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(NASA-TM-108727) TECHNOLOGY FOR SPACE STATION EVOLUTION. VOLUME 4: POWER SYSTEMS/PROPULSION/ROBOTICS (NASA) 476 p N93-27803 --THRU--N93-27824 Unclas

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Achnology Eek hace Station Evolution-

fice of Aeronautics and Space Technology

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DISPLAY 99N27803/2 93N27803*# ISSUE 10 CATEGORY 18 RPT#: NASA-TM-108727 NAS 1.15:108727 90/00/00 476 PAGES UNCLASSIFIED DOCUMENT UTTL: Technology for Space Station Evolution. Volume 4: Power Systems/Propulsion/Robotics CORP: National Aeronautics and Space Administration, Washington, DC. SAP: Avail: CASI HC A21/MF A04; 1 functional color page Workshop held in Dallas, TX, 16-19 Jan. 1990 CIO: UNITED STATES Original contains color illustrations

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MINS: / AEROSPACE ENGINEERING/ CONFERENCES/ TECHNOLOGY ASSESSMENT

USER=*EBB

ANN: NASA's Office of Aeronautics and Space Technology (DAST) conducted a workshop on technology for space station evolution on 16-19 Jan. 1990. The purpose of this workshop was to collect and clarify Space Station Freedom technology requirements for evolution and to describe technologies that can potentially fill those requirements. These proceedings are organized into an Executive Summary and Overview and five volumes containing the Technology Discipline Presentations. Volume 4 consists of the technology discipline sections for Power, Propulsion, and Robotics. For each technology discipline, there is a Level 3 subsystem description, along with the papers. For individual titles, see N93-27804 through N93-27824.

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N93-27824 #

GENERAL CONTINUE

FOREWORD

Space Station *Freedom*, now under development, is a manned low Earth orbit facility which will become part of the space infrastructure. Starting in the mid 1990s, *Freedom* will support a wide range of activities, including scientific research, technology development, commercial ventures and, eventually, serve as a transportation node for space exploration. While the initial facility will not be capable of meeting all requirements, the space station will evolve over time as requirements and on-board activities mature and change. The space station design, therefore, allows for evolution to:

- expand capability,
- increase efficiency, and
- add new functions.

It is anticipated that many of the evolutionary changes will be accomplished through on-orbit replacement of systems, subsystems, and components as technology advances. Therefore, technology development is critical to ensure the continuing operation and expansion of the facility.

The Office of Aeronautics, Exploration and Technology (OAET) has sponsored development of many of the technologies that are now part of Space Station *Freedom'* s baseline design. Evolutionary and operational aspects of *Freedom* continue to be an important thrust of OAET's Research and Technology (R&T) efforts.

This workshop has been an important step in our understanding of the space station's baseline systems, the evolutionary scenarios including the station's role in space exploration, and the technologies that will be necessary to meet evolutionary and growth requirements.

It is anticipated that application of the information acquired through the workshop will lead to further technology development efforts to benefit *Freedom* and will lead to continued collaboration between the Space Station *Freedom* Program and the technology development community.

Arnold D. Aldrich Associate Administrator for Aeronautics, Exploration and Technology 2403

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CLARIFICATION

Since the workshop was conducted in January of 1990, there have been some organizational changes throughout the agency. The Office of Aeronautics and Space Technology (OAST) has been reorganized to include the former Office of Exploration and is now called the Office of Aeronautics, Exploration, and Technology (OAET). Also, the Human Exploration Initiative (HEI) has been expanded and renamed the Space Exploration Initiative (SEI). Some of the materials in these proceedings were prepared after the workshop, and, therefore, references to new organizational entities and new programs may be found in certain sections.

TECHNOLOGY FOR SPACE STATION EVOLUTION - A WORKSHOP Technology Disciplines (POWER - ROBOTICS)

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INTRODUCTION

NASA's Office of Aeronautics and Space Technology (OAST) conducted a workshop on technology for space station evolution January 16-19, 1990, in Dallas, Texas. The purpose of this workshop was to collect and clarify Space Station *Freedom* technology requirements for evolution and to describe technologies that can potentially fill those requirements. OAST will use the output of the workshop as input for planning a technology program to serve the needs of space station evolution. The main product of the workshop is a set of program plans and descriptions for individual technology areas. These plans are the cumulative recommendations of the more than 300 participants, which included researchers, technologists, and managers from aerospace industries, universities, and government organizations.

The identification of the technology areas to be included, as well as the development of the program plans, was initiated by assigning NASA chairmen to the eleven technology disciplines under consideration. The disciplines are as follows:

- Attitude Control and Stabilization (ACS)
- Communications and Tracking (C&T)
- Data Management System (DMS)
- Environmental Control and Life Support Systems (ECLSS)
- Extravehicular Activity/Manned Systems (EVA/MANSYS)
- Fluid Management System (FMS)
- Power System (POWER)
- Propulsion (PROP)
- Robotics (ROBOTICS)
- Structures/Materials (STRUCT)
- Thermal Control System (THERM)

Each chairman worked with a panel of experts involved in research and development in the particular discipline. The chairmen, with the assistance of their panels, were responsible for selecting invited presentations, identifying and inviting Space Station *Freedom* Level III subsystem managers, and focusing the discussion of the participants. In each discipline session, presentations describing status of the current programs were made by the Level III subsystem managers and by OAST program managers. After invited presentations by leading industry, university, and NASA researchers, the sessions were devoted to identifying technology requirements and to planning programs for development of the identified technology areas. Particular attention was given to the potential requirements of the Human Exploration Initiative (HEI). The combined inputs of the participants in each session were incorporated into a package including an

overall discipline summary, recommendations and issues, and proposed development plans for specific technology areas within the discipline. These technology discipline summary packages were later supplemented by the chairmen and their panels to include the impact of varied funding levels on the maturity of the selected technologies. OAST will review the program plans and recommended funding levels based on available funding and overall NASA priorities and incorporate them into a new OAST initiative advocacy package for space station evolution technology.

These proceedings are organized into an Executive Summary and Overview and five volumes containing the Technology Discipline Presentations.

Volume IV consists of the technology discipline sections for Power, Propulsion, and Robotics. For each technology discipline in this volume, there is a Level 3 subsystem description, along with the invited papers for that discipline.

Power System Level III Subsystem Presentation

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Electrical Power System WP-04



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Donald L. Nored 0 N NASA – LeRC Ş January 16, 1990 S U Ŵ

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Key EPS Technical Requirements

- Performance
 - 75 kW at AC (100 kW Peak)
 - 37.5 kW at PMC (50kW Peak)
 - Growth to 175 kW (215 kW Peak)
- Mass
 - 94,586 lb (total launch mass)
- Assembly sequence
 - NSTS compatibility
 - MB-1, MB-6, MB-11 assembly sequence
 - Active station / evaluate passive options
- Reliability
 - Failure tolerance requirements
 - System availability requirements
- Maintainability
 - 30-yr. life through ORU replacement
 - EVA & IVA allocations (54 & 100 hr/yr)
 - Resupply mass allocation (TBD lb/yr)
- Environment
 - Low earth orbit (180-240 miles)
 - NSTS launch vehicle environment

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Rephasing Impacts

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• PMAD distribution changed from AC to DC

- + Lowest initial costs
- + Heavier system
- + Channelized system does not grow gracefully
- + Risk is probably about the same
- + Switchgear area of concern
- Polar platform hardware/software deleted
- Solar Dynamic "PGS" test eliminated
 - + Hooks and scars plus key development tests retained
 - + Viable program still in place
 - + Growth here is inevitable

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PHASE I EPS DELIVERABLES

- Photovoltaic Power Module (4) (18.75 kW)
- Photovoltaic Power Generation
- Electrochemical Energy Storage
- Power Conversion and Control Equipment
- Beta Gimbals
- Thermal Control

Space Station (75 kW)



Power Management and Distribution (PMAD) System

- EPS End to End Architecture
- Power Conversion and Distribution Equipment
- Power System Control Hardware and Software
- Common switchgear for Secondary Distribution



Solar Dynamic Definition

- Preliminary Design for Hooks and Scars
- Supporting Development for Concentrator & Receiver

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Solar Power Module Architecture for the PMC Configuration





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BLANKET CONTAINMENT BOX AND BOX POSITIONING SUBASSEMBLIES



- BLANKET COVER AND CONTAINER LATCHED TOGETHER FORMING CONTAINMENT BOX FOR RETRACTED BLANKET
- BOX STRUCTURALLY SUPPORTS BLANKET DURING LAUNCH
 - FABRICATED FROM ALUMINUM AND ALUMINUM HONEYCOMB MATERIALS
 - FOAM PADDING INTERFACES WITH FOLDED BLANKET STACK AT BASE AND COVER
- GUIDE WIRES RUN THROUGH GROMMETS ALONG BACK OF BLANKET PANELS
 - CONTROL BLANKET
 POSITIONING DURING
 EXTENSION AND RETRACTION
- BLANKETS ARE RETRACTED FOR ORU REPLACEMENT

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- SILICON CELL
 - 200 um (0.008 in.) THICK
 - 8 X 8 cm (3.15 X 3.15 m) SQUARE
- COVER SLIDE
 - 150 um THICK
 - · CERIA DOPED (CMX) GLASS
- DOW CORNING DC93-500
 ADHESIVE
- PANEL SUBSTRATE CIRCUIT WELDED TO CELL BACKSURFACE THROUGH OVERLAY PUNCHED HOLES
- AVERAGE CELL TEMPERATURE
 DURING OPERATION
 - 50 DEGREES C FOR STATION

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BYPASS DIODE ASSEMBLY



WEIGHT: 73.5 gm

- THE BYPASS DIODE IS A CIRCUIT PROTECTION DEVICE THAT:
 - MINIMIZES PERFORMANCE IMPACT OF FRACTURED OR OPEN CIRCUIT CELLS
 - ELIMINATES POTENTIAL CELL DAMAGE DUE TO REVERSE BIAS HEATUP DURING SHADOWING
- ONE DIODE IS ELECTRICALLY CONNECTED IN PARALLEL WITH EVERY EIGHT SOLAR CELL ASSEMBLIES
- DIODES WILL CONSIST OF EITHER GERMANIUM, SILICON SHOTTKY, OR PLANAR SILICON DIES SANDWICHED IN A HOUSING THAT CONTAINS LOCATIONS FOR ATTACHMENT TO THE PRINTED CIRCUIT
- LARGE AREA REQUIRED FOR HEAT DISSIPATION
- THIN DIODE REQUIRED TO PREVENT EXCESSIVE STACK HEIGHT BUILDUP IN THE STOWED BLANKET

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KAPTON WITH ATOMIC OXYGEN RESISTANT COATING

DESCRIPTION

- 1 mll KAPTON H POLYAMIDE FILM
- 1300 Å RF SPUTTERED SIO_X COATING ON BOTH SIDES

PROPERTIES COMPATIBLE WITH SOLAR ARRAY FLEXIBLE CIRCUIT DESIGN

- **PROVIDES REQUIRED EMITTANCE AND ABSORPTANCE**
- PROVIDES GOOD BONDING SURFACE FOR COPPER INTERCONNECTS
- **RESISTS FLEXIBLE CARCUIT FABRICATION PROCESSING**

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• PROVIDES SPACE VACUUM STABILITY

• **RESISTS ATOMIC OXYGEN DEGRADATION**

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SOLAR ARRAY DESIGN BENEFITS

- Minimum weight (fewer STS launches)
- Transparent blanket yields higher array efficiency
- Deployment/retraction concept minimized NA/EVA time and reduces cost
 - Demonstrated with OAST-1 flight experiment (STS 41-D)
- Large areas silicon cells minimize costs and increase reliability
 - Reduced number of cells and interconnects
 - Reduced array area/weight

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SPACE STATION FREEDOM



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PHOTOVOLTAIC POWER MODULE DIVISION

SEQUENTIAL SHUNT UNIT



SEQUENTIAL SHUNT UNIT (SSU)

- PROVIDES EFFICIENT METHOD FOR
- MATCHING ARRAY POWER TO LOAD DEMAND
- REGULATING ARRAY OUTPUT VOLTAGE
- ONE SSU PER WING
- MOUNTED TO ARRAY MAST CANISTER
- LARGE FACES OF BOX RADIATE SSU WASTE HEAT DIRECTLY TO SPACE
- BOX FACES HAVE REQUIRED THERMAL MASS TO CONTROL SUN/ECLIPSE TEMPERATURE EXCURSIONS
- AUTOMATICALLY MAINTAINS
 VOLTAGE BELOW SAFE MAX OF 200V
 - PRECLUDES COLD-ARRAY OVERVOLTAGE AT ECLIPSE EMERGENCE
- CAN BE COMMANDED BY PY CONTROLLER (PVC) TO SHUNT ALL ARRAY POWER FOR ARRAY MAINTENANCE

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SSU Performance Summary

REQUIREMENTS	SPECIFICATION	
Shunt Segments	82	
Power Dissipation All Shunts Open All Shunts Closed Standby	326 W 386 W 67 W.	
Maximum Power Capacity	(38.4) kW.	
Arry Voltage Range	140 - 180 Vdc (Adjustable)	
Voltage Regulation About Set Point	<u>+</u> 3 Vdc.	

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Gimbal Assembly



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PHOTOVOLTAIC POWER MODULE DIVISION



BETA GIMBAL/TRUSS ASSEMBLY



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PHOTOVOLTAIC POWER MODULE DIVISION



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 Battery ORU provides station power during solar eclipse periods

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Energy Storage Subsystem Performance

Performance Parameter	Unit	Station (4 Modules)
Configuration		
Total number of batteries Capacity per battery Cells per battery ORUs per battery	 Ah 	24 81 76 2
Electrical		
Nominal power rating Peak power rating Nominal average discharge voltage Average charge voltage Nominal DOD Peak orbit Nominal, one battery out, DOD Peak, one battery out, DOD 80% DOD, contingency support capability – one orbit	k₩ k₩ >>%%%% k₩	94.8 135.6 95 120 31.5 33.3 (39) (42) 45.9
Thermal		
Operating temperature range Off-nominal temperature range	°C °C	0 to +10 0 to +20

DOD = Depth of Discharge

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BATTERY CHARGE/DISCHARGE UNIT



- DEDICATED BCDU FOR EACH STATION BATTERY
- EACH BATTERY CHARGED FROM ASSOCIATED BCDU DURING SUNLIGHT
- PROVIDES VOLTAGE REGULATED BATTERY POWER TO DC SOURCE BUS DURING ECLIPSE
- BCDU INCLUDES
 - CHARGE POWER CONVERTER (CPC)
 - DISCHARGE POWER CONVERTER (DPC)
 - BATTERY FAULT ISOLATOR (FI)
 - BATTERY MONITOR AND
 INTERFACE MODULE
 - CONVERTERS, PROVIDING HOUSEKEEPING POWER
 - LOCAL DATA INTERFACE (LDI), PROVIDING CONTROL COMMANDS FROM PVC

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<u>ORUs</u>

- Radiator (1)
- Utility Plate (8)
- Pump (2)
- Junction Box (2)

Subsystem Characteristics

• Total Heat Rejection 9 kW • Battery Cell Temp (normal) $5^{0}C \pm 5^{0}C$ • Battery Cell Temp (off normal) $5^{0}C + 15/-5^{0}C$ • Electronics Junction Temp 90°C Temperature Regulation ± 1°C • Ammonia Flow Rate 3000 lbs/hr • Operating Pressure 120 psia Radiator Area 1000 ft² 4513 lbs • Total Mass (auto deployed Rad.)

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Thermal Control Subsystem



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Thermal Control Subsystem ORU Characteristics

ORU	Mass (lb)	Dimensions (in.)	Nominal Parasitic Power (W)	
Utility plate (Type 1) (Type 2)	334 299	126 x 38 x 6 126 x 38 x 6	0 0	
Pump unit	158	28 x 38 x 12	250	
Fluid junction box	93	155 x 10 x 8	0	
Radiator	1316	140 x 78 x 540	0	

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Direct Current Switching Unit



- DCSU RBI status monitored & commanded open/close
 - By PVC
 - Through local data Interface (LDI)
- DCSU contains PV control element (PVCE)
 - Provides error signal to SSU for array power regulation

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PHOTOVOLTAIC POWER MODULE DIVISION



NSTS Electrical Interfaces

- EPS start-up terminal
 - Ground/flight check (bit) of electronics
 - System power up
 - System monitoring
- Orbital interface power unit
 - Ground/flight trickle charge

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Ground/flight battery health monitoring

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PHOTOVOLTAIC POWER MODULE DIVISION



Integrated Equipment Assembly (IEA)

- Provide structural support
 - Energy Storage
 - Electrical Equipment
 - Thermal Control Subsystem ORU's
- Interface Structure
 - NSTS Orbiter Cargo Bay



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Typical PMAD Component



Load Spreader -

Beam

EVA/Rot ' Interface

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IEA Structural Framework ORU Characteristics

ORU	Mass (lb)	Dimensions (in.)
Structural framework	2,637	179 x 156 x 117
Electrical junction box	85	8 x 10 x 95
Transition structure	64	5M x 5M x 5M (on orbit)

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IEA & BGA Transition Structure to Truss Assembly Interface



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PHOTOVOLTAIC POWER MODULE DIVISION

INTEGRATED EQUIPMENT ASSEMBLY



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PHOTOVOLTAIC POWER MODULE DIVISION



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PV CARGO ELEMENT



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PHOTOVOLTAIC POWER MODULE DIVISION

PV Cargo Element

- Beta Gimbal Assembly
- Solar Array Assembly
- IEA Structural Framework
- Single Phase Thermal Control System (TCS)

- Energy Storage Subsystem
- Electrical Equipment
- PV Integration Hardware
- FSE
- Transition Structures

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Integration Hardware Characteristics

ORU	Mass (lb)	Dimensions (in.)
Cable trays	135 [.]	20 in. x 20 in. x 10 m
Truss structure (two bays)	342.4	5 m x 5 m x 10 m (on-orbit)
EVA translation rails	45.4	TBD
Truss closeout	82.5	_
PV cable set	231	_

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Truss, Ceta Rail Boxes, and Utility Trays / PV Module Interfaces



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Separate PV Module Launch Package is **Common Across Flights**



Launch Package

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PV Module Equipment

Solar Array Assembly

- Left PV Blanket & Box (2)
- Right PV Blanket & Box (2)
- Mast & Canister (2)
- SSU (2)

Beta Gimbal Assembly

- Bearing Subassembly (2)
- Cam Follower Subassembly (2)
- Roll Ring subassembly (2)
- Drive Motor Subassembly (2)
- Drive Motor Controller (2)
- Latch Platform (2)
- Core Structure (2)
- Transition Structure (2)
- MSC/RMS Grapple Fixture (2) *

Integrated Equipment Assembly

• Structure (1)

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- Transition Structure (1)
- Electrical Junction Box (2)

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- NSTS Interface Hardware (5) *
- MSC/RMS Grapple Fixture (1) *

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Thermal Control Subsystem

- Fluid Junction Box (2)
- Auto. Depl. Radiator (1)
- Pump ORU (2)
- Utility Plates Type I (2)
- Utility Plates Type II (6)
- Ammonia (1)

Electrical Equipment Subsystem

- DCSU (2)
- PVCU (2)
- DDCU (2) Inboard Modules Only
- PV Cable Set
- Startup Terminal (1) PVM #1 Only
- Orbiter Interface Power Unit (1)

Energy Storage Subsystem

- Batteries (12)
- BCDU (6)

Integration Hardware

Truss Bays *

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- Truss Closeout *
- Translation Rails & Cable Tray*

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SPACE STATION FREEDOM



PMAD System Responsibilities

Design end-to-end Power System Architecture

Design, Develop, Produce PMAD Hardware for Station

- Hardware responsibilities include:

- **O** DC/DC Converters
- **O** PV Controller
- **O** Cabling/Connectors/Switchgear for Primary Distribution
- **O** Common RPC Modules for Secondary and Tertiary Distribution
- Software responsibilities include:
 - **O** Condition Monitoring and Controls
 - **O** Energy Management
 - **O** Fault Tolerance and Redundancy Management
 - **Q** PMAD Modeling and Simulation

End-to-End PMAD System Verification and ORU/Component Verification

EPS Specifications and Standards

Deliver PMAD Hardware to Element Owners and Support Integration

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Key Power Requirements - AC

75 kW-A/100 kW-P		
25 kW peak		
25 kW peak		
12.5 kW peak		
25 kW peak		
25 kW peak		
(TBD) (10 kW)		
(TBD) (12 kW)		
Sized and installed to deliver peak power		
175 kW-A/215 kW-P		
Single point (designed negative)		

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SPACE STATION FREEDOM



ELECTRICAL SYSTEMS DIVISION

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Key Features of PMC and AC Architecture

PMC Station:

- 37.5 kW average 50 kW peak
- PMAD is divided into four DC channels each producing 9.4 kW average
- DC channel size is limited by the ability of DC switches to break fault current
- 9.4 kW channels produce 300-400 A fault currents which can be broken with existing DC switch technology
- Small channel size limits user flexibility; loads must be timelined so total is less than 9.4 kW per channel

AC Station:

- 75 kW average/100 kW peak
- Four DC channels each producing 18.75 kW average
- Improved user flexibility
- Requires high power (600–800A) DC switch





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POWER SYSTEM ARCHITECTURE

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SIMPLIFIED SYSTEM ARCHITECTURE



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 Electrical connectors for power & data

- •2 guide pins for mechanical attachment
- •EVA & robotic installation & replacement
- Fin heat exchanger thermal interface
- Coldplate temperature $\leq 50^{\circ}$ F

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Common RPC Modules for Secondary and Tertiary Distribution

RPC Module Features:

- An RPC is a remote controlled switch
- An RPC module is an ORU box containing one or more RPC's
 - Four RPC module types have been identified:
 - 1 x 130 Amp 2 x 50 Amp

 - 4 x 25 Amp
 - 8 x 10 Amp
 - All modules have same outline and mounting
 - All modules have same input connector
 - All modules have same output connector shell; pin configuration unique to module type

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RPC Module 3.50 Wedge provides the necessary 8.00 contact pressure between RPC base & coldplate to conduct **RPC Box** heat away 6.00 • J1 & J2 are electical inputs. J3 is output J3 **J2** J1 • Four RPC Types: 0 8-channel output, 10 A/channel 0 4-channel output, 25 A/channel 2-channel output, 50 A/channel ത 1-channel output, 130 A o Same overall dimensions for each type RPC. Only connector pinout configuration would differ

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Electric Power System Control Hierarchy (Rephase)



Power Management Controller

 DMS/PMAD interface, load management configuration control, system analysis

Photovoltaic Controller

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 Array regulation, battery charge/discharge control, beta gimbal control, outboard power distribution control, PV thermal control

MBSU Controller

 Primary distribution monitoring and control, DC-DC converter control

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PMAD Controls Implementation

Software implemented

- Sensor validation (detection of soft faults)
- Contingency readiness reconfiguration/load shed preplanning model
- Status data to DMS/OMS/crew/ground
- Manual override via DMS command
- GN&C data from DMS
- Fault detection isolation & recovery/Redundancy management (FDIR/RM)
- Startup-shutdown
- Pointing and tracking
- Battery charge/discharge
- PV module thermal control

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PMAD Controls Implementation

Hardware implemented

- Basic overload protection (RPC)
- Hard fault (line) protection (RBI)
- Voltage regulation

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Array control

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PMC Control Architecture Design

. Two PMCU's (1 SDP = 1 PMCU), one active, one in cold standby

- Two Bus Controllers / Monitor Interfaces (MIL-STD-1553B) in each SDP:
 - . Meets fault tolerance requirements with reduced hardware
- Two Hot PVCUs on each PV IEA
 - Supports failure of 1 PVC with no loss of PV control
- PVCU to MBSU Communication
 - Required for two fault tolerance given only two SDPs and no Tier II peer-to-peer communication

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SPACE STATION FREEDOM



PMAD Systems Fault – Tolerant Features

System/ORU/Assembly	Features			
PMAD System	Dual-source PV power, dc star distribution; cross-strapped MBSus; multiple power feeds for each module, node, and pallet; dc backup control bus; dual-redundant dedicated EPS Control Data Bus. PVCU system control with loss of both PMCUs.			
MBSU-PMC, MBSU-AC	Component redundancy; three fault-tolerant power interfaces at habitable modules; dual redundant data interfaces.			
PMCU, PVCU	Dual redundant data interfaces; redundant ORUs.			
Cables/connectors	Redundant cables and diverse routing.			

