NASA

Technology For Space Station Evolution–Proceedings

Office of Aeronautics and Space Technology

SCREEN IMAGE USER=*EBB SESSION=T20BR08 7/20/93-10:27:10-AM

DISPLAY 93N27803/2
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
CIO: UNITED STATES Workshop held in Dallas, TX, 16-19 Jan. 1990 Original contains color illustrations
MAJS: /*ROBOTICS/*SPACE STATION FREEDOM/*SPACE STATION POWER SUPPLIES/*SPACE STATION PROPULSION
MINS: / AEROSPACE ENGINEERING/ CONFERENCES/ TECHNOLOGY ASSESSMENT
ANN: NASA's Office of Aeronautics and Space Technology (OAST) 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.
ENTER:

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

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)

VOLUME IV

Robotics

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

THIS PAGE INTENTIONALLY BLANK

National Aeronautics and Space Administration
Lewis Research Center

SPACE STATION FREEDOM

Electrical Power System
WP-04

Donald L. Nored
NASA - LeRC
January 16, 1990

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

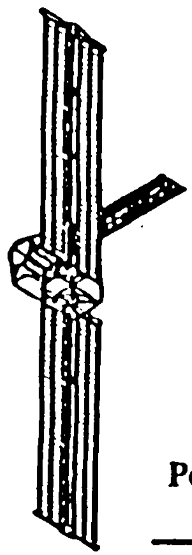
Rephasing Impacts

- 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

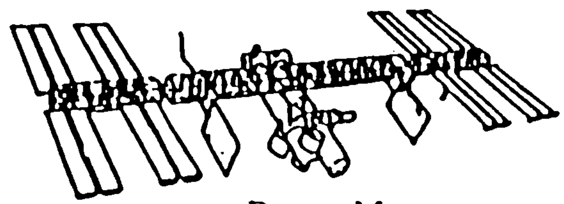
PHASE I EPS DELIVERABLES



Photovoltaic Power Module (4) (18.75 kW)

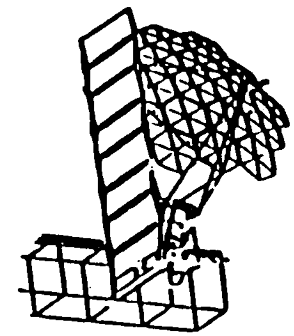
- Photovoltaic Power Generation
- Electrochemical Energy Storage
- Power Conversion and Control Equipment
- Beta Gimbals
- Thermal Control

Space Station (75 kW)



Power Management and Distribution (PMAD) System

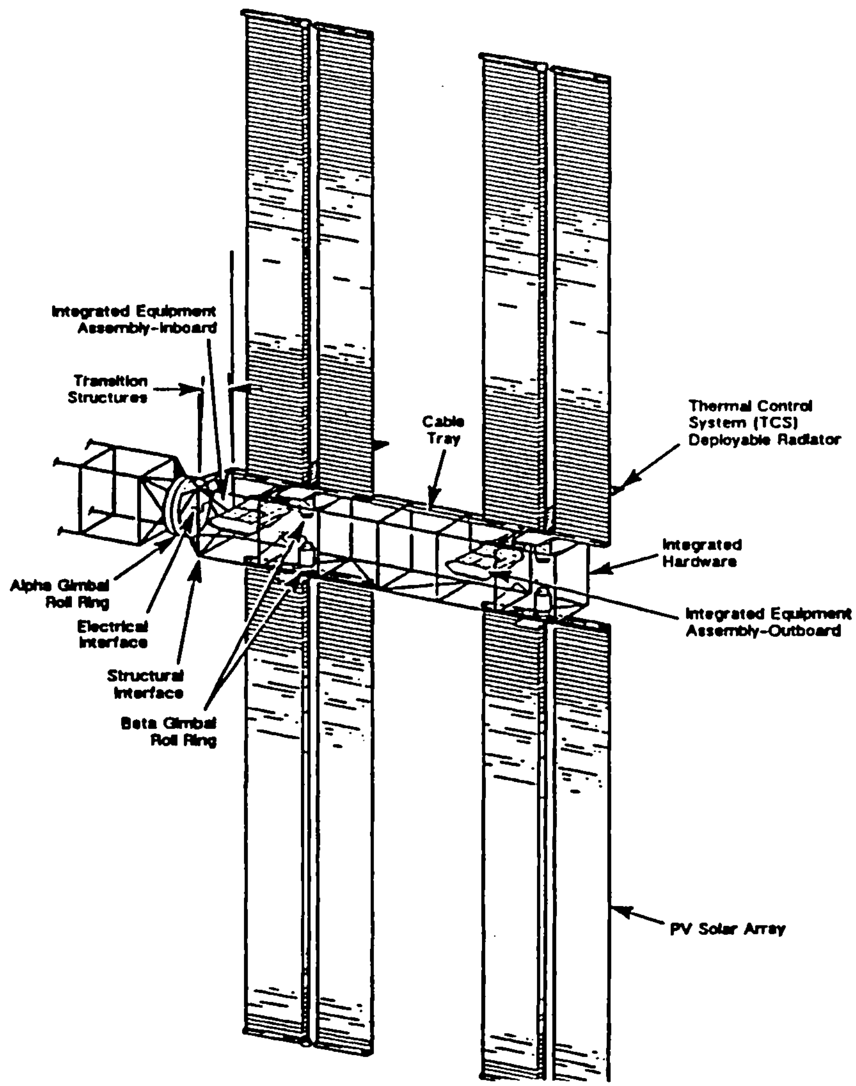
- EPS End to End Architecture
- Power Conversion and Distribution Equipment
- Power System Control Hardware and Software
- Common switchgear for Secondary Distribution



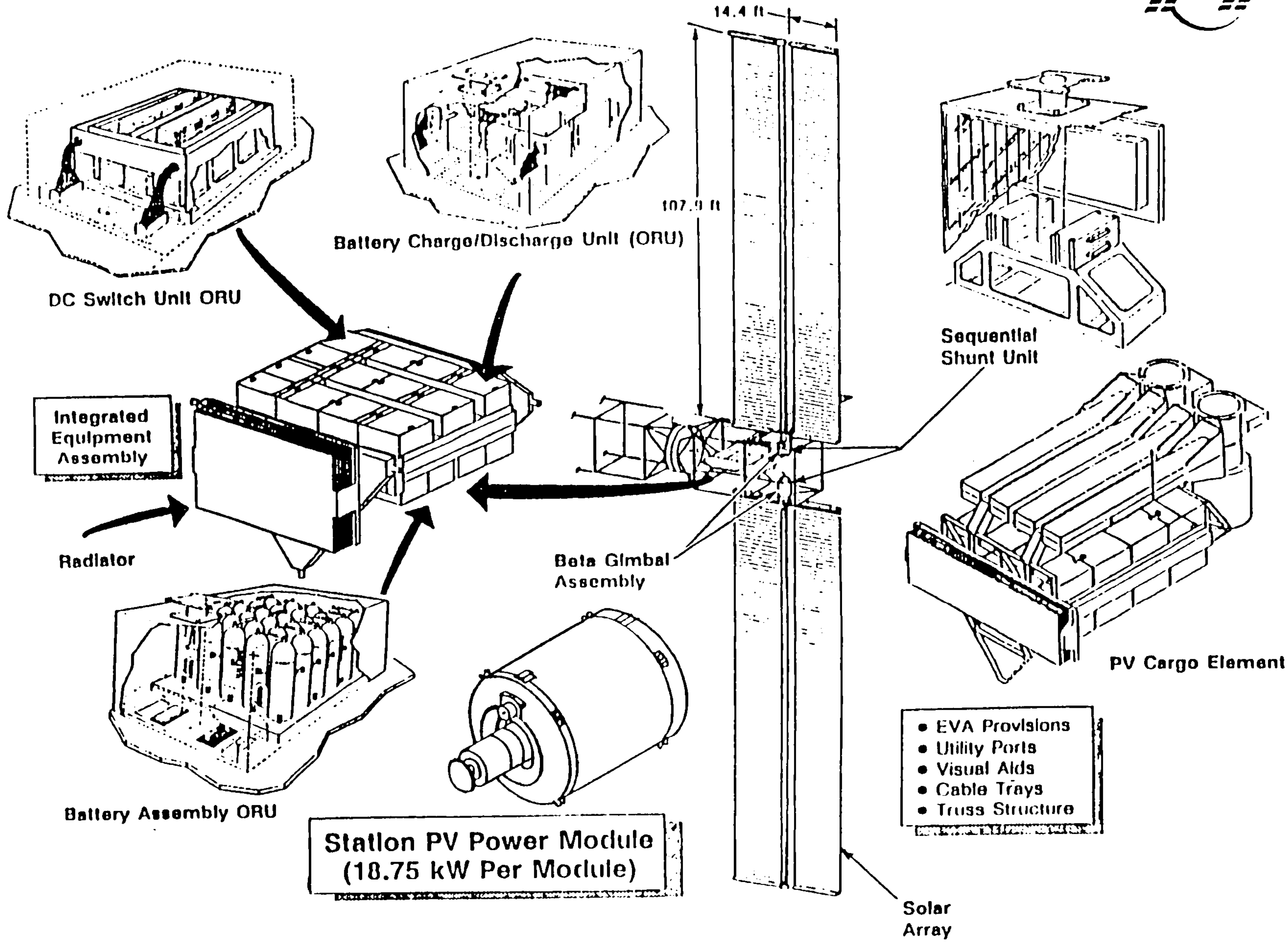
Solar Dynamic Definition

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

Inboard and Outboard Station PV Module

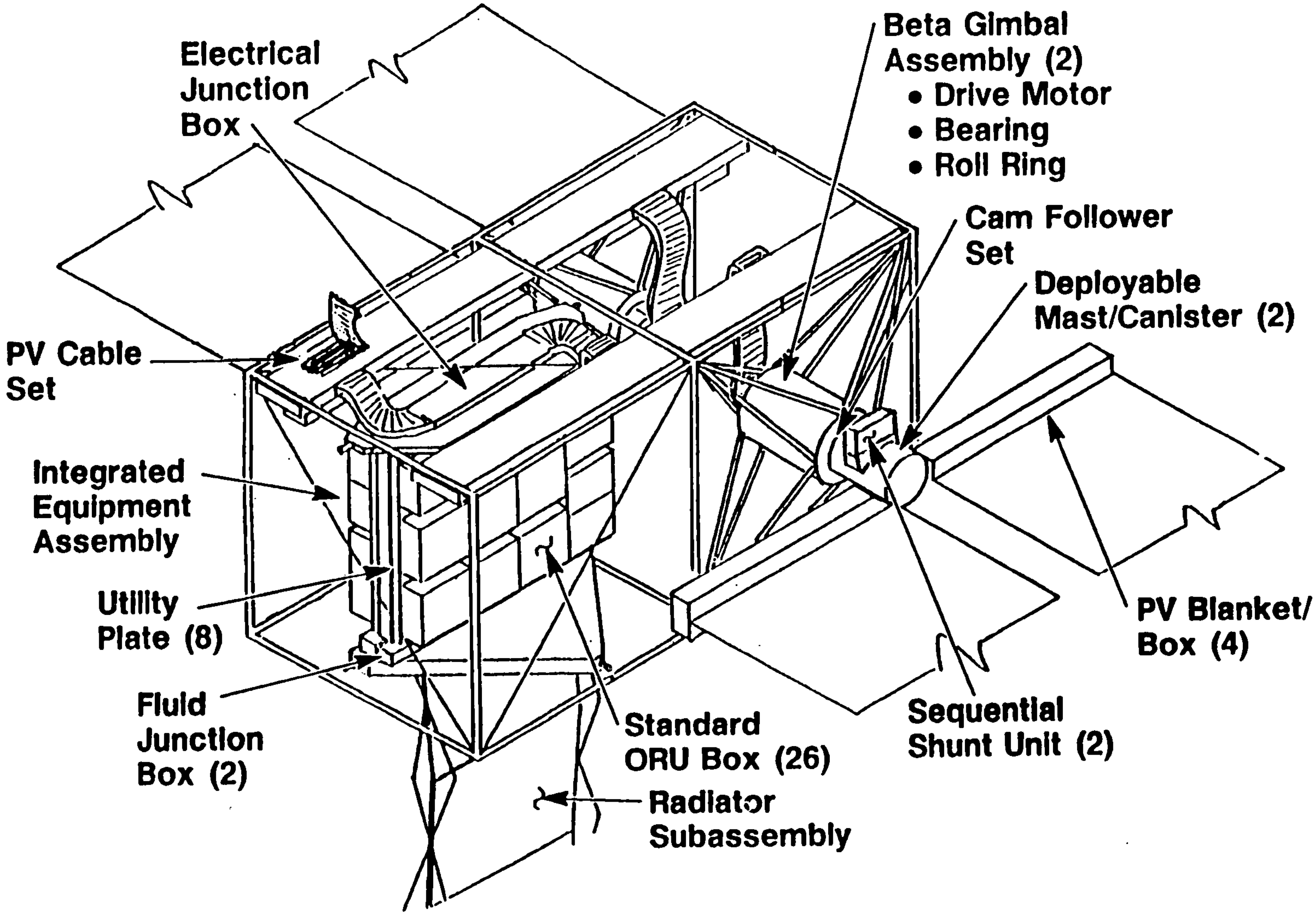


Photovoltaic Power Module Systems



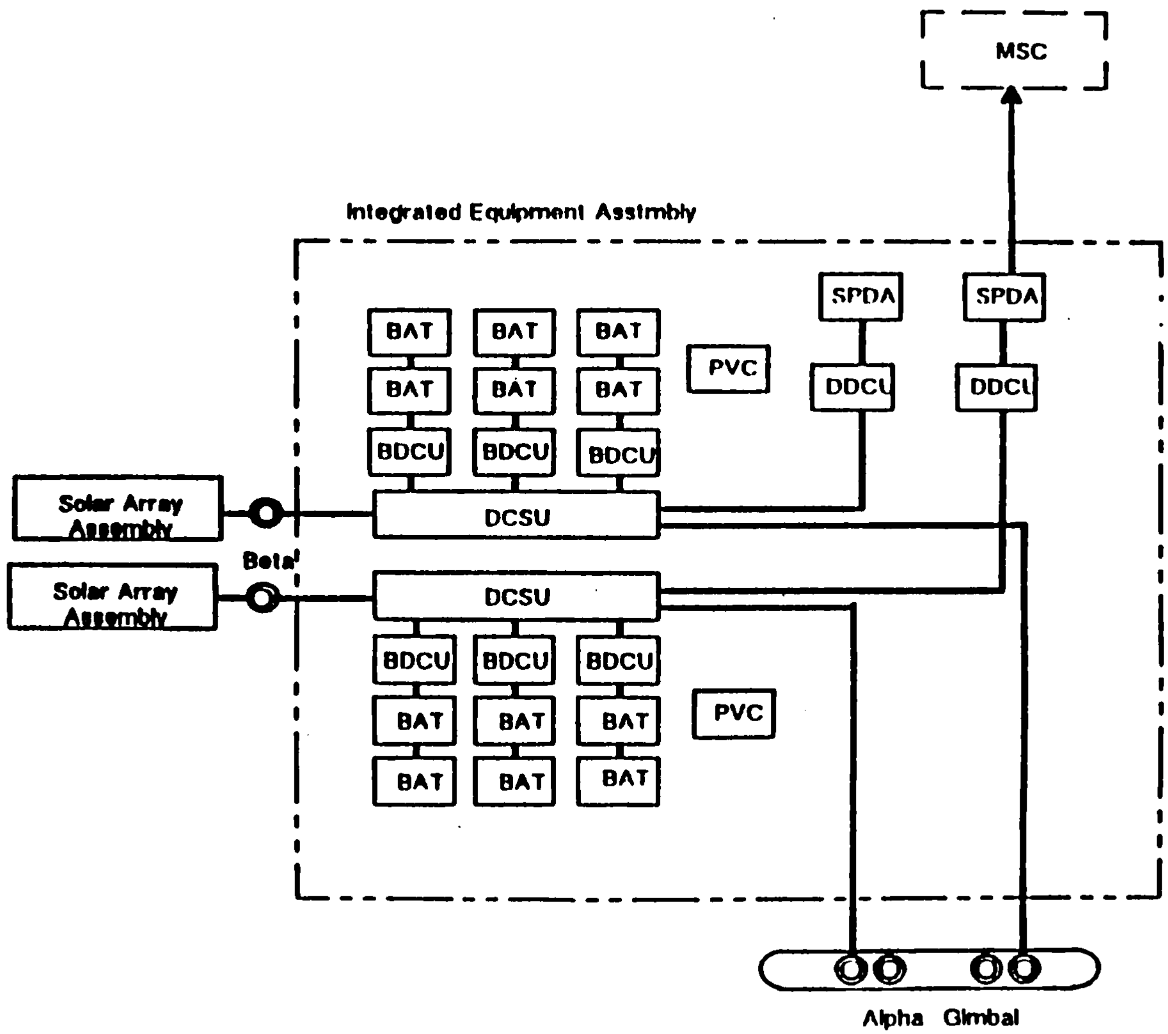
FREEDOM

PV Module



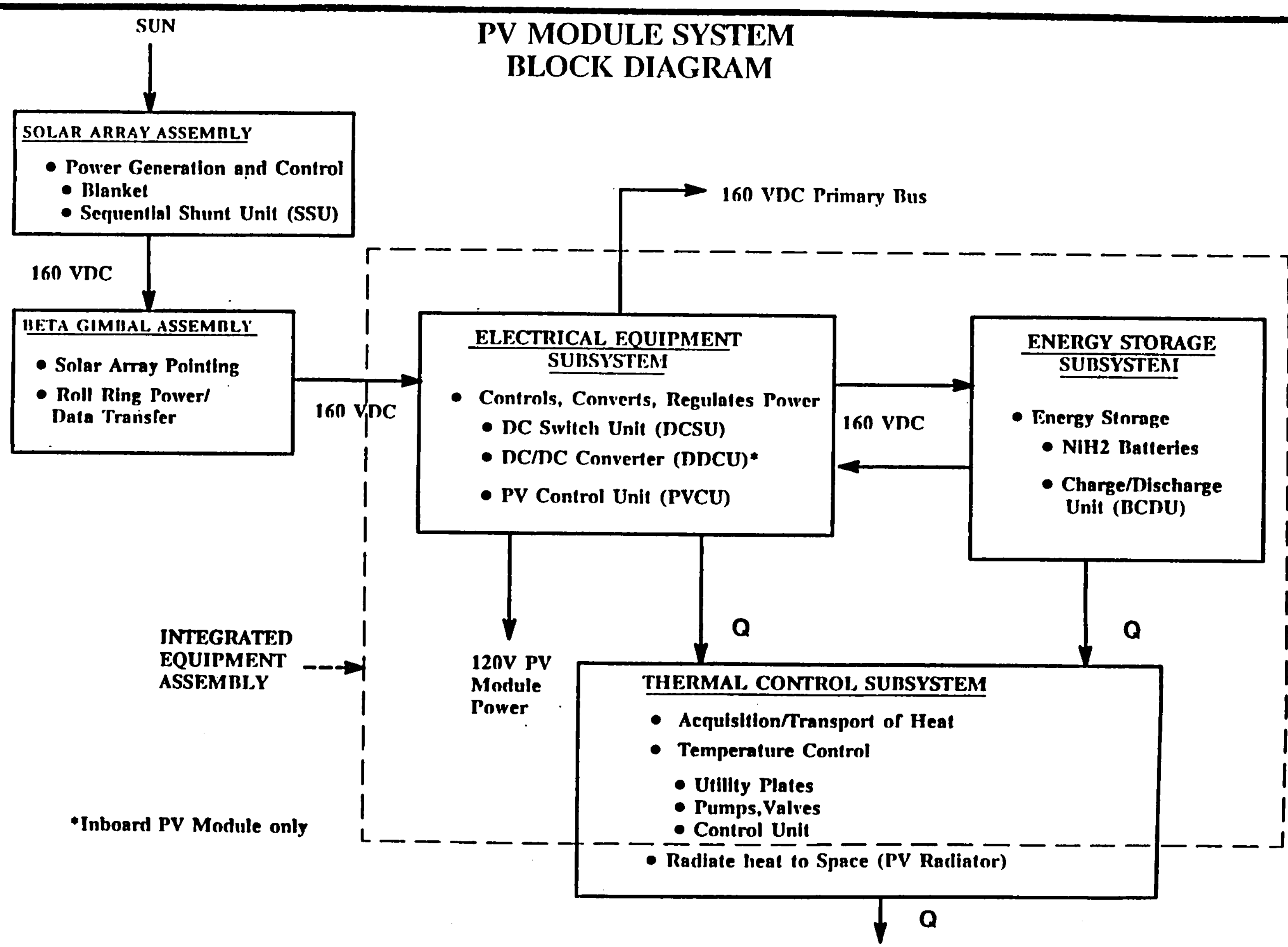
Rockwell International
Rocketdyne Division

Solar Power Module Architecture for the PMC Configuration

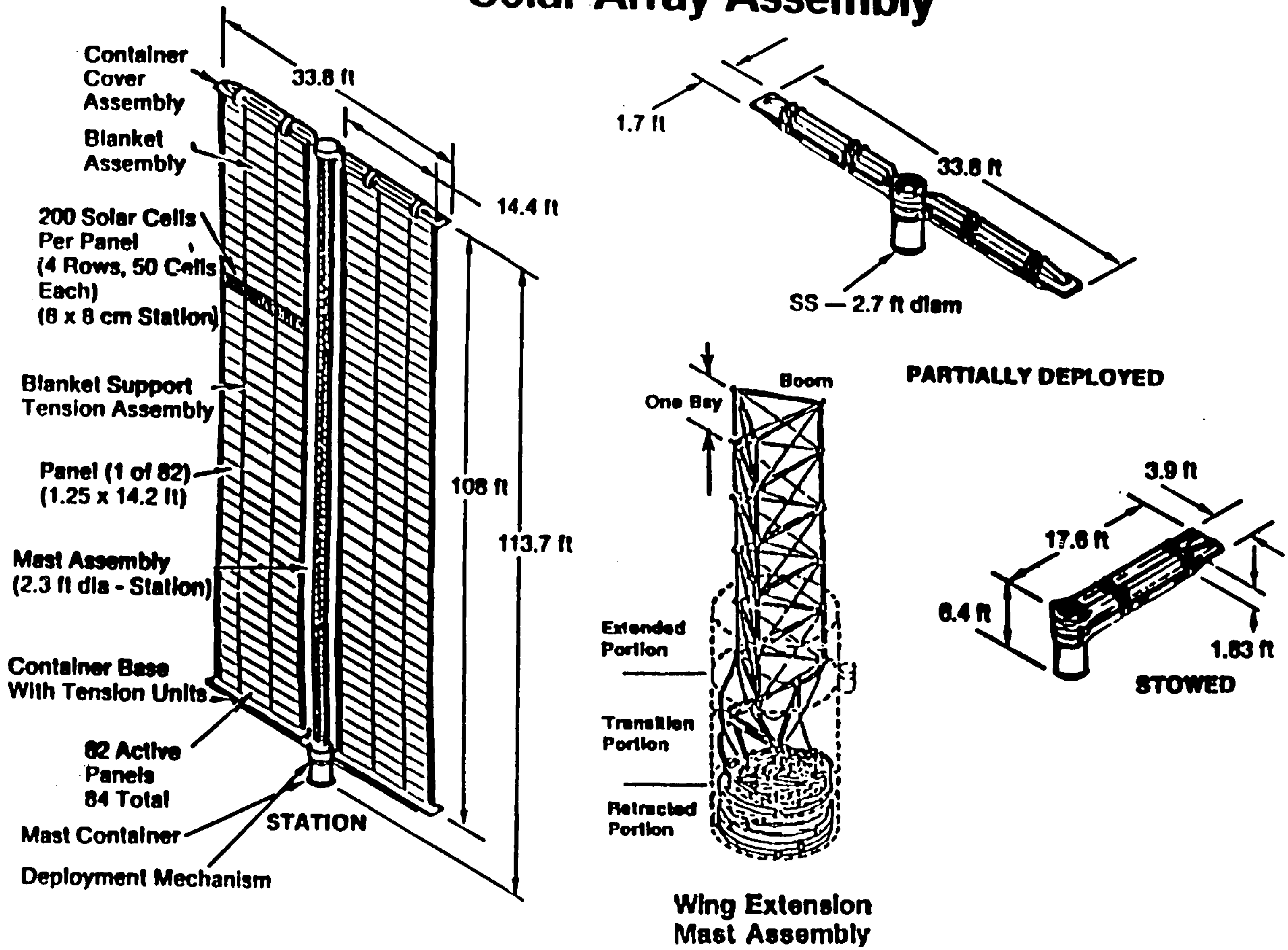


SPACE STATION FREEDOM

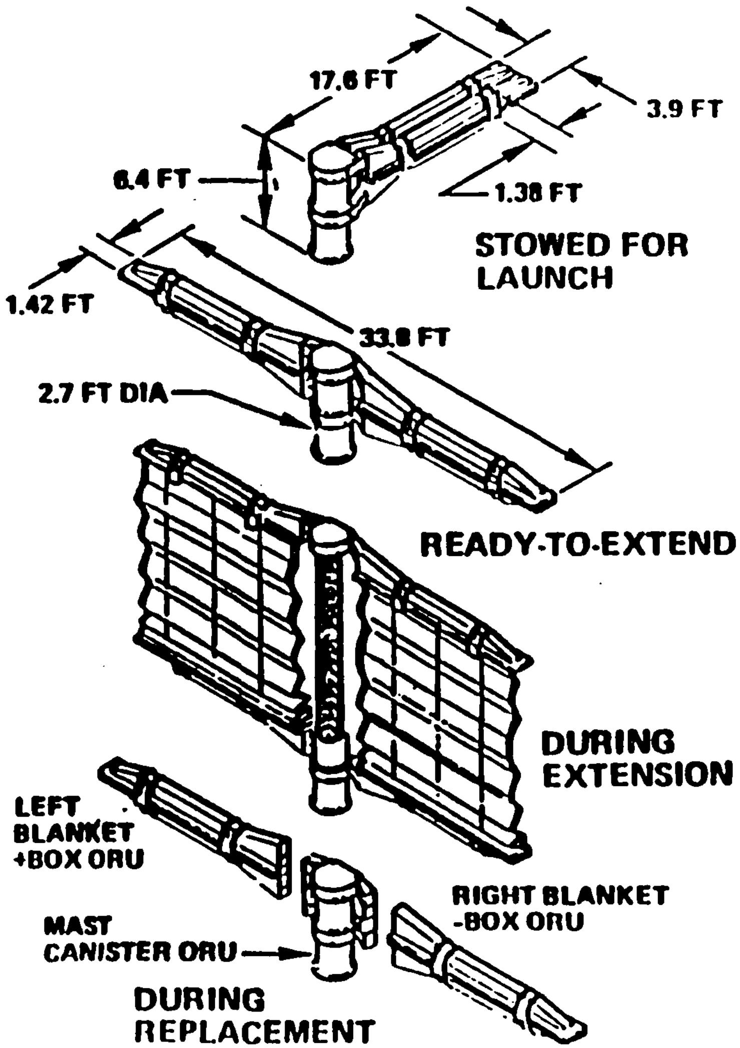
PV MODULE SYSTEM BLOCK DIAGRAM



Solar Array Assembly



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

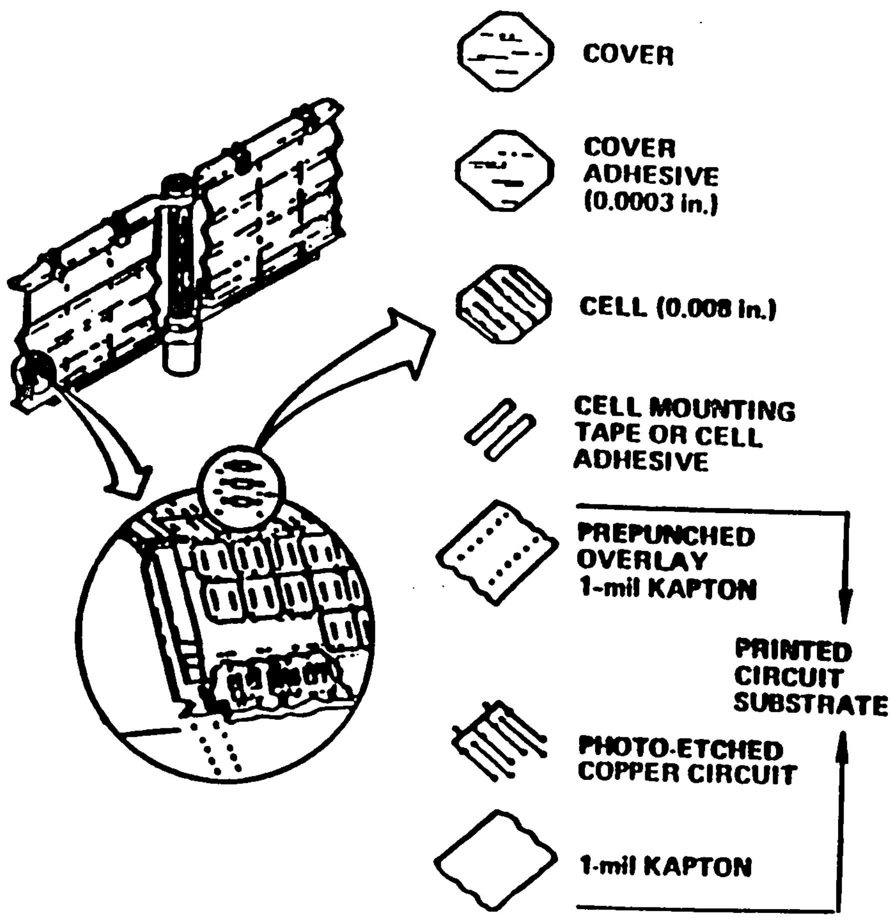
National Aeronautics and
Space Administration

Lewis Research Center

SPACE STATION FREEDOM

FREEDOM

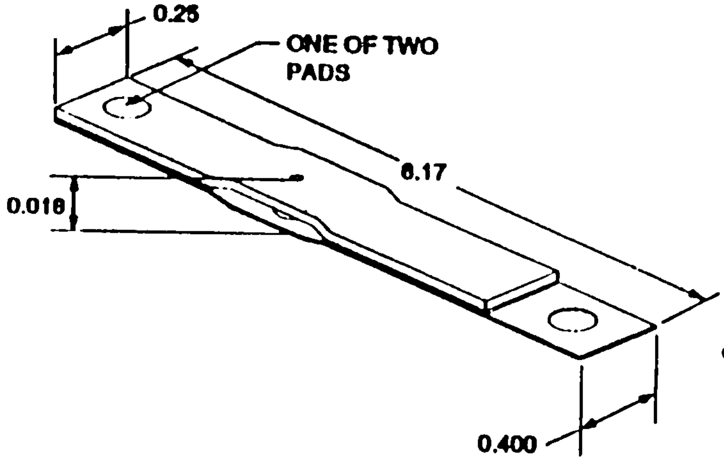
SOLAR CELL



EXPLODED VIEW OF ARRAY AND CELL SUBSTRATE

- SILICON CELL
  - 200 um (0.008 in.) THICK
  - 8 X 8 cm (3.15 X 3.15 in) 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

BYPASS DIODE ASSEMBLY



EXPANDED VIEW OF BYPASS DIODE
(DIMENSIONS IN INCHES)

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

KAPTON WITH ATOMIC OXYGEN RESISTANT COATING

DESCRIPTION

- 1 mil 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 CIRCUIT FABRICATION PROCESSING
- PROVIDES SPACE VACUUM STABILITY
- RESISTS ATOMIC OXYGEN DEGRADATION

SOLAR ARRAY DESIGN BENEFITS

- Minimum weight (fewer STS launches)
- Transparent blanket yields higher array efficiency
- Deployment/retraction concept minimized IVA/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

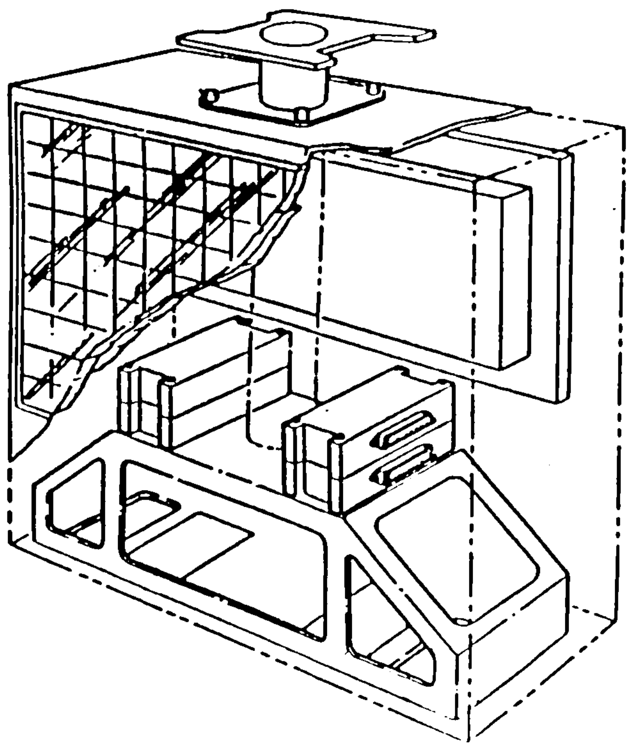
National Aeronautics and Space Administration

Lewis Research Center

SPACE STATION FREEDOM

PHOTOVOLTAIC POWER MODULE DIVISION

SEQUENTIAL SHUNT UNIT



SEQUENTIAL SHUNT UNIT (SSU)

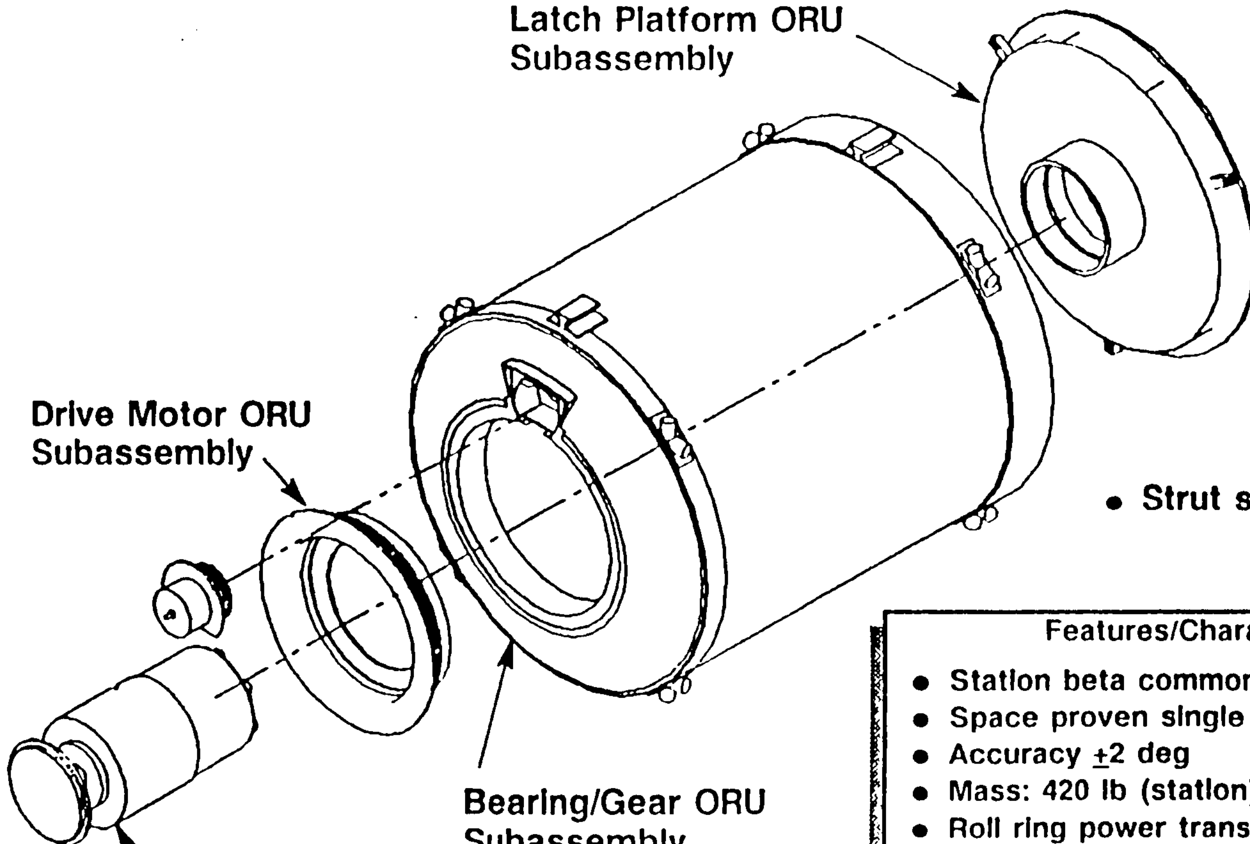
- PROVIDES EFFICIENT METHOD FOR
  - MATCHING ARRAY POWER TO LOAD DEMAND
  - REGULATING ARRAY OUTPUT VOLTAGE
- ONE SSU PER WING
- MOUNTED TO ARRAY MAST CANISTER
- LARGE FACES OF BOX RADIATE SSU WASTE HEAT DIRECTLY TO SPACE
- BOX FACES HAVE REQUIRED THERMAL MASS TO CONTROL SUN/ECLIPSE TEMPERATURE EXCURSIONS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

21

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	± 3 Vdc.

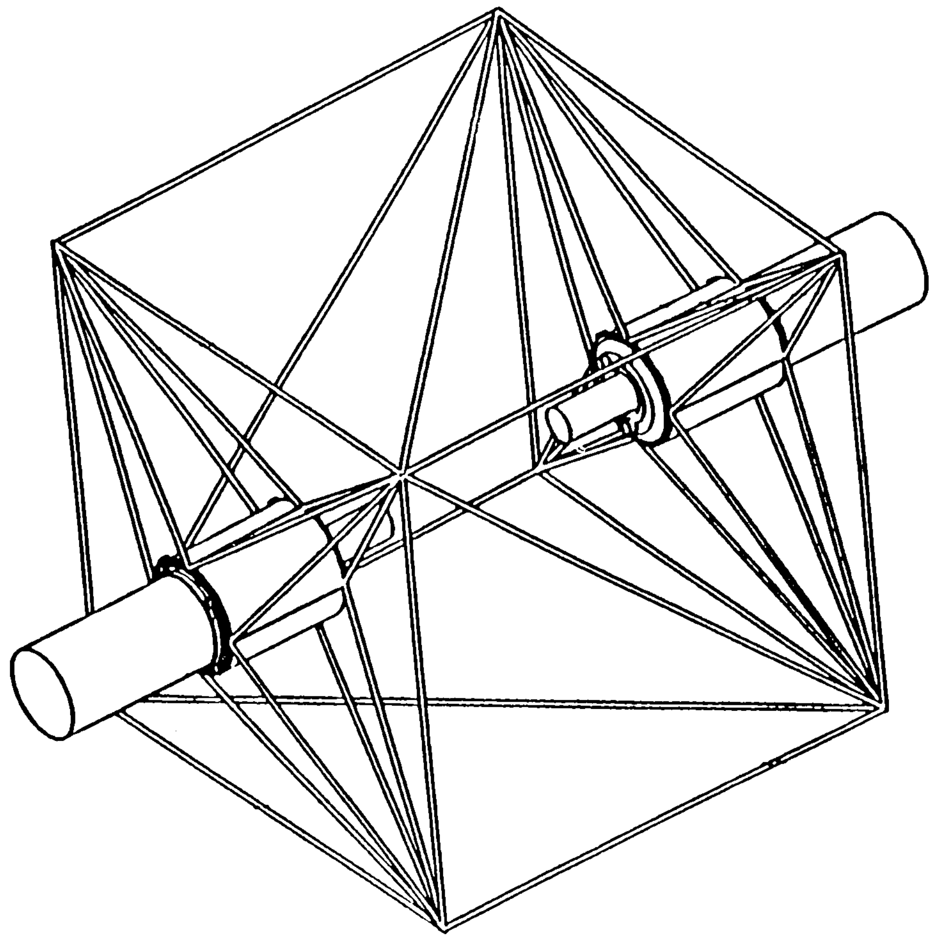
Gimbal Assembly



- Strut set

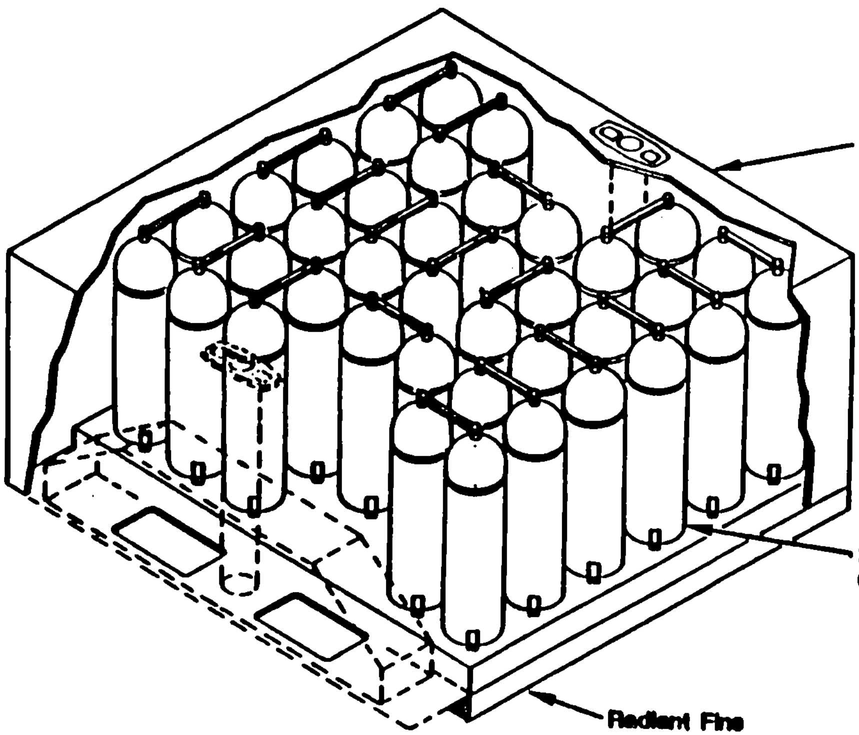
Features/Characteristics
• Station beta common with SD beta
• Space proven single wire race bearing
• Accuracy ±2 deg
• Mass: 420 lb (station)
• Roll ring power transfer (50-yr life test at NASA/LeRC)
• Power/signal circuits sized for redundancy & growth)
• Redundant drive motors 20 ft/lb torque

BETA GIMBAL/TRUSS ASSEMBLY



24

ENERGY STORAGE SUBSYSTEM
Ni/H2 BATTERY ORU



STATION
- 38 Cells per ORU
- Two ORU's per battery
- Nominal 95V
- Six Batteries per PV Module
- 24 Batteries total at Assembly Complete

REQUIREMENT
- ORU Interface Configuration 36x38x17
- Battery ORU Assembly Mass 320 lb
- Nominal/Minimum Battery Cell Capacity 81/77 Ah
- Mean Time between Replacement 5.0 yr
- Design Life 6.5 yr
- Design Cycle Life 36,000 cycles
- Storage Life 4 yr
- Nominal Depth of Discharge 35%

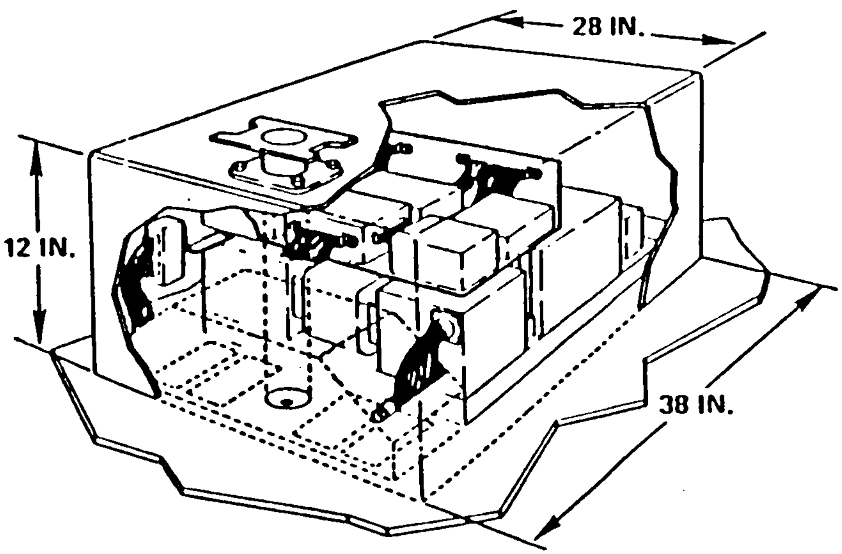
- Battery ORU provides station power during solar eclipse periods

Energy Storage Subsystem Performance

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

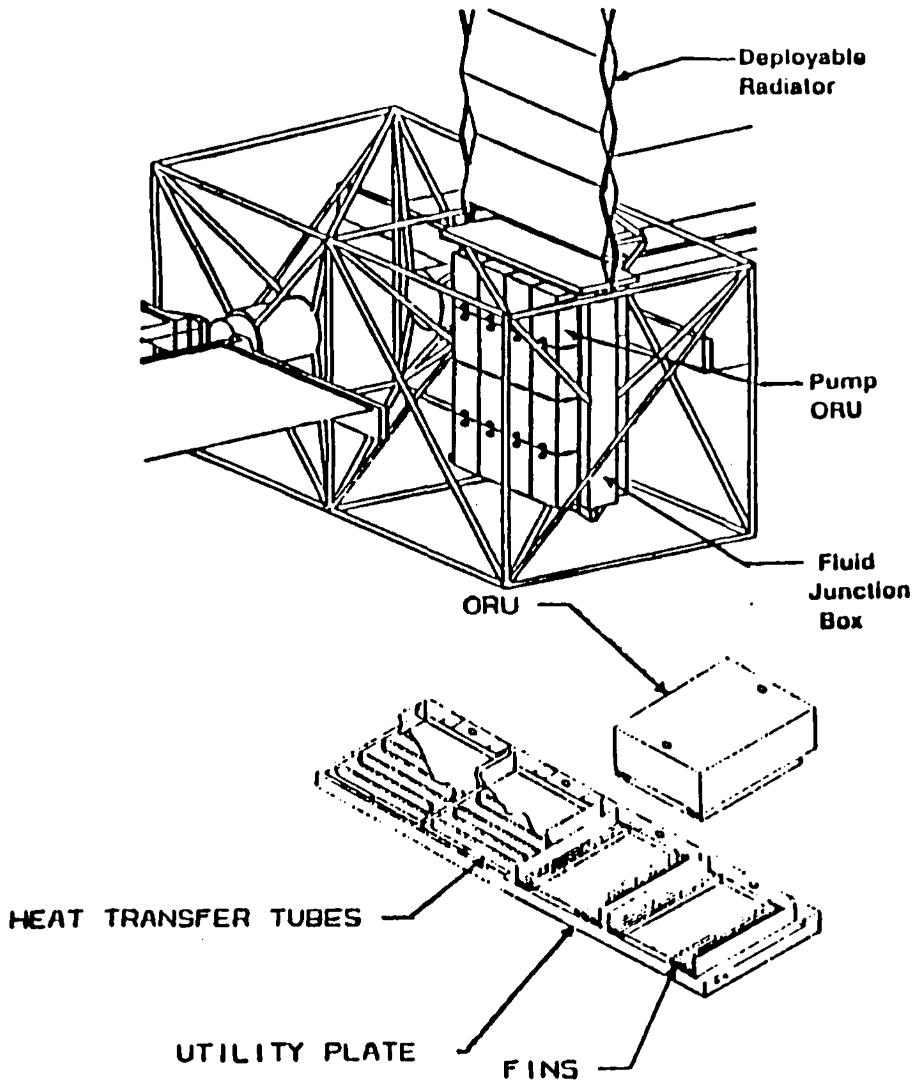
DOD = Depth of Discharge

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

SINGLE PHASE THERMAL CONTROL SUBSYSTEM

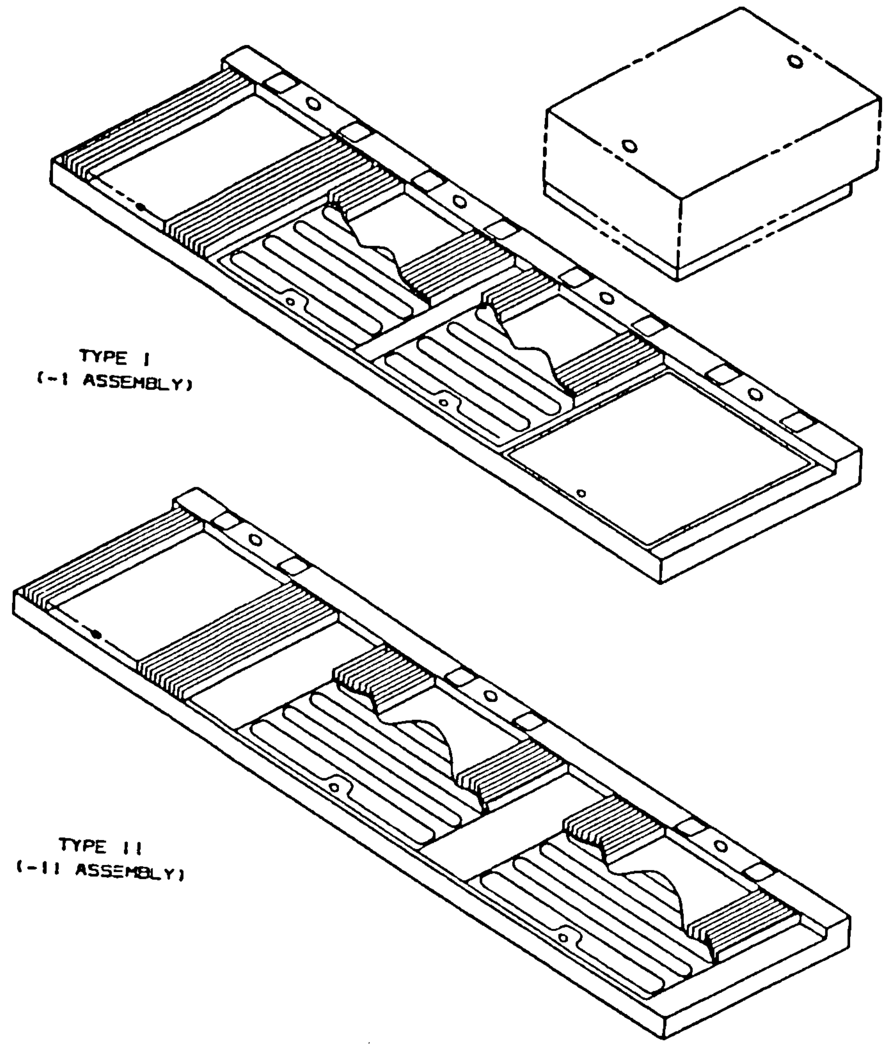


<u>ORUs</u>

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

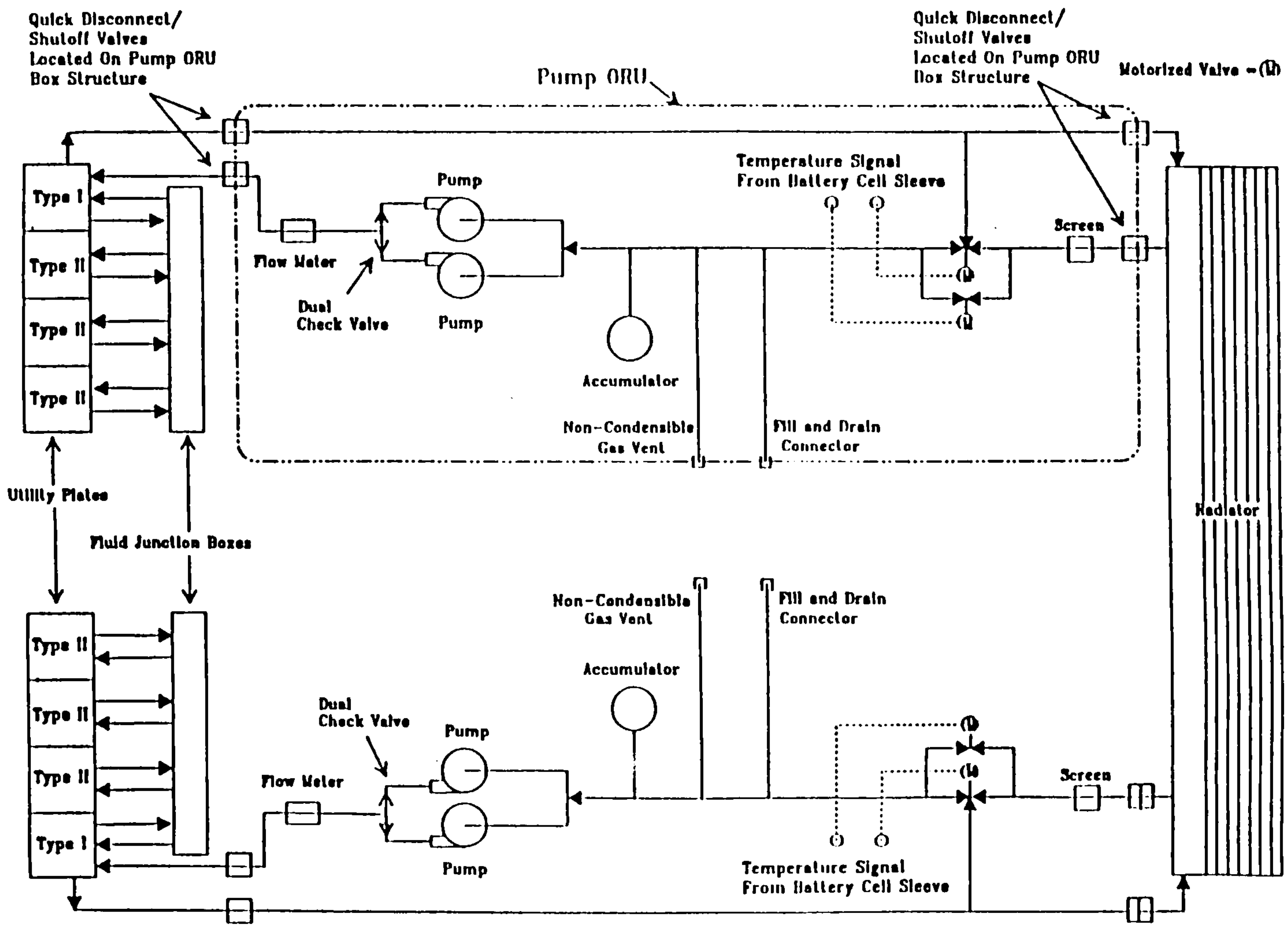
<u>Subsystem Characteristics</u>

• 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	$90^{0}C$
• Temperature Regulation	$\pm 1^{0}C$
• Ammonia Flow Rate	3000 lbs/hr
• Operating Pressure	120 psia
• Radiator Area	1000 ft^2
• Total Mass (auto deployed Rad.)	4513 lbs



Orbital Replacement Unit Box and Utility Plate Interface

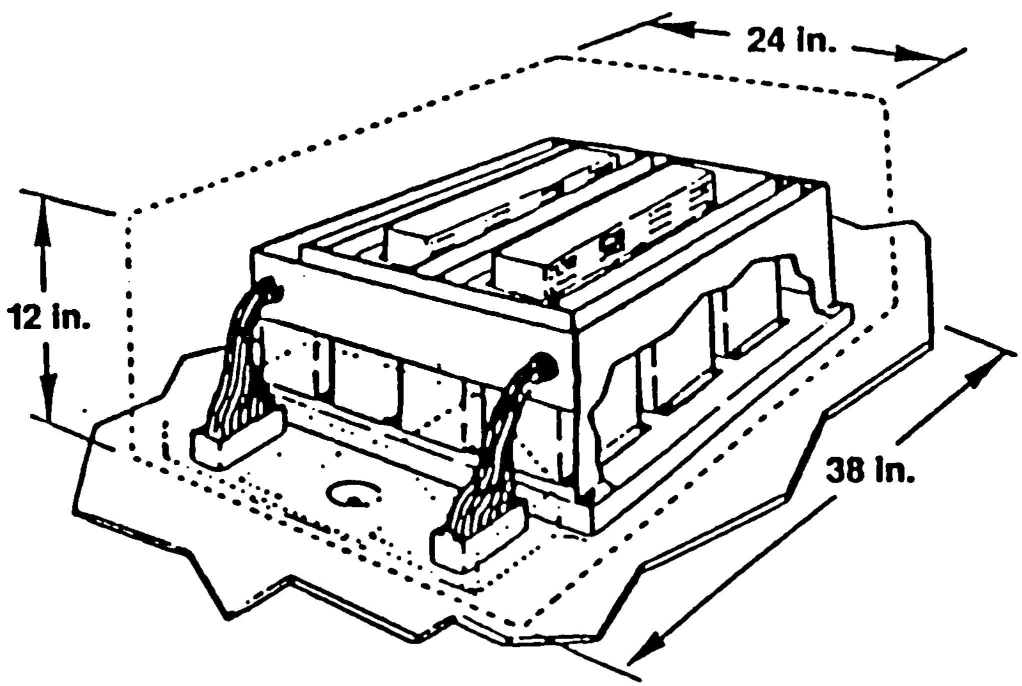
Thermal Control Subsystem



Thermal Control Subsystem ORU Characteristics

ORU	Mass (lb)	Dimensions (in.)	Nominal Parasitic Power (W)
Utility plate (Type 1)	334	126 x 38 x 6	0
(Type 2)	299	126 x 38 x 6	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

Direct Current Switching Unit



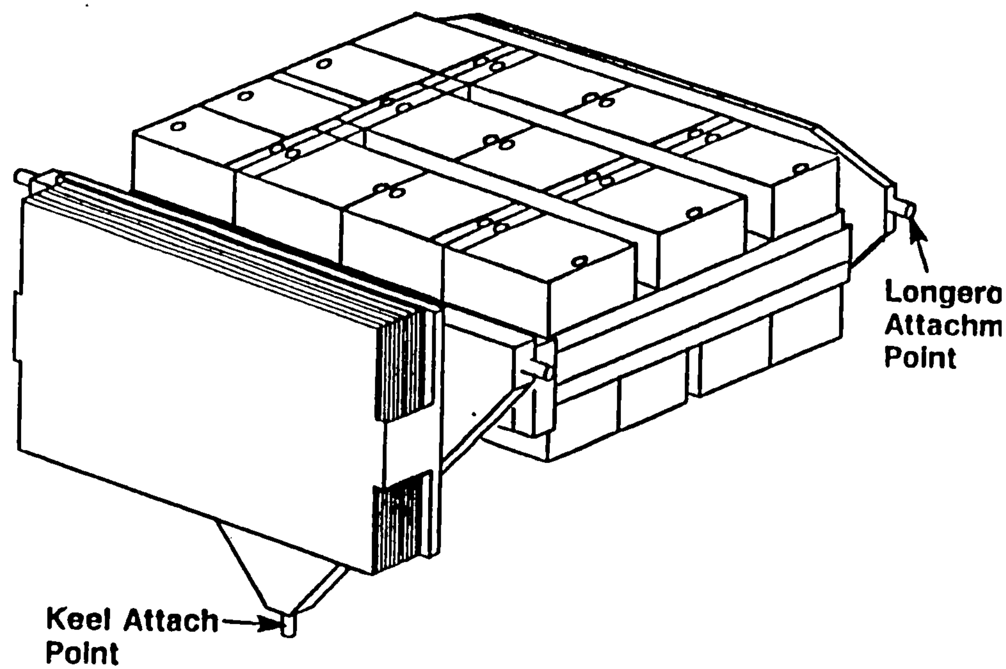
- DCSU RBI status monitored & commanded open/close
  - By PVC
  - Through local data interface (LDI)
- DCSU contains PV control element (PVCE)
  - Provides error signal to SSU for array power regulation

NSTS Electrical Interfaces

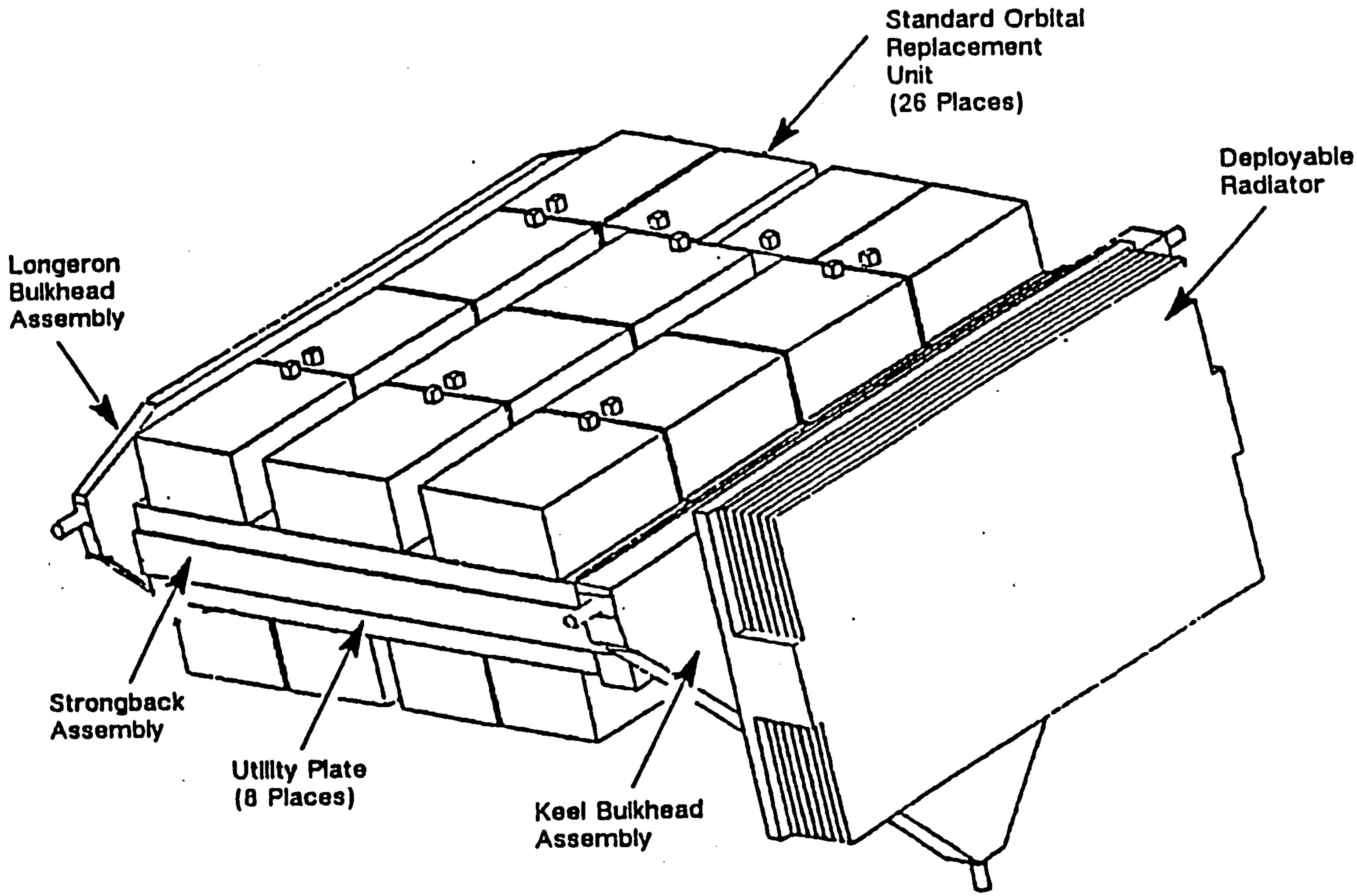
- EPS start–up terminal
  - Ground/flight check (bit) of electronics
  - System power up
  - System monitoring
- Orbital interface power unit
  - Ground/flight trickle charge
  - Ground/flight battery health monitoring

Integrated Equipment Assembly (IEA)

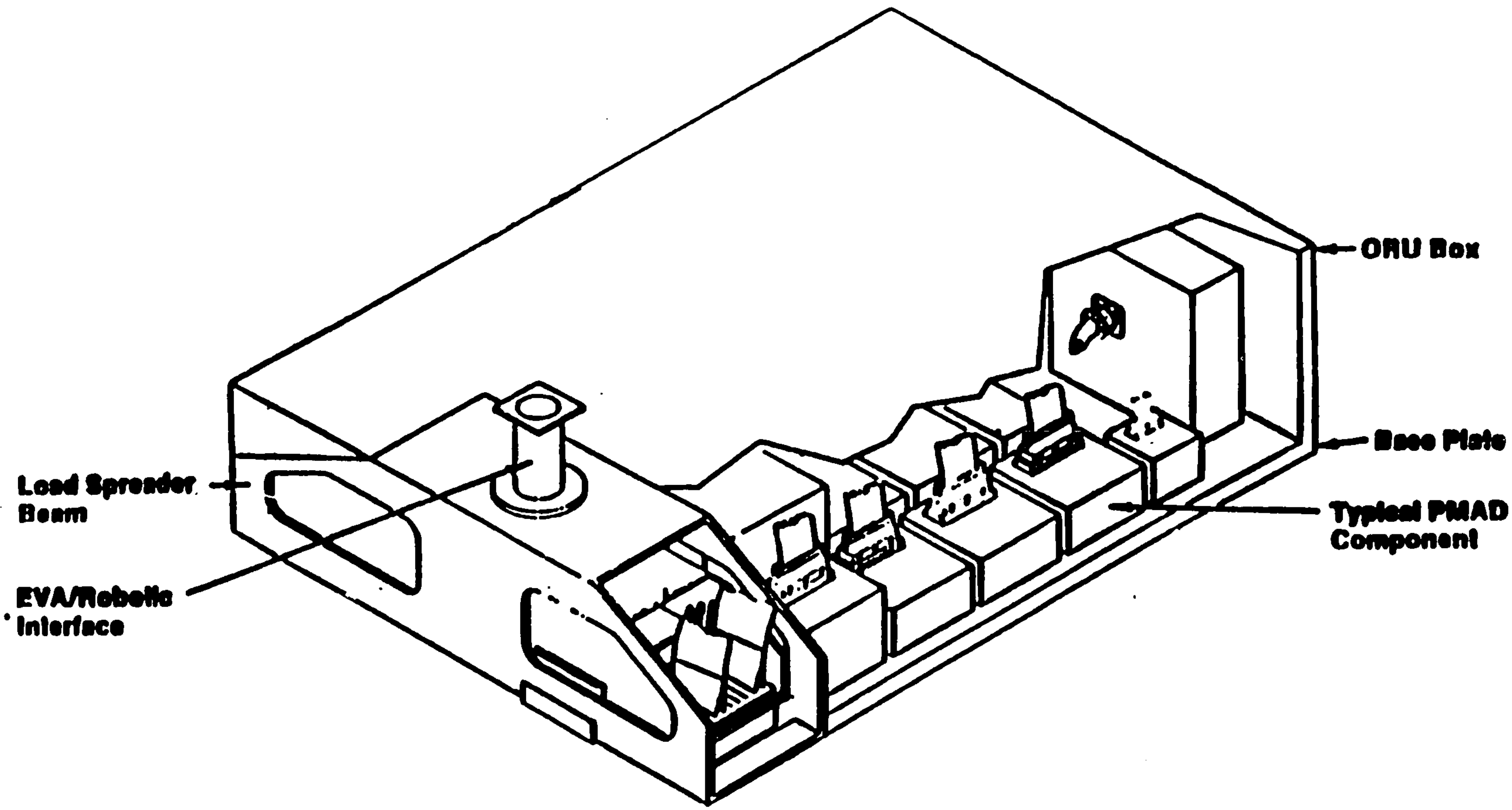
- Provide structural support
  - Energy Storage
  - Electrical Equipment
  - Thermal Control Subsystem ORU's
- Interface Structure
  - NSTS Orbiter Cargo Bay



IEA Assembly



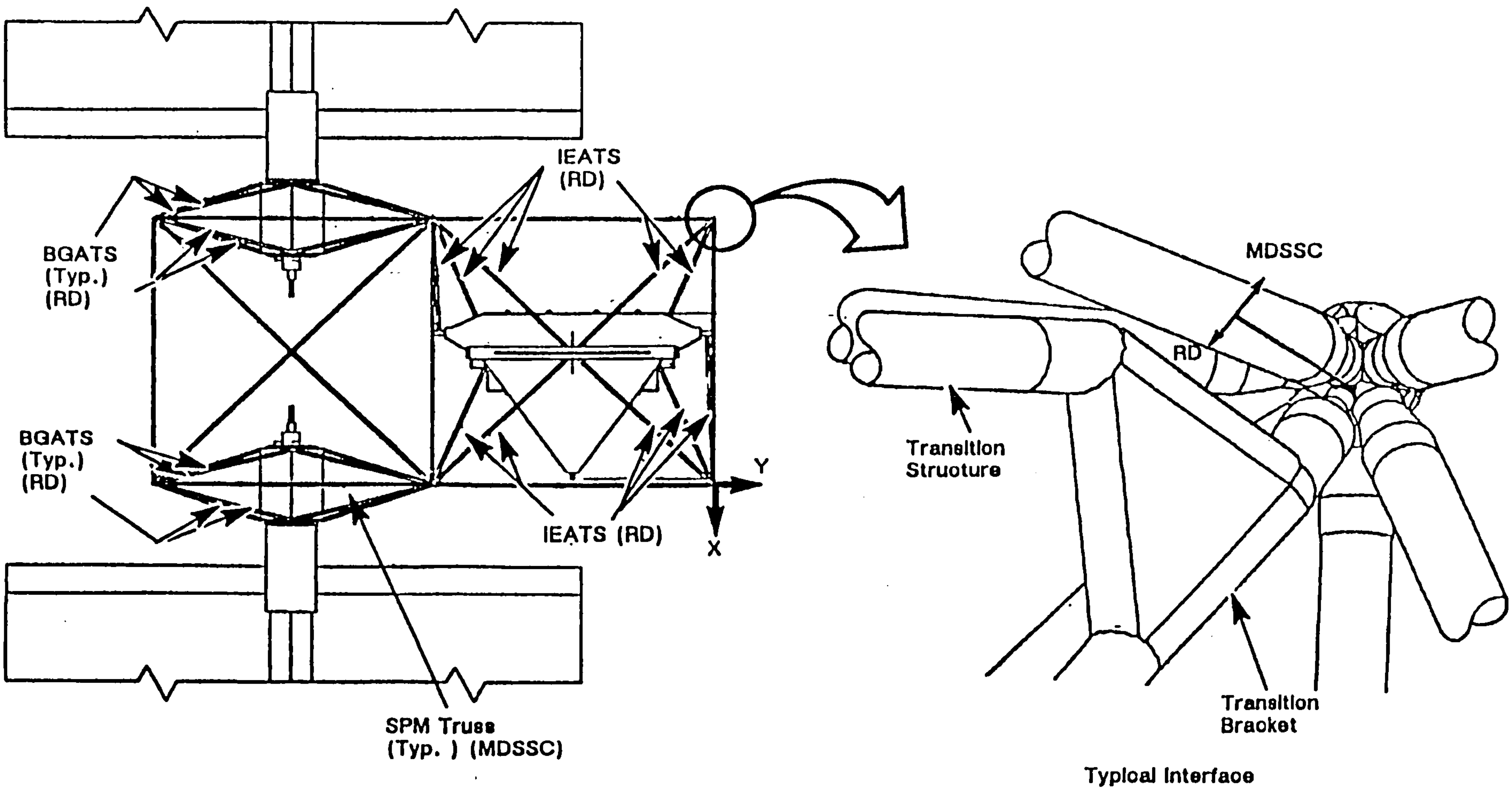
Conceptual Packaging Approach



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)

IEA & BGA Transition Structure to Truss Assembly Interface



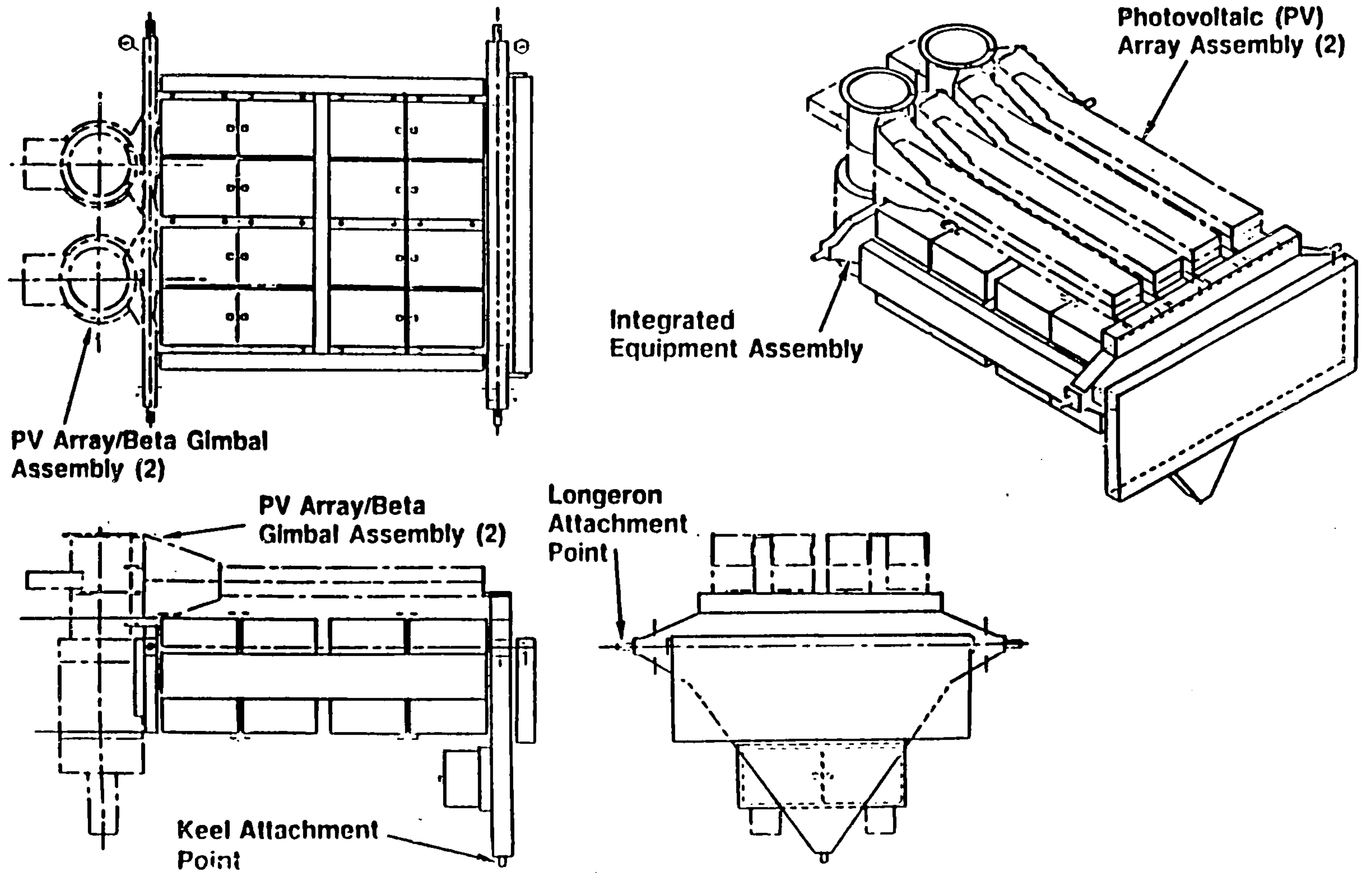
National Aeronautics and
Space Administration
Lewis Research Center

SPACE STATION FREEDOM

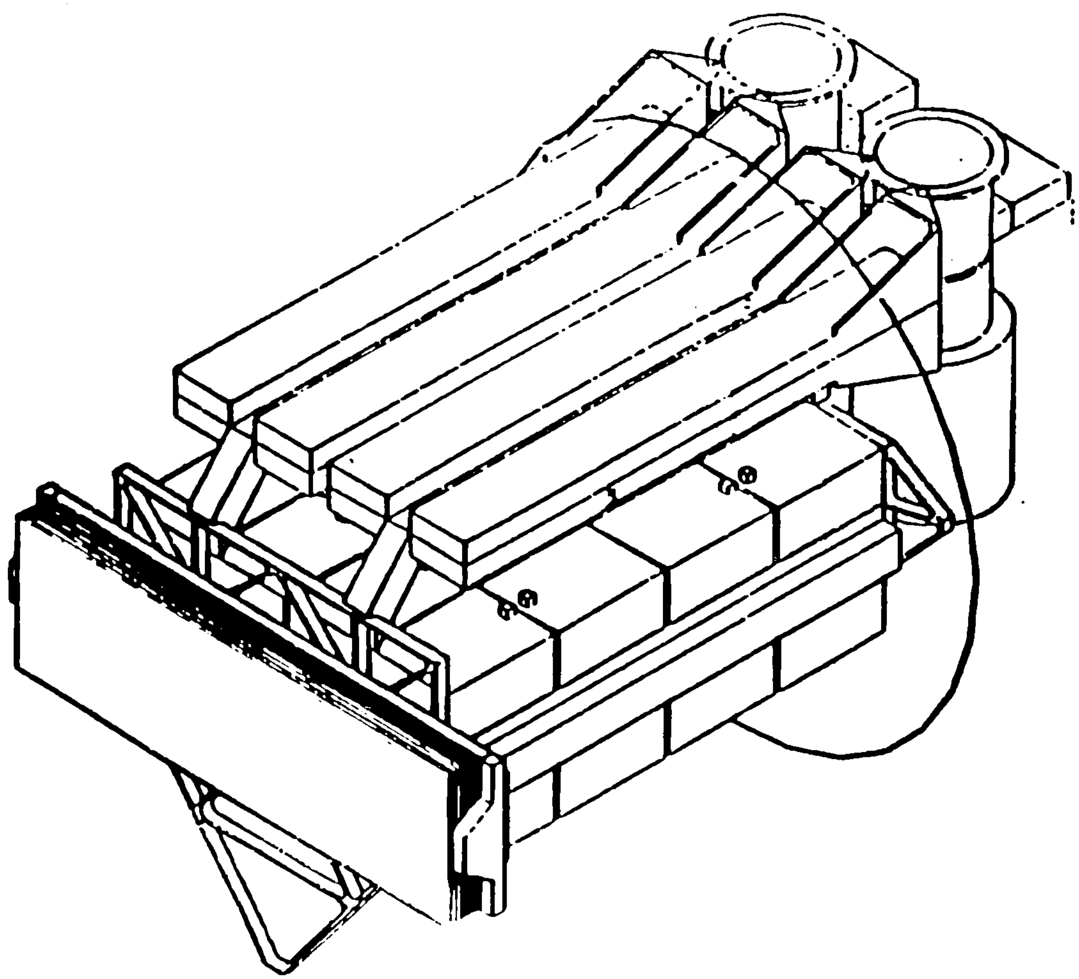
PHOTOVOLTAIC POWER MODULE DIVISION

FREEDOM

INTEGRATED EQUIPMENT ASSEMBLY



PV CARGO ELEMENT



PV Cargo Element

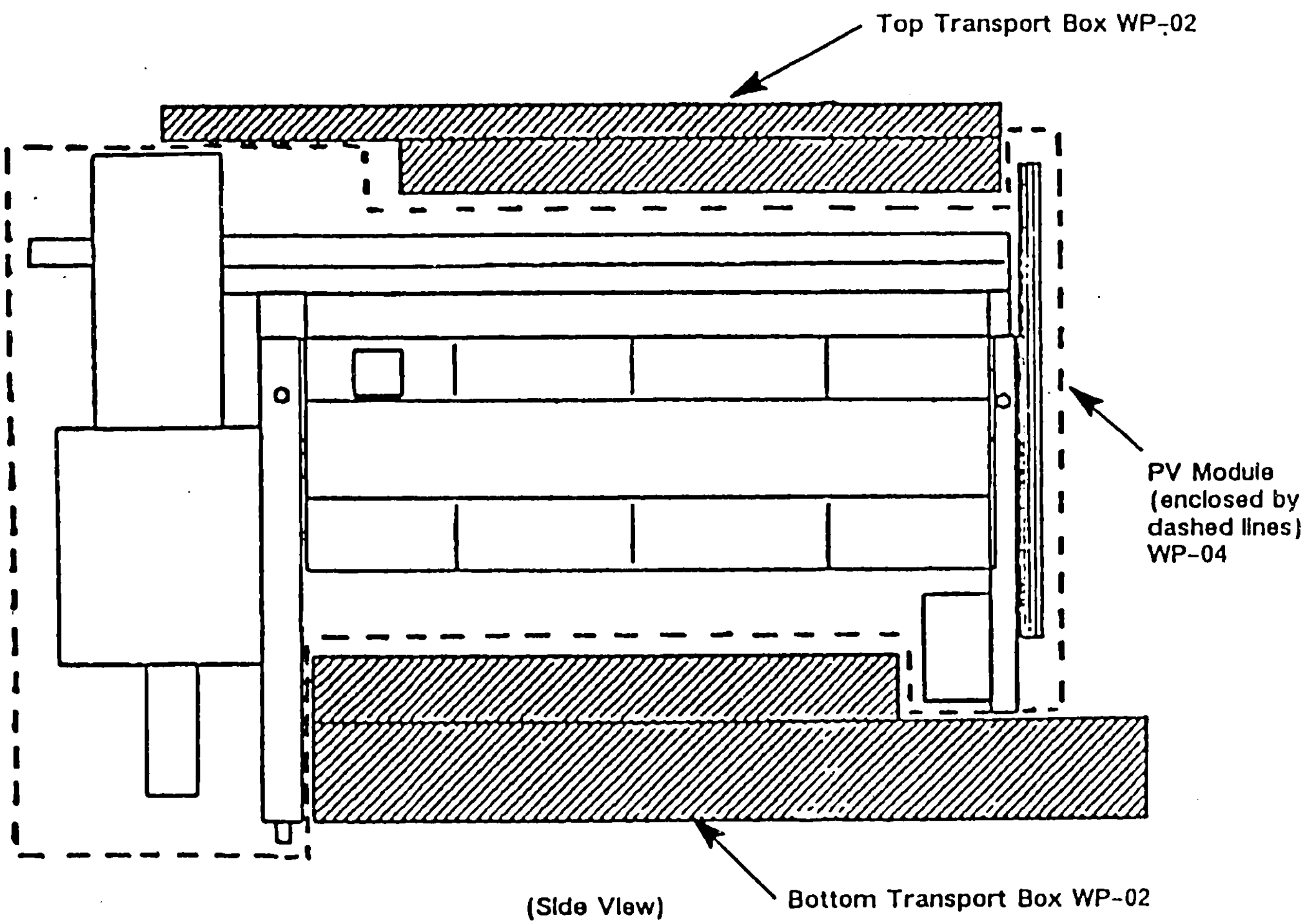
- Beta Gimbal Assembly
- Solar Array Assembly
- IEA Structural Framework
- Single Phase Thermal Control System (TCS)
- Energy Storage Subsystem
- Electrical Equipment
- PV Integration Hardware
- FSE
- Transition Structures

41

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	–

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

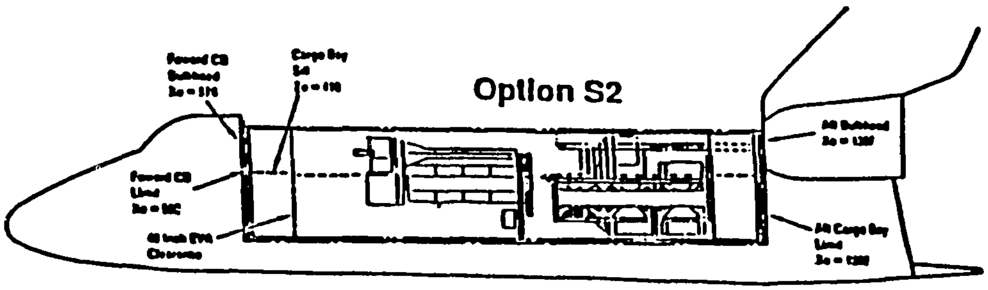


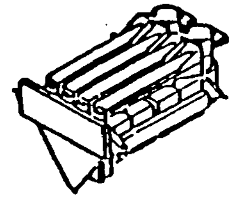
- Truss, Ceta Rails and Utility Trays Will Be Packaged In Transport Boxes
- Transport Boxes Will Be Packaged Above and Below PV Module For Access
- Transport Boxes Will Be Attached to PV Module Via Latches (Not Shown)

Note: PV Module's Integrated Equipment Assembly (IEA) Is Not Current Configuration

Separate PV Module Launch Package is Common Across Flights

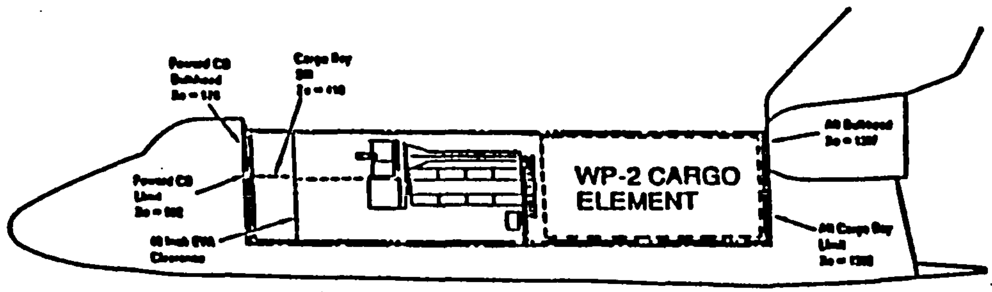
PV-1

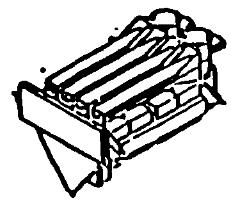




PV Module
Launch Package

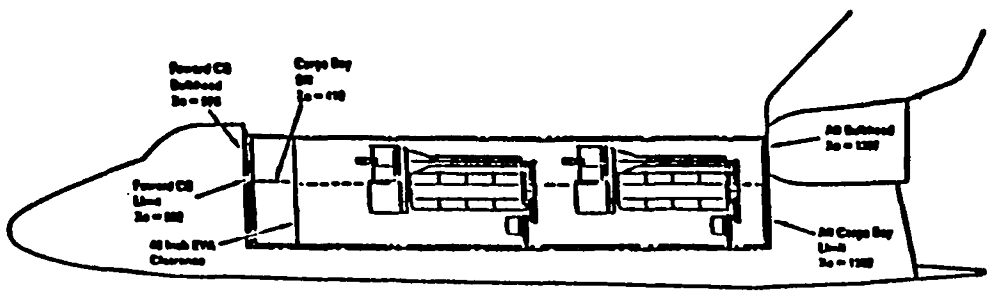
PV-2

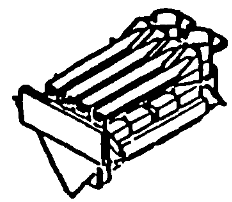




PV Module
Launch Package

PV-3 & 4





PV Module
Launch Package

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)
- Transition Structure (1)
- Electrical Junction Box (2)
- NSTS Interface Hardware (5) *
- MSC/RMS Grapple Fixture (1) *

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 *
- Truss Closeout *
- Translation Rails & Cable Tray*

* GFE

PMAD System Responsibilities

Design end-to-end Power System Architecture

Design, Develop, Produce PMAD Hardware for Station

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

Key Power Requirements - AC

- **Power:**

User	75 kW-A/100 kW-P
Habitat Module	25 kW peak
Laboratory Module	25 kW peak
Nodes	12.5 kW peak
ESA	25 kW peak
JEM	25 kW peak
APAE & MSC	(TBD) (10 kW)
Pressurized Payload	(TBD) (12 kW)
Cables	Sized and installed to deliver peak power
Growth	175 kW-A/215 kW-P
Grounding	Single point (designed negative)

