ADVANCED HYDROGEN TURBINE DEVELOPMENT

PHASE 1

Final Technical Report

December 22, 2007

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Work Performed under DOE Award: DE-FC26-05NT42644

October 1, 2005 – September 30, 2007

For

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory
Morgantown, West Virginia
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ACS	Advanced Catalytic System, Inc.
ACWP	Actual Cost of Work Performed
AN^2	Blade Annulus Area x Rotational Speed Squared
ASME	American Society of Mechanical Engineers
ASU	Air Separation Unit
AGR	Acid Gas Removal
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
BOP	Balance of Plant
CAD	Computer Aided Design
CCT	Compressor, Combustion and Turbine
CF	Centrifugal Force
CFD	Computational Fluid Dynamics
CMC	Ceramic Matrix Composites
COE	Cost of Electricity
CoP	ConocoPhillips
CRM	Chemical Reactor Modeling
CTE	Coefficient of Thermal Expansion
CTQ	Critical to Quality
DAS	Dendrite Arm Spacing
DLR	Deutsches Zentrum für Luft und Raumfart
DOE	Department of Energy
DoE	Design of Experiments
DTA	Differential Thermal Analysis
EERC	Energy and Environmental Research Center
EGR	Exhaust Gas Recirculation
EPRI	Electric Power Research Institute
ENEL	Entre Nazionale per l'Energia Elletrica
EVA	Earned Value Analysis
FOD	Foreign Object Damage
FTT	Florida Turbine Technologies
FY	Fiscal Year
GIT	Georgia Institute of Technology
GT	Gas Turbine
HADES	Hyperbaric Advanced Demonstration Environmental Simulator
HEE	Hydrogen Environment Embrittlement
HHV	Higher Heating Value
HIP	Hot Isostatic Pressing
HP	High Pressure
HRSG	Heat Recovery Steam Generator
HVOF	High Velocity Oxy-Fuel
IET	Integrated Energy Technologies
IGCC	Integrated Gasification Combined Cycle
IGTI	International Gas Turbine Institute
IGV	Inlet Guide Vane
IHE	Internal Hydrogen Embrittlement
IP	Intermediate Pressure
IPT	Integrated Product Team
ITM	Ion Transport Membrane

LCG	Low Calorific Gas
LEC	Levelized Electricity Cost
LCF	Low Cycle Fatigue
LP	Low Pressure
LTP	Long Term Program
NETL	National Energy Technology Laboratories
NPV	Net Present Value
O&M	Operation & Maintenance
OGV	Outlet Guide Vane
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PTS	Platform Turbine System
PB	Power Block
PR	Pressure Ratio
PSP	Pressure Sensitive Paint
QFD	Quality Function Deployment
R&D	Research & Development
RAM	Reliability, Availability and Maintainability
RE	Rare Earth
ROM	Rough Order of Magnitude
RDI	Research & Development Implementation
SAS	Secondary Air System
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscopy
SFG	Siemens Fuel Gasification
SOTA	State of the Art
SOW	Statement of Work
SPG	Siemens Power Generation
SSRT	Slow Strain Rate Tests
SST	Stainless Steel
TAMU	Texas A&M University
TBC	Thermal Barrier Coating
TCLA	Turbine Cooling and Leakage Air
TE	Trailing Edge
TEC	Turbine and Exhaust Casing
TEM	Turbine Exhaust Manifold
TET	Turbine Exit Temperature
TIT	Turbine Inlet Temperature
TURBD1	Aerodynamic Meanline Analysis Program
UCF	University of Central Florida
ULN	Ultra Low NOx
UTRC	United Technologies Research Center
VOC	Volatile Organic Compounds
WDS	Wavelength Dispersive Spectrometer
XRD	X-Ray Diffraction
YSZ	Yttria Stabilized Zirconia

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EXECUTIVE SUMMARY

Under the sponsorship of the U.S. Department of Energy (DOE) National Energy Technology Laboratories, Siemens Power Generation is working on the Advanced Hydrogen Turbine Development Program to develop an advanced gas turbine for incorporation into future coal-based Integrated Gasification Combined Cycle (IGCC) plants. Phase 1 of the project has been completed and significant progress has been made towards achieving DOE program goals. Figure 1 shows the Hydrogen Turbine Program timeline.
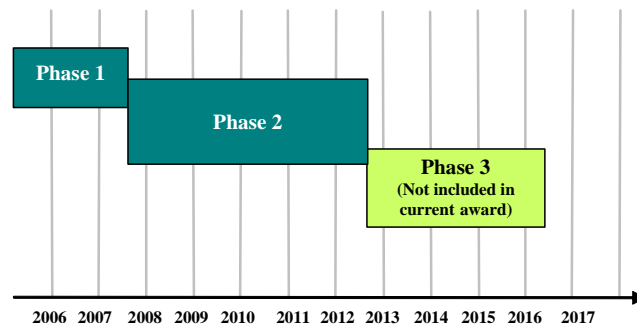
Figure 1. DOE Program Timeline

The DOE Advanced Power Systems goal is to conduct the research and development necessary to produce CO_2 sequestration ready coal-based IGCC power systems with high efficiency (45-50%, HHV), near zero emissions (<2 ppm NOx @ 15% O_2) and competitive capital cost (< $1000/kW) based on 2002 cost levels. The Advanced Turbine Program contribution to these goals is to demonstrate by 2010 a 2-3 % point improvement in combined cycle efficiency above the baseline, 20-30 % reduction in combined cycle capital cost, and emissions of 2 ppm Nox @ 15% O_2. The 2012 goal is for IGCC-based power with carbon capture. Furthermore, by 2015, the goal is to demonstrate a 3-5 % point improvement in combined cycle efficiency above the baseline and 2 ppm Nox @ 15% O_2.

Extensive thermodynamic evaluations were conducted to establish the engine and plant cycle characteristics required to meet the DOE goals. The efficiency improvements will be achieved by a two step technology approach. In 2010, the SGT6-6000G technology level can be utilized to attain efficiency improvement of 2-3% point above the baseline. Building from Siemens Platform Systems, technologies developed under this program will result in an Advanced Hydrogen Turbine which will meet the goal of 3-5% point improvement by 2015.

The challenging goal of 2 ppm NOx required evaluation and verification testing of the following 4 competing technologies in Phase 1: Diffusion, Catalytic, Premix, and Advanced Premix Combustion. The premix system technologies were down selected to two at the end of Phase 1 for further development in Phase 2. These systems show the greatest potential to meet the requirements for a high temperature with low emissions, robustness to operational variations, and minimal dilution requirement.

While initial cost estimates conducted for the total IGCC plant were above the targeted $1000/kW, a plan was established towards meeting the 20-30% reduction in Combined Cycle capital cost on a $/kW basis through development of cost effective technologies coupled with a significant increase in Gas Turbine and Combined Cycle power output.

All the scheduled DOE Milestones for Phase 1 were completed and significant technical progress was made in the development of new technologies and concepts. Advanced computer simulations and modeling, as well as subscale and full scale laboratory and rig testing were utilized to evaluate and select concepts for further development. Described below are the major Phase 1 accomplishments for The Advanced Hydrogen Turbine Development Program.

- The Research and Development Implementation Plan was prepared and submitted to DOE (DOE Milestone No. 2). This document described the planned activities, technical approach, technical barriers, technologies down selection criteria, testing and validation plans, major milestones, program critical path, schedule and cost estimates for the planned R & D activities.

- The gas turbine and plant thermal models were generated for the different cases under investigation. A thermal performance model was produced for the SGT6-6000G based IGCC plant. Performance was estimated for the current SGT6-6000G engine fired on syngas and hydrogen fuels in IGCC application, utilizing the state of the art SGT6-5000F balance of plant components (DOE Milestone No. 1).

- The performance penalty for CO_2 removal was estimated for different carbon capture rates. The results showed that there will be a severe performance penalty above 70% carbon capture rate.

- In the Design of Experiments (DoE) study, the objective was to narrow down the major GT cycle design parameters. Based on the study results, the desirable cycle Turbine Inlet Temperature, Pressure Ratio range and ASU type were identified and used during the conceptual gas turbine and plant design phase.

- The first iteration on the hydrogen-fueled, advanced GT-IGCC plant capital cost estimation was completed (DOE Milestone No. 3).

- Turbine aerodynamic studies showed that optimizing the outer flow path elevations, as well as vane and blade aerodynamics resulted in an improvement in turbine efficiency. 2D throughflow analysis was completed and preliminary airfoil mid-section layouts and cooling schemes were generated. Novel internal turbine airfoil cooling concepts were identified and prioritized (DOE Milestone No. 4). Mechanical and initial manufacturing feasibility assessment indicated that the increased annulus height turbine was feasible.

- The diffusion flame combustion system was tested up to SGT6–6000G firing temperatures on syngas and hydrogen fuels in full-scale combustor rig tests. Hydrogen content up to 70% by volume was tested. These tests confirmed that the diffusion flame combustion system could operate with NOx emission levels below 15 ppm on high hydrogen fuels at SGT6–6000G firing temperature with dilution.

- DOE Milestone No. 6 was accomplished with the completion of Baseline Combustor Test. Full scale basket testing using the baseline F – Class diffusion flame combustor with modifications was conducted. This enhanced diffusion flame combustor was tested with natural gas, hydrogen and syngas fuels at various conditions. Satisfactory results were obtained and will be utilized as a baseline to which other designs will be compared.

- High temperature bond coat oxidation and mass gain tests were conducted in a steam-enriched environment. Phase stability tests carried out on high temperature, low thermal conductivity TBC at elevated temperatures showed no appreciable phase transformation.

- A peer review was carried out on the development of high temperature capable TBC (DOE Milestone No. 5). A validation plan was generated to ensure success in advanced coating systems development.

- Significant progress was made in the development of advanced coating systems. Almost 40% spallation life improvement over start-of-the-art coatings was demonstrated for new modified bond coats and substrate materials.

- Multiple studies were conducted concluding that specific CO_2 and NOx emissions (in kg/MWhr) as well as IGCC plant capital cost (in $/kW) are reduced with increased plant efficiency. A 20% reduction in capital cost ($/kW) could be achieved with 2015 technologies.

- Reviews were conducted for the gas turbine systems and component conceptual designs (DOE Milestone No. 8) and an IGCC plant conceptual design basis was established. (DOE Milestone No. 7).

- A Customer Advisory Board was formed for the Advanced Hydrogen Turbine Development Program. The first meeting was held in May, 2006, during the Electric Power Conference and the second meeting in November, 2006, during the PowerGen Conference. A web survey was also conducted to obtain the customers' perspective on the IGCC market drivers, constraints and enablers. 56 responses were obtained, with over 60% indicating intent to build IGCC plants.

- Three technical papers were written and delivered at the following conferences: 2006, Pittsburgh Coal Conference, 2006 International Colloquium on Environmentally Preferred Advanced Power Generation and 2007 ASME IGTI Turbo Expo.

- More than 25 patent disclosures submitted on the new technologies developed in this program demonstrated that valid progress is being made toward achieving the program goals.

- Phase 1 of the program was completed on schedule and within the allotted budget. Success obtained in achieving all Phase 1 Milestones and targets ensures that the Advanced Hydrogen Turbine Development Program team will achieve equal success in Phase 2.

TECHNOLOGY DEVELOPMENT

Introduction

Siemens Power Generation (SPG) with the DOE is developing an advanced gas turbine that will operate on hydrogen and syngas derived from coal in an Integrated Gasification Combined Cycle (IGCC) plant that is CO_2 capture ready. A three (3) phase program was proposed to develop a hydrogen based turbine where successful development of this engine for hydrogen/syngas operation and its integration into an advanced gasification system would result in meeting DOE specific program goals shown in Figure 2 below.

DOE Advanced Power Systems Goals

➢ 45 – 50% HHV plant efficiency

➢ <2 ppm NOx @ 15% O_2

➢ <$1,000/kW capital cost

Advanced Turbine Program Contribution

•2-3% pt. improvement in CC efficiency over baseline	•IGCC-based power systems that capture carbon	•3-5% pt. improvement in CC efficiency over baseline
•20-30% reduction of CC capital cost compared to baseline		•H_2 Turbine with 2 ppm NOx
•2 ppm NOx on Syngas		

2010   2012   2015

Figure 2. Advanced Hydrogen Turbine Goals

A Research and Development Implementation (RDI) Plan describing the technical approach to meeting the stated DOE goals was completed in April of 2006. The first phase as described in the RDI Plan, focused on the overall conceptual gas turbine design and the gas turbine integration into an IGCC plant. Thermodynamic calculations were conducted to establish the desirable cycle parameters, component concepts were identified, and technology needs assessments were conducted.

Siemens has developed an overall program strategy that utilizes a two step approach to meet the DOE intermediate (2010) and long term (2015) efficiency goals (see Figure 3). The first step utilized G class technology which enables the intermediate (2010) efficiency targets to be achieved. The second step would employ advanced technologies with further upgrade of the engine operating conditions to meet the DOE long term (2015) goals.
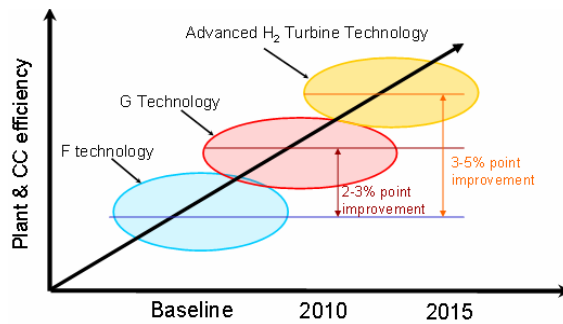
Figure 3. Proposed Two Step Approach to Meeting DOE Efficiency Goals

To ultimately ensure that the plant level goals are achieved, a process was followed to establish engine level parameters, component level targets, and necessary supporting technologies. Figure 4 shows how the technology is driven by plant level goals.
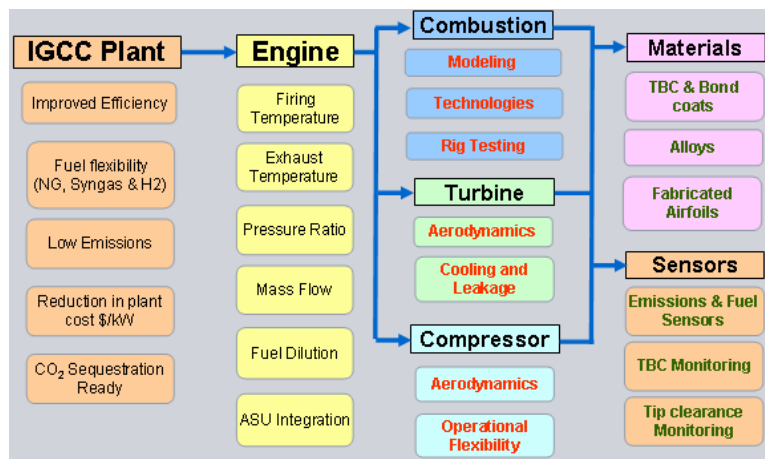
Figure 4. Approach to Identifying Technology Needs from Plant Level Goals

Iteration of gas turbine thermodynamic parameters, such as turbine inlet temperature and gas turbine pressure ratio was facilitated through a Design of Experiments approach. Component efficiency targets were established, supporting technologies identified, and Impacts of system integration effects for ASU extraction and Exhaust Gas Recirculation were evaluated.

Four competing combustion technologies were evaluated in Phase 1: Diffusion, Catalytic, and two premix based systems. Supported by collaborative efforts with Universities, the combustion development also made progress in the kinetic modeling of high hydrogen fuels. Rig testing of the 4 technologies was completed and two of the most promising premix approaches were down selected at the end of Phase 1.

An IGCC plant concept was developed to establish a basis for quantifying the impacts of the advanced hydrogen turbine in a full IGCC model. Studies were conducted to investigate air separation unit technologies, air integration impacts, as well as effects of carbon capture on overall IGCC plant performance.

The integration of the gas turbine components is facilitated through a revision controlled longitudinal database and interface documents. A secondary air systems model is being utilized to integrate the various components and manage cooling, leakage and sealing information. A two dimensional model was constructed to evaluate the thermal behavior of the advanced technology systems and provide important temperature and displacement data to the technology development areas. A risk assessment process was instituted in Phase 1 to identify risks, develop mitigations plans, and monitor risks throughout the project.

Turbine component development focused on addressing the challenges of increased temperature, reduced cooling consumption, increased mass flow, and environmental impacts of high hydrogen fuel. Aerodynamic improvements and advanced cooling schemes were identified, feasibility of an increased turbine annulus was determined, and novel concepts for component construction were developed. Collaborative efforts with Universities resulted in obtaining critical sub-scale aerodynamics and heat transfer test results.

Advancements in materials and coatings are critical to the success of the advanced hydrogen turbine development. A comprehensive roadmap was established for thermal barrier coating (TBC) system development and validation. Results were obtained from testing of TBC concepts, bondcoats, as well as modified alloys with very promising results. Novel component construction concepts developed for the turbine section were supported with manufacturing trials and initial testing of properties. Environmental testing was conducted on a series of alloys under varying conditions to further quantify the material effects from IGCC operation.

Progress was made in the development of compressor, rotor, casings and auxiliary systems and components. Prediction of compressor efficiency and surge margins was conducted for a wide parameter range to ensure the compressor concept is flexible. Effects of tip clearances and number of stages were examined. A high output rotor concept was assessed and cooling configuration concepts were identified to facilitate the use of proven highly ductile disk alloys. Casing concepts were developed to integrate the new technologies for the turbine, combustor, and turbine sections while balancing cost and performance trade-offs. Initial auxiliary systems descriptions were developed along with a review of materials and hydrogen safety topics.

The Siemens Advanced Hydrogen Turbine Development Program is closely integrated with the DOE FutureGen program (see Figure 5). The technologies being developed in this program will be evaluated for application in the FutureGen Plant. In this way, new technology developments, such as an advanced combustion system, materials and coatings, can be retrofitted and will have the potential to directly benefit the FutureGen project.
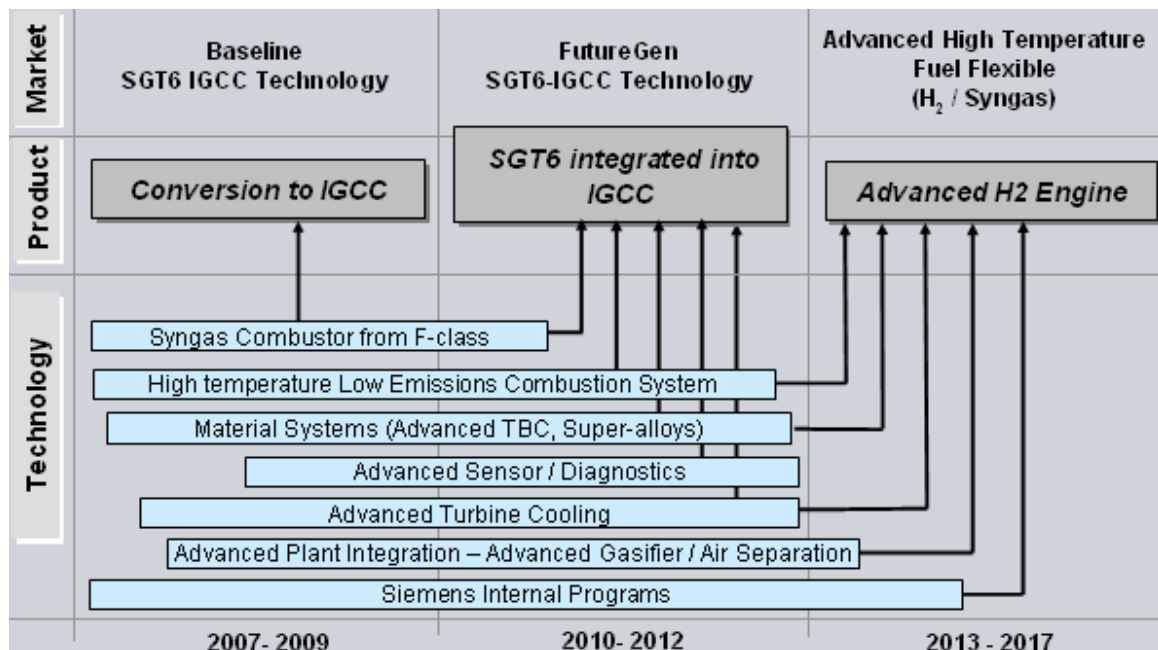
Figure 5. Hydrogen Turbine Technology Development Roadmap

Studies were conducted to quantify CO_2 and NOx emissions reduction with improved plant efficiency. Cost evaluations were conducted on an overall plant basis in support of evaluating the advanced hydrogen turbine technology contribution towards meeting the DOE cost target. A Customer Advisory Board was established to solicit input and help in determining the program strategy.

All of the Phase 1 DOE milestones were met and the budget was successfully managed through earned value analysis. More than 25 patent disclosures were developed under this program. Publications and presentations were prepared to describe the project's progress.

Plant Integration

Approach

During Phase 1, Plant Integration was involved in multiple studies of the Integrated Gasification Combined Cycle (IGCC) Plant.

A Design of Experiment (DoE) activity was developed to understand plant performance for a variety of plant and engine design options. Different variables such as pressure ratio, exhaust temperature and dilution were analyzed and their impact on overall performance studied.

Ion Transport Membrane (ITM) integration options were studied to determine the most viable one for the high hydrogen turbine application.

The following evaluations were completed: the performance impact of carbon capture on overall plant performance, the impact of Exhaust Gas Recirculation (EGR) on overall plant performance and evaluation of an advanced bottoming cycle using high steam turbine inlet temperatures above 600°C for the high and intermediate pressure sections, as well as using Ultra-Super Critical water/steam cycles.

The first iteration of the plant cost was completed, including gas turbine, power block, Gasifier, Acid gas removal, Air Separation Unit and other systems, for plants with and without CO_2 removal.

Emphasis was given to the development of a Plant Design Basis Concept where the IGCC plant performance was evaluated. The goal of this Plant Design concept was to create a baseline to enable the study of the increase in IGCC efficiency due to the gas turbine and other power block components only, without taking into consideration advancements or developments on systems outside the power block scope, such as the Air Separation Unit, CO_2 Compression System, Gasifier and Acid Gas Removal System. The Plant Design presents the systems that were selected for the baseline calculation and also what is intended to be used for the 2015 plant design.

Another activity performed during Phase 1 was an investigation of the interaction with multiple vendors from systems outside of Siemens scope, such as Acid Gas Removal System and Air Separation Unit, to develop models with realistic assumptions.

Discussion and Results

Ion Transport Membrane (ITM) for air separation appeared to be a promising technology that would benefit the overall plant performance due to its reduced auxiliary loads compared to the Cryogenic Air Separation Units. The challenge encountered by this technology is imposed by the requirements of increased pressure and temperature at the membrane inlet. Multiple integration options with the plant and the gas turbine were evaluated to make efficient use of the required heat input and compression to meet the membrane conditions. Figure 6 shows the most probable configuration for potential implementation.
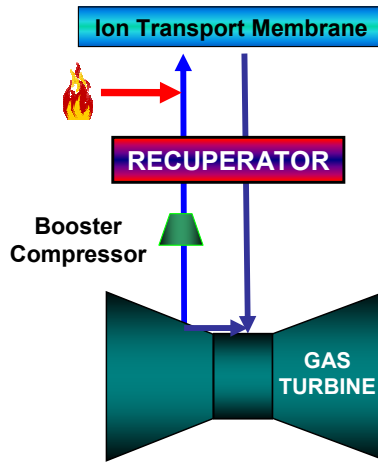
Figure 6. Ion Transport Membrane Configuration

Ion Transport Membrane is still not commercially available. Its performance and configuration for IGCC application has not been proven.

An evaluation of the impact of carbon capture on overall plant performance was done using a plant design that included a Syngas Cooler after the gasification process. It was determined that the relationship between the amount of carbon capture and the impact it has in plant performance is not linear. As shown in Figure 7, for capture rates around 90% the impact to plant efficiency is significant.
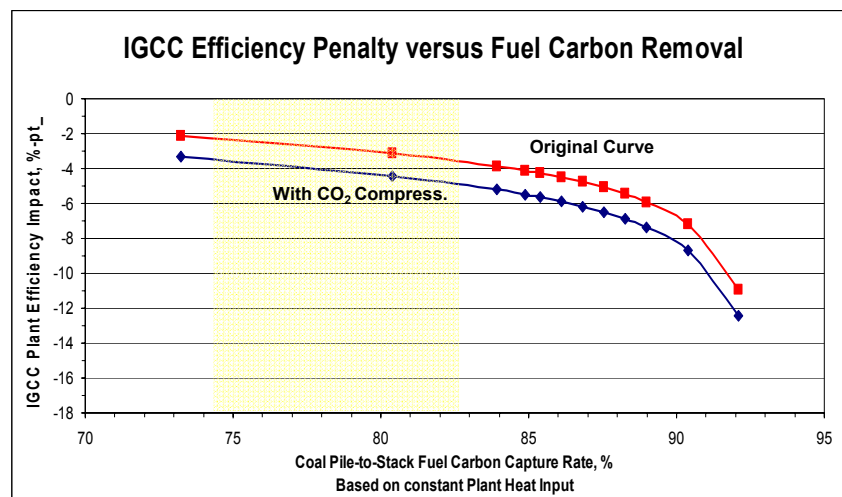
Figure 7. IGCC Efficiency Penalty Versus Fuel Carbon Removal

Increasing the carbon capture rate requires additional IP steam extraction to supply enough water for the water/shift reaction. This steam loss from the bottoming cycle represents a decrease in the steam turbine power resulting in a reduction in overall plant efficiency. Other factors such as the auxiliary load of the Acid Gas Removal and the steam consumed by the Gasifier also have an effect.