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EPS Weight Summary Engineering Design Weight * December 11, 1989

ltem_	Flight Quantity	Item Wt (Ib)	<u>Total Wt (lb)</u>
PV Module			
Solar Array Assembly	8	1,551.3	12,410
Beta Gimbal Assembly	8	462	3,360
Thermal Control Subsystem	4	4,381	17,524
Battery ORU's	48	320	15,360
Integrated Equipment Assen	nbly 4	2,913	11,484
PV Module Cabling	4	231	924
BCDU	24	168	4,032
DCSU	8	182	1,456
DDCU (PVM #1&2)	4	167	668
PVCU	8	147	1,176
SSU	8	37.5	300
O/PU	4	185	740
Start-Up Terminal (PVM #1)	1	225	225
<u>PMAD</u>			
DDCU	32	167	5,344
MBSU - PMC	4	183	732
MBSU - AC	4	201	804
PMCU	2	87.5	175
RPC (10A)	205	8	1,640
RPC (25A)	89	9	801
RPC (50A)	76	9	684
RPC (130Å)	63	10	630
PMAD Cabling	1	4,410	4,410
*	Excludes GSE		Total 84,879

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Reliability and Maintainability Allocations

		MTTR (hr)		Design	
PV Module ORUs	MTTF (yr)	EVA	IVA	IVAR	Life (vr)
Deployable Mast & Canister	15.0			2.25	30
PV Blanket & Box (L)	15.0			0.75	50 15
PV Blanket & Box (R)	15.0			0.75	15
SSU	15.0			1.50	15
Beta Gimbal Cam Follower	30.0	0.50			30
Beta Gimbal Bearing Subass'y	30.0	1.00			30
Beta Gimbal Roll Ring	10.0	0.50			30
Beta Gimbal Drive Motor	10.0			1.50	30
Beta Gimbal Assembly/Housing	60.0	3.00		0.50	60
Beta Gimbal Trans Structure	30.0	6.00			30
Battery Subass'y	5.0			1.50	6.5
BCDU	15.0			1.50	15
	15.0			1.50	15
	10.0			1.50	15
PVC/SPDA	10.0			1.50	15
	30.0	12.00			30
	60.0	4.00		0.20	60
DV Hallan Diete Terr	30.0	6.00			30
PV Utility Plate, Type	30.0			3.00	30
Pv Utility Plate, Type II	30.0			3.00	
Fully Fluid Junction Dow	15.0			1.50	30
Flootricol Junction Box	30.0			2.50	30
Padiator Subassiv	30.0			2.50	30
naulator Subass y	15.0			3.00	30

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Major Design Drivers

- Design requirements
 - Power output & quality
 - Environment (launch & on-orbit)
 - Thermal control
 - Loads & dynamics
 - Electrical isolation & grounding
 - Growth capability
 - Producibility & testability
- Integration requirements
 - System integration (architecture & interfaces)
 - NSTS integration
 - Flight by flight partitioning (including mass)
 - On-orbit assembly
 - User accommodation
 - Commonality
- Operational requirements
 - Reliability, availability & failure tolerance
 - Maintainability
 - Safety
 - Operability
 - Supportability (including resupply mass & drag)
 - Automation & robotics
- Cost (initial & life cycle)

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Power System Invited Presentations

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SPACE STATION FREEDOM SOLAR DYNAMIC POWER GENERATION

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INTERPORTATION IN THE REAL

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SPACE STATION FREEDOM

SOLAR DYNAMICS

BRIEFING AGENDA

- Prime Contract Activity
- Advanced Development
 - Heat receiver
 - Concentrator



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25-kWe Net CBC Power Module Configuration

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Rockwell International Rocketdyne Division

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CBC Receiver







SPACE STATION FREEDOM SOLAR DYNAMICS PRIME CONTRACT ACTIVITY

- Solar Dynamic Power Module preliminary design
 - Prepare design to define hardware configuration (sizes and mass). Conduct trade studies (structural/dynamic analyses, materials selection, operational procedures). Develop top level drawings.
 - Provide credible knowledge of Solar Dynamic Power Module to perform "Hooks and Scars" activities
- "Hooks and Scars"
 - Define assembly, operational and physical/functional interfaces
 imposed by the SD module
 - Provide requirements to Non-SD elements/systems to ensure that SD power can be added
- Solar Dynamic Component Development Tests
 - Concentrator (coupons, full-size facets, face up/face down)
 - Receiver (canisters, single tube test, full-size element)
 - Radiator (Hypervelocity, AO, UV, etc)
 - Integration (FP & T and receiver/concentrator interface)

Rockwell International Rocketdyne Division



Key Solar Dynamic Power Module Requirements

- Provide minimum of 28-kWe NET to inboard PV Module throughout any orbit at any time of year within prescribed orbit altitude envelope (after distribution via PMAD, provides 25-kWe at user interface)
- Provide peaking power of 32.2-kWe NET to inboard PV Module for up to 7.5 minutes during both sun and shade portions of the orbit (maximum of 15 minutes total peaking per orbit)
- Be capable of automatic startup, shutdown, and continuous operation throughout load changes, peaking, turndown, and load shedding
- Shall not produce dynamic instabilities
- Maximize the use of common hardware, software, and standard interfaces
- Be capable of long term operation by means of ORU replacement





Solar Dynamic Design & Development Team

Organization	Major Responsibilities
Rocketdyne	Prime Contractor Module Integration Interface Structure Assembly Electrical Equipment Assembly Beta Gimbal Assembly (PFE-PV) Integration Hardware Assembly (GFE-WP02) Fine Pointing & Tracking Launch Packaging and On-Orbit Module Assembly
Allied-Signal	Receiver Assembly Power Conversion Unit Assembly
Harris Corp.	Concentrator Reflective Surface Subassembly Concentrator On-Orbit Assembly Concentrator Launch Packaging
LTV	Radiator Subassembly Deployment Mechanism Base Plate





ADVANCED DEVELOPMENT

- Heat Receiver (NAS3-24669) Boeing
- Concentrator (NAS3-24670) Harris



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SOLAR DYNAMIC HEAT RECEIVER TECHNOLOGY

- Purpose
 - Address Key Technical Issues Associated With Heat Receiver
 - Provide Database to Support Detail Design
 - Demonstration Testing
- Background
 - NAS3-24669 Awarded to Boeing in October 1985
- Project Objectives
 - Identify and Resolve Technical Issues Associated With 25 kWe CBC Heat Receiver
 - Develop and Validate Analytical Methods
 - Fabricate, Test and Evaluate 25 kWe CBC Heat Receiver
- Key Design Considerations
 - Material Selection
 - TES Performance in Micro-Gravity
 - TES Compatibility With Containment Materials
 - Thermal Expansion
 - Fabricability
 - Sea Level Test In Vacuum
- Tasks
 - Conceptual Designs and Trade Studies
 - Preliminary/Detail Design
 - Fabrication, Test and Delivery





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SOLAR DYNAMIC HEAT RECEIVER TECHNOLOGY

KEY REQUIREMENTS/FEATURES

REQUIREMENTS

- Power 102 kwt (25 kwe CBC)
- Temperature 900^oF Inlet; 1300^oF Exit
- Inlet Pressure 92 psia
- Working Fluid Helium Xenon (MW 40)
- FEATURES
 - GEOMETRY Diameter 70 In. Length - 80 In. Aperture Dia. 13 In.
 - TUBING Fluid Tube 2 In. OD + 0.06 In. Wall TES Tube - 3.94 In. OD, 3.60 In. ID, 0.01 In. Wall Convolution Pitch - 0.25 In.
 - Materials TES Salt 21% LiF 79% CaFi Fluid Tube & TES Containment - Inconel 617 Felt Metal - Nickel Other - CRES

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SOLAR DYNAMIC HEAT RECEIVER TECHNOLOGY

SIGNIFICANT EVENTS

- Felt Metal Concept Demonstrated
 - Thermal Conductivity Enhancement
 - Symmetrical Salt Distribution
 - 2500 Hours Thermal Cycling
 - 5000 Hours Materials Compatibility Inconel 617 & LiF-CaF₂

- TES Containment Closure Welds Validated
 - Laser Weld of Bellows to End-Cap
 - Electron-Beam Weld of PCM Fill Tube
- Full-Size, 6-Tube Molten Salt Fill Demonstrated
- Receiver Fabrication Complete May 1990
- Thermal Vacuum Testing Complete August 1990





SOLAR CONCENTRATOR ADVANCED DEVELOPMENT

• Purpose

- Address Key Technical Issues Associated With Concentrator
- Detail Design Support
- Demonstration Testing
- Background
 - NAS3-24670 Awarded to Harris Corp. in November 1988
- Project Objectives
 - Select Design, Fabricate and Test a Viable Concentrator for SSF
- Key Design Considerations
 - Material Selection (Environmental Protection)
 - Aiming Errors
 - Facet Alignment
 - Fabricability
 - Reflectance
 - Structural Repeatability
- Tasks
 - Conceptual Design & Trade Studies
 - Preliminary/Detail Design
 - Fabrication, Test & Delivery

Rockwell International Rocketdyne Division

SOLAR CONCENTRATOR

KEY REQUIREMENTS/FEATURES

- Requirements
 - Deliver 188 kw of Thermal Energy to the Receiver
 - Pointing Accuracy: $\pm 0.1^{\circ}$ (1 σ)
 - Specular Reflectance: >0.88
 - Slope Error: <u>+</u> 2.25 mr (half cone angle)
 - Design Lifetime: 15 years
- Features
 - 19 Hexagonal Panel (456 facets)
 - Toroidal Facet Curvature
 - Parabolic Mapping
 - ≤ 2 lb. per facet
 - SiO₂ Protected, Silver Reflective Surface on Graphite Epoxy with A1 Honeycomb





SOLAR CONCENTRATOR ADVANCED DEVELOPMENT

SIGNIFICANT EVENTS

- Refined Design With Significant Commonality of Components
- Demonstrated Fabrication and Panel Structural Test Techniques
- Improved Box Beam Construction Technique
- Refined Facet Optical Specifications and Capabilities
- Demonstrated Seven Panel Assembly/Structural Repeatability
- Developed Fabrication Methods for Facets Having A Vapor Deposited Reflective Surface
- Delivered to NASA Three Vapor Deposited Reflective Surface Facets that had Measured Slope Errors Less Than 1.5 mrad
- Demonstrated Nineteen Panel Assembly/Structural Repeatability





Accomplishments In SD Development

- Module Integration
 - Initial release for Hooks and Scars document prepared
 - Fine pointing and tracking concept prepared for elevation axis
 - Four launch package options defined & prioritized
 - SD impact on GN&C in terms of aerodynamics, gyroscopic, & gravity gradient torques found to be minimal
 - Initial module assembly procedure defined
- Concentrator
 - Latch guide designed, reviewed, and placed in fabrication for LeRC NBF test (coordinated with JSC Crew & Thermal Sys. Div.)
 - NBF hardware fabrication
 - Silver-coated, high temperature facet samples produced and met requirements

- Aluminum coated, high temperature full-size facets produced
- Completed design, fabrication, and testing (optics and repeatability) of 19-Panel solar concentrator (SCAD)



FREEDOM

Accomplishments In SD Development (Continued)

- Receiver
 - Single canister and breadpan tests show no significant corrosion between Haynes 188 and Salt (> 14,000 Hrs)
 - Single-tube test has verified receiver heat transfer element performance
- Power Conversion Unit
 - Engine startup power requirement calculated
 - 15kW BRU refurbished and in test at LeRC
- Radiator Assembly
 - Hypervelocity test conducted at JSC
 - Hypervelocity test articles fabricated for future test at JSC



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POWER TECHNOLOGY DIVISION

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ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

> PRESENTATION FOR

"TECHNOLOGY FOR SPACE STATION EVOLUTION - A WORKSHOP"

JANUARY 16-19, 1990

BY

JAMES CALOGERAS NASA LEWIS RESEARCH CENTER SOLAR DYNAMICS AND THERMAL SYSTEMS BRANCH

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MISSIONS AND SYSTEMS ANALYSIS

- DETERMINE SD POWER SYSTEMS REQUIREMENTS

- CRITICAL TECHNOLOGIES WHERE ADVANCEMENT LEADS TO LARGE PAYOFF

ADVANCED CONCENTRATORS

- MORE EFFICIENT (HIGHER CONCENTRATOR RATIOS)
- AUTO DEPLOYABLE (WITHOUT ASTRONAUT ASSISTANCE)
- LONGER SERVICE LIFE

ADVANCED CONCENTRATORS

- LIGHTER WEIGHT
- MORE EFFICIENT
- SMALLER

MICROGRAVITY EFFECTS

THE LOW G FIELD ON ORBIT HAS A SIGNIFICANT EFFECT ON THE VOIDS THAT FORM IN THE HEAT STORAGE MATERIAL. RESEARCH IN LOW G ENVIRONMENTS IS BEING CONDUCTED TO LEARN HOW TO AVOID THE PROBLEMS WITH VOID FORMATION AND MIGRATION.

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SPACECRAFT ENVIRONMENT

VARIOUS ORBITS HAVE ELEMENTS, SUCH AS AO, UV, CHARGED PARTICLES, ETC., THAT ATTACK VARIOUS MATERIALS, THEREBY SHORTENING THEIR SERVICE LIFE. AN ONGOING EFFORT IS BEING CONDUCTED TO IDENTIFY THOSE MATERIALS THAT ARE IMMUNE TO THE ENVIRONMENT OR METHODS TO PROTECT THOSE MATERIALS THAT ARE.

POWER CONVERSION SUBSYSTEM

TWO HEAT ENGINE CONCEPTS ARE THE PRIME CANDIDATES FOR CONVERTING THE FOCUSED SUNLIGHT INTO ELECTRICAL ENERGY:

- STIRLING ENGINE (This engine is under development by another Branch within the Power Technology Division)

- BRAYTON ENGINE (The technology of this engine is mature)

RADIATORS

ADVANCED RADIATORS FOR SPACE ARE BEING DEVELOPED FOR CSTI HIGH CAPACITY POWER.

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POWER TECHNOLOGY DIVISION



ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM



- MISSIONS AND SYSTEMS ANALYSIS
- ADVANCED CONCENTRATORS
- ADVANCED HEAT RECEIVERS - CONCEPTS
 - THERMAL ENERGY STORAGE
- MICROGRAVITY EFFECTS
- SPACECRAFT ENVIRONMENT
- POWER CONVERSION SUBSYSTEM
 - STIRLING
 - BRAYTON
- RADIATORS

GOALS

SPECIFIC POWER

THE ELECTRIC POWER OUTPUT PER UNIT MASS OF THE TOTAL POWER SYSTEM IS AN IMPORTANT FIGURE OF MERIT THAT IMPACTS THE LAUNCH WEIGHTS AND COSTS. TO LOWER THESE, BOTH THE MASS AND EFFICIENCY OF THE SD SYSTEM AND THE COMPONENTS OF THAT SYSTEM NEED TO BE REDUCED.

REDUCTION OF HEAT RECEIVER MASS

SINCE HR WEIGHT IS THE LARGEST FRACTION OF THE OVERALL SD SYSTEM WEIGHT, ITS REDUCTION IS A PRIME GOAL OF OUR ACTIVITIES.

REDUCTION OF CONCENTRATOR MASS

WITH PRESENT TECHNOLOGY, THE CONCENTRATOR SPECIFIC MASS (INCLUDING THE SUPPORTING STRUCTURE) IS MORE THAN DOUBLE THE GOAL SHOWN. RESULTS TO DATE SUGGEST THAT THIS GOAL IS ACHIEVABLE, EVEN FOR AUTO DEPLOYABLE CONCENTRATORS.

CONCENTRATOR RATIO

THE OVERALL SD SYSTEM EFFICIENCY IS IN LARGE PART AFFECTED BY THE ABILITY OF THE CONCENTRATOR TO REFLECT AS MUCH OF THE INCOMING SUNLIGHT AS POSSIBLE (HIGH REFLECTIVITY) AND FOCUS IT INTO THE SMALLEST POSSIBLE DIAMETER (CONCENTRATOR RATIO). TO ACHIEVE A HIGH CONCENTRATOR EFFICIENCY, THE DISHED SURFACE MUST CONFORM VERY CLOSELY TO A PERFECT PARABOLIC SURFACE (TO WITHIN A SLOPE ERROR LESS THAN 1.0 MILLIRADIAN) AND MUST HAVE A VERY SMOOTH SURFACE (LESS THAN 50 TO 100 ANGSTROMS) WITH A HIGHLY REFLECTIVE LAYER (SILVER OR ALUMINUM).

REDUCTION OF RADIATOR MASS

THE STIRLING AND BRAYTON ENGINES OPERATE MORE EFFICIENTLY AT HIGH RATIOS OF THE INLET TEMPERATURE TO OUTLET TEMPERATURE. THE LOWER THE OUTLET TEMPERATURE, THE LARGER IS THE RADIATOR AREA REQUIRED TO REJECT HEAT. (THE RADIATOR AREA INCREASES AS THE FOURTH POWER OF THE OUTLET TEMPERATURE). LARGE EFFICIENT RADIATORS WILL REQUIRE THE USE OF HEAT PIPES AND VERY LIGHT WEIGHT DESIGN.

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ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

<u>GOALS</u>

SPECIFIC POWER

20-25 W/kg

REDUCTION OF HEAT RECEIVER MASS TO 20-33 kg/kWe

REDUCTION OF CONCENTRATOR MASS TO 1-2 kg/M²

CONCENTRATION RATIO

2000-5000

REDUCTION OF RADIATOR MASS TO



TECHNOLOGY APPROACH

ADVANCED CONCENTRATORS

TO MEET THE GOALS OF LIGHT WEIGHT, HIGH EFFICIENCY, LONG SERVICE LIFE, AND AUTO DEPLOY ABILITY, ACTIVITIES ARE UNDERWAY TO:

- DEVELOP METHODS FOR INCREASING THE SURFACE CONTOUR ACCURACY, THE SURFACE SMOOTHNESS AND REFLECTIVITY.
- DEVELOP THE FABRICATION TECHNIQUES REQUIRED FOR EFFICIENT CONCENTRATORS.
- IDENTIFY SPACE COMPATIBLE MATERIAL THAT WILL RESIST THE SPACE HAZARDS AND RETAIN THE DIMENSIONAL STABILITY NEEDED FOR HIGH EFFICIENCY AND LONG LIFE.
- IDENTIFY CONCENTRATOR CONCEPTS THAT CAN BE PACKAGED INTO A SMALL VOLUME FOR LAUNCHING AND THAT ARE AUTO DEPLOYABLE ON ORBIT.

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ADVANCED HEAT RECEIVERS

 TES VOID-MICROGRAVITY. ITS UNDERSTANDING IS KEY TO THE SUCCESSFUL OPERATION OF A SALT TES SYSTEM (CURRENT STATE-OF-THE-ART). EFFORTS INCLUDE BOTH ANALYTICAL AND EXPERIMENTAL ACTIVITIES TOWARD A TECHNICAL UNDERSTANDING OF THE PHENOMENON OF VOID BEHAVIOR UNDER MICROGRAVITY.

POWER CONVERSION SYSTEMS

- A MAJOR EFFORT IS IN PROGRESS AT NASA-LEWIS TO DEVELOP LIGHT WEIGHT, HIGH EFFICIENCY STIRLING ENGINE FOR USE IN SD SYSTEMS. NO WORK IS BEING DONE INSIDE NASA TO IMPROVE THE BRAYTON ENGINE; HOWEVER, DOD IS SUPPORTING BRAYTON R & D.
- INCREASE CONFIDENCE ------
 - TECHNOLOGY VERIFICATION GROUND EXPERIMENTS ARE PLANNED FOR THE MAJOR COMPONENTS OF AN SD POWER SYSTEM.

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TECHNOLOGY APPROACH

ADVANCED HEAT RECEIVERS

THE TECHNICAL APPROACH TO ADVANCED RECEIVERS IS THE INCORPORATION OF DESIGNS AND THE DEVELOPMENT OF MATERIALS DIRECTED AT SMALLER, LIGHT WEIGHT, AND MORE DURABLE RECEIVERS.

- BULK TES VOLUME (AS OPPOSED TO SMALL ELEMENTS) LESSENS THE NEED FOR STRUCTURAL SUPPORT STRUCTURE AND REDUCES RECEIVER MASS. EFFORTS ARE BEING DIRECTED TO INCREASE THIS VOLUME WITHOUT SACRIFICING ITS STORAGE PERFORMANCE OR IMPOSING STRUCTURAL STRESS.
- TES WITH HIGH THERMAL CONDUCTIVITY, HEAT OF FUSION AND DENSITY SHRINKS THE VOLUME OCCUPIED WITH THE STORAGE MATERIAL AND DECREASES THE TEMPERATURE DIFFERENCE WITHIN THE TES MATERIAL. TES MATERIALS ARE BEING INVESTIGATED THAT HAVE THESE PROPERTIES WITHOUT DETRIMENTAL EFFECTS SUCH AS CORROSION.
- CAVITY HEAT PIPE DESIGNS IN EFFECT DISTRIBUTE THE INCOMING SOLAR FLUX THROUGHOUT THE INTERIOR RECEIVER SURFACE AT A CONSTANT TEMPERATURE. THIS FEATURE WOULD CONTRIBUTE TO EXTENDING LIFE OF THE RECEIVER STRUCTURE. THE EFFORT IS TO DESIGN SUCH HEAT PIPES WITHIN THE CONSTRAINTS OF RECEIVER DESIGNS AS DESCRIBED ABOVE.



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ADVANCED SPACE CONCENTRATOR DEVELOPMENT

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TECHNOLOGY APPROACH

THE APPROACH TO CONCENTRATOR DEVELOPMENT CONSISTS OF TWO PARALLEL EFFORTS:

- IDENTIFYING SUITABLE CONCENTRATOR FOR CONCEPTS
- IDENTIFYING SUITABLE REFLECTOR CONCEPTS AND MATERIALS FOR THOSE REFLECTORS.

CONCENTRATOR CONCEPTS DEVELOPMENT

THERE ARE BASICALLY TWO TYPES OF CONCENTRATORS:

- THE REFLECTING PARABOLIC DISH TYPE
- THE PARABOLIC DOME SHAPE FRESNELL LENS TYPE.

THE WORK ON ADVANCED AUTO DEPLOYABLE PARABOLIC DISH CONCENTRATORS IS CONTINUING.

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ADVANCED SPACE CONCENTRATOR DEVELOPMENT

REFLECTOR CONCEPTS AND MATERIALS

A REFLECTOR CONSISTS OF FIVE DIFFERENT LAYERS:

- 1. A SUBSTRATE: IT IS THE PRIMARY MINOR STRUCTURE ONTO WHICH THE REFLECTING LAYER IS DEPOSITED. CANDIDATES ARE: HONEYCOMB SANDWICH PANELS, LIGHT WEIGHT FOAM SANDWICH PANELS, THIN METALLIC OR COMPOSITE MEMBRANES.
- 2. A LEVELING LAYER: USUALLY THE SUBSTRATE, FACE ONTO WHICH THE REFLECTING LAYER IS TO BE DEPOSITED IS NOT SMOOTH ENOUGH TO YIELD A HIGHLY SPECULAR REFLECTING SURFACE. HENCE, THE SUBSTRATE FACE MUST BE SMOOTHED BY POLISHING OR APPLYING A THIN (5 MICRONS TO 0.5mm) SMOOTHING LAYER. CANDIDATE MATERIALS ARE: VERY LOW VISCOSITY/HIGH SURFACE TENSION MONOMERS, POLYMERS, AND OTHER SIMILAR MATERIALS.
- 3. REFLECTING LAYER: SILVER AND ALUMINUM ARE THE MOST HIGHLY REFLECTIVE MATERIALS, SILVER BEING MORE REFLECTIVE THAN ALUMINUM. SILVER, ON THE OTHER HAND, IS EASILY CORRODED BY TERRESTRIAL CONTAINMENTS SUCH AS, MOISTURE, OXYGEN, AND OTHER GASES, AND BY AO IN LEO. ALUMINUM IS A MUCH MORE RESISTANT MATERIAL BECAUSE OF THE ALUMINUM OXIDE THAT FORMS ON THE SURFACE IN THE PRESENCE OF OXYGEN.
- 4. THERMAL-PROTECTIVE COATING: USUALLY A TRANSPARENT PROTECTIVE COATING OF SILICON DIOXIDE, ALUMINUM OXIDE, OR BOTH IS PUT ON THE REFLECTIVE LAYER TO PROTECT IT AGAINST DAMAGE BY HANDLING BY AIR BORN GASES AND VAPOERS, AND BY ATOMIC OXYGEN. A TRANSPARENT THERMAL CONTROL COATING MAY BE NEEDED TO ALLOW THE REFLECTOR TO ACHIEVE THE DESIRED OPERATING TEMPERATURE (PREFERABLY ABOVE THE CONDENSATION TEMPERATURE OF SPACE CONTAMINANTS.
- 5. THERMAL CONTROL COATING ON BACK FORCE: JUST LIKE THE FRONT FACE, THIS COATING IS ALSO USED TO MAINTAIN THE OPERATING RANGE IN THE DESIRED RANGE TO PROTECT THE SUBSTATE FROM ON ORBIT HAZARDS LIKE AO, UV, ETC.

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DISHED ALL METAL HONEYCOMB SANDWICH PANELS

(FOR SPACE SOLAR CONCENTRATORS)

THESE ONE FOOT SQUARE PANELS WERE DEVELOPED BY THE SOLAR KINETICS INC., DALLAS, TEXAS UNDER A PHASE I SBIR CONTRACT. THE PHASE II EFFORT IS NOW IN PROGRESS. THESE PANELS ARE SLIGHTLY DISHED AND HAVE A FOCAL LENGTH OF 20 FT. AS SHOWN BY THE CAPTIONS IN THE FIGURE, EACH PANEL IS A HONEYCOMB SANDWICH SUBSTRATE WHOSE FACE SHEET WAS POLISHED BUT NOT OVER COATED WITH A REFLECTIVE LAYER OF ALUMINUM OR SILVER.

THIS PHOTO SHOWS THAT:

- (1) THE SURFACE CONTOUR GOAL OF 1 MILLIRAD WAS MET. NOTE THE ABSENCE OF A WARPED REFLECTION IN ANY OF THE PANELS,
- (2) THE WEIGHT GOAL OF 1 TO 2 kg/SQ. METER IS ACHIEVABLE WITH THESE SUBSTRATE PANELS,
- (3) AN ADEQUATELY SMOOTH SURFACE MAY BE ACHIEVABLE WITH THE ELECTROPOLISHING POLISHING METHOD.