Key Features of PMC and AC Architecture

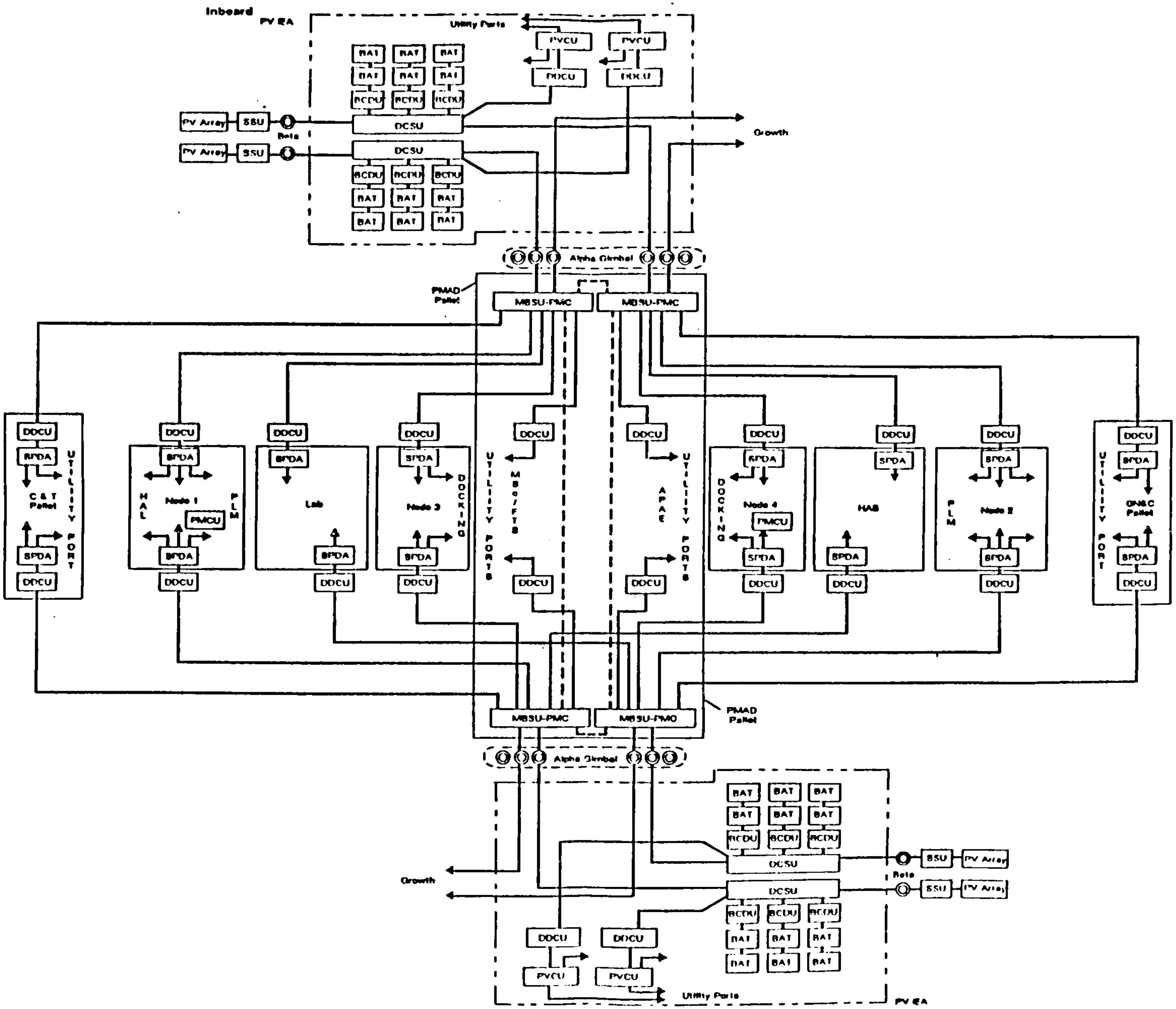
PMC Station:

- 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

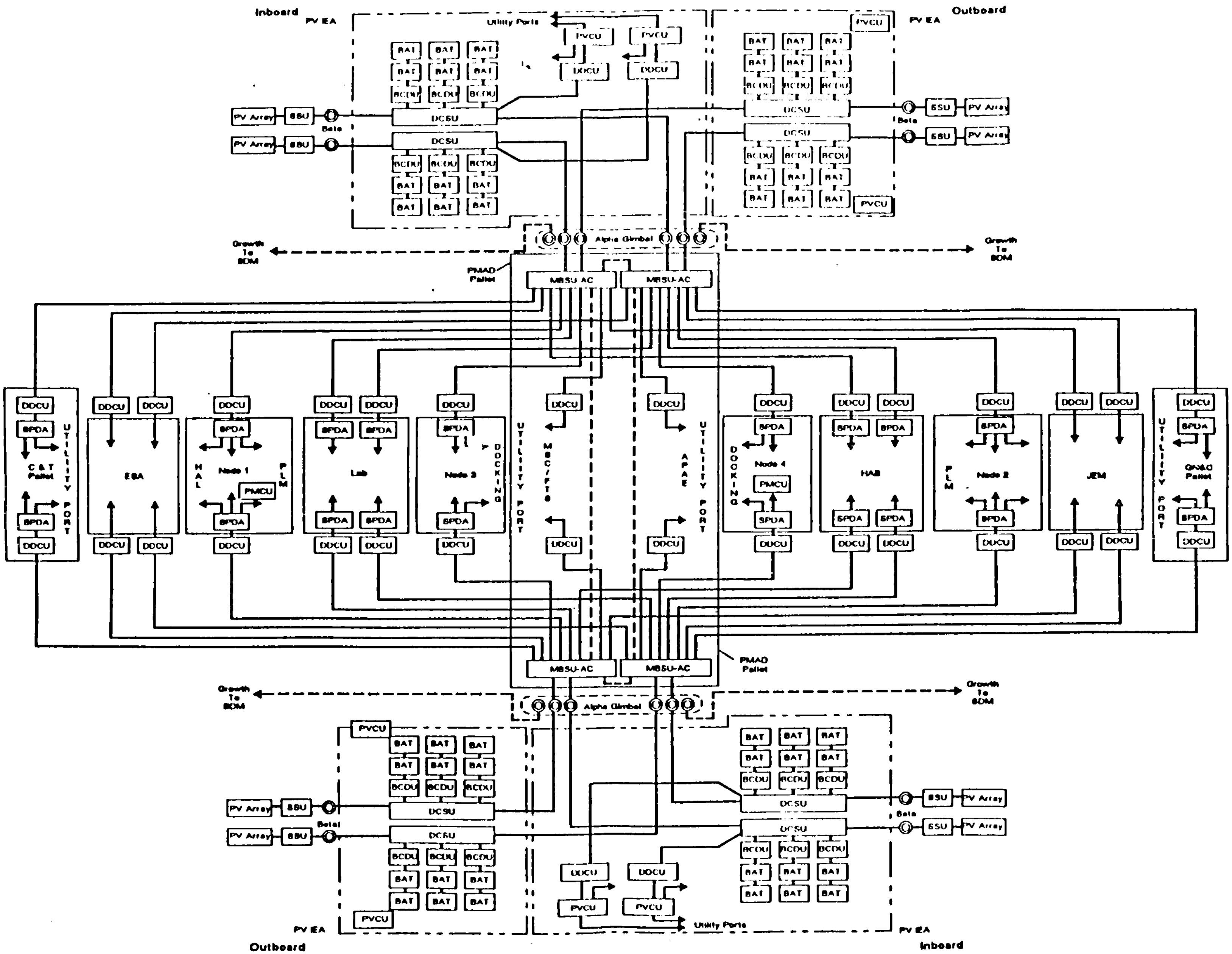
AC Station:

- 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

POWER SYSTEM ARCHITECTURE
PMC CONFIGURATION

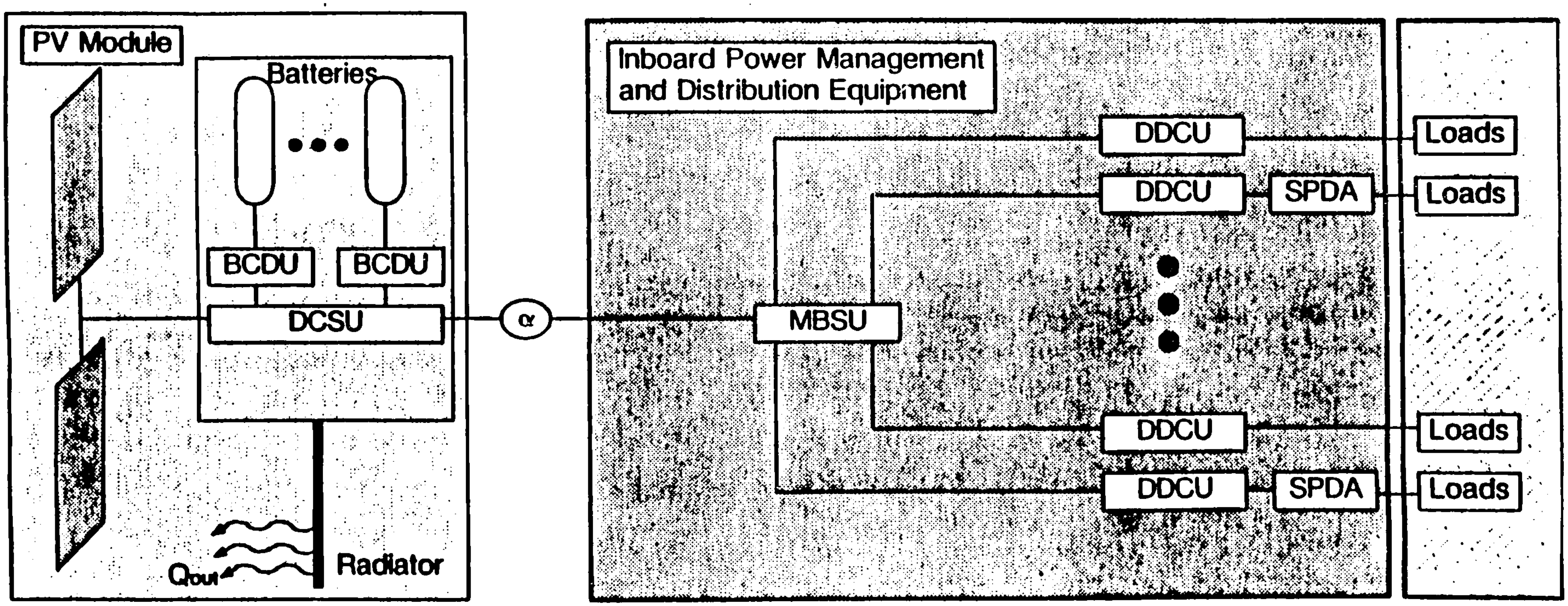


POWER SYSTEM ARCHITECTURE
AC CONFIGURATION



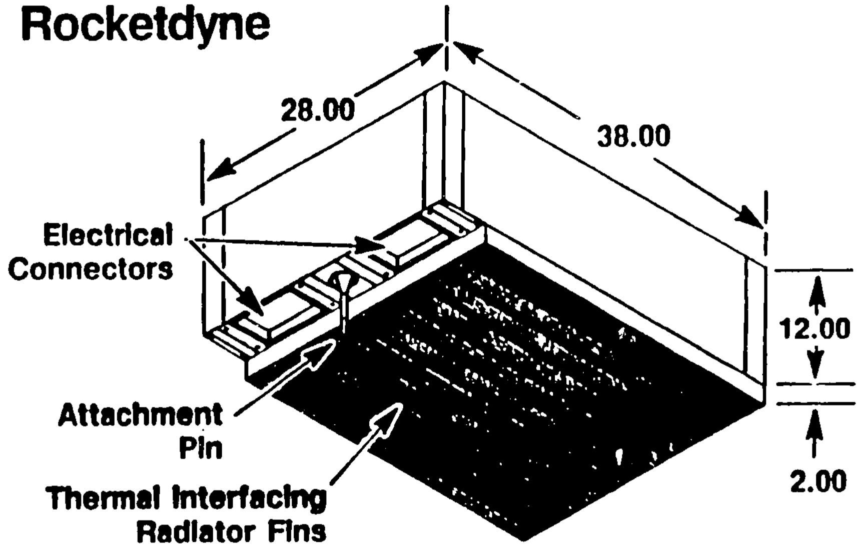
SPACE STATION FREEDOM

SIMPLIFIED SYSTEM ARCHITECTURE

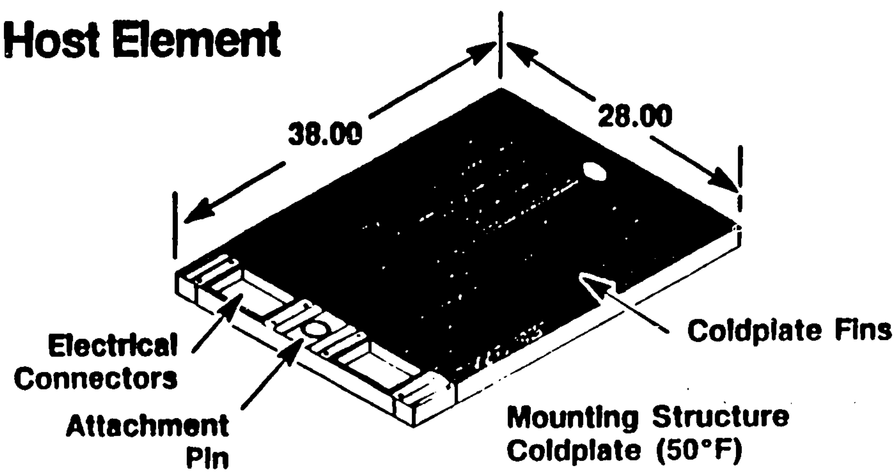


DDCU & MBSU External Interface

Rocketdyne



Host Element



- Electrical connectors for power & data
- 2 guide pins for mechanical attachment
- EVA & robotic installation & replacement
- Fin heat exchanger thermal interface
- Coldplate temperature $\leq 50^{o}$F

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:

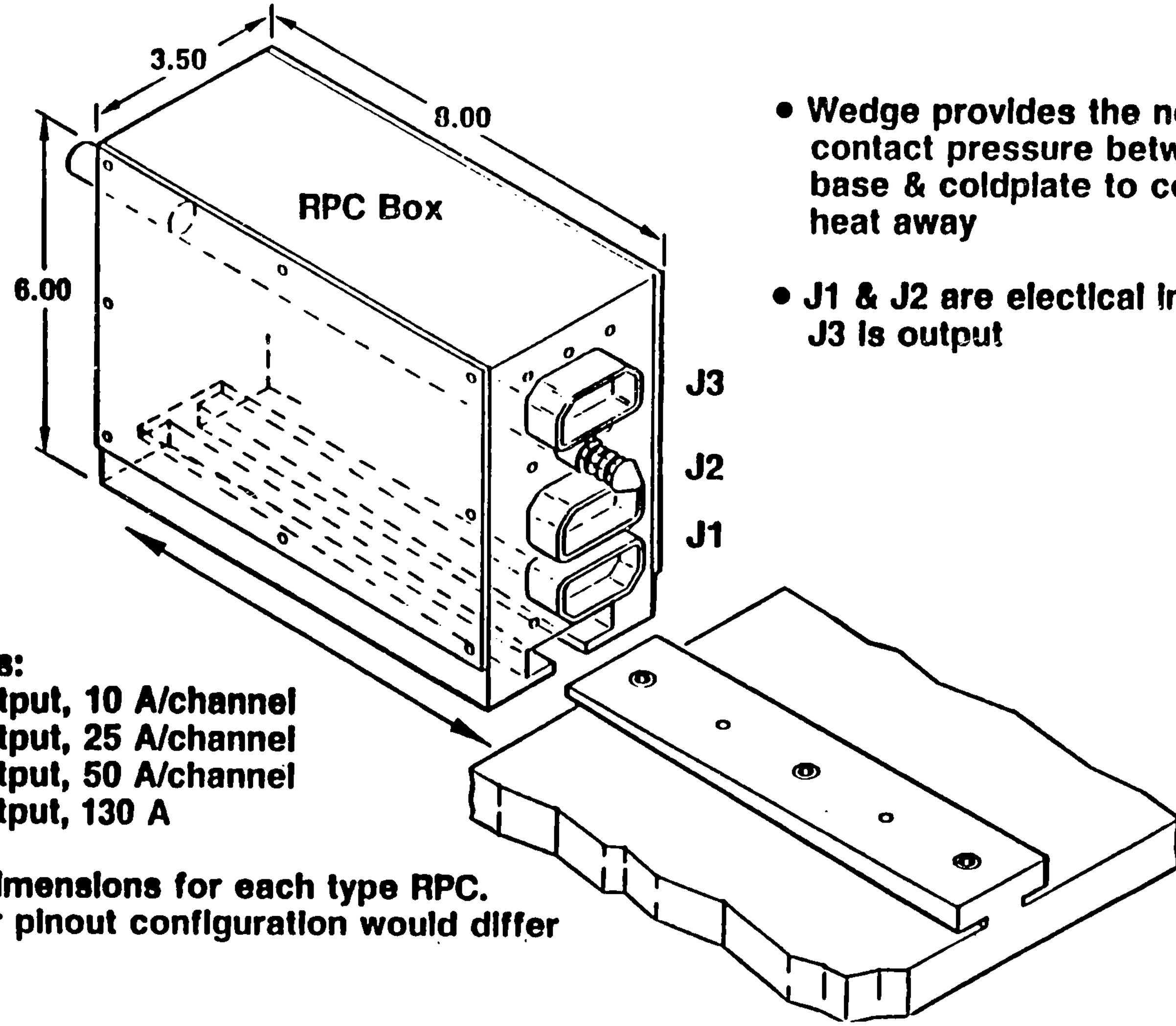
  1 x 130 Amp

  2 x 50 Amp

  4 x 25 Amp

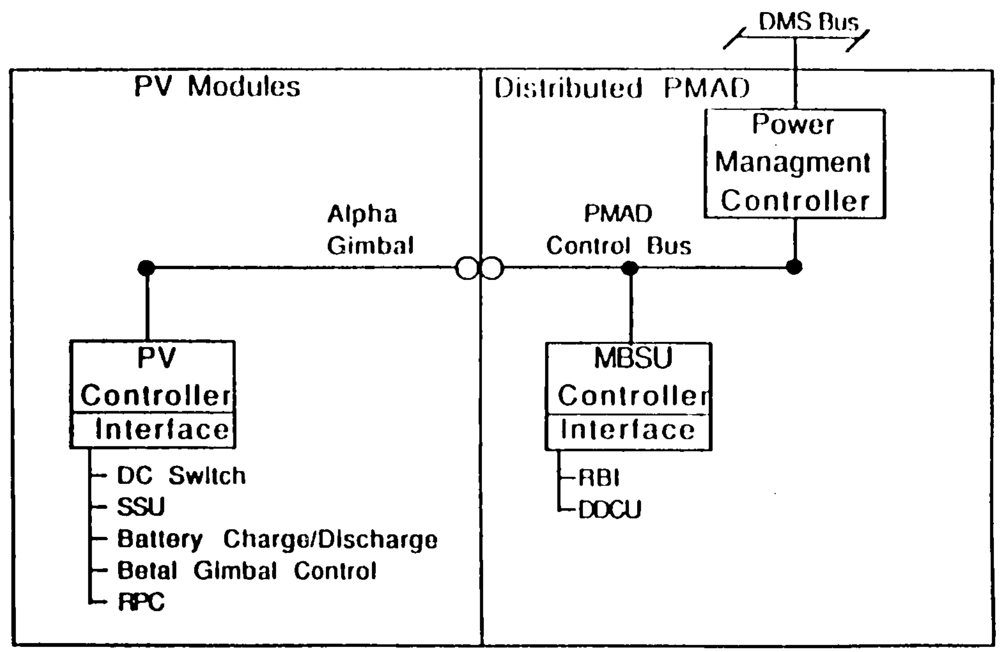
  8 x 10 Amp
- All modules have same outline and mounting
- All modules have same input connector
- All modules have same output connector shell; pin configuration unique to module type

RPC Module



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

Electric Power System Control Hierarchy (Rephase)



- **Power Management Controller**
  - DMS/PMAD interface, load management configuration control, system analysis
- **Photovoltaic Controller**
  - 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

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

56

PMAD Controls Implementation

- **Hardware Implemented**
  - Basic overload protection (RPC)
  - Hard fault (line) protection (RBI)
  - Voltage regulation
  - Array control

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

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.

EPS Weight Summary
Engineering Design Weight *
December 11, 1989

Item	Flight Quantity	Item Wt (lb)	Total Wt (lb)
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 Assembly	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
PMAD			
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 (130A)	63	10	630
PMAD Cabling	1	4,410	4,410
		Total	84,879

* Excludes GSE

Reliability and Maintainability Allocations

PV Module ORUs	MTTF (yr)	MTTR (hr)			Design Life (yr)
		EVA	IVA	IVAR	
Deployable Mast & Canister	15.0			2.25	30
PV Blanket & Box (L)	15.0			0.75	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
DCSU	15.0			1.50	15
DDCU (12.5 kW)	10.0			1.50	15
PVC/SPDA	10.0			1.50	15
PV Cable Set	30.0	12.00			30
IEA/Structure	60.0	4.00		0.20	60
IEA Transition Structure	30.0	6.00			30
PV Utility Plate, Type I	30.0			3.00	30
PV Utility Plate, Type II	30.0			3.00	30
Pump	15.0			1.50	30
Fluid Junction Box	30.0			2.50	30
Electrical Junction Box	30.0			2.50	30
Radiator Subass'y	15.0			3.00	30

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)

THIS PAGE INTENTIONALLY BLANK

Power System

Invited Presentations

THIS PAGE INTENTIONALLY BLANK

FREEDOM

SPACE STATION FREEDOM

SOLAR DYNAMIC POWER GENERATION

T. Springer
J. Friefeld

Rockwell International
Rocketdyne Division

FREEDOM

SPACE STATION FREEDOM

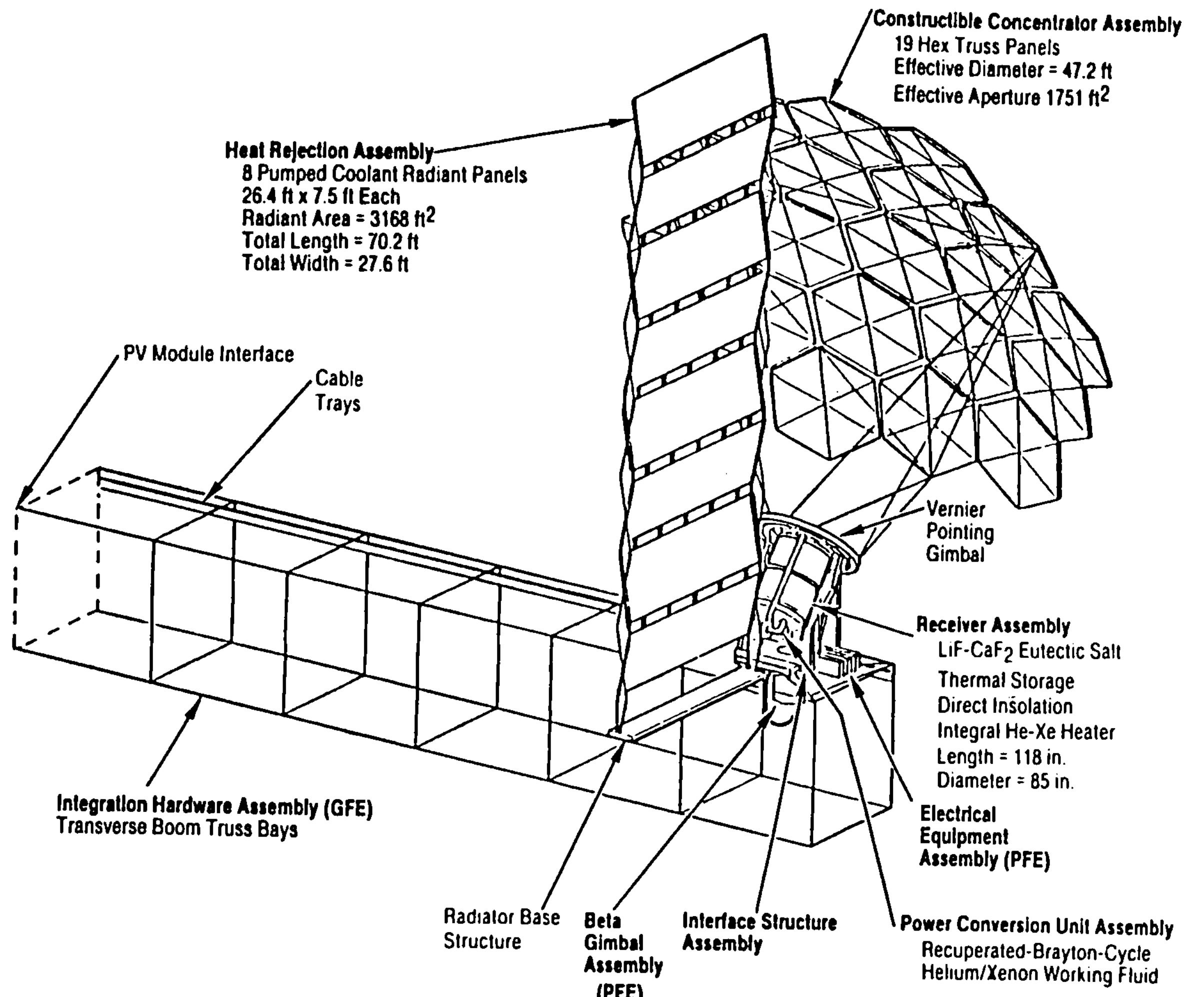
SOLAR DYNAMICS

BRIEFING AGENDA

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

Rockwell International
Rocketdyne Division

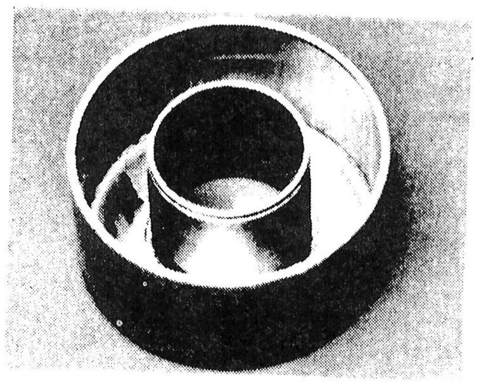
25-kWe Net CBC Power Module Configuration



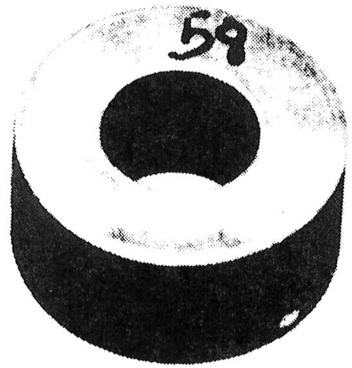
Rockwell International
Rocketdyne Division

FREEDOM

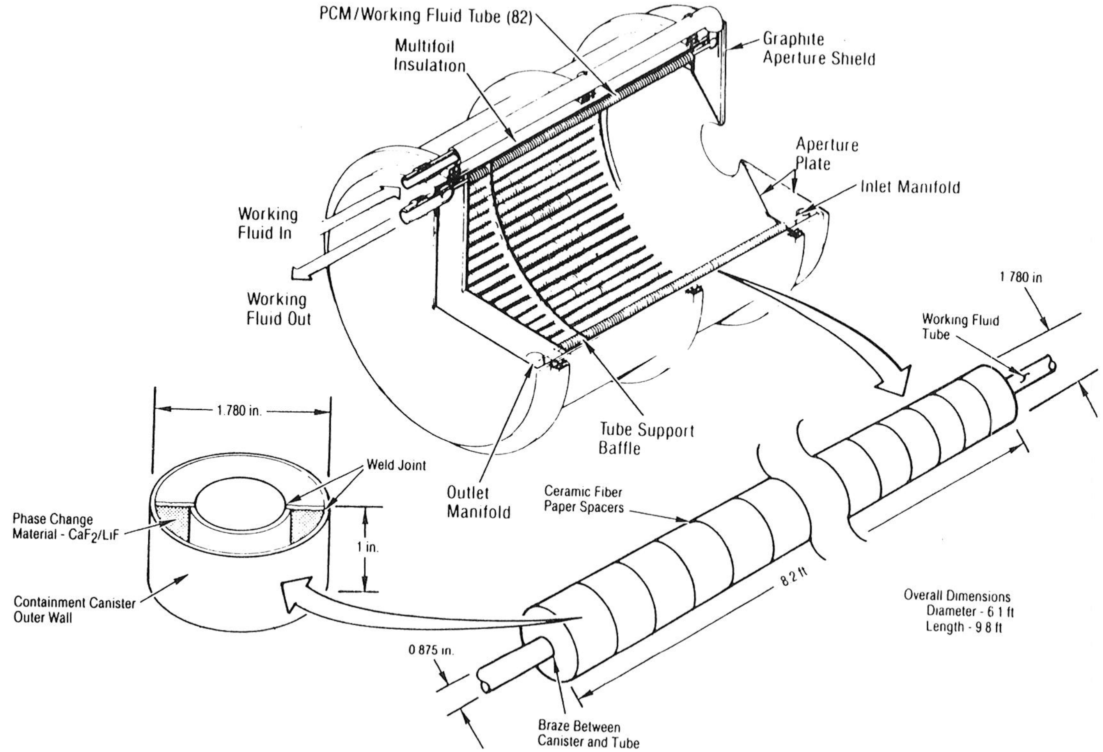
CBC Receiver



Open Canister



Completed Canister



Rockwell International
Rocketdyne Division

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

FREEDOM

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

Rockwell International
Rocketdyne Division

FREEDOM

Solar Dynamic Design & Development Team

Organization	Major Responsibilities
Rockedyne	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

FREEDOM

ADVANCED DEVELOPMENT

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

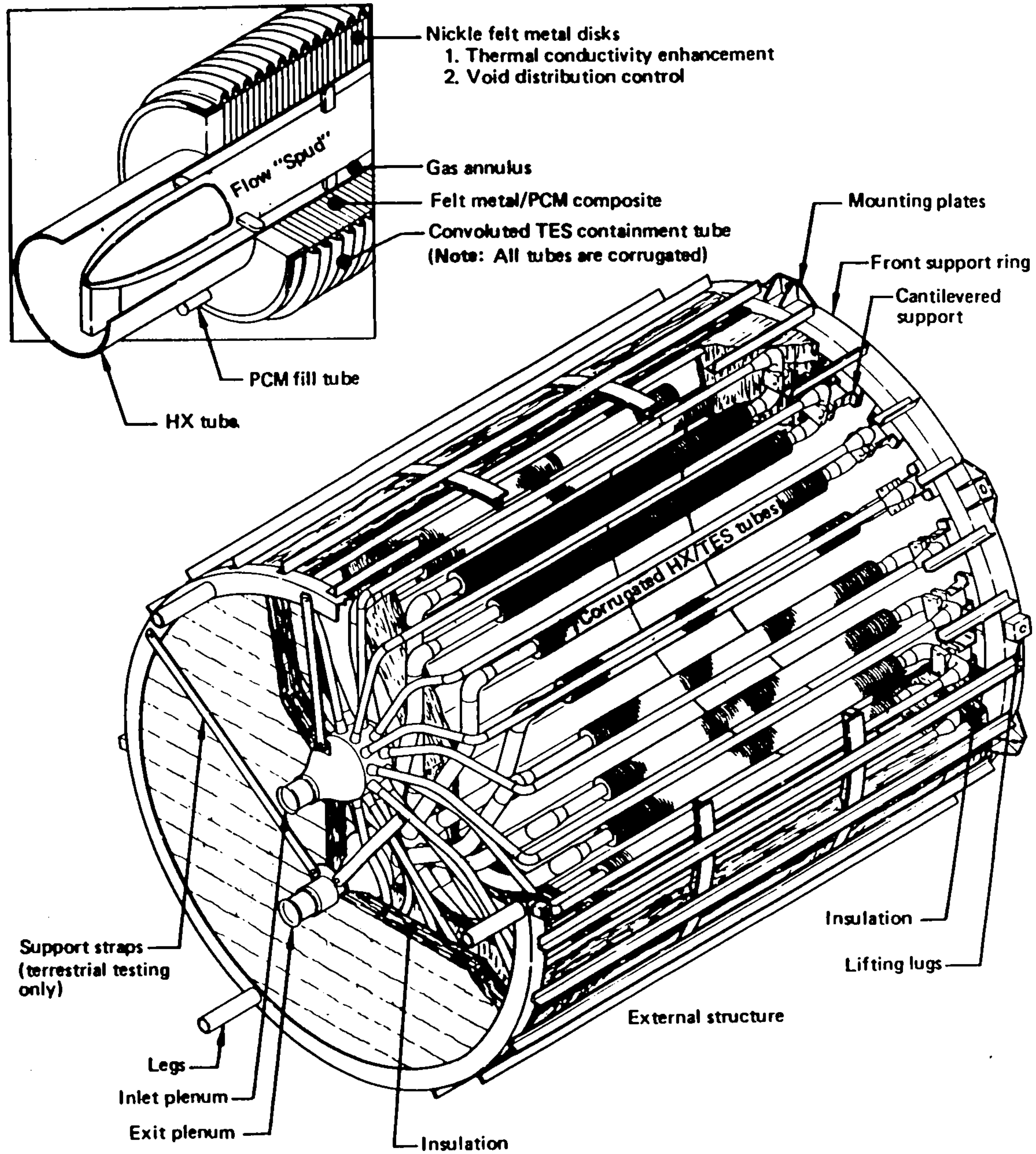
FREEDOM

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

Rockwell International
Rocketdyne Division

FREEDOM



Receiver Shown Without Aperture Assembly

STSE-1

Rockwell International
Rocketdyne Division

SOLAR DYNAMIC HEAT RECEIVER TECHNOLOGY

FREEDOM

KEY REQUIREMENTS/FEATURES

REQUIREMENTS

- Power 102 kwt (25 kwe CBC)
- Temperature 900^{O}F Inlet; 1300^{O}F 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

FREEDOM

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 & $LiF\text{-}CaF_2$
- 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

FREEDOM

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

FREEDOM

SOLAR CONCENTRATOR

KEY REQUIREMENTS/FEATURES

- Requirements
  - Deliver 188 kw of Thermal Energy to the Receiver
  - Pointing Accuracy: $\pm 0.1^{o}$ ($1\ \sigma$)
  - Specular Reflectance: >0.88
  - Slope Error: $\pm$ 2.25 mr (half cone angle)
  - Design Lifetime: 15 years
- Features
  - 19 Hexagonal Panel (456 facets)
  - Toroidal Facet Curvature
  - Parabolic Mapping
  - $\leq$ 2 lb. per facet
  - SiO_2 Protected, Silver Reflective Surface on Graphite Epoxy with A1 Honeycomb

Rockwell International
Rocketdyne Division

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

THIS PAGE INTENTIONALLY BLANK

POWER TECHNOLOGY DIVISION

AEROSPACE TECHNOLOGY DIRECTORATE

NASA Lewis Research Center

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

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

- **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.

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

- **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)

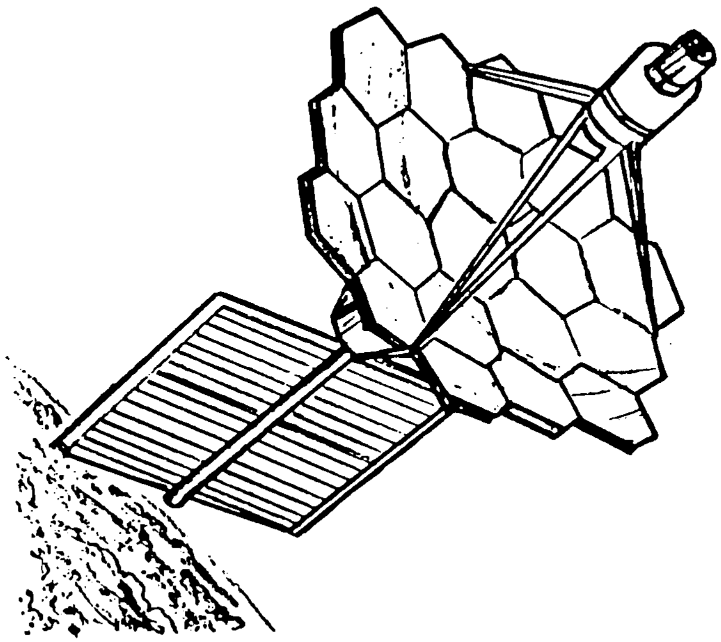
  - BRAYTON ENGINE (The technology of this engine is mature)

- **RADIATORS**

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

THIS PAGE INTENTIONALLY BLANK

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

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

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.

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

GOALS

SPECIFIC POWER	20-25 W/kg
REDUCTION OF HEAT RECEIVER MASS TO	20-33 kg/kWe
REDUCTION OF CONCENTRATOR MASS TO	1-2 kg/M^2
CONCENTRATION RATIO	2000-5000
REDUCTION OF RADIATOR MASS TO	4-5 kg/M^2 (HEAT PIPE)

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

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.

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

- **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.

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

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.

ADVANCED SOLAR DYNAMIC TECHNOLOGY PROGRAM

TECHNOLOGY APPROACH

- **ADVANCED CONCENTRATORS**
  - HIGH EFFICIENCY/ACCURACY (.5-1.50 MRAD)
  - NEW FABRICATION TECHNIQUES
  - MATERIALS SPACE COMPATIBILITY
  - DEPLOYMENT TECHNIQUES
- **ADVANCED HEAT RECEIVERS**
  - BULK TES VOLUME (AS OPPOSED TO SMALL ELEMENTS)
  - TES WITH HIGH THERMAL CONDUCTIVITY & DENSITY
  - CAVITY HEAT PIPE DESIGNS
  - TES VOID - MICROGRAVITY
- **POWER CONVERSION SYSTEMS**
  - INCREASED EFFICIENCY THROUGH TECHNOLOGY DEVELOPMENT

  1) STIRLING - MAJOR EFFORT CARRIED OUT BY LeRC STIRLING BRANCH
  2) BRAYTON - CARRIED OUT OUTSIDE OF NASA

- **INCREASE CONFIDENCE IN RELIABILITY & PERFORMANCE OF CONCENTRATOR, RECEIVER, PCS, AND RADIATOR**
  - TECHNOLOGY VERIFICATION/VALIDATION
    1) EXPERIMENTS & ANALYSIS

THIS PAGE INTENTIONALLY BLANK

ADVANCED SPACE CONCENTRATOR DEVELOPMENT

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.

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.

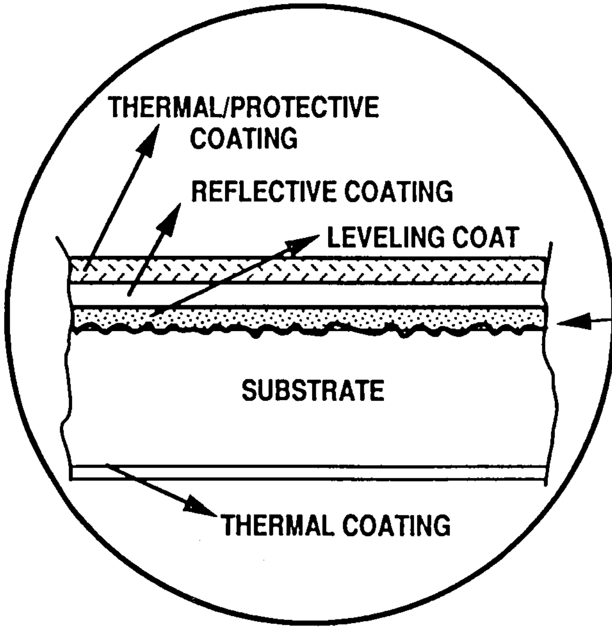
2. A LEVELING LAYER: USUALLY THE SUBSTRATE, FACE ONTO WHICH THE REFLECTING LAYER IS TO BE DEPOSITED IS NOT SMOOTH ENOUGH TO YIELD A HIGHLY SPECULAR REFLECTING SURFACE. HENCE, THE SUBSTRATE FACE MUST BE SMOOTHED BY POLISHING OR APPLYING A THIN (5 MICRONS TO 0.5mm) SMOOTHING LAYER. CANDIDATE MATERIALS ARE: VERY LOW VISCOSITY/HIGH SURFACE TENSION MONOMERS, POLYMERS, AND OTHER SIMILAR MATERIALS.

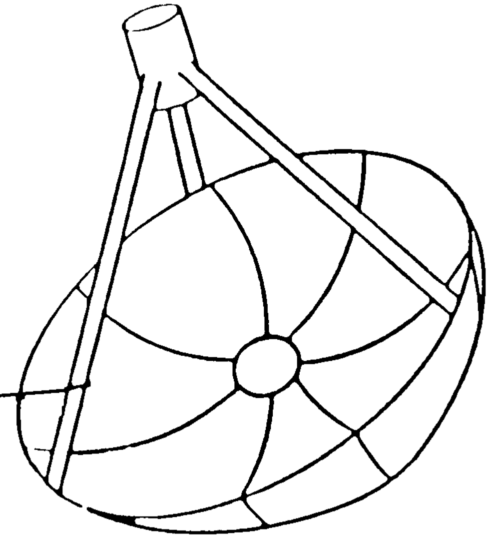
3. REFLECTING LAYER: SILVER AND ALUMINUM ARE THE MOST HIGHLY REFLECTIVE MATERIALS, SILVER BEING MORE REFLECTIVE THAN ALUMINUM. SILVER, ON THE OTHER HAND, IS EASILY CORRODED BY TERRESTRIAL CONTAINMENTS SUCH AS, MOISTURE, OXYGEN, AND OTHER GASES, AND BY AO IN LEO. ALUMINUM IS A MUCH MORE RESISTANT MATERIAL 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.

ADVANCED SPACE CONCENTRATOR DEVELOPMENT





IDENTIFY THE SUITABLE REFLECTOR CONCEPT AND MATERIALS

- SUBSTRATE TYPE
- SURFACE SMOOTHING TECHNIQUES
- SPACE COMPATIBLE MATERIALS
- COATINGS FOR PROTECTION & THERMAL CONTROL

IDENTIFY THE SUITABLE CONCENTRATOR CONCEPT(S)

- TYPE
- PACKAGING AND DEPLOYMENT SCHEME
- RECEIVER ATTACHMENT STRUCTURE

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.

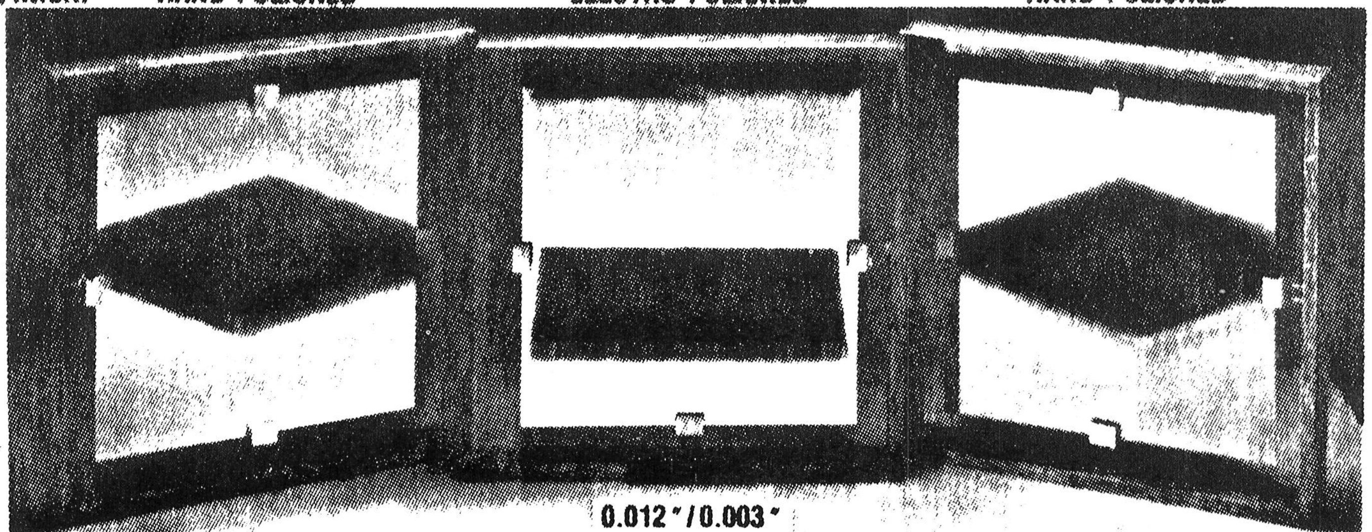
OTHER NOTEWORTHY FEATURES:

(1) ALUMINUM & TITANIUM ARE IMMUNE TO ATTACK BY THE SPACE ENVIRONMENT,

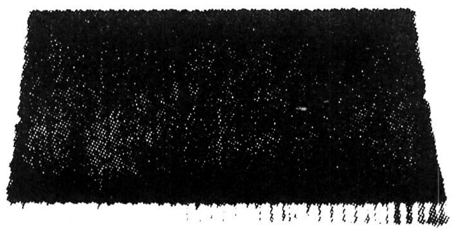
(2) THE FOCAL POINT DIAMETER WAS ABOUT 2 INCHES DIAMETER.

DISHED ALL METAL HONEYCOMB SANDWICH PANELS

MATERIAL:	ALUMINUM	ALUMINUM	TITANIUM
WEIGHT:	1.1 Kg/m^2	1.5 Kg/m^2	1.6 Kg/m^2
SLOPE ERROR:	0.8 MRAD	0.7 MRAD	0.6 MRAD
FINISH:	HAND POLISHED	ELECTRO POLISHED	HAND POLISHED



FACESHEETS:	0.007/0.003	0.012"/0.003"	0.005"/0.005"
CORE TYPE:	1/8" HEXCELL	1/8" HEXCELL	1/4" SQUARE CELL



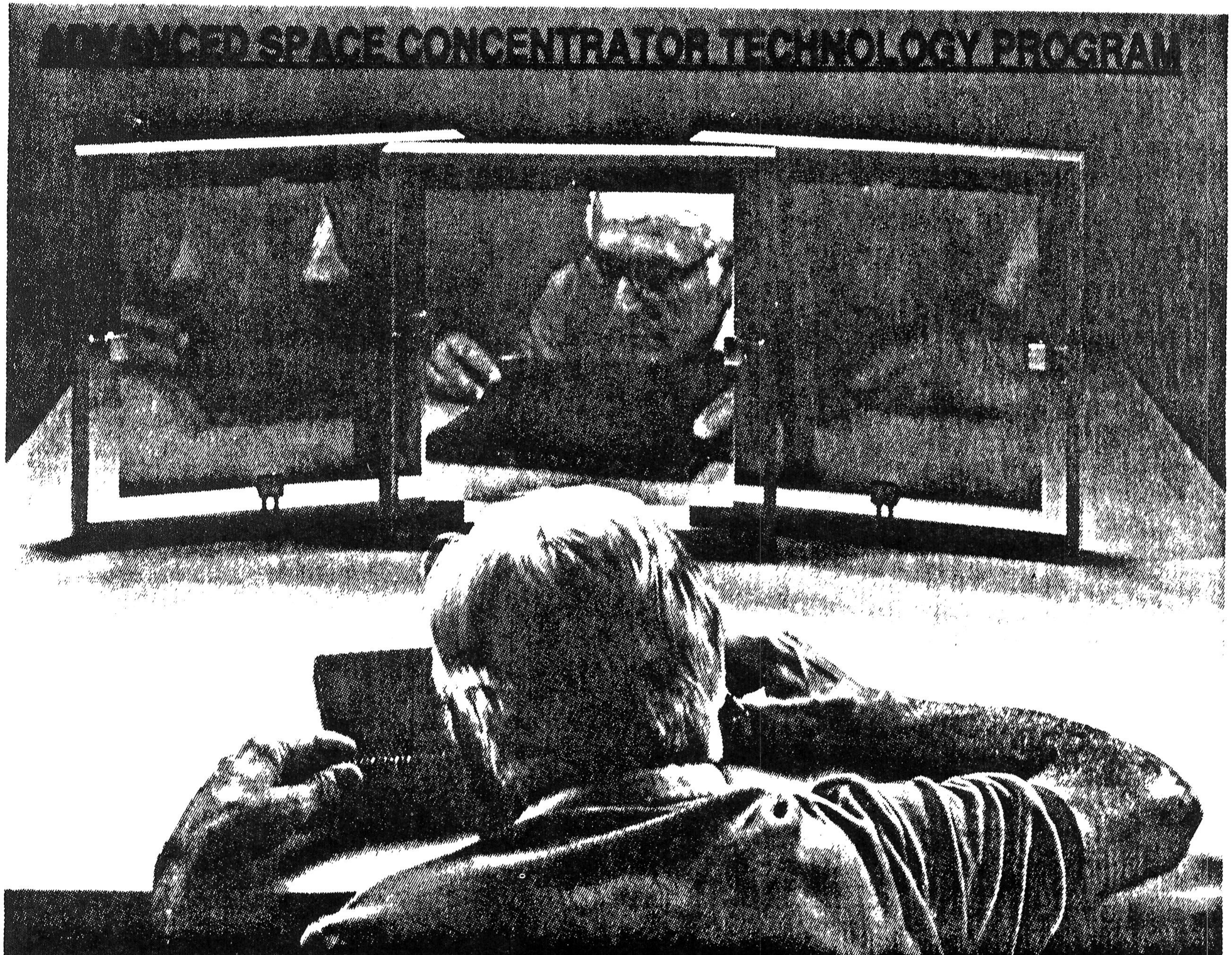
HONEYCOMB HEXCELL
0.625 in. THICK

FABRICATED BY:
SOLAR KINETICS, INC.
DALLAS, TEXAS

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.



ALUMINUM & TITANIUM HONEYCOMB SANDWICH REFLECTOR SUBSTRATES

ADVANCED HEAT RECEIVER DEVELOPMENT

o ADVANCED RECEIVER TECHNOLOGY VERIFICATION

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.

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.

-- 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. Corrosion-resistant 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.

THIS PAGE INTENTIONALLY BLANK

ADVANCED HEAT RECEIVER DEVELOPMENT

- 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-CaF_2" and storing energy to be used during the shade portion of the orbit), and the Stirling engine heater head tubes.

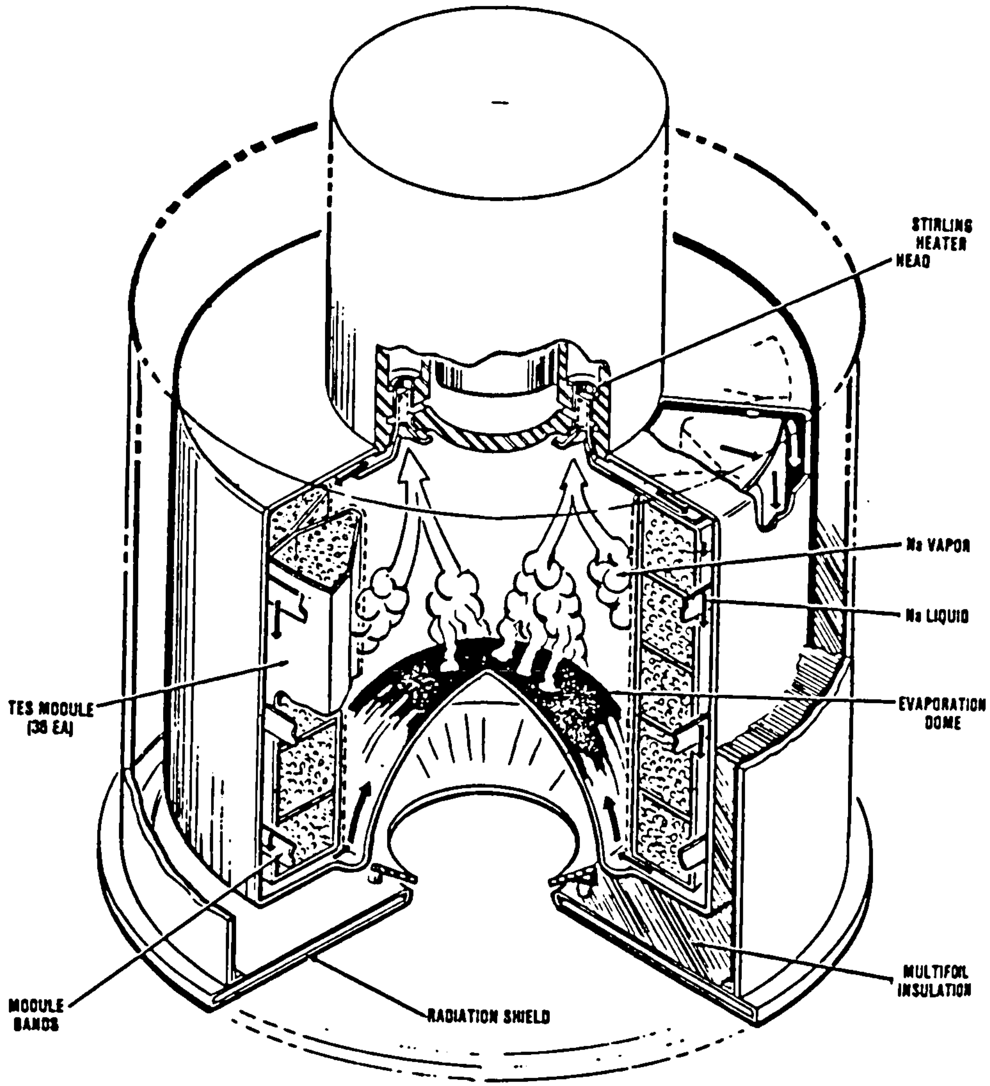
The TES material LiF-CaF_2 has a heat of fusion of 753 kJ/kg and its melting point is 1039 K. During the shade portion of the orbital cycle, heat is extracted form the TES material, now making the containment canisters the heat pipe evaporator and providing uninterrupted heat input to the engine for 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:

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

Cavity Heat Pipe Stirling Receiver

WITH FINNED TUBE/SHELL HEATER HEAD



Brayton Cavity Heat Receiver
Sundstrand Corp.

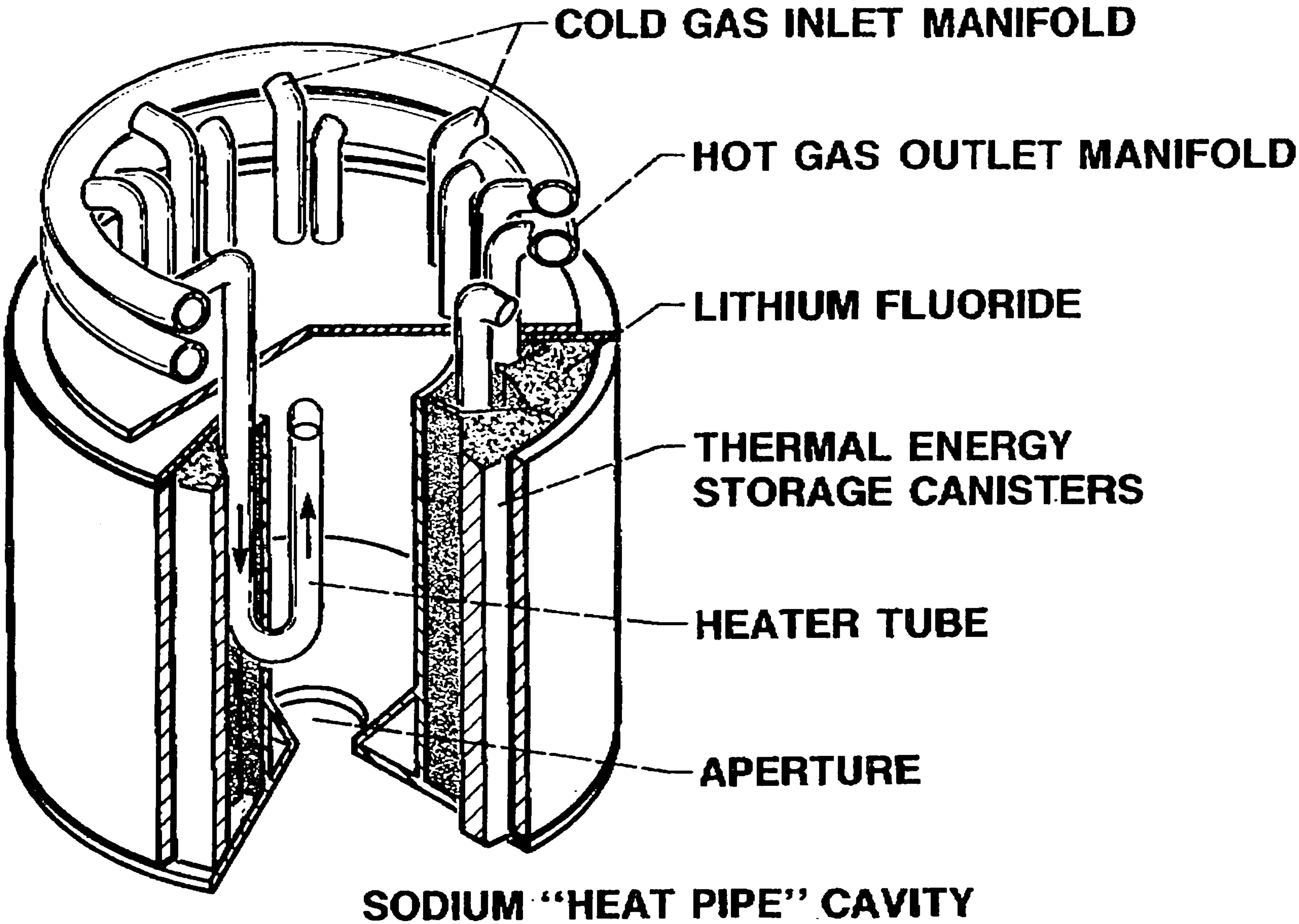
With the cavity heat pipe heat receiver all of the solar energy from the concentrator falls on a cylinder that forms the inner liner of the cavity and acts as a heat pipe evaporator during the sun portion of the orbital cycle. The energy is transferred to the sodium heat pipe working fluid by evaporating 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).

THERMAL ENERGY STORAGE TECHNOLOGY (TEST) PROJECT

OBJECTIVES

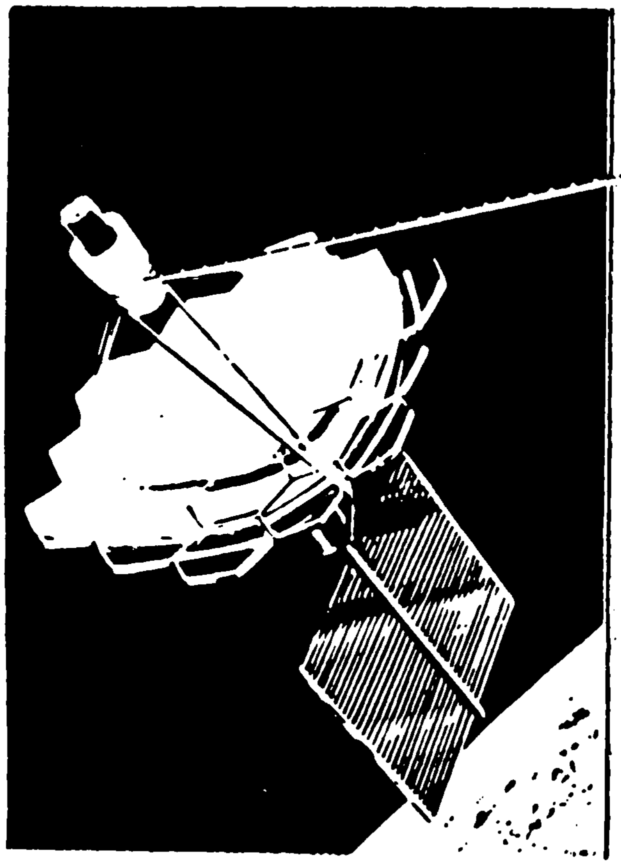
- **ANALYSIS OF TES MATERIALS BEHAVIOR - NASA/OAK RIDGE VOID EXPERIMENT, NORVEX (FUNDED BY CODE RP):**
  - DEVELOP A COMPUTER PROGRAM TO PREDICT TRANSIENT BEHAVIOR (CONTINUOUS AND REPETITIVE SOLIDIFICATION/ LIQUIFICATION) OF TES MATERIALS, PARTICULARLY VOID SHAPE AND LOCATION, UNDER MICROGRAVITY.
- **MICROGRAVITY 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.

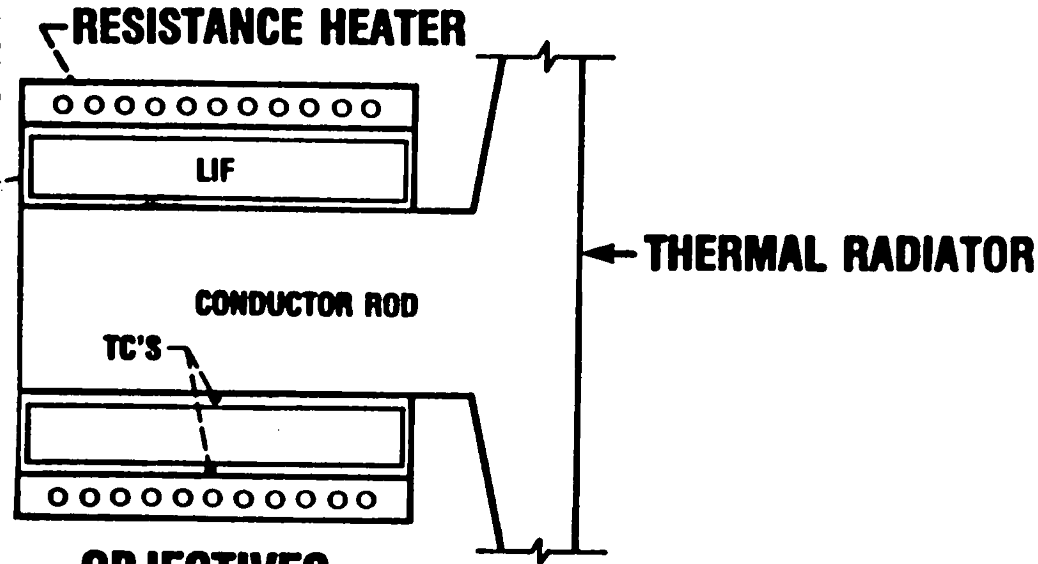
IN-REACH THERMAL ENERGY STORAGE TECHNOLOGY ("TEST")

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.

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





OBJECTIVES

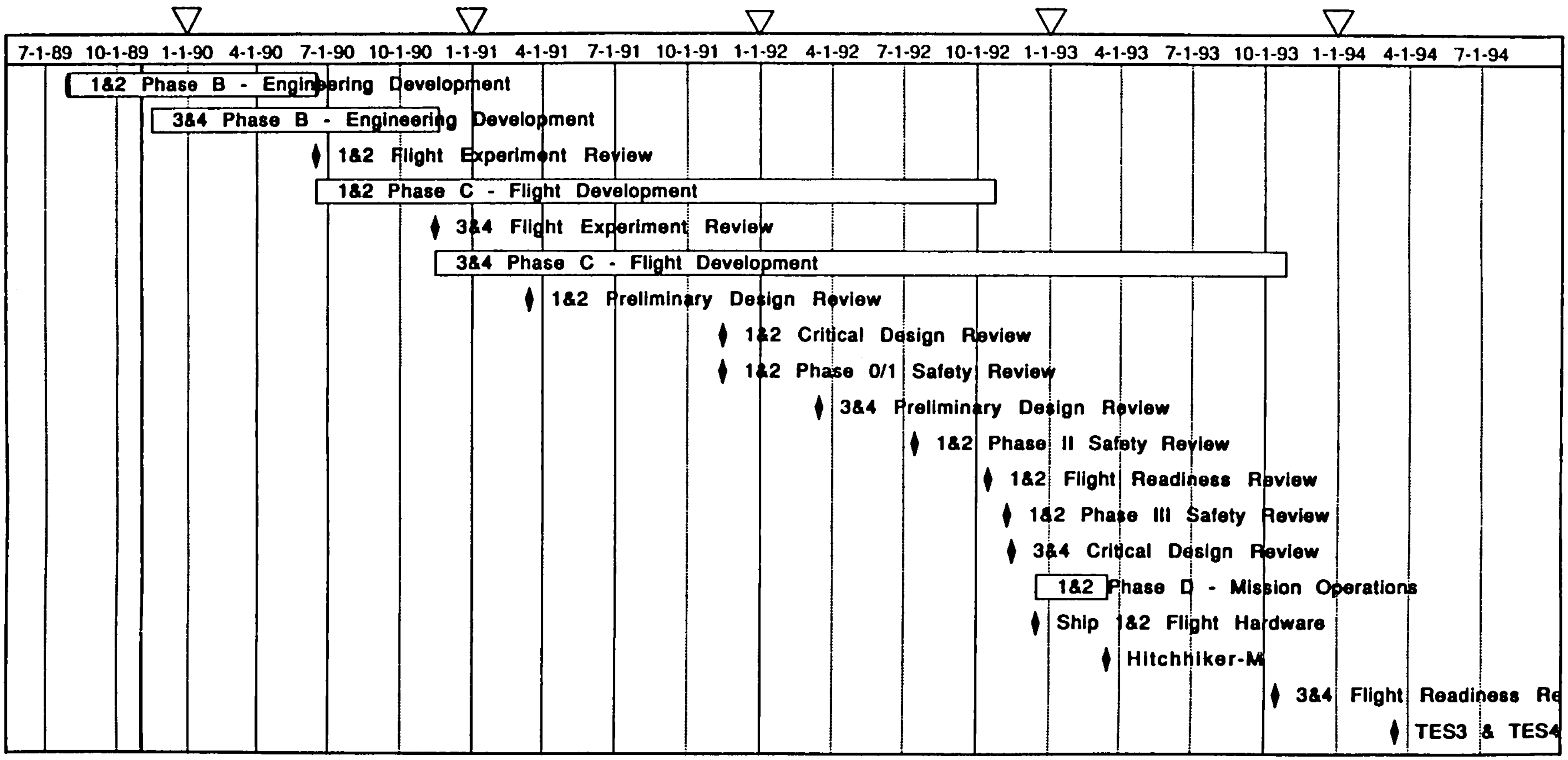
- DEVELOPMENT OF COMPUTER PROGRAM TO PREDICT TRANSIENT BEHAVIOR OF TES MATERIALS
- VERIFY CAPABILITY OF COMPUTER CODE TO ANALYZE TES IN A MICROGRAVITY EXPERIMENT

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.

THERMAL ENERGY STORAGE PROJECT



THIS PAGE INTENTIONALLY BLANK

SPACE STATION FREEDOM ELECTRIC POWER SYSTEM

Evolutionary Energy Storage

17 January 1990

Mike Domeniconi

Ford Aerospace

Evolutionary Energy Storage for Space Station Freedom

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

FREEDOM

System Requirements Evolution

- Changes in load power profile

Classification	Item	Requirements Flowdown
Low Power, Long Duration	Science Instrument	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 . . . . .

Ford Aerospace

FREEDOM

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......

Ford Aerospace

- **Transform Issues into Objectives**

FREEDOM

Candidate Energy Storage Technologies

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

Ford Aerospace

THIS PAGE INTENTIONALLY BLANK

TRW

Miniaturized Cassegrainian Solar Array Development

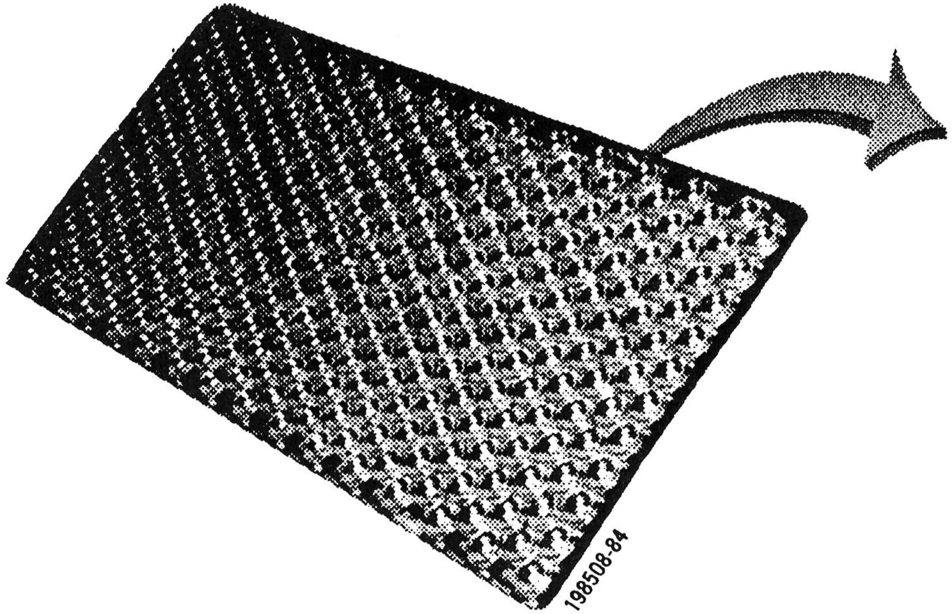
R. Patterson
M. Mills

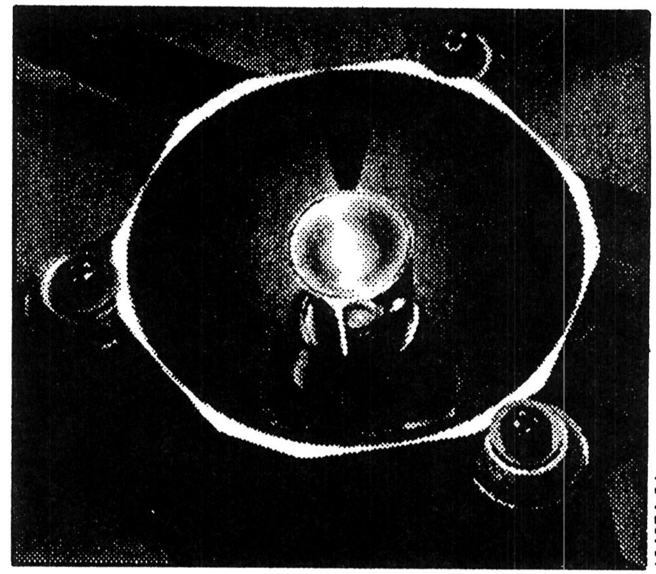
January 16-19, 1990

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

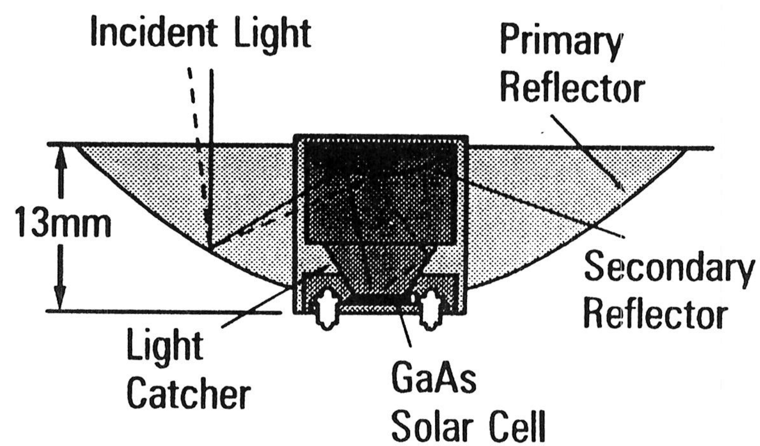
Miniature Cassegrainian Concentrator Concept

TRW

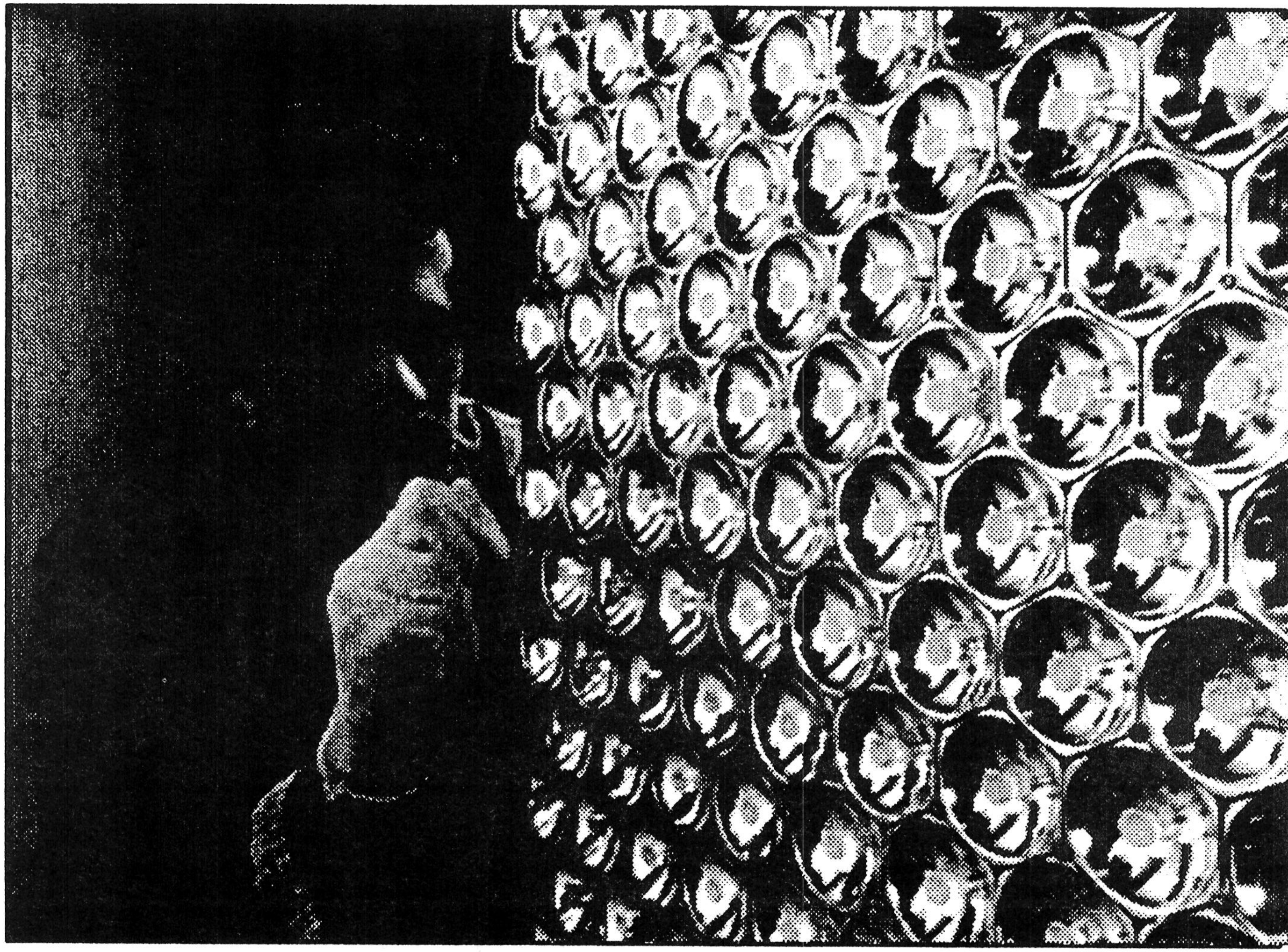




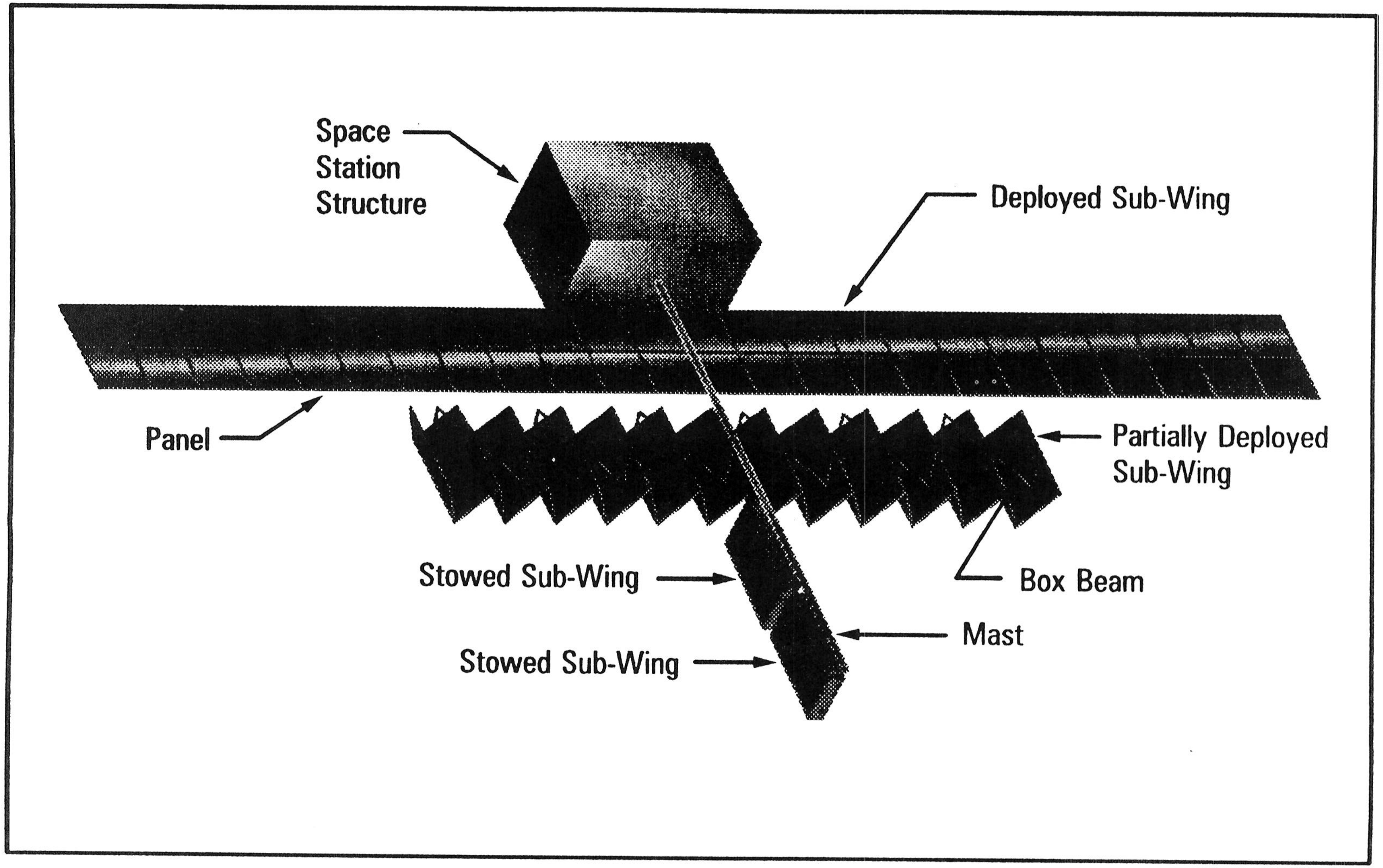
- Required cell area reduced by 99%
- Permits cost-effective use of high-efficiency solar cells
- Provides potential for significant reduction in array cost and area
- Has low profile (13 mm) which permits efficient stowage



MCC Element to Panel Integration

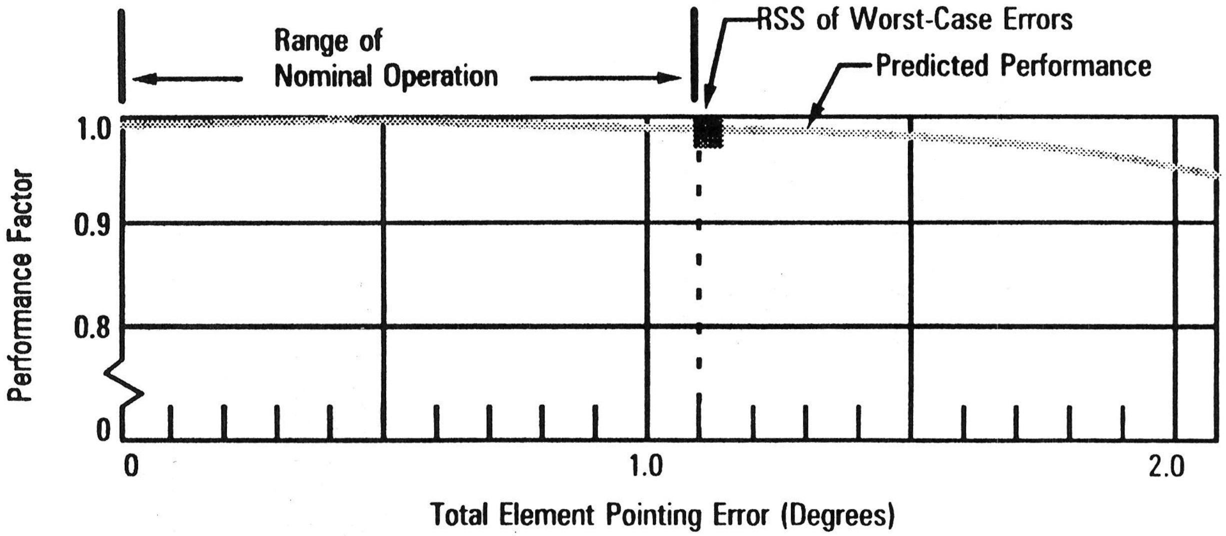

20322585

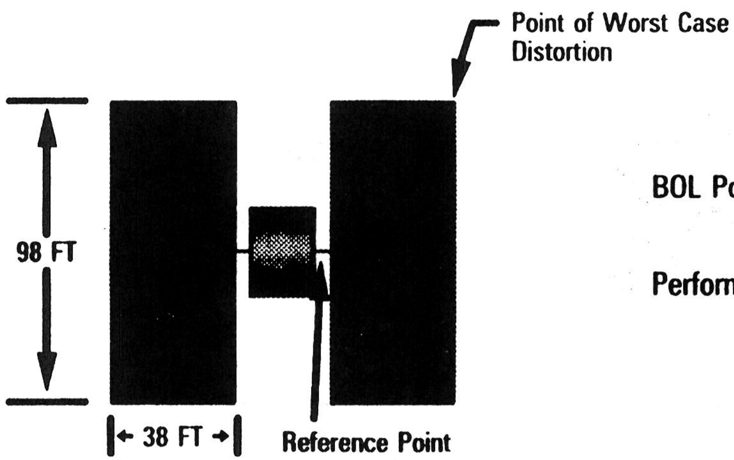
Folded Box Beam Deployment of MCC Array Sub-Wing



100-KW MCC Array System Analysis Summary

TRW





BOL Power: 100 KW

Performance: 160 W/m^2
28 W/kg

Pointing Error Component	Pointing Error (Degrees)
Thermal Distortion	±0.2
Manufacturing*	±0.8
Control Sensing	±0.1
Dynamic** Distortion	±0.7
SUM	1.8
RSS	1.1

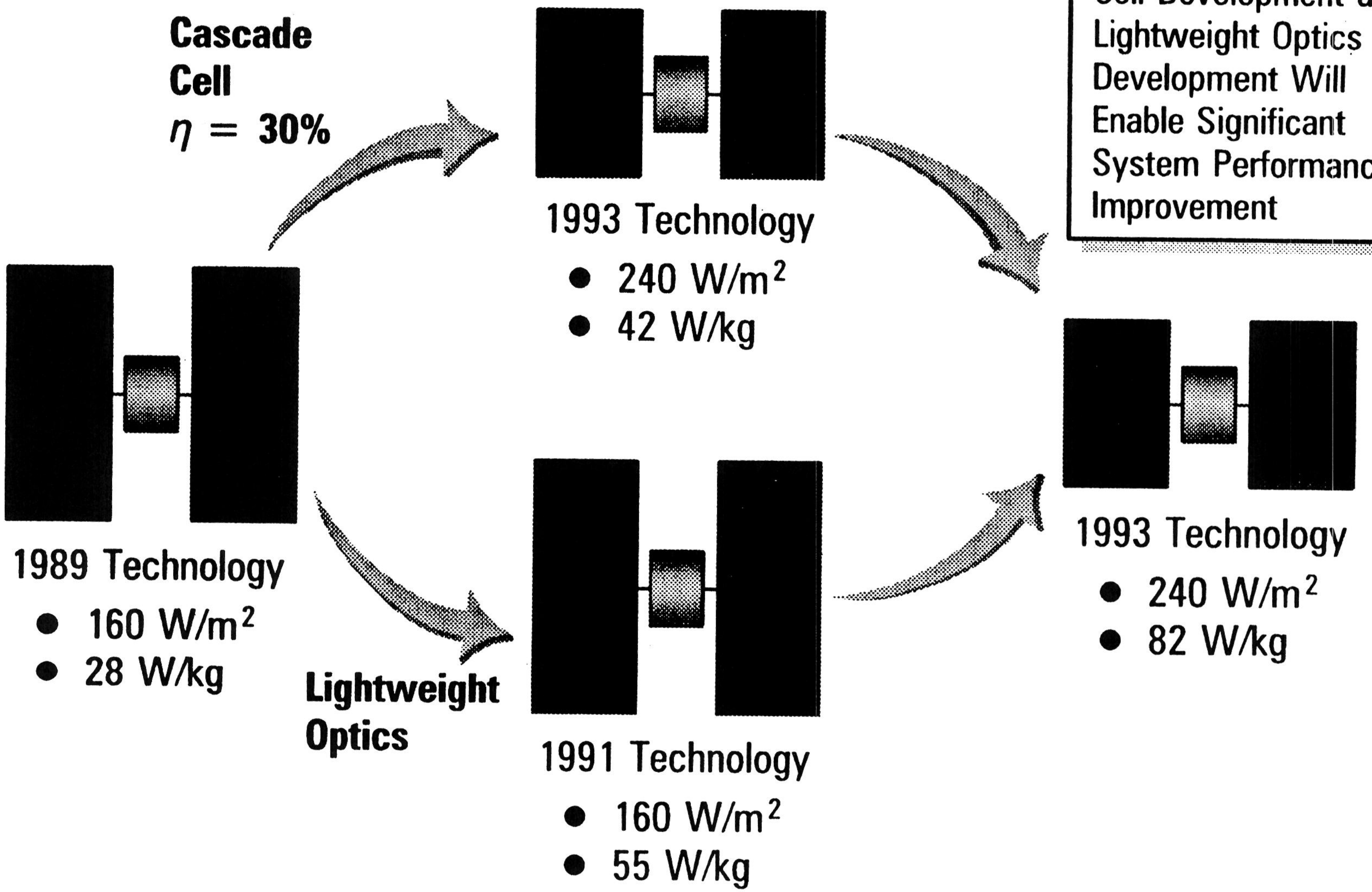
*Worst-Case Sum

**Worst-Case Crew Motion (Not Time Phased)

Array Enables Technology Evolution

TRW

Cell Development and Lightweight Optics Development Will Enable Significant System Performance Improvement



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

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
- AF MANTECH Status
- Technology Trend

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

Type	Resistivity	Thickness (mils)	BOL, AMO EFF, 28° (%)	BOL, AMO EFF, 60°C (%)	EOL, 1 MeV Electron EFF, 60° C, (%) AMO	
					3×10^{14}	1×10^{15}
Silicon (2 x 4 cm)	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%

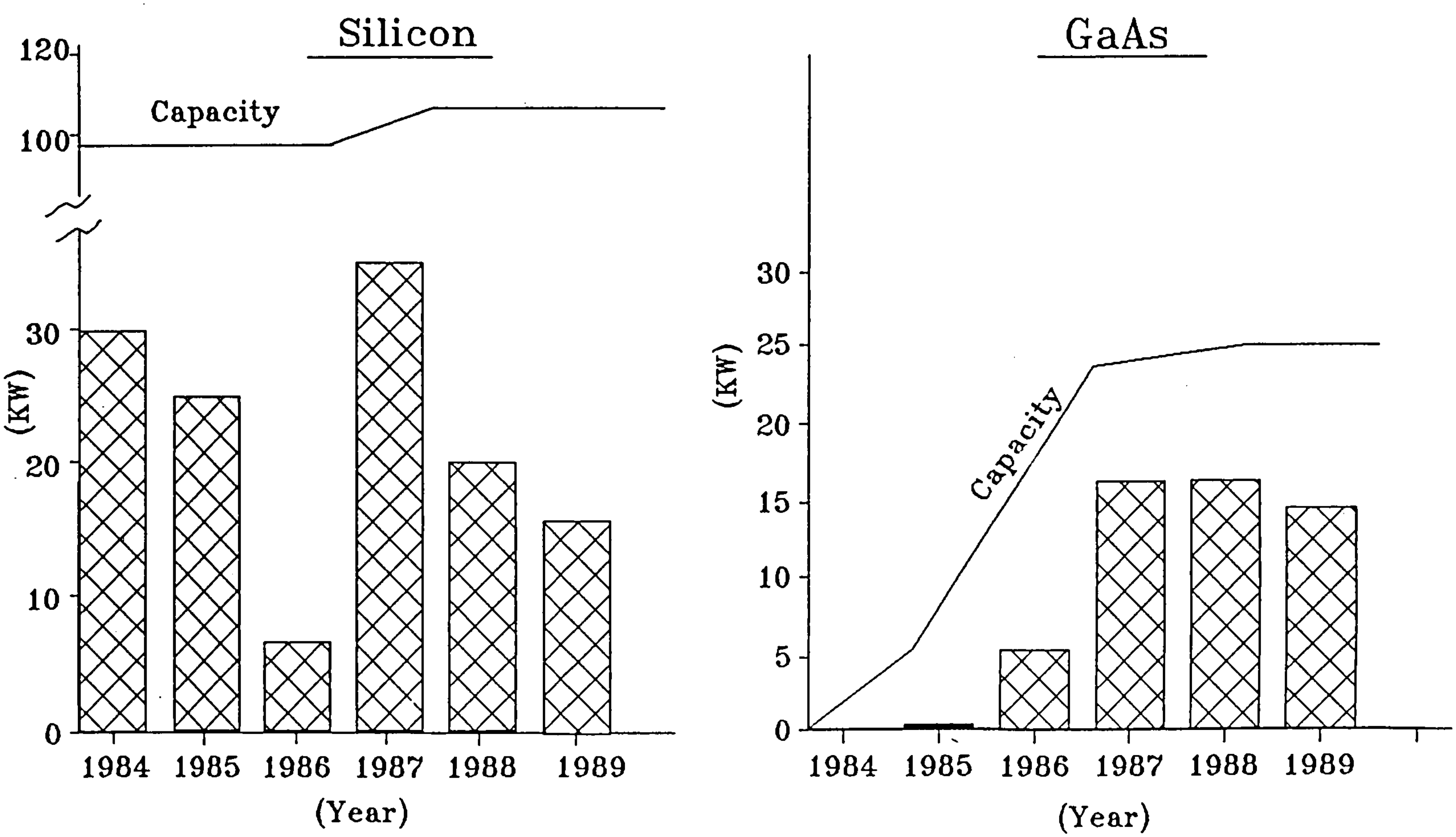
PANEL LEVEL COMPARISONS

	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 3×10^{14} 1 MeV electrons/cm^2
No temperature corrections (all 28° C)

APPLIED SOLAR ENERGY CORPORATION

PRODUCTION HISTORY



APPLIED SOLAR ENERGY CORPORATION

COMPARISON OF PERFORMANCE AND COST, SILICON vs GaAs CELLS

Cell Types	Thick-ness (Size)	Array Type	$\alpha s/E$	Oper. Temp.	Relative Cost ($/cm^2$)			Operating T and Radiation 3×10^{14} 1 MeV Electron	
					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

APPLIED SOLAR ENERGY CORPORATION

AF MANTECH PROGRAM
HIGH EFFICIENCY, RUGGED GaAs/Ge CELLS

OBJECTIVES:

- **Develop manufacturing technology for high efficiency ($>$18% AMO) lightweight ($<$0.05 gm/cm^2), large area ($\geq$4 x4 cm^2), 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**

SOLAR CELL TECHNOLOGY TRENDS

- Development of large scale, reliable MOCVD reactors for growth of thin films
- Thin, rugged GaAs/Ge replaced GaAs/GaAs cells
- High efficiency ($\eta > 18\%$), 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 $\eta > 17\%$
  - Single junction GaAs $\eta > 20\%$
  - Two junction cascade $\eta > 24\%$
- For significantly improved manufacturing technology, must have sustained demand. For few large production runs, return on investment not assured

THIS PAGE INTENTIONALLY BLANK

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

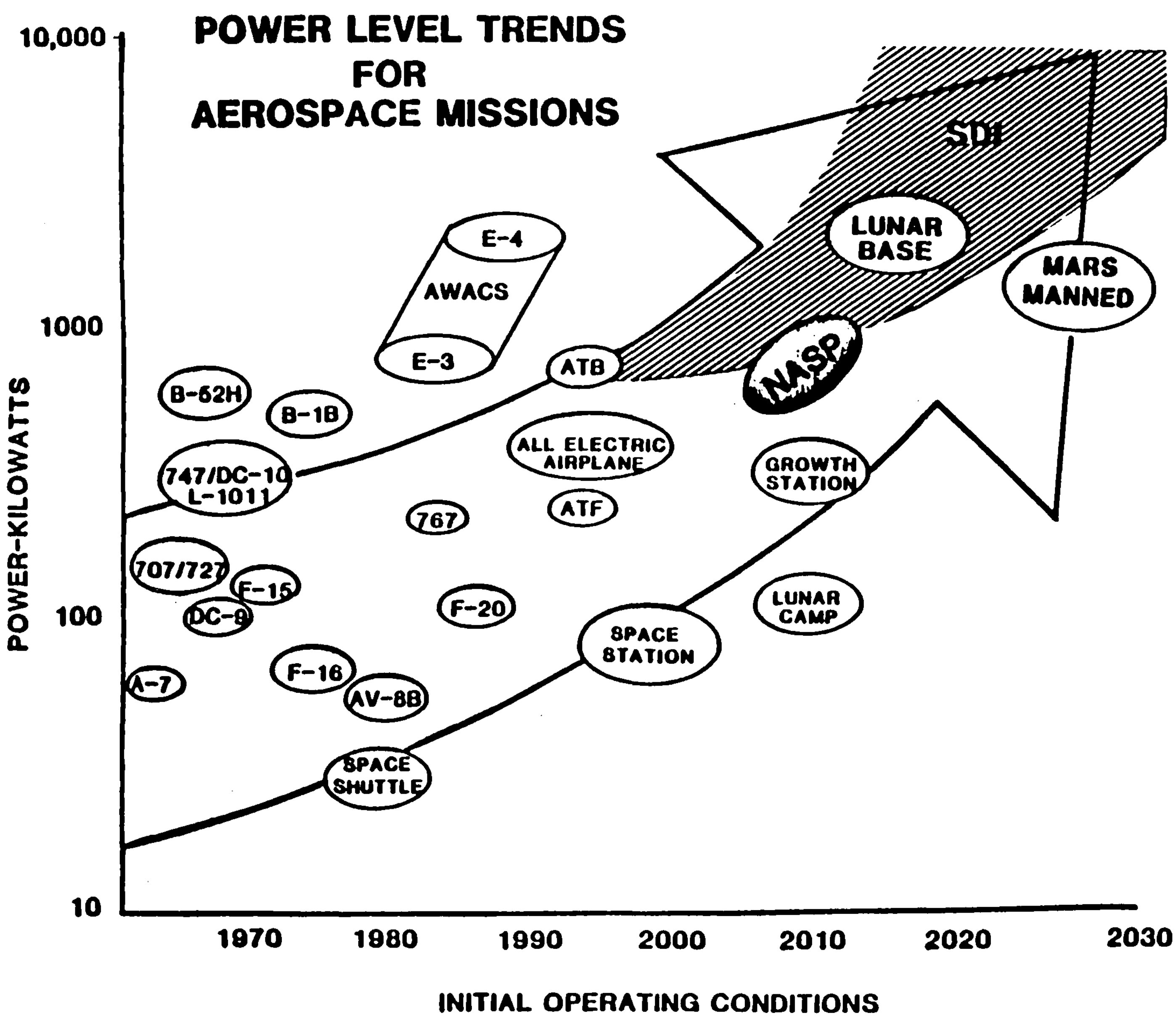
GROWING THE SPACE STATION'S ELECTRICAL POWER PLANT

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.

