quality control

process. This team participation approach also has a positive impact on quality by dramatically reducing the number of changes (by engineering and other organizations) after product release to production and the field. These changes carry quality control, configuration control, cost, customer performance, perception, and penalties."

A strong quality assurance system engineering program and policy is not achieved without upfront investment costs; but these efforts do directly affect the amount of profit and revenue an organization will generate over the later phase of the product's life cycle. As **Figure 17-3** shows, there is an initial monetary investment before and shortly after market introduction with any new product development effort. Reliability Engineering efforts are included into this initial investment. As **Figure 17-3** below depicts, there is an initial monetary investment in product design/development, and manufacturing before market introduction and in ramping up the product for this introduction, for any new product development effort the robust design and reliability engineering efforts are a significant part of this R&D investment effort.



Figure 17-3: Typical Project/Product Development Management Budget Cycle

Consider a very simplify analogy. Cost of research and development are cut so that it appears, at least '*on paper*' that the investment costs and the time to market for a product have been decreased. What would happen shortly after the product's market introduction?

Depending on how much the manufacturer had to pay for the extra customer service, the repairs, the maintenance and replacement cost that would result from inadequate development effort, depending on the conditions and the length of the coverage period of the product's warranty and service plan, either the customer or the manufacturer would have to pay for these costs.

On the surface this analogy has describe a WIN-LOSE scenario; however, cumulative affects will ultimately turn this situation into a LOSE-LOSE scenario for both

parties because the manufacturers/developer's image and reputation are tarnished and this situation *might* and often times do opens up an opportunity for competitors to gain a market place advantage. **Figure 17-4** shows the shrinkage of the profit hill as revenue and profits are lost in this scenario.



Figure17- 4: A typical Project/Product Development Management Budget Cycle due to decrease investment costs of reliability studies and prolong period of applied research. [Keys, 2010]

Many manufacturers seem to cling to a crazy idea took hold of an outdated mindset toward NPD that overemphasizes cost cutting-based tactics in the pure and applied research development phases which drives the product to market without much reliability testing instead of toward strategic durability lifecycle planning. They forget that any applied discipline, such as reliability and quality control, can be looked upon as an internal "*resource*" instead of "*unwanted costs*."

It is understandable that this lack of a participative methodology towards systems engineering principles concerning NPD reliability runs counter to the philosophy of Wernerfelt (1984), who defines a resource as anything that could be thought of as a strength of a given firm (company/organization). He contends that one category of valuable resources includes those that lead to a first-mover advantage.

First-mover advantage is the advantage gained by the initial occupant of a market segment. However, the extreme view that cutting cost, "*nega-dollars saved*" if reliability and quality control testing were done at a minimum as an advantage to market entry can be shot down.

Reliability and quality control testing should be looked upon as market place sustainability accelerators. A competitive advantage can be attained if the resource is value-creating. Although a competitive advantage has the ability to become sustained, this is not necessarily the case.

A competing manufacturer can enter the market with a resource that has the ability to invalidate the prior manufacturer's competitive advantage, which results in reduced sustainability in the context of a sustainable competitive advantage which is independent with regards to the time frame. Rather, a competitive advantage is sustainable when the efforts by competitors to render the competitive advantage redundancy have ceased.

The LOSE-LOSE scenario of NPD can be avoided if robust, reliability, quality polices and production practices and engineering efforts can led to a new product introduction that performs to the manufacturers specifications (promises to the customers) and that meets (or exceeds) the customer's expectations over a competitive useful life.

In general, the LOSE-LOSE scenario of NPD can be avoided because reliability practices predictions:

- Help assess the effect of product reliability on the maintenance activity and on the quantity of spare units required for acceptable field performance of any particular system. For example, predictions of the frequency of unit level maintenance actions can be obtained. Reliability prediction can be used to size spare populations.
- Provide necessary input to system-level reliability models and testing.
 System-level reliability models can subsequently be used to predict, for example, frequency of system outages in steady-state, frequency of system outages during early life, expected downtime per year, and system availability.
- Provide necessary input to unit and system-level Life Cycle Cost Analyses.
 Life cycle cost studies determine the cost of a product over its entire life.
 Therefore, how often a unit will have to be replaced needs to be known. Inputs to this process include unit and system failure rates. This includes how often units and systems fail during the first year of operation as well as in later years.
- Assist in deciding which product to purchase from a list of competing products. As a result, it is essential that reliability predictions be based on a common procedure.
- Can be used to set factory test standards for products requiring reliability testing. Reliability predictions help determine how often the system should fail.

- Are needed as input to the analysis of complex systems such as switching systems and digital cross-connect systems. It is necessary to know how often different parts of the system are going to fail even for redundant components.
- Can be used in design trade-off studies. For example, a supplier could look at
 a design with many simple devices and compare it to a design with fewer
 devices that are newer but more complex. The unit with fewer devices is
 usually more reliable.
- Can be used to set achievable in-service performance standards against which to judge actual performance and stimulate action.

17.5 Preparing for the 'Survival of the Fittest' by the Principle of Systems Engineering (including Reliability Analysis, Construction Feedback)

Design changes can arise at many points throughout the product life-cycle. Meeting these changes necessitates engineering changes to the design. A lifecycle systems engineering approach to NPD can help designers and technical managers evaluate proposed changes in terms of the total process cost of implementing them and executing any knock-on rework which may occur. Such support is useful since there are often multiple ways to implement a design change.

Designers can often identify alternative ways to implement a change. However, evaluating which of the multiple options would be most cost-effective to implement – or whether the change is feasible at all – can be difficult. This arises in large part since change implementation cost is influenced by the product, the redesign process and other processes which are executed concurrently.

Figure 17-3 showed that, starting with the Conceptual and Advanced Design Phase, the initial capital investment increases as pure basic research is done in order to obtain proof of concept and, the planning and forecast of the product's development future is laid out. Sometime during this phase, applied research and development takes the lead. As the product is developed, each aspect of the design which requires change must be modified by undertaking one or more redesign tasks. This might involve rework of tasks which were completed earlier in the design process as well as the execution of *"new*" design tasks.

Since processes can be viewed as networks of interconnected tasks which derive output information from input information, knock-on rework could also be required to many tasks downstream of those originally executed to redesign the affected elements of the product. Total implementation cost thus includes the cost of executing not only those redesign tasks initiated directly, but also those requiring indirect rework. Cost is also influenced by the amount of rework required for each task, which may be different from the amount of work required on the first attempt.

The system specific knowledge base of the NPD is cultivated almost in parallel with engineering and development efforts; unfortunately, however, this trend is at a lesser rate. Change must often be implemented concurrently with other design activities, for instance if the design change arises during the design process or if multiple changes are implemented concurrently. The process of implementing a change interacts with the ongoing workflow since it requires consideration of, and manipulation to, the same descriptions of the design – this could necessitate additional assumptions and drive iterations.

Furthermore, if the change must be implemented by the same personnel responsible for other workflows, resource limitations may affect the total duration of the implementation process. The implications and overheads of executing multiple concurrent workflows thus also affect the total cost of implementing a design change.

As the design 'freezes', takes form, the knowledge base is established and with this development transition, investment capital steadily increases until at some point investment reaches an apex.

As each phase of the lifecycle of a NPD progresses, **Figure 17-5** shows that the commitment to the technology development, to its configuration, to developing its performance and its performance metrics therefore its cost, etc intensifies.



Figure 17-5: The Relationships of Ease of Design Change, Knowledge Building, and Costs Incurred

This means that the engineering and development effort will have to be progressively greater than before to transform the design into a functional, somewhat robust, reliable product. The cost of development of a NPD increases with time as the product moves from the conceptual design to its preliminary design phase, where its reaches 20% of its total lifecycle cost. At the same time the ease at which the product design can be changed decreases to about 60-80% capacity.

Translated into the terms of the project/product development management budget cycle, (see **Figure 17-3 and 17-4**) the activities of early development phases, the speed in which development takes place and the correctness of the labor, effort and results, tasks and design within the early phases have a direct and imperative effort on the product's lifespan, its revenues and any profit it might generate.

Ideally, down towards the middle phases of the product's lifecycle, as the product enters the market place (see **Figure 17-3**), its investment costs decline suddenly and at some point afterwards the product will start to make a profit. It will mature at some point where within the maturation period the most profit will be generated. It is within this period that a break even point will be reached. Then, the product's usefulness will decline and eventually the product's death will occur. The product will be either replaced or discontinued.

If, however, the early phases in which applied research are extended, stretched out due to not adequately addressing the first 20% of the concept/design/development cycle, the lifespan and the productiveness of the product will be adversely affected see **Figure 17-4**. The cumulative investment of the product might become so great that the market price at which the product is offered to its potential end users might be too high for the customer to afford.

The pursuit of the life cycle profits requires producers to think continuously about a product's life cycle from both the marketing and production perspectives. Strategic

objectives and expense indicators change at different stages of the life cycle. Steady sales volume does not guaranty product's profitability. Product profitability usually declines before sales volume, so product profitability is a better measure of product performance. Using product profitability as a basis for a decision to abandon a product is still a bit risky because product cost allocation may vary considerably in different companies and is often questionable (Susman 1989). Minimizing cost and maximizing the revenue at every stage of a product's life cycle do not necessarily lead to maximum profits over the entire life of the product. Also time and competitors do not stand still. For example, selling products at high prices to enhance revenues can lead competitors to enter the market and drive prices down.

If the early phases where applied research and development are stretched out due to redesigning and rework, it late entry to the market might create an opportunity for a competitor to enter the market first. If the product cannot compete with its competitor by way of price or performance or warranty coverage, the product might see a fast death.





17.6 The Barriers to Commercialization

With regards to support for fuel cell development, one of our major problems here in the United States is to continue to remove unnecessary barriers – such as the antitrust laws, regulatory barriers towards renewable energy technologies, and the high cost of U.S. capita.

The antitrust laws are a barrier to fuel cell technology: these are 100-year-old laws that were designed for a slow-moving, domestic scene, and now are basically anticompetitive in a rapidly changing global marketplace. Unnecessarily restrictive liability and regulatory legislation also needs to be selectively modified. The antitrust laws prohibit contracts, combinations and "*conspiracies*" in restraint of trade. Because trade associations are, almost by definition, combinations of firms in the same industry, compliance with the antitrust laws are of primary importance. The Fuel Cell Industry has been very cautious and, has honored antitrust laws of the land. Fortunately, things are slowly changing. Only just recently did the Federal Trade Commission granted antitrust clearance to Plug Power Inc. for its acquisition of H Power Corp.

Regulatory barriers that must be addressed in order to enable a widespread use of fuel cells technologies are not limited to:

- How will codes and standards for permitting be determined and ultimately enforced?
- Will unmanned operation be generally permitted?
- What siting requirements and processes will be required for fuel cells?
- What emissions regulations (if any) will fuel cells be subject to comply with?
- How will competition transition charges (CTC) be assessed?
- How will distribution charges be assessed?
- Can insurance for these installations be adequately supported and obtained?
- What interconnect standards will be set for distributed resources in various utility service territories?
- What depreciation schedules will be allowed?

The answers to these questions and others will also dramatically impact the market penetration of fuel cell systems and other distributed generation technologies.

The high cost of capital in the United States has been 3 to 4 times as high as in Japan – a major deterrent to investment, innovation, and automation. Capital and installation costs include the cost to purchase and install a Disruptive Energy Resource Technology at a specified location. Capital costs refer to the total equipment cost of a power generation system (i.e., fuel cell system, combustion turbine, etc.) to the end user. The high capital cost for fuel cells is by far the largest factor contributing to the limited market penetration of fuel cell technology. In order for fuel cells to compete realistically with contemporary power generation technology, they must become more competitive from the standpoint of both capital and installed cost (the cost per kilowatt required to purchase and install a power system).

In addition to these obstacles, in a nutshell, the author of this paper believes that significant additional fuel cell research and development (R&D) would need to be conducted under a very solid systems engineering plan to achieve cost reductions and durability improvements for stationary fuel cell applications. To summarize the already discussed barriers, a systems engineering plan would be needed for successful commercialization because of the following reasons:

1. Take what you want and pay for it, says God. Spanish Proverb.

Fuel cells are still a highly immature technology, with relatively low, but growing levels of installation – and it is clear that a key feature of their uptake will be an ability to achieve first small scale, then latter, large scale productions.

To reiterate what was said before, the cost of fuel cell power systems must be reduced before they can be competitive with conventional technologies. Currently, the costs for automotive internal-combustion engine power plants are about \$25–\$35/kW; for transportation applications, a fuel cell system needs to cost \$30/kW for the technology to be competitive. For stationary systems, the acceptable price point is considerably higher (\$400–\$750/kW for widespread commercialization and as much as \$1000/kW for initial applications).

Cost reductions must be realized in raw materials, manufacturing of fuel cell stacks and components, and purchased components. Raw materials costs must be reduced by a combination of alternative (lower cost) materials, quantity pricing, and reduction in required amounts of expensive materials.

Manufacturing cost reductions can be partly realized from classical learning curve gains. However, it will likely require introduction of new and innovative manufacturing technologies or designs requiring simpler manufacturing processes. Because of the nonstandard size and specialized requirements of components for fuel cell systems, costs are unusually high at low volumes. A systematic approach is needed to reduce costs.

 Remember that Fuel Cell Systems are like Fine Wines and should be treated as such. "We will sell no wine before its time", likewise, "We will sell no FC Power System before its time!"





Figure 17-8: A glass of fine white wine
[Wikipedia, 2010]

Figure 17-7: Orson Welles selling Gallo Wine [Gallo Wine Advertisement]

That was the slogan of a famous Paul Masson winery advertising campaign. And, there's wisdom in Masson's slogan for fuel cell producers. The first units of any new product are relatively costly to produce, but experience improves the efficiency of manufacturing methods and the productivity of workers, so that costs come down on succeeding products.

Dr. W. Edwards Deming taught that by adopting appropriate principles of (systems engineering/business) management, organizations can increase quality and simultaneously reduce costs (by reducing waste, rework, staff attrition and litigation) while planning for customer loyalty. The key is to practice continual improvement and think of manufacturing as a system, not as bits and pieces. The '*learning curve*' notwithstanding, during the early stages of a FC Power System's Lifecycle, developers should be mindful of the Cost/Revenue Ratio which is a measurement of inefficiency, especially costs dealing with *rework, replacement, and customer satisfaction and reflects the industry's image*. The Efficiency Ratio, a ratio that is typically applied to corporations/organization/or firms, in simple terms is defined as expenses as a percentage of revenue (expenses / revenue), with a few variations. A lower percentage is better since that means expenses are low and earnings are high. The lower a cost/revenue percentage is the better. Example, Citigroup, Inc. 2003:

- Revenues, net of interest expense: 77,442
- Operating expenses: 39,168

That makes operating expenses / revenue = 39,168/77,442 = 0.51 or 51%. The efficiency ratio is 0.51 or 51%.

For fuel cell developers that want to get to market at a brake neck speed, the ones who go public, should be wary of their Efficiency Ratio, as will be shown later in this chapter.

Fuel Cell developers should not push their products out their door before their products have good performance, reliability and are sustainable without continuous rework, repair and replacement. If certain systems are not designed for sustainability without a continuous funneling of funds, something is wrong. Funders of *'these types'* of innovative technologies should not turned their backs on acknowledging that their *dynamic dodging* cannot be sustainable without additional fund for rework, repair and replacement might well be based (designed) upon a *beggar-thy-neighbor* policy

(principle). Instead good, old fashion, hard-working, systems engineering principles of *designing-for quality-reliability and sustainability* could be used.



Figure 17-9: Technology Validation or lack of - It is a Barrier to Commercialization [EERE, 2007]

3. Failure to work with A Master – Someone who has commercialized a Product.

"Experience by itself teaches nothing." This statement emphasizes the need to interpret and apply information against a theory or framework of concepts that is the basis for knowledge about a system. It is considered as a contrast to the old statement, "Experience is the best teacher" (Dr. Deming disagreed with that). To Dr. Deming, knowledge is best taught by a master who explains the overall system through which experience is judged; experience, without understanding the underlying system, is just raw data that can be misinterpreted against a flawed theory of reality. Deming's view of experience is related to Shewhart's concept, "Data has no meaning apart from its context."

FC power systems might surpass the sophistication of a modern car. Like the automotive industry which designs, develops, manufactures, markets, and sells motor vehicles, and is one of the world's most important economic sectors by revenue, the FC Industry has the *potential* to rival this mechanized behemoth. Like the automotive

industry, which spawned hundreds and thousands of start-ups, developers and supporters of the FC Industry must be mindful that once a few will survive to commercialize and the lucky few most likely will not die lost in the wilderness because they listened and followed their guide – A Master.

4. It's not a *job* but a '*buddy system*' we are after. Failure to grasp the potential value chain and the supply chain support required for the successful commercialization of a FC power system. Those private, governmental and public investors who fund innovative endeavors should NOT count '*how many jobs will be created*' as 'progress' criteria for candidates for potential commercialization success stories. Because, by its very complex, technical nature, the FC Industry's need for high trained, skilled workers will take care of itself. In other words, a successful commercialization of an innovative technology will depend on knowledge exchanges, collaborative relationships and the multitude of workers from a multitude of technology bases. The process of development of a FC power system, if done correctly, will produce very large internal and external employment networks. If done correctly, to organize this endeavor, system engineering approaches evaluating appropriate process progress rates will forge stronger value-creating linkages between the FC developers, the industrial community and Society in general.

5. It's not the *words*, or the *promises* – but the *actions* which yield *results*, *results* and *results*!

Instead, qualifications for funding and continue funding should be based of system performance reliability and performance history. The purpose of reliability testing is to
discover potential problems with the design as early as possible and, ultimately, provide confidence that the system meets its reliability requirements. What is helpful is for a developer to possess a Service-Oriented Architecture Design Plan (SOAD), a set of design failure strategies developed and used during the phases of systems development and integration mapping out potential service plans for systems, subsystems and components as system design and development progresses forward on the product's lifecycle.

The fuel cell industry has begun to pursue standardization of testing methods to enable comparison of results among participants: within laboratories, among different institutions, and perhaps most importantly, between supplier and customer. However, the solid oxide fuel cell (SOFC) industry has lagged in this pursuit, partially because of the uncertain relationship between material parameters, processing and performance, and partially because individual players have adopted individual testing methodologies.

The lack of testing standardization has lead to poor communication within the industry, inconsistent materials and component performance, and skepticism over results that are presented in various forums. Two important challenges for testing in any industry are the determination of the essential parameters at every stage of manufacturing, and standardization of testing, an agreement among all developers as to how the parameters should be measured.

Standardization often requires a multi-year process to coordinate and compromise amongst the various measurement methods for each parameter, followed by round-robin testing to determine precision (reproducibility) and bias (difference of the average from

an accepted ideal value if one is available). In many cases, a single parameter can be measured by multiple methods, and each method has its own standard methodology.

While standard test methods exist for physical properties of ceramic powders and the sintered parts, and consensus exists over which SOFC performance parameters are important (e.g. OCV and ASR), there is little agreement over testing apparatus, procedures or reporting at the cell, stack or device level. There are literature recommendations for preferred approaches to cell testing, but these have not been widely adopted. As a consequence, many fuel cell developers have developed an assortment of individualized devices and testing procedures.

The FC Industry is slowly moving towards coordination of conditions, data analysis and data reporting. But the question is: will the coordination *be done in the nick of time*?

6. 'Pulling' it All Together - System and Product Integrity



Figure 17-10: The Integration of 'Teamwork' towards a common Goal

The successful integration and operation of fuel processors, cell stacks, and balance of plant components (compressors, pumps, humidifiers, heat exchangers, sensors, controls, etc.) in fuel cell systems operating under real world conditions have yet to be adequately demonstrated. The one exception is the phosphoric acid fuel cell system that is marketed commercially worldwide (the United Technologies Fuel Cell PC25), but in relatively low volume to niche markets with government subsidies that help offset the high system price.

Another fuel cell company, Fuel Cell Energy claims to be a world leader in the development and production of stationary fuel cells for commercial, industrial, municipal

and utility customers. Fuel Cell Energy's 2010 Annual Report starts with, "80 Direct

Fuel Cell® (DFC®) power plants are generating power at over 50 locations worldwide.

DFC power plants have produced over 650 million kWh of power using a variety of fuels

including renewable biogas, natural gas and other hydrocarbon fuels."

But look here at Fuel Cell Energy's Efficiency Ratio. On page 9 of its 2010

Annual Report, Fuel Cell Energy's cost-to-revenue ratio in October, 2009 was 1.45.

Looking for an explanation for this *disaster*, the author found it on page 10 of Fuel Cell

Energy's 2010 Annual Report:

"have historically sold our fuel cell products below cost while the market develops and product costs are reduced. We have been engaged in a formal commercial cost-out program since 2003 to reduce the total life cycle costs of our power plants and have made significant progress primarily through value engineering our products, manufacturing process improvements, higher production levels, technology improvements and global sourcing...The overall product cost-to-revenue ratio (including warranty expenses, liquidated damages, costs to service power plants for customers with LTSAs, PPA operating costs and LCM adjustments) improved to 1.32 in fiscal 2010 from 1.45 in fiscal 2009."

The cost/revenue ratio, rather, costs/donation ratio is the only criteria which is used in assessing the efficiency or otherwise of a 'charity'. Cost/donation ratio can be used to track an individual nonprofit's progress over time. After reading the above entries, the author wondered if Fuel Cell Energy was solely in the business to spend or lose money.

Fuel Cell Energy's overall product cost-to-revenue ratio included warranty expense, liquidated damages and costs to service power plants, could all of this expense been prevented if their products were robustly and reliably designed and functionally operating upon market entry? Did Fuel Cell Energy's designers just throw the product over the proverbial *"lifecycle phase*" wall to manufacturing, then hope for the best? The information from Fuel Cell Energy's 2010 Annual report leads one to wonder if this was indeed the case, that Fuel Cell Energy prematurely pushed their products out the door.

Perhaps Fuel Cell Energy could learn a lesson or two from the early, Japanese automobile manufacturers. It's a well-known fact around the world that Americans love their cars. And for many decades, Americans overwhelmingly turned to the Big Three automakers -- General Motors, Ford and Chrysler -- to satisfy their automotive lust.

Ford revolutionized manufacturing with the assembly line and automation. These advancements called for producing large numbers of one type of vehicle (*even in the same color*), keeping the workers as busy as possible and running the plant around the clock.

While more was more, it wasn't necessarily better. Very little changed in the carbuilding process used by American automakers, and until the 1970s, there wasn't much in the way of mass-market foreign competition.

Japan got into the car business almost immediately after World War II. Early attempts by the Japanese resulted in the production of somewhat primitive knockoffs of American designs, and they didn't gain much traction at home or abroad.



Figure 17-11: Humorous representation of System Engineering dealing with a difficult situation and the consequences in pursuit for quality, reliability and functionality in NPD

Nevertheless, Japanese car exports began to rise in the 1950s. Manufacturers faced a skeptical American public who viewed Japanese exports as cheap household products and flimsy, mass-produced junk.

However, the founders and leaders of future automotive giants Toyota and Honda were determined to produce cars not only comparable to American cars, but better.

Japan, at that time, had very little natural resources – but the one resource they had was a desire to build a product which had quality and reliability and could, hopefully, function as well or better than the competition.

Originality and efficiency were their guiding principles, supported by curiosity, an ear for consumers and their burning desire to improve.

Before long, consumers in the United States (*and elsewhere*) began to notice the impressive engineering and reliability of Japanese cars, and the Big Three spent much of the 1980s and beyond pleading (*whining, whining and whining*) with domestic consumers to "*buy American*."

Limited field experiments of solid oxide, molten carbonate, and polymer electrolyte systems for stationary and transportation applications have met with limited levels of success. Needless to say, projected market entry dates for commercial applications of these fuel cell technologies have not met developer or market expectations. The fuel cell industry could learn a thing or two from Japan. The morale behind Toyota and Honda's challenges and their victories is and, to reiterate a very important systems engineering principle, '*No wine before its time!*"

7. The Disruptive Model with no clear Market Demand

Currently today, there exists no technology to leverage against except systems (products) that are vastly cheaper. Disruptive technologies are not always disruptive to customers, and often take a long time before they are significantly disruptive to established industries. They are often difficult to recognize. Indeed, as Christensen points out and studies have shown, it is often entirely rational for incumbent consumers to ignore disruptive innovations, since they compare so badly with existing technologies or products, and the deceptively small market available for a disruptive innovation is often very small compared to the market for the established technology.

8. The General Apathy/Understanding Gap about Energy Technologies and how Fuel Cells work.

Fuel cell development for stationary application, smart energy and renewable green energy are complex topics, and people are uncertain about the technology's impacts on their lives, energy security, safety, etc. Case in point, most consumers view "energy efficiency," "smart energy" and "energy conservation" as positive concepts, few fully

understand what those and other energy-related terms mean, according to a recent survey. Marketing agency EcoAlign recently conducted its sixth EcoPinion survey, testing 1,000 consumers' awareness, understanding and acceptance of phrases like "energy efficiency," "demand response" and "clean energy." For the most part, consumers viewed the terms positively. But when they were asked to match the terms to their definitions, less than one-third chose correctly. Also, fewer consumers chose correct definitions than those who were questioned in the first EcoPinion survey in October 2007. In the 2009's survey, 80 percent chose the correct definition for "clean energy." But that's a drop from 86 percent getting it right in 2007. The same thing happened with the definition for "demand response." Sixty-nine percent got it right in 2009, but 73 percent got it right in 2007. When it came to other terms like "peak pricing," "budget billing," "flat pricing," "time of use pricing" and "fuel supply pricing," consumers were either very knowledgeable about what the terms meant or were practically clueless about them. The report suggests that, due to consumer misunderstanding of some terms, to stop using industry terms like "demand response" and "peak pricing" when communicating with consumers. Even though those concepts are important when it comes to the Smart Grid, consumers did not understand them but also even made negative associations with them.

Ultimately, consumer preferences drive the choices made in energy markets, technology development, and public policy. Informing the public through educational and training materials, science curricula, and public outreach programs might help garner public acceptance for fuel cell technologies and their potential services.

17.7 Conclusion

Availability, reliability and maintainability are key considerations in most product development. With recognition that in-service failure cost can far exceed initial purchase cost, fuel cell developers are required to pay as much attention to reliability as to performance.

CHAPTER XVIII MODULARITY – PHASE TWO

18.1 Introduction

A NPD's architecture begins to emerge during the Conceptual Design and Advance Planning Phase. This happens, mostly informally, in the sketches, functional diagrams, and in early prototypes of the subsystems and/or whole system itself. Generally, the maturity of the basic product technology dictates whether the product architecture is fully defined during the Conceptual Design and Advance Planning Phase or during the Preliminary System Design Phase. When the new product is an incremental improvement on an existing conceptual design, then the product architecture is defined as an expansion upon the foundation of the original conception. This is for two reasons. First, the basic technologies and working principles of the product are predefined, and so conceptual-design efforts are generally focused on better ways to embody the given concept. Second, as a product matures, supply chain considerations and issues of product development and manufacturability begin to become more prominent. Product architecture is one of the development decisions that most impacts a fuel cell developer's ability to efficiently deliver high performance power systems. System hierarchy architecture therefore becomes a central element of the product concept in the Preliminary System Design Phase. However, when the new product is the 'first of its kind', as most fuel cell power systems are, concept development is generally concerned with the basic working principles and technology on which the product will be based. In this case, the systems architecture is often the initial focus of the system-level design therefore decisions about how to divide the product into modules and about how much modularity to impose on the systems architecture are tightly linked to several issues of importance to the entire enterprise: product change, product performance capabilities, component standardization, the product's manufacturability, and product development management. Therefore a system's architecture will later be closely linked to decisions about marketing strategy.

18.2 An Example of a Complex Design Synthesis

In formulating the entire synthesis/design of a power system (i.e. identifying all the interacting sub-systems, choosing the possible configurations and decision variables, and defining the physical constraints), it may turn out that attempting to solve the all the problems associated with the system's design (as opposed to solving sets of multiple problems) is simply impractical. The reasons for this are many [Rancruel, 2004]:

- The number of decision variables involved may simply be too large for an efficient solution.
- A single group of developers may not possess all the expertise required for dealing with the technologies, sub-systems, and components involved in the problem.

- In the integration of different subsystems and their controls the overhead might simply be too great to make the optimization viable.
- The synthesis/design of the different sub-systems may, in many cases, be done at different stages and times.

This is further complicated by the need to examine the largest number and most complete set of alternative syntheses and designs at each level of the problem in the shortest amount of time possible. Some fundamental issues, which the fuel cell developer must examined includes the following [Rancruel, 2004]:

- The effects of system decomposition on convergence to a global optimum or a set of near-global optima.
- The effects of system decomposition on the global of the electrical model of the SOFC.
- 3. The effects of material, geometric and other design changes at the component or subcomponent level.
- 4. The coupling between the physical phenomena at the component and sub-component levels and the thermodynamic, heat and mass transfer, kinetic and dynamic behavior found throughout the system.
- 5. The coupling between the dynamics of the overall system and the static and dynamic or transient responses of individual sub-systems and components and the effects these have on component geometry and material selections as well as component and sub-system integration.
- 6. The relevance of using the 1^{st} and 2^{nd} Law of thermodynamics as a measure of the relative importance of the physical phenomena taking place in the system and as a guide to

component and system level changes which alter these phenomena in ways consistent with the global optima sought for synthesis/design;

18.3 What about the Cost?

From a cost viewpoint, within the fuel cell industry, there is currently little support to help designers and managers evaluate proposed design changes in terms of the total process cost of implementing them and executing any knock-on rework which may occur. Such support would be useful since there are often multiple ways to implement a requirement change, and it is thus important to identify the most cost-effective option prior to beginning its implementation. The importance of estimating the cost of different change implementation options is not limited to the design process, but can be critical at all stages in the product life-cycle. For instance, implementing a change while a product is in production will potentially be much more expensive than making the same change during design. Thus it is important to ensure that appropriate change implementation decisions are made throughout the product life-cycle.

18.4 Modularity – The Solution

Designing a fuel cell power system is a challenging task. This stems in part from uncertainty in their behavior – for instance, in the duration and outcome of their constituent activities or in the availability of resources to perform these activities. A process' architecture plays an important role in determining a power system's behavior. Several authors have discussed how design process architectures could be modified to better deal with uncertainty and hence to create better performance.

Gurumurthy states that, including modular design tradeoffs *'early in the design process*'' will decrease life-cycle costs. Newcomb (et al) hypothesized that a modular

architecture will lead to decreased life-cycle costs even if the modules are not designed with other life-cycle characteristics specifically in mind. This is probably true in general but targeted life-cycle design will increase these benefits and add structure to the process. Newcomb (et al) suggested two principal hypotheses [Zhang, 2003]:

- 1. For a majority of products, the product's architecture (Top-Down and Bottom-Up) plays a predominant role in determining its life-cycle characteristics and
- 2. High life-cycle modularity can be beneficial across all viewpoints of interest.

Modularity, from a NPD viewpoint, requires maintaining independence between components and processes in different modules, encouraging similarity in all components and processes in a module, and maintaining interchangeability between modules. Modularity with respect to manufacturing necessitates understanding the various manufacturing processes undergone by each attribute of each component [Zhang, 2003, Keys, 1991].

Modularity is also an important design principle that helps reduce the damage caused by malfunctioning parts and the risk of unforeseen side effects of otherwise well functioning processes. Modularity gives designers the ability to localize parts of a system in order to study subsystem interactions, thus enhancing the possibility of a robust design free of errors and dysfunctional interference.

Systems that achieve performance reliability and robustness via learning face a dilemma. Improved decision making requires the collection of increasing amounts of information, but more data, without a systematic method for application, can lead to worse decisions. Modularization, due to the functional independence it creates, has been called the goal of good design. Occasionally, modules are created with some aspects of

production in mind. However, if 'production' modularization is done without fully understanding the implications of the design, although often yielding highly functional products, once the entire manufacturing process is accounted for, this unstructured modularization often leads to costly redesigns or very expensive products. In addition, the unstructured modularization makes the process difficult to repeat if it is successful and difficult to avoid if it is unsuccessful.

18.5 Modularity for Manufacturing

Modules contain a high number of components which have minimal dependencies upon and similarities to other components in the product not in the module but which have a high degree of dependency upon and similarity to other components in the module. These dependencies and similarities include those which arise from the relationships between the components' attributes and those which arise from the relationships between the components during the various phenomena the components undergo in their life-cycle. Therefore, in a module, each component is independent of all components not contained in the same module (independence). In addition, each component in a module must be processed in the same manner during each phase of it life-cycle (similarity) to reduce interdependencies between modules. The form-function relationship has therefore been replaced with a form-process relationship.

