p 273

NASA Conference Publication 10083

Beyond the Baseline 1991

Proceedings of the Space Station Evolution Symposium

Volume 2: Space Station Freedom

Part 1

Proceedings of a conference held at
South Shore Harbour Resort
and Conference Center
League City, Texas
August 6-8, 1991

NASA

(NASA-CP-10083-Vol-2-Pt-1) BEYOND THE BASELINE 1991: PROCEEDINGS OF THE SPACE STATION EVOLUTION SYMPOSIUM. VOLUME 2: SPACE STATION FREEDOM, PART 1 (NASA) 273 p
CSCL 22B G3/18

N92-17768
--THRU--
N92-17776
Unclas
0062410

NASA Conference Publication 10083

Beyond the Baseline 1991

Proceedings of the Space Station Evolution Symposium

Volume 2: Space Station Freedom

Part 1

Proceedings of a conference held at
South Shore Harbour Resort
and Conference Center
League City, Texas

NASA

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1991

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1991	Conference Publication

4. TITLE AND SUBTITLE
Beyond the Baseline 1991 - Proceedings of the Second Space Station Freedom Evolution Symposium

5. FUNDING NUMBERS

6. AUTHOR(S)
NASA and support contractor personnel funded under the Transition Definition line item - UPN 488

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Space Station Engineering Division
NASA Headquarters
Washington D.C. 20546
MC: MT

8. PERFORMING ORGANIZATION REPORT NUMBER
S-653

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington D.C. 20546

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
CP 10083

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified - unlimited

12b. DISTRIBUTION CODE
Publicly Available

13. ABSTRACT (*Maximum 200 words*)

This report contains the individual presentations delivered at the Space Station Evolution Symposium in League City, Texas, on August 6, 7, & 8, 1991. Personnel responsible for Advanced Systems Studies and Advanced Development within the Space Station Freedom Program reported on the results of their work to date. The results of SSF Advanced Studies provide a road map for the evolution of Freedom in terms of user requirements, utilization and operations concepts, and growth options for distributed systems. Regarding these specific systems, special attention is given to: highlighting changes made during restructuring; description of growth paths thru the follow-on and evolution phases; identification of minimum-impact provisions to allow flexibility in the baseline; and identification of enhancing and enabling technologies. Products of these tasks include: "Engineering" fidelity demonstrations and evaluations of advanced technology; detailed requirements, performance specifications, and design accommodations for insertion of advanced technology; and mature technology, tools and applications for SSF flight, ground and information systems.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
U	U	U	

Preface

This publication is a compilation of papers presented at the Second Space Station Evolution Symposium: "Beyond the Baseline 1991" from August 6 - 8, 1991. The symposium was structured as a forum to discuss the current status and future plans for Space Station Freedom (SSF). The primary purpose of the gathering was to review the plans and progress in ensuring a baseline design with the flexibility to accommodate a broad range of potential utilization demands and to effectively incorporate technology advances over the lifetime of the facility. The timing of the conference was chosen at the critical juncture between completion of the Delta Preliminary Design Reviews and the Program Critical Design Reviews.

The plenary papers describe the current status of the restructured Space Station Freedom design, the plans of the international partners, and future utilization of the facility. Related programs in advanced technology and space transportation are also discussed.

The technical sessions represent the results of tasks funded by Level I Space Station Engineering in Advanced Studies and Advanced Development. The charts presented are amplified here by facing page text. The work was accomplished in fiscal years 1990 and 1991 and was presented by those in government and industry who performed the tasks.

The results of SSF Advanced Studies provide a road map for the evolution of Freedom in terms of user requirements, utilization and operations concepts, and growth options for distributed systems. Regarding these specific systems, special attention is given to: highlighting changes made during restructuring; description of growth paths through the follow-on and evolution phases; identification of minimum-impact provisions to allow flexibility in the baseline, and identification of enhancing and enabling technologies.

The activities under Advanced Development and Engineering Prototype Development (EPD) are targeted to improve the functionality and performance of baseline systems, thus providing options to the program which reduce schedule and technical risks. These applications have the potential to improve flight and ground system productivity, reduce power consumption and weight, and prevent technological obsolescence. Products of these tasks include: "Engineering" fidelity demonstrations and evaluations of advanced technology; detailed requirements, performance specifications, and design accommodations for insertion of advanced technology, and mature technology, tools, and applications for SSF flight, ground, and information systems.

Dr. Earle K. Huckins, III
Director, Space Station Engineering
Office of Space Flight
NASA Headquarters

Listed below are the persons who made this symposium possible.

COMMITTEE MEMBERS

Conference Chair:

- Earle K. Huckins III
  NASA Headquarters

Program Planning Committee Technical Chairs:

- Stephen Cook
  NASA Headquarters
- Gregg Swietek
  NASA Headquarters
- Mark Gersh
  NASA Headquarters
- Peter Ahlf
  NASA Headquarters
- Alan Fernquist
  NASA Headquarters

Session Chairs:

- Lewis Peach
  NASA Headquarters
- John-David Bartoe
  NASA Headquarters
- W. Ray Hook
  NASA Langley Research Center
- Karen Brender
  NASA Langley Research Center
- Edward Chevers
  NASA Ames Research Center
- Gregg Swietek
  NASA Headquarters
- Mark Gersh
  NASA Headquarters
- Alan Fernquist
  NASA Headquarters

Administrative Co-Chairs:

- Glenn Freedman
  UH-Clear Lake
- Carla Armstrong
  Barrios Technology, Inc.

CONTENTS – Volume 2

Title | Page

SESSION VII: TELEROBOTIC SYSTEMS
SESSION CHAIR: MR. ALAN FERNQUIST, NASA HEADQUARTERS

Time	Topic	Presenter
Tuesday August 6, 1991		
8:30 - 12:00	PLENARY SESSION 1 — OUTLOOK FOR SPACE STATION FREEDOM Session Chair: Dr. Earle K. Huckins III *NASA Headquarters*	
8:30	Welcoming Remarks	Dr. Aaron Cohen *Director, NASA Johnson Space Center*
8:45	Space Station Freedom: An Investment In The Future	Dr. William B. Lenoir *Associate Administrator, NASA Office of Space Flight*
9:45	Space Station Freedom Program Status	Dr. John Cox *Deputy Manager for Operations* *Space Station Freedom* *Program and Operations*
10:15	Break	
10:30	Columbus Programme	Mr. Derek Dell *ESA Representative* *Space Station Freedom Program and Operations*
11:00	Japanese Experiment Module	Mr. Kazuhiko Yoneyama *Director, Space Station Group* *Space Station Program Department NASDA*
11:30	Canadian Space Station Program	Mr. Karl Doetsch *Director General, Space Station Program* *Canadian Space Agency*
12:00 - 1:30	Lunch	
1:30 - 5:30	PLENARY SESSION 2 — FUTURE SPACE PROGRAMS AND PLANS Session Chair: Mr. Lewis L. Peach *NASA Headquarters*	
1:30	Space Station Freedom Evolution	Dr. Earle K. Huckins III *Director, Space Station Engineering* *NASA, Office of Space Flight*
2:00	SEI: An Update	Mr. Lewis Peach Assistant *Director for Space Exploration,* *NASA Office of Aeronautics, Exploration and Technology*
2:30	Advanced Space Transportation Systems	Mr. Robert Davies *Chief, Advanced Transportation Planning* *NASA, Office of Space Flight*
3:15	National Aero-space Plane	Dr. H. Lee Beach, Jr. *Director for National Aero-Space Plane,* *NASA Office of Aeronautics, Exploration and Technology*
3:45	Break	

Time	Topic	Presenter

Tuesday August 6, 1991 *(continued)*

PLENARY SESSION 3 — FUTURE UTILIZATION OF SPACE STATION FREEDOM
Session Chair: Dr. John-David Bartoe
NASA Headquarters

Time	Topic	Presenter
4:00	Commercial Opportunities During Space Station Freedom Evolution	Mr. Richard Ott *Director, Commercial Development Division* *Office of Commercial Programs*
4:30	Technology Development on the Evolution Space Station	Dr. Judith Ambrus *Assistant Director for Large Space Systems* *NASA Office of Aeronautics, Exploration and Technology*
5:00	Expanded Research and Development on Space Station Freedom	Dr. Edmond M. Reeves *Deputy Director, Flight Systems Division* *NASA Office of Space Science and Applications*

Wednesday August 7, 1991

8:00 - 11:45

STRATEGIES FOR EVOLUTION
Session Chair: Mr. W. Ray Hook
NASA Langley Research Center

Time	Topic	Presenter
8:00	A Historical Perspective on Space Station	Mr. W. Ray Hook *Director for Space,* *NASA Langley Research Center*
8:30	MIR: A Case Study for Evolution	Dr. B. J. Bluth *Technical Assistant to the Deputy Director, Space Station Freedom Program and Operations*
9:30	Break	
9:45	Space Station Advanced Studies	Mr. Peter Ahlf *Manager, Advanced Studies,* *NASA Space Station Engineering* *NASA, Office of Space Flight*
10:15	Space Station Advanced Development	Mr. Alan Fernquist *Manager, Advanced Development* *NASA Space Station Engineering* *NASA, Office of Space Flight*
10:45	Commercial Aspects of Space Station Freedom	Mr. Kevin Barquinero *External Programs Manager,* *NASA Space Station Engineering* *NASA, Office of Space Flight*

Time	Topic	Presenter
Wednesday	**August 7, 1991** *(continued)*	
11:15	Evolution Design Requirements and Design Strategy	Mr. Donald Monell *Space Station Freedom Office,* *NASA Langley Research Center*
11:45	Lunch	
1:30 - 4:45	PARALLEL SESSION: EVOLUTION CONCEPTS AND OPERATIONS Session Chair: Ms. Karen Brender *NASA Langley Research Center*	
1:30	Baseline Operations Concept	Mr. Granville Paules *Space Station Operations and Utilization* *NASA, Office of Space Flight*
2:00	Astronaut Scientific Associate	Mr. Silvano Colombano and Michael Compton *NASA Ames Research Center*
2:30	Growth User Requirements for Space Station Evolution	Mr. Kevin Leath *McDonnell Douglas Space Systems Co.,* *Washington SE & I*
3:00	Break	
3:15	SSF Growth Concepts & Configurations	Mr. William Cirillo *Space Station Freedom Office,* *NASA Langley Research Center*
3:45	STV Fueling Options	Mr. Kenneth Flemming *McDonnell Douglas Space Systems Co.,* *Kennedy Space Division*
4:15	A Safety Analysis of Cryogenic Propellant Handling on SSF	Mr. Sam Dominick *Martin Marietta* *Astronautics Group*
1:30 - 4:30	PARALLEL SESSION: SPACE STATION DATA SYSTEMS Session Chair: Mr. Edward Chevers *NASA Ames Research Center*	
1:30	Advanced DMS Architectures	Mr. Ed Chevers *NASA Ames Research Center*
2:15	Optical Protocols for Advanced Spacecraft Networks	Dr. Larry Bergman *NASA Jet Propulsion Laboratory*
2:45	Break	
3:00	Advanced Portable Crew Support Computer	Ms. Debra Muratore *NASA Johnson Space Center*
3:30	ISE Advanced Technology	Mr. Barry R. Fox *NASA Johnson Space Center*

Time	Topic	Presenter

Wednesday August 7, 1991 *(continued)*

4:00	Real-Time Data Systems	Mr. Troy Heindel *NASA Johnson Space Center*
4:30	Computer System Evolution Requirements for Autonomous Checkout of Exploration Vehicles	Mr. Mike Sklar *McDonnell Douglas Space Systems Company* *Kennedy Space Division*

Thursday August 8, 1991

8:00 - 11:45 PARALLEL SESSION: DISTRIBUTED SYSTEMS
Session Chair: Mr. Gregory Swietek
NASA Headquarters

8:00	Advanced Photovoltaic Power Generation	Mr. Edward Fisher *Boeing Defense and Space Group* *Huntsville, Alabama*
8:25	Advanced Solar Dynamic Power Systems	Mr. Michael Zernic *NASA Lewis Research Center*
8:45	Power Management and Distribution Evolution	Mr. Michael Zernic *NASA Lewis Research Center*
9:05	Solar Alpha Rotary Joint Capability Enhancement	Mr. David Snyder *Lockheed Missiles and Space Company*
9:30	Power Management and Control Automation	Mr. James Dolce *NASA Lewis Research Center*
10:00	Power Management and Distribution Automation	Mr. Louis Lollar *NASA Marshall Space Flight Center*
10:30	Break	
10:45	Active Thermal Control System Evolution	Ms. Patricia Petete *NASA Johnson Space Center*
11:15	Thermal Control System Automation	Mr. Roger Boyer *McDonnell Douglas Space Systems Company*
11:45	Lunch	

8:30 - 11:45 PARALLEL SESSION: ENGINEERING TOOLS AND TECHNIQUES
Session Chair: Mr. Mark Gersh
NASA Headquarters

8:30	Failure Environment Analysis Tool	Mr. Dennis Lawler *NASA Johnson Space Center*
9:00	Space Station Freedom Software Reconfiguration	Mr. Larry Grissom and Bryan Porcher *NASA Johnson Space Center*

Time	Topic	Presenter
Thursday August 8, 1991 *(continued)*		
9:30	Software Life Cycle Methodologies & Environments	Mr. Ernie Fridge *NASA Johnson Space Center*
10:30	Break	
10:45	Intelligent Computer-Aided Training	Mr. Bowen Loftin *NASA Johnson Space Center*
11:15	Knowledge Based Systems Scheduler Re-Host	Ms. Lynne Cooper *NASA Jet Propulsion Laboratory*
11:45	Lunch	
1:00 - 3:00	PARALLEL SESSION: DISTRIBUTED SYSTEMS Session Chair: Mr. Gregory Swietek *NASA Headquarters*	
1:00	EMU System Evolution	Mr. Michael Rouen *NASA Johnson Space Center*
1:30	ECLSS Evolution Analysis	Mr. Sandy Montgomery *NASA Marshall Space Flight Center*
2:00	Environmental Control and Life Support System Automation	Mr. Brandon Dewberry *NASA Marshall Space Flight Center*
2:30	Environmental Control and Life Support System Predictive Monitoring	Dr. Richard Doyle *NASA Jet Propulsion Laboratory*
1:00 - 3:00	PARALLEL SESSION: TELEROBOTIC SYSTEMS Session Chair: Mr. Alan Fernquist *NASA Headquarters*	
1:00	Telerobotic System Technology	Mr. Wayne Zimmerman, Mr. Paul Backes *NASA Jet Propulsion Laboratory*
1:30	Telerobotics Ground Remote Operation	Mr. Wayne Zimmerman, Mr. Bruce Bon *NASA Jet Propulsion Laboratory*
2:00	Collision Avoidance Sensor Skin	Mr. John Vranish *NASA Goddard Space Flight Center*
2:30	Mars Aerobrake Assembly	Mr. John Garvey *McDonnell Douglas Space Systems Co. Advanced Product Development and Technology Division*

Tandem Concentrator Photovoltaic Array Applied to Space Station Freedom Evolutionary Power Requirements

Edward M. Fisher Jr.
Boeing Defense and Space Group
Huntsville Division

Space Station Evolution Symposium
"Beyond The Baseline"
August 8th, 1991

[redacted]

Tandem Concentrator Photovoltaic Array Applied to Space Station Freedom Evolutionary Power Requirements

Edward M. Fisher Jr.
Boeing Defense and Space Group
Huntsville, Alabama

Abstract

Additional power is required to support Space Station Freedom evolution. Boeing Defense and Space Group, NASA Lewis Research Center and Entech Corporation have participated in the development of a High-Efficiency Tandem Concentrator Solar Array. Boeing's high efficiency Gallium Arsenide and Gallium Antimonide solar cells make up the solar array tandem cell stacks. Entech's Mini-Dome Fresnel lens concentrators focus solar energy onto the active area of the solar cells at fifty (50) times one sun solar energy flux. Development testing for a flight array, to be launched in November 1992, is under way with support from NASA Lewis. The tandem cells, interconnect wiring, concentrator lenses and structure have been integrated into arrays and subjected to environmental testing. A tandem concentrator array can provide high mass and area specific power and can provide equal power with significantly less array area and weight than the baseline array design. Alternatively, for Station growth, an array of twice the baseline power can be designed which still has a smaller drag area than the baseline.

FREEDOM

Tandem Concentrator Photovoltaic Arrays

BOEING

- **Background of Tandem Concentrator Technology**

- APEX Mission Flight Qualification Modules

- Large Array Design for SSF Evolution

FREEDOM

Boeing Tandem Concentrator Concept

BOEING

- Boeing 30%+ efficient tandem solar cells

- 4 year NASA/Entech mini-dome concentrator effort

- Technology combination promises exceptional power to weight and power to area performance

FREEDOM

Boeing Tandem Concentrator Concept

BOEING

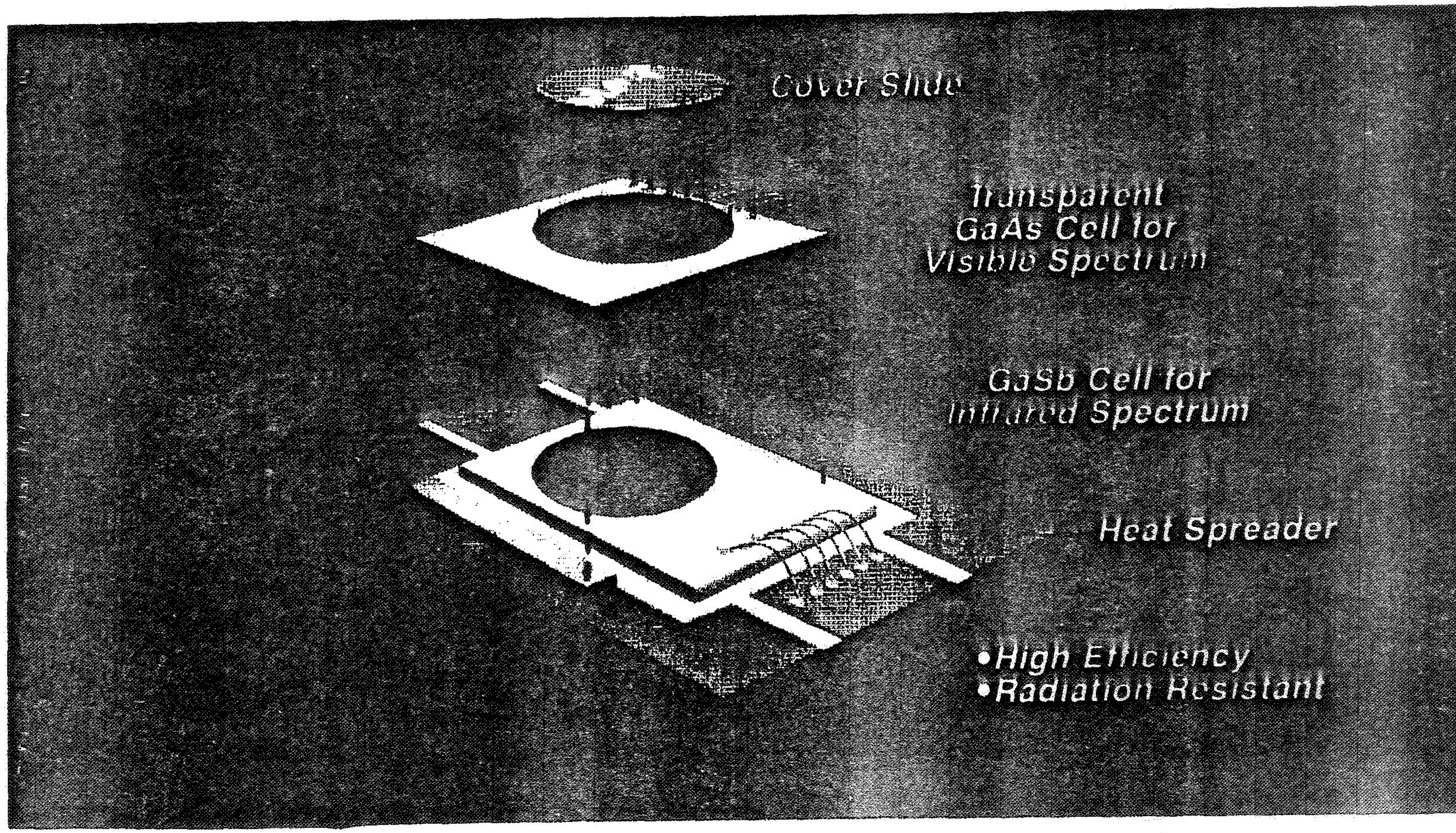
In 1990 Boeing announced a mechanically stacked tandem solar cell design capable of conversion efficiencies of more than 30% (AMO). The stack consist of an IR-transparent GaAs cell stacked on top of a GaSb cell. In an actual array the stacks are connected in triplets with the GaAs cells wired in parallel and the GaSb cells wired in series for voltage matching reasons.

The Boeing tandem cells have been flight tested at altitude in NASA's Lear-jet. The NASA data reported a conversion efficiency of 30.8% at 100 suns AMO.

For four years previous to this announcement NASA LeRC and Entech had been developing the mini-dome concentrator concept. By concentrating the sunlight on a relatively small chip with a domed fresnel lens one may substantially reduce costs by trading expensive cell material for cheaper lens and structure. Boeing contributed to this effort in the area of structural design of the panel and donated a 6 by 6 cell structure in 1991 which was used by Entech to assemble a prototype.

The marriage of these two technologies has been actively pursued since then in a joint effort to prove the concept can result in advanced photovoltaic arrays of much higher mass and area specific power than exhibited by present planar arrays while at the same time reducing cost per installed watt.

Boeing Tandem Solar Cell Design



ORIGINAL PAGE IS OF POOR QUALITY

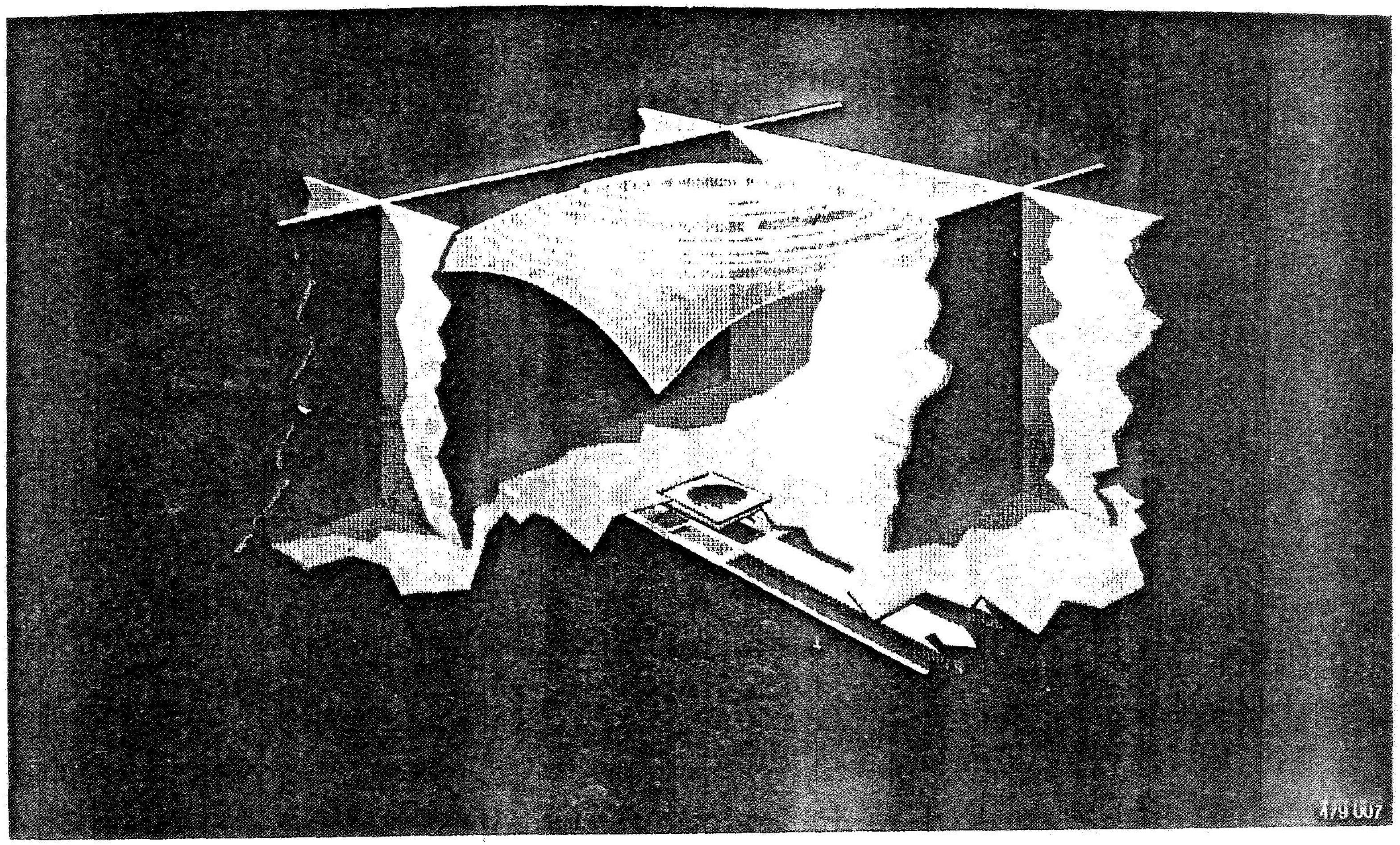
Boeing Tandem Solar Cell Design

The Boeing tandem solar cell design consists of two cells mechanically stack on top of each other. The top cell is a gallium arsenide (GaAs) chip which converts visible spectrum energy. It has been specially made to be transparent to the infrared solar spectrum which is absorbed by the bottom cell, a gallium antimonide (GaSb) chip.

The cells are mounted on a ceramic heat spreader which has had conductive areas plated to it to facilitate electrically connecting the cells to other stacks. In actual application, the stacks are wired together in triplets with the top cells of each triplet connected in parallel and the bottom cells connected in series for voltage matching reasons. The voltage matching scheme contributes several significant advantages in real-world applications.

A cover slide can be mounted on the top cell if required for radiation or plasma protection reasons. In addition, Entech has developed prismatic cover slides which, if adapted to the Boeing cell, can contribute a several percent performance increase.

Tandem Concentrator Arrangement



Tandem Concentrator Arrangement

A typical tandem concentrator arrangement consists of the domed fresnel lens, the cell stack and wiring, and the structure. The lens is actually a lamination of a glass dome and a molded silicone lens. It is cut square and bonded to the upper surfaces of an aluminum structure developed by Boeing. The cell stack is bonded to a ceramic insulator and heat spreader which is in turn bonded to the base surface of the structure. The interconnecting wiring is run inside the cavity where it is protected from atomic oxygen.

FREEDOM

Concentrator Advantages for Large Arrays

BOEING

- Significant reduction in cell material
- Smaller cells increase wafer yield
- Cost-effective to use high-efficiency cells
- Amenable to producibility increases via automation
- Structure and lens provide radiation protection

FREEDOM

Concentrator Advantages for Large Arrays

BOEING

A significant cost reduction is possible due to the much decreased amount of cell material required to produce an equivalent power output. The lenses and the structure required to support them costs considerably less than the large expanse of cell material which they replace.

Smaller chip sizes produce another advantage in that for a given size of Gallium wafer, and for a given number of surface defects, greater production yields are realized. This is due to better packing efficiency on the surface of the wafer for a larger number of small chips versus a smaller number of larger chips.

Another major advantage of the concentrator array concept is that it lends itself to high-rate production of large panels via automated methods similar to those in use in the microchip industry. At Boeing we are investigating methods for completely automated assembly of the back sheet which carries the cells and interconnecting wiring. The back sheet would later be joined to the rest of the panel structure.

Because the cell stack is completely contained within a closed structure, the degradation over time due to radiation may be lessened. This reduces the amount of overcapacity necessary to design into the system to achieve the end-of-life performance requirement. The degree of radiation protection has not yet been quantified or included in our array sizing calculations.

Tandem Concentrator Photovoltaic Arrays

- Background of Tandem Concentrator Technology

- **APEX Mission Flight Qualification Modules**

- Large Array Design for SSF Evolution

Flight Qualification Program

- Aggressive program to qualify modules for APEX
- Two 12-cell development units built & tested
  - Random Vibration and Shock (8.5 grms)
  - Thermal Vacuum (-73 to 90C)
  - Thermal Shock (-70 to 90C)
- Protoflight unit delivered to NASA LeRC in July
- Plasma test starting today at LeRC
- Two flight units to be delivered in October

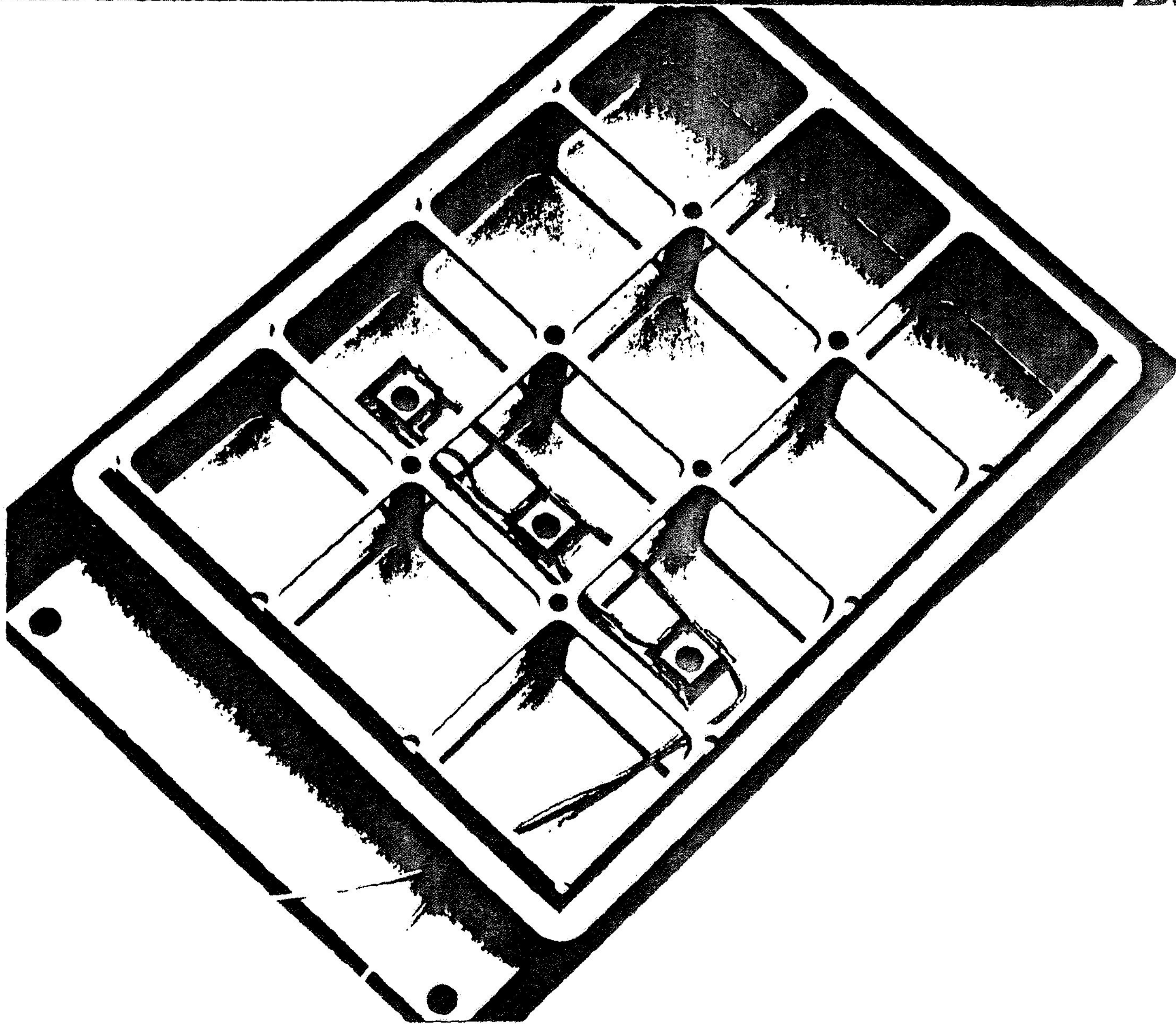
Flight Qualification Program

Since the beginning of this year an aggressive development program has resulted in the flight qualification of 12-cell tandem concentrator modules. Two development units were built and subjected to random vibration and shock tests, thermal vacuum and thermal balance tests and thermal shock tests. A protoflight unit was then assembled, subjected to full qualification testing and delivered to Lewis Research Center in July.

A plasma test article has also been delivered to Lewis Research Center and is schedule to begin plasma testing on August 8th.

Two more fully flight qualified units will be delivered in October, one of which will fly on the Pega-Star satellite and the other will take the place of the previously delivered protoflight unit. These units will have solar cells with even greater performance which is the result of on-going cell research and development.

Protoflight Unit Partial Assembly



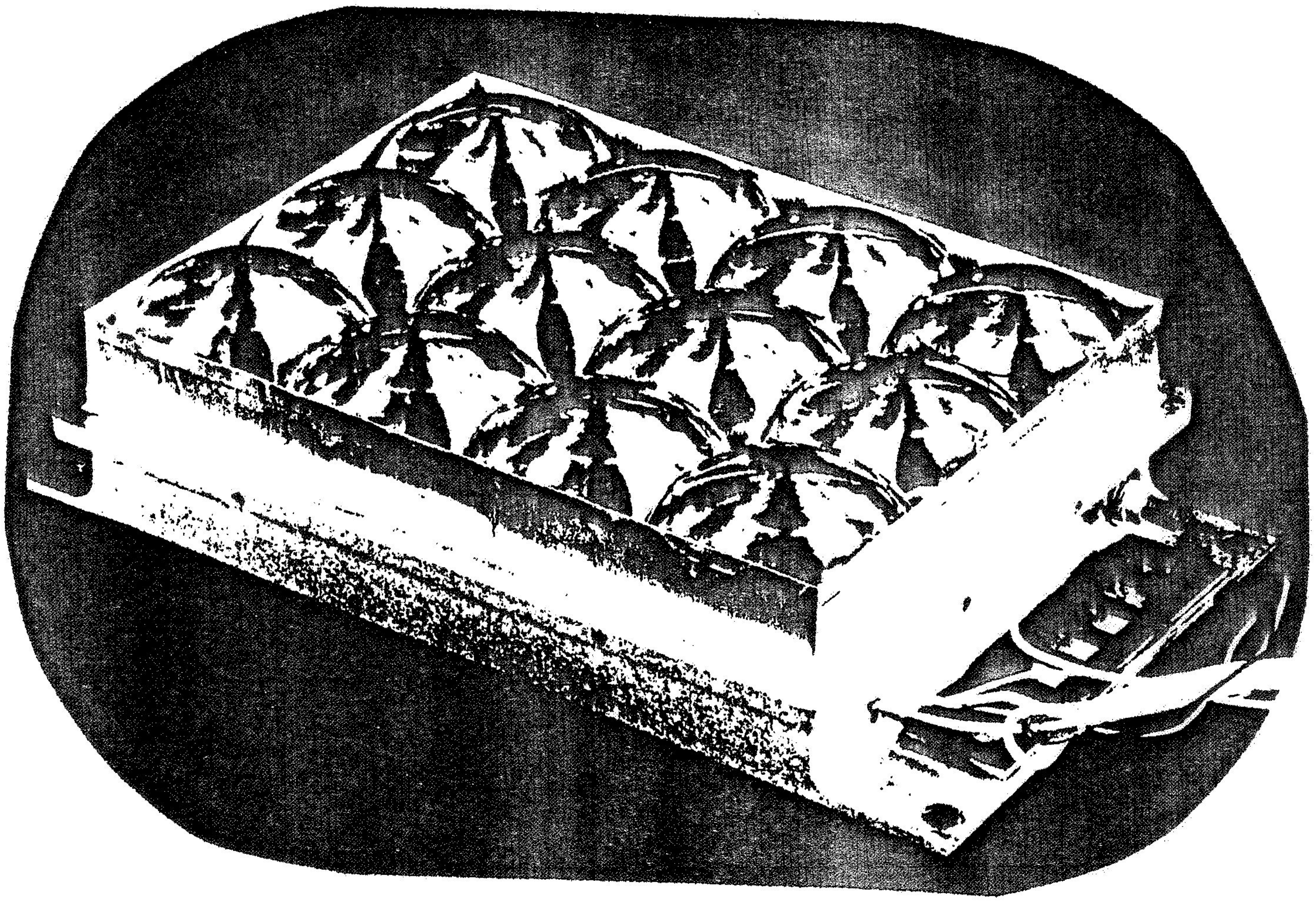
Protoflight Unit Partial Assembly

This slide shows a Boeing 12-cell protoflight unit when partially assembled. The mostly-open very light-weight aluminum structure can be seen with three cell stacks mounted on the bottom surface.

At the present time we are connecting the stacks with round wire because of the limited time available for development before the APEX mission. The preferred method is to use thick-film flat conductor and we are continuing to develop designs along those lines.

The flange which runs around the periphery at the top of the structure is specific to this design and is only for mounting a protective cover which is removed before flight.

APEX Mission Protoflight Unit



ORIGINAL PAGE IS
OF POOR QUALITY

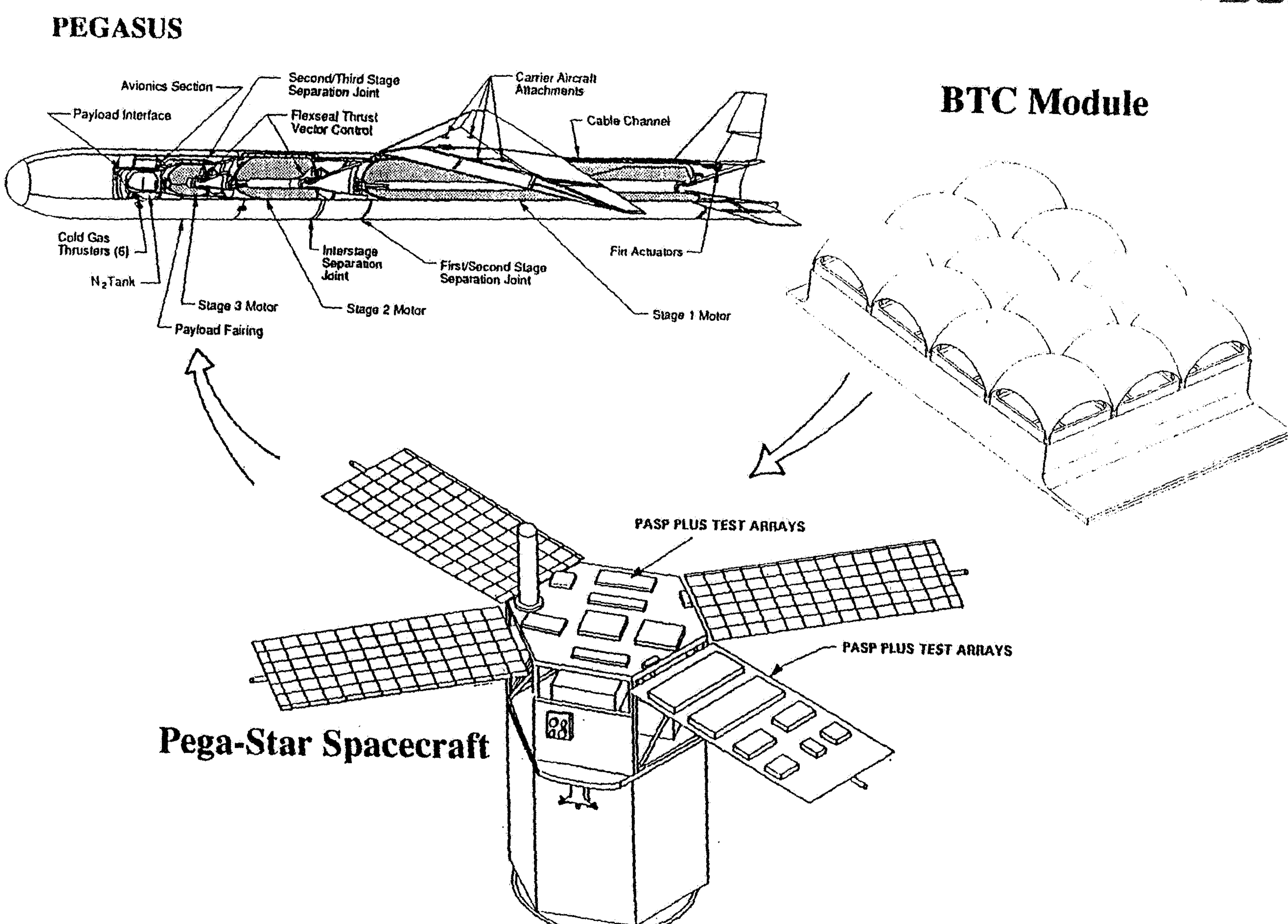
APEX Mission Protoflight Unit

This slide shows the completed protoflight unit. The lenses have been bonded to the top of the structure and a thin aluminum strip has been added as an atomic oxygen shield around the periphery. Also visible is a grounding screw and a phenolic connector strip where the interface to the spacecraft instrumentation is made.

FREEDOM

APEX Mission Diagram

BOEING



ORIGINAL PAGE IS
OF POOR QUALITY

APEX Mission Diagram

The Air Force's APEX (Advance Photovoltaic Experiment) mission will carry a total of three experiments with a minimum flight duration of one year. This flight is being conducted by the Air Force Geophysics Laboratory with experimental direction from the Air Force Wright Research Development Center's Aero Propulsion and Power Center.

One experiment is the PASP+ (Photovoltaic Array Space Power Plus Diagnostics) experiment which will test 13 different solar array designs in a high plasma and radiation environment.

The Boeing Tandem Concentrator module will be located on the sun-facing surface of the payload shelf of the Pega-Star satellite. The satellite is a 3-axis sun-stabilized platform. It will be injected into an orbit inclined at 70 degrees and fly a 350 km by 1850 km elliptical trajectory. This trajectory will repeatedly subject the experiments to high radiation levels while crossing the Van Allen belts, producing a 5 times greater exposure rate than the Space Station Freedom orbit. This is intentional to allow accelerated determination of radiation degradation rates. The orbit will also produce a highly charged plasma environment around the experimental solar arrays.

FREEDOM

Flight Experiment Characteristics

BOEING

- Direct space performance comparison of 13 arrays
- Voltage/current/temperature testing of each array
- High-bias voltage generation ($\pm$500v)
- Langmuir plasma probe
- Leakage current/arcing/radiation level sensors

Flight Experiment Characteristics

The PASP+ (Photovoltaic Array Space Power Plus Diagnostics) experiment will allow direct comparison of in-space performance of 11 different solar array types. During the flight voltage versus current curves will be generated to observe the power characteristics of each module under varying levels of illumination, bias voltage and plasma environments and at various operational temperatures.

A Langmuir probe will measure plasma characteristics while other instruments quantify arcing potential and leakage currents while the array is subject to various levels of bias voltage.

A dosimeter will be measuring ambient radiation levels to allow long-term correlation with degradation rates.

Tandem Concentrator Photovoltaic Arrays

- Background of Tandem Concentrator Technology
- APEX Mission Flight Qualification Modules
- **Large Array Design for SSF Evolution**

BTC Large Array Design Requirements

- ORU compatible with baseline Beta gimbal and power control system
- Same end-of-life power as baseline wing
- 0.1 g max. on-orbit acceleration
- 0.5 hz minimum frequency
- Plume impingement loads
- 2 degree pointing accuracy tolerance goal

BTC Large Array Design Requirements

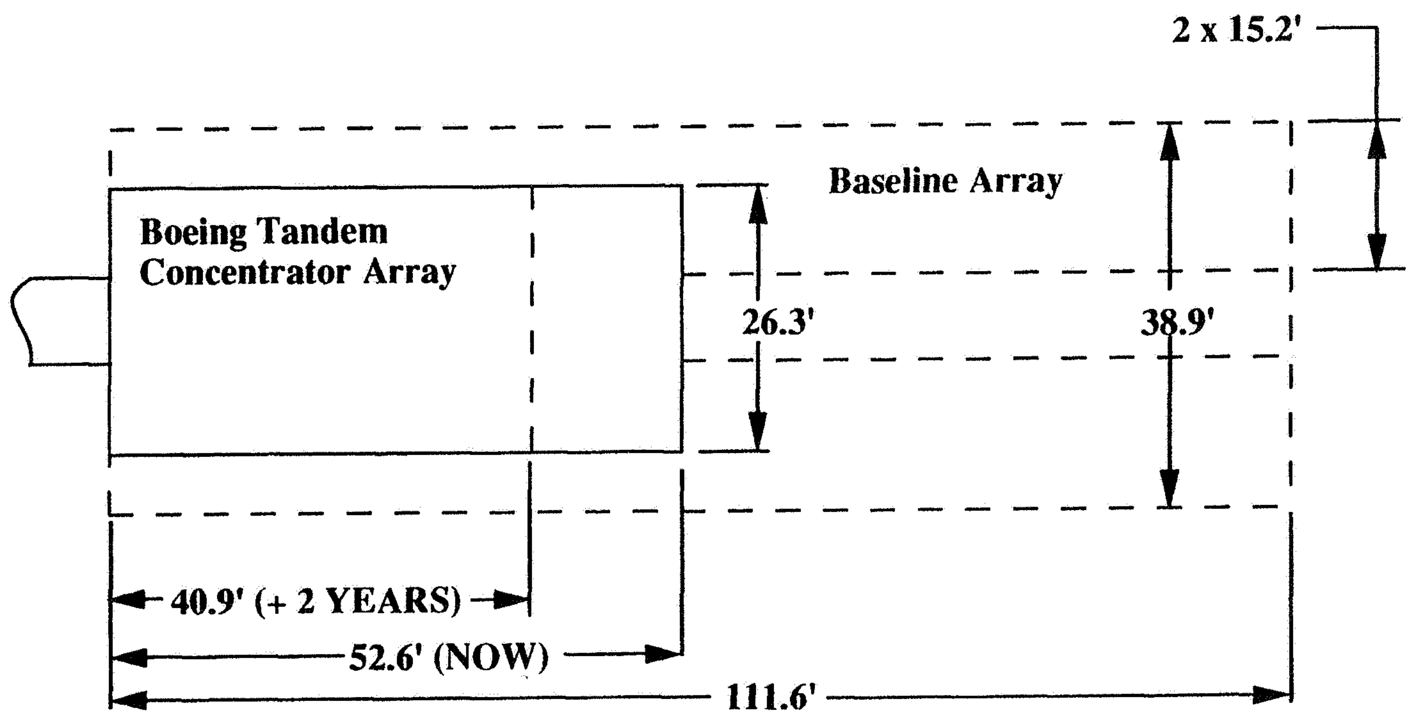
Boeing is developing designs for large tandem concentrator arrays by using the application to growth versions of Space Station Freedom as a design focus. We have therefore adopted as a requirement for the array the necessity of being an orbital replacement unit which interfaces directly to the baseline Beta gimbal and electric power distribution system. We have chosen to meet the end-of-life power and voltage requirements of the baseline array to allow easy comparisons. The design could just as well be scaled to an equivalent area as the baseline array and therefore produce more power.