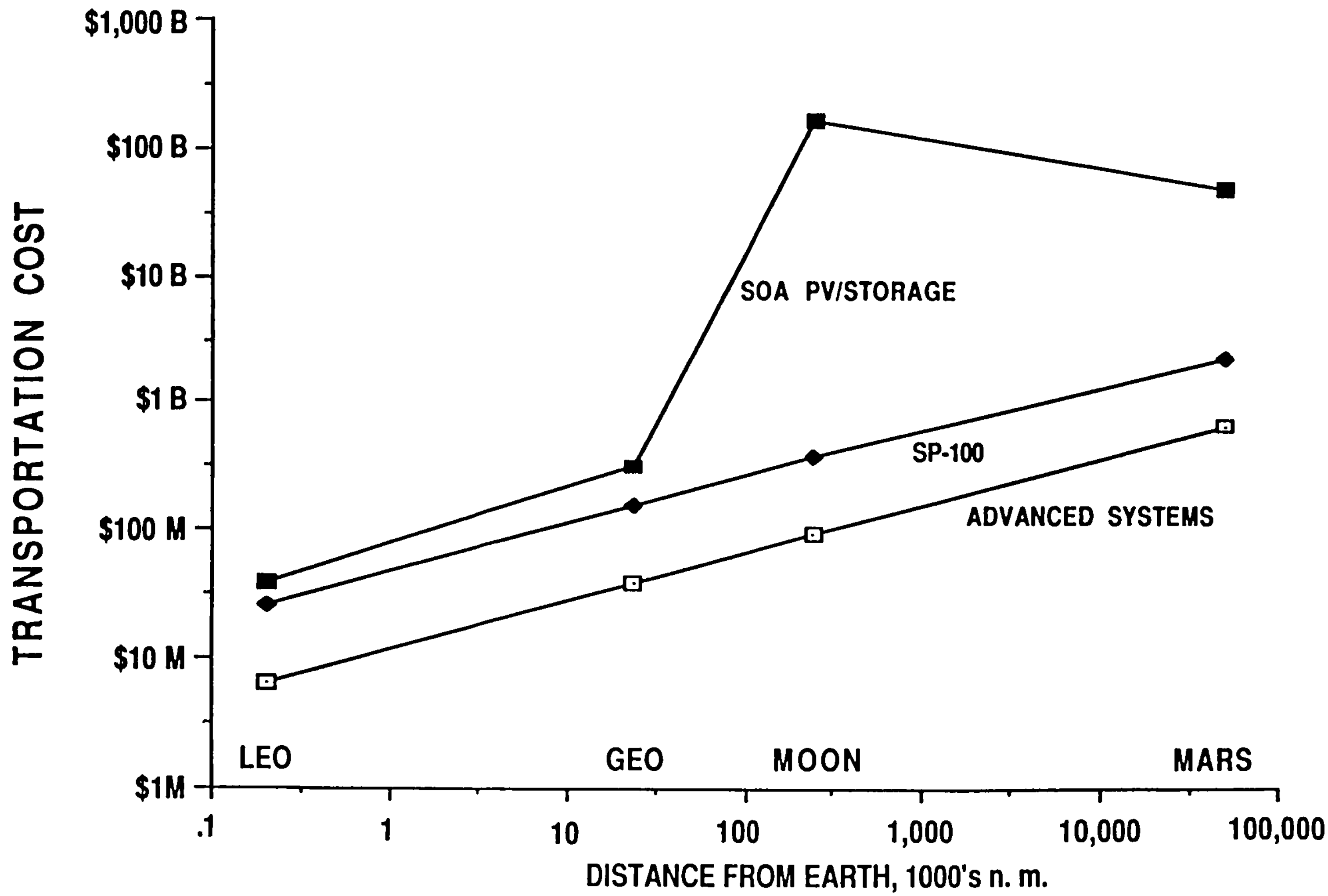

POWER LEVEL TRENDS
FOR
AEROSPACE MISSIONS
10,000
1000
100
10
POWER-KILOWATTS
1970
1980
1990
2000
2010
2020
2030
INITIAL OPERATING CONDITIONS
SDI
LUNAR BASE
MARS MANNED
NASP
E-4
AWACS
E-3
ATB
B-52H
B-1B
747/DC-10
L-1011
ALL ELECTRIC AIRPLANE
GROWTH STATION
767
ATF
707/727
F-15
DC-9
F-20
LUNAR CAMP
SPACE STATION
A-7
F-16
AV-8B
SPACE SHUTTLE

AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

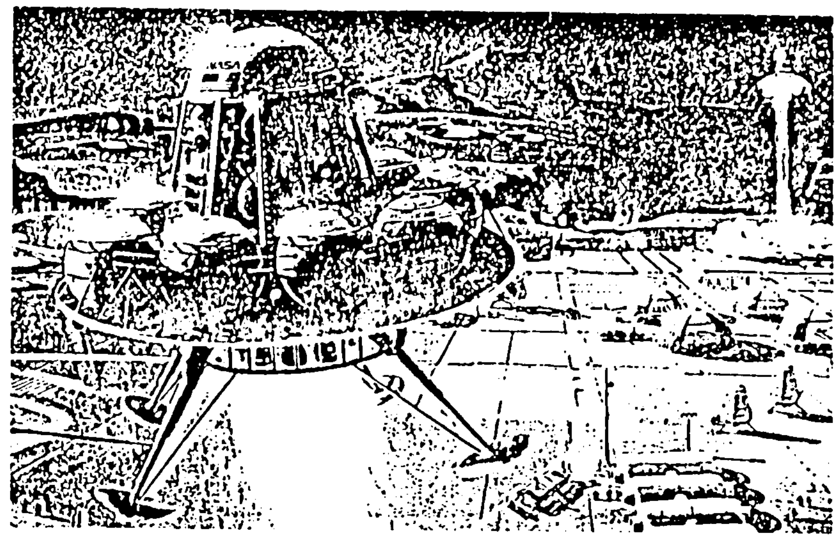
NASA
Lewis Research Center

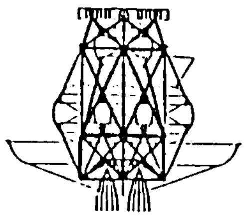
COST OF DELIVERING 100 kWe OF USABLE POWER



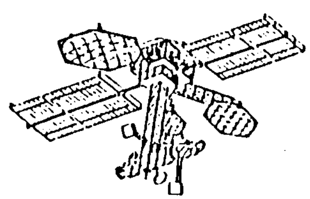
UTILITY POWER FOR THE SPACE FRONTIER

- SPACE INFRASTRUCTURE REQUIRES COMMONALITY WITH DIVERSITY
- SPACE STATION IS FIRST STEP
- TECHNOLOGY NEEDED NOW TO SET STANDARDS

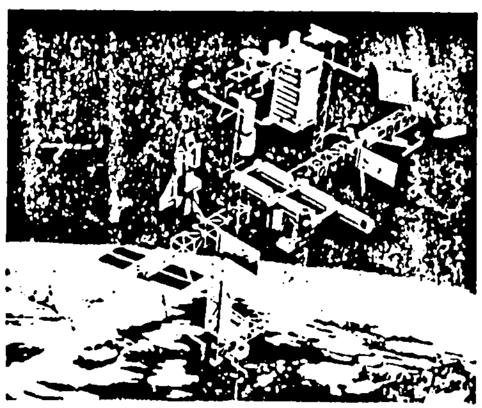




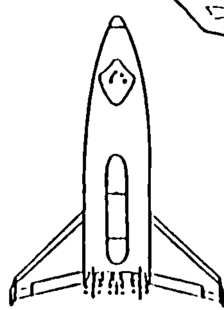
SBOTV



PLATFORM



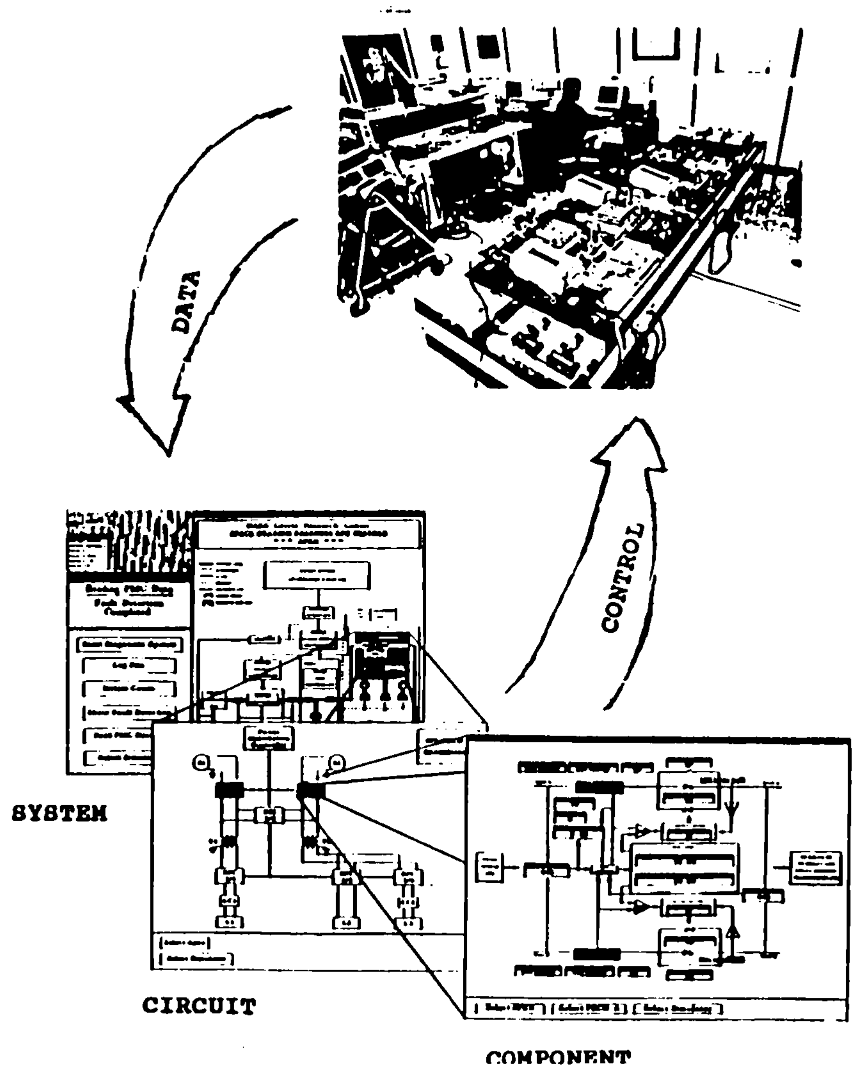
NASP



SHUTTLE II

20 kHz RESONANT PMAD
- VERSATILE
- LIGHTER WEIGHT
- SUPERIOR CREW SAFETY
- MINIMAL EMI
- LOWER COST
- GREATER RELIABILITY
- HIGHER EFFICIENCY

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



GOAL:
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:

* ENHANCED CREW EFFICIENCY THROUGH FASTER POWER OPERATIONS DECISIONS
* IMPROVED ELECTRICAL ENERGY UTILIZATION WITH OPTIMIZED LOAD POWER SCHEDULING
* INCREASED SAFETY PROVIDED BY RAPID ELECTRICAL FAULT DIAGNOSIS/RECOVERY

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**

LARGE SPACE POWER PLANTS MUST BE

FAST

SMART

SAFE

VERSATILE

GROWABLE

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 WORD
- EASY VERIFICATION, VALIDATION, STATUS, MAINTAINABILITY
- FOUNDATIONS FOR ORDERLY TRANSITION TO EXPERT SYSTEMS

COMPARISON OF CONTROL APPROACHES

DISTRIBUTED SMART - REPLICATIVE LOGIC STRUCTURES → ***SAVINGS IN -*** PEOPLE, TIME, SW, V&V

- FOUNDATIONAL WITH CONTROLLED, MEASUREABLE EVOLUTION
- TEST PIECES ON GROUND - ASSEMBLE IN SPACE
- TRENDS, FAULT PREDICTION, AUTONOMY COORDINATED

CENTRAL AUTOMATION → COMPLEX SW, V&V COSTLY

RECOMMENDATIONS FOR SPACE STATION EVOLUTION

HIGH FREQUENCY AC ⟹ GROWABLE PMAD SYSTEM

SMART COMPONENTS ⟹ GROWABLE, AFFORDABLE SOFTWARE

DISTRIBUTED LOGIC ⟹ GROWABLE AUTONOMY/FAULT TOLERANCE

JPL TECHNOLOGY FOR SPACE STATION EVOLUTION
A WORKSHOP

FREEDOM

ADVANCED MODULAR POWER SUPPLIES FOR SPACE STATION FREEDOM

S. Krauthamer

M. D. Gangal

R. C. Detwiler

January 17, 1990
Dallas, Texas

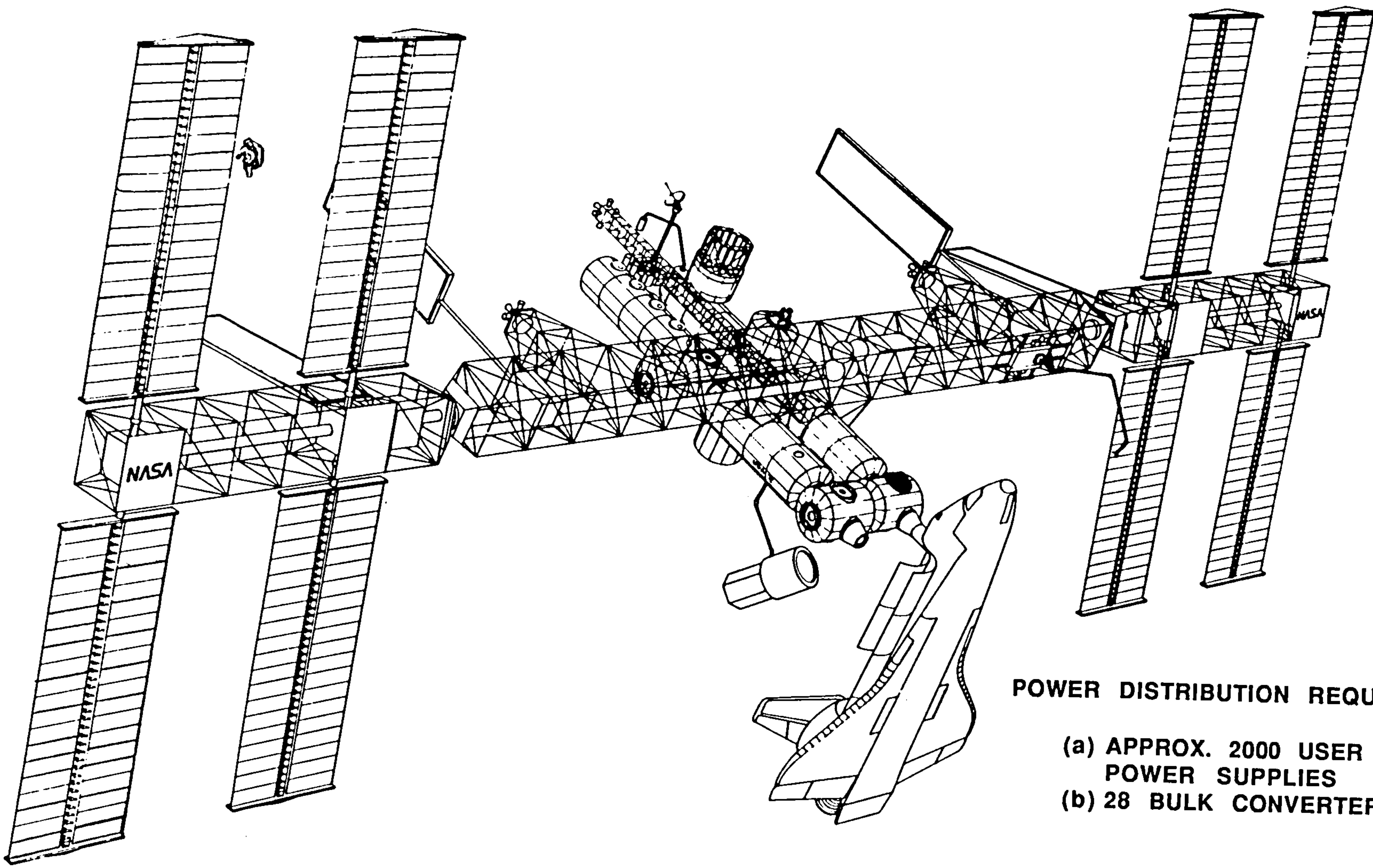
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

THIS PAGE INTENTIONALLY BLANK

CONTENTS

THIS PAGE INTENTIONALLY BLANK

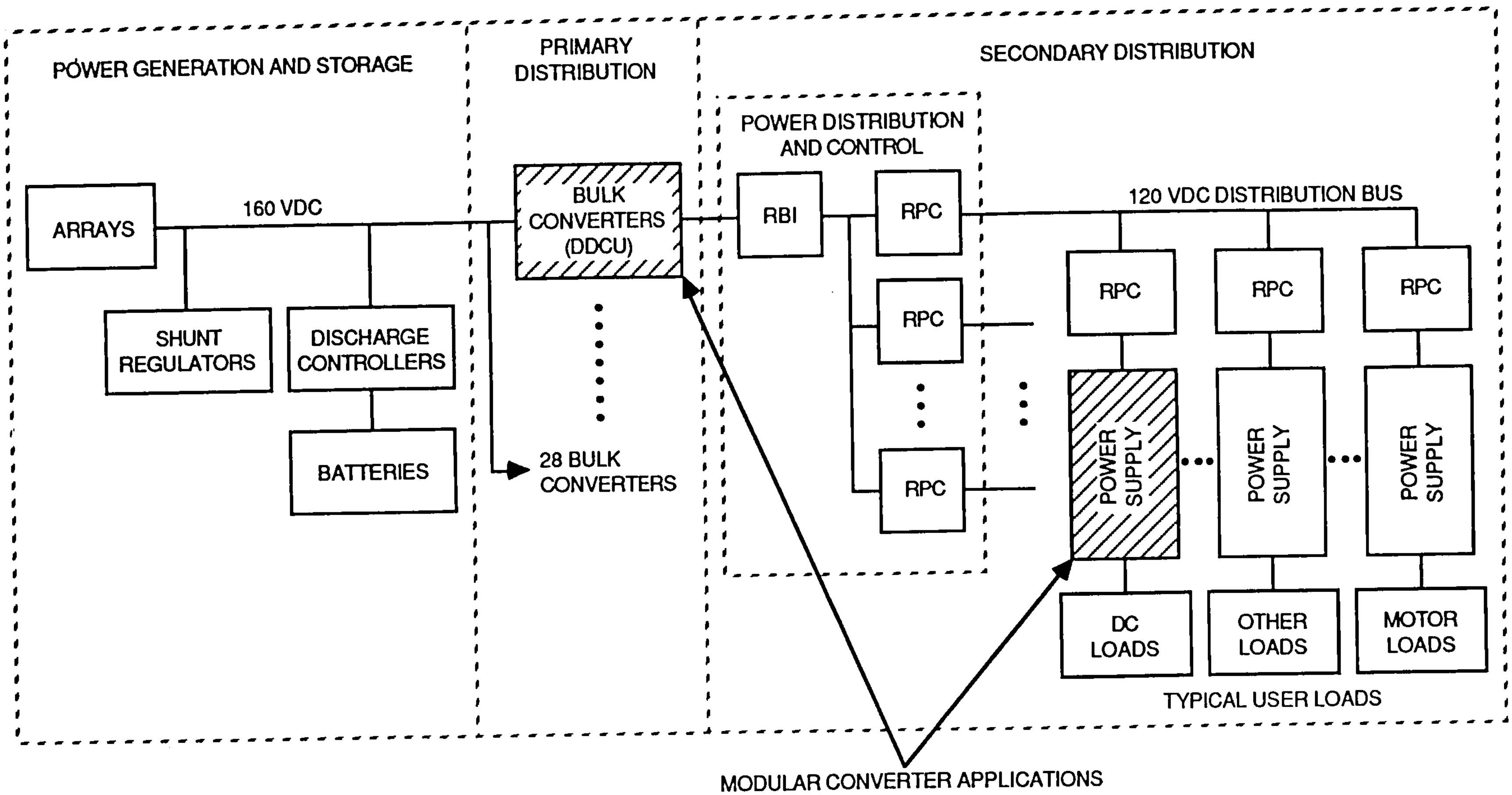
SPACE STATION FREEDOM CONFIGURATION



POWER DISTRIBUTION REQUIRES

(a) APPROX. 2000 USER END POWER SUPPLIES
(b) 28 BULK CONVERTERS

SPACE STATION FREEDOM ELECTRICAL POWER SYSTEM
TARGET APPLICATIONS



RPC - REMOTE POWER CONTROLLER
RBI - REMOTE BUS INTERRUPTER

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

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

159

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.

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

THIS PAGE INTENTIONALLY BLANK

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 discrete 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.

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.

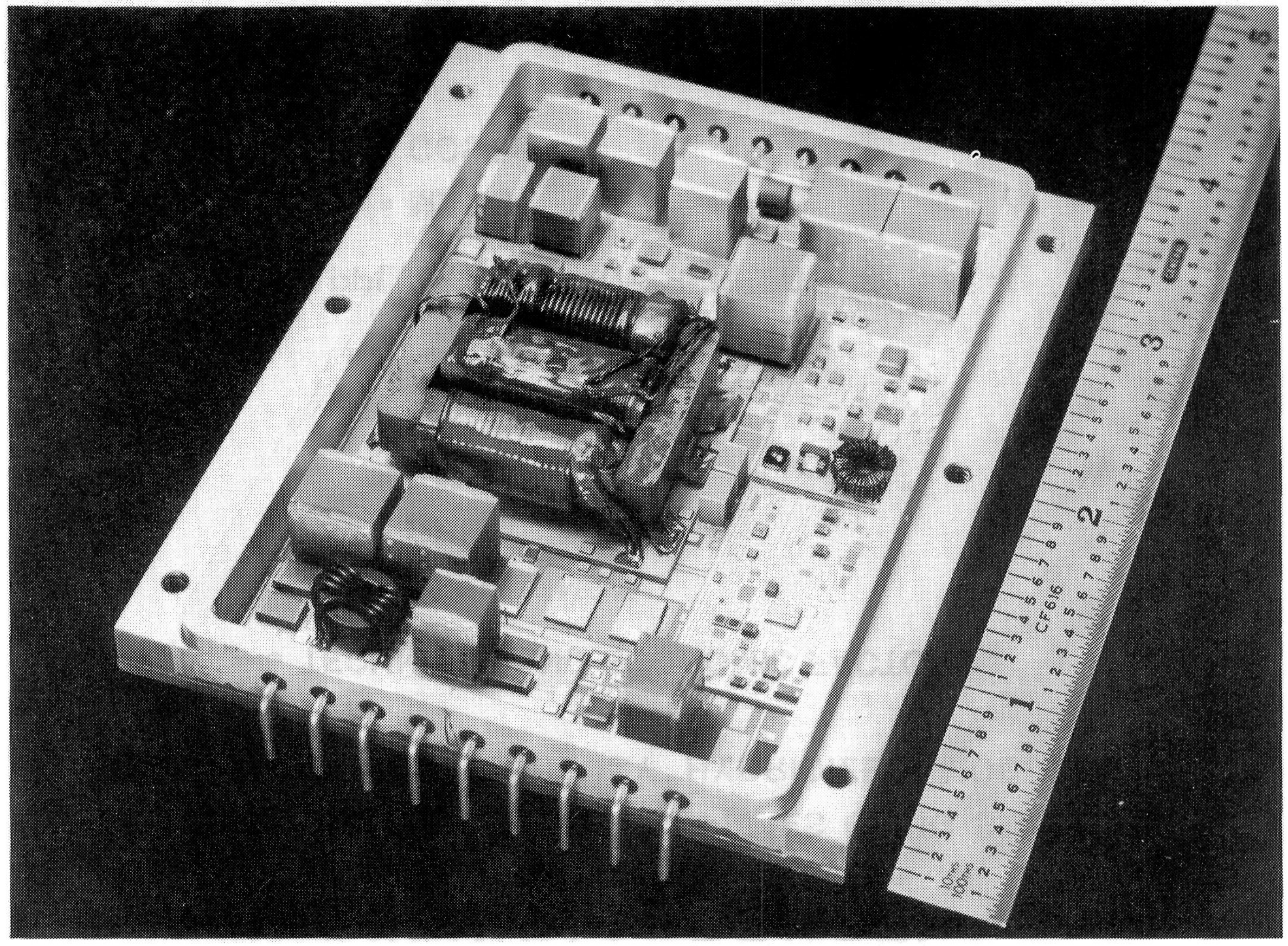
None of these units have been space qualified; the proposed development effort, therefore, is necessary.

MODULARITY CONCEPT

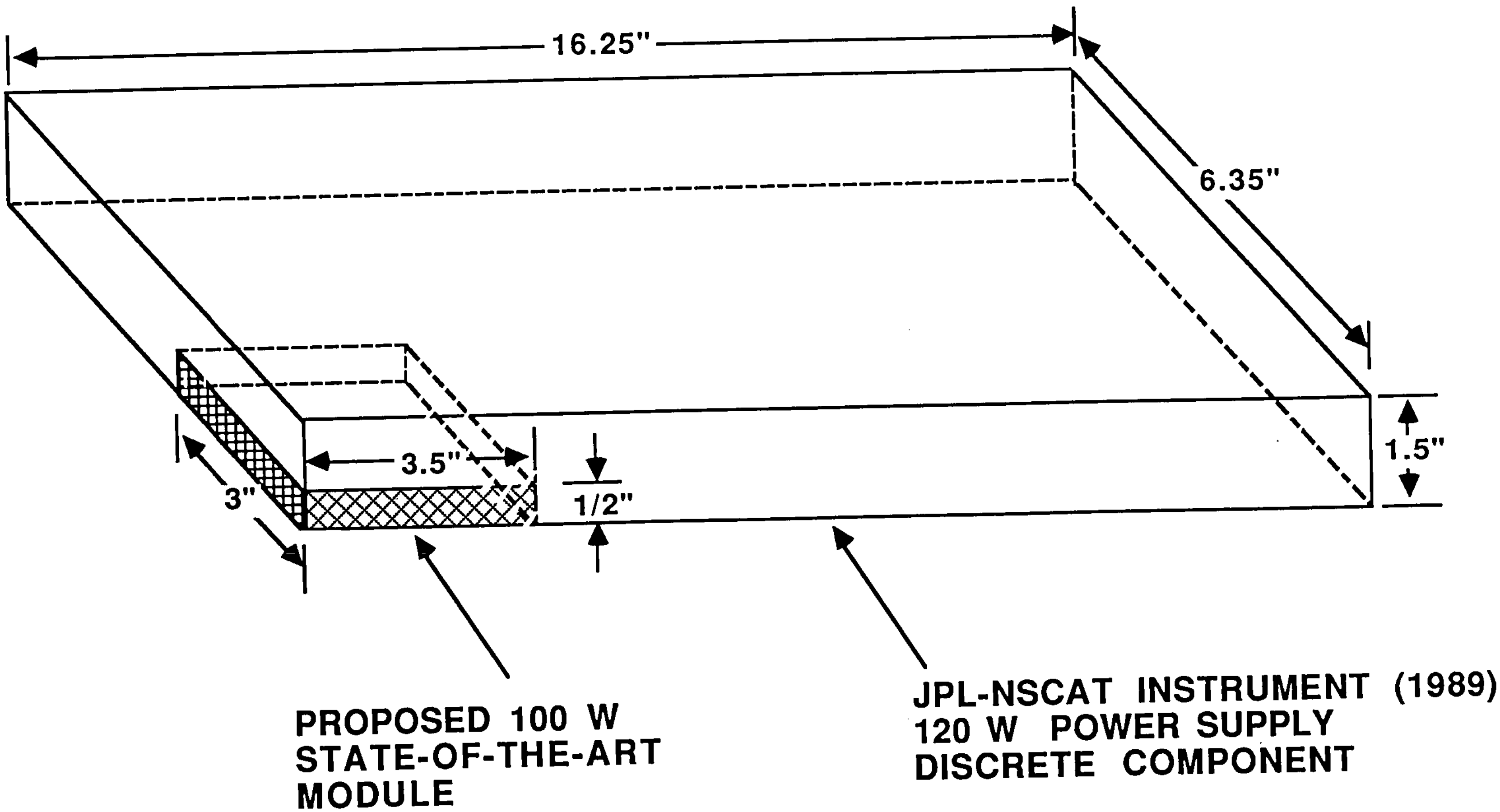
- CONCEPT: BUILD DC POWER SUPPLIES USING SMALL, HIGH-SWITCHING-FREQUENCY HYBRIDIZED MODULES.
  - TECHNICAL AND ECONOMIC FACTORS
    - EFFICIENCY
    - RELIABILITY
    - EMI
    - FLEXIBILITY
    - CONTROL
  - APPLICATIONS AND BENEFITS
    - MASS
    - COST

100-W HYBRID MODULAR POWER SUPPLY (HUGHES AIRCRAFT CORPORATION)

270-V INPUT, 5-V OUTPUT; 100-W RATING



SIZE COMPARISON OF PRESENT AND PROPOSED DESIGN



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 efficency 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.

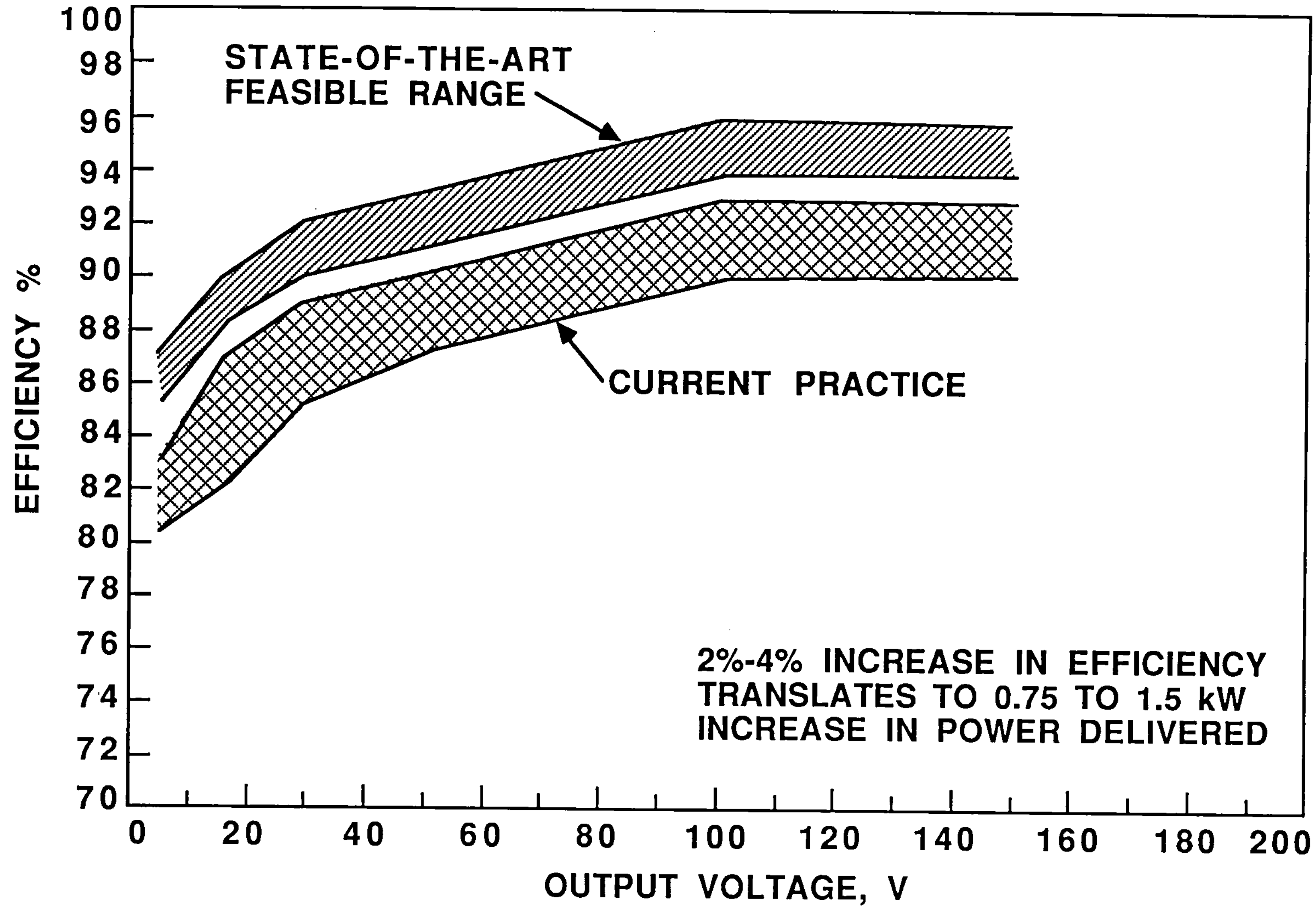
Because the final rectification stage of a module results in a voltage drop, the efficiency of the module is a sensitive function of its output voltage. Viewgraph 11 shows the efficiency of state of the art modules as a function of the output voltage. The same viewgraph shows that if techniques such 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.

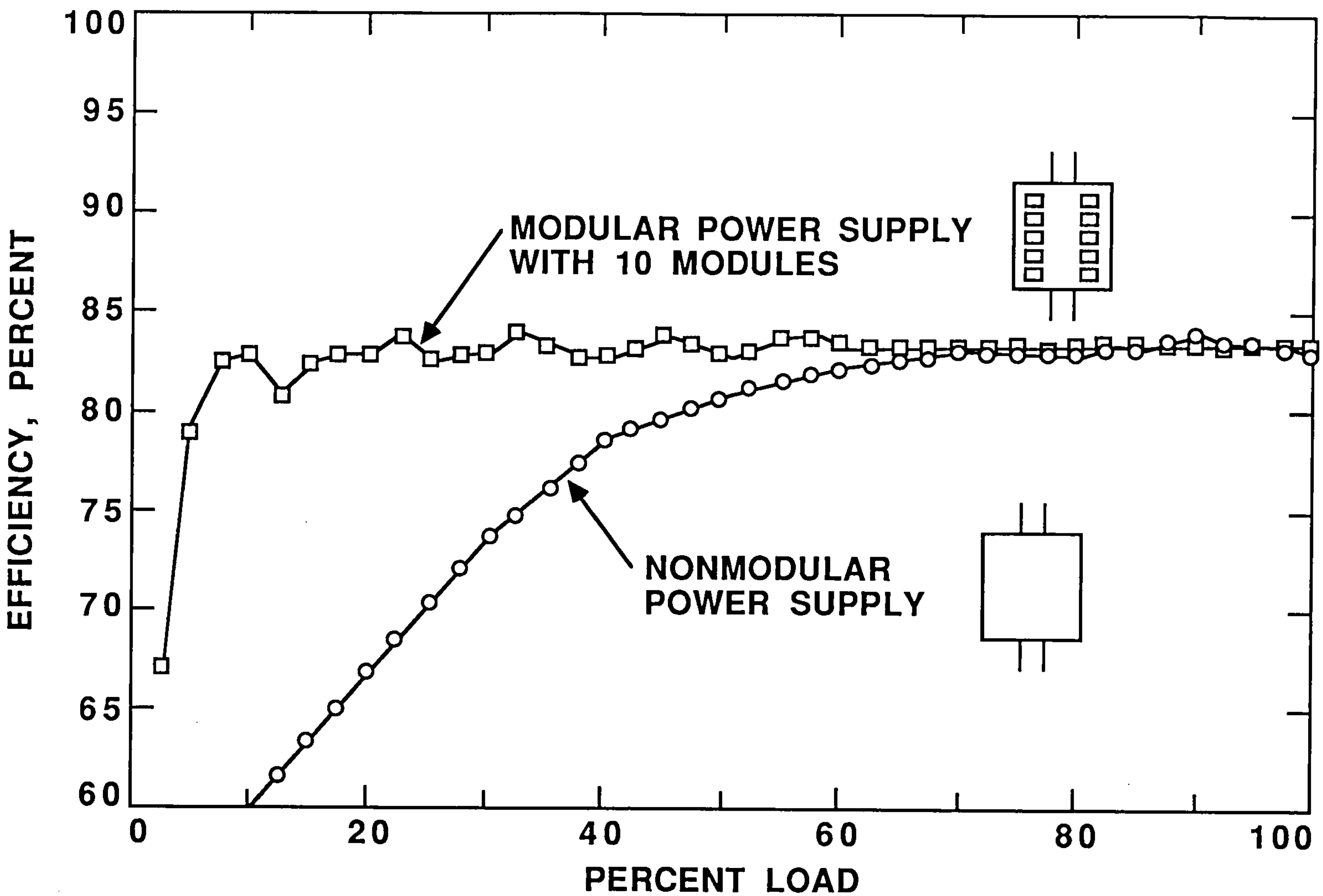
EFFICIENCY

- 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

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.

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.

EMI CONTROL

- PROTOTYPE MODULES HAVE ALREADY SHOWN COMPLIANCE WITH MIL-STD-461B

- MODULES CAN BE SYNCHRONIZED TO ENHANCE EMI CONTROL

- SMALL EXTERNAL FILTERS CAN PROVIDE FURTHER IMPROVEMENTS

MASS AND VOLUME REDUCTION

(DISCUSSION OF VIEWGRAPH 15)

Dr. Ćuk 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.

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

THIS PAGE INTENTIONALLY BLANK

USER END POWER SUPPLIES

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.

USER POWER SUPPLIES
APPLICATION CHARACTERISTICS (Cont'd)

(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

MASS AND COST BENEFITS

- MASS REDUCTION
  - ESTIMATE 1000 lb 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/lb)
  - APPROX. $15 TO $30 MILLION LIFE CYCLE COST BENEFIT DUE TO HIGHER EFFICIENCY (AT $20 MILLION/kW)

THIS PAGE INTENTIONALLY BLANK

BULK CONVERTER APPLICATION

THIS PAGE INTENTIONALLY BLANK

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)]

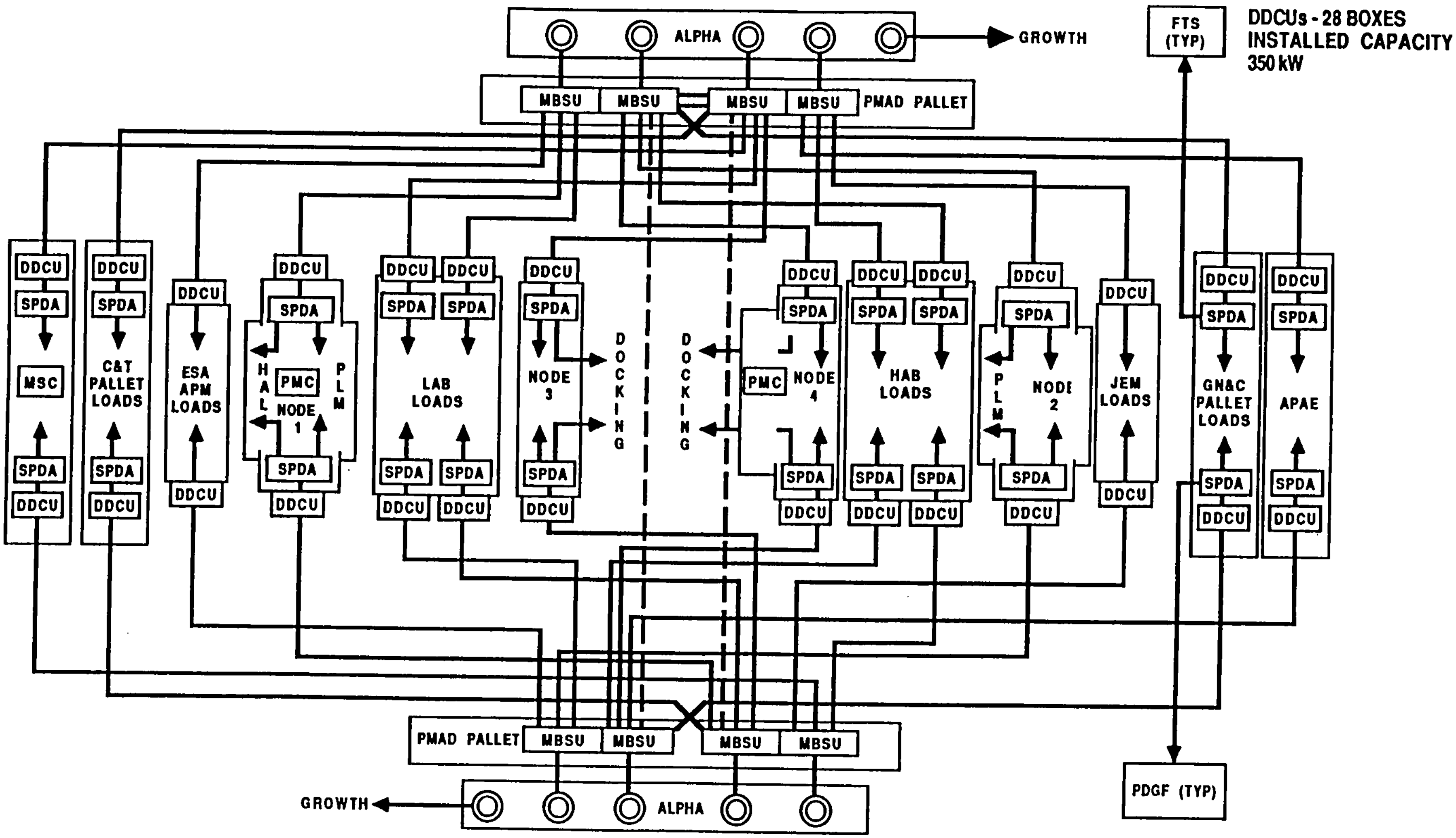
(DISCUSSION OF VIEWGRAPH 19)

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.

BULK CONVERTER APPLICATION
PROPOSED ARCHITECTURE



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.

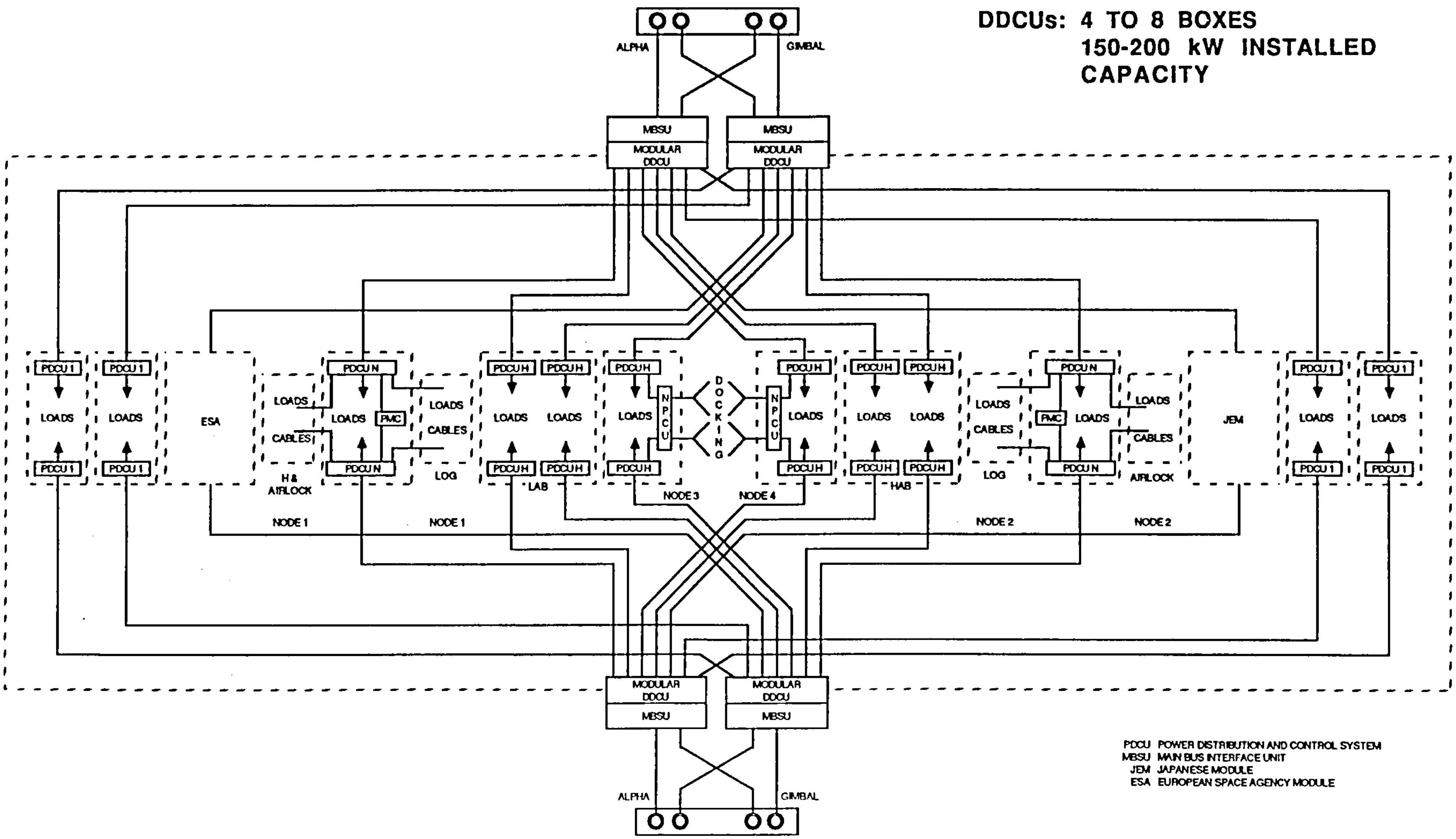
PROPOSED ARCHITECTURE [SPACE STATION FREEDOM (SSF) ELECTRICAL POWER SYSTEM (EPS)] (Cont'd)

(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.

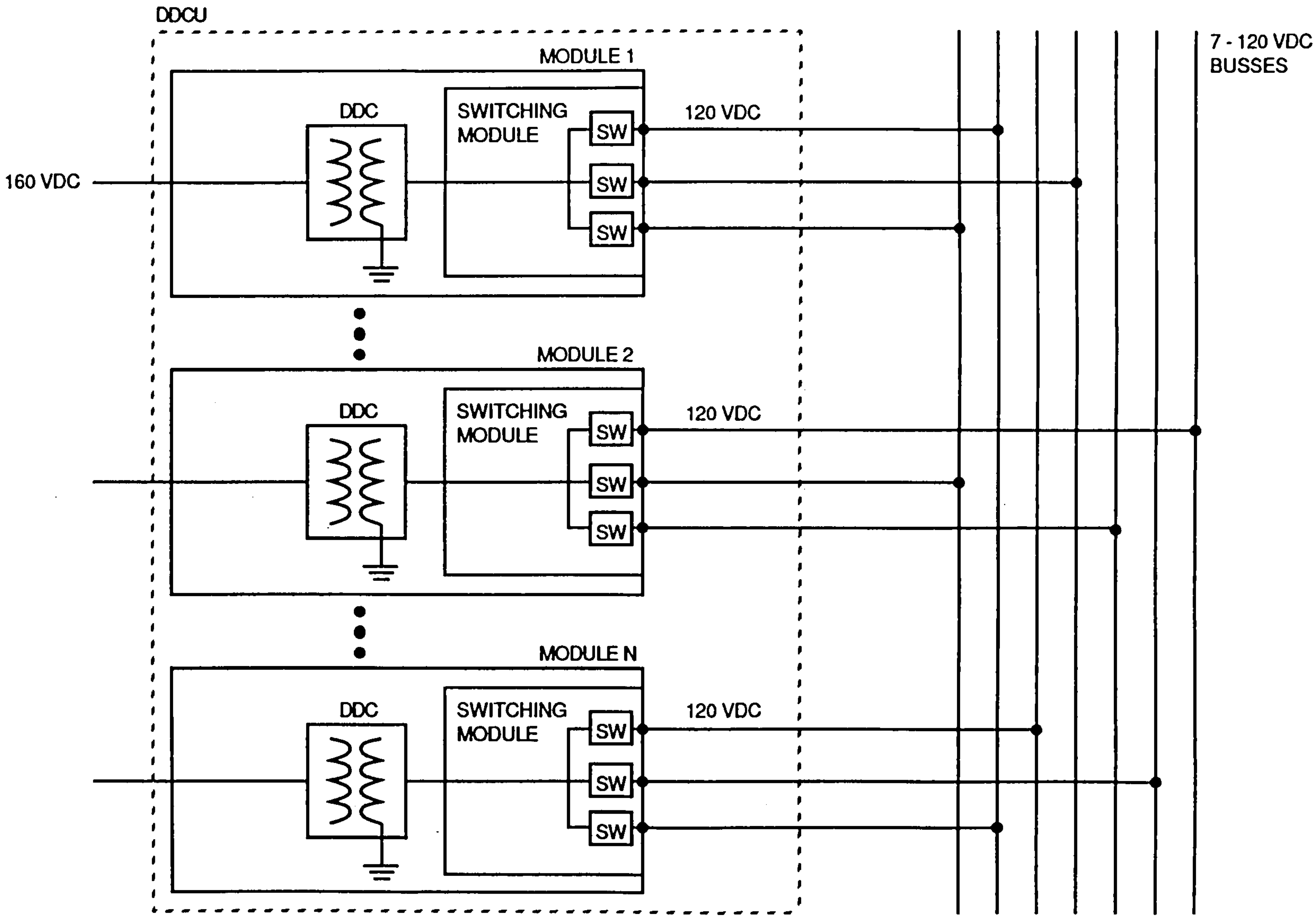
BULK CONVERTER APPLICATION
PROPOSED ARCHITECTURE

DDCUs: 4 TO 8 BOXES
150-200 kW INSTALLED CAPACITY



PDCU POWER DISTRIBUTION AND CONTROL SYSTEM
MBSU MAIN BUS INTERFACE UNIT
JEM JAPANESE MODULE
ESA EUROPEAN SPACE AGENCY MODULE

MODULAR ARRANGEMENT FOR BULK CONVERTERS



DDCU – DC/DC BULK CONVERTER UNIT
DDC – DC/DC CONVERTER
SW – SWITCH

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

THIS PAGE INTENTIONALLY BLANK

RECOMMENDATIONS

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

- PLACE HIGH PRIORITY ON THE PROPOSED MODULAR POWER SUPPLY DEVELOPMENT EFFORT

- EMPHASIZE BOTH END-APPLICATIONS

THIS PAGE INTENTIONALLY BLANK

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

PRECEDING PAGE BLANK NOT FILMED

Power plant locations need to be assessed

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

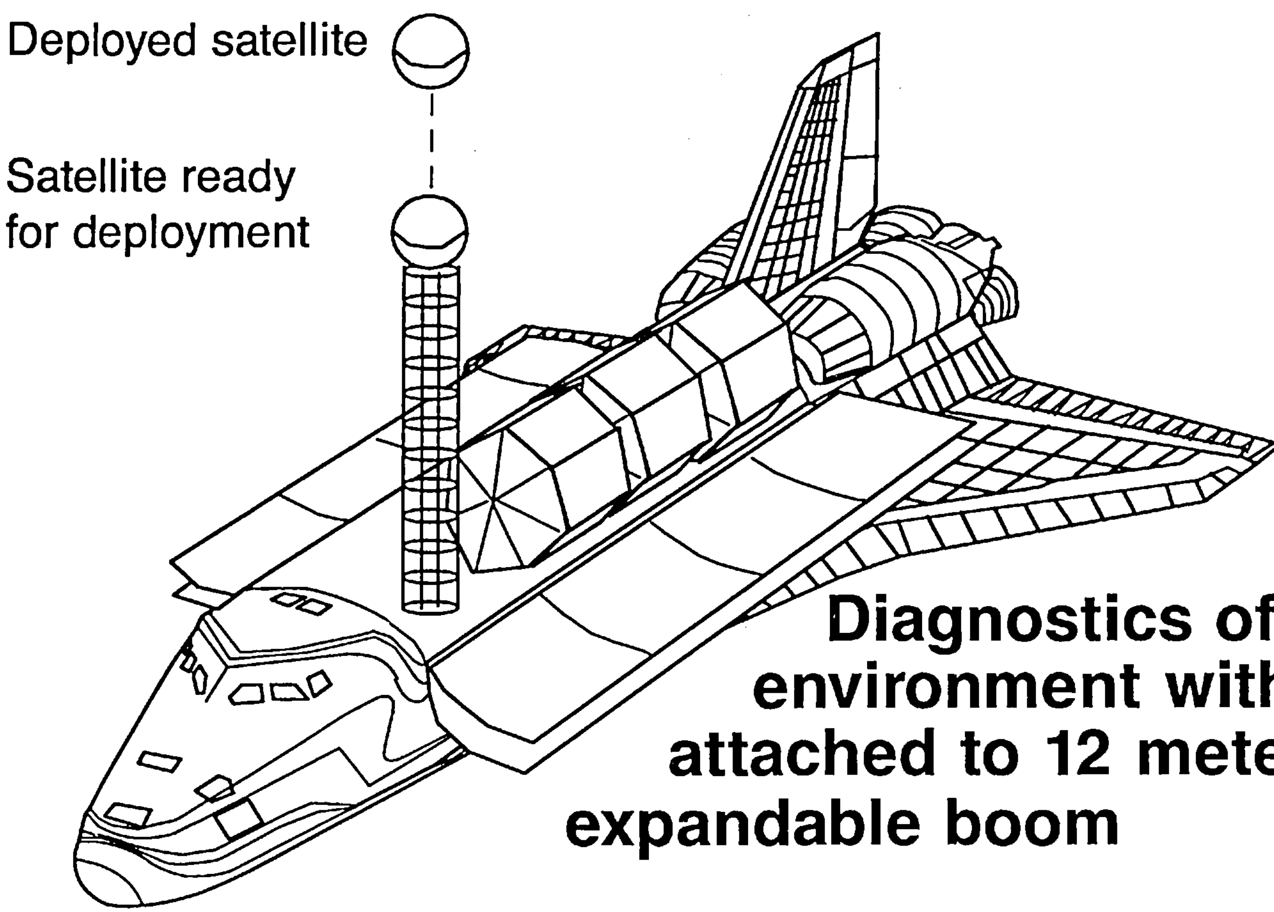
- Recommended at planning conference for ISY
- Proposed by Center for Space Power (Texas A&M)
- Investigated by Institute of Space and Astronautical Science (Japan)

Space Power System Technology (ISAS)

Working groups

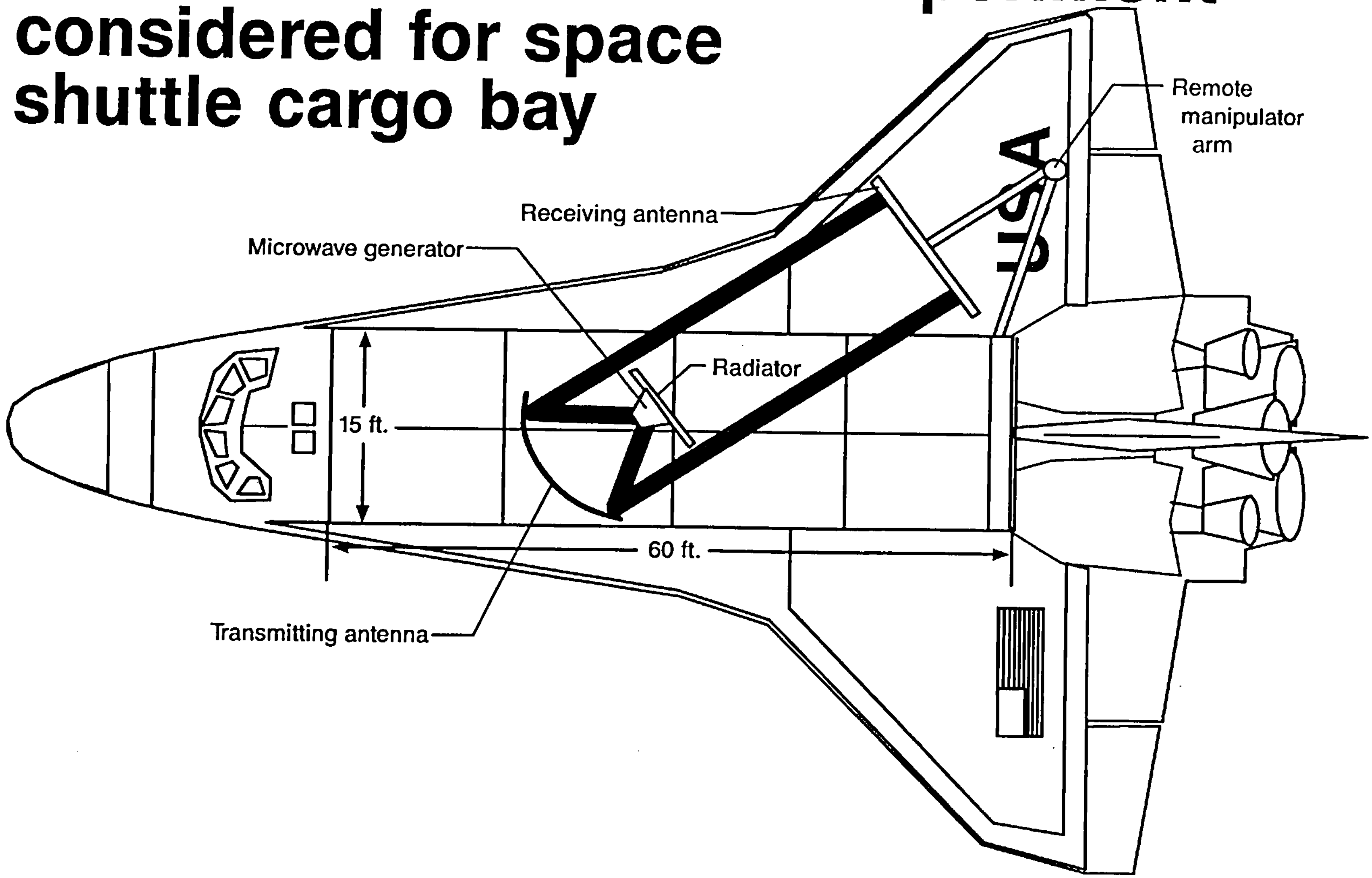
- System technology
  - Microwave power reception
  - Attitude control
  - Laser technology
  - Photovoltaic conversion
  - Thermodynamic conversion
  - Propulsion
- Experiment/observation
  - Spacecraft environment
  - Interaction with space plasma
  - Communication system
  - Biological effect

Planned TSS experiment (enabling)

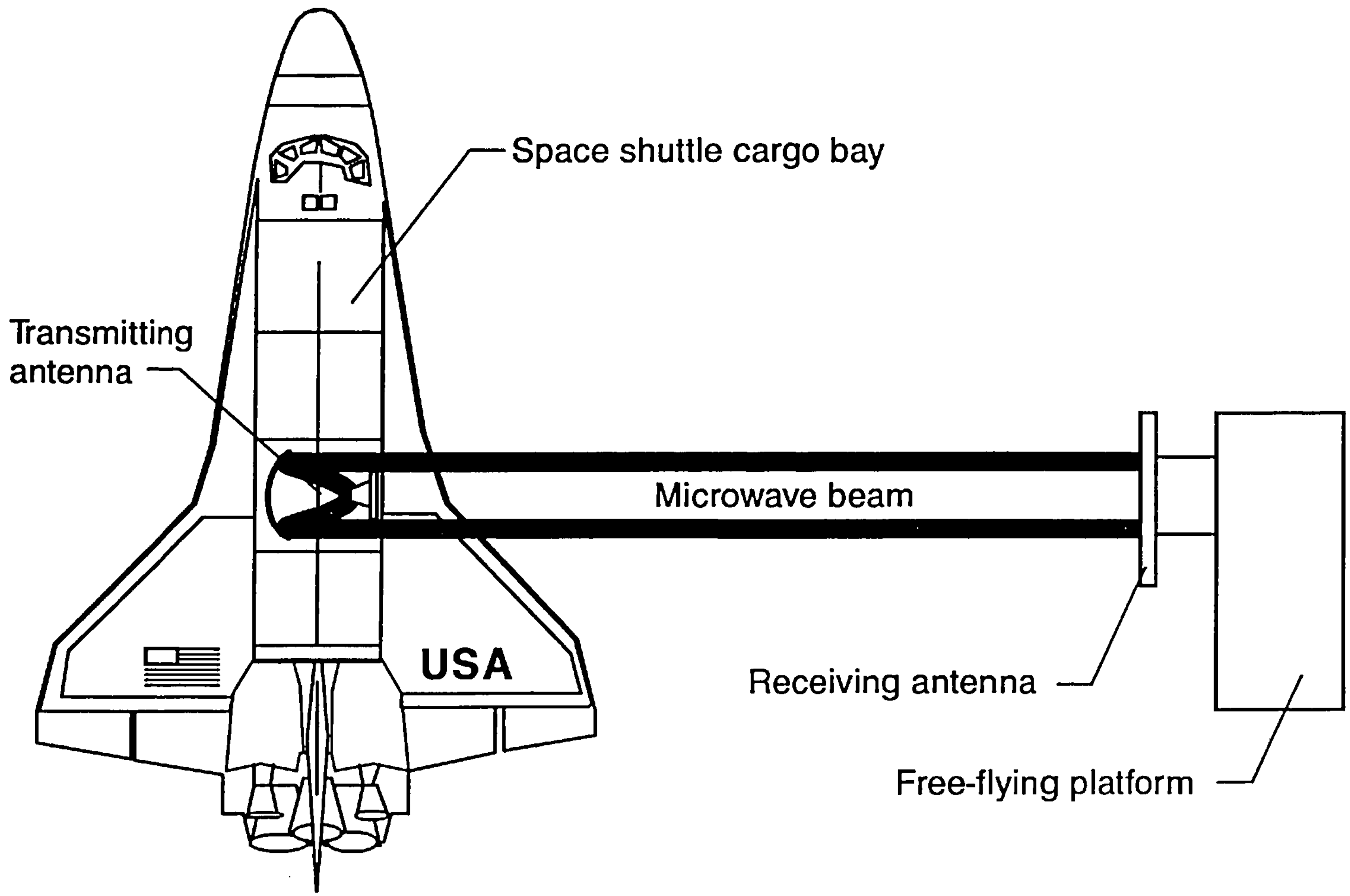


Diagnostics of plasma environment with tether attached to 12 meter expandable boom

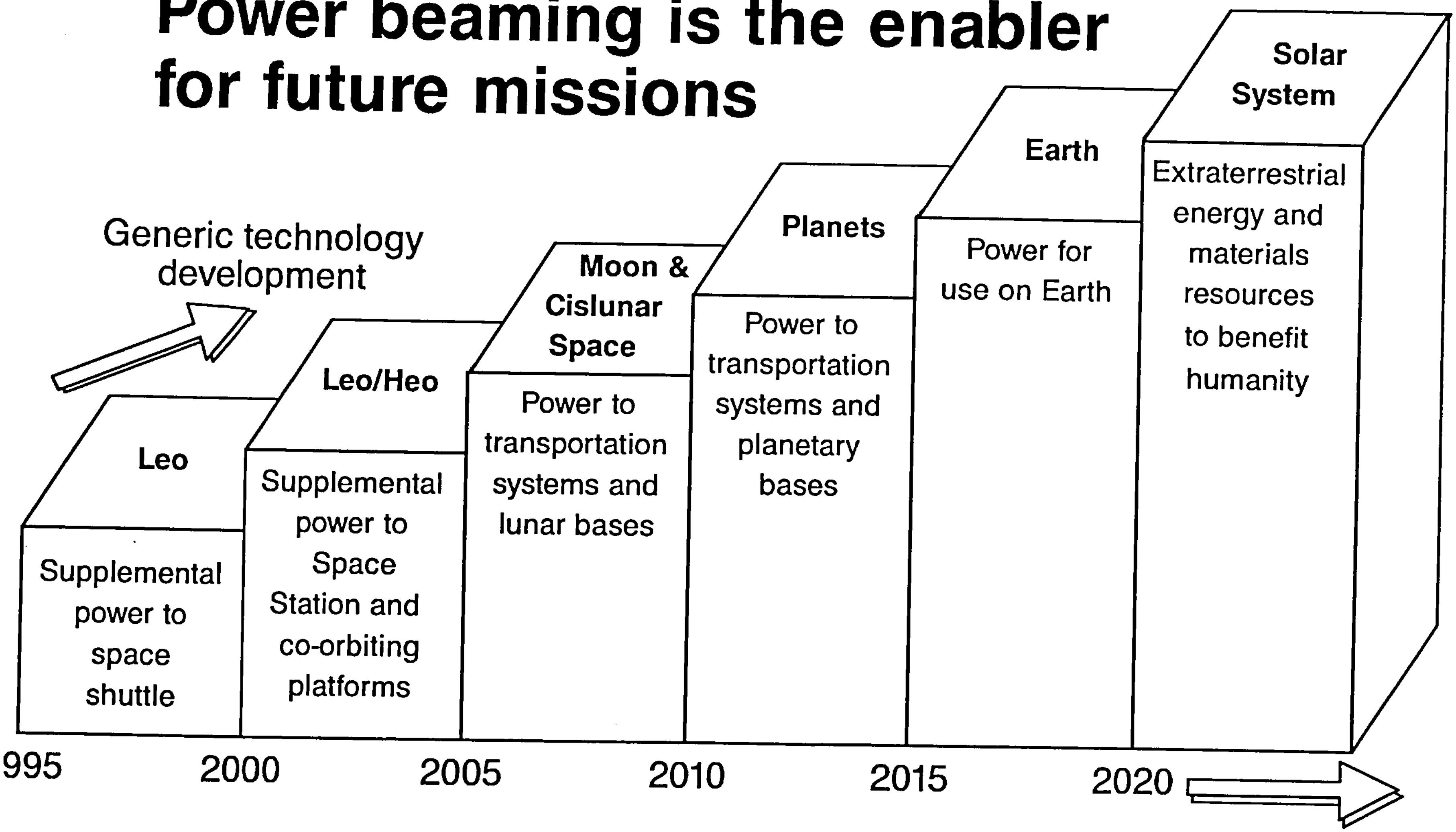
Microwave transmission experiment considered for space shuttle cargo bay



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



Power beaming is the enabler for future missions



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

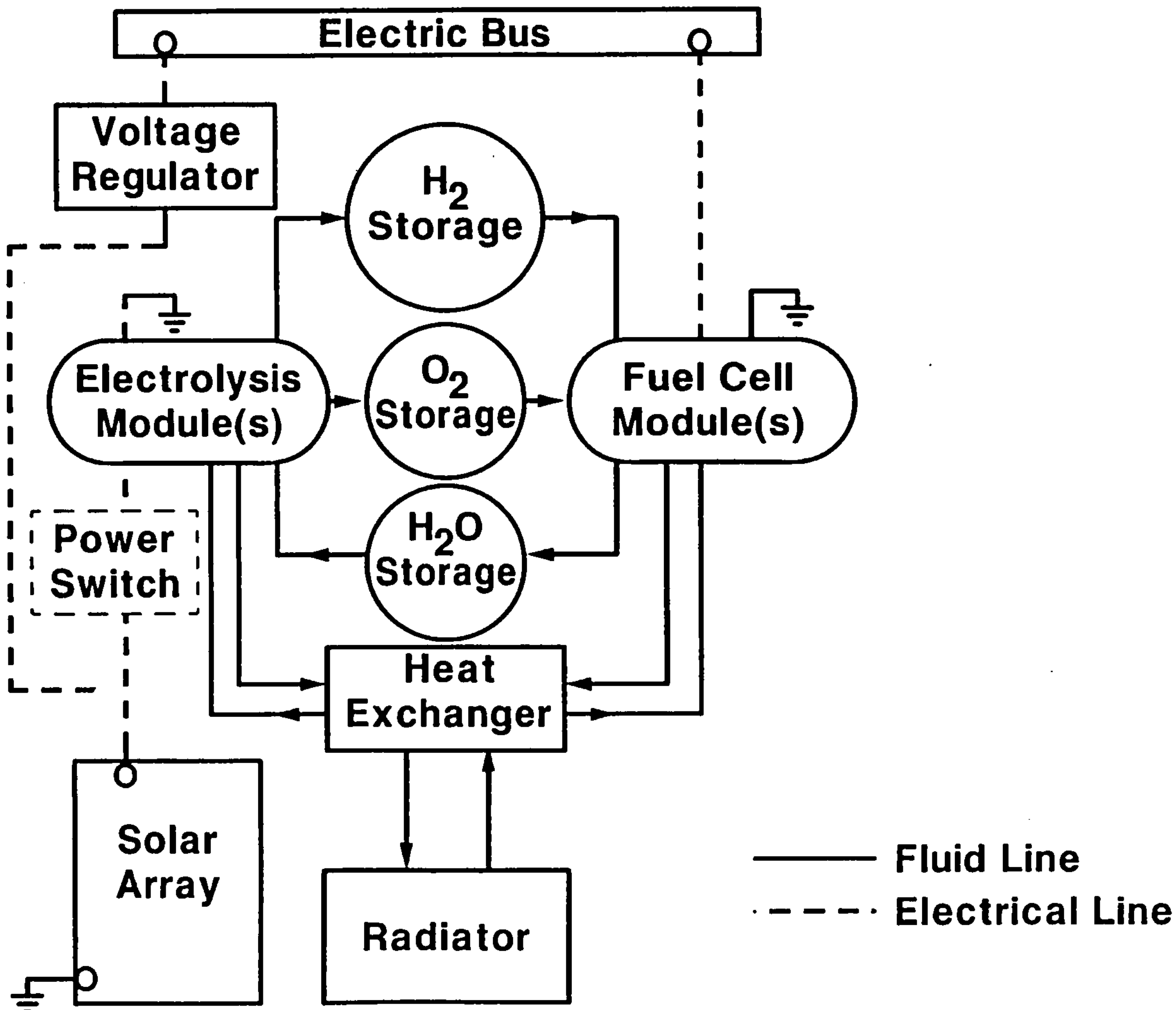
J. F. McElroy

United Technologies Corporation
Hamilton Standard Division
Windsor Locks, Connecticut

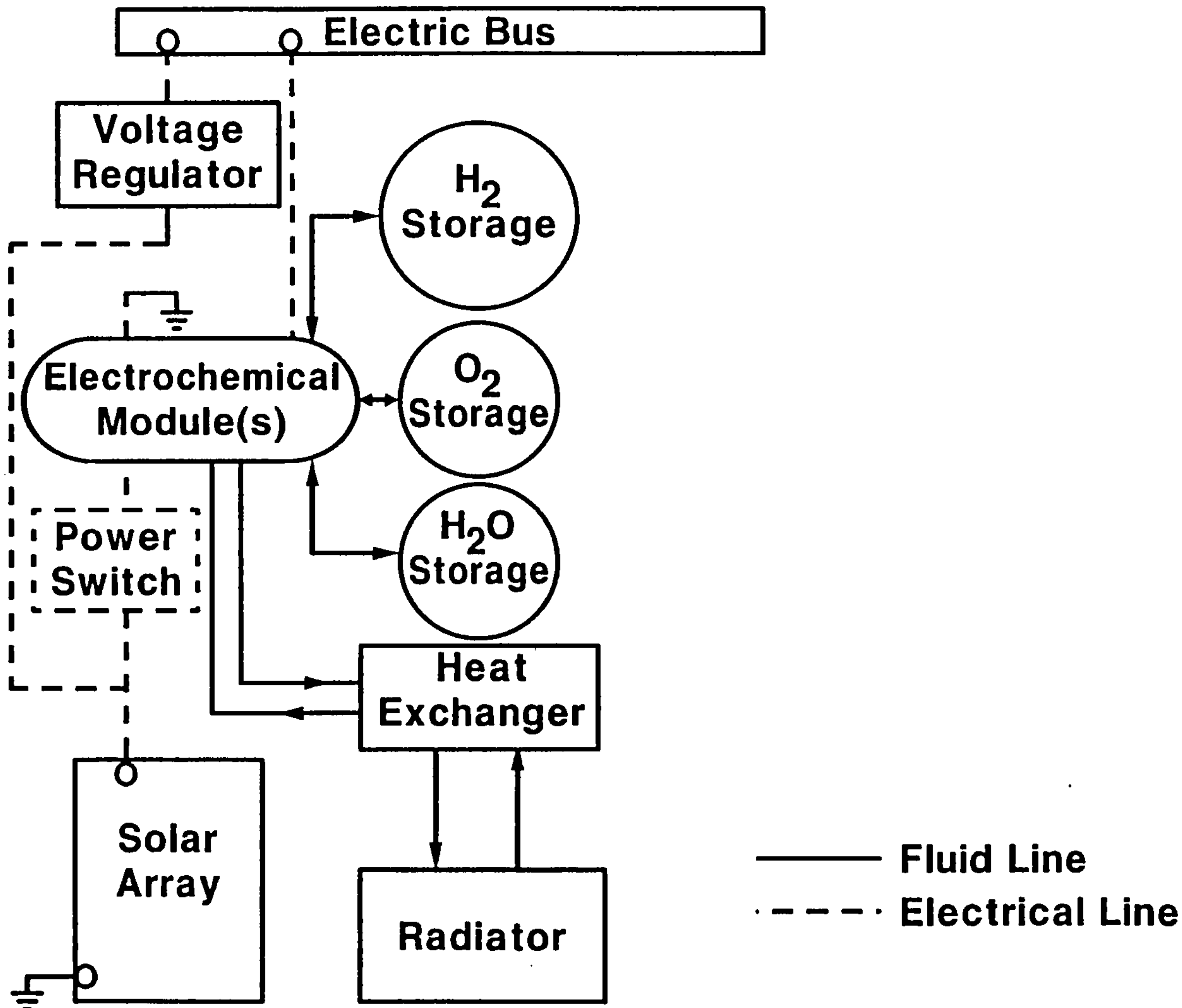
Presented at
NASA's Technology for Space Station
Evolution Workshop
January 16-19, 1990

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

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



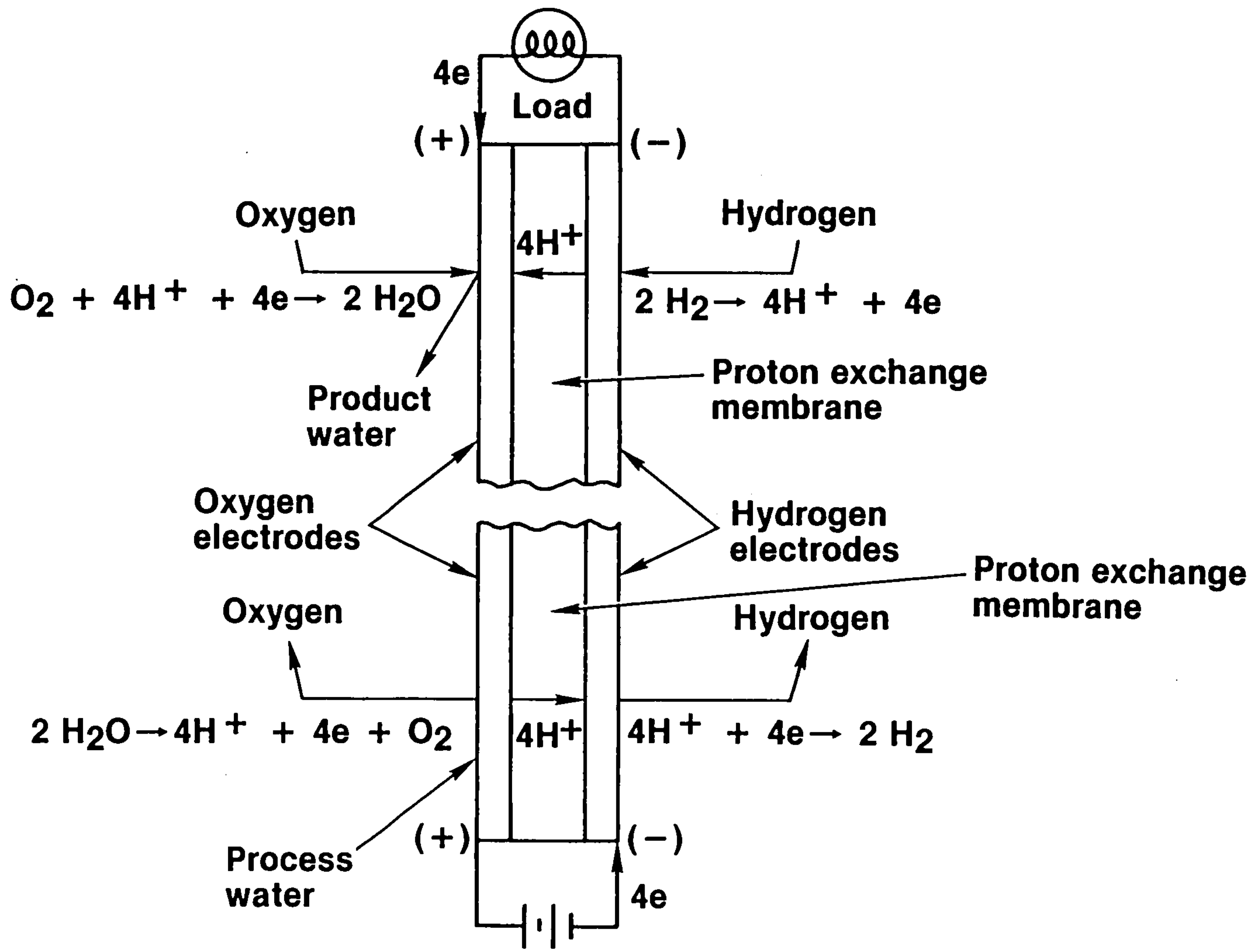
HYDROGEN-OXYGEN REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM
(Unitized Regenerative Module)