While complete modularity may be unrealistic except in the most trivial cases, a product which exhibits a higher degree of modularity is more likely to incur a lower total life-cycle cost.

Characteristic modules contain a high number of components which have minimal dependencies upon and similarities to other components in the product with regard to a particular phase of the lifecycle. Characteristic modularity may be more useful than total

product modularity for a product, especially if there are one or two characteristics which dominate the requirements and costs of a product. Developing products which are modular in terms of characteristics besides the primary drivers could result in excessive modularity and/or decreased value.

An important consideration when defining the manufacturing modularity of a product is the chosen level of abstraction of the manufacturing process itself. The manufacturing of a product is made up of many tasks. These tasks are, in turn, made up of sub-tasks. A product may be modular (independent and similar) when examined from the standpoint of the overall manufacturing processes (*e.g.*, injection molding versus forging) but at some task level, the structure may not be very modular with respect to the manufacturing process (*e.g.*, similarity of fixturing components within a module). Therefore, when defining the relative manufacturing modularity of a product, one must do so with respect to the tasks and sub-tasks of the manufacturing process. This is parallel to considering the level of abstraction of the product. Lastly, it is important that manufacturing modularity takes into account manufacturing's effect on each product attribute.

When looking for dependencies and interactions between modules and components, each attribute of the product, modules, and components must be considered. As an example, consider the Enclosure or housing of an SOFC Power System which is one modular assembly composed of many components. All of the components of the housing should be made of the similar material, should be manufactured to similar tolerance specifications, should possess the same surface condition, and should undergo

the same manufacturing process. Its product attributes include: geometry, features, tolerances, surface condition, and materials (including insulation).

Component attributes have fewer dependencies on attributes of components outside of the module, called external attributes. If there are dependencies, there should be fewer of them and they should be dependent to a lesser degree. Attribute independence yields form independence which enables modularity. Attribute independence allows for the redesign of a module with minimized effects on the rest of the product. This makes a product more agile in meeting changing requirements.

18.6 Example of Functional Dependency in relation to Manufacturing Design

From an earlier chapter it was shown that the SOFC Power System was divided into three major subsystems, namely, the Enclosure, the Cell Stack and the Balance-ofplant. The Balance-of-plant was further divided into lower level subsystems. Of the nine subsystems of the SOFC Power System, using DSM analysis, the Cell Stack proved to be its pivotal subsystem because the Cell Stack is the most functionally dependent subsystem of all of the SOFC Power System's subsystems.

Table 18-1 THE RANKING OF SUBSYSTEM FUNCTIONAL DEPENDENCY				
The Subsystems	# of Dependents			
The Cell Stack Package	7			
The Fuel Processing System	6			
The Thermal Management System	5			
The Air System	5			
The Electrical System	4			
The Hot Assembly	4			
The Waste Management System	4			
The Mechanical System	4			
The Enclosure	2			

A simplistic example of attribute dependence decreasing agility would be changing the design of the Cell Stack Package which rests on the base of and in a special chamber of the Hot Assembly. If the Cell Stack Package and the Hot Assembly were looked upon as two individual modules, and if the Cell Stack Package configuration needed to be changed to a larger dimension, say changed in width, depending on how much leeway the design of the Hot Assembly's furnace width is, the Hot Assembly might need to be change in this dimension also. Therefore, both modules (the Cell Stack Package and the Hot Assembly) would need redesign.

Each manufacturing process of each module has fewer dependencies on the processes of external components. This requires that the manufacturing processes (including all tasks) that a module undergoes are independent of the processes undergone by external components and modules. Once again, any dependencies that do exist are minimized in number and criticality. For example, the process for the three ceramic parts of the Unit Cell (the electrolyte, the ceramic cathode and ceramic anode) of the Cell Stack Package, which are fired together, is shown below. If the material of any of the three parts changes, the process of one part might need to change so that there is a different sintering time, from a modularity standpoint, it would be more effective if the process of the other components could change so that they can be fired together at the same time.



Figure 18-1: Process Flow Chart [Arthur D. Little Ltd., 2001]

18.7 A Method for Modularizing an SOFC Power System

Designers often seek modular architectures for complex systems so that their systems better accommodate unexpected changes, have parts that can be developed and evolved without further coordination, and to ease the understanding of complex designs through abstraction of details hidden within modules. In this section, a framework for modularization of high-level design abstractions will be presented below:

- 1. From the system architecture hierarchy, the pivot subsystem of the product should be identified.
- Identify the linking subsystems of the product. Subsystems which link the pivot subsystem to the rest of the system are known as 'linking subsystems'. These are the easiest subsystems to modularize.
- Identify the Relational Subsystem The least likely subsystems to modularize.

- Identify the Compliment Modules. These will be two or more subsystems which work together in order to perform an operational requirement or function.
- 5. Define the Housing Module of the Product.

Г

THE GROUI S	Table 18-2 PING (MODULATING) OF ' YSTEMS' SUBSYSTEM AN (BOTTOM-UP APPROA	THE SOFC POWER ALYSIS CH)
		Symbol
The Pivotal System	• The Cell Stack	The Cell Stack
The Linking Subsystems	The Electrical SystemThe Hot Assembly	
The Identity Relational Subsystem	 The Thermal Management System The Waste Management Subsystem 	
The Compliment Subsystem(s)	 The Fuel Processing Subsystem The Air Subsystem 	
The Rank Ordered Subsystems based on Provisional Characteristics	 The Enclosure The Mechanical Subsystem 	

18.8 The Pivotal Subsystem – The Cell Stack Module

The pivotal subsystem is the subsystem designed to perform the main function(s) of the product, in the SOFC Power System's case, that purpose is to produce electricity (and quite possibly, high quality heat).

When focusing on the Cell Stack concept, it becomes one of the most important designs of the power system because the stack must meet power requirements of the end user as well as the system itself.

The Cell Stack's dependency means, from a design point of view, that most, if not all the other subsystems must be designed to serve its requirements. Consideration for these functions should take priority over adaption to modularity.

Table 18-3RELATIONAL CHARACTERISTICS OF EACHSUBSYSTEM						
The Subsystems	# of Dependents	# of Provisions				
The Air System	5	2				
The Cell Stack Package	7	2				
The Electrical System	4	8				
The Enclosure	2	7				
The Fuel Processing System	6	1				
The Hot Assembly	4	7				
The Mechanical System	4	3				
The Thermal Management System	5	8				
The Waste Management System	4	4				

As far as provisional functions, the Cell Stack has one, maybe two purposes; to provide the electrical system with DC power and to provide the end user with heat.

As a subsystem (module) in itself, the Cell Stack Package is unique because its materials requirements are radically different from the material needs of the Enclosure or the BOP Subsystems. And the Cell Stack's material requirements must be met in order for it to produce its end products. Any manufacturing process or method must take into consideration the Cell Stack's key material properties (structural, thermal, electrical, and interfacial material properties, etc).

Going into pre-manufacturing mode, Cell Stack design criteria must be met when identifying possible failure modes and associated mechanisms in SOFC material and components: structural failure, bulk material, interfacial, loss of contact, etc.). Characteristic attributes of the Cell Stack module should be the main focus in the manufacturing process and take the following into consideration:

- 1. The geometrical changes to components.
- 2. The Cell Stack's operating conditions.
- 3. Any material modification/substitution.

18.9 The Linking Subsystems –Bridge Modules

The opposite of a modular architecture is an integral architecture. Bridge

Modules exhibit one of more of the following properties:

- Functional elements of the module are implemented using more than one subsystem.
- A single module implements many functional elements.
- The interactions between module elements are ill defined and may be incidental to the primary functions of the module.

The bridge modules of the SOFC Power System should be designed with the

highest possible performance in mind. Implementation of functional elements may be

distributed across multiple subsystems. Boundaries between the elements may be

combined into a few physical components to optimize certain dimensions of

performance; however, modifications to any one particular component or feature may

require extensive redesign of the product.

From a functions point of view, the Hot Assembly is a provisional subsystem and

it is also classified as a bridge module.

Table 18-4 HOT ASSEMBLY BRIDGE MODULE Provides physical linkage to the Cell Stack >>>>

		A	В	C	D	E	F	G	Η	1
Hot Assembly	А		Χ	Χ	Χ	Χ	Χ		Χ	
Fuel Processing System	В									
The Air System	С									
Waste Management Subsystem	D									
Thermal Management System	Е									
Electrical System	F									
Mechanical System	G									
The Cell Stack Package	Η									
Enclosure	Ι									

The Hot Assembly is a multifunctional module, which physically links the Cell Stack to the other subsystems. The Cell Stack Package rests upon and, inside it. The fuel and oxidants are transmitted from the Fuel Processing System and, the Air System via channels in the Hot Assembly. Exhaust gas is taken away from the Cell Stack Package via a channel exiting the Hot Assembly. The Cell Stack Package is electrically connected to the Hot Assembly is such a way as to provide power transport to the Electrical System. Covered in insulation packaging, the Hot Assembly is design to keep the Cell Stack Package at operational temperature and, at the same time it prevents the components closest to it from overheating. Due to the Hot Assembly's operating environment, which has manufacturing implications regarding the choice of its material and, the properties of its materials, the Hot Assembly should be treated as a separate module.

Yet, on the other hand, compared with the rest of the other BOP subsystems, except for the Electrical System, which shares this feature, the Hot Assembly is unique. Since its functional performance and architectonical constraints depend on the subsequent detail design decisions for the Cell Stack Package, the Hot Assembly could be thought of as the second module of the Cell Stack Package.

Like the Hot Assembly the Electrical System could be thought of as 'another' second module of the Cell Stack Package because of its intimate 'electrical' connection to it. Being the most provisional subsystem of the SOFC Power System by way of 'function' it is classified as a 'linking' subsystem because it has a multitude of connections and interfaces throughout the power system. Based on design criteria, the electrical system of an SOFC Power System will under go sub-modulation early on in its conceptual design.

18.10 The Identity Relational Module – the Modularity of the Thermal Management and Waste Management Subsystems of the SOFC Power System

The Thermal Management Subsystem is represented by the red field (which surrounds the pivotal, the complimentary, and the translational subsystems).



Figure 18-2: The pictorial representation of the modular groups of the SOFC Power System

The Thermal Management and the Waste Management Subsystems are abstract subsystems, meaning they are the least likely subsystems to be modularized. In regards to modulation, they are considered '*abstract*' because their components are not '*linked*' together in one continuous component-part system, like the Fuel Processing Subsystem, but their components are scattered within and throughout the Power System.



Figure 18-3: The Elements of Focus for the Modules of the Thermal Management System

Because of their abstract nature, many manufacturing processes will be involved in the manufacturing of the components of the Thermal Management and the Waste Management Systems.

During design changes for tailoring the subsystem to Design of Manufacturability, in the preservation of the Thermal Management Subsystem's characteristic attributes, it is important to incorporate each of this subsystem's elements of focus into the subsystems which the elements of focus are directly (physically) connected to. As design for manufacturability progresses, each subsystem (containing elements of focus for the Thermal Management System) should be model for important physical phenomena, thermal-fluid-electrochemical analysis, and for thermal-structural analysis.





With regards to the manufacturability of the components of the Waste Management Subsystem, fuel cell developers should keep in mind the Extended Producer Responsibility (EPR) which is a strategy designed to promote the integration of all costs associated with products throughout their life cycle (including end-of-life disposal costs) into the market price of the product. Extended producer responsibility is meant to impose accountability over the entire lifecycle of products and packaging introduced to the market. This means that developers which manufacture products are required to be responsible for the products after their useful life not only during manufacturing. A comprehensive System Waste Management Program for a power system can include:

- Environmental assessments and monitoring
- Waste and contaminant characterization
- Environmental management (handling, storage, transportation)
- Permitting assistance and community relations
- Regulatory negotiations
- Waste minimization and reuse plans
- Design of waste transfer and processing facilities
- Design of waste disposal facilities (landfills, impoundment, caps, cutoffs)
- Design of collection and treatment systems for unwanted gases.

18.11 The Compliment Modules – the Air and Fuel Processing Systems

Two chemical reactions occur at the interfaces of the SOFC Power System's Cell Stack. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electric current is created. For the Cell Stack to produce electricity, a fuel and an oxidant must be added.

The Air Subsystem and the Fuel Processing System are each other's compliments. Both must be present and functioning in order for the power system to operate. Because their functions are complimentary and very interdependent, their architectural components will be very similar in design of components (e.g. each might have compressors, piping, fans blowers, etc.).

Table 18-5 FUEL PROCESSING /AIR MODULE COMPONENTS FOR ELECTRICITY PRODUCTION

Fuel Conditioning Unit Water Management System Steam Reforming Unit Anode Portion of the Cell Stack Thermal Connections Electrical Controls Air Filtration Unit Exhaust (Return) Section Cathode Portion of the Cell Stack Thermal Connections Electrical Controls

	Α	В	С	D	E	F	G	Η	Ι	J	Κ
А											
В											
С											
D	Χ	Χ	Χ		Χ	Χ					
Е											
F											
G											
Η											
Ι							Χ	Χ		Χ	Χ
J											
Κ											

18.12 The Housing Module

From a manufacturing perspective, the remaining subsystem, namely, the Enclosure should the last system to mature. The components of the Mechanical System are mostly 'absorbed into the Complimentary Modules of the Fuel Processing System and Air System. The design for the Enclosure should focus on the needs of Balance-of-Plant and End User.

18.13 Case Study Example of a Linking Subsystem – Examples of DFM

The below case was included to determine the DFM activities necessary for bring an

SOFC Power System's modules to a pre-manufacturable prototype.

Gopinath's (et al) low cost inverter approach was created to enable small-scale fuel cell power systems commercialization and was done in hopes of encouraging the development and advancement of distributed power systems.



Figure 18-5: Block Diagram for DC–DC Converter Control (Gopinath's (et al) Design, 2004)

The below information was taken from a 2004 paper entitled, '*Development of a Low Cost Fuel Cell Inverter System with DSP Control*'. Gopinath's paper outlines the technical approach adopted to meet the specifications laid down for the 2001 Future Energy Challenge (FEC'01) organized by the Department of Energy and IEEE in August 2001. Gopinath's paper outlines the design and development of a low cost fuel cell inverter system. Gopinath's (et al) design team made well-informed design decisions to aggressively lower the cost of the final 10-kW design and 1.5-kW prototype. By use of the push-pull topology the number of MOSFETs was minimized to half that needed by a full bridge topology. IGBTs were reduced in the inverter by use of the half bridge topology as opposed to the full bridge topology.

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a commonly used technique for controlling power to inertial electrical devices, made practical by modern electronic power switches. The analog PWM controller provided a low cost solution to control the dc–dc converter. It provides a single chip control solution opposed to complex discrete analog hardware. A digital signal processor (DSP) is used to control power electronic devices to generate a third voltage, which along with the single-voltage from the supply creates a balanced three-phase power supply. The DSP control of

the dc–ac inverter provides efficiency of time and control. Readily programmable, the DSP enables easy design changes to account for various applications and allows a seamless interface with other components of the power management system. Programming capability translates into efficiency in human capital reducing costs of analysis, troubleshooting, development and manufacturing of the inverter. The topology of the Fuel cell Inverter System employed a high voltage battery floating on the dc-link. This approach did not add any additional power processing cost for management of transient loads. The advantages of Gopinath's design are as follows:

- 1. Lower parts count, easy manufacturability, and lower cost resulting in an economically viable design.
- 2. Protection and diagnostic features provide safety and convenience for the operator.
- 3. Flexibility and intelligence are incorporated to suit varying system and control requirements.

In order to take a conceptual model of a fuel cell power conditioning unit to a functional prototype ready for manufacturing, these activities must occur:

 The topology and operation of the device must be fully understood and documented.



Figure 18-6: Schematic of the Gopinath's (et al) Fuel Cell Inverter System Design [Gopinath, 2004]



Figure 18-7: Example of schematics ready for a schematic capture editor [Gopinath, 2004]

The schematic diagrams should be entered into a schematic capture editor. This is done interactively with the help of a schematic capture tool also known as schematic editor. Schematic capture is a step in the design cycle of electronic design automation (EDA) at which the electronic diagram, or electronic schematic of the designed electronic circuit is created by a designer. The circuit design is the very first step of actual design of an electronic circuit. Typically sketches are drawn on paper, and then entered into a computer using a schematic editor. Therefore schematic entry is said to be a front-end operation of several others in the design flow. Despite the complexity of modern components – huge ball grid arrays and tiny passive components – schematic capture is easier today than it has been for many years. CAD software is easier to use and is available in fullfeatured expensive packages, very capable mid-range packages that sometimes have free versions and completely free versions that are either open source or directly linked to a printed circuit board fabrication company.

- 2. The design and calculations for the power conditioning unit must be demonstrated.
- 3. A Bill of Material is generated. In this case a Bill of Materials for DC/DC Converter, bulk capacitors and its associated control & protection circuitry, A Bill of Materials for DC/AC Inverter, output filter and its associated control & protection circuitry and a Bill of Materials for Digital Signal Processor (DSP) Control Board was published (see below).

Description	Type	Rating	Quantity
MOSFETs	IRFP260N	200V, 50A	8
PWM Controller	UC3825B		1
Opto-isolated gate driver	HCPL3120		2
Power Diodes	60EPU04	400V, 60A	4
Input Capacitor	Electrolytic	100V, 22000µF	4
Bulk Capacitors	Electrolytic	250V.4500uF	2
Transformer		17kVA, 400V,38Arms	1
Inductors	Coupled	300µH, 38A	2
Sense resistors		0.01ohm,75W	4
High frequency capacitor	Film	1200V, 0.1µF	1
Snubber resistor		500ohm, 10W	2
Snubber capacitor		1000V, 150pF	1
Power resistors		56k. 7W	2
Power diode	0	600V,15A	1
DC Input connector			1
Control input connectors	0.11		6
Op-amp	LF347		1
Op-amp	LF356		1
3-input NOR gates	CD4023		1
2-input NOR gates	C4011		1
Thermal switch	5R13-90M		1
Power supply	48IMP12-051515-7		1
Heatsink			1
LEDs		9	5
Switches	4		2
LCD Display			1
Zener diodes			4
Resistors		2W	4
Resistors		1W	2
Resistors		0.25W	37
Potentiometers		10k	1
Potentiometers		2k	2
Capacitors		50V	17

Bill of Materials for DC/DC Converter, Bulk Capacitors and its associated contro & protection circuitry (refer Figures A1-A2 in Appendix A)

Figure 18-8: Bill of Materials for DC/DC Converter, Bulk Capacitors and its associated control & protection circuitry. [Gopinath, 2004]

Description	Type	Rating	Quantity
IGBT	IXSH24N60	600V, 48A	4
Gate Drive IC	IR2110		4
Filter Inductors	010111000000000	123µH, 42A	2
Filter Capacitors		18µF, 200V	2
Diodes	FR104	1000	4
Capacitors	Film	0.22µF, 1600V	4
Control input connector			1
AC output connectors			2
Thermal switch	FIIU		2
Current Transformer	D1871		4
Current sensor	LA55-P	- (i)	2
Isolation Amplifier	AD202JN		2
Opto-isolator	6N137		7
Op-amps	LF347		3
Op-amps	LM358		1
CMOS NAND gates	CD4001	0	1
Potentiometers		10k	6
Schottky diodes	LN4148	201 C C C C C C C C C C C C C C C C C C C	27
Zener diodes		- 8	3
Diodes	1N5401	25	2
Power supply	48IMP12-051515-7	±15V,5V	3
Heatsinks			4
LED		22	5
Switches			3
Resistors		0.25W	66
Capacitors		50V	24

Figure 18-9: Bill of Materials for DC/AC Inverter, Output Filter and its associated control & protection circuitry [Gopinath, 2004]

Description	Туре	Quantity
DSP	TMS320LF2407	1
CMOS AND gate	74LCX08	1
Serial communication IC	Max232	1
Signal translator	P15C3245	1
D/A converter	TLV5619	1
Voltage regulator	TPS7333	1
7.372MHz oscillator	Xe263	1
Zener diode	LM4040	1
Ferrite beads		3
Resistors	0.25W	11
Jumpers		5
Capacitors		19
RS232 header		1
Headers		1

Figure 18-10: Bill of Materials for Digital Signal Processor (DSP) Control Board [Gopinath, 2004]

4. The power conditioning unit (the inverter) must be bread boarded. The bread

boarded design will be, upon its completion, be handed over to the manufacturers

for manufacturing analysis.



Figure 18-11: Photograph of the packaged Gopinath's (et al) fuel cell inverter. [Gopinath, 2004]
5. Experiments (both simulations and actual) should be performed.



Figure 18-12: Experimental results of the TAMU fuel cell inverter system. (a) Inverter output voltage waveform when running off the fuel cell at NETL on August 14, 2001. (b) Inverter output waveforms (voltage & current) when supplying 800 W/phase. Both phase-A and phase-B were loaded equally. (c) Inverter output waveforms with phase A on 800 W/phase and phase B on 150 W switching power supply load. (d) Inverter output waveforms (voltage and current) when a step change in load was applied from 360 W to 610 W on phase A. (e) Inverter output waveforms (voltage and current) when a step change in load was applied from 610 to 360 W on phase A. (f) Inverter power request signals. [Gopinath, 2004]

6. Some type of analysis of purpose must be carried out. Because the design was

created for cost savings a cost analysis should be done. However, because

efficiency is extremely important, a design analysis for this characteristic must be

carried out as well.

		2001 F	UTUR	E ENER	GYC	HALLE	NGE			
137.975									ć	
UNIVERSITY: NAME OF MAIN CONTACT: PROJECT NAME:		Texas A&M	ity	_		-		4 4		
		Dr. Prasad Enjeti								
		TAMU Fuel Cell Inverter (10kW)								
DATE		24-Aug-01			() (
			8 8				5	-		1
	OTV	05010	1111177	MELOUDE	VOLT	VOLT	CUR	CUR	UNIT	EXTENDED
DODE	QIT	DESIG	UNIT	MEASURE	(урк)	(vrms)	(AVg)	(Arms)	COST	COST
DIODE DIODE - DUAL MODULE	4	D1,2,3,4			300		40		3.15	12.59
IGBT IGBT										
TRANSISTOR	_	-								
MOSFET	8	T1,2			200		54		9.62	76.92
SCR	-	1								
CAP (ALUM)			1.1	uF						
CAP (ALUM)	2	C2,3	4500	UF	250				39.04	78.09
CAP (ALUM)	4	61	22000	ur uF	100				- 30.30	122.25
CAP (FILM)				uF						
CAP (FILM)				uF						
CAP (FILM)	-		12 3	uF						
CAP (FILM)	-		-	UF						
CAP (FILM)	-	-		ur ur						
POWER RESISTOR	-	1	12 13	w						
POWER RESISTOR	-			W						
POWER RESISTOR				W						
CHOKE	2	L1	300	UH				38	65.09	130.18
TRANSFORMER	1	TR1		UH		400		38	23.01	23.01
TRANSFORMER		IIST				400			20.01	20.01
TRANSFORMER	-									
CONTACTORS	-									
CONTACTORS	-	-	10 - 20 10 - 20	and the		i - 13				
CONTROL				W						88.61
PACKAGING										65.45
OTHER (EXPLAIN)										00.40
TOTAL										598.09
		D	C-DC	Converter	Subsy	stem Co	osts			20 N

Figure 18-13: Cost Estimates for the DC-DC Converter Subsystem Costs. [Gopinath, 2004]

		2001 FU	ITUR		SY CH	IALLE	NGE			0
UNIVERSITY:		Tesax A&M	ty							
NAME OF MAIN CONTACT:		Dr. Prasad Enjeti								
PROJECT NAME		TAMU Fuel Cell Inverter (10kW)								
DATE:		24-Aug-01								
					VOLT	VOLT	CUR	CUR	UNIT	EXTENDED
DEVICE	QTY	DESIG	UNIT	MEASURE	(Vpk)	(Vrms)	(Avg)	(Arms)	COST	COST
DIODE - DUAL MODULE DIODE - DUAL MODULE										
IGBT	4	S1,2,3,4			600		35		8.42	33.68
IGBT										
IGB I MOSEET										
CAP (ALUM)				uF						
CAP (ALUM)				uF						
CAP (FILM)	2	C4,5	18	uF	200				3.94	7.88
CAP (FILM)				uF						
POWER RESISTOR	-		l	W						
CHOKE	2	L2.3	123	ŬН				42	52.81	105.63
TRANSFORMER	_					[
CONTACTORS										
CONTACTORS										
LOSSES				W						20.44
PACKAGING										29.44
										22.00
OTHER (EXPLAIN)										
TOTAL										198.69
		Table 5: T	C-AC	Inverter	Subsys	stem Co	sts			

Figure 18-14: Cost Estimates for the DC-AC Inverter Subsystem Costs [Gopinath, 2004]

As per the cost analysis spreadsheet provided by the FEC'01 organizing committee, the cost of the dc–dc converter was \$317.80 and that for the dc-ac inverter section was \$208.50. The total cost of the 10-kW system was \$526.30. Gopinath et al believes that with a detailed analysis of the control circuit and the ancillary components, this design can be mass produced and marketed below the target cost of \$500.

Gopinath focused on cost, but not efficiency. However, the design and concept has a good chance at advancing to its next phase of lifecycle if Gopinath's inverter design could be modified for better efficiency.

18.14 Conclusion

While designing only for manufacturing modularity and ignoring the rest of the product life-cycle is not optimal, manufacturing modularity is important. For design, manufacturing is currently one of the most influential parts of the life-cycle because it has the largest body of knowledge. Products which are modular in terms of manufacturing have decreased set up costs and decreased change time, better utilize production resources, and decrease scheduling complexity. Because of its vast knowledge base and influence, design for manufacturing facilitates developing a sound methodology. In addition, understanding manufacturing modularity is, in itself, a useful end.

At the end of the Preliminary Design Phase, some of the information needed for manufacturing an SOFC Power System should include:

For the Pivotal Subsystem:

- The design and calculations for the module.
- A frozen Cell Stack Package design, including schematics, which can be placed into a schematic capture editor.
- A preliminary fabrication/manufacturing process for the Cell Stack components.
- A feasibility study in order to determine the best practices in up scaling and mechanizing the fabrication/manufacturing/assembly of the Cell Stack components and the Cell Stack Package itself.
- Cost estimation for the Cell Stack Package Module.

Cost estimation for the manufacturing automation of Cell Stack Package assembly.

For the Bridge Modules, the Identity Relational Modules, the Compliment Modules and the Housing Module:

- The design and calculations for the modules.
- Experiments (both simulations and actual) performed to determine the functionality of the modules.
- The module must be bread boarded. This bread boarded design will be handed over to the manufacturers for manufacturing analysis.
- A materials and/or component selection design plan should be laid out, which includes a bill of material.
- A feasibility study in order to determine the best practices in up scaling and mechanizing the fabrication/manufacturing/assembly modules which includes a survey of suppliers of commercially-off-the-shelf (COTF) products in addition to forming strategic alliances with suppliers and other developers in order to manufacture customized components.
- Cost estimation for the modules.
- A frozen design which includes schematics, which can be placed into a schematic capture editor.

CHAPTER XIX

DESIGN FOR X, MATERIAL SELECTION FOR MANUFACTURING & MECHATRONICS – PHASE TWO

19.1 Introduction

As with an increase in complexity, an increase in reliability per unit complexity/function element is required to keep the power system's performance from suffering degradation. This means an increased engineering discipline is required to keep the final total system performance objectives in focus. At the same time, the product/system must be manufacturable, as required to meet or exceed the target manufacturing cost. Part of keeping the manufacturing cost under "control" is to perform good analyses of alternatives for the assembly processes involved. Should the product/system fail in the field, there must be adequate preparations made for effective field support. For these activities to transpire, certain standards, practices, and guidelines need to be in place [Keys, 2010]. Under the label Design for X (DFX), a wide collection of specific design guidelines are summarized. Each design guideline addresses a particular issue that is caused by, or affects the characteristics of a product. The design guidelines themselves usually propose an approach and corresponding methods that may help to generate and apply technical knowledge in order to control, improve, or even to invent particular characteristics of a product.

In **Figure 19-1**, the general scope of DFA (Design for Assembly) and DFM (Design for Manufacturing) is presented in the context to the Design for Life-Cycle/System Life-Cycle Engineering view. There is however some overlap of the different "DF" activities as no dynamic endeavor stands still.



Figure 19-1: A conceptual relationship of "DF's"

19.2 The DFX Practices

Innovation to disruptive technologies is a continuous process. Fuel cell developers constantly make changes to designs and processes and collect new knowledge, and it is more difficult to measure a dynamic process than a static activity. In response to technology progress, fierce market competition and changing business environments, modern industry must continually improve product functionality and quality to gain market advantage. To this end, various Design for X methodologies have been developed over the years to address the "hottest" design problems or bottlenecks in manufacturing and these methodologies can be extremely useful to fuel cell developers.

Design for X represents a suite of contemporary product development techniques. They can be effectively applied in product development to achieve concurrent improvement in quality, costs and cycle times. DFX allows not only the rationalization of the products, but also the associated processes and systems. Each Design for X label incorporates a broad collection of specific design guidelines. Each design guideline addresses aspects either caused by or affecting product characteristics. The guidelines themselves usually propose an approach and corresponding methods for generating and applying technical knowledge to control, improve, or even invent specific product characteristics. Such guidelines represent an explicit form of knowledge that contains information about "*knowing-how-to*."

The current scientific edge, therefore, resides in incorporating this know-how, as well as additional customer needs, manufacturing experience and other product life-cycle aspects, into the design of new products. In particular, taking the above factors into consideration in the early design phases is expected to significantly increase product profitability.

The integration of manufacturing issues into the design process helps to develop better products in terms of requirements fulfillment, cost, quality and development time. In general, manufacturing process constraints, capabilities and costs are considered during the embodiment and detailed design phases. Technologies to be used could also be

specified during the conceptual phase. The availability of manufacturing information and knowledge is vital to achieving Design for Manufacturing (DFM) and to avoid redesigns. It is widely acknowledged that suitable methods and tools should be used to integrate manufacturing information into the design process as early as possible. The application of DFM demands the integration of several design activities from user requirements to production. The application of DFM is particularly complex and it should be done in a concurrent engineering environment.

19.3 Systematic and Quantitative Methodologies for DFX Practices – Design for Assembly and Design for Manufacturing

Since about 1980, Boothroyd and his co-workers have been defining a methodology for DFA (Design for Assembly) for mechanical parts assembly. This approach has been implemented in Personal Computers (PC's) and is continuing to be refined and evolved. In essence, the Boothroyd approach analyzes each part in an assembly from the standpoints of: 1) necessity of existence of a separate part, 2) ease of handling, feeding, and orienting, and 3) ease of assembly. The output of the analysis includes estimate of assembly time and a rating for design efficiency.

Another similar systematic and quantitative methodology for DFA has been developed by Hitachi and refined by the General Electric Co., called the "Assembly Evaluation Method" it has also been licensed by many companies as an aid to manufacturing. These DFA tools can be great help from a life-cycle perspective; one must continually re-evaluate the output of these tools in the context of meeting the original product form, fit, function, reliability, serviceability, and maintainability [Boothroyd, 1980].

Stoll, of the Industrial Technology Institute of Ann Arbor, MI, has been expanding on the design for manufacture (DFM). Design for manufacture is defined as being concerned with the definition of product design alternatives which facilitate optimization of the manufacturing system as a whole. Stoll sites a check-off list of DFM guidelines which represent a systematic and codified list of statements of good design practice, which have been empirically derived for years of design and manufacturing experiences. They represent an evolution of common sense. A sample summary is as follows (**DFM 13 item list**) [Keys, 1990]:

- 1. Design with the minimum number of parts
- 2. Develop a modular design.
- 3. Minimize part variations.
- 4. Design parts to be multifunctional.
- 5. Design parts for multiuse.
- 6. Design parts for ease of fabrication.
- 7. Avoid separate fasteners.
- 8. Minimize assembly directions; design for top-down assembly
- 9. Maximize compliance; design for ease of assembly
- 10. Minimize handling; design for handling and presentation.
- 11. Evaluate assembly methods
- 12. Eliminate of simplify adjustments.
- 13. Avoid flexible components.