Additional requirements are a 0.1 g maximum on-orbit acceleration level (calculated from the On-Orbit Structural Design Loads Data Book, SSP 30800, dated April 15, 1990) and a 0.1 hz minimum structural first mode frequency . We have set a design requirement of 0.5 hz for ourselves, however. Power production degradation has been estimated to be 17.4% over 15 years, slightly less than the baseline array due to the higher radiation resistance of gallium-arsenide cells. We have not included the benefit of the better protection afforded by the structure and lenses as yet. Our goal is to provide a 2 degree allowance for pointing accuracy.

FREEDOM

BTC Advanced Array Design

BOEING



FREEDOM

BTC Advanced Array Design

BOEING

The Boeing SSF growth array design uses cells of 5.4 mm diameter. The spherical lens provides a focus spot of 3 mm diameter. The extra cell material will allow a 2 degree off-axis pointing error before the sunlight energy begins to move beyond the power producing area of the cell.

Each panel in the array is composed of nine structural modules each containing 576 cell stacks (192 triplets). Each module structure is approximately 36" square and 1" deep. Based on current actual performance of assembled triplets and lenses a total of 18 panels are required to provide the needed end-of-life power and minimum voltage equal to a Space Station Freedom baseline wing. Our development program has produced rapid performance increases in the past year and we predict that within 2 years an additional 25% improvement in overall performance will be achieved. The expected performance increase will reduce the number of required panels to only 14 and bring us very close to our long-term performance goals.

BTC vs. SSF Baseline Performance

	BTC	Baseline
Power (kW, BOL)	29.4	30.8
Area (m^2)	128.8	315.4
Mass (kg)	421	849
Area specific power (W/m^2)	228.4	97.7
+ 2 year projection	293.5	
Design Goal	300	
Mass specific power (W/kg)	69.8	36.3
+ 2 year projection	87.8	
Design Goal	100	

BTC vs. SSF Baseline Performance

BTC array performance numbers are calculated using present power outputs from working triplets. These numbers therefore include all actual sources of loss such as lens scatter and reflection, interconnection losses, etc. Actual triplet performance has increased dramatically during this past year's development effort and increases are expected to continue in the future.

Two year projections for the BTC array are based on an assumption of a 25% total power increase believed achievable compared to the present actual performance. These increases are expected as the result of the addition of anti-reflective coatings on the lenses, better cell and lens efficiencies, and prismatic cell covers.

Weight calculations included the mast, blankets or panels, hinges or other locking mechanisms, and wire harnesses. Not included for either array are deployment mechanisms or actuators.

Baseline array performance numbers and area and weight calculations are taken from the WP-04 Preliminary Design Review package.

BTC Array Design For SSF Growth

- Double the baseline wing power
- Panel Area required = 258 m^2
- Wing mass = 900 kg; 0.4 hz minimum frequency
- Add 4 outboard wings for a 150 kw station

BTC Array Design For SSF Growth

Given the preceeding data we can speculate on what type of design might be required for the evolutionary Space Station. Assuming that the total station power level needs to be doubled, then an array which delivers twice the baseline power per wing would be desired. Using our 2 year projected values, such an array would have an area of 258 square meters and a mass of approximately 900 kg, assuming its minimum structural frequency would be 0.4 hz. Four such wings added outboard of the baseline array would increase the power available from 75 to 150 kw.

FREEDOM

Additional Areas of On-Going IR&D

BOEING

- Mechanisms and truss design for large arrays
    - Computer simulations of deployment dynamics
- Module design optimization and producibility
- Critical component detail design, fabrication and environmental testing
- Ready to support large-scale ground demonstration in 1992

Additional Areas of On-Going IR&D

At Boeing we have an on-going IR&D program which aims to develop every aspect of tandem concentrator technology. One such area are the mechanisms and truss structures needed to deploy large photovoltaic arrays in space. Once a design concept is identified, we use computer modeling techniques to simulate the static and dynamic behavior of such deployable trusses when weightless.

We are continuing to optimized our module structural design and are trading various materials against aluminum, notable GrEp and metal matrix materials. We are also investigating thepossibility of automating the stack assembly and interconnection tasks.

As the design studies identify critical components or processes needing development, we are fabricating prototypes and subjecting them to performance and environmental testing in our test chambers in Kent, Washington. This work is starting now and will be increasing in intensity through the remainder of this year and next.

As a result of these efforts we plan to be ready to support a large-scale ground demonstration, presently envisioned as a partial array with full-size components, in late 1992.

FREEDOM

Summary of Advanced Solar Power Program

BOEING

- High-efficiency cells and lenses developed and tested

- 12-cell modules have been flight qualified and will be spaceflight tested on APEX mission in 1992

  - This flight will achieve "Technology Readiness Level 7" for tandem concentrators

- Large-array design effort focussing on SSF evolution

FREEDOM

Summary of Advanced Solar Power Program

BOEING

Boeing has developed tandem solar cells with conversion efficiencies exceeding 30% when tested with standard methods at 100 suns and air mass zero. When combined with the mini-dome fresnel lens design underdevelopment at NASA and Entech photovoltaic arrays with significant performance gains compared to the present state of the art can be expected.

In the past year Boeing has developed and space qualified 12-cell modules using lenses from Entech and the Boeing tandem cells by combining them in lightweight aluminum structures and assembled the system using in-house micro-electronic processes. Such a module will be flight tested on the APEX mission and will elevate tandem concentrator design to NASA technology readiness level seven, which is "System Validation Model Tested In Space."

Boeing also has underway a program to develop tandem concentrator tehcnology further in every aspect from the individual cells to large array designs suitable for Space Station Freedom evolutionary requirements.

National Aeronautics and
Space Administration
Lewis Research Center

SPACE STATION SYSTEMS
OPERATIONS DIVISION

SOLAR DYNAMIC TECHNOLOGY STATUS FOR SPACE STATION FREEDOM APPLICATION

Presented to
Space Station Evolution Symposium
August 8, 1991

Michael J. Zernic
LeRC/Power System Operations and Planning Branch

SOLAR DYNAMIC TECHNOLOGY STATUS FOR SPACE STATION FREEDOM APPLICATION

This presentation has been compiled jointly by the Space Station Freedom Directorate and the Power Technology Division, both at Lewis Research Center. The objective of this presentation is to emphasize the 1) rationale to incorporate solar dynamic (SD) systems onto Space Station Freedom (SSF) as the power demand increases onboard SSF, 2) SD technical progress made through the SSF Program (SSFP), 3) areas of further technology development, and 4) future plans for SD system development.

Special thanks to:

Power Technology Division
James E. Calegeras
Joseph M. Savino

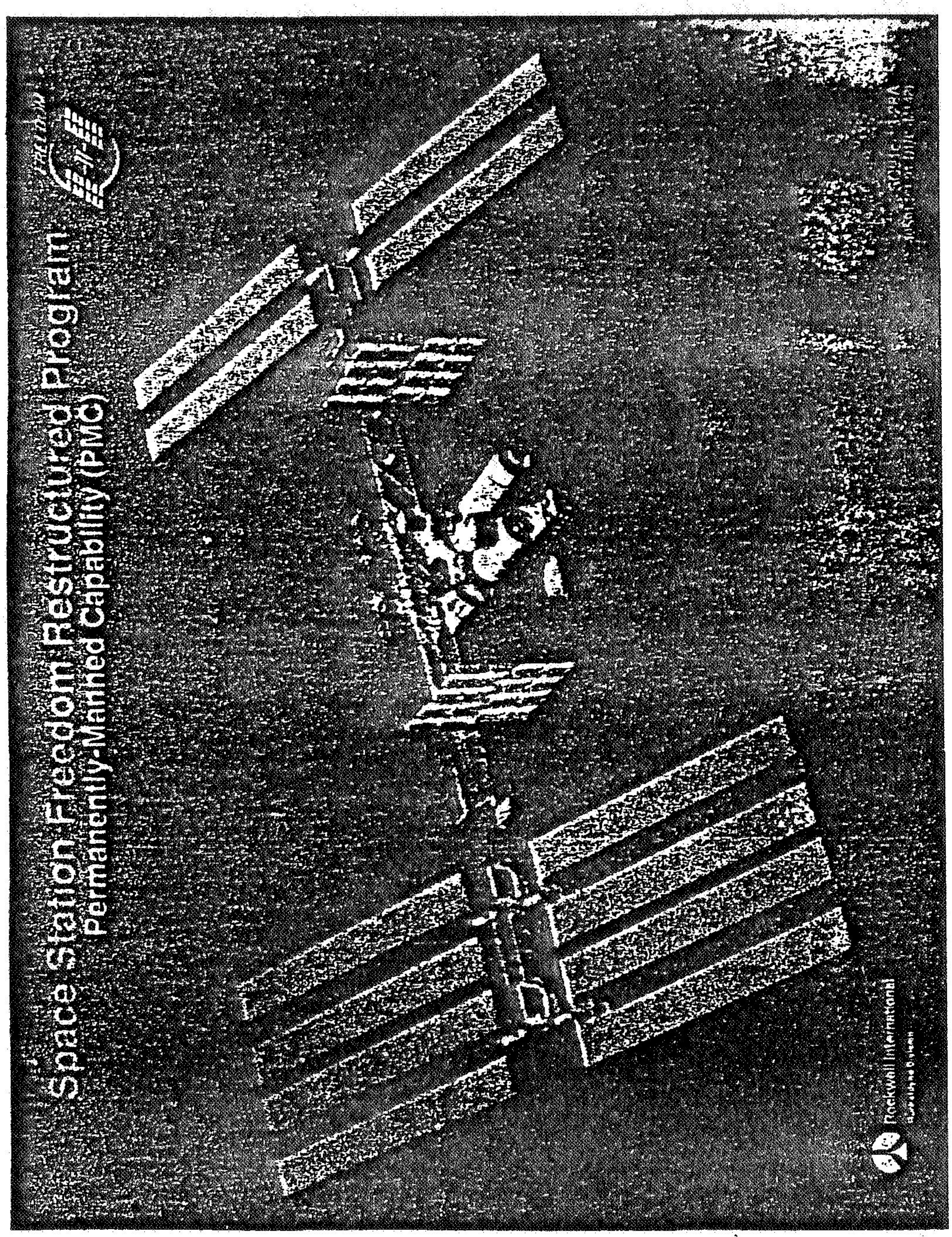
Space Station Freedom Directorate
Richard R. Secunde
Kent S. Jefferies

SSF HISTORICAL SYNOPSIS OF SOLAR DYNAMIC

- SSF PHASE B CONCLUDED THAT SD WAS THE VIABLE CHOICE TO COMPLEMENT PV
- SSF PHASE C/D COMPRISED OF 75 KW PV (PHASE 1) AND 50 KW SD (PHASE 2) + GROWTH
- SEVERAL PROGRAMMATIC CHANGES HAVE DOWNSCOPED SSF GROWTH
  - ★ SSF SD ACTIVITIES HALTED IN FY91
- ACTIVITIES ARE UNDERWAY TO REINSTATE GROWTH REQUIREMENTS (150 KW)
- OAET CONTINUES SD TECHNOLOGY DEVELOPMENT

SSF HISTORICAL SYNOPSIS OF SOLAR DYNAMIC

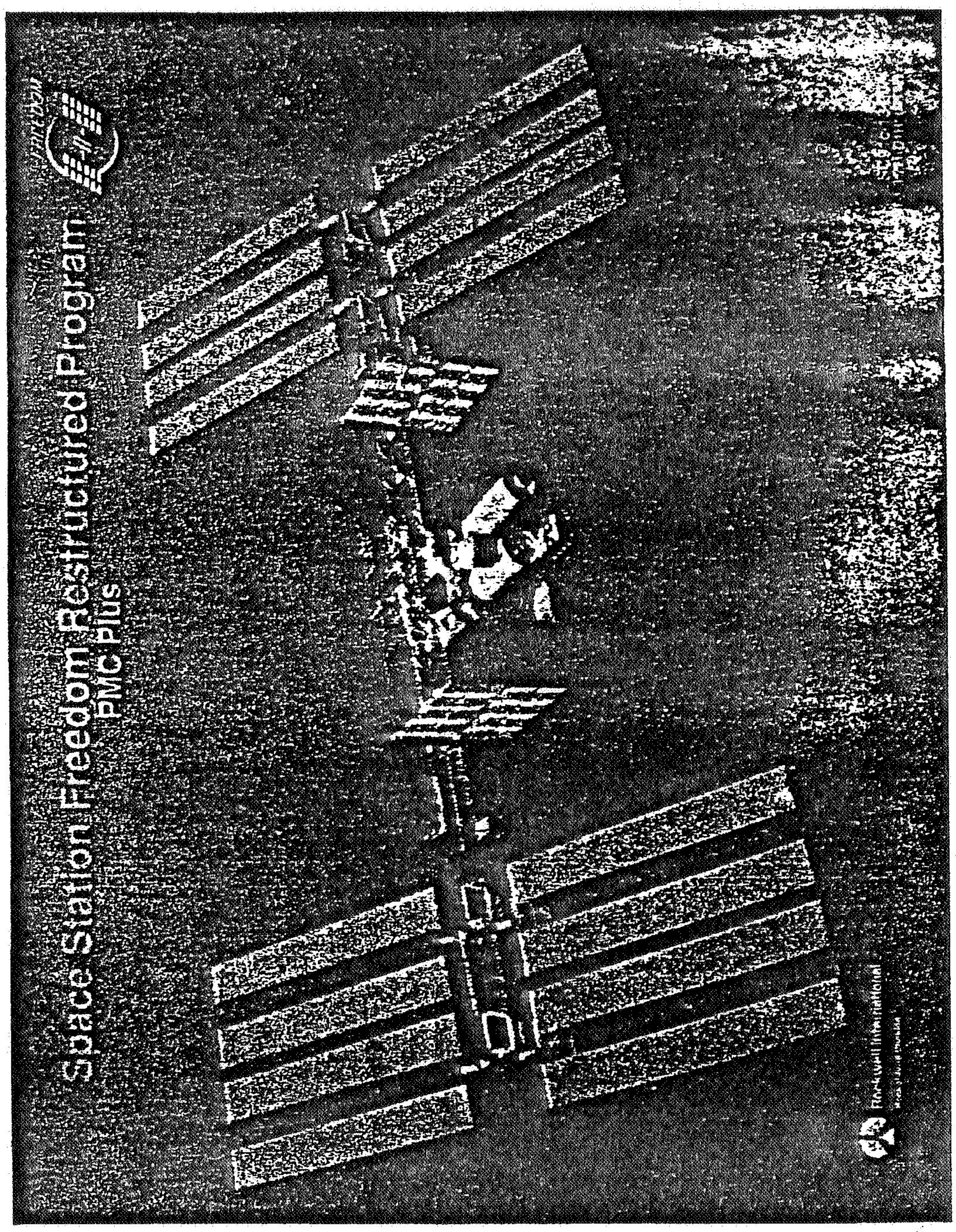
Solar Dynamic systems have existed for a long time in the form of terrestrial applications, space system concepts, and space based component testing. At the conclusion of the Phase B portion of the SSFP, it was decided that SD power was the viable choice to complement a photovoltaic (PV) system. In fact, the Phase B baseline consisted of 37.5 kw of PV and 50 kw SD split in power generation to serve SSF's demands. As an incremental approach for the progression of SSF, the Phase C/D part of the program consisted of a "Phase 1" SSF configuration of 75 kw PV, that grows to a "Phase 2" SSF configuration of an additional 50 kw SD, and has the capability to grow to 300 kw total. Since the start of the Phase C/D effort, several programmatic changes have relaxed or eliminated requirements on the baseline to be designed for growth. These changes culminated in the halt of SD activities in the SSFP in FY91. However, efforts are underway to reinstate growth requirements upon the baseline SSF that include growth and evolution of the Electric Power System (EPS) to reach a capability of 150 kw. Meanwhile, NASA's Office of Aeronautics, Exploration, and Technology (OAET) has always pursued solar dynamic advanced development, and has been the recipient of the progress made within the SSFP.


Space Station Freedom Restructured Program
Permanently-Manned Capability (PMC)
Rockwell International

SPACE STATION FREEDOM RESTRUCTURED PROGRAM PERMANENTLY MANNED CAPABILITY (PMC)

The Permanently Manned Capability (PMC) is a major milestone in the assembly of SSF. This is the baseline configuration to which programmatic requirements are satisfied, and to which SSF hardware/software is being designed. With respect to the EPS, this configuration consists of three PV Modules and six primary power channels. Each PV Module has a rated capacity of 18.75 kw average and 25 kw peak, and therefore the PMC configuration has a rated capacity of 56.25 kw average and 75 kw peak. However, peaking capability is limited and only available during insolation periods prior to the full battery complement. (The current baseline is to launch each PV Module without its full complement of batteries, and in some point in time, install the remaining batteries.) Each PV Module consists of these major items: two solar array wing assemblies, a thermal control subsystem, an electrical energy storage subsystems, and an electrical equipment subsystem. Two independent, primary power channels are fed from one PV Module, essentially one channel per PV wing. The PMC EPS design allows the addition of a fourth PV Module to add power to the Station, and achieve a "balanced" configuration of two PV Modules on the starboard and two on the port side.

C-91-03912

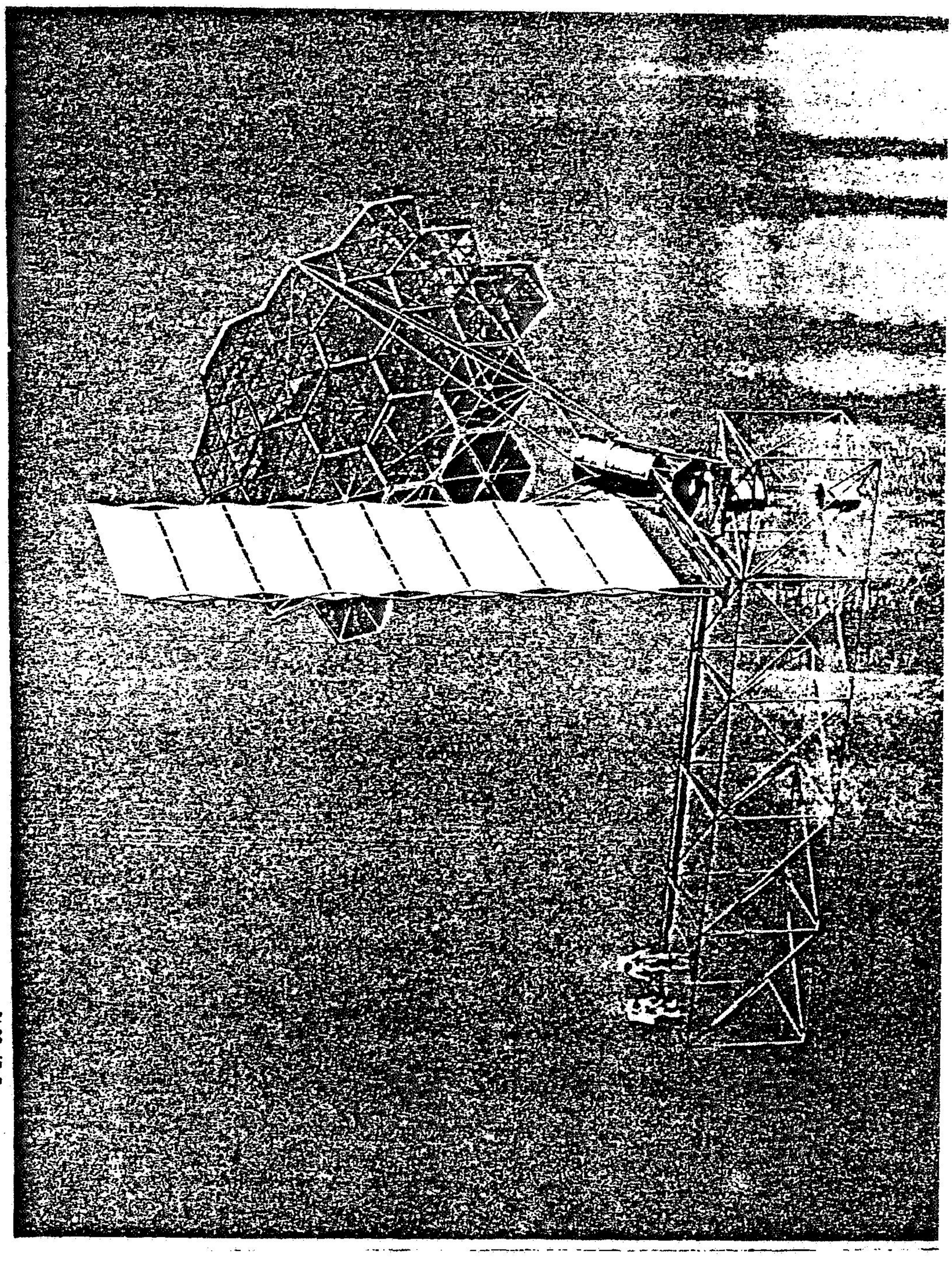


ORIGINAL PAGE IS
OF POOR QUALITY

SPACE STATION FREEDOM RESTRUCTURED PROGRAM
PMC PLUS

Permanently Manned Capability (PMC) Plus is a term used to describe the SSF configuration at a milestone just after the PMC milestone. Regarding the EPS, PMC Plus represents the addition of a fourth PV Module of the same rated capacity as the initial three PV Modules. This configuration achieves an eight channel primary power architecture at a system rated capacity of 75 kw average and 100 kw peak power with full complement of batteries.

Currently, there are no requirements at the designers level to design or plan for subsequent increase in EPS capacity.



C-87-3346

SPACE STATION SOLAR DYNAMIC POWER MODULE

Until recently, the planned design was to add solar dynamic power modules outboard of the initial PV Modules as the SSF demand for power increased. Each SD Module being designed for SSF would provide 25 kw net power to the user interface, and each consisted of:

CONCENTRATOR ASSEMBLY: 60 foot concave mirror focuses solar energy into the Receiver.

RECEIVER ASSEMBLY: Receives concentrated solar energy, and uses it to heat Helium–Xenon gas. Also, stores thermal energy for use during eclipse.

POWER CONVERSION UNIT: Hot Helium–Xenon gas drives a turbine–alternator–compressor set, producing the electrical power output.

ELECTRICAL EQUIPMENT ASSEMBLY: Controls SD module operation and converts alternator power output for delivery to users.

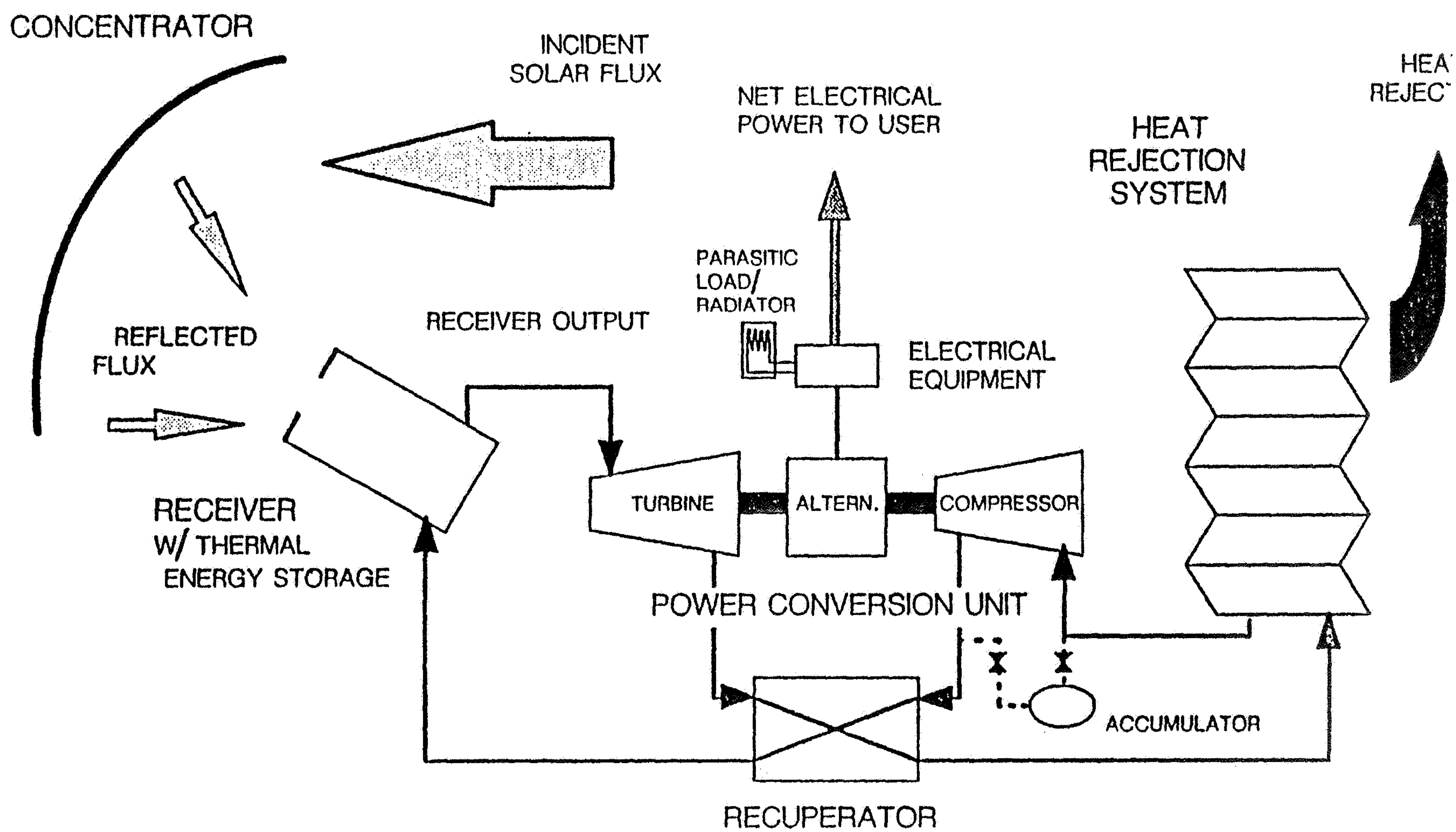
BETA GIMBAL ASSEMBLY: Points Concentrator Assembly at the sun as station moves through its orbit, and transfers power and data to the power distribution system.

VERNIER POINTING GIMBAL: Fine points Concentrator Assembly at the sun.

HEAT REJECTION ASSEMBLY: Radiates excess thermal energy to space to maintain necessary power levels and operating temperatures.

SPACE STATION FREEDOM

SOLAR DYNAMIC CLOSED BRAYTON CYCLE



SOLAR DYNAMIC CLOSED BRAYTON CYCLE

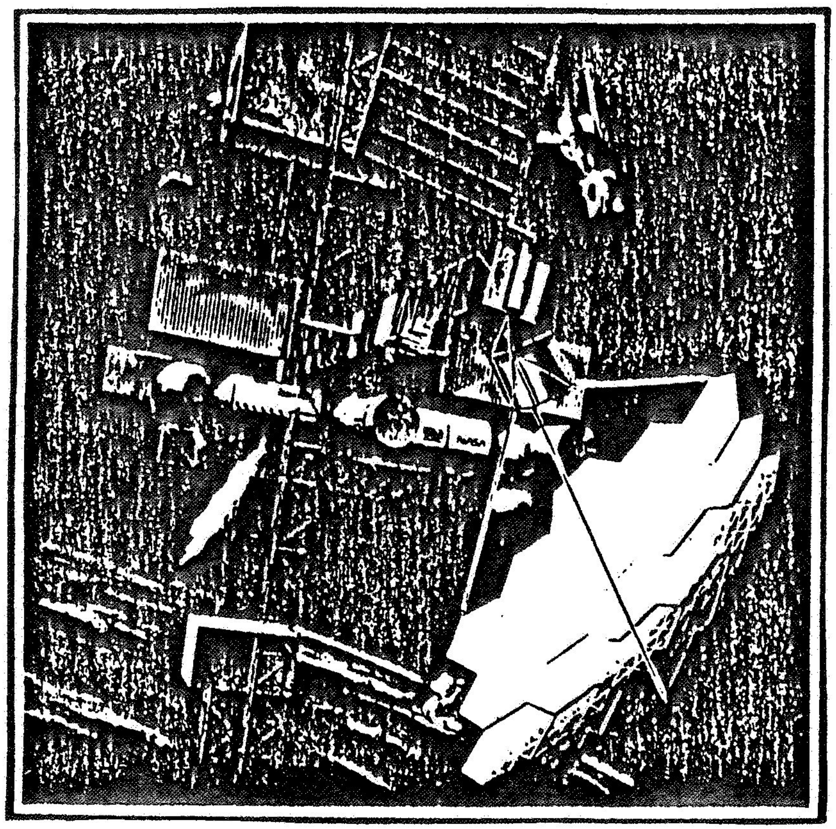
The key aspect of solar dynamics is that it functions as a system. SD not only coverts solar energy into electric energy (as is true of photovoltaics), but is also comprised of thermal energy storage and heat rejection functions as an integral part of its design.

The SD system operates when solar insolation is collected by the concentrator assembly and focused at the receiver assembly aperature. The solar energy entering the receiver assembly is transferred to the power conversion unit working fluid (helium–xenon chosen for SSF SD) and a thermal energy storage material (eutectic LiF–20CaF_2 chosen for SSF SD) for heat transfer to the working fluid during the eclipse portion of the orbit. The heated working fluid enters the power conversion unit (closed Brayton cycle chosen for SSF SD) for conversion from thermal energy into electrical energy. Power is then delivered by the power conversion unit for regulation and distribution to the user. To complete the cycle, the waste heat from the power conversion unit and the electrical equipment assembly is collected by the heat rejection assembly and radiated to the surrounding environment.

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

SPACE STATION FREEDOM

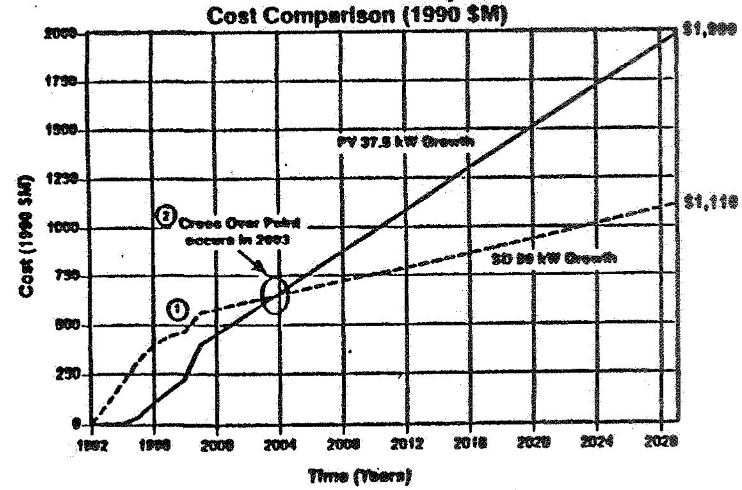


QUALITATIVE BENEFITS

- MORE FLEXIBILITY
- LONG LIFE COMPONENTS
- LESS DRAG
- LOWER MASS
- LOWER RECURRING COSTS
- LESS AGGREGATE EVA

QUANTITATIVE BENEFITS

Photovoltaic vs. Solar Dynamic
Cost Comparison (1990 $M)



Notes: 1. Step change between 1998 and 1999 is due to initial launch cost.
2. Curves based on current 18.75 kW PV and 25 kW SD power modules, in a balanced station configuration. Cross over would occur prior to year 2003 for common growth power levels.

EC91-001.4

ORIGINAL PAGE IS OF POOR QUALITY

SOLAR DYNAMIC vs. PHOTOVOLTAIC FOR SSF GROWTH

Incorporating SD as the growth power generation path for SSF is irresistibly attractive. The SD advantage goes beyond the initial, baseline PV system in that it rivals any technological advancement for any given PV component that comprises that system.

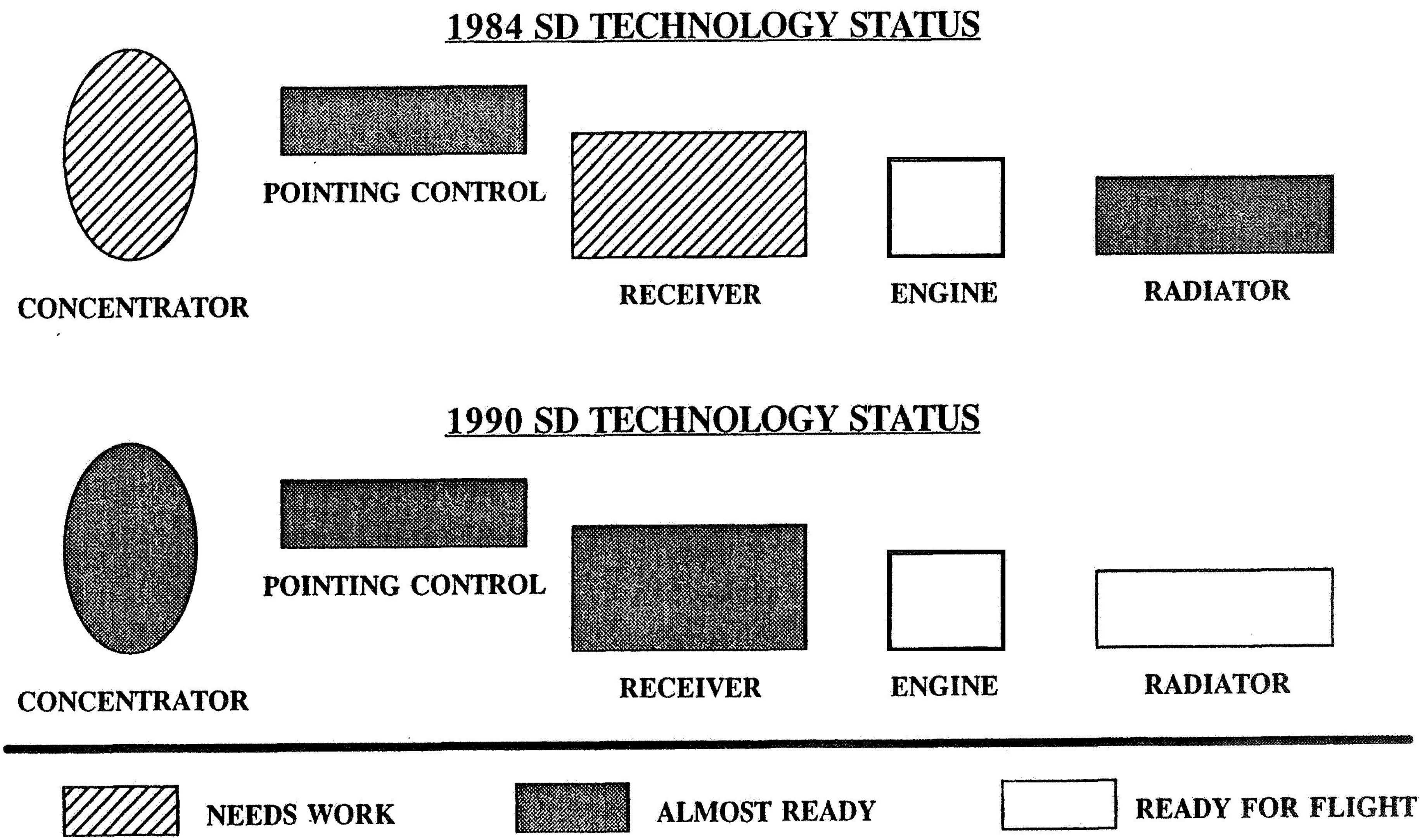
QUALITATIVE BENEFITS: For SSF, the addition of SD to complement the initial PV is a luxury that offers, not only more net power, but greater flexibility in that two types of sources in a hybrid configuration would assure an uninterrupted supply of power during periods of maintenance or in the unlikely event of a major or systematic problem in either type of source. The SD power generating and energy storage components also have longer lifetimes than the PV arrays and batteries. This results in substantial cost savings in hardware replacement, launch, and on–orbit installation costs. Because of the significantly higher solar–to–electric power efficiency, SD has a solar collection area only about 25% of that for a PV system for a given power output. This translates to about one–half the aerodynamic drag and correspondingly lower reboost requirements. Also, because SD produces more power per unit mass and has longer life components, SD means less mass to orbit. Although the SSF SD design required more manhours upfront to install than its counterpart PV, the less maintenance and resupply needed for SD quickly overcomes the aggregate manhours when the two systems are compared over the lifetime of SSF.

QUANTITATIVE BENEFITS: Studies have indicated that the various operations and hardware cost savings resulting in the use of SD power rather than PV power for SSF growth would amount to a reduction in life cycle costs of several billion dollars over the 30 year life of SSF. The results from one such study, shown here, show the comparison of adding SD vs. PV to an already existing SSF PV system. The dashed line shows the DDT&E plus production costs of 50 kw SD in the first 6 years, a noticible step indicates launch costs, and the out–year costs indicate the necessary support during the SSF lifetime. The solid line shows production only of 37.5 kw of PV in the first 6 years, launch, and out–year costs. This assumed that the DDT&E would be associated with the initial PV system. If the production costs were included, or if the growth power levels of each system were to be common (i.e., 50 kw growth for both PV and SD), then the crossover point would occur at an earlier point in time. Note that the yearly timeline is meant to only represent the SSF lifetime.

SPACE STATION SYSTEMS

OPERATIONS DIVISION

FREEDOM



SOLAR DYNAMIC TECHNOLOGY STATUS

From a technology perspective, the SD system can be broken down into five basic technology areas: concentrator, pointing control, receiver, engine, and radiator. When SSF Phase B concluded that SD would be part of the Program, it was realized that not all technology areas of SD were ready to be developed into flight hardware. However, many technological advances have occurred as a direct result of SD being a part of the SSF Program.

1984 TECHNOLOGY STATUS: The closed Brayton cycle was chosen to be the type of engine or power conversion unit because of its proven hardware history. However, the concentrator and heat receiver technology needed some work to minimize the technical risk. Nothing like the proposed SD concentrator had been assembled in space and there were thermal questions associated with the receiver. The pointing control and radiator areas were not quite ready but no technical barriers were identified to prevent a timely development.

1990 TECHNOLOGY STATUS: When SSF SD activities were halted, several aspects of SD technology had advanced. The radiator was deemed to be common with the radiator under development for the PV module, and through many tests and demonstrations the concentrator and receiver areas had progressed to the point as almost ready for flight hardware. Although the pointing control area does not show significant progress, this area had not received the attention it deserved until recently but is still deemed as an almost ready technology area.

CONCENTRATOR TECHNICAL PROGRESS

- REFLECTIVE/PROTECTIVE COATINGS
  - DEMONSTRATED REFLECTIVE COATING DEPOSITION
  - COATING DURABILITY TESTED

- OPTICAL CHARACTERIZATION
  - DIGITAL IMAGE RADIOMETER CHARACTERIZED REFLECTIVE SURFACE OPTICS
  - OPTICAL CODE DEVELOPED FOR A FULL SIZE CONCENTRATOR

- STRUCTURAL RIGIDITY/ACCURACY AND ASSEMBLY
  - DEMONSTRATED 19–PANEL ASSEMBLY AND STRUCTURAL REPEATABILITY
  - LATCHING GUIDES DESIGNED AND BUILT
  - STRUCTURAL RIGIDITY OF LATCH AND PANEL DESIGNS MODELED AND TESTED
  - CONCENTRATOR PANEL ASSEMBLY TESTS IN MSFC NBF VERIFIED CONCEPT

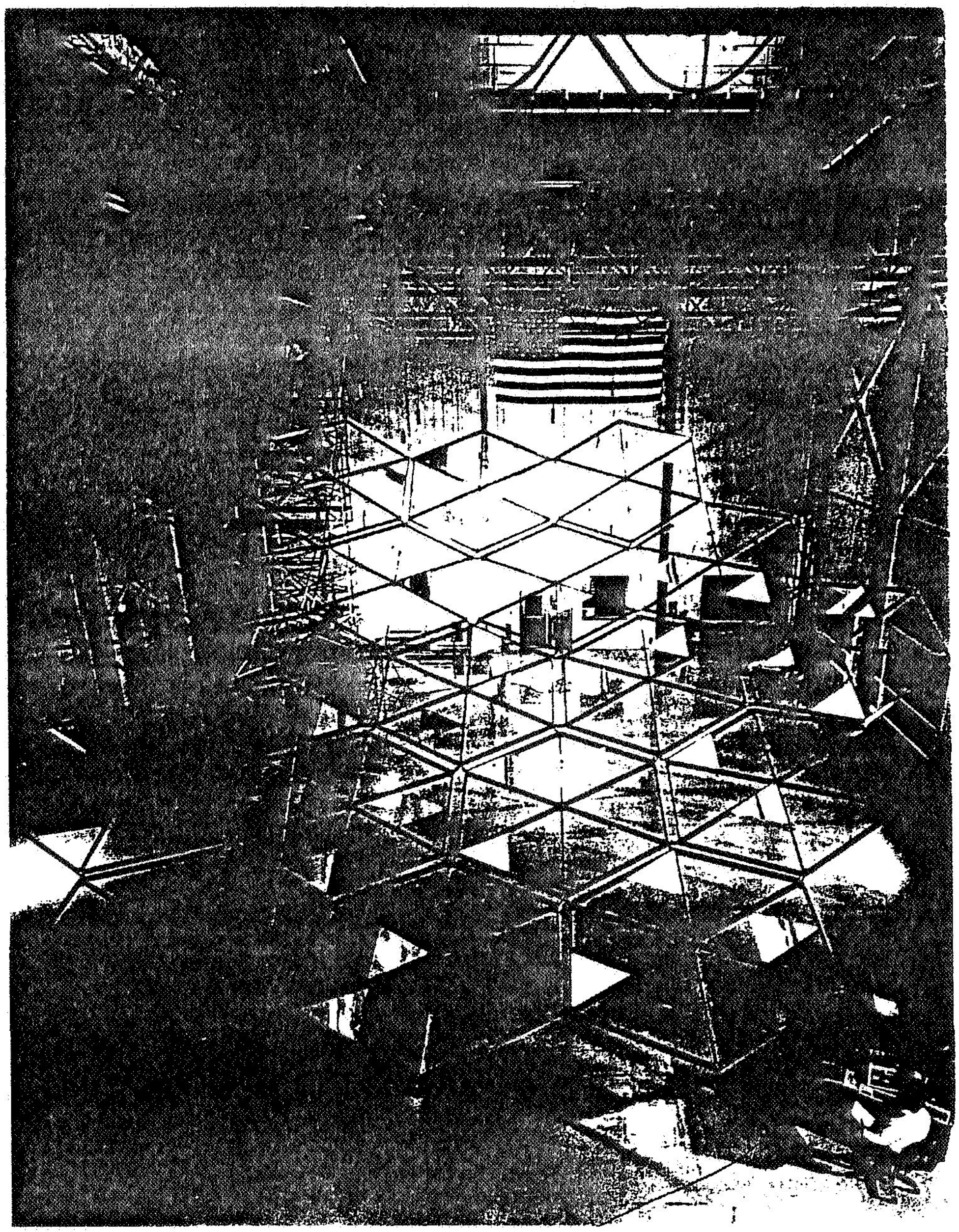
CONCENTRATOR TECHNICAL PROGRESS

Technical progress for the concentrator area can be broken down into three areas: reflective and protective coatings for the concentrator surface, optical characterization of the reflective surface and surface contour, and structural rigidity/accuracy and assembly of the concentrator panels.

REFLECTIVE/PROTECTIVE COATINGS: The need for highly reflective materials on the concentrator facets was meet by successfully demonstrating the depositing of a film of reflective coating on a concentrator facet. At the time, vapor deposited aluminum was deemed the best overall coating. Also, asher tests (simulated space environment with accelerated degradation effects) were performed on coupons of several candidate coatings to examine coating durability. LDEF data has not yet been analyzed for this purpose.

OPTICAL CHARACTERIZATION: A full size concentrator was assembled and populated with vapor deposited aluminum facets at several, predetermined locations on the concentrator. A Digital Image Radiometer (DIR) was used to characterize the reflective surface optics. Also, an optical code was developed for a full size concentrator.

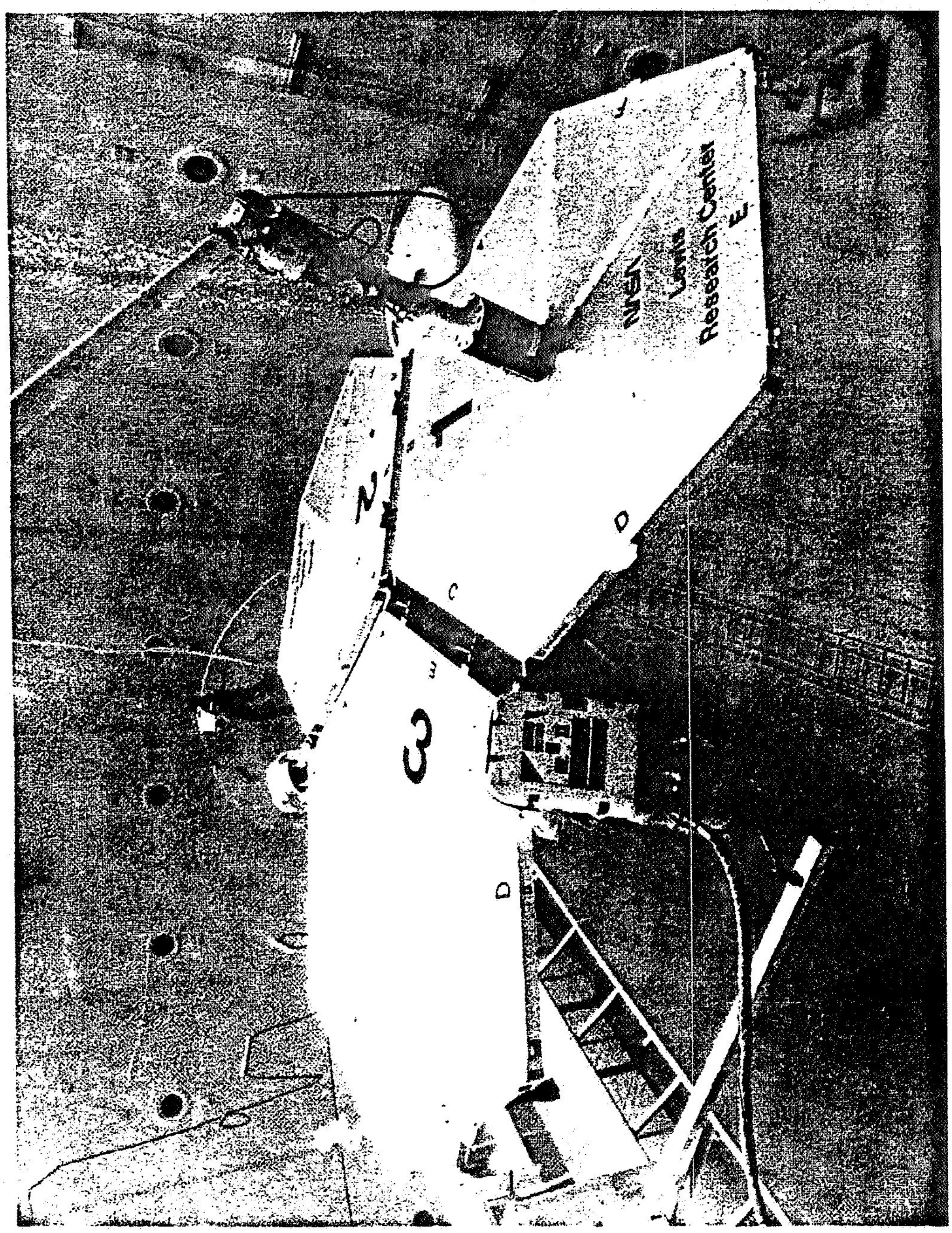
STRUCTURAL RIGIDITY/ACCURACY and ASSEMBLY: A key item for concentrator technical progress has been the demonstration of the assembly of 19 panels of a full size concentrator. In addition, several 1-g assembly/disassembly tests have assured the structural integrity of the entire concentrator, including its structural rigidity and optical accuracy. In support of this activity, latching guides were designed and built, and the structural rigidity of the latch and panel designs were modeled and tested. This area of technical progress climaxed when concentrator panel assembly tests in MSFC's Nuetral Buoyancy Facility (NBF) verified that this concept was readily achievable by astronaut interaction in a weightless environment.