215

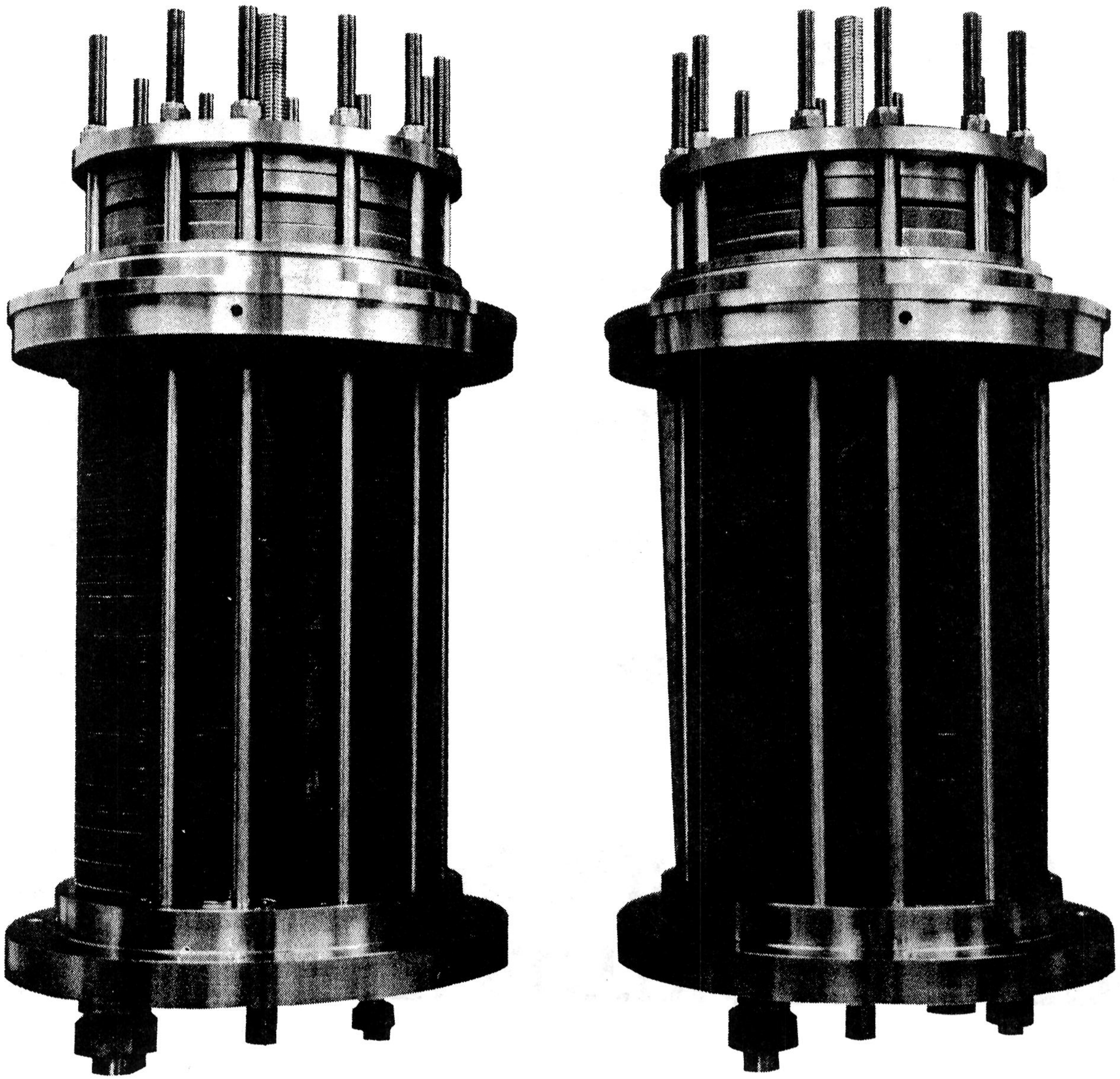
SPE ELECTROCHEMICAL CELL REACTIONS

Fuel Cell



Electrolyzer Cell

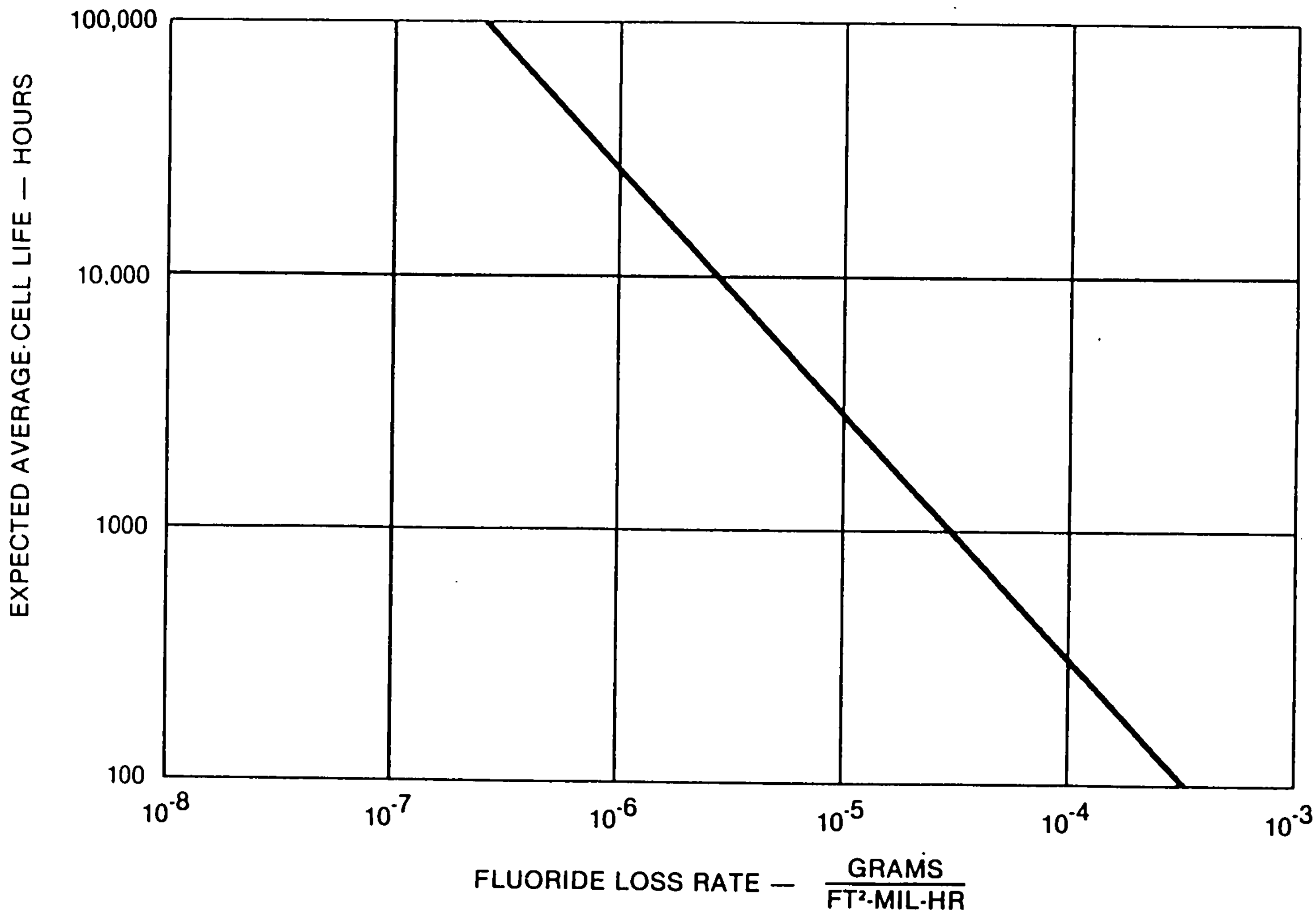
TYPICAL SPE MODULES



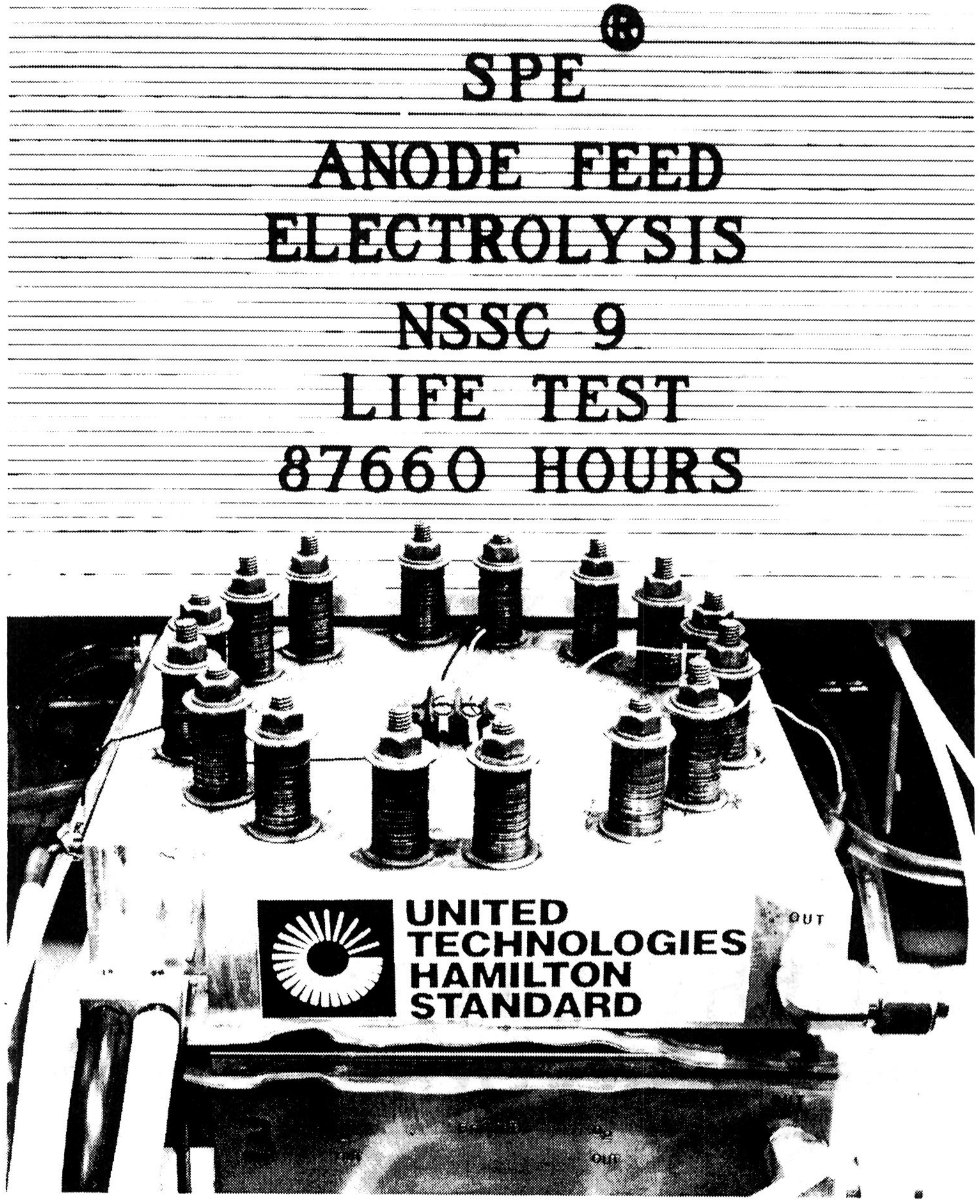
LUNAR BASE ELECTRICAL ENERGY STORAGE REQUIREMENTS

Discharge output rate	- 25KW
Discharge cycle time	~375 hours
Charge cycle time	~300 hours
System operating time	≥ 20,000 hours
High reliability	- Static phase separation
Low mass	~1000 watt-hours/kg

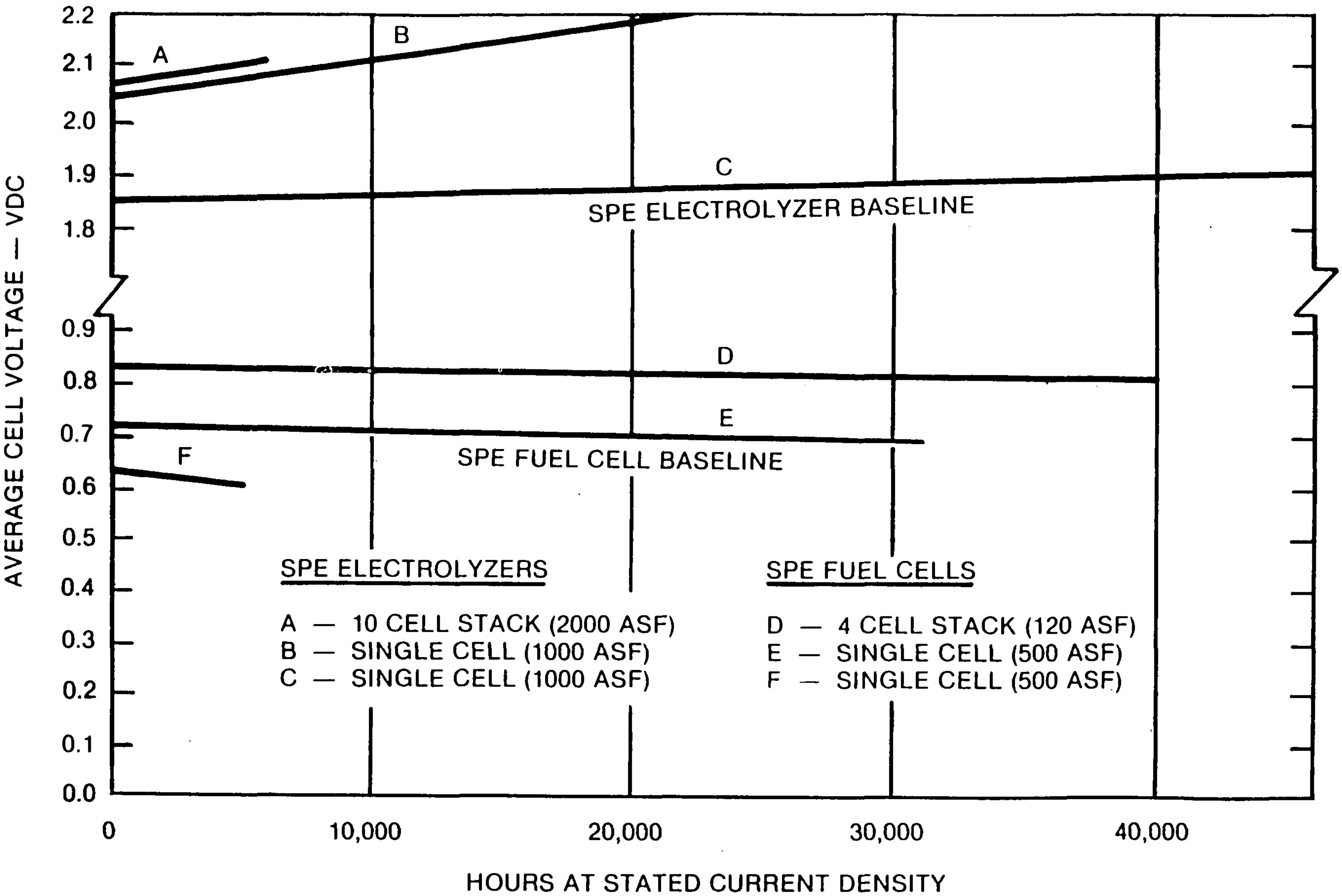
EXPECTED LIFETIMES OF SPE CELLS WITH PERFLUOROCARBON PROTON EXCHANGE MEMBRANES



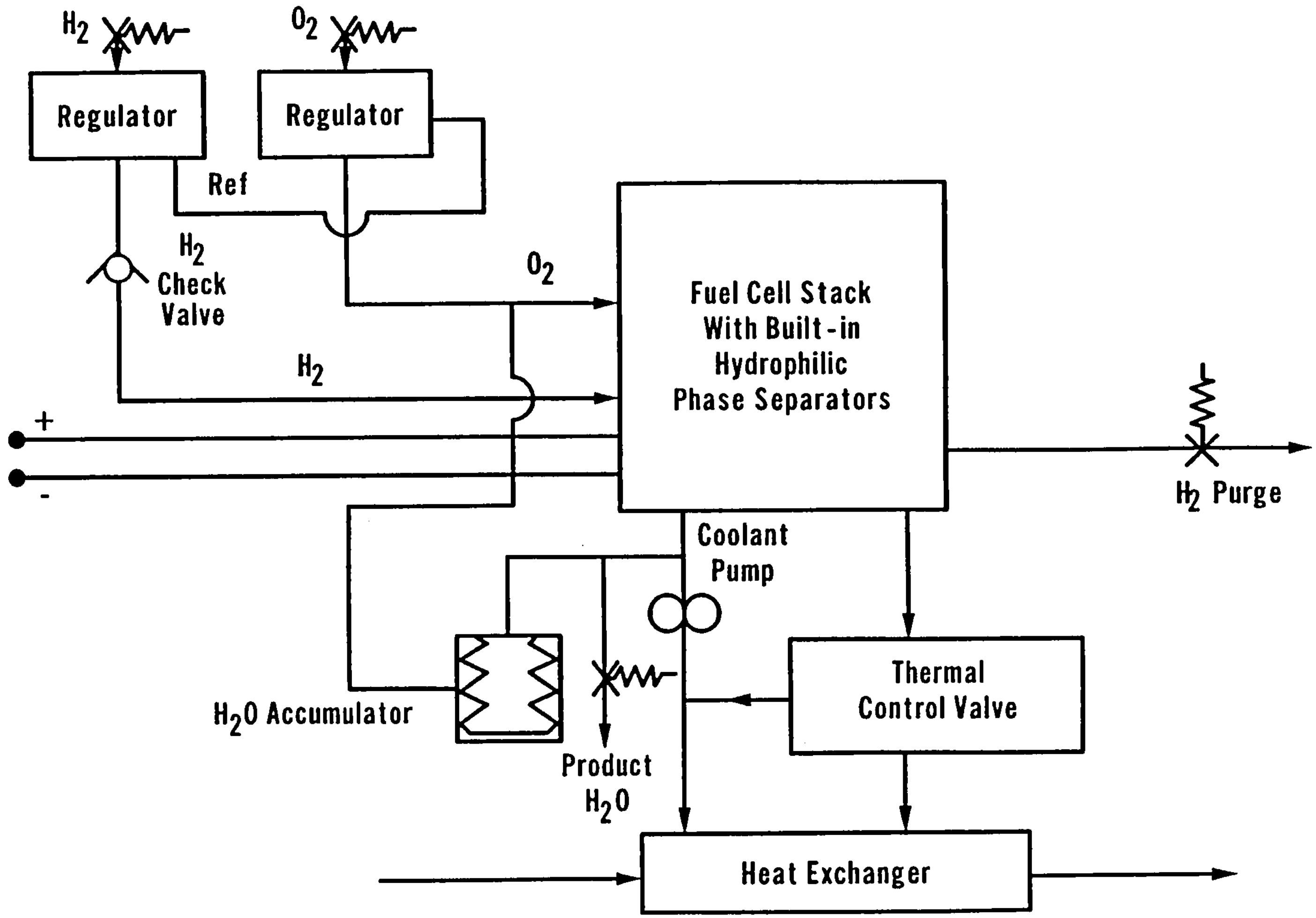
"UNINTERRUPTED" SPE ELECTROLYZER LIFE TEST



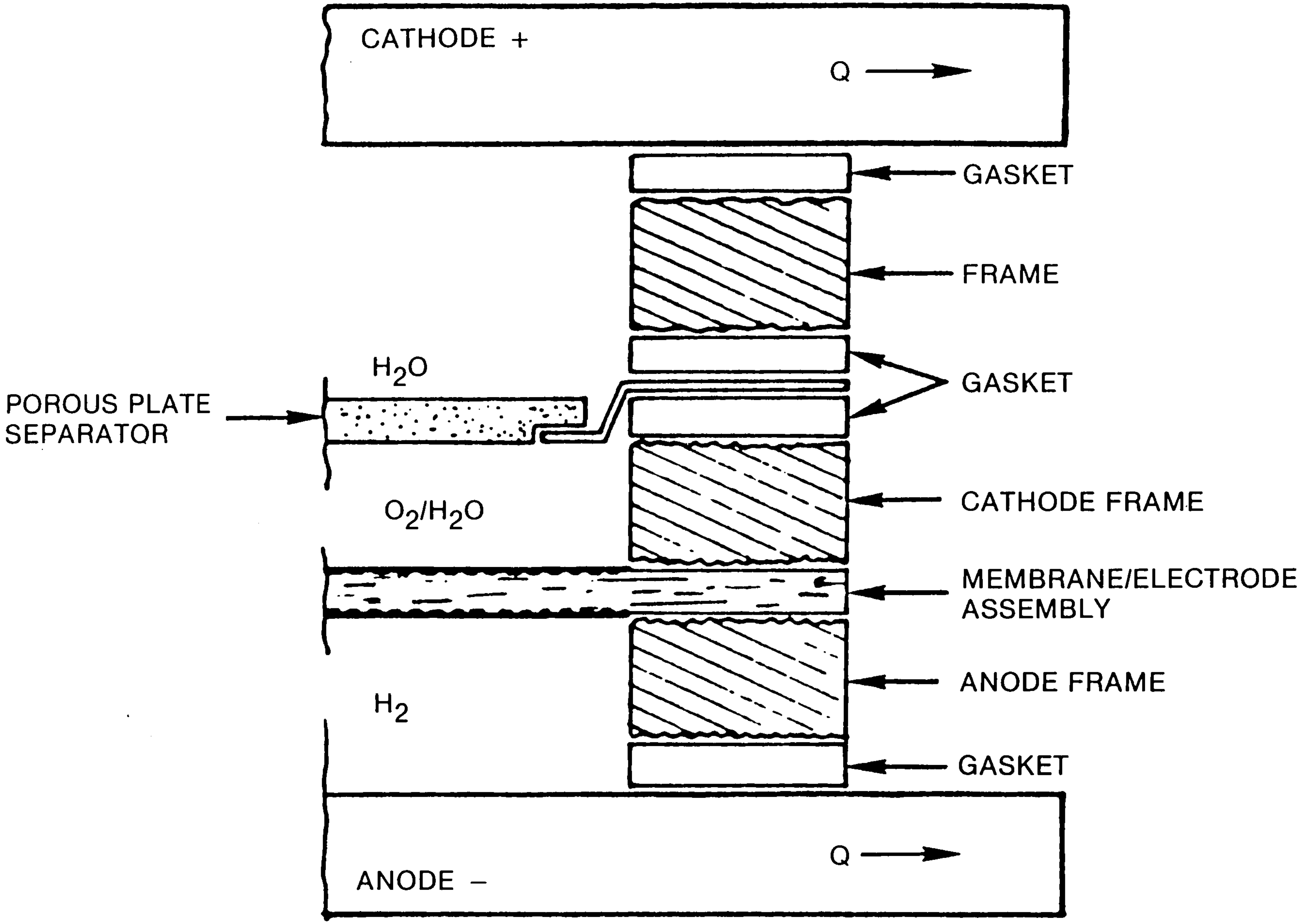
SPE CELL VOLTAGE STABILITY



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

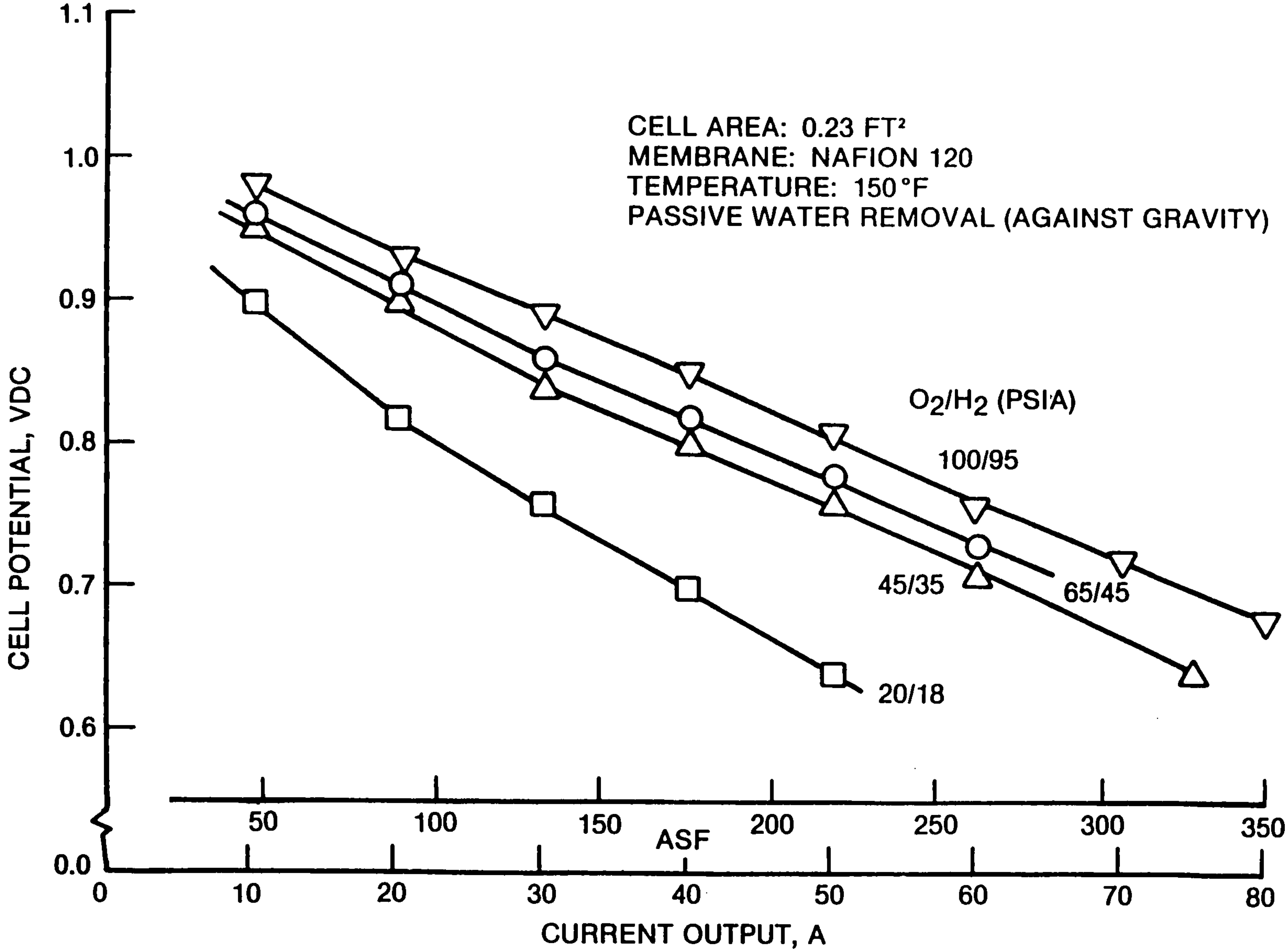


PASSIVE STATIC WATER REMOVAL SPE FUEL CELL — CROSS SECTION

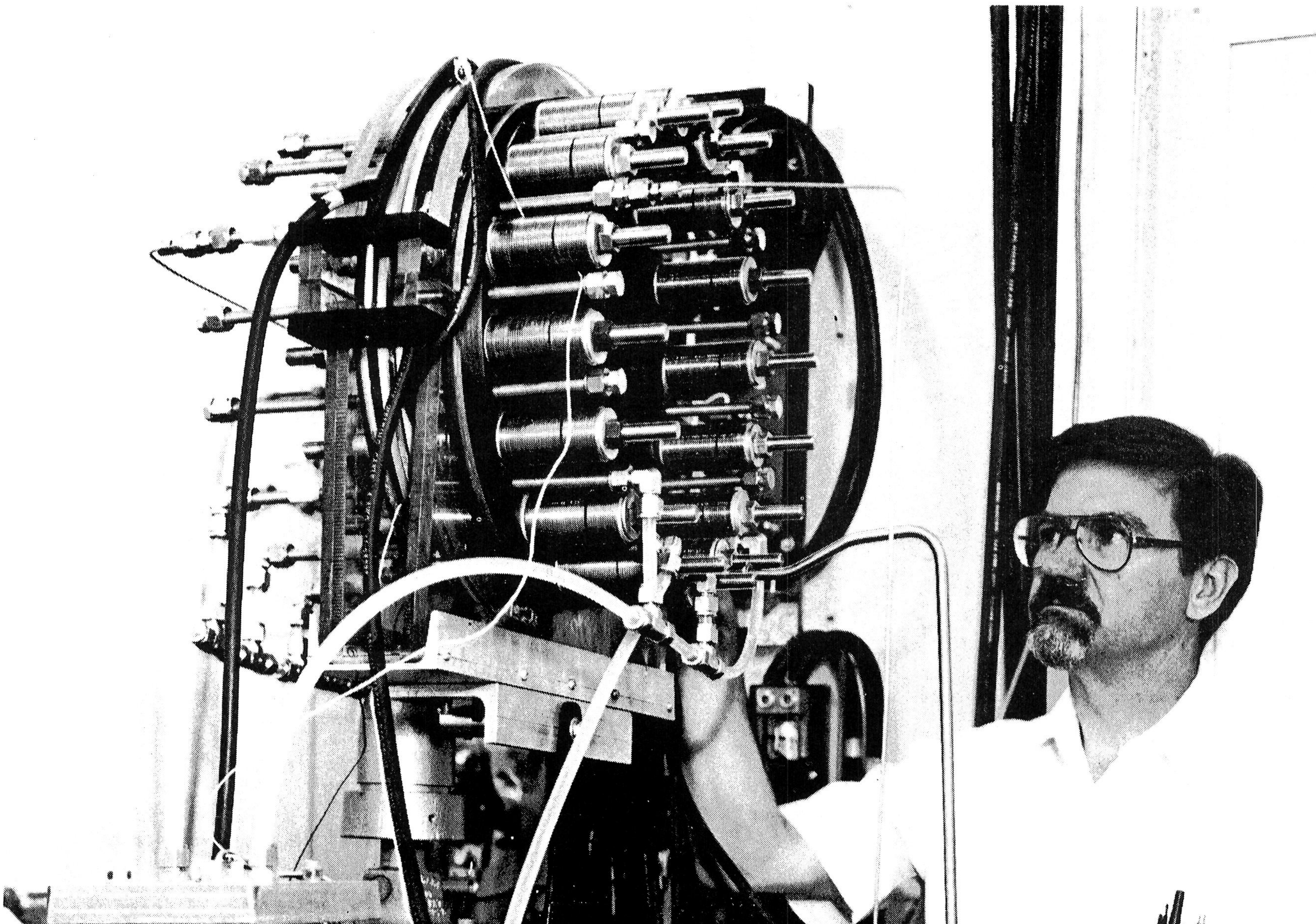


PASSIVE WATER REMOVAL SPE FUEL CELL
(Active Area 0.23 Ft^2)

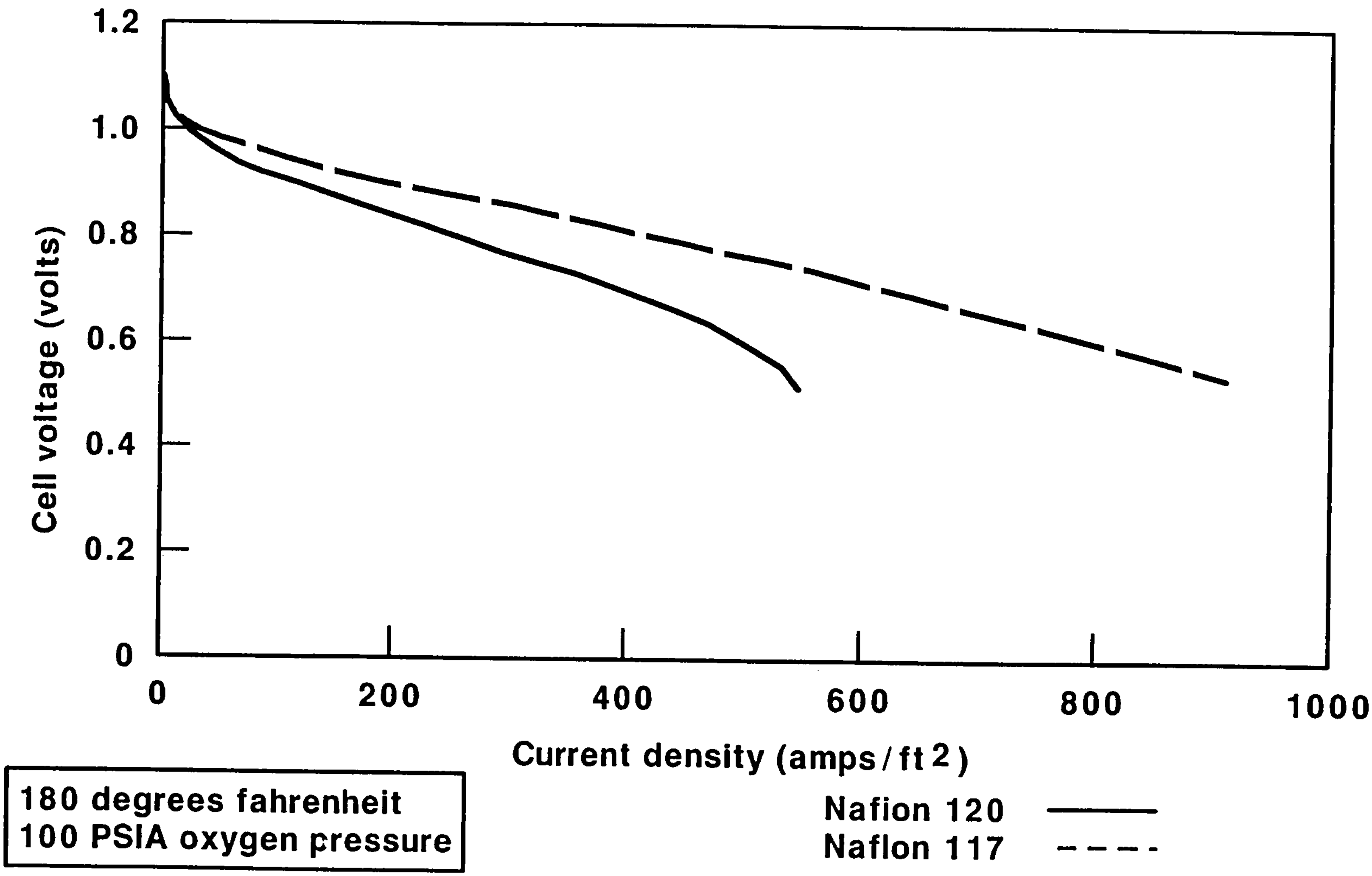
PASSIVE WATER REMOVAL SPE FUEL CELL PERFORMANCE AT 150°F



GRAVITY WATER REMOVAL SPE FUEL CELL
(Active Area 0.78 Ft^2)



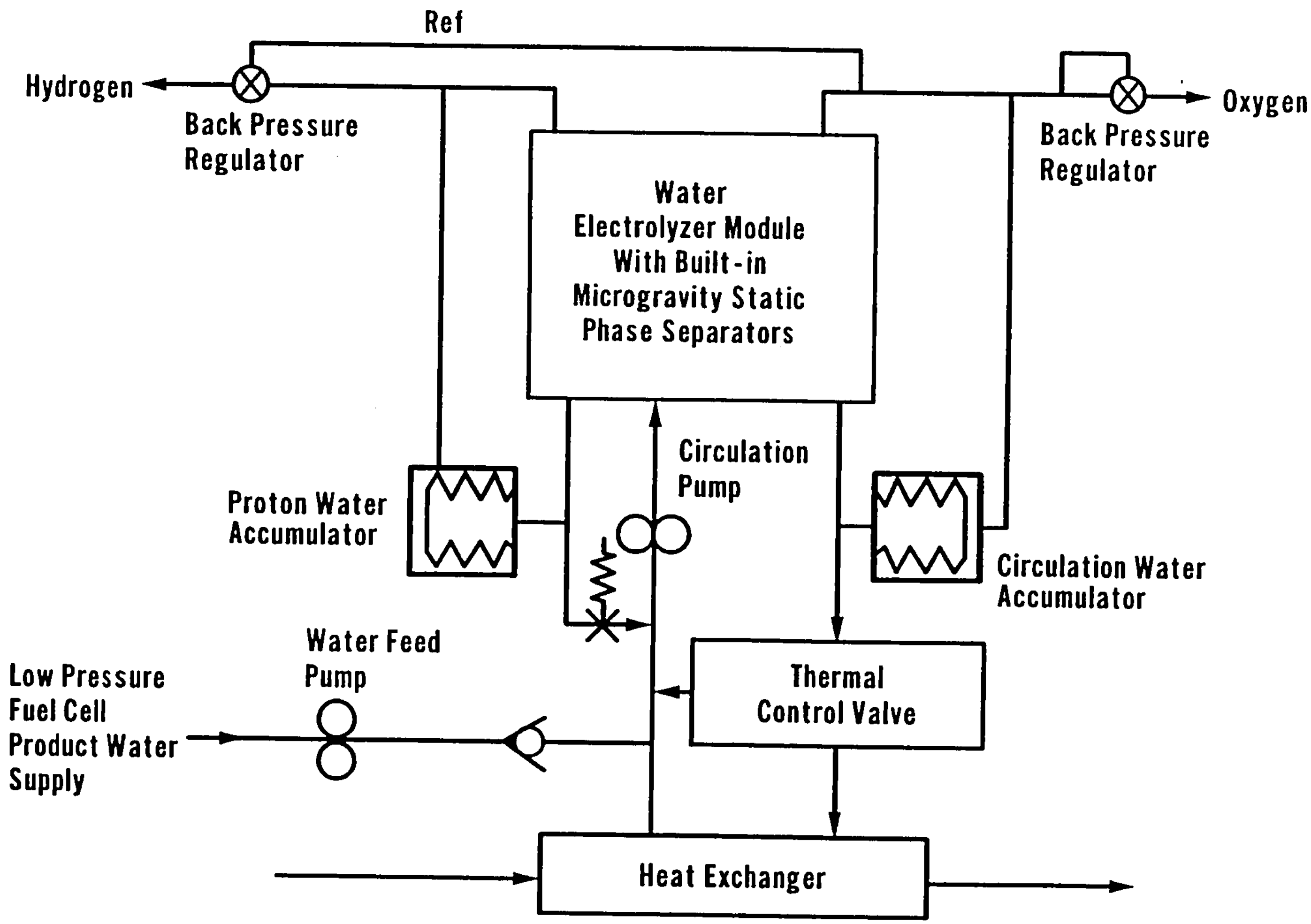
0.78 FT^2 FUEL CELL PERFORMANCE CURVE



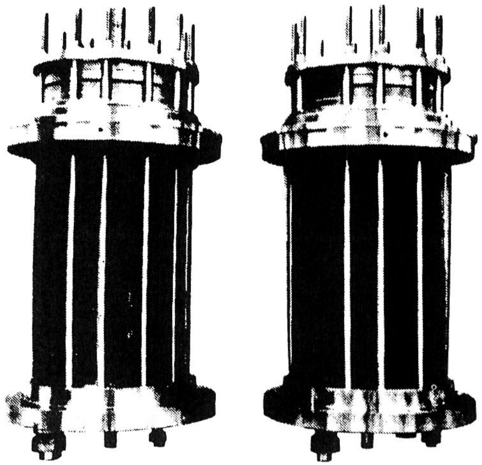
LUNAR BASE APPLICATION
25KW SPE FUEL CELL SUBSYSTEM
POWER DENSITY SUMMARY

FUEL CELL SUBSYSTEM DESCRIPTION	NAFION 120 MEMBRANE		NAFION 125/117 MEMBRANE		ADVANCED MEMBRANE	
	WATTS/#	WATTS/KG	WATTS/#	WATTS/KG	WATTS/#	WATTS/KG
"State-of-the-Art" with Porous Hydrophillic Phase Separators	47	103	84	184	140	307
"State-of-the-Art" with Gravity Phase Separation	32	70	60	131	105	230

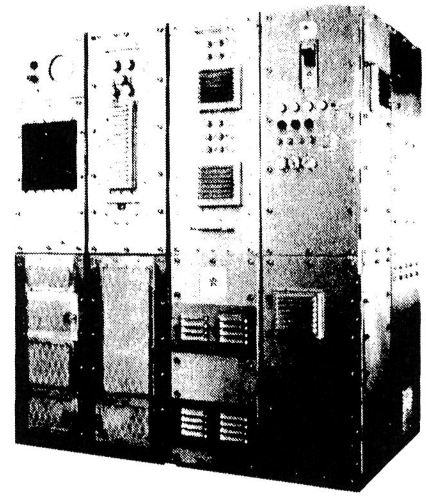
DEDICATED SPE WATER ELECTROLYZER (29# / HR) FOR MICROGRAVITY APPLICATIONS



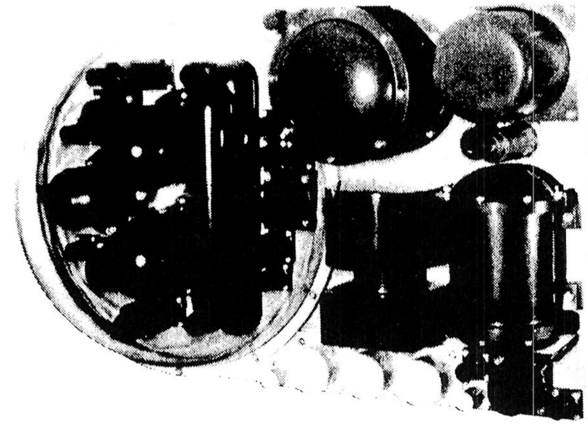
SPE WATER ELECTROLYZERS
(Active Cell Area 0.23 Ft^2)



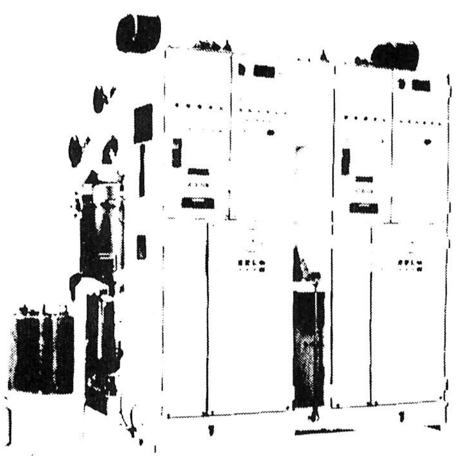
Production Modules



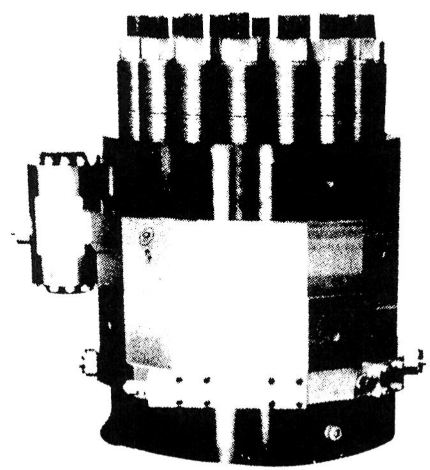
U.S. Navy Submarines
3,000 psi Qual Unit



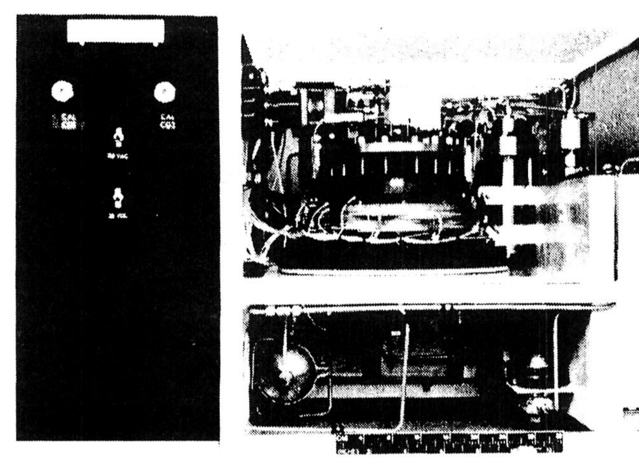
3,000 psi Propulsion
Electrolyzer Mock-Up



U.K. Navy Submarines
>30 Units Delivered

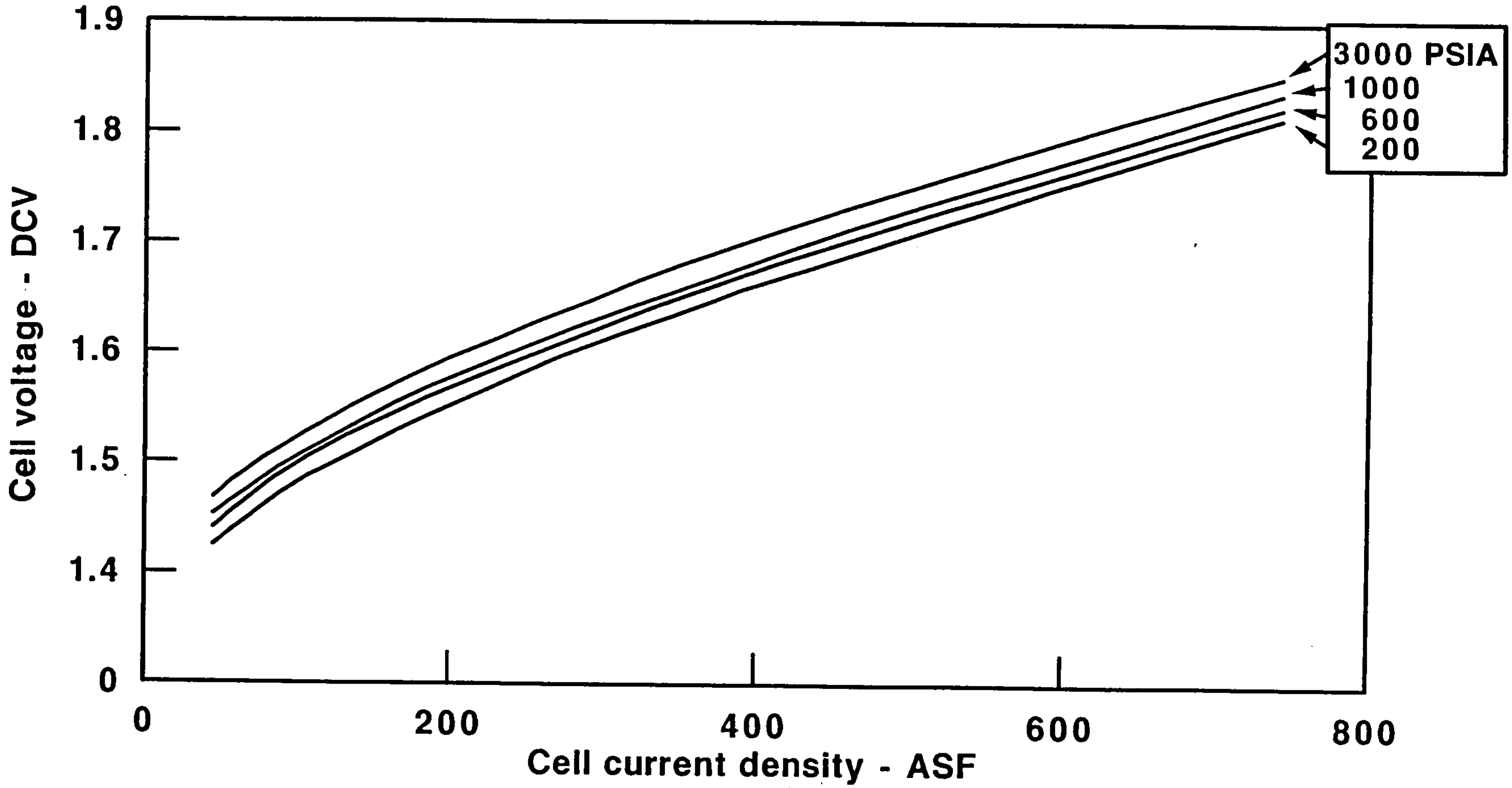


6000 psi
Development Unit

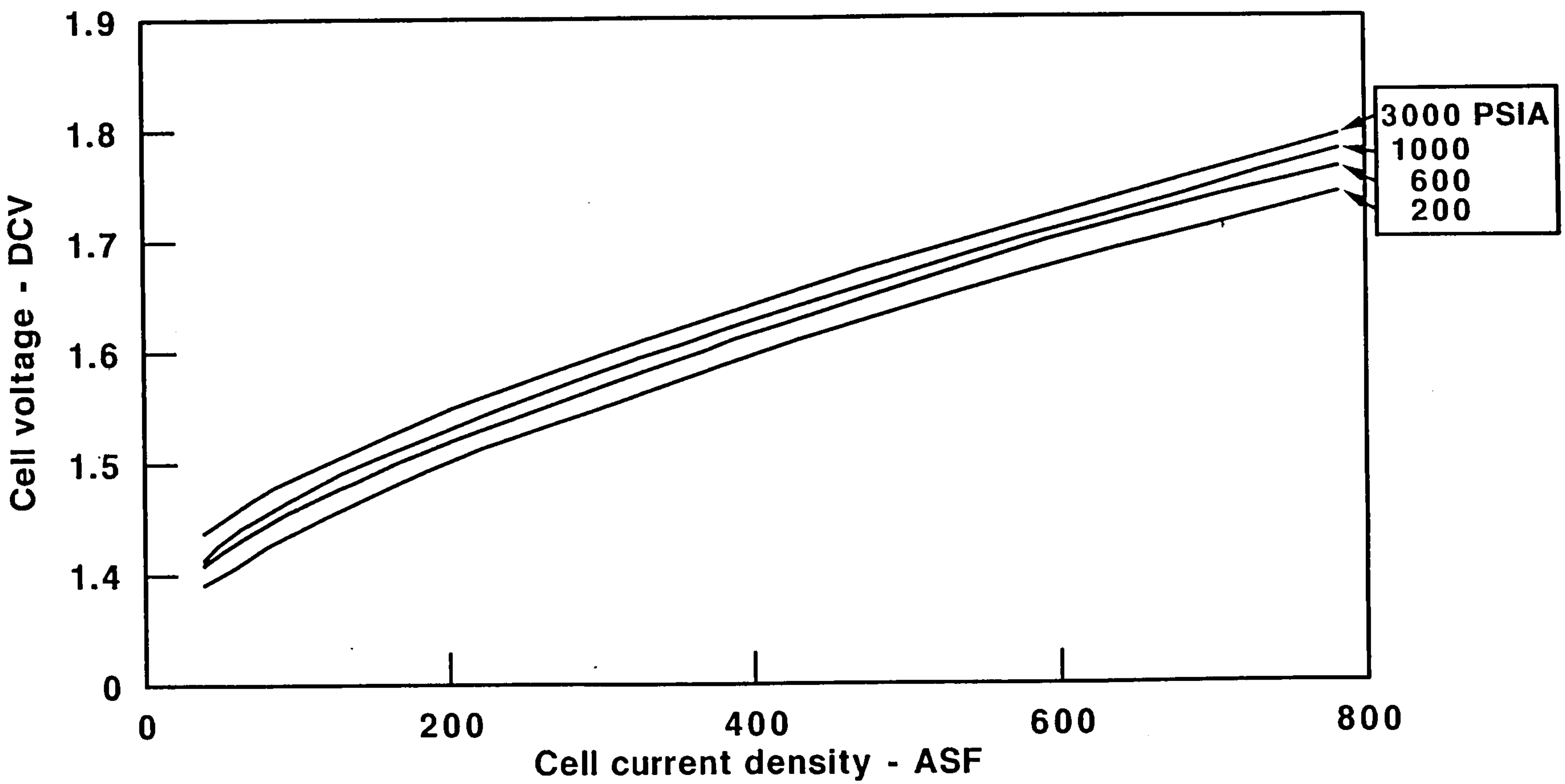


Space Station 1,000 psi
Development Unit

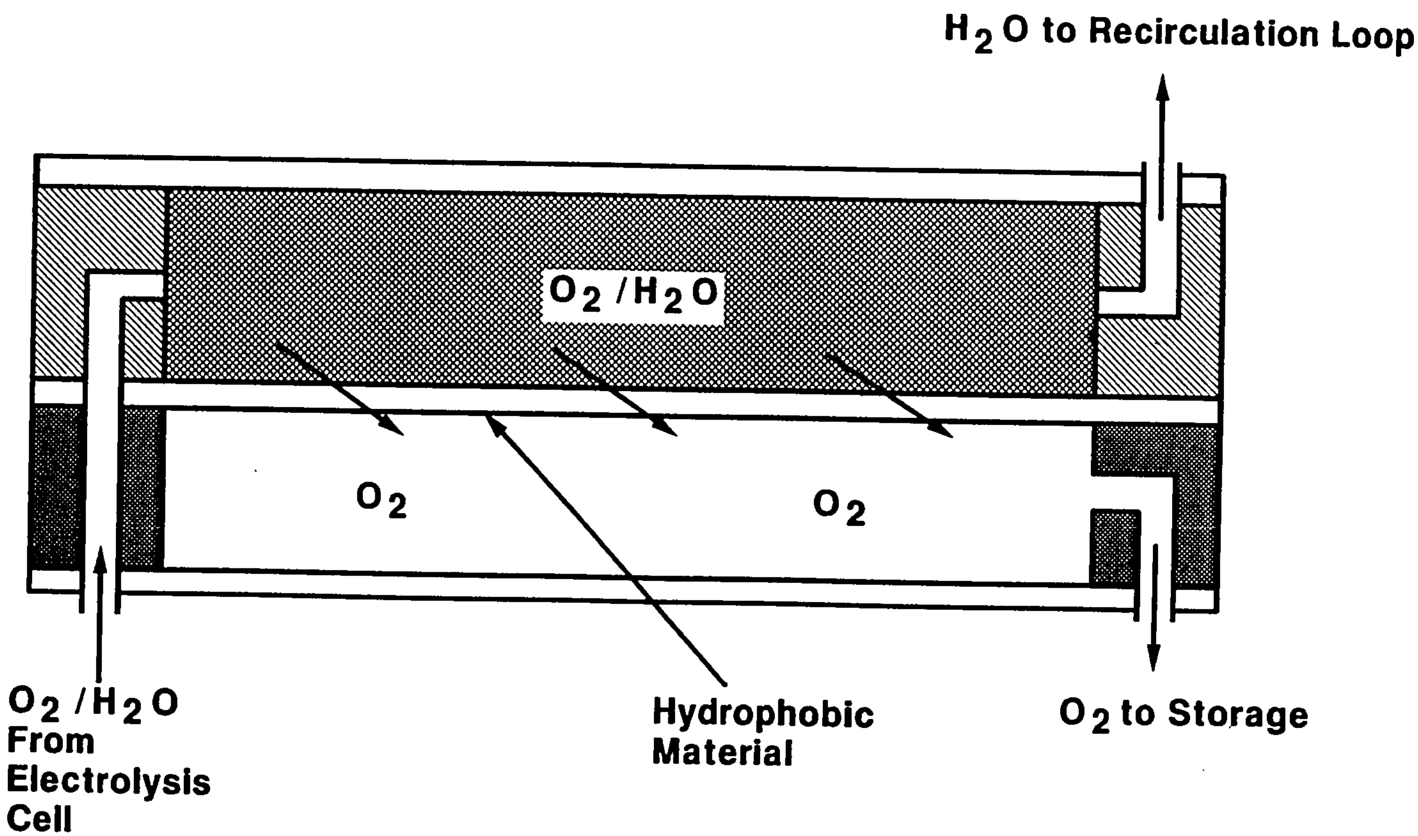
SPE ANODE FEED WATER ELECTROLYSIS CELL PERFORMANCE VS GAS GENERATION PRESSURE 12 MIL NAFION 120 MEMBRANE 120° F TEMPERATURE



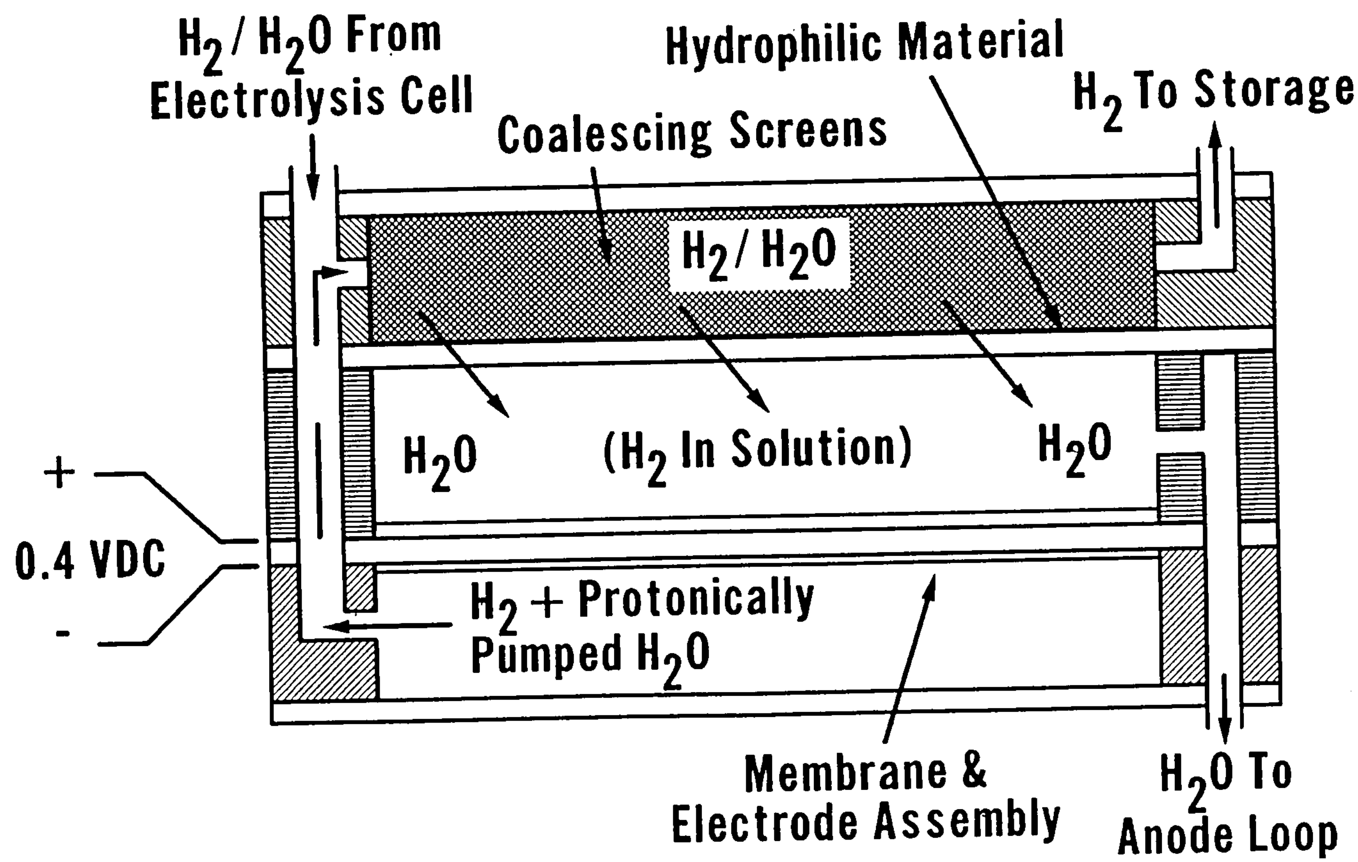
SPE ANODE FEED WATER ELECTROLYSIS CELL PERFORMANCE VS GAS GENERATION PRESSURE 12 MIL NAFION 120 MEMBRANE 150° F TEMPERATURE



HYDROPHOBIC OXYGEN PHASE SEPARATOR SCHEMATIC



HYDROPHILIC / ELECTROCHEMICAL HYDROGEN PHASE SEPARATOR SCHEMATIC

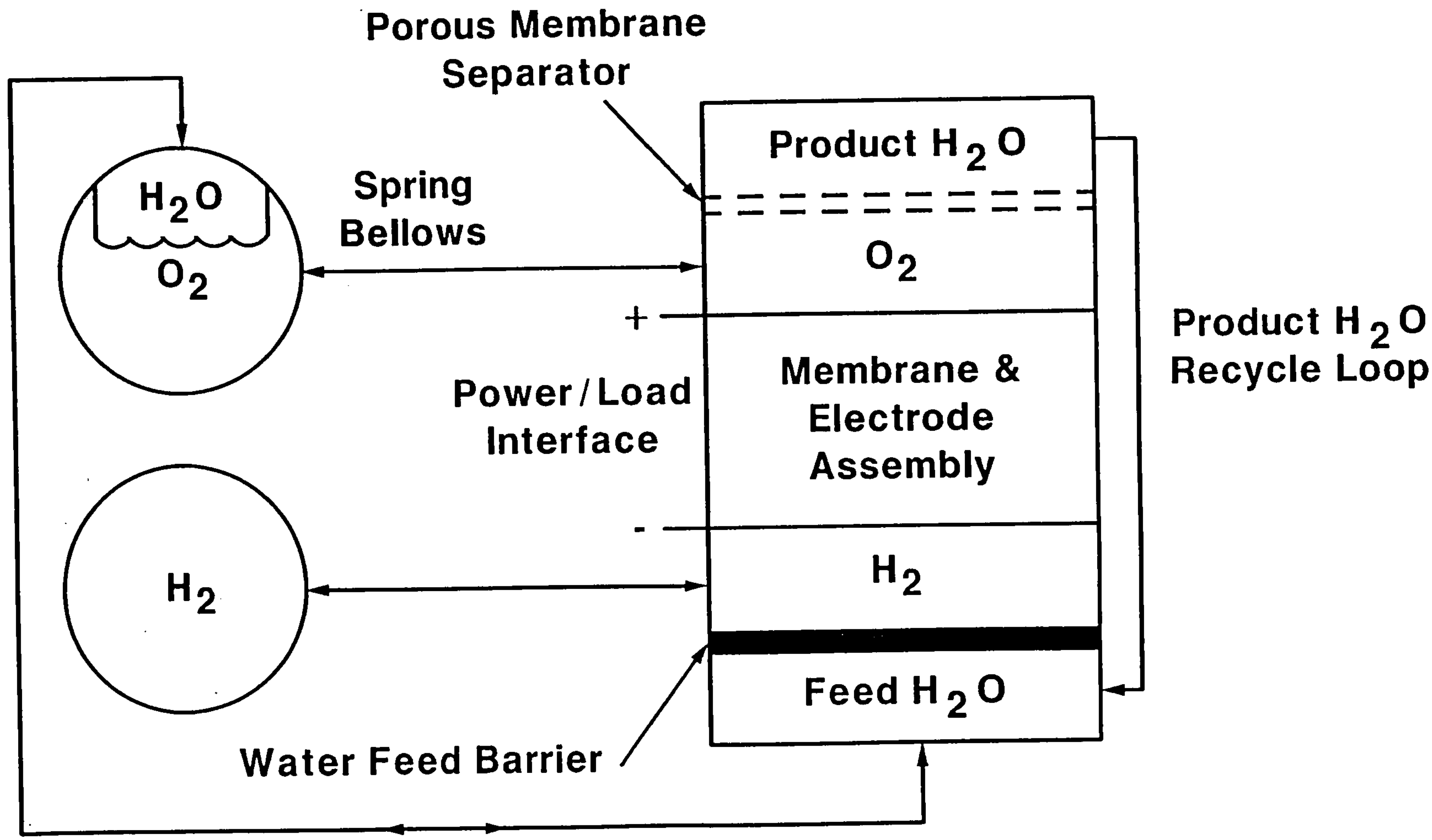


LUNAR BASE APPLICATION
SPE ELECTROLYZER (29# / HR)
SUBSYSTEM POWER DENSITY SUMMARY

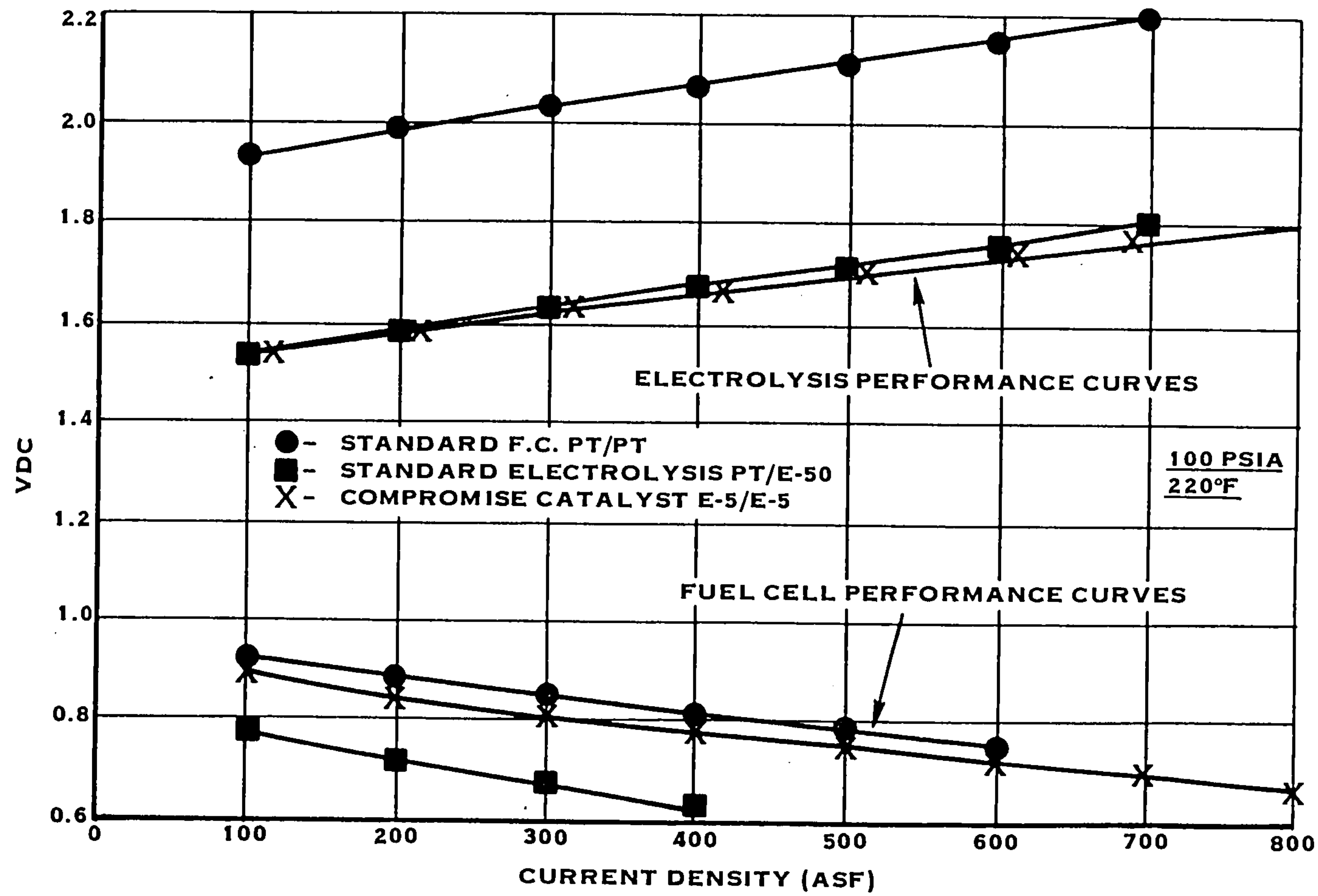
ELECTROLYZER SUBSYSTEM DESCRIPTION	NAFION 120 MEMBRANE		NAFION 125 / 117 MEMBRANE		ADVANCED MEMBRANE	
	WATTS / #	WATTS / KG	WATTS / #	WATTS / KG	WATTS / #	WATTS / KG
"State-of-the-Art" with Static Separators	117	258	149	327	172	377
Advanced Design with Static Separators	158	347	178	392	188	414

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

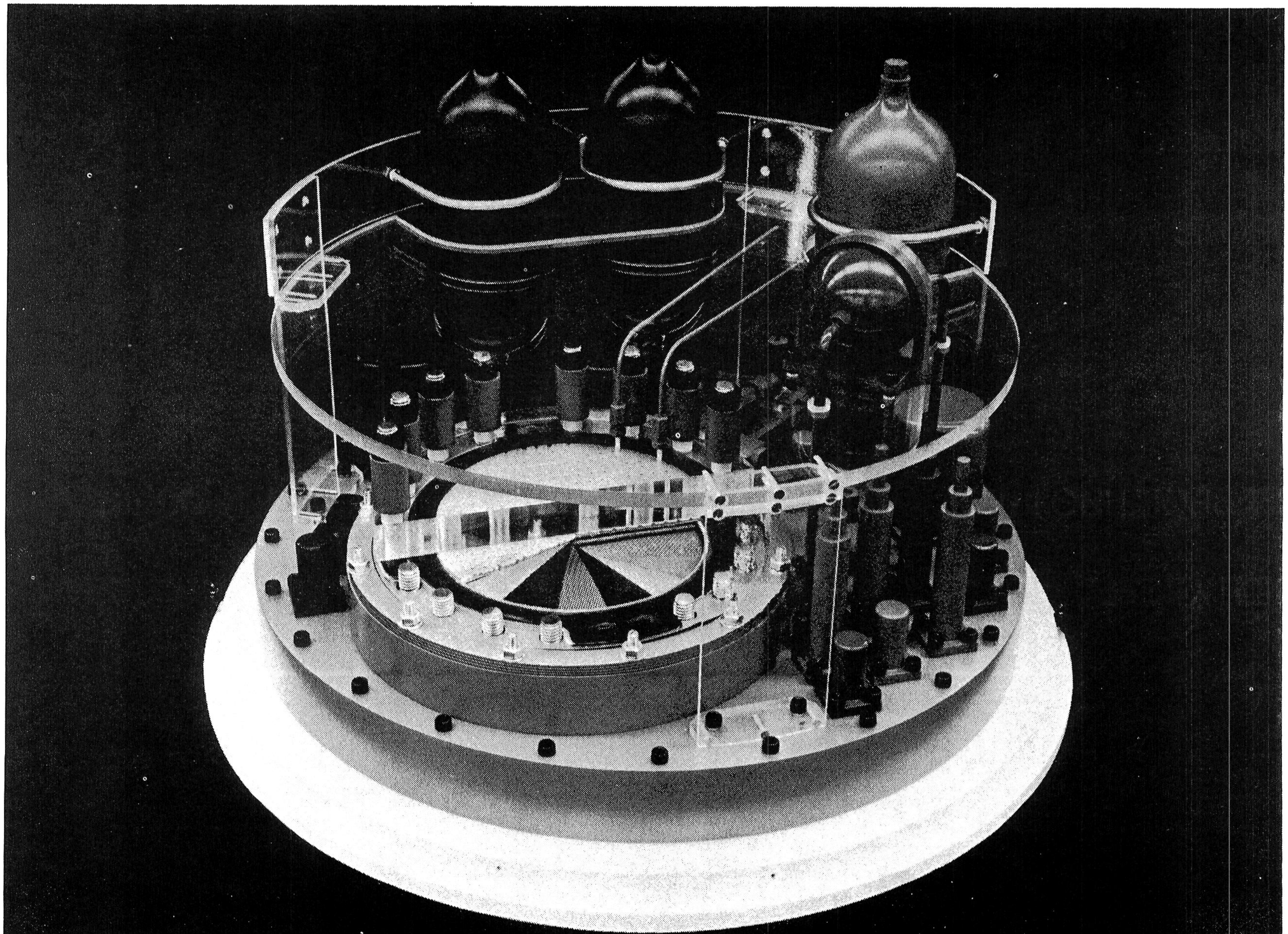
UNITIZED REGENERATIVE FUEL CELL SCHEMATIC



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



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

THIS PAGE INTENTIONALLY BLANK

INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) TECHNOLOGY DEVELOPMENTS

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

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.

OVERVIEW

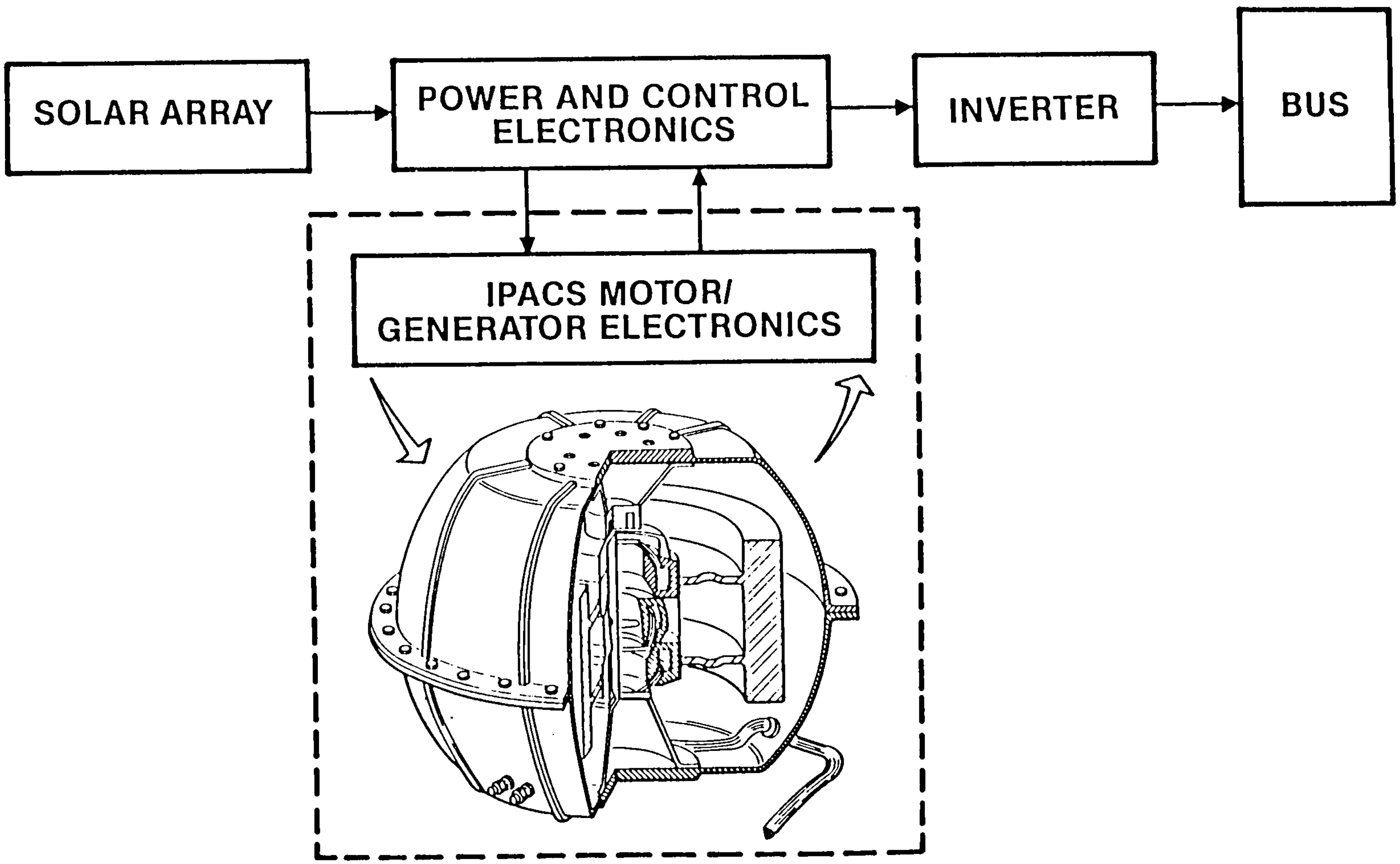
- IPACS CONCEPT
- FEATURES & MISSION APPLICABILITY
- TECHNOLOGY ADVANCEMENTS SUPPORTING IPACS
    - ROTORS--MATERIALS & SHAPE
    - MOTORS/ GENERATORS
    - BEARINGS
- SYSTEM-LEVEL TRADE COMPARISONS
- CONCLUSONS & RECOMMENDATIONS

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.

INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) CONCEPT



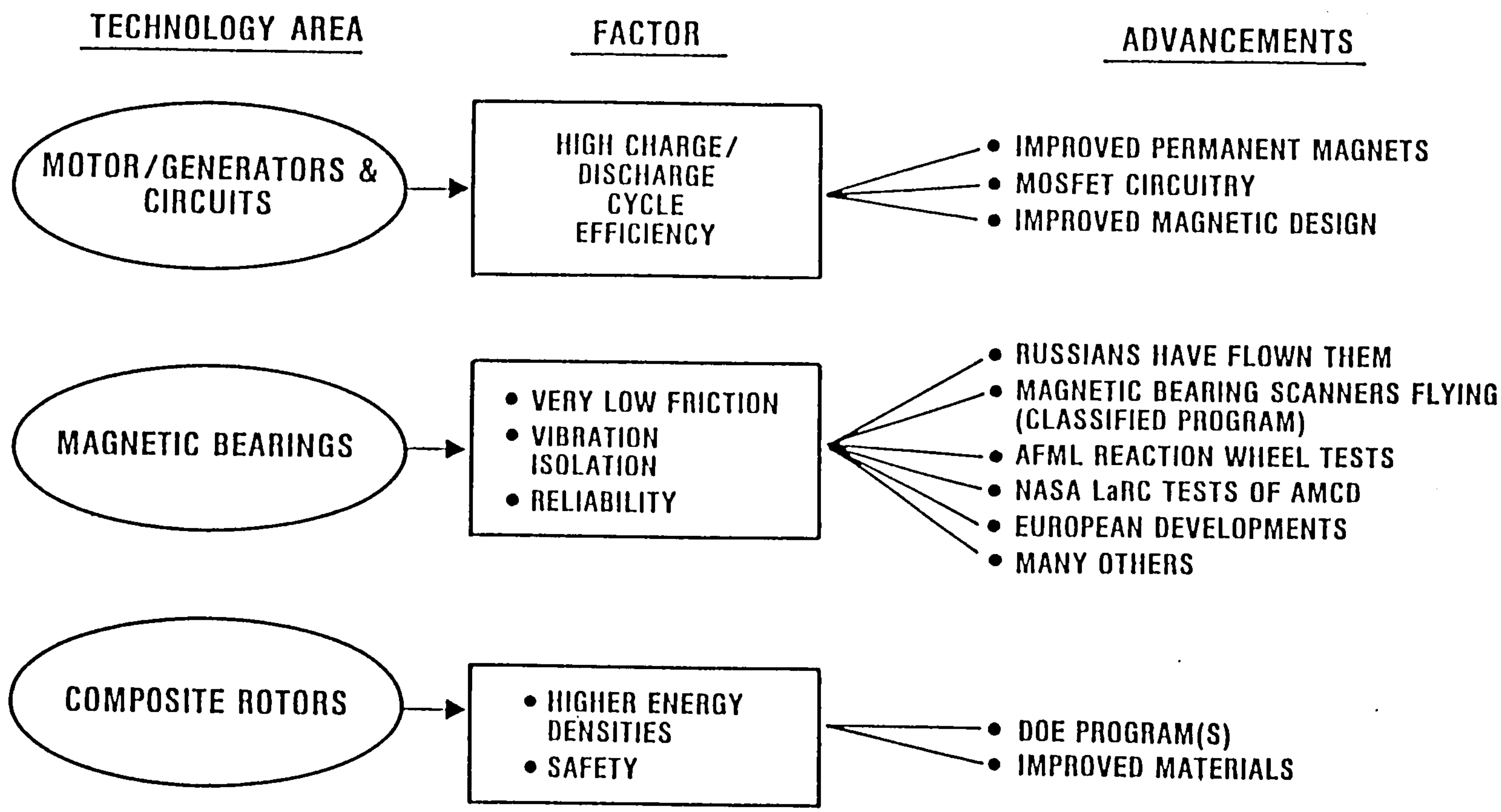
DISCUSSION VIEWGRAPH #3

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.



CONCLUSIONS:
- CHARGE/DISCHARGE EFFICIENCY MUCH IMPROVED — FROM 60% TO 85%
- LAB VERIFICATION ACCOMPLISHED IN THREE BASIC TECHNOLOGY AREAS

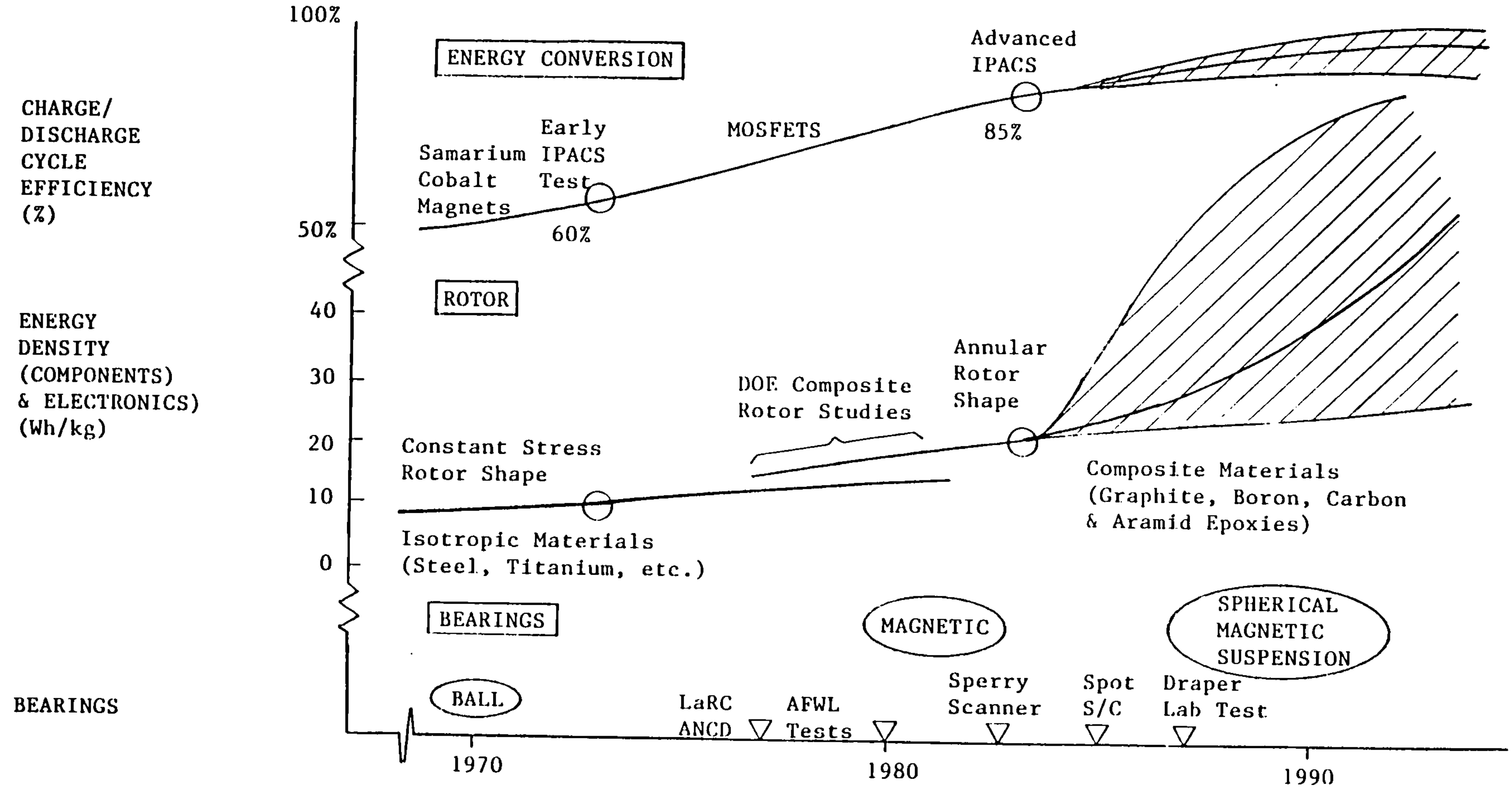
DISCUSSION VIEWGRAPH #4

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.



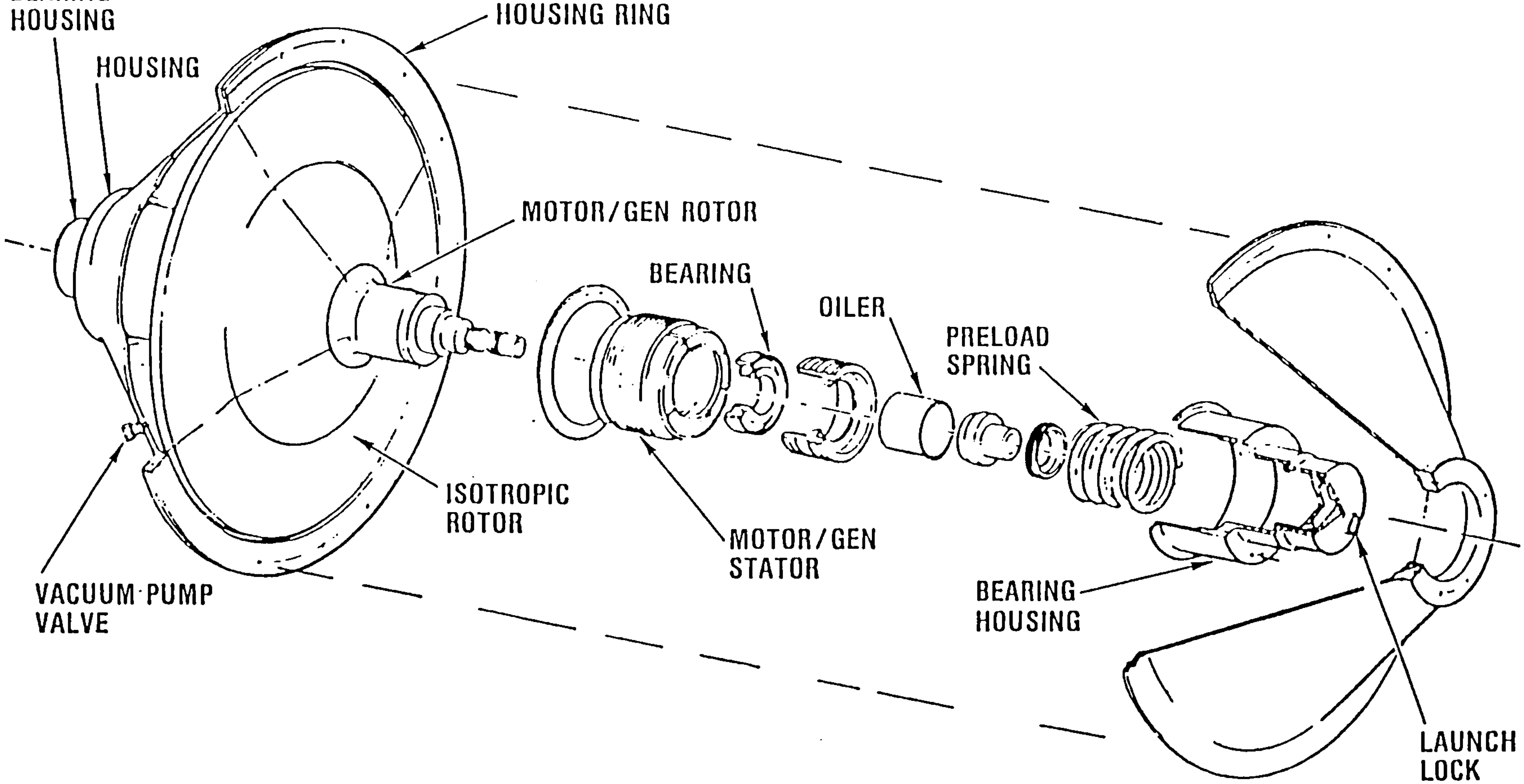
Technology advances support IPACS

DISCUSSION VIEWGRAPH #5

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).

INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (IPACS) DESIGN CONCEPT

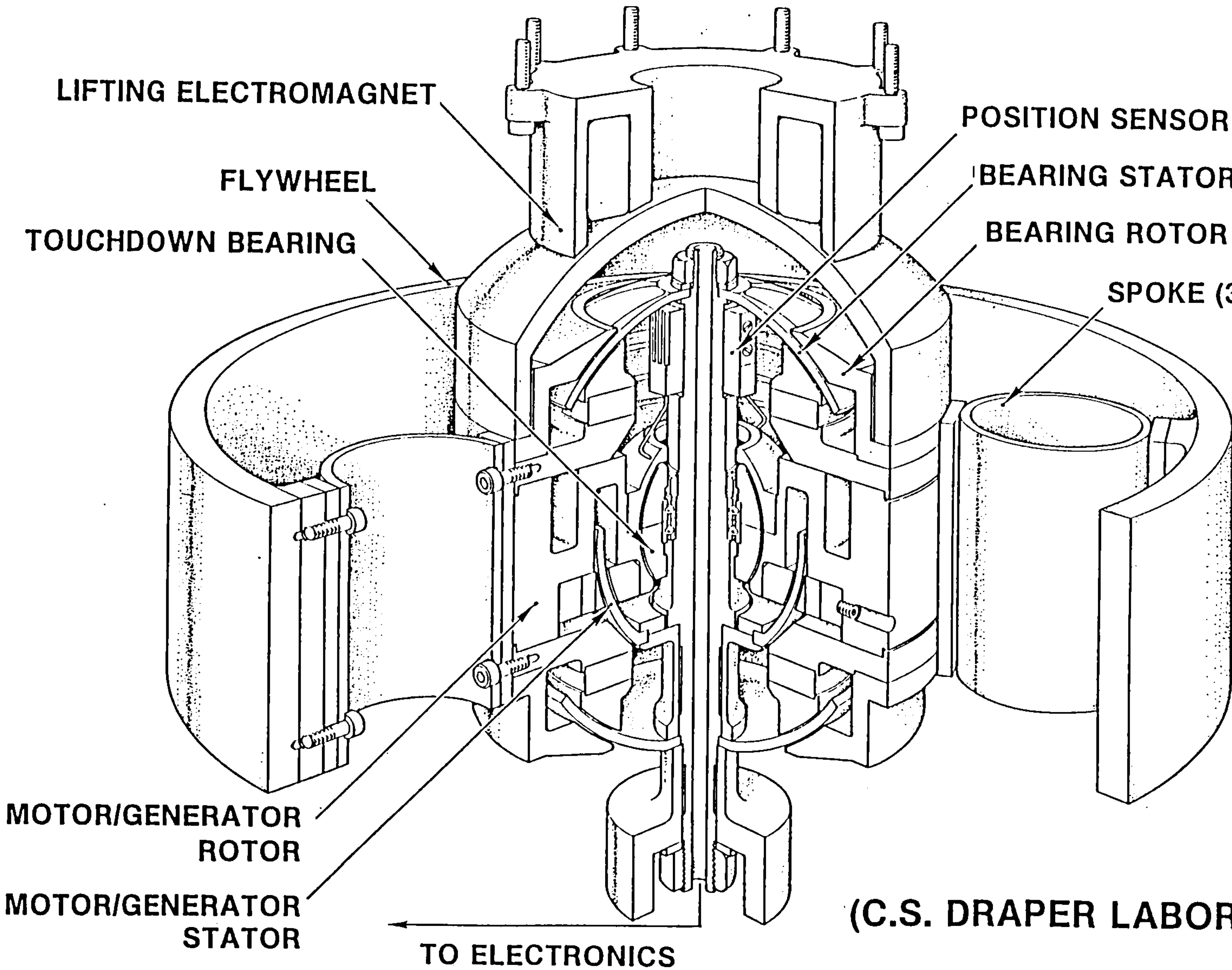
EXISTING TECHNOLOGY (1970)



DISCUSSION VIEWGRAPH #6

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.