The overall objectives of design for manufacture approach are thus to help identify product concepts which are easy to manufacture, to provide a focus on component designs which are easy to manufacture and assemble, and to help integrate manufacturing process design and product design to ensure the best matching of needs and requirements.

In the DFM process area other important factors to keep in mind include:

- 1. Deign for inspectability, incoming, outgoing.
- 2. Design for testability (of part function, and manufacturing process, in-process and final).
- Design with new technology/chance in mind (a complement to a modular design which would allow incorporating future incremental technology enhancements for easy up-grade).

When one considers DFM, Life-Cycle Engineering, and product-process integration, it has to be with a systems perspective, as also presented by Ballakur and Pratt. In order to achieve economical fast start-up manufacture, the "safest" approach, as implied by the **DFM 13 item list** (see above), is to use standard components and processes. In most cases CAD, CAE, CIM tend to define designing into known conditions and criteria. That is, the computer database and algorithms must contain the appropriate "design for" rules in place, or expected to be in place, for standard components and manufacturing processes. The latter implies a good understanding of electronic, mechanical, etc., design functions and parameters (for inspection and testing), and good understanding of the manufacturing rules and constraints (process capability and control, inspection, in-process and final test capability, etc.). These objectives are not always possible to achieve in all aspects with a new process and/or product, hence

brokering tradeoffs and compromises are required between old design rules ad new needed ones. The manufacturing process must be or become under good control (variance management) for the product to achieve acceptable production levels and costs and the life-cycle status of the manufacturing process kept in focus during a particular technology plateau.

The DFM process, considered as a subset of the life-cycle engineering process, contains three key elements; the identified product concept or need, the proposed manufacturing of all of these aspects at the onset of the project forces the development team to consider a systems view of the design process from the beginning.

By the development team continually reviewing all of these aspects as the product/process develops; key problems/challenges/tradeoffs can be analyzed and addressed so as to minimize downstream problems. The result is a minimization of the number of phases or cycles form concept to production. Design for the Life-Cycle expands this scope to include effective customer service, reparability, maintainability, and support even for the DFM manufacturing process and equipment.

While DFA, DFM, and improved understanding of a design methodology will help improve the product development engineering process, it is felt that a more encompassing scope of life-cycle engineering, thinking, and process will provide a more complete systems view for the product transformation process and represents a more complete competitive product position. This represents a systematic approach to bring a system into being with a better handle on the life-cycle costs and performance.

Historically, engineers have focused on design for technical performance. Recently, through competitive pressures, increased attention is moving to DFA and DFM.

However, the increasing sophistication of products mandates that the systems designers must consider in the early design concept and design phases the issues of reliability, maintainability, serviceability, and supportability.

19.4 Some of the design and development problems/decision that the designer and manufacturers of fuel cell systems face:

When integrating of the manufacturing processes into the development of a the fuel cell power system, the complexity of such development increases greatly because capturing and formalizing manufacturing knowledge can be a complex task. There are several reasons for this:

- There could be a shortage of systematic procedures to capture, organize and represent such information and its associated rationale.
- Although the fuel cell developers possess a vast knowledge base about the workings, operations and, theory of fuel cell science and practices, these developers might not have the manufacturing experience necessary to bring the conceptual bread board design into something that is manufacturable.
- There is a variety of data and information associated with DFM, but little explicitly represented knowledge about how to use the tools.

What all this means to the fuel cell developer is: if the fuel cell developer wants to commercialize his power system, he needs to be working with individuals and firms possessing extensive experience with DFM.

19.5 The DFX Shell: A Generic Framework for Developing Design for X Tools

Huang [Huang, 1997] briefly reviews the development and proposes a framework-the DFX shell-which can be easily extended or tailored to develop a variety of DFX tools quickly and consistently. The DFX shell is based on the model of the product realization process proposed by Duffey and Dixon. Interactions can be explained using the activity-based costing (ABC) principle, which explains that products consume activities and activities consume resources. DFX measures these consumptions and identifies opportunities for improvements in products and resources. The DFX shell can be used to develop specific DFX tools. **Figure 19-2** shows a general procedure for such development. Seven steps are involved, each focusing on establishing one major building block of the DFX tool.



Figure 19-2: Seven Steps for Developing a DFX Tool using the DFX Shell [Huang, 1997]

19.6 Requirement Analysis

The cycle starts with the first step of investigating customer requirements and establishing development specifications. Requirements analysis is carried out at an initial stage, though not necessarily in a formal and explicit manner. Three major categories of key characteristics can be identified for developing DFX tools, namely, the product's functionality, the product's operability and its focus.

19.7 Functionality Requirements

A DFX tool must fulfill some or all of the following functions:

- 1. Gather and present facts.
- 2. Measure performance.
- 3. Evaluate whether or not a product/process design is good enough.
- 4. Compare design alternatives (i.e. which design is better?).
- 5. Highlight strengths and weaknesses.
- 6. Diagnose why a design is strong or weak.
- Provide redesign advice by pointing out directions for improving a design.
- 8. Predict "what-if" effects.
- 9. Carry out improvements.
- 10. Allow iteration to take place.

The responsibility of the user of DFX tools would be to identify which of the above functions should be included in the development effort. The first five functions are the basic functions that are generally supplied by a DFX tool. The second five functions are the more advanced features, available only in a few DFX research systems. Even many well-known successful DFX tools do not perform these functions. Instead, these more sophisticated functions are usually handled by the user. One possible reason is that these tasks require intensive knowledge applied specifically to the target product(s) and

associated processes, while DFX tools are usually developed in a relatively generic sense. With regards to transferring the fuel cell power system development effort from the hands of the conceptual design into the hands of the manufacturing team, under the context of DFX, it would be advisable for the manufacturing team to consult the conceptual design team on related design and engineering decisions.

19.8 Operability Requirements

Functionality does not exist alone. It coexists with operability. Operability is defined as the ease of using the DFX tool to fulfill its functions effectively. Stoll proposes ten operability criteria for evaluating various DFX [DFM] approaches:

- *Pragmatism Training and/or practice*. Concepts and constructs used should already be familiar to the user or can easily be learnt with little effort.
- *Systematic*. A systematic procedure ensures that all the relevant issues are considered.
- *Data requirement and quantitative*. Product and process data must be easily collected and presented to the analyst or the analysis team to enable further action to take place.
- *Teaches good practice*. The use of the DFX methodology reaches good DFX principles, and actual reliance on the method may eventually diminish with use.
- *Designer effort*. The prime user, i.e. the designer of the design team, should be able to use the DFX tool effectively with little additional time and effort.
- *Management effort.* The management is not a prime user, and thus effective use of the DFX tool should not be totally dependent on management support or expectation.

- Implementation cost and effort. It costs and takes efforts to implement a DFX tool in practice. It costs and takes efforts to implement changes identified as the result of effective application of the DFX tool.
- *Rapidly effective*. Effective use of the DFX tool should produce visible and measurable benefits.
- *Stimulates creativity*. Effective use of the DFX tool should encourage innovation and creativity, rather than impose restrictions.

19.9 Focus and Flexibility Requirements

Most successful DFX tools are based on the interactions between products and processes (activities) with resources implicitly embedded in activities for consideration. The developer has to determine the stage of the product design process in which the DFX tool is to be implemented. It has been widely acknowledged that the earlier the DFX principle is applied, the greater the benefits, and the easier the application will be. This decision will have an effect in determining the type of data to be collected. If a DFX tool is to be used at the Conceptual Design and Advanced Planning Phase, then the data collection should be targeted towards major design decisions, not detailed decisions. If a DFX tool is to be used at the Preliminary System Design Phase, more information is to be collected, with the expectation of the requirement of higher accuracy to complete the task of this stage.

19.10 Modeling for Product Analysis

Product modeling is primarily concerned with the schemes for representing design decisions in relation to the subject products. There are three general categories of product information:

- *Composition*. What constitutes a system/subsystem?
- *Configuration.* How are constituent components related to each other?
- Characteristics. What describes constituent components and their relationships?

There is a wide selection of product models. Product information is available in a number of forms, such as technical illustrations, engineering drawings, and other associated documents. Although they are required in DFX analyses, they cannot be used as a base model in the DFX context to represent product design decisions concisely with increasing sophistication. The DFX shell exploits two concepts for product modeling: bill of materials (BOM) and key characteristics. A BOM is a list of the items, ingredients or materials required to produce a parent item, the end item, of the product. The important role of a BOM in DFX tools lies in the fact that it is the basis for data inputs and outputs. It is used for acquiring key characteristics of its components and their relationships.

Figure 19-3 is a typical BOM. It reflects product compositions and, to some extent, product configuration. The format and content are largely determined by the intended use.



Figure 19-3: Product Bills of Materials [Huang, 1997]

A key characteristic is an attribute or parameter that significantly influences the aspects of the product. In general, key characteristics can be divided into several categories, for example, geometry characteristics (shape, size, etc.), physical characteristics (weight, density, etc.), technological characteristics (tolerances, limits and fits, etc.), and material properties and so on. Different DFX tools may require different sets of characteristics. For example, characteristics considered in Design for Assembly (DFA) include product structure, component forms and shapes, limits and fits, component orientations, component symmetry, weight and size, component rigidity, etc.

19.11 Modeling for Process Analysis

Process modeling in the DFX shell is concerned with (1) how to represent the manufacturing process, (2) how to represent resources, (3) how to represent consumption of life-cycle activities by product elements, and (4) how to represent consumption of resources by activities. Composition, configuration and characteristics of process activities and resources should be modeled and this is obviously a key step in developing a DFX tool. Nevertheless, if the DFX user has to produce a process model which accomplishes all the above functions, the task may become very tedious or time-

consuming which involves much excessive work. Therefore, some simplification is necessary in practice. One such simplification is DFX is that either process activities or resource elements are explicitly represented as entities, and the other function is embedded as attributes or characteristics.

19.12 Flow Process Charts

Basically, a PC-F is a schematic model specifying the step-by-step sequence of activities of a process or procedure in association with a particular item. **Figure 19-4** shows a typical PC-F. The content of a PC-F may vary considerably. Information in a basic PC-F would cover the following items that describe the process and its activities: the names of the activities, the unique identification of the number of activities, and brief descriptions about activities. In addition, activity-specific information can be included in a PC-F; for example, feed rate, cutting speed, cutting depth, number of cuttings and the length of feed can be associated with machining (metal cutting) activities. A variety of other information categories can also be associated with a PC-F, which is mainly used for discharging the results from the DFX tool.



Figure 19-4: Sample screen of flow process charts. [Huang, 1997]

19.13 Operation Process Charts

A PC-O is a graphic representation of the points at which materials are introduced into the process, and of the sequence of activities such as inspections and operations. In the DFX context, PC-O is particularly relevant and useful for modeling interactions between product elements and process activities in a straightforward fashion. In this sense, the consumption of activities by products from raw materials to finished goods is explicitly represented in PC-O. In addition to product/process interactions, an extra merit of PC-O is that their ability to depict interactions between the BOM elements of the subject product, i.e. when one element is brought together with another element. **Figure 19-5** shows a typical PC-O in relation to the product's BOM used in the DFX.



Figure 19-5: Sample Screen of Operation Process Charts. [Huang, 1997]

19.14 Performance Measures

Performance measures are a measure of a product's performance. Performance

metrics Developing performance metrics usually follows a process of:

- 1. Establishing critical processes/customer requirements,
- 2. Developing measures,
- 3. Establishing targets which the results can be scored against.

Fundamental purpose behind measures is to define and then later to improve performance. The choice of performance measures dominates the way that the DFX works and the collection of the data required in compiling DFX information.

19.15 Verification

The objective of the DFX verification is to identify the strengths and limitations of the DFX tool under development, to recognize opportunities and new requirements for further improvements and developments. The following questions should be addressed at this step:

- What should be verified and tested?
- What are the criteria for verifications?
- How to conduct verifications?
- How to improve the tool?

The entire DFX package, including the development specification, product and process models, performance measures, worksheets and procedures should be subjected to tests. There are many factors that should be addressed during verification. A rule of thumb is to examine a DFX tool under verification according to the development specification established in the requirements analysis. Some of the questions that must be addressed during verification are listed as follows:

- Does the DFX tool function as intended?
- Does it provide focus of attention?
- Is it general enough to cover the specified product/process range?
- Is it easy to find the data required by the DFX tool?
- Is the output adequately accurate and useful?
- Can the practitioners understand it?
- What is the requirement level of time and effort for average practitioners?
- Does it serve as the media of communication and catalyst of coordination?

Tests should be carried out using a sufficient number and wide spectrum of test cases with full technical and managerial support. The following are just dome of the common means of verification:

- Illustrative case studies. Almost all DFX development projects exploit this technique to clarify what the tools are, to explore the criteria for achieving-the working principle behind them. Simulated cases may be invented solely for illustrative purposes. Just like the expert advice, this technique is more useful during the development process. They do not suffice alone on serving the function of final tests on the outputs.
- Benchmarking. Early successful DFX tools, such as Boothroyd-Dewhurst DFA, Hitachi AEM, and Lucas DFA, have been widely used by developers to benchmark their own systems even for DFX tools outside the domain of assembly.
- *Retrospective case studies*. Past projects are selected and the DFX tool is applied to the projects as if they had not been carried out. It is extremely useful to see if

the DFX tool can highlight areas which have been encountered, and point out potential directions for improvement which have been performed. Suggestions from the DFX test analyses may or may not be considered.

- Field improvement case studies. The DFX tool is applied to actual on-going
 product improvement projects, where actual (designs of) products and associated
 processes already exist. Verifiers should pay attention to possible contributions
 from the DFX verification analyses to the overall projects. The vast majority of
 existing DFX tools has been developed for product and process improvement.
- *Clean-sheet field case studies.* It would be desirable for DFX verification to take
 place in an environment where a new product is under development. In this
 sense, the DFX tools provide technical assistance to help generate better design
 decisions.
- Outcomes form verification should be scrutinized in determining the modification of the DFX tool. Care must be taken to maintain the right balance between functionality and operability.

19.16 A Closer Look at DFM

Design for Manufacturability (DFM) is the general engineering art of designing products in such a way that they are easy to manufacture. The basic idea exists in almost all engineering disciplines, but of course the details differ widely depending on the manufacturing technology. This design practice not only focuses on the design aspect of a part but also on the producibility. In simple language it means relative ease to manufacture a product, part or assembly. DFM comprises empirical guidelines based on good design practices. It involves the simultaneous consideration of design characteristics and constraints, some of them imposed by manufacturing. It demands an understanding of the technical limitations and capabilities of the manufacturing processes, and how they affect design solution characteristics.

Rather than following a formal method, the application of DFM is based on observation of a set of rules, objectives, and practices (e.g. **Table 19-1**). Design guidelines suggest how to better design parts for a particular manufacturing process, and how such a process may affect the shape, dimensions internal structure or other attributes of the component and/or subsystem of a product. In general, the information provided is primarily focused on the definition of the designs and configurations.



Table 19-1: An Examples of Design Guidelines [DRM Associates, 2006: http://www.npd-solutions.com]

The decision-making process and the expertise of the designer continue to be the key aspects to ensure the success of DFM, due in part to the availability of technical

information. There area variety of data and information associated with each manufacturing process, but little explicitly represented knowledge about how to use DFM. In addition, the different sources and formats make it difficult to access such information and knowledge when needed. This leads companies to develop their own particular DFM guidelines suited to their own needs.

Another reason that makes difficult DFM is the lack of systematic procedures for capturing, organizing and representing DFM knowledge and its associated rationale, (configuration management) however, systems engineering practices can make up for this deficit in developing a needed systematic procedure, that will guide designers, three goals should be achieved:

- The first goal is to define and formalize the information generated during the design process;
- 2. The second goal is to make explicit the relationship between this design information and essential DFM information; and
- 3. The third goal is to define and formalize this DFM information.

19.17 DFM Techniques

Nowadays products are developed in concurrent engineering environments where integrating manufacturing into design is fundamental. For this reason the manufacturing process has to be considered in the design as soon as possible. **Figure 19-6** shows the manufacturing relationships into design and the design phases. DFM techniques include manufacturing process selection, DFM guidelines and manufacturability analysis.

In early design, the manufacturing process selection helps designers choose the manufacturing processes that are technically and economically suitable for a given

design. The choice is made by comparing the design specifications with the attributes of the manufacturing process. The process attributes are parameters that describe a process and its capabilities and allow direct, objective comparisons to be made. In the preliminary selection the attributes are common to all processes, for example, the tolerance each process is able to obtain in apart. In a more detailed selection, the attributes are usually more specific and their values can be related to design requirements and other attributes or processing conditions.

Most of the data and information related to these guidelines are available in handbooks, standards, and in-house guidelines. Nevertheless, the lack of systematic procedures for developing these guidelines may lead to incomplete knowledge, which makes it difficult to use them without prior experience. Integrating DFM guidelines into a CAD system would help analyze the manufacturability automatically, identify the potential manufacturability problems and assess the manufacturing costs of fuel cell power systems.



Figure 19-6: Integrating manufacturing into the design process.

This automatic analysis should make it unnecessary to study and memorize manufacturability checklists, and therefore allow designers to focus on the creative aspects of the design process. An additional aim of CAMA is to capture, store and reuse the knowledge created at any phase of the product life cycle. These aims will be achieved by:

- Creating a structured mechanism for capturing interactions between the designer and the process planner or manufacturer.
- Creating a structured mechanism for capturing the post-analysis.
- Creating a capability for analyzing these structured databases.
- Incorporating an intelligent component into the designer's environment. On demand, this component can evaluate product model conformity to a selected design methodology, in particular DFM, based on the knowledge captured in the system.
- Incorporating the capability of continually modifying the knowledge captured in the system.

Implementing these capabilities ensures not only knowledge capture but also knowledge capitalization. Furthermore, the "knowledge" captured is always updated and does not become stagnant as the product evolves. Moreover, each specific developer can prioritize the different DFXs and can, with minimal effort, analyze conformity to any additional DFX at any given moment.



Figure 19-7: Closing the Knowledge Information Design loop [Molcho, 2008]

19.18 Mechatronics

Mechatronics, or more recently mechatronics systems, originated more than twenty years ago with the Japanese, as a composite word to depict the union of mechanical, computer, and electronic engineering in the design, manufacture, and performance of sophisticated products. Mechatronics have been described as the approach required to produce the next generation of machines, robots, and smart mechanisms for applications to manufacturing, large-scale construction, and work in hazardous environments.

However, because mechatronics also includes the integration of sensors for closed-loop feedback and control, the term also includes products such as smart homes, smart cars, smart highways, smart bionic human pars, smart toys, smart offices, smart robots, and artificial reality (virtual world) technology/products. Thus the mechatronics concept impacts all future high-technology electronic products. **Figure 19-8** depicts the major mechatronics environments.



Figure 19-8: Mechatronic Environments

Mechatronics requires an understanding and practice of good product/process integration and requires considerable multidisciplinary analysis and synthesis, to integrate the mechanical, computer, and electronic engineering subsystem components [Keys, 2009, 2010]. **Figure 19-9** depicts this interaction. As a complement, it also requires the practice of simultaneous or concurrent engineering to be most effective to overcome the slow disconnected progress of product/process evaluation through historically hierarchical structure of today's complex innovative developers.



Fig 19-9: Mechatronic Systems

For the purposes of analyzing, development status, and comparison of U.S. and Japan positions, a study divided Mechatronics into nine element areas:

- Flexible manufacturing systems (FMS):
- Vision systems:
- Nonvision systems:
- Assembly/inspection systems:
- Intelligent mechanisms:
- Software activities:
- Standards activities:
- Manipulators:
- Precision mechanisms.

Research and development initiatives in computer integrated manufacturing are developing the technologies needed to provide more effective new Mechatronic products. The key technology elements include:

- Computer-aided design (and drafting):
- Computer-aided engineering tools:
- Computer-aided process planning tools:
- Computer-aided manufacturing technologies (robotics, machine vision, numerical controlled machine tools, flexible manufacturing systems):
- Automated materials handling systems:
- Computer-aided inspection and testing systems:
- Manufacturing information and management systems:
- Computer integrated manufacturing (or enterprise).

These elements are being continually improved and integrated together, as well as

becoming more information and data base driven.

In the future, product (virtual) teams will require a better grounding in:

- 1. "Static" systems analysis and project management,
- 2. Product and process design implementation and integration processes,
- 3. Definition and understanding of information flow (vertical and horizontal organization) and needs to support decision making, and
- 4. The implementation of good quality assurance mechanisms.

19.19 Conclusion

Design for X methodologies can address the "hottest" design troubles or bottlenecks in NPD these methodologies can be extremely useful to fuel cell developers. Design for X methodologies represent an explicit form of knowledge that contains information about "*knowing-how-to*."

Three major categories of key characteristics can be identified for developing DFX tools, namely, the product's functionality, the product's operability and its focus. Product modeling is primarily concerned with the schemes for representing design decisions in relation to the subject products.

Design for manufacturing (DFM) considers design goals and manufacturing constraints simultaneously to identify and alleviate manufacturing problems while the product is being designed. As a consequence the lead time for product development is reduced and product quality and cost are improved. Several DFM techniques have been developed to assist the designer, such as manufacturing process selection methods, DFMA guidelines and manufacturability analysis tools. The availability of manufacturing information and knowledge is vital to achieving Design for Manufacturing (DFM) and to avoid redesigns.

The benefits of DSX practice have been widely acknowledged in the industry. Several techniques fall under the umbrella of Design for Manufacturing, and their implementation depends heavily on the context in which they will be applied. How to enhance their use by designers is still an issue. The use of a formalized design process, in which a software application is used to bring manufacturing knowledge to the forefront,

would improve DFM implementation. In such a context, a fundamental issue is to define the manufacturing information that should be presented to the designer.

Mechatronics is a multidisciplinary field of engineering, that is to say it rejects splitting engineering into separate disciplines. Originally, Mechatronics just included the combination between mechanics and electronics hence the word is only a portmanteau of mechanics and electronics. In recent years, Mechatronics is the combination of Mechanical engineering, Electronic engineering, Computer engineering, Software engineering, Control engineering, and Systems Design engineering in order to design, and manufacture useful products.

CHAPTER XX

MATERIAL SELECTION FOR MANUFACTURING – PHASE TWO

20.1 Introduction

SOFC Power Systems, as well as other renewable energy systems, must be both energy efficient and cost competitive with centralized fossil fuel power-generating stations if they are to emerge as a prominent mode of electricity production.

Manufacturing costs of SOFC Power Systems have restricted the widespread deployment of this technology. Life-cycle energy analysis (LCEA) is a critical tool in guiding the development of fuel cell technologies and their applications in the direction of energy efficiency and cost competitiveness.

20.2 What's the Problem?

Life-cycle energy analysis results for a fuel cell power system depends directly on the boundaries of the system under investigation. While economic factors may determine the current viability of FC technologies, LCEA is useful to distinguish alternative technologies in terms of their energy performance. For example, a systematic comparison
of different processing methods can be made for example, to determine which method of producing electrolyte is the most cost effective by way of energy consumption. Yet, as of late, comparisons of the results from LCEA studies conducted on fuel cell power systems has so far been hindered by the lack of study.

Several general texts and articles provide overviews of material selection for mechanical design. Dieter describes both material selections for new designs and for material substitution. Since material selection is closely tied to manufacturing process selection, Dieter describes both the material-first and the process-first approaches identified by Dixon and Poli [Fitch, 2004].

In the material-first approach, the designer begins by selecting a material class, narrowing the choices within the class, and then considering manufacturing processes consistent with the selected material. Dieter also states that most design and materials engineers instinctively use the materials-first approach, while manufacturing engineers typically gravitate toward the process-first approach [Fitch, 2004].

The work of Ashby supports material selection for a new design and within a material-first substitution assessment [Fitch, 2004]. Ashby also illustrates that for most mechanical systems, performance is limited not by a single property, but by a combination of them. For example, the materials with the best thermal shock resistance are those with the greatest values of s f/Ea; where's f' is the failure stress, 'E' is Young's modulus, and 'a' is the thermal coefficient of expansion. Ashby illustrates the use of material parameters (i.e., material properties and other material parameters related to manufacturing processes, cost, and environment) to derive performance indices. These performance indices isolate the combination of material, shape, and other information

that maximize performance within the constraints of appropriate property limits. These property limits are bounding values, within which certain properties must lie if a material is to be considered further [Fitch, 2004].

In the Conceptual Design and Advance Planning Phase, fuel cell developers mostly take the materials-first approach. In the Preliminary Design Phase, after the design is frozen, manufacturing methods are considered. Conversely, in the process-first approach, the designer begins by selecting the manufacturing process and then the material. However, it might not be wise to select processes-first approaches over materials-first approaches for certain components of the power system, namely the Unit Cells, the Separators, the Seals and ceramic inks. The materials of these components might dictate which processes must be used.



Figure 20-1: Lifecycle Energy Analysis (LEA)

20.3 What about the Energy Analysis?

According to Boustead and Hancock, [Fitch, 2004] energy analysis is a technique for examining the way in which energy sources are harnessed to perform useful functions.

For example, Boustead and Hancock use energy analysis to calculate the energy required for the following processes:

- Produce fuels ~e.g., coal, diesel, and natural gas.
- Transport freight ~e.g., by truck, by train, and by ship.
- Produce and recycle metals ~e.g., copper and aluminum.

Similarly, Brown (et al) present detailed energy analyses for 108 industrial processes ranging from meatpacking and bread baking to aluminum production and iron and steel forging [Fitch, 2004]. Chapman and Roberts also use energy analysis to calculate the energy required to produce and recycle metals. Energy analysis is also used in DFE (Design for Energy) and LCA (Life-cycle Analysis) literature as a methodology to assess the energy efficiency of products and processes. For example, Graedel and Allenby demonstrate how to calculate, based on process parameters, the energy consumed in manufacturing a material, and present a general approach for minimizing energy use in an industrial facility. Alternatively, from a product perspective, Sullivan and Hu of Ford Motor Company use Life Cycle Energy Analysis (LCEA) to calculate the life cycle energy consumption of both internal combustion engine vehicles and electric vehicles [Fitch, 2004].

During the Preliminary Design Phase, fuel cell developers need to perform similar studies. Energy Analysis should be used in the fuel cell industry because many of its activities are very energy intense. For example, testing of materials and high temperature fuel cell components can and do consume great quantities of energy when the components are tested at operational temperature (900 °C). Another example, if tape-casting is the method use to fabricate electrolyte, and in addition if ceramic electrode

layers are fired onto the electrolyte a great amount of energy is needed for these manufacturing processes.

20.4 LCEA for Material Selection

Fitch's LCEA for Material Selection is a method for estimating the life cycle energy of a component as a part of the material selection process. The method is adapted from Sullivan and Hu's method for estimating the life cycle energy of internal combustion and electric vehicles [Fitch, 2004]. The presentation here uses LCEA to estimate the life cycle energy (LCE) of automotive components. Explicitly Equations (7– 10) contain variables and relationships specific to automobiles and automotive components. However, the method may be used for non-automotive components for systems such as fuel cell components. In addition, LCE may be used in conjunction with other environmental indicators to provide a more comprehensive evaluation for material selection. In LCEA, life cycle energy is estimated at the component level as the sum of energy use at and between each stage of the life cycle for that component:

$$LCE_{i} \approx (E_{MP})_{i} + (E_{MD})_{i} + (E_{CF})_{i} + (E_{CD})_{i} \dots + (E_{PA})_{i} + (E_{PD})_{i} + (E_{USE})_{i} \dots + (E_{MAINT})_{i} + (E_{EOL})_{i}$$
(1)

Where:

 LCE_i = life cycle energy for a component made from material $_i(MJ)$

Energy consumed during each life cycle stage and for transport between each stage may be estimated as shown in Equations (2–11) First, Equation (2) estimates the material production energy, $E_{\rm MP}$, for each component. Sources of material and process data for use in these equations include Ecoinvent and the US LCI Database Project. Both use the EcoSpold format and include extensive metadata.

$$(E_{\rm MP})_i \approx m_i [(1 - \psi_i)(e_{\rm PMP})_i + \psi_i(e_{\rm SMP})_i]$$
(2)

Where:

 $(E_{\text{MP}})_i$ = material production energy for a component made from material $_i$ (MJ) mi = mass of a component made from material i (kg). ψ_i = recycled content fraction of material i

 $(^{e}\text{PMP})_{i}$ = primary material production energy per unit mass for material *i* (MJ/kg) $(^{e}\text{SMP})_{i}$ = secondary material production energy per unit mass for material *i* (MJ/kg)

Next, material delivery energy, E_{MD} , component fabrication energy, E_{CF} , and component delivery energy, E_{CD} , are omitted based on similar omission from Sullivan and Hu. The material and component delivery energies are assumed to be small relative to other types of energy. As for component fabrication energy, its omission is not expected to affect the results of the energy analysis significantly.

$$(E_{\rm MD})_i \approx (E_{\rm CD})_i \approx 0 \tag{3}$$

Where:

 $(E_{\text{MD}})_i$ = material delivery energy for a component made from material *i* (MJ) $(E_{\text{CD}})_i$ = component delivery energy for a component made from material *i* (MJ)

$$(E_{CF})_i \approx m_i (e_{CF})_i \approx 0$$
 (4)

Where:

 $(E_{CF})_i$ = component fabrication energy for a component made from material *i* (MJ) m_i = mass of a component made from material *i* (kg) $(e_{CF})_I$ = component fabrication energy per unit mass for material *i* (MJ/kg)

Next, Equation (5) estimates product assembly energy, EPA, for each component:

$$(E_{\rm PA})_i \approx m_i (e_{\rm PA})$$
 (5)

Where:

 $(E_{\text{PA}})_i$ = assembly energy for a component made from material *i* (MJ)

 m_i = mass of a component made from material *i* (kg)

^{*e*}PA = primary material production energy per unit mass for material i (MJ/kg) Next, Equation (6) estimates product delivery energy (the energy required to ship the product to the distributor), *E*PD , for each component:

$$(E_{\rm PD})_i \approx m_i(e_{\rm PD}) \tag{6}$$
$$(E_{\rm USE})_i \approx \rho_f(e_{\rm MP})_f(L_V) \left(\frac{1}{({\rm MHFE'})_i} - \frac{1}{{\rm MHFE}}\right) \tag{7}$$

Where:

 $(E_{\text{USE}})_i$ = use phase energy for a component made from material *i* (MJ)

 P_f = density of fuel (kg/gal)

 $(^{e}MP)f$ = material production energy of fuel per unit mass (MJ/kg)

 L_V = vehicle life (miles)

MHFE = metro-highway fuel economy of vehicle without component (mpg)

 $(MHFE')_I =$ metro-highway fuel economy of vehicle with component made from

material *I* (mpg)

Finally, maintenance and end-of-life energies are estimated using Equations (10, 11). These equations assign energy credits for recycling based on the difference between primary material production energy and secondary material production energy multiplied by the recycle fraction. The recycle fraction, f_i , is the average percentage of a material that is recycled at the end of a product's life [Fitch, 2004].