Figure 8 shows a schematic of how the plant efficiency is affected by each one of the factors involved for a 73% and a 92% CO_2 capture rate.
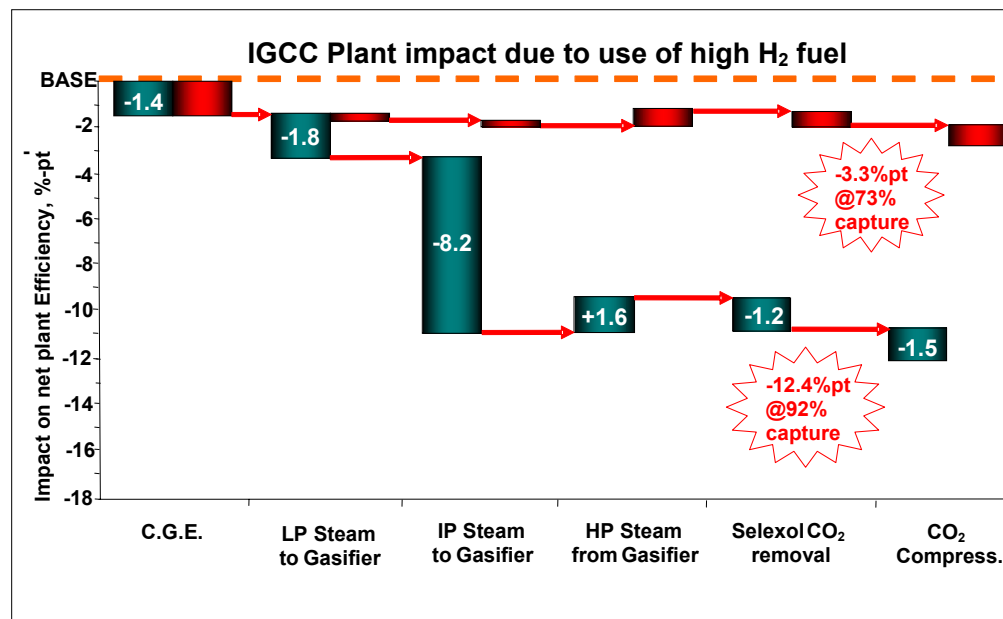
Figure 8. IGCC Plant Efficiency Impacts

As shown in the figure above, the most significant factor reducing the plant efficiency for the high carbon capture cases is the required intermediate pressure steam extraction for the water/gas shift reaction. This analysis explains why the Gasifier that uses a quench system to reduce the temperature of the raw syngas is more efficient for high carbon capture cases because the steam is already contained in the syngas. For syngas cases a Gasifier that uses a Syngas Cooler instead of the quench system will result in a higher IGCC efficiency due to the possibility of recovering the heat at a higher level with the production of high pressure steam exported to the bottoming cycle. These two configurations will be used as the baseline for using Syngas (Syngas Cooler) or Hydrogen (Quench System) in the gas turbine.

A study was performed using Exhaust Gas Recirculation (EGR) in the gas turbine. Integration with the bottoming cycle was required in order to cool the exhaust gas to the desired temperature. The exhaust gas was initially cooled in the heat recovery steam generator (HRSG) where the EGR was later extracted and further cooled using circulating water which had the coldest available temperature in the cycle. Auxiliary loads were considered for the additional cooling.

Advanced bottoming cycles with steam turbine inlet temperature above 600°C were modeled to determine the impact of being able to use an increased gas turbine exhaust temperature in the most efficient way. It was determined that for the same gas turbine configuration, the benefit in overall plant performance was approximately 0.8% points.

The Plant Concept was defined for the following scope and base reference conditions:

- Scope is from coal pile to high-side of Generator Step-up Transformers
- Ambient conditions : 15°C / 60% RH / Sea Level
- Coal Type: Bituminous Herrin # 6, AR HHV = 26,750 kJ/kg (see Table 1).
- Electrical: Frequency = 60 Hz, Power Factor = 0.9 lagging
- Air Integration is used in the Syngas Case
- Oxygen purity when applicable: 95% mol
- 90% Carbon Capture Rate
- CO_2 compression to 152 bara

Table 2 summarizes the IGCC plant systems that were used for the baseline and will be used for the 2015 evaluation.

Constituents	%
Carbon	63.36
Hydrogen	3.91
Nitrogen	0.82
Sulfur	2.63
Oxygen	9.28
Chlorine	0.03
Ash	10.0
Moisture	10.0

Table 1. As Received Coal Composition

SYSTEM	BASELINE	2015
Gasifier	Slurry fed 2-stage and Dry fed 1-stage	Slurry fed 2-stage and Dry fed 1-stage
Raw Syngas Cooling	Syngas cooler (syngas) Water quench (H_2 fuel)	HP Syngas cooler (syngas) Water quench (H_2 fuel)
CO Shift	2-stage with inter-cooling HP/IP/LP Steam gen.	2-stage with inter-cooling HP/IP/LP Steam gen.
Low Temperature Heat Recovery (LTHR)	Steam gen -> Fuel sat -> Cond heat -> Reject	Steam gen -> Fuel sat -> Cond heat -> Reject
Air Separation Unit (ASU)	Cryogenic (HP)	Cryogenic, HP or LP depending on PB Air Ext & N_2 diluent interfaces
Acid Gas Removal (AGR)	Selexol	Selexol
CO_2 Compression	0.11 kWh/kg	<0.11 kWh/kg –Possible increase in efficiencies.

Table 2. IGCC Plant Systems

The assumptions for the Gasifier, raw Syngas cooling, CO Shift, Low Temperature Heat Recovery and Acid Gas Removal will maintained fixed without assuming any improvement for the future analysis. Improvements on compressor efficiencies due to increase in size will be studied for the Air Separation Unit (ASU) and the CO_2 compression system for the 2015 application.

Design Turbine changes have a significant impact on the cycle design. Cycle design takes into consideration these GT changes so as to utilize in the most efficient way the energy contained in the exhaust. The bottoming cycle is also in charge of supplying or receiving steam from other systems such as the Gasifier, syngas cooler or the acid gas removal. The power block is optimized to meet the integration requirements with all the IGCC systems.

The gas turbine changes that will have an impact on the cycle are:
- Exhaust temperature: Higher water/steam cycle temperature, higher steam turbine efficiencies due to increased inlet temperatures.
- Exhaust flow:
  - Higher steam turbine main stream pressures
  - Reduced steam turbine leakage (proportional to total flow)
  - Possibility of Ultra Super Critical Steam
  - Zoned condenser: for two double flow low pressure steam turbines
  - Higher generator efficiencies due to increase in size

- Pressure ratio: More efficient use of air extraction and rotor air cooler heat, possibility of using high pressure recovery steam generators.

- Combustor Design Emissions: Dilution requirements.

- Combustor Design Temperature: Higher temperatures will require fuel pre-heating using high pressure water.

- Compressor Design: Air extraction flexibility

Conclusion

Multiple studies were conducted to evaluate the impact on plant performance of different gas turbine designs or plant requirements (high carbon capture). It is important to integrate the bottoming cycle with the multiple systems involved in the plant to make the most efficient use of the energy flow from coal to the grid. The IGCC plant concept described above limits the baseline to study the benefits in plant performance from changes only in the gas turbine and the power block.

Efficiency Improvements

Approach

Siemens has proposed a two step approach to meeting the DOE efficiency goals for 2010 and 2015 timeframes. The starting point, or baseline, for this technology progression is the SGT6-5000F which has been adapted to IGCC and is now commercially available. Figure 3 illustrates the two step approach.

Initial estimates of the IGCC plant efficiencies concluded that in order to reach the 2015 efficiency goals set forth by the DOE, the operating conditions would need to be further enhanced and new technologies would be required to facilitate these upgraded conditions. With the end goal of identifying technology needs, the key contributing parameters of the gas turbine thermodynamic cycle which influence the overall IGCC plant performance were identified. Figure 4 shows the Siemens technology areas driven by the plant level goals specified by the DOE.

Design of Experiments

A systematic and efficient process was needed to evaluate the wide range and numerous potential combinations of gas turbine parameters. A DoE approach was selected to narrow down the engine parameters to investigate and potentially determine an optimum parameter set which maximizes the IGCC plant performance. The following four parameters were selected: turbine inlet temperature (TIT), pressure ratio (PR), ASU type and dilution level. Cases were run on hydrogen fuel to establish the optimum engine design parameters to be used in the GT conceptual design. Figure 9 shows the DoE approach for TIT, PR / Exhaust Temperature, and ASU type. The effects of varying pressure ratio is depicted by the change in exhaust temperature.
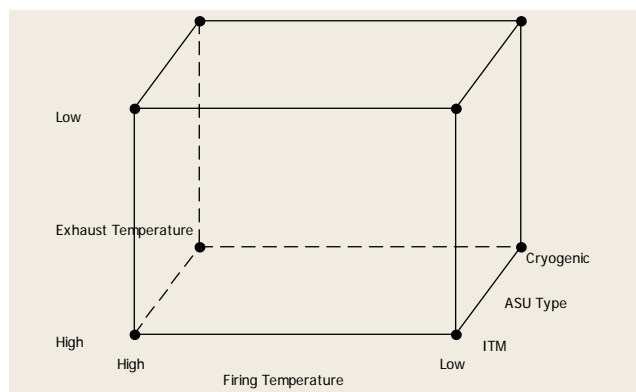

Figure 9. Design of Experiments Parameters

Air Separation Types

Two technologies were considered for the air separation system studies: Cryogenic type and Ion Transport Membrane (ITM) type. See Plant Integration for a more comprehensive description and the plant modeling assumptions. In regard to the gas turbine efficiency and more specifically the DoE process, the Cryogenic system does not affect the gas turbine thermodynamic assumptions, however, because the oxygen depleted air was returned to the gas turbine for the ITM system (See Figure 6, Plant Integration), an overall pressure loss was assumed through the ITM and external piping to most accurately predict the performance influence when integrated with this system type. In addition, the return air to the gas turbine was assumed to be cooled by a recuperator.

Gas Turbine Air Integration

There are two main reasons for utilizing air integration: 1) To reduce the amount of auxiliary power needed by the air separation unit by using high pressure air already available in the gas turbine, and 2) To provide a means to lower the mass flow through the turbine. The latter is especially important with fuels such as syngas which have a lower heating value and therefore require more fuel flow. In the 2010 technology studies, the amount of air integration was considered when optimizing the engine parameters. The mass flow was also varied by means of modulating the inlet guide vanes (IGV) and the pressure ratio was varied through mass flow adjustments and also by changing the vane 1 angle (see Figure 10).
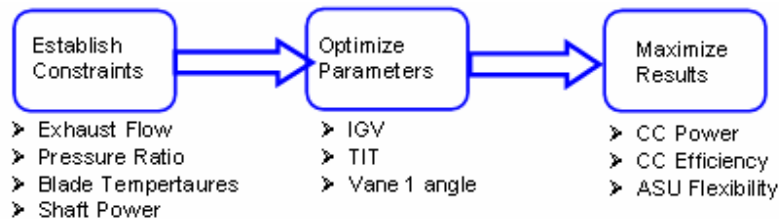
Figure 10. Technical Approach for 2010 Technology Study

For the 2015 air integration studies, the design space was expanded to allow for further optimization. In these cases, the turbine annulus was varied such that the effect of increased mass flow had minimal effect on the turbine efficiency (See figure 42, Turbine Section). This approach served the following two purposes: first, the efficiency impact of air integration could be almost isolated from the effect of mass flow in the turbine, and secondly, the optimum annulus size could be estimated based on an overall plant efficiency basis.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) was evaluated as a NOx reduction method. See Combustion section of the report. The performance impacts of employing EGR needed to be quantified to determine the impact to plant performance. Using syngas as a fuel, iterations were made until the combustor exit O_2 was approximately 2%. The exhaust gas was cooled prior to injection into the compressor inlet and turbine cooling and efficiency were held constant.

Results and Discussion

Two Step Approach

The baseline or state of the art system incorporates SGT6-5000F gas turbines adapted to an IGCC plant described in Table 1, Plant Integration. The performance for this 2X1 syngas based IGCC plant efficiency was predicted to be 39.5% HHV using Illinois #6 coal specified in Table 2, Plant Integration. To meet the 2010 efficiency targets set by the DOE, the SGT6-6000G technology level was evaluated. With the exhaust flow, pressure ratio, bleed temperatures, and shaft power constraints considered, variations of flow and turbine inlet temperature resulted in an optimum parameter set for this technology level. The study was conducted using the same baseline plant model and as received coal. It was found that the 2010 goal of 2-3% points improvement in efficiency could be met with this technology level, however, the engine conditions above the G technology level were needed to meet the 2015 efficiency targets of 3-5% points improvement above the baseline. The results of the performance range, net HHV % efficiency and net plant output in MW, calculations for syngas fuel is summarized are in Figure 11.
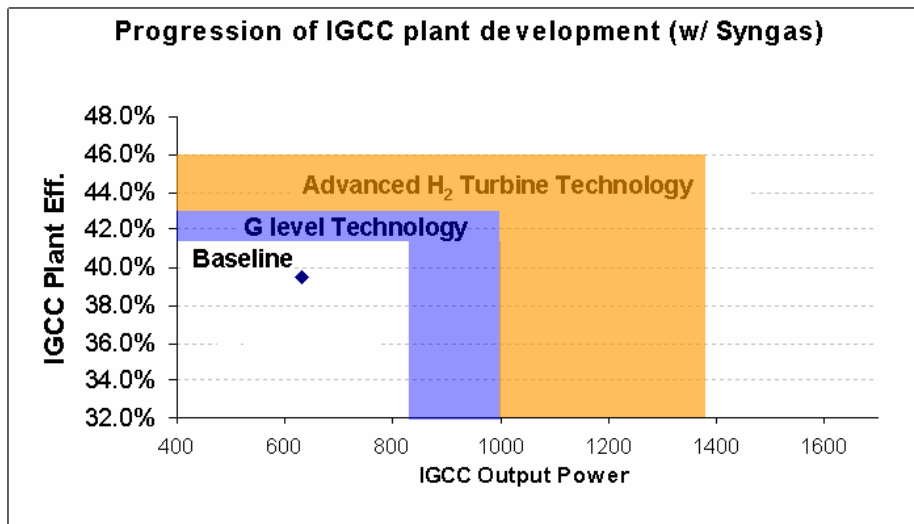
Figure 11. IGCC Performance Progression with Syngas Fuel

Design of Experiments

The advanced hydrogen turbine technology needed to maximize IGCC performance is driven by plant level goals as described in Figure 4 through establishing engine cycle parameters. First a set of 10 thermodynamic calculations bounding the range of parameters selected was performed in support of the DoE and the results were processed to determine the effects of each. The main effects plot, Figure 12, below shows the results of the first part the DoE exercise.
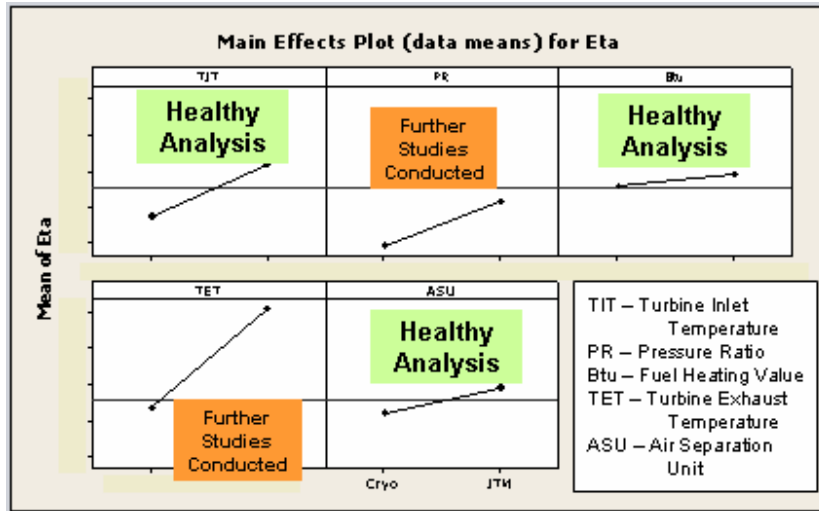
Figure 12. Design of Experiments – Main Effects Plot

The analysis concluded that higher TIT and Fuel heating value resulted in improved efficiency. Also, Ion Transport Membrane (ITM) improves efficiency over Cryogenic ASU primarily due to the reduction in auxiliary power consumption. See Plant Integration section for further discussion of this technology.

The turbine exit temperature (TET) and pressure ratio (PR) analysis was inconclusive and required additional studies. The reason for this is that the analysis showed that both PR and exhaust temperature improved efficiency, but these parameters are thermodynamically opposing, i.e. as pressure ratio is increased, exhaust temperature actually decreases. It was concluded that the DoE analysis was unable to capture the inflection or optimum point for pressure ratio which would be expected for a combined cycle optimization study. Therefore, the further analysis of pressure ratio and exhaust temperature was completed at fixed turbine inlet temperature using ITM ASU type and high hydrogen fuel. Figure 13 below shows the findings of the pressure ratio study, as summarized below:

1. At high turbine inlet temperature, higher pressure ratios are necessary to maximize overall plant performance.
2. A desirable pressure ratio range was found to be 28-32 for the cycle parameters evaluated.
3. The number of turbine stages becomes a limiting factor at higher pressure ratios.
4. The exhaust temperature becomes a limiting factor at lower pressure ratios.
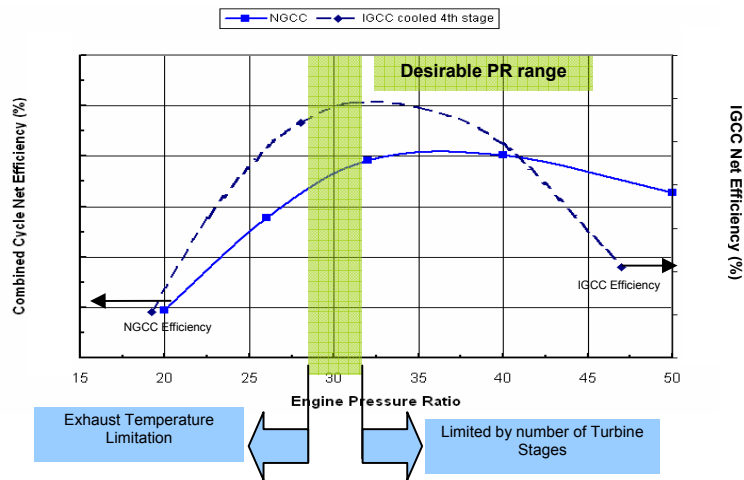
Figure 13. Design of Experiments – Main Effects Plot

2015 Component Efficiency Targets

The underlying technology advancements to achieve the objective of increased cycle efficiency are driven by the upgrades to engine operating temperature above G class firing temperature (Nominal 1427°C [2600°F] Rotor Inlet) pressure ratio as well as increased component efficiencies. In comparison to the baseline gas turbine the following improvements were achieved:

- Gas turbine power output was increased by a factor of 1.5 – 2.0
- Compressor efficiency improved by 1.0-1.5% points
- Turbine efficiency improved by 1.0-2.0 % points
- Cooling and leakage reduced by 20-30%
- Gas turbine exhaust temperature was increased by 10-20%

Technology insertion studies were utilized to establish the ranges of targeted component efficiencies. Concepts for advanced aerodynamics, heat transfer, cooling design, coatings, etc, as described in the component sections of this report, provide the input for these projections.

Gas Turbine Air Integration

A flexible gas turbine design in IGCC applications could facilitate integration with advanced gasifiers and air separation systems. While these systems are outside the scope of this development, the potential impacts to the gas turbine design could be anticipated. Air extraction from the gas turbine can be used to supplement or fully replace the need for a main air compressor in the ASU, or extraction could be necessary for applications such as ITM. For a fixed turbine design as assumed in the baseline, a level of extraction would be required so as to not exceed turbine flow limits or compressor surge margin. A study conducted for the 2010 efficiency target considered constraints in existing G class technology and optimization of turbine parameters was carried out. As shown in Figure 14, a concept is possible by which the engine could operate a wide range of air integration, across ambient temperatures, with zero extraction even with a fuel dilution level consistent with diffusion type combustors.

Compressor Air Extraction vs Ambient
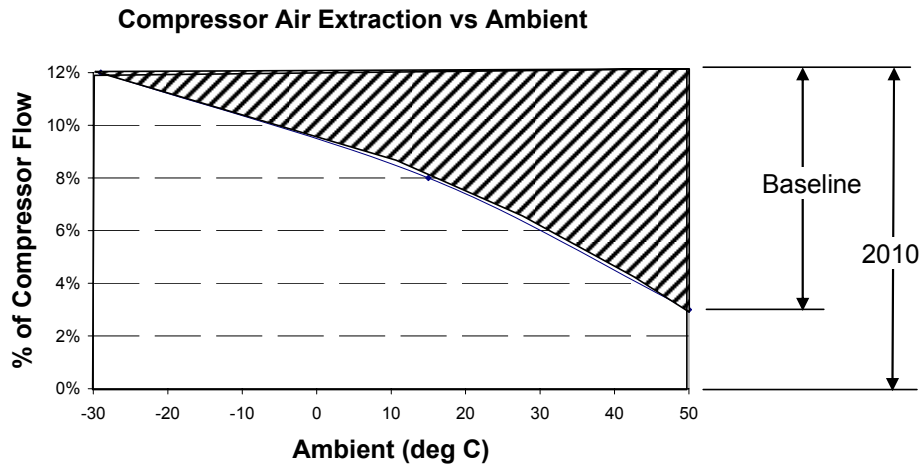
Figure 14. Air Extraction Flexibility with 2010 Technology

For the 2015 concept, several cases were run with varying air extraction levels, but in addition, the turbine annulus was optimized for each case. The results showed that the lower extraction case with the largest turbine annulus, produced the highest output and performance. Table 3 shows the performance deltas from a 75% integration case. Also, as can be seen in Figure 42, Turbine section, an increased turbine annulus is robust to flow variation and thereby provides the optimum solution for air extraction flexibility.

AIR SEPARATION TYPE	Cryogenic	Cryogenic	Cryogenic
ASU AIR INTEGRATION (%)	25	50	75
COMPRESSOR INLET MASS FLOW	Fixed		
DELTA PLANT OUTPUT, MW	+212	+100	-
DELTA PLANT EFFICIENCY, % (HHV)	+1.3	+0.7	-

Table 3. 2015 Air Integration Study

EGR study

The approach taken yielded an estimated performance debit of approximately 0.3% points compared to the non EGR case. A few technical concerns were noted which would require further investigation if EGR was pursued to reduce NOx emissions. The potential for SO_2 condensate in the EGR cooler would need to be further investigated, the effects of SO_2 and other non-typical constituents entering the compressor and ASU would need to be fully understood, and the effects of the ASU extraction air on balance of plant auxiliary loads in the ASU would have to be further refined (only roughly estimated for this analysis).

Conclusions

Thermodynamic calculations show that the DOE 2010 and 2015 efficiency targets can be met with the proposed two step approach. A DoE approach confirmed the leading contributors to IGCC plant performance are gas turbine firing temperature and exhaust temperature. The experiment also found an optimum pressure ratio for high firing temperature to be in a range of 28-32. The 2010 approach is flexible to a wide range of air integration, and the 2015 approach employs an increased turbine annulus to provide robustness to flow variation and thereby the most flexible gas turbine system. To achieve the 2015 efficiency goals, improvements are necessary in the gas turbine, such as increased output and component efficiencies. Exhaust Gas Recirculation (EGR) is thermodynamically feasible but raises technical concerns in IGCC applications which would require further investigation if this technology were to be pursued.

GT Integration

Approach

The GT Integration task focused on developing and maintaining key revision controlled interface data for the project team including physical and boundary data, developing a secondary air systems model, constructing a whole engine finite element model and instituting a risk management process.

The secondary air systems model integrates compressor, combustor, and turbine systems and is used to provide boundary data for sealing and cooling development, and as input to the whole engine finite element model. Figure 15 illustrates the iterative process used to integrate the turbine and compressor systems.
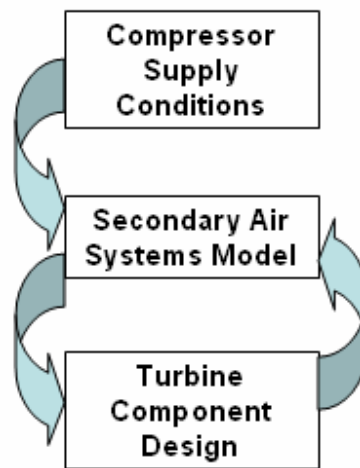
Figure 15. Integration of Turbine and Compressor Systems

Information from the longitudinal database and secondary air systems model was utilized to construct a conceptual whole engine finite element model and to calculate preliminary component temperatures and overall engine thermal behavior.

A comprehensive risk assessment was done for the entire engine, auxiliaries, and plant concepts. The Siemens risk management process (see Figure 16) was utilized to ensure testing, development, and validation plans are in place for Phase 2 to mitigate the identified risks.