OTHER NOTEWORTHY FEATURES:

- (1) ALUMINUM & TITANIUM ARE IMMUNE TO ATTACK BY THE SPACE ENVIRONMENT,
- (2) THE FOCAL POINT DIAMETER WAS ABOUT 2 INCHES DIAMETER.



DISHED ALL METAL HONEYCOMB SANDWICH PANELS

THIS PHOTO ILLUSTRATES TWO POINTS

- (1) ACCURATE SURFACE CONTOUR YIELDS A REFLECTED IMAGE WITH NO IMAGE DISTORTION (NOTE REFLECTION IN THE CENTER PANEL).
- (2) AN INADEQUATELY SMOOTH SURFACE YIELDS A BLURRED REFLECTED IMAGE. (COMPARE THE END PANEL REFLECTION WITH THAT OF THE CENTER PANEL.) THIS RESULTS IN A FOCAL POINT WITH A LARGE DIAMETER.

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ALUMINUM & TITANIUM HONEYCOMB SANDWICH REFLECTOR SUBSTRATES

ADVANCED HEAT RECEIVER DEVELOPMENT

o ADVANCED RECEIVER TECHNOLOGY VERIFICATION

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Two advanced receiver designs are being investigated; one has application for the Stirling engine, the other for Brayton. They both incorporate many common features. e.g. bulk TES storage design, heat pipe operation, with its common concerns on TES containment and on heat pipe operation throughout the heating and cooling cycle. But there are important differences also:

- -- The Stirling-Sanders Associates design has a closed receiver volume and the entire cavity surface is covered with wicking. Incoming solar heat is absorbed and transferred by the "dome" to the interior surfaces -simultaneously to the Stirling engine head and to TES. During shade, the heat absorbed by the TES provides the source to continue heating the engine. The choice of the TES material, LiF/CaF_2 , was due to the temperature requirements of the Stirling cycle. The technical areas unique to the Stirling design that are to be addressed are the dome design and the wicking system.
- -- In the Brayton-Sundstrand Corporation design the cavity is not enclosed by a "dome", but rather by an inner cylindrical receiver wall. The transfer medium is also sodium which transfers heat to the heater tubes. The TES material in this case if LiF which again has been determined by temperature requirements of the Brayton cycle for this application. The critical technical areas for Brayton are the TES container design to minimize the thermal conductivity effects and whether the design will accommodate the TES void when freezing.

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- **o** SUPPORTING TECHNOLOGY
 - -- Advanced TES Materials -- Ge and NiSi

These materials have the highly attractive properties of high density and high thermal conductivity. Virtually the only drawback is their corrosivity to most materials that could be used for containment. Both Oak Ridge and the University of South Florida are investigating candidate container materials.

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-- TES/Containment Compatibility

Containment compatibility efforts of fluoride salts and their eutectics are being undertaken at NASA-Lewis in the Materials Division through long term exposure experiments.

-- Thermal Conductivity Enhancement

Another in-house effort. this under the Electro-Physics Branch, is investigating methods to increase TES thermal conductivity. Corrosionresistant graphite fibers constitute one avenue of research.

-- Analytical Support

The University of South Florida and the Oak Ridge National Laboratory are both developing analytical codes to describe the effects of TES materials as they change phase. South Florida's effort is directed toward evaluating those parameters affecting the temperature variation of the engine working fluid as the TES material changes phase. ORNL looks at the basic mechanisms governing void behavior under microgravity and is entitled "NASA Oak Ridge Void Experiment" or NORVEX.

-- Space Flight Experiment (TEST)

No extended flight data is available for materials undergoing melting and freezing in microgravity. The TES flight experiment will be the first attempt to obtain such data. Such data will include thermal data and visual information on the void and will provide a basis for verification of the NORVEX code.

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ADVANCED HEAT RECEIVER DEVELOPMENT

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ADVANCED RECEIVER TECHNOLOGY VARIFICATION

- STIRLING SANDERS ASSOCIATES
- BRAYTON SUNDSTRAND CORPORATION

SUPPORTING TECHNOLOGY

- ADVANCED TES MATERIALS Ge-NiSi
 - OAK RIDGE NATIONAL LABORATORY
 - UNIVERSITY OF SOUTH FLORIDA
- TES/CONTAINMENT COMPATIBILITY IN-HOUSE - MATERIALS DIVISION
- THERMAL CONDUCTIVITY ENHANCEMENT IN-HOUSE - ELECTRO-PHYSICS BRANCH
- ANALYTICAL SUPPORT
 - UNIVERSITY OF SOUTH FLORIDA
 - OAK RIDGE NATIONAL LABORATORY (NORVEX)
- SPACE FLIGHT EXPERIMENT (TEST) VERIFICATION OF NORVEX CODE VOID LOCATION

Stirling Cavity Heat Pipe (CHP) Receiver

Sanders Associates, A Lockheed Company - Nashua, NH

The operation of the CHP receiver is such that incident solar flux impinges on the underside of the evaporator dome. Because the internal surface of the dome is wicked it serves as the heat pipe evaporator during the sun portion of the orbital cycle. Also, because of the internal wicking the solar flux is evenly distributed throughout the dome thus the occurrence of hot spots is greatly reduced.

The entire cavity is wicked and the heat pipe transport fluid is sodium. During the sun portion of the orbit the sodium is evaporated off of the dome and condenses on the outside surface of the thermal energy storage (TES) canisters (thus melting the TES material "LiF-CaF₂" and storing energy to be used during the shade portion of the orbit), and the Stirling engine heater head tubes.

The TES material LiF-CaF₂ has a heat of fusion of 753 kJ/kg and its melting point is 1039 K. During the shade portion of the orbital cycle, heat is extracted form the TES material, now making the containment canisters the heat pipe evaporator and providing uninterrupted heat input to the engine for the entire orbit.

This conceptual heat receiver design is currently in the critical technology evaluation phase. The critical technology issues identified for the receiver are:

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- thermal ratcheting
- evaporator dome fabrication
- identification of a wick system
- heat pipe operation

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Cavity Heat Pipe Stirling Receiver

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WITH FINNED TUBE/SHELL HEATER HEAD



Brayton Cavity Heat Receiver Sundstrand Corp.

With the cavity heat pipe heat receiver all of the solar energy from the concentrator falls on a cylinder that forms the inner liner of the cavity and acts as a heat pipe evaporator during the sun portion of the orbital cycle. The energy is transferred to the sodium heat pipe working fluid by evaporating the sodium. The energy is then given up as the sodium vapor condenses on the Brayton engine working gas tubes. Condensation also occurs on the thermal energy storage (TES) canisters, storing energy in the TES material for operation during the shade portion of the cycle.

During the shade portion of the orbital cycle, the TES canisters act as the heat pipe evaporator, transferring energy to the Brayton engine working gas tubes thus, providing uninterrupted power during the shade portion of the cycle. These processes take place at very nearly isothermal conditions.

The TES material is lithium fluoride (LiF) which was chosen because it has a melting point at which the Brayton cycle has high efficiency, 1122 K and it has a high heat of fusion, 1087 kJ/kg. However, the fluoride salts, such as LiF, have very low thermal conductivities, resulting in poor heat transfer through the TES, which in turn, results in high working gas temperature swings as the system goes from sun to shade and back to sun. Also, they expand when melting which must be addressed in the receiver design to prevent canister failure.

Critical technology experiments are underway to determine designs that minimize the thermal conductivity effects and that will accommodate the void formed by the decrease in TES material volume when freezing.

BRAYTON SOLAR RECEIVER



THERMAL ENERGY STORAGE TECHNOLOGY (TEST) PROJECT

OBJECTIVES

The two objectives of this project are to fill a need that has. to date. been lacking in understanding the effects of melting and freezing of TES materials under microgravity.

- Analyses prior to this present effort have been based on simplified, 2-dimensional work. NASA-Lewis contracted with ORNL to develop a code based on what was regarded as an essential element in receiver applications -- 3 dimensions. and which would integrate all of the different thermo-physical aspects involved with melting and freezing. The code development is to include the condition of microgravity.
- The flight program is intended to supply the first experimental data of TES operation under microgravity. No such information exists. The data then becomes the reference against which the NORVEX code is compared. Retrieval of the experiment after flight will provide visual information as well as thermal data.

ORNL has completed their first effort for both 1-g and microgravity and is in the process of validating the program (checks for internal consistency and for agreement with known results).

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POWER TECHNOLOGY DIVISION



THERMAL ENERGY STORAGE TECHNOLOGY (TEST) PROJECT

OBJECTIVES

- ANALYSIS OF TES MATERIALS BEHAVIOR NASA/OAK RIDGE VOID EXPERIMENT, NORVEX (FUNDED BY CODE RP):
 - DEVELOP A COMPUTER PROGRAM TO PREDICT TRANSIENT BEHAVIOR (CONTINUOUS AND REPETITIVE SOLIDIFICATION/ LIQUIFICATION) OF TES MATERIALS, PARTICULARLY VOID SHAPE AND LOCATION, UNDER MICROGRAVITY.
- MICROGRAVITY EXPERIMENTS (FUNDED BY CODE RX):
 - VERIFY CAPABILITY OF DEVELOPED COMPUTER CODE TO PREDICT VOID LOCATION AND THERMAL HISTORY OF TES UNDERGOING PHASE CHANGE IN MICROGRAVITY.

IN-REACH THERMAL ENERGY STORAGE TECHNOLOGY ("TEST")

Thermal energy storage is conventionally associated as being an integral part of the solar receiver. located in the focal region of the concentrator. TES serves to store heat during the sun period and transfer that heat to the working fluid during the shade period of an orbit. Better understanding of the operation of TES is required to meet the advanced solar receiver objectives of lower mass and longer life. A better understanding involves two thrusts -- analysis that describes all of the thermo-physical phenomena of TES undergoing phase change under microgravity, and a flight experiment to verify the analysis.

The schematic is configuration for experiment #1 in which a TES salt, LiF, is contained in an annular container.

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National Acronautics and Space Administration

Lewis Research Center

POWER TECHNOLOGY DIVISION



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IN-REACH THERMAL ENERGY STORAGE TECHNOLOGY ("TEST")



THERMAL ENERGY STORAGE PROJECT

This chart shows the milestone schedule for the TES flight project. Four experiments are proposed with the first two paired for a single flight and the second two likewise.

The project is presently in the Engineering Development phase. Flight date for experiments 1&2 is March 1993 on the Hitchhiker M. Experiments 3&4 follow a year later. The phases in between are steps which address technical problems about the experiment itself, then to the flight structure, and finally launch. Safety is a concern throughout. Reviews are an important part of the process. The Flight Experiment Review takes place when the Engineering Development phase has been completed. All questions about the experiment -- justification, feasibility, instrumentation -- must be answered satisfactorily before the project can proceed to the Flight Development phase. Three reviews -- Preliminary Design Review, Critical Design Review, and the Flight Readiness Review -- ensure that the entire support structure and equipment is sound and ready for flight.

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THERMAL ENERGY STORAGE PROJECT



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SPACE STATION FREEDOM ELECTRIC POWER SYSTEM

Evolutionary Energy Storage

17 January 1990

Mike Domeniconi

Ford Aerospace \sim 00 $, \infty$

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Evolutionary Energy Storage for Space Station Freedom

- System Requirements evolution
- Space Station Freedom Timeline
- Development of Technology Selection Criteria

Candidate Technologies





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System Requirements Evolution

• Changes in load power profile

Classification Low Power, Long Duration	Item Science Instrument	Requirements Flowdown Increases energy content requirement
High Power, Short Duration	Furnace	Increases power (rate) requirement
?	Satellite Servicing	?

- Space Station Time-phased constraints
 - Other EPS Components
 - Thermal Control System
 - Data Management System



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Development of Technology Selection Criteria

- Formulate Specific Goals, e.g.
 - "Identify the most cost-effective energy storage technology capable of meeting the Space Station requirements projected for the year
 - "Identify a methodology which will: Provide objective assessments; Maintain database for future assessments;
- Identify Issues, e.g.
 - Constraining Characteristics/Life Cycle Costs of Current
 Design
 - Requirements Evolution Definition
 - Adequacy of Technology Assessment
 - Obtaining Realistic Figures of Merit for Each Technology

- -- Technical Performance
- -- Technical Risks
- -- Cost (N/R & R)
- -- Life Cycle Cost
- -- Technology Readiness/Timelines/Margins
- Potential Impact on EPS Components
- Potential Impact on Other Subsystems.....



Transform Issues into Objectives

FREEDOM

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Candidate Energy Storage Technologies

CANDIDATE	POTENTIAL TECHNICAL BENEFIT	SUBSYSTEMS IMPACTED	PRINCIPAL COST CONSIDERATION		
ADVANCED Ni-H2					
Electrochemical Improvements Larger Diameter IPV Common Pressure Vessel Bipolar	Longer life, higher efficiency ~10% mass reduction @ 200Ah ~12% mass reduction @ 200Ah ~10% mass reduction; ~50% vol. reduction	Power Source, Thermal Control Structures Charge Mgmt; Thermal Control Charge Mgmt; Thermal Control	Replacement cycle Possibility of reduced number of batteries Reduced Complexity Dev/Qual; TCS Interfaces		
SODIUM SULFUR	Higher Efficiency ~60% mass and 35% vol.reduction; reduced quantity	Pwr Source, Chg Mgmt, TCS, Struc.	New Chg Mgmt, TCS; Dev/Qual (Low cycle life; TCS)		
LITHIUM SYSTEMS	locacia quanny	Pwr Source, Chg Mgmt, TCS, Struc.	New Chg Mgmt, TCS: Dev/Qual		
Inorganic Cathodes Organic/Polymer Cathodes	~50% mass & volume reduction ~50% mass & volume reduction		(Low cycle life; TCS)		
REGENERATIVE FUEL CELLS	On-board oxygen & hydrogen inventory	Pwr Source, Chg Mgmt, TCS, Struc.	New Chg Mgmt, TCS; Dev/Qual		
Hydrogen/Oxygen Low Temperature (80°C) High Temperature (1000°C) Hydrogen/Halogen	~50% mass reduction Higher Eff.; ~65% mass reduction Higher Efficiency		(Low cycle life; ICS; tanks)		
KINETIC ENERGY Flywheel	Extended life	Pwr Source, Chg Mgmt, TCS, Struc.	Storage Mgmt; Dev/Qual (Bearings; slow response time)		



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Miniaturized Cassegrainian Solar Array Development

R. Patterson M. Mills

January 16-19, 1990

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Material for Oral Presentation at the NASA Sponsored EVTEK Workshop Work Performed Under NASA MSFC Contract

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- Required cell area reduced by 99%
- Permits cost-effective use of high-efficiency solar cells
- Provides potential for significant reduction in array cost and area
- Has low profile (13 mm) which permits efficient stowage





MCC Element to Panel Integration







Folded Box Beam Deployment of MCC Array Sub-Wing

















High Efficiency Low Cost GaAs/Ge Cell Technology

Frank Ho Applied Solar Energy Corporation

Technology for Space Station Evolution Workshop January 16-19, 1990 Dallas, Texas

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APPLIED SOLAR ENERGY CORPORATION

HIGH EFFICIENCY, LOW COST GaAs/Ge SOLAR CELLS

- Performance Comparison
 - Beginning of Life
 - End of Life
 - Panel Level
- Cost Comparison
 - Solar Cell \$/W
 - Relative Area/W

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- AF MANTECH Status
- Technology Trend





APPLIED SOLAR ENERGY CORPORATION

ADVANTAGES OF Ge

- Ge stronger than GaAs, therefore suited to larger, thinner cells
- Ge wafer 40% cheaper than GaAs
- Higher mechanical yield
- Same high efficiency as GaAs (inactive junction) or potentially higher efficiency (approaching cascade cell)



COMPARISON OF TYPICAL PRODUCTION CELLS FOR SPACE APPLICATIONS

	Resistivity	Thick- ness (mils)	BOL, AMO EFF, 28° (%)	BOL, AMO EFF, 60°C	EOL, 1 MeV Electron EFF, 60º C, (%) AMO		
Туре				(%)	3 x 10 ¹⁴	1 x 10 ¹⁵	
2 ohn BS Silicon (2 x 4 cm) 10 oh BS	2 ohm-cm BSR	.8	13.4	11.47	9.5	8.37	
	10 ohm-cm BSR	8	12.5	10.82	9.4	8.38	
	10 ohm-cm BSF./R	8 *	14.8	12.81	9.5	8.20	
		2.5	13.5	11.69	9.8	8.60	
GaAs (2 x 4 cm)	.001 ohm-cm GaAs/Ge	3.5 - 12	18	16.85	14.83	12.8	

* Space Station type solar cell, BOL EFF 14.2%

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PANEL LEVEL COMPARISONS

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	CELL TYPE	BOL EFF %	CELL THICKNESS Mils	RADIATION* FACTOR	EOL W/Kg	EOL W/m ²
Rigid Standard Panel	GaAs/GaAs	18	12	.83	28	181
Rigid Light Panel	GaAs/GaAs ^{or} GaAs/Ge	18	8	.83	82	181
Rigid Light Panel	GaAs/Ge	18	3	.83	118	181
Flex Array	GaAs/Ge	19	3	.83	294	191
APSA Flex Array	GaAs/Ge	19	3	.83	304	191
Rigid Light Panel	Si	14	3	.82	103	139
Flex Panel (Large Cells)	Si	14	8	.76	152	139
APSA Flex Array	Si	14	2.2	.82	346	139

* After 3 x 10¹⁴ 1 MeV electrons/cm² No temperature corrections (all 28° C)



APPLIED SOLAR ENERGY CORPORATION

PRODUCTION HISTORY



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COMPARISON OF PERFORMANCE AND COST, SILICON vs GaAs CELLS

					Relative Cost (/cm ²)		Operating T and Radiation 3 x 10 ¹⁴ 1 MeV Electron		
Cell Types	Thick- ness (Size)	Array Type	ح∕ s∕E	Oper. Temp.	Cell	Cell * Stack	Array **	Relative Cost/W (Cell Stack)	Relative Area /W
Silicon 2 ohm-cm BSR	8 mil (2x4)	Rigid	.68/.81	60	1.0	1.0	0.98	1.0	1.0
Silicon Space Sta. 10 ohm-cm BSF/R, WT	8 mil (8x8)	Flex	.65/.87	54	1.75	0.8			
GaAs/Ge	8 mil (2x4)	Rigid	.87/.81	80	10	2.7	1.42	1.40	0.51
GaAs/Ge	3.5 mil (2x4)	Rigid	.87/.81	80	12	3.0		1.45	0.51

* Cell Stack: solar cell, cover, interconnect and substrate

**** TRW's data**



AF MANTECH PROGRAM HIGH EFFICIENCY, RUGGED GaAs/Ge CELLS

OBJECTIVES:

Develop manufacturing technology for high efficiency (>18% AMO) lightweight (<0.05 gm/cm²), large area (>4 x 4 cm²), space qualified GaAs/Ge cells.

ACCOMPLISHMENTS

- Demonstrated MOCVD growth, cell thinning and processing capable of meeting all goals above
- 4 cm x 4 cm cells, <4 mils thick exceeded 19% and 6 cm x 6 cm exceeded 17%

- Major space qualification tests completed
- Demonstrating and testing welded or soldered panel technology on lightweight substrates
- Developing high temperature contact system


APPLIED SOLAR ENERGY CORPORATION

SOLAR CELL TECHNOLOGY TRENDS

- Development of large scale, reliable MOCVD reactors for growth of thin films
- Thin, rugged GaAs/Ge replaced GaAs/GaAs cells

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- High efficiency (𝔈 > 18%), thin GaAs/Ge cell will provide much improved specific power performance
- Manufacturing cost of GaAs/Ge cell will be further reduced as demand increases
- Tight process control, quality management and automation are needed for advanced production cells
- Solar cells will continue to be "tailor-made" to meet various environment and mission requirements
- BOL, 1 sun AMO, 28° C efficiency in early 1990's
 Silicon 7>17%
 - -Single junction GaAs 7>20%
 - -Two junction cascade 7>24%
- For significantly improved manufacturing technology, must have sustained demand. For few large production runs, return on investment not assured

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GROWING THE SPACE STATION'S ELECTRICAL POWER PLANT

GALE R. SUNDBERG NASA LEWIS RESEARCH CENTER CLEVELAND, OHIO 44135

TECHNOLOGY FOR SPACE STATION EVOLUTION

A WORKSHOP

DALLAS, TEXAS

JANUARY 16-19, 1990

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GROWING THE SPACE STATION'S ELECTRICAL POWER PLANT

GALE R. SUNDBERG NASA LEWIS RESEARCH CENTER CLEVELAND, OHIO 44135

SUMMARY

For over a decade NASA LeRC has been defining, demonstrating and evaluating power electronic components and multi-kilowatt, multiply redundant, electrical power systems as part of our OAST charter. Whether we consider aircraft (commercial transport/military), Space Station Freedom, Growth Station, launch vehicles, or the new Human Exploration Initiative our conclusions remain the same: high frequency AC power distribution and control is superior to all other approaches for achieving a FAST, SMART, SAFE, VERSATILE, and GROWABLE electrical power system that will meet a wide range of mission options.

To meet the cost and operability goals of future aerospace missions that require significantly higher electrical power and longer durations, we must learn to integrate multiple technologies in ways that enhance overall system synergisms. This paper will challenge the way NASA is doing business in space electric power and propose some approaches for evolving large space vehicles and platforms in well constructed steps to provide safe, ground testable, growable, smart systems that provide simple, replicative logic structures, which enable hardware and software verification, validation and implementation.

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INITIAL OPERATING CONDITIONS

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COST OF DELIVERING 100 kWe OF USABLE POWER



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POWER TECHNOLOGY DIVISION



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UTILITY POWER FOR THE SPACE FRONTIER

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• SPACE INFRASTRUCTURE REQUIRES COMMONALITY WITH DIVERSITY

- SPACE STATION IS FIRST STEP
- TECHNOLOGY NEEDED NOW TO SET STANDARDS





PLATFORM

SBOTV







20 kHz RESONANT PMAD

- VERSATILE
- LIGHTER WEIGHT
- SUPERIOR CREW SAFETY
- MINIMAL EMI
- LOWER COST
- GREATER RELIABILITY
- HIGHER EFFICIENCY



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POWER TECHNOLOGY DIVISION



AUTONOMOUS POWER EXPERT(APEX) FOR SPACE STATION FREEDOM ELECTRICAL POWER SYSTEM TESTBED APPLICATION



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<u>GOAL</u>: DEVELOP REAL-TIME AI SOFTWARE FOR PMAD OPERATIONS & CONTROL

APPROACH:

- * COOPERATIVE(OAST/OSS) PROGRAM
- * INCREASINGLY SOPHISTICATED KNOWLEDGE-BASED DESIGNS
- *** PROOF-OF-CONCEPT ON EPS TESTBEDS**

SIGNIFICANCE:

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- * ENHANCED CREW EFFICIENCY THROUGH FASTER POWER OPERATIONS DECISIONS
- * IMPROVED ELECTRICAL ENERGY UTILIZATION WITH OPTIMIZED LOAD POWER SCHEDULING

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* INCREASED SAFETY PROVIDED BY RAPID ELECTRICAL FAULT DIAGNOSIS/RECOVERY



POWER TECHNOLOGY DIVISION



FUNDAMENTAL SYSTEM REQUIREMENTS

MUST MEET MISSION REQUIREMENTS

- RATED POWER, GOOD AVAILABILITY
- ACCOMMODATE VARYING LOAD PROFILES
- USER FRIENDLY LOADS
- CAPABLE OF GROWTH

• MUST BE SAFE

- PROTECT WIRES AND EQUIPMENT
- ELIMINATE FIRE HAZARD
- CREW
- SYSTEM STABILITY STEADY STATE AND TRANSIENT
- REDUNDANCY FOR LIFE CRITICAL LOADS

ACCURATE REAL TIME STATUS

- LOAD MANAGEMENT
- DIAGNOSTIC AND CONTROL
- DESIGN QUALIFIED ON GROUND, ASSEMBLED IN SPACE



POWER TECHNOLOGY DIVISION

NASA Lowis Research Conter

LARGE SPACE POWER PLANTS MUST BE

FAST

SMART

SAFE

VERSATILE

GROWABLE

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POWER TECHNOLOGY DIVISION



HISTORICALLY: POWER ELECTRONICS EVOLUTION

APPROACHING LIMITS OF

- POWER DENSITY
- WEIGHT
- THERMAL CAPACITY
- RELIABILITY

FURTHER GROWTH REQUIRES

- END-TO-END SYSTEM ENGINEERING CONCEPTS
- PARALLEL OPERATIONS
- FAULT TOLERANCE
- FAULT CONTAINMENT
- DISTRIBUTED SMART SYSTEM

NEED: BUILT-IN INTELLIGENCE



KEY TO AUTONOMOUS, GROWABLE SYSTEMS

SIMPLE - SMART-REPLICATIVE LOGIC STRUCTURES

- INTELLIGENCE ON A CHIP COMPONENT LEVEL : BITE
- DISTRIBUTED INTELLIGENCE IN SYSTEMS
- EACH NODE COMMUNICATES VIA COMMON WORK
- EASY VERIFICATION, VALIDATION, STATUS, MAINTAINABILITY
- FOUNDATIONS FOR ORDERLY TRANSITION TO EXPERT SYSTEMS





POWER TECHNOLOGY DIVISION

Lowis Research Center

RECOMMENDATIONS FOR SPACE STATION EVOLUTION

- HIGH FREQUENCY AC \implies GROWABLE PMAD SYSTEM
- SMART COMPONENTS \implies GROWABLE, AFFORDABLE SOFTWARE

DISTRIBUTED LOGIC

GROWABLE AUTONOMY/FAULT TOLERANCE

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ADVANCED MODULAR POWER SUPPLIES FOR SPACE STATION FREEDOM

S. Krauthamer M. D. Gangal R. C. Detwiler

January 17, 1990 Dallas, Texas

Jet Propulsion Laboratory California Institute of Technology Pasadena, California

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CONTENTS

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- INTRODUCTION
- CONCEPT AND CHARACTERISTICS
- USER POWER SUPPLY APPLICATIONS
- BULK CONVERTER APPLICATION
- RECOMMENDATIONS

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SPACE STATION FREEDOM ELECTRICAL POWER SYSTEM TARGET APPLICATIONS



SIMPLIFIED BLOCK DIAGRAM OF TYPICAL SPACE STATION FREEDOM POWER DISTRIBUTION SYSTEM SHOWING POSSIBLE APPLICATIONS OF THE PROPOSED TECHNOLOGY

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WHY MODULARITY

- VHSIC, ADVANCED VLSI CHIPS DRIVING THE POWER SUPPLY FUNCTION TO BECOME HIGHLY DISTRIBUTED
- POWER CABLING WITHIN THE RACKS LESS COMPLEX AND LOWER IN MASS
- LESS MASS AND LOSS ESPECIALLY FOR 5V DISTRIBUTION FOR ELECTRONIC COMPONENTS
- MODULES CAN BE DESIGNED USING HIGH INTERNAL SWITCHING FREQUENCIES; THE RESULT IS LOWER MASS AND VOLUME AND HIGHER RELIABILITY
- MODULAR DESIGN PROVIDES EFFICIENCY ADVANTAGES AT PARTIAL LOADS
- MODULARITY ALLOWS GRACEFUL DEGRADATION

- EXTRA REDUNDANCY CAN BE ADDED WITH SMALL INCREASE IN MASS
- MODULARITY WILL PERMIT STANDARDIZATION AND COMMONALITY; DIVERSIFIED POWER SUPPLY EFFORTS WOULD BE TOO COSTLY

OVERVIEW

- MODULARITY OPENS THE DOOR TO STANDARDIZATION OF POWER SUPPLIES, COMMONALITY, AND SUBSTANTIAL COST SAVINGS
- THE DEVELOPMENT OF STANDARDIZED SPACE QUALIFIED POWER SUPPLY BUILDING BLOCK MODULES CAN BENEFIT THE SPACE STATION PROGRAM, FUTURE SPACECRAFT, AND THE NEW MOON AND MARS INITIATIVES
- HYBRIDIZED, HIGH SWITCHING FREQUENCY MODULES CAN IMPROVE EFFICIENCY, SAVE MASS, INCREASE RELIABILITY AND REDUCE POWER SUPPLY COSTS SIGNIFICANTLY

- TWO SPECIFIC APPLICATIONS ARE DISCUSSED:
 - A) USER END DC/DC POWER SUPPLIES
 - **B) BULK CONVERTERS**

INTRODUCTION

TARGET APPLICATIONS

(DISCUSSION OF VIEWGRAPH 6)

Space Station Freedom cost models show that the life cycle cost of a kilowatt of power installed is on the order of twenty million dollars. At mature operations, the station will use hundreds of power supplies to feed house keeping and user loads. Proposed standard modular dc power supplies can provide significant cost, mass, and efficiency savings for the program.