CONCENTRATOR TECHNICAL PROGRESS

Shown here is a full scale assembled concentrator in the Power System Facility (PSF) building at Lewis Research Center. This concentrator consisted of 19 hexagonal panels, each of which would hold 24 triangular mirrored facets, when fully populated. Each panel is connected to its adjacent panel by unique latching mechanisms. This particular test was only populated with relatively few facets, but were positioned in predetermined, strategic locations. Several methods were used to gain data on the optical characteristics of the facets and concentrator. One method was the use of a Digital Image Radiometer (DIR). This utilized a bank of position adjustable overhead lights that would illuminate a particular facet to be tested and the reflected light would be recorded by a TV camera and fed into a computer for analysis. Another method used, that was similar to DIR but more tedious, was the tracing of a laser beam from overhead to measuring the position of the reflected beam. Also, a more comprehensive test involved the positioning of a light source at the concentrator focal point and recording data.

Of utmost significance was the ability for the repetitious assembly and disassembly of these 19 panels in 1-g without any significant differences in the optical accuracy when retested, using DIR for example. This confirmed the structural rigidity and optical accuracy of the latch and panel designs.



CONCENTRATOR TECHNICAL PROGRESS

Shown here is a picture taken during a SD concentrator assembly test in the Nuetral Buoyancy Facility (NBF) at Marshall Space Flight Center. These series of tests, Concentrator Panel Assembly Tests (COPAT), were conducted around August 1990 and were a critical part of the early design evaluation process that allowed for reduced technical and schedule risks for: latch and guide mechanism design, baselining the concentrator configuration, and flight operations and procedures.

The objectives of these tests were to evaluate the feasibility of current concentrator latch mechanisms and guides designed for on-orbit assembly, evaluate anticipated flight operations and assembly procedures for the concentrator, evaluate astronaut positions for on-orbit assembly, and to assess handhold locations and position to gain the required leverage and line-of-sight for assembly.

The primary accomplishment from the COPAT test series was that the precision latch and guide concept and associated assembly procedures/orientations were demonstrated. These tests demonstrated the ability of successful on-orbit assembly of the SD concentrator, or in general, large space structures.

RECEIVER TECHNICAL PROGRESS

- THERMAL STORAGE MATERIALS COMPATIBILITY AND MECHANICAL STRENGTH
  - SALT EXPOSURE (20,000 hrs) HAD NO IMPACT ON CONTAINMENT MATERIAL
  - MECHANICAL PROPERTIES DATABASE WILL ENHANCE STRUCTURAL ANALYSES
- THERMAL ENERGY STORAGE PERFORMANCE IN MICRO-GRAVITY
  - CONSERVATIVE TES DESIGN APPROACH ADOPTED
    - ☆ SALT COMPARTMENTALIZATION
    - ☆ CONDUCTION PATHS
  - "ALL-ATTITUDE" CANISTER TESTS QUANTIFIED VOID IMPACTS
  - STRUCTURAL ANALYSES & THERMAL TESTING CONFIRMED CANISTER INTEGRITY
- RECEIVER THERMAL PERFORMANCE
  - TESTS CONFIRMED CONSTANT TURBINE INLET TEMPERATURE W/ CYCLIC INPUT
  - SINGLE TUBE TEST VERIFIED TES CONFIGURATION (6500 hrs of cyclic testing)
  - ALTERNATIVE, FULL SCALE RECEIVER TESTED IN THERMAL/VACUUM TANK

RECEIVER TECHNICAL PROGRESS

Technical progress for the concentrator area can be broken down into three areas:

MATERIALS COMPATIBILITY & MECHANICAL STRENGTH: This area addressed the interaction between the thermal energy storage (TES) material, the material that contained the TES material and thermal cycling. The containment material, Hanes 188, was exposed the TES material, a eutectic lithium flouride calcium flouride ($LiF-20CaF_2$) salt, for 20,000 hours isothermally at 1093 degrees K. This, along with mechanical strength tests and pertinent previously recorded information showed no impact between the TES material and the containment material.

TES PERFORMANCE IN MICRO-G: Micro-gravity effects on the behavior of the TES material undergoing thermal cycling posed an interesting challenge. Location and effect of voids in the salt created during the continous freeze/thaw cycles was the prime concern. Therefore, a conservative design approach was adopted by containing the salt in many small compartments (canisters) that minimized the void concern and provided excellent conduction paths between the incoming solar energy, the containment material, the salt, and the working fluid which is to be heated. Canister tests in 1-g quantified the void impacts. These tests heated the canisters held at various attitudes relative to gravity and essentially made the canisters gravity insensitive. Structural analyses and "worst-case" thermal testing of the canisters confirmed the integrity of the canister. Therefore, since TES performance was verified by ground testing and analysis, no flight test is required for this conservative design approach.

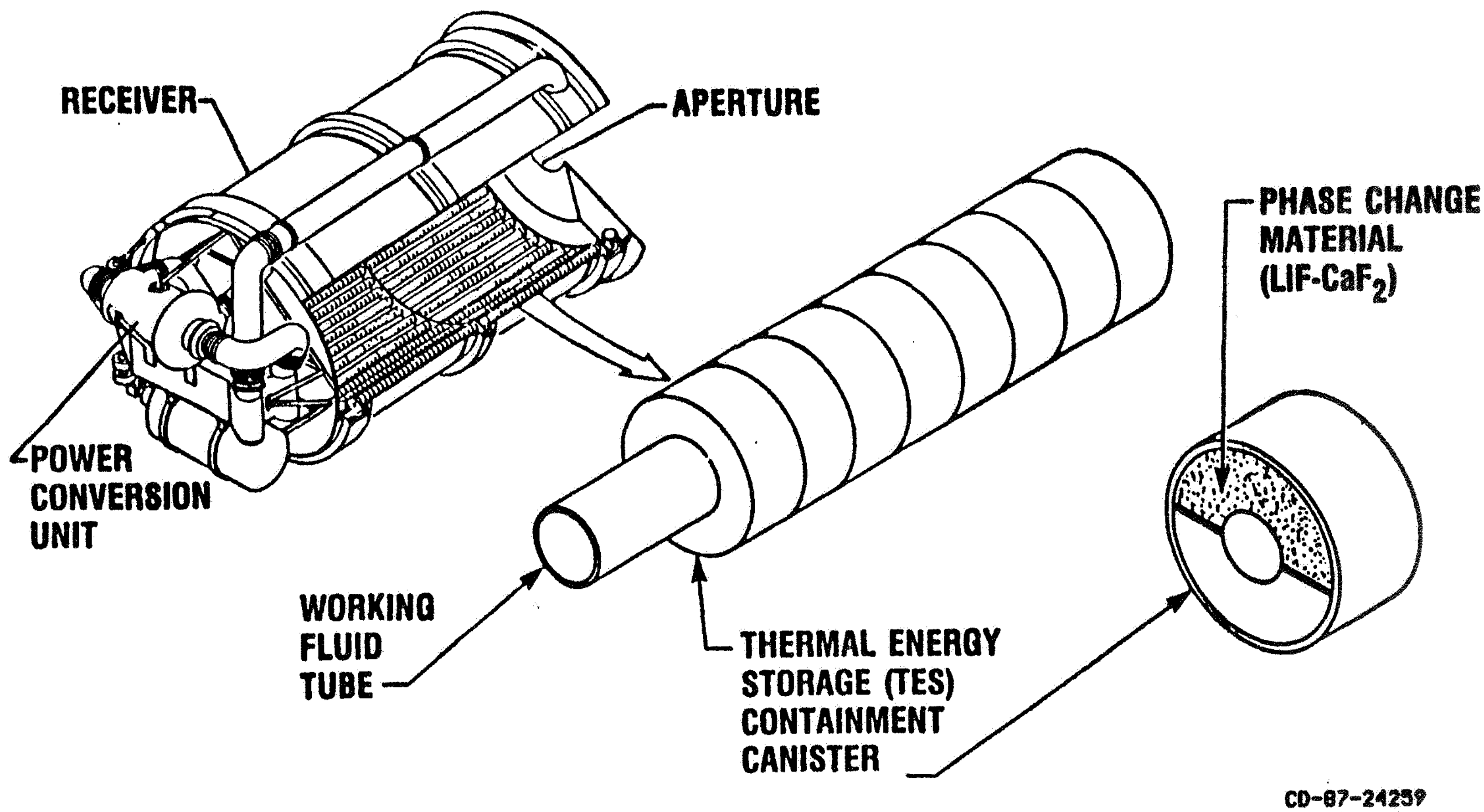
THERMAL PERFORMANCE: From the standpoint of the heat receiver as a whole, tests have confirmed that a relatively constant turbine inlet temperature is achieved with cyclic solar input. Also, a single tube test with its respective number of canisters verified operation of the TES configuration (6500 hours of cyclic testing). As an alternative, an independent design concept has been tested at full scale in a thermal/vacuum environment. This concept uses a metallic "felt" (analogous to a brillo pad) as the TES containment material that is wrapped around the working fluid tubes and is also aimed at minimizing the effect of salt voids. Also, a solar lamp array (for vacuum use) was developed that was placed inside the receiver to radially, axially, and in time simulate solar flux in a controlled manner.

National Aeronautics and
Space Administration

Lewis Research Center

SPACE STATION FREEDOM

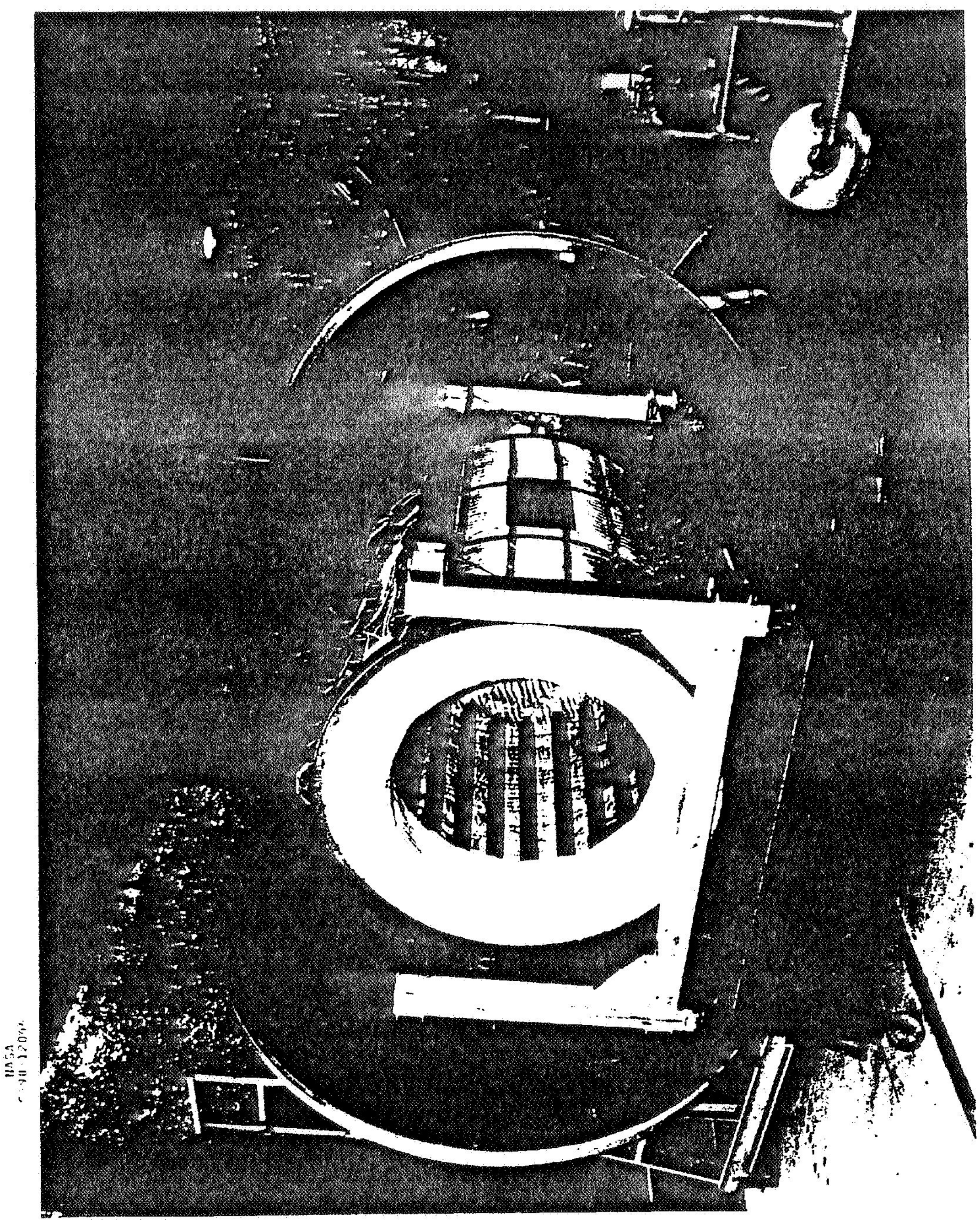
THERMAL ENERGY STORAGE



RECEIVER TECHNICAL PROGRESS

Shown here is a drawing of the heat receiver to be used in the SSF SD design. The equipment shown on the left face of the cylindrical receiver is the power conversion unit (closed Brayton cycle engine). Note that the inside of the receiver contains many working fluid tubes, in which each tube holds several thermal energy storage containment canisters.

This conservative design approach was found to not warrant a flight test.



ORIGINAL PAGE IS
OF POOR QUALITY

RECEIVER TECHNICAL PROGRESS

Shown here is the full scale alternative receiver designed by Boeing. The receiver is shown being loaded into the thermal/vacuum tank at the Boeing facility. The solar lamp array was then placed inside the receiver to simulate solar flux in the tank environment.

RADIATOR TECHNICAL PROGRESS

- MICROMETEOROID AND SPACE DEBRIS IMPACT
  - FLUID PASSAGE SURVIVABILITY TESTED
  - SURVIVABILITY BETTER THAN ANALYTICAL PREDICTIONS
- DURABILITY OF THERMAL COATINGS
  - AO, UV, AND THERMAL CYCLING TESTS OF 19 CANDIDATE COATINGS
- COMMONALITY WITH PV DEVELOPED RADIATOR
  - ACCOUNT FOR DIFFERENT WORKING FLUID
  - ACCOUNT FOR LARGER POWER DISSIPATION

RADIATOR TECHNICAL PROGRESS

Technical progress for the radiator area can be broken down into three areas: micrometeoroid and space debris impact, durability of thermal coatings, and commonality with the SSF developed PV radiator.

MICROMETEOROID/SPACE DEBRIS IMPACT: Technical and design issues have arisen with the growing concern of micrometeoroid or space debris impacts on the survivability of certain hardware, especially over long operating lifetimes. Of special concern were the fluid passages that constitute the heat rejection system. It was necessary to investigate the effect of space particle impacts on the functionality of the radiator. Sections of the radiator underwent particle impact testing and the integrity of the fluid passages and their function survived better than analytically predicted.

THERMAL COATINGS: Coatings necessary to optimize the radiator efficiency and survive orbital thermal cycling were tested. Atomic oxygen, UV radiation, and thermal cycling tests of 19 candidate coatings were conducted.

COMMONALITY WITH PV RADIATOR: An effort was made to minimize technical risk by investigating the possibility of common radiators between the SD module and the PV module developed in the baseline SSF Program. This was in fact possible with the exception of a different working fluid to account for higher inlet temperatures, and the radiator area would need to be slightly larger to account for larger power dissapation.

Because no technical barriers were found and the affirmation that SD could benefit from the development of the SSF baselined PV module radiator, this technology area for SD is now deemed as ready for flight development.

ASD SYSTEMS TECHNOLOGY

SOLAR DYNAMIC TECHNOLOGY PERFORMANCE GOALS

PERFORMANCE REQUIREMENT	CURRENT SOA	ADVANCED SOLAR DYNAMICS (ASD)
ORBITAL SYSTEMS		
• SPECIFIC POWER	5 - 8 W/kg	16 - 20 W/kg
• CONCENTRATOR		
- MASS	4 kg/sq. m.	1 - 2 kg/sq. m.
- CONTOUR ACCURACY	4 MILLIRADIANS	1 MILLIRADIAN
• RECEIVER		
- MASS	50 kg/kW	25 kg/kW

JC-91.01-3-pm

ASD SYSTEMS TECHNOLOGY

SOLAR DYNAMIC TECHNOLOGY PERFORMANCE GOALS

* The system specific power is affected by the total system efficiency and the total system weight. The R&D done in the Advanced Solar Dynamic Program to increase the efficiency of the major components and subsystems and to reduce their size and weight point to the improvements that can be made in the specific power of the ASD systems for future space applications.

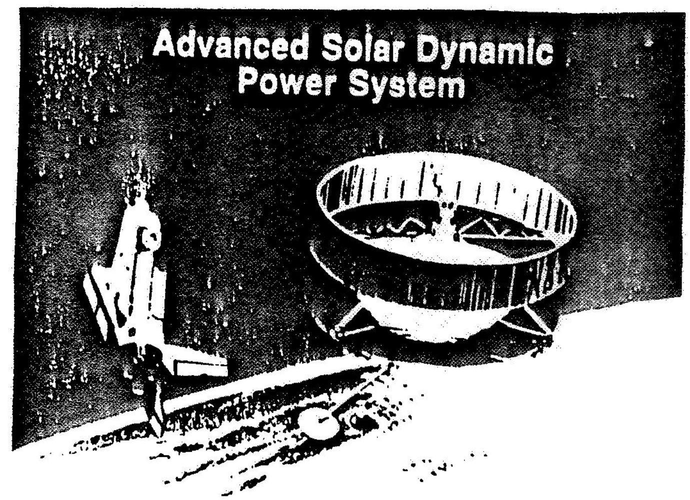
* The concentrator is one candidate for major improvements. Conceptual design studies were conducted in an effort to identify new and innovative concepts that would be lighter weight and more efficient. Of particular interest were concepts that would have the potential for achieving:
  - concentration ratios of at least 2000 to 5000. (SOA values are 1000 or less.) To achieve these high CRs means the surface contour accuracies have to be less than 1.0 milliradian.
  - high specular reflectance over the solar spectrum. Reflectances of 90 percent or more are possible using silver or aluminum as the reflecting material. Aluminum is not as reflective as silver, but it is immune to the space environment whereas silver is not. Hence for the near term, aluminum will be the prime candidate reflecting material because it is easier to work with than silver. For the long term, silver would be the preferred material.
  - low weight. The innovative concepts studied all the potential for achieving significant weight reductions. However, some have different degrees of risk associated with thier development.
  - autodeployability. This feature would be a great saving of valuable time on orbit if astronauts are not needed to assemble and deploy the concentrator.
  - long service life. The materials of construction are a critical factor that affects the service life. The space environment is a hazardous one for many materials. Therefore, the design of a concentrator must always include the optimum combination of materials so that in addition to meeting the performance requirements, it will survive for a long time, more than 10 tO 15 years.

* Since the heat receiver is the heaviest component in a solar dynamic power system, the development of light weight receivers is essential if the system specific power is to be increased substantially. To reduce the size of the receiver, ways must be found to increase the solar flux within the receiver cavity without creating hot spots and "thermal racheting". The goals of the program then are:
  - reduce the specific weight by a factor of two.
  - eliminate hot spots while at the same time reducing the receiver size.
  - eliminate "thermal racheting" through design of the TES canisters.
  - transfer of heat efficiently within the receiver by the use of heat pipe principles.

ASD SYSTEMS TECHNOLOGY

OBJECTIVES:

- IDENTIFY/ANALYZE INNOVATIVE COMPONENT/SYSTEM CONCEPTS
- DEVELOP HIGH EFFICIENCY, LOW MASS AUTO-DEPLOYABLE ADVANCED CONCENTRATOR TECHNOLOGIES
- IDENTIFY AND DEVELOP ADVANCED HEAT RECEIVER TECHNOLOGIES
- DEVELOP ADVANCED THERMAL ENERGY STORAGE TECHNOLOGIES



JC-91.01-2-pm

AEROSPACE TECHNOLOGY DIRECTORATE

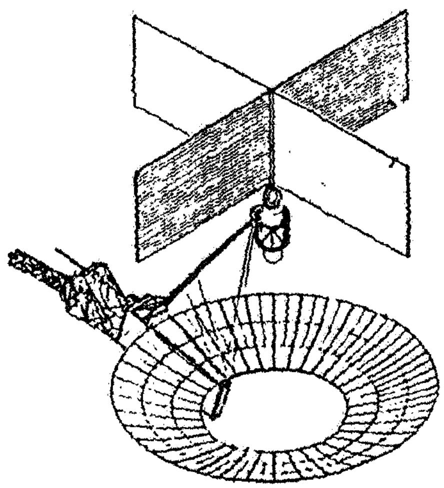
POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center

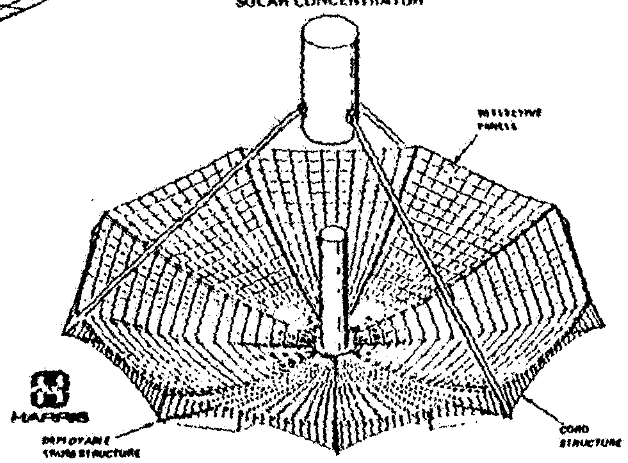
ASD SYSTEMS TECHNOLOGY

ADVANCED CONCENTRATORS

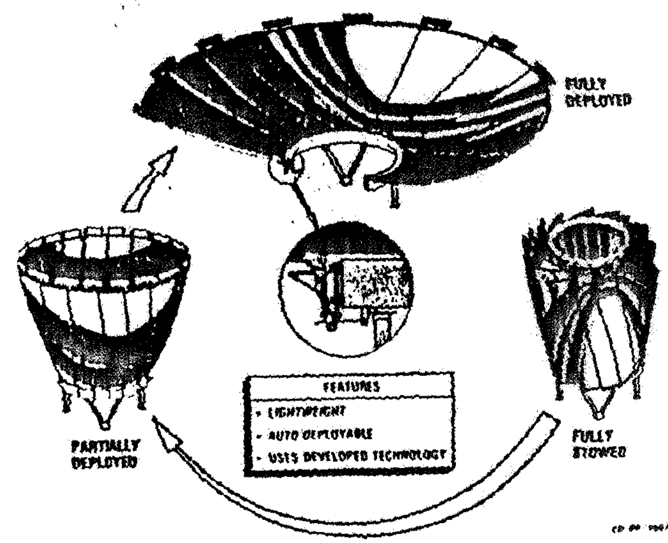
ACUREX CORP. SOLAR DYNAMIC POWER SYSTEM CONCEPT



25 KW SPLINED RADIAL PANEL SOLAR CONCENTRATOR



NASA/CSU-AMC PROTOTYPE AUTO-DEPLOYABLE CONCENTRATOR



FEATURES:

- ALL METAL HONEY COMB SANDWICH REFLECTOR PANELS
- AUTODEPLOYABLE
- HIGH SPECULAR REFLECTANCE (90%)
- HIGH CONCENTRATION RATIO (>2000)

ORIGINAL PAGE IS OF POOR QUALITY

ADVANCED CONCENTRATORS

Shown on this viewgraph are three of the four solar concentrator concepts that were devloped in the Advanced Solar Dynamic Program. The two on the left, designed by the Acurex Corp. and the Harris Corp., along with the one not shown, designed by Science Application International Corp., were contracted attempts to meet the goals set forth in the earlier VG on Goals. The concentrator concept on the right, referred to as the hinged folding panel type, is being developed under a NASA Lewis Grant by the Advanced Manufacturing Center of the Cleveland State University, Cleveland, Ohio. Of the four concepts, the one with the lowest development risk is the NASA/CSU-AMC concept because it builds on similar technology that was developed successfully in the 1960s.

The Acurex, Harris, and SAIC concepts have not been carried beyond the initial conceptual design phase due to the lack of funding.

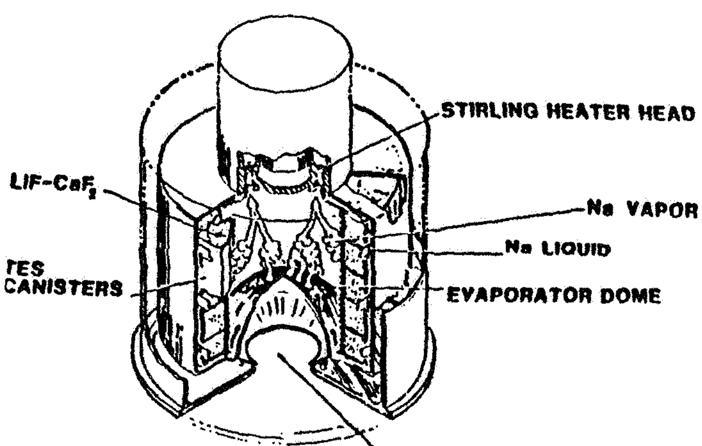
Because the hinged folding petal concept was judged to have the most promise for early development, CSU-AMC was asked to go forward a preliminary design of 2-meter diameter unit that was intended to be a reduced scale demonstration article to validate the fabrication techniques and the autodeployment features. Again, because of the lack of funding, the effort was focussed on developing the techniques for making the reflector panels. This work is nearing completion. A single reflector panel for the 2-meter concentrator is scheduled to be delivered to NASA Lewis in August 1991. This panel will have overcome some major technical problems with concentrators, namely that of being able to fabricate accurately contoured panels with a high specular reflectance that will also resist degradation by the space environment. This is one of the major technical accomplishments to come out of Advanced Solar Dynamic Program.

A parallel facet development was undertaken by the Solar Kinetics Inc., Dallas Texas under a SBIR contract. The technical effort is very close to completion. An all aluminum reflector facet which has been bonded with epoxy adhesives is scheduled to be delivered to be delivered to NASA Lewis in the near future.

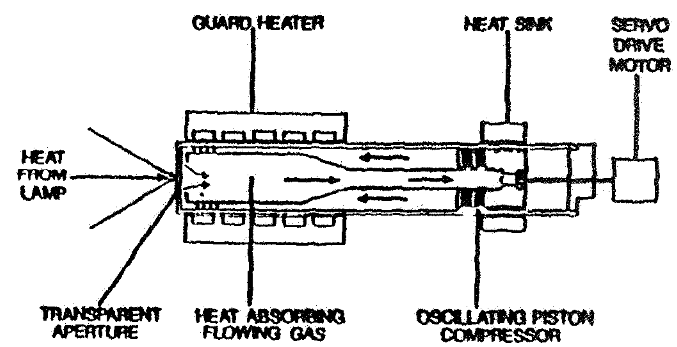
ASD SYSTEMS TECHNOLOGY

ADVANCED RECEIVERS

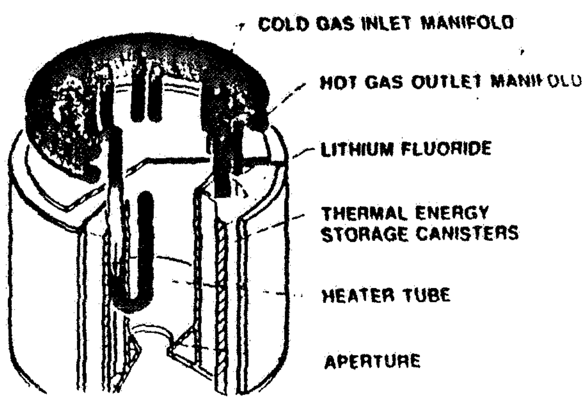
STIRLING SOLAR RECEIVER



500 WATT DIRECT FLUID ABSORPTION RECEIVER EXPERIMENT



BRAYTON SOLAR RECEIVER



FEATURES:

- DIRECT FLUID ABSORPTION RECEIVER
  - REDUCES RE-RADIATION LOSSES
- STIRLING & BRAYTON RECEIVERS
  - HEAT PIPE CAVITIES (UNIFORM HEAT FLUX)
  - WEDGE SHAPED TES CANISTERS (NO RACHETING)

JC-91 01-5-om

ASD SYSTEM TECHNOLOGY

ADVANCED HEAT RECEIVERS

* A solar dynamic receiver designed for space application differs from one designed for terrestrial use in that enough energy must be stored during the sun portion of the orbit (54 minutes) to operate the heat engine during the eclipse (36 minutes). This is done by melting containers of a fluoride salt that are heated during the sun portion of the cycle along with supplying heat to the engine.

* Two receivers designed for the ASD program one for the Brayton Cycle and one for the Stirling cycle both feature a heat pipe cavity for uniform distribution of the solar flux. The Stirling receiver uses a hemispherical dome to receive the solar flux while the Brayton receiver uses a cylinder configuration.

* Both of these receivers were designed to avoid two problems associated with heat receivers:

  - Hot spots are generated when heat is not removed from a surface of high flux fast enough to avoid high surface temperatures. The heat pipe feature redistributes the flux in a manner to avoid the generation of hot spots.

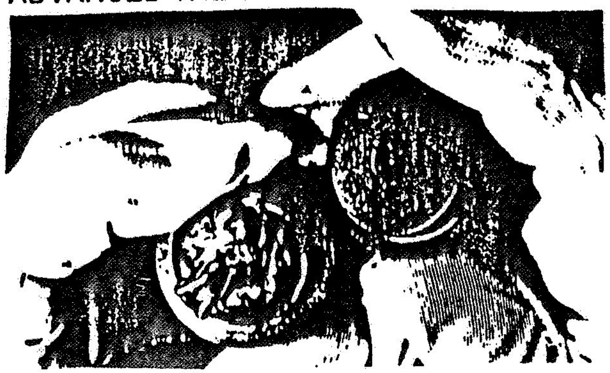
  - The thermal energy storage (TES) materials used in heat receivers expands upon melting as much as 30 percent. If provision is not made to allow melting TES flow into a void over expansion of the walls can result causing rupture of the container. If this happens repeatedly over many cycles it is called "thermal ratcheting". Both of these receivers use wedge shaped containers that are designed to avoid thermal ratcheting.

* The direct fluid absorption receiver uses a small amount of halogen gas to make the working fluid absorb the thermal energy directly in the gas instead of heat transfer from metal surfaces to the gas by convection. This means that losses from reradiation are reduced. This will reduce the concentrator and pointing requirements.

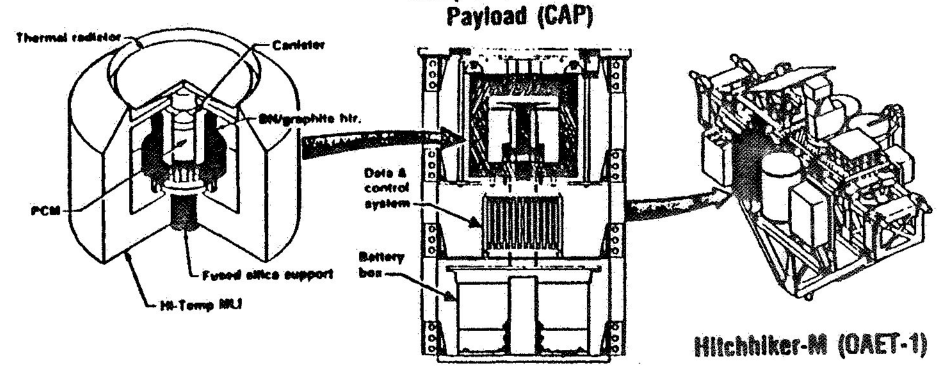
ASD SYSTEMS TECHNOLOGY

THERMAL ENERGY STORAGE

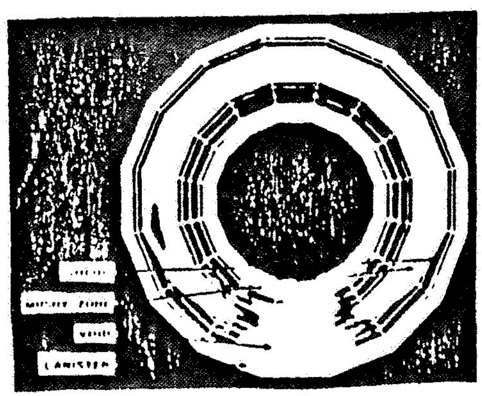
ADVANCED THERMAL ENERGY STORAGE DEVELOPMENT



THERMAL ENERGY STORAGE TECHNOLOGY FLIGHT EXPERIMENT



NORVEX CODE DEVELOPMENT



FEATURES:

- NORVEX CHARACTERIZES VOID FORMATIONS IN MICROGRAVITY
- TEST FLIGHT EXPERIMENT TO VALIDATE NORVEX
- GERMANIUM SELECTED FOR ADVANCED TES

91 01-6-pm

ASD SYSTEMS TECHNOLOGY

THERMAL ENERGY STORAGE

A solar dynamic power system for orbital space applications must have some means for storing energy during the sun phase for use during the dark phase of the orbit. The most effective way of doing this is to store thermal energy by melting a material with a high heat of fusion and then extracting it during the shade phase of the orbit. One problem is that of selecting a material that will melt and freeze at the desired operating temperature required for the efficient operation of the heat engine that is chosen to convert the heat to useful mechanical and the electrical power. A number of substances have been identified that are good candidate heat storage materials: fluoride salts and germanium. One having selected the material with the desired melting /freezing temperature, the next problem to overcome is how to cope with the high expansion (30% for lithium fluoride) that occurs on melting and the shrinkage on freezing. This chacteristic has been a problem of some concern because if it is not solved, serious damage and failure of the receiver is sure to occur. In the ASD program, a number of projects have been undertaken to resolve this issue.

A comprehensive computer code has been developed for the purpose of understanding and predicting the behavior of the material in the molten state in a microgravity environment. How the voids migrate around the container is of considerable importance because they could wander to locations where hot spots could form. To validate this code with experimental data, a flight experiment has been designed for execution aboard the Space Shuttle. This experiment, designated Thermal Energy Storage Technology (TEST) flight experiment is scheduled for 1993.

Other supporting research has been conducted on such problems such as:
* finding container materials that will resist the corrosive effects of the molted salts.
* developing receiver/container designs that circumvent the problems that void formations can cause.
* finding TES materials that have a higher heat of fusion.

ASD SYSTEMS TECHNOLOGY

2 KILOWATT GROUND TEST EXPERIMENT

OBJECTIVE:

VERIFY THE READINESS OF SOLAR DYNAMIC SYSTEM TECHNOLOGIES

JC-91.01-7-pm

2 KILOWATT GROUND TEST EXPERIMENT

APPROACH:

- DESIGN, DEVELOP, FABRICATE, AND GROUND TEST A 2.0 kWe SOLAR DYNAMIC SPACE POWER SYSTEM THAT:
  - IS SCALABLE TO 20 kWe RANGE
  - IS FLIGHT - CONFIGURED
  - INCORPORATES RELEVANT FEATURES OF SSF SOLAR DYNAMIC POWER MODULE DESIGN

JC-91 01-8-om

PROJECT ELEMENTS

- SYSTEM DESIGN AND ANALYSIS
- SUBSYSTEM DDT&E
- INTEGRATED SUBSYSTEM TESTS
  - CONCENTRATOR/HEAT RECEIVER TEST IN A SOLAR FACILITY (SANDIA OR EDWARDS)
  - THERMAL FLUID LOOP (RECEIVER/PCU/RADIATOR) TESTS IN VACUUM CHAMBER
  - MULTI-SOURCE POWER SHARING TESTS IN EPL TANK 5
  - TOTAL SYSTEM TESTS WITH SOLAR SIMULATOR IN VACUUM CHAMBER

JC-91.01-9-pm

TECHNOLOGY ISSUES ADDRESSED

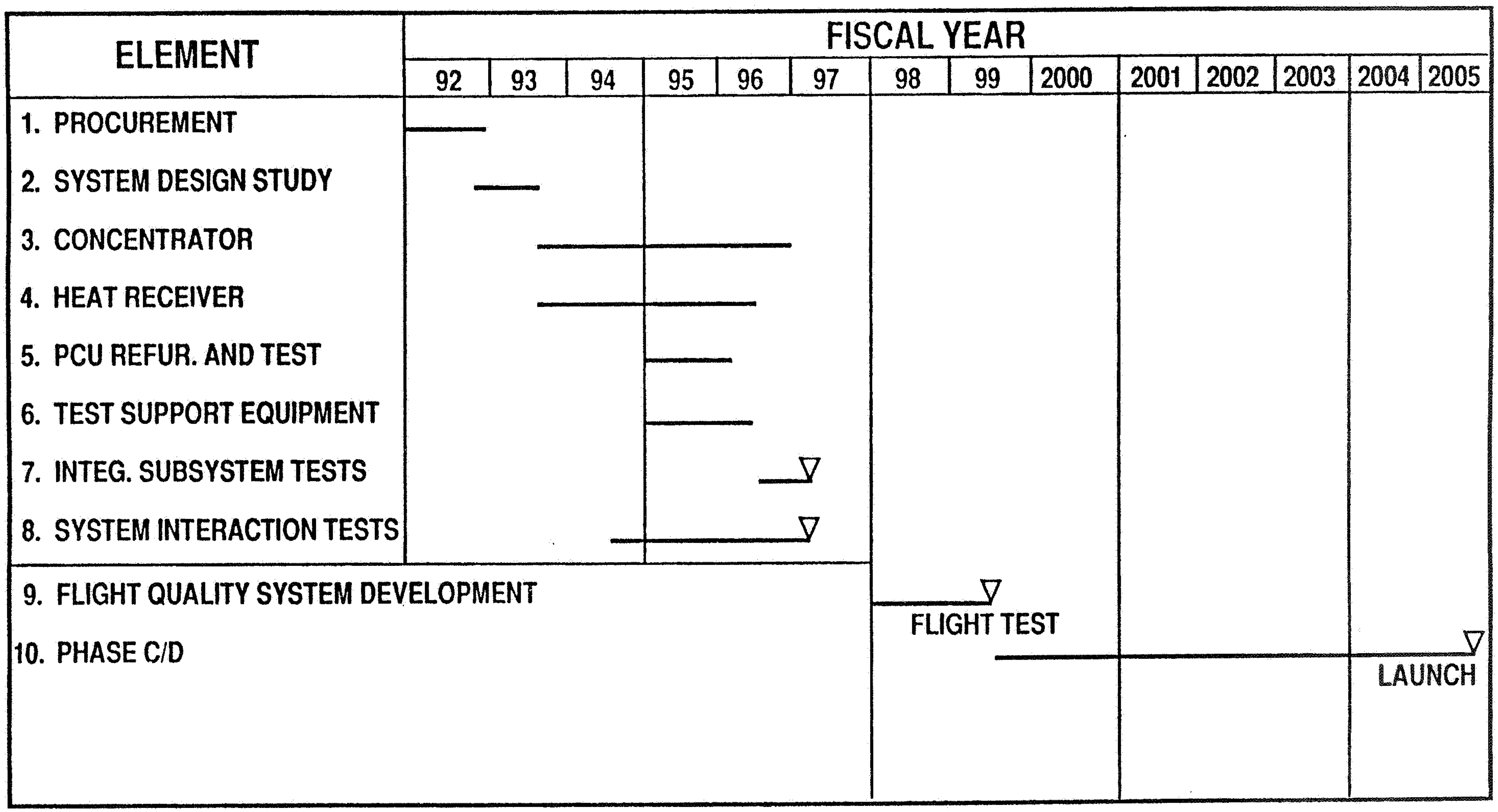
SYSTEM LEVEL

- SOLAR DYNAMIC SYSTEM INTERACTIONS
- SCALABILITY
- POWER SHARING (AC & DC) SOURCES

SUBSYSTEM LEVEL

- CONCENTRATOR
  - FABRICATION PROCESSES
  - OPTICS
  - DEPLOYMENT
- PCU
  - START-UP
  - TRANSIENT OPERATION
  - OFF-DESIGN OPERATION
- HEAT RECEIVER
  - HOT SPOTS
  - THERMAL RATCHETING
- RADIATOR
  - DEPLOYMENT
- CONTROLS
  - PARALLEL OPERATION
  - LOAD FOLLOWING

2 kW GROUND TEST EXPERIMENT SCHEDULE & FUNDING REQUIREMENTS



JC-91.01-11-pm

SD STATUS SUMMARY

- SOLAR DYNAMIC SYSTEMS HAVE HISTORICAL CREDIBILITY
- SD POWER IS THE PRUDENT CHOICE FOR SSF GROWTH POWER
- SOLAR DYNAMIC TECHNOLOGY IS READY
- NASA/OAET IS COMMITTED TO FURTHER SD FOR SPACE APPLICATIONS
- GROUND TEST FOR A SPACE BASED SD SYSTEM IS ACTIVELY BEING PURSUED

SD STATUS SUMMARY

Solar Dynamic systems have obtained credibility throughout their history. From gaining momentum in their development in the 1960s, to terrestrial testing and applications, to progress made in the Space Station Freedom Program, SD is a bonafide contender for space applications. One such application is for SD to be the growth power generating system onboard SSF. Compared to the SSF baselined PV system, or any technological advance in any one area of a PV system, SD is irresistibly attractive and is the prudent choice for SSF growth power.

It has been presented that all facets of SD technology are now ready. Significant progressed has been achieved in the past few years that verifies technology readiness, and, in fact, NASA and its Office of Aeronautics, Exploration, and Technology (OAET) are committed to further the progress of SD in becoming reality for space applications.

Finally, in the spirit of SD commitment and to assure ourselves that these technologies can indeed perform exceptionally well together as a system, a ground test for a whole space based SD system is actively being pursued. This activity has been earmarked a budget in the range of $15–20M beginning in FY92 and lasting approximately five years. This activity is structured such that development of flight qualified hardware would be the next natural step in the progression of solar dynamic systems.

SPACE STATION FREEDOM ELECTRIC POWER SYSTEM EVOLUTION ANALYSIS STATUS

Presented to
Space Station Evolution Symposium
August 8, 1991

Michael J. Zernic
LeRC/Power System Operations and Planning Branch

SPACE STATION FREEDOM ELECTRIC POWER SYSTEM EVOLUTION ANALYSIS STATUS

This presentation has been compiled as a status of the Electric Power System (EPS) Evolution Analysis for Space Station Freedom (SSF) as directed by Headquarters Code MT, stated in Task Order No. 7, NASA Contract NAS3-25711, and performed by the Rocketdyne Division of Rockwell International.

This presentation will examine the ability of the SSF baselined EPS to transition to operate at a greater system capacity beyond the SSF Permanent Manned Capability (PMC) milestone. Specifically, a status of a current analysis will be discussed concerning additions (new or duplications), modification, change-out, or combination thereof of baseline EPS hardware/software needed to accomplish the power generation, distribution, operation, and utilization needed to meet evolving SSF mission objectives. This discussion will result in several EPS architectural options that facilitate the addition or substitution of new technologies.

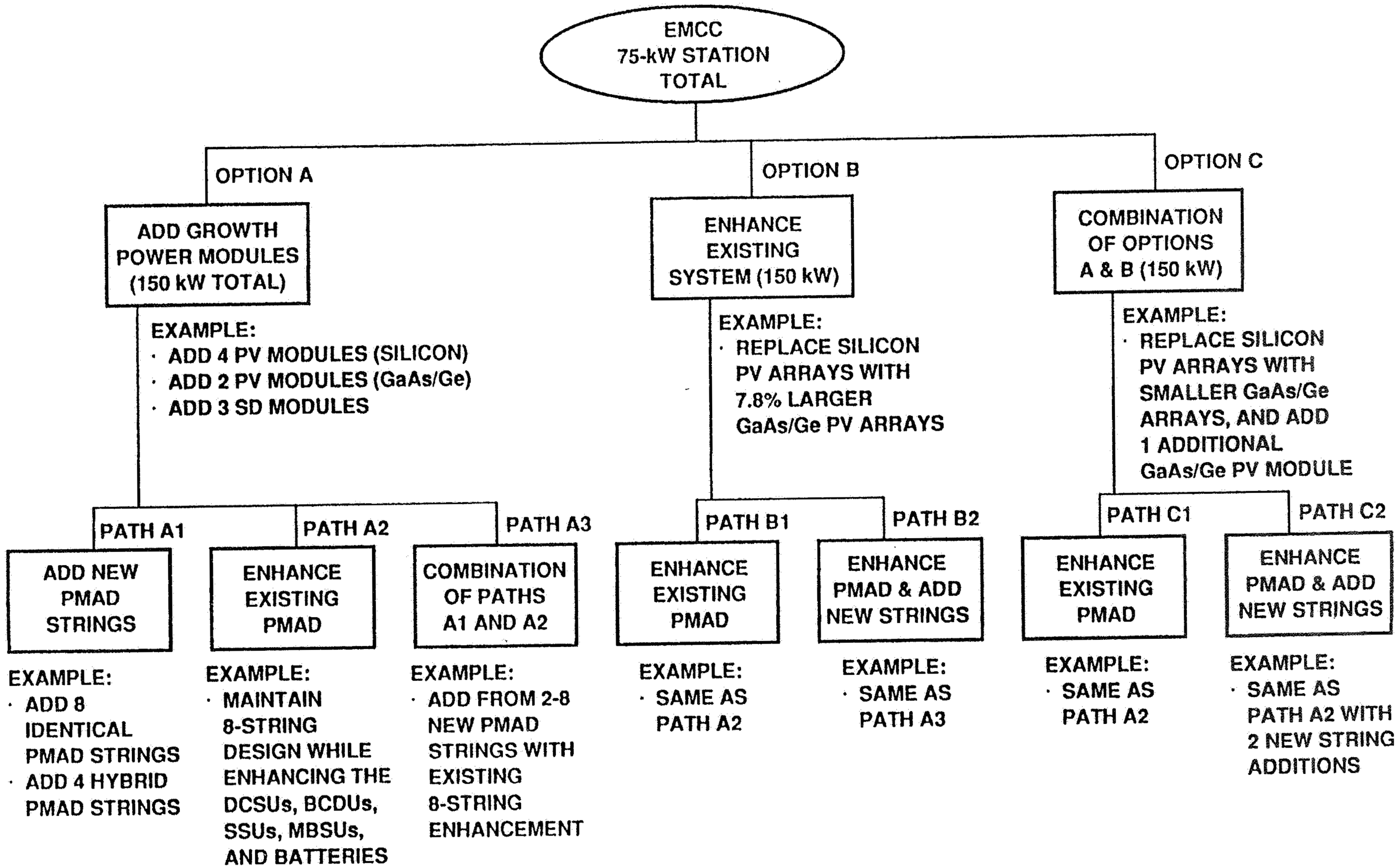
Rocketdyne acknowledgements:

Scott Boller
Burl Bolerjack
Dan Saine

Reference: EPS Evolution Analysis Trade Study Final Report, December 21, 1990
(Study based on SSF pre-restructured program and emphasized solar dynamic additions)

C-2

Potential Growth/Evolution Configurations



2 AUG 91
FILE: BASE-CHN.DRW
BOLERJACK/JLM

Configuration (PMC+). After the station has reached the eight man crew capability (EMCC), the addition of more power modules (growth) to provide 75 kW of additional power, or the enhancement (evolution) of the existing (baseline) Electric Power System (EPS) design to provide the needed 7 kW of power, will bring the total station power to 150 kW.