Whereas, the recycled content fraction, $Ø_i$, for a material is the average percentage of recycled matter used in the production of new material. The allocation used here for open-loop recycling is identical to Sullivan and Hu, Vigon (et al) who discuss additional allocation methods for both open and closed loop recycling. Also, despite its mention by Sullivan and Hu, credit for energy recovery is omitted from this analysis because Sullivan and Hu do not present relevant energy recovery data.

$$(E_{\text{MAINT}})_{i} \approx m_{i} \left(\frac{L_{V}}{L_{C}} - 1 \right) [(1 - \psi_{i})(e_{\text{PMP}})_{i} \dots + \psi_{i}(e_{\text{SMP}})_{i} + (e_{\text{CF}})_{i} + (1 - \phi_{i})e_{\text{DE}} \dots - \phi_{i}[(e_{\text{PMP}})_{i} - (e_{\text{SMP}})_{i}]]$$
(10)

$$(E_{\text{EOL}})_i \approx m_i [(1 - \phi_i) e_{\text{DE}}] - \phi_i [(e_{\text{PMP}})_i - (e_{\text{SMP}})_i]$$
(11)

Where:

$(E_{\text{MAINT}})_I$	= maintenance energy for a component made from material i (MJ)
$(E_{\rm EOL})_I$	= end-of-life energy for a component made from material i (MJ)
m _i	= mass of a component made from material i (kg)
L_V	= vehicle life (miles)
L_C	= component life (miles); assumed< <i>LV</i>
Ψ_i	= recycled content fraction of material i
$(e_{\rm PMP})_i$	= primary material production energy per unit mass for material i (MJ/kg)
$(e_{\rm SMP})_i$	= secondary material production energy per unit mass for material i
(MJ/kg)	
$(e_{\rm CF})_i$	= component fabrication energy per unit mass for material i (MJ/kg)
	= recycle fraction of material i
$e_{\rm DE}$	= disposal energy per unit mass of material i

20.5 Comparison and Results of Energy Analysis Methods

[Fitch, 2004] Ashby uses a metric called Energy Content (EC) And Kampe uses his Lifetime Energy Consumption Index (LEC8). When component masses for each material are known, Equations (12, 13) may be used to calculate EC and LEC8 for a component made from a given material.

$$\mathrm{EC}_{i} \approx m_{i} [(1 - \psi_{i})(e_{\mathrm{PMP}})_{i} + \psi_{i}(e_{\mathrm{SMP}})_{i}]$$
(12)

$$\operatorname{LEC}_{i}^{\prime} \approx m_{i} [(1 - \psi_{i})(e_{\mathrm{PMP}})_{i} + \psi_{i}(e_{\mathrm{SMP}})_{i} + C_{E}]$$
(13)

Where:

 EC_i = energy content for a component made from material *i* (MJ)

LEC'i = Lifetime Energy Consumption Index for a component made from material i (MJ)

 m_i = mass of a component made from material *i* (kg)

 ψ_i = recycled content fraction of material *i*

 $(e_{\text{PMP}})_i$ = primary material production energy per unit mass for material *i* (MJ/kg)

 $(e_{\text{SMP}})_i$ = secondary material production energy per unit mass for material *i* (MJ/kg)

 C_E = Exchange Constant ~236.8 MJ/kg for a 120,000 mile vehicle life (MJ/kg)

LCEA can be used in the new product design, the system engineering and process engineering of SOFC Power System by facilitating:

ing incoming of bot of tower by stem by fuentiat

- 1. Material selection/ changes,
- 2. Equipment selection/ changes
- 3. Improved purchasing choices,
- 4. Improved operating practices,
- 5. Disposition practices, and
- 6. Improved logistics.

20.6 LCEA for PV (Photo-Voltic) Modules – Example of the LCEA Practices

In 1997, Gregory A. Keoleian's study was to define LCEA metrics for guiding the design of the United Solar UPM-880 standard PV module. His paper presented a detailed description of the LCEA methodology and the application of LCEA methodology. The case study investigated a United Solar Systems Corporation tandem junction amorphous silicon PV module. Although a comprehensive analysis was precluded by some unavailable data, by explicitly stating assumptions and boundary conditions the results of this LCEA provided valuable insight and allowed recommendations to be made for improving the design of PV modules. Keoleian's study could serve as the framework defining the LCEA metrics for guiding the design of SOFC Power Systems.

20.7 Conclusion

Life cycle energy analysis is an approach in which all energy inputs to a product are accounted for, not only direct energy inputs during development, manufacturing, but also all energy inputs needed to produce components, materials and services needed for the manufacturing process.

While economic factors may determine the current viability of FC technologies, LCEA is useful to distinguish alternative technologies in terms of their energy performance. Life-cycle energy analysis results for a fuel cell power system depends directly on the boundaries of the system under investigation.

Comprehensive energy modeling of a PV system is essential for assessing its full potential as a sustainable energy technology. Likewise, life-cycle energy analysis is a fundamental tool for evaluating and guiding the development of SOFC Power Systems.

CHAPTER XXI

STRATEGIC PARTNERSHIPS – PHASE TWO

21.1 Introduction

Determining the strength of the competitive forces that influence a company is the heart and soul of the industry analysis [Roby, 2010, Silverman, 2010].

For E. & J. Gallo Wineries, the strongest of Porter's five 'competitive' forces, rivalry among competing sellers, is high. Porter's five 'competitive' forces is a framework for industry analysis and business strategy development formed by Michael E. Porter of Harvard Business School in 1979 [Jones & George, 2003, Porter, 1979]. It draws upon industrial organization economics to derive five forces that determine the competitive intensity and therefore attractiveness of a market. Attractiveness in this context refers to the overall industry profitability. An "*unattractive*" industry is one in which the combination of these five forces acts to drive down overall profitability. A very unattractive industry would be one approaching "*pure competition*", in which available profits for all firms are driven down to zero. Porter's five forces include - three forces from "*horizontal*" competition: threat of substitute products, the threat of established rivals, and the threat of new entrants; and two forces from "*vertical*" competition: the bargaining power of suppliers (of the value chain) and the bargaining power of customers. The number of competitors within the wine industry is countless and constantly on the rise.

The fuel cell industry, in particular, the SOFC developers hoping to commercialize, can learn a thing or two from the E. & J. Gallo wineries. Despite their knowledge that rivalry among competing wine sellers is high, E&J Gallo are able to sustain a relatively strong competitive advantage against their competitors because of their strategic fits across their value chain [Roby, 2010].

21.2 An Example of the Problems Fuel Cell Developers Face

The quality of fuel cell components depend heavily on the quality of the raw materials which are used. However, many fuel cell developers have very little control over the quality or the processes of the raw materials they use. Here is an example which is a representation of the problems many fuel cell developers have with their supply chains.

Two ceramic layers which are applied to the electrolyte substrate via a screen printing process are composed of rare earth metals (the filler material) in an organic binder matrix. These fillers must have certain physical characteristics in order to properly function as ion and electronic conductors. Suppose that the materials supplier that produces the rare earth metal powders has a particular process for fabricating these powders. Suppose that because the fuel cell developer orders only small amounts of the powders at a time, at irregular times, the material supplier irregularly starts and stops the processes necessary for fabricating the powders. Essentially, because the process is not a

consistent one, there is no guarantee that each batch of powder will be of similar quality and many times they are not.

Between batches many things could happen which could also affect the powder process which the fuel cell developer might not know about at the time he orders and receives the powder but will nevertheless affect the quality of the fuel cell components. Two examples of what could happen are: machinery replacement and personnel changes. Suppose that Charlie, the supplier's lab technician, who has been making powders for twenty-five years, is the only one who knows how to make the powders that the fuel cell developer needs. Between batches, Charlie retires and at the same time of Charlie's retirement, the supplier installs new machinery. The supplier's remaining staff will have two challenges: recreating Charlie's recipes and mastering the new machinery. There are learning curves associated with both activities and making the fuel cell developer's powder becomes a trial-and-error process, at the expense of the fuel cell developer. Often times, in the real world, this scenario is play out and the powders are dissimilar enough to cause fabrication and cell performance problems. Many times these problems may not be realized until much time has passed and in the world of NPD – time is money.

Fuel cell developers can, and do face another problem - discontinued products. Suppose a fuel cell developer has an electrolyte supplier that produces good quality electrolyte. "Good quality" meaning the electrolyte is very flat, has good strength to resist breakage and is very conductive. One more thing, the supplier sells his electrolyte at a very low price.

Now suppose that supplier for whatever reason goes out of business. Not all raw materials and products are of the same quality. The fuel cell company may or may not

find an electrolyte that has the same quality or a supplier willing to sell his electrolyte at the old supplier's price hence the fuel cell developer's productions costs goes up. Depending on the price increase the fuel cell developer might go out of business if he can not afford the new price and the story of his product will end.

21.3 Design for Logistics

The research on Design for Logistics (DFL) has provided principles, such as the use of common components, modularity and postponement that are aimed at making a new product more logistics-friendly [Gubi, 2010, Neuman, 1996].

Also, are the metrics for assessing how well a new product fits into an existing supply chain [Appelquist, 2004]. Yet, Novak and Eppinger (2001) remark that the practice of analyzing supply chain performance in product development is not as common as one would expect, and because of this very reason many fuel cell developers are facing unnecessary extinction. Analytical models for aiding these analyses have been published but according to Taylor (1997), there is still a need for more applied research and case studies involving industrial participants[Appelquist, 2004].

21.4 Maybe there's another approach; maybe, they should try Strategic Alliances?

Strategic alliances require [Lonngren, 2010] the condition of at least two organizations in a value chain with compatible goal structures, which are combined for the purpose of sustaining and achieving significant advantages in competitiveness. Furthermore in this type of coupling it is suggested that all parties are strengthened to collaborative behavior. Bresnen and Marshall (2000) agree to this and constitute that a partnering always should be enforced by a commitment between the involved parties. One must differentiate between strategic alliances that are short-term partnerships created for a single project, so-called "*collaborative strategic alliances*", and long-term alliances embodying "*cooperative strategic alliances*". While collaborative alliances are fully capable of promoting competition among the organizations, long-term alliances emphasize the importance of reflective and mutual learning, as well as the transfer of knowledge, attributes that presuppose a certain measure of trust among the partners.

Most prior research has focused on vertical integration or strategic outsourcing in isolation to examine their effects on important performance outcomes [Holcomb, 2007]. In contrast, the author believes that the simultaneous pursuit of vertical integration, strategic outsourcing and forming strategic alliances can enrich a fuel cell developer's organization making it possible to successfully commercialize. Rothaermel (et al) believes that baseline proposition is that of balancing vertical integration and strategic outsourcing in the pursuit of taper integration [Holcomb, 2007]. Rothaermel's (et al) results provide strong support for the notion that carefully balancing vertical integration and strategic outsourcing when organizing for innovation helps firms to achieve superior performance. "Taper Integration" occurs 'when firms are backward or forward integrated but rely on outsiders for a portion of their supplies or distribution'. Thus, taper integration arises when a firm sources inputs externally from independent suppliers as well as internally within the boundaries of the organization or disposes of its outputs through independent outlets in addition to company-owned distribution channels. Taper integration implies that some activities are pursued in a parallel manner, both in-house and through outsourcing [Holcomb, 2007].

Fuel cell developers must decide which integrations (vertical, horizontal or taper) their companies will form with regards to their supply chain management. Regardless of its choice in integration, fuel cell developers must form types of strategic alliances. On entering into strategic alliances, fuel cell developers should be aware of possible repercussions and effects, in particular those outlined in the following three points (Love (et al), 2002) which are [Keys, 2010, Klose, 2005]:

- Self-governance a fuel cell developer must understand its own capabilities and limits.
- 2. Responsiveness- a fuel cell developer must be able to recognize those changes that will have an adverse impact on operations as soon as possible.
- 3. Flexibility- a fuel cell developer must be able to respond to changes in its organization or to changes in its product design needs and demands.

An example of a fuel cell developer using strategic partnership is Versa Power Systems (VPS), a developer integrated in projects by partners ranging from government agencies (the U.S. Departments of Energy and Defense) and private sector aerospace and energy concerns to organizations focused on energy [Borglum, 2007]. On June 3, 2011 Versa Power announced a cooperative agreement to develop and integrate Versa Power's SOFC technology into Wärtsilä products. Wärtsilä is a global leader in the marine and energy markets. This co-operation with VPS supports the commercialization of fuel cell products by strengthening the development and supply partnerships.

A possible solution to the problem example introduced in the beginning of this chapter is for a fuel cell developer to fabricate the powders 'in house', an activity which would fall under the category of taper integration. Ceramic Fuel Cell Limited, (CFCL) an

Australian company, has already done this. In addition to scaling up its own manufacturing capability, in order to further secure a volume supply of components, during the half-year of 2010, the CFCL entered a volume cell supply agreement with leading German ceramics company HC Starck [Ceramic News, 2008]. Under the agreement HC Starck agreed to supply, and the company agreed to purchase, a minimum volume of fuel cell components at fixed prices, subject to Ceramic Fuel Cells' specification and quality requirements. CFCL believes this agreement is an important step in securing its supply chain for critical components, as well as delivering significant cost savings. In order to make the fuel cell components for supply to CFCL, HC Starck has agreed to order a minimum volume of zirconia powder from Ceramic Fuel Cells' United Kingdom powder plant, located in Bromborough. Ceramic Fuel Cells will supply the zirconia powder at agreed prices and quality specifications.

21.5 Conclusion

In the Preliminary Design Phase, a fuel cell developer should look for strategic alliances and partnerships with its suppliers, utilities, and its potential manufacturers. Being freed of the burdens of materials/components acquisition and fabrication, etc, fuel cell developers should then focus their efforts on designing and developing their systems, taking their conceptual systems design into a preliminary system design ready for manufacturing and scale-up.

CHAPTER XXII

THE OTHER SIDE OF THE STORY – PHASE THREE AND BEYOND

22.1 Introduction



Figure 22-1: NPD Planning is very much like playing (strategizing) a game of Chess

Once management of a fuel cell developer approves the planning and systems design, the product development cycle is rotated to the design & prototype phase of the NPD lifecycle. During this time, marketing uses knowledge of the potential customer and how the power system will be used to help guide product design. The design goal is to create a power system that would hopefully surpass (traditional product) specifications by addressing how the power system will be used. The Enclosure, the BOP and the Cell Stack engineers will define and verify the product/process architecture and will attempt to use the latest technology to improve the power system quality and/or lower costs.

The marketing group then defines system target market parameters, develops sales and profit forecasts. These forecasts require interaction with engineering and manufacturing who chose components, interact with suppliers, and develop cost estimates based on the material and processes needed for manufacturing.

The Preliminary System Design phase naturally evolves into the prototype testing phase that involves building early systems prototypes with the objective of maximizing performance and matching customer expectations. Early prototypes are built and often used by the marketing group for early customer interaction.

This paper is concerned with comprehensive lifecycle phases of new product development (NPD). New product development is an activity that takes place primarily at the beginning of the product life cycle. Furthermore, the entire life cycle of the product can be divided into smaller, and relatively homogenous, blocks that represents life cycle stages or phases that a product experiences during its life. Each phase includes a number of characteristics that can be translated into process or product requirements. As these requirements are collected together, the comprehensive set of product requirements can be formulated. Hence, the identification of distinct life cycle phases and associated product requirements. The emphasis on and importance of a distinct life cycle phase can be determined by evaluating the activities and accomplishments of each phase and the costs associated with them, and by assessing the various systems engineering process over the entire life cycle (see **Figure 22-2**).



Figure 22-2: The NPD System Engineering Process and Milestones – Revisited

22.2 Uncertainty throughout and within the NPD Lifecycle – What can be done about it?

"Complexity" means different things to different people, and it is used in myriad ways (Thomson et al. 2005); it is surely an everyday term in engineering. The concept of complexity is not entirely clear, and it often implies the following attributes: a phenomenon that consists of many parts, many relationships/interactions among the parts and combined effects that are not easily predicted and may often be novel (Corning 1998).



Figure 22-3: Management faced with total cost Visibility [Blanchard, 2008]

Moreover, the cost associated with the designs and development, within the lifecycle of an SOFC Power System, often has been declared complex. The cost estimation for such as product, within a systems engineering approach, should be described as an exercise in setting up a framework of strategic, tactical, and engineering cost planning. Why is this so? The costs of fuel cell systems include: the cost of operation, the costs of system effectiveness, maintenance and life-cycle support and retirement. In the design of systems, it is important to view all decisions in the context of total cost (tactical, and strategic and developmental future planning) if one is to properly assess the risks associated with the decisions in question.

In addressing the aspect of economics, one often wonders if there is a lack of total cost visibility linked with fuel cell development. For many systems, design and development costs (and production costs) reliability warranted, are relatively well known; however, what about the costs associated with fuel cell system operations and maintenance? In considering the cause-and-effect relationship, could it more likely be shown that a major portion of the projected life-cycle cost for a given fuel cell system stems from the consequences of reliability decisions made during the early stages of advance planning and system conceptual design.

In the Conceptual Design Phase, it is often difficult to define the "*real*" requirements for fuel cell power systems because of the lack of a good definition of the problem(s) to be solved and the subsequently lack of good communications between the designers, engineers, business professionals, vendors, the ultimate user and others involved. Also the system developer from the beginning might not know exactly at the initial start of the design process who the ultimate '*custome*r' might be, hence this problem is magnified considerably for disruptive/innovative technologies, ones who do not have markets.

Development costs notwithstanding, from past experience, it is clear that many of the engineering problems, and the exigent development issues common to the SOFC

industry have been the direct result of not applying a disciplined "system approach" to meet the desired objective. The overall requirements of the system in question were not well defined from the beginning; the approach followed was to design it now and fix it later! In essence, the system design and development process has suffered somewhat from a lack of good early planning and the subsequent definition and allocation of requirements in a complete and methodical manner. In regards to requirements, the old trend has been to keep things "loose" in the beginning by developing a system-level specification that is very general in content, providing an opportunity for the introduction of the "latest and greatest" in technology developments just prior to going into the construction/production stage. In any event, the introduction of late changes and the lack of good configuration control can be rather costly.



Figure 22-4: The first four phases of the NPD Lifecycle are shown: the First Major Phase in the context of Cost impact due to design changes [Keys, 2010, Blanchard, 2008]

Figure 22-4 provides a comparison of the cost impact due to the incorporation of changes early in the design process versus those incorporated later. Keys pointed out

another important principle when he wrote and confirmed Blanchard's observation that, 'The important thing we do know is that this early period is really when 'do it right the first time' is critical for establishing the new technology knowledge base to effectively support the new intelligent/learning organization. Establishing the new entrepreneurial metrics and preliminary controls are critical to this new technology birthing processes.'

Today, there is an emphasis on total system versus the components of a system. It is true that the system as a whole and throughout its entire lifecycle, to ensure that the functions that need to be performed are being accomplished in an effective and efficient manner. At the same time, the components of the system need to be addressed within the context of some overall system configuration.

22.3 The Cross-Functional Teams working within the NPD Lifecycle

The simplicity of projects made it possible for most of the important project information to exist in a few *"knowledge workers"* heads and, be relatively easily *communicated* among these people.

However, as products and processes increased in complexity and sophistication, the complex elements of designing, developing, manufacturing, maintenance and service, etc., were subdivided into smaller more manageable pieces and the workforce specialized.

Over time, a conceptual model of the product/process development lifecycle evolved consisting of stages or phases. This sequential process, while important in the development evolution, carried the problem of a lack of coordination, interfacing, and integration of many of the different product design elements and parties involved leading to, (to name a few): many product delays, extra and/or re-engineering, numerous changes

in design, poor quality, over-runs in budget and productions costs and high maintenance costs.



Figure 22-5: Formulation of Multi-Specialty Project Teams for NPD

22.4 Lifecycle System Testing/Reliability/Quality Control/Maintenance Effort

To iterate what was said earlier in this paper, as the system design and development activity of an SOFC power system progresses, there needs to be an ongoing testing, reliability, quality control and maintenance effort. This evaluation system must start at the beginning of the design process and it will evolve and mature as the product evolves and matures. The objective of any these efforts are to acquire a high degree of performance as intended and to sustain the power system's performance. Acquiring that confidence throughout the lifecycle phases of the SOFC Power System is accomplished by a successful evolutionary test evaluation plan.



Testing

Figure 22-6: Testing Plan for the NPD Lifecycle [Blanchard, 2008]

22.5 The Manufacturable Prototype Summary

In this thesis, certain designated activities need to be emphasized in the top-down approach, because the whole systems engineering approach to NPD design must be viewed as a whole and an understanding of subsystems interaction must be known, quantified and controlled. As should in the first two phases of development, the designated activities were shown to be lifecycle oriented, in other words, activities which will be addressed within and throughout the rest of the entire NPD lifecycle. The frontend analysis approach was maximized and configuration baselines established for the phases' activities.

An overall systems engineering new product development progress summary needs to be defined to be able to assess/confirm progress to the defined milestones objectives of each phase. At the end of the Preliminary System Design Phase, a manufacturable prototype along with its configuration management and documentation were created.

The manufacturable prototype, which was developed in the first two phases of the NPD Lifecycle, will be deemed ready for advancement to the next phase, after the following conditions have been met:

- The Market Analysis has pinpointed one or more entry point markets for the power system.
- The Systems Hierarchy Architecture of an SOFC Power System has a well developed reliability baseline (models, block diagrams, failure mode, effect, and criticality analysis, fault-tree analysis, etc).

- The Systems Hierarchy Architecture of an SOFC Power System has a well developed quality engineering baseline based on qualitative data.
- The Systems Hierarchy Architecture of an SOFC Power System has a well developed maintenance baseline (reliability-centered maintenance).
- A Bottom-up Design Approach accomplished a system/subsystem/component design capable of manufacturability (specification trees should be created, rank order of evaluation parameters should be create, etc.).
- A tolerance range for the Operational Requirements has been documented.
- DFX (M) documentation has been developed using Subsystem Evaluations and Feasibility Analysis.
- The Optimizing Systems Design Analysis has been evaluated.
- The Configuration Management for Rework/Redesign has been designated.
- The Design Decisions for the Unit Cell, the Cell Stack Package have been made.
- Automation of the Cell Stack Package assembly has been created.
- The System Design Modularity for Manufacturing has been selected.
- Processes for manufacturing have been selected.
- Life-cycle Energy Analysis for Manufacturability has been conducted.
- Strategic Partnerships, both vertical and horizontal, have been formed.

22.6 The Detail System Design & Development Phase

Moving on from the Preliminary System Design Phase, the next lifecycle period is the Detail System Design & Development Phase which is the phase during which the needed improvements in the power systems' materials, processes and designs are refined, and during which the system is tested and proven to be commercially producible. The objective of this phase is to make the needed improvements in materials, designs and processes, and to confirm that the power system will perform as specified by constructing and testing power system prototypes or pilot systems.

During this developmental stage at least the following activities must be completed:

- Optimize the power system's subsystem and/or modules through design iterations using computer models or other acceptable analyses and tests.
- Identify critical materials, develop components and manufacturing process steps to the extent required to meet technical performance and economic objectives.
- Conduct the tests for evaluating critical materials, components and process steps.
- Design and fabricate a pilot prototype suitable for scaling up in a later stage.
- Conduct final tests after engineering optimization and modifications have been implemented.

The completion of the activities common to this development stage will usually result in the following engineering information:

- Proof performance specifications met by presenting qualitative data on the working models or their components.
- A description of the potential manufacturing methods, listing critical materials and processes that are required.
- A description of the operational safety and environmental factors that may influence the final power system design.
- Proof of expected reliability of the power system, its subsystems and their components.

 Refined marketing strategy with a particular attention paid to cost estimates for future up-scale production.

22.7 The Pilot (Pre-Production) Prove-in-Phase

Launching new products is perhaps the most prevalent way for start-up high tech companies to establish themselves in a market and is a common strategy for incumbent firms to retain their industry position and grow top line profits. To reap the rewards from new product introductions, the characteristics of the new product, such an SOFC Power System, must first be conceived, developed, and ultimately sold in the marketplace.

While new products hold the promise of greater profitability, the process from start to finish is costly, time-consuming, and fraught with uncertainties. According to the National Science Foundation, in the US alone industrial R&D expenditure reached a level of \$291 billion annually in 2004, with that number expected to grow in the years to come (NSF, 2006). At the same time, R&D expenditure alone does not guarantee commercial success as new product failure rates are estimated to be as high as 80 percent. In a host of how do firms determine where to direct their R&D resources to ensure a healthy commercial return on their investment? What considerations go into formulating new product strategy while managing the associated risks? Once a new product has been developed, how does the firm price it to achieve maximal return?

Addressing these kinds of questions requires the company to balance three primary considerations. First, the company needs to have an understanding of what market opportunities exist in terms of which end users can be targeted and with what specific benefits. Second, the company needs to have a handle on the development feasibility of any proposed new product aimed at addressing a given market opportunity.

These two aspects of new product strategy introduce market and technical uncertainty, respectively, into NPD decision-making. Market uncertainty reflects the fact that before a new product is actually launched, there will exist some degree of doubt as to whether consumers perceive the benefits that the new product can provide to be large enough to offset any adoption obstacles – such as switching costs and risks of product failure. Fuel cell developers and their supporters should not go into a venture wearing 'rose-colored' glasses, because technical uncertainty reflects the fact that development challenges may be difficult to overcome – resulting in more R&D investment than initially expected or a delay in the timing of introduction. Technical uncertainty may also be associated with having to forecast the variable manufacturing costs the new product will entail. Across a number of studies, it has been shown that approximately 46 percent of new products fail in the technical phase, i.e., do not result in a result in a working product, while 35 percent of new products that were technically completed failed post launch due to lack of market acceptance. However, as a firm navigates through these sources of uncertainty, yet a third factor must be reckoned with – namely, competition. In the context of developing new products, the presence, or in some case the potential threat of, rivals can have considerable implications for which opportunities a firm ultimately chooses to pursue. On the one hand, new product development is a way for firms to pro-actively improve their standing relative to competition but, on the other hand, anticipating competitors' actions and plans may critically affect how a firm sets its own new product strategy.

With these considerations in mind, the Pilot (Pre-Production) Prove-in-Phase of engineering development is that period during which a power system is prepared for introduction into the marketplace. The objective of this stage is to develop the

manufacturing techniques and establish test market validity of the power system. The goal of this stage is to create a preproduction β field trial prototype. Although much information may be acquired through the use of simulation methods, during the commercial validation and production preparation phase, at least the following activities must take place:

- A preproduction β field trial prototype has been completed.
- The preproduction processes (for the components/parts of the SOFC power system) have been determined.
- Manufacturing procedures and equipment have been developed.
- Effectiveness and completeness has been demonstrate:
 - Of the final system design and its performance.
 - Of the installation and start-up plans for the manufacturing process.
 - Of the selection of production tools and technology necessary to produce an SOFC Power System.
 - Of the selection of materials, components and subsystems/component vendors and logistics.
- The market acceptance of the power system has been tested.
- A field support system for the power system has been designed.

Engineering analysis data and information developed during this phase should contribute to a comprehensive commercial introduction plan.

In order to achieve this goal the scale, quality and reliability of these activities should be representative of commercial operations. The costs of the manufacturable prototype should permit production of sufficient quantities for market trials. The completion of activities common to the commercial validation and information production preparation phase of development will usually result in the following engineering information:

- Power System performance data based on the manufacturable prototype.
- Data regarding the power system's maintainability and reliability.
- Data on manufacturing and production of the power system's modules.
- List of materials, components or subsystem suppliers.
- Plans for spare parts production and availability.
- Installation and operation cost data.
- Updated operating safety and environmental safety data.
- Updated test market characteristics and data.
- Warranty and service plans.

Commercial market validation is accomplished by attention to and deployment of the following:

- Confirming acceptable manufacturing techniques and time/cost projections.
- Confirming installation within acceptable time and cost constraints.
- Operability achievable under partial/full-scale production.
- Compliance with health, safety and other applicable industry standards.
- Productability and performances by means of appropriate tests.

22.8 Some more considerations for the Pilot (Pre-Production) Prove-in-Phase

The Pilot (Pre-Production) Prove-in-Phase has two stages. Pilot production is the phase that tests the whole system by integrating designs, detailed engineering, tools,

equipment, components, assembly sequences, and employees. It involves using the individual components that are built and tested on production equipment. Assembling and testing the final product is performed in the factory. The pilot production phase results in many units produced while modifying the manufacturing processes if necessary.

Once the pilot production phases have been refined, the production phase starts high yield volume production. The volume increases incrementally once the NPD team is confident with the quality of the final product at each level. Products are tested for compliance with quality and cost targets resulting in improvement of processes to meet these expectations. Engineering then evaluates and tests the pilot units, solves problems, and works with marketing to train field service personnel. Marketing trains the sales force and prepares the order entry process systems (Hayes, Wheelwright & Clark, 1988).

The assembly line should be designed to be as flexible as possible in order to adapt to the new products or processes it will be expected to produce. This flexibility allows the assembly line to produce a variety of products. Companies can no longer make the same item in large volumes for an extended period because product life cycles are shrinking. The goal is to make entire families of products or a unique item on the same production line. A flexible production line cuts down on the cycle time for any new products in the future. The decrease in cycle time increases profitability of companies and makes them more competitive. This is especially important in high technology areas because the rate at which newer generations of products are entering the market is shorter for each successive generation. To stay competitive, companies must offer the latest technological advancements to their customers (Michael, Summe, & Uttal, 1990).

22.9 The Manufacturing & Distribution Phase

The Manufacturing & Distribution Phase requires marketing to formulate the channel strategy. Distribution channels are filled and new channels are explored. A channel distribution map is an effective tool to help plan distribution strategy. This map displays sales and market share information by channel over a particular period. The map makes it easer to see trends and competitors' changes in channel activity. Channel information is gathered from trade publications, surveys and other forms of market research (Wheelwright & Clark, 1992). A number of alternative 'channels' of distribution may be available for fuel cell power systems:

- Distributor, who sells to retailers via direct marketing.
- Retailer sells to end customers
- Direct Distribution (Direct Marketing), where an organization sells its products directly to the end customer. For example in case of online purchases (Internet Marketing and E-commerce) there will be the seller and customer. For this the seller and the customer may depend on various shipping providers.

With these considerations in mind, the Manufacturing & Distribution Phase of engineering development is the period during which the manufacturing or process facility is built and full-scale production runs are made. The objective of the Manufacturing & Distribution Phase is to put the SOFC Power Systems into commercial production and optimize the manufacturing process consistent with the market demands. The goal of this phase is a market-ready product that has been frozen with respect to major design

changes. All the activities in this phase result in production maturity of the product, minimizing the need for later extensive modifications.

During the initial stage of the Manufacturing & Distribution Phase, there is substantial investment in completion of the following activities:

- Prepare final commercial level designs.
- Detail the manufacturing process.
- Finalize quality control procedures for all levels of procurement, manufacturing and assembly or production.
- Finalize the distribution system, including shipment, warehousing and customer assistance process.
- Construct manufacturing facilities—equip and ready for commercial operation.
- Make trial runs of the plant under full-production conditions.

During subsequent phases of the Manufacturing & Distribution Phase, the following activities must be continuously ongoing:

- Minor evolutionary modifications of the production process or procedures might be undertaken for the following reasons:
 - To enhance power system function.
 - To reduce power system cost.
 - To improve power system quality and reliability.
 - To improve customer acceptance of the power system.

The need for extensive modifications requiring reentry into previous phases should be examined.

The completion of activities common to the Manufacturing & Distribution Phase of development will usually result in the following engineering information:

- Production/product drawings and/or schematics.
- Manufacturing or production flow charts.
- Production material lists, specifications and prices for raw materials.
- Operational manuals on the production process.
- Quality control and reliability standards with supporting documentation.
- Final market acceptance survey based on pilot runs or prototype tests.
- Identification of the distribution plan and customer assistance plans.
- A report on the early production test runs describing production rates, quality and

accorded	anaina	oring 1	nrohlama	that	nood	to ha	addraccad	in thic	ctaga
associated	CHEINE	cinig i	provicins	unai	neeu i	10 UC	auuresseu	пп ипъ	stage.
	0	0							ω

Table 22-1					
QUALITY/TESTING TOOLS FOR NPD STAGES (EXAMPLES)					
NPD Stage	Quality/Testing Tools				
The Conceptual Design and Advance	Technology Road mapping				
Planning Phase	QFD/VOC				
	Tear-down Analysis				
The Primarily System Design Phase	Cost Models				
	Target Costs				
	Function Analysis				
	Zero Look VE				
The Detail System Design &	First Look VE				
Development Phase	DFA				
	DFM Process Selection				
	DFMEA				
The Pilot (Pre-Production) Prove-in-	Second Look VE				
Phase	PFMEA				
The Manufacturing & Distribution					
Phase					
The Operational Use & Logistic System					
Support Phase (sustainability)					
22.10 The Operational Use & Logistic System Support Phase (Sustainability)

By the time sales are occurring, the sales force knows the details of the power's systems technology and its uses. It is also familiar with the after-sales service support available. The sales force also understands and responds to customers' requirements, needs, wants, methods of using the power system, and their complaints. All of this activity starts in full force as the power system enters its Operational Use & Logistic System Support Phase.

Once a power system is sold, the distributor should then provide after-sales servicing, offer regular servicing and repairs, deal with customer complaints, anticipate customer dissatisfactions and their needs and wants for the future. Customer feedback is used to control and improve the quality assurance system of the product, in this case the SOFC Power System. This feedback promotes design changes to existing systems or after-sales service organizations and is used for new product development planning stages for next generation power systems.

The organization monitors customers through surveys, interviews, focus groups, and complaint handling. Through these means the corporation will use after-sales service customer feedback to understand customers' operations, how they use products, and what problems they have (Salter, 1991).