The development of a small number of standard space qualified power supplies with the Space Station as an initial consumer may have a significant benefit to future spacecraft and the new Moon and Mars initiatives.

To the users of the Station, the new approach will permit the use of "distributed" power supply design with the user able to specify just what is needed and use it only where needed. The cost of user power supplies may be \$70 to \$80 million; R&D to reduce it may be worthwhile.

The modular design approach can also provide benefits to the bulk conversion application. The proposed design incorporates multiple modular converters in the primary/secondary bus interface that can provide significant cost, mass, efficiency, and reliability improvements for the program while meeting the design requirements.

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POWER SUPPLIES FOR FREEDOM

- USER-END POWER SUPPLIES ON FREEDOM FOR HOUSEKEEPING AND PAYLOADS
 - APPROX. 2000 POWER SUPPLIES OF FLIGHT HARDWARE
 - ESTIMATE MORE THAN 5000 UNITS OF NON-FLIGHT HARDWARE FOR DEVELOPMENT WORK
 - ESTIMATED COST IN EXCESS \$80 MILLION FOR FLIGHT AND DEVELOPMENT HARDWARE
 - FOCUS ON DC POWER SUPPLIES
 - HALF OF ALL POWER SUPPLIES (APPROX. 1000) FEED DC LOADS
 - 5, ±15, 28 VOLTS ARE TYPICAL OUTPUT VOLTAGES
- BULK CONVERTER UNITS (DC TO DC CONVERTER UNIT, DDCU)
 - 12.5 kW UNITS INTERFACE 160V POWER SUPPLY BUSES TO 120V DISTRIBUTION BUSES
 - 28 UNITS, 350 kW ONLINE CAPACITY AT ASSEMBLY COMPLETE

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THE CONCEPT

AND CHARACTERISTICS

MODULARITY CONCEPT

(DISCUSSION OF VIEWGRAPHS 7, 8, AND 9)

Manufacturers of power supplies for space applications have used modular designs before to minimize the development costs of units of different size. Loral, for example, has built half, one, and two kilowatt units using 250 W modules. The European and Japanese partners of Space Station Freedom have been considering the use of two to four kW dc/dc converter modules to build larger converters interfacing the station power distribution. These units are based upon <u>discrete</u> electrical components.

Recently, developments in hybridized power supplies using high switching frequencies in the 100 kHz to 10 MHz range provide the basis for pushing this modular design approach much further with significant advantages.

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Several 20 to 250 W dc/dc converters designs have been developed at MIT, CALTECH, VPI, AT&T and other places and some are now available via their industrial partners. These designs are very compact and have been hybridized. None are space qualified yet. If used as building blocks, they offer many advantages not feasible in the discrete component designs cited above.

None of these units have been space qualified; the proposed development effort, therefore, is necessary:

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MODULARITY CONCEPT

• CONCEPT: BUILD DC POWER SUPPLIES USING SMALL, HIGH-SWITCHING-FREQUENCY HYBRIDIZED MODULES.

- TECHNICAL AND ECONOMIC FACTORS
 - **EFFICIENCY**
 - RELIABILITY
 - EMI
 - FLEXIBILITY
 - CONTROL
- APPLICATIONS AND BENEFITS
 - MASS
 - COST

100-W HYBRID MODULAR POWER SUPPLY (HUGHES AIRCRAFT CORPORATION) 270-V INPUT, 5-V OUTPUT; 100-W RATING





EFFICIENCY

(DISCUSSION OF VIEWGRAPHS 10, 11, AND 12)

Efficiency is perhaps the most important consideration. One kW of installed capacity of the Space Station amounts to approximately twenty million dollars of Life Cycle Costs (LCC). Thus, a one percent increase in the efficiency of the proposed 100 Watt converter costing about \$10,000 may save twice that in LCC. In design, every effort should be made to increase the efficiency of the module as well as the whole converter.

Because the final rectification stage of a module results in a voltage drop, the efficiency of the module is a sensitive function of its output voltage. Viewgraph 11 shows the efficiency of state of the art modules as a function of the output voltage. The same viewgraph shows that if techniques such as synchronous rectification and design optimization are applied, higher efficiencies in the shaded band can be achieved. It is sufficient to see in this overview that a 2% to 4% improvement in efficiency may be feasible, assuming that about 37.5 kW of the station power goes to dc loads. This improvement in the efficiency is equivalent to 0.75 to 1.5 kW power savings or a life cycle cost benefit of 15 to 30 million dollars.

Another aspect of modular design is the improvement in the efficiency at partial loads. A typical efficiency curve for a power converter is shown in Viewgraph 12; the efficiencies at partial and "keep alive" levels of operation are quite low due to high parasitic light load losses. If a modular design is used in which a provision is made to turn off the unloaded modules, the synthesized efficiency-load characteristics would look like that shown in Viewgraph 12. Operation at partial load and at "keep warm" levels are quite common. Measureable savings can be made in the parasitic losses at lightly loaded conditions.

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EFFICIENCY

• INCREASES IN EFFICIENCY OCCUR AT TWO LEVELS:

- AT THE MODULE LEVEL 2% 4% INCREASE OVER CURRENT PRACTICE
- AT THE BULK CONVERSION LEVEL 2% 4% SYSTEM EFFICIENCY INCREASE DUE TO IMPROVED EFFICIENCY AT PARTIAL LOADS BY SWITCHING OFF UNLOADED MODULES

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MODULE EFFICIENCY



EFFICIENCY: MODULAR vs. NONMODULAR UNITS



RELIABILITY

(DISCUSSION OF VIEWGRAPH 13)

The reliability of a power conversion subsystem is dependent of the following elements of design: 1) Thermal stress; 2) Electrical stress; 3) Parts count and complexity; 4) Selection of parts (class of part).

Improved reliability is dependent upon thermal stress. Operating temperature of a power conversion device is dependent on heat dissipation, mass radiating area, and cooling methods. Inherently, the smaller size of hybrids gives the designer the flexibility to optimize the size for cooling effectiveness. Hybridized power converter modules have a low profile making it easier to remove heat; cooler junction temperatures add significantly to the life of the circuit.

We have seen earlier that as the switching frequency increases, the sizes of the inductors and capacitors decreases. One benefit of smaller size is that it permits use of highly reliable ceramic capacitors instead of tantalum capacitors.

Although it remains to be shown, the improvements may be so substantial (up to 250,000 hrs MTBF) that from a reliability point of view, the hybrid circuit may be treated as a single part. If this is demonstrated, the reliability of the whole power distribution system can be improved significantly.

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Larger power converters built by paralleling smaller modules have inherent fault tolerance capability. The failure of a module need not cause the failure of the whole unit. In space applications requiring redundancy, the modular approach provides some elegant low mass, high efficiency design options.
RELIABILITY

- CERAMIC FILTER CAPACITORS FOR HIGH FREQUENCY CONVERTERS ARE MORE RELIABLE THAN TYPICALLY USED TANTALUM CAPACITORS
- HYBRID CONSTRUCTION HIGHLY RELIABLE
- HIGHER EFFICIENCY AND LOW PROFILE CAN IMPROVE THERMAL CONTROL
- MODULARITY PROVIDES GRACEFUL DEGRADATION
- BUILT-IN SPARES CAN PROVIDE ADDITIONAL REDUNDANCY

EMI CONTROL

(DISCUSSION OF VIEWGRAPH 14)

The EMI standard (MIL-STD-461B) places absolute limits on powerline currents as a function of frequency irrespective of the power rating or voltage of the power converter. The permissible conducted current decreases by 30 dBs/decade to 2 MHz and then remains constant.

It is easier to design a low power module to meet the EMI specifications than a high power unit because of the lower bus current and resulting lower conducted EMI current. When multiple modules are placed in parallel, care must be taken to ensure that the currents do not exceed the EMI limits. Synchronizing the modules helps reduce the generated EMI currents. If all modules used in a large system like the Space Station are designed to use the same switching frequency, say, 100 kHz, or multiples thereof, synchronization can be easily implemented.

Numerous commercial hybrid power supply module vendors indicate compliance with various EMI specifications including MIL-STD-461B. Due to high switching frequencies, small EMI filters are required.

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EMI CONTROL

- PROTOTYPE MODULES HAVE ALREADY SHOWN COMPLIANCE WITH MIL-STD-461B
- MODULES CAN BE SYNCHRONIZED TO ENHANCE EMI CONTROL

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- - SMALL EXTERNAL FILTERS CAN PROVIDE FURTHER IMPROVEMENTS

MASS AND VOLUME REDUCTION

(DISCUSSION OF VIEWGRAPH 15)

Dr. Cúk of Cal Tech points out that a rough figure of merit for current switching rate capability of semiconductors is the product of power and switching frequency. For a given power level, progressively higher frequencies lead to smaller magnetics and overall mass. Although precise comparisons based upon the figure of merit cannot be made from available product data, because a modular design would not necessarily use individual casings for each module, and because frequency of operation would be higher, the mass of the modular design is expected to be less compared to a single unit design.

A higher figure of merit tends to represent a lower mass. Although the improvements do not continue with ever increasing frequency, the present state-of-the-art permits the use of frequencies up to 2 MHz, although some designs as high as 10 MHz have been prototyped.

Mass and volume improvements are possible because high switching frequencies require physically smaller filters.

Some of the mass reduction provided by the modular design approach can be used to further improve the efficiency. This can be accomplished by slightly larger magnetics which may reduce hysteresis losses, or by increasing redundancy by using an increased number of units in parallel. Also some mass and volume savings can be traded to get better heat removal and to add redundant units to increase reliability and fault tolerance.

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MASS AND VOLUME

- HIGHER SWITCHING FREQUENCIES LEAD TO LOWER POWER SUPPLY MASS
- HIGHER SWITCHING FREQUENCY AND HYBRIDIZATION LEADS TO COMPACT SIZE
- ESTIMATES OF MASS SAVINGS WILL BE DISCUSSED FOR EACH APPLICATION

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USER END POWER SUPPLIES

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USER POWER SUPPLIES APPLICATION CHARACTERISTICS

(DISCUSSION OF VIEWGRAPH 16)

Advanced high density components (e. g. VHSIC) and interconnection technologies force the power conditioning function to become highly distributed throughout the entire electronics system. Future systems will contain increased numbers of power conditioning modules, each of which processes smaller amounts of power and is located closer to the electronic load circuits that it powers. The Module output power will be as required.

The advantages of distributed power include: a) Reduction in the complexity of system wiring and associated shielded cables; b) Elimination of voltage drop associated with distribution from a central power converter, especially at lower input voltages; c) Improved reliability, reduced common mode noise; d) Elimination of resonances in cables and; e) Improved transient response due to high frequency converter switching.

A number of control and safety features can be easily built-in into the modules. This further enhances the usefulness of the power supplies to the end users.

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USER POWER SUPPLIES APPLICATION CHARACTERISTICS (Cont'd)

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(DISCUSSION OF VIEWGRAPH 16)

The usage of 120 Vdc distribution inside the racks would result in, a smaller cables mass. When parallel power supply modules are used, only the number of units required by the load will be turned on. This will result in higher efficiency and lower parasitic losses.

These modules can be controlled via a IEEE-1553B bus interface. They can operate over the broad input voltage range specified and provide the necessary isolation to the load. They can provide current limiting, soft start, and short circuit protection. These power supply modules can be used as a single power unit and in addition multiple units can be utilized for bulk converters interfacing primary and secondary distribution.

APPLICATION CHARACTERISTICS

- TAILOR POWER SYSTEM USING COMMON POWER SUPPLY COMPONENTS WHERE THEY ARE NEEDED
- DISTRIBUTED POWER SUPPLIES
 - BOARD LEVEL POWER SUPPLIES OPTIMIZE POWER DISTRIBUTION
 - LOWER MASS AND WIRING COMPLEXITY DUE TO 120V DISTRIBUTION IN THE RACKS
 - USE ONLY WHAT IS NEEDED
- SPECIAL FEATURES: MODULES CAN PROVIDE
 - IMPROVED PROTECTION CHARACTERISTICS
 - CURRENT LIMITING CAPABILITY
 - IMPROVED SHORT CIRCUIT PROTECTION
 - IMPROVED TRANSIENT RESPONSE
 - SAFETY CHARACTERISTICS
 - ELECTRICAL ISOLATION
 - ABILITY TO HANDLE INPUT VOLTAGE VARIATION
 - CONTROLLABILITY
 - DIGITAL CONTROL AND IEEE-1553 BUS INTERFACE

USER POWER SUPPLIES

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MASS AND COST BENEFITS

- MASS REDUCTION
 - ESTIMATE 1000 Ib MASS SAVINGS
- EFFICIENCY IMPROVEMENT
 - 2 TO 4% IMPROVEMENT TRANSLATES TO 0.75 TO 1.5 kW POWER DELIVERED (ESTIMATE BASED UPON DELIVERED POWER SUPPLIES FOR DC LOADS ONLY)
- COST BENEFITS
 - APPROX. \$3.75 TO \$5 MILLION DUE TO MASS REDUCTION (AT \$5000/Ib)
 - APPROX. \$15 TO \$30 MILLION LIFE CYCLE COST BENEFIT DUE TO HIGHER EFFICIENCY (AT \$20 MILLION/kW)

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BULK CONVERTER APPLICATION

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BULK CONVERTER APPLICATION

- MODULAR DESIGN
 - ONE FOR ONE REPLACEMENT OF BULK CONVERTERS (DDCUs)
- A SWITCHING MATRIX IS USED WITH MODULAR CONVERTERS TO REDUCE BOX COUNT

PRESENT ARCHITECTURE [SPACE STATION FREEDOM (SSF) ELECTRICAL POWER SYSTEM (EPS)] (DISCUSSION OF VIEWGRAPH 19)

VG-19 shows the present concept of the SSF EPS architecture in-board of the alpha gimbal. The power rating of SSF is 37.5 kW generated by photovoltaic panels. The spacecraft is divided into two separate 18.75-kW distribution systems. Primary power is generated at 160 Vdc. In the present baseline, four main bus switching units (MBSUs), one in each quadrant of the EPS network, control the distribution of power to the elements of Space Station Freedom. The four MBSUs supply 160-Vdc power to 28 dc-to-dc Converter Units (DDCUs) that interface with the loads via dc Power Distribution Control Units and with other devices.

Twenty eight buses in the space station's utility tray provide the interface between the four MBSUs and the 28 DDCUs. The DDCUs are associated with the loads and mounted on or near them. A single dedicated dc bus feeds each DDCU.

The DDCUs convert 160-Vdc power to regulated 120 Vdc. Each is rated at 12.5 kW, and provides electrical isolation between the 160-Vdc bus and the 120-Vdc bus.

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BULK CONVERTER APPLICATION PROPOSED ARCHITECTURE

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PROPOSED ARCHITECTURE [SPACE STATION FREEDOM (SSF) ELECTRICAL POWER SYSTEM (EPS)]

(DISCUSSION OF VIEWGRAPHS 20, 21)

The proposed architecture is similar to the present one, except for the location and design approach to the utilization of the DDCUs.

VG-20 depicts the proposed EPS architecture. The DDCUs are shown adjacent to the MBSUs. This is a significant change, reflecting their proposed relocation on the central EPS PMAD pallet instead of on the surface of modules and nodes. By locating the DDCUs in a single envelope, see VG-21, flexibility is gained in sizing the units. Instead of each DDCU being dedicated to a single fixed module, node, or pallet, the DDCUs are available to be switched selectively to any combination of buses, as the need arises. The details of this design are provided below. As in the present architecture, the proposed centralized DDCUs are internally modularized. Of these, approximately one-half are active at any given time; the others are "connected" spares (usually turned off).

Individual modules within the DDCU (DDC module) may be sized in the range of 250 W to 5 kW.

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PROPOSED ARCHITECTURE [SPACE STATION FREEDOM (SSF) ELECTRICAL POWER SYSTEM (EPS)] (Cont'd)

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(DISCUSSION OF VIEWGRAPHS 20, 21)

The approach, see VG-21, is to use multiple DC/DC converter modules instead of a single 12.5-kW interface DC/DC converter. By using switches, these modules can be switched to a desired secondary bus and provide the desired power requirements to a particular load. A failure of a single module does not impair power rating, as a replacement redundant module is switched into service. The result of this technique is to provide high levels of reliability without requiring the required installed kilowatt capacity of a single large interface DDCU. The reduction in installed DDCU capacity will result in a relatively proportional mass reduction. In line with the reduction in active DDCU capacity, the part load losses are expected to be proportionally reduced, resulting in improved EPS efficiency and reduced cost.

BULK CONVERTER APPLICATION PROPOSED ARCHITECTURE



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MODULAR ARRANGEMENT FOR BULK CONVERTERS



MASS AND EFFICIENCY

• MODULAR BULK CONVERTER (DDCU) DESIGN

- EFFICIENCY IMPROVEMENT 2% 4% RESULTING IN 0.75 TO 1.5 kW ADDED POWER DELIVERED
- WITH SWITCHING MATRIX AND CHANGES IN BUS ARCHITECTURE

- MASS REDUCTIONS OF MORE THAN 1500 lbs.
- BOX COUNT REDUCED FROM 28 TO 4 TO 8

COST REDUCTIONS IN BULK CONVERTER APPLICATION

- MASS AND EFFICIENCY IMPROVEMENTS REDUCE COSTS
 - \$7.5 MILLION SAVINGS FROM MASS REDUCTIONS
 - \$15 TO \$30 MILLION LIFE CYCLE COST REDUCTION DUE TO IMPROVED EFFICIENCY (THIS REFLECTS 37.5 kW ADDITION)
- OPTIMIZED, STANDARDIZED, AND SPACE QUALIFIED MODULES REDUCE DEVELOPMENT COSTS COMPARED TO NONSTANDARDIZED DESIGNS
- RELIABILITY INCREASES REQUIRE LESS LOGISTICS, ON-ORBIT STORAGE, AND MAINTENANCE COSTS

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RECOMMENDATIONS

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RECOMMENDATION TO OAST

- FUND JOINT DEVELOPMENT EFFORT LeRC-JPL
 - JPL MODULE DEVELOPMENT
 - LeRC: PACKAGING DEVELOPMENT
- DEVELOP SPACE QUALIFIED 10W THROUGH 250W MODULES
 - 2 TO 4% HIGHER EFFICIENCY THAN EXISTING UNITS
 - STATE-OF-THE-ART SWITCHING FREQUENCY
 - COMPLIANT WITH REQUIREMENTS OF SPACE STATION
- DEMONSTRATE PARALLEL OPERATION
 - DEVELOP CONTROL LOGIC
 - DEVELOP BREADBOARDS AND DEMONSTRATE PARALLEL OPERATION
 - DEMONSTRATE PERFORMANCE OVER THE FULL RANGE OF DESIGN LOADS
- DEMONSTRATE BULK CONVERTER ARRANGEMENT
 - MULTIPLE-MODULE, MULTI BUS CONFIGURATION

- ELECTRICAL ISOLATION
- FAULT TOLERANCE

RECOMMENDATIONS TO THIS WORKSHOP

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- PLACE HIGH PRIORITY ON THE PROPOSED MODULAR POWER SUPPLY DEVELOPMENT EFFORT
- EMPHASIZE BOTH END-APPLICATIONS

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Power Beaming Options for the Space Station

Presented by Dr. Peter E. Glaser Vice President Arthur D. Little, Inc. Cambridge, MA

Presented to NASA, OAST Workshop January 16-19, 1990 Dallas, TX

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Power plant locations need to be assessed

- Integrated with Space Station
- Tethered
- Free-flying (beamed power)

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• Earth-based (beamed power)

Power is prerequisite for Space Station evolution

- Near-term: 25 kW (supplemental power)
- Mid-term: 100-500 kW (mission support)
- Long-term: > 500 kW (infrastructure element)

Beamed power has potential benefits

- Flexibility of power plant location
- Reduced drag on Space Station
- Orbital altitude optimized for space shuttle
- Growth path to power supply for exploration missions

There are two major beamed power options

- Lasers
 - Generation (demonstrated)
 - Transmission (demonstrated)
 - Reception (to be developed)
- Microwaves
 - 2.45 GHz (end-to-end system demonstrated)
 - 35 GHz (demonstrated in laboratory)

Power beaming requires in-space demonstration

• Recommended at planning conference for ISY

- Proposed by Center for Space Power (Texas A&M)
- Investigated by Institute of Space and Astronautical Science (Japan)

Space Power System Technology (ISAS)

Working groups

- System technology
 - Microwave power reception
 - Attitude control
 - Laser technology
 - Photovoltaic conversion
 - Thermodynamic conversion
 - Propulsion
- Experiment/observation
 - Spacecraft environment
 - Interaction with space plasma
 - Communication system
 - Biological effect

Planned TSS experiment (enabling)




Possible power transmission configuration from space shuttle to free-flying platform





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Beamed power can be developed to support Space Station when:

- Experiments are undertaken in the near-term
- Environmental and societal factors are considered
- Cooperative programs with industry are developed
- Beamed power technologies support multiple space power system applications

SPE® REGENERATIVE HYDROGEN/OXYGEN FUEL CELLS FOR EXTRATERRESTRIAL SURFACE AND MICROGRAVITY APPLICATIONS

J. F. McElroy

United Technologies Corporation Hamilton Standard Division Windsor Locks, Connecticut

Presented at NASA's Technology for Space Station Evolution Workshop January 16-19, 1990

SPE[®] is a registered trademark of Hamilton Standard Division, United Technologies Corporation



HYDROGEN-OXYGEN REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM (Dedicated Electrochemical Modules)



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HYDROGEN-OXYGEN REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM

(Unitized Regenerative Module)