This study identified three possible options by which SSF's power generation capability could be increased. The first option, labled Option A, adds growth power modules to be attached outboard of the existing Photovoltaic (PV) Modules. These power modules could consist of four more identical silicon array PV Modules, two gallium arsenide on germanium (GaAs/Ge) array PV Modules, or three Solar Dynamic (SD) Modules. The second option, Option B, would provide the additional 75 kW of power by enhancing the existing EPS. An example of this growth by evolution is replacing the existing silicon array PV Modules with slightly larger (7.8%) GaAs/Ge array PV Modules. The third option, Option C, would accomplish the generation of an additional 75 kW through a combination of both growth and evolution (Options A and B). One example of this option is to replace the silicon array PV Modules with smaller GaAs/Ge array modules along with the addition of another GaAsGe module. The number of PV Modules would then total five, each having two independent distribution strings.

For each power generation option, this study identified at least two Power Management and Distribution (PMAD) paths by which the growth/evolution power could be distributed.

For Option A, three unique PMAD paths have been identified. Path A1 would simply add new PMAD strings. Examples of this path include adding eight more baseline design PMAD strings to be used with the four silicon array PV Modules, adding four hybrid PMAD strings to distribute the power from the two GaAs/Ge array modules, or even three hybrid strings for the three SD Modules. These growth PMAD strings would remain independent from the existing PMAD system. Path A2 would simply enhance the existing PMAD system with new and allow the growth power cabling to "plug into" the hybrid PMAD system at the existing outboard PV Modules. Path A3 would modify the existing PMAD system to accommodate a portion of the growth power, and add anywhere from two to eight new PMAD strings to distribute the remaining power.

For Option B, two PMAD paths have been identified. Path B1 would enhance the existing PMAD system to accommodate the higher output of the GaAs/Ge array modules. ORUs to be replaced at their mean replacement interval (MRI) would include the Dc Switching Units (DCSUs), the Battery Charge/Discharge Units (BCDUs), the Sequential Shunt Units (SSUs), the Main Bus Switching Units (MBSUs), and the Batteries. This path is similar to Path A2. Path B2 is the same as Path A3.

For Option C, two PMAD paths have been identified. Path C1 is similar to Path A2, and Path C2 is also similar to Path A2, with the addition of two new PMAD strings.

Growth/Evolution Path Comparisons

Advantages	A1	A2	A3	B1	B2	C1	C2
Requires minimum "down time" of existing EPS	X						
Maintains "independent string" PMAD philosophy	X		X		X		X
Requires minimum EVA hours for installation and checkout				X			
Requires minimum hooks and scars to baseline design				X			
Requires the development of a minimum number of new ORUs	X						
Requires the minimum launch mass				X			
Utilizes existing PMAD ORU mean replacement intervals for upgrading		X	X	X	X	X	X

2 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

Growth/Evolution Path Comparisons (Continued)

Disadvantages	A1	A2	A3	B1	B2	C1	C2
Requires maximum "down-time" of existing EPS							X
Violates "independent string" PMAD philosophy		X		X		X	
Requires maximum EVA hours for installation and checkout	X						
Requires maximum hooks and scars to baseline design	X						
Requires the development of a maximum number of new ORUs						X	
Requires the maximum launch mass	X						
Requires growth ORUs be launched along with existing ORUs	X	X	X	X	X	X	X

2 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

are shown on this table. A brief description of the rationale for each selection follows.

The advantage of Path A1, requiring *the minimum "down time" of existing* EPS, is the result of adding growth PMAD strings, and not having to disrupt the existing system to do so, with the exception of Alpha joint-related operations.

Those paths which provide one PMAD string per array, or SD Module, maintain the "independent string" philosophy, and consist of Paths A1, A3, B2, and C2.

Path B1 requires both the minimum extravehicular activity (EVA) hours for installation, assembly, and checkout of the new hybrid PMAD ORUs, and the minimum number of hooks and scars to accommodate the addition of 75 kW to the station. The rationale behind this selection is that no new power modules will be added in Option B, and no new PMAD strings will be added in Path B1.

The *minimum* number of new ORUs to be developed is associated with Path A1 as a result of the possibility that all growth EPS hardware could be "off-the-shelf."

Path B1 also requires the least amount of hardware to be launched specifically for the growth/evolution of the EPS. This is the result of making use of the natural MRIs for the existing hardware.

Those paths which utilize the existing PMAD's natural MRIs as opportunities for replacement with enhanced ORUs include: A2, A3, B1, B2, C1, and C2.

Path C2 has *the disadvantage of requiring* the maximum "down time" as a result of both upgrading the existing PMAD system and adding new PmAD strings.

Those paths which violate the "independent string" philosophy include A2, B1, and C1 due to the fact that additional power is being introduced into the EPS without providing additional channels for the power to be distributed.

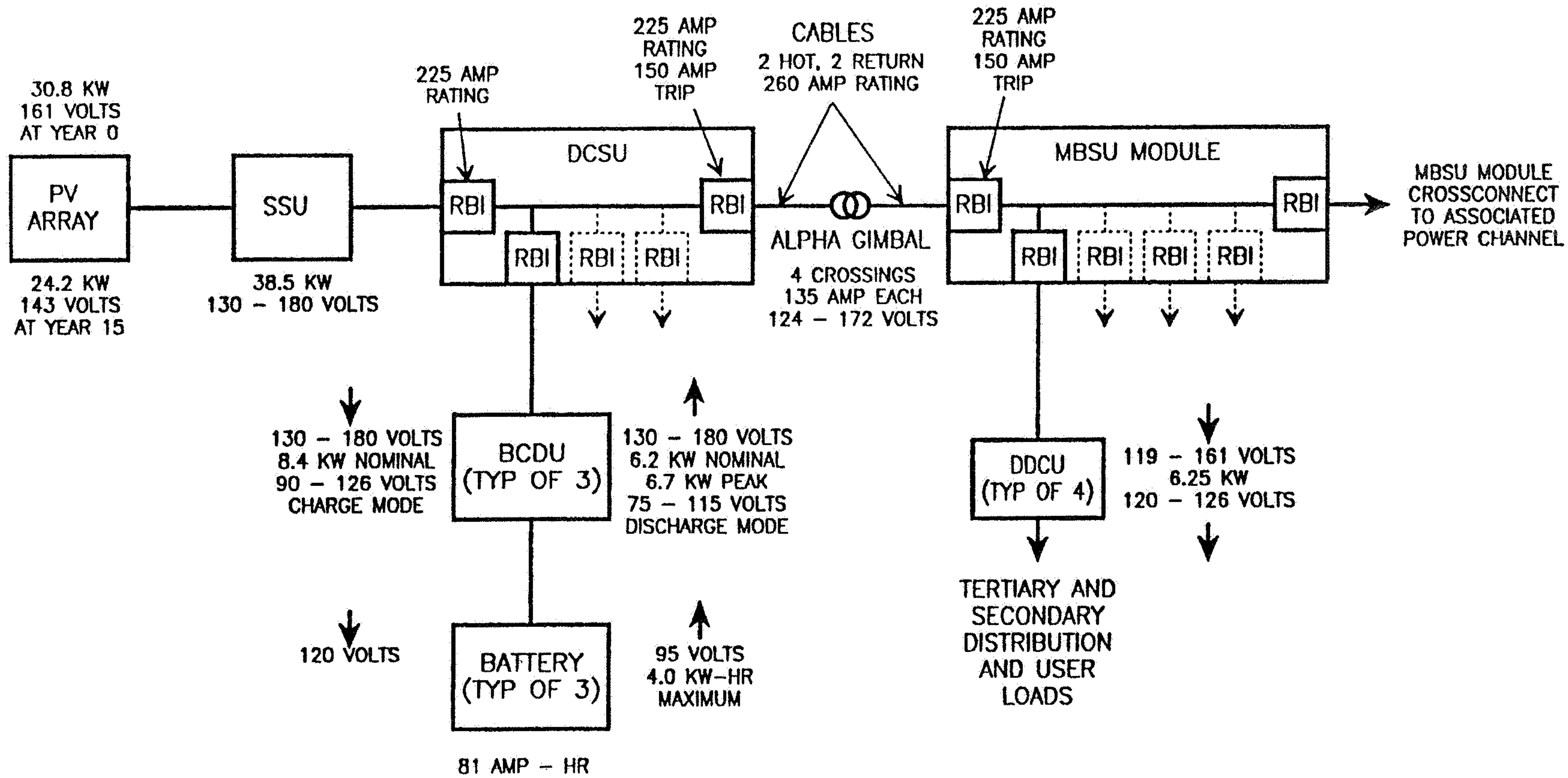
Path A1 would require the most of both EVA hours and hooks and scars, since the entire existing EPS could be duplicated.

The maximum number of new ORUs to be developed would be required by Path C1 where, not only would all of the new ORUs for Path A2 be needed, but also additional ORUs to accommodate growth power modules such as SD.

The maximum launch mass would most likely be realized by Path A1 where an entire EPS could be added to the existing system.

All paths would require growth ORUs to be launched along with existing ORUs if growth ORUs include those associated with SD Modules.

SSF Baseline Power Channel
Typical of Eight at PMC+



1 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

Space Station Freedom (SSF) Electric Power System (EPS) function is overall power generation, control, storage, and distribution to the loads. SSF will go through a number of distinct configurations during its growth to full baseline capability. This presentation is oriented Permanently Manned Capability Plus (PMC+), in which there are eight power channels with a full complement of batteries. The EPS Orbital ment Units (ORUs) descriptions are as follows:

Photovoltaic Array - Each power channel contains one wing, made up of two solar array blankets, each blanket containing 82 panels with 200 silicon (Si) solar cells per panel. The panels are wired to provide 82 strings of 400 cells each per wing. These strings provide the power input to the SSU.

Sequential Shunt Unit (SSU) - Each power channel contains one SSU, which functions to control the PV array output. It accepts the 82 strings of power from the wing and, based on a voltage setpoint from the control system, either connects strings in parallel to the output bus or shunts them in order to provide the required power to the DCSU bus.

DC Switching Unit (DCSU) - This ORU contains the DC switchgear to control power flow to and from the energy storage system and to the main bus switching unit, through the Alpha Gimbal. It provides the fault clearing and ORU isolation capability for the primary power distribution system.

Battery Charge/Discharge Unit (BCDU) - The energy storage system is made up of three independent BCDUs, each with an associated battery. The BCDU controls the flow of power into the battery during insolation, and controls the power flow from the battery during eclipse, to maintain the DCSU bus voltage at a setpoint received from the control system.

Battery - The battery is made up of two battery ORUs, each containing 38 Nickel Hydrogen cells. These cells are connected in series to form an 81 ampere-hour battery with an average voltage of 95 volts.

Alpha Gimbal - This ORU provides for primary power flow across the rotating joint. It is made up of roll rings each of which provide one power crossing. Each power channel requires four crossings, two hot and two return, for a total of 16 power crossings per Alpha Gimbal.

Main Bus Switching Unit (MBSU) - This ORU is made up of two MBSU modules, with each power channel feeding one module. It contains the DC switchgear to control power flow to the secondary DC to DC power converters and provides fault clearing and ORU isolation capability. It also provides cross-connect capability between two associated MBSU modules and to other MBSUs.

to DC Conversion Unit (DDCU) - This ORU converts the primary distribution power to secondary distribution regulated power for the users. these units are fed from each MBSU module.

Potential for Growth

- The baseline power channel (DCSU to MBSU) is physically capable of distributing 18.75 kW (200% baseline) to the users (150 kW total)
    - Limiting component is DCSU output and MBSU RBIs fault current interrupt capability (480A)
    - Present RBIs cannot interrupt 200% baseline fault current
- Alternatives
    - Replace baseline RBIs with enhanced RBIs capable of limiting/interrupting growth fault current
    - Duplicate each power channel
        - Provide additional RBIs of existing type in DCSU (1) and MBSU (2); add four Alpha Gimbal crossings (16 total); and add additional cables (2 hot, 2 return) per channel
- The SSUs, BCDUs, and DCSU input RBI require redesign to handle the increased source power
- Growth in user power may require replacing MBSUs with units containing additional RBIs for growth DDCUs in high-power usage locations.

2 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

sent RBI design is capable of interrupting 480 Amp, baseline fault current. Increasing the source to 200% baseline will result in a onal increase in potential fault current.

eral alternatives exist for increasing the power channel distribution capability.

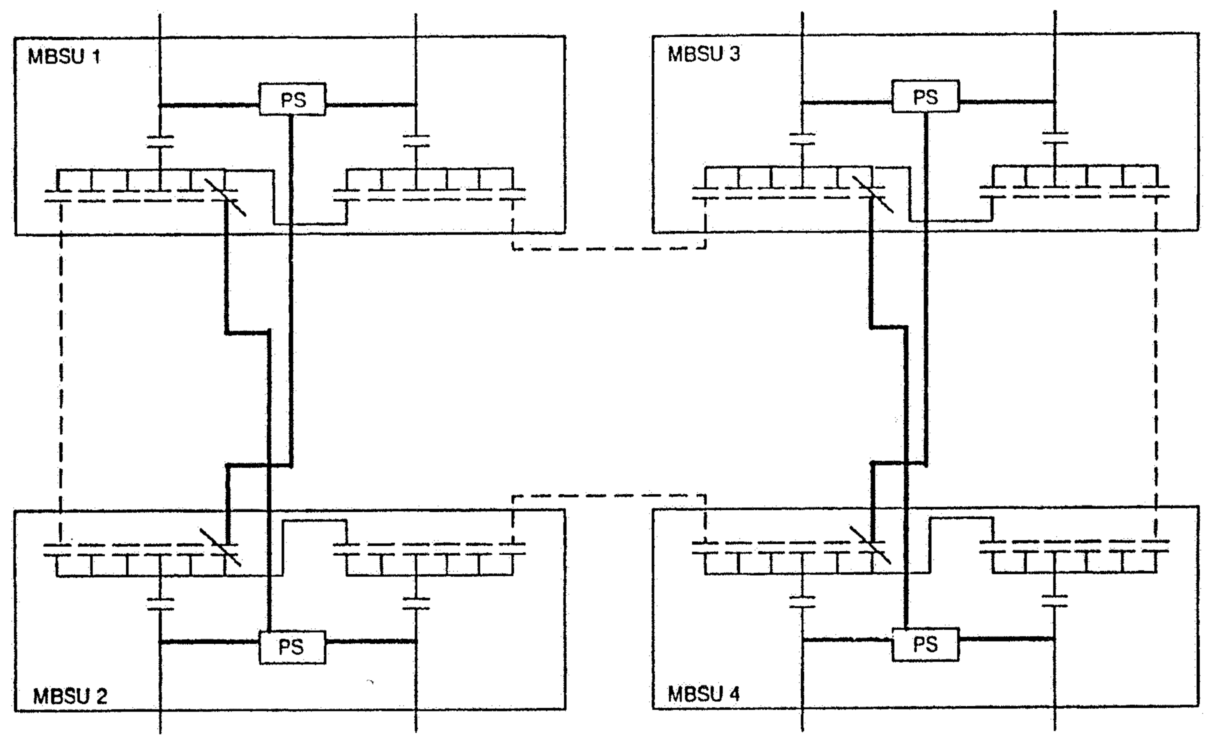
New RBIs can be developed to handle (limit/interrupt) the increased fault current. This would require replacing the SSF DCSUs and MBSUs with units containing the enhanced RBIs.

Another option, if growth is in total channel power and not in number of channels, is to duplicate the baseline distribution channel. Again the DCSUs and MBSUs would be replaced, this time with units containing additional baseline RBIs. This would require additional cables from DCSU to Alpha Gimbal to MBSU, and an additional four Alpha Gimbal power crossings per channel. If growth is number of power channels (two additional wings , for ten total) this would be a total duplication of two baseline power channels. The Alpha Gimbal still be required to provide eight additional crossings and a location would need to be established for the additional MBSU.

either alternative, the SSUs, BCDUs, and DCSU input RBI would have to be redesigned and replaced with units capable of handling 200% : power.

hough the baseline DDCU complement is capable of handling a total of 162.5 KW, this power may not be available in locations where its One option is to replace the MBSUs with units containing additional RBIs for growth DDCUs in locations where the additional power is l.

Potential for Growth



DDCU GROWTH CAPABILITY

31 July, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

. This RBI is closed only when power has been lost to one module and it is desired to power its loads from the associated power channel. ıed lines show cross-tie capability between MBSUs and serve a similar purpose, in that an entire MBSU can be repowered if desired. These o will never be closed between energized buses (paralleling power channels). The dark power lines, connecting an MBSU power supply normally closed RBI in the opposite MBSU represent the control power feed for each MBSU (Port feeds control power to Starboard and Starboard to Port). This leaves four feeder RBIs per MBSU module (32 total) for DDCU power feeds. The baseline EPS provides 26 (inboard the Alpha Gimbals) representing total user power capability of 162.5 KW. Two NSTS (shuttle) power converter units are also from the MBSU RBIs, leaving 4 spare RBIs for growth DDCUs (25 KW).

SSF Source Growth

- Growth in array source power capability to 200% baseline is not feasible using baseline silicon solar cells (14% eff.) due to weight, volume, and resupply constraints
  - An alternative is gallium arsenide on germanium (Ga As/Ge) cells (25% eff.), presently in limited development
    - Preliminary study indicates 206% baseline power with a 7.8% increase in wing area
  - Add Solar Dynamic Power Modules
- Growth in source energy storage capability to 200% baseline is not feasible using the baseline nickel hydrogen batteries (NHB) due to weight, volume, and cooling requirements
  - An alternative is the sodium sulfur battery (SSB) technology
    - SSB has a specific energy of 50 watt-hours/pound compared to 18 watt-hours/pound for NHB
    - The SSB operates at 300 to 400 deg C significantly reducing load on the thermal control system
    - Replacing NHB with SSB can double storage capability while reducing ORU volume by 75%

2 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

ıese cells have an enhanced efficiency (25% vs 14% for Si). The GaAs/Ge cell also exhibits increased radiation tolerance, its output voltage ted to degrade 3% over a 15 year lifetime as compared to 6% for the Si cell.

ncrease to 200% baseline power, using GaAs/Ge cells, can be accomplished in several ways with variable impact on the baseline design.

Maintain eight power channels and replace the Si cells with GaAs/Ge. This option has a large impact on wing and SSU designs. A preliminary study indicates that the wing would be made up of 208 strings of 170 cells in series. These strings could be paralleled to provide 104 input strings to the SSU (compared with the 82 string baseline input). A wing providing 206% baseline power is estimated to increase in area by 7.8% and weight by 4.9%.

An alternative is to increase the number of channels to ten (two additional wings) and redesign the wings for the GaAs/Ge cells. These wings would be smaller than baseline, each containing 162 strings of 170 cells wired up with two strings each paralleled to provide 82 input strings to the SSU. The total wing area would still increase approximately 7.8% and two additional power channels are required; however the SSU and DC switchgear redesigns are minimized.

Another alternative for additional power channels is the Solar Dynamic power module. However this option was analyzed, in great detail under NASA Contract NAS3-25082 and written up in a final report " EPS Evolution Analysis Trade Study" Technical Directive B-0001-127, and will not be further addressed by this study.

wth in source energy storage capability to 200% of baseline is not feasible using the baseline nickel hydrogen batteries (NHB) due to weight, and cooling requirements. One alternative is the sodium sulfur battery (SSB).

The SSB has a specific energy of 50 watt-hours per pound (compared to 18 watt-hours per pound for the NHB). Also, while the NHB is limited to about a 35% depth of discharge (DOD) due to life cycle considerations, the SSB can be taken to 50% DOD without impacting the cell life.

The SSB is a high temperature battery operating in a range of 300 to 400 deg. C. It also has coulombic efficiency of 100%, such that no excess charge current is required , and the SSB cell will not self discharge (no trickle charge required). This greatly enhances the cell efficiency and simplifies the on-orbit cooling requirements, and associated load on the thermal control system (TCS). The baseline NHB battery operates at 0 to 10 deg. C and, due to the heat generated during charge by its inherent coulombic inefficiency (5 to 10 % additional charge must be returned to the battery), it is a much larger load on the TCS.

The energy storage system capability can be doubled, using the SSB technology, with a 75% reduction in ORU volume and an 80% decrease in weight.

A five year SSB development program, for flight prototype modules was started in 1986 and is nearing completion. A flight test is planned as part of a Air Force program.

Power Growth Through Control Enhancement

- DDCU Unequal Power Share Capability
  - Provides additional power to the users by balancing power provided by each source
  - Allows full utilization of available source power
  - Eliminates the DDCU power limitation based on least source capability
- Peak Power Tracking
  - Adjusts the SSU output voltage setpoint to operate the array near its peak power point
  - Recent testing at NASA-LeRC PSF Test Bed established capability to detect and operate near the peak power point
  - Provides estimated 8% increase in user power

1 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

ıseline design.

Twelve of the total 26 DDCUs (46%) are operated in parallel, each fed from a different power channel. The baseline DDCU control hardware forces the DDCUs to share power equally. Therefor the power output is limited by the power channel with the least capability. This results in some channels being fully loaded, while others are underutilized. By modifying the DDCU controls, the DDCUs can be allowed to share power unequally, resulting in increased power to the users and less wasted power.

Peak power tracking refers to controls algorithms/hardware, associated with the SSU, that allows the array to operate at a voltage which results in maximum power being delivered to the DCSU. A solar array has operating characteristics which can be described on a current verses voltage (I/V) curve. At the peak power point on that curve, a small change in voltage results in a equal change in current. If the DCSU bus voltage can be controlled, such that the SSU operates the array at this point, then maximum power is being produced by the array. Some recent preliminary testing, at the NASA LeRC PSF test lab, has confirmed the ability to detect and operate close to this peak power point. Estimates are that power to the users can be increased by about 8% if this type control is implemented.

Non-Work Package 4 Hooks and Scars

- Guidance Navigation and Control (GN&C)
- Data Management System (DMS)
- Central Thermal Control System (TCS)
- Truss
- Integrated Truss Assembly (ITA) Cabling
- Propulsion Element Modules
- Pressurized Modules Penetration/Bus Amp Rating
- Solar Alpha Rotary Joint (SARJ)

5 August, 1991
FILE: BASE-CAP.DOC
BOLERJACK/JLM

electrical power to the users, several non-Work Package 4 (WP-04) hooks and scars are necessary depending on the particular option and path selected. Hooks and scars are design accommodations to facilitate the addition or update of computer software and hardware, respectively.

The GN&C provides attitude and orbital corrections of the SSF. The GN&C must be able to control the SSF throughout growth/evolution.

The DMS provides the standard processing support for all SSF systems and must have the capacity to control the SSF throughout growth/evolution.

The central TCS must accommodate the added heat dissipation requirements due to the growth/evolution power levels.

The Truss structure must have the required stiffness to support the addition of growth or evolved power modules, as well as provide the necessary vacant space needed for growth/evolution hardware.

The ITA cabling from the Alpha Gimbal to existing or growth/evolution MBSUs, as well as from growth/evolution MBSUs to the new users, needs to be, or have the capacity to be installed.

The propulsion element, including the Resistojet and H/Ox (or Hydrazine) Thruster, must provide the capability to reboost the growth SSF.

The existing and new pressurized modules should have the capacity to accommodate growth/evolution power through both their power penetrations and buses. Sufficient amp ratings of these conductors will allow flexibility in allocating growth power.

The SARJ must be capable of allowing the addition of more or higher amp-rated roll rings, to accommodate the power crossing requirements needed by the selected option.

Future Work/Considerations

Requirements to complete task

- Finilize Growth/Evolution Task Order
- Conduct Detailed Option Evaluations
- Identify any Problems or limitiaions
- Identify Option Associated Hooks and Scars
- Submit Final Report Documenting Study Results

Future Work

- Recommend Studies to Evaluate New Technology Feasibility
- Continue EPS Growth/Evolution Option Evaluation

SPACE STATION FREEDOM SOLAR ALPHA JOINT GROWTH CAPABILITY

DAVID SNYDER

LOCKHEED MISSILES AND SPACE CO. 8/8/91

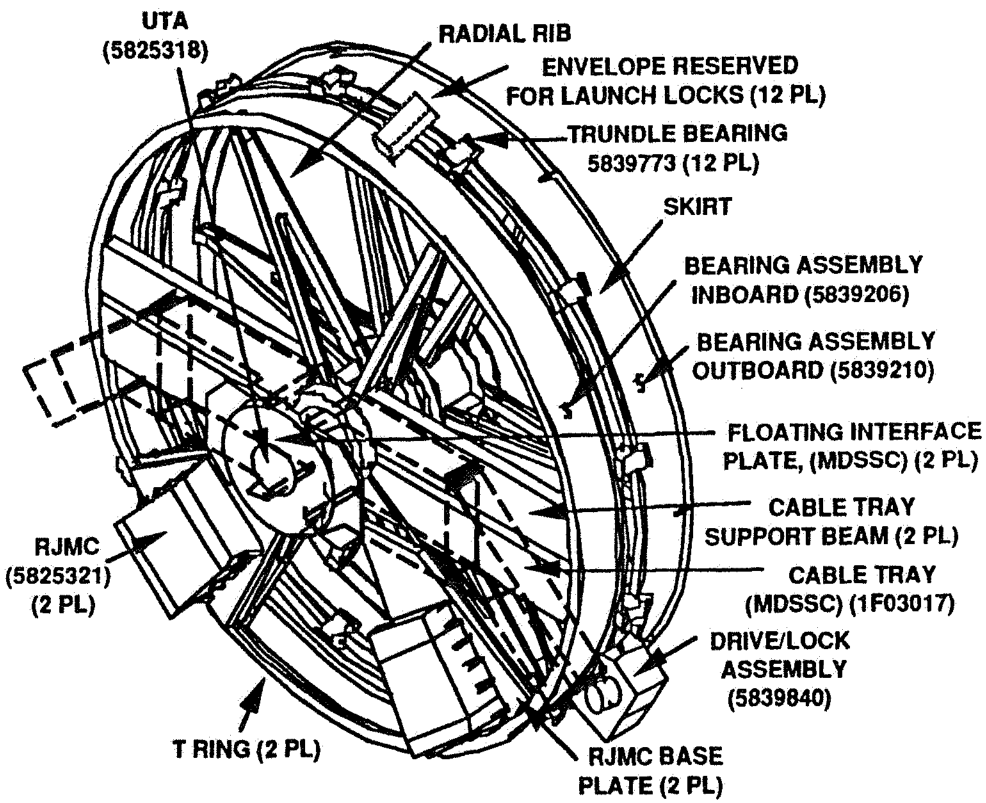
SPACE STATION FREEDOM

AGENDA

SOLAR ALPHA ROTARY JOINT GROWTH CAPABILITY

- BASELINE REQUIREMENTS AND CAPABILITY
- BASELINE CONFIGURATION
- PRELIMINARY ASSESSMENT OF KEY GROWTH ISSUES

SOLAR ALPHA ROTARY JOINT ASSEMBLY



SARJ ASSEMBLY - ISO

FUNCTIONS:

- PROVIDES STRUCTURAL CONTINUITY AND CONTINUOUS ROATION BETWEEN THE INBOARD AND OUTBOARD MB-1 PIT SECTIONS
- PROVIDES CONTINUOUS POWER, DATA, AND VIDEO TRANSFER

SPACE STATION FREEDOM

SARJ CAPABILITY

SARJ ROTATION :
- 360 deg continuous rotation
- 3.80 to 3.95 deg/min tracking rates
- 30 deg/min search rate in either direction
- 0.005 deg/sec/sec acceleration in either direction
- 3.8 E+06 slug feet^2 inertia load (Growth)

POINTING CAPABILITY :
- Accuracy - 0.58 deg in either direction
- Stability - 0.50 deg in either direction
- Jitter - 0.01 deg/sec

CONTROL SYSTEM :
- Closed position loop bandwidth - 0.01 to 1.00 Hz
- Transient response (Position overshoot) - no greater than 30 percent
- Break-out command from zero rate - less than 30 percent of max. torque

UTILITY TRANSFER :
- Power - 18 Crossings
  - 60 KW of 160 VDC thru 4 circuits
  - 2 Grounds
- Data/Video - 36 Crossings

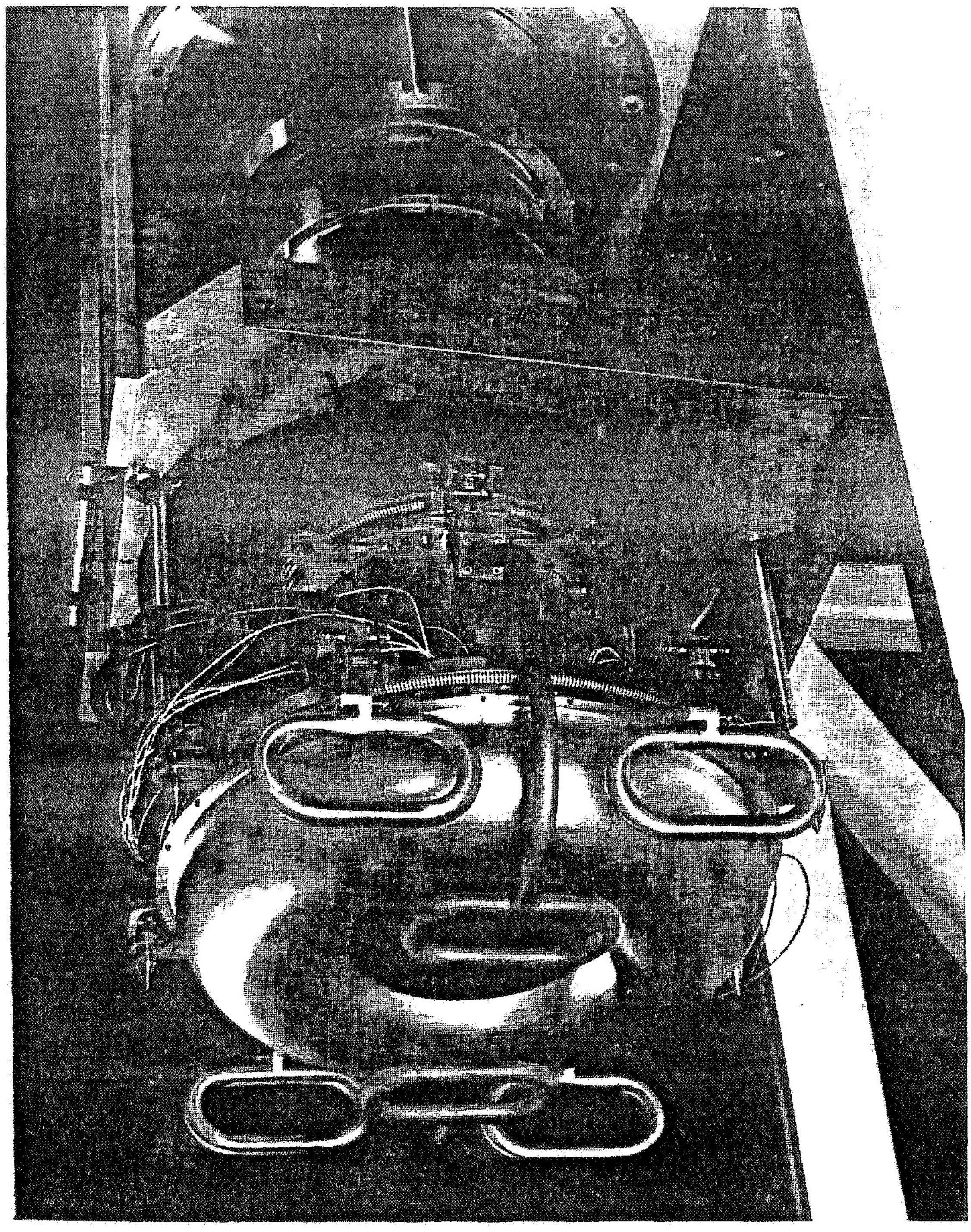
SARJ CAPABILITY

STRUCTURAL CAPABILITIES :

- Rigidity Capability:
  - Bending
    - 4.4 E+10 $lb\text{-}in^2$
  - Torsional
    - 4.5 E+9 $lb\text{-}in^2$
  - Shear
    - 1.0 E+06 lb
- Bearing Assembly Structural Loading Capability :
  - Operational loads :
    - Bending (Mx , Mz) - 125,000 in -lb
    - Torsion (My) - 27,500 in -lb
  - Max Operational Loads :
    - Bending (Mx , Mz) - 264,000 in -lb
    - Torsion (My) - 89,000 in -lb

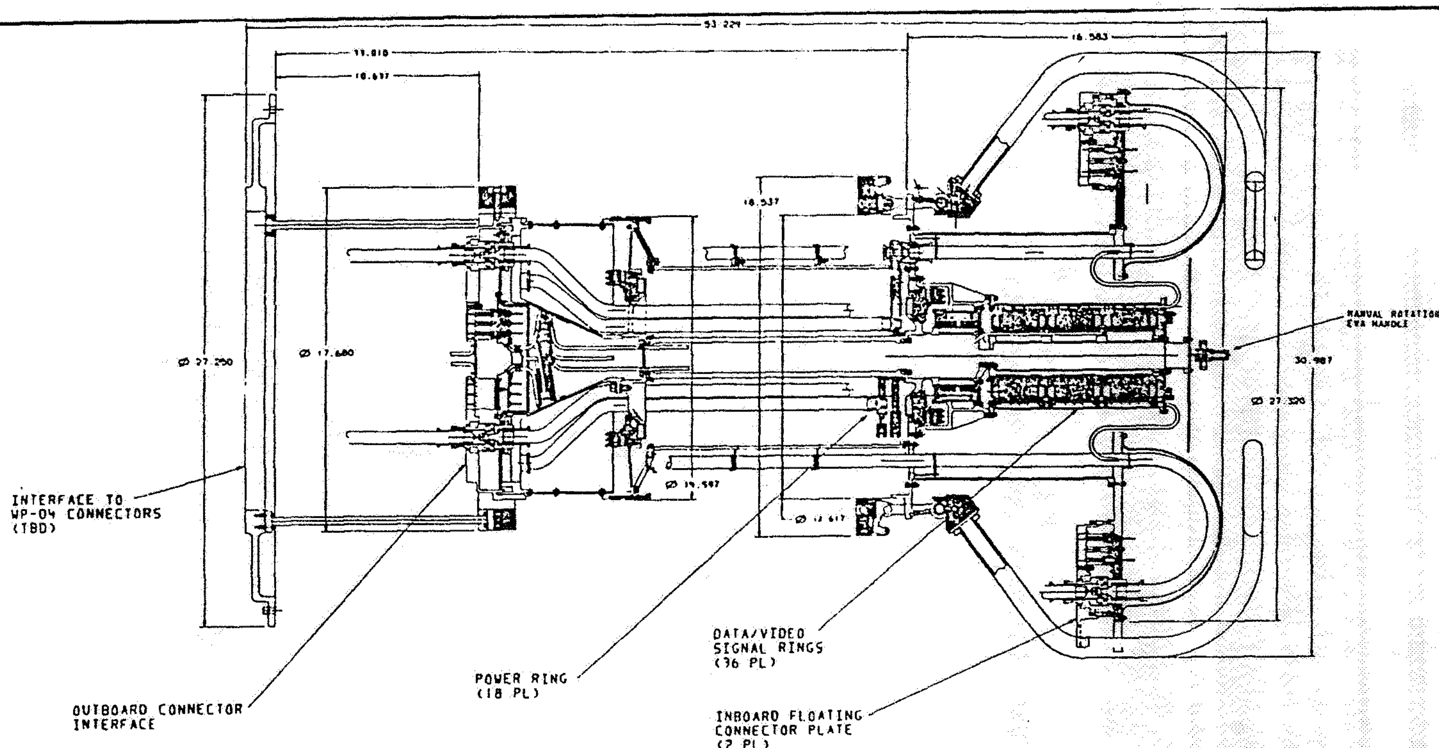
ALLOCATIONS:

- Weight - 2491 lb
- Power - 45 W Nominal



SPACE STATION FREEDOM

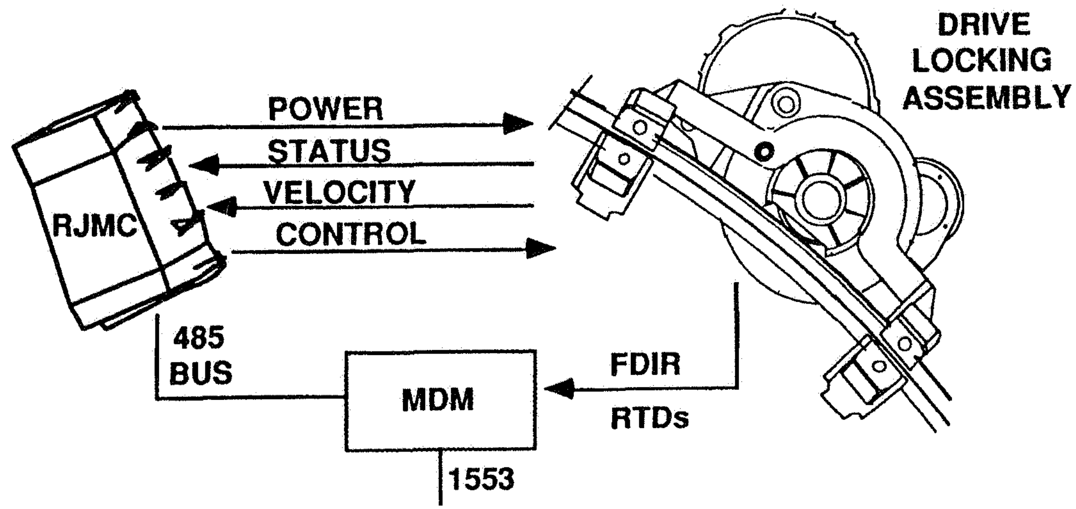
SARJ PIT UTILITY TRANSFER ASSEMBLY



- UTILITY TRANSFER:
  - 60 KW 4 CIRCUITS OF 4 WIRE STATION POWER , 2 STATION GROUNDS
  - 10 1553 DATA CIRCUITS
  - 5 VIDEO EIA/RS 170A
  - 6 SPARE RINGS
- CONTINIOUS ROTATION
- UTA IS AN ORU WITH ACCESS ON THE WP-02 SIDE
- INTERFACING CONNECTORS ARE ALL REPLACEABLE

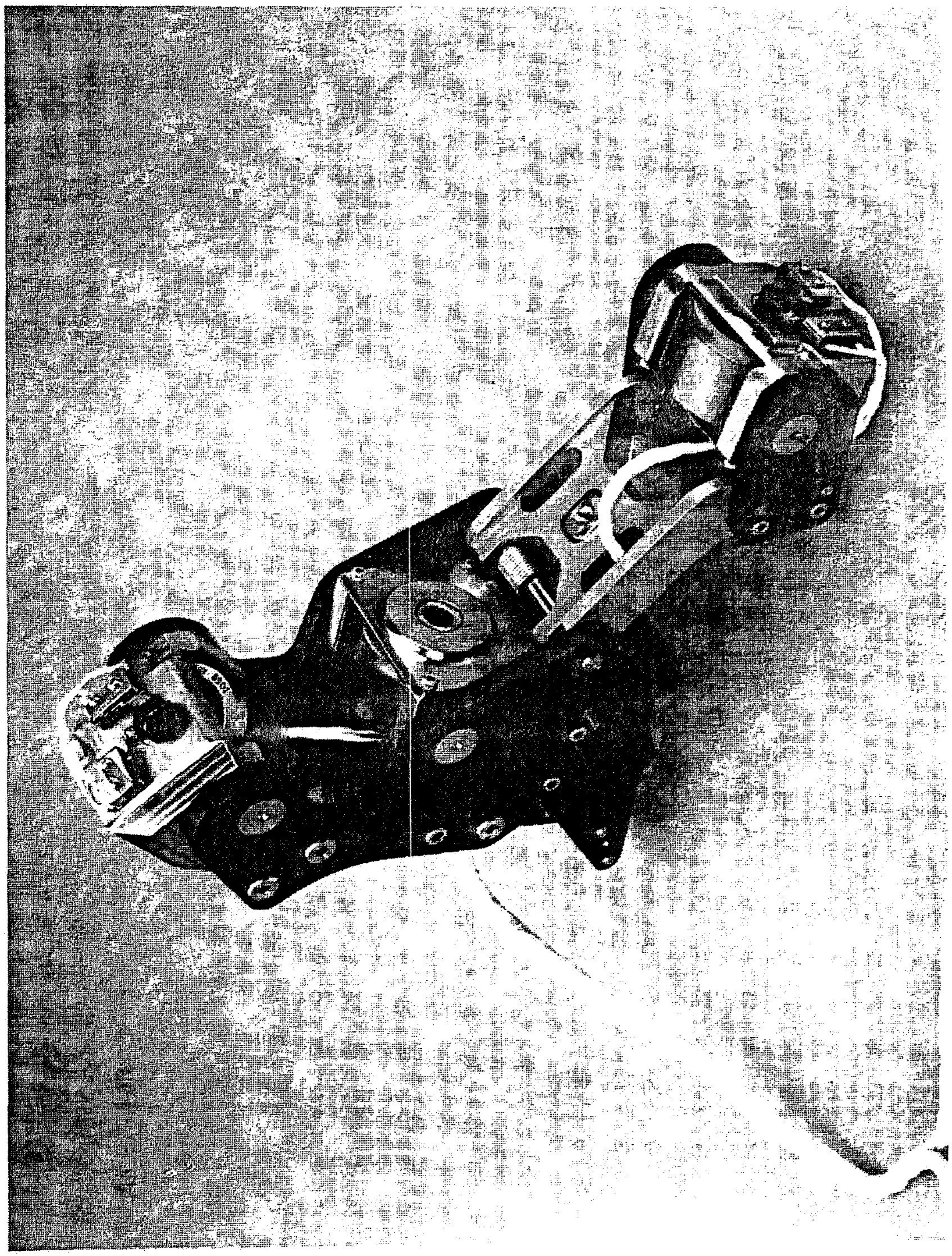
SPACE STATION FREEDOM

DRIVE / CONTROL SYSTEM



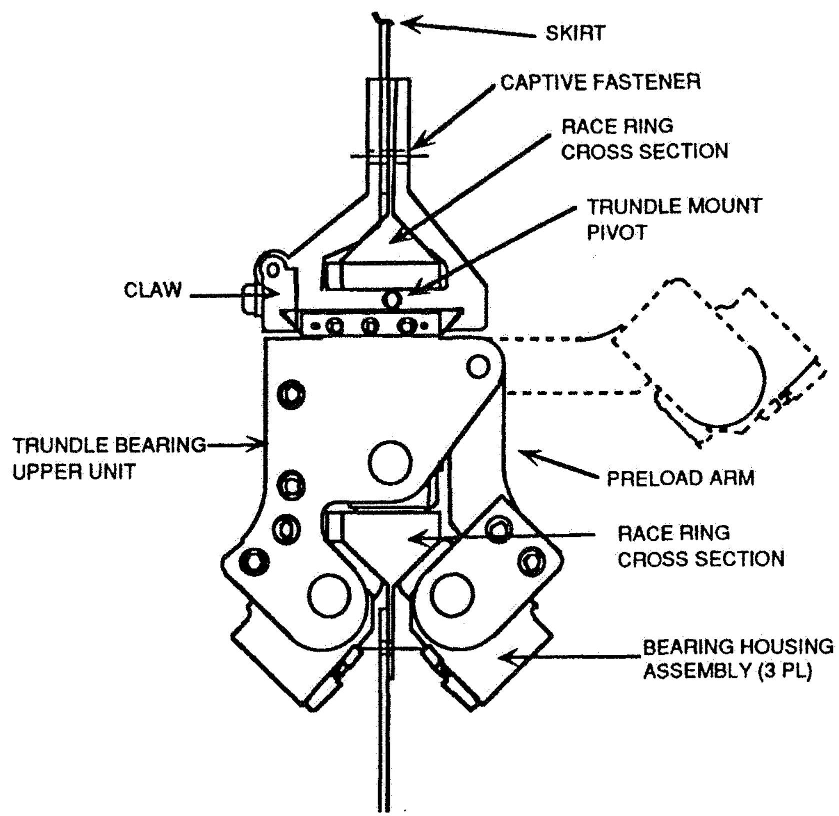
DESIGN DESCRIPTION

- PROVIDES SOLAR ALPHA JOINT DRIVE TORQUE: 2400 ft lb WITH A 283:1 GEAR RATIO
- PROVIDES LOCKING OF INBOARD AND OUTBOARD SEGMENTS
- PROVIDES PRECISE POINTING AND ALIGNMENT OF PIT FOR SOLAR TRACKING AND MOBILE TRANSPORTER TRANSLATION
- DRIVE LOCKING & ENGAGE/DISENGAGE FUNCTION INTEGRATED INTO ONE UNIT



SPACE STATION FREEDOM

SARJ TRUNDLE BEARING / RACE RING



FUNCTIONS:

TRUNDLE

- **CONTINUOUS LINE CONTACT OF BEARING TO RACE**
- **TRUNDLE PACKAGE REVERSIBLE FOR ALTERNATE RACE RING OPERATION**
- **SELF-ALIGNING BEARING PACKAGE**

RACE RING

- **TRIANGULAR RACE RING**
- **DRIVE GEAR ON O.D.**
- **15-5 PH CORE MATERIAL**
- **WEAR COATING FOR RACE AND GEAR APPLICATION: NITRIDED**

SPACE STATION FREEDOM

DRIVE SYSTEM AND TRUNDLE DESIGN

- DRIVE CAPABILITY BASED ON OPERATIONAL LOADING
  - DRIVE CAPABILITY : 2 X JOINT FRICTION + ACCELERATION
  - JOINT FRICTION IS DIRECTLY PROPORTIONAL TO TRUNDLE PRELOAD
  - TRUNDLE PRELOAD IS SIZED TO PREVENT GAPPING DURING OPERATIONAL LOAD EVENTS
- TRUNDLE STRUCTURAL CAPABILITY BASED ON OPERATIONAL AND MAXIMUM ON-ORBIT LOADS (LOCKED)
  - TRUNDLE PRELOAD IS SIZED TO PREVENT GAPPING DURING OPERATIONAL LOAD EVENTS
  - MAXIMUM ON-ORBIT LOADS SIZE THE TRUNDLE FOR STRESS.

GROWTH SUMMARY

- POWER AND DATA TRANSFER

  GROWTH CAN BE ACCOPLISHED AT A RELATIVELY LOW COST THROUGH ORU UPGRADES. SCARS FOR GROWTH SHOULD BE PLACED IN THE DESIGN BY THE END OF FY91

- STRUCTURAL

  GROWTH CAN BE ACCEPTED IF THE CAPABILITY OF THE BEARING ASSEMBLY STRUCTURE IS NOT EXCEEDED.

- DRIVE SYSTEM

  GROWTH CAN BE ACCOMPLISHED THROUGH ORU REPLACEMENT UP TO THE CAPABILITY OF THE EXISTING GEAR DESIGN.