Figure 16. Risk Management Process

Results and discussion

Layouts of component concepts were integrated into the longitudinal database. Continuous updates were managed in the database and three revisions were issued during Phase 1. The overall engine layout successfully integrated the various concepts and a first assessment of engine length and shipping envelope was found to be within acceptable limits based on past engine developments. An interface data base was also developed to provide revision controlled boundary data to the component teams. The longitudinal was used as the basis for development of the whole engine model and also provided physical data for the secondary air systems model and thrust calculations. Workshops were conducted to generate concepts for with ITM air separation systems. Three main ITM integration scenarios were identified integration as well as sketches of various engine configuration concepts which could potentially manage the interfaces (see Figure 17).
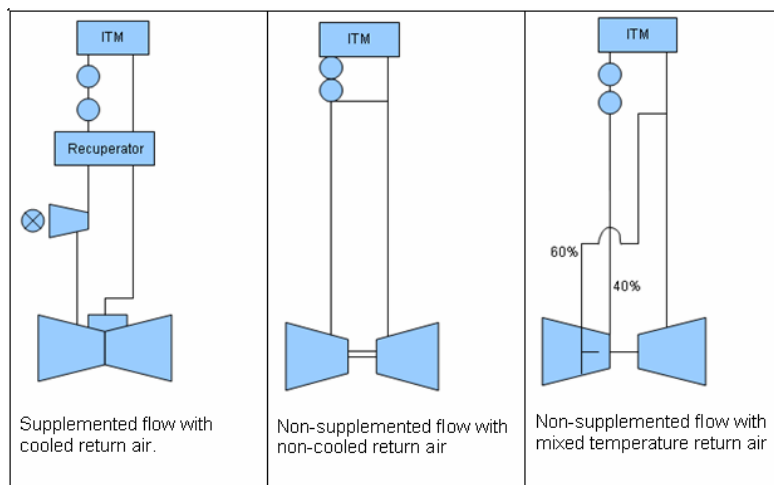
Figure 17. ITM Integration Scenarios

The secondary air system model was based on input from the compressor, turbine, and other components. Iterations with component design teams resulted in a converged system which identified needs for improved sealing in various areas and confirmed component estimates for cooling supply conditions. A whole engine model was constructed with input from the longitudinal database and secondary air systems model. Estimated thermal displacements from the whole engine model are being utilized for sealing concept development and as input to the rotor and casing design teams.

The results of the risk assessment were compiled from workshops conducted with each of the subtask teams. The risk assessment was conducted to identify areas where testing, development and validation approaches are necessary to mitigate risks. A risk breakdown structure was created to ensure risks are categorized for monitoring throughout the risk management process and the identified risks were plotted for each subtask through the use of plausibility charts (see Figure 18). This type of reporting is good for projects which are in the early development stages, where impacts are difficult to quantify and probabilities are more qualitatively based on expert opinion and past experience.
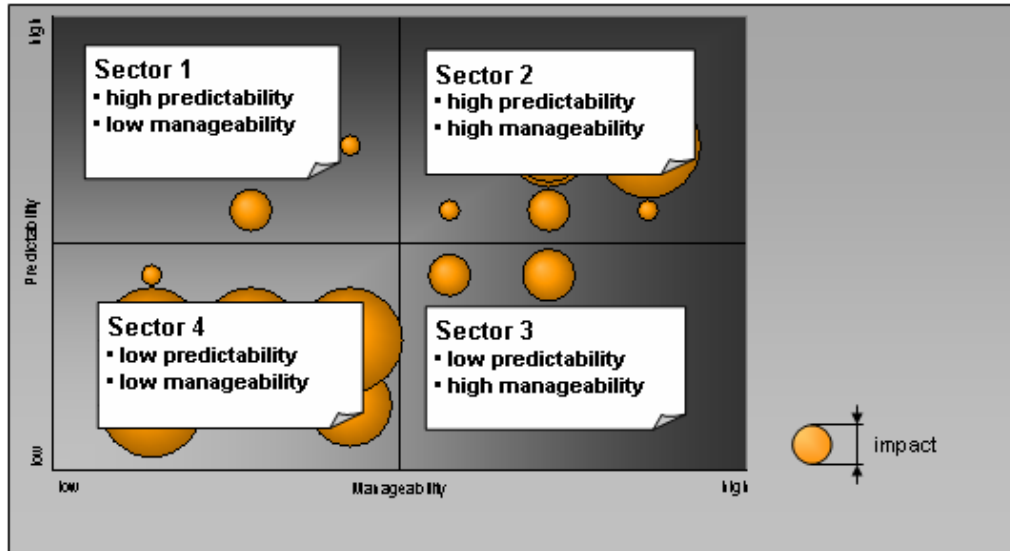
Figure 18. Sample Plausibility Chart

Sector 1:

There should be only a relatively in low number of uncertainties in this sector, especially for R&D projects (compared to the other sectors). Because of the nature of R&D, uncertainties in this sector are indicating that experiences are available but there is very limited control or mitigation.

Sector 2:

Typically there are some uncertainties in this sector for R&D projects related to side issues. It should not be the major part of all issues. Uncertainties are indicating that experiences are available, but the ability to mitigate them is high.

Sector 3:

The major portion of all uncertainties is expected to be here in typical R&D projects. High impact for some issues in this area is not avoidable (nature of R&D). The level of experience available is typically low or medium. The issues are not state of the art (SOTA), but feasibility seems to be medium or high. It can be tested and/or simulated and it is related to core competencies of Siemens or the major influence factors are driven by Siemens.

Sector 4:

There should be only a relatively low number of uncertainties in this sector, especially for R&D projects. Uncertainties are indicating that success of the R&D project is highly dependent on the success of other related R&D which cannot be controlled under the current project.

The results of the risk assessment showed no Sector 1 uncertainties and very few Sector 4 uncertainties. Sector 4 uncertainties were associated with technologies or components supplied by outside vendors which were in some way changed from current state of the art. However, in

most cases, new technology development was not anticipated and close coordination with suppliers throughout the development phase would increase the manageability of these uncertainties and thus mitigate risks.

The majority of risks were in Sectors 2 and 3 as expected. For each of these identified risks, a plan was developed for mitigation, including development, testing and validation of new technologies.

High impact uncertainties were identified based primarily on performance and emissions effects. There was not sufficient detail on a component level to evaluate cost uncertainties. However, the potential cost impact of increasing technology levels is understood to be a challenge for reaching the DOE targets. All major uncertainties are addressed with testing and development plans.

Conclusions

The GT Integration task is managing the interfaces with component areas by use of revision controlled databases for the longitudinal cross section and boundary data information. A secondary air system model was developed to integrate the compressor, turbine and other components. The initial results of this model have identified areas for sealing improvements. A whole engine model is being utilized to estimate thermal behavior of the engine to provide key interface data for sealing design displacements and component temperatures. A risk management process was instituted in Phase 1 to identify risk and develop mitigation plans. For the risks identified, testing and development programs are in place and the risks will be revisited periodically to determine if changes to the plan are necessary.

Compressor

Approach

A 1D meanline compressor performance prediction tool was utilized to predict the performance and surge margin of various compressor configurations to meet the engine cycle requirements. Tip clearance effects on performance were studied.

Results and Discussion

The advantages of the meanline code are that it has a design mode, it is faster to run a whole speed line than a 2D throughflow code and it has a built in surge criterion. Also, it has a tip clearance model, which is important for this compressor with small rear stage blade heights.

The current engine cycle pressure ratio is not finalized, therefore low pressure ratio and high pressure ratio designs were investigated in an attempt to bound the problem. Depending on the level of integration, there is a range of inlet mass flows to the compressor being considered. Therefore, a range of pressure ratios and mass flows were considered, resulting in four possible operating boundaries which were all assessed with the 1D meanline code.

The compressor design builds on the current Advanced Compressor design with additional stages added to the rear to meet the pressure ratio requirement. In addition, for each of the four operating points considered (high flow, high pressure ratio; low flow, high pressure ratio; high flow, low pressure ratio and low flow, low pressure ratio), two different configurations were studied; one with higher aspect ratios and lower solidities and the other with lower aspect ratios and higher solidities.

All configurations were designed to have the same OGV exit Mach number and design point surge margin level. The low aspect ratio cases actually result in a longer compressor but with a lower part count because of the one less stage.

Within the studies, the level of integration (air bled from the combustor shell for plant use) changed during operation, the required compressor mass flow was varied, and the compressor was maintained at a constant pressure ratio. This resulted in a significant change to the compressor operating line and hence the available surge margin (see Figure 19).
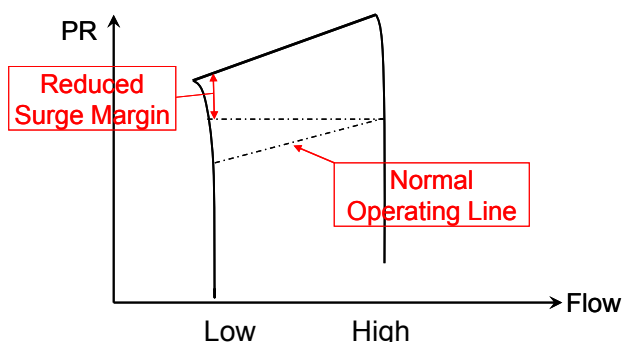
Figure 19. Surge Margin Variation with Compressor Design Mass Flow

The various configurations were conducted at alternate flow conditions and the impact on efficiency and surge margin was assessed (see Table 4).

Configuration	hi flo hi pr	hi flo hi pr	lo flo hi pr	lo flo hi pr	lo flo lo pr	lo flo lo pr	hi flo lo pr	hi flo lo pr
Delta Eta [%]	-0.1	0.0	0.0	-0.4	-0.2	-0.2	0.2	-0.3
Surge Margin [%]	22.3	22.1	33.6	34.7	33.6	34.1	22.7	22.9
Delta SM [%]	-5.4	-5.8	4.8	5.0	5.0	5.0	-5.1	-6.0

Table 4. Result of Compressor Design at the Alternate Flow Condition

As would be expected, going from the low flow to the high flow gives an increase in surge margin (up to 5%), but the lower operating line gives a less efficient compressor. Going in the other direction (from high flow to low flow) causes an expected decrease in surge margin. The effect on efficiency is relatively small.

With decreasing blade height, tip clearance to height ratios will increase. Unless measures are taken to improve tip clearance control, increasing rotor length and higher temperatures will cause the tip clearances to become larger. The model used in the calculations assumed the current tip clearance for the last stage of the Advanced Compressor and this clearance level was then assumed for the additional stages. This resulted in increasing tip clearance to height ratio for the additional stages.

For the high flow, low PR case, with high aspect ratio airfoils and lower solidities, a tip clearance sensitivity study was conducted, where the clearance of the additional stages was increased up to double the baseline value and then reduced down to zero (for the entire compressor) in order to see the potential efficiency improvements achievable with better tip clearance control.
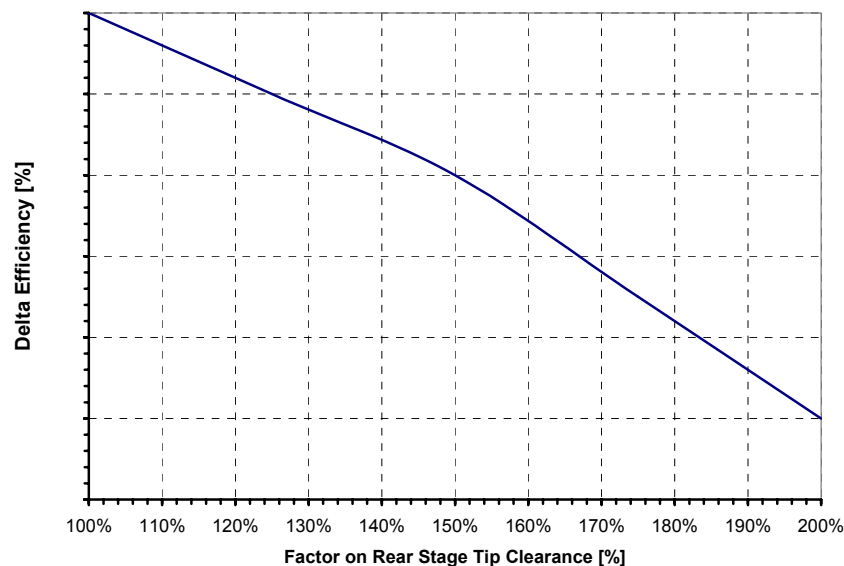
Figure 20. Impact on Compressor Efficiency of Increasing Rear Stage Tip Clearances

Figure 20 shows that doubling the rear stage tip clearances will cause a loss of compressor efficiency. The increase in clearance will also result in a loss of surge margin, which, if too severe, could require an additional stage in the compressor design.
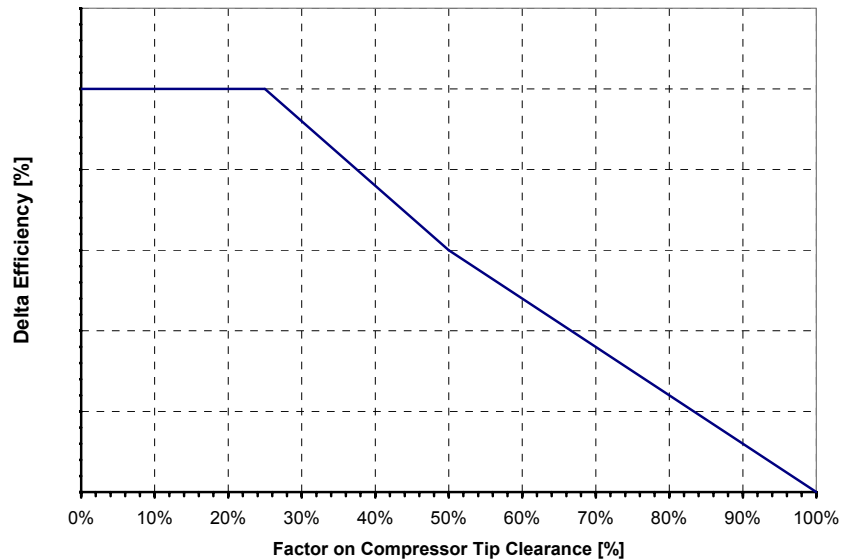
Figure 21. Impact on Compressor Efficiency of Decreasing Compressor Tip Clearances

Figure 21 shows the potential benefits of better tip clearance control on the compressor's performance, as predicted by the 1D meanline program.

Conclusions

A 1D meanline compressor performance prediction tool has shown that the design of the compressor for the engine can be achieved with the addition of between 2 and 4 stages (depending on the cycle pressure ratio) to the rear of the current Advanced Compressor. With higher aspect ratio and lower solidity airfoils, the same design can be achieved with 3 to 5 additional stages (i.e. one further additional stage). This results in a shorter rotor length with a higher part count. These results assume the current last stage clearance values can be maintained for the additional stages. Any increase in clearance will reduce the compressor efficiency and available surge margin but there are potential efficiency gains that can be achieved by bettering current level of tip clearances. Further studies using 2D and 3D CFD tools will be conducted to further assess the impact of tip clearances on the compressor's performance.

Combustion

Approach

Four potential combustion systems were evaluated to meet the program targets for emissions and engine efficiency on syngas and hydrogen fuels. These included the diffusion system, the premixed system, the catalytic system and the distributed combustion system. Preliminary design work and prototype testing was performed on each of these designs to evaluate the potential to meet the program goals when operating on syngas and hydrogen fuels. A final down selection was performed and the premixed and distributed combustion systems were selected as the focus for further development for Phase 2 of the program. Through University collaboration, fundamental data on laminar flame speeds and ignition delay for syngas and hydrogen gas mixtures was obtained. This data will be employed during Phase 2 to develop the design tools necessary to design an advanced gas turbine combustor for operation on syngas and hydrogen fuels.

Results and Discussion

University Support

Most of the design tools for gas turbine combustors have been developed for natural gas fuel. It is expected that operation on syngas and hydrogen will require a substantial modification to these tools. As part of this program it was recognized that there was a lack of fundamental chemical kinetic data for syngas and gases with high hydrogen concentrations. University programs were initiated with the University of Central Florida and with Georgia Institute of Technology to obtain the fundamental data necessary for gas turbine design with syngas and hydrogen.

Ignition Delay Experiments at University of Central Florida (UCF)

The ignition delay measurements in the UCF shock tube were completed. These experiments produced data for H_2 and $H_2/CO/CO_2/CH_4$ mixtures at pressures up to 30 atmospheres with various levels of water dilution. Experimental work was performed at the UCF shock tube facility shown in Figure 22. The goal of these experiments was to obtain the ignition delay data necessary to validate the chemical kinetic models for hydrogen and syngas mixtures in the range of conditions important to gas turbine combustion.
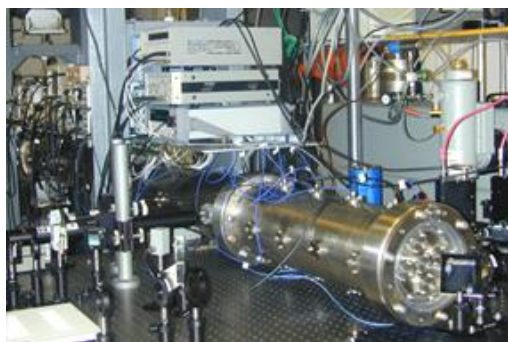
Figure 22. UCF Shock Tube Facility

During this program, ignition delay data were obtained for the temperatures in the range 800°K to 1300°K and pressures ranging from 8 to 30 atmospheres. Gas mixtures were tested for a variety of fuels typical of syngas from IGCC applications with and without carbon capture technology and including various levels of dilution. During this program some areas were identified where the existing models deviate from the experimentally measured ignition delay times. Figure 23 shows an example of one area where there is a significant variation between the models and the experiment in the low temperature region.
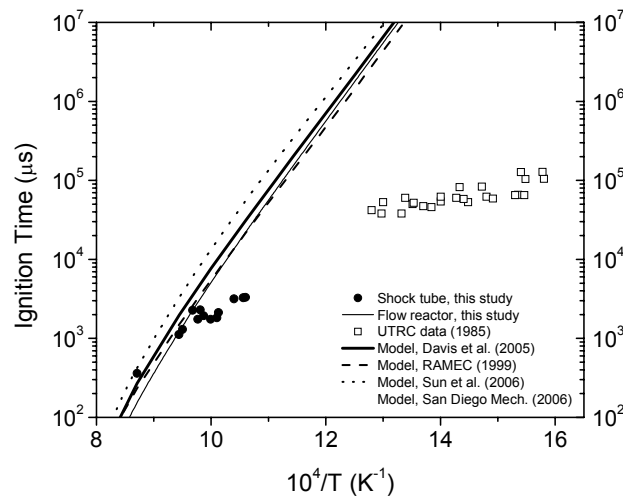
Figure 23. Ignition Delay Data for Syngas

Figure 24 shows the impact of water addition on the measured ignition delay for a typical syngas mixture. As expected, the addition of water increases the ignition delay times and this trend is predicted by the model.
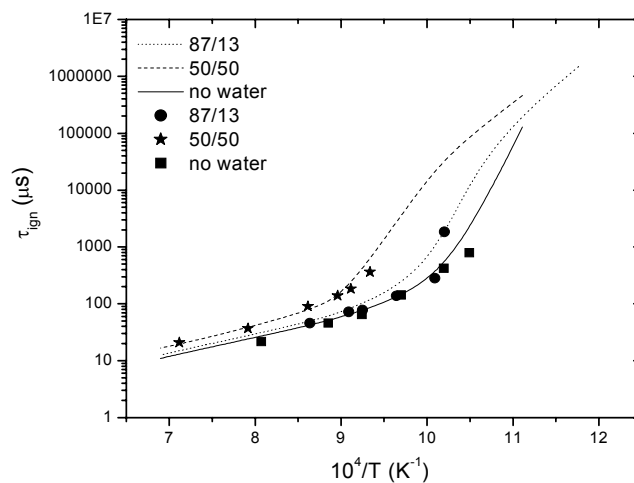
Figure 24. Effect of Water Injection on Ignition Delay Time

Flame Speed Experiments at Georgia Institute of Technology (GT)

The laminar flame speed measurements at Georgia Institute of Technology were completed. Laminar flame speed measurements have been performed on H_2/CO mixtures at pressures up to 20 atmospheres. Initial work was performed on turbulent flame speeds for H_2/CO mixtures.

The goal of the Georgia tech program was to obtain laminar flame speed data for H_2/CO mixtures at elevated pressures up to 30 atmospheres. Figure 25 shows the test rig used for the Georgia Tech flame speed experiments. Because of the high flame speeds of these mixtures it is only possible to obtain laminar flame speed data for strained flames or flames with helium dilution. Figure 26 shows data obtained for strained flames compared to the modeling results from the CHEMKIN OPPDIFF code. Figure 27 shows data obtained for diluted flames with O_2/He (10:90) as the oxidizer compared with model calculation using the CHEMKIN PREMIX code. The model calculations were performed with the GRI[2], Davis[3] and Li[4] chemical kinetic mechanisms. During this phase of the program laminar flame speed data was obtained for H_2/CO mixtures at pressures up to 20 atmospheres. In Phase 2 this laminar flame speed data will be used along with the ignition delay measurement from UCF to update the existing chemical kinetic mechanisms to include syngas and fuels with high hydrogen content. In addition to updating the detailed chemical kinetic mechanism for typical syngas fuels, simplified chemical kinetic mechanisms will be developed for use in CFD modeling.
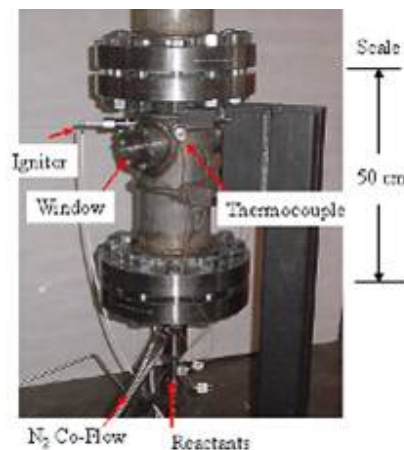
Figure 25. Flame Speed Rig at Georgia Tech
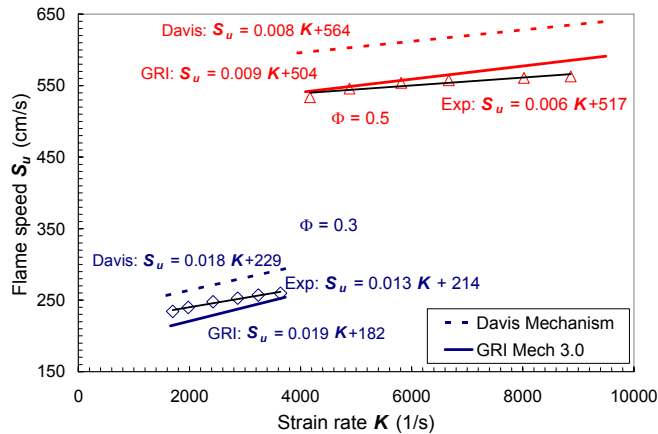
Figure 26. Flame Speed Measurements for Strained Flames
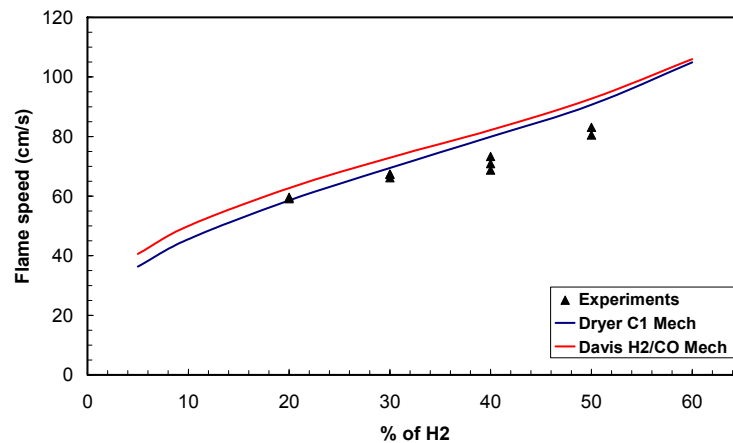
Figure 27. Laminar Flame Speeds of H_2/CO Flames at 15 atm and 600 K and Phi =0.6

Design of a flashback resistant premixed combustor for fuels with high hydrogen content requires knowledge of the turbulent flame speed of the mixture. The turbulent burning velocity is dependent not only on the chemistry of the flame but also on the properties of the turbulence of the flow. Turbulent flame speed data are available for natural gas flames but only limited data are available for H_2/CO mixtures at conditions of interest to gas turbine combustors. The next step in this program is to obtain turbulent flame speed data for H_2/CO mixtures at elevated pressures.

Diffusion Flame Combustion

In the diffusion flame combustion system the fuel and air enter the combustor in separate streams and react in the combustion zone. This design produces a highly stable combustion system and is commonly used for alternative fuels. The disadvantage of the diffusion flame combustion system is that it produces high NOx emissions and requires a significant amount of dilution flow with either steam or nitrogen to meet current emission targets. During this program the diffusion flame combustor for the SGT6-5000F was

adapted to syngas and high hydrogen fuels. High pressure rig testing was performed on this design.

Catalytic Combustion

The catalytic combustor has the potential for the lowest emissions of any design. Under DOE contract, DE-FC26-03NT41891, Siemens has been developing a fuel flexible catalytic combustion system using the RCL^{TM} (Rich Catalytic Lean) technology for application to the SGT6-5000F engine operating in IGCC. The modifications to this design necessary for syngas operation have been identified and subscale module testing has been performed to verify this design.