Customer feedback introduces a range of human experiences and should be monitored, understood and used by the company. This feedback is important because customer attitude directly affects repeat purchases of products. Satisfaction resulting from

a purchase feeds back into the confidence and attitude of the buyer. That, in turn, affects the intentions to buy a product. When goods and/or services are purchased, consumers anticipate their expectations regarding the products will be met. Once this has occurred, the consumers' attitude and confidence are boosted. This generally increases the customers' intentions to buy the product again and to promote products by word of mouth (Howard, 1989). Without customer satisfaction, there will be little second time purchases and the market will easily be lost to competitors who produce products that do satisfy customer expectations.

For traditional, established companies, this customer feedback was kept within the marketing department. Complaints were stifled so other areas of the organization would never know the real problems. All systems engineering practices for the SOFC Power System NPD effort proposed in this paper strongly suggests that end user complaints be considered, documented and studied to improve future system design, internal processes and satisfy customer expectation.

The Operational Use & Logistic System Support Phase of engineering development is the period during which the power system realizes a useful life. The objective of this phase of development is to maintain maximum value of the power system through continued consideration of engineering improvement. The goal of this phase is an optimum, competitive power system.

During the Operational Use & Logistic System Support Phase at least the following activities must be practiced:

- Provide on-site technical instructions and updates for safe and effective use of the power system.
- Prepare, distribute and encourage use of instruction manuals for the assembly, operation and maintenance of the power system.
- Design, produce and distribute "consumables" used in the power system.
- Design and introduce timely but minor improvements in materials, components, systems and software.
- Produce and distribute spare parts.
- Set up and provide warranty services.
- Introduce new applications developed for the power system.
- Identify new product spin-offs or major system design changes that would require going back into earlier stages to be re-identified as a power system.
- Disseminate alerts and undertake remedial action for unplanned product deficiencies or changing safety and environmental requirements.

A company that can develop new products, and processes them quicker and more efficiently than its competitors has a competitive advantage. However, to sustain this advantage and be competitive in the future, development capability must be continually improved and expanded (Wheelwright & Clark, 1992). In order for fuel cell companies to build NPD capability rapidly, they must learn from the best-in-class organizations. The future environments will be changing so rapidly that learning by experience will be too expensive (McNair & Leibfried, 1992). The bulk of the expenses will be due to the extended time and effort it takes for an organization to get its products into the hands of the customers. Delays in product introduction adversely affect the profits over the life of the product. Incorporating benchmarking practices will become the preferred method of improving development capacity. Benchmarking is "*the continuous process of measuring product, services, and practices against their toughest competitors, or those companies recognized as industry leaders*" (Camp, 1989). Benchmarking can be used across the organization to identify NPD practices that support critical objectives of the organization. According to a study by the Internal Benchmarking Clearinghouse, although 95% of the companies interviewed do not know how to benchmark, 79% of them believe that companies must benchmark in the future to survive (Biesada, 1992).

Benchmark practices start with an understanding of core issues such as unmet customer needs, performance gaps, problem areas, and strategic advantages. Performance measurements and external organizations are selected. These external organizations can include other departments within a company, other companies in the industry, or companies outside the industry that happen to perform a particular process well. Internal benchmarking is the analysis of existing practice within various departments or divisions of the organization to determine the best performing activities and drivers. Internal benchmarking is a good start for companies that want to become proficient at benchmarking. Benchmarking is a process of gathering information. Therefore, if a firm can't gather data from within, the company probably won't get it from anywhere else. Competitive benchmarking examines direct competitors and their strengths and weaknesses to plot a successful strategy. Industry benchmarking is an examination of everyone in the same industry for the purpose of analyzing industry trends and performance metrics. Best-in-class benchmarking examines many industries in order to search for innovative practices that can be applied within an organization. This type is the

most powerful form of benchmarking because it can result in quantum leaps in performance. Best-in-class benchmarking provides a mechanism to change a process to make dramatic performance improvements. For example, if a manufacturing company wants to optimize its cash management process, it could study the industry and learn from those manufacturing companies that best perform cash management. However, it would be much better to examine companies in an industry that have impeccable cash management skills, such as a financial service company whose resource conversion technology is managing cash. This type of benchmarking will bring an innovative process to the industry as well as to the company (McNair & Leibfreid, 1992). Benchmarking information can be acquired from varieties of sources. Among these are published material (trade magazines, management literature such as Lexis/Nexis or Value Line), insights gained at trade meetings, contracting trade associations, gathering intelligence at trade shows, conversations with industry experts (interviews are informative but expensive), customer feedback, consortia of benchmarking partners, employees and former employees.

22.11 Conclusion

In order for fuel cell developers to improve their chances of commercialization of traveling further down the road of the product's lifecycle with the goal of gaining a competitive advantage, developers should utilize throughout and within each lifecycle phase the following strategies:

1. All business, systems engineering and development strategies must have well defined and clearly communicated throughout the organization.

- 2. Formal cross functional teams should be created for development and research.
- 3. Prototype designs should be built and used for performance and market research testing purposes.
- 4. Fuel cell developers must work toward expanding potential concepts and ideas using analytical techniques for NPD development.
- 5. Mechanisms are to be put in place to feedback project learning into the organization to improve ongoing and future projects.
- 6. Effective career development should be in place for all product development team members.

These practices can then be incorporated into the modernized NIST/NSPE Reference Model that facilitates the development of new products. The modernized NIST/NSPE Reference Model is an arrangement of product development stages that result in the commercialization of innovative/disruptive, new products. The stages for the modernized NIST/NSPE Reference Model consist of:

- 1. The Conceptual Design & Advance Planning Phase,
- 2. The Preliminary System Design Phase,
- 3. The Detail System Design & Development Phase,
- 4. The Pilot (Pre-Production) Prove in Phase,
- 5. The Manufacturing & Distribution Phase, and
- 6. The Operational Use & Logistic System Support Phase.

The modernized NIST/NSPE Reference Model helps organize functional inputs and promotes continuous improvement of the NPD process by providing a framework for new product development efforts. The proposed the modernized NIST/NSPE Reference Model facilitates the coordination of functional inputs by arranging tasks in time and fitting the tasks together through cross-functional integration. The modernized NIST/NSPE Reference Model is circular (within a concurrent engineering framework) in design in order to lend itself to continuous improvement by incorporating systems engineering practices and methods into the planning/decision/design activities of each phase of the innovative NPD product's lifecycle.

CHAPTER XXIII

DISCUSSION AND CONCLUSION

23.1 Introduction

An investigation of the challenges of commercializing SOFC Power Systems and the importance of achieving commercialization through the use of the systems engineering process were the topics of this paper. The challenges of commercializing SOFC Power Systems are numerous; and, within this paper a few of these challenges have been examined. Richard T. Stuebi of the Cleveland Foundation said (regarding the fuel cell industry's inability to successfully commercialize), '*It does not mean that these thresholds can not be attained; they just haven't been attained yet.*' At the start of this project the author of this paper hypothesized that the main reason why the fuel cell industry has not successfully attained the commercialization threshold was due to a lack of systems engineering practices.

23.2 Discussion

The evaluation and study of the fuel cell industry and its engineering/design practices, in particular the SOFC industry's, was done using the framework of a NPD Lifecycle model which was first conceived in the 1990's by a Task Group put together by the National Institute of Standards and Testing in cooperation with the National Society of Professional Engineers (NIST/NSPE). The original goals of this paper were to modernize NIST/NSPE Task Group's twenty year old document and fashion it into a guidance template for new product development for innovative and disruptive technologies.

The guidance template's update tailoring was too influenced by the systems engineering experience, guidance and philosophy of L. Ken Keys, Benjamin S. Blanchard and others. The main point of this modernization of a six-phase NPD Lifecycle model, very simply, in a nutshell was to convey that, systems engineering is essentially the function that oversees any design effort to ensure that the resulting design does what it's supposed to be. The most visible job of the system engineer then is to turn the customer's desires into functional requirements, and then turn those requirements into a functional, reliable, robust product which satisfies or exceeds the expectations of the end user. The means by which all of this is done by: defining the lifecycle phases of the product, defining the activities of each lifecycle phase, and within each phase, control the design/development activities of the NPD effort.

Because fuel cell technology is innovative, an obscure technology at that, because of proprietary issues associated with its development, the workings, processes, and design of a power system is mostly not accessible to many people. Also, many individuals do

not possess or/and have a desire to acquire intimate knowledge of this disruptive technology. Yet, in order for one to understand and appreciate the technical challenges fuel cell developers face, a person needs to have a basic knowledge of the functions and design of a fuel cell power system. It was the author's hope that the reader after reading this paper would gain that knowledge. In order to cover the topics which the author felt were necessary; this paper expanded and became lengthier than intended.

The author also hoped that the systems engineering process, a path which provides cost savings for complex systems, which also provides fuel cell developers with a better chance at commercialization, was demonstrated via topics related to some of the major activities of the first two phases of the NPD six-phase lifecycle reference model.

Dr. Keys has been an academic leader in continuing to reaffirm the importance of the systems life-cycle engineering view. Through the systems engineering process one can eliminate the historical separation of the acquisition or design for lowest "out the door" cost and the 'use' phase (the phase Dr. Keys has called the Operational Use & Logistic System Support Phase). Keys believes that before the 'use' phase for products is reached, problems are addressed to eliminate the 'would-be' customer-related issues that would most likely spring up, to prevent product recalls, to prevent degraded performance or failure, and to eliminate expensive repairs for 'not accessible' elements, etc. The author hopes that Key's theme of the systems life-cycle engineering view is pronounced throughout this paper.

Benjamin S. Blanchard's System Engineering Management, fourth edition, was one of the main reference sources for this paper because Blanchard's text covers all the

aspects of systems engineering theory, practice and planning. The text starts with a foundation of the basics, such as definitions, system engineering life cycle, analysis and concurrent engineering. It then builds upon this foundation by addressing all of the elements of a well-managed system engineering program: integrated product and process development, TQM, configuration management, support and logistics. The author found that in Blanchard's text each element of systems engineering practice or method was discussed in detail and placed into the context of a total system engineering environment.

23.3 The Aims

The author believes that the major challenges of commercializing an SOFC Power System were addressed. Within the context of the first phase of NPD, in the early parts of this paper, an example of a power system was broken down into subsystems and the functions of each subsystem were explained. Afterwards when the workings of each subsystem were hashed out in greater detail, the technical challenges each subsystem was most likely to experience was discussed. The effectiveness of '*doing it right the first time*' and using systems engineering practices in redesign was shown to produce cost savings. Situations and problems which cause rework to occur were included in this paper. Barriers to fuel cell commercialization were defined in detail. The consequences of not incorporating quality assurance and reliability practices into a NPD project were also examined.

The author would very much like to have continued exploring the last four phases of the NPD Lifecycle model, but due to the time constraint, that was not possible. Too much time was used researching and attempting to 'show' the reader the activities of the

first two phases. However, when researching each activity of the first two phases, the author began to comprehend and appreciate the beauty and the value of a systematic process for breaking a product's lifecycle down into phases, for applying the 'how to's' of NPD, for understanding the 'whys' behind the engineering activities, and for understanding the importance of arriving at the end of a phase quickly because, to the new product, development is a life or death matter.

23.4 The Steps throughout the Research Process

If the combustion engine is the heart of an automobile, then the heart of an SOFC Power System is its Cell Stack Package. The study began by giving the readers a short history of the rudimentary material concept; a concept which grew into a technology associated with and enabled manned space flights, and as of current times, grew into a technology for efficient energy conversion.

The main technical themes of this thesis were the importance of: The System View, Configuration Management, Quality Management, Reliability Engineering, and Systems Testing Engineering and Maintenance Plan.

The System View emphasized beginning a NPD using a 'Top-Down' Approach, systems viewed as whole complex organisms hence a study of the organism's parts and subsystems interactions must be known, quantified and controlled. Configuration management focuses on a product's consistent performance, its functions, and its physical attributes for the purpose of establishing and maintaining these characteristics. Systems Testing Engineering, Quality Management, Reliability Engineering, Systems Testing Engineering and Maintenance Planning must be achieved throughout the entire lifecycle of a product, at each level of the product's overall system hierarchy.

An overview of the NIST/NSPE Reference Document was presented which had six phases:

- 1. The Conceptual Design & Advance Planning Phase,
- 2. The Preliminary System Design Phase,
- 3. The Detail System Design & Development Phase,
- 4. The Pilot (Pre-Production) Prove in Phase,
- 5. The Manufacturing & Distribution Phase, and
- 6. The Operational Use & Logistic System Support Phase.

The System/Product Baseline Milestones were:

- Functional Configuration Identification (System Specifications).
- Allocated Configuration Identification (Development, Product, Material Specifications).
- Product Configuration Identification (Process, Product, Material Specifications).
- Updated Product Configuration Identification (Updated Product Configuration Identification Confirmation, New Product Release to Manufacturing).
- Product Configuration Identification and Control Confirm logistics, customer service/support system).

The introduction, the definition and activities of the Conceptual and Advance Design Phase were discussed followed by the introduction of the subject of this systems engineering study. A mock-up SOFC Power System was broken down into its system Hierarchy Architecture using a Part Centric Top-Down Design Approach.

It could not be stressed enough how important testing and system evaluation are to NPD. Hence, the discussion of these topics was initiated before the introduction of the Operational Requirements and Technology Baselines for the subsystems of the SOFC Power System.

The Operational Requirements and Technology Baselines for the Fuel Processing Subsystem, the Air Subsystem and the Waste Management Systems, the Electrical System, the Thermal Management System, the Hot Assembly and the Cell Stack Package were introduced.

An innovative problem solving technique and the procedural steps for defining the initial definition knowledge baselines using the Input-Output-Resource-Constraints (IORC) Process System were detailed

The Conceptual Design and Advance Planning Phase was concluded with a discussion about Design Structure Matrix (DSM) a technique which provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems of systems design.

The introduction, the definition and activities of the Preliminary Systems Design Phase were discussed followed by an examination of the Bottom-Up Design Approach. In practice this design approach pieces together components/parts of the subsystems of the SOFC Power System to give rise to a grander system, the emergence of the power system itself. Therefore the end goal of the Bottom-up Design Approach is to translate the conceptual design mock-up into a prototyping design worthy of manufacturing. To start the Bottom-Up Design Approach, trade-offs studies are performed so that the "optimum" design is one in which compromises are acceptable. Fuel cell developers use optimization trade-off studies like the Hawkes' case study to develop their optimum prototype model.

The Cell Stack Package, being the pivotal subsystem of the SOFC Power System deserves special attention in the areas of material and configuration development. A '*small*' sample of design questions were presented and these design features were discussed to give the reader a 'feel' for what is involved in the design and configuration of the Unit Cell and the Cell Stack Package. Much of the design, configuration and processes used to create the Unit Cell and the Cell Stack Package are of a proprietary nature.

Until a working prototype design is 'frozen', in the Preliminary System Design Phase, fuel cell power system designs are continuously modified and changed. A system engineering approach built upon the work of Clarkson (et al) would most definitely benefit fuel cell developer by way of providing a systematic approach to redesign. A chapter was dedicated to this topic.

In the 'real world', fuel cell developers, unlike engineers-in-training, simply do not find answers to their design and development questions from a text book, they make decisions based on their experience, and the data and information they have at hand. The Analytic Hierarchy Process (AHP) is a structured technique for dealing with complex decisions. Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem. The author believes that AHP could greatly benefit developers and designers, so a chapter about this topic was included into this paper.

The topic of testing in the Preliminary Systems Design Phase picks up where the last chapter on testing left off. In addition, this chapter explains, using real world examples, what value and wisdom the practice of testing and reliability engineering offer

fuel cell developers. Developmental costs versus the activities of the six lifecycle phases are examined with the emphasis on timely progress towards product completion. This chapter also examines and describes how a prolonged developmental period could cause the premature and untimely death of a new product.

A potentially manufacturable architecture, for the power system, begins to emerge during the Conceptual Design and Advance Planning Phase. The advantage of modularity, towards producing a manufacturable product, from a NPD viewpoint, was investigated.

A chapter was dedicated to the topics of Design for X and Design for Manufacturability (DFM). Under the label Design for X (DFX), a wide collection of specific design guidelines addressed particular issues that are caused by, or affects the characteristics of a product. For fuel cell developers who have reached the Preliminary Systems Design Phase, DFM will most likely be explored. The application of DFM is particularly complex and it should be done in a concurrent engineering environment. Many industrial sectors experience an increased NPD progress via their reliance on Mechatronic which is the integrating various engineering disciplines where the most substantial benefits are seem at the team-level and the individual level.

In the Preliminary Systems Design Phase, life-cycle energy analysis should be investigated by fuel cell developers because many of SOFC production processes are energy intense. A chapter was dedicated to this topic.

In the Preliminary Systems Design Phase, the necessary to expand both vertically and horizontally will cause fuel cell developers to reach a decisive cross-road, where deciding on the wrong route to take might and, often times do, cause the product's

untimely death due to resource allocation, supply chain, and funding problems. When choosing Strategic Partnerships alliances, both types of organizational integration are needed. Fuel Cell developers face many challenges; many of these challenges are self inflicting, while others are external. Developers, their partners, their funders must be aware of the commercialization barriers. Only by acknowledging the problems, by correcting their self-imposed problems by strict systems engineering practices, and becoming active in promoting public awareness, only then can fuel cell developers have a chance to overcome most of their obstacles which block their way towards market entry.

The conditions, the activities and information needed which confirmed that the SOFC Power System prototype was ready to enter its third phase of development was summarized and this paper ended with a brief description of the next four life cycle phases of the NIST/NSPE Reference Document.

One conclusion which can be drawn from this study is that using just a few of the systems engineering practices is not the '*silver bullet*', or the '*cure-all*' for design and development problems fuel cell developers face. What *is* the answer – it is a systematic program designed (with all of its systems engineering tools active and in use) to address design and development issues in the context of a lifecycle phase approach.

23.5 Future Work

This thesis hoped to generate study in criterion formation for NPD. Formalized criterion for each lifecycle phase could be utilized as a standard rule used to evaluate development progress of new products to reduce failure or the risk associated with funding agencies selecting innovative technologies which are doomed to fail. A checklist for each phase could be created to ensure quality assurance of engineering, process

compliance, code standardization and error prevention, and others systems engineering practices.

Because few practical examples exist, alternative System Hierarchy Architecture Models could be constructed to reflect different sets of assumptions. For example, changes in net-metering laws could lead to situations where micro-power generation for export could be financially desirable. In this case, the needs of the individual user are less important and the aggregate power demand becomes more central to the calculations. Alternative hybrid systems combining other intermittent renewable energy sources, such as windmills or micro hydro, would also lead to alternative models with potentially dramatically different conclusions. To determine which hydrogen production process is the most economical under certain operational situations, designing an alternative power system which uses Partial Oxidation as its means to produce hydrogen instead of steam reforming would be another example.

Research and development of quality control and assurance measures in SOFC power systems should also be investigated. The reliability issues plaguing fuel cell developers today could be prevented if a systematic implementation of industry-wide, reliability and quality standards were explored, developed and used. More research needs to be done for SOFC reliability studies and implementation of quality assurance measures in NPD of power systems' design. For example, because the SOFC industry is in its infancy, many balance of plant components are taken from other devices that were designed to a different set of specifications. A case in point, fuel pumps used in the automotive industry have much higher flow rates and pressures than would be desirable in a typical small scale SOFC device. Additional '*pulse dampening'* devices must then be

added to accommodate the ill-fitting pumps which leads to additional reliability questions.

In addition to detailing and defining the activities of each phase of the NPD's lifecycle, the milestones of each phase should have been explored further to detail their activities, goals, information generation and future planning.

Two additional market analysis should be performed which the author would encourage others to pursue.

Kerry Crawford, a former General Electric employee, believed an SOFC/Electric Locomotive Hybrid had the potential to become a commercialize wide-market success. The author of this thesis believes Crawford is correct because the transition or change from the existing technology to the innovative compliment would not be too great. Depending on results of the analysis, the SOFC could be sat within a power station or onboard the train. An electric locomotive is a locomotive powered by electricity from overhead lines, a third rail or an on-board energy storage device. An electrically propelled locomotive with on-board fuelled prime movers, such as diesel engines are classed as diesel-electric locomotives because the electric generator/motor combination only serves as a power transmission system. Electricity is used to eliminate smoke and take advantage of the high efficiency of electric motors; however, the cost of railway electrification means that usually only heavily-used lines can be electrified. Electric locomotives benefit from the high efficiency of electric motors, often above 90%. Additional efficiency can be gained from regenerative braking, which allows kinetic energy to be recovered during braking to put some power back on the line. Newer electric locomotives use AC motor-inverter drive systems that provide for regenerative braking.

Instead of targeting the '*average*' homeowners, perhaps niche markets should be investigated. A '*gated community*' is a form of a residential community or housing estate containing strictly-controlled entrances for pedestrians, bicycles, and automobiles, and often characterized by a closed perimeter of walls and fences. Gated communities usually consist of small residential streets and include various shared amenities. Gated communities are a type of common interest development, but are distinct from intentional communities.

According to a USA Today article, in cities and suburbs from New York to Los Angeles, wealthy homeowners no longer are the only ones retreating behind gates. The desire to lock out the outside world cuts across all income groups, according to the first Census Bureau survey to measure how many Americans live in walled or gated communities. In countries with a low Human Development Index and/or high Gini coefficient, gated communities attempt to provide security as well as expatriates.



Figure 23-1: Concept of Heaven [http://www.cartoonstock.com/directory/g/gated_communities.asp}

"We think of affluent people and mini-mansions in exclusive enclaves, but we don't think about the multifamily, higher density, lower-income residents also being in

that type of development," says Tom Sanchez, an associate professor of urban affairs and planning at Virginia Tech. He analyzed the data for the university's Metropolitan Institute. The popularity of gated communities is on the rise nationwide, according to developers and housing experts. In a nation still confronting post-9/11 jitters, living behind walls and knowing your neighbors create a safety zone for many. Security is also a top concern for baby boomers as they head toward retirement. "*It's spreading to the middle class*," says Ed Blakely, co-author of *Fortress America: Gated Communities in the United States* and the dean of the Milano Graduate School at New School University in New York. "*About 40% of new homes in California are behind walls*", he says. Most subdivisions approved by Palm Beach County, Fla., in the past five years are gated. The analysis of the Census Bureau's 2001 American Housing Survey, a sampling of 62,000 households that is representative of the nation's 119 million households, shows that:

- More than 7 million households about 6% of the national total are in developments behind walls and fences. About 4 million of the total is in communities where access is controlled by gates, entry codes, key cards or security guards.
- Homeowners in gated communities live in upscale and mostly white developments. But renters, who are more ethnically diverse and less affluent, are nearly 2 and 1/2 times as likely as homeowners to live behind gates or walls.

Whether they own or rent, Hispanics are more likely to live in such communities than whites or blacks. That may be partly because there is a large Hispanic population in the West and Southwest, areas with the largest concentration of gated communities.

 Gated developments are more prevalent in Sun Belt metro areas such as Dallas, Houston and Los Angeles than in older urban areas in the Midwest and Northeast. But they're becoming popular in places like New Orleans, Long Island, N.Y., Chicago, Atlanta and the suburbs of Washington, D.C

Dr. Keys believes that premiere residential community economic model(s) should be studied because electricity and heat could become amenities, if the community had its own power system. The author believes that affluent individuals who want and can afford novelty, are conscientious about energy, want freedom from grid supplied power, might want a 'gated community' that is powered by an SOFC. With electricity and heat as amenities, gated communities could offer their residence according to Keys' approach to design a community plan framework having the following benefits:

- Freedom from black and brown-outs, added security of Grid Independent power.
- In addition to supplying household power, the electricity produced could be utilized to operate swimming pools' pumps and other equipment.
- Power to recharge the electric cars.

The heat produced from the SOFC Power System could be used for home heating, hot water production (tankless water heaters), swimming pools, hot tubs, saunas, and greenhouses.

A number of important systems engineering needs for SOFCs were identified by the author using Keys' papers as references. These topics need further study. They are as follows:

- There's a need for further economic evaluation of design tradeoffs over a power system's life-cycle.
- More computer-aided estimating should be used in the design efforts towards manufacturability.
- Researching the timing and the location of the introduction of the power system into the α/β field trial demo.
- Appropriate measures of system efficiency and effectiveness.
- Model system performance cost as impacted by design.
- Criteria for system evaluation to determine an optimum system/product definition and design over power system life-cycle.
- Methodology of needs determination
- Cost control of systems engineering management
- Develop computer-aided methodologies which embrace a life-cycle orientation for the activities of engineering analysis and design (extending CAD/CAM to Marco CAD).
- Establish an optimal conceptual design with full recognition of its impact on operational feasibility.
- Research directed to create strategies for compressing the development cycle through the integration of manufacturing engineering, quality assurance, and other elements in the design process as needed.
- Develop of quality assurance, testing and control standards of Cell Stack
 Packages, fuel cell components and materials.

The NIST/NSPE Reference Document could be a revised and expanded even further to be the topic of doctorial research, or it could be a popular professional text for academic professors, scientists, and business professionals, as well as, a text book for college and public libraries.

BIBLIOGRAPHY

- 1. Acharya, Prabha; Enjeti, Prasad; Pital, Ira J; *An Advanced Fuel Cell Simulator* Power Electronics & Fuel Cell Power systems Laboratory Department of Electrical Engineering, TAMU February (2004).
- 2. Adler, S.B & Chen, X.Y. & Wilson J.R. *Mechanisms and Rate Laws for Oxygen Exchange on Mixed-Conducting Oxide Surfaces* www.sciencedirect.com (2006).
- Adler, Margot, *Behind the Ever-Expanding American Dream House*, National Public Radio, 2006, <u>http://www.npr.org/templates/story/story.php?storyId=5525283</u> Retrieved, 5/5/11.
- 4. Adner, Ron, *When Are Technologies Disruptive? A Demand-Based View* of the Emergence of Competition, Strategic Management Journal Strat. Mgmt. J., 23: 667–688 (2002).
- Advameg, Inc., How Things are Made; Automobile <u>http://www.madehow.com/Volume-1/Automobile.html</u> (2011), Retrieval Date June 1, 2011.
- 6. Advance Industrial Science and Technology, Successful Development of Honeycomb-type Micro Fuel Cells, (2006). <u>http://www.aist.go.jp/aist_e/latest_research/2006/20061204/20061204.htm</u> <u>1</u>, Retrieved: 3/4/11.
- 7. Aguiar, P; Lapena-Rey, N.; Chadwick, D.; Kershenbaum, L.; *Improving Catalyst Structures and Reactor Configurations for Autothermal Reaction Systems: Application to Solid Oxide Fuel Cells*, Chemical Engineering Science 56 (2001).
- 8. Ahamad, Naveed; Wynn, David C.; Clarkson, P. John; *Estimating The Process Cost of Implementing Engineering Change Alternatives*, 2nd Nordic Conferences on Product Lifecycle Management, January (2009).
- 9. Ahmed, S., An industrial case study: Identification of competencies of design engineers. Journal of Mechanical Design, 129, pp. 709-716. (2007)
- 10. Ahmed, S.; Krumpelt M., *Hydrogen from Hydrocarbon Fuels for Fuel Cells*, International Journal of Hydrogen Energy, 26 (2001).
- 11. Allen, Michael; Prateepchaikul, Gumpon *The Modeling of Biodiesel Reaction* Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hadyai, Thailand, 2000.

- 12. Altingm Leo; Legarth, Jens Brobech; *Life Cycle Engineering and Design*, Annals of the CIRP Vol. 44/2, 1995.
- 13. Amin, S. Massoud and Wollenberg, Bruce F. "Toward a Smart Grid". IEEE P&E Magazine. Vol. 3, No.5, pgs 34-41, 2005.
- 14. *An Introduction to Steam Boilers and Steam Raising,* <u>www.gc3.com/Default.aspx</u> Retrieved: 10/13/10.
- 15. Anderson, Edward G ; Jolgekar, Nitin *A Hierarchical Product Development Planning Framework* Production and Operations Management (Vol 14, 2005).
- 16. Antalffy, Leslie P.; Chaku, Pran N.; Canonico, Domenic A; Pfeifer, Jeff A; & Alcorn, Douglas G. *The Potential for Using high Chromium Ferritic Alloys for Hydroprocessing Reactors*, www.sciencedirect.com (2002).
- 17. Apfel, H.; Rzepka, M.; Tua, H.; Stimming, U; *Thermal Start-Up Behaviour and Thermal Management of SOFC's* Department of Physics Technische Universitat Munchen December (2005).
- 18. Appelquist, P, *Modelling in product and supply chain design: literature survey and case study*, Journal of Manufacturing Technology Management, Vol. 15 Iss: 7, pp.675 686 (2004).
- 19. Appleby, A.J., *Issues in Fuel Cell Commercialization*, Journal of Power Sources September 1995.
- 20. Argo Press *Test and Evaluation Master Plan* <u>www.argospress.com/Resources/systems-</u> <u>engineering/testandevaluamastplan.htm</u> (2009), Retrieval Date 11/1/ 2010.
- 21. Armstrong, Donald J.; Swan, David H.; Hibbs, Bart D; Jensen, Brian R.; McAlwee, Gerald S; *Thermal Management for a Vehicle Mounted for Fuel Cell System* United States Patent Number 6,682,841B1 January 27, 2004.
- 22. Arriagada, Jaime and Olausson, Pernilla and Selimovic, Azra Artificial Neural Network Simulator for SOFC Performance Prediction Department of heat and Power Engineering, Division of Thermal Power Engineering, Lund University Box 118 S-221 00 Lund, Sweden Accepted May 31, 2002, Journal of Power Sources, 112 (2002) 54-60.

- 23. Astrom, K; Fontello, E; Virtanen, S. *Reliability Analysis and Initial Requirements for FC systems and Stacks*, Science Direct, 171 (2007).
- 24. Avgouropoulos, G.; Ioannides, T., CO Tolerance of Pt and Rh Catalysts: Effect of CO in the gas-phase Oxidation of H2 over Pt and Rh Supported Catalysts Applied Catalysis B: Environmental 56 (2005).
- 25. Badrinarayanan, Paravastu; *PEM Fuel Cell Water And Thermal Management: A Methodology to Understand Water and Thermal Management in an Automotive Fuel Cell System* Birla Institute of Technology and Science, Pilani, India (1999).
- 26. Ballard White Paper, *International Standards for Stationary Fuel Cell Power Systems* Product Engineering Department April (2009).
- Banka, N. and Lin, Y. J. "Mechanical Design for Assembly of a 4-DOF Robotic Arm Utilizing a Top-down Concept." Robotica. Vol 21 pages 567-573. (2003).
- 28. Barak, Moshe & Mesika, Pnina *Teaching Methods for Inventive Problem-Solving in Junior High School*, Graduate Program for Science and Technology Education, Ben Gurion University of the Vegev, Beer Sheva 84105, Israel Thinking Skills and Creativity 2 (2007).
- 29. Baratto, Francesco; Diwekar, Urmila M.; Manca, Davide; "*Impacts* assessment and trade-offs of fuel cell-based auxiliary power units Part I: System performance and cost modeling". Journal of Power Sources, Vol. 139 pages 205–213. (2005).
- 30. *Basic Mechanisms of Heat Transfer* Wolverine Tube Heat Transfer Data Book <u>http://www.wlv.com</u> Retrieved: 06/23/11.
- 31. *Basic of Ceramic Chip Capacitors* Johanson Dielectrics www.johansondielectrics.com ,December (2007).
- 32. Basso, Tom *IEEE Standard for Interconnecting Distributed Resources with the Electric Power System* National Renewable Energy Laboratory Golden. Colorado June (2004).
- 33. BekkTech LLC, Fuel Cell Testing Products and Services <u>http://www.bekktech.com/nCondAndASR.html</u> (2000-2011) Retrieval Date: 5/25/11.
- 34. Belko, Bill; *HSC VS. Doctor Blade Tape Casting A Comparison* http://www.ragantech.com/compare.html, (2008) Retrieval Date: 11/3/10.