SPACE STATION FREEDOM

POWER GROWTH ASSESSMENT

- POWER:

<u>GROWTH CAPABILITY</u>

- CURRENT UTA HAS NO SPARE POWER RINGS

<u>OPTIONS:</u>

- FLOW GROWTH POWER THROUGH EXISTING RINGS
  + EVALUATE FOR THERMAL IMPACTS
- REALLOCATE POWER CHANNELS IN UTA TO ACCEPT NEW CHANNELS
  + NO IMPACT ON UTA
- ADDITIONAL POWER RINGS TO UTA
  + MODIFY EXISTING UTA

    PRE-PIT DESIGN EXISTS AND HAS BEEN TESTED FOR AN ADDITIONAL SIX POWER RINGS

    INTERFACES DO NOT CURRENTLY SUPPORT THIS GROWTH (UTA ADAPTERS, CABLE TRAYS, UTA)
  + LIMIT IS 24 RINGS DUE TO BEARING ASSEMBLY HUB DIAMETER AND UTA DESIGN COSTS

DATA GROWTH ASSESSMENT

DATA:

<u>GROWTH CAPABILITY:</u>

6 SPARE ROLL RINGS (3 1553 CHANNELS)

(ADDITIONAL RINGS AVIALABLE DUE TO PIT CHANGES)

<u>GROWTH REQUIREMENT: TBD</u>

<u>OPTIONS:</u>

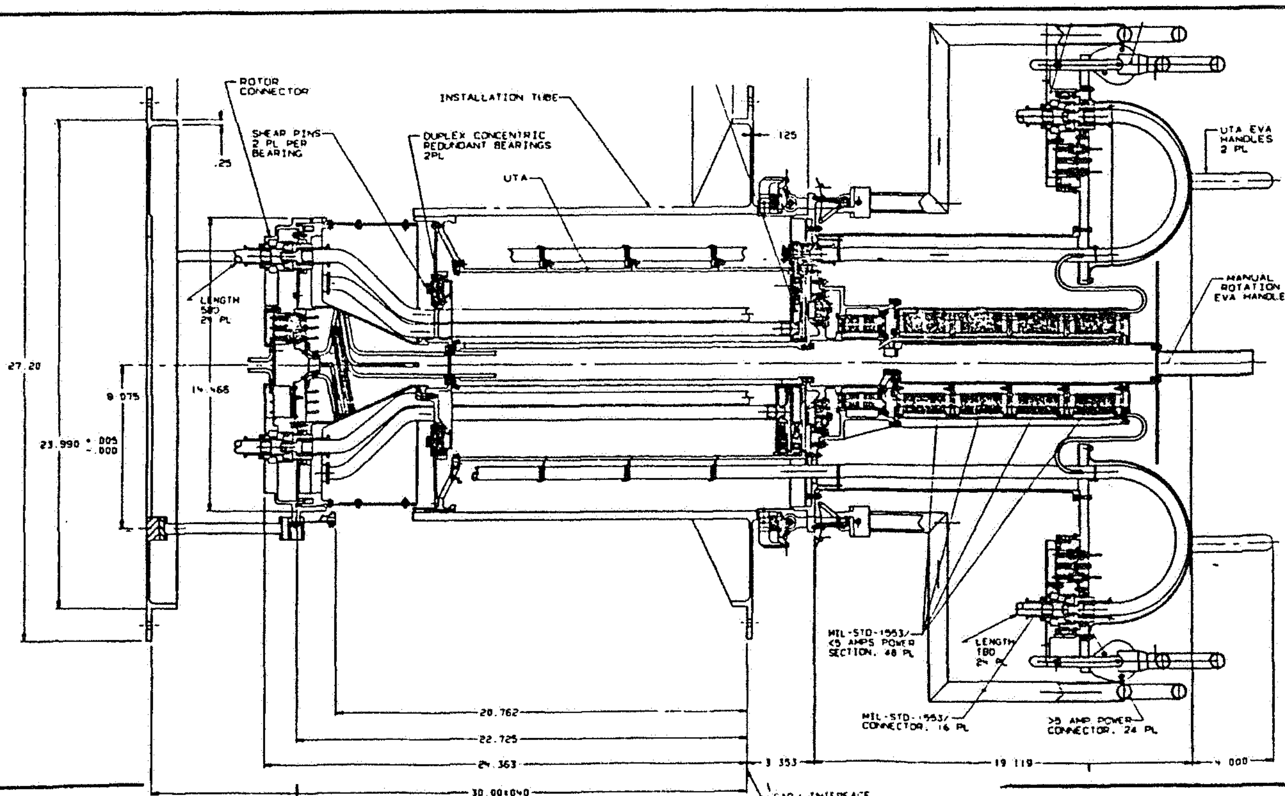
6 OR LESS RINGS: USE EXISTING UTA

7 OR MORE CHANNELS:

- UTA DESIGN EXISTS FOR 48 ROLL RINGS
  - + 18 CHANNELS FOR GROWTH POSSIBLE
  - + INTERFACES DO NOT SUPPORT GROWTH (CABLE TRAY , UTA ADAPTERS, UTA)
- USE Ku BAND COMMUNICATION AND BYPASS SARJ
- LIMIT IS 48 RINGS DUE TO BEARING ASSEMBLY HUB DIAMETER AND UTA DESIGN COSTS

SPACE STATION FREEDOM

SARJ PRE-PIT UTILITY TRANSFER ASSEMBLY



- UTILITY TRANSFER:
  - 75 KW 24 POWER ROLL RINGS
  - 48 DATA/VIDEO ROLL RINGS (24 CIRCUITS POSSIBLE)
- CONTINIOUS ROTATION
- UTA IS AN ORU WITH ACCESS ON THE WP-02 SIDE
- INTERFACING CONNECTORS ARE ALL REPLACEABLE

ORIGINAL PAGE IS OF POOR QUALITY

SPACE STATION FREEDOM

STRUCTURAL GROWTH CAPABILITY

STRUCTURE:

<u>GROWTH CAPABILITY:</u>

- NON-ORU COMPONENTS (SKIRT, RACE RING, RIBS, T-RING, HUBS)
    + NO GROWTH CAPABILITY
- ORU COMPONENTS (TRUNDLE PACKAGES):
    + BEARING ASSEMBLY CAPABILITY

<u>OPTIONS:</u>

- NON-ORU COMPONENTS: REPLACE ENTIRE MB-1 SEGMENT OR PROVIDE ADDITIONAL CAPABILTIY (COST AND SCHEDULE IMPACT ON MB-1)
- ORU COMPONENTS: DESIGN NEW COMPONENTS AND REPLACE ON ORBIT

DRIVE SYSTEM GROWTH CAPABILITY

DRIVE SYSTEM

GROWTH CAPABILITY:

- ROTARY JOINT MOTOR CONTROLLER (RJMC)
    + NO GROWTH CAPABILITY
- DRIVE MOTORS
    + NO GROWTH CAPABILITY

OPTIONS:

- DRIVE MOTORS AND RJMCS ARE REPLACEABLE ORUS
- CAPABILTIY LIMITED BY RACE RING BULL GEAR STRESS

Automated
Power Management and Control

Space Station Freedom

James L. Dolce

ENGINEERING PROTOTYPE DEVELOPMENT FOR POWER MANAGEMENT AND CONTROL

A comprehensive automation design is being developed for Space Station Freedom's electric power system. A joint effort between NASA's Office of Aeronautics and Exploration Technology and NASA's Office of Space Station Freedom, it strives to increase station productivity by applying expert systems and conventional algorithms to automate power system operation. The initial station operation will use ground-based dispatchers to perform the necessary command and control tasks. These tasks constitute planning and decision-making activities that strive to eliminate unplanned outages. We perceive an opportunity to help these dispatchers make fast and consistent on-line decisions by automating three key tasks: failure detection and diagnosis, resource scheduling, and security analysis. Expert systems will be used for the diagnostics and for the security analysis; conventional algorithms will be used for the resource scheduling.

To demonstrate the benefits of automating these tasks we plan to operate the Space Station Freedom Power Test-Bed using our prototype automation technology in our Engineering Support Center (a mission control type of environment). In addition, we plan to demonstrate cooperative problem solving between this test-bed and the Common Module Power Distribution Test-Bed located at the Marshall Space Flight Center. These latter demonstrations will investigate using expert systems that cooperate to diagnose failures whose effects propagate across system boundaries and that cooperate to recover and restore the performance lost through such failures.

CONTROLLING SPACE POWER SYSTEMS

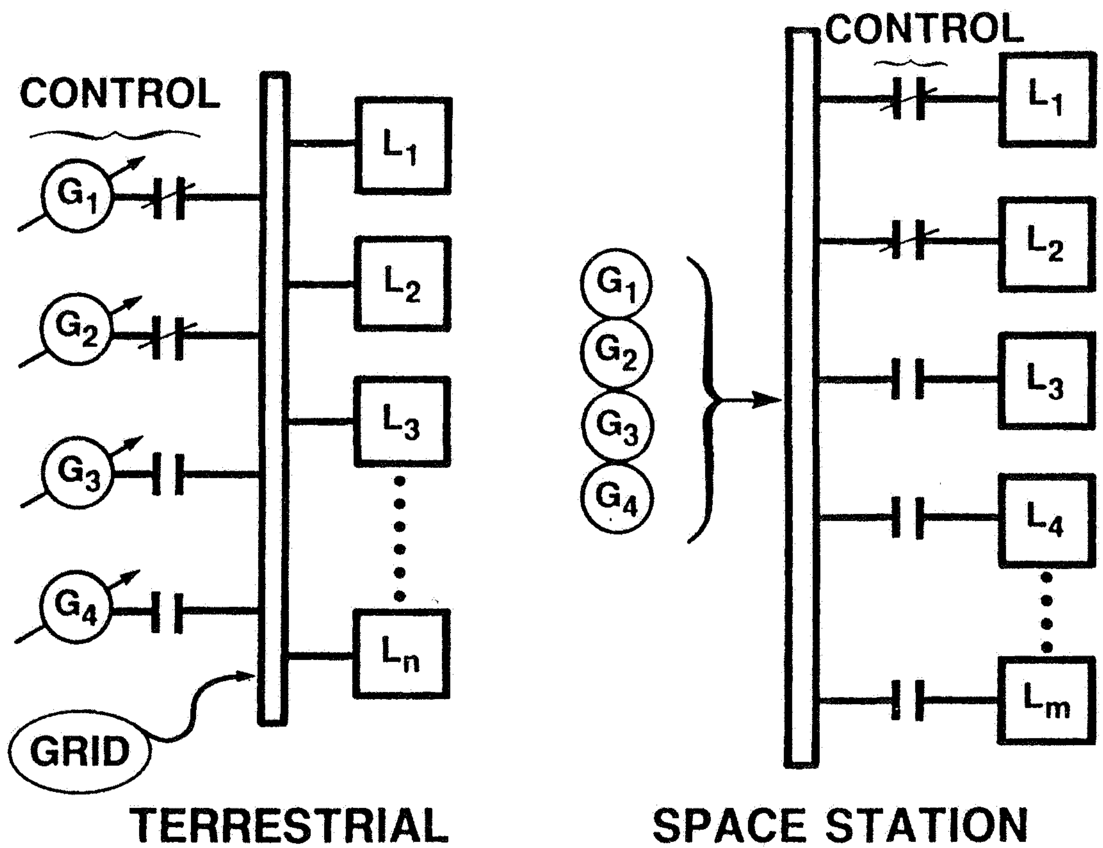
Many similarities between the space station's power system and terrestrial power utilities are apparent. Both systems incorporate generation, storage (usually a pumped water reservoir for the terrestrial -- batteries for us), transmission lines, circuit breakers, and power consumers. Both systems rely heavily on human decision-making for safe, economic operation. But, the strategy that controls the operation of the two systems is fundamentally different. This difference arises at the power supply.

In terrestrial utilities, ample generation is usually available for the demanded loading; when it is not, power is purchased from the grid. The control strategy is to modulate generation capacity to match the demand's changes. Any shortage is covered by interchange with the grid. Every effort is made to meet the load demands by managing the injection of power into the transmission network. Controlling the loads themselves is reserved for extreme failures when there is no acceptable alternative.

The space station's power system has no tie-line to a neighboring utility. Generation cannot be modulated to accommodate demand as in electric utility companies. The power aboard the spacecraft is produced by the solar energy conversion systems which are controlled to maximize energy production. With solar power systems producing only about 7 watts of power for every kilogram of equipment, Space Station Freedom will never grow to be a power rich environment. This makes space power an expensive, limited resource to be judiciously allocated among the on-board users to maximize payload productivity. Energy utilization is controlled by adding and deleting loads from the system. This requires that the load demand be as determinate as possible so that each watt can be allocated. Although this procedure maximizes payload productivity, it generates an extremely difficult scheduling problem aboard complex spacecraft such as Space Station Freedom.

The goal of building a Space Station as an infrastructure for space research complicates the scheduling problems even further. Previous spacecraft have been dedicated to specific pre-determined experiments whose schedules are maximized before flight. A research environment requires the flexibility to generate detailed schedules throughout a thirty year span. Space Station Freedom must provide just such an environment and reap the concomitant development challenges.

CONTROL STRATEGY



CD-87-28006

WHY ADVANCED DEVELOPMENT?

The Space Station prime program has many difficult problems to solve. The electric power system itself has endured the complications of a major component change from 20 kHz AC distribution to DC generation and distribution. Added to these problems are the more recent restructuring activities which emphasize ground control instead of flight control. All of these factors distract the prime program from addressing productivity. Overall, the major design objectives for SSF's electric power system are to build a fail-safe system, to operate within tolerances that provide the required amount of energy, and to create a power system that will be productive. The prime program must first focus on the safety and capacity objectives that create a working, robust flight power system. Unfortunately, the productivity issues do not receive the same attention. The advanced development program has the luxury of avoiding the direct developmental issues and can spend its resources on identifying and building products that will work with the flight power system to augment its capabilities and enhance its productivity for the long term.

Why Advanced Development?

Ranked prime program objectives:

1. Safety
2. Operation
3. Productivity

Advanced development = maximizing productivity

CD-91-53432

MAJOR OBJECTIVE: MAXIMIZE PRODUCTIVITY

Our major objective is the maximization of productivity which manifests itself as efficient and effective operation of the Space Station. To accomplish this we consider two subobjectives of productivity: maximization of resource availability and minimization of operating costs. Maximization of power availability combines a maximization of usage and a minimization of restoration time. To maximize usage we consider load scheduling to be our primary strategy. With it we plan to devise a flexible tool which will be able to automatically schedule this scarce resource throughout the envelope of changing operational configurations. To minimize restoration time we are developing several diagnostic tools to investigate the merits of different approaches to determine failure causes. With strong diagnostic aids at hand, an operator will improve his abilities to respond to anomalies, whether he is ground-based or a member of the crew. To further augment the abilities of the operator we are developing replanning tools which will recommend possible remedial options after a fault has occurred or if a potential problem is brewing. Minimizing operating costs combines operating the power system as close to nominal as possible and minimizing the amount of involvement of the operator. Nominal operations may be traded for performance, especially in emergency situations involving crew. The major component of the power system that involves costly maintenance is the batteries. Optimizing battery usage will increase battery life and reduce the expenses involved in removal and installation of new batteries. Operators, whether ground based or flight crew, have significant duties to perform. We can minimize their involvement in routine power system operations by providing expert system consultation during reconfiguration and replanning.

ORIGINAL PAGE IS
OF POOR QUALITY

Maximize Productivity

- Maximize available power
  - Maximize usage
    - Resource scheduling
  - Minimize restoration time
    - Diagnosis
    - Replanning
- Minimize operating costs
  - Maximize battery life
  - Minimize operators' involvements

CD-91-53429

POWER MANAGEMENT AND CONTROL AUTOMATION

In the fall of 1990, Congress mandated an eight billion dollar budget reduction for the Space Station Freedom Program. To meet this reduction, NASA has reduced the scope of the Space Station's objectives. One of the strategies was to move automation from aboard the space station to the ground control center. This new baseline design places the ground-based flight controllers as the principal decision-makers in the moment-to-moment operations. To make quality decisions, these flight controllers must have an acumen sharpened through years of experience. We believe that expert systems can capture much of this knowledge and help the flight controllers to make faster and more consistent decisions by reducing their cognitive workloads.

Power Management and Control Automation

- Baseline emphasizes ground operations
  - Intensive human involvement
  - Expertise

- Expert systems reduce cognitive workload

CD-91-53337

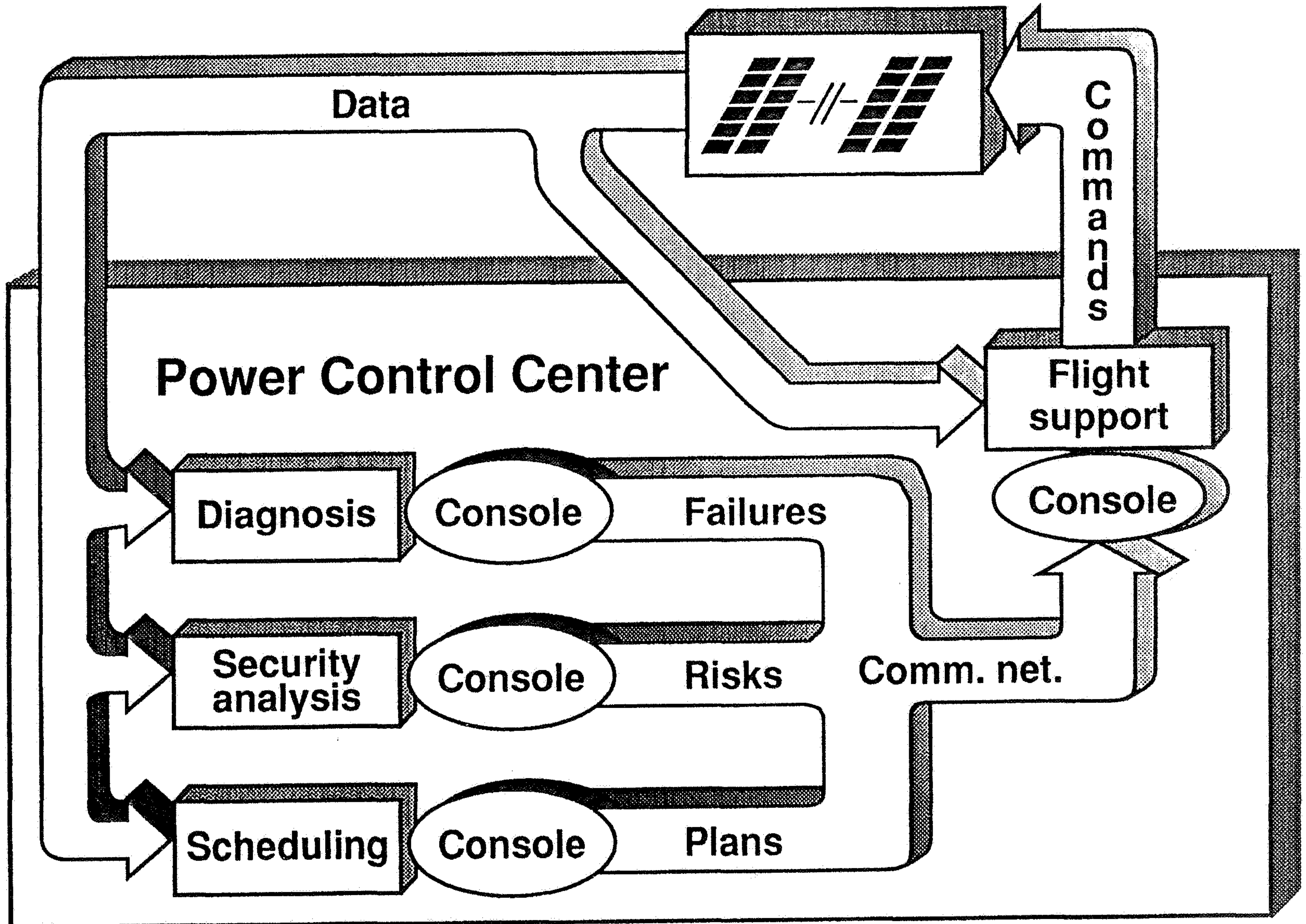
POWER CONTROL CENTER CONCEPT

Our concept for ground-based control focuses on partitioning the control decisions for the electric power system into four decision-making entities. The first, the flight support system, is responsible for issuing the commands to the electric power system aboard the space station. It monitors the system's status and prompts the flight controller for appropriate responses. This is the fastest responding control system. When addressing failure events, this system must detect the failure and isolate affected systems so that the station's integrity is not jeopardized. In addition, the corresponding flight rules must be executed to minimize system degradation. Three other systems are used to aid the command and control activities of the flight support system. These systems are slower to respond than the flight support system and perform detailed event analyses (diagnosis and security analysis) and operations planning (scheduling). The diagnosis system uses available telemetry data to determine the most likely cause of a failure. The security analysis system conducts contingency ("What if...?") analyses to determine the risk of continued operation. The results of these event analyses alter the operating constraints and mission objectives which in turn require a revised operating plan. The scheduling system provides this plan by allocating resources according to the constraints identified by the event analysis systems. Human operators coordinate the exchange of information among these four systems.

FREEDOM

SSF POWER AUTOMATION

NASA Lewis Research Center



CD-91-53338

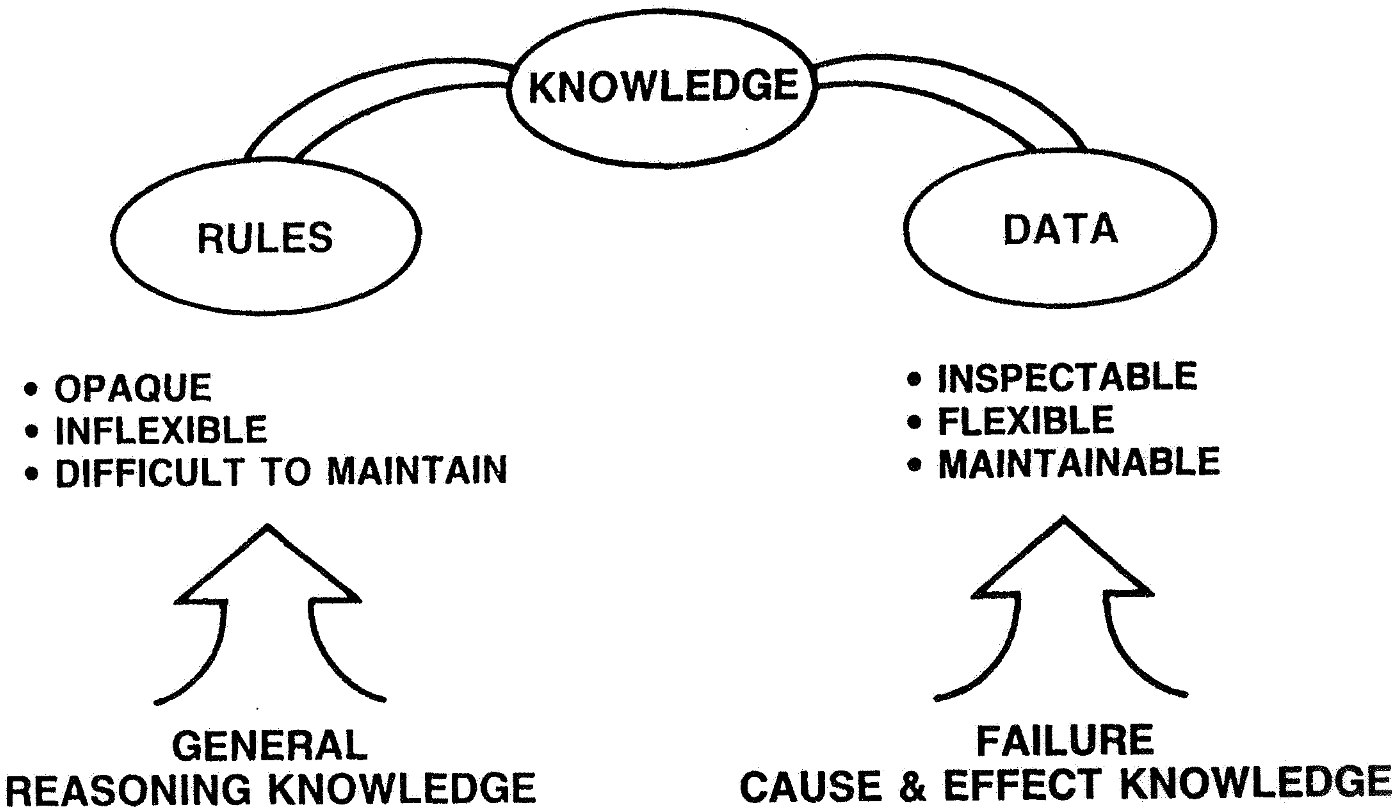
PRODUCTION SYSTEMS FOR DIAGNOSIS

The diagnostic system is an expert system that uses set-covering rather than a series of if-then rules to encode the failure knowledge. In this software, a data base linking all known system failures to their known symptoms is built and searched to generate the failure cause hypotheses for observed symptoms. Antecedent driven rules control hypothesis generation and determine the most likely cause. Nonmonatonic inference is implemented using reasoned assumptions and rule conflicts are identified and resolved using Petri net transitions. The failure knowledge, however, is stored as data and is easily maintained. This diagnostic system uses a standard reliability analysis tool -- the failure modes and effects analysis -- to produce the symptom and failure data base. Symptoms are detected using rule-based classifiers which process the telemetered measurements.

NASA
C-87-2412

National Aeronautics and
Space Administration
Lewis Research Center

PRODUCTION SYSTEM



CD-87-25526

SECURITY ANALYSIS

System security analysis is a risk assessment. It examines the liabilities of continued operation by identifying contingencies and estimating their consequences. The contingencies are either sudden disturbances or gradual performance degradations that could lead to overloads, voltage degradation, source shutdown, or load shedding. If the risk of continued operation is judged acceptable, the system is classified "secure" and system operation proceeds according to the current plan. If there are risky contingencies, the system is judged "insecure" and preventive control strategies are recommended.

Three distinct activities are required to analyze system security:

1. Generate and test contingencies: Worrisome failures that are present under all operating conditions as well as operating-state dependent failures such as transmission outages are compiled and submitted for analysis. The analysis calculates the operating margins for each of these failures.

2. Project trends: Incipient failures such as gradual degradation in battery storage capacity or inconsistencies between proposed consumption and production are detected by specialized software. The anomalies are forecasted and added to the list of contingencies to be analyzed at that time.

3. Judge security: A "system" is secure if there are no contingencies that result in an emergency state. If the operating margins calculated in the analysis are insufficient, the system is judged "insecure" and control actions are recommended that will attain an acceptable operating risk.

Security Analysis

Security is freedom from risk

1. Known contingencies
2. Incipient failures

Analysis yields a risk judgement

1. Generate & test
2. Project trends
3. Evaluate consequences & judge risk

CD-91-53339

NIH2 BATTERY HEALTH MONITORING SYSTEM

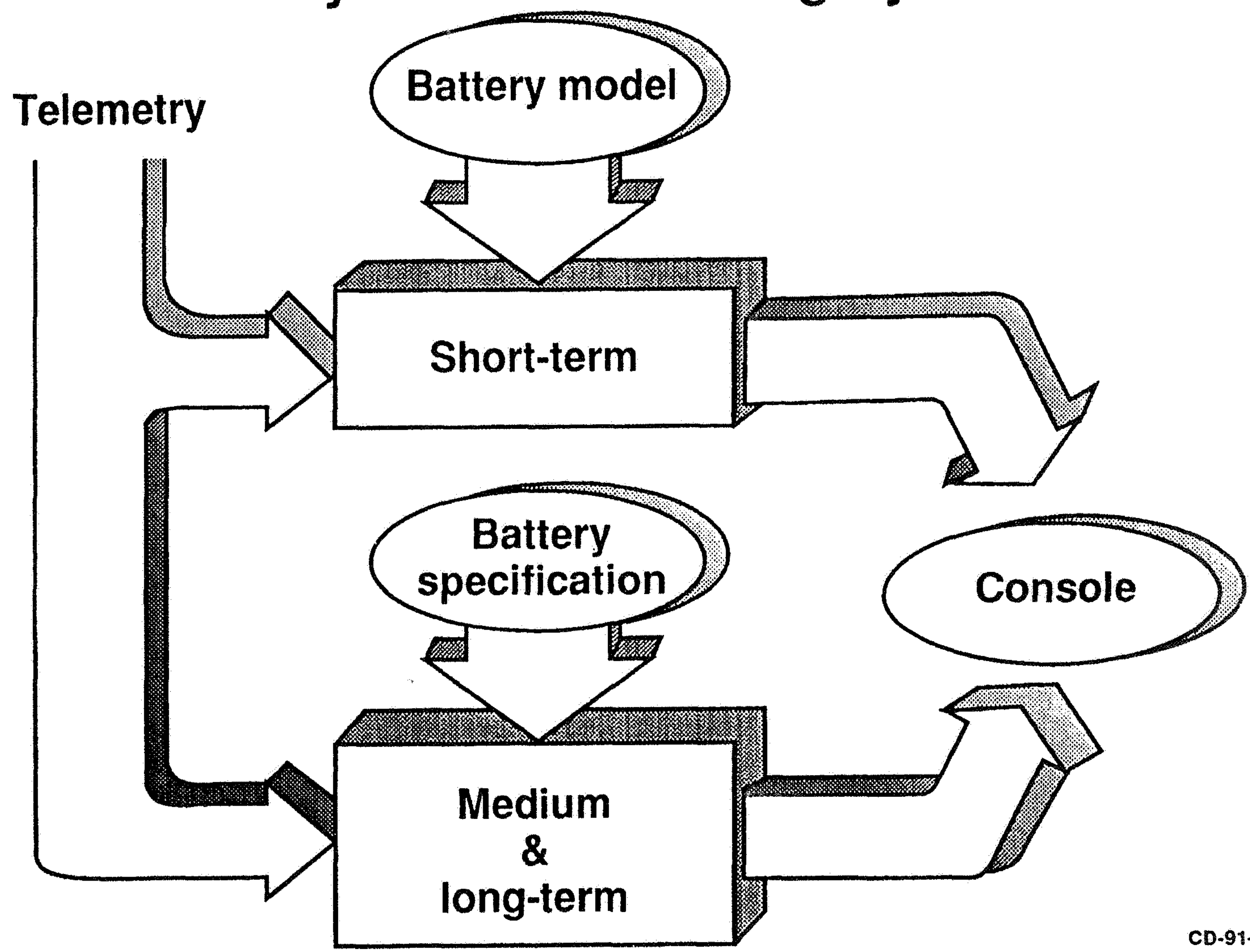
A significant part of the security analysis problem is monitoring the health of the battery system and projecting any loss of capability. A battery health monitoring system is being developed that detects anomalies in the batteries, provides problem diagnosis, and projects expected life estimates. This system uses a combination of analytic models and tabulated aging characteristics to identify incipient failures. Three trends are maintained: short-term, medium-term, and long-term.

The short-term trend data (3 orbits) address battery current and voltage, cell pressure and temperature, and depth of discharge. The data are smoothed. Trends are identified and compared with results from an empirical analytic model of the battery. Deviations are used to detect events such as sensor failure, cell short circuit, and cell rupture.

Medium-term (100 orbits) and long-term (3000 orbits) data address cell pressures and voltages at the end of the charging period and at the end of the discharging period, recharging ratio, Watt-hour efficiency, depth of discharge, and cell temperatures. These data are smoothed and trends are identified and compared with the batteries' expected aging characteristics. The comparisons detect the anomalies that develop over many orbits such as: cell soft short, slow cell leak, high internal resistance, internal corrosion, excessive overcharge, abnormally high operating temperature, and gradual loss of charge carrying capacity.

The system displays these health trends and alerts the system operator should there be any deviations from the expected.

Battery Health Monitoring System



CD-91-53340

SYSTEM MANAGEMENT AND SPACE STATION FREEDOM AUTOMATION

One of the key concepts in our automation scheme parallels the systems management approach to project management and design. This approach is utilized in our scheduling tool by incorporating a two-level hierarchy for distributing the computational requirements and the regions of responsibility. The hierarchical design resembles the manager and subordinate with respect to their roles and responsibilities. This system is based on the concept of participative management where the manager describes the work to be done and then leaves the subordinate alone while the work progresses. Communication between the levels is minimized. Detailed information resides with the person who will be using it. In this fashion we build a computer system that can be distributed across different machines reducing computational overload and minimizing data passing.

Along with distributing our scheduling process, we are defining an explicit value system to be used in evaluating the proposed schedules. Maintaining the separation of responsibility each subordinate system will maintain and define its value for a specific schedule which can be interpreted on the higher level. Each subsystem will maintain its own system integrity and evaluate schedules with respect to its own system level constraints. These evaluations will be passed up to the higher level where they will be interpreted within the context of the entire system rather than the local point of view.

SYSTEMS MANAGEMENT & SPACE STATION FREEDOM AUTOMATION

REQUIREMENTS:

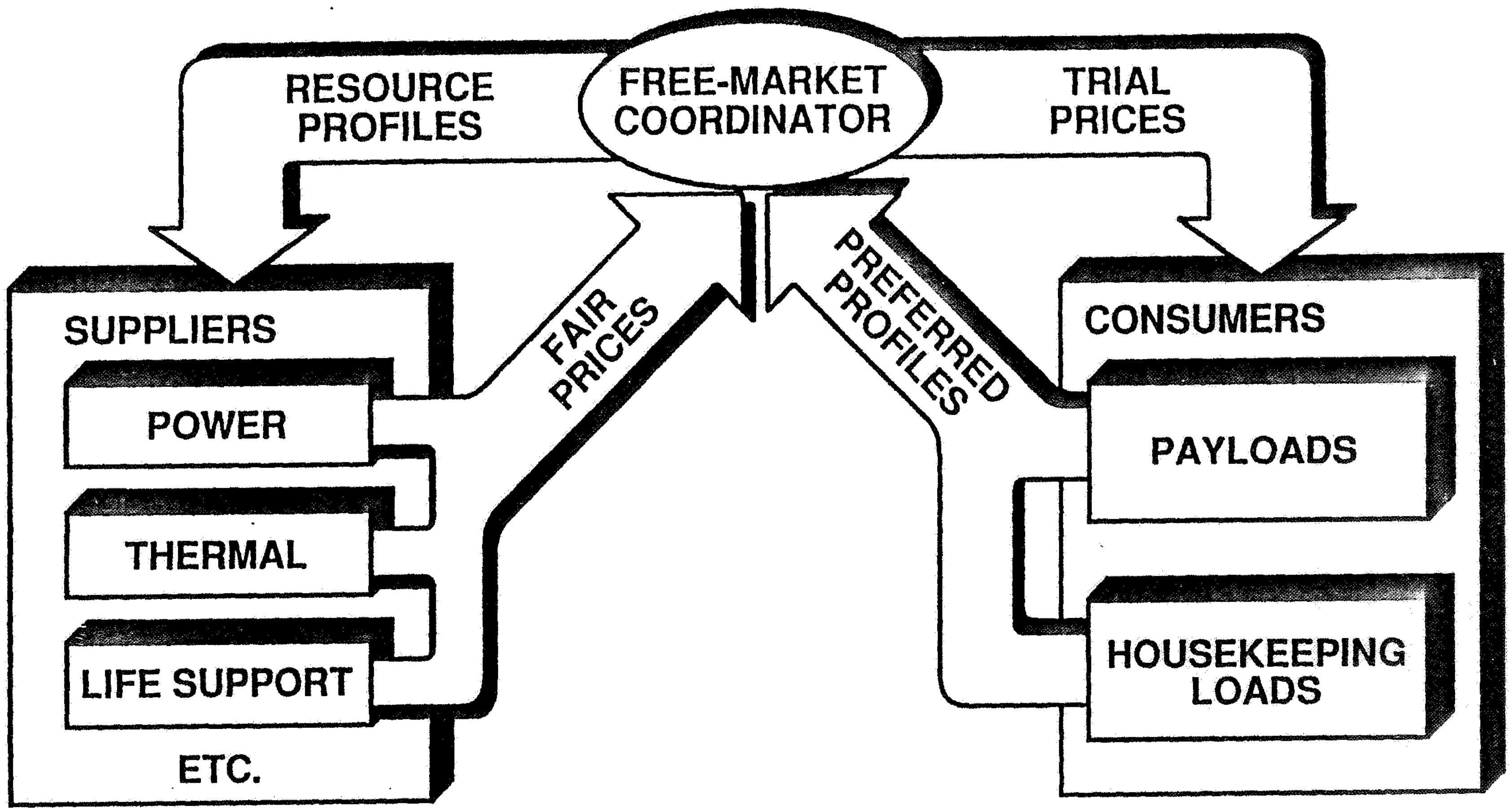
1. TWO-LEVEL HIERARCHY
2. EXPLICIT VALUE-SYSTEMS
3. LOCAL CONSTRAINTS

CD-90-48739

FREE MARKET ECONOMY MODEL FOR SCHEDULING RESOURCES

Using the systems management approach we have developed a value-driven distributed scheduler that models a free market economy. This scheduling technique is based upon three agents, resource suppliers, resource consumers and an overall market coordinator. The resource suppliers are the various subsystems on the Space Station. They maintain their local systems and evaluate proposed schedules based upon usage of their resource. Consumers are the payloads and various housekeeping tasks aboard the Space Station. Each consumer describes the various options for each desired activity along with defining a specific numeric value for each of these options. The schedule is determined by setting initial prices for each resource throughout the scheduling horizon which are sent to each of the consumers. The consumers evaluate how much each of their options would cost and choose the one with the highest net benefit where net benefit is the difference between the value of the option minus the cost of the resources used. The selected options are aggregated by the market coordinator who sends the appropriate total usage profile to the resource supplier. Each supplier looks at the proposed schedule of usage and compares it to what he knows he can supply throughout the orbit. He will then send a set of price adjustments to the market coordinator to drive usage to his specific abilities. His goal is to maximize usage of his resource, operating neither in a deficit nor in a surplus condition. The market coordinator continues this iterative process until the prices converge and the schedule options are stable.

One of the benefits of this approach is that the explicit value system can be used to identify how good the proposed schedule is before the solution has converged. Consumers and suppliers define utility functions that are used to evaluate the proposed operating condition generated by each proposed schedule. The utility functions are sent to the market coordinator who can evaluate the entire state of the Space Station operation and decide whether or not to continue iterating. Scheduling needs to be responsive to different operating states of the Space Station. Some schedules will be routine, others will be emergency schedules needed very quickly to return to a sensible operating condition. Using explicit values and utility functions allows us the flexibility to provide for many different operational scenarios.


RESOURCE
PROFILES
FREE-MARKET
COORDINATOR
TRIAL
PRICES
FAIR
PRICES
PREFERRED
PROFILES
SUPPLIERS
POWER
THERMAL
LIFE SUPPORT
ETC.
CONSUMERS
PAYLOADS
HOUSEKEEPING
LOADS

CD-90-46581

POWER CONTROL CENTER CONCEPT - REVISITED

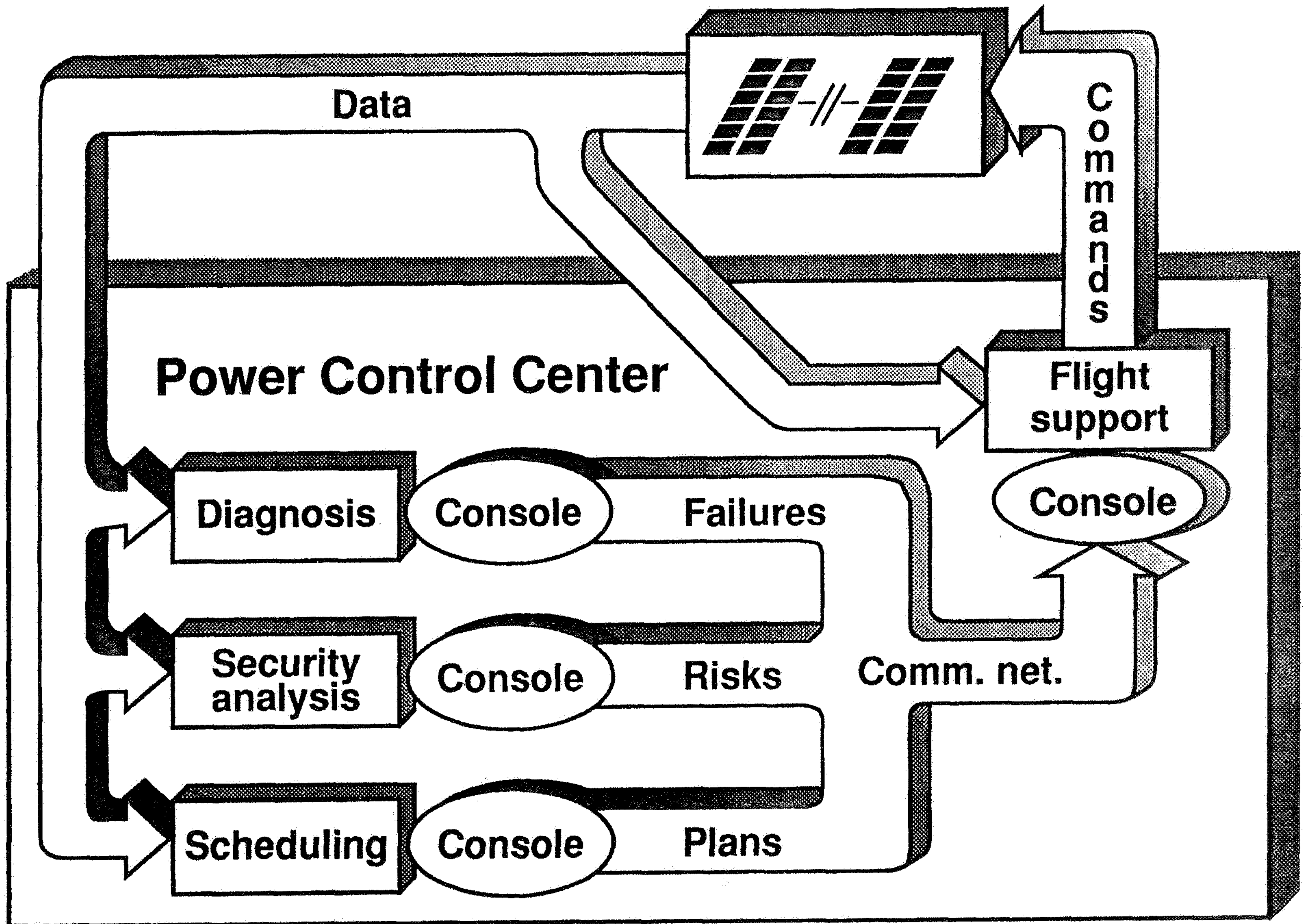
To revisit the motives behind our program, we have responded to the Space Station restructuring effort by focussing our products as ground-based tools for operators. We see the use of our intelligent decision-making aids as improving the overall Station productivity by enabling decisions to be made faster and more accurately.

We have been investigating the Engineering Support Center at LeRC as our potential site for the power control center. Using the ESC we will be able to communicate directly to the LeRC Power Management testbed, as well as receive actual telemetry when appropriate. In this environment we will also be able to link to the MSFC payload operations center and exchange data necessary to diagnose and recover from power system failures that propagate from the primary system into the secondary.

FREEDOM

SSF POWER AUTOMATION

NASA
Lewis Research Center



CD-91-53338

MSFC -- LERC COLLABORATION

Development of different expert systems for the power system on board the Space Station has been a direct response to the programmatic partitioning of the primary power system generation and storage and distribution from the secondary power distribution network. This partitioning has provided a manageable subset of the system for each of the developers. However, certain failures will propagate across these system boundaries and it is necessary to begin investigation of these effects.

A data link between testbeds at NASA-LeRC and NASA-MSFC has provided information to begin these investigations. This link has been used to demonstrate cooperating expert systems during this past year. The demonstration addressed a power generation failure that required the secondary system to perform intelligent load shedding at the module level. We are planning to continue this effort by investigating failures that ripple through the secondary distribution and whose recovery requires cooperation between both systems. In the context of the control center environment we are not planning any direct testbed links for the coming year. We want to study how to coordinate the entire power system operation using the control center environment. This will prepare us for real operational scenarios.

MSFC – – LeRC Collaboration

Cooperating expert systems

Diagnosis

Recovery

Effects that propagate across system boundaries

CD-91-53341

LeRC POWER MANAGEMENT AUTOMATION EVOLUTION

When the Space Station program began, the electric power system was a 20kHz AC distribution system. Pioneering work had been done at LeRC in development of this technology. Many power system experts were available to provide the information required for intelligent control and diagnostic tools. Our program took advantage of these factors and developed a diagnostic tool in KEE for 20kHz switchgear which communicated with a scheduler for replanning usage after a system failure. These tools also communicated directly to prototype Ada flight code controlling 20 kHz switchgear. Development of these products and their integration has provided us with valuable insight into the problems that can occur. This work culminated in an integrated demonstration with a MSFC testbed over a long distance communication network. The products from this work are being modified to apply to the DC testbed configuration and will also be integrated into the power control center.

Parallel efforts began when the Space Station program switched from 20kHz AC to DC distribution. A diagnostic product using ART was developed along with a value-driven scheduler and the beginnings of the security analysis system. These products had been targeted for integration with the DC testbed directly as a demonstration of their potential use as flight decision-making aids. Due to the restructuring efforts and the current emphasis on ground-based control, we have reevaluated the thrust of our program. We are, however, continuing with integration of our products and the DC testbed directly. This serves as a preliminary step before integrating with the LeRC engineering support center, the ESC. We are developing the interfaces required to make an initial communication path between our advanced development machines and the testbed control computer using its current operator interface system protocol. Testbed work is very intense at the moment and this approach creates minimum impact on their efforts. We are also investigating the interfaces required for integration of the power system testbed and the ESC. The ESC will provide our advanced development products a rich environment of processed data and graphics interfaces. Our initial design features the advanced development machines communicating on a subnetwork and using one of the ESC machines for passing the data to and from our products. This minimizes the impacts on both the ESC and our program. After this interface has been developed and used to investigate testbed and automation product performances, we plan to generate specific application programs that would dirctly reside on the ESC processors.

Evolution

20 KHz AC System 1988-1991

- Scheduler
- Diagnostic
- Integrate with testbed
- Cooperative demo with MSFC testbed

DC System 1990-1992

- Scheduler
- Diagnostics
- Security analysis
- Integrate with testbed using OIS
- Integrate with testbed using ESC
- Link ESC with MSFC testbed
- Develop products as ESC application

CD-91-53433

IN A NUTSHELL

In the ever changing environment of the Space Station program, power system management and control continue to be critical development items. Our advanced development program is focussed on developing decision-making aids for operators, either ground-based or flight-based. In the efforts to fully utilize electric power at all times, we need much automation. We are striving to provide automation tools which will allow the Station to flexibly and productively manage of one of its critical resources, energy.

We are targeting our products for the ground-based control centers knowing that this is where they are needed initially. Operating a Space Station will be a monumental effort and products to reduce the workload will prove themselves well worth their development cost. As Space Station develops, the need for these products will be onboard. We are prepared to continue our efforts and provide flight-quality products.