Premixed Combustion

The premixed combustion system represents the state of the art in low NOx combustion systems for natural gas operation. In this program the Siemens ULN gas turbine combustor was modified for fuel flexible operation on natural gas, syngas and hydrogen. Initial testing was performed with diluted hydrogen gas and the results were encouraging but several challenges remain to be solved.

Distributed Combustion

The distributed combustion system adds an additional stage downstream of the main combustion zone. This additional stage reduces NOx emissions by reducing the residence time at high temperatures and reduces combustor dynamics by spreading the reaction zone. As part of this program, a prototype transition was designed with the capability of fuel injection. This design was tested and a substantial improvement in both NOx emissions and combustor dynamics was obtained at elevated firing temperatures.

Combustion System Evaluation

In Phase 1 of this program the diffusion flame, catalytic, premixed and distributed combustion systems were studied for applicability to IGCC and potential to meet the program goals. As part of this evaluation, initial design work and prototype testing was performed for each of the candidate designs.

Diffusion Combustion System

In the diffusion flame combustion system the fuel and air are injected into the combustion system as separate streams and they mix together and burn in the reaction zone. In this program the Siemens diffusion flame combustor was adapted to syngas operation in the SGT6-5000F engine. High pressure testing of the diffusion flame combustion system was performed for syngas and hydrogen at conditions typical of the SGT6-5000F. The impact of steam and nitrogen dilution was studied and firing temperatures were increased to SGT6-6000G conditions. Stable operation was achieved on all loads and NOx emissions below 15 ppm NOx were achievable on both fuels with either nitrogen or steam dilution. Figure 28 shows the emissions results for different fuels and dilutions as a function of stoichiometric flame temperature. With sufficient dilution it is possible to achieve low emission with this design.
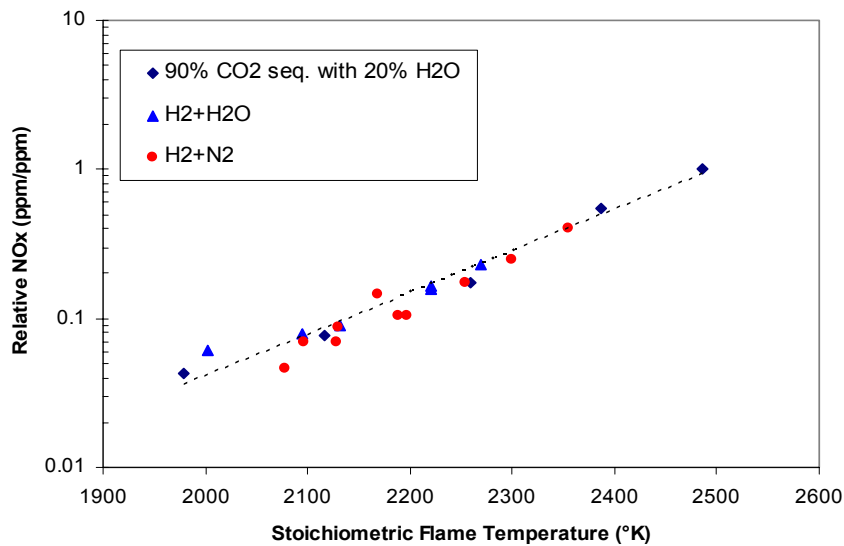
Figure 28. Emissions Data from the Diffusion Flame Combustor

Catalytic Combustion System

As part of DOE contract DE-FC26-03NT41891 Siemens has been developing a fuel flexible catalytic combustor for application to the SGT6-5000F engine operating on syngas. This design utilizes the RCL^{TM} (rich catalytic lean) technology where a portion of the fuel is mixed with the air and reacts in the presence of a catalyst at conditions above the rich flammability limit. The remaining air is used to backside cool the catalyst. At the exit of the catalyst reactor both streams mix and they react in the homogeneous combustion zone. Figure 29 illustrates the basic concept for the catalytic stabilized combustor.
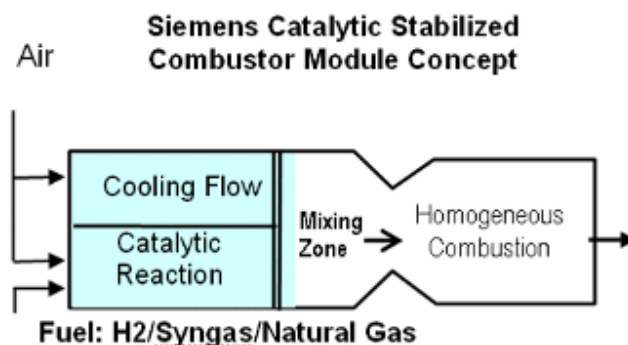
Figure 29. RCL Catalytic Combustion Concept

For natural gas operation, a catalytic module was designed based on the rich catalytic concept and a catalytic basket was designed using six catalytic modules. This design has shown emissions performance of less than 2 ppm NOx at the module level and less than 3.5 ppm NOx at the full basket level on natural gas fuel at SGT6-5000F conditions. The procedure used for the catalytic combustor development is to verify the performance of the catalytic module at full pressure, then verify the full basket design. Under DOE contract DE-FC26-03NT41891, the catalytic module designed for natural gas was adapted for dual fuel

operation on natural gas and syngas. Full pressure testing was performed on this design with both syngas and natural gas fuel at the Siemens catalytic module test facility. The NOx emission results obtained during this test are shown in Figure 30. While operating on natural gas the design was capable of meeting the 2 ppm NOx emission requirement at SGT6-5000F conditions. On syngas, single digit NOx emissions were achievable but the emissions were significantly higher than on natural gas. At elevated firing temperatures the catalytic module experienced flashback in the downstream mixing region indicating that the flashback margin is not sufficient for syngas operation. Design changes to improve flashback resistance and to reduce emissions were identified.
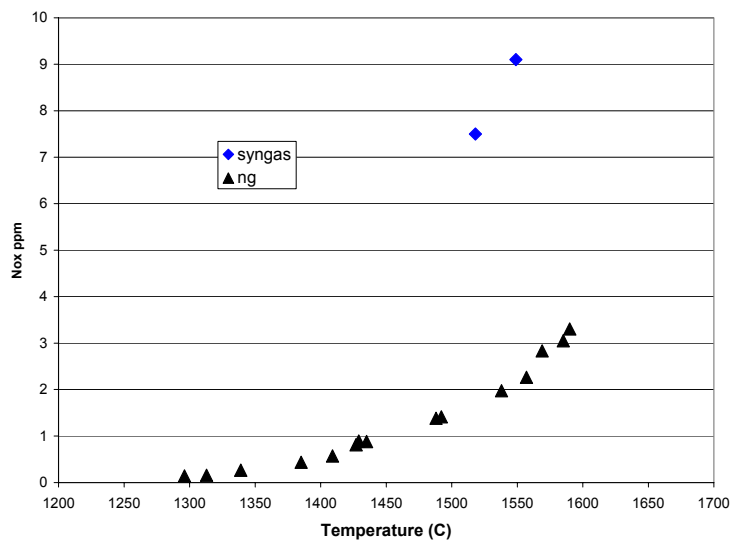
Figure 30. Emission Measurements from the Catalytic Module

Premixed Combustion System

One of the challenges in the design of a combustion system which is capable of operation on both natural gas and syngas is the wide variation in fuel flows required due to the large differences in heating values. This is especially an issue with a premixed combustor design such as the ULN design which has multiple fuel injection stages. Considerable redesign of the nozzle internal passages is necessary to accommodate the differences in fuel flow. The changes necessary to accommodate these fuels were identified and the basic ULN premixed design was adapted for dual fuel operation on natural gas and syngas. Figure 31 shows the main fuel nozzle fabricated for syngas/diluted hydrogen testing. An additional independent fuel stage was added to the design for operation on either syngas or diluted hydrogen. In addition to the main nozzle, changes were also made to the pilot nozzle and the combustor basket to allow operation on syngas fuels.

CFD analysis was used to optimize the design of the fuel injectors on both fuels. Modifications for flashback control were incorporated into the design of the basket and the fuel nozzles. Two different nozzle designs and two different basket designs were fabricated for testing.

Figure 31. Syngas Premixed Fuel Injection Design

The Siemens high pressure combustion test facility at ENEL was used for validation of the ULN design for operation on syngas and high hydrogen fuels. An initial test campaign was conducted with the base ULN design with mixtures of methane and hydrogen to determine the operational limits of the design. From this testing, the flashback limits of the design as a function of primary zone temperature were determined as shown in Figure 32.
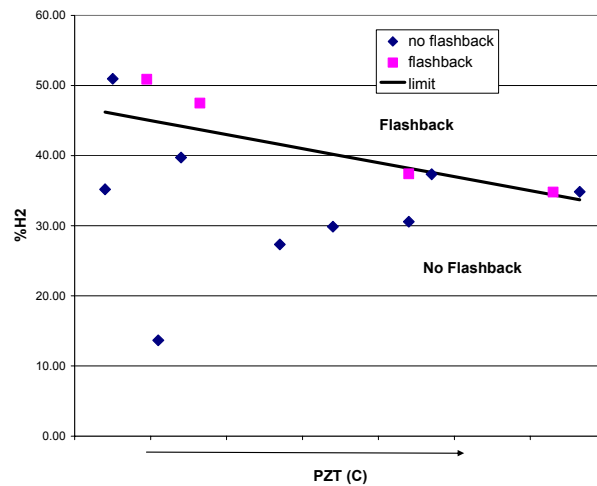
Figure 32. Flashback Limits on the ULN Design for CH$_4$/H$_2$ Mixtures

Initial validation testing was performed on the ULN syngas design at the ENEL facility. During the test period, CO was not available so the ULN syngas design was tested with diluted hydrogen fuel. The hydrogen fuel was diluted with nitrogen to obtain approximately the same Wobbe number as target syngas. This resulted in a mixture of approximately 50% hydrogen, 50% nitrogen by volume.

Figure 33 shows the data obtained during these tests compared with the flashback limits obtained from the original ULN tests on hydrogen. Facility issues with the syngas flow meter prevented completion of the transfer to the syngas stage. Because of the issues with the fuel transfer the highest hydrogen concentration tested was approximately 70% hydrogen – 30% methane.   Closed symbols represent stable operation, open symbols represent flashback data points. Although facility problems prevented accurate determination of the flashback limits for the ULN syngas design during this round of testing, it is clear that the new design was able to operate at higher hydrogen concentrations and higher temperatures without flashback than the baseline design.

H2 Volume Percent of Burnable Fuel vs. PZT
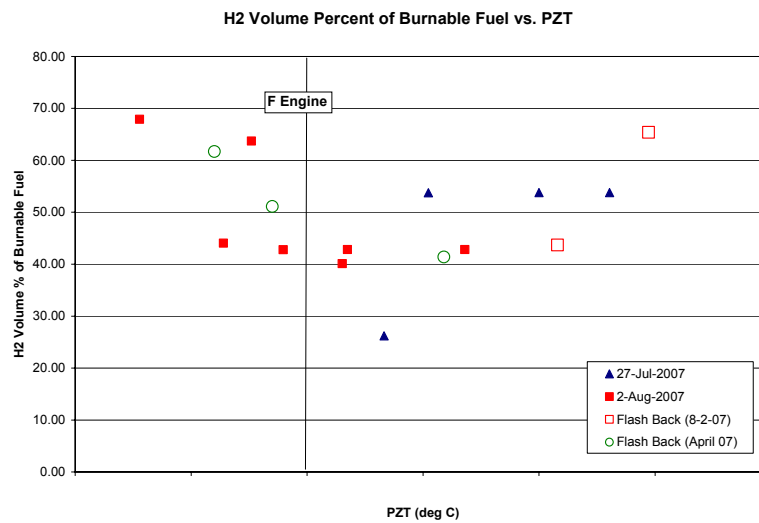
Figure 33. Flashback Data for ULN Syngas Design

In order to compare the performance of various nozzle designs the flashback data is are presented in non-dimensional form. The non-dimensional parameters used are the Wobbe number and Damkohler number.

The Wobbe number is defined as a function of the lower heating value of the fuel and the fuel and air densities as follows:

$$Wo = LHV \sqrt{\rho_f * \rho_a}$$

The Damkohler number is defined as:

$$Da = \frac{\tau_{mix}}{\tau_{chem}}$$

Where

$$\tau_{chem} = \alpha / S_L^2$$

$$\tau_{mix} = D / U$$

$$\alpha = thermal\ diffusivity$$

$$S_L = La\min ar\ flame\ speed$$

$$D = diameter$$

$$U = axial\ velocity$$

The Wobbe number is a standard parameter for evaluation of interchangeability of fuel nozzles. The Damkohler number has proven to be a good indicator of flashback. High Damkohler numbers indicate high flame speeds relative to the free stream velocity, and therefore indicate potential flashback. Figure 34 contains the data from the original ULN test, the ULN syngas test and the undiluted syngas design point. The original ULN tests were performed at Wobbe numbers typical of natural gas nozzles. With the ULN syngas nozzles the operation of the design was extended to lower Wobbe numbers typical of syngas mixtures. Operation was confirmed at Damkohler numbers in the range of the design syngas fuel.
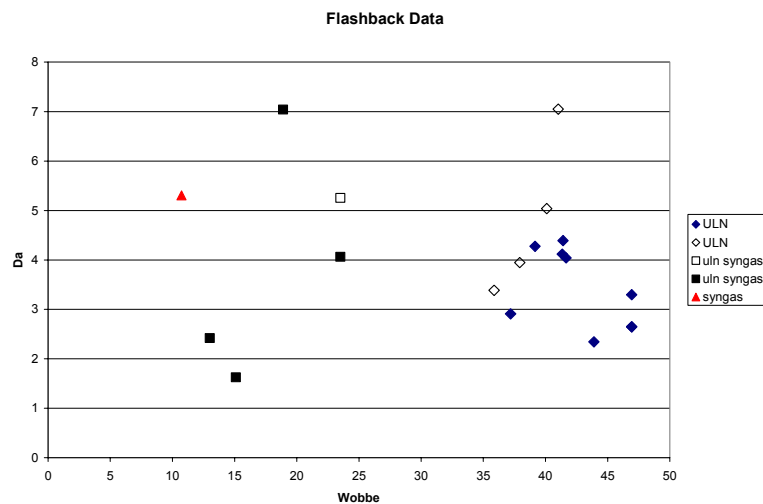
Figure 34. Flashback Data for ULN Design

The operability of the ULN syngas design on low BTU fuels was demonstrated. The design was able to operate without flashback at the design range of Damkohler and Wobbe numbers. Flashback was easily detected and controlled with the ULN design. Additional work is necessary to optimize this design for emissions.

Distributed Combustion System

The distributed combustion system adds an additional combustion zone down stream of the primary combustor. The theory is that the addition of the downstream combustion stage will lower dynamics by distributing the heat release over a larger area and will reduce NOx emissions by reducing the residence time at elevated temperatures. The key to the success of this design is proper mixing of the fuel in the downstream stage before combustion takes place.

To evaluate the distributed combustion system, a prototype transition was designed and built with an internal fuel manifold for testing of different fuel injection concepts. Initial high pressure testing of this concept was performed in the high pressure test rig at ENEL using the Siemens DLN burner. Figure 35 shows a schematic of the experimental configuration and Figure 36 shows the prototype transition with fuel injection.
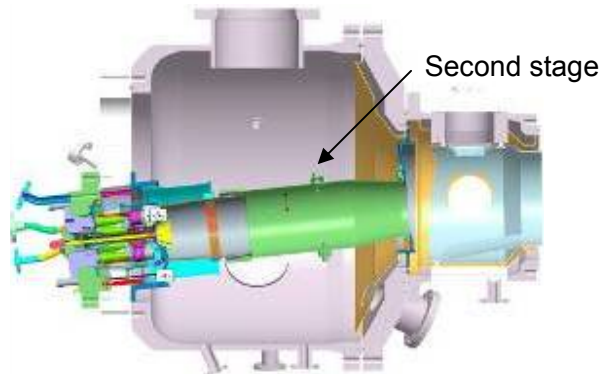
Figure 35. Distributed Combustion Test Configuration

Figure 36. Prototype Transition with Fuel Injection

For the distributed combustion tests the primary combustor was operated at F class firing temperatures and fuel was added to the downstream stage to increase the firing temperature by as much as 250°C above the main combustor operating temperature. In Figure 37, the combustor dynamics and NOx emissions are compared against data with the firing temperature increase obtained from the primary combustor only. Clearly, the distributed combustion system has a beneficial effect on both NOx emissions and combustor dynamics. From this data it is clear that as a single combustor is operated at elevated temperatures, both the NOx emissions and the combustor dynamics increase dramatically. Generally, there is a maximum temperature beyond which the combustion system cannot be operated with stable dynamics. With the additional heat input supplied to the second stage, the NOx emissions increased, but at a much slower rate than would be seen for a single stage. When the heat input is divided between the main combustor and

the second stage, there is no increase in combustor dynamics within the range of firing temperatures investigated.

a)   b)
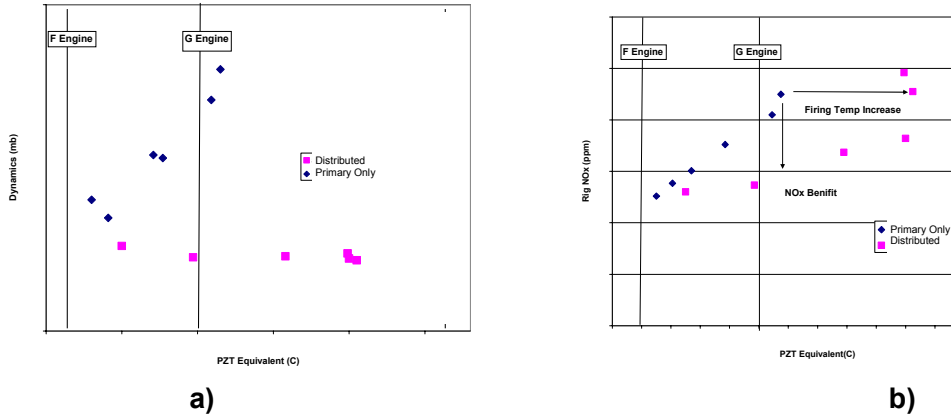
Figure 37. Effect of Distributed Combustion on a) Dynamics and b) Emissions

Initial testing on the distributed combustion system was performed with a premixed primary combustor (premix 1) which is capable of 15 ppm NOx at SGT6-5000F firing temperatures. To get low NOx emissions from the distributed combustion system it is necessary to use a more advanced combustion design for the primary combustor such as the premix 2 design which is capable of less than 9 ppm NOx at SGT6-5000F firing temperatures. Figure 38 shows the emissions data for the distributed combustion system for both head end configurations. Also compared on the curve are the estimated NOx emissions for the head end combustor only. Figure 38 shows that the reduction of NOx in the primary combustion zone carries over to the distributed combustion system. As before, significantly lower NOx emissions and combustor dynamics are possible at elevated firing temperatures with the distributed combustion system. Figure 39 shows the data plotted as increase in NOx above SGT6-5000F firing temperature versus increase in firing temperature. This figure clearly shows that the NOx produced in the downstream combustion stage is independent of the primary combustor design.
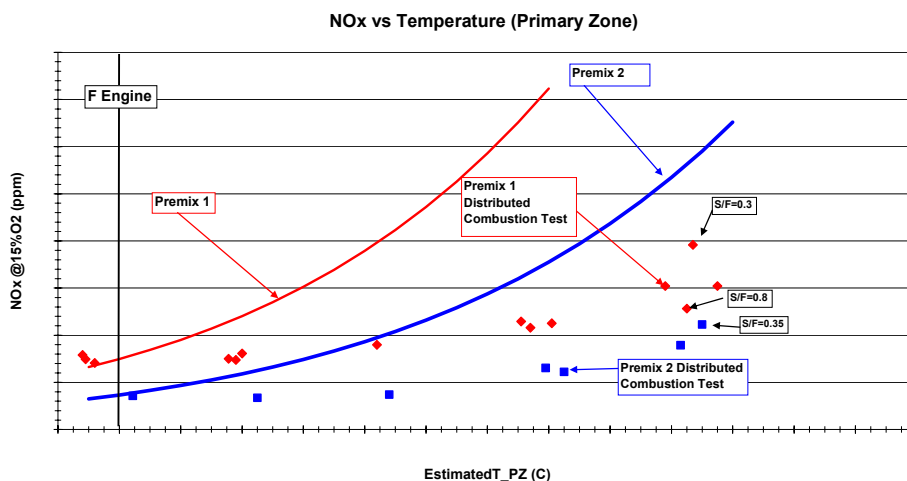
Figure 38. Impact of Distributed Combustion System on NOx Emissions

As currently designed, the distributed combustion system uses steam dilution in the downstream stage. The steam dilution was required for cooling of the fuel injection nozzles and to increase the penetration of the fuel jet into the main flow stream. As can be seen from Figure 38 at elevated firing temperatures there is an impact of the steam to fuel ratio on NOx emissions. As part of this test program the steam dilution was replaced with nitrogen. Figure 39 shows that with nitrogen dilution the emissions were significantly increased. Even when the nitrogen dilution had higher emissions, it still had the same improvement in combustor dynamics at elevated firing temperatures.
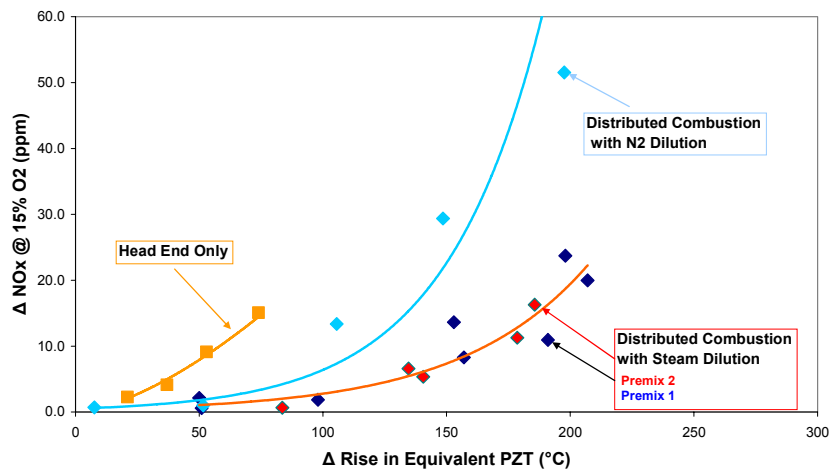
Figure 39. Impact of Dilution on Distributed Combustion System

To validate the fuel flexibility of the distributed combustion system, testing was performed with hydrogen fuel in the downstream stage. With hydrogen fuel in the downstream stage the same benefits in emissions and combustor dynamics were observed.

In summary the distributed combustion testing showed:

- Complete burnout of CO at all conditions
- Successful operation at 250°C above F class temperatures
- Operation demonstrated on both natural gas and hydrogen
- Significant reduction in NOx emissions over a single stage
- Significant reduction in combustor dynamics over a single stage
- No hardware distress during testing
- NOx production in the downstream stage was independent of the primary zone NOx
- Steam injection was more effective than nitrogen

In order to optimize the performance of the distributed combustion system, new modeling techniques must be developed. CFD calculations with reduced kinetic mechanisms proved not to be valid for prediction of emissions from the distributed combustion system. To accurately model the emission performance of the distributed combustion system, it is necessary to include the detailed chemical kinetics with simplified models for the fluid

mechanics. A CRM model was created for the distributed combustion system using the jet mixing correlations of Holdeman, et al[5] to model the penetration and spread of the fuel jet. This model was applied to the existing data for the distributed combustion system and the results are summarized in Figure 40. This model predicts all the trends of the existing data including the diluent effects (nitrogen or steam) and fuel type (hydrogen or natural gas). This model will be utilized in Phase 2 of the program to optimize the nozzle design for the downstream combustion stage.
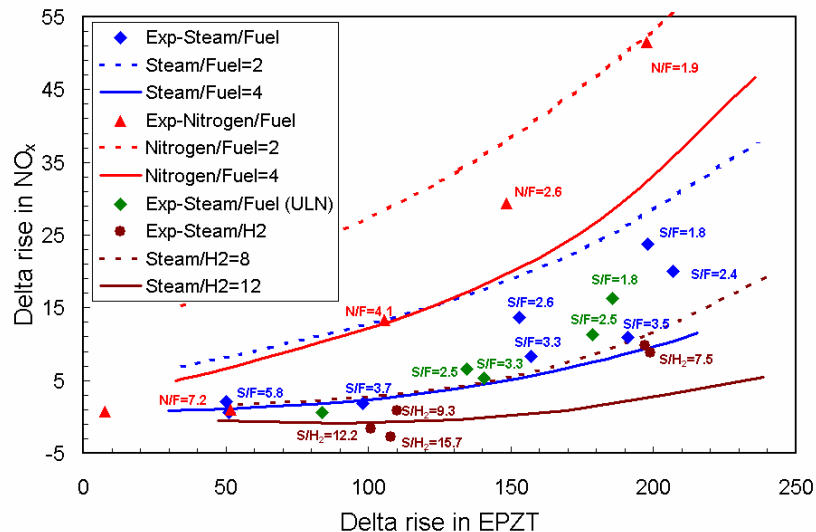
Figure 40. CRM Modeling Results for the Distributed Combustion System

Conclusions

The goal of Phase 1 of this program was to down select from the four candidates the two most promising technologies for further study in Phase 2 of the program. Considerable data were obtained on the four candidate combustion systems. The diffusion system was the simplest design and showed promise of NOx emissions in the range of 10 – 15 ppm at SGT6-5000F and SGT6-6000G conditions but required a substantial amount of dilution flow to meet these emission levels. The catalytic design showed the potential for the lowest emissions of any design but had a high initial cost and risk. Initial testing showed the feasibility of the catalytic design for syngas fuels. The premixed design showed the potential for operation on syngas and high hydrogen fuels. Additional design work is still needed for both the catalytic and premixed systems before they can be applied to IGCC applications. Because there is considerably more operational experience on natural gas with the premixed design it is considered to be a lower risk option that the catalytic design. The distributed combustion system showed considerable promise for fuel flexibility, high temperature operation without combustion dynamics and reduced NOx emissions. Based on the results of this program, the premixed combustion system and the distributed combustion system were chosen as having the most potential and will be the focus of Phase 2 of the program.