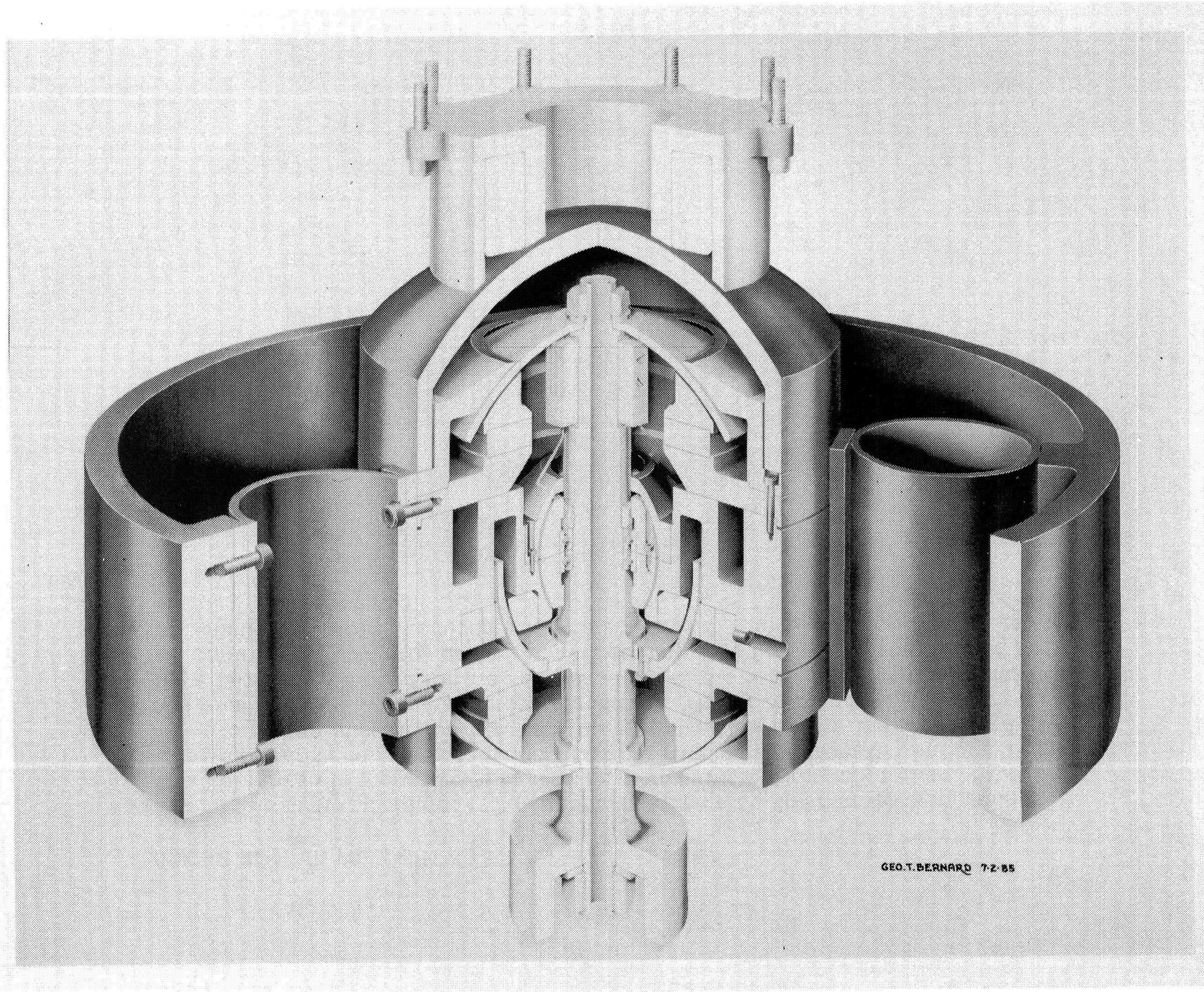
COMBINED ATTITUDE REFERENCE AND ENERGY STORAGE SYSTEM (CARES) MODULE



(C.S. DRAPER LABORATORIES)

DISCUSSION VIEWGRAPH #7

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


GEO.T.BERNARD 7-2-85

DISCUSSION VIEWGRAPH #8

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.

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

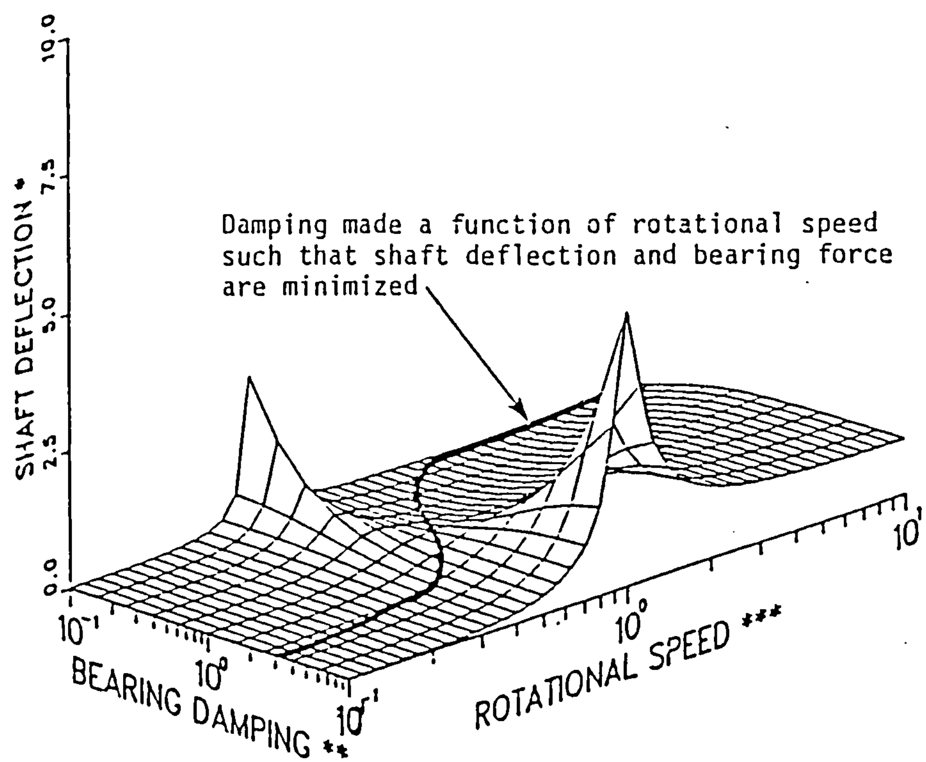
- FACILITATED BY WIDE BANDWIDTH CAPABILITY & LOW DISTURBANCE FEATURES

DISCUSSION VIEWGRAPH #9

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



* NORMALIZED BY UNBALANCE DISTANCE
** NORMALIZED BY BEARING FREQUENCY
*** NORMALIZED BY SHAFT FREQUENCY

DISCUSSION VIEWGRAPH #10

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.

DOE Flywheel Developments

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

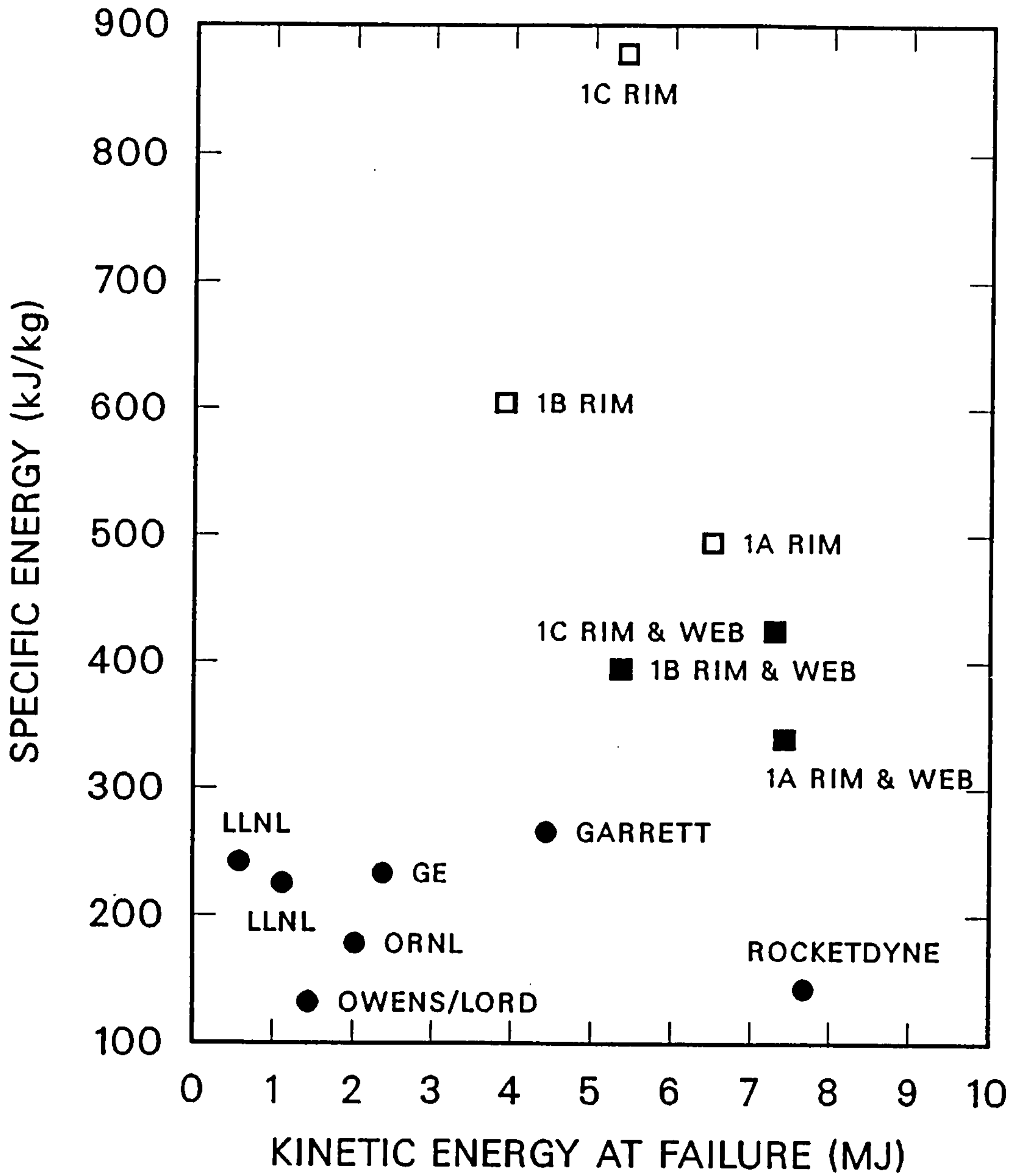
DISCUSSION VIEWGRAPH #11

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.

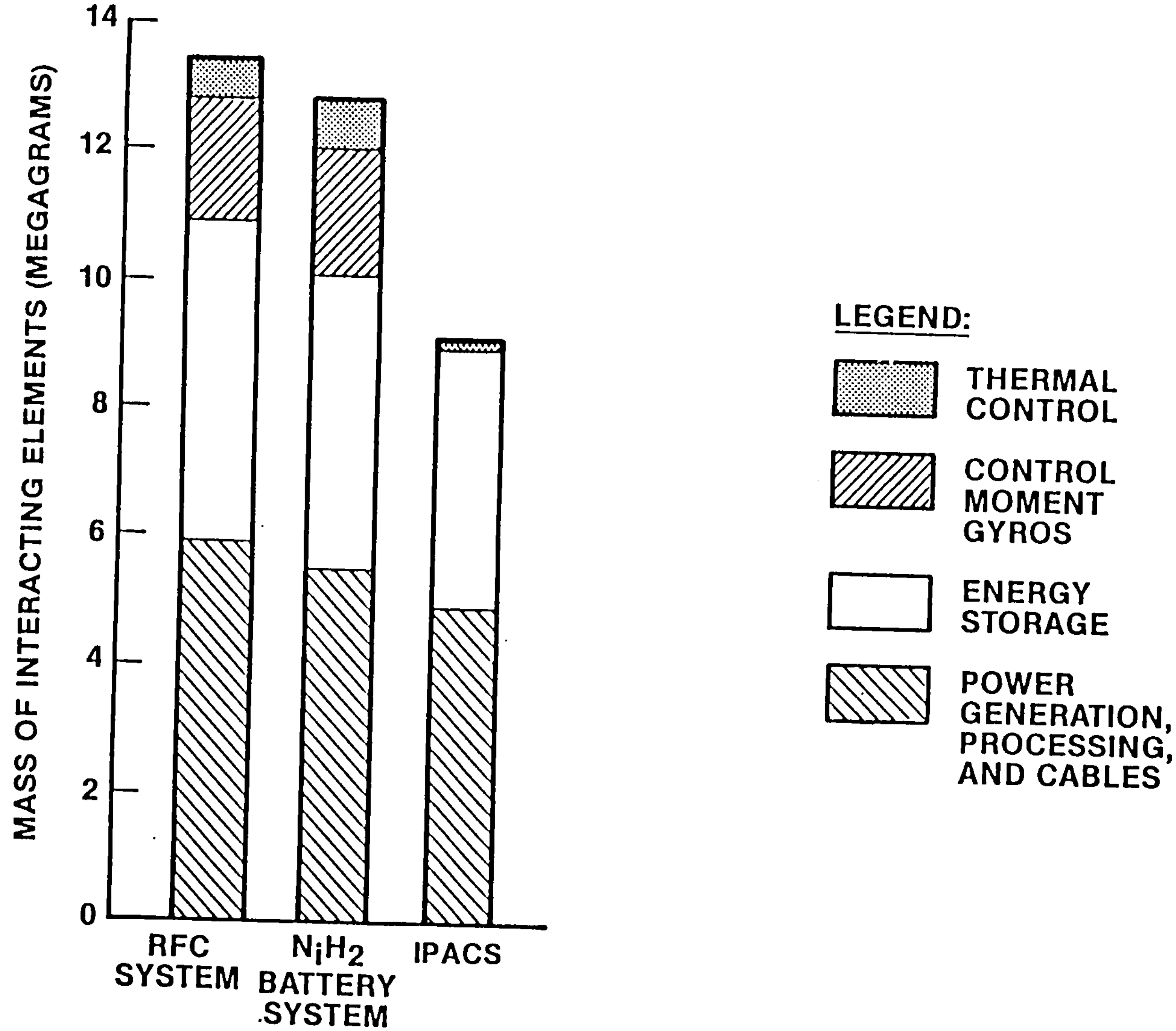


OAK RIDGE FLYWHEELS DEMONSTRATED IMPRESSIVE GAINS

DISCUSSION VIEWGRAPH #12

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.

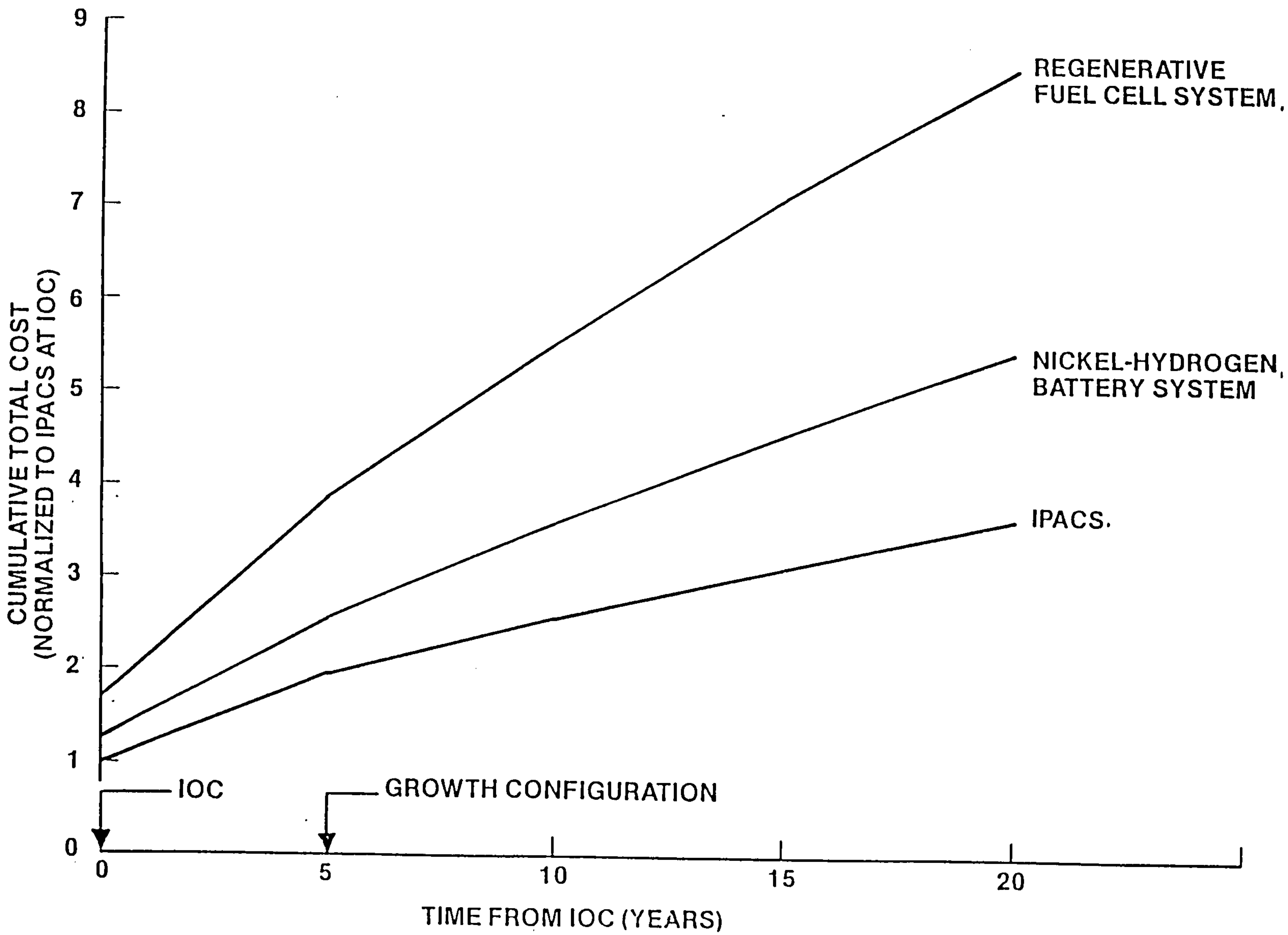
COMPARISON OF SYSTEM MASS (IOC)



DISCUSSION VIEWGRAPH #13

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.

CUMULATIVE TOTAL COST HISTORIES



DISCUSSION VIEWGRAPH #14

Key features of the approach are outlined in the viewgraph.

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

DISCUSSION VIEWGRAPH #15

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.

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

DISCUSSION VIEWGRAPH #16

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

THIS PAGE INTENTIONALLY BLANK

FUEL CELL ENERGY STORAGE
FOR
SPACE STATION ENHANCEMENT

to

Technology for Space Station Evolution Workshop

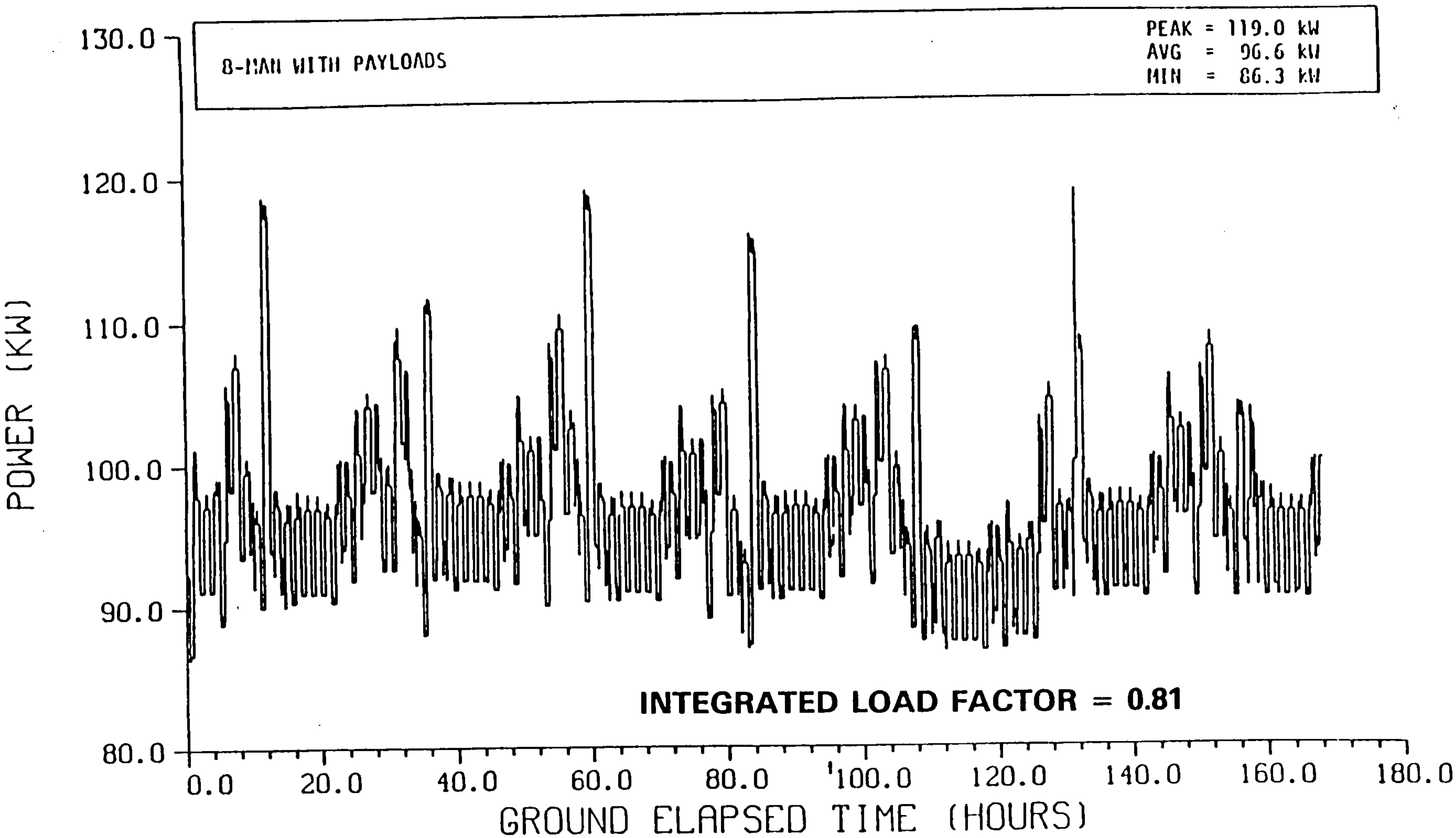
January 1990

J.K. Stedman
(203)727-2211

International Fuel Cells®

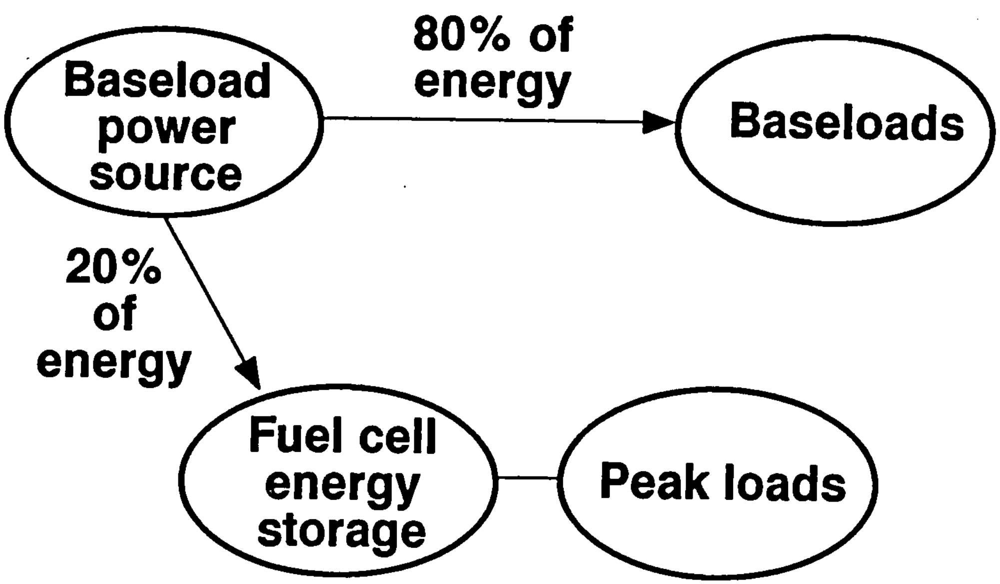
P.O. Box 739
195 Governors Highway
South Windsor, Connecticut 06074

POWER PROFILE
TOTAL POWER

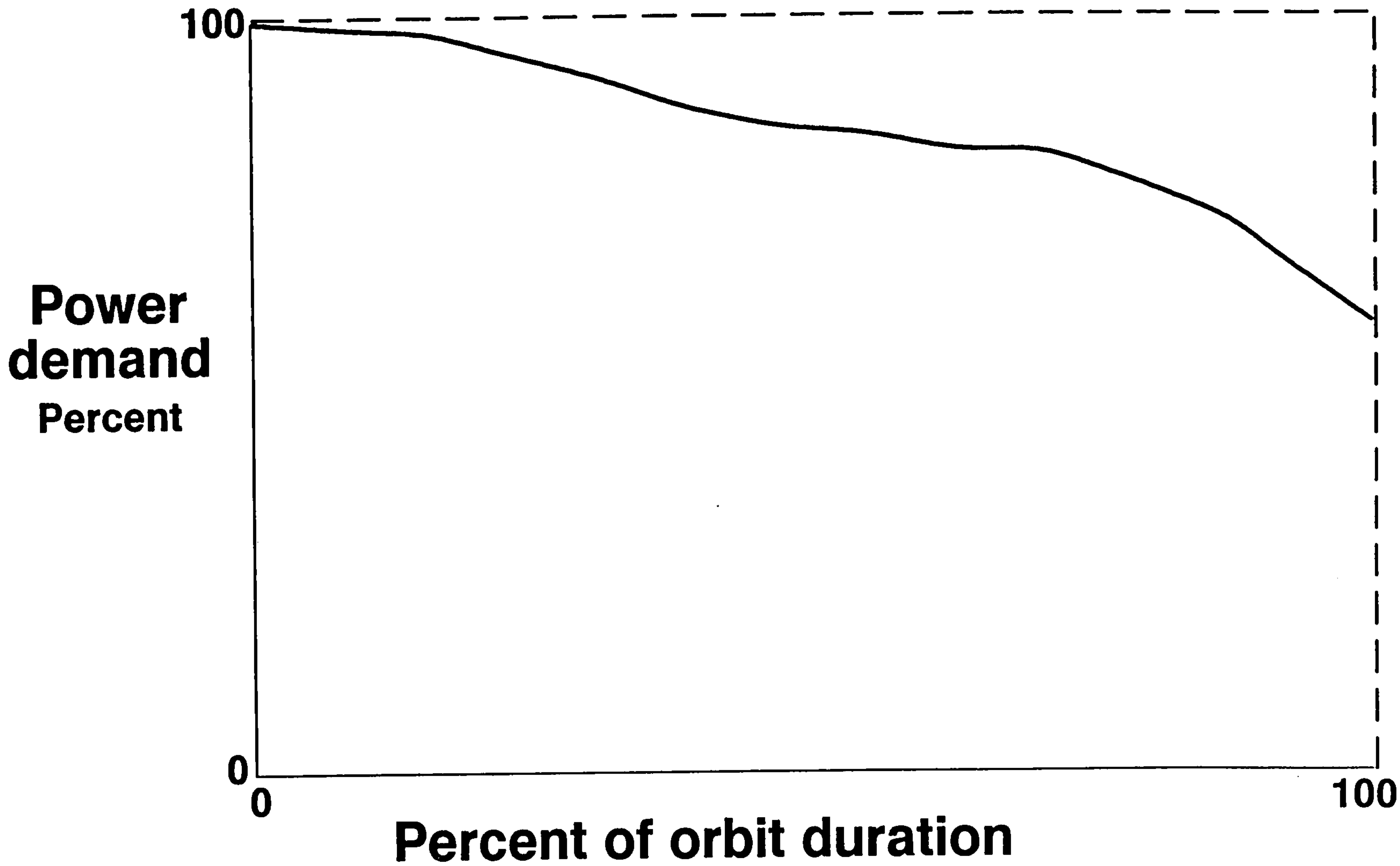


THE CONCEPT

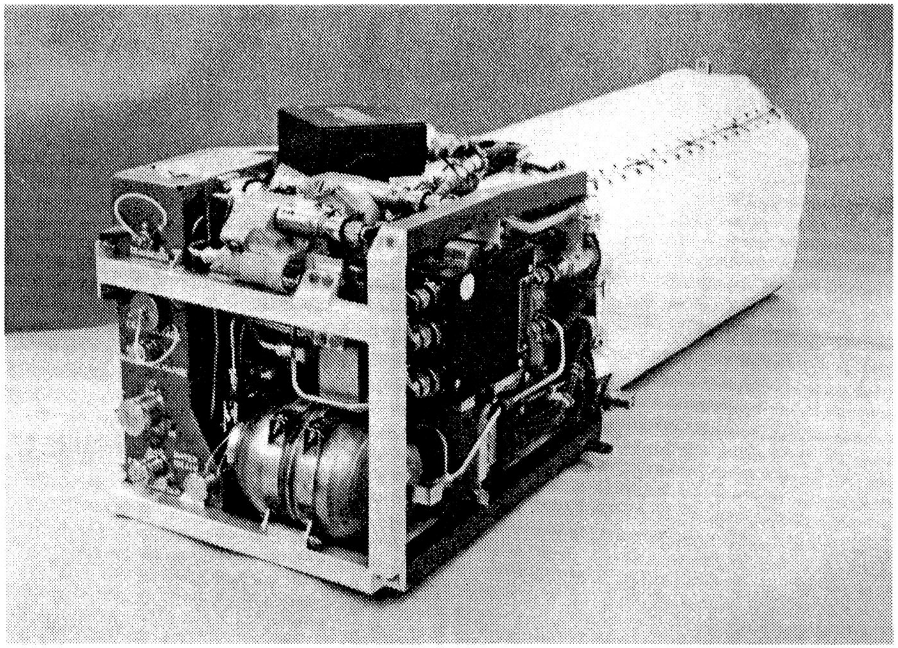
- PV/Battery and Solar Dynamic are baseload power systems
- Space station will have load factor less than one (shuttle ~0.8)



SPACE STATION ENERGY DEMAND



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

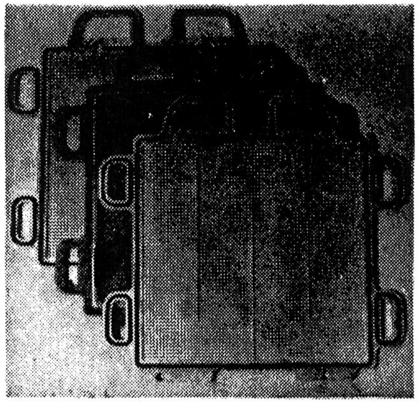
EMA/EAPU

- EDO goals

  plus

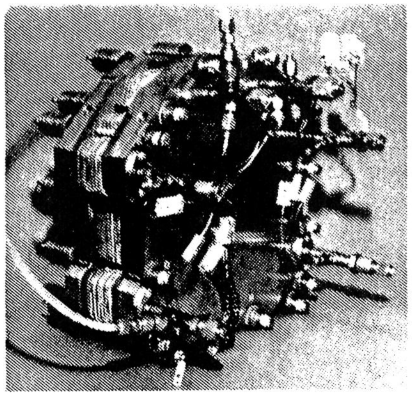
- Increased power
- Reduced weight

TECHNOLOGY ADVANCES SUPPORT ORBITER ENHANCEMENT



Present Orbiter Cell

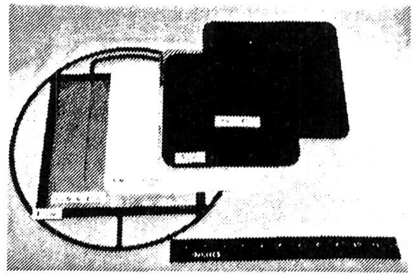
\+



NASA-LeRC Cell

- Long life

\+



SDIO/USAF Cell

- High power
- Light weight
- Improved materials

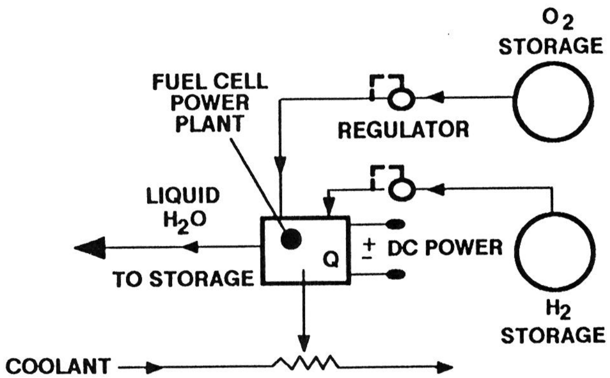
→ *Advanced Orbiter Cell*

- EDO
- EMA/EAPU

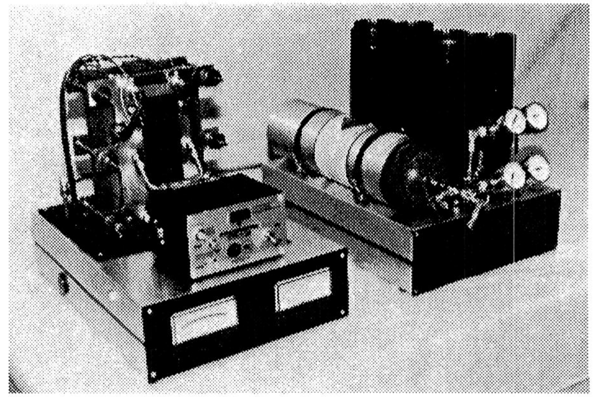
EMA
PRELIMINARY REQUIREMENTS

	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	← Physically interchangable →	

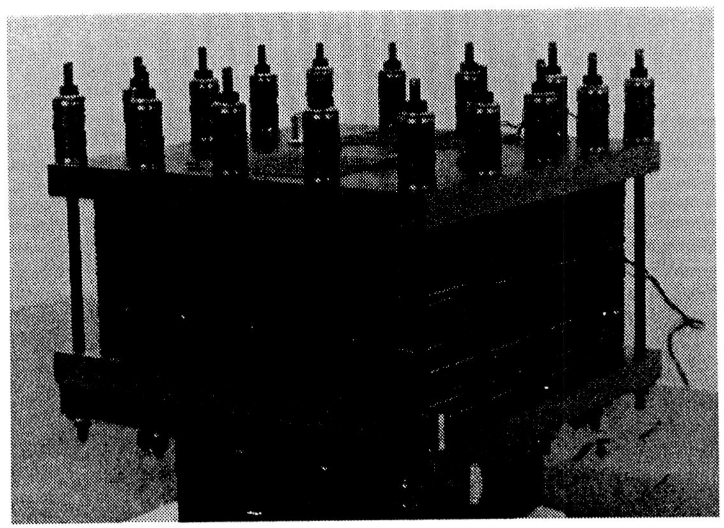
PEM TECH BASE PROGRESS



Simple concept



Lab scale
Demo power plant



Proof of principle stack
5 kW

UNUSED ENERGY ESTIMATE

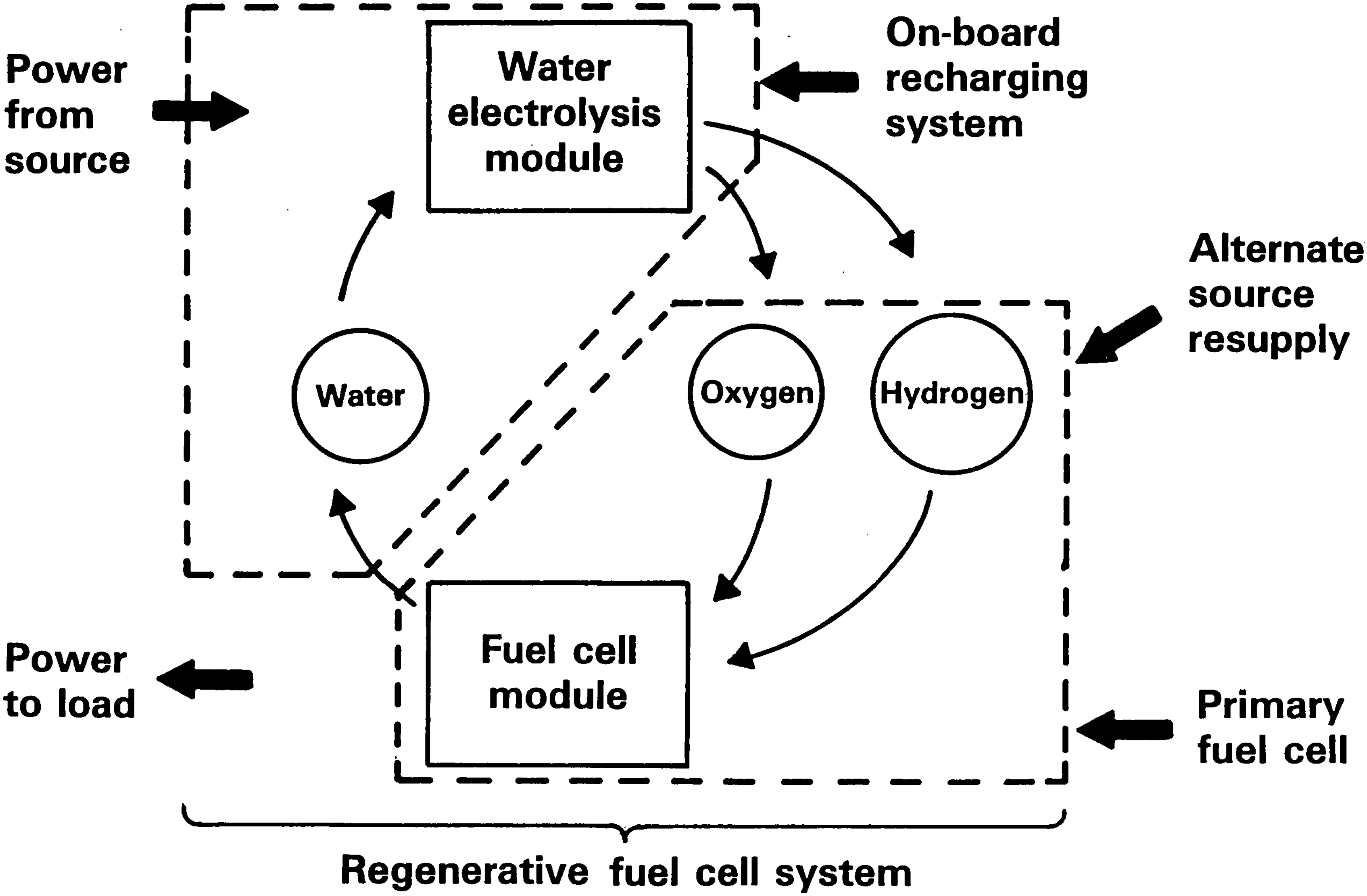
80% Load Factor

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

STATION ENERGY STORAGE

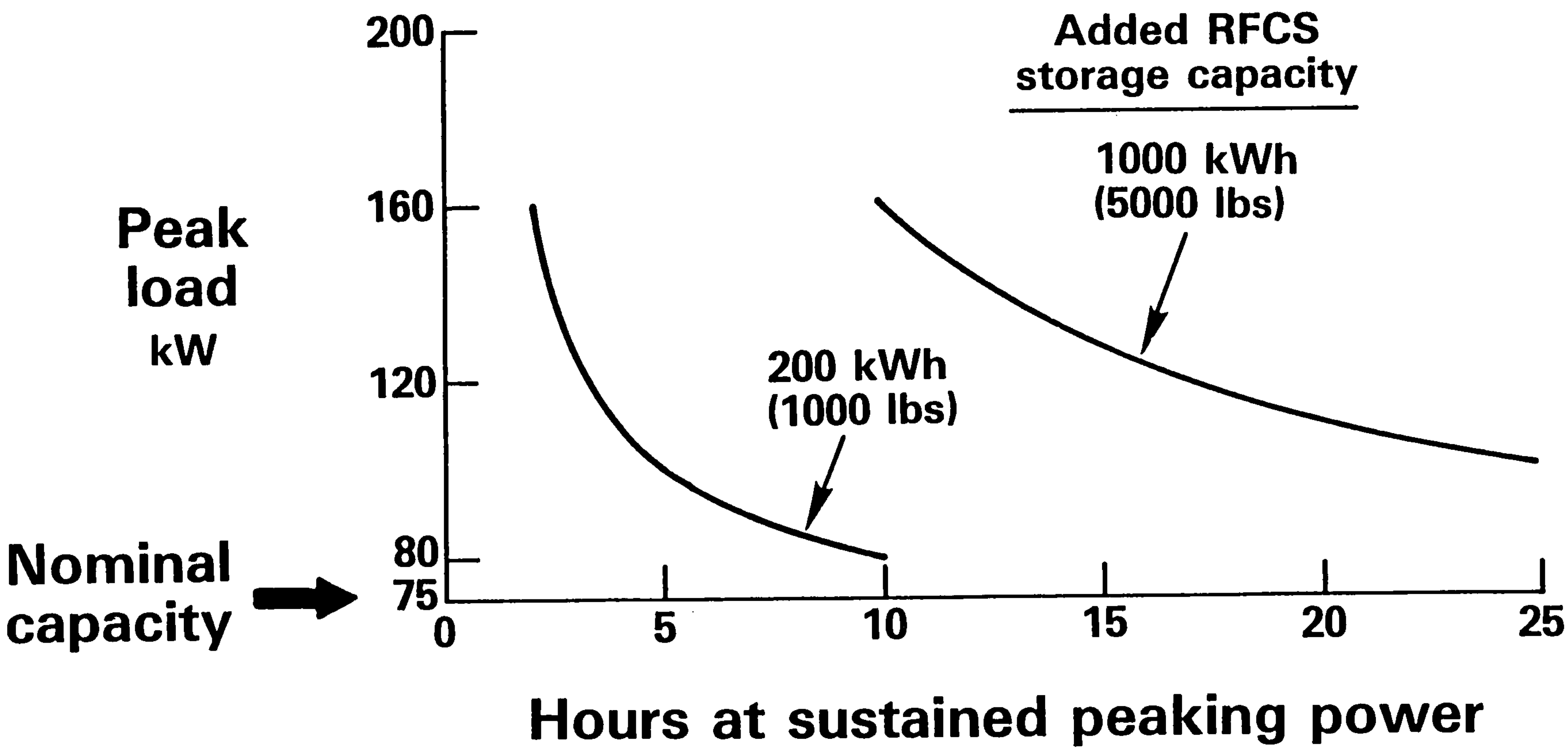
- **Unique RFCS capability provides discriminator**
  - Inter vs intra orbit energy storage
- **Capability enhances**
  - User load requirements
  - Margin for undefinable needs
  - Contingency
  - Survival
  - Construction
  - Unknowns

FUEL CELL SYSTEM MODULARITY



IOC STATION
PEAK POWER CAPABILITY

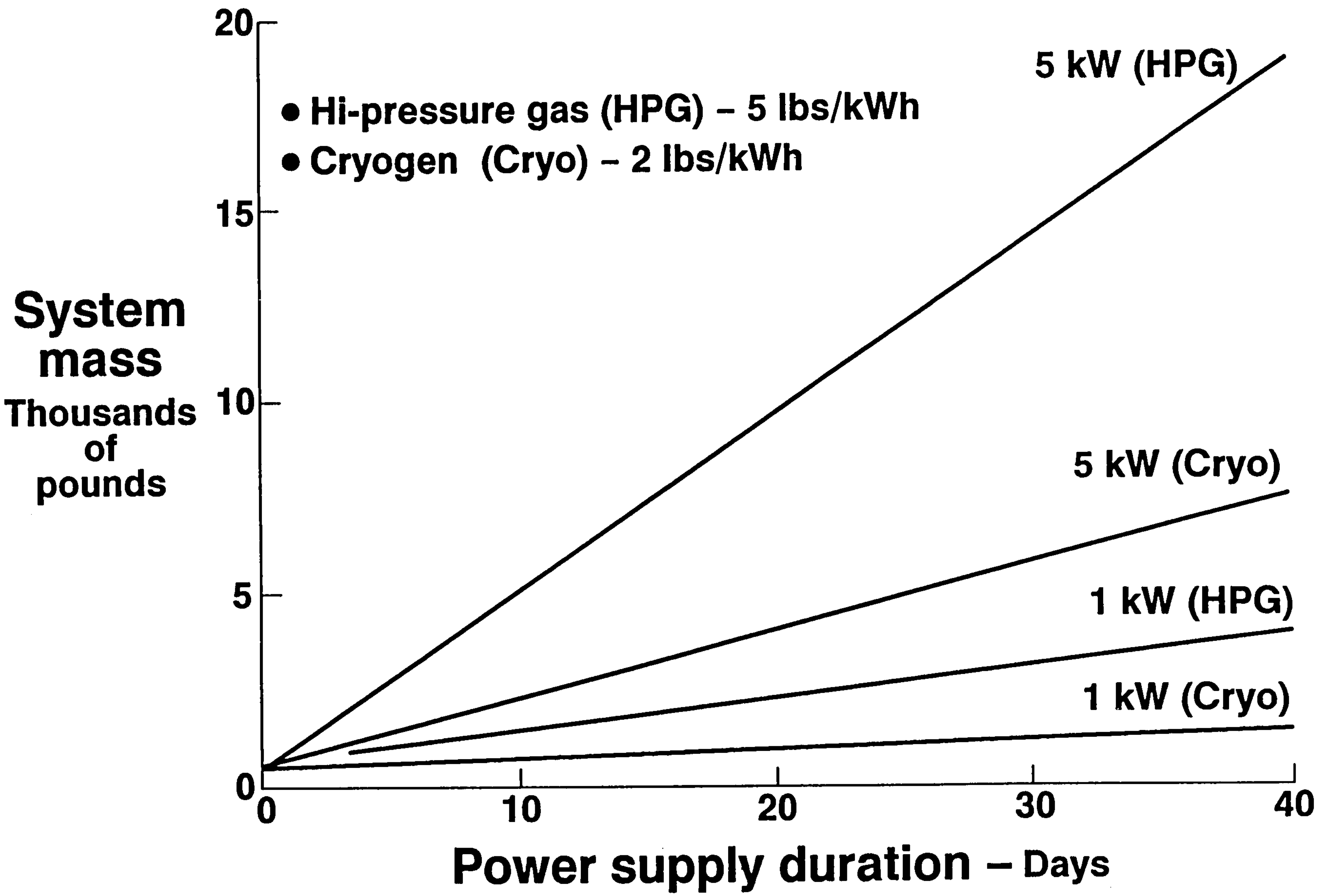
75 kW Nominal Capicity



ENERGY STORAGE SYSTEM DEVELOPMENT

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

Primary Fuel Cell
SURVIVAL POWER SUPPLY



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

NASA Marshall Space Flight Center

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.

The Case for Power System Automation

- Reduce ground support personnel
- Alleviate downlink communications requirements
- Provide greater crew availability for mission support
- Effectively utilize resources for larger, more complex load configurations
- Reduced response times for reconfiguration after faults

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.

SSM/PMAD Approach to Automation

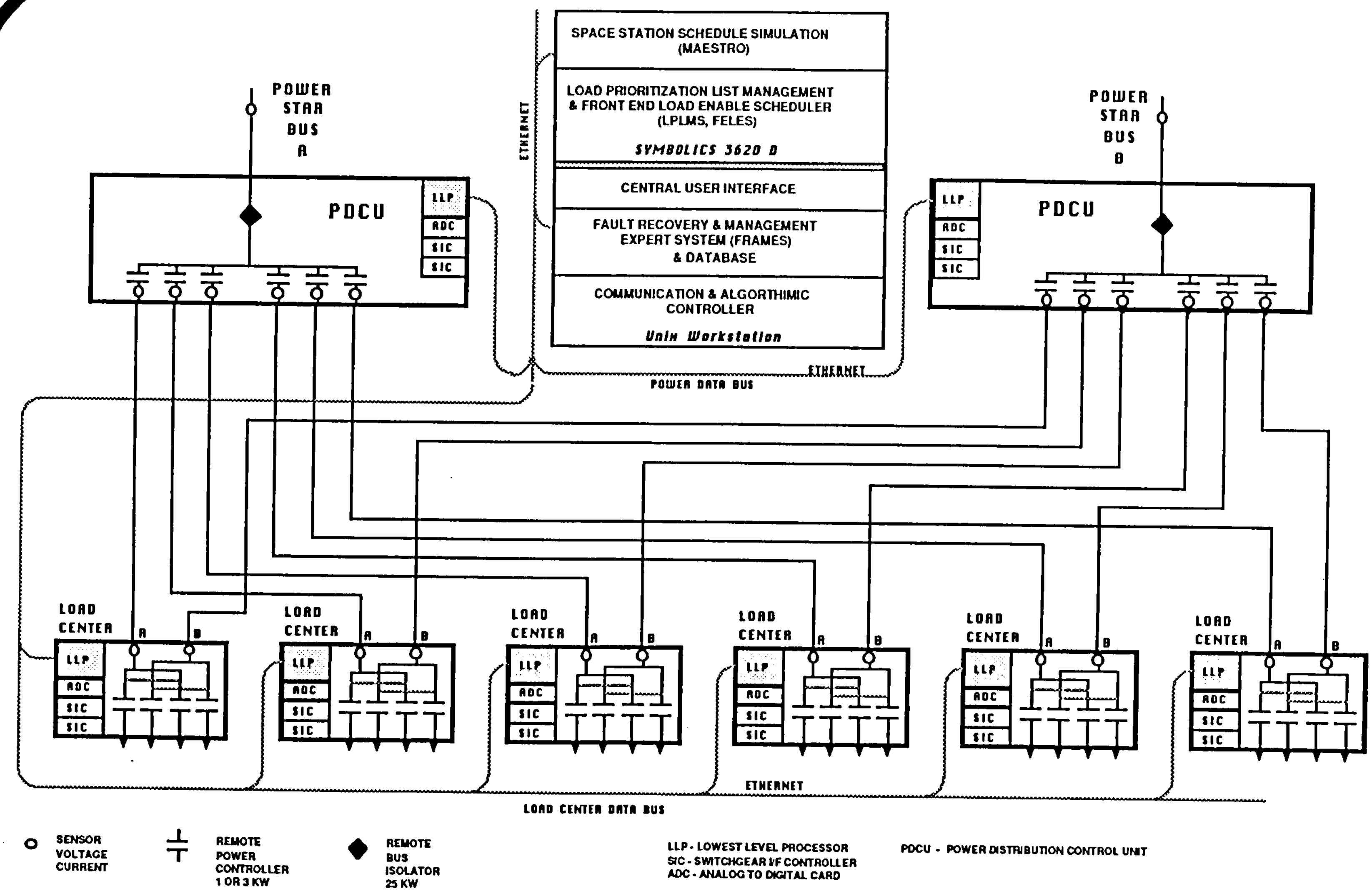
- Use fast, simple, dependable hardware at the lowest level as the "first line of defense".
- Provide adequate sensors to understand the system state.
- Distribute processors through the system to control low level hardware, gather sensor data, and communicate with higher level control.
- Coordinate system-wide activity through intelligent controllers.

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.

SSM/PMAD Test Bed

- Test bed emulating the hab/lab Power Distribution and Control architecture
- Started under Advanced Development -- 1985 -- Hardware and Automation contracts to Martin Marietta Aerospace
- Presently funded by Codes SS, ST, and RC
- Original configuration for 20kHz with ring bus primary distribution modified for 120V DC and radial distribution

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.



SSM/PMAD Topology

(Upgraded Communications/Processors)

NASA Marshall Space Flight Center

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.

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.

Functional Partitioning

FUNCTION PARTITIONING

- DEVELOPED 26 RULES FOR FUNCTION PARTITIONING OF SSM/PMAD
- DEVELOPED PARTITIONING OF FUNCTIONS:

FUNCTION	PARTITION	APPLICABLE PARTITIONING RULES
Various functions under power cond., dist., dist. mgmt., load mgmt, and health mgmt	Hardware, algorithmic software, expert system, or expert-aided crew	One or more of the 26 rules

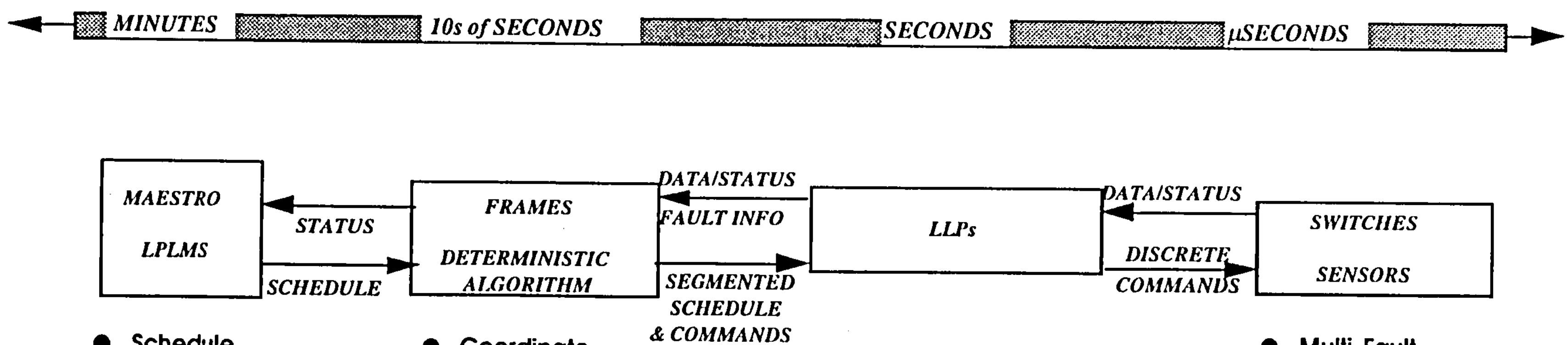
- DEVELOPED PRELIMINARY ESTIMATES OF SOFTWARE RELATED CONTROL PARAMETERS:

FUNCTION	NECESSARY CAPABILITY			ESTIMATED DIFFICULTY OF DEVELOPMENT			DESIRABLE RESPONSE TIME
	SIMPLE	COMPLEX	EXPERT	LOW	MODERATE	HIGH	
EXAMPLES:							
-Minor Scheduling			X			X	5 Minutes or less
Load Shedding	X				X		Less than 10 seconds

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.

SSM/PMAD Control

- **3 Artificial Intelligence Systems**
  - Maestro
  - LPLMS
  - Frames
- **Deterministic control at rack Lowest Level Processors (LLP)**
- **Smart Switches**



- Schedule
- Prioritization
- Dynamic Rescheduling

- Coordinate system control
- Monitor /Assess System Performance
- FDIR

- Monitor /Assess Rack Performance
- Implements Schedule
- Implements Reconfiguration
- "Essential" Load Redundancy

- Multi-Fault Protection
- Reduce Data

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.

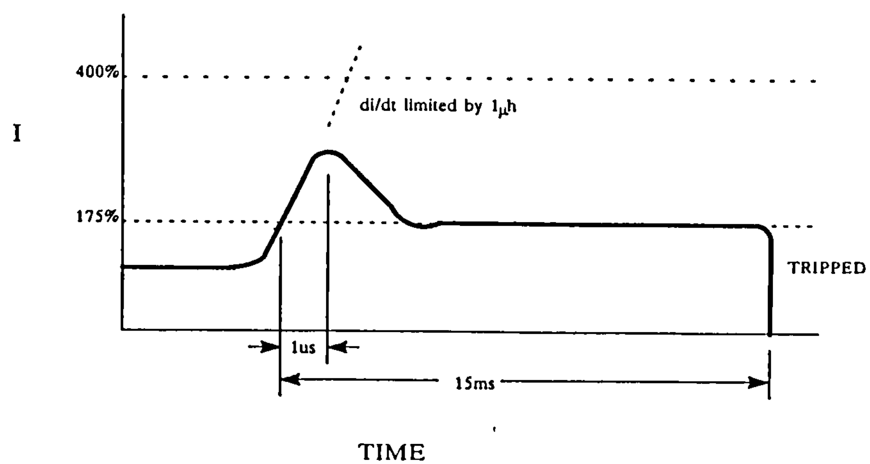
Rack Level Autonomy

- Remote Power Controllers (RPCs) provide immediate protection.
- RPCs are grouped into Load Centers. Load Centers are controlled by Lowest Level Processors (LLPs).
- LLPs execute a schedule which is downloaded to them.
- LLPs shed loads which use more than scheduled power.
- LLPs can switch loads to the secondary bus when necessary.
- LLPs communicate with higher level controllers through the CAC.

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.

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:
  - CURRENT INSTANTANEOUSLY > 400% RATED CURRENT
  - CURRENT LIMITING > 15msec
  - I^2t > LIMIT
  - UNDERVOLTAGE
  - OVERTEMPERATURE



Fault Recovery and Management Expert System (FRAMES)

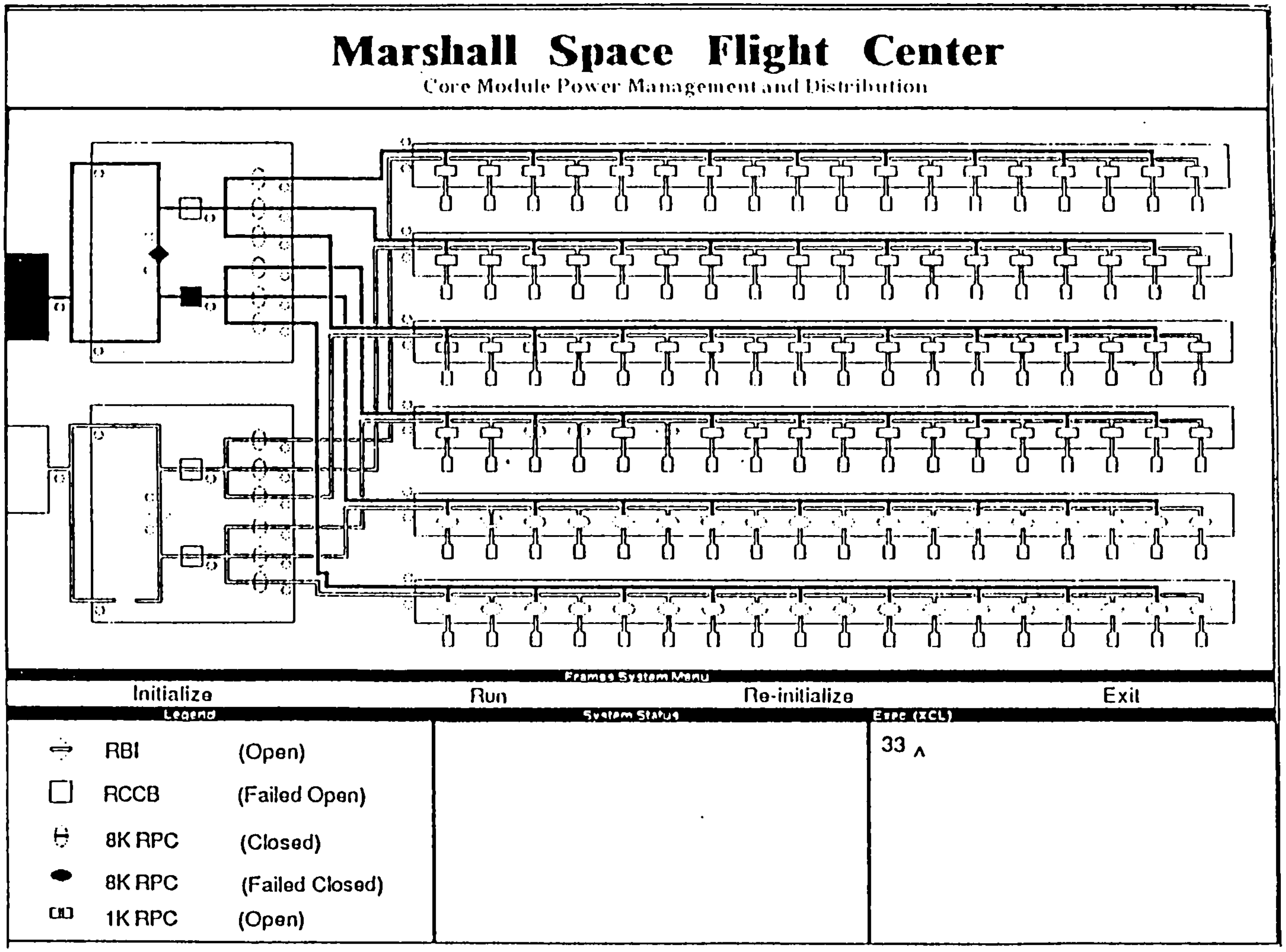
FRAMES is one of the three AI systems in the SSM/PMAD breadboard. Each LLP notifies FRAMES any time it recognizes an anomaly, such as tripped breakers or shed loads. Messages giving sensor readings are also sent to FRAMES. FRAMES uses the information which comes to it to characterize the system state. 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.

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


Marshall Space Flight Center
Core Module Power Management and Distribution
Frames System Menu
Initialize
Run
Re-initialize
Exit
Legend
System Status
Exec (XCL)
33 ^
RBI (Open)
RCCB (Failed Open)
8K RPC (Closed)
8K RPC (Failed Closed)
1K RPC (Open)

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.

Planning/Scheduling

MAESTRO

- 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

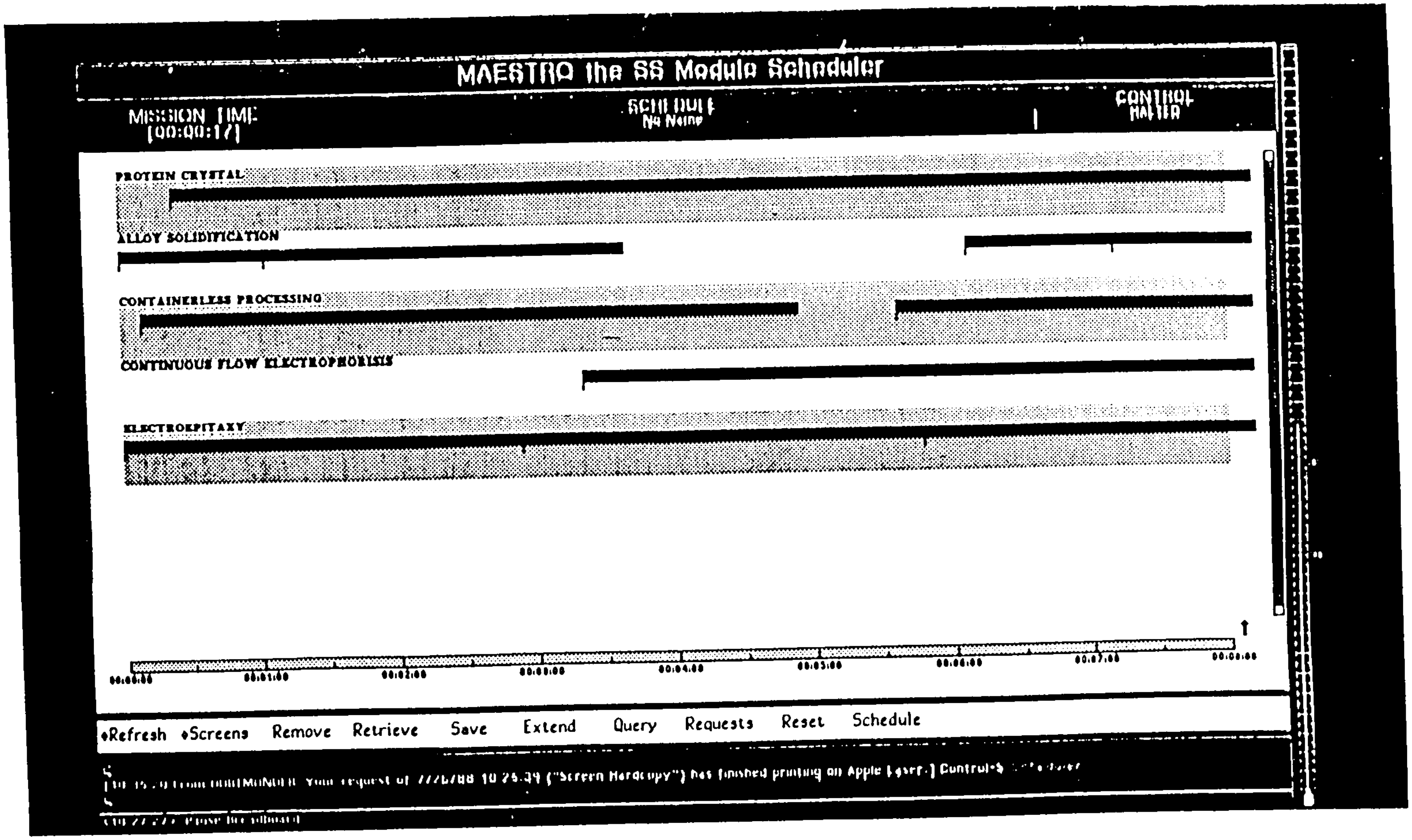
Loads Priority List Management System (LPLMS)

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

Typical MAESTRO Screen

Showing Equipment Editor

SSM/PMAD


MAESTRO the SS Module Scheduler
MISSION TIME
[00:00:17]
SCHEDULE
No Name
CONTROL
HALTED
PROTEIN CRYSTAL
ALLOY SOLIDIFICATION
CONTAINERLESS PROCESSING
CONTINUOUS FLOW ELECTROPHORESIS
ELECTROEPITAXY
Refresh
Screens
Remove
Retrieve
Save
Extend
Query
Requests
Reset
Schedule

Typical MAESTRO Screen

Showing Schedule

SSM/PMAD

MAESTRO Equipment Editor

DESCRIPTION

Modes for Equipment
ALLOY SOLIDIFICATION

NAME	MAX POWER	MAX CURRENT	REDUNDANT	TEST
Prep	100	0.481	YES	NO
Heat	940	4.519	YES	NO
Soak	1080	5.192	YES	NO
Cool	100	0.481	YES	NO
Off	0	0.000	YES	NO

Locations for Equipment
ALLOY SOLIDIFICATION

RPC	LOCATION
F15	Subsystem Distributor 1
F01	Subsystem Distributor 1

POWERED EQUIPMENT

- Cameras and Locker 1
- Cameras and Locker 2
- Cameras and Locker 3
- Cameras and Locker 4
- Digital Thermometer 1
- Digital Thermometer 2
- Digital Thermometer 3
- Digital Thermometer 4
- Digital Multimeter 1
- Digital Multimeter 2
- Digital Multimeter 3
- Digital Multimeter 4
- Digital Record Oscilliscope 1
- Digital Record Oscilliscope 2
- Digital Record Oscilliscope 3
- Digital Record Oscilliscope 4
- Electro Magnetic Shield Locker 1
- Electro Magnetic Shield Locker 2
- Electro Magnetic Shield Locker 3
- Freeze Dryer
- Video Camera / Recorder 1
- Video Camera / Recorder 2

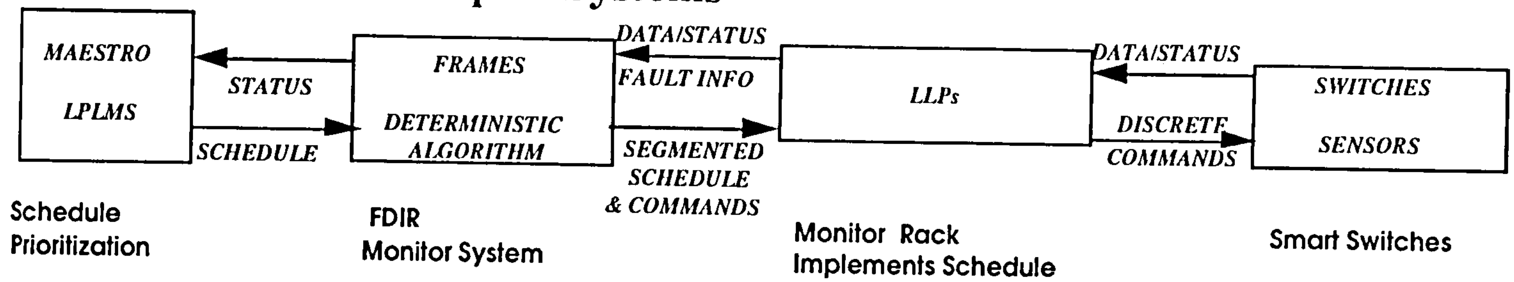
♦Refresh ♦Screens Add Location Add Mode Save Library Show Location Show Modes

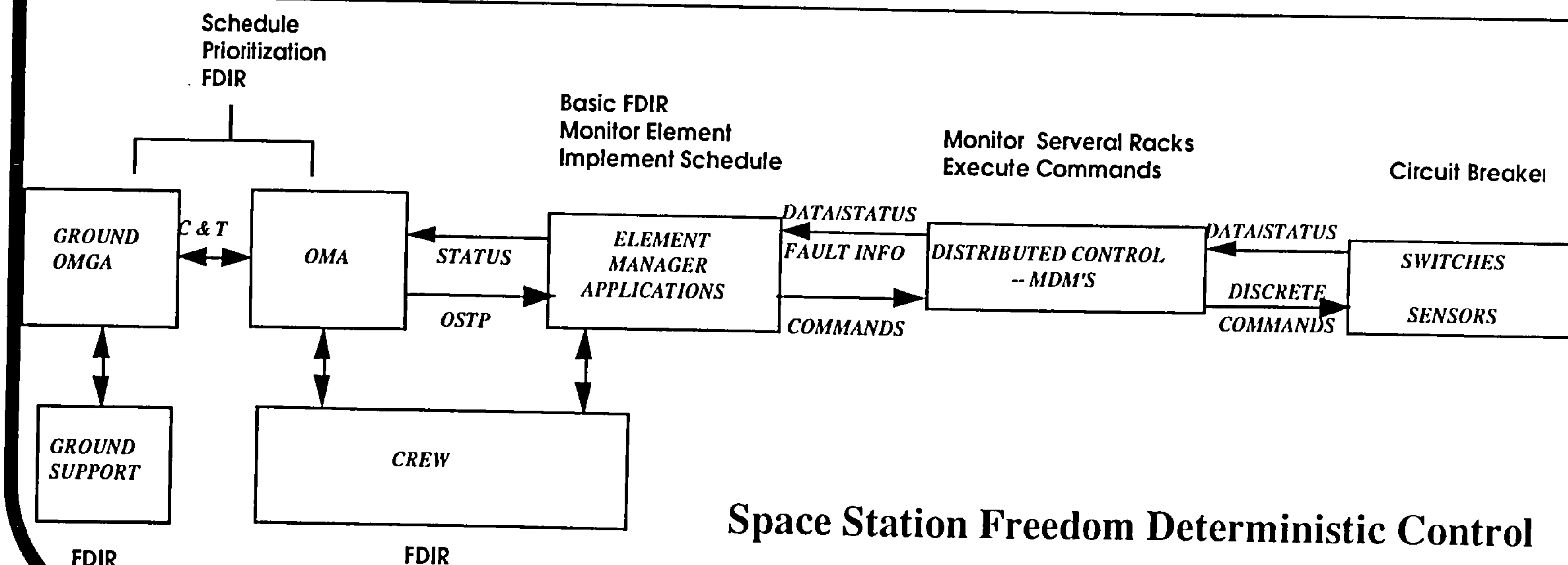
NASA Marshall Space Flight Center

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).

SSM/PMAD & Space Station Freedom Comparison

SSM/PMAD -- Deterministic & Expert Systems





Space Station Freedom Deterministic Control

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.

Ongoing Enhancement to SSM/PMAD

- Upgrade of communications (Ethernet)
- Expansion of Intermediate Levels of Autonomy
- Consolidated, improved user interface
- Upgrade FRAMES Knowledge Base Management System
- Operation with LeRC Automation Test Bed

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.

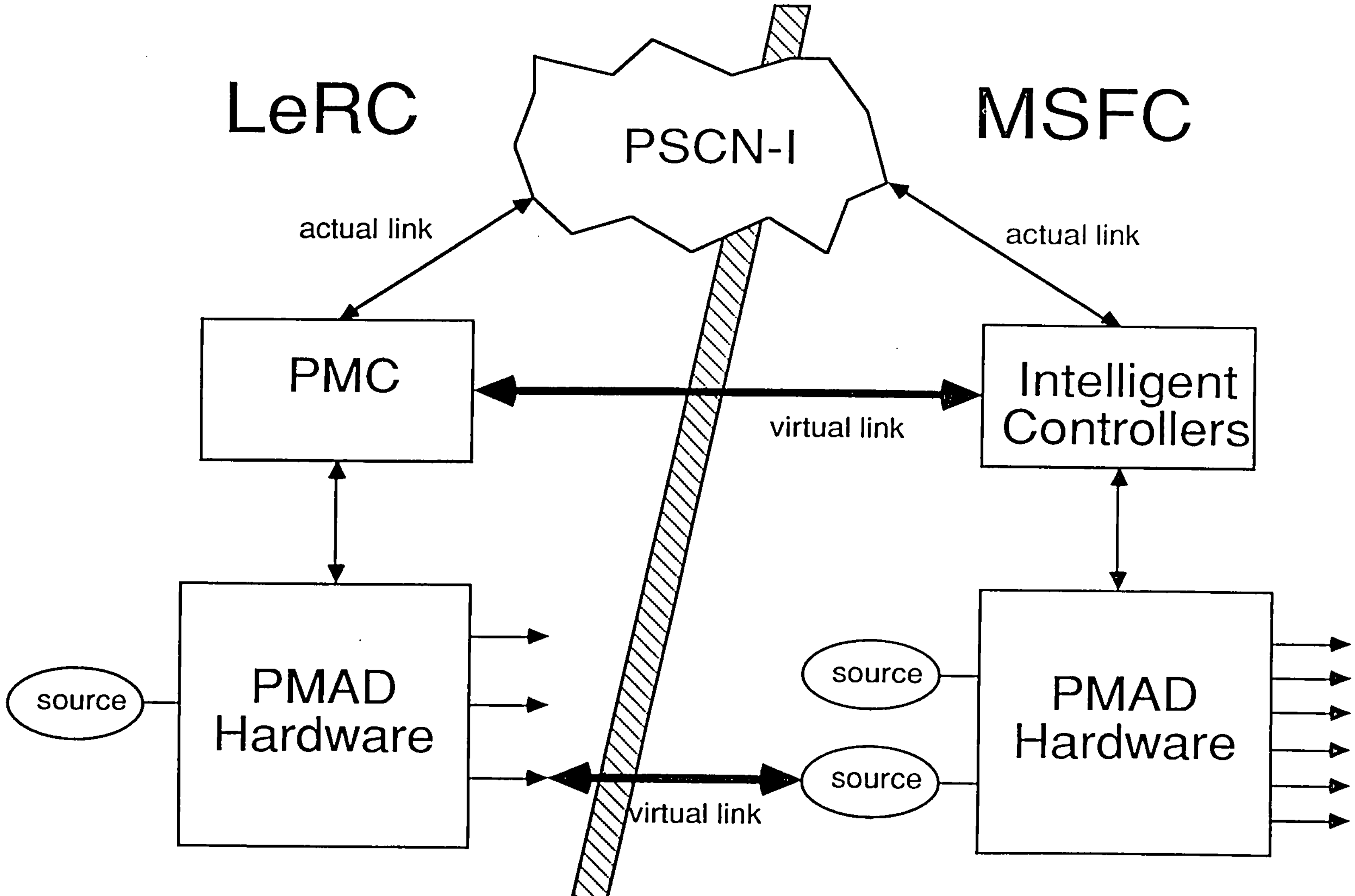
The actual communications link between the centers is via TCP/IP using the PSCN-I service. Both virtual links will be built on this connection, though the second connection may initially be done manually, with communication by telephone.

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.

THIS PAGE INTENTIONALLY BLANK

SSM/PMAD Overview



MSFC/LeRC Communications Link

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

SSM/PMAD

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

NASA Marshall Space Flight Center

THIS PAGE INTENTIONALLY BLANK

Propulsion System

Level III

Subsystem Presentation

THIS PAGE INTENTIONALLY BLANK

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

SPACE STATION
PROPULSION SYSTEM

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 propulsion requirement is for reboost, which will consume, on average, approximately 2.8 million lbf-sec of impulse per year, which represents over 95% of the propellant required.

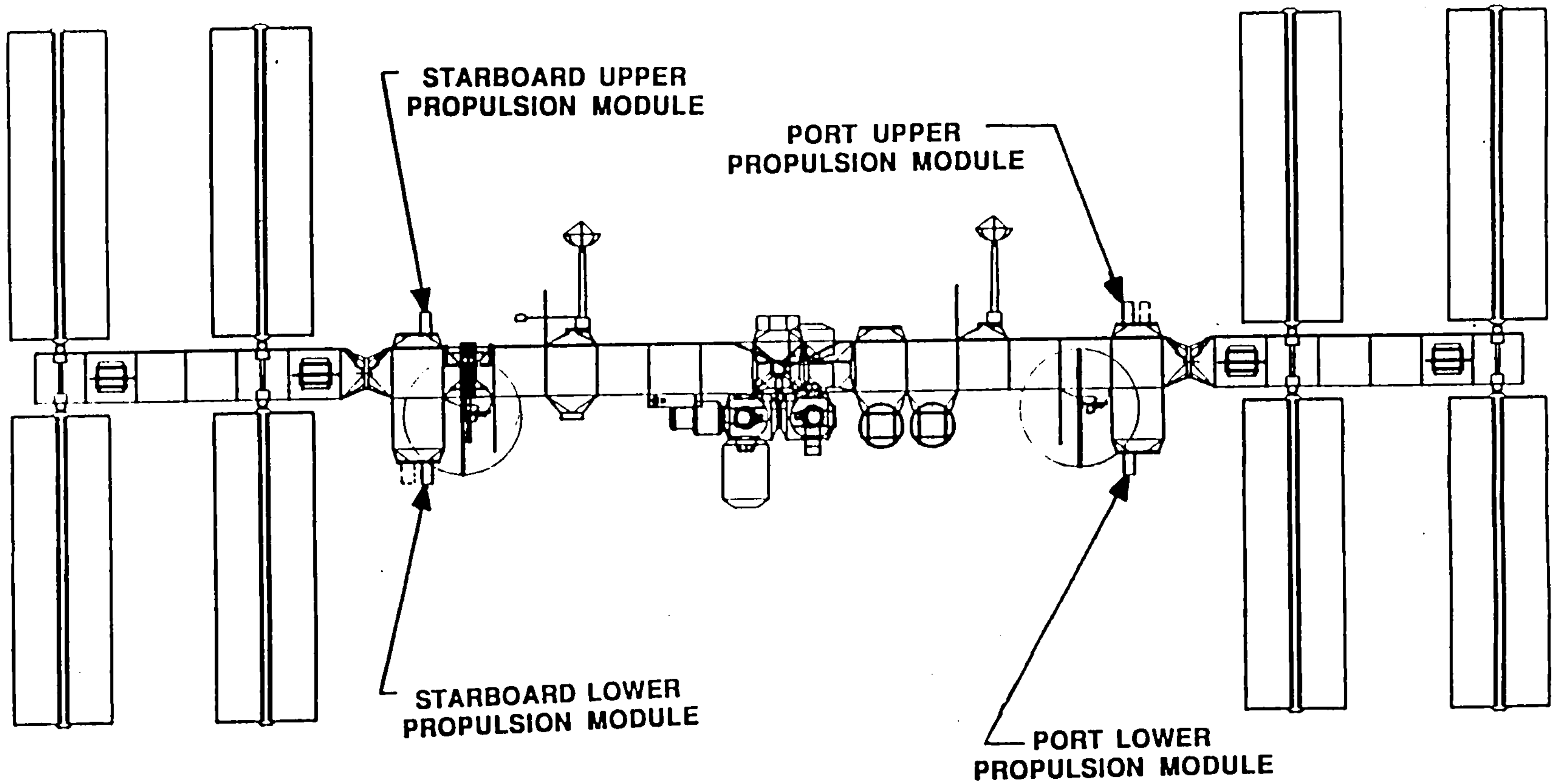
Other propulsion requirements are to utilize waste fluids to produce useful impulse and to maintain sufficient propellant reserves, such that if a resupply is missed, the Station can still perform nominal operations.

- SPACE STATION PROPULSION SYSTEM REQUIREMENTS
  - PROVIDE THRUST FOR:
    - ATTITUDE CONTROL
      - LARGE DISTURBANCE DAMPING
      - CMG DESATURATION
      - CMG BACK-UP
    - TRANSLATION
      - ATMOSPHERIC DRAG MAKE-UP (REBOOST)
      - ORBIT ALTITUDE ADJUSTMENTS
      - COLLISION AVOIDANCE
  - UTILIZE WASTE FLUIDS TO PRODUCE USEFUL REBOOST IMPULSE
  - 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.

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.

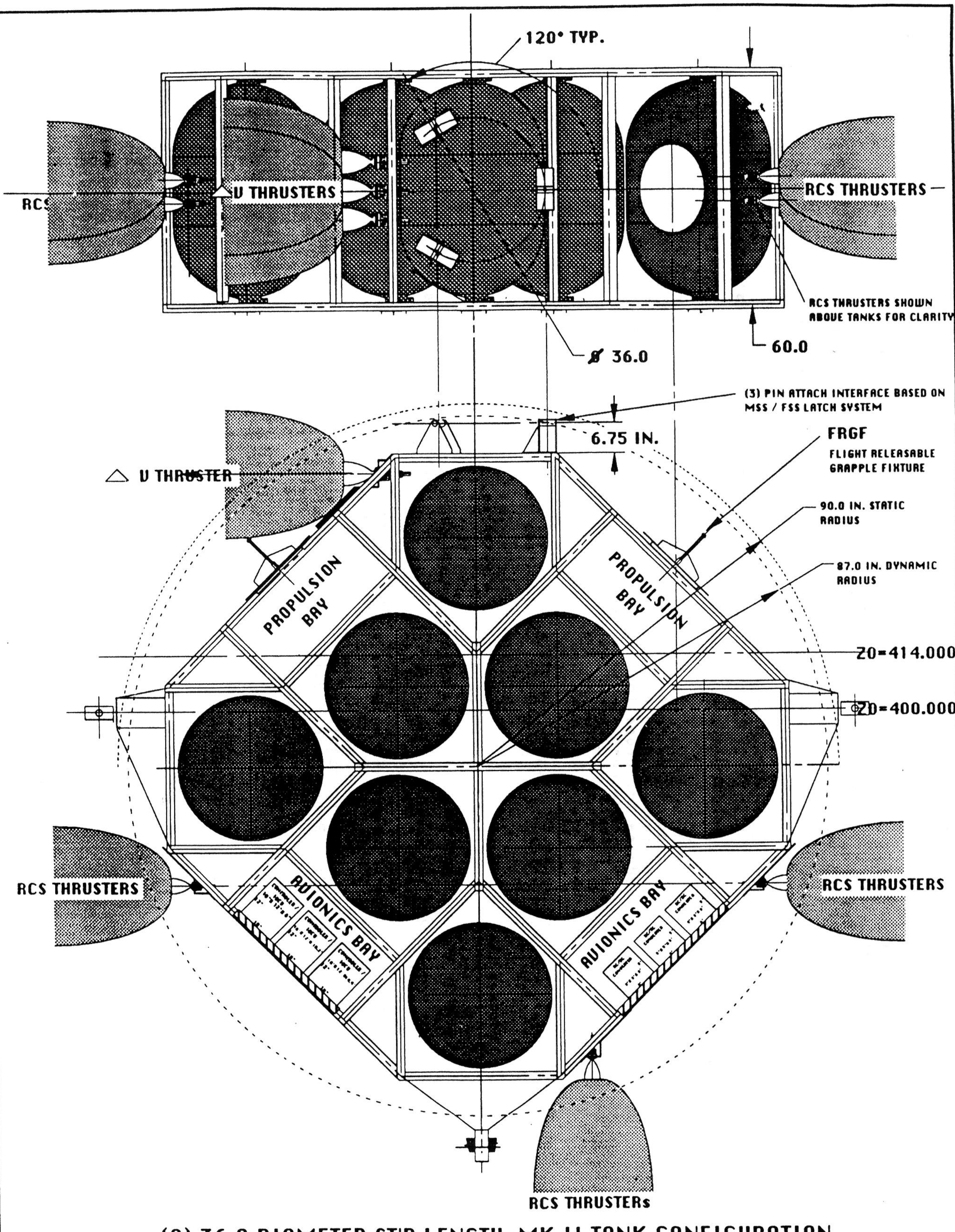
The Propulsion System concept is as follows: At each end of the transverse boom are two propulsion locations, one each above and below the boom. At each of the propulsion locations, there are two module interfaces, such that two modules can be collocated next to each other. When one of the modules is 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 with power, data and structural interfaces. There are no fluid connections 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.

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

- SPACE STATION PROPULSION SYSTEM DESIGN
  - BLOWDOWN HYDRAZINE SYSTEM
    - CHOSEN FOR SIMPLICITY AND MATURITY OF HARDWARE, DEVELOPMENT COST AND SCHEDULE, AND POWER CONSUMPTION
    - IMPACTS TO GN&C BEING EVALUATED
  - MODULAR SYSTEM
    - PROPELLANT RESUPPLY VIA MODULE REPLACEMENT
    - NO FLUID CONNECTIONS BETWEEN MODULES
    - STRUCTURAL, POWER AND DATA INTERFACES ONLY
  - 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.



(8) 36.0 DIAMETER ST'D LENGTH MK II TANK CONFIGURATION

P.R.FORRESTER 1-8-90
SCALE: 1/8
REDUCED SCALE: 1/32

SPACE STATION PROPULSION SYSTEM DRIVERS

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.

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

- O SPACE STATION PROPULSION SYSTEM DRIVERS
  - O ALTITUDE STRATEGY
    - O ORBITER CAPABILITIES
    - O SPACE STATION CONFIGURATION
    - O ATMOSPHERIC DENSITY (SOLAR ACTIVITY)
  - O THRUST SIZE
    - O STRUCTURAL CONCERNS
    - O TOTAL BURN TIME FOR REBOOST
  - O REDUNDANCY REQUIREMENTS
    - O CREW SAFETY
    - O STATION ORBIT DECAY - ALTITUDE STRATEGY
  - O RESUPPLY
    - O MASS FRACTION
    - O MANIFESTING CONCERNS
    - O 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.

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

- O HYDRAZINE TECHNOLOGY DEVELOPMENT
  - O 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
    - O ELECTRONIC PRESSURE REGULATION

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.