In a Nutshell

Productivity

Control center environment

Flight potential

CD-91-53430

NASA — MSFC

THE SSM/PMAD AUTOMATED TEST BED PROJECT

LOUIS F. LOLLAR

THE SSM/PMAD AUTOMATED TEST BED PROJECT

In conjunction with MSFC's Work Package One responsibilities and MSFC's previous OAET work in electrical power system autonomy, the SSM/PMAD autonomous subsystem project was initiated in 1984. The project's goal has been to design and develop an autonomous, user-supportive PMAD test bed simulating the SSF Hab/Lab module(s). Funded primarily by the SSF Advanced Development Program from FY85-88 and with additional joint funding from OAET (Code RC) during FY89-91, an eighteen kilowatt SSM/PMAD test bed model with a high degree of automated operation has been developed. To date over $3.2 million has been invested in hardware and software development. This advanced automation test bed contains three expert/knowledge based systems that interact with one another and with other more conventional software residing in up to eight distributed 386-based microcomputers to perform the necessary tasks of real-time and near real-time load scheduling, dynamic load prioritizing, and fault detection, isolation, and recovery (FDIR).

The approach has been to establish the technology through key "operational" demonstrations, prepare for early ground-based implementation in the various SSF control centers, and then to migrate the technology "on-board" as confidence builds and as schedules permit. A parallel effort was begun to establish communication links between the SSM/PMAD test bed and the primary PMAD automated test bed at LeRC in order to investigate major automated subsystem interactions. A first generation "operational" prototype has been successfully demonstrated along with a Phase I MSFC/LeRC test beds communications link.

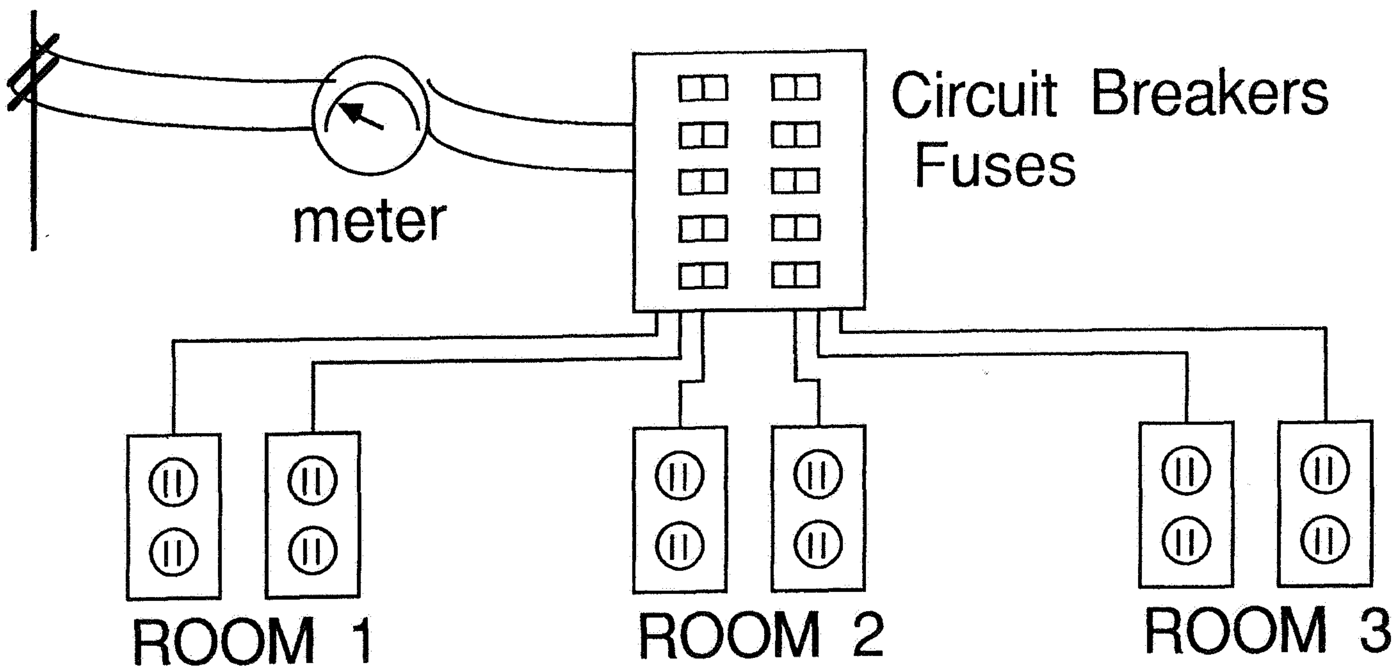
OUTLINE

- THE PMAD PROBLEM
- OBJECTIVES
- TECHNICAL APPROACH
- BASELINE INTEGRATION
- EVOLUTION AND GROWTH
- SUMMARY

OUTLINE

This presentation will begin with a look at the PMAD "problem" and include a short background and history of the SSM/PMAD project. Next, the objectives of the project will be presented followed by a discussion of the technical approach and description of the project. The next topics will consist of how the project integrates with the baseline program and how the technology may evolve into the "on-board" station. A final summary will then be presented.

TYPICAL HOUSE PMAD



- Easy Circuit Breaker Access
- Simple Switchgear
- Trip Levels Set High
- Load Flexibility
- Cost Managed

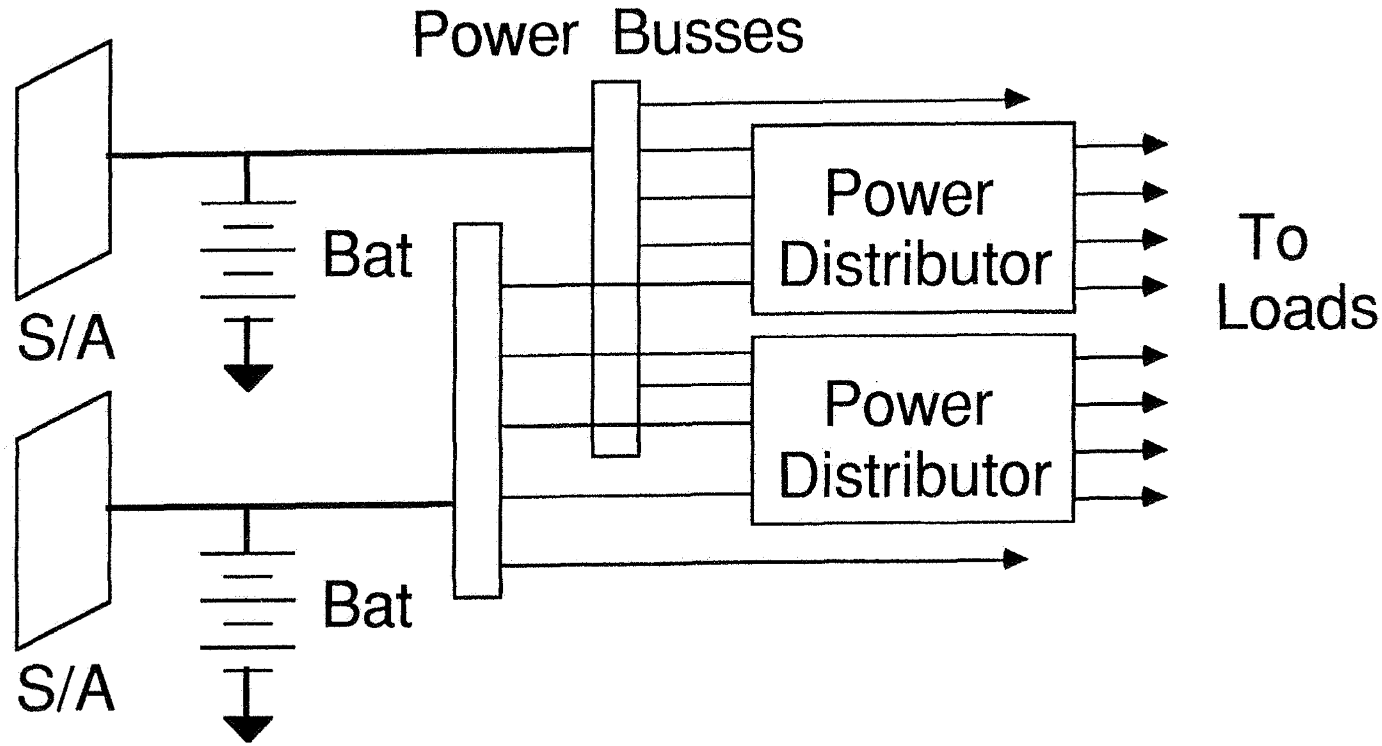
TYPICAL HOUSE PMAD

The typical house PMAD system consists of a power meter, a circuit breaker box, and the various loads and outlets (a few of which have ground fault protection). The power feed (240/120 Vac, 60 Hz) comes from a transformer mounted on a pole or underground through a Watt-hour (Energy) meter into a control box consisting of a group of circuit breakers (and in some cases fuses). This power is then distributed through the breakers to the various loads. Typical loads are: electric oven, clothes dryer, heating/air conditioning, water heater, lighting, and the outlets.

This system contains easily accessible circuit breakers (fuses) which are electrically simple electomechanical devices. Their trip levels (amount of current required to "open" the device) are set high which means a major fault or an extraordinary number of loads in a particular outlet is required to cause the breaker to trip. This is done to prevent a user from having to spend his entire life resetting breakers. The system allows complete load flexibility. The only requirements for any load is to be of the correct voltage/frequency and to draw less current than the breaker setting. Finally, the use of energy in this system is cost managed. If you can afford it, you can use as much energy as you like.

NASA — MSFC

TYPICAL SPACECRAFT POWER SYSTEM



- Complex Circuit Breakers with Limited Access
- Circuit Breakers Sized for Specialized Loads
- Complex Loads with Unique Power Profiles
- Load Managed (Limited Energy Avalible)

TYPICAL SPACECRAFT POWER SYSTEM

The typical spacecraft power subsystem to date has been less than 5 kW total power and has consisted of two or more power channels (solar array, battery, and bussing) feeding power distributors to the specialized loads. The systems have been primarily low voltage dc (28 Vdc nominal) distribution using planar silicon solar arrays and Nickel based batteries.

In comparison to the terrestrial power system, the spacecraft power system has electrically complex circuit breakers with very little access capability (if at all). These breakers are also sized for practically each specialized load. The loads themselves typically have complex power profiles (power vs. time) and require an extensive scheduling team to combine the power profiles to maximize energy usage. This leads to the final point. A spacecraft has to be load managed in order to maximize its most precious resource - energy. For example, if a load begins to use more energy than its initial allotment, then either this load is shed or energy is shifted from a more efficient load or another load is shed.

NASA — MSFC

AUTOMATION PROJECTS AT MSFC

- Autonomously Managed Power System (AMPS) - 1978-1985

  OAET Funded

- Battery (NiCd & NiH2) Test Expert Systems - 1983-Present

  Hubble Space Telescope Funded

- Space Station Module/Power Management and Distribution (SSM/PMAD) Automated System - 1985-Present

  OSF and OAET Funded

AUTOMATION PROJECTS AT MSFC

As background, there have been three primary automation projects at MSFC. The first, AMPS, was started in the late 70's to investigate large spacecraft power systems and how to automate them. The AMPS project, funded by OAET (Code RP) and contracted to TRW, consisted of three phases. Phase I identified a reference 250 kW-class power system based on projected 1980's technology. The basic result was a distributed multiple power channel system, using concentrator solar arrays, Nickel-Hydrogen batteries, and high voltage dc (200 Vdc nominal) distribution. Phase II focused on how to automate the system. The basic results were using distributed microcomputers and pushing the computing power as far down the architecture as possible. Phase III involved constructing a three power channel (25 kW) subsection of the reference power system to design and demonstrate the automation theories. The project was stopped shortly before full completion, but the basic automation theories were able to be demonstrated.

The second project area was the Hubble Space Telescope power system test bed. This project area introduced MSFC into the area of expert/knowledge based systems. Two separate systems were developed to automate and perform fault diagnosis on the HST power test bed which was (and is) operating 24 hours a day. When a test bed problem occurs, the system is safed and the test engineer is automatically called. During the travel time of the engineer to the test, the expert system has analyzed the situation and produced a diagnosis and explanation before the engineer arrives. These systems also are able to do multiple orbit trends analyzes. These systems were named the Nickel Cadmium Battery Expert System (NICBES) and the Nickel Hydrogen Battery Expert System (NIHES). The two systems were a result of the HST battery change in 1989.

The final active project area is the SSM/PMAD automation test bed project which is the topic of this presentation. The project was started in 1985 with funding from the Phase B advanced development program for Space Station. Martin-Marietta of Denver was awarded both the hardware and automation contracts. Presently, the project is funded through the Advanced Development Office of Space Station (Code MT) with OAET (Code RC) funding two subtasks which are more research in nature.

NASA — MSFC

OBJECTIVES OF THE SSM/PMAD AUTOMATION PROJECT

- Risk Reduction for the Space Station Module by Developing a PMAD System that Demonstrates Autonomous Monitoring, Control, and FDIR Capabilities

- Identify Design Impacts to the Design, Development, and Operation of the SSF, Both Baseline and Evolution

OBJECTIVES OF THE SSM/PMAD PROJECT

The objectives for the project are to provide risk reduction for the Space Station Hab/Lab Modules power subsystem and to identify any design impacts both to the baseline and the evolution station.

The first objective is being met by having designed a high fidelity hardware test bed of the power subsystem and then to demonstrate autonomous control through the use of advanced and conventional software. The basic system has been designed and operational-type testing is being performed to evaluate and update the software/hardware.

All information from the design and test is made available to all SSF work packages, but especially to WP01 and WP04. This information is used to help guide design decisions for the baseline station. In addition, this information can be used to help in module power subsystem operations and to aid in future hardware/software upgrades to the evolving station.

NASA — MSFC

BENEFITS OF AUTOMATED PMAD

- Enhance Safety
- Increase Productivity
- Cost Avoidance in Operations Personnel
- Increase Reliability
- Improved Fault Isolation and System Recovery

BENEFITS OF AUTOMATED PMAD

Automating the SSM/PMAD subsystem will produce many benefits. Five of these benefits are listed below:

(1) Safety is enhanced through the use of fast, intelligent hardware which can safe faults rapidly. Also, a critical load which loses power during a fault can be re-powered in a few seconds (less than 3) using a dual power feed and a small, but efficient computer.

(2) Productivity is increased by allowing the power system operator (ground or flight) to focus on more critical tasks than the operation of the power subsystem. Through the use of dynamic re-scheduling, even in off-nominal situations, the source energy to load energy ratio can be maximized.

(3) Skylab required twenty ground support personnel and a flight crew of three to operate an 8 kW power system. Using automation techniques, as SSF evolves, the number of personnel required to operate the power system can remain constant. Further, as the user interface matures, the technical expertise required by an operator could be reduced.

(4) Reliability is increased by the system consistency offered by the automated software. Also, system hardware stress is reduced through intelligent load scheduling and load energy balancing.

(5) System faults are safed, isolated, and diagnosed [redacted] in a few milliseconds to seconds which allows for quicker repair and reduced downtime.

TECHNICAL APPROACH

- Use Advanced and Conventional Software Techniques to Automate a SSF Fidelity Test Bed

- Use a Distributed Function Approach; the More Time Critical Functions are Performed Nearest the User

- Develop a User - Supportive Graphics Interface

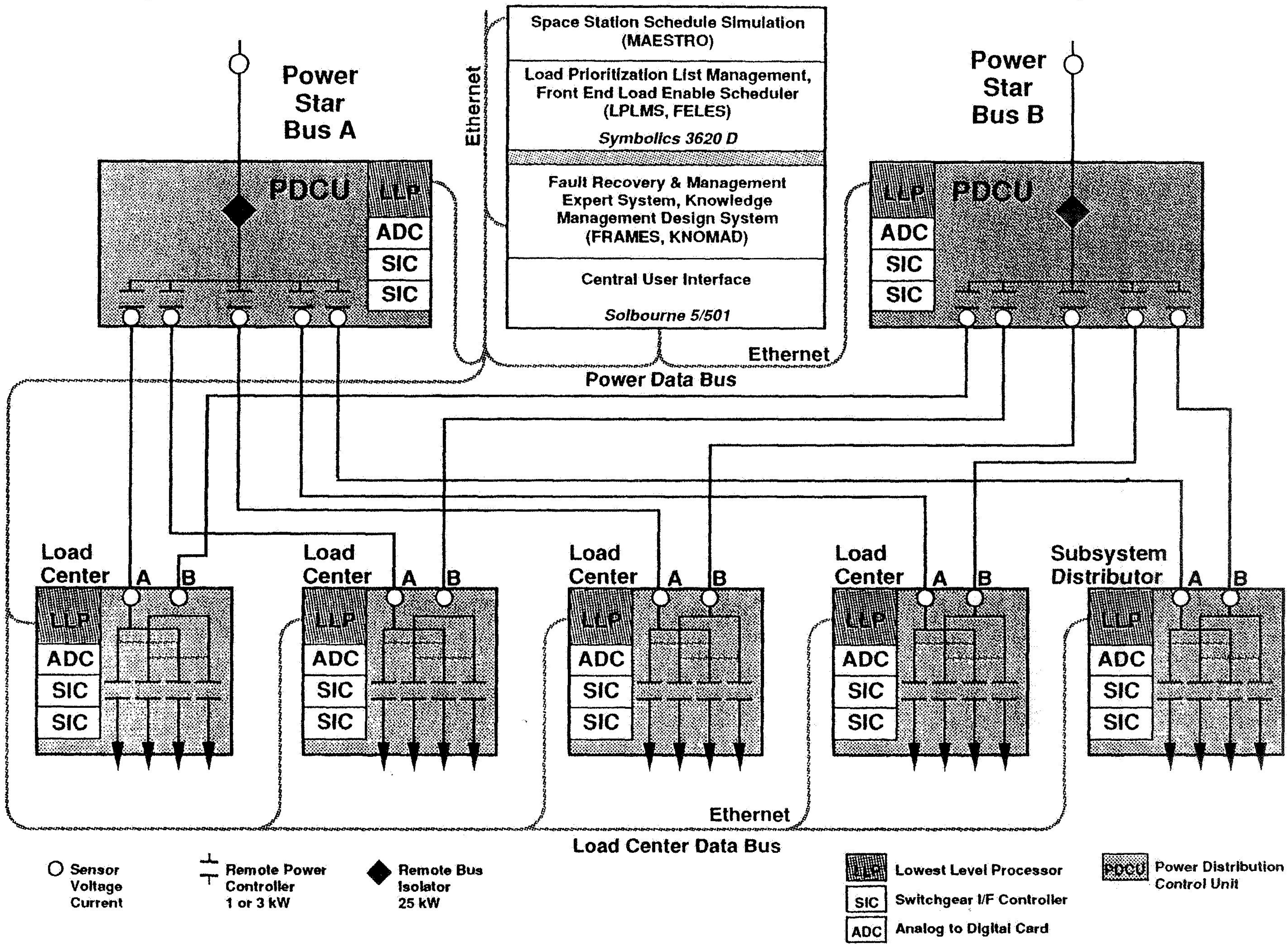
TECHNICAL APPROACH

The technical approach to the project was to build a test bed model of the SSM/PMAD subsystem and then to add the automation software and any additional hardware needed for full autonomous operation. The automation software would be a combination of standard software and the latest advanced software techniques. The present software architecture consists of three expert/knowledge based systems and numerous specialized conventional programs.

One of the first steps taken was to analyze the power system operation process and then to break these processes into their various functions. The next step was to arrange these functions according to their time criticalities and then to distribute the functions in such a way as to maximize their speed. Thus, the critical time functions are performed nearest the loads using conventional software with the less time critical functions being performed further from the loads, but using more powerful hardware/software tools.

The last key to the project was to use a powerful user-supportive graphics interface to allow for the fourth expert in the system, namely, the human system operator. The interface has become an integral part of the operation of the system as well as providing valuable information as to how the system is determining its control decisions.

Space Station Module/Power Management and Distribution System



HARDWARE/SOFTWARE SCHEMATIC DIAGRAMS OF THE SYSTEM

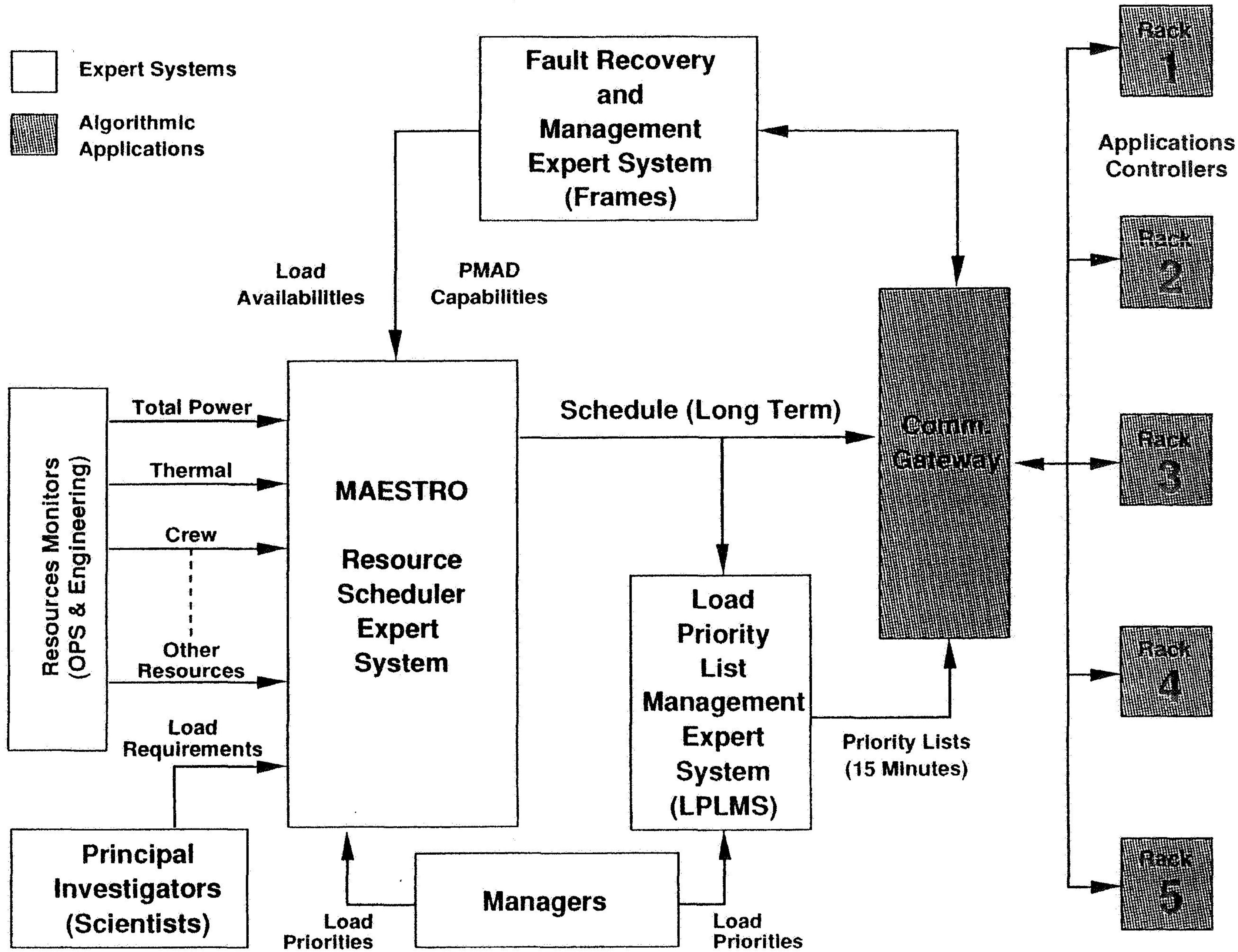
This test bed hardware has two power distribution control units (PDCUs) and three load centers. The basic system design allows for two additional load centers. Further, the test bed includes remote bus isolators (RBIs), remote controlled circuit breakers (RCCBs), and remote power controllers (RPCs). Lastly, a lowest level processor (LLP) is included in each PDCU and load center. In the software area of the test bed, autonomy is pushed down to the lowest levels, specifically, to the LLPs and through the switch interface processors to the "smart" switchgear. Three Artificial Intelligence (AI) systems - the Fault Recovery And Management Expert System (FRAMES), the Load Priority List Management System (LPLMS), and the Master of Automated Expert Scheduling Through Resource Orchestration (MAESTRO) -reside above and communicate with the other processors through the Communications and User Interface (CUI) software.

The system software is distributed through several different types of processors and at different hierarchical levels. The LLPs are located at the level nearest the power hardware. The CUI software is notified of any anomalies by the LLP. FRAMES, MAESTRO, and LPLMS share the highest level of the hierarchy. Each step up this hierarchy reveals a decrease in speed (microseconds at the switchgear level, milliseconds to seconds at the LLP level, seconds to minutes at the AI level and an increase in sophistication.

The LLPs consist of Intel 80386 based computers and an Ethernet communication board. A LLP is located in each load center, subsystem distributor, and PDCU. Each LLP is responsible for controlling the switches associated with it and for keeping track of all the sensor readings and switch positions in its center. The LLP also executes scheduled changes in switch positions, sheds any loads which exceed their scheduled maximum, and switches redundant loads to their secondary bus if the load's primary source is interrupted. The LLP passes any or all of this information to the CUI software.

The CUI software is resident in a Solbourne 5/501 UNIX based workstation. The CUI software routes information to the various LLPs, controls LLP initialization, and serves as the man/machine interface for the entire system. Messages are passed from the three AI systems to the LLPs through the CUI via Ethernet communication links.

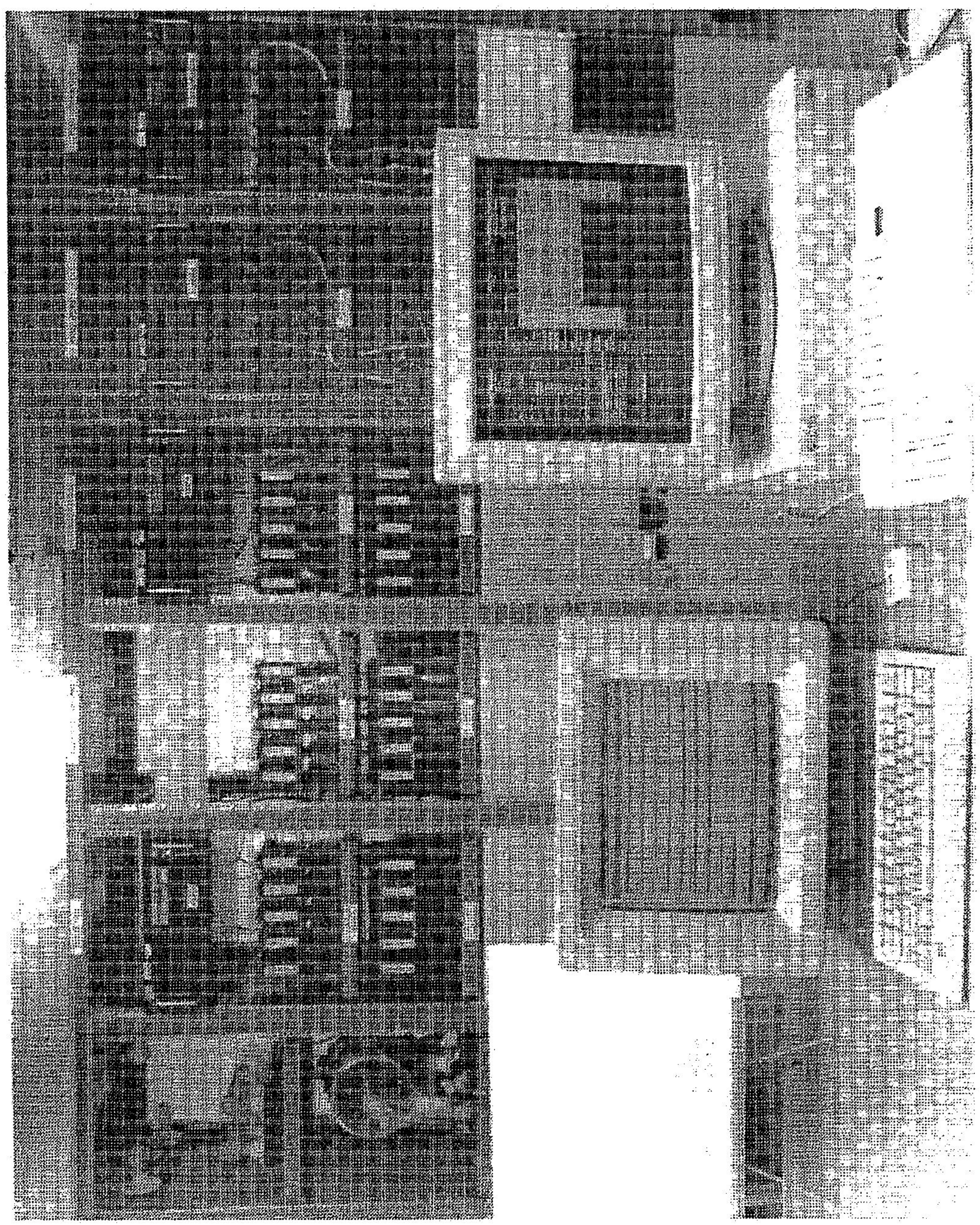
SSM/PMAD MANAGEMENT AND SOFTWARE LOGIC FLOW DIAGRAM



The FRAMES resides on the Solbourne 5/501 workstation and is implemented in the Common Lisp Object System (CLOS). This expert system watches over the entire EPS looking for anomalies and failures. FRAMES is responsible for detecting faults, advising the operator of appropriate corrective actions, and, in cases involving critical loads, autonomously implementing corrective actions through power system reconfigurations. FRAMES recognizes and adjusts to hard faults which the smart switchgear handles immediately, as well as handling soft faults, cascaded faults, and independent multiple faults.

The LPLMS resides on the Solbourne 5/501 workstation and is implemented in LISP. The LPLMS keeps track of the dynamic priorities of all payloads while developing and downloading current load shedding lists for the LLPs every fifteen minutes in preparation for contingencies which necessitate load shedding. This way, load shedding is implemented quickly in each load center or subsystem distributor. The LPLMS maintains a real time dynamic representation of all the module loads and relevant facts so that applicable rules can fire to reorder portions of the load shedding list as situations change. The loads in a laboratory module may have dynamic properties. A critical noninterruptible materials processing experiment involving crystal growth will undoubtedly have a different priority as it nears completion. Other factors may change priorities such as equipment malfunctions. An expert system such as the LPLMS is crucial in determining which loads must be shed in the event of perturbations to the available power. The LPLMS insures that critical loads not be shed unnecessarily.

MAESTRO resides on a Symbolics 3620D and is implemented in LISP. Special interfaces have been developed for MAESTRO which allow a great deal of flexibility in interactions with the scheduler. MAESTRO is a resource scheduler developed by Martin Marietta and can schedule and reschedule a number of payloads with various scheduling constraints. This AI system generates the baseline schedules for the EPS and accepts information from the other processors on when and how to reschedule module payloads. MAESTRO uses pieces of several AI technologies including object-oriented programming, heuristically guided search, activity library, expert functions, etc. MAESTRO schedules loads with regard to numerous resource constraints such as available crew members, supplies for payloads, interdependence of payloads, power profiles, and thermal status.

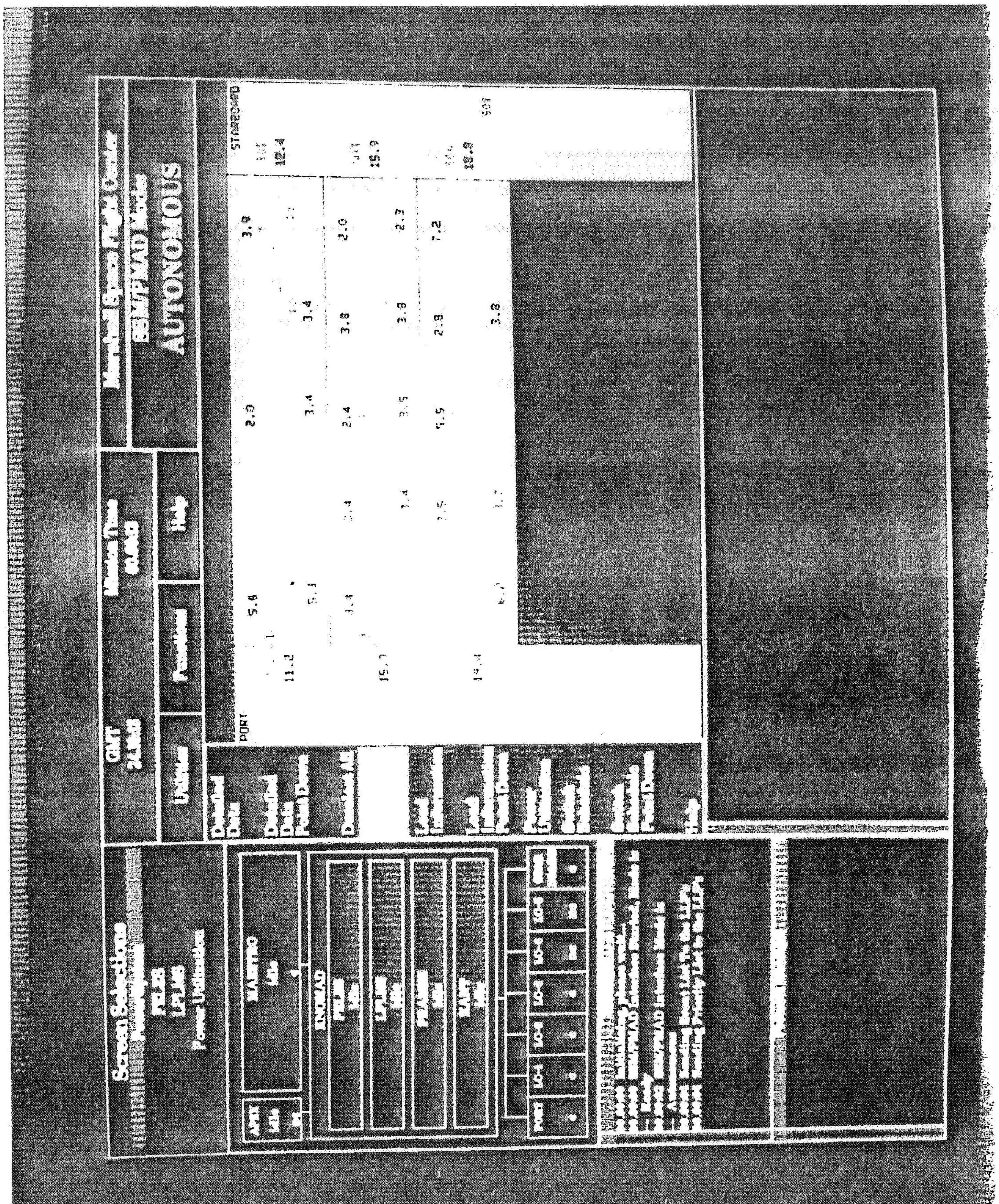


SCHEMATICS DESCRIPTION (CONTINUED) PLUS PHOTOGRAPH

In order to efficiently operate these three expert systems together, a simultaneous multi-agent knowledge manager function called the Knowledge Management and Design (KNOMAD) system was designed and built. KNOMAD utilizes a distributed database management function to provide a modified blackboard management capability. The KNOMAD architecture is layered. The central layer is the database which provides a place for storing working memory data, for transferring and sharing data, and for storing long term data. The database is modular and may be implemented as a distributed database. As a distributed database, multiple cooperating knowledge agents, each in different physical locations, could be supported. The next layer consists of an interface to the database that provides a frame system for abstracting both data and procedure as well as a mechanism for storing simple facts. The top layer is the place where various tools are defined and implemented. All of the tools make use of the same data representation and thus easily share data across domains and functions. FRAMES was implemented in KNOMAD in June of 1990 with LPLMS and a MAESTRO interface being implemented in April 1991.

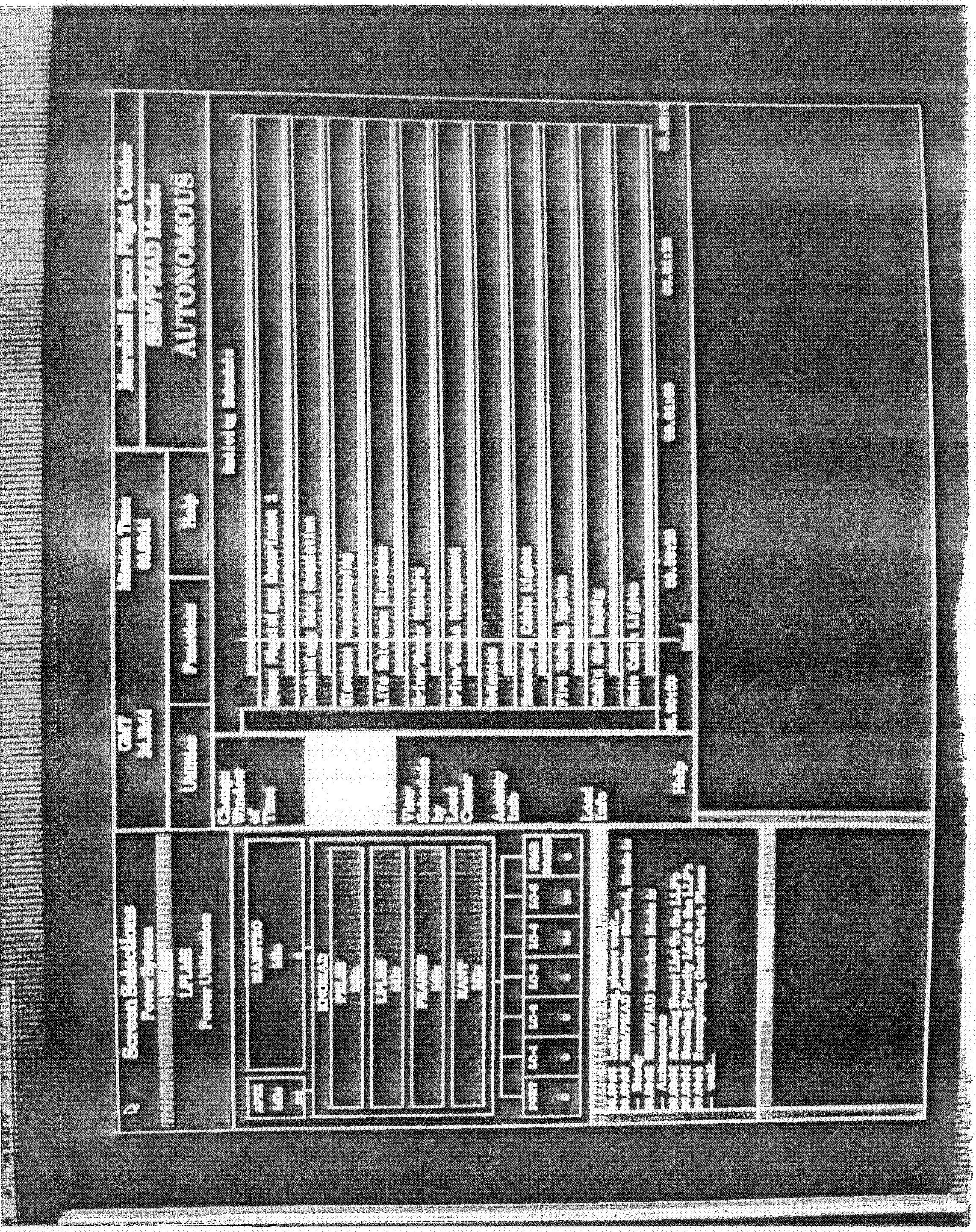
PHOTOGRAPH

In the front of the photo, the Solbourne workstation is on the right and the Symbolics AI workstation is on the left. Looking at the racks, The PDCU racks are on the right with the three load center racks to the left of the PDCUs. The far left rack consists a few representative loads. The majority resistive loads are located in an annex building to this room. Each rack, from top to bottom, consists of an LLP, a group of 1 kW or 3 kW RPCs, a group of RPC controller cards (behind the silver plate), housekeeping power supplies, and cooling fans. Load Center 2's (Material Science Rack) LLP is located on a table to the right of the Solbourne (easier access).


Marshall Space Flight Center
SSM/PMAD Mode
AUTONOMOUS
Screen Selections
GMT
Mission Time
Utilities
Functions
Help
PORT
STARBOARD

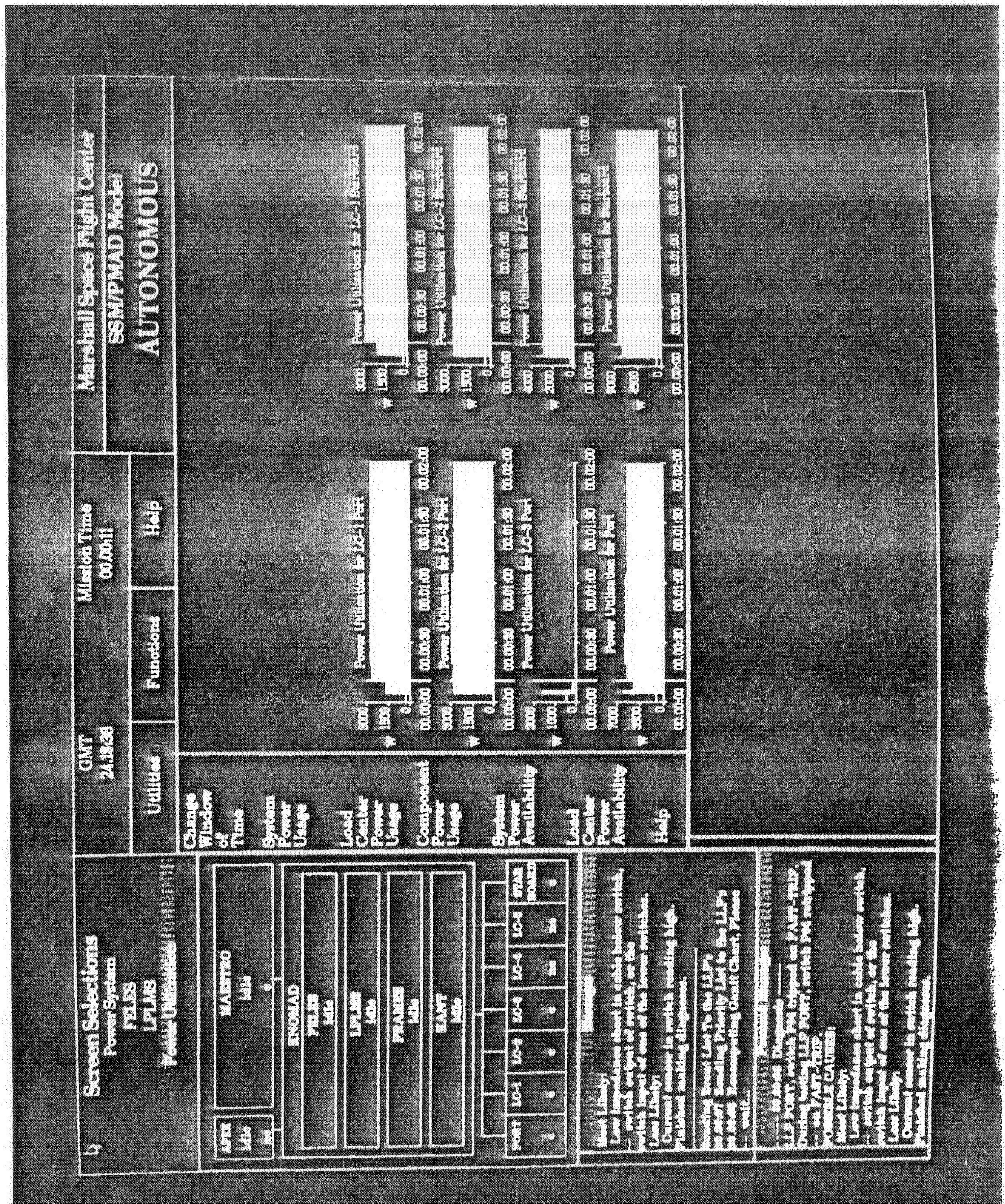
USER INTERFACE PHOTOGRAPH (POWER SYSTEM SCREEN)

This photo of the user interface features the power system screen (PSS) which is the primary screen for normal operation. Located in the center right window, the PSS displays power flow through the use of white filled in "pipes" and RPC open/close through a toggle switch icon. The 1 kW RPC rectangles and the 3 kW RPC ovals are colored green for nominal operation, red for faulted conditions, and brown for out-of-service. They also display their designator (small print) and the amount of current flow through the RPC (bold number). The diamonds represent the RBI and the small circles represent additional voltage and current sensors. The selection rectangle to the left of the PSS is for obtaining more detailed information for each or all RPCs. When requested, this information is displayed underneath the PSS in the "scratch-pad" window. The various modes (Ready, Created, Manual, Autonomous) are displayed above and to the right of the PSS. Various Utility, Function, and Help requests are made through pull down windows just above the PSS. Located to the left center of the PSS, the KNOMAD screen dynamically displays Ethernet connections, the various application programs, and their status. The message screen(s) at the bottom left gives textual data for the messages being passed through the system. Through the Utilities menu, a Focused Message window can be brought up which displays filtered messages as chosen by the user. The final active screen is the Screen Selection window in the upper left corner of the interface. When selected, one of four sub-screens replaces the PSS for further information.


Marshall Space Flight Center
AUTONOMOUS
Screen Selections
Power System
Power Utilization
Utilities
Help

USER-INTERFACE (FELES SCREEN)

This is a photo of the FELES screen selection. This screen shows a timeline for each scheduled load and a marker showing the present time on the schedule. Again, additional information can be requested through the rectangle box to the left of the FELES screen.


Marshall Space Flight Center
SSM/PMAD Model
AUTONOMOUS
GMT
Mission Time
Utilities
Functions
Help
Screen Selections
Power System
MAESTRO
Change Window of Time
System Power Usage
Load Center Power Usage
Component Power Usage
System Power Availability
Load Center Power Availability

USER-INTERFACE (POWER UTILIZATION SCREEN)

This photo displays the Power Utilization screen which displays a power versus time load profile for each PDCU, load center, and the individual loads. The white marker displays the present time and the white line displays actual power usage versus time.

BASELINE INTEGRATION

- SSF Fidelity PMAD Testbed
- Operational Demonstration Held Before CDRs
- Prepare for Early Ground-Based Implementation
  - Payload Operations Control Center - MSFC
  - Module Engineering Support Center - MSFC
  - Space Station Control Center - JSC
- Establish Functional Links with LeRC EPS Automated Testbed
- Establish Key Relationships with Baseline Personnel

BASELINE INTEGRATION

As mentioned earlier, one goal of this project is to maintain as close of ties as possible to the baseline design of the SSF. Listed below are a few of the ways in which this goal is being accomplished.

(1) As much as possible, we are attempting to make our testbed mimic the baseline PMAD testbed. In most cases, this will require us to disable many of the advanced features of the original testbed, especially in the RPCs, the sensors, and the lower level processors.

(2) We are presenting operational demonstrations before the critical design reviews in order to provide more and better data to guide decision making. The first operational demonstrations are being held this summer with a second more advanced demonstration to be held next summer. The CDRs for the WP01 PMAD are scheduled for early 1993.

(3) We are planning for an early ground-based implementation in order to support the POCC at MSFC, the ESC at MSFC, and the SSOC at JSC. Implementation could be accomplished by porting real-time or near real-time flight data into the SSM/PMAD computers and then perform system fault diagnosis with both the ground hardware data and the flight data.