SPE ELECTROCHEMICAL CELL REACTIONS



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TYPICAL SPE MODULES



LUNAR BASE ELECTRICAL ENERGY STORAGE REQUIREMENTS

Discharge output rate - 25KW

Discharge cycle time \sim 375 hours

Charge cycle time \sim 300 hours

System operating time

High reliability

Low mass

 \geq 20,000 hours

- Static phase separation

 \sim 1000 watt-hours/kg

EXPECTED LIFETIMES OF SPE CELLS WITH PERFLUOROCARBON PROTON EXCHANGE MEMBRANES

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"UNINTERRUPTED" SPE ELECTROLYZER LIFE TEST



SPE CELL VOLTAGE STABILITY



HOURS AT STATED CURRENT DENSITY

DEDICATED SPE FUEL CELL (25KW) SCHEMATIC FOR MICROGRAVITY APPLICATIONS



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PASSIVE STATIC WATER REMOVAL SPE FUEL CELL — CROSS SECTION





PASSIVE WATER REMOVAL SPE FUEL CELL PERFORMANCE AT 150°F

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GRAVITY WATER REMOVAL SPE FUEL CELL (Active Area 0.78 Ft²)



0.78 FT² FUEL CELL PERFORMANCE CURVE

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LUNAR BASE APPLICATION 25KW SPE FUEL CELL SUBSYSTEM POWER DENSITY SUMMARY



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DEDICATED SPE WATER ELECTROLYZER (29#/HR) FOR MICROGRAVITY APPLICATIONS



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SPE WATER ELECTROLYZERS (Active Cell Area 0.23 Ft²)

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Production Modules





3,000 psi Propulsion **Electrolyzer Mock-Up**



Space Station 1,000 psi **Development Unit**



U.K. Navy Submarines >30 Units Delivered





6000 psi **Development Unit**

SPE ANODE FEED WATER ELECTROLYSIS CELL PERFORMANCE VS GAS GENERATION PRESSURE 12 MIL NAFION 120 MEMBRANE 120° F TEMPERATURE

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SPE ANODE FEED WATER ELECTROLYSIS CELL PERFORMANCE VS GAS GENERATION PRESSURE 12 MIL NAFION 120 MEMBRANE 150° F TEMPERATURE



HYDROPHOBIC OXYGEN PHASE SEPARATOR SCHEMATIC

H₂O to Recirculation Loop



HYDROPHILIC/ELECTROCHEMICAL HYDROGEN PHASE SEPARATOR SCHEMATIC



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LUNAR BASE APPLICATION SPE ELECTROLYZER (29#/HR) SUBSYSTEM POWER DENSITY SUMMARY



Watts Power Input at 100% Thermal Efficiency (~59KW)

UNITIZED REGENERATIVE FUEL CELL SCHEMATIC



UNITIZED REGENERATIVE FUEL CELL COMPARISON OF PERFORMANCE DURING FUEL CELL AND ELECTROLYSIS MODES

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UNITIZED REGENERATIVE SPE FUEL CELL MOCK-UP



SUMMARY

- In the shorter term the dedicated SPE Fuel Cell and SPE Elecrolysis approach meets many of NASA energy requirements including:
 - Low system mass
 - Long lifetimes
 - Stable voltage
 - Passive phase management
- In the longer term the unitized regenerative SPE Fuel Cell offers additional advantages:
 - Lower complexity
 - Higher reliability (lower number of parts/passive fluid and thermal management)
 - Lower mass

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INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) TECHNOLOGY DEVELOPMENTS

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PRESENTED TO:

TECHNOLOGY FOR SPACE STATION EVOLUTION WORKSHOP

16-19 JANUARY 1990

CO-AUTHORS:

DAVID B. EISENHAURE, SATCON TECHNOLOGY CORPORATION BOB BECHTEL, NASA MARSHALL SPACE FLIGHT CENTER RICHARD HOCKNEY, SATCON TECHNOLOGY CORPORATION RON OGLEVIE, CONSULTANT MITCH OLSZEWSKI, OAK RIDGE NATIONAL LABORATORY

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DISCUSSION VIEWGRAPH 1

Integrated Power and Attitude Control System (IPACS) studies performed over a decade ago established the feasibility of storing electrical energy in flywheels and utilizing the resulting angular momentum for spacecraft attitude control. Such a system has been shown to have numerous attractive features relative to more contemporary technology, and is appropriate to many applications (including high-performance slewing actuators). Technology advances over the last two decades in composite rotors, motor/generator/electronics, and magnetic bearings are found to support the use of IPACS for increasingly sophisticated applications. It is concluded that the concept offers potential performance advantages as well as savings in mass and life-cycle cost.

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OVERVIEW

- IPACS CONCEPT
- FEATURES & MISSION APPLICABILITY
- TECHNOLOGY ADVANCEMENTS SUPPORTING IPACS

- ROTORS--MATERIALS & SHAPE
- MOTORS/ GENERATORS
- BEARINGS
- SYSTEM-LEVEL TRADE COMPARISONS
- CONCLUSONS & RECOMMENDATIONS

DISCUSSION VIEWGRAPH #2

The IPACS concept provides for the storage of electrical energy as kinetic energy in mechanical rotors. Energy storage wheels can generally be made to provide higher energy densities than most other long-life energy storage devices. When significant amounts of energy are stored in this fashion, appreciable amounts of angular momentum are produced. This angular momentum may be utilized for attitude control of the spacecraft.

To accomplish the dual function of energy storage and attitude control, the IPACS wheels are configured in such a way that they will satisfy simultaneous energy (power) and momentum (control Torque) demands, and to do so with negligible interaction between the two functions. Although this may seen to be an imposing requirement, it is easily accomplished with wheel configurations that are similar to the momentum wheel (MW) and control moment gyro (CMG) configurations appropriate to many applications. In most spacecraft applications the IPACS units replace the functions performed by batteries and momentum storage/transfer equipment. The obvious merits of IPACS are its potential for satisfying two functions with common hardware and long life. Similar components have demonstrated very long life in space missions.

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INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) CONCEPT



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The energy storage wheel historical legacy is rich with focused and supporting technology developments that are applicable to the development of an advanced IPACS. This is particularly true for the advances in composite rotors, magnetic bearings, and motor/generator/circuitry technology that have occurred during the last 12 years. The three basic technology areas that are the fundamental components of an advances IPACS are listed on the left side of the viewgraph. Improvements in power processing circuitry, magnetic materials, and magnetic system design have increased the energy recovery efficiency (round-trip charge/discharge cycle efficiency) from approximately 60% to over 85%. In a spacecraft photovoltaic power system, this efficiency has a strong effect on the overall system sizing (including the solar array).

During the last decade, magnetic bearing technology has gone from an interesting laboratory curiosity to a proven technology with several flight applications having operated successfully in orbit, and many more applications proven in the laboratory. Notable among these are a Soviet flight experiment of a magnetically suspended reaction sphere, the flight of a rotating scanner with magnetic bearings by the Sperry Flight Systems Division, and the operational flight of European reaction wheels with magnetic bearings. Also, the use of magnetic suspension for vibration isolation and high-accuracy pointing have been thoroughly studied and proven in the laboratory. The merits of very low friction losses, maintenance-free long life, and freedom from vibration disturbances, for example, are very attractive. These suggest "leap-frogging" past the use of ball bearings with the attendant problems of lifetime, vibration, maintenance, and the long-duration testing needed to validate bearing design.

The composite rotor technology is the key to achieving higher energy densities. The recent Department of Energy composite energy storage wheel development and testing programs have provided a valuable legacy that was not available a decade ago. Considerable data have been provided on various materials, rotor shapes, composite rotor fabrication, and testing techniques. In addition, advantages in basic composite materials technology are continuing to be made at a high rate.

The advances in the three technology areas described above suggest that an advanced IPACS employing a composite structure rotor, magnetic bearings, and advanced motor/generator/electronics is a feasible and cost-effective replacement for the systems used in the contemporary spacecraft of today.

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The historical development of the three key technology areas is shown in the viewgraph.

ENERGY CONVERSION - The advent of the samarium cobalt magnets permitted IPACS energy conversion efficiencies to first become competitive with batteries. Significant improvements in magnetic materials have been made subsequently. The advent of improved circuitry, such as metal oxide field effect transistors (MOSFETS) has greatly reduced the switching and conduction losses. The combined result is an improvement in roundtrip conversion efficiencies from approximately 60% in the early 1970's to an estimated 85% today. Further improvements in circuitry are projected to push the efficiency into the 90% range by the early 1990's.

ROTOR DESIGN - Early IPACS's employing non-isotropic rotor materials (such as steel or titanium) achieved a deliverable system energy density of approximately 11 WH/KG (including the mass of the rotor, energy conversion, bearings, gimbals, and vacuum housing equipment). The most efficient rotor shape appeared to be the constant stress (or exponential) shape. Subsequent development of the non-isotropic (composite) materials and the composite rotor design studies sponsored by the U.S. Department of Energy (DOE) in the late 1970's and early 1980's produced a legacy of valuable design data. Annular (or hoop) type rotor shapes were found to utilize the non-isotropic properties of composites most advantageously and produce the highest energy densities. An advanced IPACS concept designed in 1984 had an expected deliverable system energy density of 22 WH/KG. This included all mass items chargeable to energy storage and attitude control actuators, and had very conservative derating factors included for a 20 year fatigue life and structural factors for safety. Newer composite materials and less conservative safety factors will now permit the achievement of about 60 WH/KG. It is safe to project that system energy densities of 100 WH/KG will be achievable by the early 1990's.

BEARING/SUSPENSION - Ball bearing systems employing thin-film lubrication have proven to be highly reliable and have modest friction losses. Magnetic suspensions offer the advantages of lower losses, very long life, and improved freedom from vibration disturbances. Laboratory testing of the NASA/LaRC Annular momentum control device (AMCD), and the U. S. Air Force Materials Laboratory (AFML) magnetically suspended reaction wheel have established their feasibility. Subsequent flights of a magnetically suspended scanner, reaction wheels with magnetic bearing on the European Spot spacecraft, and a russian reaction sphere experiment have demonstrated operational feasibility. Large angle magnetic suspensions have been developed which combine the dual functions of a magnetic spin bearing and a rotor gimbal system.

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Technology advances support IPACS

The viewgraph shows an early IPACS design this concept was developed by Rockwell International under contact to NASA. This concept utilized a titanium constant stress rotor, ball bearings, and a permanent magnet motor. This system demonstrated a deliverable system energy density of approximately 11 WH/KG (including the mass of the rotor, energy conversion, bearings, gimbals, and vacuum housing equipment).

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INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) DESIGN CONCEPT EXISTING TECHNOLOGY (1970)

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A novel advanced IPACS system employing a large angle gimbaling magnetic bearing is shown in the viewgraph. This system provides a suspension which serves the dual functions of a magnetic spin bearing and a rotor gimbal system. The concept includes spherically shaped armature and stator surfaces. It permits tilting the rotor through angles up to approximately 20 degrees with only a small penalty in bearing mass (approximately 3 % of the rotating mass). This additional bearing mass to obtain the gimbaling function is quite small when compared to more conventional gimbal ring structures and six axis torquers which have masses approximately equal to the gimbaled mass. For space station type applications, IPACS rotors have an excess of angular momentum and can satisfy the attitude control requirements within this gimbal angle constraint.

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COMBINED ATTITUDE REFERENCE AND ENERGY STORAGE SYSTEM (CARES) MODULE



Viewgraph depicts an artist conception of the system described in the prior viewgraph.

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Some of the advantages of magnetic bearings for spinning rotor applications are summarized in the viewgraph. The suspension is actively controlled in three degrees of translational freedom and two of the rotational degrees of freedom. For this reason, the suspension can also be employed as both a translational and rotational structural vibration damping actuator. The actively controlled magnetic suspension can be used for the compensation of the rotor dynamic resonances. The control schemes provide for gain scheduling as a function of rotor speed so as to minimize rotor deflections and interaction with rotor dynamic resonances.

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MAGNETIC BEARING ADVANTAGES

LOW LOSSES

• FRICTION/POWER LOSSES SMALL RELATIVE TO BALL BEARINGS

ROTOR VIBRATION SUPPRESSION

LOW-BANDWIDTH SUSPENSION ISOLATES ROTOR VIBRATION SOURCES

- ROTOR BALANCE REQUIREMENTS EASED
- ACTIVE SUSPENSION FACILITATES ACTIVE CONTROL OF ROTOR DYNAMIC RESONANCES (SEE FIGURE)

- BEARING NOISE REDUCED

ACTIVE SPACECRAFT STRUCTURAL DAMPING

- FACILITATES VERY WIDE BANDWIDTH CONTROL
- TRANSLATIONAL CONTROL AS WELL AS ROTATIONAL (5 D.O.F. PER ACTUATOR)

PRECISION CONTROL

• FACILITATED BY WIDE BANDWIDTH CAPABILITY & LOW DISTURBANCE FEATURES

Viewgraph shows the effect of magnetic bearing gain scheduling as a function of speed on rotor dynamic performance.

SHAFT DEFLECTION FORCED RESPONSE DUE TO MASS UNBALANCE BEARING FEEDBACK (CONVENTIONAL BEARING) RATIO OF BEARING TO SHAFT FREQUENCY = 0.5

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--- NORMALIZED BY SHAFT FREQUENCY

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Over the last ten years, the government has funded the design and development of a large number of composite flywheel rotors. This research, which received early support from NSF-RAND, has recently been funded almost exclusively by DOE and its predecessor, ERDA. As indicated the viewgraph, this program has resulted in the development and test of ten composite rotor systems.

In addition to the DOE-developed systems, a number of promising composite systems exist that DOE ruled out for consideration based on either high cost or unavailability. These systems include metal matrices, such as boron/aluminum or silicon carbide/aluminum, and more conventional composites, such as boron/epoxy. Usable energy densities of approximately 200 Wh/kg have been demonstrated with advanced graphite rotors.

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DOE Flywheel Developments

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Developer	Design	Materials
Garrett	Multi-material multi-ring rim	S2-G/K-29/K-49; A1 Hub
Garrett	Multi-material multi-ring rim	S2-G/K-29/K-49; Gr Hub
Brobeck	Multimaterial rim with tension balanced spokes	S2-G/K-49 K-29 Spokes AL/K-49 Hub
Rocketdyne	Rim with overwrap and twin-disk hub	Gr, A1 Hub
Hercules	Contoured rim	Gr, A1 Hub
GE	Alpha-ply laminated disk	S2-G, A1 Hub
GE	Alpha-ply laminated disk with rim	S2-G, Gr Rim; A1 Hub
LLNL	Tapered-thickness laminated disk	Gr, A1 Hub
LLNL	Constant-thickness laminated disk	Gr, A1 Hub
AVCO	Radially-circumferentially laminated disk	K-49, A1 Hub

Recently significant new research was conducted at Oak Ridge National Laboratory (Martin Marietta). On October 17, 1985, an experimental energy storage demonstration was conducted in Oak Ridge. A small flywheel rim denoted as Demo 1A was constructed of carbon composites and dynamically tested in a spin test chamber at the Oak Ridge Gaseous Diffusion Plant. One low speed run was conducted to permit trim balancing, and then the unit was accelerated to a speed of 1055 m/s. The construction of this demonstration unit is similar to the planned construction for the outer portion for larger flywheel rims. The success of this early demonstration unit provides a confirmation of the ability to fabricate, assemble, and test thick-walled composite sections.

Both the specific energy (89 Wh/kg) and the total energy (7.687 MJ) of the flywheel (rim and hub) tested exceeds any reported performance of the DOE flywheel development program. Especially impressive is the fact that the rim specific energy of 500 wh/kg is an operational value not an ultimate (at failure) figure.

Since this early test, a number of additional rims have been fabricated and tested. As indicated by these results, failure of the rim occurred at a peripheral velocity of 1405 m/s. At this speed, the rim specific energy was 878 kJ/kg. Based on this failure point, it appears reasonable that an operating speed of 1220 m/s can be used with confidence. At this speed, the rim specific energy is 663 kJ/kg. The performance of these flywheels represents a significant advance over previous rotors.

For comparison nickel nitrogen batteries used in the Hubbel space telescope has a system energy density of less than 20 watt hours per kg at a 50% depth of discharge.

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The viewgraph presents the system mass density of the various candidates, and illustrates the need for trading energy storage candidates on a system level basis. The advantage of IPACS is attributable primarily to it's higher energy conversion efficiency and the elimination of the need for control moment gyros.

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COMPARISON OF SYSTEM MASS (IOC)

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Life-cycle cost data for the three system was also developed and is given in the viewgraph. The data is normalized to the IPACS cost at IOC and presumes that additional equipment is added to the system over the first five years to double its power capacity. The data also includes operational and servicing costs. It can be seen that the IPACS approach results in considerable cost savings, both for initial development and operations.

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Key features of the approach are outlined in the viewgraph.

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PRINCIPAL FEATURES OF IPACS

- PROVIDES ENERGY STORAGE & MOMENTUM TRANSFER (ATTITUDE CONTROL)
- VERY LONG LIFE (MANY CYCLES)
- SUPPORTS HIGH PEAK POWER
- PERFORMANCE
 - HIGH CHARGE/DISCHARGE CYCLE EFFICIENCY: >85%
 - HIGH ENERGY DENSITY: > 22 Wh/kg (CONSERVATIVE)
- EASILY ADAPTED TO LARGE ATTITUDE MANEUVER REQUIREMENTS
- ADAPTABLE TO MANY MISSIONS AND APPLICATIONS---COST/WEIGHT ADVANTAGES FOR MOST OF THEM

Based on the key features of the IPACS design some general guidelines for the applicability of the concept to various space missions have been derived and are summarized in the viewgraph. Missions include a Space Station, various low earth orbital spacecraft, and a geosynchronous orbit spacecraft (Tracking and data relay satellite). The IPACS was found to be quite viable for all these applications.

More recently, greater emphasis has been placed on the rapid attitude slewing maneuvers required by some surveillance spacecraft and the Strategic Defense Initiative (SDI) applications. In some of these applications, not only is a great deal of transferable momentum needed, but the kinetic energy of the slewing body is also quite large. The energy transfer required is so large that it imposes very large peaking torquing power requirements (many horsepower). The IPACS capability to store and deliver high peak power, and regeneratively brake rapid slewing maneuvers, is ideally suited to these applications.

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IPACS MISSION APPLICABILITY

MOST APPROPRIATE FOR MISSIONS/APPLICATIONS REQUIRING:

- BOTH ENERGY STORAGE & MOMENTUM TRANSFER ATTITUDE CONTROL
- MODERATE TO LARGE CONTROL REQUIREMENTS (SUCH AS RAPID SLEWING MANEUVERS, OR MOMENTUM STORAGE REQUIREMENTS)

• HIGH CHARGE/DISCHARGE CYCLE LIFE

OR

MISSIONS THAT MIGHT OTHERWISE EMPLOY PHOTOVOTAIC/ BATTERY SYSTEMS & MOMENTUM TRANSFER EQUIPMENT

The IPACS concept is found to be attractive for many space missions and offers savings in performance, system mass, and cost. In addition to the more traditional applications, it is emerging as a high-performance slewing actuator candidate for surveillance and SDI missions, which require large peak slewing power transfer as well as momentum transfer.

The fundamental IPACS technologies int he three basic areas of rotor design, energy conversion, and magnetic bearings are now mature and will support the development of advanced IPACS applications. It remains to integrate these three fundamental technologies into flight type units and validate their performance int he laboratory. It is recommended that such a technology program be implemented to support future applications.

CONCLUSIONS AND RECOMMENDATIONS

- IPACS CONCEPT FEATURES ATTRACTIVE FOR MANY SPACE MISSIONS/APPROACHES
- TECHNOLOGY ADVANCES IN 3 BASIC AREAS NOW MATURE
 - COMPOSITE ROTORS
 - MAGNETIC BEARINGS
 - MOTOR/GENERATORS
- WILL SUPPORT ADVANCED IPACS DEVELOPMENT
- OFFERS PERFORMANCE ADVANTAGES, AND SAVINGS IN COST AND MASS
- RECOMMEND IPACS TECHNOLOGY DEVELOPMENT

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FUEL CELL ENERGY STORAGE FOR SPACE STATION ENHANCEMENT

to -

Technology for Space Station Evolution Workshop

> January 1990 J.K. Stedman (203)727-2211



P.O. Box 739 195 Governors Highway South Windsor, Connecticut 06074



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THE CONCEPT

- PV/Battery and Solar Dynamic are baseload power systems
- Space station will have load factor less than one (shuttle ~ 0.8)





ORBITER FUEL CELL POWERPLANT



Characteristics

Power_____ 12 kW (21 kW max)

Weight_____ 260 lb

Durability____ 2000 hour TBO

Status

 Satisfies present mission requirements

ORBITER ENHANCEMENTS REQUIRE ADDITIONAL FCP CAPABILITIES

EDO

- Extended durability
- Enhanced safety
- Improved reliability
- Reduced reactant consumption
- Simplified monitoring/checkout

EMA/EAPU

- EDO goals
 - plus
- Increased power
- Reduced weight
TECHNOLOGY ADVANCES SUPPORT ORBITER ENHANCEMENT



- Improved materials

EMA PRELIMINARY REQUIREMENTS

	Orbiter/EDO	EMA Goal
Power output (rated/peak)	12 kW/15 kW	12 kW/60 kW
Voltage	28 Vdc	28/270V dc/ac
Weight	262 lb	262 lb
Transparency	Physe intercharter	ically> angable

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PEM TECH BASE PROGRESS



UNUSED ENERGY ESTIMATE

80% Load Factor

	Daily		
Station capacity	energy capacity	Unused enerav	
kW	kWh	kWh	
37.5	900	180	
75	1800	360	
300	7200	1440	

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STATION ENERGY STORAGE

• Unique RFCS capability provides discriminator

• Inter vs intra orbit energy storage

• Capability enhances

- User load requirements
- Margin for undefinable needs
- Contingency
- Survival
- Construction
- Unknowns

FUEL CELL SYSTEM MODULARITY



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IOC STATION PEAK POWER CAPABILITY

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75 kW Nominal Capicity



ENERGY STORAGE SYSTEM DEVELOPMENT

- Enhanced Orbiter fuel cell powerplant being developed
- Electrolysis unit for enhanced space station planned

• Combine for regenerative fuel cell system







SUMMARY

- Regen fuel cell can enhance space station
 - Peaking
 - Emergency
- Same technology for Lunar/Mars exploration program
- Technology and engineering programs required to achieve potential

SSM/PMAD

Automation of Space Station Module Power Management and Distribution System

Prepared by Robert Bechtel, Dave Weeks and Bryan Walls

for the

Technology for Space Station Evolution Workshop

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This vugraph describes the primary reasons for needing automation of the electrical power system within the habitation and laboratory modules of Space Station Freedom. As the systems become more complex and are required to distribute power to a larger number of loads, these factors will become increasingly more important. Future needs in the automation area will necessitate the development of advanced techniques both in terms of software and hardware.

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Circuit breakers are very effective at quickly safing a power system. They represent the only technology available which can react in time and also be remotely controlled and monitored. Though conceivably a very fast computer could read sensors, recognize high current, and order a switch open before damage could occur, it is unlikely with today's technology, less reliable than circuit breakers, and offers no advantage over a remotely switchable circuit breaker.

Knowledge of the actual state of a system is necessary for effective control. Determining sensor locations and designing them into the system, instead of adding them on later, reduces the cost and increasing the reliability of the system as a whole.

A problem with numerous sensors is the flood of data they produce. What does one do with it? The answer proposed here is to sort it out locally, and only pass up summaries unless more is needed. Often "situation nominal" is much more relevant than a stream of data, no matter how accurate.

The central controllers act as an interface for human users, put system in an acceptable state if a problem occurs, assist users in identifying and correcting problems, record and allow modification of the system configuration, and provide the lowest level processors the data they need for normal operation.

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The Space Station Module Power Management and Distribution (SSM/PMAD) test bed has been established at MSFC through the space station advanced development funding starting in 1985. Subsequent automation upgrades and improvements have been realized through space station evolutionary funding and OAST participation. The test bed is currently supporting advanced automation activities as well as prime space station development testing.

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The topology of the SSM/PMAD is the same as for the present space station baseline design. The primary power distribution assembly (PDCU) redistributes 120 VDC power to each of up to six rack load center locations through 3kw remote power controllers (RPC). The power is then fed to the loads through 1 or 3 kw RPCs within the rack. Each rack load center and PDCU is controlled by a dedicated lowest level processor (LLP). The overall test bed control is done by the Symbolics 3620 D and the Unix workstations. The space station module topology identifies the PDCU as a secondary power distribution assembly and the rack load center as a tertiary power distribution assembly, but the functions these elements perform are identical. The control architecture of the test bed is similar to that baseline for the space station. This similarities will be discussed later.

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As part of the automation development approach to the SSM/PMAD, a function partitioning of the module PMAD was conducted. This was conducted in four steps: (1) list and define potential types of controlling entities for functions; (2) develop rules and guidelines to partition functions; (3) define PMAD to sufficient level of functional detail to allow partitioning of single contolling entity to each function; and (4) partition controlling entities/definitions of (1) to each function defined in (3) using rules and guidelines of step (2).

Controlling entities are hardware (settable but not programmable in the usual sense), algorithmic software (conventional software), expert system (incorporating knowledge, experience, and problem solving approach of human experts), crew partition (controlled by onboard and/or ground support personnel), and expert-aided crew (same as crew except the person(s) are aided by expert system or by outside expert person).

The partitioning rules pertain to function types categorized as simple (well understood functions/processes such as simple mathematics/logic with predictable inputs and outputs), complex (technically understood functions using knowledge from accepted text books/procedures, but requiring advanced scientific skills or training to implement), and expert (functions usually understood only by recognized experts and requiring their knowledge and judgment to implement).

Definition of the SSM/PMAD task was accomplished by mapping a functional breakdown of the PMAD task. Power Management & Distribution was broken down into power conditioning, power distribution, and power network control. Each of these in turn was broken down into three or four divisions. The power network control divisions were broken down into two deeper layers.