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

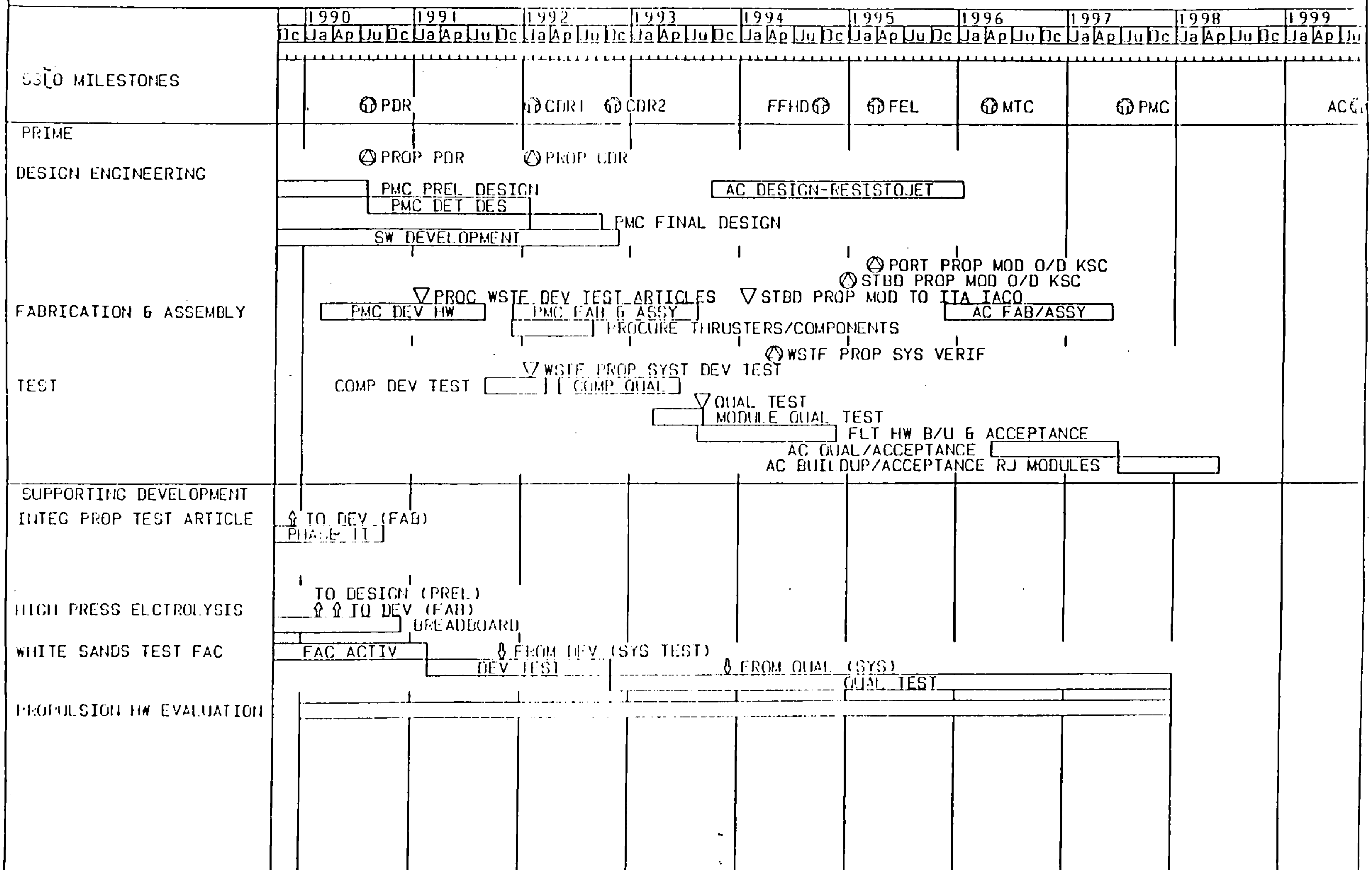
- O WASTE FLUID DISPOSAL SYSTEM
  - O MDSSC CURRENTLY EVALUATING THE BEST METHOD OF WASTE FLUID DISPOSAL
    - O RESISTOJETS
      - O ADVANCED DEVELOPMENT WORK
      - O HIGH POWER REQUIRED DURING OPERATION
    - O WASTE GAS INJECTION INTO HYDRAZINE THRUSTERS
      - O ADVANCED DEVELOPMENT WORK
      - 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.

INTEGRATED SCHEDULE - PROPULSION SYSTEM (TIER I)



Metier Artemis PIMSS Barchart Drawing System 2-NOV-89 8:51 am Page 1 of 1

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

- O 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
    - O 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.

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

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.

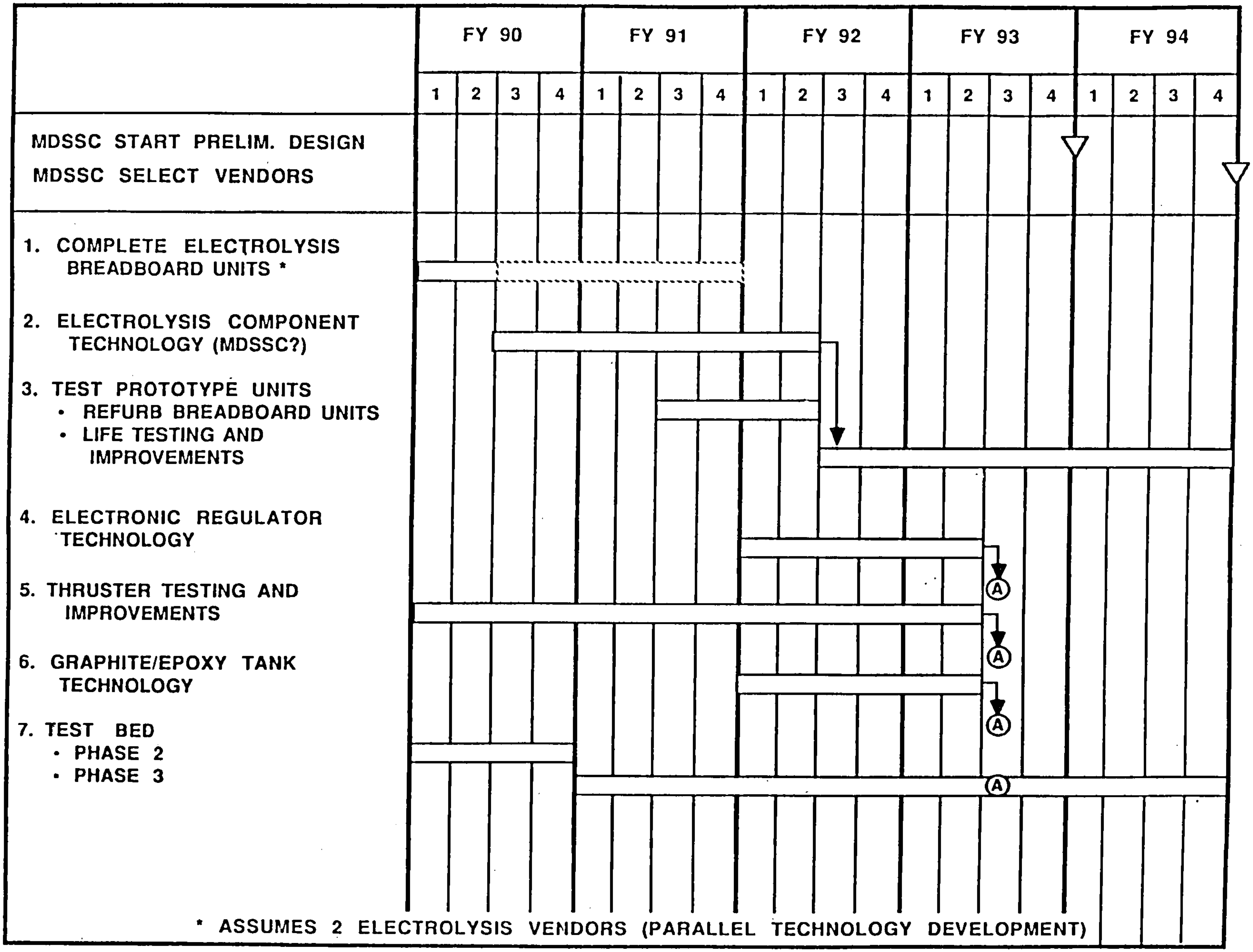
SPACE STATION PROPULSION SYSTEM	PROPULSION AND POWER	
	J. HENDERSON	01/16/90

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

O2/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.

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.

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

- 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

THIS PAGE INTENTIONALLY BLANK

Propulsion System

Invited Presentations

THIS PAGE INTENTIONALLY BLANK

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

SPACE STATION PROPULSION

INTEGRATED PROPULSION TEST ARTICLE

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.

SPACE STATION PROPULSION INTEGRATED PROPULSION TEST ARTICLE	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.

SPACE STATION PROPULSION
INTEGRATED PROPULSION
TEST ARTICLE

PROPULSION AND POWER

J. HENDERSON

01/16/90

- O PHASE I CONFIGURATION DESCRIPTION
  - O ELECTROLYSIS UNIT
    - O NAVY OXYGEN GENERATION PLANT (OGP)
      - O 3000 PSI OPERATION
      - O DEVELOPMENT UNIT
    - O ELECTRONIC REGULATORS
      - O CAPABLE OF VARYING INLET PRESSURE TO THRUSTERS TO COMPENSATE FOR:
        - O TEMPERATURE VARIATIONS
        - O THRUST SELECTION
        - O DESIRED O/F RATIO
    - O THRUSTERS EVALUATED
      - O 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.

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.

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

- O PHASE II TESTING
  - O RECONFIGURE TEST ARTICLE
    - O LONG DISTRIBUTION LINES
    - O 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.

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

- O ELECTROLYSIS UNIT DEVELOPMENT CONTRACTS AWARDED IN 1988
  - O PARALLEL DEVELOPMENT OF TWO HIGH PRESSURE ELECTROLYSIS TECHNOLOGIES
    - O 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
    - O EXTENSIVE TESTING PLANNED AT JSC FOLLOWING HARDWARE DELIVERY
      - O STAND-ALONE TESTING
        - O DEMONSTRATE OPERATIONAL CHARACTERISTICS
      - O IPTA TESTING
        - O DEMONSTRATE SYSTEM OPERATION

THIS PAGE INTENTIONALLY BLANK

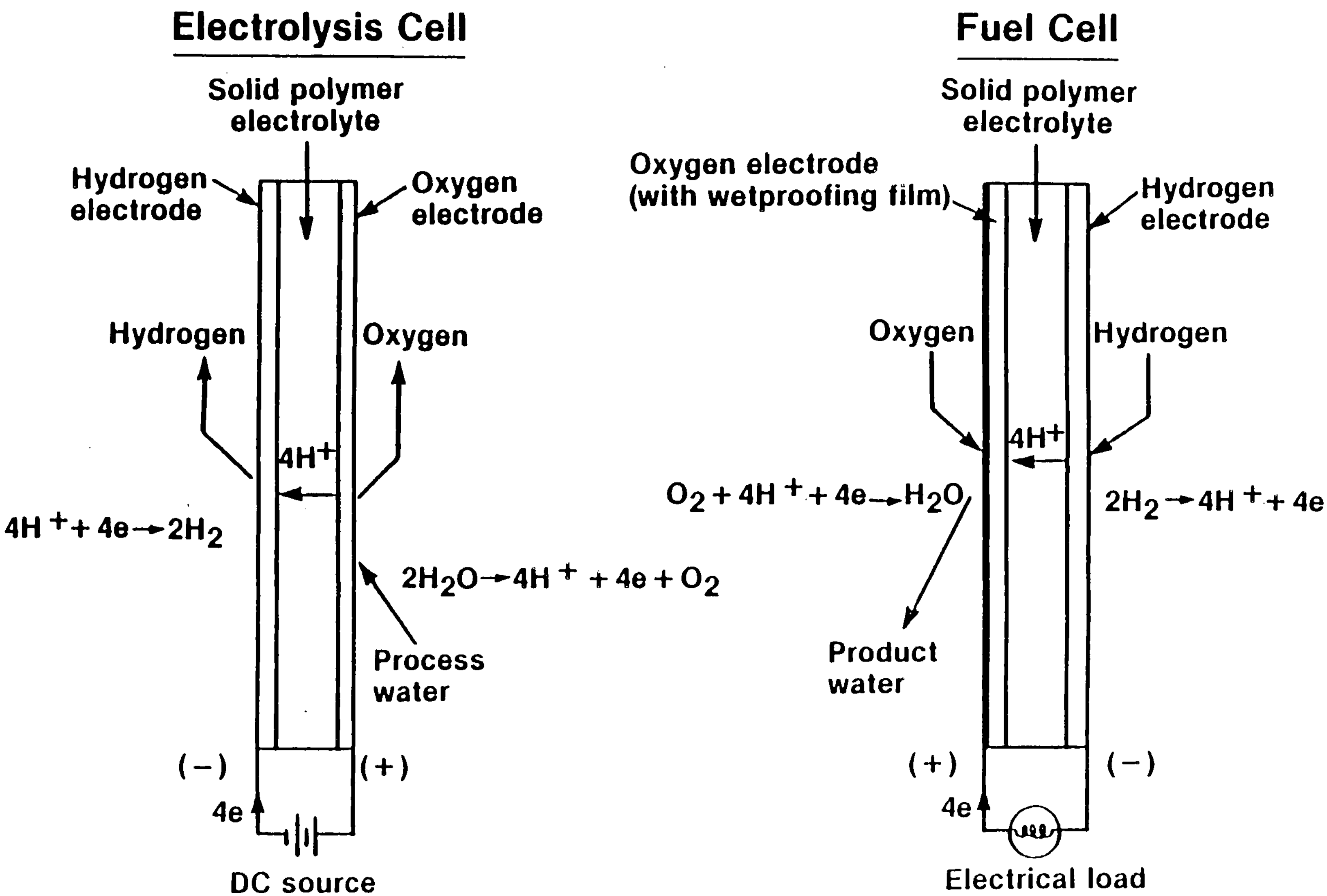
SPE® ELECTROLYZERS FOR SPACE PROPULSION

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

® Registered trademark of Hamilton Standard, Division of United Technologies Corporation

SPE ELECTROCHEMICAL CELL REACTIONS



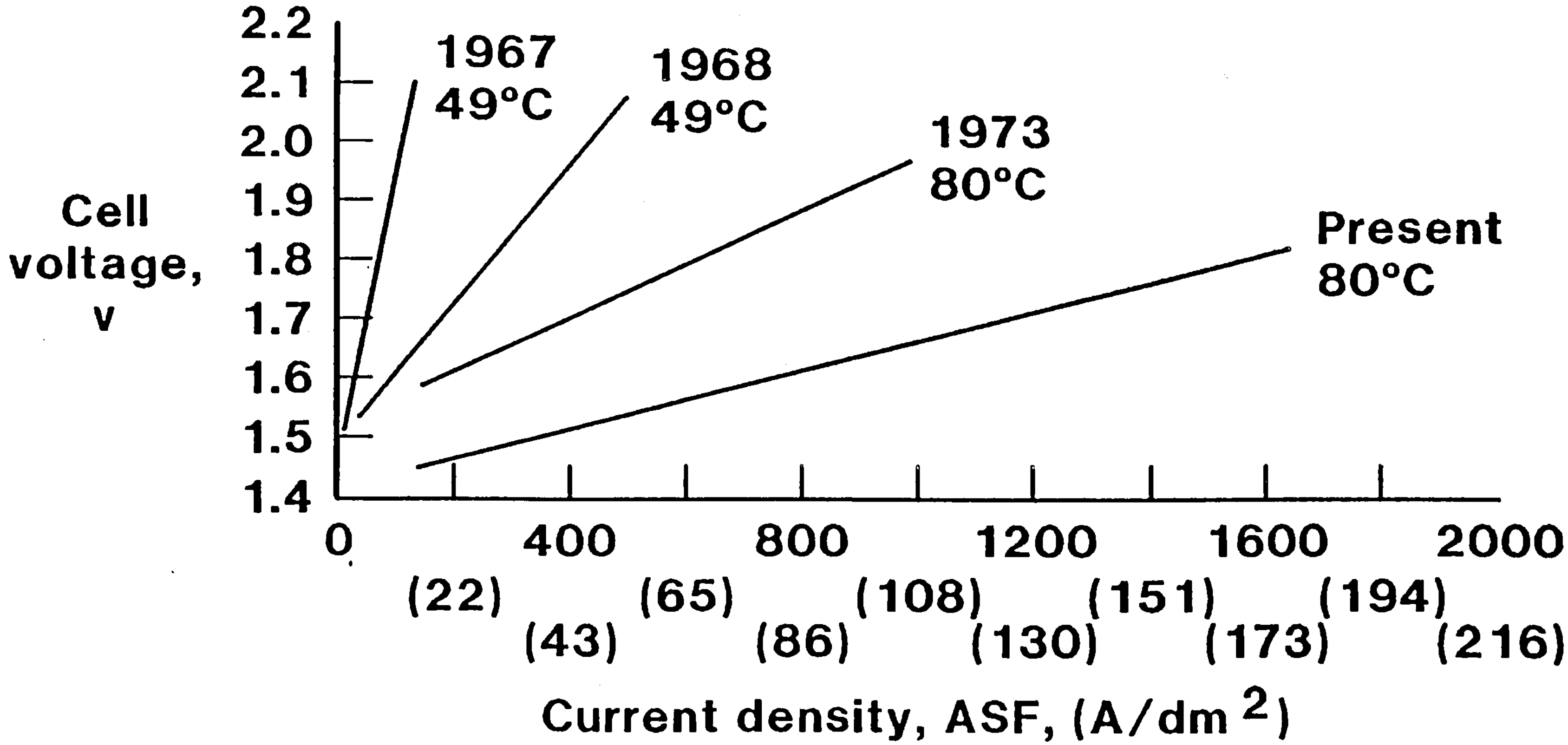
SPE FUEL CELL / ELECTROLYZER FEATURES

- 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 reactants- tested 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

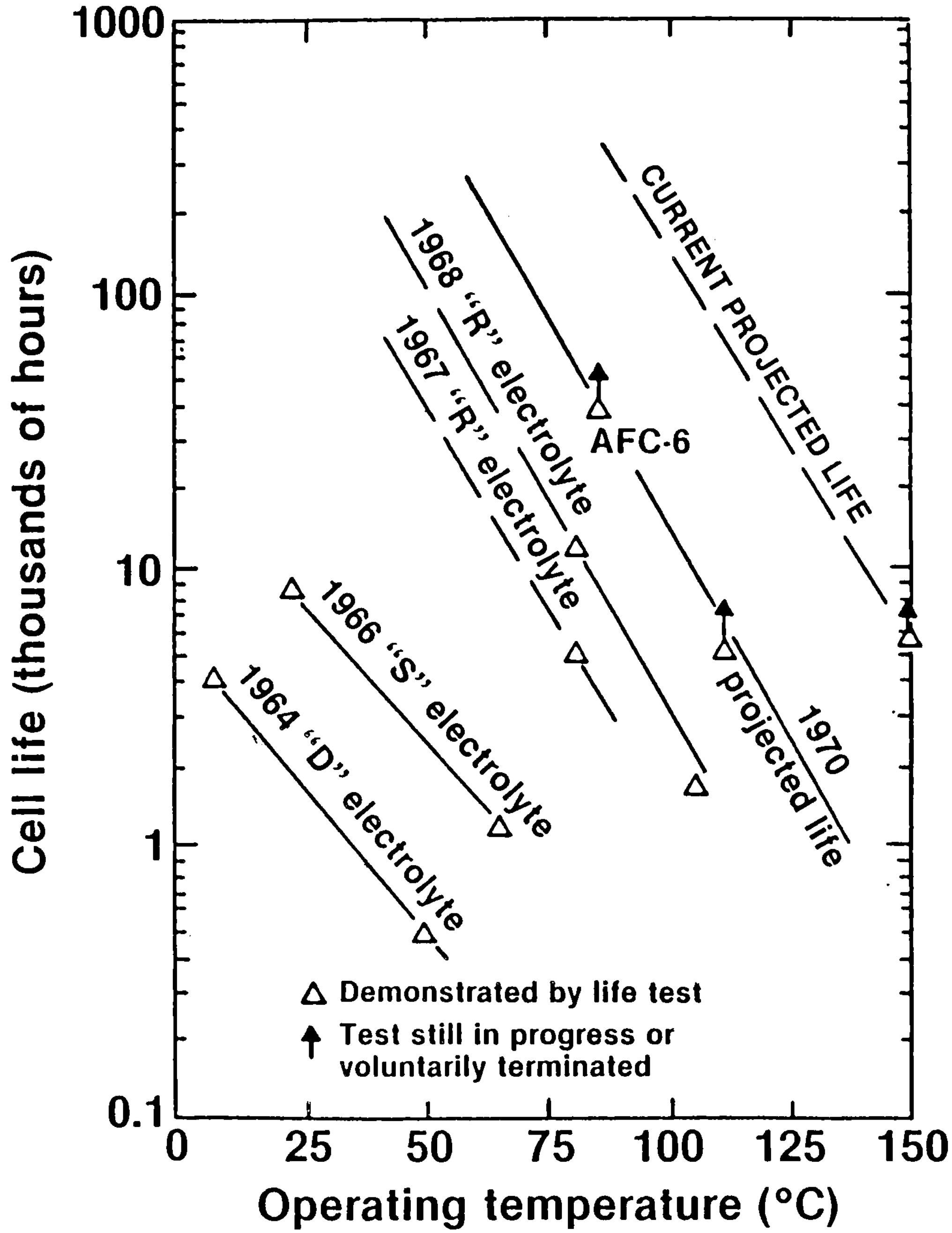
SPE FUEL CELL/ ELECTROLYZER FEATURES (Cont'd)

- 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

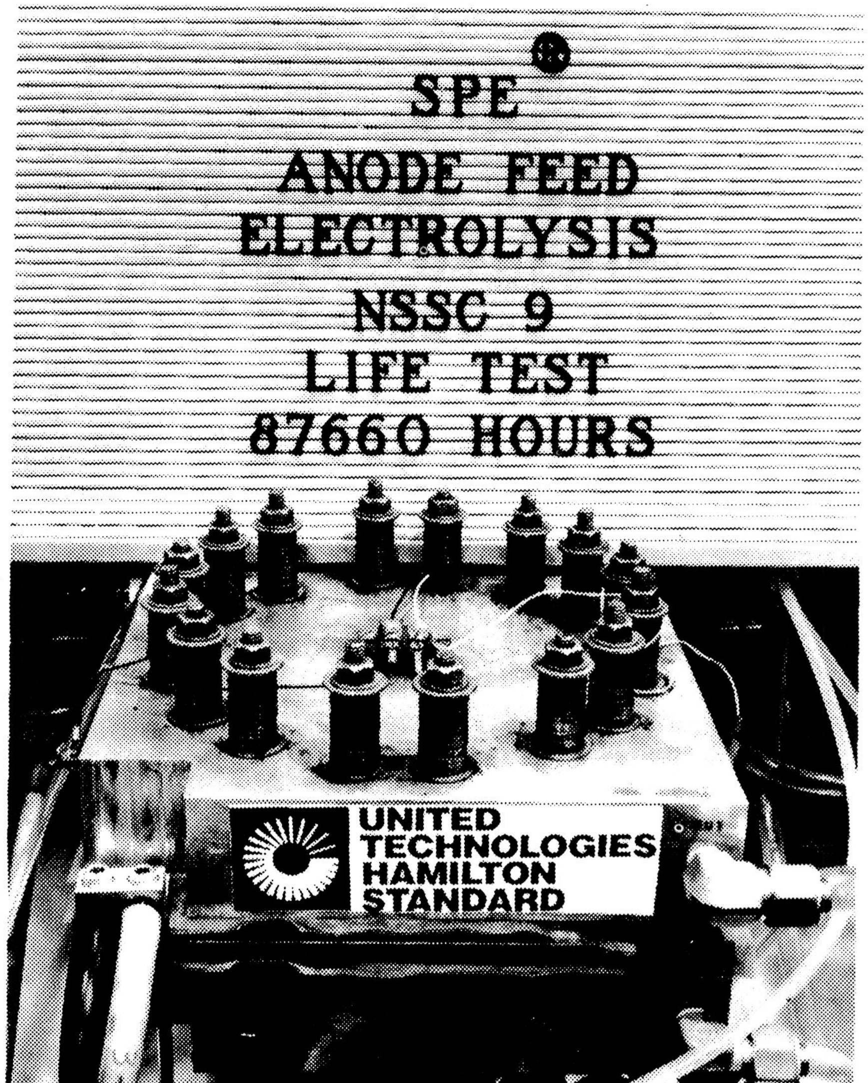
WATER ELECTROLYSIS PERFORMANCE HISTORY



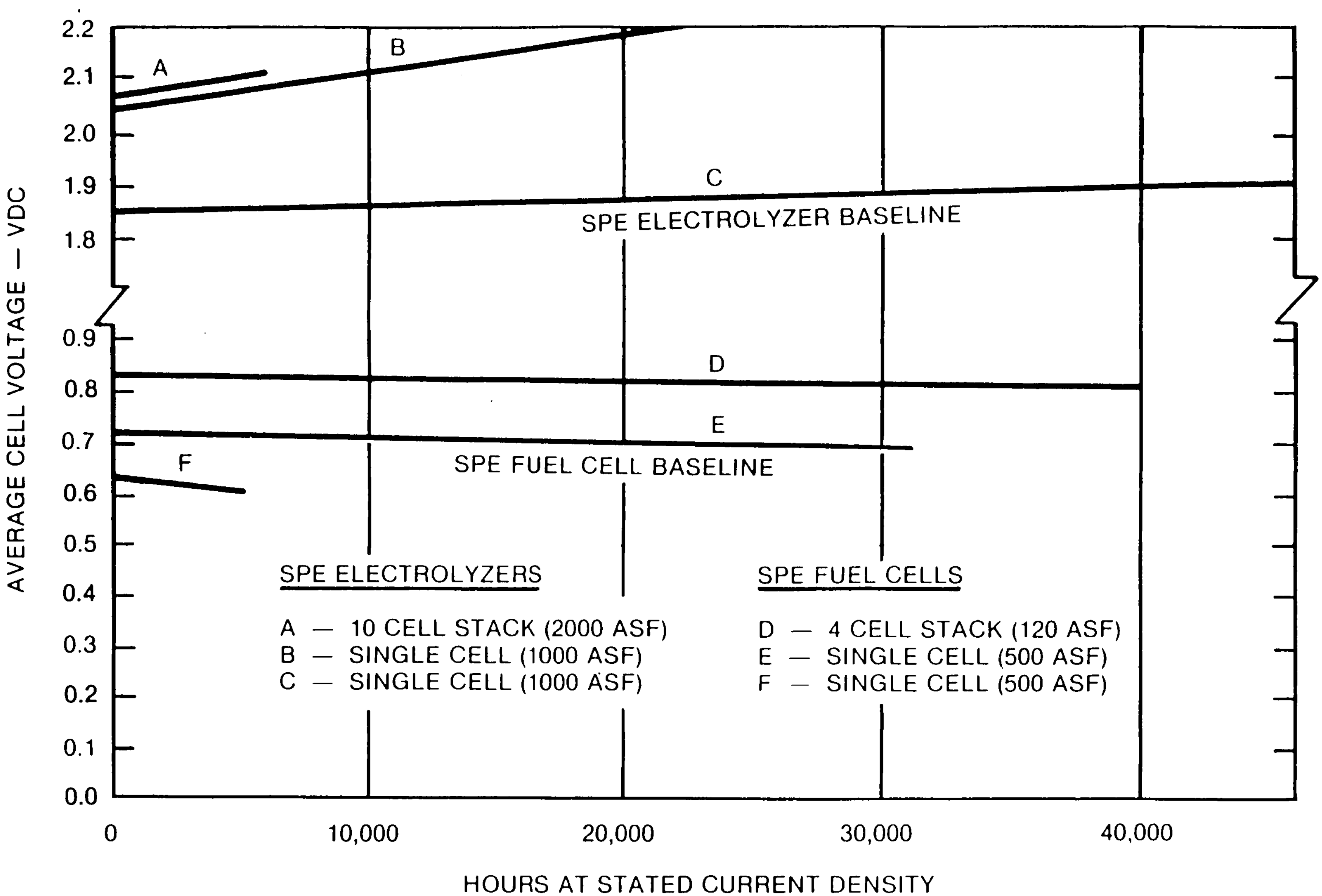
SPE CELL LIFE CAPABILITY



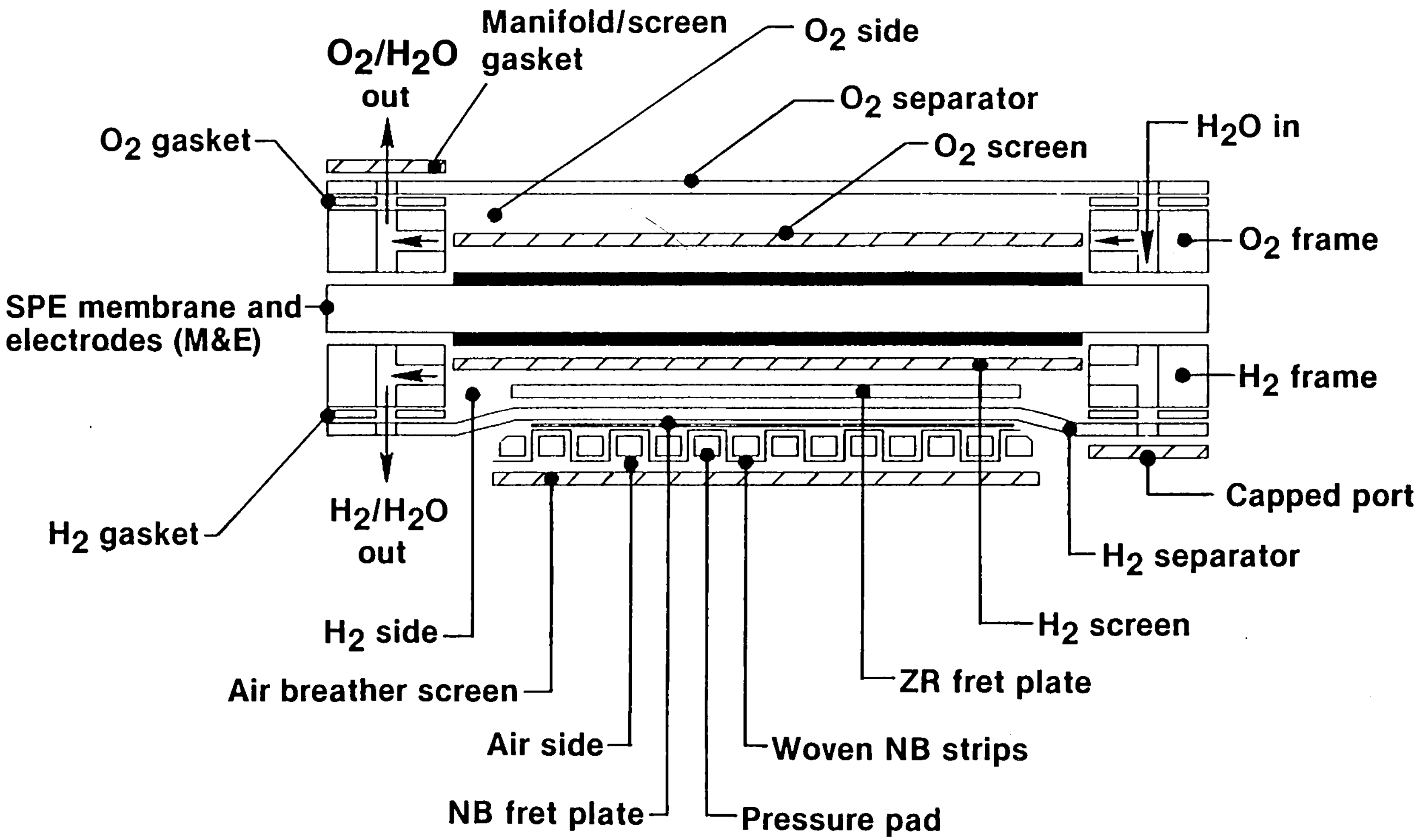
"UNINTERRUPTED" SPE®
ELECTROLYZER LIFE TEST



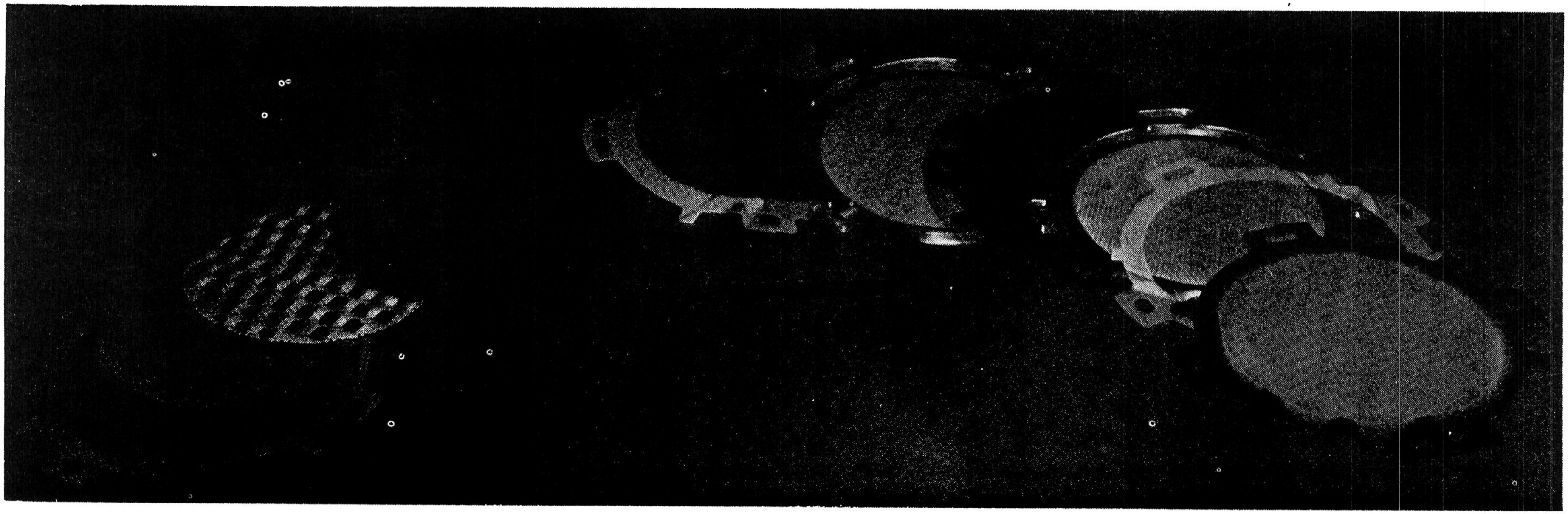
SPE CELL VOLTAGE STABILITY



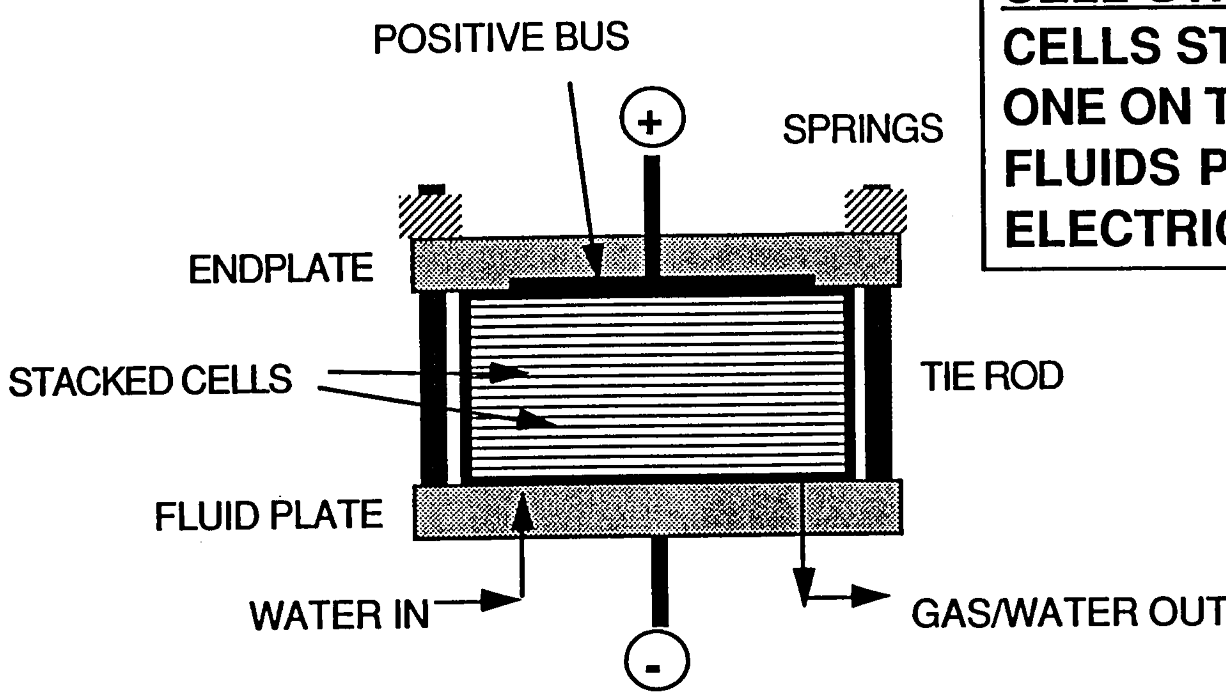
STATE-OF-THE-ART SPE CELL STRUCTURE



0.23 FT^2 CELL HARDWARE



INTRODUCTION: *ELECTROLYSIS CELL STACK*



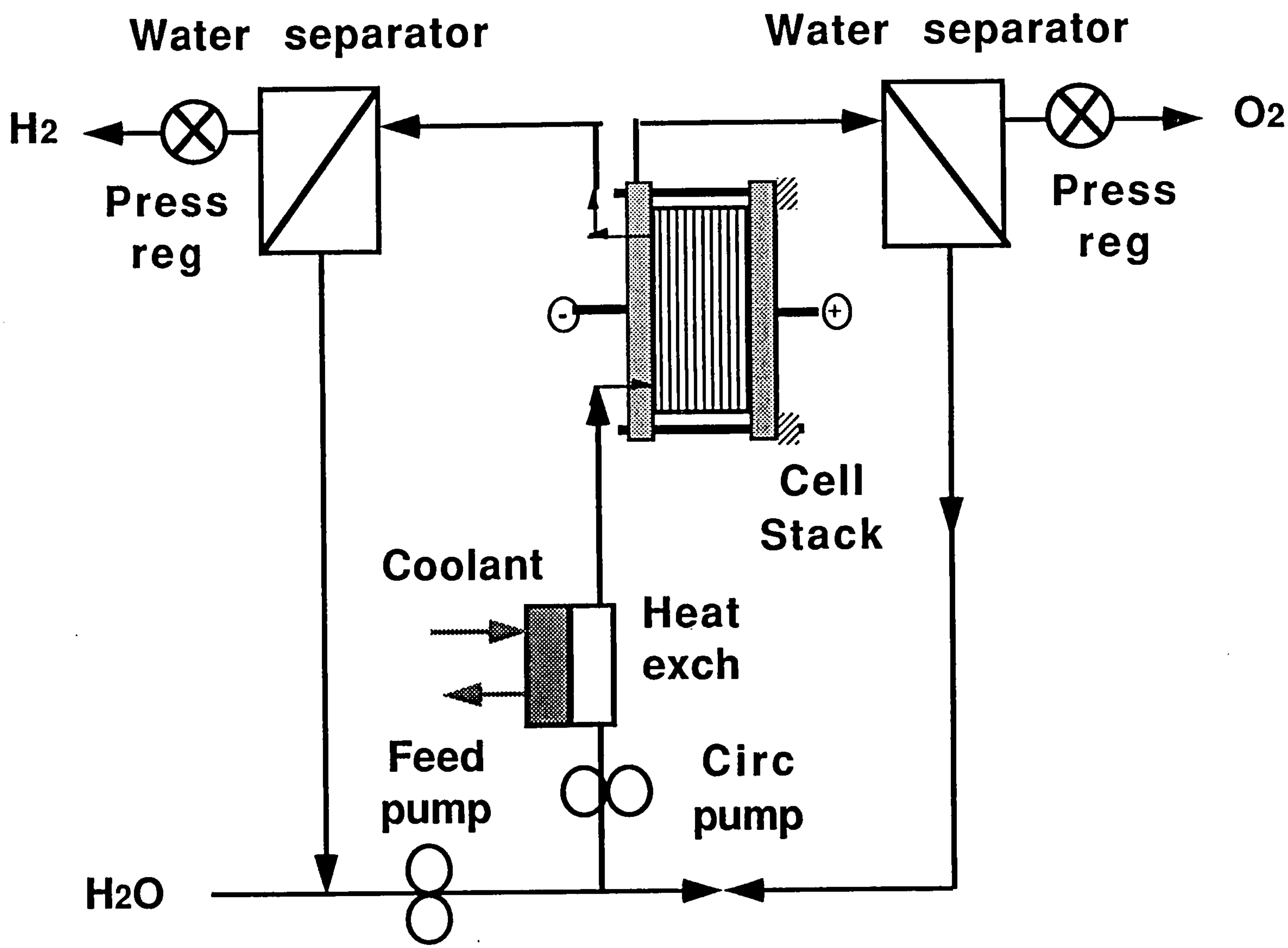
CELL STACK:
CELLS STACKED ONE ON THE OTHER
FLUIDS PARALLEL
ELECTRICAL SERIES

LOADING MECHANISM:
CELLS HELD BETWEEN ENDPLATE AND FLUID PLATE
CLAMPING FORCE APPLIED BY SPRINGS
FORCE TRANSFERRED BY TIE RODS

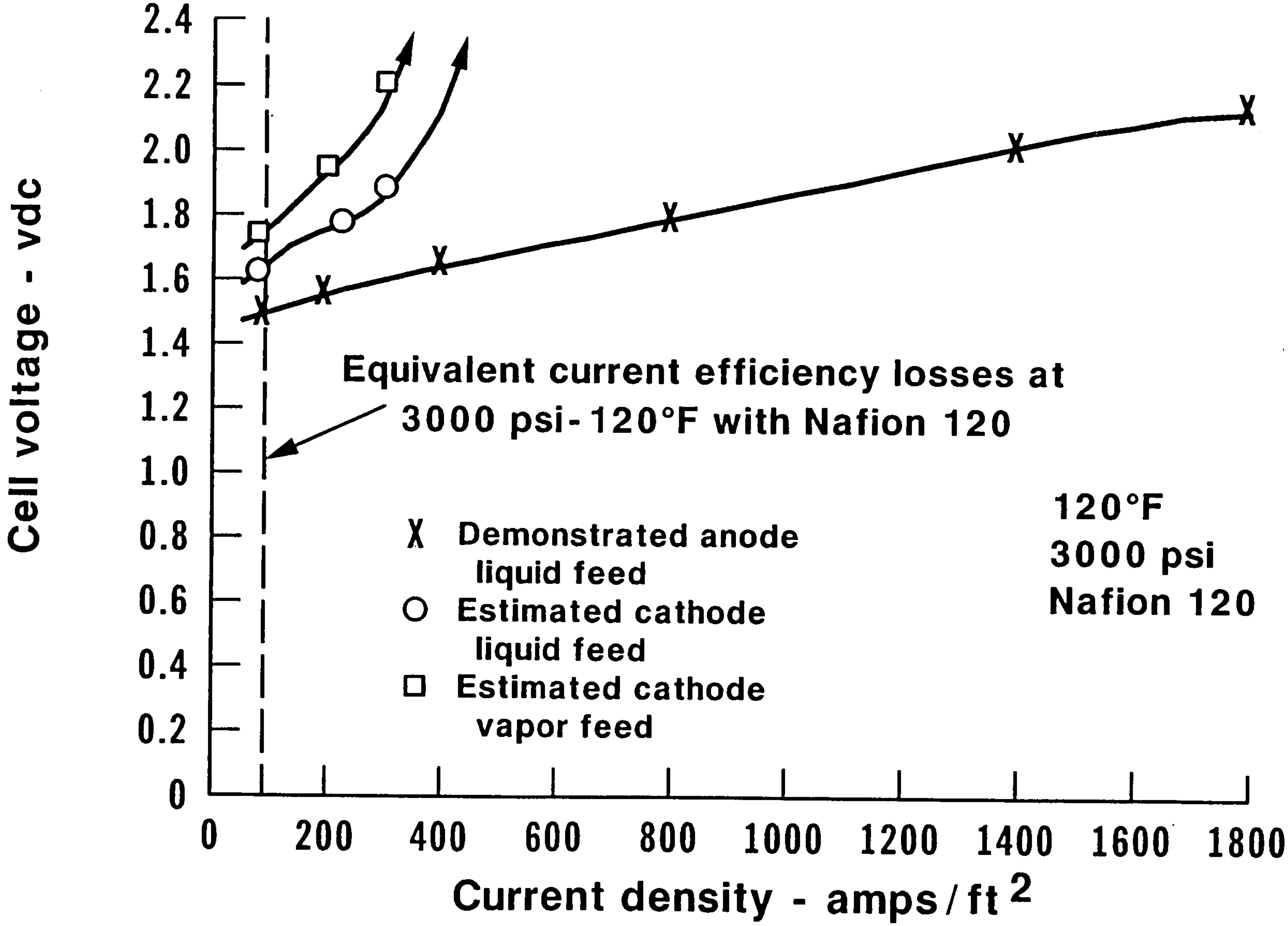
MODES OF SPE ELECTROLYZER OPERATION

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

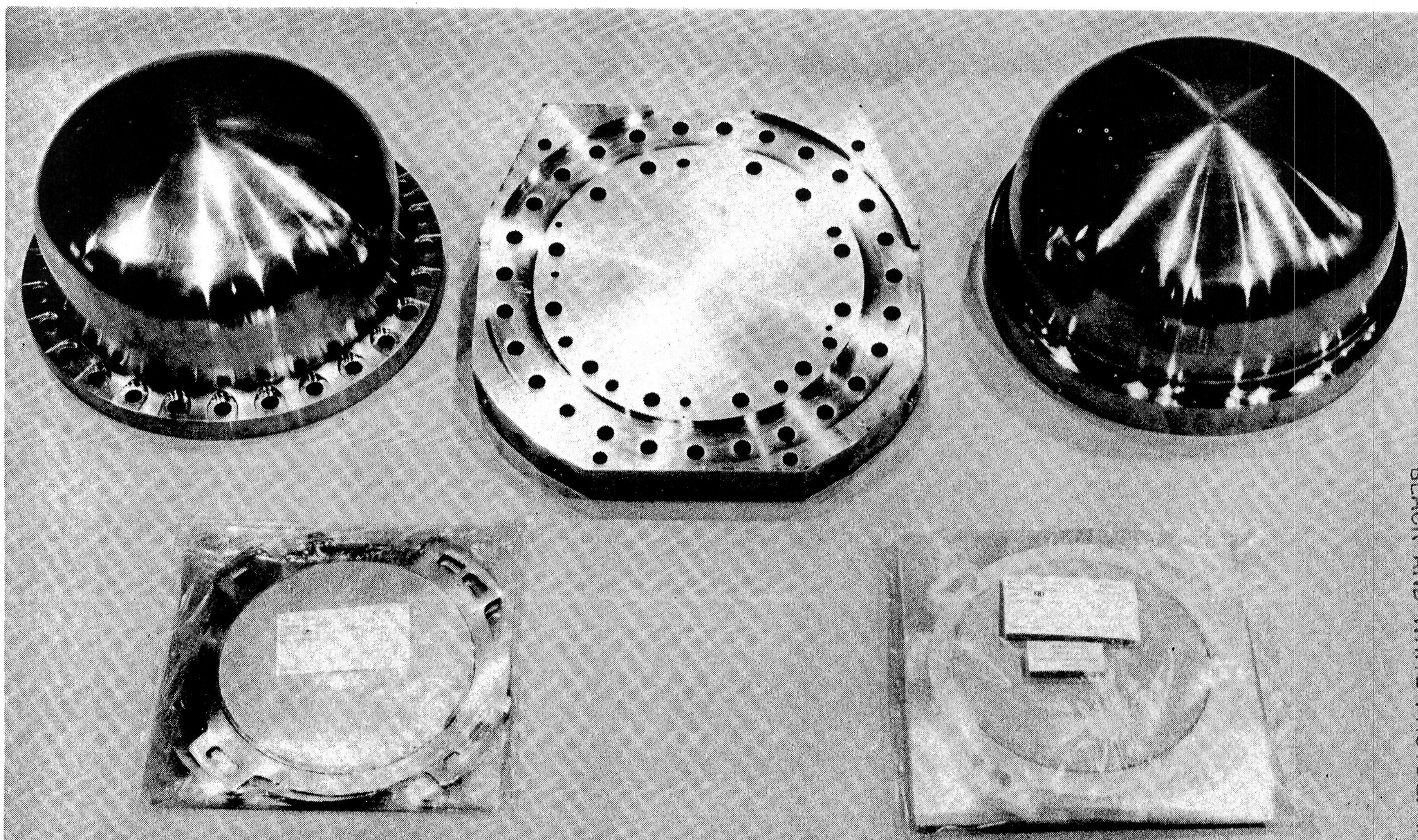
INTRODUCTION: *ELECTROLYSIS SYSTEM*



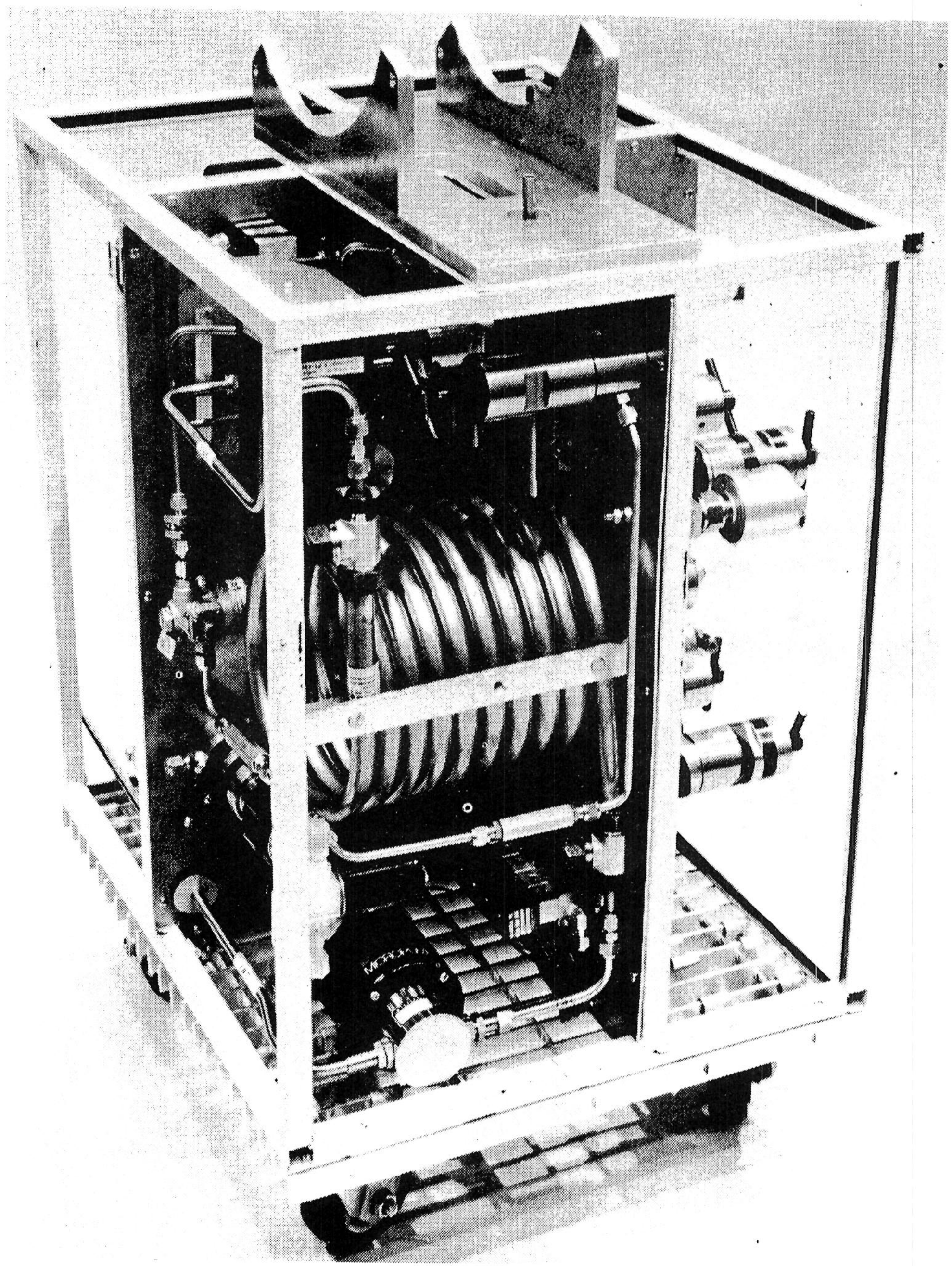
TYPICAL HIGH PRESSURE SPE ELECTROLYSIS PERFORMANCE



INTEGRATED PROPULSION TEST ARTICLE — ELECTROLYZER MODULE COMPONENTS



INTEGRATED PROPULSION TEST ARTICLE — SPECIAL TEST FIXTURE



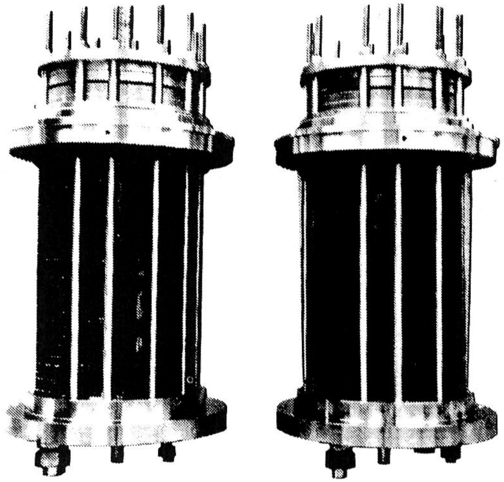
DEMONSTRATED LIFE - LIQUID ANODE FEED SPE ELECTROLYZER AS OF APRIL 1988

Type of Service/Product Description Navy Electrolyzers	Electrolysis Rate lbs/hr h20	Cell Area ft2	Operating Pressure PSI	Number of Stacks	Number of Cells Per Stack	Total Number Of Cells	System Hours	Stack Hours	Cell Hours
US Navy:									
Nuclear Submarine O2 Generation									
3000 psi System - Qualification Unit (OGP#2)	21	0.23	300 to 3000	2	100	200	1,000	1,000	100,000
3000 psi system - Preprototype (OGP#1)	21	0.23	300 to 3000	2	100/83	183	10,000	13,000	1,181,000
Development System (Breadboard)	21	0.23	300 to 3000	2	100	200	14,000	28,000	2,800,000
Development Stack OGP Program	1	0.23	300 to 3000	1	5	5	1,900	1,900	9,500
Development Stack OGP Program	2	0.23	300 to 3000	1	10	10	1,500	1,500	15,000
Development Stack OGP Program	4	0.23	300 to 3000	1	20	20	2,500	2,500	50,000
Development Stack OGP Program	7.4	0.23	300 to 3000	1	35	35	3,900	3,900	136,500
Development Stack NSSC 4	0.2	0.23	ambient	1	1	1	87,500	87,500	87,500
Development Stack NSSC 7	0.2	0.23	ambient	1	1	1	82,500	82,500	82,500
Development Stack NSSC 9	0.2	0.23	ambient	1	1	1	87,500	87,500	87,500
United Kingdom Navy:									
Nuclear Submarine O2 Generation									
Development Stack S/N#1	12.5	0.23	150	1	58	58	3,000	3,000	174,000
Development Stack S/N#2	15	0.23	150	1	70	70	6,000	6,000	420,000
Production Stacks: Various Production units (22 total)	15 to 17	0.23	150	22	70 or 81	1,731	classified	classified	classified
NASA/JSC Electric Energy Storage System	3	0.23	150	1	22	22	2,000	2,000	44,000
TOTAL - NAVY/NASA design (does not include classified data and various laboratory test data)				38		2,537	303,300	320,300	5,187,500
ES1000 Series:									
Constructor John Brown - England	34	1	100	1	34	34	2,000	2,000	68,000
Public Service Electric & Gas, New Jersey	16	1	100	1	14	14	10,000	10,000	140,000
South Bagdad Thermal Power Station - Bagdad, Iraq	24	1	100	2	12	24	35,000	70,000	840,000
Delta #4 Power Project - Nigeria	24	1	100	2	12	24	100	200	2,400
Development Unit- High Current Density (EPRI)	6	1	100	1	6	6	2,000	2,000	12,000
Monsanto Mound Laboratories - Moundsville, Ohio	8	1	100	2	5	10	100	200	1,000
Intermountain Power Project - Delta Utah	10	1	100	1	10	10	8,000	8,000	80,000
Laboratory Series:									
Gas Chromatograph Hydrogen Generator (various world-wide customers)	0.02	0.05	60 H2 amb O2	12000	3	36,000	42,000,000	42,000,000	126,000,000
Total Commercial Products (Liquid Anode Feed) (note: total does not include all ES 1000 systems)				12,010		36,122	42,057,200	42,092,400	127,143,400
GRAND TOTAL - LIQUID ANODE FEED				12,048		38,659	42,360,500	42,412,700	132,330,900

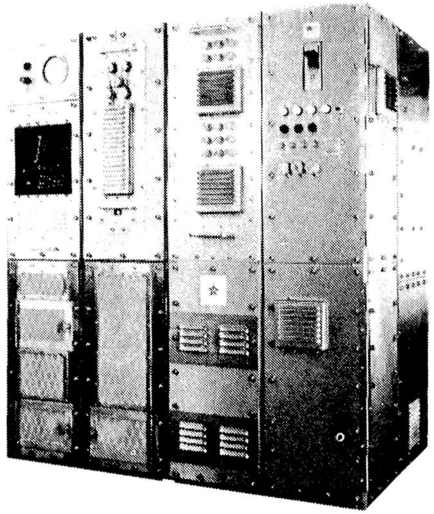
With Over **5 Million** Cell Hours of Successful Operation the Selected SPE Cell Design is Well Established

And supported by over **130 Million** Cell Hours of Anode Feed Operational Experience

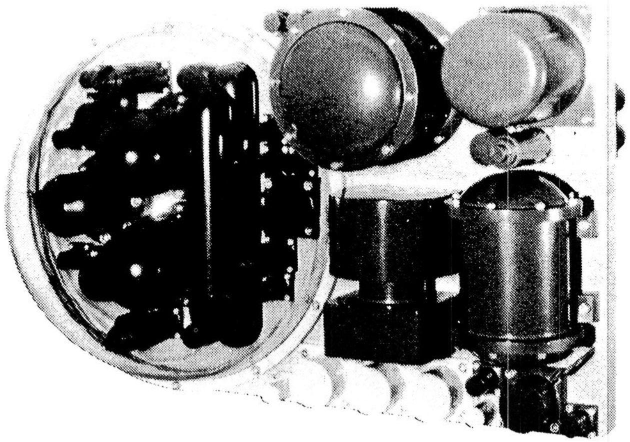
SPE WATER ELECTROLYZERS
(Active Cell Area 0.23 Ft^2)



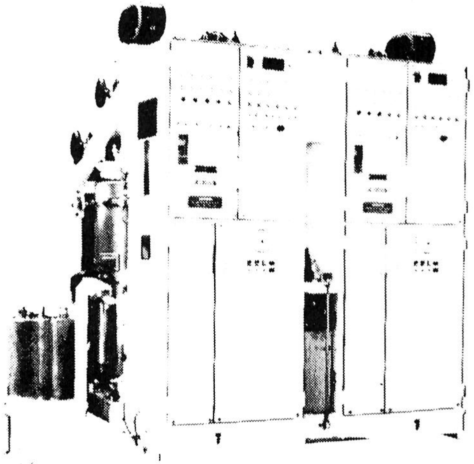
Production Modules



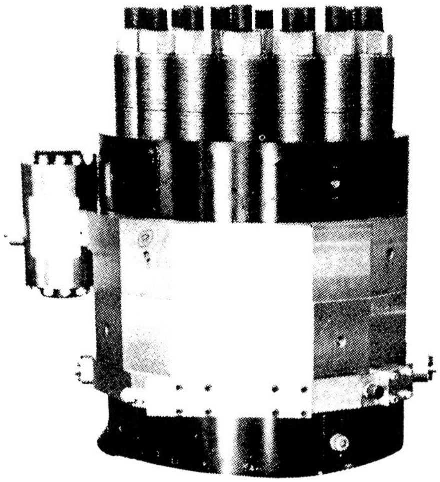
U.S. Navy Submarines
3,000 psi Qual Unit



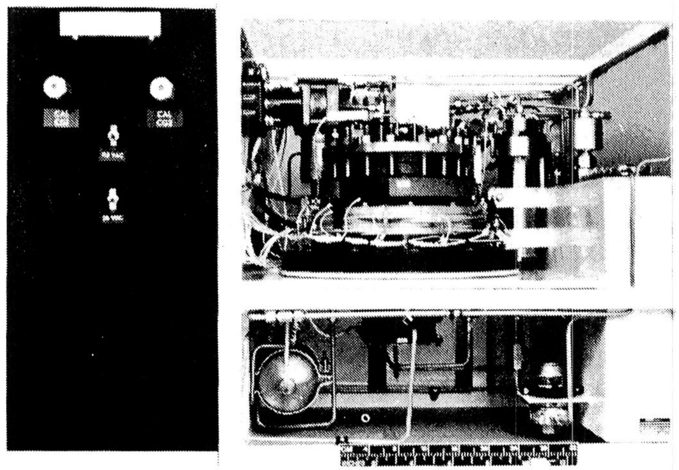
3,000 psi Propulsion
Electrolyzer Mock-Up



U.K. Navy Submarines
>30 Units Delivered



6000 psi
Development Unit



Space Station 1,000 psi
Development Unit

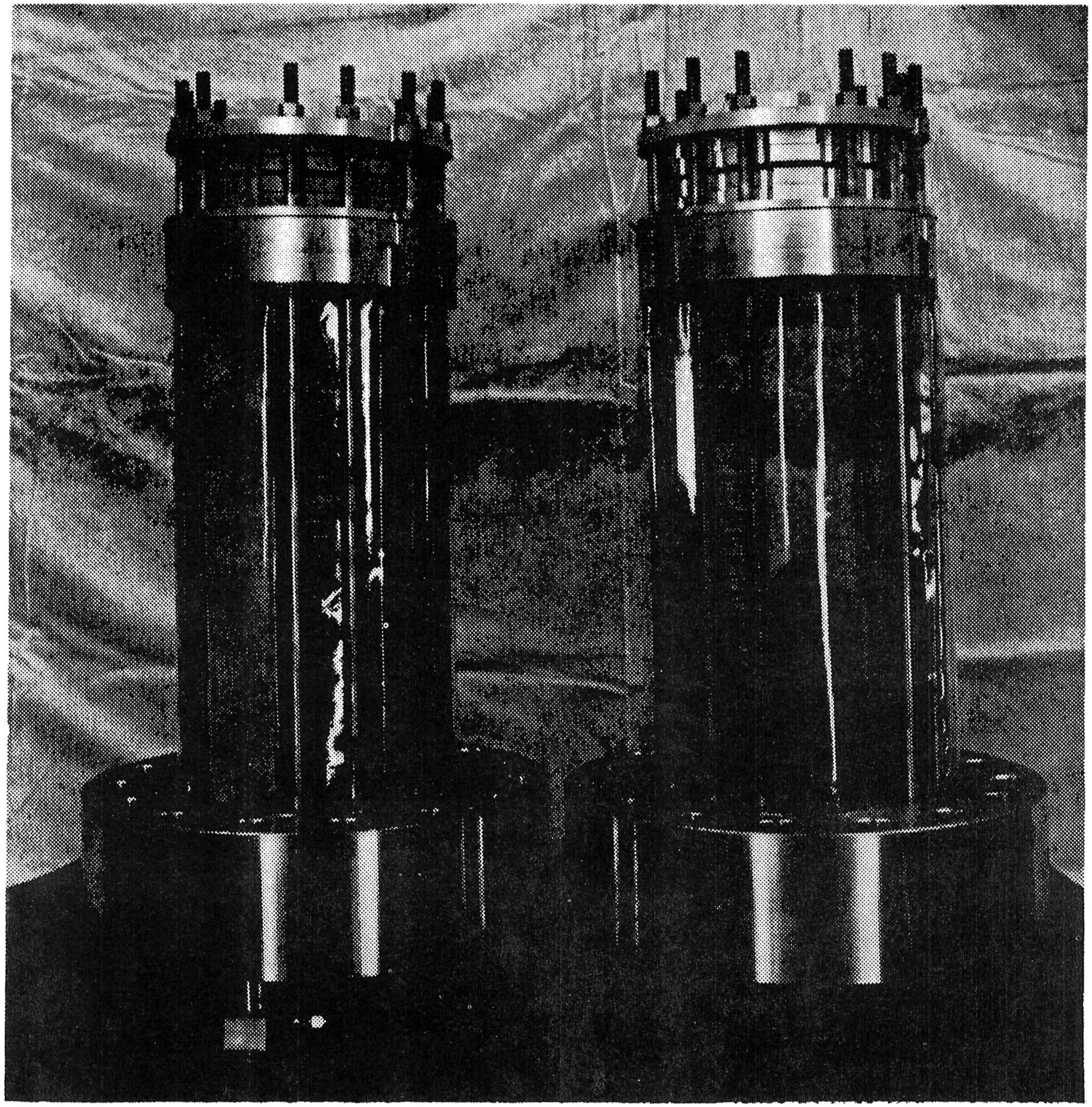
HIGH PRESSURE WATER ELECTROLYSIS EXPERIENCE

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

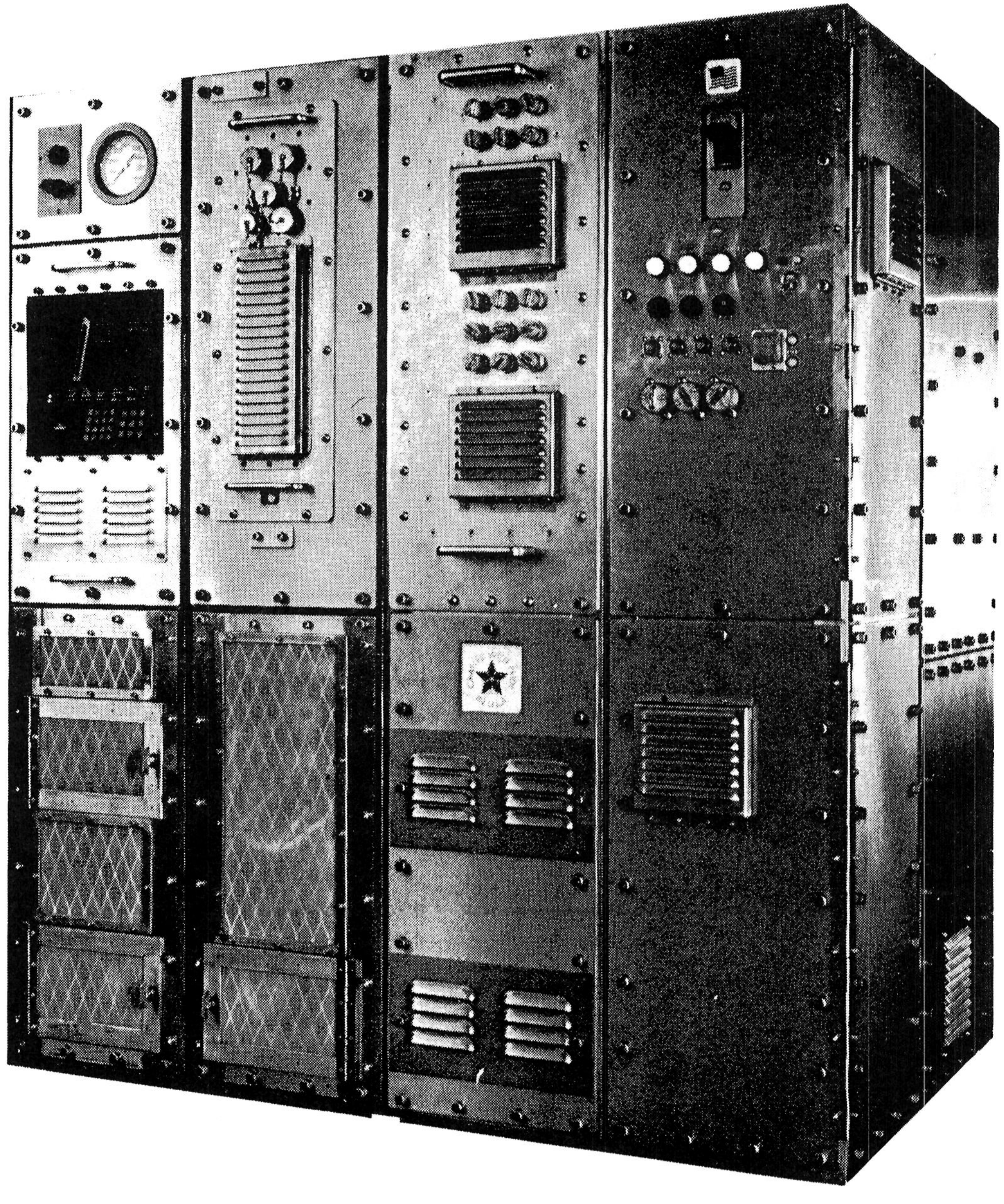
COMPARATIVE DATA

SPE	KOH
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 ~ 16 years w / redundancy	Cell life ~ 2 yrs
65 dB structureborne noise Can withstand >700 psid across membrane	85 dB cell noise Inches water control req'd
Redundant cell stack ~75% availability (<50% req'd)	Availability less than req'd - based on experience

225 SCFH U.S. NAVY SPE OXYGEN GENERATOR MODULE



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

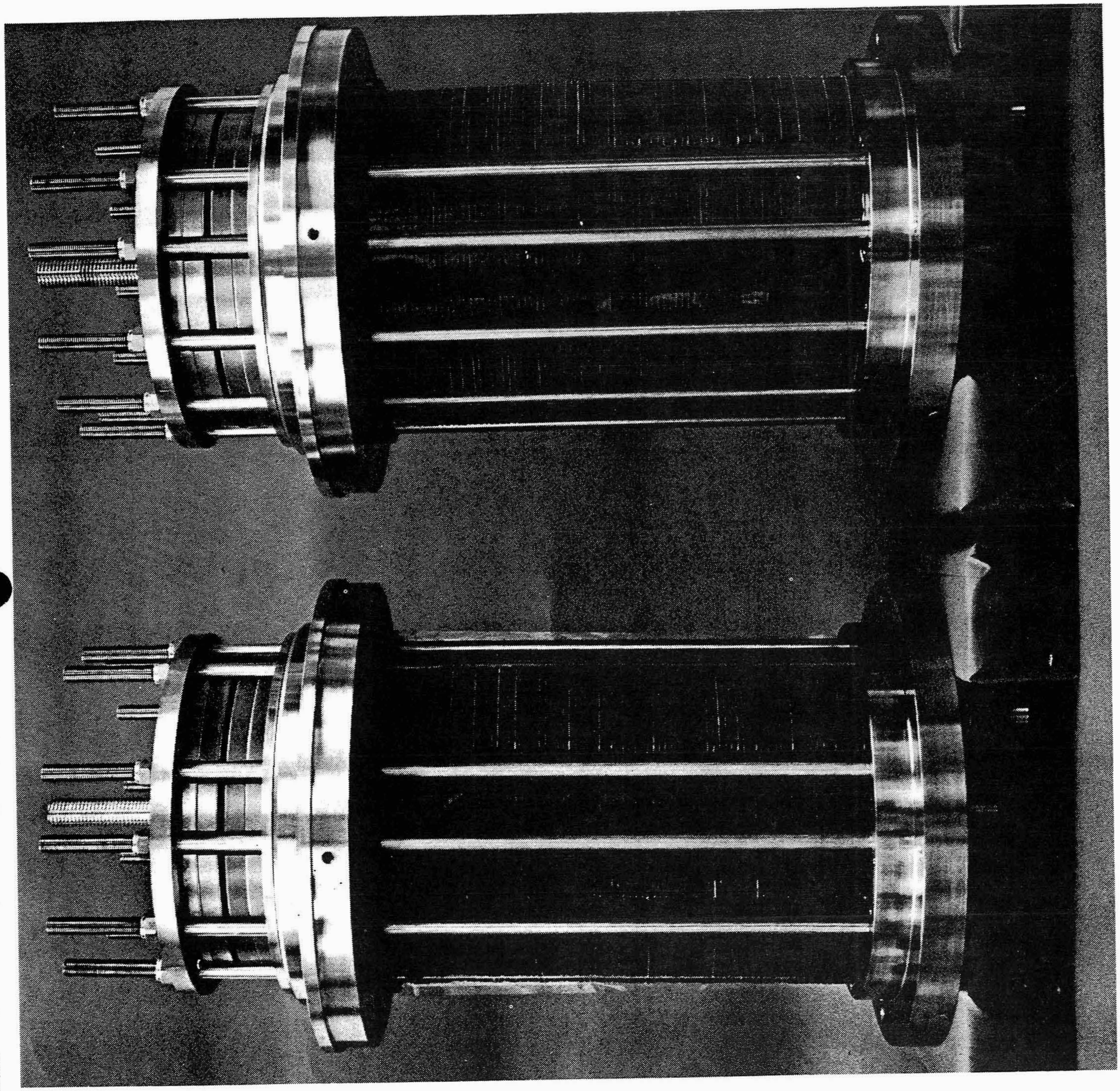
- SPE electrolyzer systems (~25kW) are in production with >30 systems delivered to date.

C-5

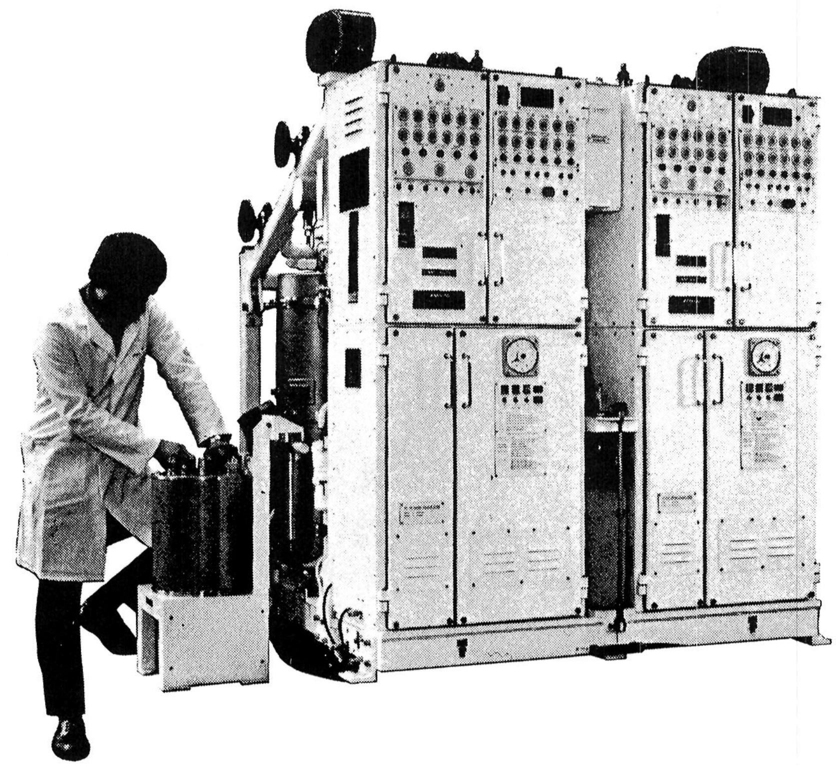
ROYAL NAVY ANALYSIS

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



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



COMMERCIAL SPE ELECTROLYSIS PROGRAMS

1973 - Present

- Laboratory H_2 generator in production since 1973
  - $>$ 10,000 units produced to date (UL listed)
  - Units in use throughout world
- ES-1000 H_2 generator system commercially available since 1983
  - 7 systems plus 6 modules shipped to date
  - Excellent reports from customers
- Large scale systems ready for commercialization

THIS PAGE INTENTIONALLY BLANK

Robotics

Level III

Subsystem Presentations

PRECEDING PAGE BLANK NOT FILMED

PAGE 398 INTENTIONALLY BLANK

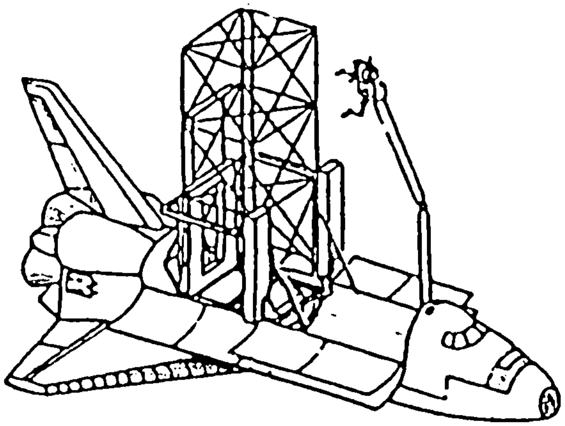
THIS PAGE INTENTIONALLY BLANK

Flight Telerobotic Servicer

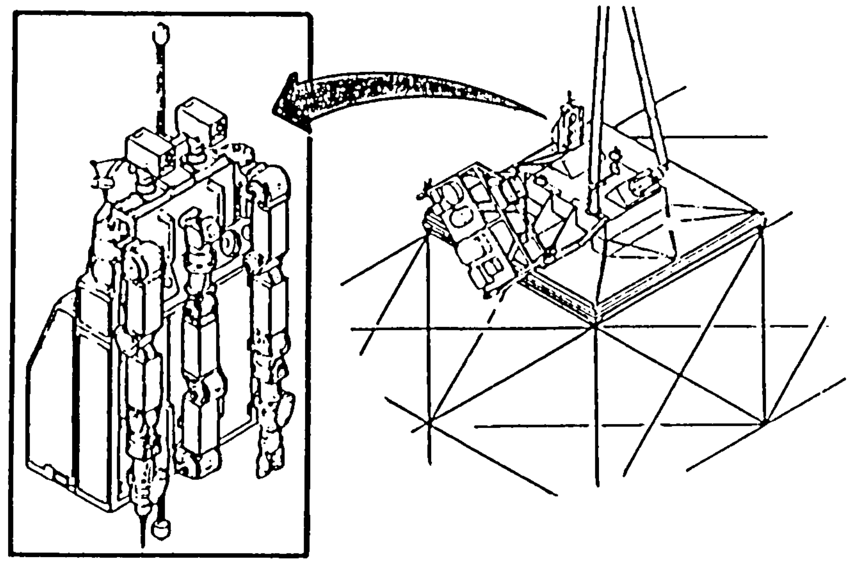
Dennis Haley
Martin Marietta

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

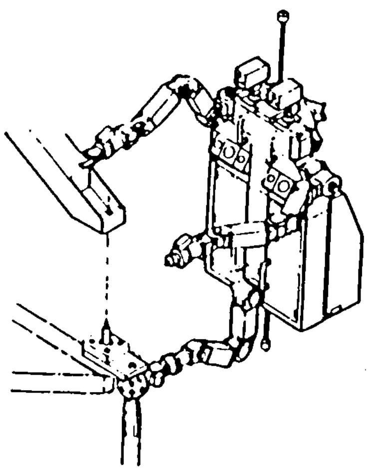
SSFTS Operations from the Orbiter Payload Bay



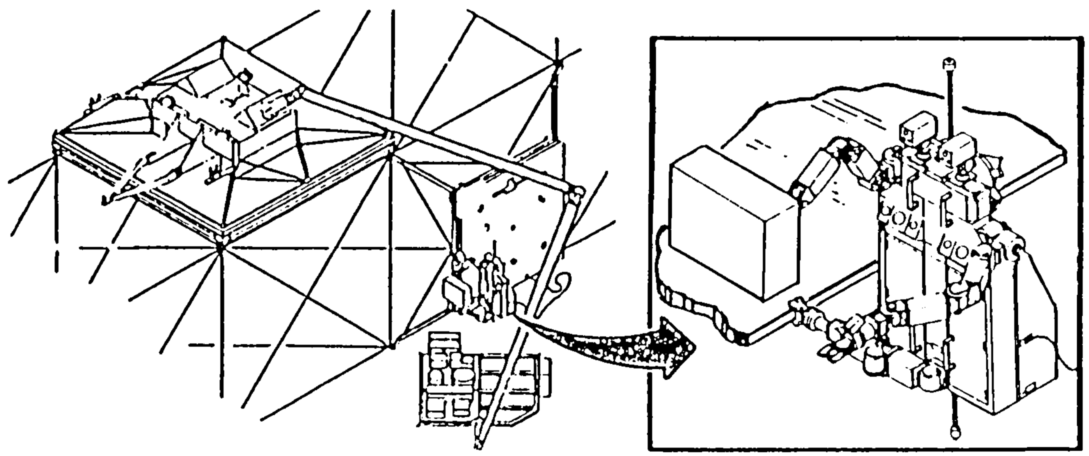
Transporter Attached Operations on Freedom



Fixed Base Independent
Operations on Freedom

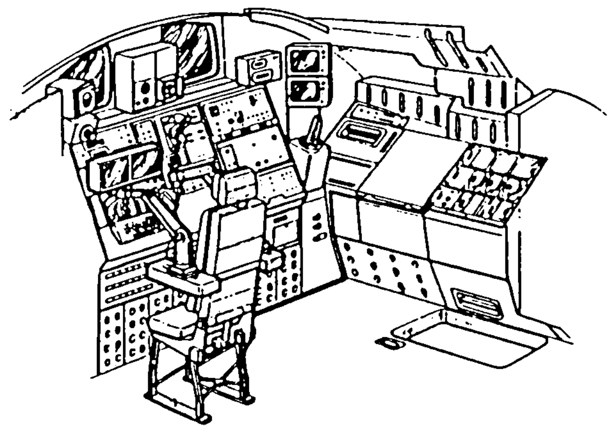


Fixed Base Dependent Operations on Freedom

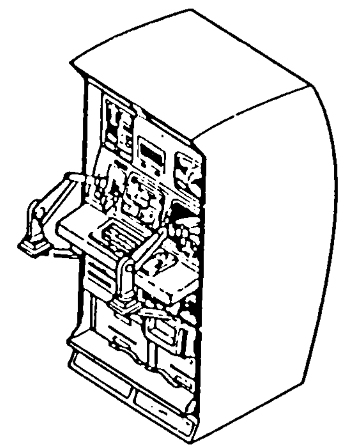


SSFTS Elements

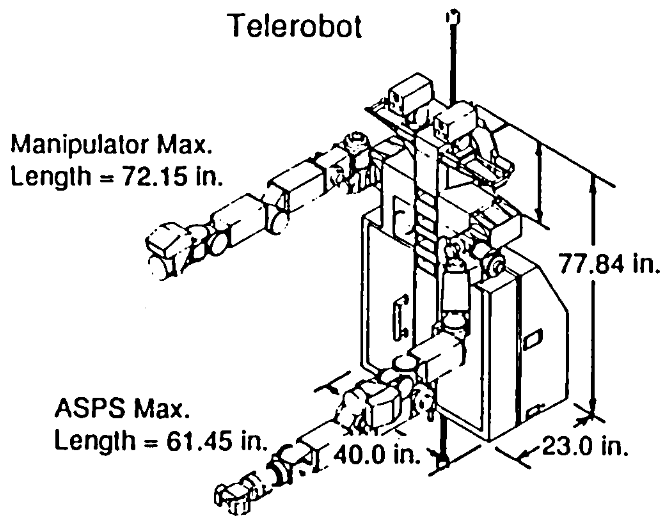
STS Workstation



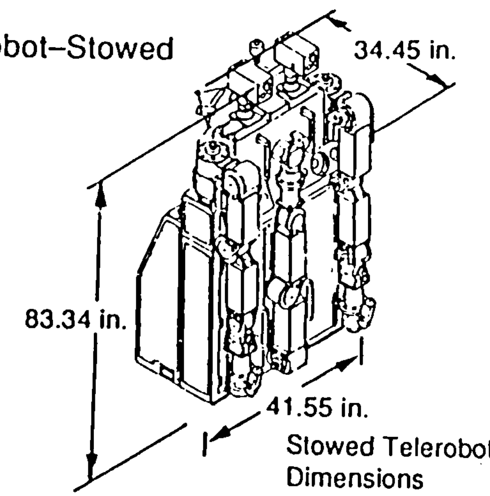
Space Station Workstation



Telerobot



Telerobot–Stowed



FTS Mission Operations

Assembly Operations

- Truss Assembly
- SIA Installation
- Thermal Utility Tray Installation and Coupling
- Standard ORU Module Installation
- Nonstandard ORU Installation
  - Ku- and S-Band Antenna
  - Radiator Panels
  - RCS Modules
  - Alpha and Beta Gimbals
  - Etc

Servicing/Maintenance Operations

- Propellant Resupply
- Cryogenic Resupply
- Expendable Module Replacement
- ORU Replacement
- Calibration

Inspection Operations

- Meteoroid Physical Damage
- Thermal Fluid Leak
- Cabling Connectivity
- Module Leaks
- Temperature Probing
- Assembly Inspection

FTS General Requirements

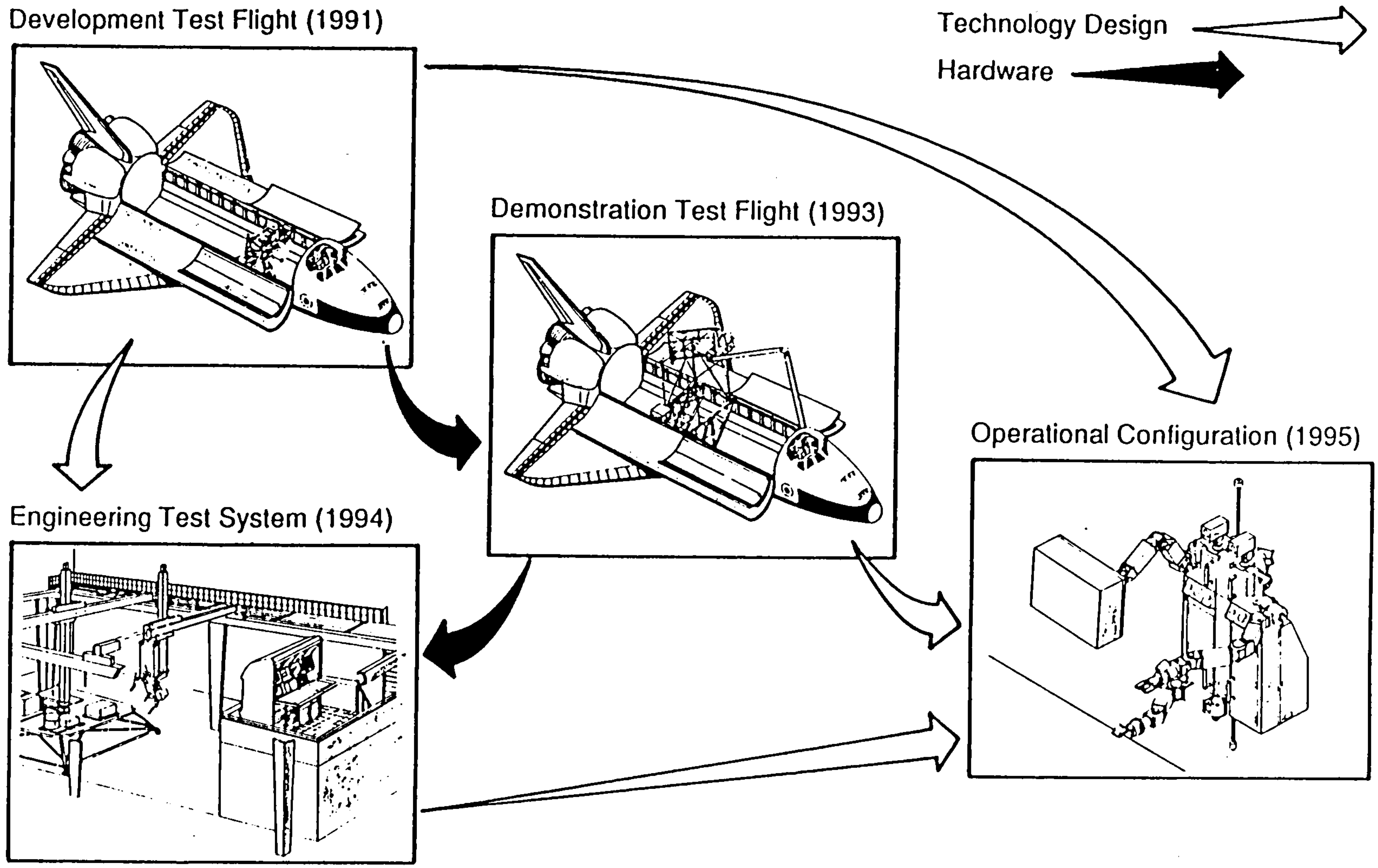
Manipulator Tip Force:	20 lb
Manipulator Tip Torque:	20 ft/lb
Manipulator Repeatability:	0.005 in.
Manipulator Incremental Motion:	0.001 in.
System Weight:	1500 lb
System Power:	2000 watts Peak, 1000 watts Average, 350 watts Standby
System Lifetime:	Indefinite On-Orbit Life through Periodic Maintenance; MTBF Consistent 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