(4) We have completed a Phase I link with a LeRC automated test bed. A simple fault handling scenario was then successfully demonstrated. This will form the basis for a full LeRC SSF automated test bed/MSFC SSF automated test bed link to be completed late in 1992. This will allow for ground system testing between the two major power SSF subsystems.

(5) Relationships are being established with all key baseline personnel. These include, but are not limited to: MSFC and Boeing power system design engineers, MSFC and Boeing SSF project offices, LeRC and Rocketdyne power system design engineers, MSFC and Boeing system integrators and operations personnel, JSC mission control system personnel, and various Level 1 and 2 personnel at NASA Headquarters.

NASA MSFC

GROWTH AND EVOLUTION OPTIONS

- Establish the Automation Techniques on the Ground
- Port Software to a Portable Workstation and "Plug-In" to the On-board System
- "Intelligent" RPC Retrofit
- Rack(s) Retrofit

GROWTH AND EVOLUTION OPTIONS

In order to meet our goal of on-board automation, a series of key and orderly steps to flight are being planned. The first step is to establish the ability to automate the actual SSF PMAD through ground based implementation. The next step would be to act as a power system engineer surrogate through the use of powerful portable computer workstations being designed. The automation software could be downloaded into the workstation, flown to SSF, and then attached to the on-board data stream. A next step would be to retrofit "intelligent" RPCs which are now being designed. A final step would be to incorporate the automation equipment more permanently by mounting the system in new rack(s) and performing a rack(s) retrofit.

NASA MSFC

SUMMARY

- PMAD Risk Reduction Through the Use of Autonomous Monitoring, Control and FDIR
- Basic Concepts Have Been Established and New Technologies Applied to a Testbed Model of the SSF PMAD
- A First Generation Operational Prototype Has Been Successfully Demonstrated
- Preparing for Early Ground-Based Implementation Supporting the Control Centers
- Evolves to "On-Board" Operation

SUMMARY

This paper has described the various activities at NASA/MSFC for advancing the state-of-the-art in spacecraft electrical power system automation. Based on the AMPS and SSM/PMAD projects, a hierarchical approach of distributed processing is being developed. In addition, AI and in particular, knowledge-based systems, are proving to be invaluable in accomplishing tasks not possible with conventional software. We are demonstrating PMAD risk reduction through the use of autonomous monitoring, control, and FDIR. Basic concepts have been established with a first generation operational prototype having been successfully demonstrated. The next steps involve integrating the testbed into the ground based support centers and then evolving onto the SSF. Thus, NASA/MSFC is progressing toward the eventual goal of a totally autonomous power system (with human override).

Johnson Space Center
Crew and Thermal Systems Division

Patricia A. Petete

N92-17775

Active Thermal Control System Evolution

Space Station Evolution Symposium
August 8, 1991

Lockheed
Engineering & Sciences Company

Brian E. Ames

Abstract

The "restructured" baseline of the Space Station Freedom (SSF) has eliminated many of the growth options for the Active Thermal Control System (ATCS). Modular addition of baseline technology to increase heat rejection will be extremely difficult. The system design and the available real estate no longer accommodate this type of growth.

As the station matures during its thirty years of operation, a demand of up to 165 kW of heat rejection can be expected. The baseline configuration will be able to provide 82.5 kW at Eight Manned Crew Capability (EMCC). The growth paths necessary to reach 165 kW have been identified.

Doubling the heat rejection capability of SSF will require either the modification of existing radiator wings or the attachment of growth structure to the baseline truss for growth radiator wing placement. Radiator performance can be improved by enlarging the surface area or by boosting the operating temperature with a heat pump. The optimal solution will require both modifications. The addition of growth structure would permit the addition of a parallel ATCS using baseline technology. This growth system would simplify integration. The feasibility of incorporating these growth options to improve the heat rejection capacity of SSF is under evaluation.

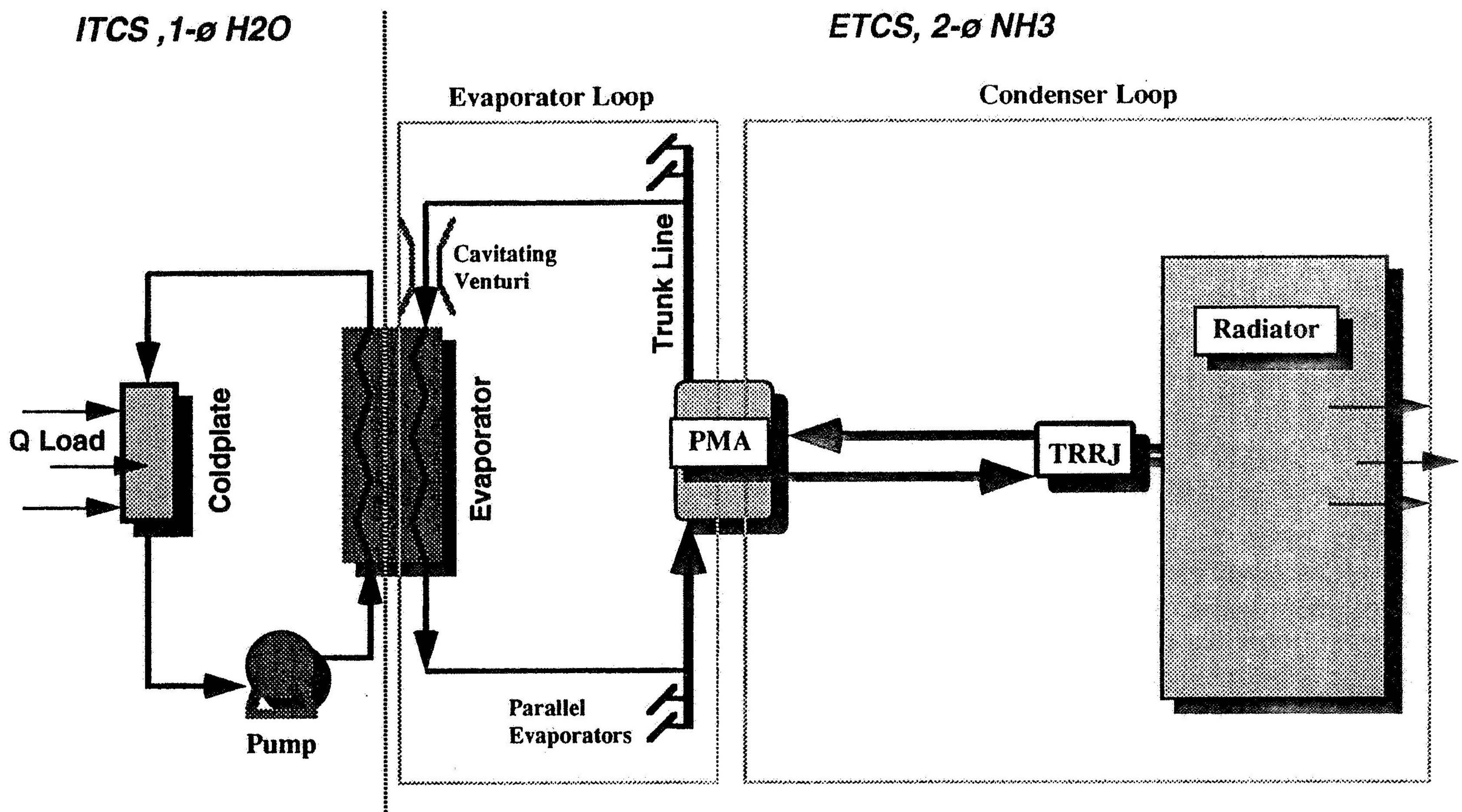
Agenda

- Baseline Configuration
- Significant Restructuring Impacts
- Evolution Goals
- Growth Paths
  - / ETCS Evaporator Loop
  - / ETCS Condenser Loop
- Enhancing/Enabling Technologies
- Conclusions

Agenda

This presentation will cover six areas. It begins with a discussion of the baseline ATCS configuration. Next, the impacts that restructuring has had on evolution is reviewed. Then the follow-on phase and evolution phase goals are briefly discussed. The growth paths that can obtain the evolution phase are defined. The impacts and desirability of each growth path are examined. Advanced technologies that could reduce these impacts are presented, and finally conclusions for this system are offered.

ATCS



ITCS ,1-ø H2O
ETCS, 2-ø NH3
Evaporator Loop
Condenser Loop
Cavitating
Venturi
Trunk Line
Radiator
Q Load
Coldplate
Evaporator
PMA
TRRJ
Pump
Parallel
Evaporators

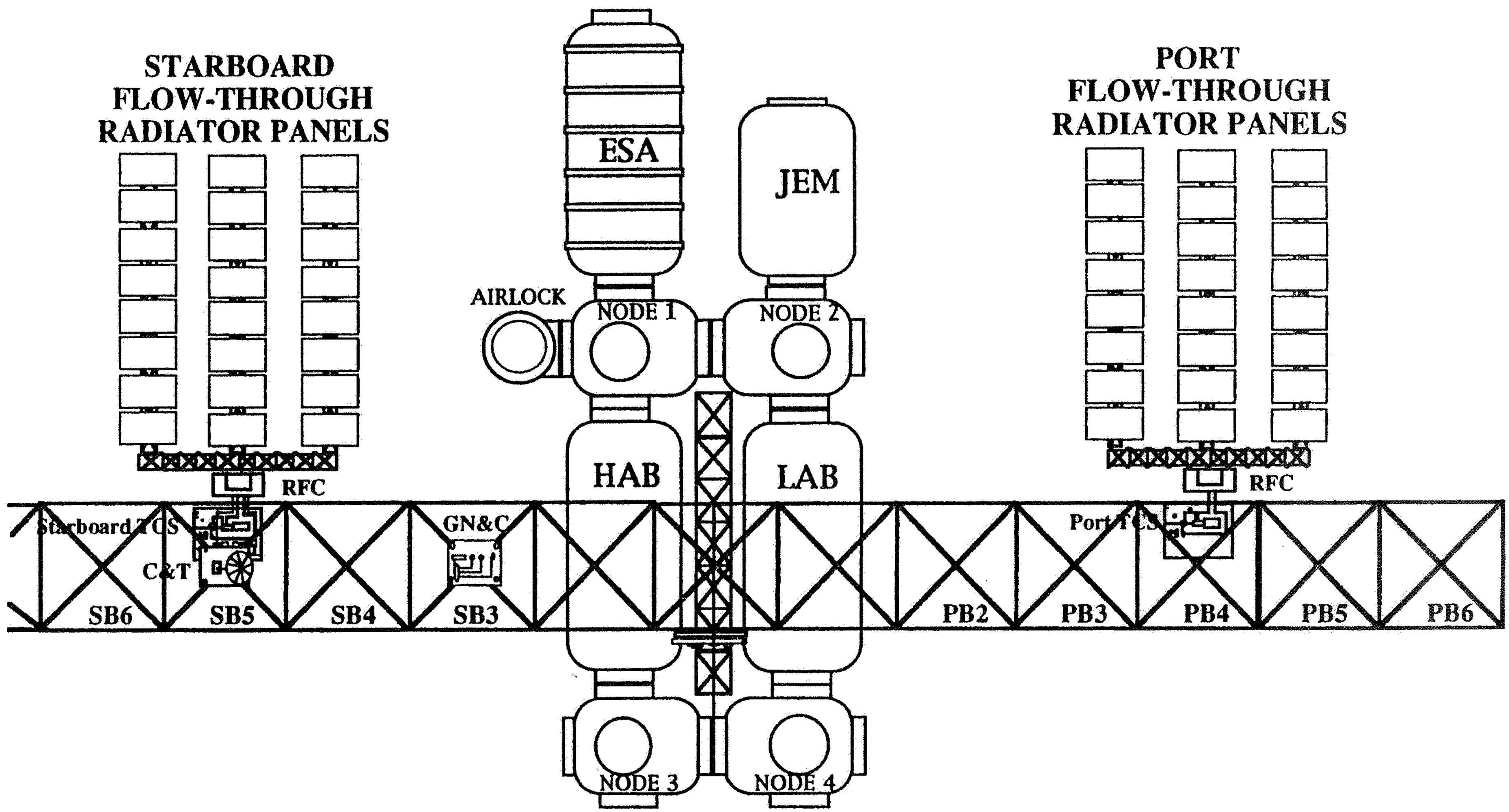
ATCS Baseline Configuration

The ATCS is divided into two subsystems.

The Internal Thermal Control System (ITCS) is a single-phase water loop located in the modules and nodes. The water loop collects heat from the cold plates and transfers it to the water/ammonia evaporator.

The central or External Thermal Control System (ETCS) uses two-phase ammonia in the external bus and radiators. The trunk line supports parallel evaporators located at the modules and nodes. As the ammonia vaporizes in the evaporators, the ETCS evaporator loop collects waste heat from the ITCS. The ammonia leaves the evaporator as a two-phase fluid. The Pump Module Assembly (PMA) separates the two phases of ammonia and transfers the vapor to the ETCS condenser loop. As the radiators reject heat to space this vapor condenses and is returned to the PMA.

PIT Configuration



Drawn By: K. Andish, April 1991

PIT Configuration

The external thermal bus is routed throughout the station by way of the Utility Distribution System (UDS). Three independent loops are used in the external thermal bus. The two 35 °F loops are low temperature buses that support the starboard flow-through radiator wing. The remaining 62 °F loop is a moderate temperature bus that supports the port flow-through radiator wing. The two phase quality of the ammonia stream keeps the external bus temperature within a seven degree setpoint during heat acquisition and rejection.

Heat is rejected by dual thermal radiator wings made up of flow-through panels that rotate for optimum thermal orientation during orbit.

The two radiator wings are coincident with the TCS fluid management equipment, which is located on mounting plates of the pre-integrated truss structure. The total EMCC heat rejection capability of the ATCS will increase from 20.6 kW at Man-Tended Capability (MTC) to 61.9 kW at Permanently Manned Capability (PMC), and finally to 82.5 kW at EMCC.

Significant Restructuring Impacts

Growth Paths

- Heat acquisition and transport growth options are similar to "Turbo" configuration.
- Heat rejection growth options have been curtailed.

Heat Rejection / Radiator Surface Area Constraints

- MT location prevents radiator wing addition in the +x direction.
- Smaller baseline truss prevents radiator wing relocation or growth in the +/- y direction due to module or PV array interference.
- Growth of radiator surface area in the -x direction at the PIT location is the only option with the baseline truss.
- Radiator wing addition to growth structure is a possible option.

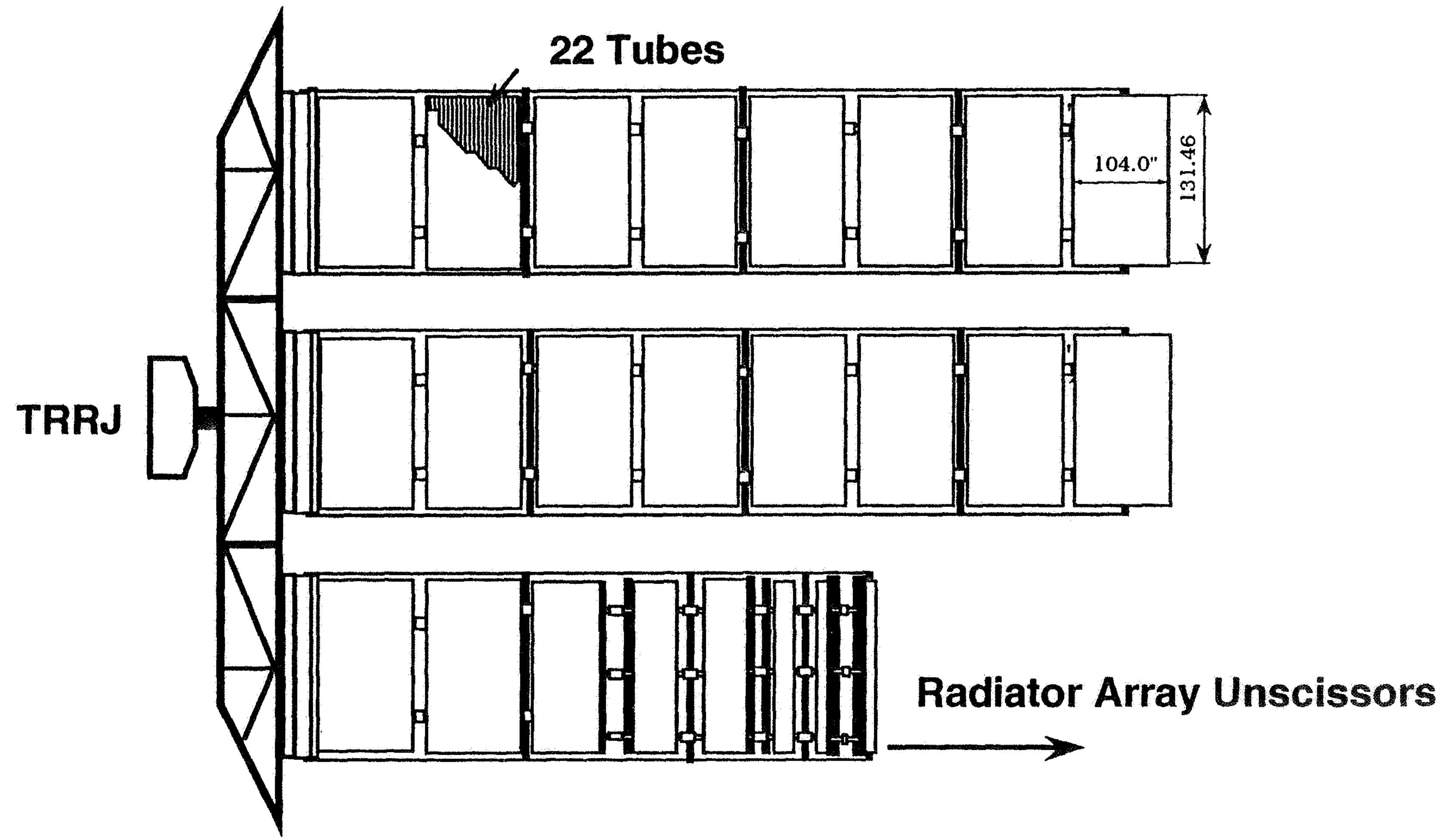
Significant Restructuring Impacts

Line addition is the most promising of the heat transport growth paths. This option is still feasible with restructuring. Because there is less space on the Pre-Integrated Truss (PIT) than the "Turbo" modular truss, the integration of the fluid lines may be more difficult.

Heat rejection growth options have been curtailed. The original evolution growth path called for modular addition of baseline technology. Radiator wings were to be placed in the +x direction (velocity vector). Wing addition in this location is no longer possible. Restructuring has placed the Mobile Transporter (MT) along the face of this truss. Real estate is not available anywhere on the now smaller baseline truss for radiator wing addition. The existing radiator wings can not grow in the y direction due to interference from the modules or PV arrays. These radiator wings could only grow in the -x direction.

Radiator wing addition would require the addition of growth structure. Non-baseline heat rejection technologies must be used, if this approach is not followed.

Radiator Wing



Drawn By: K. Andish, April 1991

Radiator Wing

The ATCS radiator wing is the only significant technology change to come out of restructuring. The direct condensing, flow-through radiators were selected over the heat pipe radiators to reduce weight, cost, and program risk.

The radiator wing contains three Orbital Replacement Units (ORU's). Each ORU has eight radiator panels with 22 tubes each. The baseline radiator is more susceptible to Micrometeorite/Orbital Debris (MM/OD) impact damage due to its flow-through design. The anticipated debris environments during the early years of station operation are considered acceptable for this design. As the debris environments become more severe, an alternate heat pipe (HP) radiator ORU could be implemented. The HP radiator is less affected by MM/OD impact because the condenser and HP fluid do not come into direct contact. Single point damage to a flow-through radiator panel would result in the loss of the entire panel. Single point damage to the current HP radiator panel design would result in the loss of 1/22 of a panel. Fluid leakage from this damage is significantly less for the HP radiators. If radiator ORU's were replaced as a maintenance item, this could benefit evolution goals. The opportunity could be used to upgrade the heat rejection capability of the radiator wing by either increasing the operating pressure or surface area of the radiator ORU. These upgrades will be discussed in detail.

ATCS Evolution

- Proposed Requirement:

  The thermal distribution system shall allow for growth proportional to the heat rejection requirement from EPS plus parasitic and metabolic loads.

- Follow-on Phase:

  / Scars are not needed

  ATCS Load = 82.5 kW

- Evolution Phase:

  / Scars are recommended
  / EPS Load = 150 kW
  / Parasitic Load > 150 kW * 0.8 = 12 kW
  / Metabolic Load = 2.5 kW for 12 crew

  ATCS Load > 150 kW + ~12 kW + 2.5 = 165 kW

ATCS Evolution

The ATCS is being design for 82.5 kW at EMCC also referred to as the Follow-on phase. In our studies, the evolution phase is assumed to be twice this value, because the EPS requirement is doubled. An exact heat rejection value cannot be determined until the DDCU load sharing is better understood. The two parameters besides EPS load that most affect heat load are the parasitic and metabolic loads..

Parasitic Load

Parasitic load is the result of DDCU inefficiency. The coldplates collect and transfer this heat to the ATCS.

DDCU efficiency is a function of load. The DDCU has a maximum efficiency of 92%, when power output is at 6.25 kW. As power output decreases from this level, DDCU efficiency decreases.

At 75 kW of power, it is not possible for all the DDCU's to operate at 6.25 kW. Twelve of the 30 baseline DDCU's could provide 75 kW of power at maximum efficiency, while the other 18 would be idling at minimum efficiency. This combination of fully loaded and idling DDCU's is the worst case scenario, and would result in an average efficiency significantly lower than 92%. The waste heat generated by the DDCU's will be larger than the 6 kW (75 kW * 8%) value for a realistic load allocation.

DDCU Heat Loss as a Function of Power Output

Power Output	Thermal Heat Dissipation
6.25 KWE	598 watts
3.0	315
1.25	163
0.001	163
0.0	50

Metabolic Load

The crew generates sensible and latent heat by metabolic processes. The minimum metabolic heat load is the amount necessary to maintain life. The maximum load is the predicted crew activity limit. The air regeneration system collects and transfers this heat to the ATCS.

The metabolic load has an expected range of 6,720 to 16,800 Btu/crew-day, and a nominal value of 11,200 Btu/crew-day

Metabolic Load = 16,800 Btu/crew-day = 0.206 kW for 1 crewmember = 2.47 kW for 12 crew

Growth Paths
ETCS Evaporator Loop

Path 1 - Size baseline trunk lines for growth

Baseline trunk lines are connected to the following:
- Path 1.a - Baseline PMA sized for evolution capacity
- Path 1.b - Upgraded PMA
- Path 1.c - Growth PMA

Path 2 - Replace baseline trunk lines with upgraded lines

Replacement trunk lines are connected to the following:
- Path 2.a - Baseline PMA sized for evolution capacity
- Path 2.b - Upgraded PMA
- Path 2.c - Growth PMA

Path 3 - Add growth trunk lines

Growth trunk lines are connected to the following:
- Path 3.a - Baseline PMA sized for evolution capacity
- Path 3.b - Upgraded PMA
- Path 3.c - Growth PMA
- Path 3.d - Growth PMA, Vapor Compression Cycle (VCC) HX

Growth Paths: ETCS Evaporator Loop

A matrix has been developed that contains the growth paths available for ATCS evolution.

For the evaporator loop, there are three possible paths. The growth heat transport can be accommodated by increasing trunk line size (Path 1), replacing trunk lines in orbit with lines of greater capacity (Path 2), or by adding additional trunk lines in orbit to support growth (Path 3).

There are three common subpaths that can be used to transfer this heat to an ETCS condenser loop. The blank underline implies more than one growth path can be followed to reach this point. The trunk line could be connected to one of the following:

- A baseline PMA that has been sized for evolution capacity. This PMA would transfer the increased load to the existing ETCS condenser loops. These loops would have to be modified for this increased capacity (Path _.a).
- An upgraded PMA that replaces the baseline one in orbit. This path also assumes the existing ETCS condenser loops are used (Path _.b).
- A growth PMA is added in orbit. This path assumes a growth ETCS condenser loop is also installed in orbit. This path will require the addition of growth structure for radiator wing addition (Path _.c).

Path _.d ties the baseline and growth PMA outlet heat loads together into the existing radiator wings by the use of a Vapor Compression Cycle (VCC) heat exchanger (HX). This subpath is only associated with Path 3. A parallel or growth condenser loop is needed for the HX interface.

Growth Paths
ETCS Condenser Loop

Path _._.1 - Surface area growth is limited to baseline radiator wing location

Path _._.2 - Radiator wing addition is possible due to growth structure

Path _._._.a - radiator surface area is held constant, temperature is increased
Path _._._.b - radiator surface temperature is held constant, area is increased
Path _._._.c - radiator surface temperature and area are increased

Path 4 - Growth modules contain independent body-mounted heat rejection systems

Growth Paths: ETCS Condenser Loop

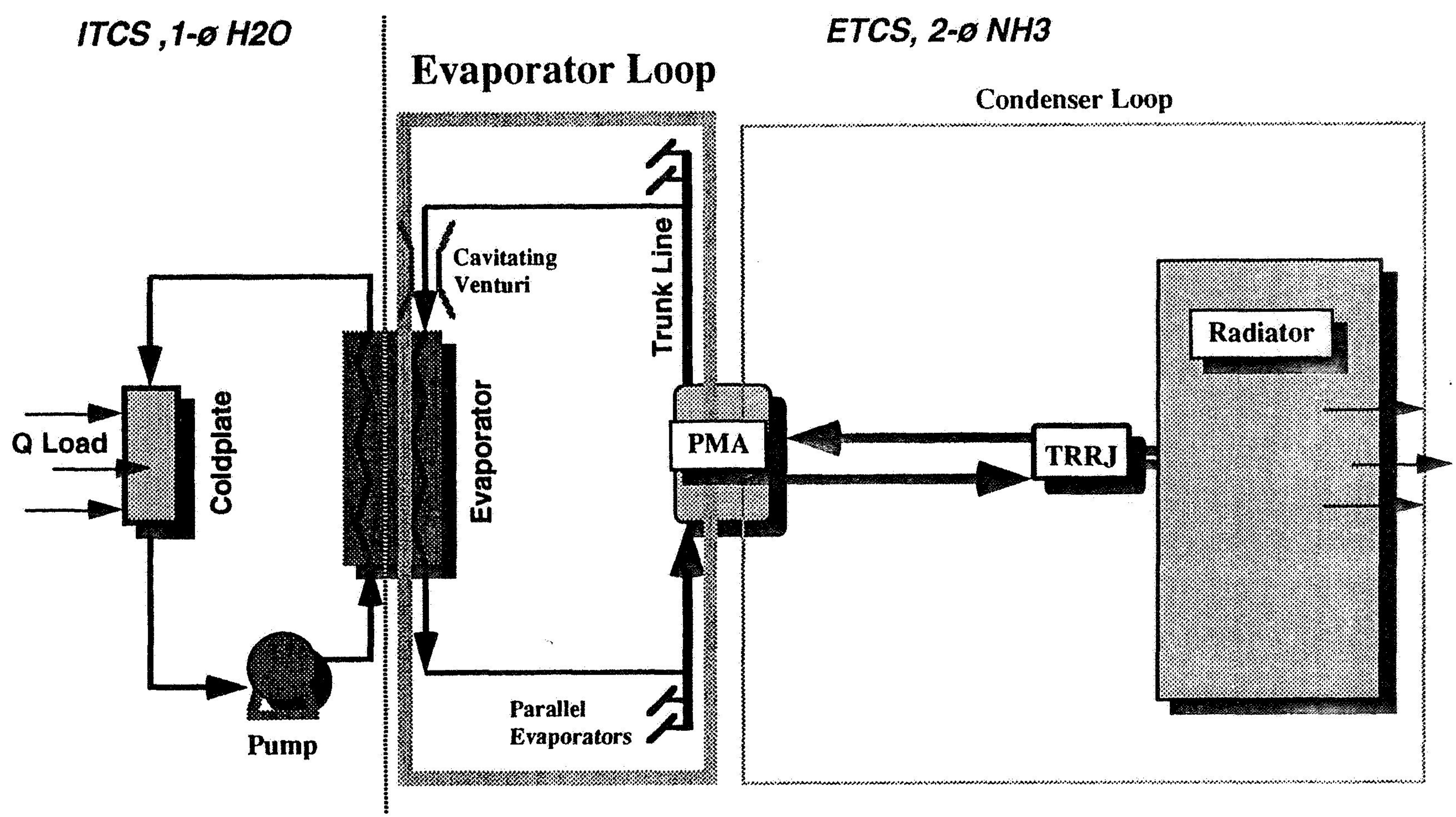
For the condenser loop, there are two distinct growth paths. Heat rejection can be increased by the modification of the existing radiator wing (Path _._. 1) and/or the addition of radiator wings due to growth structure (Path _._.2).

If the baseline radiator wing location is used, wing modifications are essential. In the case of wing addition, modifications could also be beneficial. The radiator wings could reject more heat to space if the surface temperature is increased (Path _._._.a), if the surface area is increased (Path _._._b), or if both parameters are optimized (Path _._._.c).

A fourth possible path is to have growth modules provide their own heat rejection using body-mounted radiators. This growth path is not desirable because interference from the Station environment, such as shadowing, would cause the heat rejection capability of the body-mounted radiators to be less than a centralized system could offer.

Advanced technologies, such as high efficiency low weight radiators, can be applied within the growth path matrix.

ETCS Evaporator Loop Evolution



ETCS Evaporator Loop Evolution

The next four charts will discuss the evolution of the evaporator loop.

Growth Path Impacts
ETCS Evaporator Loop

Heat Transport Line

- Path 1: Size baseline lines for evolution capacity
  - / Increase in upfront costs due to redesign
  - / Increase in upfront system weight
  - / Potential schedule impact due to redesign
- Path 2: Line replacement
  - / EVA intensive
  - / UDS tray removal
  - / UDS tray addition
  - / Increase in UDS fluids tray real estate
  - / Impact on baseline operations during modifications
  - / Potential contamination of SSF environment
- Path 3: Line addition
  - / EVA required (< 1/2 of path 2)
  - / UDS tray addition
  - / Double real estate of UDS fluids tray

Growth Path Impacts: ETCS Evaporator Loop

Each growth path has its own set of scars and related impacts to the Station.

Path 1 requires doubling the heat transport capability of baseline equipment. This path would reduce program cost and risk, but there are upfront penalties. Launch weight would increase, and the current system would have to be redesigned. This would increase cost and could result in a possible schedule slippage.

Path 2 assumes real estate is not available for line addition, and any growth would require line replacement. For the current baseline, this assumption is false. Line replacement has the worst growth path impacts and would only be considered as a last resort.

Path 3 assumes growth lines are added for the evolution phase. This path requires the addition of UDS fluid line trays in space. This assembly will require either EVA or robotic assistance. The significant impact here is system integration and assembly operations.

Growth Path Impacts (Cont.)
ETCS Evaporator Loop

Growth/Baseline Heat Rejection Tie-in Location

- Path _.a: Size baseline PMA for evolution capacity
  - / Increase in upfront costs due to redesign
  - / Increase in upfront system weight
  - / Schedule impact due to redesign
- Path _.b: PMA replacement
  - / Scar mounting brackets for an increase in PMA volume
  - / Scar real estate around PMA interface for growth line replacement
  - / Scar EPS for increased RFMD demands
  - / Impact on baseline operations during modifications
  - / EVA required
- Path _.c: PMA addition, Growth radiator wing
  - / Scar for growth structure attachment point
  - / EVA required (greater duration than Path _.b)
- Path 3.d: PMA addition, VCC HX
  - / Scar baseline truss for growth PMA addition
  - / Scar EPS for growth PMA support
  - / Scar baseline truss for VCC HX addition
  - / VCC HX integration will impact baseline operations
  - / EVA required (greater duration than Path _.b)

Growth Path Impacts: ETCS Evaporator Loop (Cont.)

As already discussed, there are four evaporator loop subpaths. These subpaths can act as the tie-in location for the baseline and growth evaporator loops if the existing radiator wing locations are used.

Path _.a requires doubling the heat transport capability of the baseline PMA. This path would reduce program cost and risk, but there are upfront penalties. Launch weight would increase and the current system would have to be redesigned. This would increase cost and would result in a schedule slippage due to Rotary Fluid Management Device (RFMD) redesign.

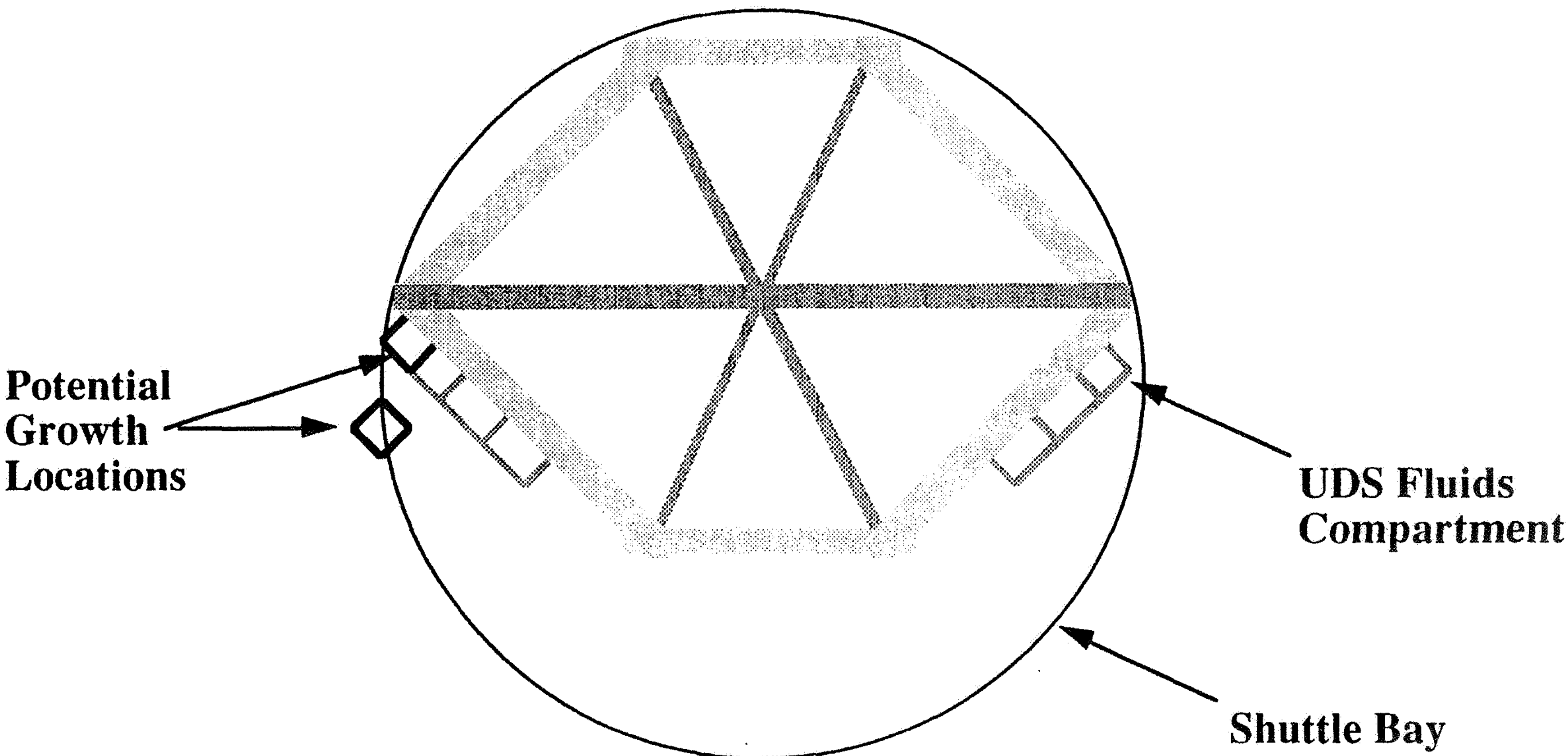
Path _.b assumes the baseline PMA will be replaced with a growth PMA on orbit. The Station must be scarred for this option. Real estate must be reserved for the larger volume the growth PMA requires. The EPS would need to provide more power than the baseline design. Each of the three buses would be shut down during their respective PMA replacement.

Path _.c assumes a parallel ATCS is added for growth. The Station would need to be scarred for structure and line attachment. Radiator wing and UDS tray could be delivered as part of a growth PIT section. EVA may be required for structure attachment and running UDS lines to the attachment point.

Path 3.d requires real estate and EPS scars to support a growth PMA that ties into the existing radiator wing location. The installation of the VCC HX would shut down the bus while it was being added.

Growth Trunk Lines: Path 2

ETCS Evaporator Loop



Generic Utility Inboard Profile

Growth Trunk Lines: ETCS Evaporator Loop

As will be discussed later, line addition is the most likely growth path. The baseline PIT is densely packed due to the Shuttle bay envelope restriction. This restriction does not exist for growth components added on orbit, and thus opens up real estate for UDS fluids tray addition. There are two potential locations for the growth tray. If the tunnion pins used for launching the PIT are removed, the growth tray can be placed next the the baseline tray. The tray can also be elevated above the baseline tray.

Growth Path Desirability
ETCS Evaporator Loop

	Desirability
Heat Transport Line	
• Path 1: Size baseline lines for evolution capacity	1
• Path 2: Line replacement	3
• Path 3: Line addition	2
Growth/Baseline Heat Rejection Tie-in Location	
• Path _.a: Size baseline PMA for evolution capacity	1
• Path _.b: PMA replacement	2
• Path _.c: PMA addition, Growth radiator wing	1
• Path 3.d: PMA addition, VCC HX	3

Growth Paths Desirability: ETCS Evaporator Loop

Desirability is a subjective engineering assessment of the growth paths which considers integration, risk, and weight parameters. More analytical assessments are being developed.

Path 1 would have the lowest risk and cost to the program. The impediment to this option is the present fiscal reality and schedule requirements.

Path 2 has the highest risk and cost of this group. It is a last resort option.

Path 3 is the compromise option. Its allows future evolution without placing undue cost or schedule impacts on the baseline.

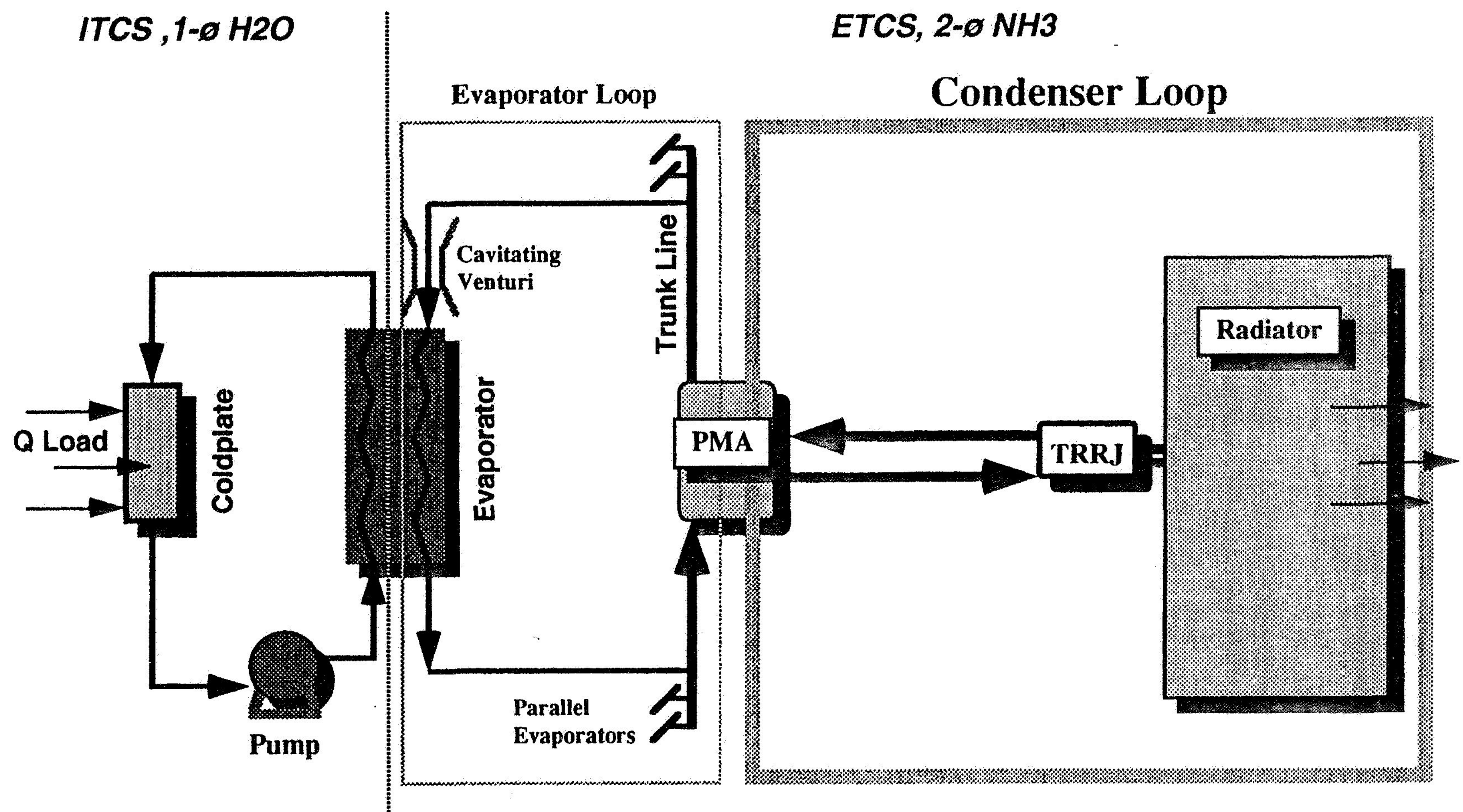
Path _.a would have a low risk and cost to the program. The impediment to this option is the present fiscal reality and the schedule impact involved with redesign.

Path _.b is a promising option if the baseline radiator wing location must be used.

Path _.c this option is rated the same as Path _.a, because the integration of a growth PIT structure containing an ETCS condenser loop into the Station would involve less EVA than upgrading the baseline ETCS condenser loop.

Path 3.d is less efficient than Path _.b at about the same level of cost and risk. This path is promising, if a heat pump option is selected and an expansion valve upstream of the PMA is considered a risk or a higher performance fluid is used inside the VCC.

ETCS Condenser Loop Evolution



ETCS Condenser Loop Evolution

The next seven charts will discuss the *evolution* of the condenser loop.

Growth Path Impacts
ETCS Condenser Loop

Heat Rejection Location

- Path _._.1: Surface area growth is limited to baseline rad. wing location
  / Impact on baseline operations during modifications
  / EVA required
- Path _._.2: Radiator wing addition is possible due to growth structure
  / EVA required

Heat Rejection Parameters

- Path _._._.a: Radiator surface temperature is increased
  / Scar for vapor compressor and expansion valve addition
  / Scar EPS for vapor compressor support
  / SSF environment impact due to radiator temperature increase
  / Replace lines downstream of PMA or VCC HX
  / Replace flow-through radiator ORU's (maintenance item)
  / TRRJ impact
  / Schedule impact due to development and testing of vapor compressor

Growth Path Impacts: ETCS Condenser Loop

There are two distinct growth paths for the condenser loop.

Path _._.1 is the modification of the existing condenser loop to obtain evolution heat rejection capability. This path would impact operations since each loop would be shut down during upgrades. The EVA required could be larger than Path _._.2.

Path _._.2 is the addition of a condenser loop to a PIT growth structure. Baseline operations would not be curtailed during condenser loop addition. EVA would be required. A growth structure attachment point scar is needed.

Both of these paths could impact drag, structural dynamics, and an increased potential for micrometeorite collision. These impacts are currently being modeled.

The three subpaths modify the radiator wings to obtain greater heat rejection capability.

Path _._._.a uses a heat pump to increase the radiator surface temperature. A scar for heat pump equipment addition is needed. The EPS would need to be scarred to deliver more power to the RFMD. Baseline equipment inside the VCC would have to be replaced to account for higher operating pressures. If the radiator ORU's are replaced as a maintenance item, their upgrade would not significantly impact the evolution program. The effect of the heat pump on the Station's thermal environment is currently being modeled.

Growth Path Impacts (Cont.)
ETCS Condenser Loop

Heat Rejection Parameters (Cont.)

- Path _._._.b: Radiator surface area is increased
  / Scar for increased load to structure
  / Replace TRRJ
  / GN&C impact
- Path _._._.c: Radiator surface temperature and area are increased
  / Scar for vapor compressor and expansion valve addition
  / Scar EPS for vapor compressor support
  / SSF environment impact due to radiator temperature increase
  / Replace lines down stream of PMA
  / Replace Radiator ORU's
  / Replace TRRJ
  / Schedule impact due to development and testing of vapor compressor
  / Scar for increase load to structure
  / GN&C impact

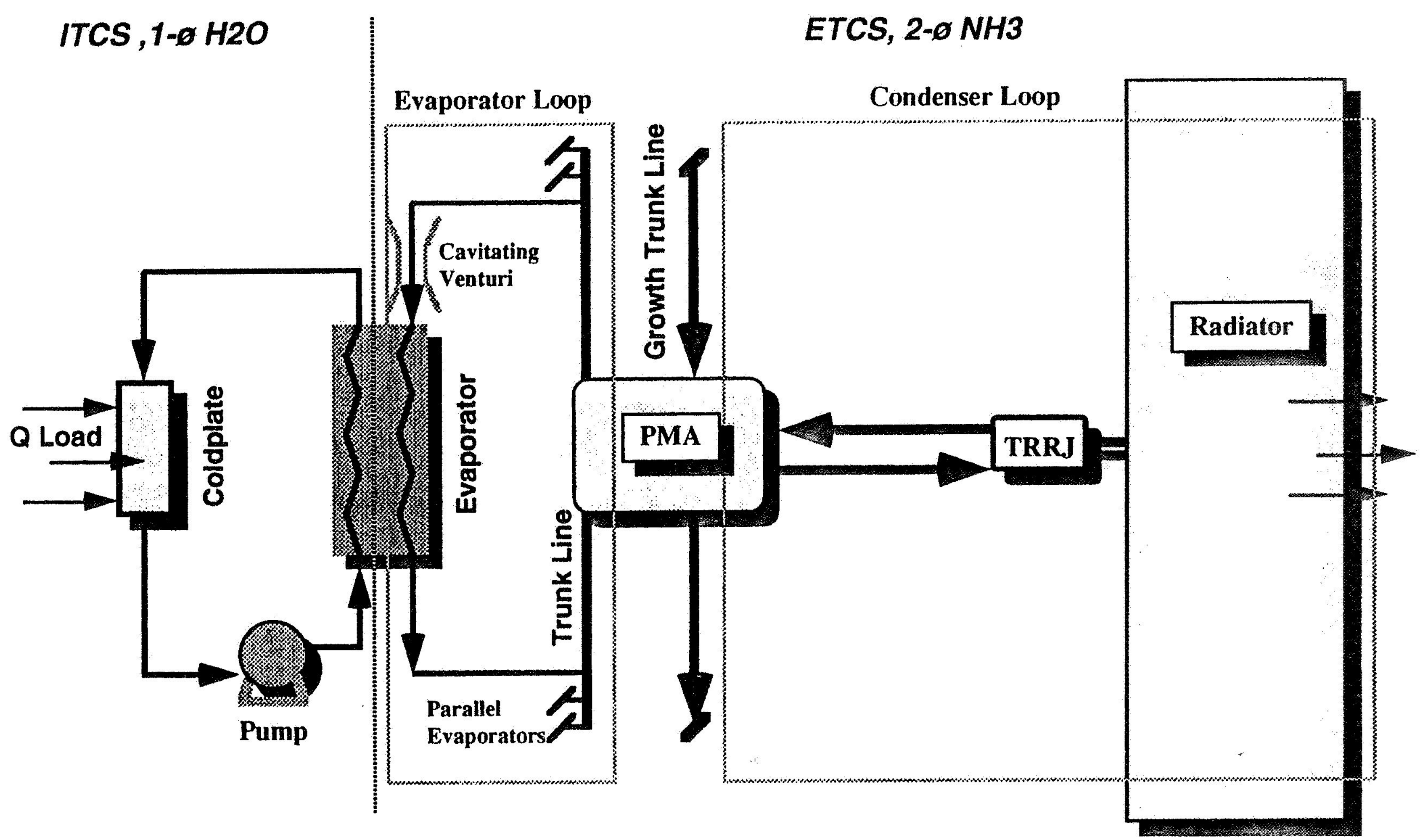
Growth Path Impacts: ETCS Condenser Loop (Cont.)