Turbine

Approach

The Phase 1 development of the DOE Hydrogen Turbine System established the guidelines for the conceptual development of the turbine system and the advanced turbine components. The Siemens Platform Turbine is the basis for the conceptual Hydrogen Turbine design and retains commonality with the Platform Turbine rotor.

Substantial increase in the performance level of the hydrogen turbine compared to the baseline requires a unique aerodynamic design in order to optimize turbine efficiency. Additionally, the performance targets for the hydrogen turbine system components will require significant technology advancements. The overarching performance targets for the turbine section of the advanced hydrogen turbine are high rotor inlet temperature (RIT), low total cooling and leakage air (TCLA), high mass flow, and a high pressure ratio.

Given these guidelines and the ranges established for the performance targets, conceptual development of the DOE hydrogen turbine system was initiated during Phase 1. The approach was to use the conceptual designs to identify a suite of critical technologies that could be used to achieve the turbine's aggressive performance goals in aerodynamics, airfoil cooling, and sealing. The intent was to identify technologies that could be placed on a technology development path that targets validation by the end of Phase 2 for insertion into the advanced hydrogen turbine design. The technology options come from a wide array of sources; some are evolutionary developments in the technology, while many others represent significant leaps in the technology. In addition to fulfilling the requirements of the DOE hydrogen program, it is anticipated that these turbine technologies will represent the next generation turbine technology, as well as being available for insertion in the existing fleet.

The available technologies that were identified in the Phase 1 conceptual development tasks were documented and a preliminary risk assessment was conducted. The focus of this risk assessment was on development risk as opposed to operating and commercial risk. Each risk was assessed in terms of its "impact" on the engine/turbine/component performance, life, cost, and the "likelihood" of occurrence and mitigation plans were developed. This risk assessment served as the basis for the preparation of the Phase 2 proposal. It will be revisited and refined early on in Phase 2 and will be maintained throughout the duration of the program.

The major risks identified include:

- High rotor inlet temperature and low cooling air flow
- High cooling air temperatures
- Part yield due to complex casting designs
- Prime reliance on thermal barrier coatings
- Corrosion of alloys due to syngas exposure

For conceptual turbine design, preliminary or estimated engine parameters were used to develop a conceptual turbine layout, flow path, and turbine components. The turbine flowpath was optimized using Siemens standard tool for 1D aerodynamic meanline analysis to evaluate and optimize the performance of candidate flowpaths and velocity triangles. Definition of the flowpaths included number of stages, stage work study (stage turning, mach numbers, and temperatures), turbine annulus, etc. Numerous 1D aerodynamic meanline models were run to

estimate the performance of various configurations. A high flow / low integration configuration was chosen as a baseline for the studies performed in Phase 1. This case requires a large Row 4 blade with High AN^2 to enable aero efficiency gains. High AN^2 blade designs have previously been avoided due to manufacturing limitations and low component life.

A key component of turbine performance evaluation is the required TCLA. The 1D aerodynamic meanline performance code has the capability to estimate TCLA changes due to changes in gas temperature, estimated airfoil surface areas, pressure, etc. The effect of incorporating hydrogen turbine cooling technologies on TCLA was evaluated by running iterations of the meanline code using cooling parameters developed by the heat transfer group. In many cases, heat transfer validation testing will be required to establish correlations for the proposed cooling concepts.

The established TCLA target in the high heat load environment of the hydrogen turbine is a challenging goal, and will limit the available cooling flow for each component. Therefore, the hydrogen turbine components will require a step change in cooling technologies beyond the current state-of-the-art. It is anticipated that a high level of cooling technology, combined with a low conductivity TBC will be necessary to achieve the low cooling flows. The advanced cooling technology must have high cooling efficiency, and at the same time must be a robust cooling scheme. The degree of part complexity required to achieve such cooling has been avoided in current turbine designs due largely to manufacturability and cost. Manufacturing limitations will be addressed as a part of this program.

The Phase 1 turbine development activities included developing conceptual design solutions for the advanced hydrogen turbine components, conducting studies to evaluate and quantify the benefit of the various new concepts, and selecting design concepts to be pursued in Phase 2

During the initial concept development process of Phase 1, a number of airfoil cooling concepts were developed for the most challenging turbine blades and vanes. Afterwards, a Quality Function Deployment (QFD) matrix was used to evaluate and compare each of the airfoil cooling concepts. The matrix included four major categories:

1) Performance – the impact of the concept on efficiency or power
2) Design – the achievement of the functional requirements
3) Manufacturing – core, casting and machining development efforts
4) Cost – tooling, development and production

A panel of technical experts having extensive experience in turbine cooling, aerodynamics, mechanical design and manufacturing was convened to evaluate each concept relative to one another. The results of both individual rankings and averages were compiled for comparison within a single category.

Near the conclusion of the Phase 1 conceptual design work, the overall technology status and gaps were assessed. Compared to the current state-of-the-art, the required leaps in technology in the following areas were quantified: TBCs, cooling, leakage and sealing, aero, high AN^2 blade 4, and design tools. Due to the nature of the perceived challenges of developing DOE hydrogen turbine system components, an integrated product team (IPT) structure was established that will work together during Phase 2 of the project. This structure includes the design, materials, and manufacturing teams.

Results and Discussion

Aero Design

The flowpath and velocity triangles of the advanced hydrogen turbine were optimized by running numerous 1D aerodynamic meanline models to estimate the performance of various configurations. The following were general considerations for developing candidate aerodynamic configurations. First, the hydrogen turbine should have the same inner flowpath and number of blades as the Platform Turbine, if feasible. Second, due to the increased turbine inlet temperature and pressure ratio, turbine stage loading (i.e. stage work) is increased relative to current designs. High turning airfoils are desired to achieve the high level of loading, while at the same time minimize TCLA by minimizing the blade count, which reduces both the leakage paths and the surface area of metal exposed to the hot gas path. However, the cost of increased airfoil turning is decreased aerodynamic efficiency, and at some point the aerodynamic losses more than offset the gains achieved by reducing the TCLA allotment for that component. These limits were explored for the stage 1 and stage 2 components. Figure 41 shows that conceptual H_2 blade achieves higher turning by utilizing a thicker cross-section. There are additional perceived advantages of the thicker cross-section. First, there is more room to incorporate multiple pass cooling schemes. Second, leading edge radius of curvature is larger, which should improve TBC life at this location.

The following is a summary of three noteworthy aerodynamic studies:

- Evaluate the possibility of reducing stage 1 and stage 2 loading by either (1) shifting work to stages 3 and 4, or (2) a 5 stage design. These configurations resulted in increased turbine aerodynamic efficiency, but decreased turbine power and/or efficiency due to increased cooling requirements and leakage paths (i.e. increased TCLA).

- Evaluate the effect of increasing the diameter of the front stages. This was predicted to increase turbine efficiency/engine performance, but was not selected due to concerns that the increased centrifugal stresses from rotating components may require a change to a more expensive disk material.
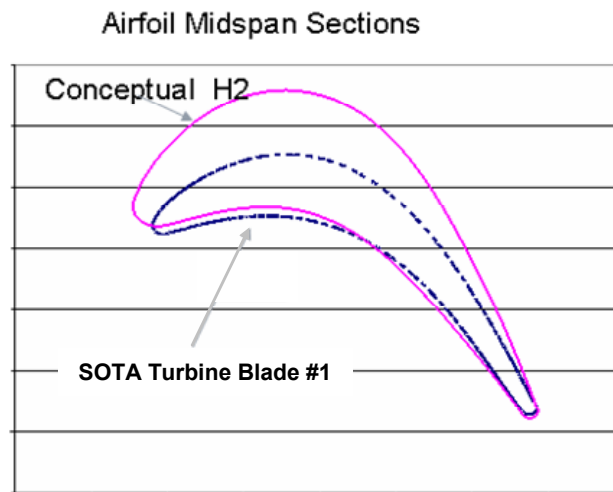

Airfoil Midspan Sections

Figure 41. Comparison of Blade 1 Midspan Sections (flow turning is more than 25% greater in the conceptual H$_2$ blade)

The most important aerodynamic study was the evaluation of various levels of turbine exit flow, which is determined by exit annulus area. A large exit annulus area leads to a large blade 4 design with high AN^2, which is a measure of the pull stress on the blade. This study evaluated the relationship between turbine mass flow, turbine integration and the limits of the blade 4 configuration. As illustrated in Figure 42, increased turbine exit annulus area is required to avoid a significant decrease in turbine/exhaust efficiency at the higher turbine exit flow levels that are achieved in low integration configurations. This efficiency loss is due to excessive pressure loss due to a high turbine exit/diffuser inlet Mach number. It should be noted that even with the increased annulus area, turbine exit Mach number is increased relative to existing designs. The large annulus flowpath was chosen for baseline studies based on efficiency gains, especially at high mass flow conditions. High mass flow capability is important because it improves plant flexibility in terms of integration with the ASU.

This study identified blade 4 as a critical part to achieving the target flowpath for the advance hydrogen turbine. The baseline flowpath includes a blade 4 with an AN^2 value that is significantly higher than the current state-of-the-art blade 4 design. In addition, the blade 4 must be a cooled component since the gas path temperatures are higher than in current designs.

Due to the criticality of blade 4, more detailed aerodynamic design work was performed on this component in order to perform preliminary manufacturing and mechanical feasibility studies. On the first iteration, the blade count was reduced on account of unacceptable aerodynamics. Specifically, it was determined (for the higher blade count) that the airflow was "choked" near the base of the blade due to the thick airfoil cross-sections that were required to support pull stress. Further work, including the CFD analysis shown in Figure 42, indicated that the lower airfoil count design was acceptable aerodynamically with no predicted flow separations or excessive pressure loss. The predicted airfoil surface Mach numbers exceed current criteria, but appear feasible.
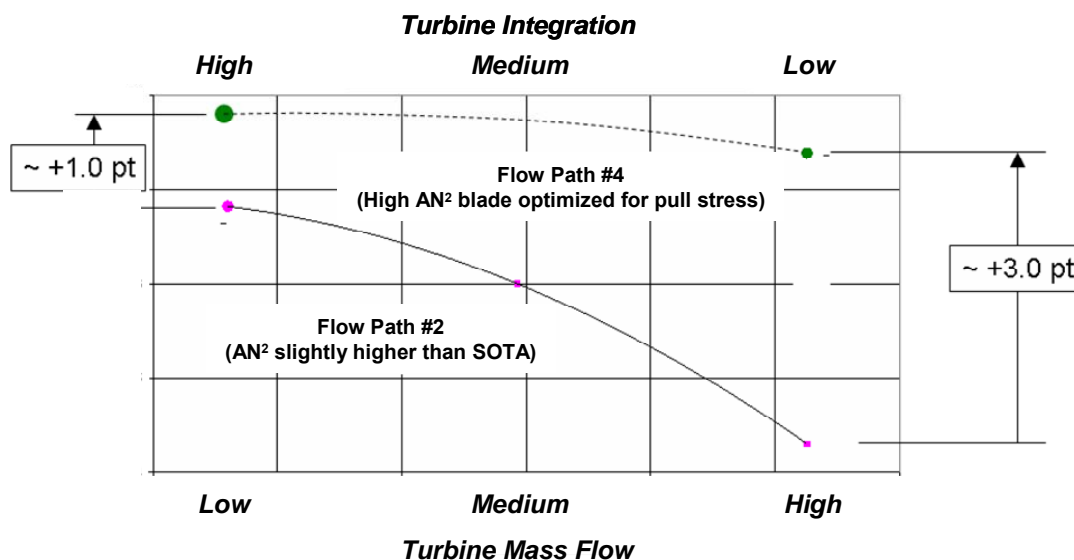
Figure 42. Turbine Flow/Exit Annulus Area Study
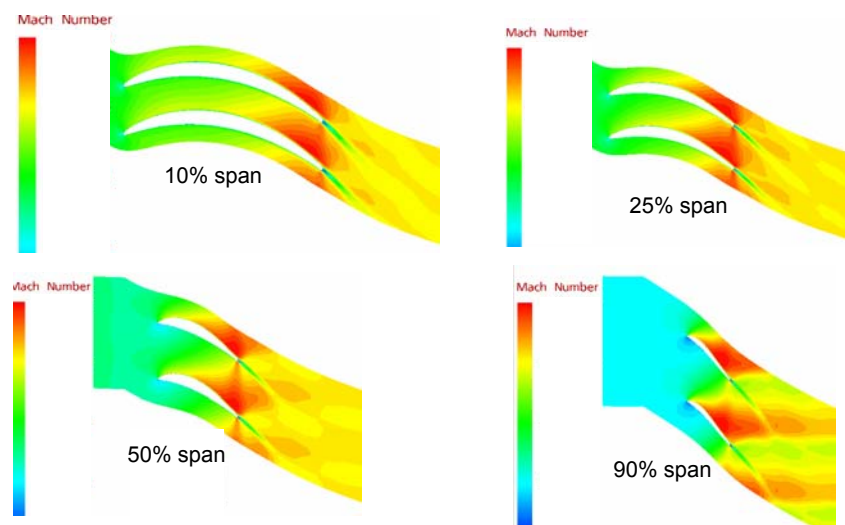
Figure 43. Blade 4 Surface Mn Contour (3D CFD)

A profile and cross-section of the high AN^2 blade 4 design was generated from the aerodynamic profiles (shape shown in Figure 43). The mechanical study indicated that the high AN^2 blade 4 design is feasible, however, it is a significant leap beyond the current state-of-the-art. It should be noted that this geometry was optimized for blade pull stresses, and no allowances were made during this iteration to enhance manufacturability of the part. Figure 44 shows the blade 4 shape.

External Surfaces
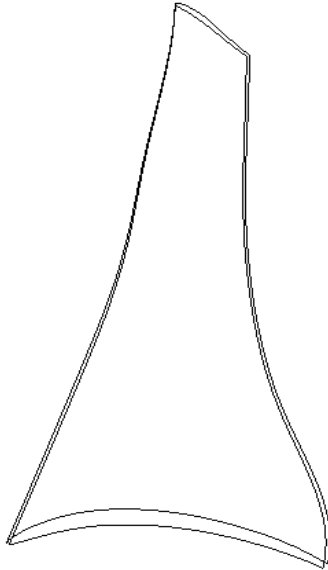
Figure 44. High AN^2 Blade 4 Shape

Materials Selection

A wide range of materials are being considered for the various component concepts. Potential materials include cast Ni-based superalloys in any form (conventionally cast (CC), directionally solidified (DS), or single crystal (SX)). Other materials under consideration and/or being developed by the Materials Group include oxide dispersion strengthened (ODS) superalloys, rareearth modified Ni-based alloys, thermal spray metal (e.g., HVOF sprayed alloys), powder metallurgy alloys made by direct metal fabrication methods, and oxide/oxide CMCs. Additional details regarding the advanced materials development and characterization work is presented in the Materials section of this report.

Ni-based alloy (CC and DS) materials property data were assumed for the thermal and structural analysis conducted in the feasibility study. For blade 1, vane 2, and potentially blade 2, it may be necessary to use single crystal alloys due to the thin walls necessary for maximum cooling effectiveness. For the remaining flow path components, DS or CC alloys should be sufficient.

One of the most significant technology gaps of the advanced hydrogen turbine is the high heat loads of the hot gas parts. Advanced thermal barrier coatings (TBCs) will be relied upon to drop the temperature sufficiently so that the component design meets life targets for oxidation, LCF, creep, etc. Advanced TBC development activities are also presented in the Materials section of this report.

Preliminary Component Design - Thermal

Preliminary blade and vane designs were developed for turbine stages 1 through 4. A common attribute for each of the turbine components is that advanced cooling technologies will be required to meet the low TCLA target in the high heat load environment of the advanced hydrogen turbine. To achieve the requisite cooling with minimal flow, these cooling technologies must have both high cooling efficiency and good predictability/reliability. For that reason, the first step in preliminary component design was to identify airfoil cooling concepts for each of the components. Two general approaches were used to achieve cooling concepts with high cooling efficiency. These two categories are described below:

Enhanced Convection

These concepts utilize relatively large channels, but maximize cooling effectiveness by various means, including blocking the flow with pins or ribs to increase the internal Mach number. Some of the more promising concepts achieved a large number of radial passes through the airfoil, each having surface enhancements such as trip strips.

Near-Wall Channels

In these concepts, high cooling air velocity was achieved by forcing the airflow through small channels near the surface of the airfoil. These concepts were sometimes called "4-wall" concepts, because the cooling channels were between an inner wall and an outer wall. These concepts look like an airfoil within an airfoil.

Figure 45 shows that a concept in each category was developed for the first three stages, and single cooling concept was developed for the last stage. Each concept was developed sufficiently to allow for a Quality Function Deployment (QFD) assessment to be made. The two concepts for blade 1 are summarized. The blade 1 "enhanced convection" concept is a multi-pass serpentine with each of the cavities bridged by an array of pins to conduct heat from the outer wall. A schematic of the Blade 1 "near-wall channel" concept is shown in Figure 45. Figure 46 summarizes the results of the QFD assessment for the two blade 1 concepts. The QFD scores reflect the fact that, in general, the nearwall channel concepts are more challenging from a manufacturing standpoint.

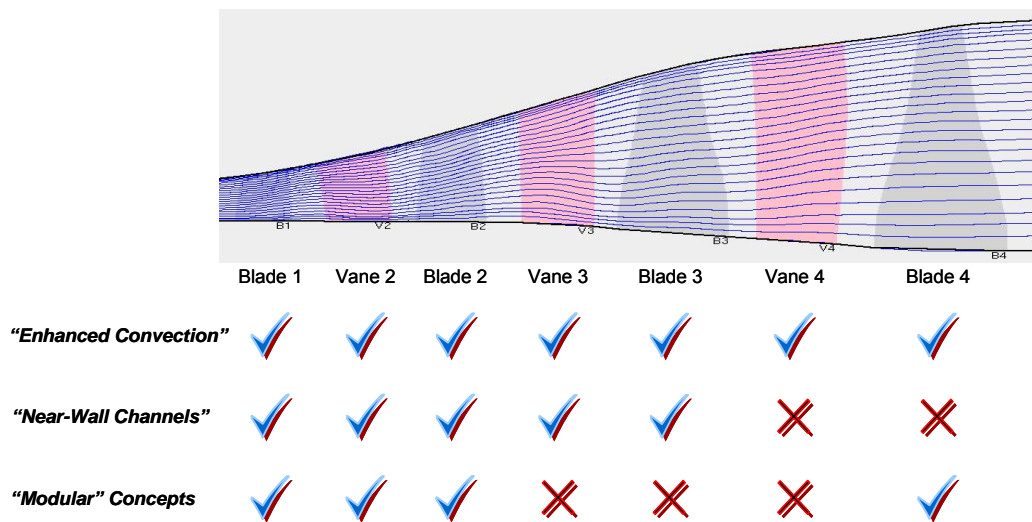|	Blade 1	Vane 2	Blade 2	Vane 3	Blade 3	Vane 4	Blade 4
"Enhanced Convection"	✓	✓	✓	✓	✓	✓	✓
"Near-Wall Channels"	✓	✓	✓	✓	✓	✗	✗
"Modular" Concepts	✓	✓	✓	✗	✗	✗	✓

Figure 45. Categorization of Preliminary Component Design Concepts Evaluated in Phase 1.
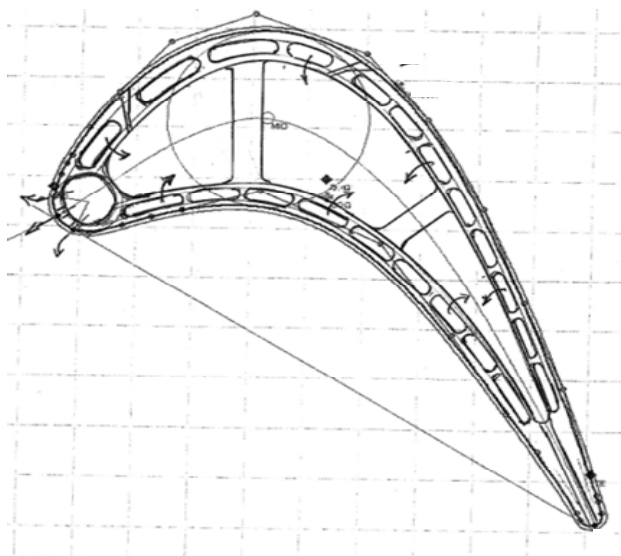
Figure 46. Near Wall Channel Concept for Blade 1

Categories	"Enhanced Convection" Concept	"Near Wall Channel" Concept
Performance	7.07	6.53
Design	6.13	5.78
Manufacturing	4.93	3.52
Cost	1.93	1.2
Average (Weighted) Score	5.02	4.26

Table 5. QFD Scorecard for the Two Blade 1 Concepts

Regardless of the cooling concept, the airfoil will most likely have relatively thin walls to reduce the metal temperature to achieve the required LCF life. Thin walls are particularly beneficial in the case of localized TBC spallation. Analysis has shown that for thick walls, localized TBC spallation results in a metal temperature above the melting temperature of the exposed metal.

Since a tapered wall section is required to achieve an equiaxed microstructure, conventional cast (CC) alloys cannot achieve thin wall sections. In addition, CC and DS alloys contain grain boundaries that may span the thickness of the thin-walled section, creating a fatigue crack initiation site. Therefore, to achieve thin walls in a cast metal part, it may be necessary to go to a single crystal (SX) superalloy. The casting problems and low yield usually experienced with complex single crystal castings will be addressed by pursuing modular and/or fabricated component concepts where the airfoil shrouds are cast and/or fabricated separately. Reducing casting complexity is one reason for utilizing modular designs. Modular approaches are also being considered as a way to reduce thermal fights, increase reparability, and to make it easier to incorporate advanced materials. Recommendations to pursue selected modular component concepts will be made based on the results from the Phase 2 design tasks. Figure 45 shows the components for which modular concepts have been generated.

In the investment casting process, ceramic cores are used to form the cooling channels within a metal casting. The current core manufacturing processes are limited by the complexity of the geometry and by the size of the features. To advance the state-of-the-art in cooling technologies, new core manufacturing technologies are being explored to achieve higher cooling efficiencies. In Phase 1, a proof of concept ceramic core was fabricated with a geometry that could not be produced by conventional core manufacturing methods.

One of the most significant technology gaps for the advanced hydrogen turbine was highlighted during thermal analysis with the advanced TBC coating. The thermal gradient and the total temperature drop through the advanced TBC layer are greater than experience with current state-of-the-art TBC. Validation testing will be required to demonstrate the capability of the new TBC.

Another significant technology gap is the manufacturing capability for the high-AN[2] blade 4, which is near the size limit for conventional casting methods. An assessment from a manufacturing feasibility study indicates that blade 4 casting should be feasible, but may require a long lead time to develop the process.

Preliminary Component Design – Mechanical

The Phase 1 activities focused on thermal design of the components, and only a few components were evaluated for mechanical stress. The following lists some of the activities that were performed during Phase 1:

- All of the blades were evaluated for pull stress, and the blade 4 geometry was optimized for pull stress.

- A thermal stress analysis was performed on the Blade 1 – "enhanced convection" concept.

- A thermal stress analysis was performed on the Vane 2 – nearwall channel concept. Stress concentrations were identified near the trailing edge.

Heat Transfer Studies

A number of potential advanced cooling concepts have been proposed, but in many cases correlations do not yet exist that would enable design with these concepts. A few promising concepts were identified and programs were set up at two Universities to develop the necessary heat transfer correlations. Note that these promising cooling concepts are all utilized in variations of the blade 1 concept with enhanced convective cooling.

A program was set up at Texas A&M University to investigate two different cooling concepts. The first study will develop heat transfer correlations for airfoil leading edge internal cooling concepts that combine impingement cooling with turbulators to enhance heat transfer. The second study will investigate the effectiveness of a new blade tip design for the row 1 blade that is intended to minimize tip metal temperatures, thereby reducing the risk of oxidation in this region.

Another program was set up at the University of Central Florida to provide experimental data in support of the development of the advanced internal cooling conceptual designs that were proposed in Phase 1. Two subtasks have been identified. The first subtask involves the experimental study of the effect of advanced turbulator configurations within the internal cavity of a blade leading edge. The second subtask involves an experimental study of the trailing edge internal cavity of the blade.

Total Cooling and Leakage (TCLA) Estimates

Numerous turbine component aerodynamic designs were evaluated using an internal meanline aerodynamic performance code for the cycle studies that ultimately resulted in the selection of the high AN^2 flowpath with low integration with the ASU. Initial cooling and leakage flow estimates for each turbine configuration were made within the meanline performance code by inputting appropriate values of parameters that adjust technology levels for internal heat transfer, film effectiveness, gas temperature profile, pattern factor, base alloy, and TBC material properties and capabilities. External heat transfer coefficients are calculated using correlations internal to the code. The level of cooling was further controlled by setting a maximum bondcoat

surface temperature to achieve acceptable LCF life (based on current materials capabilities). For row 3 and 4 blades, the cooling was controlled by the creep life requirements.