- 35. Belosevic, Srdjan; Paprika, Milijana; Komatina, Mirko; Stevanovic, Zarko; Mladenovic, Rastko; Oka, Nikola; Dakic, Dragoljub; *Experimental and Numerical Investigation of Heat Exchanger Built in Solid Fuel Household Furnace of an Original Concept* Energy and Buildings 37 (2005).
- 36. Belovich, Joanne M. "An Algae dewatering method for Biofuels production." Cleveland State University. <u>www.csuohio.edu</u>, (2010), Retrieval Date: 9/15/10.
- 37. Benedict, E.; Collins, T.; Gotham, D.; Hoffman, S.; Karipides, D.; *Losses In Electric Power Systems* ECE Technical Reports, Paper (1992).
- 38. Beshty, Bahjat S, Whelan, James A., *Fuel Cell Integrated With Steam Reformer* United States Patent Number 4,670,359 June 2, 1987.
- Betz, Frederick, "Managing Technology, Competing Through New Ventures, Innovations and Corporate Research". Prentice-Hall Inc., Pub. Englewood Cliffs, NJ (268 pg), pg. 50. (1987).
- 40. Biomass Energy Centre. *"What is Biomass?"* <u>www.biomassenergycentre.org.uk</u> (2008), Date Retrieved: 9/3/10.
- 41. Bishopa, Justin D.K.; Amaratungaa, Gehan A.J.; Rodriguez, Cuauhtemoc; Linking Energy Policy, Electricity Generation and Transmission using Strong Sustainability and Co-Optimization Electric Power Systems Research 80 (2010).
- 42. BizLogx LLC, *Technology Commercialization Framework*, Ohio Third Frontier, (2004).
- 43. Blanchard, Benjamin S. "Systems Engineering Management (4th Ed.)." John Wiley & Sons, Inc. (2008).
- 44. Blomen, Leo J.M.J and Mugerwa, Micheal N. *"Fuel Cell Systems"*. Plenum Press, New York. A Division of Plenum Publishing Corp. (edited by), (1993).
- 45. Bloom, Ira D.; Ley, Kevin L.; *Compliant Sealants for Solid Oxide Fuel Cells and Other Ceramics* United States Patent Number 5,453,331 September 26, 1995.
- 46. Bonaccorsi, Andrea and Lipparini, Andrea, *Strategic Partnership in New Product Development: An Italian Case*, Product Innovation Management, 1994.

- 47. Boothroyd, Geoffrey, *Product design for manufacture and assembly*, Computer-Aided Design, Volume 26, Issue 7, July 1994, Pages 505-520
- 48. Boothroyd, G. (et al), *Design for Assembly and Disassembly*, <u>CIRP Annals</u> <u>- Manufacturing Technology</u>, <u>Volume 41, Issue 2</u>, 1992, Pages 625-636
- 49. Borglum, Brian *Development of Solid Oxide Fuel Cells at Versa Power Systems* Fuel Cell Seminar & Exposition Calgary, Alberta, Canada October (2007).
- 50. Bossel, Ulf "Well to Wheel Studies, Heating Values and the Energy Conservation Principle." European Fuel Cell Forum. (2003).
- 51. Bouk, Dan.; Burnett, D. Graham. *"Knowledge of Leviathan: Charles W. Morgan Anatomizes His Whale"*. Journal of the Early Republic, Volume 28, issue 3, p. 433-466 (2008).
- 52. Brahim, C. *Electrical properties of thin bilayered YSZ/GDC SOFC electrolyte elaborated by sputtering* Journal of Power Sources 156, pg. 45–49, (2006).
- 53. Bram, Martin; Rechers, Stephen; Drinovac, Pere; Monch, Josef; Steinbrech, Rolf W.; Buchkremer, Hans Peter; Stover, Detlev; *Deformation Behavior and Leakage Tests of Alternate Sealing Materials for SOFC Stacks* Journal of Power Sources 138 (2004).
- 54. Braun, R.J.; Klein, S.A.; Reindl, D.T.; *Evaluation of System Configurations for Solid Oxide Fuel Cell-Based Micro-Combined Heat and Power Generators in Residential Applications* Journal of Power Sources 158 (2006).
- 55. Braun, Robert J.; Klein, Sanford A; Reindl, Douglas T.; Assessment of Solid Oxide Fuel Cells in Building Applications Phase 1: Modeling and Preliminary Analyses Solar Energy Laboratory University of Wisconsin-Madison November (2001).
- 56. Brightling, John: Farnell; Peter; Foster, Craig; *Steam Reforming 50 Years* of Development and the Challenges for the Next 50 Years Johnson Matthey Catalysts, UK September (2005).
- 57. Browning, Tyson R.; *Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions* IEEE Transactions on Engineering Management August (2001).
- 58. Bujalski, Dr. Waldemar; *Solid Oxide Fuel Cells (SOFC)*, College of Engineering and Pyhsical Sciences University of Birmingham (2008).

- 59. Burke, A. Alan.; Carreiro, Louis G.; *Solid Oxide Fuel Cells in Unmanned Undersea Vehicle Applications* Naval Undersea Warfare Center, Division Newport, RI August (2008).
- 60. Burnette, David; *The Performance of Planar Solid Oxide Fuel Cells Using Hydrogen-Depleted Coal Syngas* A thesis presented to the faculty of the Russ College of Engineering and Technology of Ohio University November (2007).
- 61. Bureau of Energy Efficiency, *Electrical System*, <u>http://220.156.189.23/energy_managers_auditors/documents/guide_books</u> <u>/3Ch1.pdf</u>, (*Retrieved: 10/31/10*.
- 62. Burstein, G.T.; *A Hundred Years of Tafel's Equation: 1905-2005* Corrosion Science 47 (2005).
- 63. Business Insights, *Leading Fuel Cell Technologies Applications, costs, economic competitiveness and future prospects* <u>http://www.ipmarketingadvisor.com/content/wp-</u> <u>content/uploads/2009/07/leading-fuel-cell-technologies-brochure.pdf</u> Retrieval Date December 22, 2010.
- 64. Cable, Thomas L.; Brakas, Adam B.; Ruhl, Robert C; Milliken, Christopher E.; *Method for Steam Reforming Hydrocarbons Using A Sulfur-Tolerant Catalyst* United State Patent Number 6,238,816B1 May 29, 2001.
- 65. Cable, Thomas L.; Petrik, Michael A.; *Electrochemical Apparatus and Process* United States Patent Number 5,589,285 December 31, 1996.
- 66. Cable, Thomas L.; Petrik, Michael A.; *Electrochemical Apparatus* United States Patent Number 5,445,903 August 29, 1995.
- 67. Cable, Thomas L.; Petrik, Michael A.; Lee, Benson P.; *Microspheres for Combined Oxygen Separation, Storage and Delivery* United Sates Patent Number 5,766,317 June 16, 1998.
- 68. Cable, Thomas L.; Petrik, Michael A.; Lee, Benson P.; *Microspheres for Combined Oxygen Separation, Storage and Delivery* United Sates Patent Number 5,910,238 June 8, 1999.
- 69. Calise, F.; Ferruzzi, G.; Vanoli, L.; *Parametric Energy Analysis of a Tubular Solid Oxide Fuel Cell (SOFC) Stack through Finite-Volume Model*, Applied Energy 86 (2009).

- 70. Campbell, Rhonda *How much Electricity Does the Average Home Use?* http://www.ehow.com/about_5166858_much-electricity-average-homeuse.html (1999-2011) Retrieval Date: 01/15/11.
- 71. Canovaa, I.C.; de Souzaa, D.P.F.; Costa, N.R.; de Souza, M.F.; *Influence* of *Rare Earths on the Sintering of Zirconia-Yttria* Deparamento de Engenharia de Materiais, Iniversidade Federal de Sao Carlos, Brazil August (1998).
- 72. Caretto, Larry. "Fuel Cells". Mechanical Engineering 694C Seminar in Energy Resources, Technology and Policy". California State University, Northridge. (2002).
- 73. Cavallucci, Denis & Rousselot, Francois & Zanni, Cecilia *Linking Contradictions and Laws of Engineering System Evolution within the TRIZ Framework*, Volume 18 Number 2 (2009).
- 74. Ceramic News, Ceramic Fuel Cells Partners with HC Starck to Secure Volume Supply of Fuel Cell Components, <u>http://www.ceramgroup.com/news/jan/cfc.htm</u>, 2008.
- 75. Chai, Kay-Hin; Zhang, Jun; Tan, Kay-Chaun; *A TRIZ-Based Method for New Service Design* Journal of Science; Volume 8 Issue No. 1; August 2005.
- 76. Chan, Vincent (et al), *Design for Assembly*, 2005, <u>http://deed.ryerson.ca/~fil/t/dfmdfa.html</u>, Retrieved: 11/21/11
- 77. Charity Navigator *How Do We Rate Charities?* <u>http://www.charitynavigator.org/index.cfm?bay=content.view&cpid=35</u> (2011), Retrieval Date 7/31/11.
- 78. Chatopadhyay, Gopinath; Rahman, Anisur: *Development of Lifement Warranty Policies and Models for Estimating Costs* Reliability Engineering and System Safety 93 (2008).
- 79. Chellappan, Mirunalini Venkatagiri, Fuel Cell Based Battery-less Ups System, (2008) Texas A&M University, <u>http://repository.tamu.edu/handle/1969.1/86026</u> (Retrieved: 12/14/10).

- 80. Cheng, Zhe; Zha, Shaowu; Liu, Meilin *Influence of Cell Voltage and Current on Sulfur Poisoning Behavior of Solid Oxide Fuel Cells* Journal of Power Sources 172 (2007).
- 81. Choi, Woojin, Enjeti, Prasad N., & Howze, Jo W., Development of An Equivalent Circuit Model of a Fuel Cell to Evaluate the Effects of Inverter Ripple Current, Power Electronics & Fuel Cell Power Systems Laboratory, Department of Electrical Engineering, Texas A&M University, (2004). <u>http://enjeti.tamu.edu/journal-papers/fuel-cell-inv-</u> <u>ripple-current.pdfpages</u> (Retrieved: 12/23/10).
- 82. Chou, Yeong-Shyung; Stevenson, Jeffery W.; Singh, Prabhakar, *Thermal Cycle Stability of a Novel Glass-Mica Composite Seal for Solid Oxide Fuel Cell: Effect of Glass Volume Fraction and Stresses* Journal of Power Sources 152 (2005).
- 83. Choudhary, T.V.; Goodman, D.W.; *Co-Free Fuel Processing for Fuel Cell Applications*, Catalysis Today 77 (2002).
- 84. Ciferno, Jared P. and Marano, John J. "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production". U.S. Department of Energy National Energy Technology Laboratory. (2002).
- 85. Clarkson, P.John; Simons, Caroline; Exkert, Claudia; *Predicting Change in Propagation in Complex Design* Journal of Mechanical Design 125 September (2004).
- 86. Cogeneration & On-Site Power Production, *Gearing up for the Market Commercialization of Stationary Fuel Cells on the Horizon?* http://www.cospp.com/articles/print/volume-8/issue-4/features/gearing-up-for-the-market-commercialization-of-stationary-fuel-cells-on-the-horizon.html (January 2007) Retrieval Date 9/30/10.
- 87. Coleman, Jr., James L. "*The American whale oil industry: A look back to the future of the American petroleum industry?*" Nonrenewable Resources, Volume 4, issue 3, p. 273 288. (1995).
- 88. *Comparison of Fuel Cell Technologies* U.S, Department of Energy Hydrogen Program <u>www.hydrogen.energy.gov</u> December (2008).

- 89. Consumers' Directory of Certified Efficiency Ratings for Residential Heating and Water Heating Equipment, GAMA Directory by the Gas Appliance Manufacturers Association; <u>http://energyauditscleveland.com/home-energy-audits/cleveland-ohio-home-energy-audits.shtml?gclid=CI7-vOGJ5qkCFZQ5KwodHAPdag</u>, Retrieval Date 9/30/10.
- 90. Cook, Stephen C,; Ferris, Timothy L.J.; *Re-evaluating Systems Engineering as a Framework for Tackling Systems Issues*, Systems Research and Behavioral Science 24 (2007).
- 91. CoorsTek, Amazing Solutions *Ceramic Fuel Cell Components* http://www.coorstek.com/products/fuelcells.asp?gclid=CLnLyMulpqgCF ZFoKgodoktQIw (2011) Retrieval Date: 7/31/11.
- 92. *Corona and Induced Current Effects* PG&E Delta Distribution Planning Area Capacity Increase Substation Project August (2005).
- 93. Cost Analysis of Fuel Cell Systems for Transportation; Compressed Hydrogen and PEM Fuel Cell System Tiax LLC, October (2004).
- 94. Craver Jeff, Project Manager Space and Missile Defense Technical Center A Systems-Engineering Approach to Technology Development Program Management October 26, 2006.
- 95. Crawford, R.M.; Marr, W.W; Padilla, A. Jr.; Wang, P.Y.; *The Safety Consequences of Local Initiating Events in an LMBFR*, Argonne National Laboratory December (1975).
- 96. Crow, Kenneth Failure Modes and Effects Analysis (FMEA) http://www.npd-solutions.com/fmea.html, Retrieval Date December 12, 2010.
- 97. Cziesla, Dr. Frank & Bewerunge, Dr. Jurgen, & Senzel, Andreas Lunen -State-of-the-Art Ultra Supercritical Steam Power Plant Under Construction Power-Gen Europe (2009).
- 98. Dale, Steinar (et al), Loss Modeling in T&D Systems: Is \$25 Billion Worth Losing? Public Utilities Report, 2002.
- 99. Dalla Betta, R.A.; Barnes, J.; Faz, T.; Ho, Liu, H.; Nicole, J; Socolovskii, V.; Yee, D; *Plate-Based Fuel Processing System* Hydrogen, Fuel Cells, and Infrastructure Technologies FY 2003 Progress Report (2003).

- 100. Damm, David L; Fedorov, Andrei G.; *Radiation Heat Transfer in SOFC Materials and Components* Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA November (2004).
- 101. Das, Tuhin; Weisman, Ryan A Feedback based Load Shaping Strategy for Fuel Utilization Control in SOFC Systems American Control Conference June (2009).
- 102. De Weck, Olivier, *Fundamentals of Systems Engineering*, Lecture 8 Systems Integration and Interface Management, MIT, (2009).
- 103. DeGuire, Eileen, *Solid Oxide Fuel Cells* <u>http://www.csa.com/discoveryguides/fuecel/overview.php</u> (April 2003) Retrieval Date September 25, 2010.
- 104. Department of Energy (DOE) (2003) "Fuel Cell Report to Congress (Barriers to Commercialization Fuel Cells)". The Interior & Related Agencies Appropriations Conference Report (House Report 107-234), (2001).
- 105. Dicks, A.L.; Martin, P.A. *A Fuel Cell Balance of Plant Test Facility*, Journal of Power Sources, (1998).
- 106. Dinka, Peter; Mukasyan, Alexander S., *Provskite Catalysts for the Auto-Reforming of Sulfur Containing Fuels*, Journal of Power Sources, 167 (2007).
- 107. DOE, "Low Cost, High Efficiency Reversible Fuel Cell and Electrolyzer System." Technology Management Inc. (2001).
- 108. DOE *Fossil Energy*. http://www.fossil.energy.gov/programs/powersystems/fuelcells (Date Accessed: 9.3.2010).
- 109. DOE, Literature Survey of Biomass Gasification Technologies, 2003. http://www.fischer-tropsch.org/DOE/DOE_reports/fc26-00nt40937-03/fc26-00nt40937-03-3.pdf (Retrieved: 11/17/2010).
- 110. DOE. "Smart Grid." www.oe.energy.gov, (Date Accessed: 09.15.2010) (2010).
- 111. Dombrowski, U & Crespo, I. & Zahn T. Adaptive Configuration of a Lean Production System in Small and Medium-sized Enterprises German Academic Society for production Engineering (2010).

- 112. Drake, P.R.; Using the Analytic Hierarchy Process in Engineering Education, International Journal Engineering Education Vol 14 No 3 (1998).
- 113. DRM Associates and PD-Trak Solutions *New Product Development Body* of *Knowledge* <u>http://www.npd-solutions.com/bok.html</u> (2008) Retrieval Date November 12, 2010.
- 114. Duffy, Hugh Cost Revenue Ratio A Measure of Inefficiency <u>http://www.imro.ie/node/770</u> (July 1998) Retrieval Date September 26, 2010.
- 115. Duquette, Jea; Petric, Anthony; *Silver Wire Seal Design for Planar Solid Oxide Fuel Cell Stack* Journal of Power Sources 137 (2004).
- Durel, John Measuring an Employees Value to your Organization Qm2 for Nonprofit Organizations <u>http://qm2.org/mbriefs/25.html</u> (2004) Retrieval Date January 11, 2011.
- 117. Echome Magazine, <u>www.ecohomemagazine.com/renewable-energy/fuel-</u> <u>cell-power.aspx</u> (Date Accessed: 9.2.2010)
- 118. EERE, Technology Validation, (2007) <u>http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/</u>, (Date Accessed: 9.2.2010)
- EG&G Technical Services, Inc. "Fuel Cell Handbook (Seventh Edition)". Under Contract No. DE-AM26-99FT40575. U.S. Department of Energy. (2004).
- 120. Eichman, Josh; Brouwer, Jack; Samuelsen, Scott; *Exploration and Prioritization of Fuel Cell Commercialization Barriers For Use in the Development of a Fuel Cell Roadmap and Action Plan for California* Seventh International Fuel Cell Science, Engineering and Technology Conference (2009).
- 121. *Electrical Energy Equipment: Fan and Blowers* Energy Efficiency Guide for Industry in Asia <u>www.energyefficiencyasia.org</u> UNEP (2006).
- 122. *Electrical System* Bureau of Energy Efficiency, <u>www.emt-india.com</u>, (2002). Accessed: 6/6/11.
- 123. Ellis, Mike and Craver, Jeff, *Technology Program Management Model* (*TPMM*). Space and Missile Defense Technical Center, 2006.

- 124. Energy Center of Wisconsin. "Fuel Cells for Distributed Generation (A Technology and Marketing Summary)". Report 193-1. (2001).
- 125. Energy Research Corporation. "Biomass Fuel Cell Power for Rural Development: Creating Options for Rural Communities in a Deregulated Electric Utility Market",(1997).
- 126. Energy white paper: meeting the energy challenge http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/energ y/whitepaper (2007) Retrieval Date 01/22/2011.
- 127. ERCOT Protocols, Section 13: Transmission and Distribution Losses January (2009).
- 128. Erickson, Robert W.; *DC-DC Power Converters*, Article in Wiley Encyclopedia of Electrical and Electronics Engineering, (2007).
- 129. Evens, Nick et al, *Strategic thinking about disruptive technologies*, Strategy & Leadership, VOL. 37 NO. 1, pp. 23-30, (2009).
- 130. Faghri, Amir, Challenges and opportunities of thermal management issues related to fuel cell technology and modeling, International Journal of Heat and Mass Transfer 48 (2005) 3891–3920.
- 131. Farhad, Siamak; Hamdullahpu, Feridun; Yoo, Yeong, *Performance Evaluation of Different Configurations of Biogas-Fuelled SOFC Micro-CHP Systems for Residential Applications*, International Journal of Hydrogen Energy 35 (2010).
- 132. Farrautoa, Robert J.; Liua, Ye; Ruettingera, Wolfgang; Ilinicha, Oleg; Shorea, Larry; Giroux, Tom; *Precious Metal Catalysts Supported on Ceramic and Metal Monolithic Structures for the Hydrogen Economy;* Engelhard Corporation (now BASF Catalysts) Iselin, NJ, USA (2007).
- 133. Fergus, Jeffery W.; *Electrolytes for Solid Oxide Fuel Cells* Auburn University Materials Research and Education Center June (2006).
- 134. Finnerty, Caine; Tompsett, Geoff A.; Kendall, Kevin; Ormerod, R. Mark; SOFC System with Integrated Catalytic Fuel Processing Journal of Power Sources 86 (2000).
- 135. Fischer, Bernd; Behrends, Andreas; Fruend, Dietmar; Lupton, David E; Merker, Jurgen; *High Temperature Mechanical Properties of the Platinum Group Metals Stress-Repture Strength and Creep Behaviour at Extremely High Temperatures* Department of Materials Technology, University of Applied Science Jena, Germany Platinum Metal Review (1999).
- 136. Fitch, P (et al), Life Cycle Energy Analysis as a Method for Material Selection, J. Mech. Des., Volume 126, Issue 5, (2004).
- 137. Flitt, Harvey J.; Schweinsberg, D. Paul; *Evaluation of Corrosion Rate* from Polarization Curves not Exhibiting a Tafel Region Corrosion Science 47 (2005).
- 138. Florida Power & Light Company "Agreement for Generator Balancing Service". Docket No. ER07-1070-00. (2007), (Date Accessed: 09.15.2010).
- 139. Flow & Level Measurements *Mass Flow meters* Transactions Volume 4 http://www.omega.com/literature/transactions/volume4/T9904-10-MASS.html, Retrieval Date March 4, 2011.
- 140. Forsber, Charles, The Advanced High-Temperature Reactor: High-Temperature Fuel, Molton Salt Coolant, and Liquid-Metal-Reactor Plant 1st International Conference on Innovative Nuclear Energy Systems for Sustainable Development of the World, Tokyo, Japan November (2004).
- 141. Frankfurt, Phil Doran "*The Financier's Perspective: The Business of Fuel Cells for Stationary Applications*". Eye for fuel cells Conference Le Plazza Hotel, Brussels. (2001).
- 142. Fuel Cell & Hydrogen Energy Association *Combined Heat and Power CHP*, <u>www.fchea.org</u>, Retrieval Date June 30, 2011
- 143. *Fuel Cell Application Handbook Performance Testing and Design Validation* Yologawa Corporation of America, T&M Division, 2002.
- 144. Fuel Cell Materials Our Products Yttria-Stabilized Zirconia 8 mole% TC Grade <u>http://www.fuelcellmaterials.com/product.cfm?prod=49</u> (2011) Retrieval Date June 3, 2011.
- 145. *Fuel Cell Report to Congress*, The Conference Report (House Report 107-234, Page 120) Public Law 107-63, (2003).
- 146. Fuel Cells 2000. <u>http://www.fuelcells.org</u> (Date Accessed: 9.3.2010).
- 147. *Fuel Cells and Hydrogen: The Path Forward*: A Comprehensive Strategy for Federal Investment In Fuel Cell Technology and Fuel Infrastructure January (2003).
- 148. Fuel Cells for Distributed Generation A Technology and Marketing Summary, Energy Center of Wisconsin March (2000).

- 149. *Fuel Cells*, Journal of Power Sources Volume 125, Issue 2 January (2004).
- 150. Furtado, J.G.M.; Oliveira, R.N.; Revista Matéria, v. 13, n. 1, pp. 147 153, 2008.
- 151. Gaiceanu, Marian & Orsello, Gianmichele, Load-Following Model of the Solid Oxide Fuel Cell Power Conditioning System, 2nd International Conference on Modern Power Systems MPS 12-14 November 2008, CLUJ-Napoca, Romania, (2008).
- 152. Galea, Natasha M & Knapp, Daniel & Ziegler, Tom *Density Functional Theory Studies of Methane Dissociation on Anode Catalysts in Solid*-*Oxide Fuel Cells: Suggestions for Coke Reduction* <u>www.sciencedirect.com</u> (2007).
- 153. Gao, Shanshan et al, *Electro-Coagulation-Flotation Process for Algae Removal*, Journal of Hazardous Materials 177 (2010) 336–343.
- 154. Garman, David K., *Fuel Cell Report to Congress*, (ESECS EE-1973), Department of Energy (DOE), 2003.
- 155. Gaynor, Robert, Mueller, Fabian; Jabbari, Faryar; Brouwer, Jacob; *On Control Concepts to Prevent Fuel Starvation in Solid Oxide Fuel Cells* Journal of Power Sources 180 (2008).
- 156. Gemmem, Randall S.; *Analysis for the Effect of Inverter Ripple Current on Fuel Cell Operation Condition* Presented at the 2001 International Mechanical Engineering Congress and Exposition November (2001).
- 157. Gentry, Julie, J., Carrier involvement in buyer-supplier strategic partnerships, Logistics Information Management Volume 9 · Number 6 · 1996 · pp. 54–61.
- 158. George, Raymond A.; Bassette, Norman F.; *Reducing the Manufacturing Cost of Tubular SOFC Technology* Journal of Power Sources 71 (1998).
- 159. Georgievski M. & Sharda, N. *Re-engineering the Usability- Testing Process for Live Multimedia Systems*, Volume 19, Number 2 (2006).
- 160. Gerhardt, Don J. *Managing Value Engineering in New Product Development*, Ingersoll Rand, 2011.
- 161. Gilleo, Ken Screen-printed Power? Screen Printed Fuel Cells maybe in Our Future <u>http://www.thefreelibrary.com</u> (November 2003) Retrieval Date April 7, 2011.

- 162. Giroux, Thomas; Hwang, Shinn; Liu, Ye; Ruettinger, Wolfgang; Shore, Lawrence; Monolithic Structures as Alternatives to Particulate Catalysts for the Reforming of Hydorbarons for Hydrocarbons for Hydrogen Generation www.sciencedirect.com February (2004).
- 163. Golden, Garry "US Fuel Cell Council proposes \$1.2 billion to support Smart Grid & Electric Vehicles." Future Blogger. <u>http://memebox.com/futureblogger/show/1508-us-fuel-cell-council-proposes-1-2-billion-to-support-smart-grid-electric-vehicles</u> (Date Accessed: 09.15.2010) (2009).
- 164. Gopinath, Rajesh; Kim, Sangsun; Hahn, Jae-Hong; Enjeti, Prasad N.; Yeary, Mark B.; Howze, Jo W.; *Development of a Low Cost Fuel Cell Inverter System With DSP Control* IEEE Transactions On Power Electronics, Vol. 19nO 5, September (2004).
- 165. Govindaraju, N.; Liu, WN.; Sun, X.; Singh, P.; Singh, R.N.; A Modeling Study on the Thermomechanical Behavior of Glass-Ceramic and Self-Healing Glass Seals at Elevated Temperatures Journal of Power Sources 190 (2009).
- 166. Griff Paper & Film *Tape Casting* <u>www.paperandfilm.com</u>, (2009) Retrieval Date October 3, 2010.
- 167. Grose, Thomas, *The Revolution*, Prism-Magazine, January 2011.
- 168. Gubi, Ebbe, *Design for Logistics*, Center for Industrial Production, Aalborg University, Denmark, <u>http://ifpsm.com/sites/default/files/Design_for_Logistics.pd</u> (Retrieved: 10/01/2010).
- 169. Guylas, Carol *Negawatts are Creating a Market for Energy Savings* http://cleantechnica.com/2008/05/08/negawatts-are-creating-a-market-forenergy-savings/, (May 2008), Retrieval Date April 15, 2011.
- 170. Haga, K.; Endo, H.: Nakajima, T.; Ishizu, T.; Iizuka, H; *Development of Integrated Analytical Tools forLevel-2 PSA of LMFBR* Japan Nuclear Energy System Safety Division, December (2009).
- Halinen, M.; Saarinen, J.; Noponen, M.; Vinke, C.; Kiviaho, J.; *Experimental Analysis on Performance and Durability of SOFC Demonstration Unit* VTT Technical Research Center of Finland, August (2009).

- 172. Han, Minfang et al, Fabrication, *Microstructure and Properties of aYSZ electrolyte for SOFCs,* Journal of Power Sources 165 (2007) 757–763.
- 173. Hawkes, A., *Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers*, Journal of Power Sources, Volume 149, 26 September (2005).
- 174. *Heat Exchangers with Low- and Medium- Finned Trufin* Wolverine Tube Heat Transfer Data Book <u>http://www.wlv.com</u>, Retrieval Date April 10, 2011.
- 175. Holcomb, Tim R., *Toward a model of strategic outsourcing*, Journal of Operations Management, Volume 25, Issue 2, March 2007.
- 176. *How Stuff Works*. <u>http://www.howstuffworks.com/fuel-cell.htm</u>, Date Accessed: 9.3.2010).
- 177. Huang, G.Q., Mak, K.L., The DFX shell: A generic framework for developing design for X tools, Robotics and Computer-Integrated Manufacturing, Volume 13, Issue 3, September 1997, Pages 271-280
- 178. Howland, John E. *Programming Methodology* <u>http://www.cs.trinity.edu/About/The_Courses/cs301/07.programming.met</u> <u>hodology/07.prog.meth.j.html</u>, Retrieval Date December 2, 2010.
- 179. Hubbert, M. King. "*Nuclear Energy and the Fossil Fuels*". Publication No. 95. Shell Development Company. American Petroleum Institute. (1957).
- 180. Hydrogen Fuel Cars & Vehicles Website. "Allis Chalmers Fuel Cell Powered Tractor, 1959", (2010), <u>www.hydrogencarsnow.com</u>, (Date Accessed: 9.03.2010).
- 181. Innovation Zen. *S-Curve*. <u>www.innovationzen.com</u> (Date Accessed: 9.2.2010)
- Introduction to Basic I-Triz <u>http://www.ideationtriz.com/source/122_Cont.htm</u>, Retrieval Date September 1, 2010.
- 183. *Introduction to Fuel Cells and Alternative/Renewable Energy Sources* Learning Activity Plan Texas State Technical College (2005).

- Ittel, Steven Dale; Crawford, Jeffery; Spin -Printing of Electronic and Display Components Unites States Patent Number 7,618,704B2 November 17, 2009.
- 185. Ishikawa, Kaoru, How to use Company Wide Quality Control in Foreign Countries (CWQC)-Report No. 15, The Center for Quality and Productivity, University of Wisconsin-Madison, 1986.
- Jahromi, S.A. Jenabali; Janghorban, A., Assessment of Corrosion in Low Carbon Steel Tubes of Shiraz Refinery Air Coolers, Engineering Failure Analysis 12 (2005).
- 187. James F. Price, A Coriolis Tutorial, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, 2006 http:// www.whoi.edu/science/PO/people/jprice, Retrieval Date September 1, 2010.
- 188. Janousek, Martin; Glatz, Wolfgang; Honegger, Kaspar; *Current Collector* for SOFC Fuel Cells United States Patent Application Publication Publish No US 2002/0182468 A1 December (2002).
- 189. Jarratt, Timothy (el at) *Development of a Product Model to Support Engineering Change Management*, Proceedings of the TMCE Lausanne, Switzerland, 2004.
- 190. Jiang, Tsung Leo; Chen, Ming-Hong; *Thermal-Stress Analyses of an Operating Planar Solid Oxide* Department of Aeronautics and Astronautics, National Cheng Kung University, Taiwan January (2009).
- 191. Jonas, Otakar *Chemical Data for Steam Generating Cycles* Journal of Solution Chemistry, Volume 17, Number 8 (1988).
- 192. Jones, G and George, J, *The Manager as a Planner and Strategist: Chapter 8*, McGraw-Hill Irwin, 2003.
- 193. Joo, Jong Hoon et al, *Thick-Film Electrolyte (thickness <20 m)-Supported Solid Oxide Fuel Cells*, Journal of Power Sources 180 (2008) 195–198.
- 194. *Journal of Nuclear Materials*, February (1985).
- 195. Junior, Angelo Varandas; Miguel, Paulo Augusto Cauchick *A Preliminary NPD Analysis in a Steel Company* Product Management Volume 7 (June 2009).

- 196. Katikaneni, S.; Yuh, C; Abens, S,; Farooque M.; *The Direct Carbonate Fuel Cell Technology: Advances in Multi-Fuel Processing and Internal Reforming* Catalysis Today 77 (2002).
- 197. Katikaneni, Sai, *Fuel Processing for Fuel Cell Applications*, Catalysis Today 77 (2002).
- 198. Kawahara Y Evaluation of high-Temperature Corrosion Life using Temperature Gradient Corrosion Test with Thermal Cycle Component in Waste Combustion Environments Material and Corrosion 57, Number 1 (2006).
- 199. Kazempoor, P.; Dorer, V.; Ommi, F.; Evaluation of Hydrogen and Methane-Fuelled Solid Oxide Fuel Cell Systems for Residential Applications: System Design Alternative and Parameter Study International Journal of Hydrogen Energy 34 (2009).
- 200. Kee, Robert J. and Zhu, Huayang. "Solid-oxide fuel cells (SOFC) with hydrocarbon and hydrocarbon-derived fuels". Presented at the International Symposium on Combustion. California Institute of Technology. (2004).
- 201. Keith, Jason CACHE Modules of Energy in the Curriculum Fuel Cells Pressure Drop in a Water Gas Shift Reactor Michigan Technological University October (2008).
- 202. Keoleian, Gregory A., *Application of Life-cycle Energy Analysis to Photovoltaic Module Design*, PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, VOL. 5, 287±300 (1997)
- 203. Keys, L. K, Personal correspondence about the systems engineering development and the SOFC Power System Technology. (2010).
- 204. Keys, L. K. "Continuing Technology Management Challenges for the Automobile Industry." Technology Management, Vol. 1, pp. 226-234. (1995).
- 205. Keys, L. K. "Management and Organizational Challenges to Technology (Paradigm) S-Curve Change Management." International Journal of Technology Management. Volume 14, No. 2/3/4, page 265-276. (1997).
- 206. Keys, L. K. "Management of Technology: The Renewed Importance of Invention and Innovation." Proceedings of the Industrial Engineering 50th Anniversary Solutions Conference, Banff, AB, Canada pp. 183-189. (1996).