The Power Network Control functions, provisionally assumed to require software development were then evaluated. Determination of which subfunctions could be controlled entirely by a single type of controlling entity were followed by an estimation of the necessary capability or complexity of each subfunction. This was followed by first order estimates of the difficulty of developing the software necessary to control the subfunctions.

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Finally, the actual partitioning of the entire SSM/PMAD task was performed. Tables were developed to follow the functional breakdown partitioning rules and software development estimates.

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This viewgraph shows the control logic flow of the SSM/PMAD. Control operations which must be performed as quickly as possible to prevent damage to the power system (immediate) are done in the hardware, ie:various abnormal operating modes as discussed in the following RPC description. Functions requiring response times in the seconds or tens of seconds, or which are not time critical can be performed at appropriately higher levels. However, it is still desirable to perform power system control at as low a level as possible to minimize dependency on global type communication networks.

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Rack Level Autonomy -- Switches, Sensors, LLPs, and CAC

The RPCs designed for this breadboard actually consist of two parts: a power stage, which is a switch with resetable over-current protection and a current sensor, and a Generic Card (GC). The GC uses a state machine to offer protection against various abnormal conditions, and to communicate with the Switch Interface Card (SIC) and the power stage. Individual sensors are attached to an A-to-D converter which is also attached to the SIC. Each Lowest Level Processor (LLP) communicates with up to two SICs in a Load Center -- one for each bus.

The LLP turns RPCs on or off according to a schedule downloaded to it. It also monitors all the sensors and RPCs. If an RPC trips, the LLP notifies FRAMES of the kind of trip as part of a full status update. The LLP performs in the same way if an RPC is using more power than it is scheduled for, even if the level wouldn't trip the RPC. The LLP orders that RPC off and reports the fault. If the schedule marks an RPC as redundant, the LLP will attempt to turn on a load's redundant RPC if the primary one trips or is shed. Finally, the LLP stores a priority list for it's loads so, in the event of a reduction in system power, lower priority loads will be shed first.

The Communications and Algorithmic Controller (CAC) acts as the communications interface between the LLPs and the higher level controllers. It is the central control point in manual mode operation.

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Testing in the SSM/PMAD has shown that current limiting capability at the load center level can in fact help in preventing the propagation of faults to other loads within the rack or to the distribution bus. Including protection against as many abnormal operational circumstances as possible can facilitate isolation of faults and hence increase power system reliability for other loads. Pre-reduction of data at the switch level can alleviate processor communication delays. A "smart", current limiting RPC with the characteristics shown on the vugraph and capable of protecting against several fault modes has been developed for the SSM/PMAD. A similar version was also developed for use in the 20khz version of the SSM/PMAD.

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SSM/PMAD

SPACE STATION MODULE EPS TEST BED 120VDC REMOTE POWER CONTROLLER (RPC) CHARACTERISTICS

1 AND 3 kW (8.3 and 25 Amp) RATINGS

IRFP 351 MOSFETS

REMOTE COMMAND ON/OFF/RESET

• CURRENT MEASUREMENT

- di/dt LIMITED BY 1μh
- ACTIVE CURRENT LIMITING @ 175% RATED CURRENT
- TRIPS ON:
 - O CURRENT INSTANTANEOUSLY > 400% RATED CURRENT O CURRENT LIMITING > 15msec O I^{2} t > LIMIT O UNDERVOLTAGE O OVERTEMPERATURE



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Fault Recovery and Management Expert System (FRAMES)

FRAMES is one of the three AI systems in the SSM/PMAD breadboard. Each LLP notifies FRAMES any time it recognizes an anomaly, such as tripped breakers or shed loads. Messages giving sensor readings are also sent to FRAMES. FRAMES uses the information which comes to it to characterize the system state. If a failure is diagnosed, it notifies the user via its user interface, and sends a message to Maestro, the system scheduler. Components are marked failed. if it is believed they are broken, or out-of-service if they are not usable (eg. a circuit-breaker above is failed). This information is passed on to Maestro for use in rescheduling.

The FRAMES user interface shows the whole system state. Every switch and sensor in the system is displayed, and shows whether or not it is powered, failed, or out-of-service. Switches also show whether they are opened, closed, or tripped. Components are mousable for further information, including sensor values and values of various flags.

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SSM/PMAD

FRAMES

Monitors breadboard, reporting anomalies to user and to Maestro.

- Evaluates anomalies to determine if failure has occurred, and diagnoses failure based on reported symptoms.
- Notifies user and other expert systems of conclusions, including any switches considered out of service.
- User interface allows examination of breadboard sensor reading and switch statuses.
- Uses rules developed through work with Power Engineers.
- Coordinate system-wide activity through intelligent controllers.

TYPICAL FRAMES SCREEN

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Maestro

Maestro is a resource scheduler which can schedule numerous activities using multiple constraints. In the SSM/PMAD breadboard the constraints currently used include number of crew members required, equipment resources, and power resources. Power is allocated not just by how much is available to the whole system, but also by the ability of intervening components to supply the power.

Maestro's interface converts the schedule into a list at the component level. Information includes start and stop times and upper and lower power levels at each component.

Dynamic rescheduling may be done in the event of a fault. Maestro has access to Activity, Schedule, and Equipment Libraries, and uses encoded knowledge gained from expert schedulers to schedule within constraints.

Load Priority List Management System (LPLMS)

The third of the AI systems, the Load Priority List Maintenance System (LPLMS) uses information from the event list and the activity library, along with its own rules, to dynamically assign relative priority to each active load in the system. A new list is sent down to the LLPs at least every 15 minutes (less than 15 if a contingency occurs). The load priority list can be used to shed loads in case of a reduction in power.

SSM/PMAD

Planning/Scheduling

MAESTRO

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- Schedules all SSM/PMAD load for crew period (and longer) based on need/availability of resources
- Resources include available power, distribution system capacity, crew members needed, equipment, etc.
- Enables operation during contingencies until new baseline schedule is generated
- Tracks and accommodates PMAD configuration changes
- Reduced response times for reconfiguration after faults

Loads Priority List Management System (LPLMS)

- Handles dynamic priorities of up to 500 loads
- Generates global load shedding list every 15 minutes



Typical MAESTRO Screen Showing Equipment Editor

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MISSION TIME [90:90:17]	ST-TH FRUT F N4 Neine	
PROTEIN CRYFFAL		
I TITOA POLIDIAICY LION		
CONTAINERLESS PROCESSING		
CONTINUOUS FLOW ELECTROPHON	1518 J	
ELECTROLPITAXY		
		t
14.46.88 88.11.89	80,02,08 80,01,08 80,04,88 80,05,88	84:04:05 80:07:08 00:00:46
•Refresh •Screens Remove Re	trieve Save Extend Query Requests Reset S	Schedule
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Typical MAESTRO Screen

Showing Schedule


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This chart compares the control of the SSM/PMAD (as described previously) with the Space Station Freedom baseline. The basic levels of control are essentially the same for the SSM/PMAD and Space Station Freedom baseline. One major goal of the advanced automation task is to transfer FDIR (fault detection, isolation, and recovery) to a module level controller thereby eliminating need for significant involvement of crew and/or ground personnel. In addition, control, contingency, and reconfigurations functions are migrated to lower levels as part of the advanced automation tasks. Advanced automation will also permit a much larger portion of scheduling the onboard short term plan (OSTP) to actually be done onboard. The cost of these advances is increased processing capability. At present, the Space Station Freedom lab module baseline provides only 15 controller MDMs to control approximately 29 active rack locations (although this number will be increased to one controller MDM in each rack at assembly complete).

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Planned Modifications to SSM/PMAD

By the middle of 1990, some fairly major changes to the automation portion of the SSM/PMAD should be in place. These include a new unix-based computer to host both the FRAMES and CAC functions, 80386 computers with Ethernet to replace the current LLP processors, and some major changes in the structure of FRAMES, with it rehosted in a powerful Knowledge Base Management System environment. The user interface will be significantly upgraded, also.

Under OAST funding, research is under way in how to improve cooperation among the three expert systems, and in adding intermediate modes of autonomy. In the current system, the user has the choice of autonomous operation, or of taking over the whole system. The intermediate modes will provide choices between these two extremes, so a user can have the help of an intelligent assistant.

As the system matures and stabilizes, portions will be transferred into the Ada language, running on general purpose processors. Stricter validation and verification will be observed than is desirable in the present prototypical phase. At the close of this phase, the system should be mature enough to be moved into the mainstream of the Space Station Freedom Program.

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Proposed MSFC/LeRC Communications

A communications link is now available between MSFC's AMPSLAB facility, which includes the SSM/PMAD breadboard, and the Lewis Research Center Power Technology Division laboratory, with their Autonomous Power Expert System (APEX). Two virtual links are envisioned between the two PMAD systems.

The first link will involve the schedulers for the two systems. Initially interaction will be limited to a request for some level of power from SSM/PMAD for each of the two power buses. APEX would then assign levels, possibly different from those requested, for the buses. As the systems mature, the negotiation will become more sophisticated; SSM/PMAD will provide justification for its request, and APEX will be expected to compare SSM/PMAD's request with those from it's other loads to provide an overall "fair" schedule according to balanced priorities.

The second proposed link will be between one of the loads on the APEX brassboard and one of the dc sources on the SSM/PMAD system. The power drawn by the load will be varied to reflect the power being used in the SSM/PMAD breadboard, thus emulating a single end-to-end power system.

The actual communications link between the centers is via TCP/IP using the PSCN-I service. Both virtual links will be built on this connection, though the second connection may initially be done manually, with communication by telephone.

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SSM/PMAD Overview

MSFC/LeRC Communications

- A virtual link between the intelligent controllers allows negotiation for power resources.
- A second virtual link between one of the LeRC load and a MSFC source allows emulation of a single breadboard.
- Each breadboard can still be operated independently.
- The actual communications link is available using TCP/IP on the PSCN-I.

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The primary technology drivers which need to be addressed to allow progress towards full automation of the module electrical power system are summarized.

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Future Technology Needs for Power System Automation

- Develop cooperating expert systems
- Automation techniques for:
 - Larger, more complex systems
 - Handle Incipient Failures
 - Perform FDIR for multiple, independent failures
- Improve user-oriented explanation/ interface facilities
- **Refinement of Algorithms & Rules**
- Improved Sensors/Switches:
 - Accuracy/Reliability
 - Data Reductrion
 - Fault Analysis
- Increase DMS capability:
 - Reduce Power
 - Permit More Processing Capability
 - Reduce Latency

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Propulsion System Level III Subsystem Presentation

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SPACE STATION	PROPULSION AND POWER	
PROPULSION SYSTEM	J. HENDERSON	01/16/90



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SPACE STATION PROPULSION SYSTEM REQUIREMENTS

There are several requirements that the Space Station Propulsion System has to meet. The Propulsion System for the Station is no different from most other propulsion systems in that it is required to provide thrust for attitude control torques and translation maneuvers. Since primary attitude control is done via Control Moment Gyro's (CMG's), the Propulsion System will only be used for damping disturbances which exceed the CMG's capability, for desaturation of the CMG's and for CMG back-up. The translation requirements are for compensation of atmospheric drag (reboost), orbit altitude adjustment which might be necessary, and collision avoidance. By far the biggest approximately 2.8 million lbf-sec of impulse per year, which represents over 95% of the propellant required.

Other propulsion requirements are to utilize waste fluids to produce useful impulse and to maintain sufficient propellant reserves, such that if a resupply is missed, the Station can still perform nominal operations.

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	SPACE STATION	PROPULSION AND POWE	PROPULSION AND POWER	
NASA DESIGN + DEVELOPMENT + TEST	PROPULSION SYSTEM	J. HENDERSON	01/16/90	

0 SPACE STATION PROPULSION SYSTEM REQUIREMENTS

O PROVIDE THRUST FOR:

O ATTITUDE CONTROL

- O LARGE DISTURBANCE DAMPING
- O CMG DESATURATION
- O CMG BACK-UP

0 TRANSLATION

- O ATMOSPHERIC DRAG MAKE-UP (REBOOST)
- O ORBIT ALTITUDE ADJUSTMENTS
- O COLLISION AVOIDANCE

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O UTILIZE WASTE FLUIDS TO PRODUCE USEFUL REBOOST IMPULSE

O MAINTAIN SUFFICIENT PROPELLANT RESERVES IN THE EVENT OF A MISSED RESUPPLY

SPACE STATION PROPULSION CONFIGURATION

The Propulsion System modules are located above and below the transverse boom at each end. At each location, there are two module interfaces, such that two modules can be sitting side by side. This is done so that one of the modules can be completely depleted prior to being removed from the Station, and the remaining module can be activated, so that there is no loss of propulsion capability.

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SPACE STATION MODULAR HYDRAZINE PROPULSION SYSTEM



FRONT VIEW

SPACE STATION PROPULSION SYSTEM DESIGN

During the "Scrub '89" exercise, the Space Station Propulsion System design was changed from a Water Electrolysis/Oxygen-Hydrogen system to a modular hydrazine system. The change was made to reduce the risk to the program and to reduce the up-front development costs. A blowdown hydrazine system was baselined because of the simplicity of the system and the maturity of the system hardware. Hundreds of satellites have been constructed and flown with blowdown hydrazine systems. GN&C is concerned about the variation of thrust between modules and the complexity of the software to control and target the Station.

The Propulsion System concept is as follows: At each end of the transverse beem are two propulsion locations, one each above and below the beem. At each of the propulsion locations, there are two module interfaces, such that two modules can be collocated next to each other. When one of the modules is depleted of propellant, it is returned to the ground and the adjacent module is utilized. The modules are propulsion systems, containing everything that is required to produce thrust: propellant tanks, isolation valves, thrusters, heaters, instrumentation and avionics. The only interface with the truss is which can be mated on-orbit. In this way concerns over propellant spillage and leakage is minimized. All maintenance on the system is done only on the ground. Because of the Station Critical requirement for performing reboost, each module is dual fault tolerant.

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SPACE STATION	PROPULSION AND POWER	
PROPULSION SYSTEM	J. HENDERSON	01/16/90

O SPACE STATION PROPULSION SYSTEM DESIGN

- 0 BLOWDOWN HYDRAZINE SYSTEM
 - O CHOSEN FOR SIMPLICITY AND MATURITY OF HARDWARE, DEVELOPMENT COST AND SCHEDULE, AND POWER CONSUMPTION
 - O IMPACTS TO GN&C BEING EVALUATED
- 0 MODULAR SYSTEM
 - **O PROPELLANT RESUPPLY VIA MODULE REPLACEMENT**
 - **O** NO FLUID CONNECTIONS BETWEEN MODULES
 - O STRUCTURAL, POWER AND DATA INTERFACES ONLY
- O EACH MODULE DUAL FAULT TOLERANT FOR PERFORMING REBOOST

PRELIMINARY PROPULSION MODULE CONFIGURATION

The Propulsion Module consists of all of the hardware required to meet the Station requirements: propellant tanks, isolation valves, attitude control thrusters, reboost thrusters, avionics, thermal control, etc. It is designed to fit in the Orbiter Payload Bay.

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The Propulsion System design is driven by many external factors. Here is a short list of the most important parameters:

1) The Space Station is not going to be maintained at a fixed altitude, but rather will be allowed to vary in altitude such that the Orbiter Logistics can be optimized, while maintaining adequate Station Orbit life-time. This orbit altitude is a function of Station Configuration (Mass and Frontal area) and also the atmospheric density, which varies with the eleven year solar cycle. Because of these considerations, the Propulsion System impulse requirement is a function of the Orbiter capability, overall Station configuration and the atmospheric density.

2) The Propulsion System thrusters were sized to 25 lbf each back when the Station was staying at 270 nmi constant altitude, which meant that the reboost impulse was much less than it is today. When the altitude strategy was changed to the variable altitude strategy, the burn times for performing reboosts increased significantly. An average reboost with four 25 lbf thrusters takes about 2 hours to perform. The maximum reboost takes over four hours to perform. With a modular blowdown hydrazine system, thrusters are not available 'off-the-shelf' for these burn times, and the reboosts will only be done with two of the modules for propellant utilization purposes. This means that the thrust size for the reboost thrusters should be increased. There are structural concerns which are being worked. The attitude control thrusters would remain at 25 lbf.

3) Because the Station is operating lower in the atmosphere, the Propulsion System is required to keep the Station from re-entering. At times, the margin against re-entry is as little as 90 days. This means that the Propulsion System must be dual fault tolerant for station survival (i.e. reboost).

4) The requirement for propellant resupply introduces a set of requirements on the Propulsion System. The first is to optimize the package in the payload bay, both the mass and the volume. Since the capability of the Orbiter is fixed, the challenge is to design the module such that the most propellant is brought up in the lightest and smallest package. Since there will be other items being brought up to the Station at the same time as the Propulsion system is being resupplied, compatibility with those other elements (unpressurized logistics module, pressurized logistics module, etc.) is a design driver. Finally, since the modules will be flying routinely in the Orbiter Payload Bay, the safety requirements that are imposed on any other payload must be met by the Propulsion Modules.



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O SPACE STATION PROPULSION SYSTEM DRIVERS

- 0 ALTITUDE STRATEGY
 - O ORBITER CAPABILITIES
 - **0** SPACE STATION CONFIGURATION
 - O ATMOSPHERIC DENSITY (SOLAR ACTIVITY)
- 0 THRUST SIZE

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- **O STRUCTURAL CONCERNS**
- **0** TOTAL BURN TIME FOR REBOOST
- **O REDUNDANCY REQUIREMENTS**
 - **O** CREW SAFETY
 - **O** STATION ORBIT DECAY ALTITUDE STRATEGY
- 0 RESUPPLY
 - 0 MASS FRACTION
 - **0** MANIFESTING CONCERNS
 - 0 PAYLOAD BAY SAFETY

HYDRAZINE TECHNOLOGY DEVELOPMENT

In order to minimize the number of thrusters required for each module, the capability of being able to deplete the entire module through a single reboost thruster is desirable. The current demonstrated through-put of hydrazine thrusters in the 100 lbf range is approximately 1 Million lb-secs (4300 lbm of propellant). If the modules contain 4500 lbm of hydrazine, then every time a module is reserviced, a thruster would have to be replaced. If the modules are bigger than this, then there would have to be additional thrusters or the life of the thrusters must be improved.

Because of the costs associated with installing additional thrusters, extending the life of hydrazine thrusters is being pursued. A supporting development program is progressing to modify existing designs and demonstrate additional thruster lifetime, with the goal of at least doubling the life of the thrusters. An RFP will be distributed soon with delivery of thrusters expected in the fall of 1990. These will then be tested at our test facility at JSC.

Other technology development programs may be necessary, depending on the final propulsion system configuration. Configurations which are being examined include systems with metering valves to provide a constant inlet pressure to the thruster from a blowdown system, a system with a pump and accumulator to provide a constant inlet pressure to the thrusters, or an electronic regulator for providing constant tank pressure. These configurations may be required due to concerns by GN&C over the potential thrust mismatch between propulsion modules.

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 SPACE STATION
 PROPULSION AND POWER

 PROPULSION SYSTEM
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- O HYDRAZINE TECHNOLOGY DEVELOPMENT
 - 0 LONG LIFE HYDRAZINE THRUSTER
 - O CURRENT TECHNOLOGY THRUSTERS ONLY DEMONSTRATED TO APPROXIMATELY 1 MILLION LB-SEC
 - O SUPPORTING DEVELOPMENT PROGRAM PLANNED TO INCORPORATE INTO EXISTING DESIGNS FEATURES TO EXTEND THE LIFE
 - O SPECIFYING A MINIMUM LIFE OF 2 MILLION LB-SEC
 - O CONTRACTS EXPECTED BY MAY

- O TESTING TO BE CONDUCTED AT JSC NEXT YEAR
- O OTHER TECHNOLOGY DEVELOPMENT MAY BE NECESSARY, DEPENDING ON RESULTS OF ON-GOING TRADE STUDIES
 - O METERING VALVE TO PROVIDE CONSTANT THRUST FROM A BLOWDOWN SYSTEM
 - O PUMP FOR MAINTAINING CONSTANT THRUSTER INLET PRESSURE
 - 0 ELECTRONIC PRESSURE REGULATION

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WASTE FLUID DISPOSAL SYSTEM

The Waste Fluid Disposal System was the resistojet. However, during Scrub '89, the power requirements for the resistojet were questioned. With this in mind, a trade study was initiated at the WP-02 contractor to determine the 'best' method of waste fluid disposal. The options are as follows:

1) Resistojet: Much advanced development has occurred on the resistojet, including work by in the late 60's-early 70's by Marquardt and much more recent work by LeRC. The problem with the resistojet is that, depending on the flowrate and the temperature desired, up to 500 W are consumed per resistojet. With all six resistojets firing, the resistojet module would be consuming 3 KW of power, approximately 4% of the entire Station generating capability.

2) Waste gas disposal using Hydrazine thrusters: Work was done on this concept by Rocket Research during Phase B. The concept was demonstrated, however, additional work needs to be done to characterize the performance of the thruster when an oxidizing gas is introduced to the combustion chamber. It also has the disadvantage in that a consumable which must be resupplied from the ground is consumed to heat the waste gases.

3) Thermal Energy Storage: This concept involves slowly heating a phase change material using low power heaters, and then passing the waste fluids through a heat exchanger to heat the gases. This concept would not have the instantaneous power consumption of the resistojets, but would probably consume more energy (low power for long periods of time) due to thermal losses. This concept also does not have a consumable which must be resupplied.

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The MDSSC trade study is expected to be completed in mid-February, 1990.

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	SPACE STATION	PROPULSION AND POWER	
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DENGH + DEVELOPMENT + TEST			

- O WASTE FLUID DISPOSAL SYSTEM
 - O MDSSC CURRENTLY EVALUATING THE BEST METHOD OF WASTE FLUID DISPOSAL

O RESISTOJETS

- O ADVANCED DEVELOPMENT WORK
- O HIGH POWER REQUIRED DURING OPERATION

O WASTE GAS INJECTION INTO HYDRAZINE THRUSTERS

- O ADVANCED DEVELOPMENT WORK
- O OXIDIZING GASES WERE NOT EVALUATED
- O CONSUMABLE REQUIRED

O THERMAL ENERGY STORAGE

- O SIMILAR TO SOLAR DYNAMIC ENERGY STORAGE
- O LOW POWER REQUIRED
- O NO CONSUMABLE

O TRADE STUDY TO BE COMPLETED BY MID FEBRUARY, 1990

INTEGRATED SCHEDULE - PROPULSION SYSTEM

The Propulsion System Integrated Schedule shows the classical DDT&E approach to flight hardware: Preliminary Design, Detailed Design, Development Testing, Final Design, and Qualification Testing. Due to cost reasons, the Propulsion System Development and Qualification Testing will be done at the NASA-JSC White Sands Test Facility (WSTF).

The Supporting Development Schedule reflects the remaining work from the Water Electrolysis/Oxygen-Hydrogen System, the preparation of the WSTF facility for Development and Qualification testing, and the Long Life Hydrazine thruster effort.

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SPACE STATION PROPULSION SYSTEM EVOLUTION

The choice of hydrazine for the long term Station means that the program will be paying a large life cycle cost for propellant resupply because of hydrazine's low specific impulse. Because of this, the WP-02 contractor has been tasked with performing a trade study to determine what Propulsion System should be used for the long term. Options include the present modular hydrazine system, a distributed hydrazine system, several bipropellant systems, and the old baseline, a distributed Water Electrolysis/Oxygen-Hydrogen system. All of the propellant combinations for the bipropellant system utilize Nitrogen Tetroxide (NTO) as the oxidizer. The fuels being considered are Monomethyl Hydrazine (MMH), Hydrazine, and a blend of 50% Unsymetrical Di-Methyl Hydrazine (UDMH) and 50% hydrazine called A-50.

In addition to these propellant combinations, combinations of systems were included for study. Since the program is developing the modular hydrazine system, this system could be used for attitude control and contingency purposes, and a dedicated, high performance reboost system could be used for atmospheric drag compensation.

The trade study is expected to be completed by the end of January, 1990.

 SPACE STATION
 PROPULSION AND POWER

 PROPULSION SYSTEM
 J. HENDERSON

 01/16/90

0 SPACE STATION PROPULSION SYSTEM EVOLUTION

- O HYDRAZINE MAY NOT BE THE BEST PROPELLANT CHOICE FOR THE LONG TERM SPACE STATION
 - O SPECIFIC IMPULSE OF APPROX. 235 LBF-SEC/LBM
 - O LIFE CYCLE COST OF PROPELLANT RESUPPLY OF HYDRAZINE IS SIGNIFICANT

- O TRADE STUDY IN WORK BY THE WP-02 CONTRACTOR TO DEFINE 'BEST' CHOICE FOR LONG TERM SPACE STATION
 - 0 MODULAR HYDRAZINE
 - O DISTRIBUTED HYDRAZINE
 - O DISTRIBUTED BI-PROPELLANT
 - O DISTRIBUTED WATER ELECTROLYSIS/OXYGEN-HYDROGEN SYSTEM
 - O COMBINATION MODULAR HYDRAZINE/BIPROPELLANT
 - O COMBINATION MODULAR HYDRAZINE/ELECTROLYSIS
- O TRADE STUDY TO BE COMPLETE BY END OF JANUARY, 1990

PROPELLANT SELECTION TRADE STUDY

These are the criteria which are being used for the propellant selection trade study, both qualitative and quantitative evaluations. When these evaluations are completed, the results will be presented to Level III and Level II so that any technology development that may be required can be funded.