The estimated leakage was based on the sealing effectiveness from existing turbine frames. However, this is a challenging target that will require the development of advanced sealing concepts to achieve the same level of performance in a higher pressure ratio environment. Advanced rim and interstage seal concepts have been developed to meet the requirements of the advanced hydrogen turbine. Since testing will be required to characterize the sealing effectiveness, potential test facilities were identified in Phase 1 of the project.

Conclusions

During Phase 1 of the DOE Program, "Enabling Turbine Technologies for High-Hydrogen Fuels", a subtask was initiated to evaluate the feasibility of an advanced hydrogen turbine system that meets the stated goals of the program. The subtask emphasized conceptual development and feasibility assessment of advanced turbine component technologies and the development of experimental plan for validation of design concepts.

The Phase 1 studies indicate initial feasibility of the advanced hydrogen turbine that meets the aggressive targets, including increased rotor inlet temperature (RIT), lower total cooling and leakage air (TCLA) flow, higher pressure ratio, and higher mass flow through the turbine compared to the baseline. In addition, the advanced hydrogen turbine is sufficiently flexible to meet a range of requirements. Feasibility was demonstrated by the combination of a number of technologies, including advanced cooling concepts, advanced thermal barrier coatings (TBCs), novel manufacturing/fabrication approaches, and many others. Maintaining efficiency with high mass flow syngas combustion is achieved using a large high AN2 blade 4, which has been identified as a significant leap beyond the state-of-the-art.

A risk management process was used to identify risks and develop mitigation plans in Phase1. Risks will continue to be monitored and mitigated through testing and analysis in Phase 2.

Rotor

The overall goal of this phase of the project was to assess the feasibility of rotor system concepts towards meeting the DOE Advanced Hydrogen Turbine Program goals by enabling higher pressure ratio, operating temperatures and power output. The Siemens Platform rotor system was used as a basis for the concept development.

The following topics concerning gas turbine rotor feasibility were assessed during Phase 1 of this project and are described in this report:
- Compressor thermal assessment and rotor cooling concepts
- Peer review of material assessment and selection for rear compressor disks
- Rotor construction assessment
- Power transmission assessment
- Turbine disc thermal and primary stress structural assessment

Compressor Thermal Assessment and Rotor Cooling Concepts

Approach

A brainstorming workshop was held to identify possible air cooled rotor concepts to satisfy the rotor mechanical integrity with an elevated design point pressure ratio. A weighted comparison of each of these concepts, according to several key criteria, was then performed in order to rank and make an initial down selection of concepts. The weighted comparison results were reviewed in workshop with contribution from each of the major gas turbine design disciplines.

Discussion and Results

More than 10 rotor cooling concepts that utilize cooling air to reduce the rear compressor discs metal temperature were initially identified and included in the weighted comparison. The criteria of the weighted comparison included: thermal environment for rotor components, gas turbine performance, manufacturing cost and assembly, raw material cost, rotor bolting spans, material requirements, and rotor integrity and complexity.

The workshop identified three preferred rotor concepts for further evaluation. It was concluded that a thermal assessment of the three preferred aircooled rotor concepts be performed in Phase 2 in order to determine:

1. If each concept could satisfy the rotor mechanical integrity with elevated design point pressure ratio.
2. The effect that each concept would have upon engine efficiency.
3. The extent to which thermal insulating techniques could benefit each concept.

Peer Review of Material Assessment and Selection for Rear Compressor Discs

Approach

The proposed elevated compressor pressure ratio would increase flow path temperatures above the current conventional temperature limit of standard materials. Therefore, a materials peer review was held and potential rotor materials were compared based on mechanical integrity,

cost, performance and risk. A primary path was selected by the peer review team which was comprised of rotor experts, materials experts, and forging experts.

Discussion and Results

During the materials peer review, the mechanical integrity issues associated with the IN706 / IN718 family of Nickel based rotor alloys were discussed and the decision was made to remove the Nickel based materials from the list of potential materials. The focus will be on steel based materials and use of cooling air to keep the metal temperatures down within the allowable temperature limits.

Conclusions

Cost, performance and mechanical integrity considerations dictated that an air cooled compressor configuration with conventional steel rotor material is preferred. Nickel based materials (IN706 & IN718) have been eliminated.

Hence, the rotor design will follow the following order of preference:

- Air cooled steel disc construction.
- Uncooled compressor using steel discs and possibly higher chrome content steels in the rear stages.
- Uncooled compressor using steel discs and hybrid rear compressor discs. The hybrid discs may be dual heat treat discs, or dual chemistry discs. This path will require a materials development program.

Power Transmission Assessment

Approach

A preliminary assessment of primary rotor components' (flange coupling, journal, front hollow shaft, Hirth couplings, torque tube, and center tie bolt) ability to transmit the required design point power level, and corresponding transient fault torques, was performed.

Discussion and Results

An initial determination of the interstage Hirth coupling diameters required for the design point power level was determined by extrapolation from the relationship between interstage coupling diameters and nominal rated power for previous Siemens gas turbine designs.

The initial required power limit resulted in a first estimate of the rotor discs' bore diameters that would limit their blade load capacity. Several options to minimize this limitation were then determined and evaluated. Ultimately, the limitation was overcome by deriving a more optimum angle for the Hirth serrations teeth with regard to power transmission, while maintaining the requirements for teeth strength.

The preliminary rotor power transmission assessment results indicate that the target rotor power transmission capability can be achieved, given that the interstage couplings include certain established design features.

This assessment resulted in a first estimate of the following parameters:

1. Turbine-generator flange coupling primary dimensions.
2. Minimum shaft diameters of intermediate shaft and compressor bearing journal.
3. Nominal prestress (tension) of the center tie bolt design.
4. The primary dimensions of the Hirth interstage couplings between rotor components
5. Primary dimensions of the rotor torque tube between the turbine and compressor regions.

Turbine Disc Thermal and Primary Stress Structural Assessment

Approach

An assessment was performed of the turbine disc primary stresses, based upon the present blade pull data and thermal results from the first release of full engine thermal model. The intent of this assessment is to determine if the average membrane stress of each turbine disc at steady state conditions would exceed the Siemens internal requirements based upon the material's yield and creep rupture strengths at the disc average temperature. Also, an initial determination of the center bolt tension required for the design point power level was determined by extrapolation from the relationship between nominal center bolt tension and nominal rated power.

Discussion and Results

Since the turbine blade cover plates have not yet been designed, the assessment did not include centrifugal force loads of the cover plates. While a final selection of the disc material has not been made, an assumed low-alloy steel material with similar applications within Siemens was assumed for this study.

The results of this assessment indicate that the turbine discs' primary stresses meet the target requirements, given the presently selected material for the turbine discs.

Given initial center bolt tension level and a nominal membrane stress target, based upon previous Siemens design experience, an initial center bolt diameter was determined. Based upon the design point power level, the initial center bolt diameter concept agreed well with the bolt diameter and nominal power relationship extrapolation for previous Siemens centerbolt designs.

The preliminary rotor construction assessment resulted in a first estimate of the following parameters:

1. Nominal prestress (tension) of the center tie bolt design.
2. Minimum diameter of center tie bolt design.
3. Maximum unsupported span of center tie bolt design.
4. Minimum bore diameter of the rotor discs.

Conclusions

Phase 1 was concluded with an internal feasibility review of the current rotor design concept encompassing all of the described rotor topics and the associated technical risks. Preliminary

results showed feasibility of a rotor system capable of increased power output, operating at pressure ratios above the baseline.

Casings

DOE Hydrogen Casing components have unique technical challenges associated with each component due to vastly different boundary conditions and requirements from present industrial turbines. Potential solutions were identified and basic analysis conducted to assess each approach and related risks. Discussion of each component is provided below.

Inlet Casing

Current preliminary Inlet Casing (see Figure 47) and bearing support configurations uses the latest production design approach and material as a baseline. Flowpath definition was extracted from the 2D longitudinal database. Journal bearing sizing to support the rotor configuration provides a low stress approach. Two remaining challenges which will be further addressed in the next phase were identified:

- Accommodating the estimated thrust load
- Refining bearing removal processes and clearance envelope.
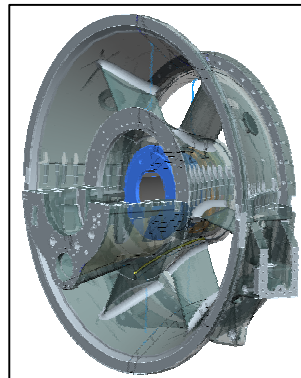
Figure 47. Inlet Casing

Risk Mitigation and Assessment

Suppliers were contacted to inquire about thrust bearing capabilities. Although the estimated thrust exceeds recent production designs, calculations show designing one with such capability will not be an issue due to the larger OD and ID of the thrust bearing. Thrust reversal possibilities will also be evaluated in the next phase.

Compressor Intermediate Casing and CCT (Compressor, Combustion and Turbine)

The preliminary Intermediate case and CCT case configurations (see Figure 48) were derived from interface information from longitudinal database and integrated with the advanced transition conceptual models. Casing wall thickness, split flange width and bolting patterns were modeled using recent production engine design as a starting point. Meeting casing mechanical

strength and life requirement at high temperature and high pressure is the main technical challenge. Bolting approach for CCT due to high temperature and high pressure load will need to be assessed.

Risk Mitigation and Assessment

Two preliminary concepts were developed for CCT:

1) Cooled casing
2) High temperature material concepts.

A cooled casing was found to be the preferred option to balance cost and performance. The next phase will require more detail cooling calculation and design features to further quantify the benefits and a final down selection will be done at the end of Phase 2 on the basis of total life cycle costs. A high temperature capable alloy system will be kept as a back-up option.

Two CCT bolting options were proposed: high performance bolt material and cooled bolting. Cost analysis of these options will be performed in the next phase. Expanded research on high performance bolt material selection, the current preferred option, will be conducted as well. Patent search on bolt cooling and possible alternative designs using similar principles will be conducted. Testing of bolt material may be necessary and this will be determined early in the next phase.
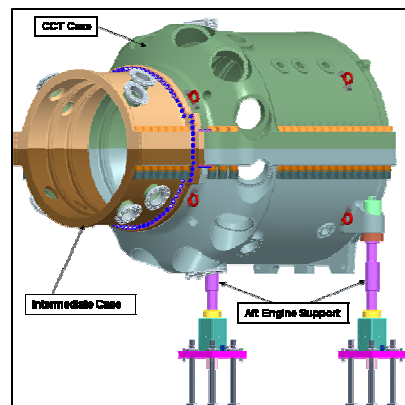
Figure 48. Compressor Intermediate Casing and CCT

Exhaust Casing Assembly (TEC)

Exhaust casing concepts were derived from the longitudinal database to enable high gas path temperatures. High exhaust temperature increases the likelihood of creep and fatigue life issues, especially in the strut joint areas, therefore concepts were developed for cooling and potential use of high temperature capable materials. Figure 49 shows the TEC assembly.

Risk Mitigation and Assessment

Two concepts were proposed and evaluated:
1) Dual cooling exhaust
2) High nickel alloy exhaust

The dual cooling exhaust concept was selected as the preferred option but will need further refinement of the cooling requirement and evaluation of the performance impact. A cost analysis on high nickel alloy exhaust cylinder will also be performed in the next phase as a back-up option.
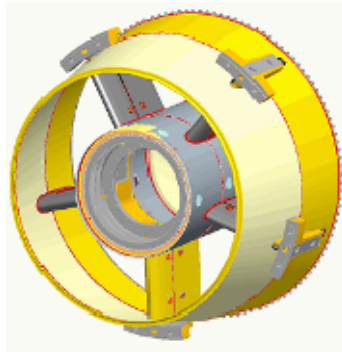
Figure 49. TEC Assembly

Conclusion

Study results show that there are feasible solutions to overcome the technical challenges for the casing and associated bolting systems. The preferred options for casings are cooled concepts which can allow for the use of the most economical materials, however, there may be a performance impact which must be carefully considered in the down selection of a final approach at the end of the next phase. Down selection on the basis of overall life cycle costs will include the potential trade off on cost and performance. The main focus for the next phase will be to further assess and develop the preferred options and determine the cost impact of pursuing high temperature materials.

Materials

High Temperature Bondcoats

Approach

The development of high temperature oxidation and corrosion resistant bondcoats has been undertaken through an evaluation of the current Siemens bondcoat with three new compositions containing alternative elemental additions. A mixed DoE approach has been utilized to assess the oxidation and corrosion characteristics of these bondcoats. All four bondcoats were TBC coated and then tested at elevated temperatures in both laboratory air (Casselberry Laboratory) and in air containing 10% water vapor (University of Pittsburgh).

Results and discussion

Testing in Air

The influence of bondcoat composition on TBC spallation life was evaluated via thermal cycling tests in laboratory air. The test coupons were thermally cycled every twenty-four hours from temperatures in excess of 1000°C down to ambient temperature and back to the elevated temperature. The TBC spallation life as a function of bondcoat composition was evaluated at three different temperatures. Figure 50 shows the results of the TBC spallation testing performed in laboratory air as a function of bondcoat composition and test temperature.
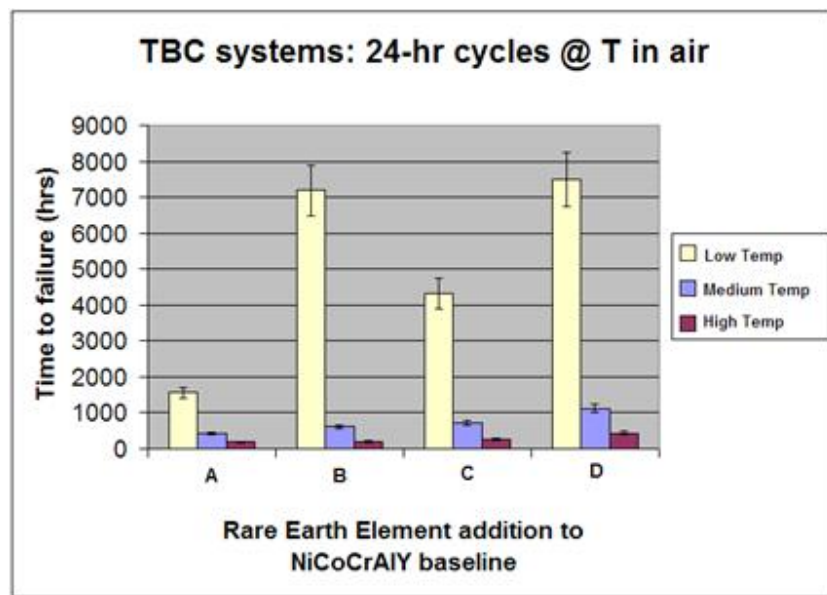

Figure 50. TBC Spallation Life as a Function of Bondcoat Composition and Temperature (all temperatures were in excess of 1000°C)

At all temperatures, the modified bondcoat "D" performed the best. At high temperatures, modified bondcoat "C" had slightly lower performance than "D". At lower temperatures, the modified bondcoat "B" showed excellent performance, again having only slightly lower performance than the modified "D" bondcoat. At all temperatures, the modified "A" bondcoat showed poor performance.

Micrographs of the "A", "B", "C" and "D" modified bondcoat samples exposed at the lowest of the elevated temperatures are shown in Figure 51 after final failure. Due to the trends observed at the higher temperatures, further evaluation of the "A" modified bondcoats will be discontinued due to excessive internal oxidation concentrated near the surface, as this is believed to contribute to the premature failures observed at both high and low temperatures.
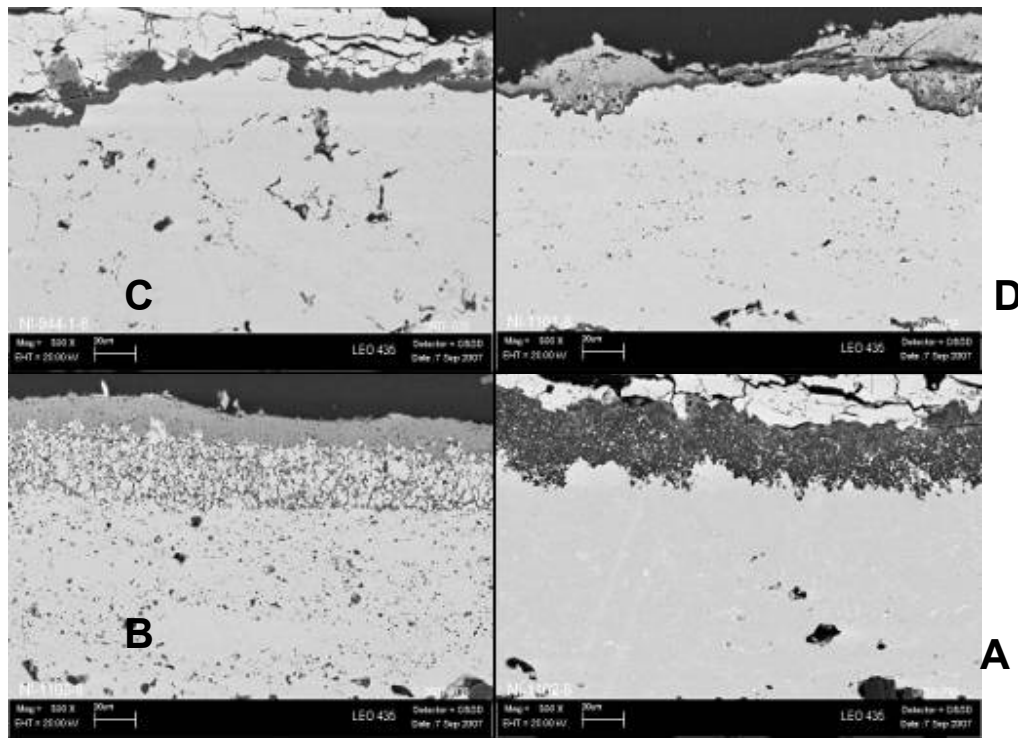
Figure 51. Micrographs Showing the Microstructures of Modified Bondcoats Exposed at Elevated Temperature in air Following TBC Spallation

The "C" and "D" modified bondcoats exhibited excellent performance during the testing of button samples. This performance will need to be verified with pins. The "B" samples exposed at the lower temperature showed a large amount of internal oxidation, but due to the homogeneity and the formation of a relatively dense oxide layer at the surface was able to survive nearly as long as the "D" composition at this lower temperature. Although the performance of the "B" modified bondcoat at higher temperatures was not as good as that of the "C" and "D" modified bondcoats, an additional elemental addition is proposed and will be evaluated as a further addition to the "B" composition in an attempt to minimize internal oxidation.

Testing in Air Containing 10% Water Vapor

Two sets of bondcoated specimens were exposed at elevated temperature in air with 10% water vapor under cyclic conditions (24-hour cycles).

The determination of beta phase depletion is one of the key criteria in characterizing bondcoat performance. Micrographs showing the amount of depletion for the "C" modified and the "D" modified baseline NiCoCrAlY bondcoat are presented below in Figure 52. The bondcoats with the other two alloy modifications, exhibited 100% β phase depletion after 911 hours of cyclic exposure (air + water vapor).
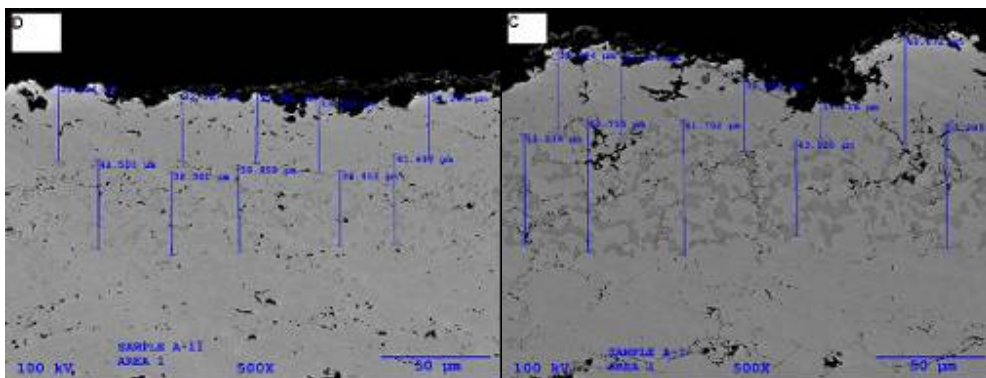

Figure 52. Cross Sections Showing Beta Phase Depletion for "C" and "D" Modified Bondcoats (911 hours of cyclic oxidation in air + 10% water vapor at elevated temperature)

Conclusions

A determination for the direction of future research with regards to elemental additions based upon the data presented in "Results" can be made. Additions of three of the elements evaluated show possible benefit to the typical MCrAlY based bondcoat chemistries. The data acquired in Phase 1 needs to be reproduced along with oxidation studies of the original three (D, C, B) with an additional elemental addition of 1.5wt%B+0.5wt%F and 1.5wt%B+1wt%F. Since C and D show the best results at higher temperatures, combinations of these will be undertaken to hone in on the ideal composition in a multi-point DoE.

Bondcoat development has previously introduced multiple individual elemental additions for the purpose of reducing oxidation and TBC spallation. In Phase 2, the focus will continue these efforts with concentration on elemental additions with respect to interaction and combined benefit. This will involve running tests at multiple temperature regimes and water vapor environments to establish conformity with current and future high temperature operating conditions. Modifications employing pre- and/or post-processing methods, multi-layer, and beneficial secondary phases for bondcoats will also be evaluated.

High Temperature Capable TBCs

Approach

Thermal barrier coatings having low thermal conductivity (K) are being developed. Such coatings will minimize the transfer of heat from the hot gas path to the surface of the underlying alloy, significantly lowering the base alloy temperature and increasing the TBC surface temperature.

It is important that the TBC exhibits excellent phase stability over the operating temperature range. The extreme environments in the turbine section demand that the TBC materials have good sintering resistance. The new TBC materials are being developed to be compatible with conventional and new bondcoat and superalloy materials.

During Phase 1, the TBC development has focused on the thermal properties and phase stability. The influence of compositional and processing changes have been investigated, and the resultant coatings have been evaluated for Phase stability, thermal conductivity and spallation resistance in the predicted operating temperature range.

Results and Discussion

The two TBC coatings being evaluated have met the room temperature thermal conductivity requirement provided by Turbine Design (Figure 53). The samples were heat treated at temperatures between 700°C and 1400°C for 500 hours to establish the high temperature thermal conductivity curve. The thermal conductivity measurements were performed at Oak Ridge National Laboratory (ORNL) and the compiled data is presented below. This high temperature thermal conductivity requirement was also successfully demonstrated.
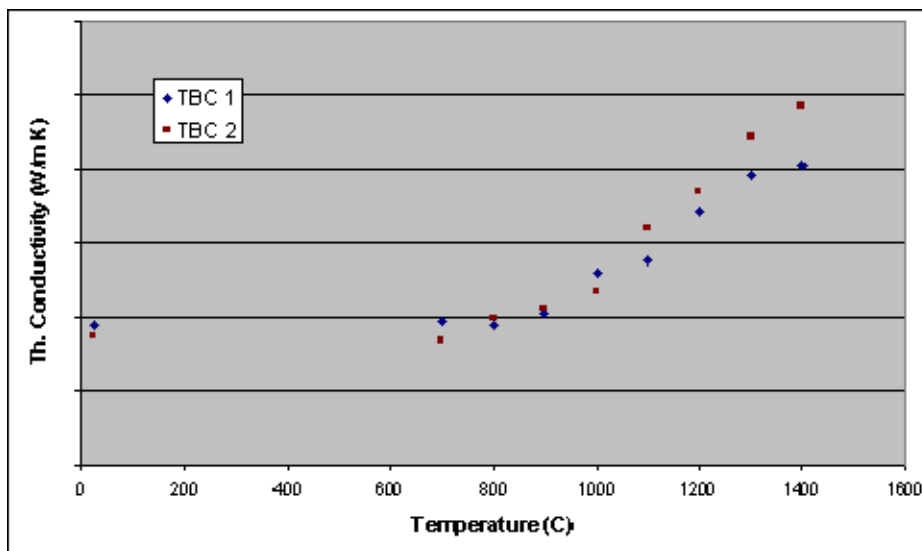
Figure 53. High Temperature Thermal Conductivity Curves for two TBC Compositions

In addition to the thermal conductivity measurements, the process sensitivity of the thermal conductivity of the two TBC compositions was established using a DoE approach. It was observed that a process window needs to be established to meet the TBC requirements (Figure 54).

Thermal conductivity variation determined by varying processing parameters

Figure 54. The TBCs Under Development have Demonstrated to have Phase Stability at Temperatures between 1500° and 1850°C

Figure 55. No Phase Changes Occur At Temperatures Up To 1850 °C

Coating spallation studies are currently being performed to evaluate TBC performance at elevated temperatures. Spallation studies have been carried out on various combinations of base alloys.