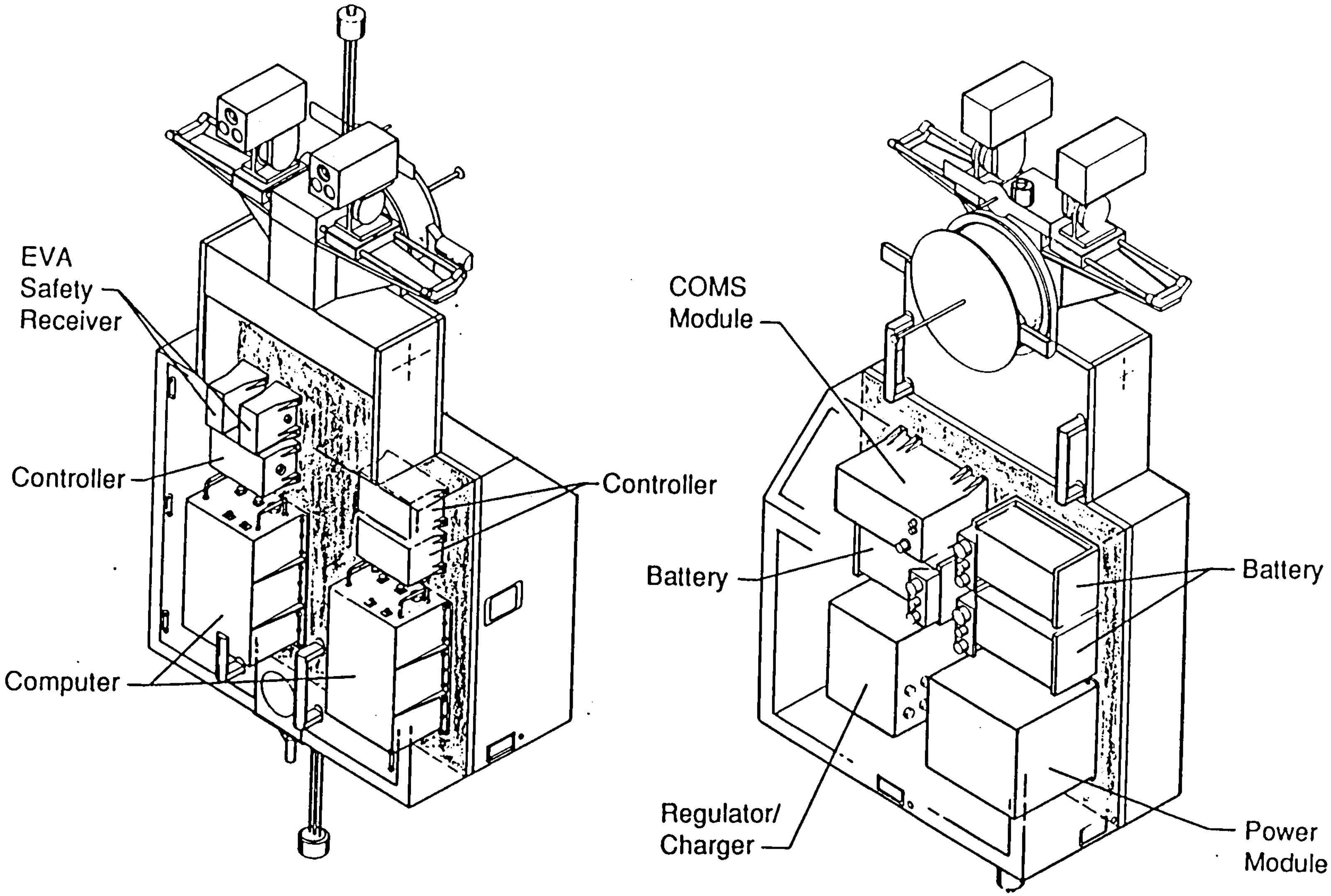
System Shall Avoid Unplanned Physical Contact (Collision)

System Shall Be Capable of Detecting Failures and Automatically Assuming a Safe State

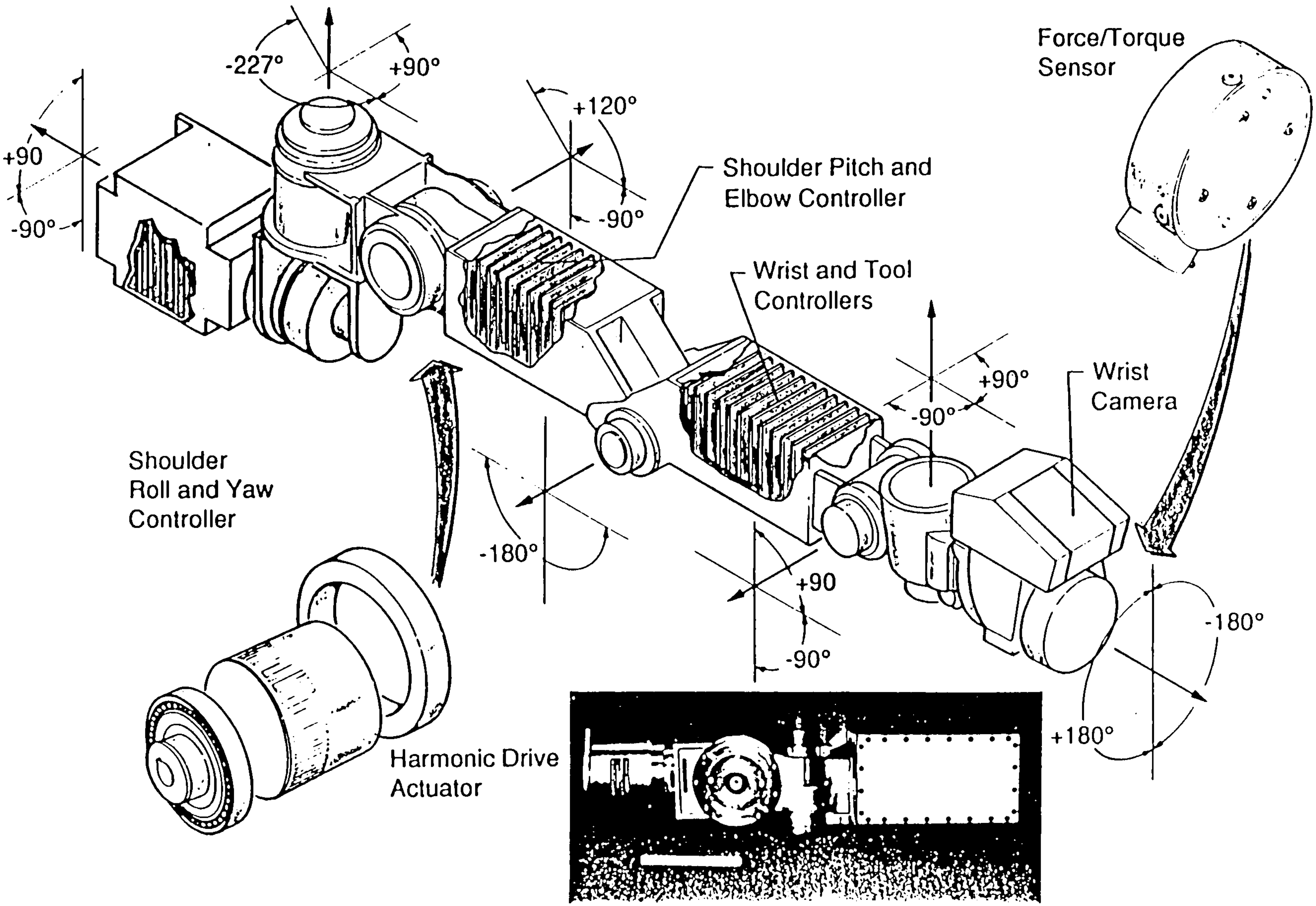
Flight Telerobotic Servicer Hardware and Technology Development Flow



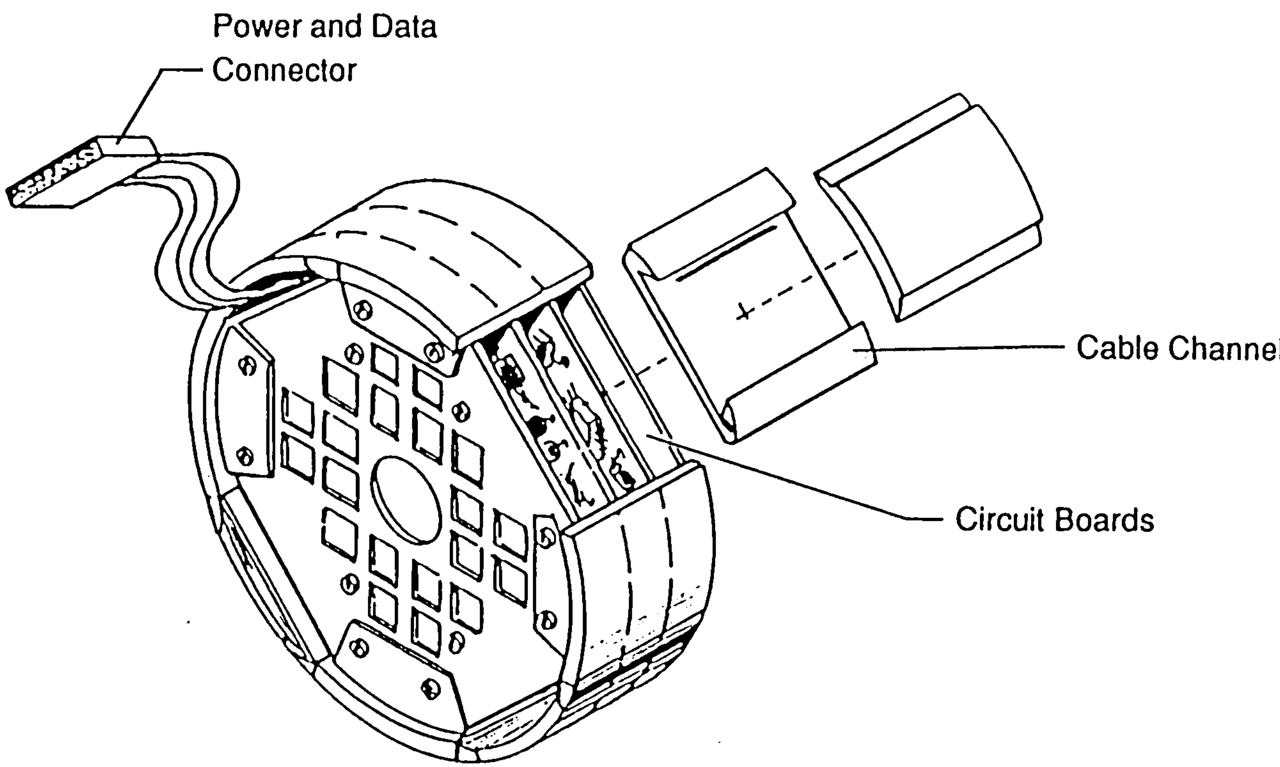
Flight Telerobotic Servicer–Telerobot



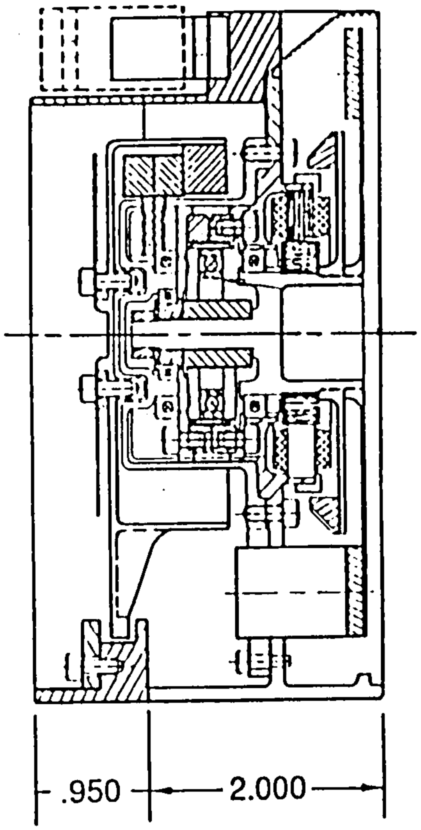
FTS Manipulator

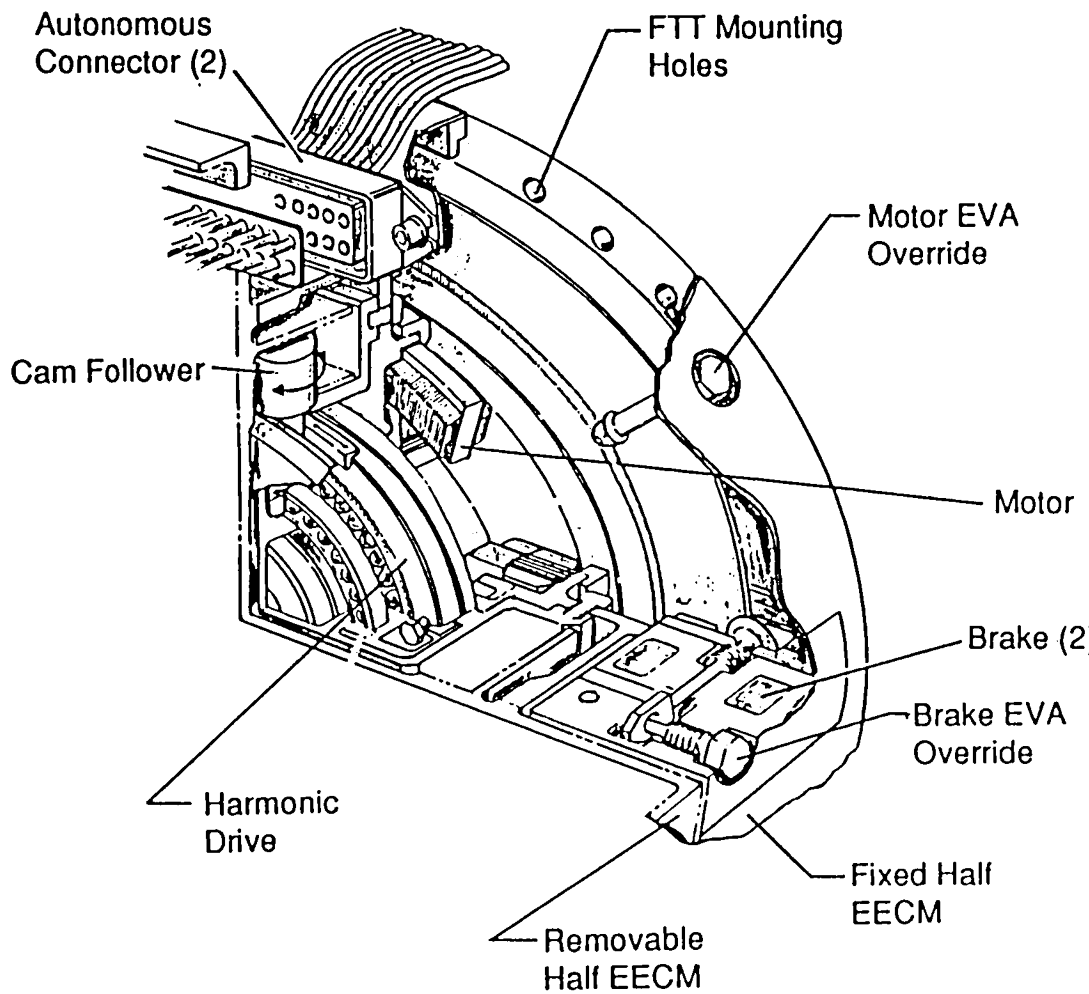


JR3 Force-Torque Transducer

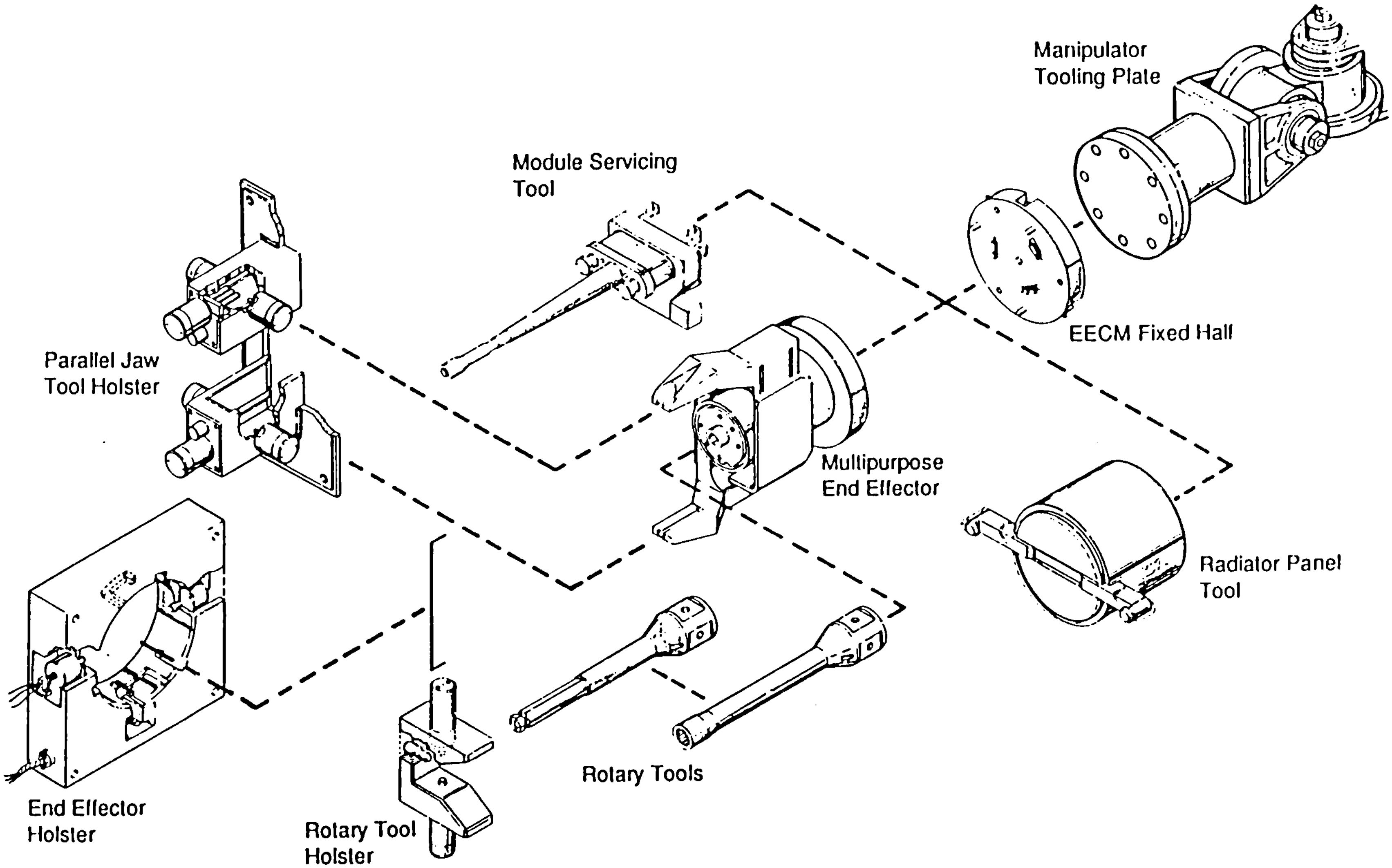


End Effector Changeout Mechanism

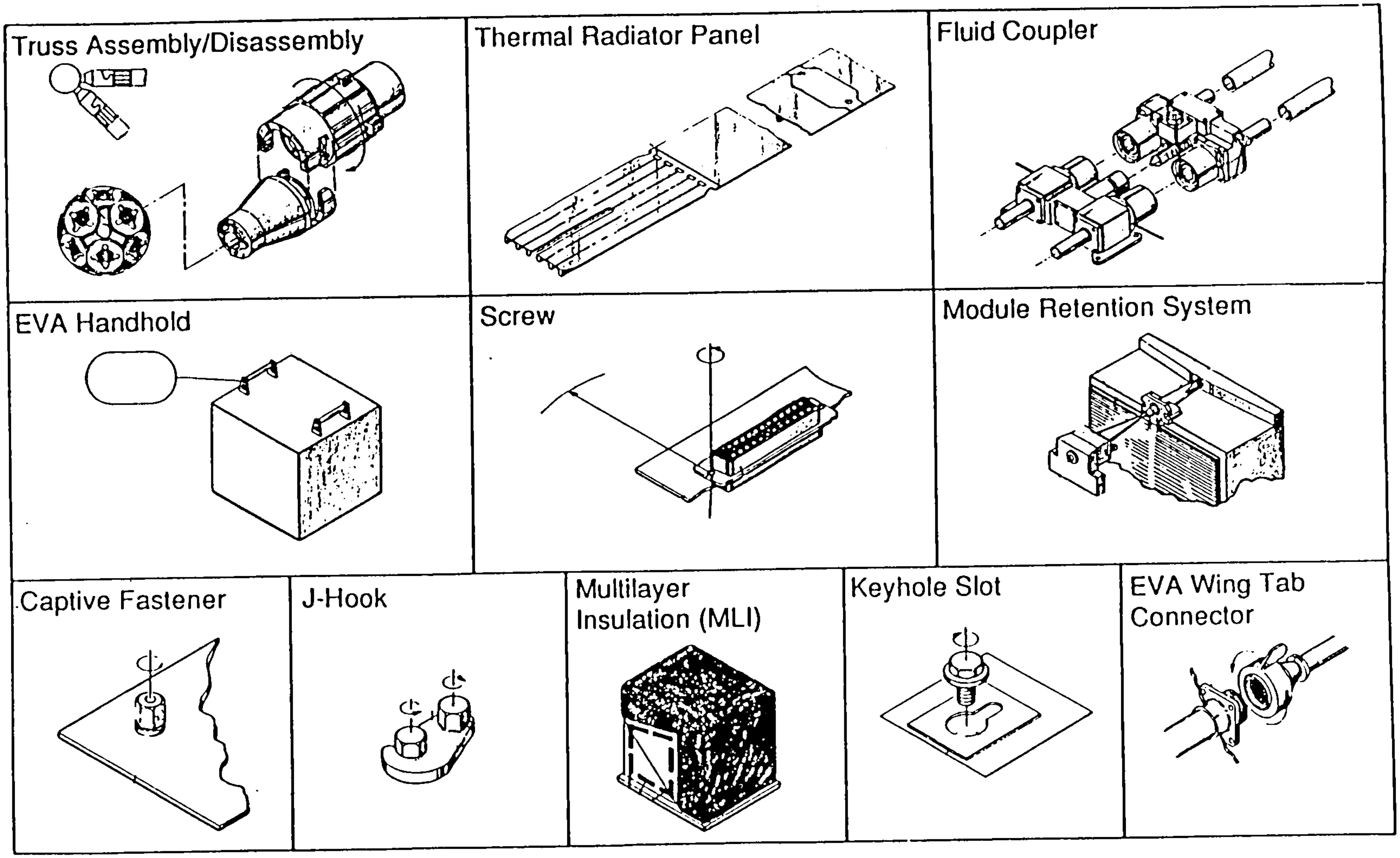




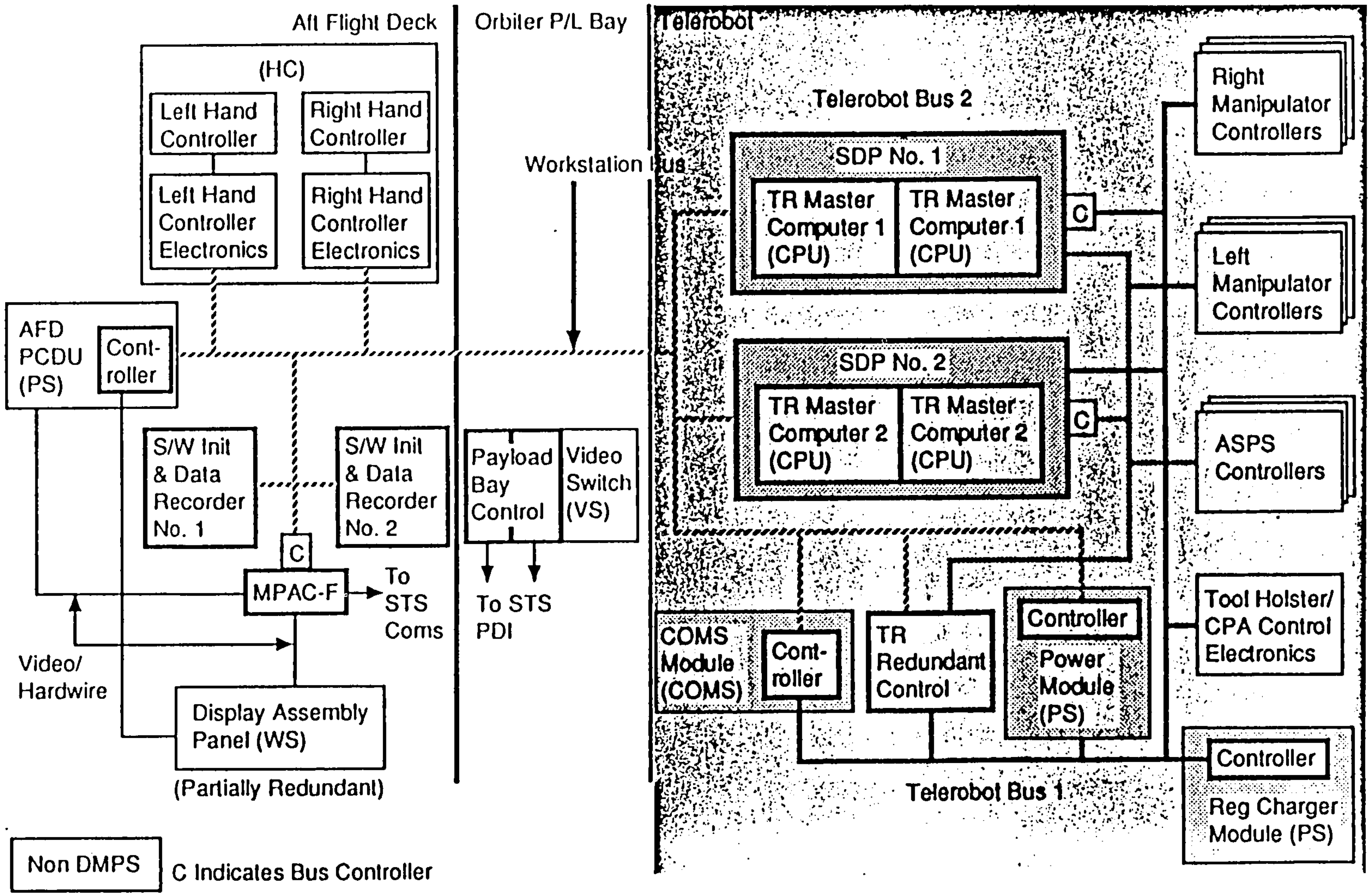
Flight Telerobotic Servicer–End-of-Arm Tooling



User Interfaces

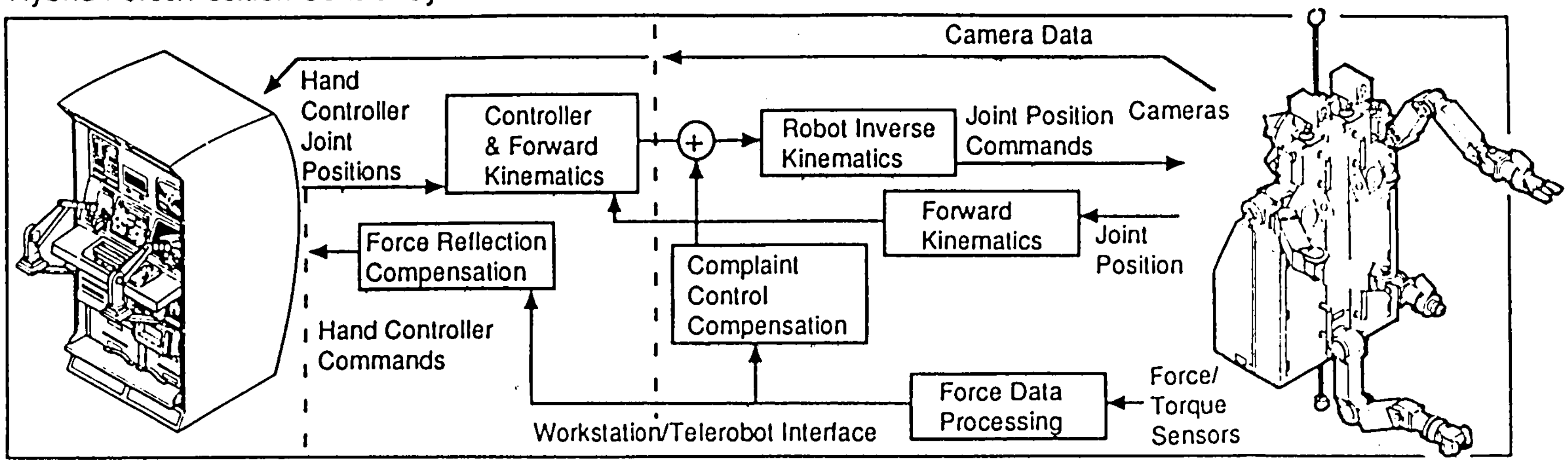


FTS Data Management and Processing

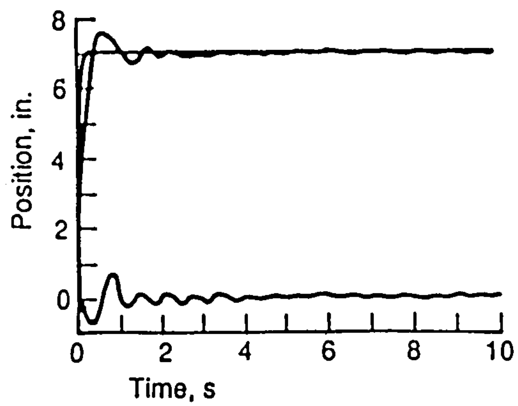


Control Subsystem

Hybrid Force/Position Control System

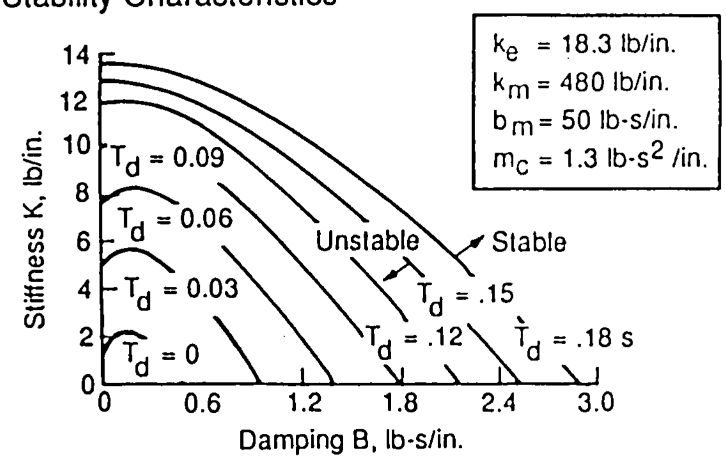


ORU Changeout Response



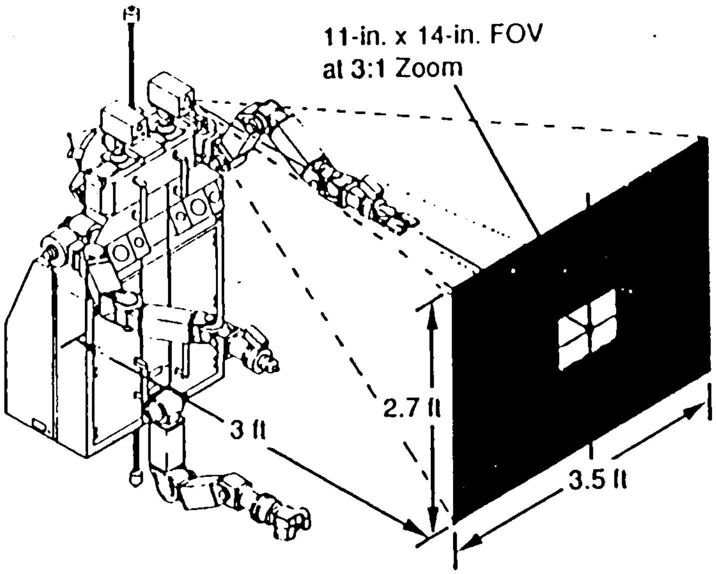
ORU Changeout Response

Stability Characteristics

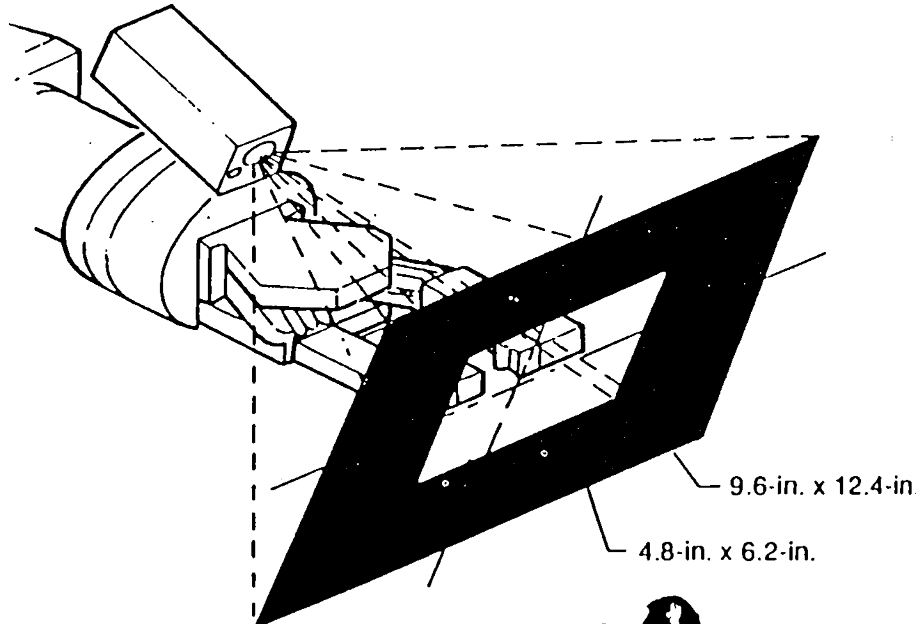


FTS Vision Subsystem and Camera Positioning Assembly

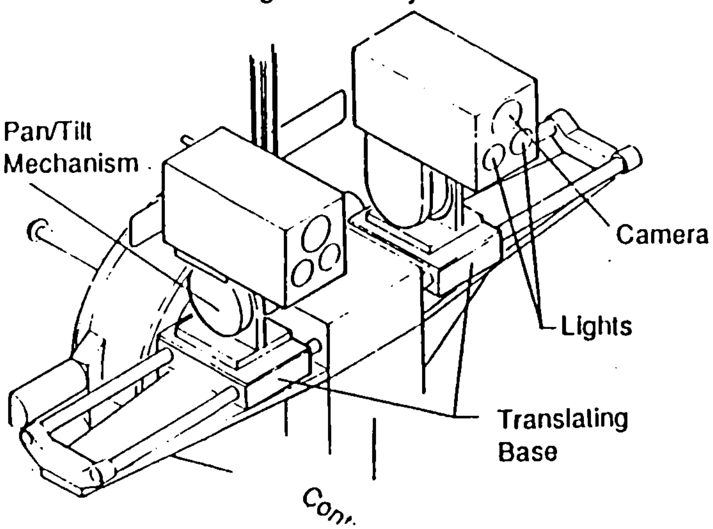
Head-Mounted Cameras

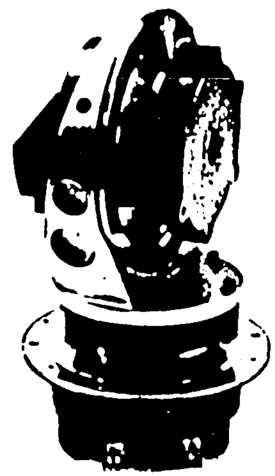


Wrist-Mounted Camera



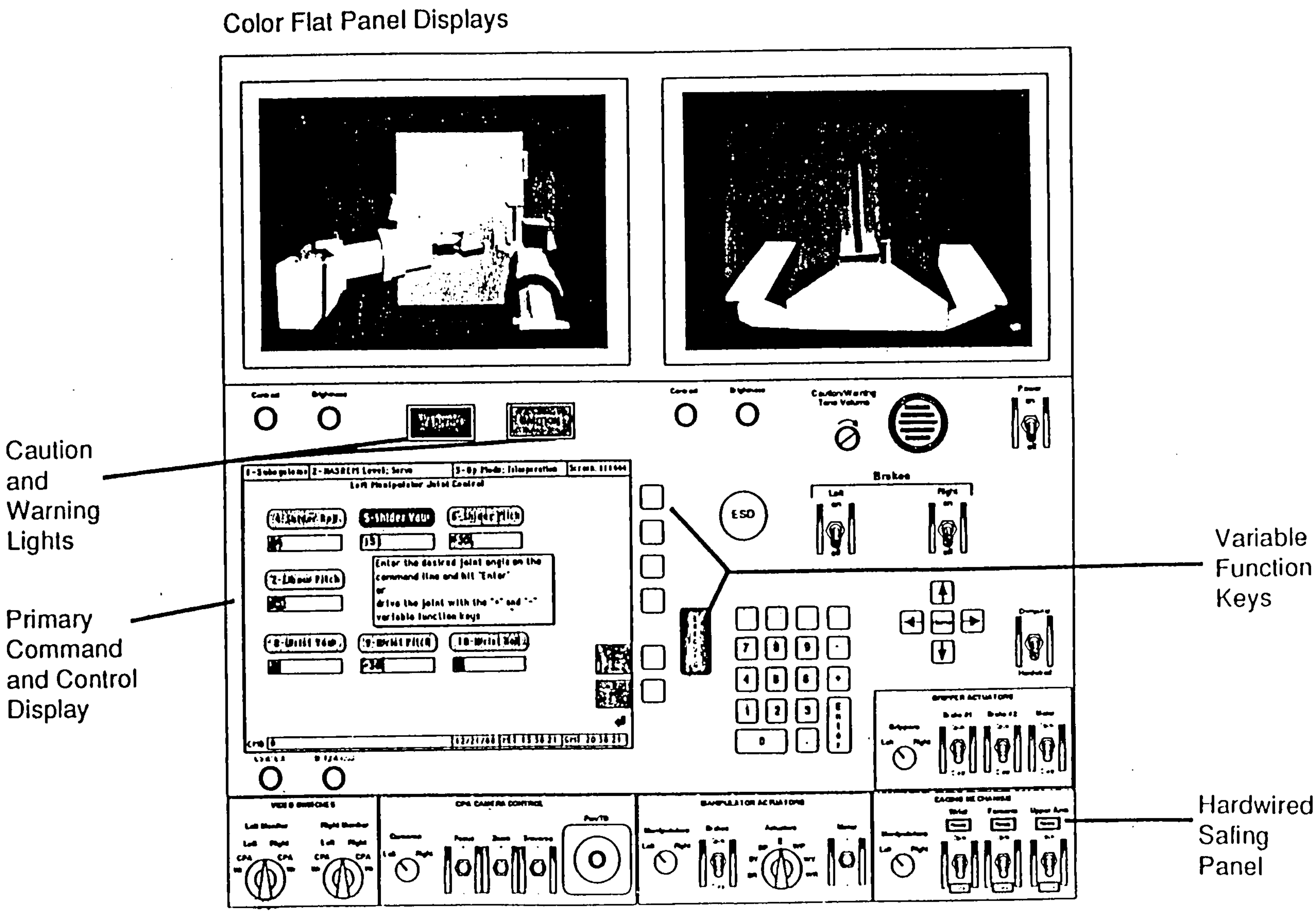
Camera Positioning Assembly



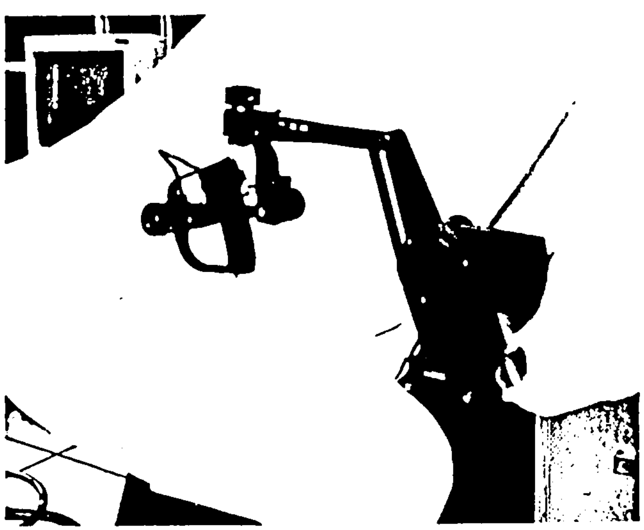


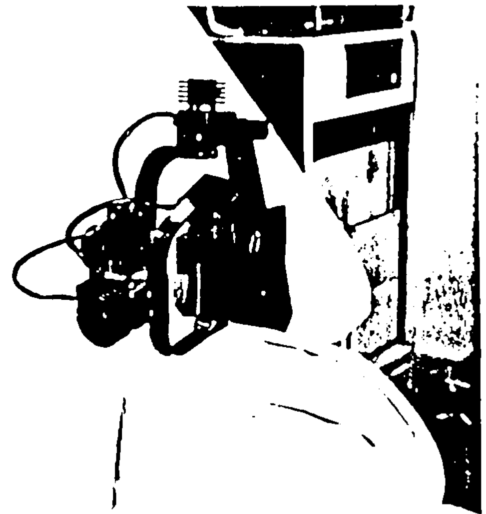
Two-Axis Gimbal
Drive Assembly

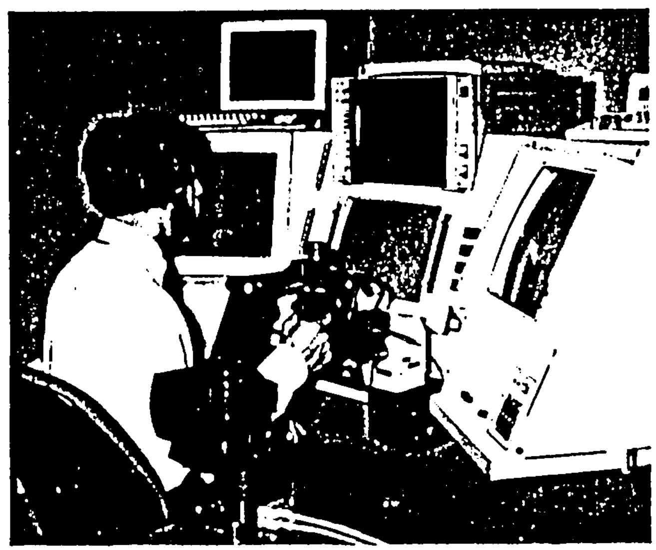
FTS Workstation Display Assembly Panel



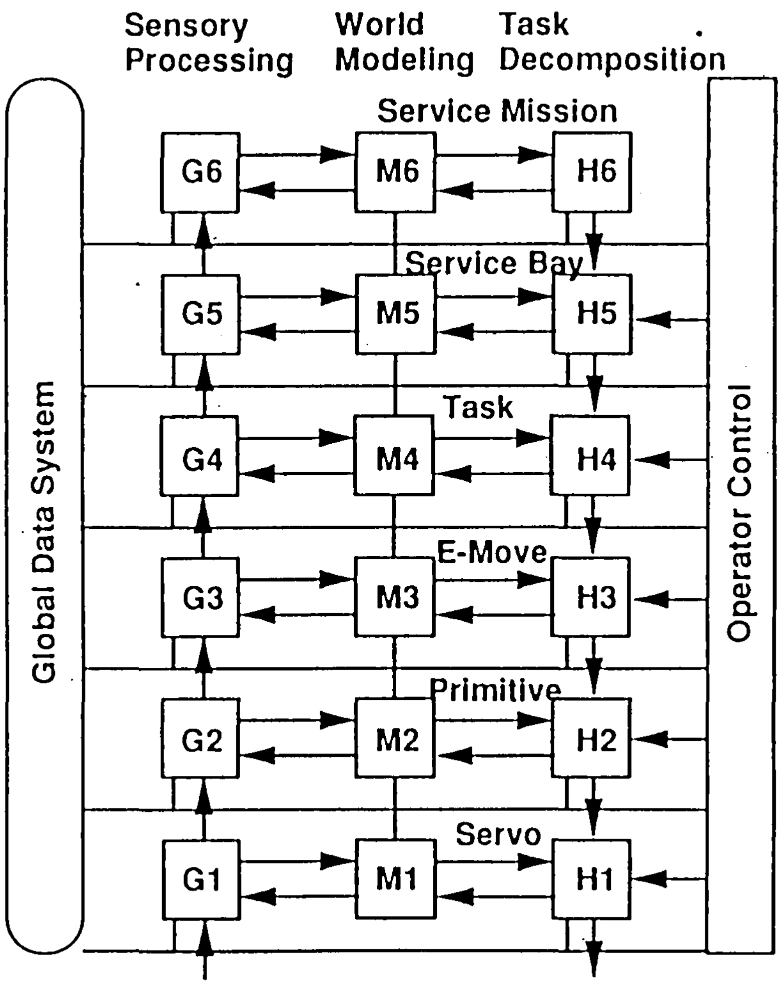
Mini-Master Hand Controller







FTS NASREM System Architecture

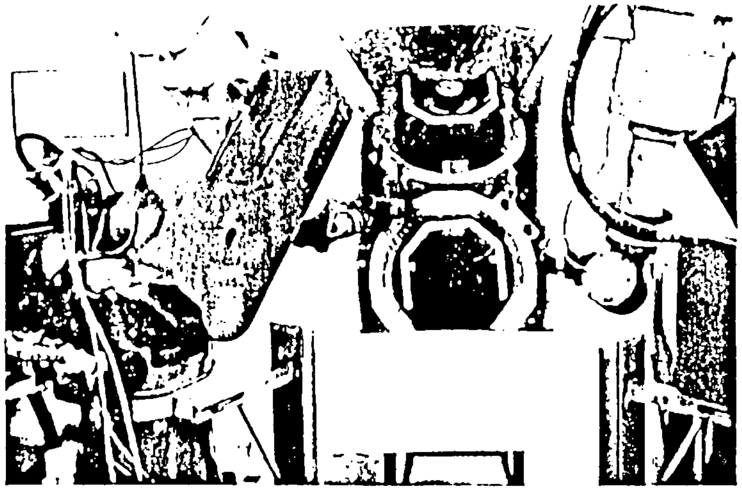


Levels 1 through 4 Implemented for FTS

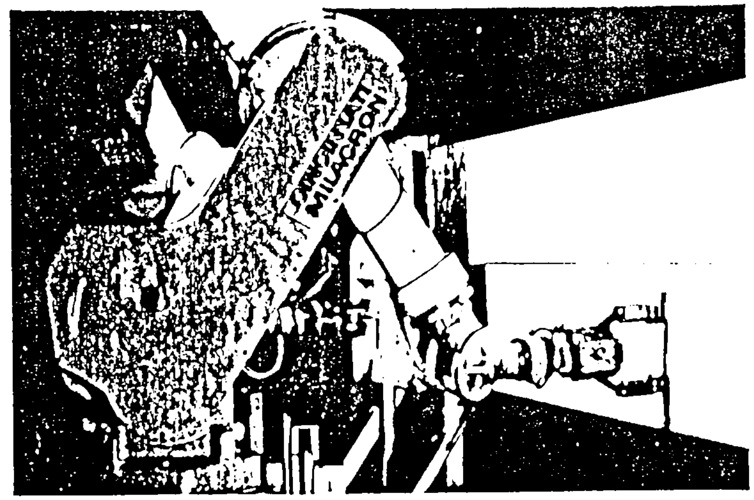
Lvl	Telerobot Control	Man-Machine Interface
4	– Task Planning	
3	– Management of Perception, Manipulation, Positioning, Safety, and Support Functions – Manipulator and ASPS Path Planning	– Peripheral Equipment and Support Function Management – Command and Display Processing
2	– Camera, EE, EECM, Holster, ASPS EE, ASPS EECM Control – Power, Thermal, Comm Control – EE, Caging, Power, Thermal, DMPS, Safety Functions – Manipulator and ASPS Trajectory Generation	– Hand Controller High Level Functions – Power and Thermal Control
1	– Manipulator, EE, and ASPS Servo Control – Manipulator Collision Avoidance – Manipulator Servo Safety	– Handcontroller Servo Control

Servicing Operations Demonstrated

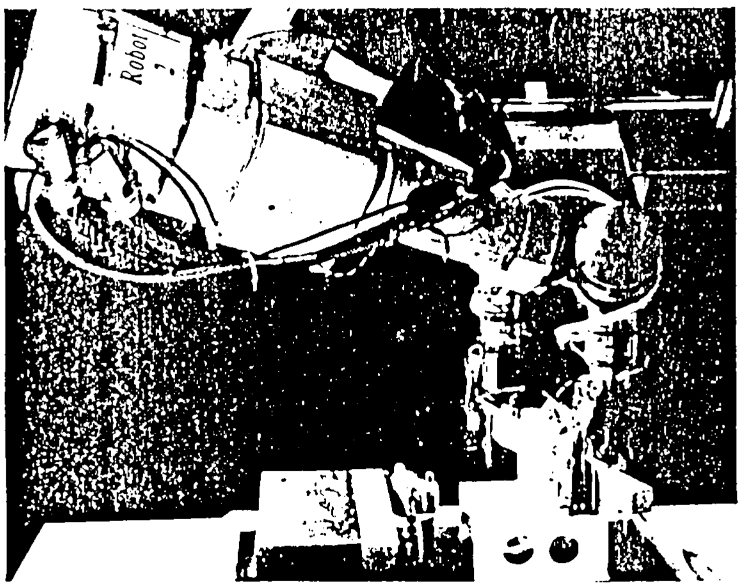
REPLACING HST REACTION WHEEL



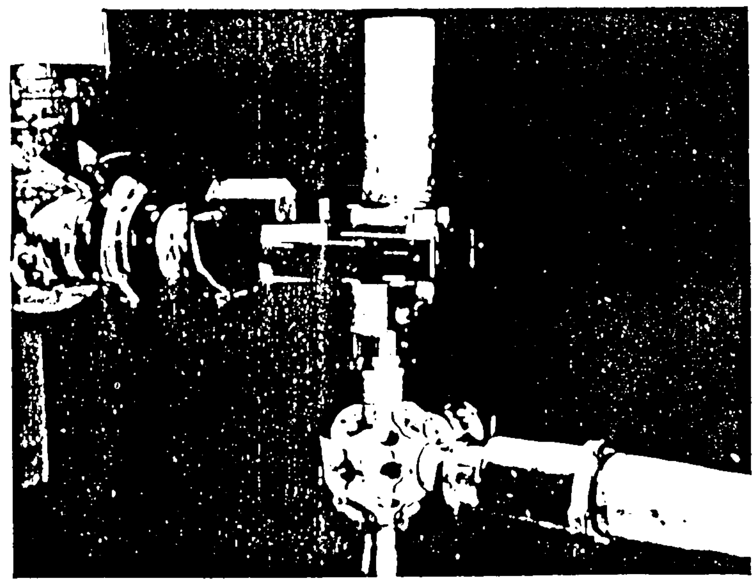
REPLACING RADIATOR ASSEMBLY



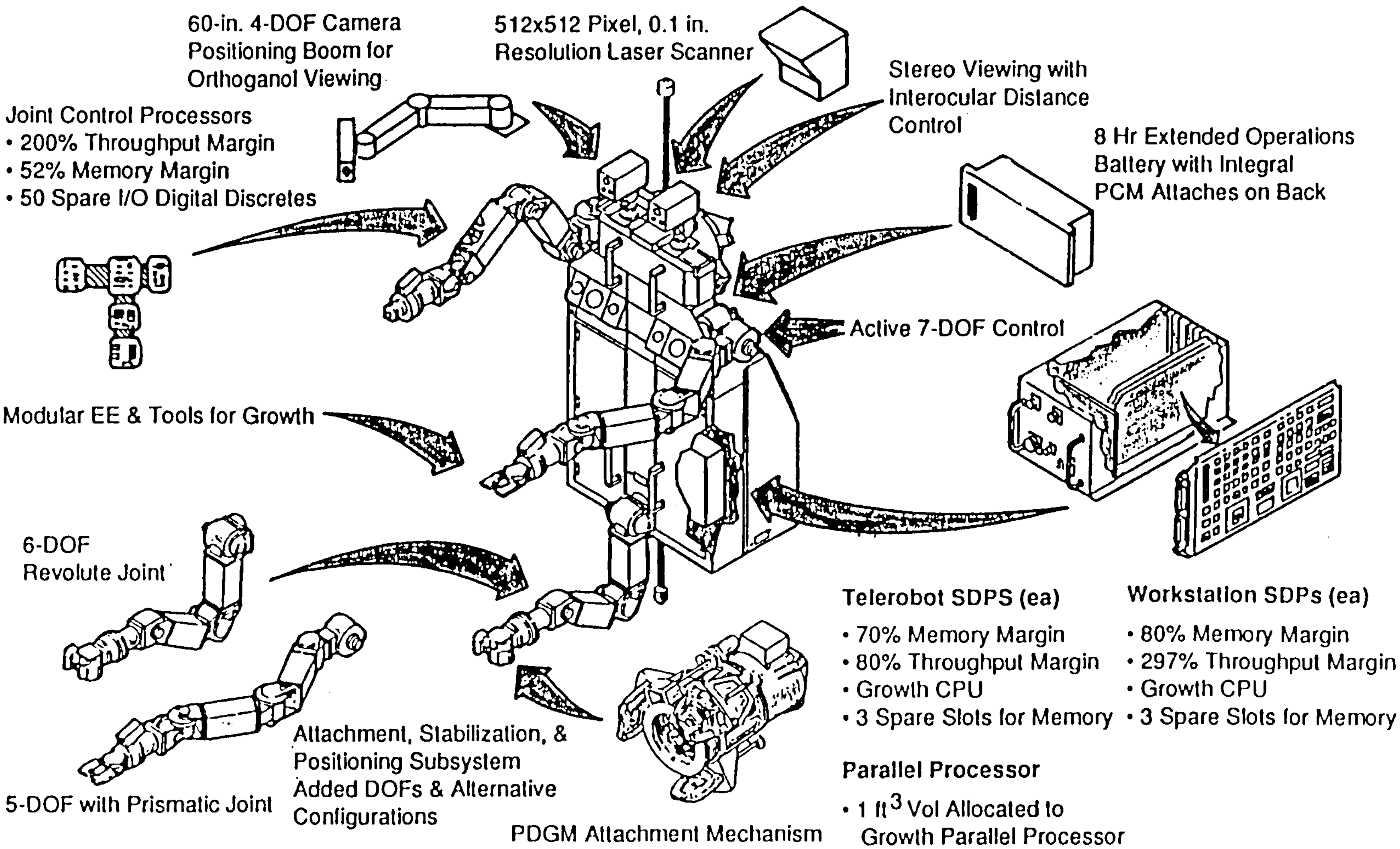
THERMAL UTILITY & REFUELING CONNECTORS



TRUSS ASSEMBLY



FTS Growth Accommodations



Government of Canada Gouvernement du Canada

Canadian Space Agency Agence spatiale canadienne

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

Government of Canada / Gouvernement du Canada

Canadian Space Agency / Agence spatiale canadienne

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:

- attached payload servicing (external)
- Space Station assembly
- Space Station maintenance (external)
- transportation on Space Station
- deployment and retrieval functions
- EVA support"

Canada

MSS Overall Configuration

Space Segment

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

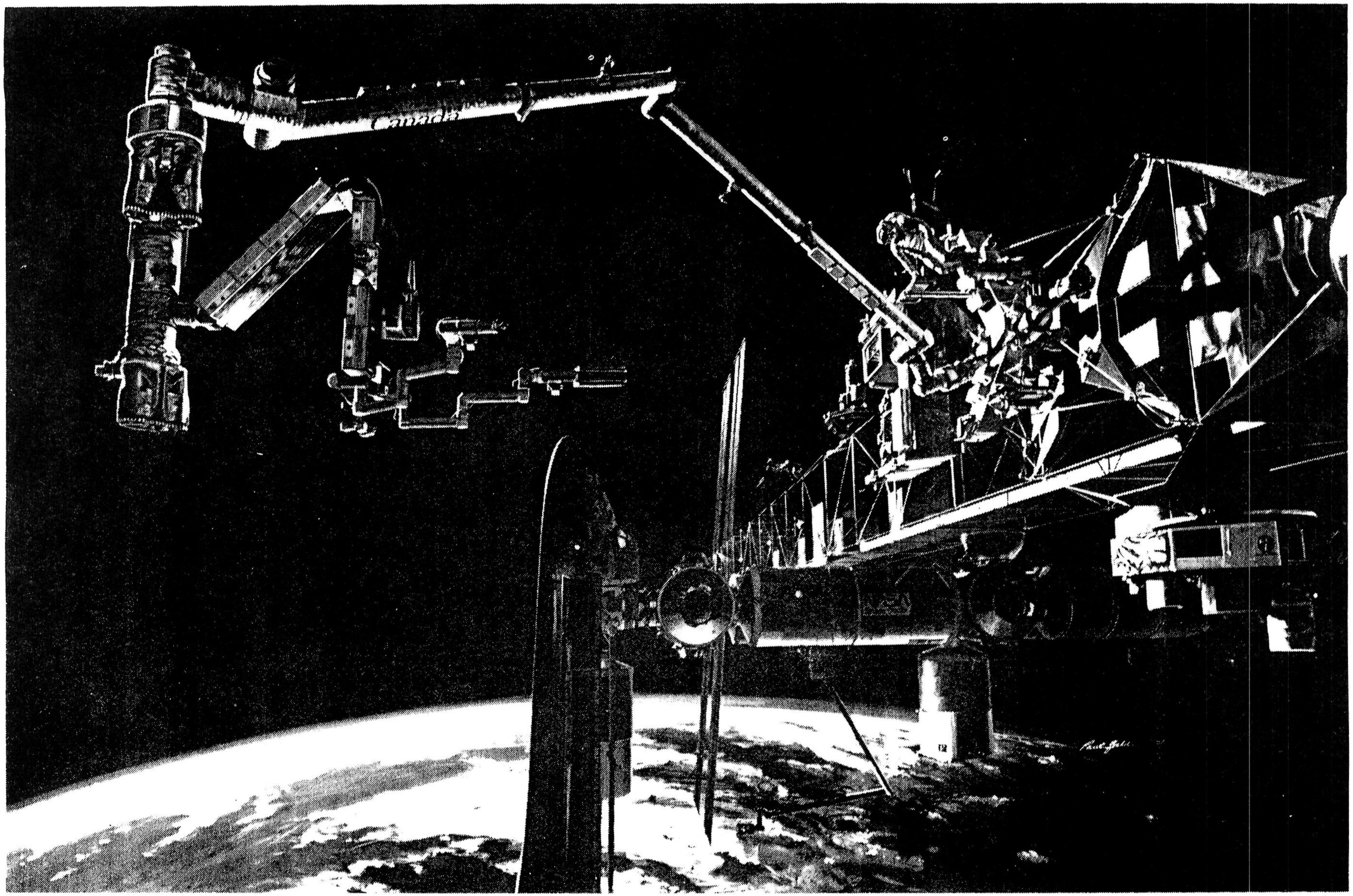
Ground Segment

- Ground Operations Facility, the Engineering Support Centre

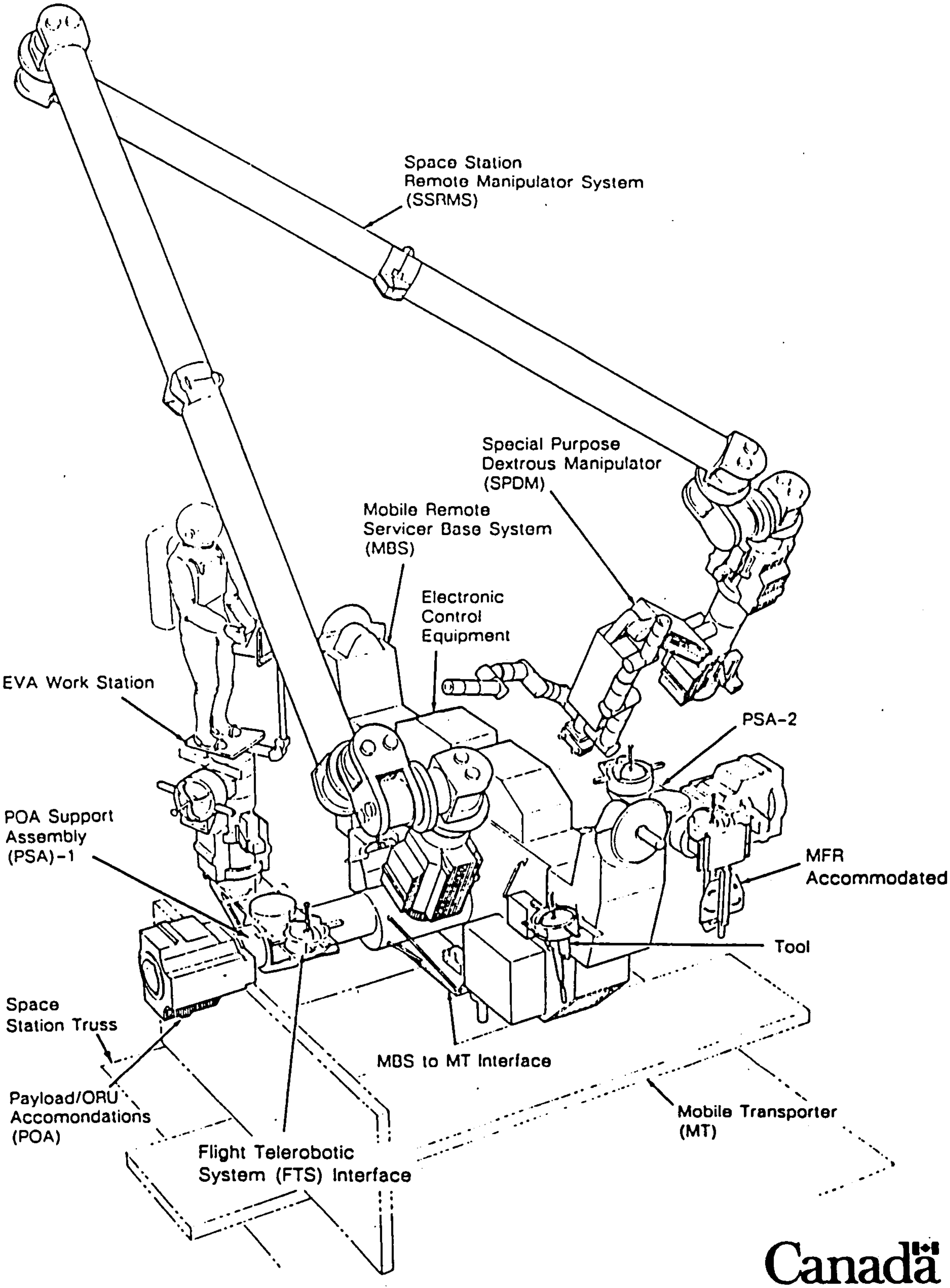
Support Systems

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

MOBILE SERVICING SYSTEM (MSS)

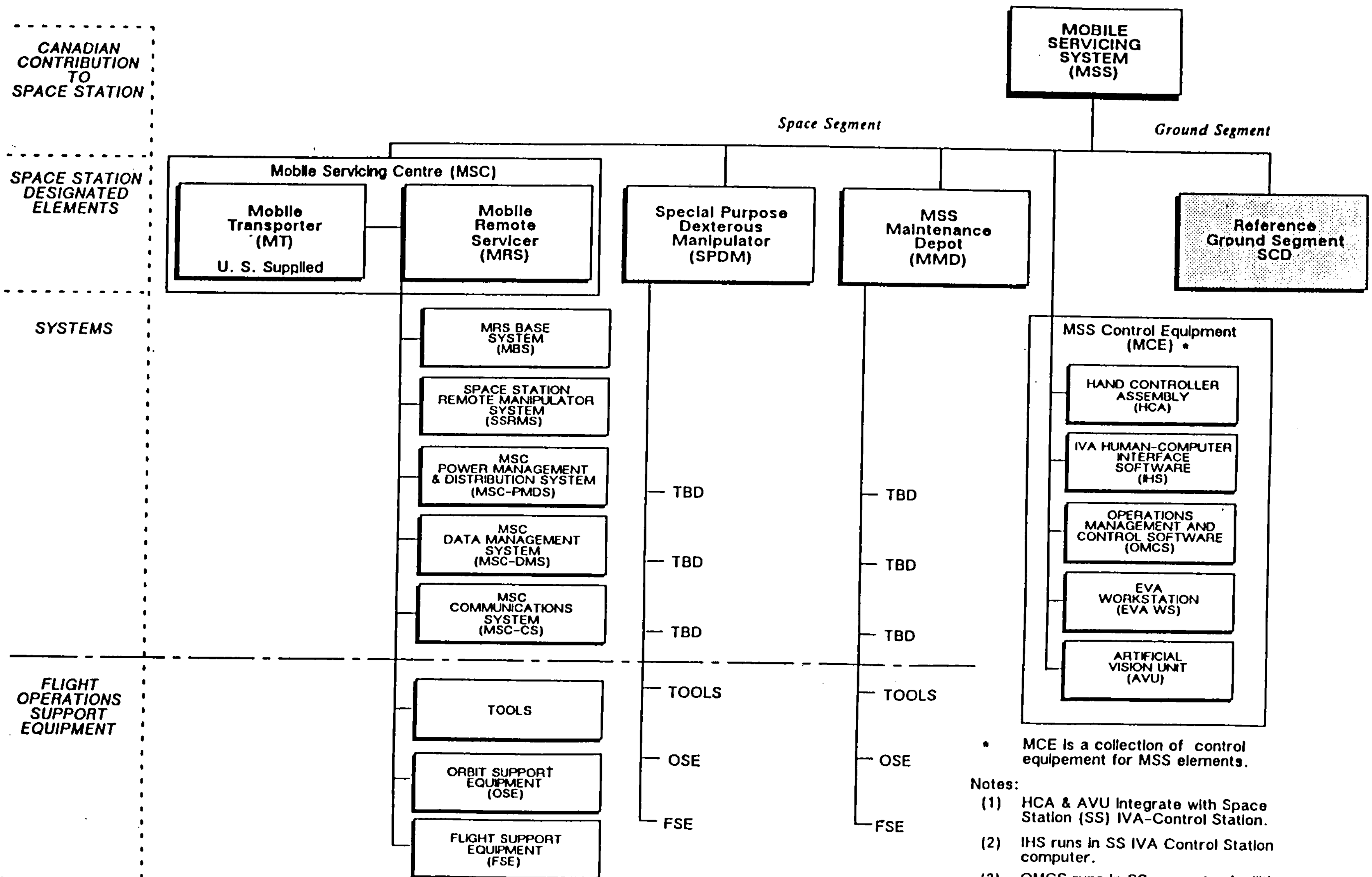


Mobile Servicing Centre (MSC)



Canada

Mobile Servicing System (Space Segment) Hierarchy



* MCE is a collection of control equipement for MSS elements.

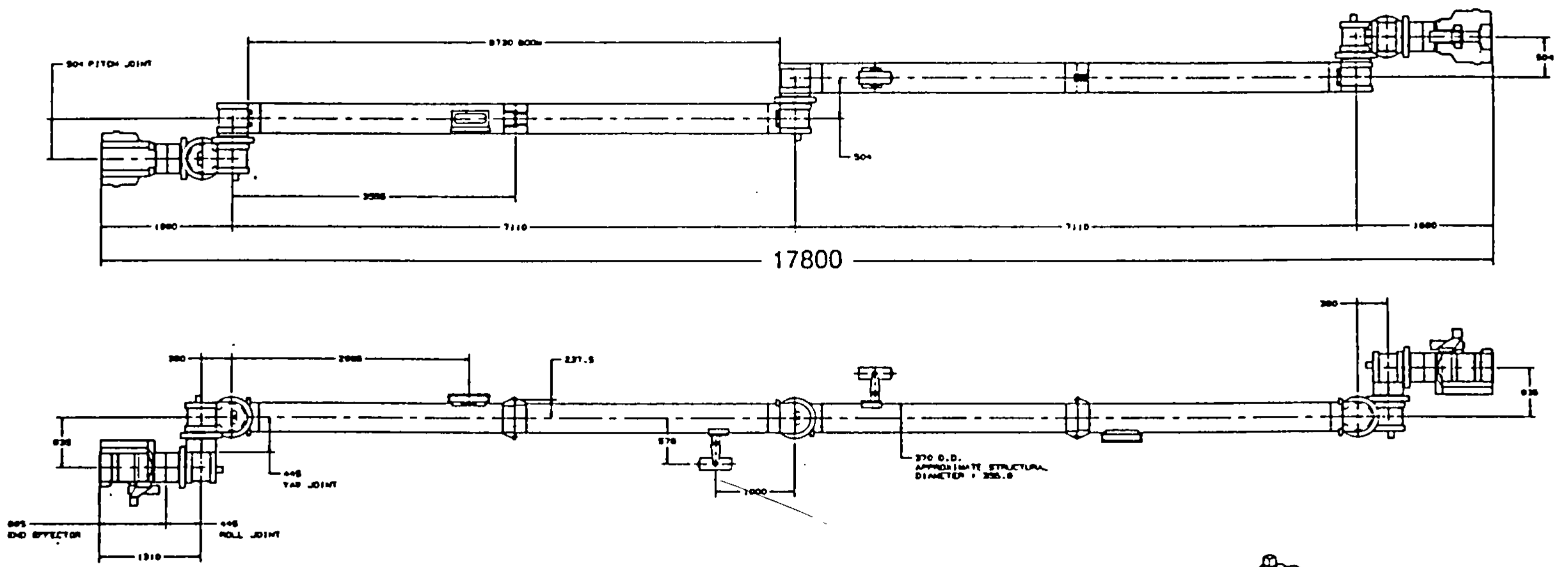
Notes:

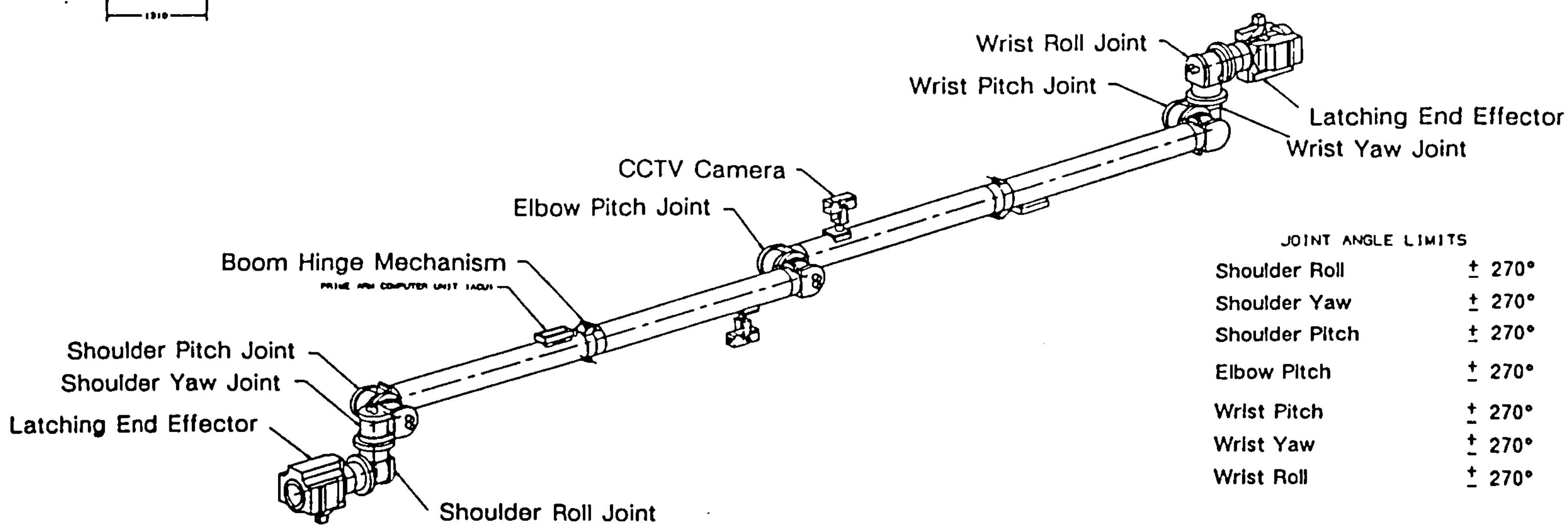
(1) HCA & AVU integrate with Space Station (SS) IVA-Control Station.

(2) IHS runs in SS IVA Control Station computer.

(3) OMCS runs in SS computer facilities for MSS.

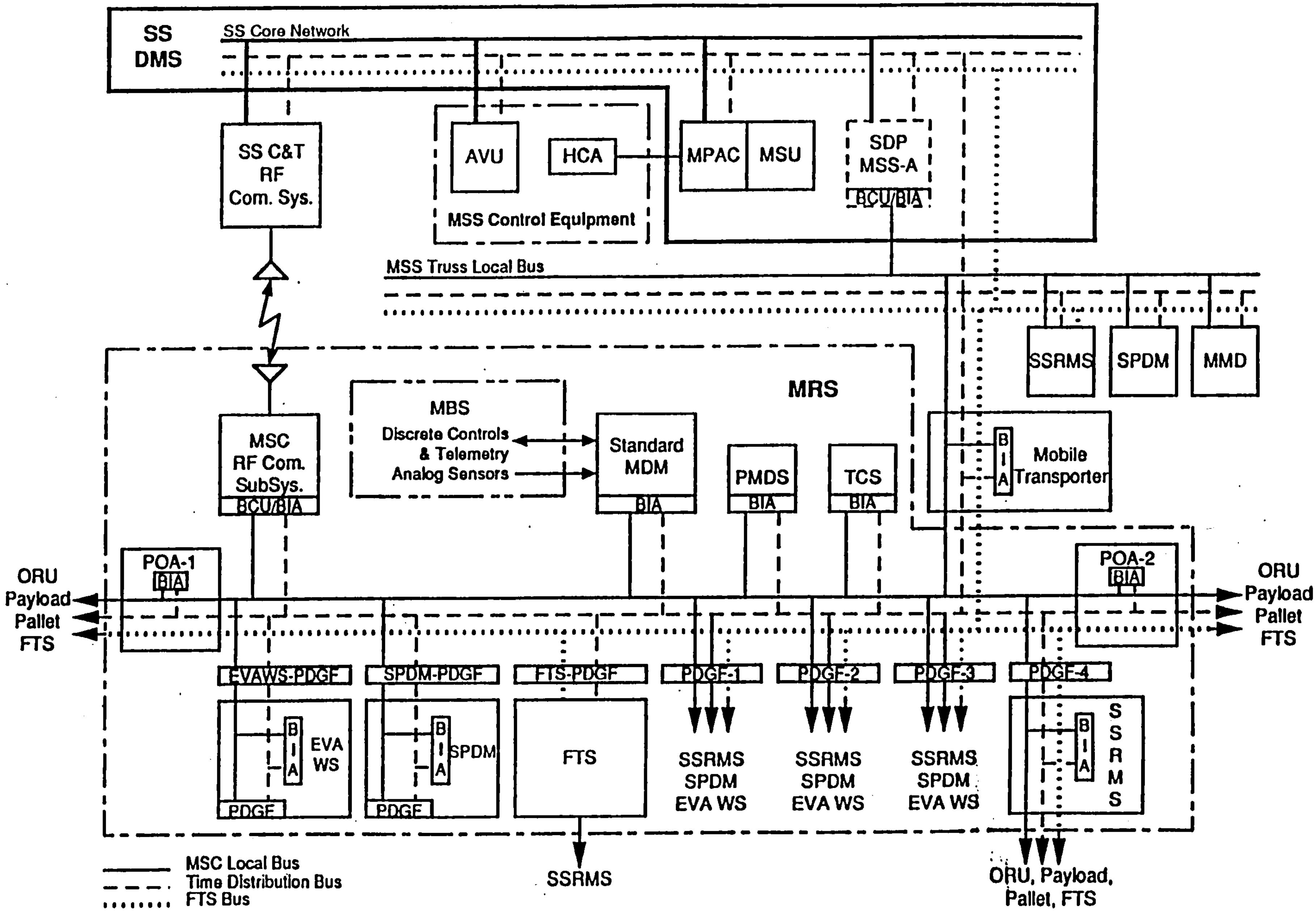
SSRMS Configuration





JOINT ANGLE LIMITS

Shoulder Roll	± 270°
Shoulder Yaw	± 270°
Shoulder Pitch	± 270°
Elbow Pitch	± 270°
Wrist Pitch	± 270°
Wrist Yaw	± 270°
Wrist Roll	± 270°



MSS Data Distribution and Interfaces

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
  - RCS
  - SIA and PIA (for attached payloads)

Perform Dextrous Tasks for

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

Government of Canada / Gouvernement du Canada

Canadian Space Agency / Agence spatiale canadienne

Functional Requirements for SPDM (cont'd)

Dextrous Tasks for Assembly and Maintenance include

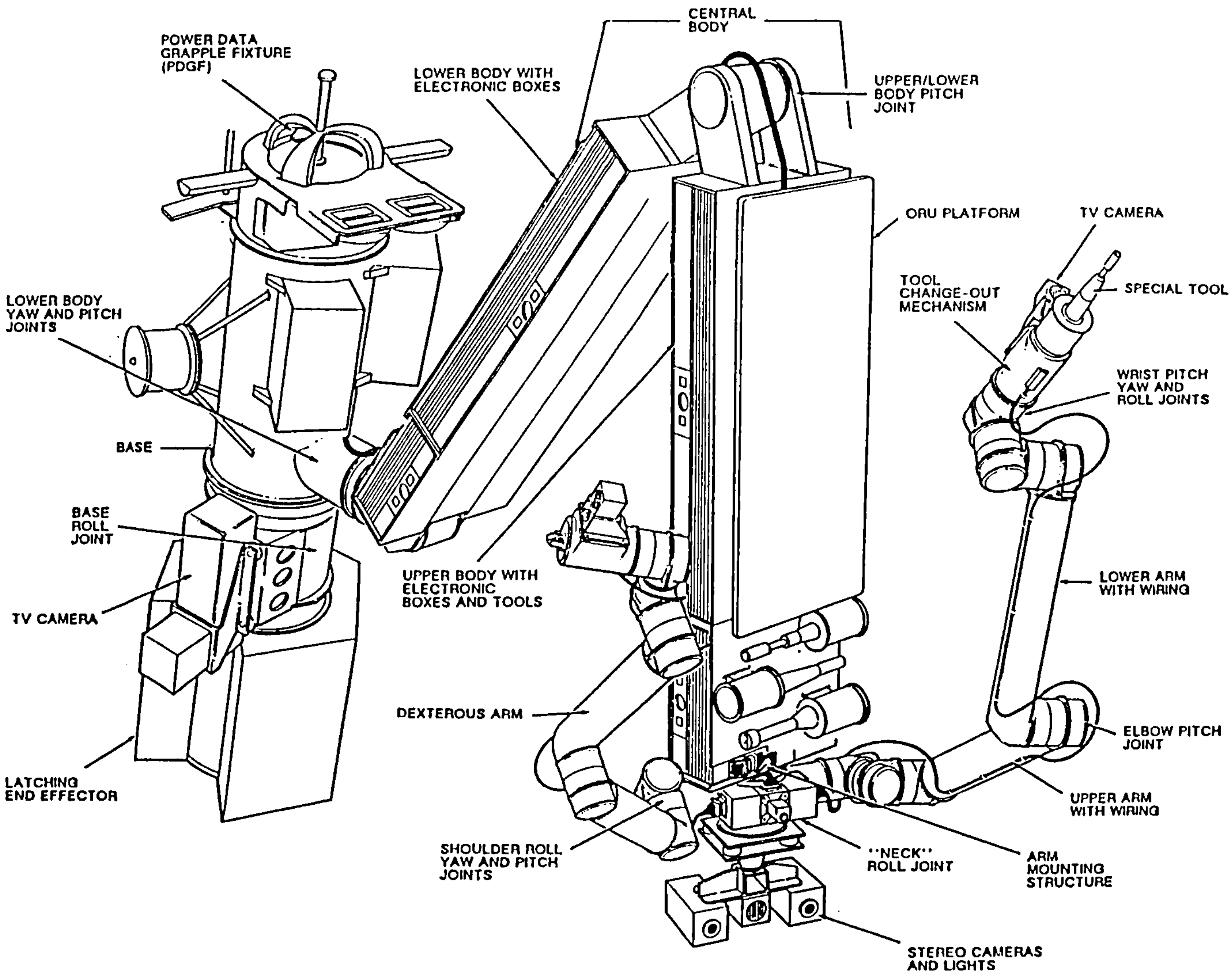
- Exchange ORU'S
- Attach / Detach ORU Interfaces
- Connect / Disconnect Utilities
- Mate / Demate Connectors
- Remove / Install Thermal Covers & Blankets
- Clean Surfaces
- Inspect and Monitor with Vision System
- Provide Lighting to Support EVA
- Position Tools & Materials to Support EVA
- Provide TV Views to Monitor EVA Activities

Canada

Government of Canada Gouvernement du Canada

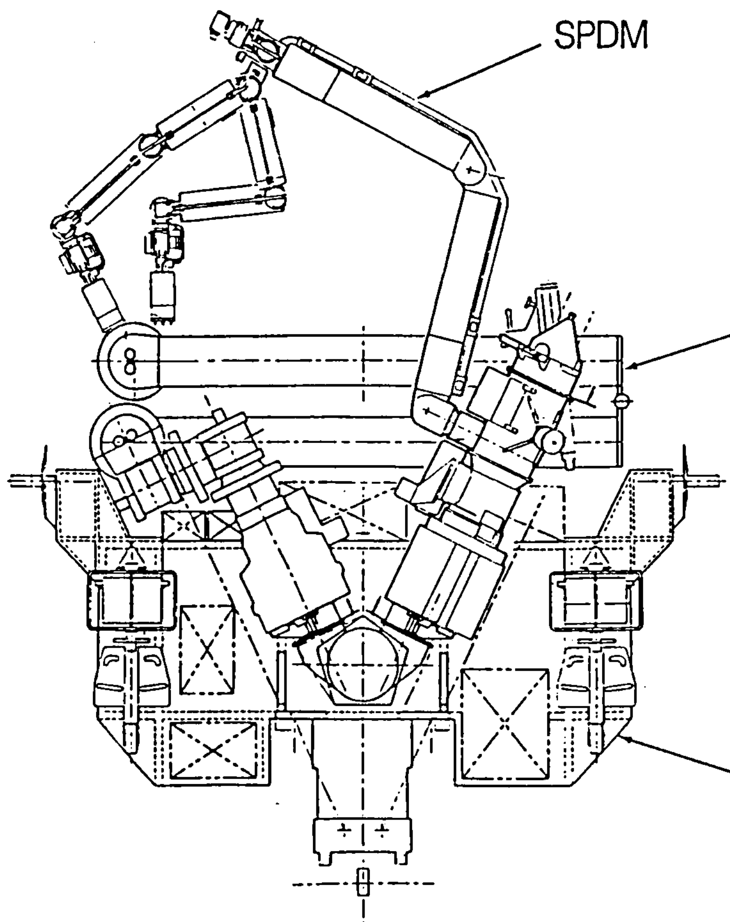
Canadian Space Agency Agence spatiale canadienne

SPDM Configuration

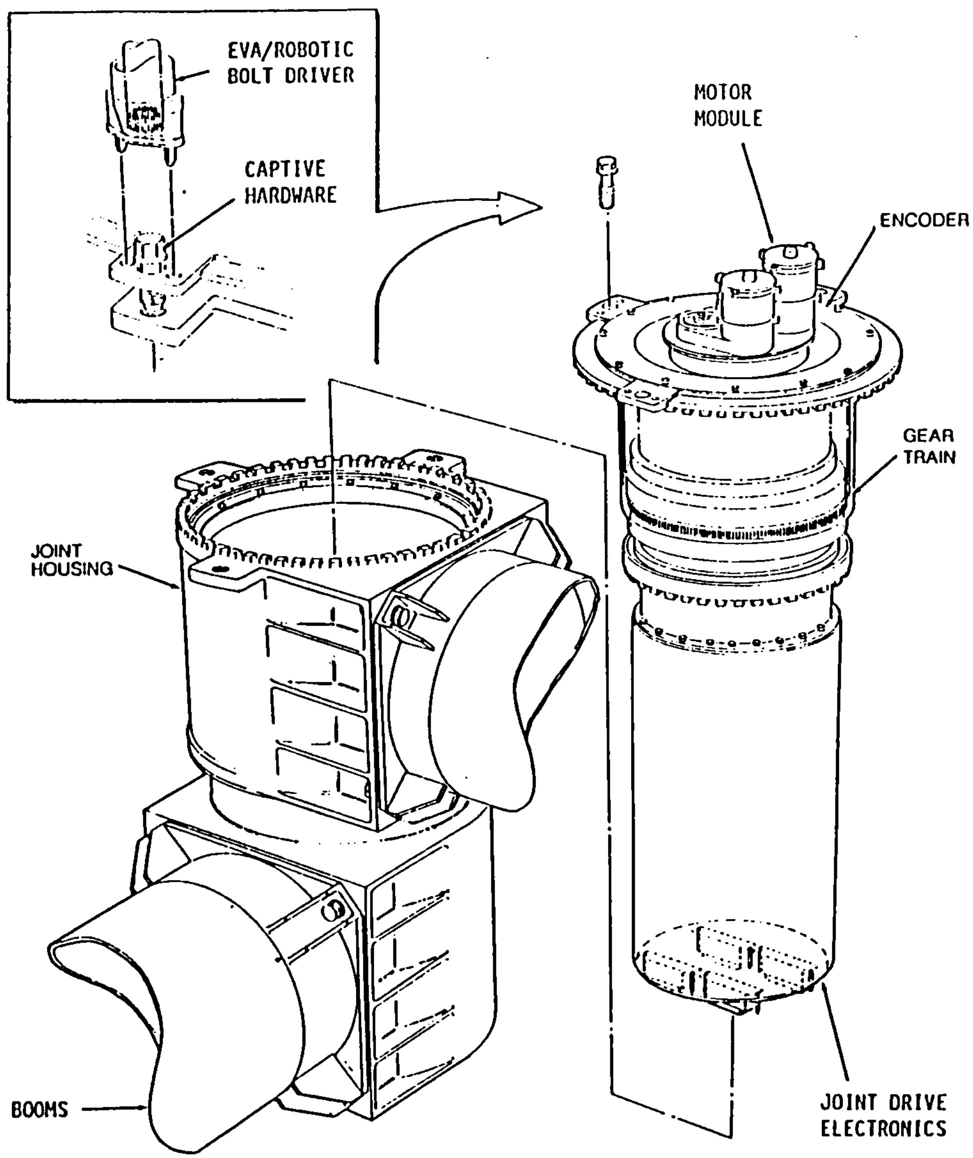


Canada

SPDM Operating From MBS for SSRMS Maintenance

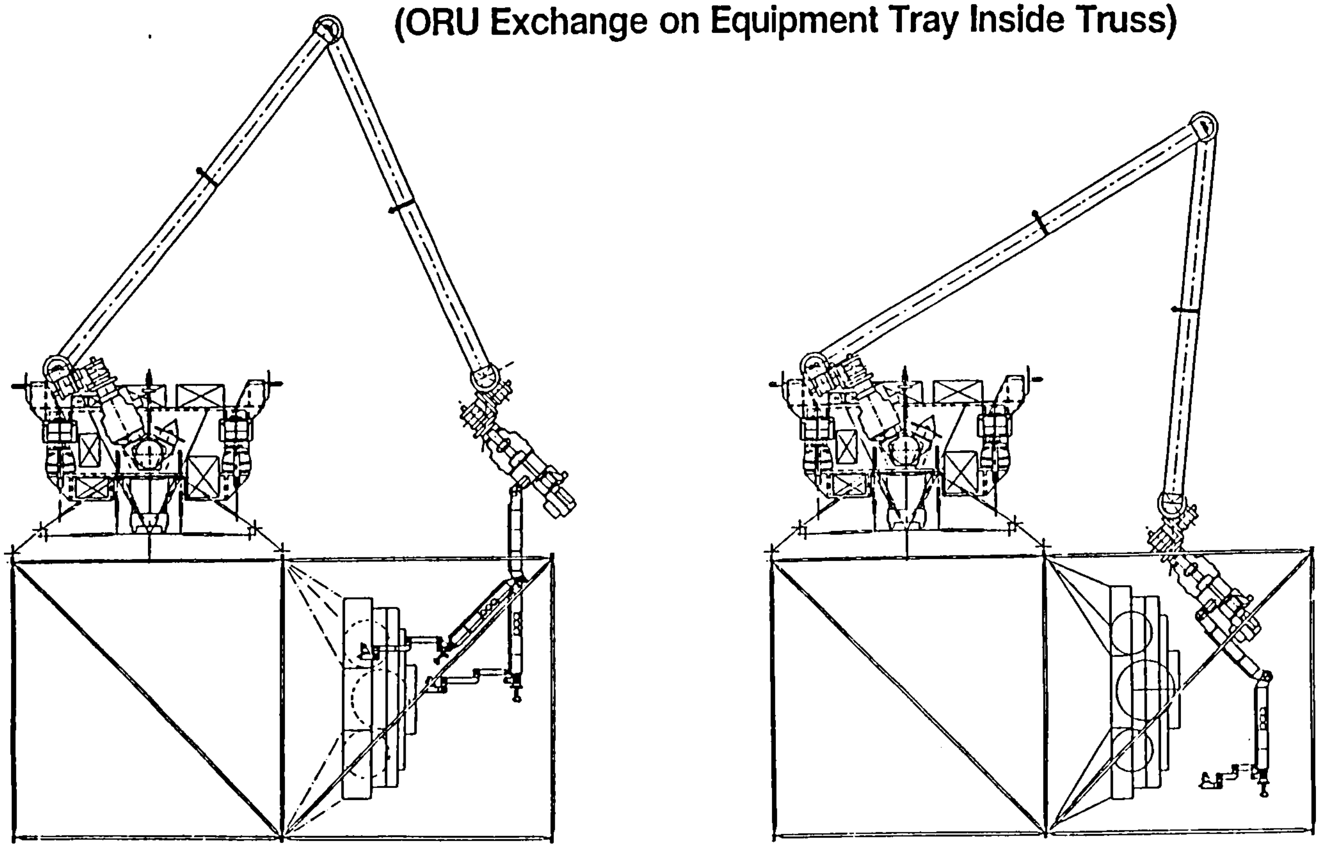


Typical Joint



SPDM Operating At The End Of SSRMS

(ORU Exchange on Equipment Tray Inside Truss)

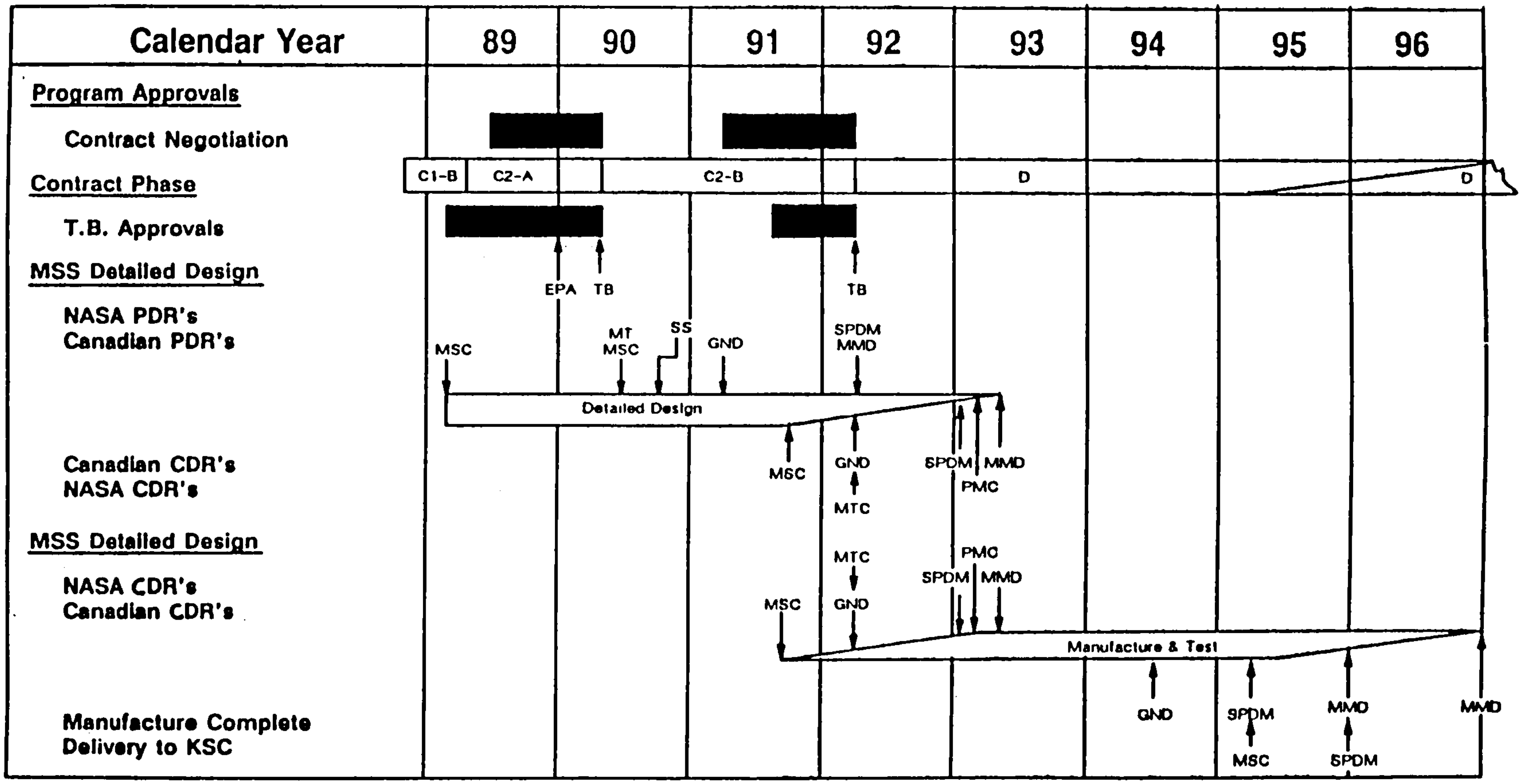


(a) (b)

Space Station Freedom Program Office

Mobile Servicing System Development Schedule

Canada



CDR - Critical Design Review
PDR - Preliminary Design Review
EPA - Effective Project Approval

GND - Ground Support System
MMD - Maintenance Depot
MSC - Mobile Servicing Centre
MTC - Man Tended Configuration
MT - Mobile Transporter

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

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

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

Government of Canada
Gouvernement du Canada

Canadian Space Agency
Agence spatiale canadienne

Automation and Robotics Technologies
MSS Baseline

machine perception

Target-Based Vision

- position, orientation, rate determination

Collision Avoidance

- collision warning

control

Force/Moment Accommodation

- limiting of applied forces and torques

Canada

Automation and Robotics Technologies
MSS Baseline (cont.)