	SPACE STATION	PROPULSION AND POWER	
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- **O PROPELLANT SELECTION TRADE STUDY**
 - **O QUANTITATIVE EVALUATION CRITERIA**
 - 0 DDT&E COSTS
 - 0 LAUNCH COSTS
 - **O RESUPPLY COSTS**
 - **O MAINTENANCE COSTS**
 - O GROUND HANDLING COSTS
 - 0 POWER
 - O QUALITATIVE EVALUATION CRITERIA
 - O GROUND HANDLING
 - O GN&C
 - O MATERIALS AND PROCESSING
 - **O RELIABILITY**
 - **0** LOGISTICS
 - **0** TEST AND VERIFICATION
 - 0 EVA
 - O CONTAMINATION
 - 0 MAINTAINABILITY
 - 0 SAFETY
 - **O** SYSTEM INTEGRATION

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TECHNOLOGY NEEDS FOR WATER ELECTROLYSIS/OXYGEN - HYDROGEN SYSTEM

Several items were identified by the WP-02 contractor in their proposal as requiring additional development. These items include: the electrolysis unit and electrolysis unit components, the high pressure/light weight storage tanks, and the electronic regulators.

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- O TECHNOLOGY NEEDS TO WATER ELECTROLYSIS/OXYGEN-HYDROGEN PROPULSION SYSTEM
 - **O HIGH PRESSURE ELECTROLYSIS UNITS**
 - O STACK
 - 0 COMPONENTS
 - 0 REGULATORS
 - **O PHASE SEPARATORS**
 - 0 VALVES
 - **O** THRUSTERS
 - **0** HIGH PEESSURE/LIGHT WEIGHT STORAGE VESSELS
 - **O** ELECTRONIC PRESSURE REGULATION
 - **O** SYSTEM LEVEL TESTING

02/H2 TECHNOLOGY PLAN

This is a suggested technology plan that would be pursued if the Water Electrolysis/Oxygen — Hydrogen system is selected by the WP-02 contractor as the system of choice for the long term Station. This schedule includes electrolysis unit development, electrolysis component development, electronic regulator development, thruster testing and improvements, Graphite/Epoxy tank testing, and finally System level breadboard testing.

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O2 / H2 PROPULSION TECHNOLOGY PLAN



TECHNOLOGY NEEDS FOR BIPROPELLANT SYSTEMS

Even though bipropellant systems are "state of the art", additional development for on-orbit servicing of the system is required. Obviously, if the systems are going to be serviced on-orbit, the first component that needs to be developed is the automatic couplings for the transfer of hazardous fluids. Other technologies that require development are the capability to vent off the pressurant gas from the system (if the system is a pressure regulated system) without expelling liquid propellant. This could be accomplished by new zero-g liquid separation techniques or by the development of Oxidizer compatible diaphragms. Also, to make the refueling system as light at possible, transfer pumps could be developed..

The hydrazine/NTO system is attractive from the lack of carbon and carbon compounds in the thruster exhaust. If this is the system chosen, then considerable work still needs to be done on thrusters using this propellant combination.

One of the problems with NTO is the formation of iron nitrate. This problem can be eliminated by constructing the system only of titanium. One of the problems is that there are no titanium bellows for valves. This means that components being constructed using titanium contain bimetallic joints where materials containing iron are utilized. The development of titanium bellows is required for building a true all titanium system.

Finally, leakage of regulators over long periods of time has historically been a problem with space craft. This is why most systems flown are blowdown systems. In order to utilize a pressure regulated system for the bipropellants, regulator designs which can better handle contaminates and reaction products from the propellants need to be developed. The area of electronic pressure regulators means that high response and high seal loading can both be attained.

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- **O** TECHNOLOGY NEEDS FOR BIPROPELLANT SYSTEMS
 - O IF ON-ORBIT PROPULSION SYSTEMS SERVICING REQUIRED:
 - **O** FLUID TRANSFER COUPLINGS
 - **O OXIDIZER DIAPHRAGMS**
 - O ZERO-G VENT CAPABILITY (LIQUID/VAPOR SEPARATION)
 - O TRANSFER PUMPS (POTENTIAL)

O HYDRAZINE/NTO THRUSTERS IF THAT PROPELLANT COMBINATION SELECTED

O ALL-TITANIUM OXIDIZER SYSTEMS

O. TITANIUM BELLOWS

O ZERO-LEAK REGULATORS IF PRESSURE REGULATED SYSTEM SELECTED

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Propulsion System Invited Presentations

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SPACE STATION PROPULSION INTEGRATED PROPULSION TEST ARTICLE	PROPULSION AND POWER			
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SPACE STATION PROPULSION INTEGRATED PROPULSION TEST ARTICLE

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INTEGRATED PROPULSION TEST ARTICLE

At the end of Phase B, the baseline Propulsion System on the Space Station was a Water Electrolysis/Oxygen-Hydrogen (WEOH) system. The idea was to utilize the excess water from the Orbiter Fuel cells as the propellant. Add the fact that Oxygen/Hydrogen has a high specific impulse and the resupply quantities for the Station are greatly reduced. However, with the newer altitude strategies, and the overall water balance on the Station, it appears that a considerable amount of water would have to be resupplied.

Because of the lack of advanced development on the WEOH system, JSC embarked on a test program called the Integrated Propulsion Test Article (IPTA). Started in 1987, this system consisted on a 3000 psi electrolysis unit, high pressure (3000 psi) gas storage, electronic pressure regulation and available thrusters. Phase I testing began in 1988 and consisted of end-to-end system operation demonstration, proving the feasibility of the WEOH concept.

Phase II testing will utilize much of the Phase I test hardware, but will be configured to better simulate the envisioned Space Station distributed system. Testing is to begin, in April, 1990.

In addition to the system demonstration, contracts are on-going in the area of high pressure electrolysis units.

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	SPACE STATION PROPULSION INTEGRATED PROPULSION TEST ARTICLE	PROPULSION AND PC	PROPULSION AND POWER			
)		J. HENDERSON	01/16/90			

O SPACE STATION BASELINE WAS A WATER ELECTROLYSIS/OXYGEN-HYDROGEN SYSTEM

O UTILIZE 'WASTE' WATER FROM THE ORBITER FUEL CELLS

O HIGH SPECIFIC IMPULSE PROPELLANT COMBINATION

O INTEGRATED PROPULSION TEST ARTICLE FIRST TESTED IN 1988

O INTEGRATED BREADBOARD SYSTEM USING AVAILABLE HARDWARE

- O HIGH PRESSURE ELECTROYSIS UNIT (3000 PSI)
- O ELECTRONIC PRESSURE REGULATION
- O ROCKETDYNE AND BELL THRUSTERS
- O PHASE I DEMONSTRATED END-TO-END SYSTEM OPERATION

O WATER IN - THRUST OUT

O PHASE II TO DEMONSTRATE OPERATION WITH SYSTEM MORE CLOSELY RESEMBLING THE PROPOSED SPACE STATION CONFIGURATION

O PHASE II TESTING TO BEGIN IN APRIL, 1990

O ELECTROLYSIS UNIT DEVELOPMENT

PHASE I CONFIGURATION DESCRIPTION

The Phase I IPTA consisted of a high pressure electrolysis unit, high pressure gas storage tanks, electronic pressure regulation, and available thrusters. The electrolysis unit was a unit borrowed from the Navy called the Oxygen Generation Plant (OGP). This unit was a development test article which has accumulated many hours of run time. It is used to generate Oxygen at high pressure (3000 psi). With very little modification, it successfully generated both hydrogen and oxygen for storage in high pressure tanks, and subsequent usage in the thrusters.

Electronic regulators were procured from Marotta for control of the gas flow rates. This is required due to potential temperature differences between the oxygen and hydrogen. They can also be used to vary the thrust and also to maintain or vary the O/F ratio being delivered to the thruster.

Available thrusters were used for Phase I testing. Two thrusters were tested: a Bell thruster which was originally built for a LeRC contract, and an IRAD thruster from Rocketdyne.

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O PHASE I CONFIGURATION DESCRIPTION

- O ELECTROLYSIS UNIT
 - O NAVY OXYGEN GENERATION PLANT (OGP)
 - O 3000 PSI OPERATION
 - O DEVELOPMENT UNIT
 - **0** ELECTRONIC REGULATORS
 - O CAPABLE OF VARYING INLET PRESSURE TO THRUSTERS TO COMPENSATE FOR:
 - **O** TEMPERATURE VARIATIONS
 - **O** THRUST SELECTION
 - O DESIRED O/F RATIO
 - **0** THRUSTERS EVALUATED
 - 0 BELL LEWIS CONTRACTED THRUSTER.
 - O ROCKETDYNE IRAD THRUSTER ON LOAN TO JSC

PHASE II TESTING

Phase II testing will demonstrate the envisioned Space Station configuration. Long distribution lines between the high pressure gas storage and thrusters are being installed. The capability to fire multiple thrusters is being built into the test article so that system dynamics can be studied. Thermal conditioning of the propellants to simulate long thruster firings and determine the effect of varying the thruster inlet temperature and pressure will be an additional capability.

The propellant storage capacity will also be increased so that longer thruster firings can be performed. Electronic pressure regulation will be installed upstream of the distribution lines to simulate the planned Station configuration. Finally, as the new breadboard electrolysis units become available, they will be installed in the IPTA to determine system compatibility and concerns.

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When testing resumes, we will have the capability of operating a WEOH breadboard system which closely simulates the envisioned Space Station configuration over a wide range of operating conditions.

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	SPACE STATION PROPULSION	PROPULSION AND POWER				
	TEST ARTICLE	J. HENDERSON	01/16/90			

O PHASE II TESTING

- O RECONFIGURE TEST ARTICLE
 - **O** LONG DISTRIBUTION LINES
 - **0 MULTIPLE THRUSTERS**
 - O THERMAL CONDITIONING OF PROPELLANT
 - **O LARGER PROPELLANT CAPACITY**
 - O ELECTRONIC REGULATION TO CONTROL DISTRIBUTION PRESSURE IN ADDITON TO THRUSTER INLET PRESSURE
 - O BREADBOARD ELECTROLYSIS UNIT AS IT BECOMES AVAILABLE
- O TESTING TO DEMOSTRATE OPERATION OF A SYSTEM CLOSER RESEMBLING THE STATION CONFIGURATION OVER A LARGE OPERATING RANGE

ELECTROLYSIS UNIT DEVELOPMENT

Contracts were let in 1988 to two electrolysis unit manufacturers to develop breadboard high pressure electrolysis units. The two manufacturers are developing two different technologies, Hamilton Standard is modifying their OGP technology for space applications (lower weight, smaller packaging, etc) which utilizes a Solid Polymer Electrolyte, and Life Systems, Inc is developing an Static Vapor Feed unit. The delivery of the first unit is expected in March, 1990.

The delivered unit will consist of the cell stack and all necessary hardware to operate the unit at 3000 psi. Extensive testing is planned for the units at JSC following delivery. Stand-alone testing will demonstrate the operational characteristics of the particular device. And then the unit will be installed in the IPTA to demonstrate system operation.

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	SPACE STATION PROPULSION INTEGRATED PROPULSION	PROPULSION AND POWER				
	TEST ARTICLE	J. HENDERSON	01/16/90			

O ELECTROLYSIS UNIT DEVELOPMENT CONTRACTS AWARDED IN 1988

- O PARALLEL DEVELOPMENT OF TWO HIGH PRESSURE ELECTROLYSIS TECHNOLOGIES
 - 0 ACID CELL/SOLID POLYMER ELECTROLITE HAMILTON STANDARD
 - O ALKALINE CELL/STATIC VAPOR FEED LIFE SYSTEMS, INC.
- O DELIVERY OF THE FIRST BREADBOARD UNIT IS EXPECTED BY MID-MARCH
- O HARDWARE WILL CONSIST OF CELL STACK AND ALL NECESSARY HARDWARE TO OPERATE THE UNIT
 - 0 EXTENSIVE TESTING PLANNED AT JSC FOLLOWING HARDWARE DELIVERY
 - O STAND-ALONE TESTING
 - **O** DEMONSTRATE OPERATIONAL CHARACTERISTICS
 - **0** IPTA TESTING
 - **O** DEMONSTRATE SYSTEM OPERATION

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SPE[®] ELECTROLYZERS FOR SPACE PROPULSION

E. M. Shane United Technologies Corporation Hamilton Standard Division Windsor Locks, Connecticut

Presented At: NASA's Technology For Space Station Evolution Workshop January 16-19, 1990

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SPE ELECTROCHEMICAL CELL REACTIONS



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SPE FUEL CELL/ ELECTROLYZER FEATURES

- No free corrosive liquid sole electrolyte is solid sheet of sulfonated fluoropolymer similer to teflon
 - Normality is fixed cannot change with operating conditions or life - cannot be diluted by product or process water
 - Location & volume of electrolyte are fixed cannot leak, creep, leach out or be expelled by acceleration forces or pressure differentials
 - Membrane forms rugged barrier separating reactantstested to 5000 psid without blow-through
- >10 year life demonstrated with stable performance
 - >100,000 load hrs completed on electrolysis cells,
 >60,000 hr on fuel cell stack
 - $< 1 \mu v / hr$ degradation
 - Fuel cell operates on commercial grade reactants
 - No carbonate formation
- Excellent load following similar to a battery

SPE FUEL CELL/ ELECTROLYZER FEATURES (Cont'd)

Simplified cell construction

- Low cost
- High yield with consistent performance
- High reliability
- Mature technology with extensive hardware experience
 - Two successful space power applications
 - SPE electrolyzers in production for military and commercial applications
 - 30 years of development, manufacturing and operational experience
 - Technology status results from cumulative development funding from many programs



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SPE CELL LIFE CAPABILITY

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"UNINTERRUPTED" SPE" ELECTROLYZER LIFE TEST



SPE CELL VOLTAGE STABILITY



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STATE-OF-THE-ART SPE CELL STRUCTURE



0.23 FT² CELL HARDWARE



SPE® PROPULSION ELECTROLYZER FOR NASA'S INTEGRATED PROPULSION TEST ARTICLE

INTRODUCTION: ELECTROLYSIS CELL STACK



FORCE TRANSFERRED BY TIE RODS

MODES OF SPE ELECTROLYZER OPERATION

- ANODE PROCESS WATER LIQUID FEED
- CATHODE PROCESS WATER LIQUID FEED
- CATHODE PROCESS WATER VAPOR FEED

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SPE® PROPULSION ELECTROLYZER FOR NASA'S INTEGRATED PROPULSION TEST ARTICLE

INTRODUCTION: ELECTROLYSIS SYSTEM





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vdc Cell voltage

INTEGRATED PROPULSION TEST ARTICLE — ELECTROLYZER MODULE COMPONENTS



INTEGRATED PROPULSION TEST ARTICLE — SPECIAL TEST FIXTURE



DEMONSTRATED LIFE - LIQUID ANODE FEED SPE ELECTROLYZER AS OF APRIL 1988

Type of Service/Product Description Navy Electrolyzers	Electrolysis Rate	Cell Area ft2	Operating Pressure PSI	Number of Stacks	Number of Cells Per Stack	Total Number Of Cells	System Hours	Stack Hours	Cell Hours	1
US Navy: Nuclear Submarine O2 Generation 3000 psi System - Qualification Unit (OGP#2) 3000 psi system - Preprototype (OGP#1) Development System (Breadboard) Development Stack OGP Program Development Stack OGP Program Development Stack OGP Program Development Stack OGP Program Development Stack NSSC 4 Development Stack NSSC 7 Development Stack NSSC 9	21 21 21 1 2 4 7.4 0.2 0.2 0.2	0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23	300 to 3000 300 to 3000 300 to 3000 300 to 3000 300 to 3000 300 to 3000 300 to 3000 ambient ambient ambient	2 2 1 1 1 1 1 1	100 100/83 100 5 10 20 35 1 1 1	200 183 200 5 10 20 35 1 1 1	1,000 10,000 14,000 1,900 1,500 2,500 3,900 87,500 82,500 87,500	1,000 13,000 28,000 1,900 1,500 2,500 3,900 87,500 82,500 87,500	100,000 1,181,000 2,800,000 9,500 15,000 50,000 136,500 87,500 82,500 87,500	With Over <u>5 Million</u> Cell Hours of Successful Operation the Selected SPE Cell Design
United Kingdom Navy: Nuclear Submarine O2 Generation Development Stack S/N#1 Development Stack S/N#2 Production Stacks: Various Production units (22 total) NASA/JSC Electric Energy Storage System	12.5 15 15 to 17 3	0.23 0.23 0.23 0.23	150 150 150 150	1 1 22 1 38	58 70 70 or 81 22	58 70 1,731 22 2,537	3,000 6,000 classified 2,000 303,300	3,000 6,000 classified 2,000 320,300	174,000 420,000 classified 44,000 5,187,500	is Well Established
classified data and various laboratory test data) ES1000 Series: Constructor John Brown - England Public Service Electric & Gas, New Jersey South Bagdad Thermal Power Station - Bagdad, Ira Delta #4 Power Project - Nigeria Development Unit- High Current Density (EPRI) Monsanto Mound Laboratories - Moundsville, Ohio Intermountain Power Project - Delta Utah Laboratory Series: Gas Chromatograph Hydrogen Generator (various world-wide customers)	34 16 24 24 6 8 10 0.02	1 1 1 1 1 1 0.05	100 100 100 100 100 100 100	1 1 2 1 2 1 1 2 1	34 14 12 12 6 5 10 3	34 14 24 6 10 10 36,000	2,000 10,000 35,000 100 2,000 100 8,000	2,000 10,000 200 2,000 200 8,000 42,000,000	68,000 140,000 840,000 2,400 12,000 1,000 80,000	And supported by over <u>130 Million</u> Cell Hours of Anode Feed Operational Experience
Total Commercial Products (Liquid Anode Feed) (note: total does not include all ES 1003 system: GRAND TOTAL - LIQUID ANODE FEED	5)			12,010	B	36,122 38,659	42,057,200	42,092,400	127,143,400	

SPE WATER ELECTROLYZERS (Active Cell Area 0.23 Ft²)



Production Modules



U.S. Navy Submarines 3.000 psi Qual Unit



3,000 psi Propulsion Electrolyzer Mock-Up



U.K. Navy Submarines >30 Units Delivered



6000 psi Development Unit



Space Station 1,000 psi Development Unit
HIGH PRESSURE WATER ELECTROLYSIS EXPERIENCE

U.S. NAVY ROYAL NAVY SUBMARINES SUBMARINES

- SYSTEM WATER > 20 LBS H_2O/HR > 15 LBS H_2O/HR ELECTROLYSIS RATE
- OPERATING PRESSURE ~ 3,000 PSI ~ 1,800 PSI
- YEARS IN SERVICE > 30 > 25
- NUMBER OF SYSTEMS IN ~ 270 ~ 24
 SERVICE
- ESTIMATED OPERATING HOURS ~ 5000 HRS/SYSTEM-YR ~ 4000 HRS/SYSTEM-YR
- ESTIMATED TOTAL SYSTEM > 1×10^{7} HOURS > 1×10^{6} HOURS EXPERIENCE

COMPARATIVE DATA

SPE	КОН
225 SCFH/pure oxygen	150 SCFH/<2% hydrogen in oxygen
300-3000 psi out	3000 psi out
Rapid start/shutdown	>2 hour start-up
Failsafe shutdown	Attended shutdown
Nitrogen conservative	High nitrogen usage
Unattended operations	Attended operations
Module life \sim 16 years w/redundancy	Cell life ~ 2 yrs
65 dB structureborne noise	85 dB cell noise
Can withstand >700 psid across membrane	Inches water control req'd
Redundant cell stack \sim 75% availability (<50% req'd)	Availability less than req'd based on experience

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225 SCFH U.S. NAVY SPE OXYGEN GENERATOR MODULE



ORIGINAL PAGE BLACK AND WHITE PHOTOGRAPH

OXYGEN GENERATING PLANT (OGP)



ROYAL NAVY SPE ELECTROLYZER

- Royal Navy selected SPE electrolyzer to replace alkaline electrolyzers in nuclear submarine oxygen generator systems
- Alkaline was established system for >25 years
- SPE electrolyzer system fully qualified for submarine environment and at sea

393

• SPE electrolyzer systems ($\sim 25kW$) are in production with >30 systems delivered to date.

ROYAL NAVY ANALYSIS Comparison of SPE vs established alkaline electrolyzer

Parameters	SPE performance as % of KOH
Output	120
Size	63
Weight	44
Cost	78
Through life cost	42
Cooling water	74
Power	93
Maintenance	20

ORIGINAL PAGE



A DUPLEX LOW PRESSURE ELECTROLYSER (LPS) OXYGEN GENERATING SYSTEM FOR NAVAL USE



COMMERCIAL SPE ELECTROLYSIS PROGRAMS 1973 - Present

• Laboratory H₂ generator in production since 1973

- > 10,000 units produced to date (UL listed)
- Units in use throughout world
- ES-1000 H₂ generator system commercially available since 1983
 - 7 systems plus 6 modules shipped to date
 - Excellent reports from customers
- Large scale systems ready for commercialization

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Robotics Level III Subsystem Presentations

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Flight Telerobotic Servicer

Dennis Haley Martin Marietta

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STS and S.S. Freedom Operations Are Supported by SSFTS Design

SSFTS Operations from the Orbiter Payload Bay



Transporter Attached Operations on Freedom



Fixed Base Independent Operations on Freedom



Fixed Base Dependent Operations on Freedom



SSFTS Elements

STS Workstation

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FTS Mission Operations

Assembly Operations

- Truss Assembly
- SIA Installation
- Thermal Utility Tray Installation and Coupling

- Standard ORU Module Installation
- 404

Servicing/Maintenance Operations

- Propellant Resupply
- Cryogenic Resupply
- Expendable Module Replacement

Inspection Operations

- Meteoroid Physical Damage
- Thermal Fluid Leak

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- Cabling Connectivity

- Nonstandard ORU Installation
 - Ku- and S-Band Antenna
 - Radiator Panels
 - RCS Modules
 - · Alpha and Beta Gimbals
 - Etc
- ORU Replacement
- Calibration

- Module Leaks

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- Temperature Probing
- Assembly Inspection

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FTS General Requirements

Manipulator Tip Force:20 lbManipulator Tip Torque:20 ft/lbManipulator Repeatability:0.005 in.Manipulator Incremental Motion:0.001 in.System Weight:1500 lbSystem Power:2000 watts Peak, 1000 watts Average, 350 watts StandbySystem Lifetime:Indefinite On-Orbit Life through Periodic Maintenance; MTBFConsistent with a Two-Year Servicing Interval with an
Operations Duty Cycle of 30 Hours per Week

System Shall Be Two-Fault Tolerant Against Inadvertent Release of Material System Shall Avoid Unplanned Physical Contact (Collision) System Shall Be Capable of Detecting Failures and Automatically Assuming a Safe State

Flight Telerobotic Servicer Hardware and Technology Development Flow



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Flight Telerobotic Servicer-Telerobot

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FTS Manipulator



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JR3 Force-Torque Transducer



End Effector Changeout Mechanism



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Flight Telerobotic Servicer–End-of-Arm Tooling



User Interfaces



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FTS Data Management and Processing



Control Subsystem

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Hybrid Force/Position Control System





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FTS Vision Subsystem and Camera Positioning Assembly

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FTS Workstation Display Assembly Panel

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Color Flat Panel Displays



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Mini-Master Hand Controller



FTS NASREM System Architecture

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Servicing Operations Demonstrated

REPLACING HST REACTION WHEEL



THERMAL UTILITY & REFUELING CONNECTORS



REPLACING RADIATOR ASSEMBLY



TRUSS ASSEMBLY



FTS Growth Accommodations



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THE MOBILE SERVICING SYSTEM

NASA - OAST TECHNOLOGY FOR SPACE STATION EVOLUTION - A WORKSHOP

Dallas, Texas

January 16, 1990

David G. Hunter

Acting Robotics Manager Canadian Space Station Program

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CANADIAN ROLE ON SPACE STATION (NASA/MOSST MEMORANDUM OF UNDERSTANDING)

"Canadian elements will be developed to play the predominant role in satisfying the following functions for the Space Station:

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- attached payload servicing (external)
- Space Station assembly

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- Space Station maintenance (external)
- transportation on Space Station
- deployment and retrieval functions

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- EVA support"

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MSS Overall Configuration

Space Segment

- Mobile Servicing Centre (MSC)
- Special Purpose Dexterous Manipulator (SPDM)
- MSS Maintenance Depot (MMD)
- MSS Control Equipment (MCE)

Ground Segment

Ground Operations Facility, the Engineering Support Centre

Support Systems

- Manipulator Development and Simulation Facility (MDSF)
- Technical and Management Information System (TMIS)
- Software Support Environment (SSE)

MOBILE SERVICING SYSTEM (MSS)




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Mobile Servicing System (Space Segment) Hierarchy



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SSRMS Configuration



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Functional Requirements for SPDM

Perform Dextrous Tasks for Assembly & Maintenance of:

- Mobile Servicing Centre, including Mobile Transporter
- External Space Station Systems
 - □ Power System
 - □ Alpha & Beta Gimbals
 - □ C&T System
 - □ GN&C System
 - DMS System
 - \square RCS
 - □ SIA and PIA (for attached payloads)

Perform Dextrous Tasks for

- Handling Small Payloads (external)
- EVA-Support
- Safe Haven Support





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Functional Requirements for SPDM (cont'd)

Dextrous Tasks for Assembly and Maintenance include

- Exchange ORU'S
- Attach / Detach ORU Interfaces
- Connect / Disconnect Utilities
- Mate / Demate Connectors
- Remove / Install Thermal Covers & Blankets
- Clean Surfaces

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- Inspect and Monitor with Vision System
- Provide Lighting to Support EVA
- Position Tools & Materials to Support EVA
- Provide TV Views to Monitor EVA Activities

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SPDM Configuration



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SPDM Operating From MBS for SSRMS Maintenance



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SPDM Operating At The End Of SSRMS



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Space Station Freedom Program Office Mobile Servicing System Development Schedule

Calendar Year 89 90 91 92 93 94 95 96 **Program Approvals Contract Negotiation** C1-B CZ-A C2-B D D **Contract Phase** T.B. Approvals **MSS Detailed Design** EPA TB ŤΒ NASA PDR's SS SPDM MT MSC **Canadian PDR's** GND MMD MSC Detailed Design Canadian CDR's GND SPOM MMD MSC ŧ NASA CDR's PMC MTC **MSS Detailed Design** PMC мтс SPOM MMD ŧ NASA CDR's MSC GND **Canadian CDR's** Manufacture & Test MMD MMD **9PDM** GND Manufacture Complete **Delivery to KSC** 5PDM MSC

- CDR Critical Design Review
- PDR Preliminary Design Review
- EPA Ellective Project Approval
- GND Ground Support System MMD - Maintenance Depot
- MMU Maintenance Depo
- MSC Mobile Servicing Centre MTC - Man Tended Configuration
- ATC Man Tended Configuratio
- MT Mobile Transporter

- PMC Permanently Manned Configuration
- SPDM Special Purpose Dexterous Manipulator
- SS Space Station

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Objective of Advanced Technology Development

Minimize crew workload

- □ Automate all routine operations and mundane tasks
- Develop a hierarchical command structure; evolutionary shifting of control functions from operator to machine
- Automate monitoring of operations; crew intervention only when alarms occur
- □ Improve Human–Machine interfaces
- Increase autonomy and minimize ground support of MSS operations
 - Improved on-orbit access to design data, maintenance procedures, test procedures and archived operational data.