Conclusions

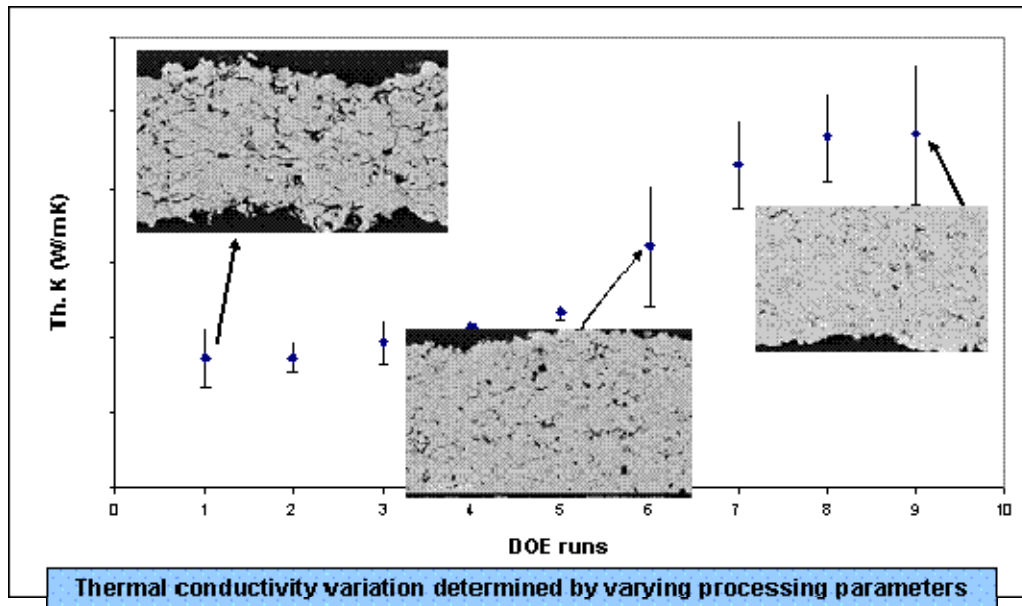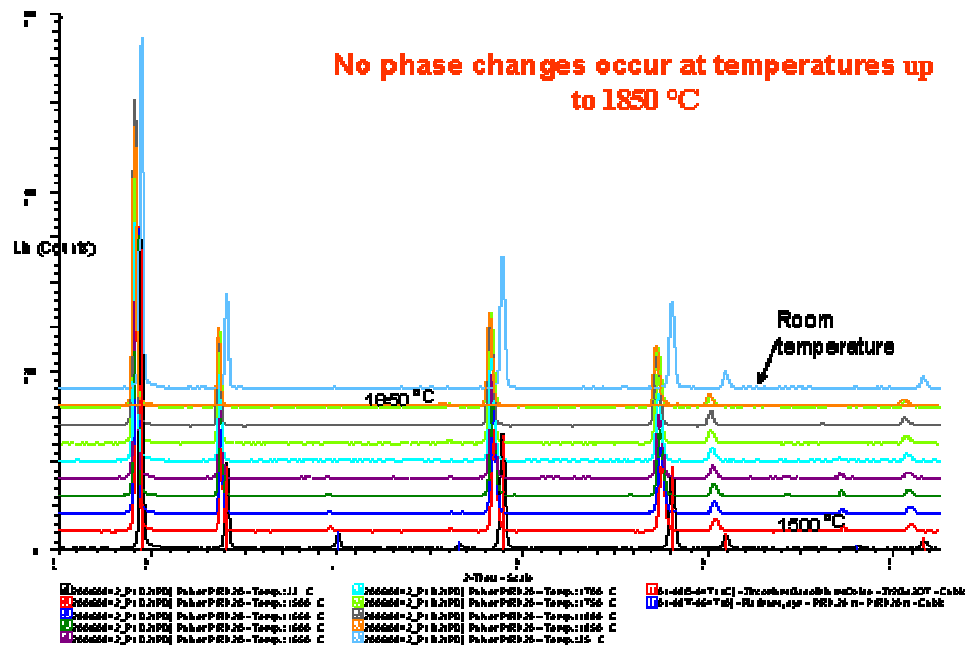The results from Phase 1 identified two TBC compositions which satisfy the thermal conductivity requirements and have demonstrated phase stability up to temperatures of 1850°C (see Figure 53). Phase 2 will focus on high heat flux testing in relevant environments for establishing the surface temperature limits. The work will focus on long term performance studies and process control efforts to define the process limits for the selected composition.

Rare Earth Modified Superalloys

Approach

This sub-project seeks to increase the oxidation resistance and coating compatibility of the hot section superalloy materials through the addition of very small amounts of rare earth elements.

Sulfur has an extremely detrimental effect on the strength of alloy grain boundaries. The same problem occurs at alloy-coating boundaries. The sulfur atoms preferentially form thin layers along the grain boundaries, reducing the boundary adhesion. These layers are typically a few atom layers thick. Reducing the sulfur contamination to below 4 ppm dramatically increases the temperature at which surface oxide spallation occurs.

Rare Earth (RE) elements are extremely reactive, and as a consequence, when added to the melt, they readily form sulfides and oxy-sulfides. This removes the sulfur from the surface and grain boundaries, and thus has a beneficial effect on both the oxidation resistance and the coating performance.

In collaboration with the University of Florida, a literature and patent review was performed to identify the rare earth elements with the greatest potential to impart the desired improvement in oxidation resistance.

The study revealed the importance of RE elements on the oxidation behavior of nickel base superalloys at high temperatures by controlling the rates of growth of rate and improving the spallation resistance of the oxide scale.

- Various proposed models have been able to satisfactorily explain the effect of rare earth elements on the oxidation performance.

- The effect of RE elements on the mechanical properties is not well illustrated in the literature, although they seem to have an effect on the microstructure and thermal fatigue behavior of the alloy.

Differences in thermodynamic properties and melting points of the RE sulfides were considered, and this data was utilized as a basis to select the rare earth elements which would be added to the base alloy.

Four RE elements were selected as minor alloying additions to the base alloy CM247LC. A 180 kg (400 lbs) master heat of Alloy (CM)247LC was procured to support the RE alloy modification

trials. From this master heat, sixteen individual heats of RE modified Alloy (CM)247LC were cast into test bars by Howmet Whitehall.

Results and discussion

The retention levels of the RE elements was found to vary significantly. The concentration of one RE element was found to be between two and three times higher than the aim, while other RE elements has final concentrations that were approximately half of the target level.

Material for oxidation testing and coating compatibility evaluation was given the full standard Alloy (CM)247LC heat treatment: A total of twenty eight 13 mm diameter x 3 mm thick button samples have been machined from each of the sixteen alloys. Eighteen button samples from each alloy are being utilized for oxidation studies, and the remaining ten button samples from each alloy were coated (Sicoat 2464 bondcoat + 8YSZ TBC) for the coating compatibility trials.

One as-cast bar from each of the sixteen alloy compositions was macroetched to characterize the structure. Optical microscopy was used to evaluate the microstructures, including grain size determination, volume fraction γ/γ' eutectic and dendrite arm spacing (DAS). The γ/γ' eutectic volume fraction was determined using manual point counting on SEM backscattered micrographs.

Scanning electron microscopy was used to examine microstructural features in greater detail. The majority of the evaluation was undertaken using secondary electron imaging on etched microstructures. However, backscattered electron imaging was used on unetched samples to determine elemental segregation and to examine precipitates. Microprobe analysis was also undertaken to quantitatively identify the compositions of various phases.

Differential thermal analysis (DTA) was performed on a sample of each as-cast alloy. Material for DTA was machined to provide samples with a thickness of between 0.75 cm to 1.5 cm weighing at least 250 g. These samples were heated at a rate of 20°C/min and compared to a pure Ni reference sample. Only "on-heating" data was generated to avoid any effects of supercooling.

In general, the microstructures of all sixteen alloys were very similar. Preliminary measurements of the grain size (on the order of millimeters in size) and dendrite arm spacings measured in all of the as-cast samples were relatively coarse, indicating that the samples had experienced very slow solidification rates.

Additional work is in progress to quantitatively characterize the effect of the RE additions on the volume fraction of the γ/γ' eutectic. However, initial measurements appear to indicate that the RE additions resulted in a small increase in the γ/γ' eutectic.

The results of the DTA testing also indicate that the RE additions had a limited impact on the transformation temperatures. The solidus and γ'-solvus temperatures of the as-cast samples were very similar for all of the alloys. The liquidus temperatures of the alloys with RE additions were approximately 10°-20°C lower than the baseline alloy without any RE additions. It should be noted that the observed γ'-solvus temperatures in the as-cast DTA testing indicates that the samples were solidified under slow cooling rates; this is consistent with the metallographic observations.

The initial oxidation tests (24 hrs cycles) on each of the fifteen modified alloys plus base Alloy (CM)247LC ran at three different temperatures. At the end of Phase 1 the tests had completed approximately 900 hours. There was an emerging trend that the standard Alloy (CM)247LC was oxidizing more rapidly than the modified alloys. Despite this, accurate separation of the relative behavior based purely on the oxide spallation is not realistic after such short exposures. As a consequence, the next extraction of samples for microstructural analysis of the oxide surface, will be performed after 1200 hours of testing and, will be used to rank the materials by microstructural and physical size changes.

Coated samples of each material using standard production bondcoats and standard 8YZ TBC are also currently being exposed to cyclic oxidation at three temperatures. At the end of Phase 1 these tests have run approximately 700 hrs without spallation.

Fabricated Airfoils for 'Near wall' Cooling

Approach

The goal of this sub project is the development of a process for constructing near wall cooling features for advanced airfoils.

Two different approaches are being explored:

- Bonding of thin skins
- Thermal spraying of skins

Each path poses unique challenges and each has its relative merits. Bonding is a relatively mature technology, but the complex three dimensional geometries associated with airfoil shapes present a major challenge. The thermal spray approach offers greater flexibility of alloy selection for the skin and can accommodate complex airfoil shapes, however the achievement of the required interfacial properties will be a challenge.

Results and Discussion

Bonding of Thin Skins

Bonding trials were performed by Integrated Energy Technologies (IET) to investigate the potential of using diffusion bonding as a technique to join Alloy (CM)247LC to both Haynes 230 and Haynes 214. The set-up of the coupon bonding is shown in Figure 56 below:
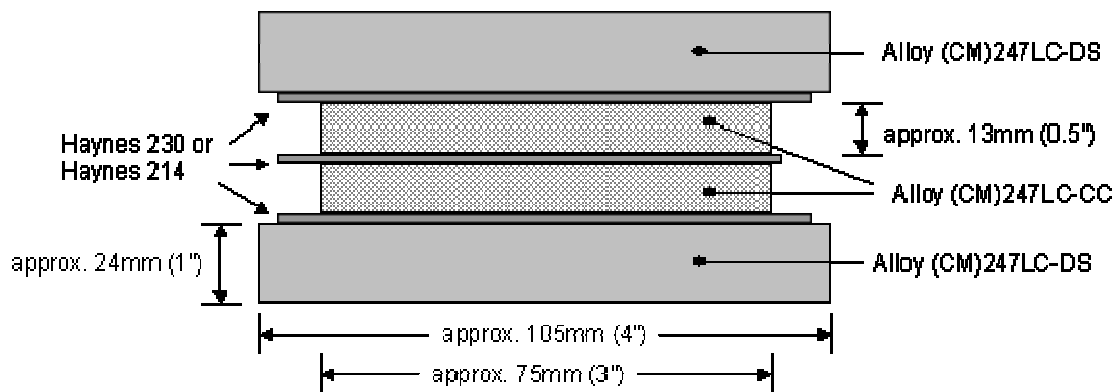
Figure 56. Bonding Arrangement

Two coupons containing Haynes 214 and two coupons containing Haynes 230 were produced. After bonding, the coupons were sectioned for metallographic evaluation and mechanical testing (tensile and creep).

Metallographic examination revealed that there was incomplete bonding at the edges of the coupons extending inwards along the bond line for approximately 10 mm. The central sections of the bonded coupons appeared to be well bonded with no evidence of cracks or porosity.

The mechanical testpieces were manufactured with the bonded joints within the parallel gauge section and normal to the loading axis. During the testpiece machining operations a couple of the stress rupture testpieces failed at the bond line. These failures were attributed to incomplete bonding which was observed near the edges of the bonded coupons.

Tensile results

The tensile tests were performed at a temperature of 760°C (1400°F). The bonded Haynes 214 testpieces failed with a UTS approximately equivalent to the 0.2% yield stress of the baseline unbonded Haynes 214. The bonded Haynes 230 testpieces failed with an average UTS value approximately 20% lower than the 0.2% yield stress of the baseline unbonded Haynes 230. All of the tensile tests failed prior to or shortly after reaching the 0.2% yield stress. All testpieces failed at elongations of less than 2%.

Stress rupture results

All of the stress rupture tests were performed at a temperature of 760°C (1400°F). Although only three Haynes 230 diffusion bonded samples were tested, all the samples exhibited stress rupture properties which lay within 15% (in terms of stress) of the Haynes 230 base alloy, and two of the samples exhibited properties within 6% of the Haynes 230 base alloy.

The stress rupture properties of the bonded Haynes 214 samples were less consistent than the bonded Haynes 230. Two of the Haynes 214 diffusion bonded samples failed on loading with an

initial applied stress of 165 MPa. All of the remaining Haynes 214 testpieces failed in times considerably lower than the baseline Haynes 214 alloy.

Thermal spraying of skins

The thermal spray approach comprised HVOF coating of Haynes 230 alloy onto machined blocks of Alloy (CM)247LC-CC. Simulated cooling channels were machined into the block surfaces and filled with a commercial masking material, MachBloc® before spraying. After spraying the blocks were sectioned and scanning electron microscopy (SEM) was performed to characterize the coating microstructure and morphology.

The MachBloc® masking material was not effective in this application, as shown in Figure 57 below. The HVOF spray plume bounced off the masking material and did not bridge the channels to form a skin as desired. Characterization of the coating showed good density and excellent bond line (interface) cleanliness and properties, so the fundamental approach is sound. The key will be to find a different masking material that will survive the intense HVOF spray but still allow the coating to adhere to the masking surface.
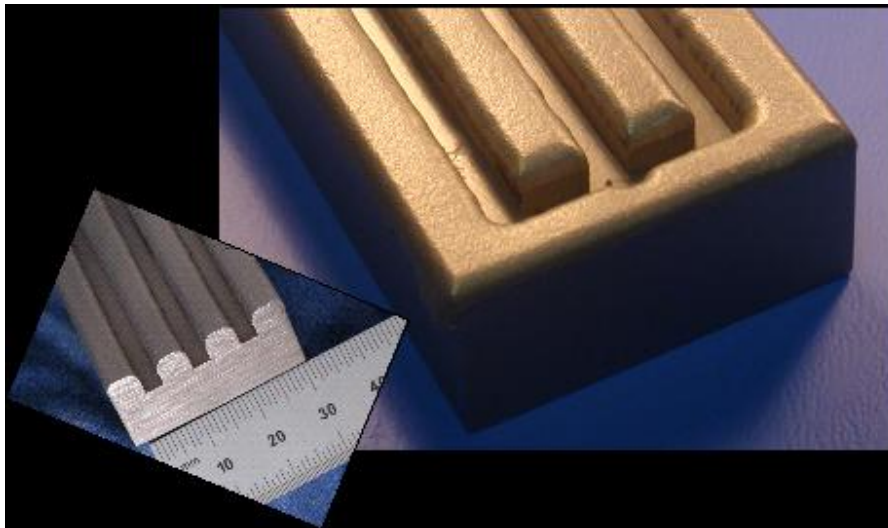

Figure 57. Channel Block after Coating. Note the rounded morphology of the coating over the block pillars.

Figure 58 shows a cross section through the coated channel block. The coating was rounded atop each pillar. This will not be a problem for actual components since the rounded edge can be designed to fall within a scrap region of the part, such as a trailing edge extension. The insets in Figure 58 show larger magnification views of the microstructure of the coating. Note the layered structure that is formed on the rounded edges. This too can be designed to fall in a scrap edge and so will not affect the final part but is something that will need to be accounted for in the core design and in the pattern of the robotized HVOF spray program to ensure that the gun direction is approximately perpendicular with the part surface.
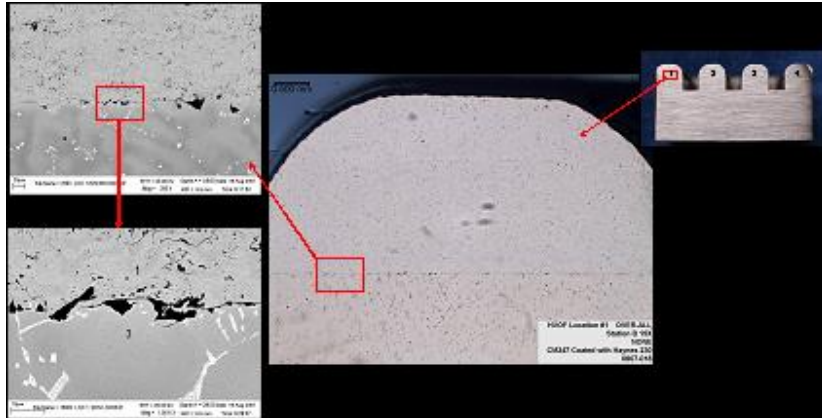
Figure 58. Cross Section through the Coated Channel Block

Conclusions

The potential to join Alloy (CM)247LC to both Haynes 230 and Haynes 214 using diffusion bonding has been demonstrated. Some additional development will be required to optimize the bonding conditions. The trials were conducted using flat plates of material; the fabrication of three dimensional contoured surfaces represents a much greater challenge.

The initial HVOF spray deposition trials were partially successful. The deposited material exhibited a good bulk and interfacial microstructure. Hot isostatic pressing could be employed to close the porosity. The masking trials were not successful due to the choice of masking material. Additional new masking materials have been identified and these will be evaluated in Phase 2.

Environmental Validation

Approach

Understanding the high temperature degradation mechanisms in advanced materials is of fundamental importance in developing strategies to enhance and predict component durability in gas turbine engines. To accomplish this, high temperature test facilities are a most valuable tool for simulating the harsh environments to which the materials will be exposed. There are a limited number of test facilities available for the assessment of materials and coatings under realistic high temperature, high pressure engine conditions.

The Hyperbaric Advanced Demonstration Environmental Simulator (HADES) for Hot Section Material Systems has been developed by Florida Turbine Technologies (FTT) and offers a potential opportunity for the affordable testing of materials and coatings under realistic engine conditions. The capabilities of the HADES rig have been evaluated during Phase1.

Results and discussion

The work in Phase 1 focused on the testing of the coating system in the high pressure/high temperature environments in the HADES rig. To evaluate the environmental impact, testing was also carried out using a high temperature, atmospheric burner rig in simulated high heat flux environments. The results of these tests are presented below:

An instrumented TBC specimen was utilized to determine the test rig conditions in the HADES rig, and an additional TBC specimen was tested at these conditions for repeatability. Metallographic studies are planned to evaluate the microstructure and correlate the results back to test rig model. The results of the testing of the instrumented specimen are presented in Figure 59. The thermocouple was located underneath the TBC and the bondcoat. The graph shows the variation of the temperature along with varied fuel/air ratio. One of these fuel/air ratios was used to test another TBC coated specimen.
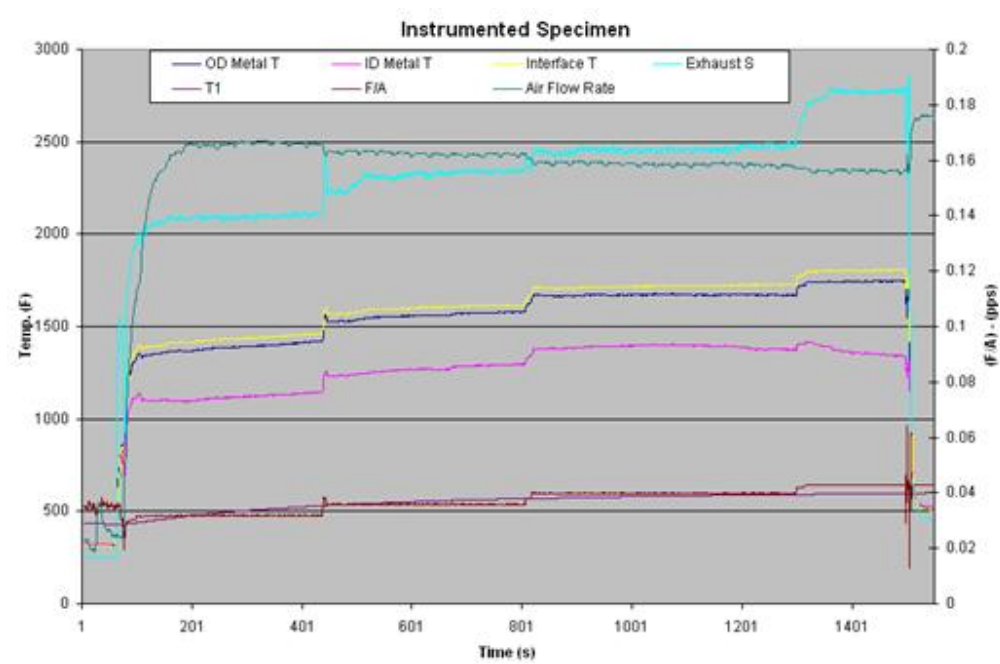

Figure 59. Temperature Variation As A Function Of Time At Various Test Piece Locations In The HADES Test Facility

A second TBC coated specimen was run for 4 hours. The main intent was to achieve repeatable conditions and carry out metallographic evaluation to correlate back to calculated combustion temperatures from emissions. The specimen is shown below (see Figure 60), where the test area is slightly gray but erosion of the coating was observed at the exhaust end. This was mainly attributed to the water droplet erosion due to leaks at the exhaust end. The specimen was sectioned to evaluate the microstructural changes around the circumference and also along the length of the specimen. The tests showed varied beta depletion along the length of the sample, for both tests. This can be attributed to the varied heat transfer conditions between the hot gas surface of TBC and cooling water flowing through the specimen in reverse direction. The other concern in this test was the varied depletion around the circumference of the specimen at one location. This suggests varied heat flux conditions around the sample. More instrumented test pieces are being prepared to evaluate the surface temperatures. The rig is currently being diagnosed for the condition of the critical components. Long term tests are also planned.
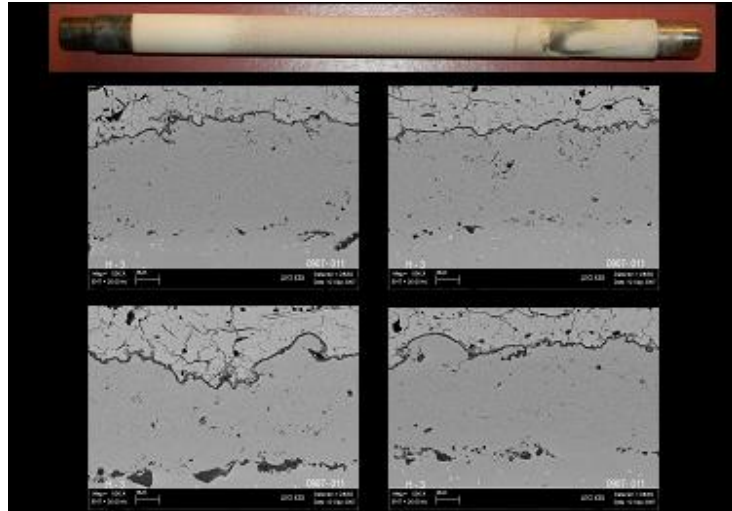
Figure 60. Beta Phase Depletion around the Circumference of the Specimen at one Longitudinal Location

Testing was also performed using the burner rig at Cranfield University. The high heat flux test results from burner rig environment are presented below. The test matrix consisted of bare alloys, bondcoated and TBC coated specimens. The results below are taken from a test on natural gas with added contaminants. It was observed that bare metals suffered extensive degradation. The bondcoated specimen does show improved resistance, however a failure is initiated at the end of the testpiece. The TBC coated specimen experienced the lowest extent of damage.
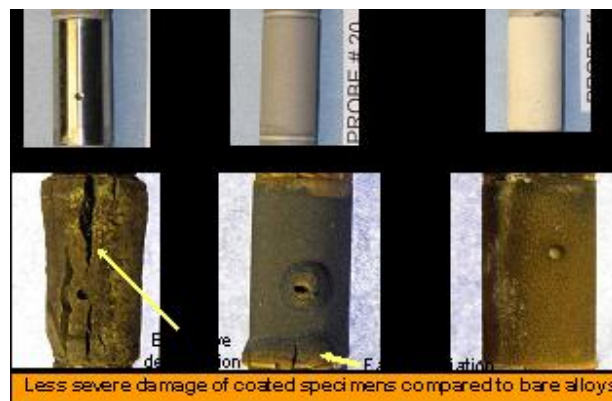
Figure 61. Coated and Uncoated Testpieces after Exposure in the Cranfield Burner Rig

The qualitative ranking of alloys and coatings in environmental conditions was also performed using isothermal tests. The simulated natural gas/syngas/high hydrogen combustion environments were produced using bottled gas at relevant temperatures for test durations of 500 hours. Significant variations in alloy degradation were observed as a function of gas composition. Bondcoats exposed to syngas combustion environments formed a mixed oxide spinel layer on top of an alumina layer. This is contradictory to its behavior in natural gas where

the spinel forms after all the aluminum rich phase has been depleted and alumina formed (see Figure 62).
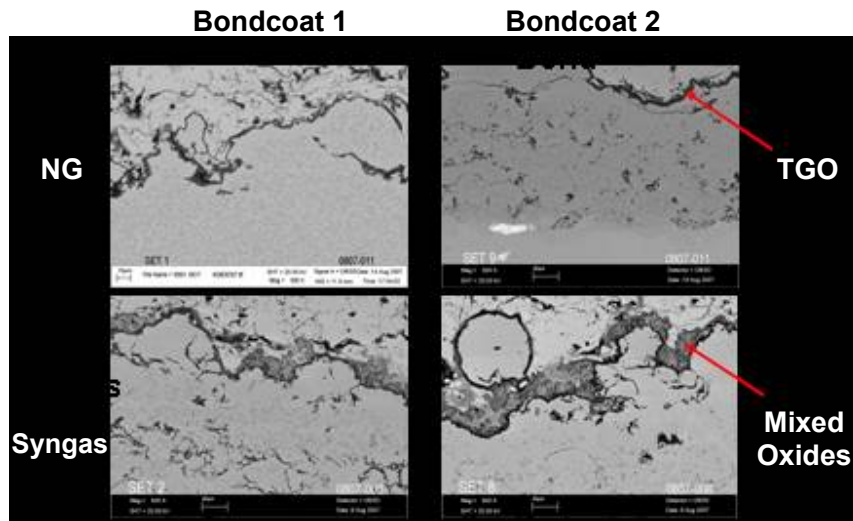
Figure 62. Oxides Formed after Exposure to Combusted Syngas and Natural Gas

The results from Phase 1 will be utilized to establish a test plan for alloy and coatings performance in H_2 turbine relevant conditions. The program focused on test rig evaluation in Phase 1 to demonstrate the test conditions and establish a baseline. The Phase 2 efforts will be focused further on long term high heat flux testing in simulated environments to support materials and coatings development.