- 207. Keys, L. K. "Program/Projects Management and Integrated Product/Process Development in High Technology Electronic Products Industries". IEEE, Vol. 14, No. 3. pp. 602-612. (1991).
- 208. Keys, L. K. *"Systems Life Cycle Engineering and DF 'X'* IEEE Transactions on CHMT, Vol. 13. No. 1, pp. 83-93. (1990).
- 209. Keys, L. K. "*The increasing importance of Engineering and Technology Management to the Twenty-First Century.*" Proceedings of the IIE Annual Solutions (Research) Conference, Orlando, FL pp. 1-19. (2006).
- 210. Keys, L. K., Rao, R and Balakrishnan, K. "Concurrent Engineering for Consumer, Industrial Products and Government Systems." IEEE Transactions on CHMT, Vol. 15. No. 3. pp. 282-287. (1992)
- 211. Keys, L. K. (el at), *Mechatronics, systems, elements, and technology: a perspective,* Components, Hybrids, and Manufacturing Technology, IEEE Components, Packaging, and Manufacturing Technology Society, Volume 14 Issue 3, 1991.
- 212. Keith, J.M., Pressure Drop in a Water Gas Shift Reactor, Michigan Technological University, <u>www.chem.mtu.edu/~jmkeith/fuel_cell_curriculum</u>, Retrieved: 11/20/11.
- 213. Khaleel, Mohammad A; Moorehead, Stewart J; Koeppel, Brian J; Nguyen, Ba Nghiep *Modeling and Control of a Solid Oxide Fuel Cell Auxiliary Power Unit* Hydrogen, Fuel Cells, and Infrastructure Technologies FY 2003 Progress Report (2003).
- Khalil, T., "Customized Management of Technology: The Key to Competitiveness and Economic Wealth". McGraw-Hill, Pub., Boston, MA, pg 483. (revised Figure 2). (2000).
- 215. Ki, Jeongpill; Kim, Daejong; *Computational Model to Predict Thermal Dynamics of Planar Solid Oxide Fuel Cell* Journal of Power Sources, September (2009).
- 216. Kim, Seok et al, *Effects of Chemical Treatment of Carbon Supports on Electrochemical Behaviors for Platinum Catalysts of Fuel Cells*, Journal of Power Sources 159 (2006) 42–45.
- 217. King, D.L.; King D.A.; Whyatt, G.A.; Fischer, C.M.; Xuang, X.; Yang, X.; *Integrated 10kWe Hydrodesulfurizer-Microchannel Steam Reformer for Fuel Cell Power from JP-8 and Road Diesel* Pacific Northwest National Laboratory, Richland, WA, Retrieval Date September 1, 2010.

- 218. Kirk, Stephen J., Deli'Isola, Alphonse; Sustainability/LEEd and Life Cycle
 Their Role in Value Based Design RS Means, Reed Construction Data, (2003).
- 219. Kirubakaran1, A., Jain, Shailendra and Nema, R.K., *The PEM Fuel Cell* System with DC/DC Boost Converter: Design, Modeling and Simulation International Journal of Recent Trends in Engineering, Vol 1, No. 3, (May 2009).
- 220. Klein, Sanford A. & Reindl, Douglas T. Assessment of Solid Oxide Fuel Cells in Building Applications Phase 1: Modeling and Preliminary Analyses (2001) http://www.ecw.org/prod/207-R.pdf (Retrieved: 01/03/2011).
- 221. Klose, Andreas, *Facility location models for distribution system design*, European Journal of Operational Research, Volume 162, Issue 1, 1 April 2005.
- 222. Koh, Young-Hag et al, *Design and Fabrication of Three-Dimensional* Solid Oxide Fuel Cells, Journal of Power Sources 161 (2006) 1023–1029
- 223. Kondo T, Watanabe Y, Yi Y.S., Hishinuma A An Evaluation of Potential Material-Coolant Compatibility for Applications in Advanced Fusion Reactors, Journal of Nuclear Materials (1998).
- 224. Kor, Yasemin Y.; Mahoney, Joseph T; Michael, Steven C; *Resources, Capabilities and Entrepreneurial Perceptions* www.business.uiuc.edu/Working_Papers/05-0120.pdf (2005).
- 225. Kouridis, Ntziachristos, L., and el at. "A wind-power fuel-cell hybrid system study on the non-interconnected Aegean islands grid". Renewable Energy, 30, 1471–1487. (2005).
- 226. Kovacevic, G., Tenconi. A., & Bojoi, R, Advanced DC–DC Converter for Power Conditioning in Hydrogen Fuel Cell System, International Journal of Hydrogen Energy, Volume 33, (2008).
- 227. Kram, Jerry W. "*Power without the Burn*." Biodesel Magazine. <u>http://www.biodieselmagazine.com/article.jsp?article_id=2125&q=&page</u> <u>=all</u> (Date Accessed: 09.15.2010) (2008).
- 228. Kritzer, Peter Corrosion in High-Temperature and Supercritical Water and Aqueous Solutions, <u>www.sciencedirect.com</u> (2004).

- 229. Krumpelt, M.; Krause, T.R.; Carter, J.D.; Kopasz, J.P.; Ahmed, S.; *Fuel Processing for Fuel Cell systems in Transportation and Portable Power Applications,* Catalysis Today 77 (2002).
- 230. Kynkaanniemi, Tanja; *Product Road mapping in Collaboration* VTT Publications 625 (2007).
- 231. Lai, Dr. Jih-Sheng; A High-Efficiency Low-Cost DC-DC Converter for SOFC Virginia Polytechnic Institute & State University Future Energy Electronics Center, May (2004).
- 232. Lai, Dr. Jih-Sheng; *Fuel Cell Current Ripple Reduction With Active Control Technique* SECA Core Technology Program Review Meeting Tampa, Fl January (2005)
- 233. Lako, P.; *High-Temperature Fuel Cell Systems* Vleem 2 EC/DG Research Contract ENG1-CT2002-00645 (2002).
- 234. Lammey, Alan. "Bulls Now Talking Up "Peak Gas" as new cause for long-term concern". Natural Gas Week. http://65.99.200.75/showthread.php?t=6055&page=90, (2006), (Date Accessed: 9.2.2010)
- 235. Lant, T.; Robinson, D.L.; Spafford, B.; Storesund, J; *Review of Weld Repair Procedures for Low Alloy Steels Designed to Minimize the Risk of Future Cracking;* International Journal of Pressure Vessels and Piping 78 (2001).
- 236. Lanzini, A.; Santarelli, M.; Orsello G.; *Residential Solid Oxide Fuel Cell Generator Fuelled by Ethanol: Cell, Stack and System Modeling with Preliminary Experiment* Department of Energy, Politecnico di Torino, Torino, Italy April (2010).
- 237. Larminie, James and Dicks, Andrew. "Fuel Cell Systems Explained (Second Edition)". John Wiley & Sons Ltd. (2003).
- 238. Larsen, Peter Halvor; Brodersen, Karen *Method for the Manufacture of Reversible Solid Oxide Cells* U.S. Patent Number US 2008/0124602 A1 May 29, 2008.
- 239. Lee, Kwang Ho; Strand, Richard K., SOFC Cogeneration System for Building Applications Part 1: Development of SOFC System-Level Model and the Parametric Study, Renewable Energy 34 (2009).

- 240. Lee, Kwang Ho; Strand, Richard K.; SOFC Cogeneration System for Building Applications, Part 2: System Configuration and Operating Condition Design Renewable Energy 34 (2009).
- 241. Lee, W.B.; Lau, Henry; Liu, Zhou-zhi; Tam, Samson; *A Fuzzy Analytic Hierarchy Process Approach in Modular Product Design* Expert Systems, Vol 18, No. 1, February (2001).
- 242. LeFevre, E. Walter, "Engineering Stages of New Product Development", National Society of Professional Engineers (NSPE), NSPE Pub #3018, Alexandria, VA, (1990).
- 243. Li, Xianguo; Sabir, Imran; *Review of Bipolar Plates in PEM Fuel Cells: Flow-Field Designs* International Journal of Hydrogen Energy 30 (2005).
- 244. Lin, Chih-Kuang; Chen, Tsung-Tina; Chyou, Yau-Pin; Chiang, Lieh-Kwang; *Thermal Stress Analysis of a Planar SOFC Stack* Journal of Power Sources 164 (2007).
- 245. Lisbona, Pilar; Corradetti, Alessandro; Bove, Roberto; Lunghi, Piero; *Analysis of a Solid Oxide Fuel Cell System for Combined Heat & Power Applications Under Non-nominal Conditions* Department of Engineering, University of Perugia, Italy March (2007).
- 246. Little, Arthur D., Conceptual Design of POX/SOFC 5kWnet System: Final Report, Department of Energy, January 8, 2001.
- 247. Liu, Di-Jai; Krumpelt, Michael; Chien, Hual-Te; Sheen, Shuh-Haw; *Critical Issues in Catalytic Diesel Reforming for Solid Oxide Fuel Cells,* Journal of Materials Engineering and Performance Volume 15 No 4 August (2006).
- 248. Liu, James; *Kinetics, Catalysis and Mechanism of Methane Steam Reforming,* Worcester Polytechnic Institute Department of Chemical Engineering, January, (2006).
- 249. Liu, Lin & Kim, Gap-Yong, Chandra, Abhijit Modeling of Thermal Stresses and lifetime Prediction of Planar Solid Oxide Fuel Cell Under Thermal Cycling Conditions, www.elsevier.com (2009).
- 250. Liu, Q.L. et al, Anode-supported solid oxide fuel cell with yttria-stabilized zirconia/gadolinia-doped ceria bilalyer electrolyte prepared by wet ceramic co-sintering process, Journal of Power Sources 162 (2006) 1036–1042.

- 251. Liu, Xinsheng; Ruettinger, Wolfgang; Xu, Xiaoming; Farrauto, Robert: Deactivation of Pt/CeO2 Water-Gas Shift Catalysts Due to Shutdown/Startup Modes for Fuel Cell Applications, Applied Catalysis B: Environmental 56 (2005).
- 252. Liu, James A., *Kinetics, catalysis and mechanism ofmethane steam reforming*, Thesis WORCESTER POLYTECHNIC INSTITUTE Department of Chemical Engineering(2006).
- 253. Lo Faro, Massimiliano; La Rosa, Daniela; Nicotera, Isabella; Antonucci, Vincenzo; Arico, Antonino Salvatore; *Electrochemical Investigation of a Propane-Fed Solid Oxide Fuel Cell Based on a Composite Ni-Perovskite Anode Catalyst* Applied Catalysis B: Environmental 89 (2009).
- 254. Lo"nngren, Hans-Martin, *Aggregated construction supply chains: success factors in implementation of strategic partnerships,* Supply Chain Management: An International Journal, Volume 15 · Number 5 · 2010 · 404–411.
- 255. Lu, K.; Mahapatra, M.K.; *Network Structure and Thermal Stability Study of High Temperature Seal Glass* Journal of Applied Physics 104, (2008).
- 256. Lu, N. et al., *The modeling of a standalone solid-oxide fuel cell auxiliary power unit.* Journal of Power Sources 161 (2006) 938–948.
- 257. Lu, Yixin; Schaefer, Laura; Li, Peiwen; *Numerical Study of a Flat-Tube High Power Density Solid Oxide Fuel Cell Part 1 Heat/Mass Transfer and Fluid Flow* Journal of Power Sources 140 (2005).
- 258. Ma, Xiaoliang; Sun, Lu; Song, Chunshan; A new Approach to Deep Desulfurization of Gasoline, Diesel Fuel and Jet fuel by Selective Adsorption for Ultra-Clean Fuels and for Fuel Cell Applications Catalysis Today 77 (2002).
- 259. Ma, Xiaoliang; Velu, Subramani; Kim, Jae Hyung; Song, Chunshan; Deep Desulfurization of Gasoline by Selective Adsorption Over Solid Adsorbents and Impact of Analytical Methods on ppm-Level Sulfur Quantification for Fuel Cell Application, Applied Catalysis E: Environmental 56 (2005).
- 260. Magistri, L. *Heat Exchangers for Fuel Cell and Hybrid System Applications*, J. Fuel Cell Sci. Technol. , Volume 3, Issue 2, May 2006.
- 261. Make It From.Com *Design for X* <u>http://www.makeitfrom.com</u>, (2010) Retrieval Date October 22, 2010.

- Mann, Darrell, Systemic Innovation, *The Four Pillars of Triz,* <u>http://www.osaka-u.ac.jp/php/nakagawa/</u>, Retrieval Date October 30, 2010.
- 263. Mazumder, Sudip K.; Acharya, Kaustuva; Haynes, Comas Lamar; Williams, Robert, Jr.; von Spakovsky, Micheal R.; Nelson, Douglas J.; Rancruel, Diego F.; Hartvigsen, Joseph; Gemmen, Randy S.; Solid-Oxide-Fuel-Cell Performance and Durability: Resolution of the Effects of Power-Conditioning Systems and Applications Loads IEEE Transaction on Power Electronics, Vol 19. No. 5 September (2004).
- 264. McGrail, Tony, *Transformer Frequency Response Analysis: An Introduction, Doble Engineering Company, based in Watertown, Massachusetts, USA.* (2005), <u>http://www.doble.com/content/news/</u> (Retrieved: 12/25/2010).
- 265. McNeill, John R. "Global Century Series Something New Under the Sun: An Environmental History of the 20th Century World". W. W. Norton & Company. (2001).
- 266. Measurement of Scientific Technological Actives *Oslo Manual* -*Guidelines for Collection and Interpreting Innovation Data* Third Edition, OECD and Eurostat Publishing, (2005).
- 267. Merrifield, D. Bruce "Industrial Competitiveness: The Role of Intelligent Systems." Ablex Publishing Co. (1990).
- 268. Meyer, Don P.E.; Stephenson, Geoff P.E; *Estimating System Leak Rates Unsing Spreadsheet Models to Measure Pressure Loss* TECHBriefts 2005 No 1 Burns & McDonnell, (2005).
- 269. Milliken, Chris, Group Leader of Productions and Materials at Technology Management Inc. *Personal correspondence about the subsystems of a SOFC Power System*. (2010).
- 270. Milliken, Christopher E.; Hawk, Carrie Manon, Brakas, Adam B., *Technique for Rapid Cured Electrochemical Apparatus Component Fabrication* United States Patent Number 6,399,233B1 June 4, 2002.
- 271. Milliken, Christopher E.; Petrik, Michael A.; Ruhl, Robert C.; *Solid Oxide Fuel Cell Stack Assembly Having Tapered Diffusion Layer* United States Patent Number 7,163,759B2 January 16, 2007.
- 272. Murkowski, Philip *The Modern Commercialization of Science is a Passel* of Ponzi Schemes Nicholas Mullins Lecture, <u>http://ebookbrowse.com/search/philip-mirowski</u>, 2010.

- 273. Mizutani, Y. et al., *First demonstration program of solid oxide fuel cells in Japan at Aichi EXPO 2005*, Fundamental Research Dept., Toho Gas Co., Ltd., (2005).
- 274. Mobius, Hans-Heinrich; *On the History of Solid Electrolyte Fuel Cells*, Journal Solid State Electrochem (1997).
- 275. Moehrle, Martin G. *What is TRIZ? From Conceptual Basics to a Framework for Research* Volume 14 number 1 (2005)
- 276. Moehrle, Martin G. Morpho TRIZ Solving Technical Problems with a Demand for Multi-Smart Solutions Volume 19 Number 14 (2010)
- 277. Moehrle, Martin G.; Wenke, Sven; *Exploring Problems with Function* Analysis. Experimental Insights for Team Management, CREATIVITY AND INNOVATION MANAGEMENT, Volume 15 Number 2 2006
- 278. Mogensen, M.; *Standardization in SOFC Testing* Chapter 10 www.cee1.org, (Retrieved 10/01/10)
- Molcho, G. (et al), Computer aided manufacturability analysis: Closing the knowledge gap between the designer and the manufacturer, CIRP Annals Manufacturing Technology Volume 57, Issue 1, 2008, Pages 153-158
- 280. Molenda, J.; Swierczek, K.; Zajac, W.; *Functional Materials for the IT-SOFC* Journal of Power Sources 173 (2007)
- 281. Montagna, Francesca Decision Aiding Tools in innovative Product Development Contexts Res Eng. (2011)
- 282. Moore, Geoffrey A. Crossing the Chasm, Marketing and Selling High-Tech Products to Mainstream Customer (revised edition), HarperCollins Publishers, New York, (1999).
- 283. MSRI News, MSRI Delivers 2kW SOFC Stack, (2009).
- 284. Muller, Matthias M.; Padberg, Frank; *About the Return on Investment of Test-Driven Development* Universitat Karlsruhe, Germany
- 285. Mulliken, Bruce. "Solar Hydrogen Power for homes". Green Energy News Website: EnergyDeals Blog. <u>http://energydeals.wordpress.com/2010/09/08/solar-hydrogen-power-for-homes/</u>, (2008), (Date Accessed: 9.2.2010).

- 286. Multi-Year Research, Development and Demonstration Plan, 2007 *Technical Plan - Fuel Cells* <u>http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.</u> <u>pdf</u> (Retrieved: 12/31/10).
- 287. Musa, A (et al), Performance of Internal and External Reforming Molten Carbonate Fuel Cell Systems, J. Fuel Cell Sci. Technol. -- February 2007
 -- Volume 4, Issue 1, 65
- 288. N.E.M Business Solutions, *An Introduction to Steam Boilers and Steam Raising* <u>http://www/gc3/com/Default.aspx</u>, 2010. (Retrieved: 12/31/10).
- 289. Nallagowden, Perumal; Mukerjee, Ravindra N.; Masri, Syafrudin: *Tracing and Prediction of Losses for Deregulated Operation of Power Systems* European Transactions on Electrical Power 21 (2011).
- 290. NASA, *Learning Curve Calculator*, <u>http://cost.jsc.nasa.gov/learn.html</u>, Retrieved: 06/12/2010.
- 291. National Fuel Cell Research Center "*The Challenges*". <u>http://www.nfcrc.uci.edu/2/FUEL_CELL_INFORMATION/FCexplained/</u> <u>challenges.aspx</u> (Date Accessed: 09.17.2010) (2009).
- 292. National Fuel Cell Research Center *NFCRC Tutorial: Solide-Oxide Fuel Cells (SOFC)* <u>http://www.nfcrc.uci.edu/EnergyTutorial/sofc.html</u> Retrieval Date November 22, 2010.
- 293. National Fuel Cell Research Center, Fuel Cell Power Plant: Major System Components. (2009). <u>http://www.nfcrc.uci.edu/2/FUEL_CELL_INFORMATION</u> (Retrieved: 12/26/10).
- 294. *National Hydrogen Energy Roadmap* Unite States Department of Energy, April 2-3, 2002.
- 295. National Instruments *High-Voltage Measurements and Isolation General Analog Concepts* <u>http://sine.ni.com</u>, (Retrieved: 12/26/10).
- 296. National Society of Professional Engineers. "Engineering Stages of New Product Development." (1990).
- 297. National Research Council Canada, <u>http://www.nrc-</u> <u>cnrc.gc.ca/eng/programs/ifci/high-temperature-fuel-cells/materials.html</u>, 2010.

- 298. Navrotsky, Alexandra *Thermodynamics of solid electrolytes and related* oxide ceramics based on the fluorite structure <u>http://pubs.rsc.org/en/Content/ArticleLanding/2010/JM/C0JM01521K</u> (2010) Retrieval Date October 25, 2010.
- 299. Nebiyeloul-Kifle, Yonas; *Application of the Design Structure Matrix to Integrated Product Development Process* Massachusetts Institute of Technology May (2005).
- 300. Nehrir, C. & Wang, C., Modeling and Control of Fuel Cells: Distributed Generation Applications, Wiley IEEE (2009).
- 301. Neij, Lena, *Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments*, Energy Policy 36 (2008) 2200–2211.
- 302. NETL, Solid State Energy Conversion Alliance (SECA), 2010, http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/primer/cell .html, Retrieved: 11/20/11.
- Neuman, John, Supply chain integration: vision or reality? Supply Chain Management Volume 1 · Number 2 · 1996 · pp. 7-10.
- 304. New.com. "*Report: Smart Grid Market could double in 4 years*." Smart Grid. <u>www.smartgridnews.com</u> ,(Date Accessed: 09.15.2010) (2009).
- 305. Newnet. "American Recovery and Reinvestment Act funds Smart Grid and Fuel Cell Technology." www.newenergyworldwork.com, (2009), (Date Accessed: 09.15.2010).
- 306. Ni, M.; Leung, M.K.H; Leung, D.Y.C., *Mathematical Modeling of Proton-Conducting Solid Oxide Fuel Cells and Comparison with Oxygen-Ion-Conducting Counterpart* Wiley Fuel Cells No. 4 (2007).
- 307. Nichols, David K. "Barriers to the Commercialization of Stationary Fuel Cells". Rolls Royce Fuel Cell Limited. (2007).
- 308. Nielsen, Gerard us Petrus Lambertus; Sijpkes, Andre Harmen; Attrition Resistant Particulate Catalyst United States Patent Application NO US2009/0124496 A1 May 14, 2009.
- 309. O'Connor, Tom; *Household Electrical Energy Usage* H20'C Engineering http://gl-zephyr.blogspot.com/2010/09/biodiesel-bulletin-september-2010.html, 2010, (Date Accessed: 09.15.2010).

- 310. Ostergaard, Poul Alberg; *Modeling Grid Losses and the Geographic Distribution of Electricity Generation* Renewable Energy 30 (2005).
- Otuska, Nobuo Effects of Fuel Impurities on the Fireside Corrosion of Boiler Tubes in Advanced Power Generating Systems - a Thermodynamic Calculation of Deposit Chemistry <u>www.elsevier.com/locate/corsci</u>, (2002).
- Panasonic, *High Efficiency Achieved by Electricity Generation at Home*, (2010). <u>http://panasonic.net/ha/e/FC/doc02_00.html</u> (Retrieved: 12/14/10).
- 313. Patel, Prachi "*A Better Platinum Catalyst for Fuel Cells*." Technology Review, <u>www.technologyreview.com</u> (Date Accessed: 09.17.2010) (2010).
- 314. Paterson, I.R. & Wilson J.D., Use of Damage Monitoring Systems for Component Life optimization in Power Plant www.sciencedirect.com (2002).
- 315. Peng; Hong-jian; Xie, You-Qing; Wei, De-liang; *Atomic States and Properties of Ru-Electrocatalyst* Transaction Nonferrous Metals Society of China 16 (2006).
- 316. Perrin, I.J. & Fishburn, J.D. A Perspective on the Design of High-Temperature Boiler Components <u>www.sciencedirect.com</u> (2007).
- 317. Porrill, Dave, Constructing an Effective Maintenance Plan, Reliable Plant, <u>http://www.reliableplant.com/Read/338/effective-maintenance-plan</u>, 2010. Retrieved: 11/1/10.
- 318. Porter, Michael, *How Competitive Forces Shape Strategy*, *Harvard Business Review*, 1979.
- 319. Powell, Jeanne W.; Lellock, Karen L., *Development, Commercialization,* and Diffusion of Enabling Technologies: Progress Report Advanced Technology Program April (2000).
- 320. Power, Damien, *Supply chain management integration and implementation: a literature review*, Supply Chain Management: An International Journal 10/4 (2005) 252–263.

- 321. Prasad, Biern Survey of Life-Cycle Measures and Metrics for Concurrent Product and Process Design, Artifical Intelligence of Engineering Design, Analysis and Manufacturing, 14, (2002).
- 322. Prepared by NAHB Research Center, Inc. Prepared for U.S. Department of HUD "Institutional Factors Affecting Commercialization of Fuel Cells". Partnership for Advancing Technology in Housing. (2000)
- 323. *Product Data and Applications Guide, The PureCell Model 400 Energy Solution* Energy Reinvented July (2010).
- 324. Public Utilities Commission, Competitive Retail Natural Gas Supplier, (2010)
 <u>http://www.puco.ohio.gov/apps/RegulatedCompanyList/index.cfm?IID=1</u>
 <u>1</u> (Retrieved: 12/17/2010).
- 325. Qin, Daiyi; Lapszewicz, Jack; Jiang, Xuanzhen; Comparison of Partial Oxidation and Steam-CO2 Mixed Reforming of CH4 to Syngas on Mg-O-Supported Metals Division of Coal & Energy Technology, Australia April (1994)
- 326. Raciti, A; *A Model for NPD: "The New Product Development Cycle"* <u>http://scis.nova.edu</u>, The New Product Development Cycle, Retrieval Date October 17, 2010
- 327. Rademakers, Laurens. "Carbon Negative Bioenergy to cut Global Warming could drive Deforestation." Mongabay. <u>http://news.mongabay.com/2007/1106-carbon-negative_becs.html</u>, (2007), (Date Accessed: 09.15.2010).
- 328. Ramani, Vijay; *Fuel Cells*, The Electrochemical Society Interface, Spring, 2006.
- 329. Rapolu, Kalyan, *Design of a 5 KW Residential Fuel Cell System Using Anaerobic Digestion of Animal Waste* <u>http://attra.ncat.org/attra-pub/anaerobic.html</u>, Retrieval date: 09/01/2010.
- 330. Recknagle, K.P.; Williford, R.E.; Chick, L.A; Rector, D.R.; Khaleel, M.A. *Three-Dimensional Thermo-Fluid Electrochemical Modeling of Planar SOFC Stacks* Journal of Power Sources 113.
- 331. *Renewable and Ultra-Clean Base load Power Generation*, Fuel Cell Energy Annual Report (2010).
- 332. Reuters. "*Exxon says N. America gas production has peaked*". http://www.reuters.com/article/idUSN2163310420050621, (2005), (Date Accessed: 09.15.2010).

- 333. Richardson, Curtis A. *Heat exchanger for heating of fuel cell combustion air* United States Patent Number 7255157 August 14, 2007.
- 334. Richter, Flint, *Sizing A Grid-Tied PV System with Battery Backup*, Home Power, Issue 139, 2010.
- 335. Rivera-Tinoco (et al), *Learning Curves for Solid Oxide Fuel Cells*, 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, (2010).
- 336. Robert Rose, Fuel Cells and Hydrogen: The Path Forward, A Comprehensive Strategy For Federal Investment In Fuel Cell Technology And Fuel Infrastructure, (2003). www.fuelcellpath.org. (Retrieved 11/17/2010).
- 337. Robles, Guillermo Cortes, *Case-based reasoning and TRIZ: A coupling for innovative conception in Chemical Engineering*, Chemical Engineering and Processing 48 (2009) 239–249.
- 338. Roby, Norm, Sonoma's Big Boutiques, <u>http://www.thewinenews.com/augsep97/boutiques.html</u> (Retrieved: 10/11/2010)
- 339. Romanosky, Robert; Rawls, Patricia A; & Purgert, Robert M. Advanced Materials for Ultra Supercritical Boiler Systems U.S. Department of Energy (2007).
- 340. Ross, David Improving Thermal Processing Of Solide-Oxide Fuel Cells http://www.industrialheating.com (April 2004) Retrieval Date October 1, 2010.
- 341. Rostrup-Nielsen, Jens R.; *Conversion of Hydrocarbons and Alcohols for Fuel Cells* Advance Article on the Web, October (2000), PCCP (2001).
- 342. Roychoudhury, Subir; Lyubovsky, Maxim; Walsh, D.; Chu, Deryn; Kallio, Erik; *Design and Development of a Diesel and JP-8 Logistic Fuel Processor* Journal of Power Sources 160 (2006).
- 343. Ruhl, Robert C.; *High Efficiency System for Low Cost Conversion of Fuel to Vehicle Hydrogen* United States Patent Number US2006/0068248A1 March 30, 2006.
- 344. Ruhl, Robert C.; Milliken, Christopher E.; Petrik, Michael A.; *Apparatus and Method for Cooling High-Temperature Fuel Cell Stacks* United States Patent Number 6,489,050B1 December 3, 2002.

- 345. Ruhl, Robert C.; Milliken, Christopher E.; Petrik, Michael A.; *Electrochemical Apparatus with Reactant Micro-Channels* United States Patent Number 6,631,892B1 March 26, 2002.
- 346. Ruhl, Robert C.; Milliken, Christopher E.; Petrik, Michael A.; *Electrochemical Apparatus with Reactant Micro-Channels* United States Patent Number 6,878,480B2 April 12, 2005.
- 347. Ruhl, Robert C.; Milliken, Christopher E.; Petrik, Michael A.; *Solid Oxide Fuel Cell Hot Assembly* United States Patent Number 6,440,596B1 August 27, 2002.
- 348. Ruhl, Robert C.; *Multipurpose Reversible Electrochemical System* United States Patent Number 6,811,913B2, November 2, 2004.
- 349. Ruhl, Robert, *Low Cost, High Efficiency Reversible Fuel Cell (and Electrolyzer) Systems*, Technology Management Inc.2003.
- 350. Ruhl, Robert, Vice President of Technology at Technology Management Inc. *Personal correspondence about the subsystems of a SOFC Power System, (2010).*
- 351. Samlex America, *Inverters General Information* <u>www.samlexamerica.com/customer_support/application_notes.htm</u> (2011), Retrieval Date May 5, 2011.
- 352. Sangal, Neeraj; Jordan, Ev; Sinha, Vineet; Jackson, Daniel; *Using Dependency Models to Manage Complex Software Architecture* OOPSLA (2005).
- 353. Santnagelo, Paolo & Tartarini, Paolo Fuel Cell Systems and Traditional Technologies. Part I Experimental CHP Approach www.sciencedirect.com (2006).
- 354. Sap, *Process Flow Hierarchy*, April 2001. <u>http://freetechebooks.com</u> (Retrieved 11/17/2010).
- 355. Sarkar, Somwrita; Dong, Andy; Gero, John S; *A Problem Decompositon Method for Conceptual Design* International Conference on Research into Design University of Sydney Australia (2009).
- 356. Satyapal, Sunita "Fuel Cell Technologies: FY 2010 Budget Request Briefing". U.S. Department of Energy. (2009).

- 357. Scorn, Daniel "*France: Vive Les Nukes*". 60 Minutes. <u>www.cbsnews.com/stories/2007/04/06/60minutes</u>, (2007), (Date Accessed: 9:2010).
- 358. Scholz, Oliver, The Pontiac Fiero Design Concept: Excitement for the '80s, <u>http://www.fierofocus.com/Tech%20Tips/Pdf's/Articlds/Design_concept.p</u> <u>df</u>, (Date Accessed: 9:2010).
- 359. Science Daily, 'Green' Way to Generate Heat and Electricity with Use of Fuel Cells. (2010) <u>http://www.sciencedaily.com/releases/2010/11/101129111733.htm</u> (Retrieved: 12/10/2010).
- 360. Scientific American "*Biomass: Can Renewable Power Grow on Trees?*" <u>www.scientificamerican.com</u>, (2009), (Date Accessed: 09.15.2010).
- Shamsuzzohal, A.H.M.; Bhuiyan, Nadia; *Design Structure Matriz (DSM): New Directions* Department of Industrial and Production Engineering, Shah Jalal University of Science and Technology, Bangladesh, November (2005).
- 362. Sharon, Amira; Dori, Dov; deWeck, Olivier; Model-Based Design Structure Matrix: Deriving a DSM from an Object-Process Model Second International Symposium on Engineering Systems, MIT, Cambridge, Massachusetts, June 15-17, 2009.
- 363. Shibli, Ahmed & Starr, Fred Some Aspects of Plant and Research Experience in the Use of New high Strength Martensitic Steel www.sciencedirect.com (2006).
- 364. Shidhu, TS; Prakash, S; Agrawal, RD; & Bhagat Ramesh *Erosion*-*Corrosion Behaviour of ni-Based Superalloy Superni-75 in the Real Service Environment of the Boiler* Volume 34 Part 2, (2009).
- 365. Sidky, Ahmed S. (et al), *Problem Identification and Decomposition within the Requirements Generation Process*, Department of Computer Science, Virginia Tech, (2002).
- 366. Siliconix, Vishay Low-Power Universal-Input Power Supply Achieves High Efficiency <u>www.vishay.com</u>, (2009).