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- □ Tools for on–orbit planning of MSS operations.
- Increase the operational effectiveness of the MSS.

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Basic Requirements for Advanced Technology

■ Focused effort in selected areas

- Application specific
- Probable success
- Modular and add-on type concepts
- □ At the completion of proof-of-principle demonstration (POPD) concepts proceed along the MSS Program life-cycle

- Compatibility between MSS and Space Station A&R concepts
 - Commonality
 - Effective utilization of station resources
- Evolutionary approach
- □ Future growth
- Technology transparency
- □ Progressive evolution from teleoperation towards autonomous operation





machine perception

control

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Automation and Robotics Technologies MSS Baseline

Target-Based Vision

- position, orientation, rate determination

Collision Avoidance

- collision warning

Force/Moment Accommodation

- limiting of applied forces and torques

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Automation and Robotics Technologies MSS Baseline (cont.)

Coordinated Control

- two manipulatorsSSRMS/SPDM

Command Language

- hierarchical _
- object-oriented
- extensible

Achievable Level of Automation

- auto-trajectories
- automated tracking and grappling



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control



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Automation and Robotics Technologies Planned for Incorporation

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Enhanced Vision System

- depth recovery
- shape recognition
- object recognition

Collision Avoidance

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- machine assisted trajectory planning
- on-line trajectory management

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information management

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> Automation and Robotics Technologies Planned for Incorporation (cont.)

Expert Systems Applications

- fault detection and diagnosis
- on-orbit integration, test and maintenance information system

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planning system

Achievable level of Automation

task level automation

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Robotics Invited Presentations

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Section: Introduction

Title: Definitions

1. Defining "Agent-Independent Planning"

"Agent-Independent Planning" is a method of automated planning that allows the generation of task plans from a set of goals, without having to be concerned with constraints imposed by the agent that will execute the plan. In the domain of Space Station Freedom (SSF), these plans can be considered a sequence of tasks for intra-vehicular and extra-vehicular operations activity. Plans, or operations procedures, are developed by considering general constraints on the planning environment and task sequences. For execution of these procedures, the plans are translated into the specific operations language of a particular agent. This methodology allows plans and their environment to be modeled in a fashion that separates different classes of constraints into independent sets.

2. Defining "Agent"

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An "agent" is any entity that will perform the plan. Again, in the domain of Space Station Freedom, an agent might be a crewmember, robot, or some automated system. Each of these agents has a unique set of instructions which it understands, whether English sentences, robotic programming commands, or software instructions. Each agent also has its own set of capabilities and constraints when executing a plan. These constraints are modeled and used independently from general planning constraints. The key benefit from this methodology in that these operations procedures may be developed virtually independently from robotic/automated systems or crew skills necessary to execute them. This allows systems to be developed without changes in one component adversely impacting another.

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- Section: Motivation
- Title: Space Station Freedom Robotics Environment

1. Different Kinds of Robotic System Implies Redundant Programming

The number of ways to automate a single task through robotics is proportional to the number of robotic systems. That is, to direct different robots to do the same task would likely require a different software program for each robot. Suppose an robot on board of SSF had been programmed to remove certain types of pumps from a rack. If that robot were replaced with a new robot of increased capability, this new robot would likely require fresh programming to perform the same pump removal tasks. While this problem of redundant programming is not unique to the domain of Space Station Freedom, it is intensified under the new challenges associated with its long life cycle (30 years).

2. New Challenges Created By SSF Life Cycle

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The long period of planned station operation poses significant challenges to integrating advanced technology. The primary concern is the evolution of technology over this extended life This evolution will realize a continuous set of upgrades cvcle. in robotic capabilities, including greater precision of robotic movement, increased dexterity of robotic manipulators, and advanced capabilities in vision, force, range, and other sensors. Similarly, operations procedures will evolve through continuous additions and modifications, increasing the range of workload for However, crew time for intra-vehicular and extrathe crew. vehicular activity will certainly remain a resource of great These conditions will enhance the potential to offset expense. some of this expanding workload from crewmembers to robots, particular as the advent of increased robotic capabilities allows them to perform more advanced operations. Hence, we are faced with a changing set of operations procedures, a changing set of robots to perform them, and the challenge of maintaining their integration.

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Section: Motivation

Title: Transition from Crewmember to Robots

1. Maintaining Integration Between Crew, Robots, and Procedures

The transfer of workload from crewmembers to robots must be performed in a safe, consistent, and robust manner. Certainly robots (and their programming) must be verified as capable of safely performing the transferred work. Also, it must be verified that exactly the same operations are accomplished, whether performed by crew or robot. With advancing technology producing upgraded robotic capabilities, it is reasonable to predict the transfer of workload not only from crew to robots, but also from robots to robots. This transfer must maintain a robust integration with crew and procedures, such that problem of redundant programming does not impact system development.

2. Transition Table

Certain transition needs imply specific aspects of an approach to satisfy the requirements of a safe, consistent and robust system. Activities which require skills only possessed by humans may be transferred to robots as their capabilities increase. To maintain consistent and robust development of operations procedures, these activities must be modeled in a representation which can be applied to both crew and robots. Similarly, plans that are developed for execution by robots of one set of capabilities should remain applicable to robots possessing advanced capabilities. In order to apply these plans across robotic platforms, procedures must be represented separately from constraints imposed by capabilities of particular robotic systems. Given a system that can construct plans for robots with varying capabilities, it follows that this system should also be able to apply plans to crewmembers with varying skills.

In general, modeling operations procedures and their environment separately from robotic or crew agents allows the development of operations plans free from impact by changing robotic capabilities or crew skills. Agent-Independent Planning provides a facility for this robust development of both agents and operations plans. The approach used by this methodology allows plans to be generated and later validated for execution by any agent that is modeled in the system.

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Section: Approach

Title: Agent-Independent Planning System Flow

1. Generation

Plans for operations procedures are modeled and stored in a task library. Operations tasks are represented through hierarchical abstraction, with each task decomposing into a network of lowerlevel tasks. Temporal logic operators connect the nodes of this network and represent the time relationships among the tasks. Temporal and nonlinear planning techniques combine tasks from the task library with objects in the planning environment to formulate a viable sequence of procedures to satisfy the operations goals. This plan considers only the constraints associated with objects and the temporal relationships among tasks.

2. Validation

An agent-independent plan is transformed into an agent-dependent plan by matching the constraints already present among tasks and object in the plan with those of a given agent. An agent's physical constraints are validated with respect to the physical constraints of the objects it must manipulate. An agent's functional constraints are validated with respect to the tasks and their temporal constraints. In essence, this validation declares whether the agent is capable of performing the given plan.

3. Translation

Once a plan has been tailored for a particular agent, the tasks of this plan can be broken down to the primitive-level tasks; that is, those with no further decomposition. Using the model from the agent knowledge base, these primitive level tasks are translated into specific instructions for the agent. For crewmembers, these instructions are English sentences composing crew activity plans. For robots, these instructions are the programming language of the robot controller, or robot system software commands. For an automated software system, such as a graphic simulator, these instructions correlate to a set of software commands to drive the automation. It is these primitive tasks, however, that provide a layer of independence between agent-independent plan and agent-specific instructions.

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Section: Approach

Title: Independence Between Plans and Agents

1. Motion Primitives and Modeling

The non-decomposable tasks, or primitive tasks, provide the common interface between agents and the planning environment. For our work in robotic applications, a small set of these primitives has been established that describe physical motion (move, push, pull, grasp, release, rotate etc.). Models of the planning environment (whether agents, object, or tasks) all relate to this set of primitives. The agents' and objects' physical and functional constraints are represented in terms of pre-conditions and effects on these primitive tasks. Object-oriented models of agent and object properties allows descriptions of agents and objects to be combined through inheritance.

For each primitive task, an agent model contains an appropriate set of instructions for the execution of that task. Primitive tasks are hierarchically abstracted into more natural concepts, allowing plans to be developed to an appropriate level for crewmembers, but remain decomposable into robotic instructions. The preconditions and effects associated with the primitive tasks are also abstracted to provide constraints for nonlinear planning techniques. Temporal logic operators which form networks among the abstractions are used in temporal planning to generate all viable "sequences" (whether parallel or sequential activity) for plan execution.

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Section: Status

Title: Current Testbed

1. Intelligent Planner

A system has been developed in Common Lisp on a Texas Instruments Explorer workstation which models, generates, validates, and translates plans for maintenance and repair operations to be performed in a rack-like environment by crewmembers, robots, and a graphic robotic simulator. Separate knowledge bases describe agents, objects, and the plan (task) library. Agents and objects are modeled according to classes of their capabilities. For example, a class of objects which require power to be disabled before manipulation by an agent can universally impose a power constraint on all its members. Such class representation allows inheritance of groups of constraints by merely having membership in the appropriate class. A more detailed discussion of this work can be found in:

W. S. Davis, "Robotic Task Planning: Independent of Agents but Dependent on Time," Proceedings 1989 IEEE International Conference on Robotics and Automation, May 1989, Scottsdale Arizona, pp. 690-696.

2. Agents

A PUMA 560 robot possessing vision, force/torque, and tactile sensors receives plans in a language mostly consisting of VAL II controller commands. The sensors are used for safety in plan execution by detecting force thresholds on sensitive objects and potential object collisions in the planning environment. A graphical robotic simulator models the racks and their objects along with various robotic agents. This simulator maintains the inverse kinematics for the given agent and simulates its behavior of issued commands. It currently models both one- and two-armed PUMA robots to verify the dynamic translation capabilities of the planner. The planner generates sequential instructions for the one-armed agent, whereas parallel instructions are produced for the two-armed agent. The planner also generates sets of English sentences describing operations activities. These plans are issued to a crewmember using a DecTalk speech synthesis system, with the crewmember providing feedback to the planner through a Verbex voice recognizer.

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Section: Status

Title: Benefits of Approach

1. Generation

The temporal logic representation allows the planner to generate plans which incorporate all possible orderings of execution by an agent. This is significant in providing plans which can be applied to agents possessing differing capabilities in sequential/parallel execution. The techniques of hierarchical abstraction allow operations procedures to be built up to a level which is natural for operations engineers. Hence, these procedures can be modeled by non-robotic developers, but still be translated for a specific robotic agent. Such a benefit will make robotic automation accessible to a broader group of developers.

2. Validation

The ability to determine whether an agent is capable of plan execution is central to the robust theme of compatibility. New robotic designs can be modeled and verified against operation procedures already in existence. Similarly, modifications to operations procedures can be validated to ensure compatibility with any existing robotic hardware. By validating procedures for both crewmembers and robots, areas of future robotic development can be targeted to bridge any gaps in human and robotic capabilities.

3. Translation

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A plan be generated only once for it to be translated as often as needed for whatever agents are needed. Translation separates the development of operations procedures from the specific execution details, thus establishing consistency in procedure development. By incorporating developed plans into the plan library, they can be re-used for future robotic applications. Since development of procedures is independent from development of robotics, a change in the robotic execution can still use a previously generated plan.

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Section: Status

Title: Directions for Future Research

1. Planning Investigations

Adding nonmonotonic properties to the temporal logic will vastly improve the computational complexity of current temporal logic algorithms. It will provide the ability to efficiently re-tract assertions made in the planning models. Such a capability will be significant in generating plans from abstract, or timevariable data. This nonmonotonicity will also be incorporated into replanning strategies to reformulate the temporal networks of the plan models. Explanation facilities will be incorporated into the planner to extract rationale from temporal and functional constraints and explain the planner's decision to crewmembers.

Robotic Agent Investigations 2.

Models for representing agents will be refined for better inheritance of agent characteristics. Methodologies for inheriting agent-specific instructions will be examined. These representations are targeted toward a stronger model of an agent's sensing capabilities. As a testbed for these models, we will incorporate a three-fingered end-effector for dexterous manipulation of objects. Issues in active and passive compliance with the environment will be studied, with the eventual goal of active compliance with a crewmember, and the receipt of cooperative plans.

Human Interface Investigations 3.

Models for crew skills will be developed to allow the planner to generate English sentences with varying amounts of detail. Different classes of crew skills will be incorporated into the agent knowledge base to help guide the explanation of planner rationale to ssdent

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SHUTTLE REMOTE MANIPULATOR SYSTEM

• THE SPACE SHUTTLE PAYLOAD DEPLOYMENT AND RETRIEVAL SYSTEM IS THE STATE OF THE ART FOR IN-SPACE TELEOPERATIONS

• THE PDRS CONSISTS OF THE REMOTE MANIPULATOR SYSTEM AND ITS ANCILLARY EQUIPMENT MOUNTED ON THE SPACE SHUTTLE ORBITER

• THE PDRS FUNCTIONALITIES ARE:

- GRAPPLE, TRANSPORT, ORIENTATION, AND RELEASE OF PAYLOAD
- TRACK, CAPTURE, GRAPPLE, TRANSPORT, ORIENTATION, AND BERTHING OF A SATELLITE
- EVA CREW TRANSPORT, POSITIONING, ORIENTATION VIA GRAPPLED MANIPULATOR FOOT RESTRAINT
- LOCAL ILLUMINATION VIA RMS-MOUNTED LIGHT
- DIRECTIONAL, AUGMENTED VIEWING VIA RMS-MOUNTED CCTV
- FREESTREAM EXPERIMENT SENSOR POSITIONING
- POWER AND DATA INTERFACE SERVICES FOR PAYLOADS
- RESOURCE FOR CREATIVE SOLUTIONS TO UNPLANNED PROBLEMS

FLIGHT TELEOPERATOR SYSTEM FUNCTIONS



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SHUTTLE RMS TECHNOLOGY





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MOBILE SERVICING CENTER FUNCTIONS

- ASSEMBLY AND EXTERNAL MAINTENANCE OF SSF
- SERVICING OF ATTACHED PAYLOADS
- TRANSPORTATION OF PAYLOADS AND HARDWARE ABOUT THE STATION
- DEPLOYMENT AND RETRIEVAL OF FREE-FLYING STABILIZED SPACECRAFT
- BERTHING OF STS (ORBITER) AND OMV
- UNLOADING ORBITER CARGO BAY
- SUPPORT OF EVA

MOBILE SERVICING CENTER TECHNOLOGY



Flight Telerobotic Servicer–Telerobot



FLIGHT TELEROBOTIC SERVICER TECHNOLOGY





TECHNOLOGIES REQUIRED FOR SPACE STATION ASSEMBLY

- FORCE/TORQUE FEEDBACK
- CONSTRAINED MOTION CONTROL FUNCTIONALITY/FORCE TORQUE CONTROL
 - RATE COMMAND TO CONTACT TRANSITION
 - RATE COMMAND WITH VARIABLE RESISTANCE LOADING
 - SPLIT AXIS MODES

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- DISPLAY OF COMPLEX ASSEMBLY WORKSPACES TO CREW
- PRACTICAL COLLISION AVOIDANCE (LIMITED MACHINE VISION)
- SINGLE WORKSTATION CONTROL OF MULTIPLE, HIERARCHIAL (AND SOME PARALLEL) MANIPULATORS

TELEOPERATION APPLICATIONS

• ON-ORBIT SERVICING OF SATELLITES

- ON-ORBIT MAINTENANCE OF SPACE STATION FREEDOM
- **ON-ORBIT SERVICING OF PLATFORMS**
- ON-ORBIT ASSEMBLY OF LUNAR AND MARS EXPLORATION VEHICLES

TECHNOLOGY NEEDS FOR SPACE STATION EVOLUTION

- FAILURE DETECTION, ISOLATION, AND AUTOMATIC RECONFIGURATION OF A TELEOPERATOR SYSTEM
- ADVANCED CONTROL LAWS INCORPORATING CONTROL STRUCTURE INTERACTION
- STABILIZATION/DISTURBANCE REJECTION IN MANIPULATOR/PLATFORM COUPLING DYNAMICS
- WORLD MODEL PLANNED MOTION EXECUTION, INCLUDING COLLISION DETECTION AND AVOIDANCE
- ADAPTIVE CONTROL COORDINATION OF MULTIPLE ARM/END EFFECTOR SYSTEMS
- INTELLIGENT INFORMATION FUSION DISPLAY SYSTEMS
- MULTI-MODE OPERATOR CONTROL INCLUDING HIGH LEVEL SUPERVISORY CONTROL
- ADVANCED AUTOMATION TECHNOLOGY APPLIED TO TELEROBOTICS
- MULTIPLE END EFFECTOR CAPABILITY

Twenty Year Forecast of NASA Robotics Requirements for Space Exploration

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from

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Telerobotics Capabilities for Space Station Operations

David Akin

Massachusetts Institute of Technology

Technology for Space Station Evolution Workshop January 16-19, 1990 Dallas, Texas

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FTS EVOLUTION

 $x = x_{1} + x_{2} + x_{3} + x_{4} +$

DAVID E. PROVOST GODDARD SPACE FLIGHT CENTER

TECHONOLOGY FOR SPACE STATION EVOLUTION --A WORKSHOP

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TASK STATES

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EPS RADIATOR PANEL INSTALLATION

- 1. Unstow FTS from shelter
- 2. Unstow PDGFs from shelter and store in payload bay
- 3. Move to IEA bay
- 4. Install PDGFs
- 5. Detach diagonal truss member
- 6. Position FTS for radiator panel installation
- 7. Unstow magazine from payload bay
- 8. Position magazine for radiator panel installation
- 9. Attach radiator panel guide
- **10.** Install panels
- 11. Stow magazine in payload bay
- 12. Detach FTS from PDGF
- 13. Attach diagonal truss
- 14. Detach PDGFs from nodes and store in bay

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- 15. Position orbiter to shelter
- 16. Stow PDGFs
- 17. Stow FTS

GENERIC TASK DEFINITIONS

RETRIEVE ROBOT

Transport work system (e.g. RMS, OMV, MSC) active FTS action is positive release of the grapple fixture

TEST ROBOT FTS is active system

DELIVER ROBOT WORK SYSTEM Transport work system (e.g. RMS, OMV, MSC) active FTS action is a positive "grab" of grapple fixture

ORIENT TORSO FTS positioning system is active system *Requires:* Observe, designate, and plan path, utilization of FTS positioning system to approach zone of manipulation

MOVE ARMS TO VICINITY OF WORK

FTS manipulator arms are active systems *Requires:* Observe, designate, and plan path, move end effectors to vicinity of work

GENERIC TASK DEFINITIONS (continued)

ATTACH.

FTS end effector and arms are active systems

Requires: Iterate until seating verified: Observe/sense, designate, and plan path, align (may use vision force feedback, guides, etc.), move

DO WORK

490 7-6 FTS is active system

Requires: Observe, designate activities for completion of task and plan path required to complete task

Will include one or more of the following: move, insert, drive, push, pull, twist, turn, engage, disengage, count turns, follow, deploy, lock, align

DETACH

FTS manipulator arms and end effectors are active systems *Requires:* Observe, designate, and plan retract path, align/null store energy, disengage end effector, retract

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MOVE ARMS TO SAFE POSITION

FTS manipulator arms are active systems *Requires:* Observe, designate, and plan path, move

EPS RADIATOR PANEL INSTALLATION TASKS: WITH DIAGONAL TRUSS REMOVAL

TASK 1	AETRIEVE ROBOT	TEST ROBOT	DELIVER ROBOT WORK	ORIENT TORSO	MOVE ARMS TO VICINITY	ATTACH	DO WORK	DETACH	MOVE ARMS TO SAFE	COMMENT	TOTAL STEPS
			SYSTEM	<u> </u>	OF WORK				POSITION		
1d	1										
10		1		L	L			[I		
TOTAL	1	1	0	0	0	0	0	0	0		2

TASK	RETRIEVE	TEST	DELIVER	ORIENT	MOVE	ATTACH	DO	DETACH	MOVE	COMMENT
2	ROBOT	ROBOT	ROBOT	TORSO	ARMS TO		WORK		ARMS TO	
	1	[WORK		VICINITY				SAFE	
			SYSTEM		OF WORK				POSITION	
2b				1	1					
. ?c						1				
2d							1			Drive bolt out.
20							1			Move node filting
21								1		
2g	0	0	0	2	2	2	4	2	0	Repeat 20-21-2 times.
2h				1	1					
21						1				
2j					1					
2h	·					1				
21							1			Unlatch and separate joint.
2m		•						1		
20					1					· • •
2p						1				
2q					1		1			Align PDGF
21										Engage and latch PDGF
25								1		
21								1	1	
20	0	0	0	1	4	3	3	3	1	Hejioal 2h 2i
TOTAL	0	0	0	5	11	9	12	q	2	

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TASK	CASE	RETRIEVE ROBOT	TEST ROBOT	DELIVER ROBOT	ORIENT TORSO	MOVE	ATTACH	DO WORK	DETACH	MOVE ARMS TO
				WORK System	j	VICINITY OF WORK	<u>(</u>			SAFE POSITION
SIA	1	2.5	2.5	2.5	15.6	20.5	18.0	12.3	18.0	8.2
INSTALL	2	1.6	0.8	1.2	8,9	24.4	2 0. 9	16.7	20.9	4.7
ł	3	1.9	1.5	1.0	9.2	23.8	22.3	13.1	22.3	4.9
l	4'	1.7	1.2	1.7	13.3	22.5	17.3	17.9	17.3	6.9
PALLET	1	2.2	0.7	5.8	8,0	24,8	17.5	15.3	17.5	8.0
INSTALL	2	1.9	0.0	4.9	8.0	25.3	17.3	17.9	17.3	7.4
INSIDE/	3	2.2	0.7	58	8.0	24.8	17.5	15.3	17.5	80
AWP	4	1.9	0.0	4 9	80	25.3	17.3	17.9	17.3	7.4
PALLET	1	1.8	0.9	4.4	11.5	20.4	19,5	13,3	19.5	6.0
INSTALL	2 ′	1.3	0.0	22	7.1	24.1	22.3	15.6	22.3	4.9
OUTSIDE/	3	1.4	0.0	3.6	11.5	21.6	18.7	18,5	18.7	7.9
AWP	4	1.5	0.5	2.5	6.6	23.7	23.2	13.6	23.2	5.1
ORU	1	3.1	05	5.2	9.9	20.9	16.2	18.3	16.2	9.4
CHANGE- OUT	2	2.3	0.4	3.4	9.0	23.7	14.7	20.7	14.7	11.3
RADIATOR WITHOUT TRUSS REMOVAL	1	0.3	0.2	0.3	7.5	25.8	15.9	28.1	15.9	6.0
RADIATOR WITH TRUSS REMOVAL	t	0.3	0.2	0 3	7.6	27.0	16.1	27.2	16.1	5.3

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SUMMARY (PERCENT)

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allen NON-CONTACT ALIGNMENT (assumes motion will be within a small volume and Active or passive active primarily in orientation) (e.e. leds) passive target (primary source of data is a camera image and a gather low level vision system exists) sensor data complex (e.g. (initial condition is that target is in Predefined simple (e.g. geometric shapes) field of view and sufficiently large bulls-evel process dala: structured e.g.exiract for processing) target ? centrolds of LEDS gather sensor dala High level ٨ yes n o vision system ? process datas r.g.estract gather cerners sensor data Object ye 1 n 0 recognition process data: A Automatic necessary e.g.extract 7 . . calculation of no ? corners and error to goal compare with ? model calculate gather gather next point sensor scasor toward goal dala data ٨ felcop next plan path process data: geal point process data: toward goal pathplanner falls e.g.fuse sensor e.g. torget medalities search rouline move A process datas e.g.terget receg. contines y e s . |x - x | < Æ đ return to sppropriate exit branch (1866451)

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TASK STEPS