Auxiliaries

Approach

Key Auxiliary Systems identified were based on the systems developed for the SGT6-5000F IGCC frame and the SGT6-6000G standard auxiliaries. These systems include, but are not limited to, Fuel Gas System, Syngas System, Hydrogen Gas System, Steam Injection System, Turbine Cooling Air System, Extraction Air System, Lube Oil System, Control Oil System, Instrument Air System, Nitrogen Systems, Drain Systems, Inlet System, Exhaust System, Piping Systems, Compressor Bleed System, Fire Protection Systems, Electrical Systems, Automation Systems, and various smaller systems.

Preliminary schematics of the new auxiliaries have been developed based upon the piping and instrument diagrams for the SGT6-5000F IGCC designs. These are at the system level and are generic in content. Preliminary system descriptions for each of the auxiliary systems were also developed utilizing the SGT6-5000F IGCC as a basis.

A review of materials was conducted to identify materials concerns with a focus on hydrogen embrittlement and hydrogen induced metal dusting. A review of hydrogen safety literature was also conducted.

Results and Discussion

Key auxiliary systems were defined based on boundary conditions presented for the first iteration. Impacts on requirements at auxiliary boundaries and Balance of Plant were identified. Preliminary schematics and basic system descriptions were developed for each of the identified auxiliary systems.

To identify materials for review, two documents were identified in support of defining alternative materials 8 and 9. Figure 63 shows the materials used in the power generation industry and their associated creep strengths.
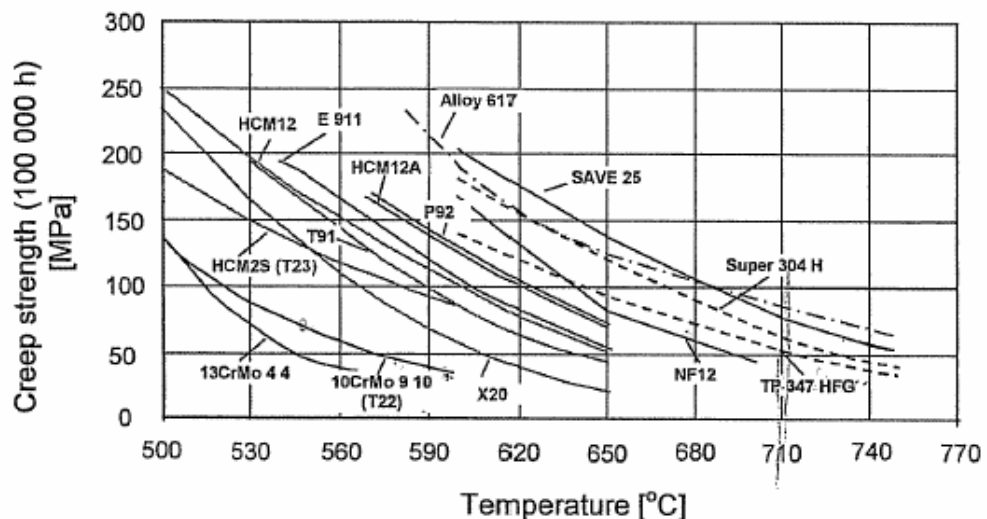

Figure 63. Creep Strengths [9]

H_2 Safety Programs literature review identified several organizations that are currently upgrading or creating their existing hydrogen safety specifications (ASME, ASTM, NFPA, etc.). Initial documents from the following sources were utilized:

- 2003 Seattle Fuel Gas Code
- European Industrial Gases Association
- Bureau De Normalisation Du Quebec
- Department of Energy
- California Energy Commission
- National Aeronautics and Space Administration

Hydrogen safety reviews indicated many implications for transportation and use of this fuel type. The chart below summarizes these concerns in comparison to natural gas.

Properties[a]	Hydrogen	Natural Gas (Methane)	Implications
Molecular weight	2.016	16.04	Hydrogen is more leak prone
Density at NPT	0.08 kg/m^3	0.68 kg/m^3	Hydrogen leaks are substantially more buoyant and they diffuse faster, which causes concentration to drop below LFL more quickly.
Diffusion Coef. at NPT	0.61 cm^2/sec	0.16 cm^2/sec	
LFL-UFL in air	4.1-75% Vol.	5.0-15% Vol.	Confined hydrogen leaks into air are more likely to ignite
Min. Ign. Energy	0.02 mJ	0.29 mJ	
Boiling temp. at 1 atm	-253°C	-162°C	Liquid hydrogen spills dissipate to less-than-LFL more quickly than LNG spills
Heat of vap. at 1 atm	446 kJ/kg	509 kJ/kg	Hydrogen-air combustion energy release in a confined volume is less
Volumetric LHV[b]	9,600 kJ/ m^3	34,000 kJ/ m^3	Ignited hydrogen-air mixtures are more likely to detonate
Burning velocity	3.0 m/sec	0.36 m/sec	
Leak detectability	low	low	Both hydrogen and natural gas leaks are difficult to detect unless gas is odorized
Flame detectability	low	medium	Hydrogen flames are more difficult to see or detect with instruments

Table 6. Hydrogen Safety Reviews [10]

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Conclusion

Initial basic system configuration schematics and working system descriptions have been produced to define key boundary data and support estimation of costs. Review of existing materials in use for hydrogen transportation show benefits or tradeoffs for materials that could be used in this type of application. hydrogen safety will become a larger risk than natural gas fuel as the work done to date in other areas has shown direct implications for this type of use.

PROGRAM MANAGEMENT

The Program Management task monitored and controlled the project budget, scope, and milestones, communicated project objectives to the team, and communicated project status and accomplishments to the DOE. As can be seen in Table 7, all of the DOE milestones for Phase 1 were met.

Phase I	Quarterly Milestones	Completion Date
Jan-06	Baseline IGCC Thermal Model Development	12/10/2005
Apr-06	RDI Plan Submission	3/31/2006
Jul-06	1st Iteration of Plant Cost	6/30/2006
Oct-06	Prioritization of Internal Turbine Cooling Passage Concept	9/30/2006
Jan-07	Thermal Barrier Coating Conceptual Design	12/30/2006
Apr-07	Baseline Combustor Test Completion	2/28/2007
Jul-07	IGCC Plant Conceptual Design	6/12/2007
Oct-07	Engine Conceptual Design	9/20/2007

Table 7. Phase I Quarterly Progress Indicators

Earned Value Analysis (EVA) was utilized to track program cost and schedule performance starting in FY07. The data types and formulas used in this tool are listed below.

Planned Value (PV) – The original budgeted cost associated with the scheduled work performed.
Actual Cost (AC) – The actual dollar value spent during the period.
Earned Value (EV) – The value of the work actually completed.
Cost Performance Index (CPI) = EV / AC – The sum of all individual EV budgets divided by the sum of all individual ACs is known as the cumulative CPI. It is generally used to forecast the cost to complete a project.
Schedule Performance Index (SPI) = EV / PV – This is often used with the CPI to forecast overall project completion estimates. The results for FY07 first quarter are given below:

    Overall Program CPI: 0.95
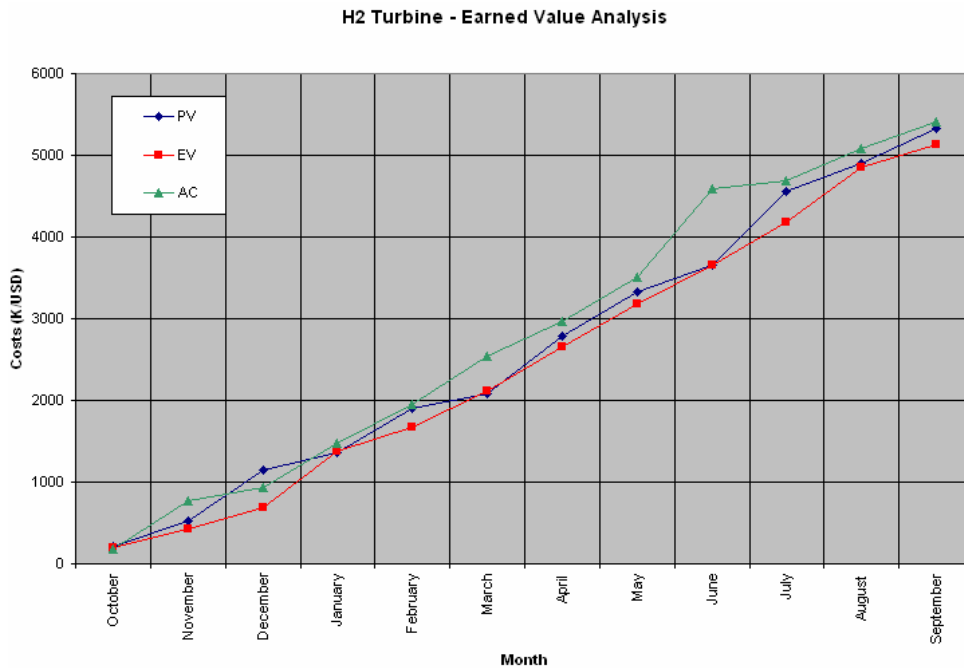   Overall Program SPI: 0.96

Figure 64. Overall Program Earned Value Analysis Chart for FY07

Customer Advisory Board

Customer Advisory Board Meetings

Two Customer Advisory Board meetings were held during Phase 1 with a selected group of customers. The purpose of these meetings was to gain market feedback on future gas turbines and IGCC power plants to support Siemens Power Generation (SPG) product offerings and the DOE Hydrogen Turbine R&D program. The format encouraged dialogue and feedback from the selected participants and included sharing the results of the above customer survey, sharing the progress of our Hydrogen Turbine R&D program and an update on our IGCC product offering.

Customer Survey

The Hydrogen Turbine / IGCC marketing web-survey was initiated in Phase 1. Invitations were sent out to 112 target industry experts, IGCC developers, operators and technology managers. 56 responses were received. Among the responses received, over 60% of the respondents indicated their companies are intending to build an IGCC plant within 10 years.   Figure 65 shows the distribution of positions being identified in the survey.
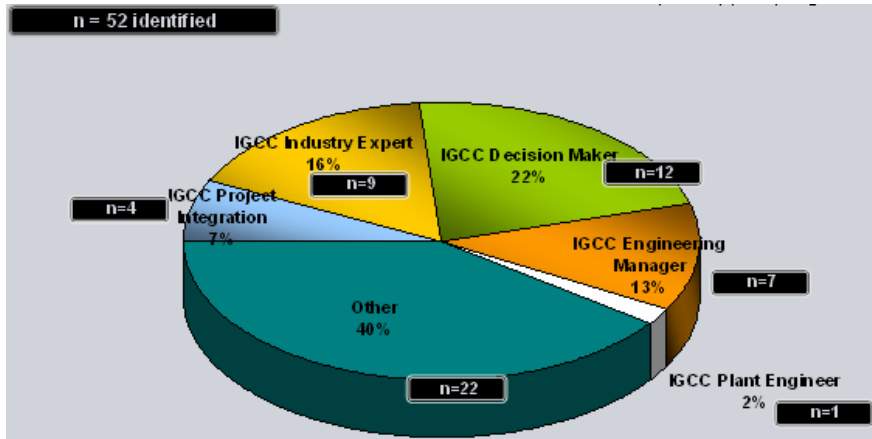
Figure 65. IGCC Industry Respondents Position Distribution

Across the community of respondents that were intending to build IGCC plants, there were significant differences in opinion on plant size, expected efficiency, use of hydrogen as a fuel, and air integration level. This could indicate that agreed upon models for IGCC plants have not emerged in the industry thinking. Thus, while designing a Gas Turbine for IGCC application, flexibility should be one of the key design criteria to ensure applicability to a not completely defined market expectation of the potential technology.

Plant availability, capital cost and technology demonstration was concluded to be the major concern of IGCC developers. Some primary design criteria identified by the customers include baseload operation, pre-combustion CO_2 capture capability, natural gas operation during gasifier down time, adequate plant efficiency to minimize $/kW capital cost and monitoring and diagnostic systems.

Concerning CO_2 sequestration performance penalty, over 60% of the IGCC intent target group indicated an expectation of over 10% on the plant efficiency impact. This reflects a consistency between the current market expectation and the existing technology capability (see Figure 66).
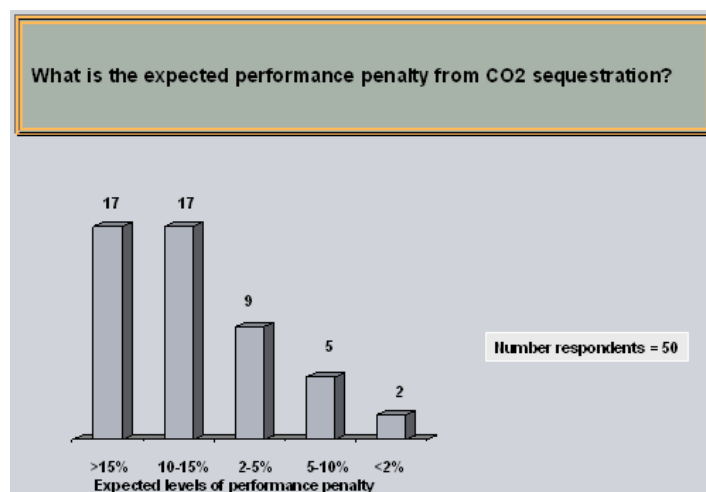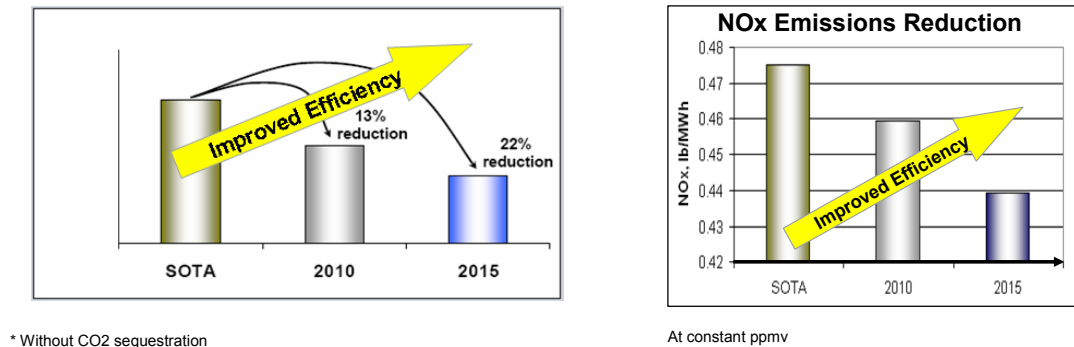

Figure 66. Performance Penalty Expectation for CO$_2$ Sequestration.

Emissions and Cost Studies

Studies conducted during Phase 1 to quantify the impacts of improved plant efficiency on CO_2 and NO_x emissions showed lower emissions on a lb/MWhr basis for both CO_2 and NO_x with increasing efficiency (see Figure 67).

* Without CO2 sequestration

At constant ppmv

Figure 67. Emissions Reduction with Advanced GT Technology

The Hydrogen Turbine-IGCC plant capital cost was carried out. The initial estimate was based on the SGT6-5000F IGCC plant cost database and the preliminary GT and plant configurations as well as comparison with the SGT6-6000G cost deltas. The final plant price estimate was scaled from 2006 dollars to 2002 dollars to give a better comparison to the $/kW target value as per DOE's instruction. The estimate included the following:

1. Power Block (Equipment + Construction): 2 Hydrogen-fueled GTs, 2 HRSGs, 1 Steam Turbine, 3 Generators and all associated Auxiliaries/Controls/BOP Equipment.

2. Gasifier and ASU (Equipment + Construction): Full Slurry Quench Gasifier (with initial charge of chemicals and catalysts, syngas cooling and particulate removal), Coal Handling, Slurry Preparation, Slag Handling, Acid Gas Removal with CO_2 Compressor, Sulfur Recovery, Sour Water System, Tail Gas Treating, CO Shift Sour, ITM ASU with Oxidant Feed and General Facilities.

The estimate did not include interest during construction, prepaid royalties, preproduction costs or land.

The estimated $/kW value was above the $1000 / kW Advanced Power Systems target value. It should be pointed out that the GT, which is the object of this development effort, itself represents a small percentage (5-10%) of the total price. Even the Power Block (GTs, ST, HRSGs, BOP) represents only a fraction of the total capital cost.

A first-order sensitivity study was carried out to estimate the impact of syngas-fueled plant efficiency on cost. In the study, the efficiency of the power block was increased from current levels to "advanced hydrogen turbine" levels, and the cost of the power block was adjusted accordingly. As shown in Figure 68, a higher plant efficiency (with advanced GT technology) will result in more power increase than price increase, and will reduce the plant capital cost in $/kW
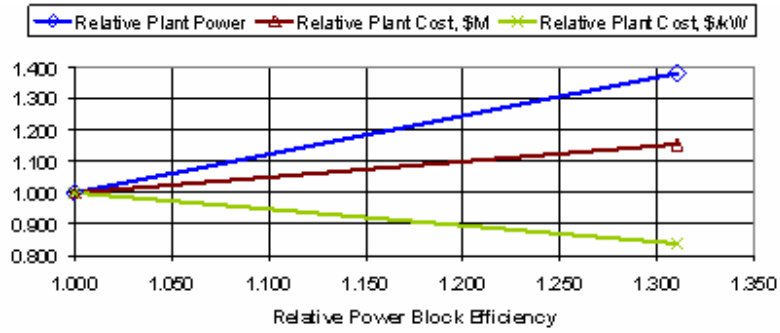
Figure 68. Efficiency Impact on Plant Power and Plant Costs ($/kW)

In order to address the DOE turbine goal for 20-30% reduction of combined cycle cost [7] from the baseline, an approach to maximize plant output and minimize cost increase is needed. Figure 69 illustrates this approach.
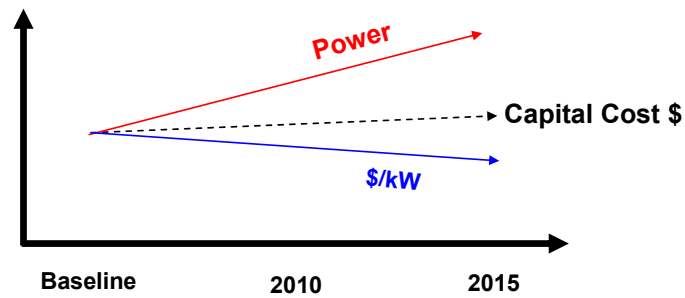

Figure 69. Reducing Plant Cost ($/kW) with Increased Plant Output

CONCLUSIONS

Siemens has developed a roadmap to achieve the DOE goals for efficiency, cost reduction, and emissions through innovative approaches and novel technologies which build upon worldwide IGCC operational experience, platform technology, and extensive experience in G-class operating conditions. In Phase 1, the technologies and concepts necessary to achieve the program goals were identified for the gas turbine components and supporting technology areas and testing plans were developed to mitigate identified risks.

Multiple studies were conducted to evaluate the impact in plant performance of different gas turbine and plant technologies. 2015 gas turbine technologies showed a significant improvement in IGCC plant efficiency, however, a severe performance penalty was calculated for high carbon capture cases. Thermodynamic calculations showed that the DOE 2010 and 2015 efficiency targets can be met with a two step approach.

A risk management process was instituted in Phase 1 to identify risk and develop mitigation plans. For the risks identified, testing and development programs are in place and the risks will be revisited periodically to determine if changes to the plan are necessary.

A compressor performance prediction has shown that the design of the compressor for the engine can be achieved with additional stages added to the rear of the compressor. Tip clearance effects were studied as well as a range of flow and pressure ratios to evaluate the impacts to both performance and stability.

Considerable data was obtained on the four candidate combustion systems: diffusion, catalytic, premix, and distributed combustion. Based on the results of Phase 1, the premixed combustion system and the distributed combustion system were chosen as having the most potential and will be the focus of Phase 2 of the program. Significant progress was also made in obtaining combustion kinetics data for high hydrogen fuels.

The Phase 1 turbine studies indicate initial feasibility of the advanced hydrogen turbine that meets the aggressive targets set forth for the advanced hydrogen turbine, including increased rotor inlet temperature (RIT), lower total cooling and leakage air (TCLA) flow, higher pressure ratio, and higher mass flow through the turbine compared to the baseline. Maintaining efficiency with high mass flow Syngas combustion is achieved using a large high AN_2 blade 4, which has been identified as a significant advancement beyond the current state-of-the-art.

Preliminary results showed feasibility of a rotor system capable of increased power output and operating conditions above the baseline. In addition, several concepts were developed for casing components to address higher operating conditions.

Rare earth modified bond coat for the purpose of reducing oxidation and TBC spallation demonstrated an increase in TBC spallation life of almost 40%. The results from Phase 1 identified two TBC compositions which satisfy the thermal conductivity requirements and have demonstrated phase stability up to temperatures of 1850°C. The potential to join alloys using a bonding process has been demonstrated and initial HVOF spray deposition trials were promising. The qualitative ranking of alloys and coatings in environmental conditions was also performed using isothermal tests where significant variations in alloy degradation were observed as a function of gas composition.

Initial basic system configuration schematics and working system descriptions have been produced to define key boundary data and support estimation of costs. Review of existing materials in use for hydrogen transportation show benefits or tradeoffs for materials that could be used in this type of applications. Hydrogen safety will become a larger risk than when using natural gas fuel as the work done to date in other areas has shown direct implications for this type of use.

Studies were conducted which showed reduced CO_2 and NOx emissions with increased plant efficiency. An approach to maximize plant output is needed in order to address the DOE turbine goal for 20-30% reduction of combined cycle cost from the baseline. A customer advisory board was instituted during Phase 1 to obtain important feedback regarding the future direction of the project.

The technologies being developed for the Hydrogen Turbine will also be utilized, as appropriate, in the 2010 time frame engine and the FutureGen Plant. These new technologies and concepts also have the potential to accelerate commercialization of advanced coal-based IGCC plants in the U. S. and around the world, thereby reducing emissions, water use, solid waste production and dependence on scarce, expensive and insecure foreign energy supplies.

Technology developments accomplished in Phase 1 provide a solid foundation for ensuring successful completion in Phase 2 and providing that the challenging program goals will be achieved.

PUBLICATIONS AND PRESENTATIONS

<u>Publications:</u>

Advanced Hydrogen Turbine Program, Pittsburgh Coal Conference September 2006

Advanced Hydrogen Gas Turbine Development Program, ASME Paper GT2007-278692.

<u>Presentations:</u>

Customer Advisory Board Meeting, Electric Power Conference, Atlanta GA May 2006

International Colloquium of Environmentally Preferred Advanced Power Generation (ICEPAG) Conference, September 2006.

Customer Advisory Board Meeting, Orange County Convention Center, Orlando FL November 2006

EPRI Hydrogen Combustion Workshop, March 2007

Advanced Power Systems Peer Review, Pittsburgh PA, July 2007

PATENT DISCLOSURES

Disclosure	Topic or Area
2006E01936US	Advanced Combustion Systems
2006E03152US	Advanced Combustion Systems
2006E03513US	Advanced Combustion Systems
2006E03908US	Super Alloys
2006E04689US	Turbine Cooling
2006E04691US	Turbine Cooling
2006E04697US	Turbine Cooling
2006E08621US	Super Alloys
2006E09861US	Super Alloys
2006E20223US	Advanced Combustion Systems
2006E21343US	Advanced Combustion Systems
2006E21604US	Advanced Combustion Systems
2006E21646US	Turbine Sealing
2007E03893US	Turbine Sealing
2007E03928US	Advanced Combustion Systems
2007E03929US	Advanced Combustion Systems
2007E03936US	Modular and Fabricated Components
2007E04032US	Turbine Sealing
2007E04033US	Turbine Sealing
2007E05275US	Modular and Fabricated Components
2007E09759US	Modular and Fabricated Components
2007E04028US	Modular and Fabricated Components
2006E03819US	Super Alloys
2007E22619US	Modular and Fabricated Components
2007E23326US	Modular and Fabricated Components
2007E23341US	Turbine Sealing

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10. "*Failure Modes and Effects Analysis for Hydrogen Fueling Options*", California Energy Commission, Consultant Report, November 2004, report No. CEC-600-2005-001.