Coordinated Control

- two manipulators
- SSRMS/SPDM

Command Language

- hierarchical
- object-oriented
- extensible

Achievable Level of Automation

- auto-trajectories
- automated tracking and grappling

Government of Canada / Gouvernement du Canada

Canadian Space Agency / Agence spatiale canadienne

Automation and Robotics Technologies Planned for Incorporation

machine perception

Enhanced Vision System

- depth recovery
- shape recognition
- object recognition

control

Collision Avoidance

- machine assisted trajectory planning
- on-line trajectory management

Government of Canada / Gouvernement du Canada

Canadian Space Agency / Agence spatiale canadienne

information management

Automation and Robotics Technologies Planned for Incorporation (cont.)

Expert Systems Applications

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

Achievable level of Automation

- task level automation

THIS PAGE INTENTIONALLY BLANK

Robotics

Invited Presentations

THIS PAGE INTENTIONALLY BLANK

Introduction | Motivation | Approach | Status

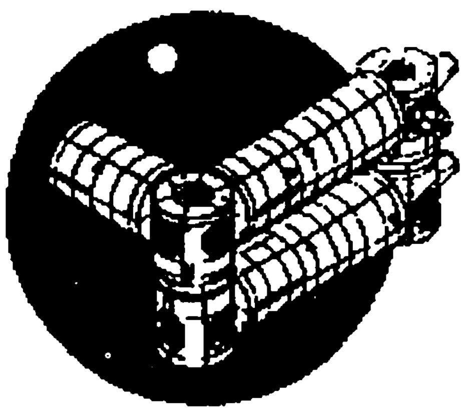
BOEING
Huntsville
AI Center

AGENT-INDEPENDENT PLANNING

Presenter: Bill Davis

Organization: Boeing Computer Services
Artificial Intelligence Center
P.O. Box 240002, MS JA-74
Huntsville, AL 35824-6402
(205) 461-2348
email: *bill@huntsai.boeing.com*

Session: Robotics



Technology for
Space Station Evolution
Workshop

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"

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.

BOEING
Huntsville
AI Center

Definitions

Question: What is agent-independent planning?

Answer: Constructing plans to satisfy a set of goals, regardless of the agent that will perform them.

Question: What is an agent?

Answer: Any entity that effects action on the environment. Includes:

- Robots
- Crewmembers
- Automated Systems (software & hardware)

Key Benefit: Development of procedures is ***independent*** from development of robotics / automation / crew skills to perform them

Section: Motivation

Title: Space Station Freedom Robotics Environment

1. Different Kinds of Robotic System Implies Redundant Programming

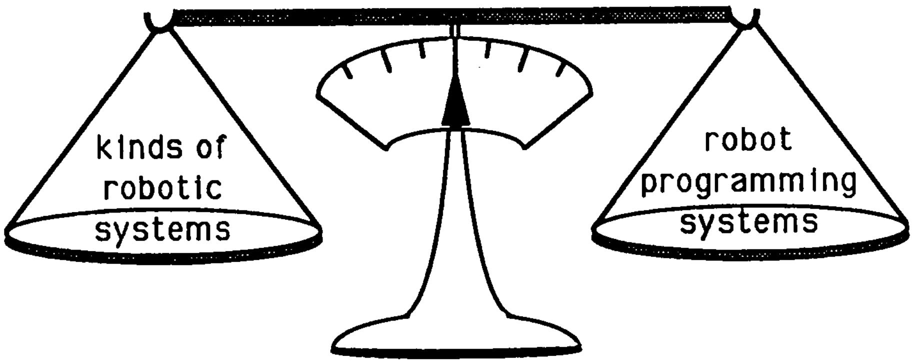
The number of ways to automate a single task through robotics is proportional to the number of robotic systems. That is, to direct different robots to do the same task would likely require a different software program for each robot. Suppose an robot on board of SSF had been programmed to remove certain 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

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 cycle. This evolution will realize a continuous set of upgrades 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 the crew. However, crew time for intra-vehicular and extra-vehicular activity will certainly remain a resource of great expense. These conditions will enhance the potential to offset 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.

BOEING
Huntsville
AI Center

Space Station Freedom Robotics Environment



For each procedure, potentially many ways exist to automate it (one per robotic system).

Space Station Freedom long life cycle creates new challenges:

- Evolving technology
- Continuous set of upgrades in robotics
  - greater precision
  - increased dexterity
  - advanced sensor abilities
- Continuous additions to SSF operations
- Extremely high cost of intra- and extra-vehicular activity

As technology advances, great potential exists to transfer expanding workload from crew to new robotic/automated systems.

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.

BOEING
Huntsville
AI Center

Transition from Crewmembers to Robots

- Need to maintain the transition from crewmembers to robotics systems in a manner that is **safe, consistent,** and **robust.**.

Transition Need			Transition Approach
Crewmembers	→	Robots of new capabilities	System that can model & reason about activities for crewmembers and robots alike
Robots of current capabilities	→	Robots of new capabilities	System that can model & reason about activities separately from capabilities constrained by specific robotic hardware
Crewmembers with skill set X	→	Crewmembers with skill set Y	System that can reason with different models for different agents

Agent-Independent Planning can model and generate an operations plan and validate its execution for an array of robotic, human, or software agents

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 lower-level 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

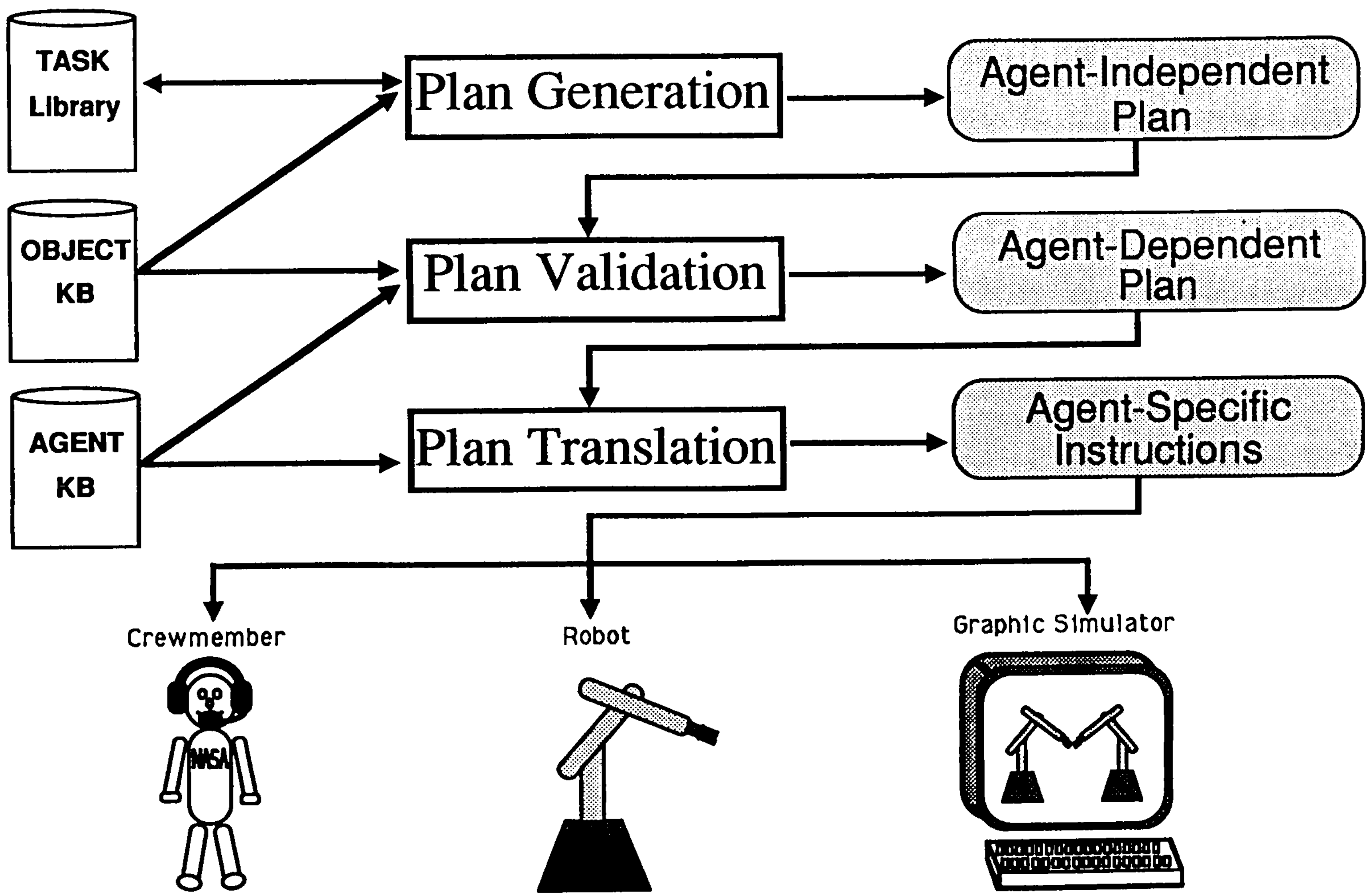
An agent-independent plan is transformed into an agent-dependent plan by matching the constraints already present among tasks and object in the plan with those of a given agent. An agent's physical constraints are validated with respect to the physical constraints of the objects it must manipulate. An 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.

BOEING
Huntsville
AI Center

Agent-Independent Planning System Flow



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.

BOEING
Huntsville
AI Center

Independence Between Plans and Agents

Independence is achieved by establishing a ***common interface*** between agents and their environment. In terms of robotics, this interface is action (physical motion).

motion primitives

Agent Models	Object Models	Task Models
• physical descriptions • functional descriptions (constrains how agents can cause action) • object-oriented representation allows agent "classes" to be built up by inheriting various characteristics	• physical descriptions • functional descriptions (constrains how objects are affected by action) • object-oriented representation allows development of composite object characteristics	• tasks compose "temporal networks" • networks form a hierarchical abstraction of the motion primitives • nonlinear and temporal planning use tasks as plan operators

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.

Introduction | Motivation | Approach | Status

BOEING Huntsville AI Center

Existing Testbed

Intelligent Planner

- Models, Generates, Validates and Translates Plans
- Maintains Models of Plans, Agents, And Objects
- Uses Techniques of Temporal Logic, Nonlinear Planning, and Hierarchical Abstraction

Agents

- Puma 560 Possessing Vision, Force/Torque, and Tactile Sensors
- Graphical Robotic Simulator Modeling One and Two Armed Robots
- Human Interaction via Voice Recognition and Synthesis Systems

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

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.

Introduction | Motivation | Approach | Status

BOEING
Huntsville
AI Center

Benefits of Approach

Generation: *autonomously creates plans from existing task library*

- temporal logic allows reasoning about all possible methods for execution
- non-robotic developers can model activities

Validation: *determines whether an agent is capable of plan execution*

- new robotic designs can be verified against existing procedures, and vice versa
- areas for future robotic development can be discovered and analyzed

Translation: *convert same plan into instructions for different agents*

- procedure consistency
- re-usable software for robotic applications

Abstraction Prevents Plan Obsolesence From Future Sophistications In Robotics

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 time-variable 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.

2. Robotic Agent Investigations

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.

3. Human Interface Investigations

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

Introduction | Motivation | Approach | Status

BOEING
Huntsville
AI Center

Directions for Future Research

Planning Investigations

- Nonmonotonic Properties With Temporal Logic
- Replanning
- Explanation Of Planner Decisions

Robotic Agent Investigations

- Agent Modeling
- Dexterous Manipulator

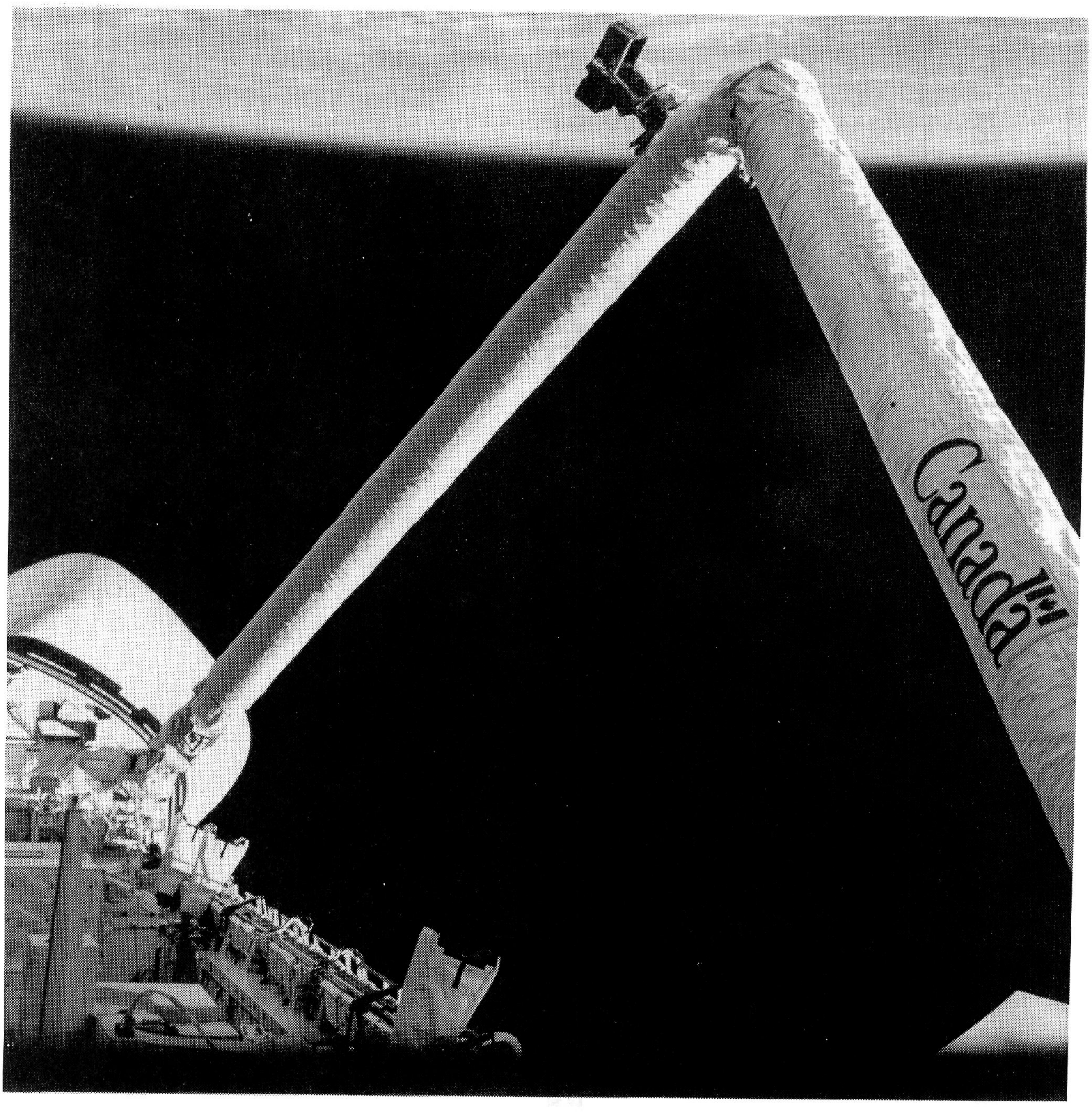
Human Interface Investigations

- Crew Skill Modeling
- Presentation of Explanations

THIS PAGE INTENTIONALLY BLANK

SPACE TELEOPERATIONS TECHNOLOGY FOR SPACE STATION EVOLUTION

GERALD J. REUTER
TELEOPERATOR SYSTEMS BRANCH
JOHNSON SPACE CENTER


Canada

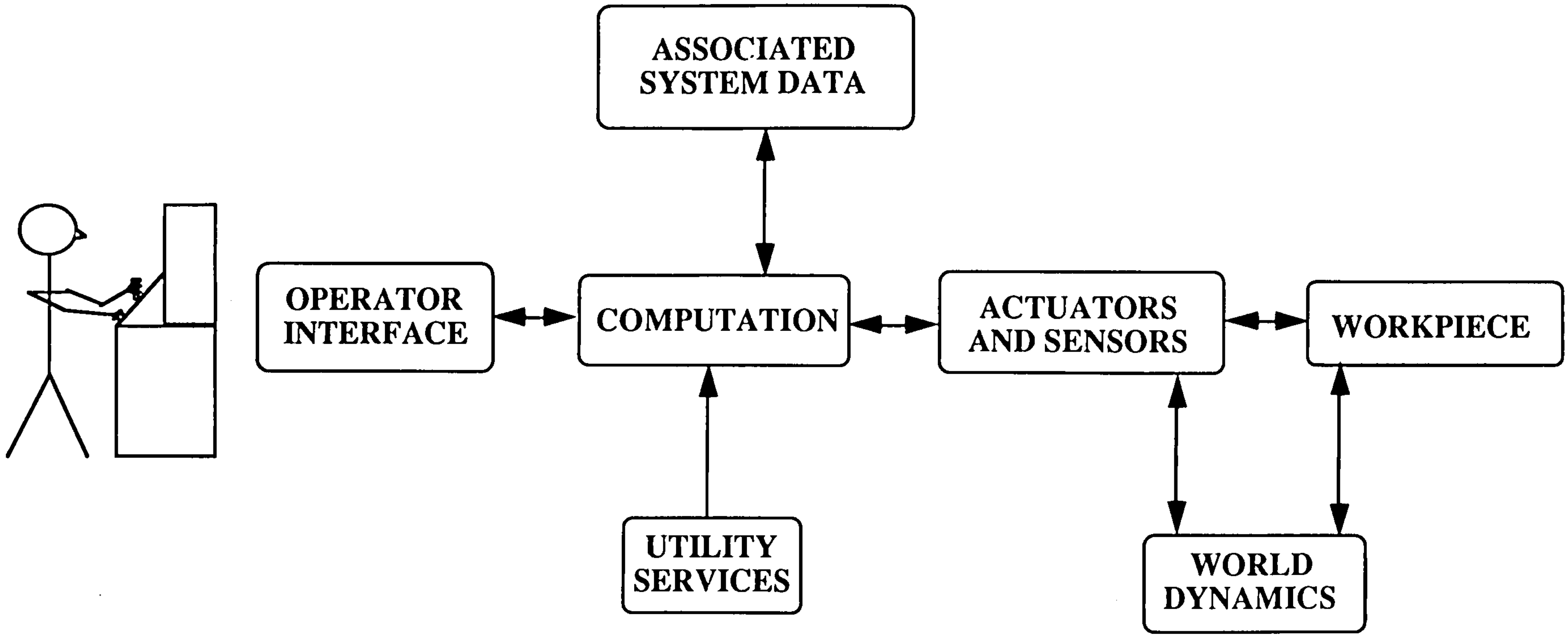
SHUTTLE REMOTE MANIPULATOR SYSTEM

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

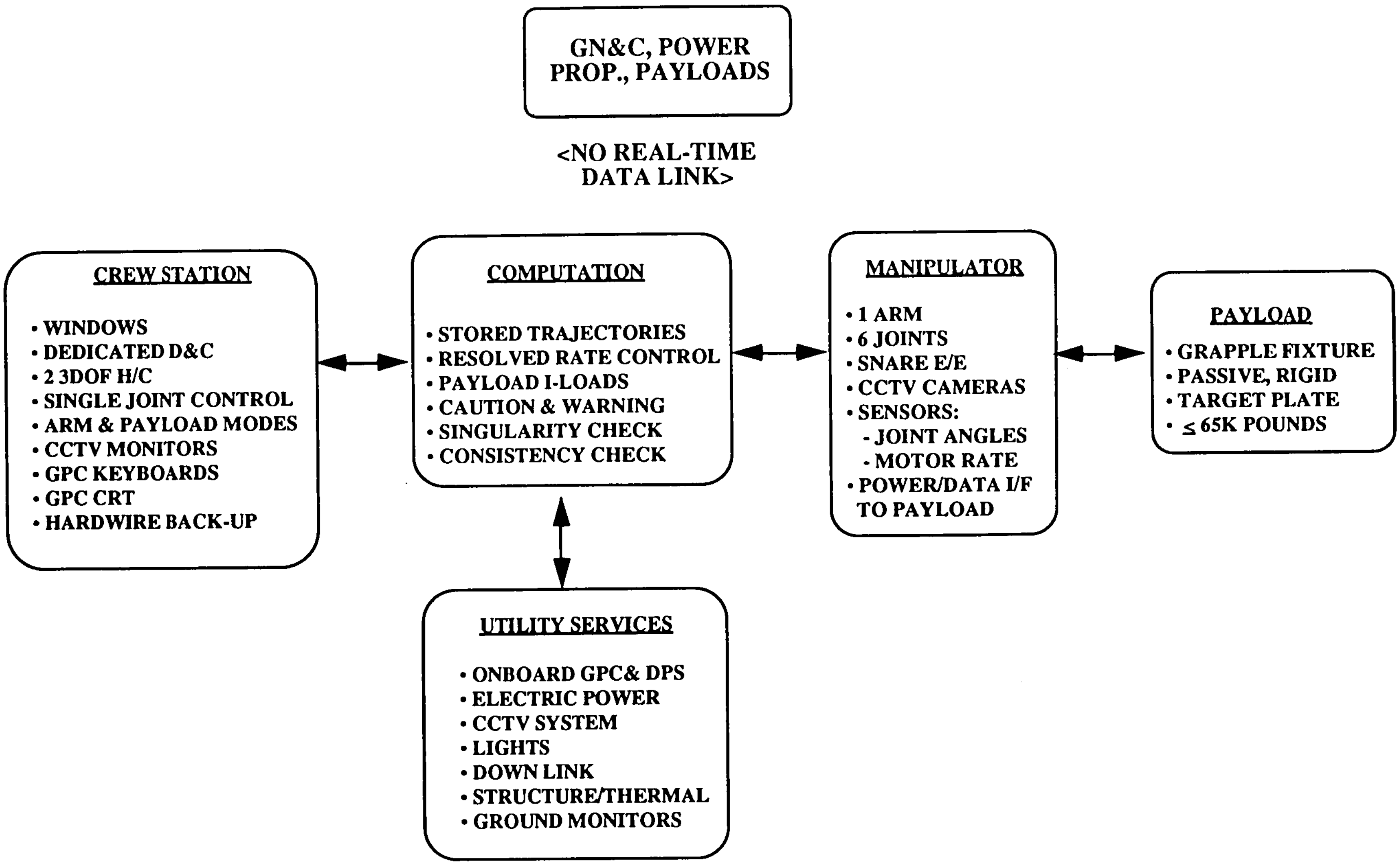
- THE PDRS CONSISTS OF THE REMOTE MANIPULATOR SYSTEM AND ITS ANCILLARY EQUIPMENT MOUNTED ON THE SPACE SHUTTLE ORBITER

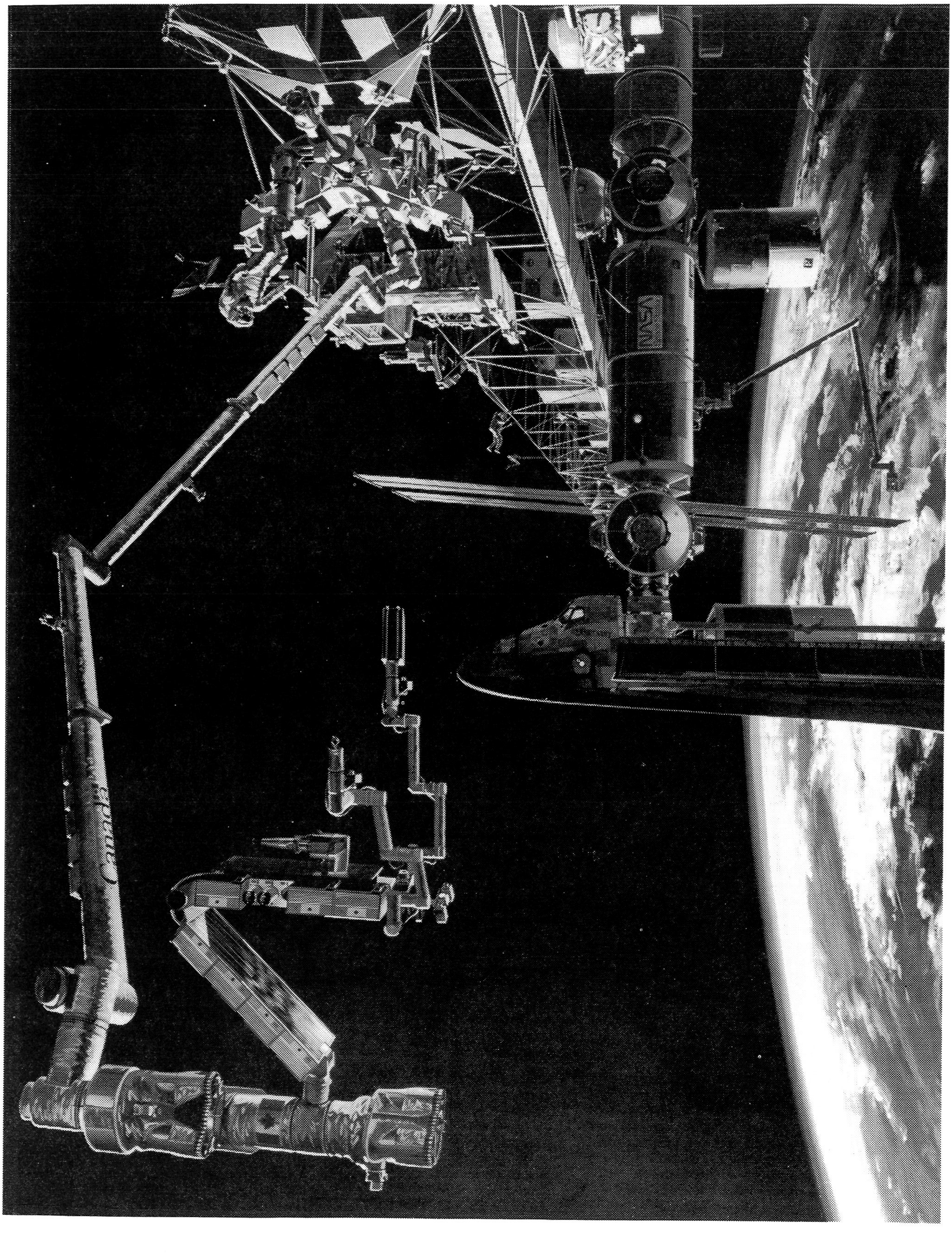
- THE PDRS FUNCTIONALITIES ARE:
  - GRAPPLE, TRANSPORT, ORIENTATION, AND RELEASE OF PAYLOAD
  - TRACK, CAPTURE, GRAPPLE, TRANSPORT, ORIENTATION, AND BERTHING OF A SATELLITE
  - EVA CREW TRANSPORT, POSITIONING, ORIENTATION VIA GRAPPLED MANIPULATOR FOOT RESTRAINT
  - LOCAL ILLUMINATION VIA RMS-MOUNTED 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



SHUTTLE RMS TECHNOLOGY

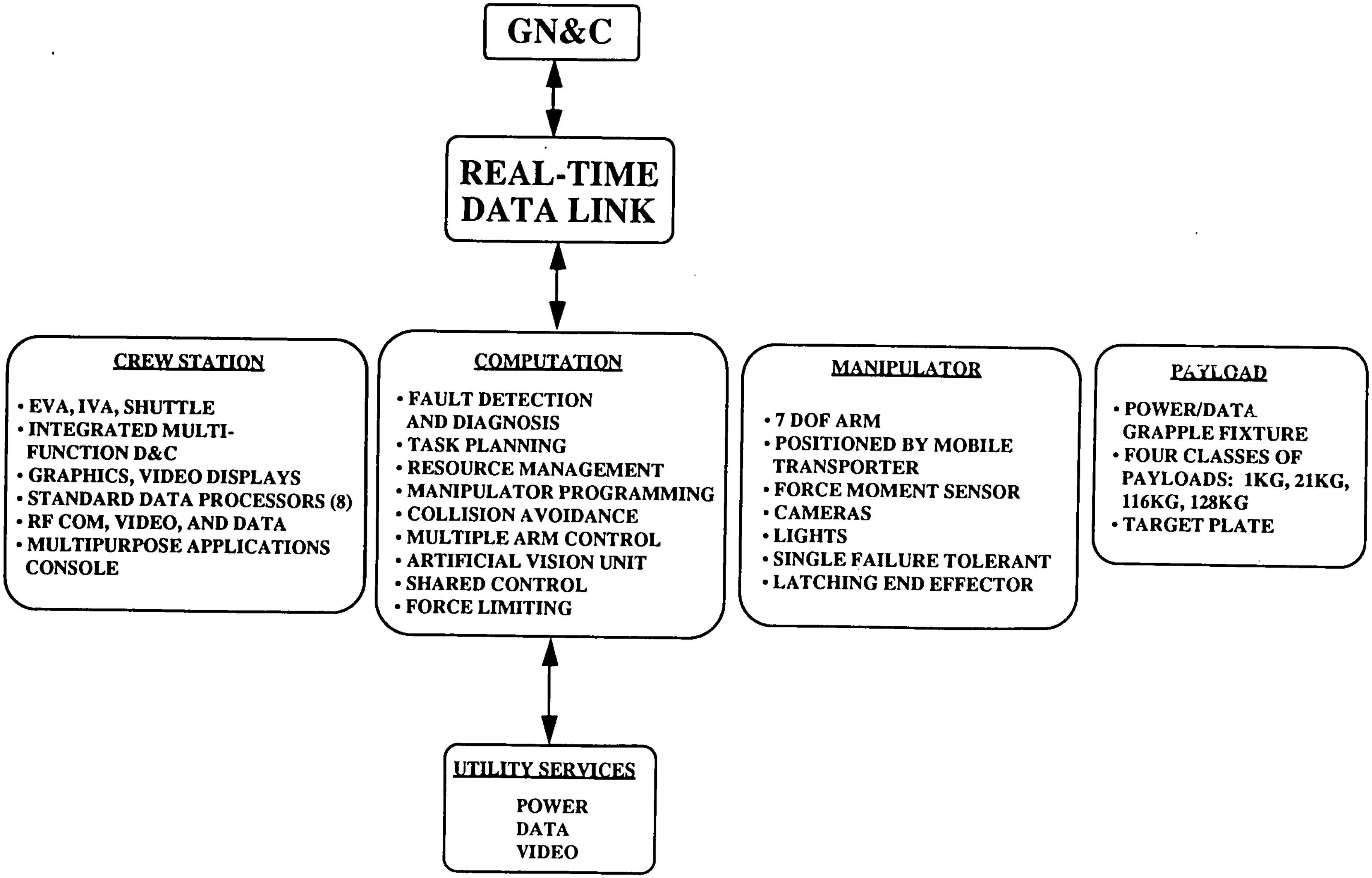



Canada
NASA

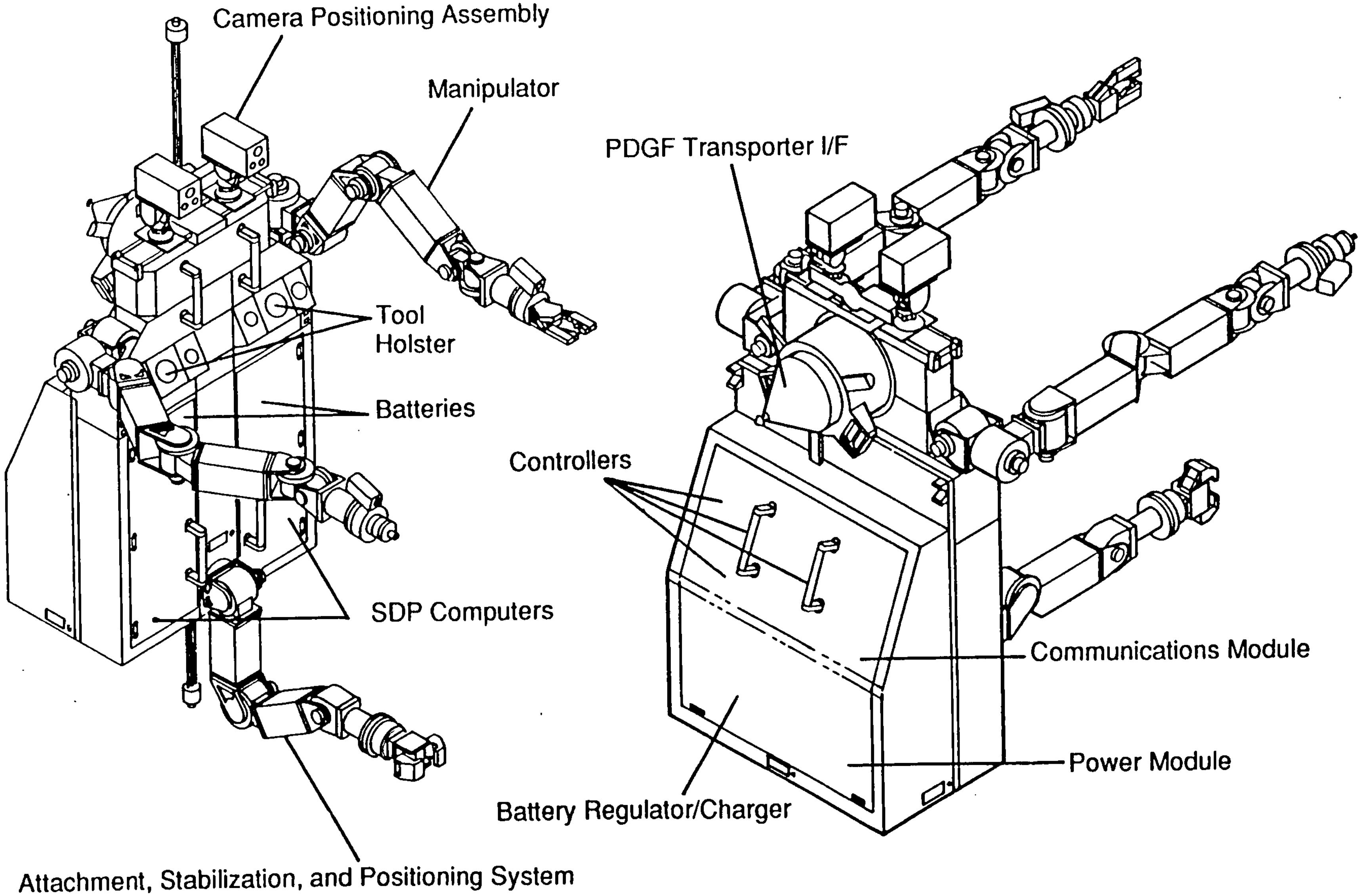
MOBILE SERVICING CENTER FUNCTIONS

- 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

CREW STATION

- EVA, IVA, SHUTTLE
- INTEGRATED MULTI-FUNCTION D&C
- GRAPHICS, VIDEO DISPLAYS
- STANDARD DATA PROCESSORS (4)
- RF COM, VIDEO, AND DATA
- MULTIPURPOSE APPLICATIONS CONSOLE
- MASTER/SLAVE CONTROL
- COLOR FLAT PANEL DISPLAYS
- FORCE REFLECTIVE HAND CONTROLLERS

COMPUTATION

- NASREM ARCHITECTURE
- POSITION/RESOLVED RATE COMMANDS
- CARTESIAN CONTROL
- POSITION BASED IMPEDANCE CONTROL
- ACTIVE COMPLIANT CONTROL
- FORCE REFLECTION
- HYBRID FORCE/POSITION CONTROL

MANIPULATOR

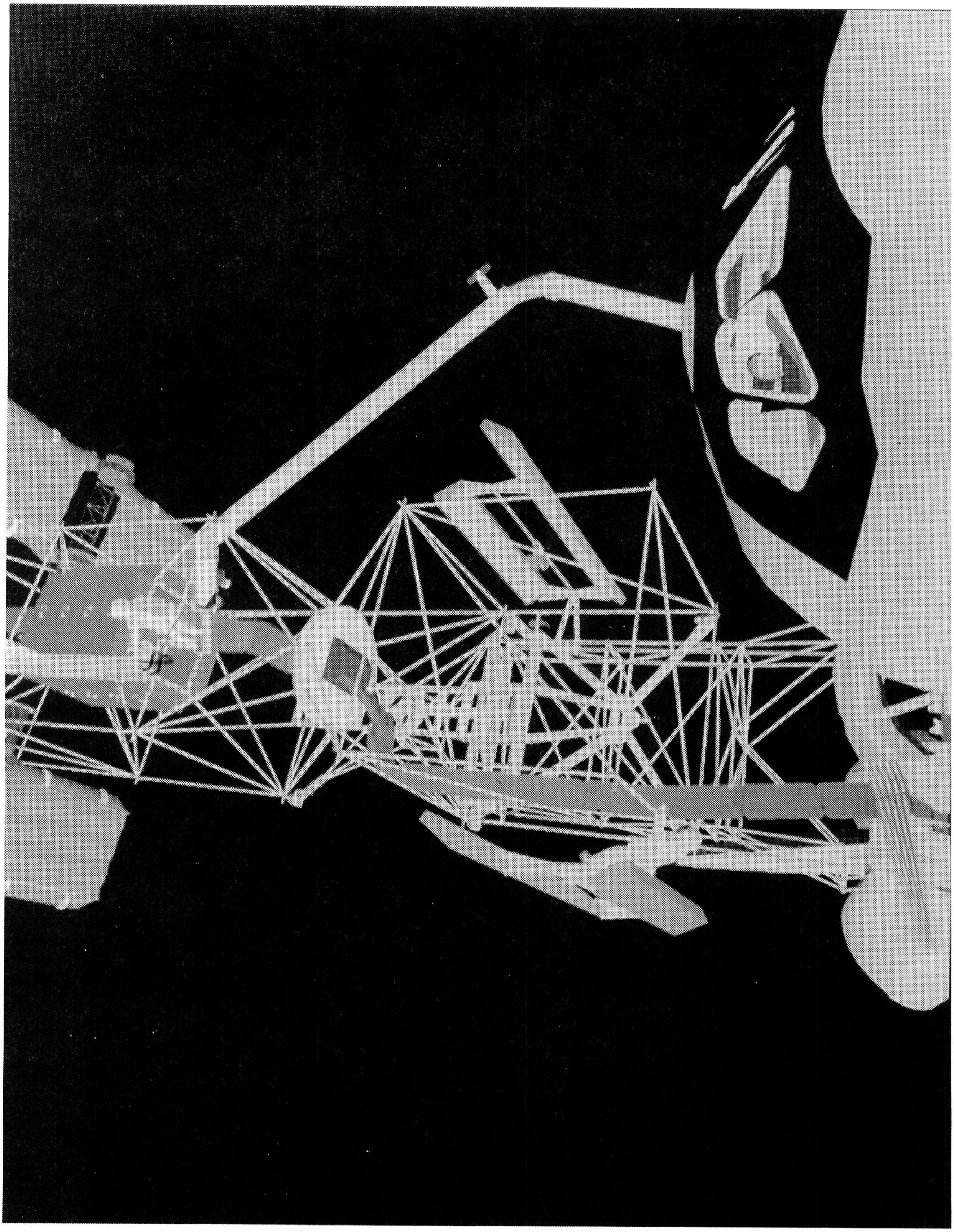
- TWO 7 DOF ARMS
- 5 DOF ASPS
- POSITIONED BY SRMS, SSRMS
- JOINT SENSORS
  - POSITION
  - TORQUE
- DUAL BASES
- HARMONIC DRIVE
- ROTARY PARALLEL JAW END EFFECTOR
- CAMERAS
- LIGHTS

PAYLOAD

- ORU's
- TOOLS SETS
- INTERCHANGEABLE TOOLS

UTILITY SERVICES

POWER
DATA
VIDEO



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
- 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

from

Consortium of Texas Research Universities
University of Texas at Arlington
University of Texas at Austin
Texas A&M University
Rice University

D. Tesar
512-471-3039

PAPER UNAVAILABLE AT TIME OF PUBLICATION

Telerobotics Capabilities for Space Station Operations

David Akin

Massachusetts Institute of Technology

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

PAPER UNAVAILABLE AT TIME OF PUBLICATION

FTS EVOLUTION

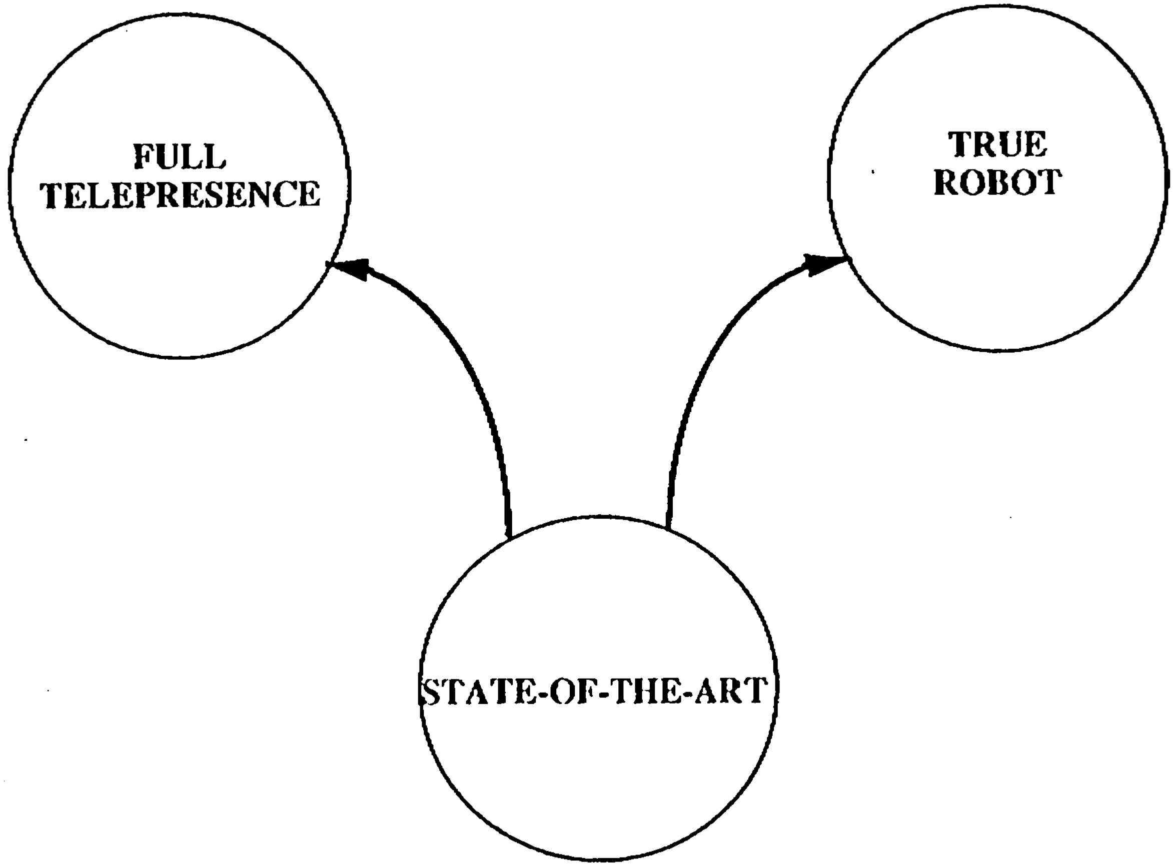
DAVID E. PROVOST
GODDARD SPACE FLIGHT CENTER

TECHONOLOGY FOR SPACE STATION EVOLUTION --A WORKSHOP

GOAL

IDENTIFY near term technology development which would have significant impact on the evolution of the FTS toward autonomous operation.

PATHS FOR FTS EVOLUTION



IDENTIFICATION OF HIGH PAYOFF TECHNOLOGY

- FTS mission utilization team scripted representative tasks
- Task scripts analyzed for commonality
- Generic task definitions developed
- Scripted tasks mapped into generic task definitions

FREQUENTLY PERFORMED ACTIONS

- Orient torso
- Move arms to vicinity of work
- Attach
- Detach

PRIMARY TASK STATES

- Path Planning
- Non-contact alignment
- Contact Planning and Control

TASK STATES

PATH PLANNING

- movement through large volumes
- primarily translation
- free space motion

NON-CONTACT ALIGNMENT

- movement through small volumes
- primarily orientation
- free space motion

CONTACT PLANNING AND CONTROL

- movement through small volumes
- contact with environment
- compliance strategies required

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
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
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

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	RETRIEVE ROBOT	TEST ROBOT	DELIVER ROBOT WORK SYSTEM	ORIENT TORSO	MOVE ARMS TO VICINITY OF WORK	ATTACH	DO WORK	DETACH	MOVE ARMS TO SAFE POSITION	COMMENT	TOTAL STEPS
1d	1										
1e		1									
TOTAL	1	1	0	0	0	0	0	0	0		2

TASK 2	RETRIEVE ROBOT	TEST ROBOT	DELIVER ROBOT WORK SYSTEM	ORIENT TORSO	MOVE ARMS TO VICINITY OF WORK	ATTACH	DO WORK	DETACH	MOVE ARMS TO SAFE POSITION	COMMENT	TOTAL STEPS
2b				1	1						
2c						1					
2d							1			Drive bolt out.	
2e							1			Move node fitting	
2f								1			
2g	0	0	0	2	2	2	4	2	0	Repeat 2b-2f 2 times.	
2h				1	1						
2i						1					
2j					1						
2k						1					
2l							1			Unlatch and separate joint.	
2m								1			
2o					1						
2p						1					
2q					1		1			Align PDGF.	
2r							1			Engage and latch PDGF	
2s								1			
2t								1	1		
2u	0	0	0	1	4	3	3	3	1	Repeat 2h-2t	
TOTAL	0	0	0	5	11	9	12	9	2		48

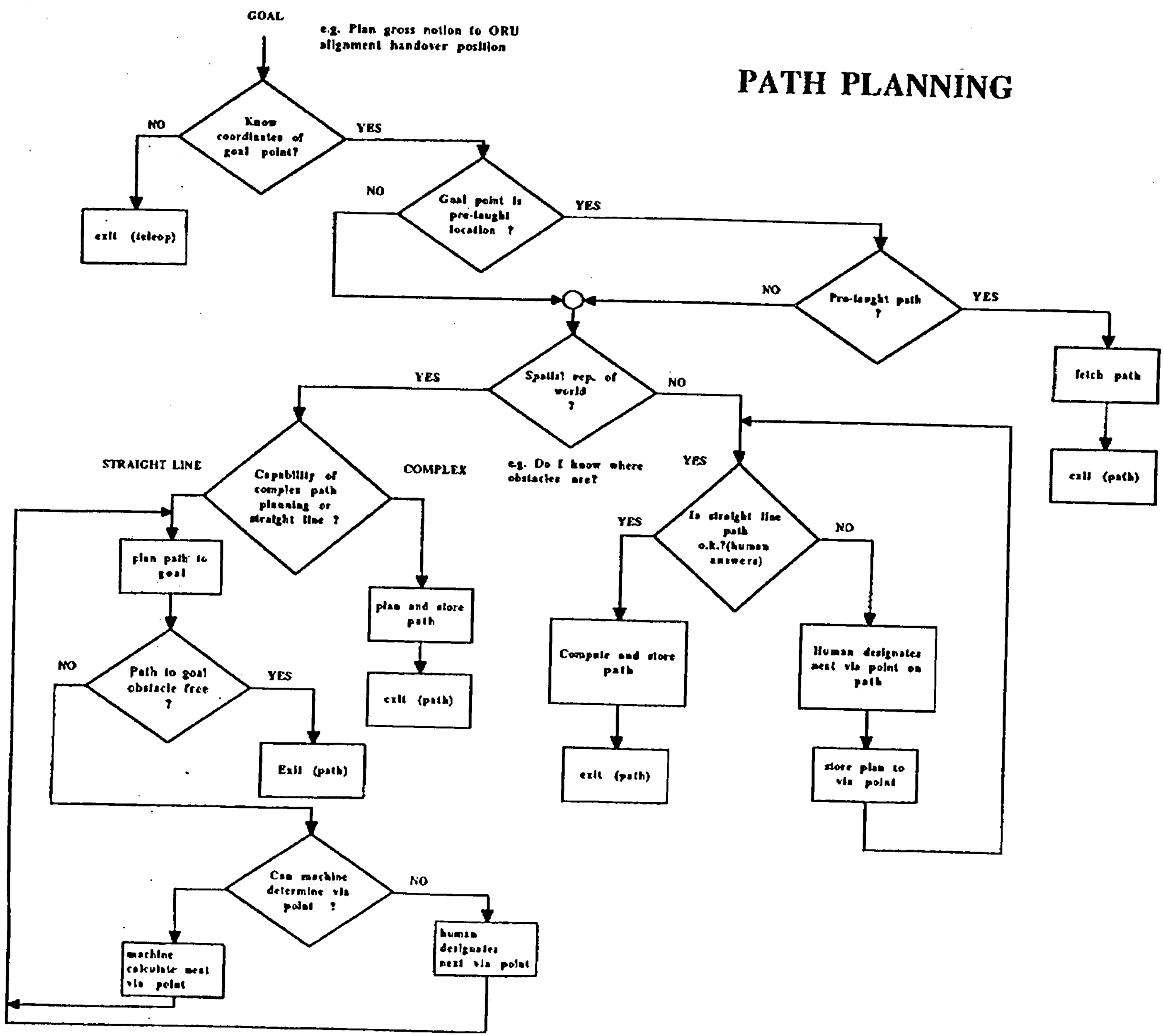
SUMMARY (PERCENT)

TASK	CASE	RETRIEVE ROBOT	TEST ROBOT	DELIVER ROBOT WORK SYSTEM	ORIENT TORSO	MOVE ARMS TO VICINITY OF WORK	ATTACH	DO WORK	DETACH	MOVE ARMS TO SAFE POSITION
SIA INSTALL	1	2.5	2.5	2.5	15.6	20.5	18.0	12.3	18.0	8.2
	2	1.6	0.8	1.2	8.9	24.4	20.9	16.7	20.9	4.7
	3	1.9	1.5	1.0	9.2	23.8	22.3	13.1	22.3	4.9
	4	1.7	1.2	1.7	13.3	22.5	17.3	17.9	17.3	6.9
PALLET INSTALL INSIDE/ AWP	1	2.2	0.7	5.8	8.0	24.8	17.5	15.3	17.5	8.0
	2	1.9	0.0	4.9	8.0	25.3	17.3	17.9	17.3	7.4
	3	2.2	0.7	5.8	8.0	24.8	17.5	15.3	17.5	8.0
	4	1.9	0.0	4.9	8.0	25.3	17.3	17.9	17.3	7.4
PALLET INSTALL OUTSIDE/ AWP	1	1.8	0.9	4.4	11.5	20.4	19.5	13.3	19.5	8.8
	2	1.3	0.0	2.2	7.1	24.1	22.3	15.6	22.3	4.9
	3	1.4	0.0	3.6	11.5	21.6	18.7	18.5	18.7	7.9
	4	1.5	0.5	2.5	6.6	23.7	23.2	13.6	23.2	5.1
ORU CHANGE-OUT	1	3.1	0.5	5.2	9.9	20.9	16.2	18.3	16.2	9.4
	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	1	0.3	0.2	0.3	7.6	27.0	16.1	27.2	16.1	5.3

APPROACH TO DEFINING EVOLUTION ALTERNATIVES

- Use "decision tree" process flow diagrams
- Identify technological dichotomies
  - environmental structuring
  - sensor processing capabilities
  - control algorithms
  - human interaction
- Choose a path through tree

PATH PLANNING

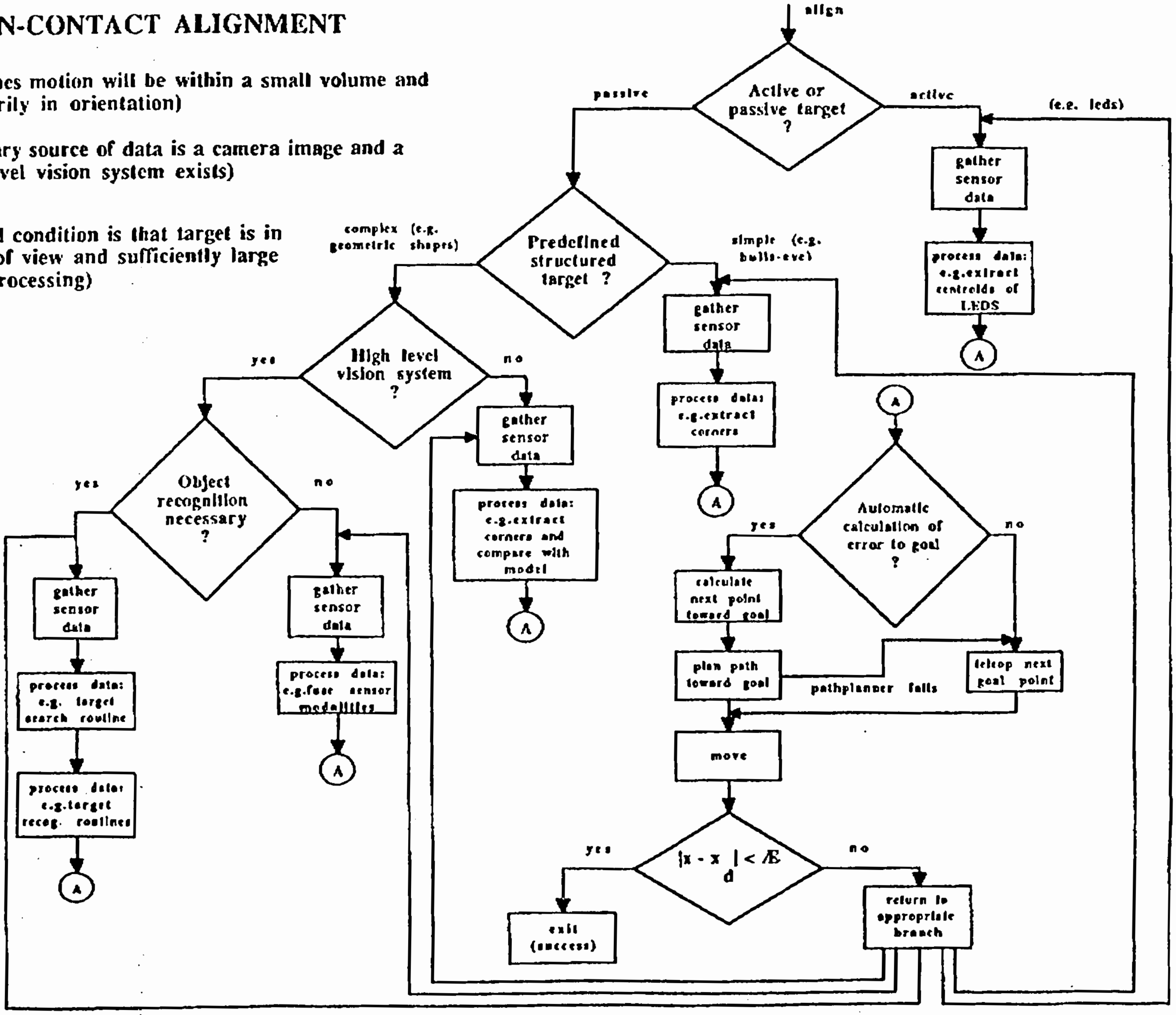


NON-CONTACT ALIGNMENT

(assumes motion will be within a small volume and primarily in orientation)

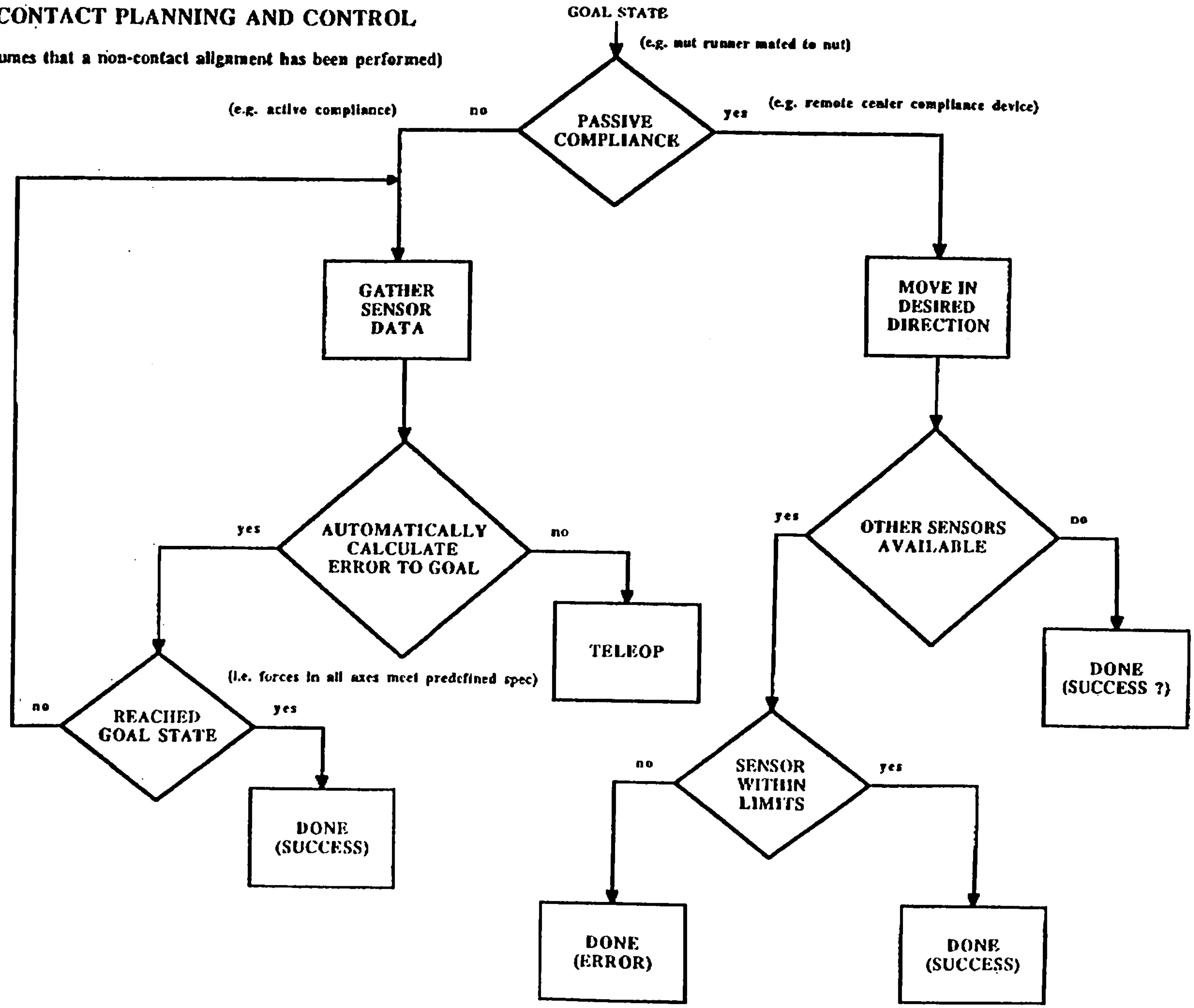
(primary source of data is a camera image and a low level vision system exists)

(initial condition is that target is in field of view and sufficiently large for processing)



CONTACT PLANNING AND CONTROL

(assumes that a non-contact alignment has been performed)

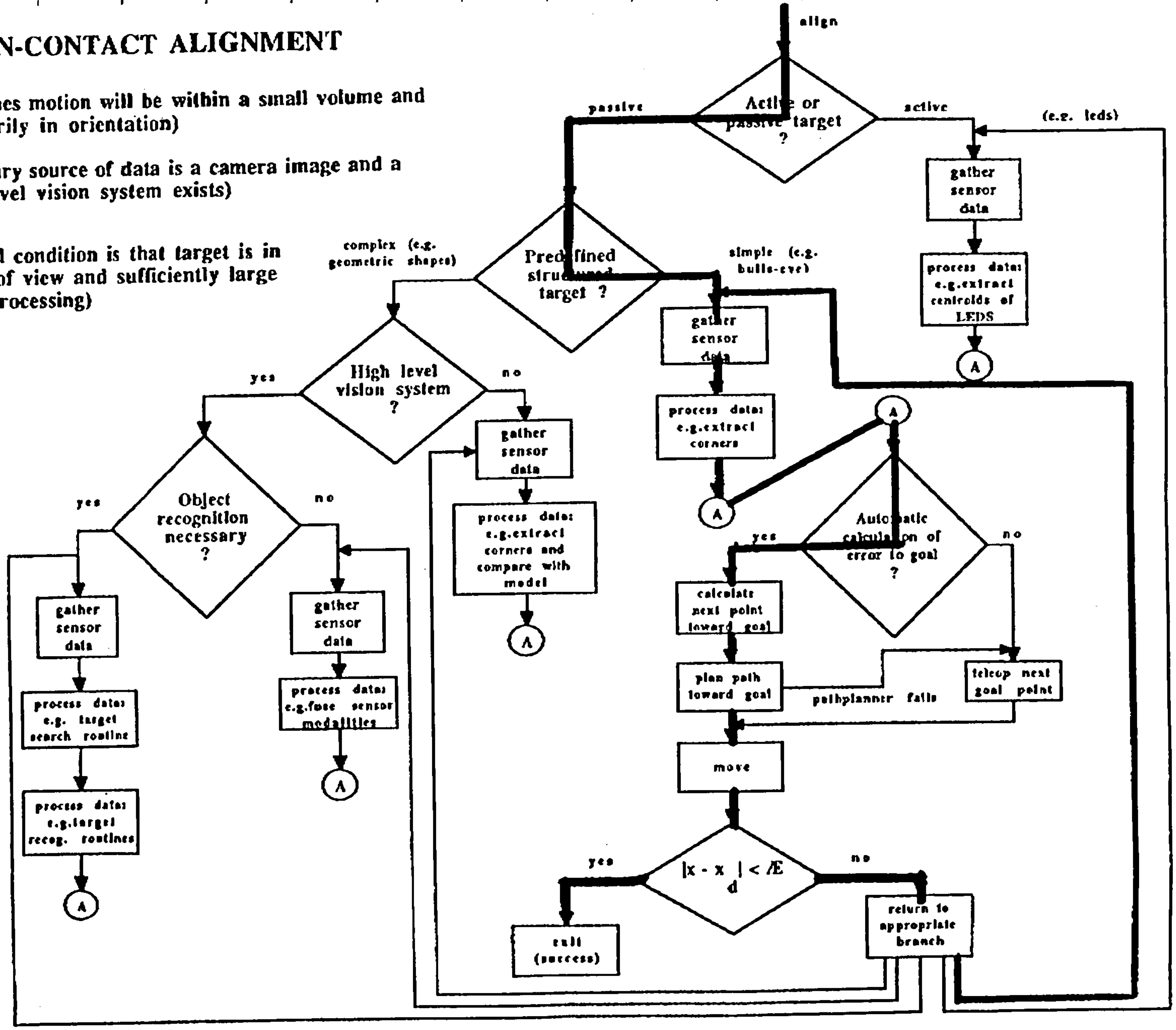


NON-CONTACT ALIGNMENT

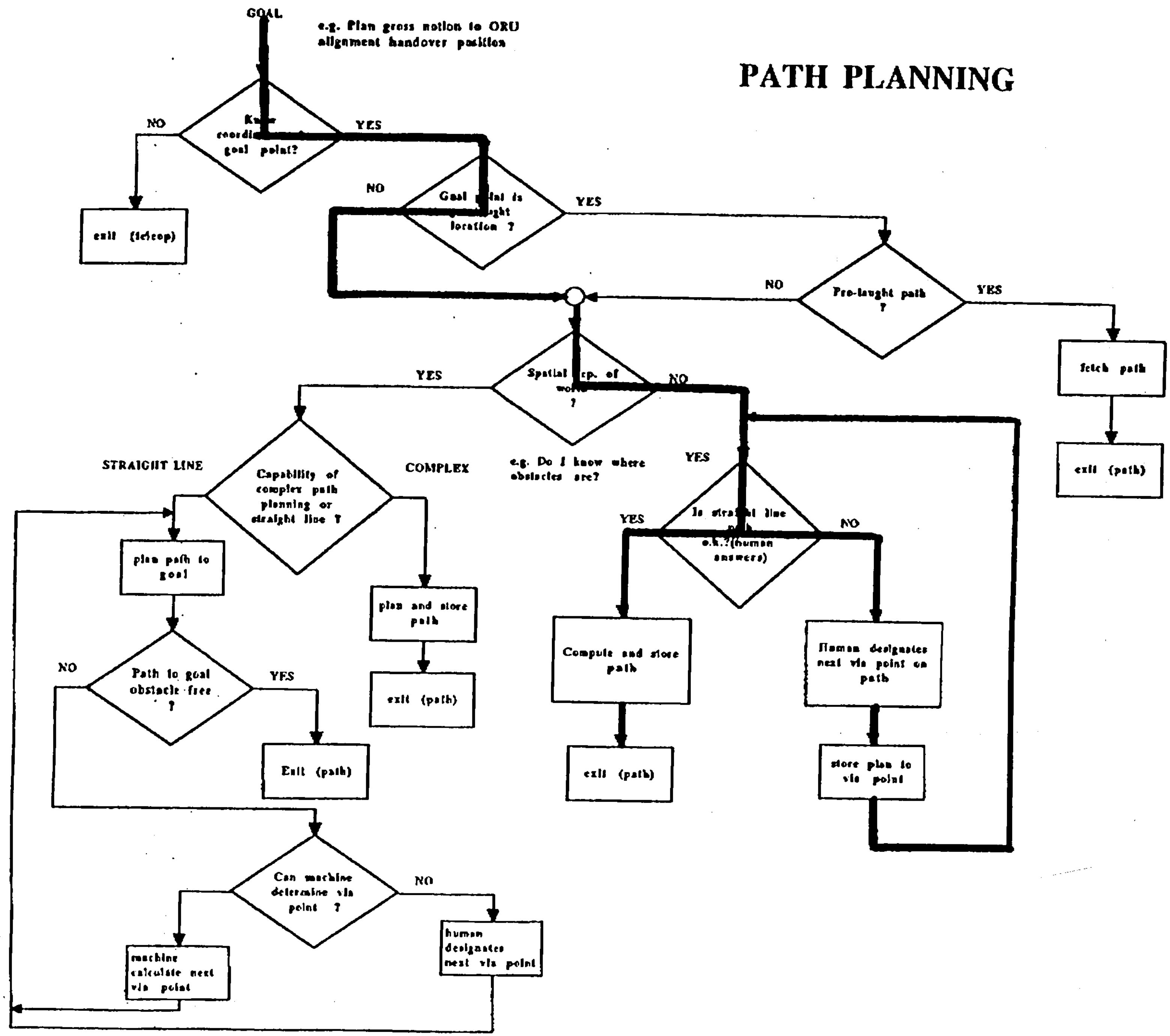
(assumes motion will be within a small volume and primarily in orientation)

(primary source of data is a camera image and a low level vision system exists)

(initial condition is that target is in field of view and sufficiently large for processing)

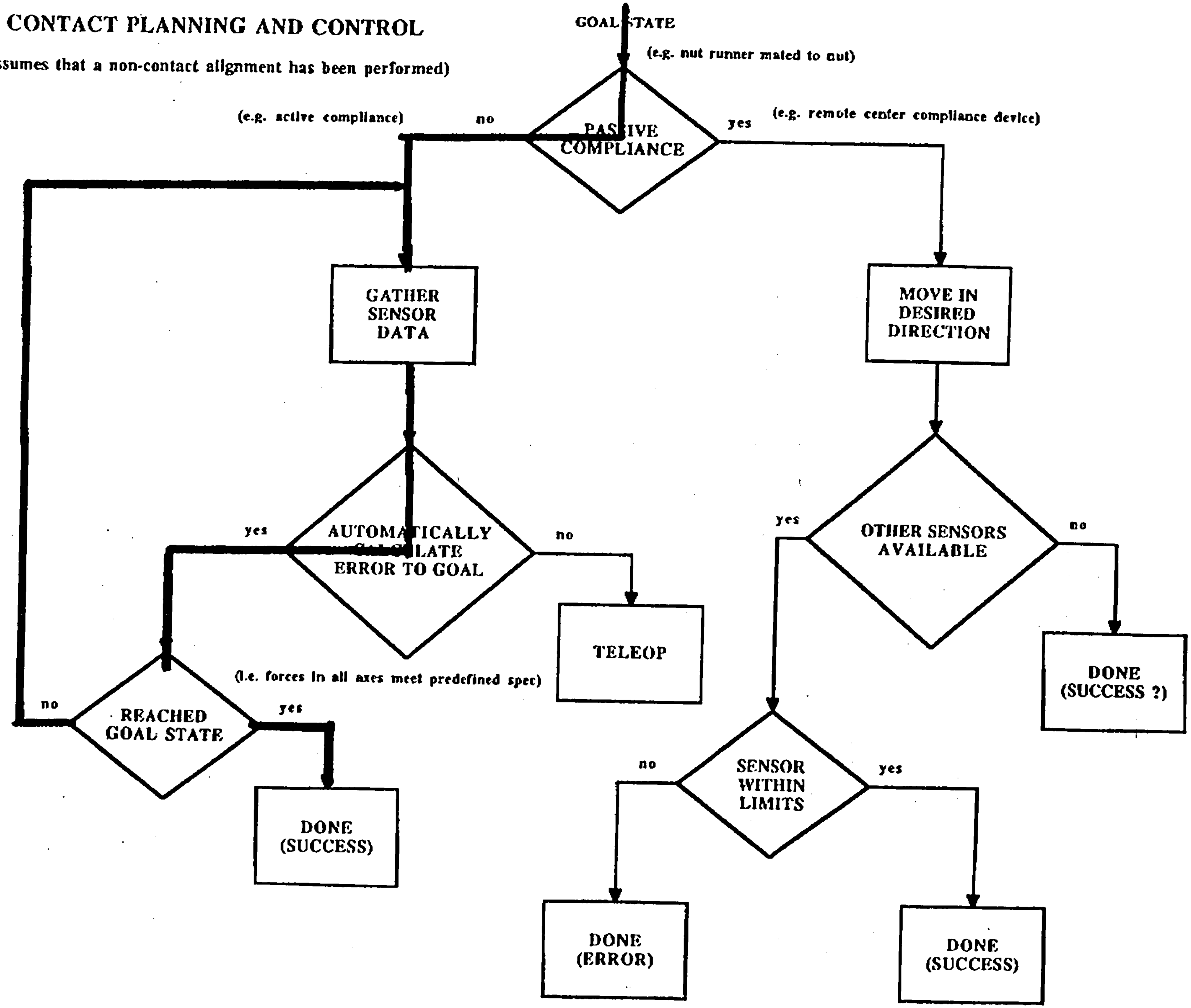


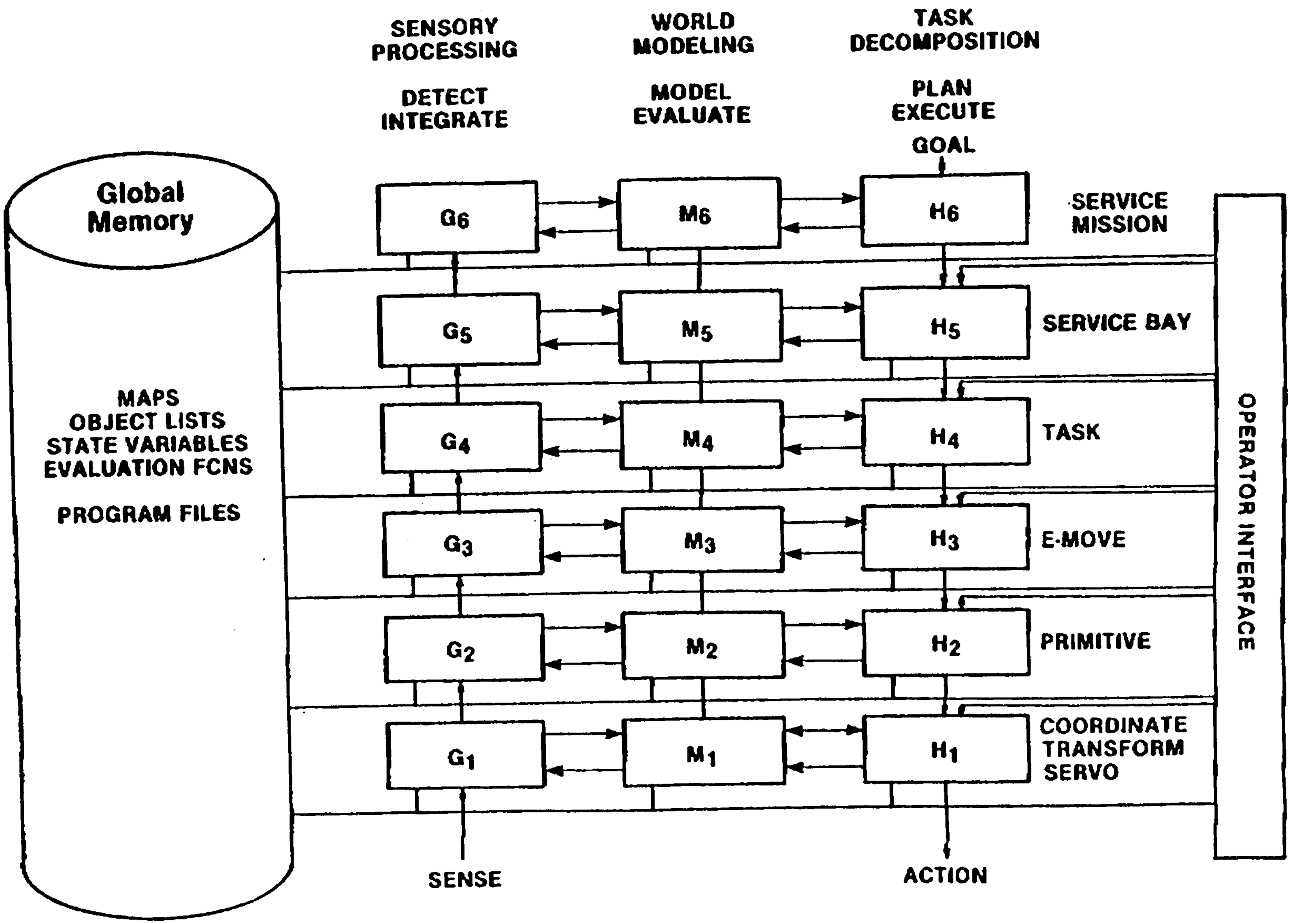
PATH PLANNING

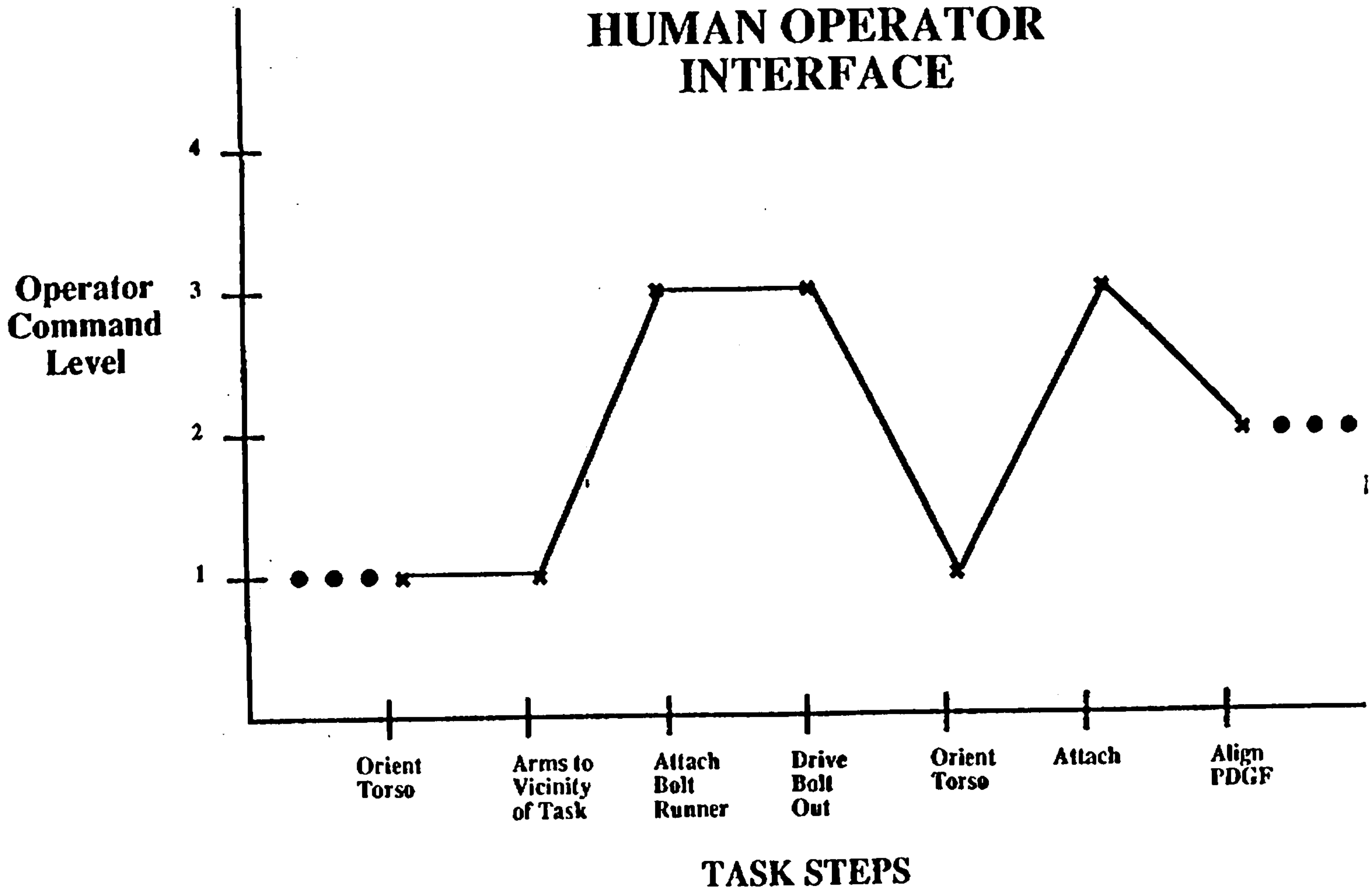


CONTACT PLANNING AND CONTROL

(assumes that a non-contact alignment has been performed)




SENSORY PROCESSING
DETECT INTEGRATE
WORLD MODELING
MODEL EVALUATE
TASK DECOMPOSITION
PLAN EXECUTE
GOAL
Global Memory
MAPS
OBJECT LISTS
STATE VARIABLES
EVALUATION FCNS
PROGRAM FILES
G6
M6
H6
SERVICE MISSION
G5
M5
H5
SERVICE BAY
G4
M4
H4
TASK
G3
M3
H3
E-MOVE
G2
M2
H2
PRIMITIVE
G1
M1
H1
COORDINATE TRANSFORM SERVO
OPERATOR INTERFACE
SENSE
ACTION


HUMAN OPERATOR INTERFACE
Operator Command Level
4
3
2
1
Orient Torso
Arms to Vicinity of Task
Attach Bolt Runner
Drive Bolt Out
Orient Torso
Attach
Align PDGF
TASK STEPS

CONCLUSIONS

- Described methodology for determining high payoff automation tasks
- Described tradeoffs between autonomy and human assistance for:
  - non contact alignment
  - path planning
  - contact alignment and control

* U.S. GOVERNMENT PRINTING OFFICE: 1990--730-163/E4549