- Silverman, Murray (et al), Competition in the Global Wine Industry: A U.S. Perspective, <u>http://online.sfsu.edu/~castaldi/bie/globcase.htm</u>, (Retrieved: 9/12/2010).
- 368. Singh, Raj; Parihar, S.S.; *High Temperature Seals for Solid Oxide Fuel Cells (SOFC)* Seca Core Technology Workshop, Tampa Fl, January (2005).
- 369. Singhal, S.; Kendall, K.; *Oxide Fuel Cells: Fundamentals, Design and Applications* Elsevier, New York (2003).
- 370. Smart New Gird.com *New Effort Exploring Ways to Reduce T&D Loss and Save Power* <u>http://www.smartgridnews.com/artman/publish</u> (November 2009), Retrieval Date October 14, 2010.
- 371. SOFC Fuel Cell Model Theory Fluent Inc. July (2006).
- 372. Song, Chunshan; Fuel Processing for Low-Temperature and High-Temperature Fuel Cells Challenges, and Opportunities for Sustainable Development in the 21st Century, Catalysis Today 77 (2002).
- 373. Souchkov, Valeri "Accelerate Innovation with TRIZ" ICG T&C, (2007).
- 374. Southworth, Finis *Very High Temperature Gas Cooled* Idaho National Engineering & Environmentally Laboratory November (2002).
- 375. Spendelow, Jacob; Marcinkoski, Jason: *DOE Hydrogen Program Record* <u>http://www.hydrogen.energy.gov</u> (September 2010), Retrieval Date March 3, 2011.
- 376. Srisiriwat, Nawadee; Srisiriwat, Anuchart Solid Oxide Fuel Cell Integrated with Supercritical Water Oxidation Fueled by Ethanol Thammast Institute Journal Science Technology Vol 15 September (2010).
- 377. Stafford, Judith A. and McGregor, John D. "Top-Down Analysis for Bottom-up Development." Proceedings of the 2004 Workshop on Component-Oriented Programming (WCOP) held at the European Conference on Object-Oriented Programming (ECOOP 2004), Oslo, Norway. (2004).
- 378. Starck, H.C.; *Kerafol Set Up SOFC Alliance* Fuel Cells Bulletin, (2010), <u>http://www.elsevierscitech.com/nl/fcb/home.asp July 2010</u>, Retrieval Date March 13, 2011.

- 379. Statement of Work, Sow Writing Guide, Companion Document to the Canadian Institute for Procurement and Materiel Management (CIPMM) Course: "How to Write Better RFP Statements of Work" RFP Solutions Inc. Ottawa, Canada, 2007.
- 380. Status of Limber Safety Technology 2. Reactivity Monitoring in a LMBFR at Shut Down Risley Nuclear Power Development Establishment United Kingdom Atomic Energy Authority March (1981).
- 381. Status of SOFC Development, Technology Management Inc, May (2003).
- 382. Stuebi, Richard T. Regulatory Impediments to the Commercialization of Stationary Fuel Cells The Cleveland Foundation, March (2007).
- 383. Strait, Megan (et al), *Synthesis Gas Reformers*, <u>http://www.owlnet.rice.edu/~ceng403/nh3ref97.html</u>, retrieved: 5/13/11.
- 384. Subramanian, *Flow through Packed Beds and Fluidized Beds*, <u>http://web2.clarkson.edu/projects/subramanian/ch301/notes/packfluidbed.</u> <u>pdf</u>, Retrieved: 5/6/11.
- 385. Sun, Chunwen; Hui, Rob; Qu, Wei; & Yick, Sing *Progress in Corrosion Resistant materials for Supercritical Water Reactors* <u>www.elsevier.com</u> (2009).
- 386. Sunden, Bengt *High Temperature Heat Exchangers* Department of Heat and Power Engineering, Lund University (2005).
- 387. Surface Condenser <u>http://en.wikipedia.org/wiki/Surface_condenser</u> (2011), Retrieval Date July 1, 2011
- 388. Suwanwarangkul, R.; Croiset, E.; Entchev, E.; Charojrocjkul, S.; Pritzker, M.D.; Fowler, M.W.; Douglas, P.L.; Chewathanakup, S.; Mahaudom, H. *Experimental and Modeling Study of Solid Oxide Fuel Cell Operating with Syngas Fuel* CANMET Energy Technology Center, Canada, <u>http://www.energy-based.nrct.go.th</u>, Retrieval Date July 15, 2011.
- 389. *System Model* Source: <u>www.wikipeda</u> Retrieval Date July 11, 2011.
- 390. *Systems Engineering Fundamentals* Department of Defense Systems Management College January (2001).
- 391. *Systems Engineering* Victorian Certificate of Education Study Design, Victorian curriculum and Assessment Authority (2006).

- 392. Talbot, David, *Lifeline for Renewable Power*, Technology Review, Jan/Feb. 2009.
- 393. Talukdar, Sarosh N.; Apt, Jay; Ilic, Marija; Lave, Lester B., Morgan, Granger M. *Cascading Failures: Survival versus Prevention* The Electricity Journal, November (2003).
- 394. *Technical Factors Affecting Commercialization of Fuel Cells*, NAHB Research Center, Inc July (2001).
- 395. *Technology Commercialization Framework* BizLogic LLC September (2004).
- 396. Technology Innovation Office, Bonneville Power Administration, *Renewable Energy Technology Roadmap* (Wind, Ocean Wave, In-Stream Tidal & Solar Photovoltaic) (2008), (Retrieved 11/17/2010).
- 397. *Technology Readiness Assessment (TRA) Deskbook* United States Department of Defense July (2009).
- 398. Teknomo, Kardi. Analytic Hierarchy Process (AHP) Tutorial, (2006) <u>http://people.revoledu.com/kardi/tutorial/ahp/</u>, Retrieved: 12/12/10.
- 399. Texas A&M, Energy Engineering, *Electric Power*, <u>http://energyengineering.org/electric-power</u>, (Retrieved: 10/10/10).
- 400. Than, Su Thet Mon; Lin, Khin Aung; Mon, Mi Sander; *Heat Exchanger Design*, World Academy of Science, Engineering & Technology (2008).
- 401. The BioenergySite.com "A Promising Oil Alternative: Algae Energy" http://www.thebioenergysite.com/news/244/a-promising-oil-alternativealgae-energy (2008), (Date Accessed: 09:15:2010).
- 402. The Manager's Guide *Definitions of Systems and Systems Engineering* http://themanagersguide.blogspot.com/2010_08_01_archive.html (August 2010) September 13, 2010
- 403. The Washington Post "A Promising Oil Alternative: Algae Energy" http://www.washingtonpost.com/wp-dyn/content/ (Date Accessed: 09.15.2010) (2008)
- 404. The Wine Economist *No Wine Before It's Time* <u>http://wineeconomist.com/2009/02/10/no-wine-before-its-time/</u>, Retrieval Date: May 22, 2011.

- 405. Thijssen, Jan, *The Impact of Scale-Up Production Volume on SOFC Manufacturing Cost*, National Energy Technology Laboratory, April (2007).
- 406. TIAX LLC "Grid-Independent, Residential Fuel-Cell Conceptual Design and Cost Estimate". Final Report for DOE NETL in subcontract to Parsons Infrastructure & Technology Group, Inc. Subcontract Number 736222-30005. (2002).
- 407. Tietz, F., Buchkermer, H.P., Stover, D., *Components Manufacturing for Solid Oxide Fuel Cells* Solid State Ionics, 152-153 (2002).
- 408. Tomasulo, Katy. "Though still far from mainstream hydrogen fuel cells are slowly becoming available for home energy, tied to the grid or to a solar system". ECOHOME. (2009).
- 409. Tomov, R.I. Direct Ceramic Inkjet Printing of Yttria-Stabilized Zirconia Electrolyte Layers for Anode-Supported Solid Oxide Fuel Cells, Journal of Power Sources 195 (2010) 7160–7167.
- 410. Trading Economics, Electric power transmission and distribution losses (kWh) in the United States, <u>http://www.tradingeconomics.com/china/electric-power-transmission-anddistribution-losses-kwh-wb-data.html</u>, (2011), Retrieval Date November 11, 2010.
- 411. *Triz*, <u>http://em.wikipedia.org</u>, Retrieval Date: May 22, 2011.
- 412. Tu, Hengyong & Stimming, Ulrich Advances, Aging Mechanisms and Lifetime in Solid-Oxides Fuel Cells <u>www.sciencedirect.com</u>, (2004).
- 413. Ullman, David, *The Ideal Engineering Decision Support System*, Robust Decisions Inc., <u>http://www.robustdecisions.com/theidealenginsyste1.pdf</u>, Retrieved: 11/20/11.
- 414. U. S. Energy Information Agency, *Questions About Natural Gas...*, (2010). <u>http://tonto.eia.doe.gov/ask/ng_faqs.asp#outlook_fuel_prices</u> (Retrieved: 12/10/2010).
- 415. U.S Energy Information Administration Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State <u>http://www.eia.gov/cneaf/electricity/epm/table5_6_a.html</u> (December 2010), Retrieval Date March 15, 2011.

- 416. U.S. Department of Energy *Fuel Cells Technologies Challenges* http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_challenge s.html (2011), Retrieval Date April 2, 2011.
- 417. U.S. Department of Energy, *Distributed/Stationary Fuel Cell Systems*, <u>http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/systems.html</u>, (2011), Retrieved: 4/12/11.
- 418. U.S. Department of Energy *Types of Fuel Cells* <u>http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html</u> (2011) Retrieval Date April 2, 2011.
- 419. U.S. Department of Energy, Federal Program Federal Energy Management Program, FEMP Designated Product: Residential Gas Furnaces, 2009.
- 420. US Energy Information Administration (EIA), *Residential Energy Consumption Survey (RECS)*, <u>http://38.96.246.204/consumption/residential/reports.cfm</u>, Retrieved: 4/5/11.
- 421. U.S. Department of Housing and Urban Development, *Institutional Factors Affecting Commercialization of Fuel Cells*, <u>www.pathnet.org</u>. 2000.
- 422. United Technologies. <u>http://www.utc.com</u> (Date Accessed: 9.3.2010).
- 423. University of Cambridge *DoItPoMS Electrolyte* <u>http://www.doitpoms.ac.uk</u> Retrieval Date: November 11, 2010.
- 424. US Department of Defense, *Technology Readiness Assessment (TRA)* Deskbook, 2003.
- 425. US Energy Information Administration, *Retail Unbundling Ohio*, (2010).
 <u>http://www.eia.doe.gov/oil_gas/natural_gas/restructure/state/oh.html</u> (Retrieved: 12/17/2010).
- 426. US Fuel Cell Council "*Antitrust Guidelines for U.S. Fuel Cell Council, Inc.*" <u>www.hydrogenandfuelcellsafety.info/antitrust_guidelines.pdf</u>. (Date Accessed: 09.17.2010) (2010).
- 427. US Fuel Cell Council. "About Fuel Cells: How do they work?" <u>http://www.usfcc.com/about/how.html</u> (Date Accessed: 10.11.2010). (2010).

- 428. Valentine, Julie Ann *Steam to Carbon Ratio Control In Steam Reforming* of Hydrocarbons United States Patent Number 6,758,101 B2, July 2004.
- 429. Valerdi, Ricardo; Wheaton, Marilee; *ANSI/EIA 632 Standardized WBS for COSYSMO* University of Southern California & The Aerospace Corporation. Published by the American Institute of Aeronautics and Astronautics, Inc., (2005).
- 430. Van den Oosterkamp, P.F.; *Critical Issues in Heat Transfer for Fuel Cell Systems* Presented at the Heat Transfer in Components and Systems for Sustainable Energy Technologies April (2005).
- 431. Vanderburg, Willem H.; *Is a Second Negawatt Revolution Within Reach?* Bulletin of Science, Technology & Society, Vol 21 No. 6 (2001).
- 432. Vernon, Chris "*UK gas and electricity crisis looming*". Energy Bulletin. http://www.energybulletin.net/node/8422, (Date Accessed: 09.15.2010) (2005).
- 433. Vert, Vicente B.; Serra, Jose M.; Jorda, Jose L.; *Electrochemical Characterization of MBaC03ZnO7+8 (M=Y,Er,Tb) as SOFC Cathode Material With Low Thermal Expansion Coefficient* Electrochemistry Communications 12 (2010).
- 434. Virkar, Anil V., *Polarization in Anode-Supported Solid Oxide Fuel Cells*, University of Utah Presented at Boston University, Boston, MA, 2003.
- 435. Viswanathan, R & Coleman, K & Rao, U. *Materials for Ultra-Supercritical Coal-Fired Power Plant Boilers* <u>www.sciencedirect.com</u> (2006).
- 436. Vittal, Vija; Abdelsalam, Hamed; Anderson, Brian; Davis, Brad; Irwin, Curtis *Fuel Cell Project* Mid American Energy, May (2003).
- 437. Von Spakovsky, M.R. & Olsommer, B. Fuel Cell Systems and System Modeling and Analysis Perspectives for Fuel Cell Development Energy Conversion Management (2002).
- 438. Wachsman, Eric D.; Singhal, Subhash C.; *Commercialization, Research and Challenges,* American Ceramic Society Bulletin, Vol. 89, No. 3, (2009).
- 439. Wall, Alexandra Jardine, *Fueling the Roman economy: The use of fuel wood in Roman industry, 200 BC – 400 AD*, Senior Thesis, Department of History, Columbia College, Columbia University, 2009.

- 440. Wantland, J.L.; Clapp, N.E., Fbntana, M.H.; Gnadt P.A.; Hanus, N.; Dynamic Boiling Tests in a 19-PIN Simulated LMFBR Fuel Assembly Oak Ridge National Laboratory (1977).
- 441. Weekly Corporate Growth Report "*Antitrust approvals and other news.*" All business website. <u>http://www.allbusiness.com/buying-selling-businesses/purchasing-a-business-valuation/949545-1.html</u> (Date Accessed: 09.17.2010). (2002).
- 442. Wheeler, Foster, *Steam-Hydrocarbon Reformer Furnace Design*, <u>http://www.fosterwheeler.it</u>, Retrieval Date December 15, 2010.
- 443. Wheeldon, Ian R.; Pepply, Brant A.; Wieland, Helmut; *Compact Methanol Steam Reformer with Integrated Hydrogen Separation* United States Patent Number US7,115,148 B2, October 3, 2006.
- 444. Wiens, Ben *The Future of Fuel Cells* <u>http://www.benwiens.com/energy4.html</u>, (May 2010) Retrieval Date December 15, 2010.
- 445. Wikipedia, Various Articles, <u>http://en.wikipedia.org</u>, Retrieval Date 9/30/10 to 9/15/11.
- 446. Williams, Mark C.; Strakey, Joseph; Surdoval, Wayne A.; *The U.S.* Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program, Journal of Power Sources 143 (2005).
- Wilson, Lane; Choi, Y.; Dong, J.; Abernathy, H.; Koep, E; Liu, Y.; Liu, M.; *Fundamental Studies of Electrodes for SOFCs* Georgia Institute of Technology January (2005).
- 448. Winkler, Wolfgang; Lorenz, Hagen; *The Design of Stationary and Mobile Solid Oxide Fuel Cell-Gas Turbine Systems* Journal of Power Sources 105 (2002).
- 449. Winter, Michael; Clarkew, David R.; *Oxided Materials with Low Thermal Conductivity* Journal of The American Ceramic Society (2006).
- 450. Wise Geek *What is a Negawatt?* <u>http://www.wisegeek.com/what-is-a-negawatt.htm</u>, (2011) June 2, 2011.
- 451. Woods, James, *What people do when they say they are conserving electricity*, Energy Policy 36 (2008) 1945–1956.

- 452. Woody, Tod, *An Affordable Way to Buy Fuel-Cell Power*, The New York Times, 2011, <u>http://green.blogs.nytimes.com/tag/bloom-energy/</u> (Retrieved: 9/30/11).
- 453. Wu, Shaomin; Clements-Croome, Derek; Fairey, Vic; Albany, Bob; Sidhu, Jogi; Desmond, Duncan; Neale, Keith; *Reliability in the Whole Life Cycle of Building Systems* Engineering, Construction and Architectural Management Vol 13 No 2, (2006).
- 454. Vantage Interactive Inc., *Analytic Hierarchy Process (What is AHP)*, www.vantage-interactive.com Retrieved 5/25/2011.
- 455. Xu, Lida; Li, Zongbin; Li, Shancang; Tang, Fengming; *A Decision* Support System for Product Design in concurrent Engineering Decision Support Systems 42 (2007).
- 456. Xue, D.; Dong, Z.; *Optimal fuel cell system design considering functional performance and production costs* Journal of Power Sources, April (1998).
- 457. Yakabe, Hisataka; Fujita, Kenhiro; *Monitoring Method for the Fuel Utilization in SOFC Systems* Product Development Department, Tokyo Gas Company, 2011.
- 458. Yang, Chris Fuel Cell Fundamentals Introduction to Fuel Cell Science and Engineering Hydrogen Economy, ITS UCDavis, http://www.its.ucdavis.edu, Retrieval Date 9/30/10.
- 459. Yang, Lei; Cheng, Zhe; Liu, Meilin; Wilson, Lane; *New Insights into Sulfur Poisoning Behavior of Ni-YSZ Anode from Long-Term Operation of Anode-Supported SOFC's* Energy & Environmental Science, August (2010).
- 460. Yano, Masaya et al, *Recent advances in single-chamber solid oxide fuel cells: A review*, Solid State Ionics, 177 (2007) 3351–3359.
- 461. Yao, Albert W.L., Chi, S.C.; *Analysis and Design of a Taguchi-Grey Based Electricity Demand Predictor for Energy Management* Energy Conversion and Management, 45 (2004).
- 462. Yassine, Ali A.; Whitney, Daniel E.; Lavine, Jerry; Zambito, Tony.; *Do-It-Right-First-Time (DRFT) Approach to Design Structure Matrix (DSM) Restructuring* Proceedings of DETC (2000).

- 463. Ying-Je Huang, Albert (et al) *Learning for Suppling as a Motive to be the Early Adopter of a New Energy Technology: A Study on the Adoption of Stationary Fuel Cells*, Energy Policy 36 (2008).
- 464. Yoon, Kyung Joong; Zink, Peter A.; Pal, Uday B.; Gopalan, Srikanth *Performance Analysis of Single Step co-Fired Solid Oxide Fuel Cells* (*SOFC's*) Boston University, <u>http://www.bu.edu</u>, Retrieval Date 9/13/10.
- 465. Younes, Ziad; Ilic, Marija; *Generation Strategies for Gaming Transmission Constraints: Will the Deregulated Electric Power Market Be an Oligopoly?* Decision Support Systems 24 (1999).
- 466. Yuan, Jinliang; *Balance of Fuel Cell Power Plant (BOP, Department of Energy Sciences Lund Institute of Technology Sweden December (2008).*
- 467. Zhang, Jim and Smith, Kirk R "Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions." Environ Health Prospect. 115(6) 848-855. (2007).
- 468. Zhang, Xueqing & Xiaoming, Mao & AbouRizk, Simaan M. Developing a Knowledge Management System for Improved Value Engineering Practices in the Construction Industry www.elsevier.com/locate/autocon (2009).
- 469. Zhang, Y; Gershenson, J.K. *An Initial Study of Direct Relationships Between Life-Cycle Modularity and Live-Cycle Cost*, Concurrent Engineering: Research and Applications Vol. 11 No. 2, June (2003).
- 470. Zhou, Lu; Guo, Yu; Sakurai, Makoto; Kameyama; Hideo; *Study of Porous Anodic Alumina Supported Plate-Type Catalysts During Daily Start-Up and Shut-Down Operation of Methane Steam Reforming* Applied Catalysis A: General February (2009).

APPENDICES

APPENDIX A

SOME OF THE BENEFITS OF A FC CHP SYSTEM

A-1 Introduction





Some of the advantages of an SOFC Power System are thus stated in the above figure, namely, clean exhaust, low vibration and noise. Since a cogeneration system generates and uses electricity at the same place, it does not cause transmission loss, and can effectively use heat produced by electricity generation to heat water and air. Therefore, SOFC Power Systems will eliminate wasted energy and reduces CO_2 emissions. Fuel cell type cogeneration systems generate electricity using the chemical reaction of fuel, so the exhaust is clean.

A-2 Example: The Hot Water Heater vs. the Fuel Cell Power System

The following example shows the comparison between the primary energy input for a home using a gas water heater and that for a home using a fuel cell based on the estimated household electrical energy consumption and hot water consumption.

A home requires 4,275 kWh to heat water and, 5,733 kWh of electricity, which is a

total of 10,088kWh of energy.

When a gas water heater is used:

To produce energy required for heating water in a home (4,275 kWh), gas equivalent

to 5,625 kWh should be input as fuel.

Energy Loss = Input Fuel – Energy Needed = (5,625 - 4,275)*kWh = 1,330 kWh (Loss)

To produce electrical energy required for a home (5,733 kWh), 15,536 kWh of energy

must be input by a Power Station.

Energy Loss = Input from Power Station – Energy Needed = (15,536 – 5,733)*kWh

= 9,803 kWh (Loss)

* Power Loss Ratio (Ratio of energy that has to travel from Power Station) = 63%
 *Total Energy consumed (Gas Water Heater)

 = Input from Power Station + Input Fuel
 = (15,536+5,625) = 21,161kWh

*Total Energy Wasted = 1,330 kWh + 9,803 kWh = 11,133kWh

When a fuel cell is used:

To produce energy required for heating water in a home (4,275 kWh), gas equivalent

to 10,088 kWh must be input as fuel.

Energy Loss = Input Fuel – Energy Needed = (10,088 - 4,275)*kWh = 5,813 kWh (Loss) Since the fuel cell generates 3,308 kWh of electricity while heating the required amount of water, the home needs another 2,425 kWh of electrical energy.

Energy Deficit = Energy Needed – Power Generated = (5,733–3,308)*kWh = 2,425 kWh (Deficit)

• To make up the electrical energy shortfall (2,425 kWh), 6,572 kWh of energy

must be input by a power station.

Energy Loss = Input from Power Station – Energy Needed = (6,572 – 2,425)*kWh = 4,147kWh (Loss)

*Total Energy Wasted = 5,813 kWh + 4,147kWh = 9,960kWh

*Total Energy consumed (Fuel Cell)

= Input from Power Station + Input Fuel = (10,088+6,572) = 16,660kWh

*Energy Savings Amount (Gas Heater Application – Fuel Cell Application) = (21,161-16,660)*kWh = 4,501kWh



Figure A-2: The Cost Savings of a CHP

As described above in **Figure A-2**, primary energy of 21,161 kWh must be input for a home using a gas water heater. If the home adopts a fuel cell, the primary energy to be inputted will be 16,660 kWh, bringing about primary energy conservation of 4,502 kWh. This is equivalent to a reduction of CO_2 emissions by 1,465 kg/year (CO_2 conversion factor). The CO_2 conversion factor is based on:

- 1. Gas: 2.29 kg-CO₂/m3;
- Electricity: 0.69 kg-CO₂/kWh (Based on the factor of CO₂ emissions by thermal power plants specified in a 2007 reference issued by the New Energy Foundation).
- 3. The CO₂ emission reduction is 637 kg/year based on the factor of CO₂ emissions by all power plants.
- Estimation conditions: Electricity generation efficiency at thermal power plants:
 36.9% (based on the Law Concerning the Rational Use of Energy) Gas water heater efficiency: 76% Panasonic fuel cell operation simulation.

APPENDIX B

DATA COMPILED FROM THE RESIDENTIAL ENERGY CONSUMPTION SURVEY (RECS)

Census Division	Number of	Average Monthly	Average Retail Price	Average Monthly Bill (Dollars
		Consumption	(Cents per	and
State	Consumers	(kWh)	Kilowatthour)	cents)
New England	6,136,238	623	17.47	\$108.90
Connecticut	1,447,250	724	20.33	\$147.25
Maine	696,822	521	15.65	\$81.60
Massachusetts	2,661,985	610	16.87	\$102.85
New				
Hampshire	591,160	623	16.26	\$101.38
Rhode Island	432,102	566	15.60	\$88.35
Vermont	306,919	576	14.90	\$85.83

Residential Average Monthly Bill by Census Division, and State 2009

-
Census	Number	Average	Average	Average Monthly
Division	of	Monthly	Retail Price	Bill
		Consumption	(Cents per	(Dollars
State	Consumers	(kWĥ)	Kilowatthour)	and cents)
Middle				
Atlantic	15,582,581	690	14.84	\$102.38
New Jersey	3,430,837	676	16.31	\$110.29
New York	6,916,413	581	17.50	\$101.71
Pennsylvania	5,235,331	842	11.65	\$98.09
East North				
Central	19,531,947	779	10.92	\$85.09
Illinois	5,074,861	728	11.27	\$82.04
Indiana	2,733,611	992	9.50	\$94.30
Michigan	4,253,786	644	11.60	\$74.69
Ohio	4,880,393	878	10.67	\$93.66
Wisconsin	2,589,296	689	11.94	\$82.28

Residential Average Monthly Bill by Census Division, and State 2009

Census Division State	Number of Consumers	Number of Average Monthly Consumers (kWh)		Average Monthly Bill (Dollars and cents)
West North				
Central	9,001,636	942	9.14	\$86.10
Iowa	1,324,182	864	9.99	\$86.25
Kansas	1,209,522	906	9.53	\$86.37
Minnesota	2,290,881	802	10.04	\$80.48
Missouri	2,687,756	1,061	8.54	\$90.66
Nebraska	799,623	1,003	8.52	\$85.49
North Dakota	322,466	1,150	7.58	\$87.17
South Dakota	367,206	1,024	8.49	\$86.88

Residential Average Monthly Bill by Census Division, and State 2009

Residential Average Monthly Bill by Census Division, and State 2009

Г

Census Division	Number of	Average Monthly Consumption	Average Retail Price (Cents per	Average Monthly Bill (Dollars and	
State	Consumers	(kWh)	Kilowatthour)	cents)	
South Atlantic	25,669,340	1,123	11.32	\$127.16	
Delaware	393,836	917	14.07	\$129.07	
District of					
Columbia	217,635	712	13.76	\$97.94	
Florida	8,493,591	1,133	12.39	\$140.33	
Georgia	4,061,862	1,132	10.13	\$114.64	
Maryland	2,188,390	1,026	14.98	\$153.72	
North Carolina	4,175,829	1,124	9.99	\$112.30	
South Carolina	2,083,432	1,182	10.44	\$123.47	
Virginia	3,189,118	1,170	10.61	\$124.06	
West Virginia	865,647	1,116	7.90	\$88.16	

Census Division State	Number of Consumers	Average Monthly Consumption (kWh)	Average Retail Price (Cents per Kilowatthour)	Average Monthly Bill (Dollars and cents)	
East South					
Central	7,972,331	1,215	9.61	\$116.72	
Alabama	2,128,009	1,233	10.66	\$131.42	
Kentucky	1,922,294	1,150	8.37	\$96.26	
Mississippi	1,243,260	1,213	10.22	\$124.00	
Tennessee	2,678,768	1,248	9.32	\$116.35	
West South					
Central	14,390,523	1,148	11.04	\$126.66	
Arkansas	1,315,041	1,076	9.14	\$98.38	
Louisiana	1,946,996	1,273	8.10	\$103.19	
Oklahoma	1,643,674	1,097	8.49	\$93.13	
Texas	9,484,812	1,140	12.38	\$141.20	

Residential Average Monthly Bill by Census Division, and State 2009

Census Division State	Number of Consumers	Average Monthly Consumption (kWh)	Average Retail Price (Cents per Kilowatthour)	Average Monthly Bill (Dollars and cents)
Mountain	8,867,490	878	10.18	\$89.38
Arizona	2,544,383	1,076	10.73	\$115.42
Colorado	2,111,623	687	10.00	\$68.69
Idaho	659,776	1,080	7.80	\$84.27
Montana	464,517	856	8.93	\$76.48
Nevada	1,054,927	938	12.86	\$120.66
New Mexico	844,865	642	10.02	\$64.30
Utah	932,016	780	8.48	\$66.16
Wyoming	255,383	887	8.58	\$76.12
Pacific				
Contiguous	17,342,577	703	12.15	\$85.43
California	12,910,856	580	14.74	\$85.45
Oregon	1,623,388	1,017	8.68	\$88.23
Washington	2,808,333	1,091	7.68	\$83.72
Pacific				
Noncontiguous	682,512	632	21.31	\$134.59
Alaska	269,669	654	17.14	\$112.13
Hawaii	412,843	617	24.20	\$149.25
U.S. Total	125,177,175	908	11.51	\$104.52

Residential Average Monthly Bill by Census Division, and State 2009

APPENDIX C

THE DAILY ITEMIZED HYPOTHETICAL HOUSEHOLD'S ENERGY REQUIREMENTS								
Description of Household Appliance	Quantity	Watts	PF	Total Watts	Time in service (hrs.)	Watt*hours	kW*hours	Current (Amps.)
			120	V AC INFOI	RMATION			
Incandescent Lamp A	1	60	1	60	2	120	0.120	0.50
Incandescent Lamp B	1	60	1	60	1	60	0.060	0.50
Incandescent Lamp C	1	30	1	30	3	90	0.090	0.25
Incandescent Lamp D	1	10	1	10	4	40	0.040	0.08
Microwave	1	400	0.89	449	2	899	0.899	3.75
Electric Stove	1	100	1	100	3	300	0.300	0.83
Garbage Disposal	1	50	0.89	56	0.16	9	0.009	0.47
Dishwasher	1	200	0.89	225	1	225	0.225	1.87
Coffee Maker	1	50	0.89	56	0.5	28	0.028	0.47
Fan & Vent	1	35	0.89	39	2	79	0.079	0.33
Clocks	2	2	1	4	24	96	0.096	0.03
Televisions	1	100	1	100	6	600	0.600	0.83
DVD Player	1	10	1	10	1	10	0.010	0.08

THE DAILY ITEMIZED HYPOTHETICAL HOUSEHOLD'S ENERGY REQUIREMENTS								
Description of Household Appliance	Quantity	Watts	PF	Total Watts	Time in service (hrs.)	Watt*hours	kW*hours	Current (Amps.)
	120 V AC INFORMATION							
TOTAL OF 120V AC 1649 6151 6.151 13.74								

240 V AC INFORMATION								
Central Air Unit	1	1500	0.89	1685	6	10112	10.1	7.02
						10,112		
	TO	TAL OF 2	240V AC	1,685			10.1	7.02
						16,263		
]	TOTALS	3,335			16.3	20.77

The Hypothetical Example's Considerations

Things with Motors

There are appliances like refrigerators which although appear to be "on" all day, actually are running between 12 to 15 hours a day (turning off and on as needed). Air conditioning units run on and off all day depending on the cooling needs of the home and the outdoor temperature.

Ghost Loads

"Ghost" loads are devices that typically consume a small amount of energy (<1W) but are running 24 hours a day. Examples of typical ghost loads would be AC adapters, clocks, VCRs, TVs, microwaves and printers. Many of these devices require power to maintain their clocks running (e.g. VCR, TV and microwave). Although the amount of energy consumed on an hourly basis is small, the fact that they run all day can easily add as much as 100W*Hrs per day. Ghost loads will not be included in the hypothetical example.

Apparent Load

Estimating a customer's maximum power load and then specifying a FC Power System to match or slightly exceed the load estimation. The apparent loads (voltamperes) might be larger than the real loads (watts). Although FC Power Systems are expressed in kW, electrical specifications typically state power in volt-amps (VA). This is an important distinction, as a load with a low power factor may not draw many watts, or "real power", but its VA load, or "apparent power", may be higher. For example, a washing machine with a power factor (PF) of 0.5 (the ratio between "real power" and "apparent power") might consume 500 W, but it'll draw about 1,000 VA (120V * 8.3A)

855

from a power source. An example: A 500 W load with a 0.5 PF will draw 500W/0.5 = 1,000 VA/120VAC = 8.33 A. If the PF was 1.0 (i.e., purely resistive), the load current would be (500W/1.0)/120VAC = 4.17 A.

In an electrical system, a load with a low PF draws more current than a load with a high PF, for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires, among other things. And, since FC Power Systems are current-limited power sources, and the low PF loads draw relatively high current, less current is available to power other loads, thereby effectively reducing the Power System's functional capacity.

The power factor of common loads varies from quite low (i.e., about 0.5 for washing machines), to high (i.e., 1.0 for resistive load). Applying an average power factor of 0.85 to a group of typical loads is a reasonable rule.