Path _._._.b increases the surface area of the radiator in the -x direction. Unless a light weight radiator ORU is developed, the TRRJ would have to be replaced. Baseline radiator ORU structure cannot be doubled in length. The resulting frequency would violate Guidance, Navigation and Control (GN&C) requirements.

Path _._._.c is the optimization of greater radiator surface area and higher temperature. Since the impacts for both Path _._._.b and _._._.c are listed, it appears this is an undesirable option. The opposite is true. By optimizing each parameter, we can hopefully diminish the severity of each impact on the Station. For example, the radiator surface area could be increased until the frequency limit is reached. Then the heat pump could raise the heat rejection to the evolution value. This would reduce the power requirement and structural impacts.

Modification of Existing Radiator Wings

Increase Radiator Area in -x Direction: Path 3.b.1.c



- GN&C and structural loads are a concern

Modification of Existing Radiator Wings
Increase Radiator Area in -x Direction: Path 3.b.1.c

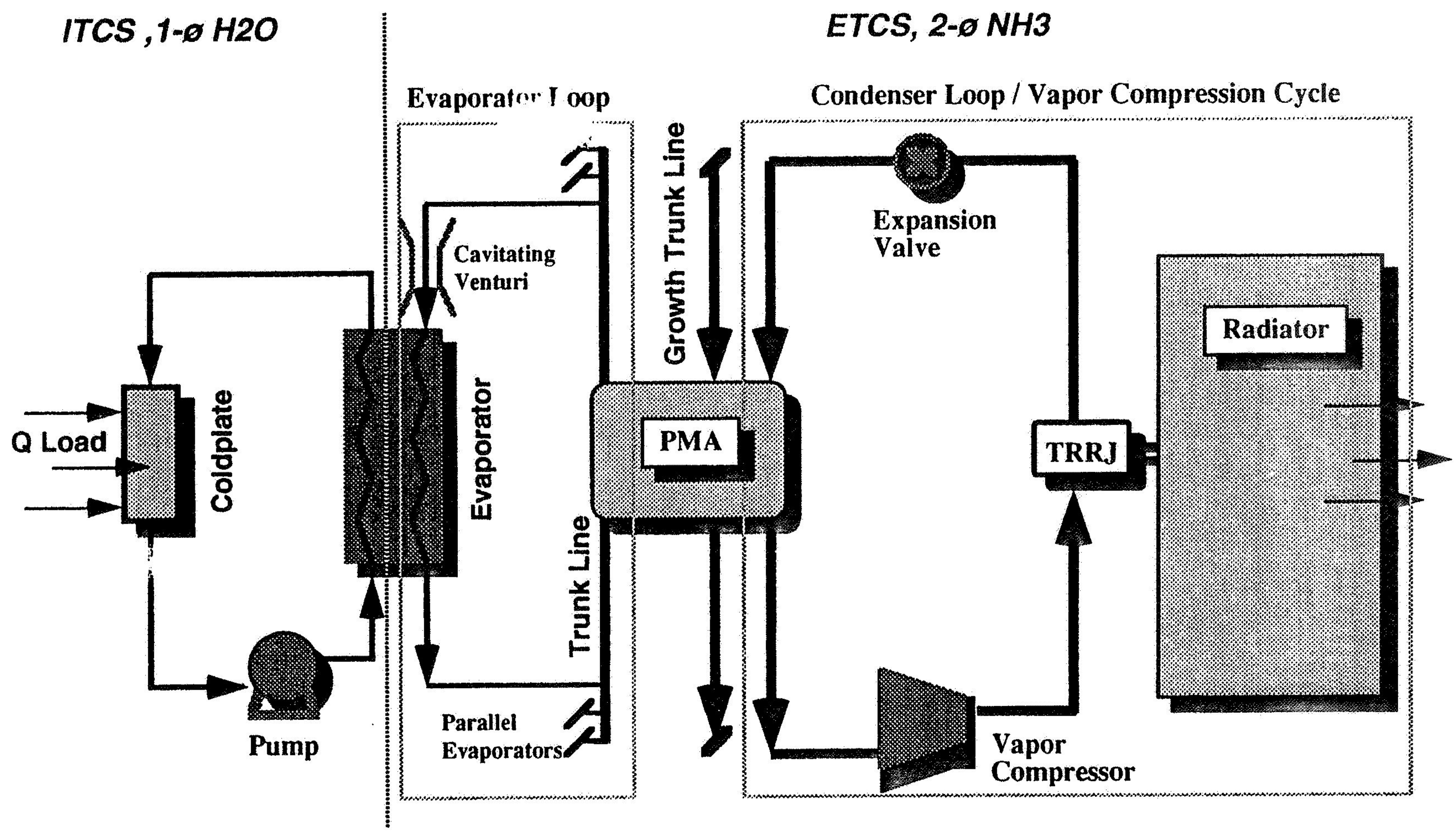
In this example, the baseline and growth evaporator loops are parallel systems. They tie into the same condenser loop using an upgraded PMA. Depending on the PMA design, there may be an impact on the lines in the condenser loop. As mentioned earlier, the radiator ORU's may be replaced before the evolution phase as a maintenance item. At that time, it may be possible to use radiator ORU's with greater surface area in the -x direction. Unless an advanced lightweight radiator is used, the TRRJ will have to be replaced.

The following are potential limiting factors for growth in the -x direction:

- Frequency
- Load
- Drag
- Plume impingement

Frequencies of the radiator panel structure are proportional to the square of the length. Currently this frequency is about 1/4 Hz. Doubling the length of the radiator ORU may produce a frequency of about 1/16 Hz. This could present a problem because frequencies lower than about 1/10 Hz are of concern to flight control people (JSC 31000). Structural scars would be necessary.

Modification of Existing Radiator Wings
Heat Pump Integration into ATCS by Upgraded PMA: Path 3.b.1.a



- 18 kW of power is required to reach the evolution goal

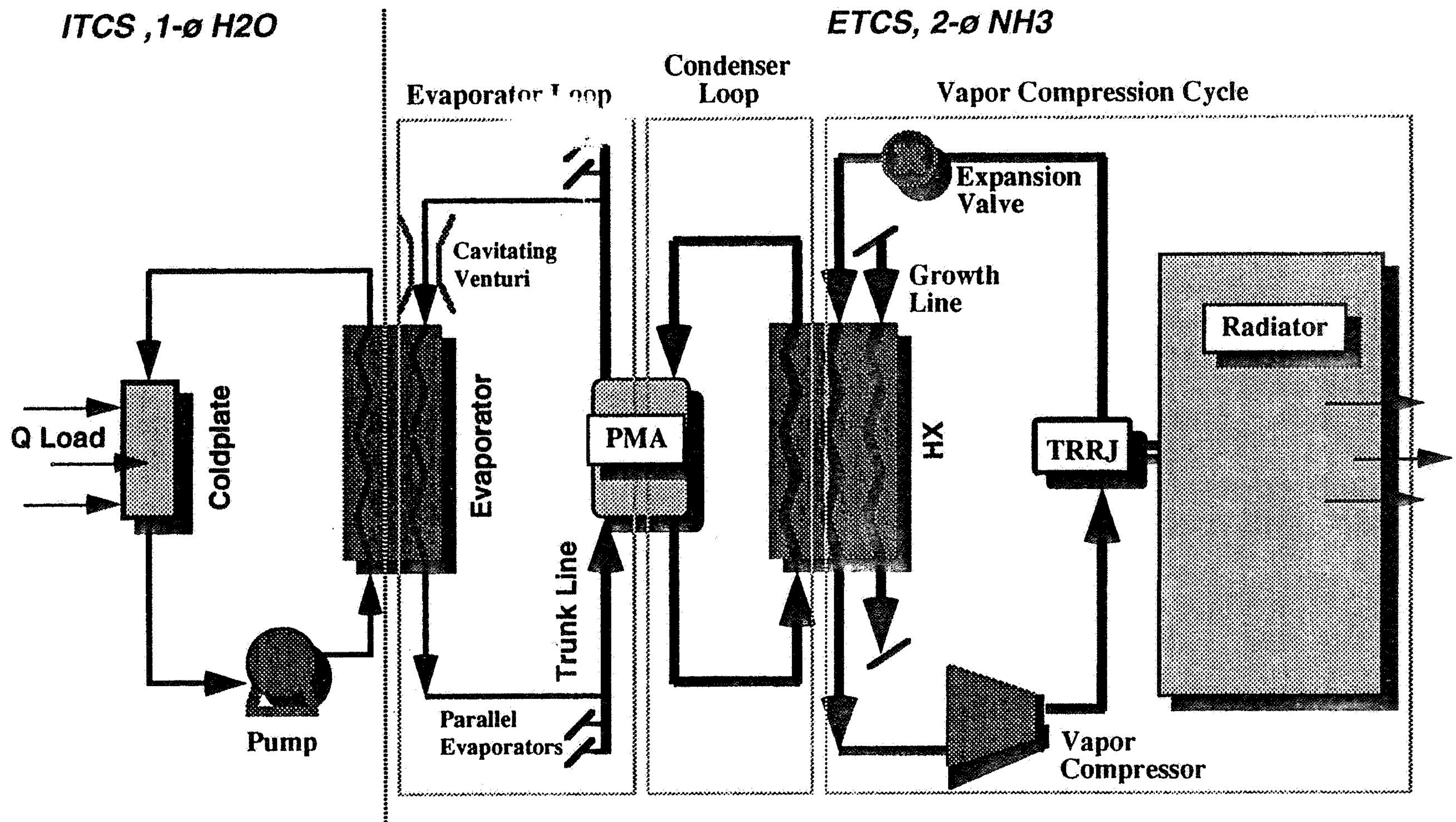
Modification of Existing Radiator Wings
Heat Pump Integration into ATCS by Upgraded PMA: Path 3.b.1.a

Again, the baseline and growth evaporator loops are parallel systems. They tie into the same condenser loop using an upgraded PMA.

By the addition of the vapor compressor and expansion valve, the condenser loop has become a VCC. As the vapor compressor raises fluid temperature it also raises the pressure. The operating pressure of the system is 120 psi (Saturated ammonia at 64 °F). With this pressure limit, the VCC lines and radiator ORU's would have to be replaced. The impact on the baseline TRRJ is undetermined. The maximum operating pressure of the system is 286 psi (Saturated ammonia at 120 °F). This is a transient or start-up pressure. The system will be pressure vessel tested at this pressure. If the VCC could be operated at 286 psi, the lines, TRRJ, and radiators would not need to be replaced due to heat pump operations.

This Path uses an upgraded PMA which is the most efficient method of using a common heat rejection location for the baseline and growth heat loads. The evolution phase would require 18 kW of power to run the vapor compressor.

Modification of Existing Radiator Wings
Heat Pump Integration into ATCS by Growth HX: Path 3.d.1.a



- 19 kW of power is required to reach the evolution goal

Modification of Existing Radiator Wings
Heat Pump Integration into ATCS by Growth HX: Path 3.d.1.a

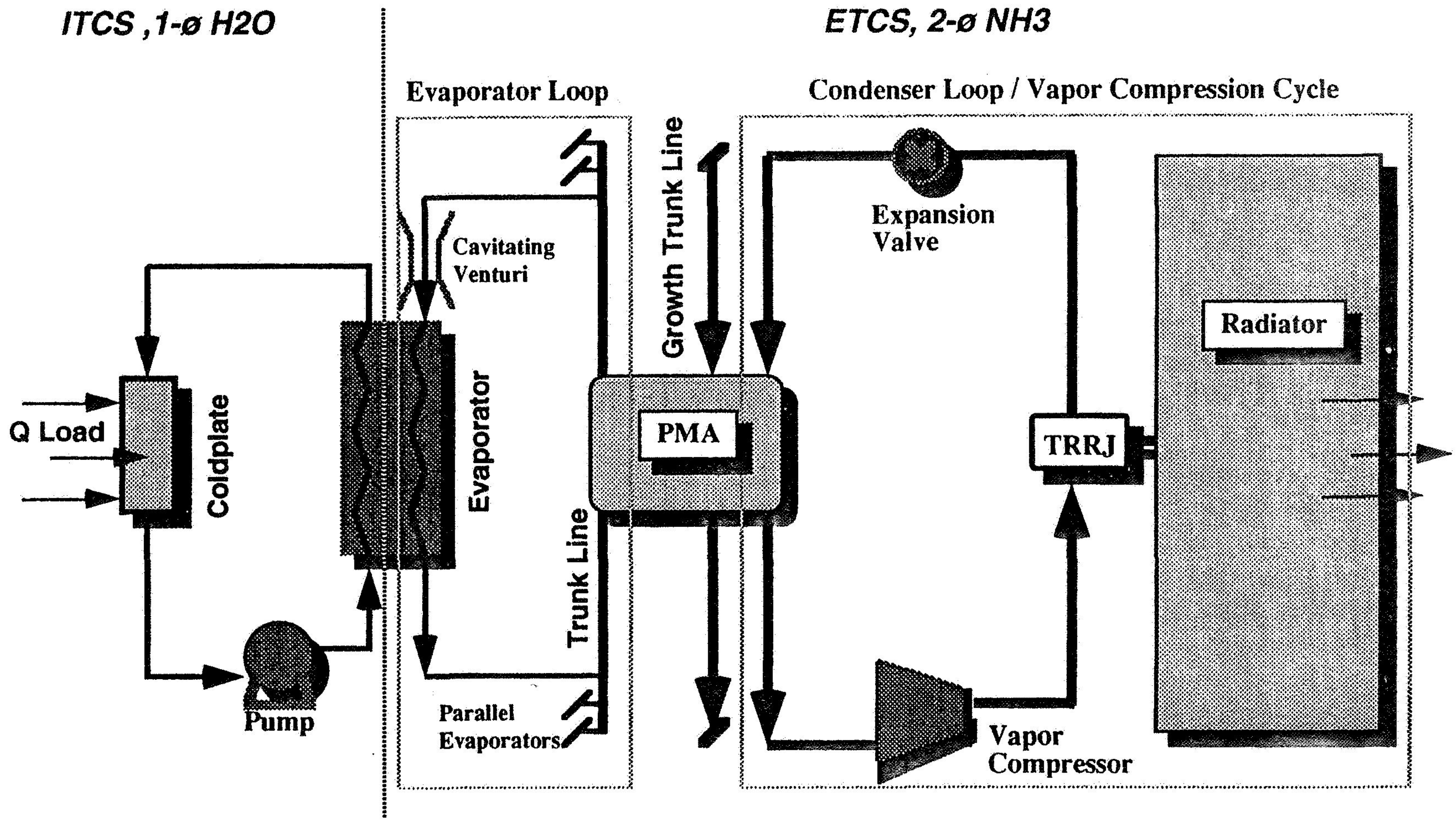
In this path a parallel growth evaporator and condenser loop is added to the ATCS. The condenser and VCC loops are distinct. In order to use the same radiator wing, the baseline and growth condenser loops tie together with a growth HX downstream of the PMA's. A 5 °F temperature drop across the VCC HX is assumed. Due to this temperature drop, more power is consumed by the vapor compressor to obtain the same heat rejection capability as Path 3.b.1.a.

Path 3.d.1.a has two advantages over Path 3.b.1.a. The growth HX isolates the the VCC from the rest of the ATCS. This protects the PMA in case of an expansion valve failure. It also allows the investigation of an alternate fluid that may have higher performance capabilities within the heat pump operating parameters, or a lower pressure that allows the use of baseline equipment.

The evolution phase would require 19 kW of power to run the vapor compressor.

Modification of Existing Radiator Wings

Increase Radiator Area/Heat Pump Integration: Path 3.b.1.c



- **Optimization of the two parameters is the most promising of the existing radiator wing modification options**

Modification of Existing Radiator Wings
Increase Radiator Area / Heat Pump Integration: Path 3.b.1.c

The power consumption that the vapor compressor requires to reach the evolution phase is high. An ATCS / EPS trade study is being conducted to determine the growth balance between these two systems.

Path 3.b.1.c is a promising option in that the optimization of greater area and higher temperature may prevent a limiting parameter from becoming a "show stopper". A limiting parameter is a parameter that would require a significant redesign or alteration in order to proceed with growth. This option increases the surface area until the limiting parameter, possibly frequency, is reached. The heat pump is then used to enhance heat rejection. The greater surface area will decrease the power needed to reach the evolution phase.

Growth Path Desirability

ETCS Condenser Loop

Heat Rejection Location	Desirability
• Path _._.1: Surface area growth is limited to baseline radiator wing location	2
• Path _._.2: Radiator wing addition is possible due to growth structure	1

Heat Rejection Parameters	
• Path _._._.a: Radiator surface temperature is increased	2
• Path _._._.b: Radiator surface area is increased	2
• Path _._._.c: Radiator surface temperature and area are increased	1

Growth Path Desirability: ETCS Condenser Loop

Path _._.1 would require less weight and have less structural impact on the Station than Path 2. The advantage of radiator wing addition is that it requires less EVA operations because much of the integration can occur on the ground.

If Path _._.1 is used, Path _._._.c is the favored subpath because it decreases the severity of the upgrade impacts.

Enhancing/Enabling Technologies

General Requirements

- Increase ATCS capacity while occupying less real estate than growth baseline technology would at the same heat rejection level.
- Maintain power consumption within realistic parameters.
- Limit technology research and investment to available development time frame and funding.

Heat Acquisition

- Advanced evaporator technology

Heat Transport

- Two-phase pump technology
- Distribution line technology

Heat Rejection

- Light weight deployable heat pipe radiator ORU's
- High efficiency heat pump technology
- Heat storage

Enhancing/Enabling Technologies

Advanced technologies can enhance the growth paths by removing some volume and weight impacts.

The following are advanced technology requirements:

- Increase ATCS capacity while occupying less real estate than growth baseline technology would at the same heat rejection level.
- Maintain power consumption within realistic parameters.
- Limit technology research and investment to available development time frame and funding.

Heat Acquisition

- Develop high heat flux, low pressure drop HX's to decrease weight, volume, and power.

Heat Transport

- Develop a pump with lower power consumption and higher reliability for the increased flow rates associated with higher heat rejection.
- Develop low-leakage quick disconnects and non-permeating ammonia lines which are compatible with robotic assembly.

Heat Rejection

- Increase heat rejection capability of SSF through the development of high efficiency lightweight fins. As the SSF environment degrades, replace flow-through radiator ORU's with heat pipe radiator ORU's to decrease the potential for ammonia loss due to impacts . Develop an extended-life surface coating to allow for radiator design with prolonged beginning-of-life properties.
- Develop high temperature and pressure heat pipes which allow the heat pump to run more efficiently. Develop very high capacity heat pipes to enable greater transport capacity than current designs.
- Develop heat pump systems which operate in a reduced gravity environment. Heat pump technology significantly reduces radiator area.
- Develop a high density heat storage subsystem for heat load leveling to accommodate peak loads. Heat storage reduces radiator area needed for peak loads.

Conclusions

Heat Transport Line Addition

- Real estate is available for line addition.
  - / Impacts due to line addition are being determined

Modification of Existing Radiator Wings

- The ATCS evolution goal can be obtained by the use of a heat pump.
  - / The EPS impact is significant.
  - / A EPS/ATCS trade study is in work.
- Doubling the radiator surface area using baseline technology will violate GN&C requirements.
- An optimization study on increasing radiator temperature and area is in work.

Radiator Wing Addition

- Addition of PIT structure containing radiator wings is a promising approach.
  - / Structural dynamics and GN&C impacts are under evaluation.

Conclusions

The ATCS evolution goal can be obtained. Studies continue to determine the minimum impact growth path.

The reservation of real estate for growth structure attachment, upgraded PMA volume, and UDS fluid tray addition are the suggested minimum impact scars. These scars would preserve the current growth path options. Structural dynamics studies are being conducted to determine additional scars.

S8-18

N92-17776

MP628424

Thermal Control System Automation Project (TCSAP)

sponsored by
Space Station Level 1 Engineering Prototype Development

Space Station Evolution Conference

South Shore Harbour Conference Center
League City, Texas

Roger L. Boyer
McDonnell Douglas Space Systems Company
Thermal Systems
August 8, 1991

INTRODUCTION

Good morning! My presentation today is on the Thermal Control System Automation Project (TCSAP). Before going into the meat of the project, I would like to take this opportunity to recognize those responsible. This project is managed by Mark Gersh of Space Station Level 1 Engineering. It is monitored locally here at NASA JSC by Nick Mesloh of the Crew and Thermal Systems Division and Bryan Basham of the Automation & Robotics Division. Those responsible for the work performed to date at McDonnell Douglas include Tim Hill, William Morris, Charlie Robertson, and myself.

AGENDA

- External Thermal Control System (ETCS) Background
- Project Objectives and Benefits
- Technical Approach
  - High Fidelity Simulator (HFS)
  - RODB-like Software
  - Knowledge Based System (KBS)
  - Integrated System Scenario
- Baseline Integration and Evolution
- Summary

Roger Boyer
8-8-91

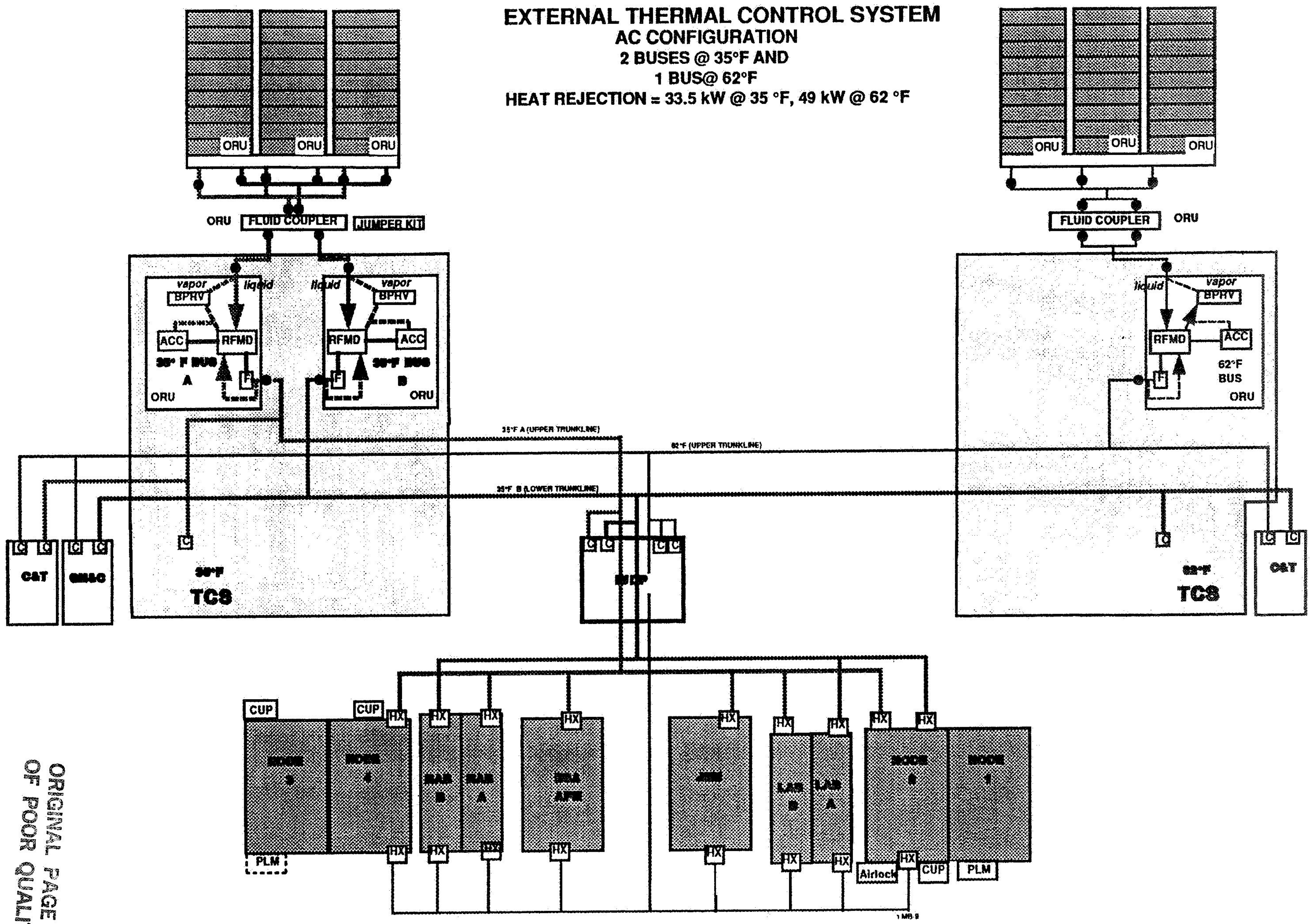
AGENDA

After hearing about the ATCS in the previous presentation, I'll provide only a brief introduction of the ETCS and identify the issues associated with it that drive the need for additional Fault Detection, Isolation, and Recovery (FDIR) capability. That will allow me to lead into what TCSAP is about and the benefits that SSFP can gain from it.

During my presentation, you will see several acronyms specific to TCSAP. The principal ones are: FDIR, High Fidelity Simulator (HFS), Runtime Object Database (RODB), and Knowledge Based System (KBS).

After discussing the technical approach taken by this project, I will walk you through a scenario of the Integrated System, identify how TCSAP's milestones are aligned with those of the TCS / SSF, and present our plans for migrating the system to on-board.

EXTERNAL THERMAL CONTROL SYSTEM
AC CONFIGURATION
2 BUSES @ 35°F AND
1 BUS@ 62°F
HEAT REJECTION = 33.5 kW @ 35 °F, 49 kW @ 62 °F



ORIGINAL PAGE IS
OF POOR QUALITY

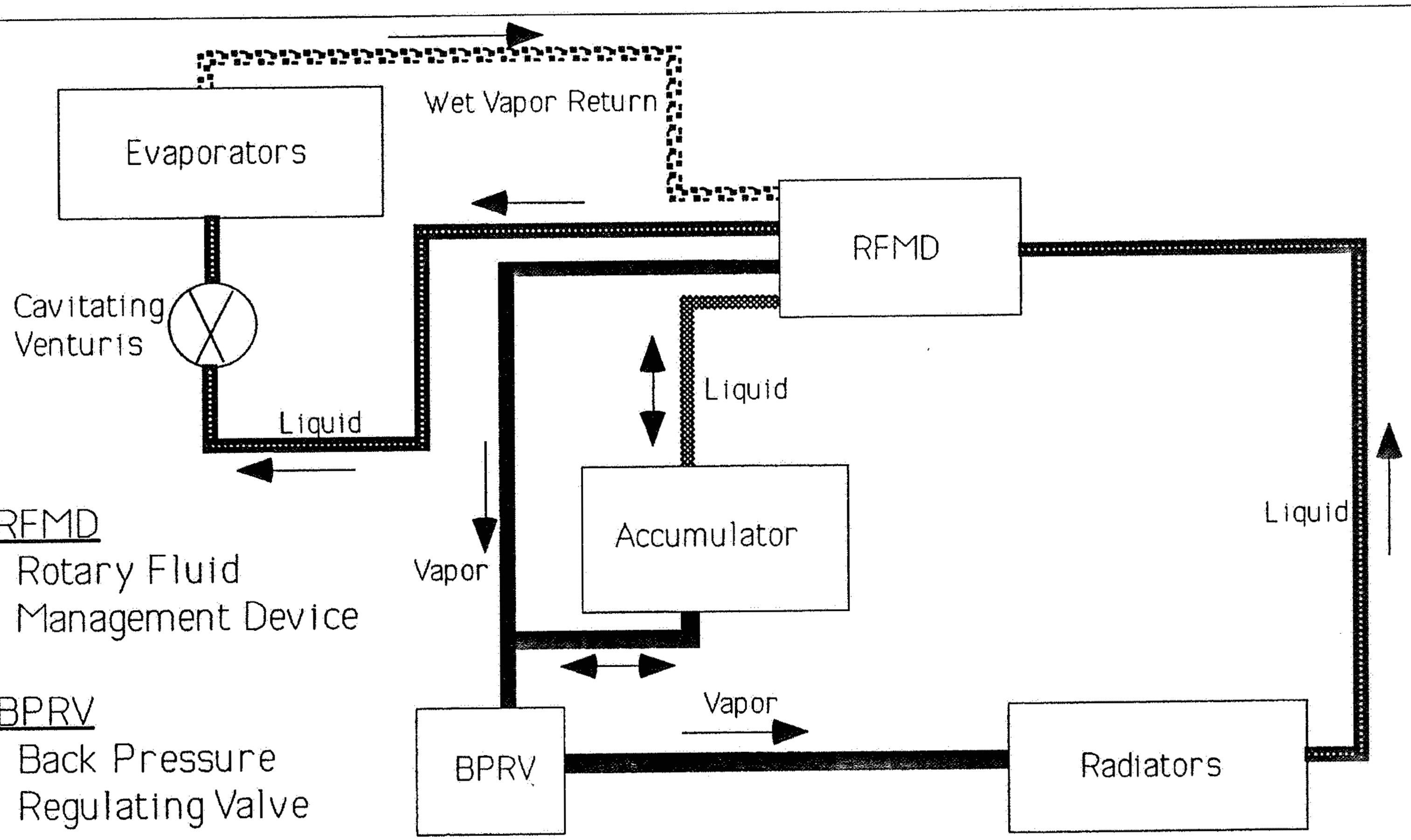
ETCS ASSEMBLY COMPLETE

- This figure shows the integrated baseline ETCS Assembly Complete (AC) configuration for SSF, as discussed in the preceding presentation. Note that there are three fluid loops (or buses): two at 35 oF and one at 62 oF. Also note that the two 35 oF buses do not share the same heat loads.

- Each bus includes both active and passive components. The active components (e.g., the Rotary Fluid Management Device) can fail during operation for a variety of reasons (e.g., loss of power, mechanical failure, and flow blockage). The passive components (e.g., cold plates) can leak or become blocked. As a result, a variety of failure modes can exist for a variety of different components. Overall, the dynamics of the ETCS allows some time for FDIR following most anticipated failure modes. For those events where time is critical, FDIR is performed on-board.

Roger Boyer
8-6-91

ETCS FUNCTIONAL SCHEMATIC



RFMD
Rotary Fluid Management Device

BPRV
Back Pressure Regulating Valve

Roger Boyer
8-8-91

ETCS FUNCTIONAL SCHEMATIC

- The ATCS design has evolved from the single-phase fluid system used in the Apollo and Space Shuttle programs to a two-phase system on SSF. For a single-phase system, heat loads are applied in series along the fluid flow path prior to entering the radiators. A centrifugal pump is used to provide the pumping head for the system. However, for SSF, greater heat loads are required and electric power is limited. Therefore, a two-phase fluid system is needed.

- Again this figure was discussed in the preceding presentation. The important points to draw from it are the multi-phase conditions of the ammonia within the ETCS and the variety of equipment utilized. The RFMD pumps liquid ammonia to the evaporators and cold plates, which remove heat from various locations / equipment around the station. The cavitating venturi provide flow control to the evaporators. A two-phase mixture is returned to the RFMD, which separates the vapor from liquid. The RFMD pumps the vapor to the radiators, which condense the fluid to a subcooled state. The RFMD also maintains inventory control along with the accumulator. The BPRV maintains setpoint temperature by controlling system pressure. Not shown are the various sensors or instrumentation on the bus, which can fail in such a way as to provide erroneous or misleading data to the FDIR software and crew.

Roger Boyer
8-6-91

BASELINE FDIR

- 2 Standard Data Processors (SDPs) on-board.
- Time and safety critical FDIR will be handled on-board.
- Sensor data downlinked to ground operations (Space Station Control Center and Engineering Support Center).
- Ground operations will be man-tended 24 hours per day for the duration of SSF.

Roger Boyer
8-6-91

TCSAP OBJECTIVES

- Develop a Knowledge-Based System (KBS) that utilizes a combination of rule and model-based reasoning to perform Fault Detection, Isolation, and Recovery (FDIR) on the SSF External Thermal Control System (ETCS).

- Develop an ETCS High Fidelity Simulator (HFS) and Runtime Object Database (RODB)-like software for cost effective development & testing of the FDIR software.

- Develop an evolution plan to migrate automated FDIR functionality from ground to on-board.

BENEFITS

- Improve ETCS FDIR reliability.
- Increase ETCS FDIR functionality.
- Enhance ETCS safety.
- Reduce costs associated with testing the KBS.
- Improve SSF ground support productivity.
- Enhance crew and ground training with both the HFS and KBS.

Roger Boyer
8-8-91

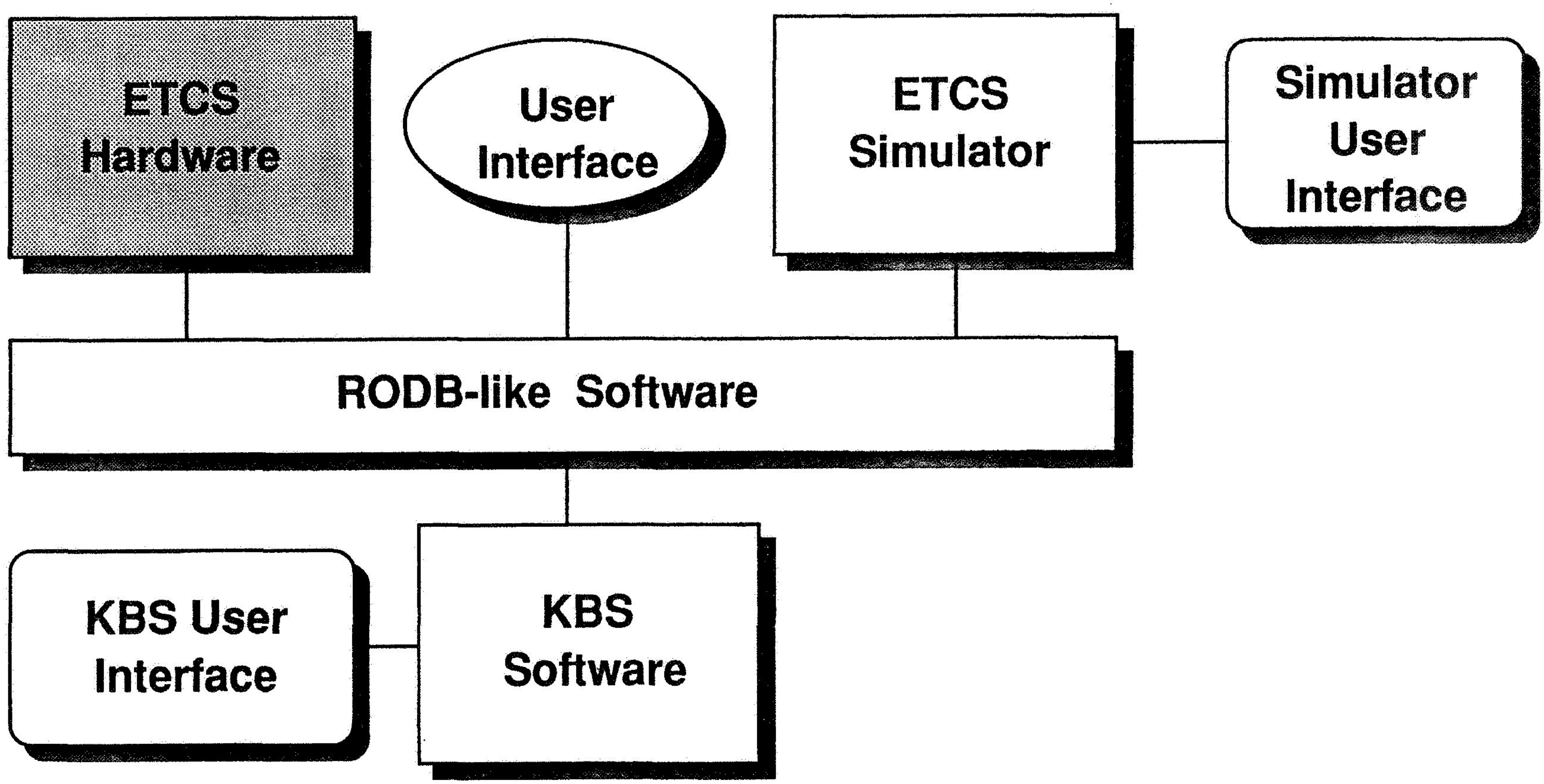
BENEFITS

There are several benefits associated with using advanced automation on the ETCS and the approach being taken by TCSAP.

- ETCS FDIR reliability can be improved by extensive testing against the HFS and comparing to ETCS thermal testbed results.
- ETCS FDIR functionality can be increased by using model based reasoning to identify novel faults. Novel faults are those faults not identified in the system's Failure Mode and Effects Analysis (FMEA).
- ETCS safety can be enhanced as a result of improving its FDIR reliability and functionality.
- Costs associated with testing the KBS can be minimized by using the HFS instead of the actual ETCS hardware. Furthermore, testing the actual hardware under certain fault scenarios can be dangerous and potentially damaging to the hardware itself.
- SSF ground support productivity can be improved by reassigning manpower from round-the-clock system monitoring to other tasks.
- Both crew and ground training can be enhanced with the HFS and KBS.

Roger Boyer
8-6-91

TCSAP SOFTWARE ARCHITECTURE



Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed

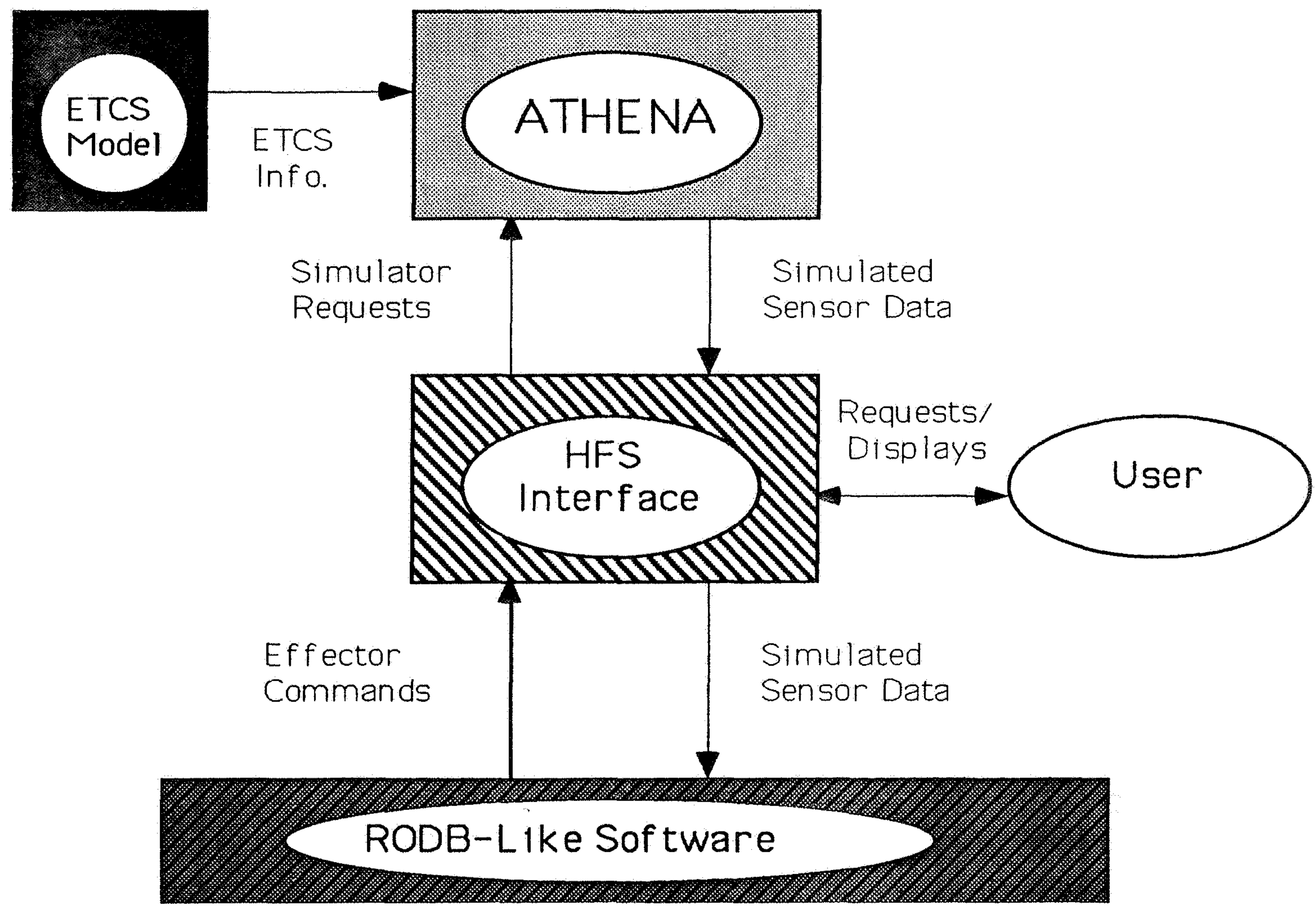
Roger Boyer
8-8-91

TCSAP SOFTWARE ARCHITECTURE

- This figure identifies the major TCSAP software components and how they are integrated. Note that hardware data can be generated by either the actual hardware or simulator and read by the RODB-like software. The RODB-like software provides the appropriate data to the KBS. Each software component has its own user interface for monitoring and control, if so desired. The simulator user interface is required for fault injection and can be used in a stand-alone mode. The RODB-like user interface is solely for monitoring. The KBS user interface is used for both monitoring and control.

Roger Boyer
8-6-91

HFS ARCHITECTURE



Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed

Roger Boyer
8-8-91

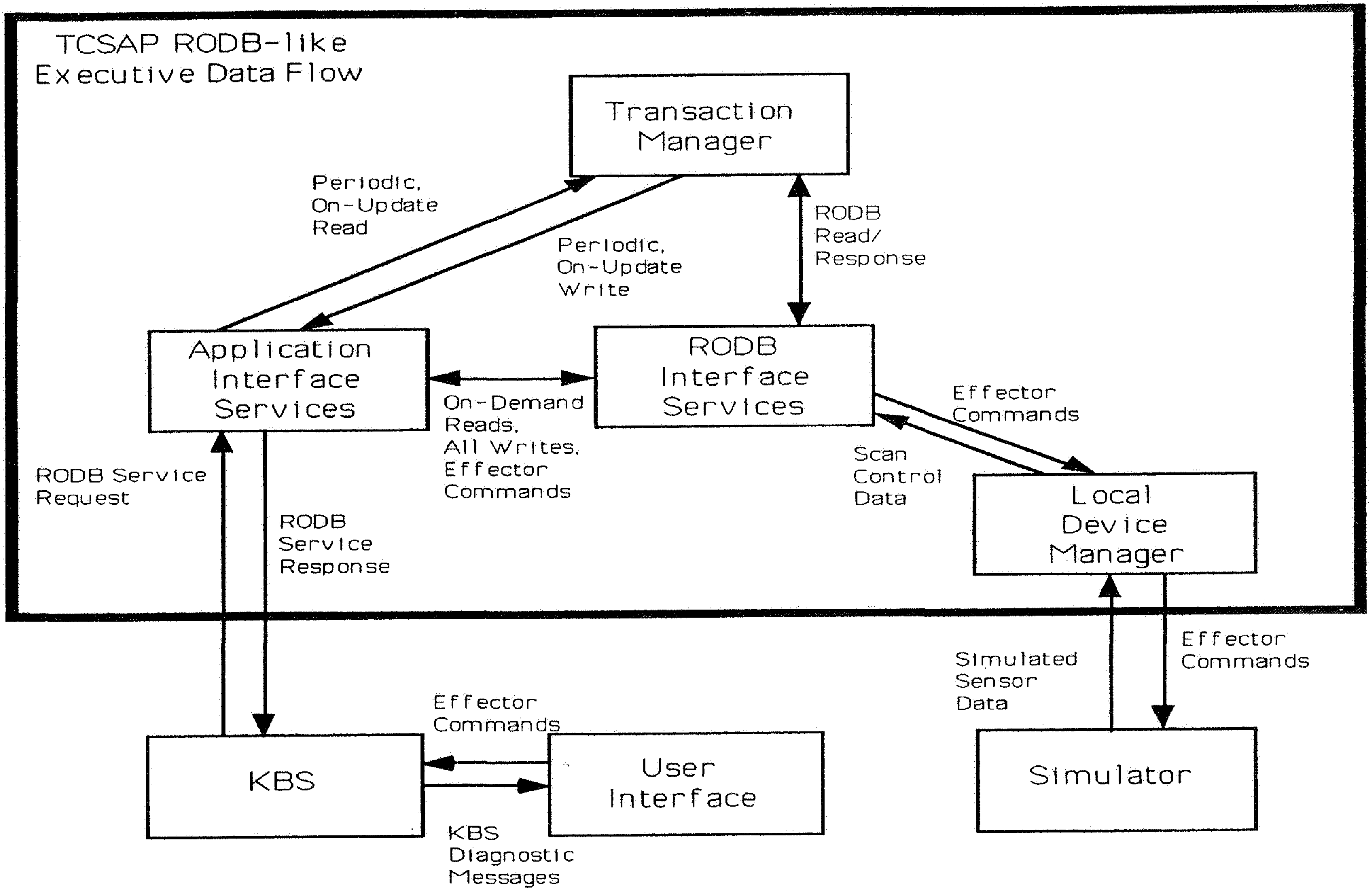
HFS ARCHITECTURE

- The HFS is made up of three major components. The Advanced Thermal-Hydraulic Energy Network Analyzer (ATHENA) represents the heart of the HFS with its six equation set of conservation equations, 1-D heat conduction models, and special process correlations (e.g., two-phase pressure drop). ATHENA requires application specific information concerning the physical dimensions, component connectivity, and component functionality. The HFS interface provides sensor data to and receives effector commands from either the user or RODB-like software.

- The HFS must run to as close as real-time as possible and still provide hardware-like sensor data. The HFS must also allow a modular means of updating component models as the ETCS design evolves.

Roger Boyer
8-6-91

TCSAP RODB DATA FLOW



Space Station Freedom
McDonnell Douglas • GE • Honeywell • IBM • Lockheed

Roger Boyer
8-8-91

TCSAP RODB DATA FLOW

- The RODB-like software developed by TCSAP performs the same functions as the baseline RODB, except only for the ETCS. The ETCS subsystem has essentially four data packages associated with it: the Transaction Manager, The Application Interface Services, the RODB Interface Services, and the Local Device Manager.

- The Local Device Manager reads the sensor values received from the simulator/hardware, performs limit checks, and stores the sensor values into the appropriate sensor object.

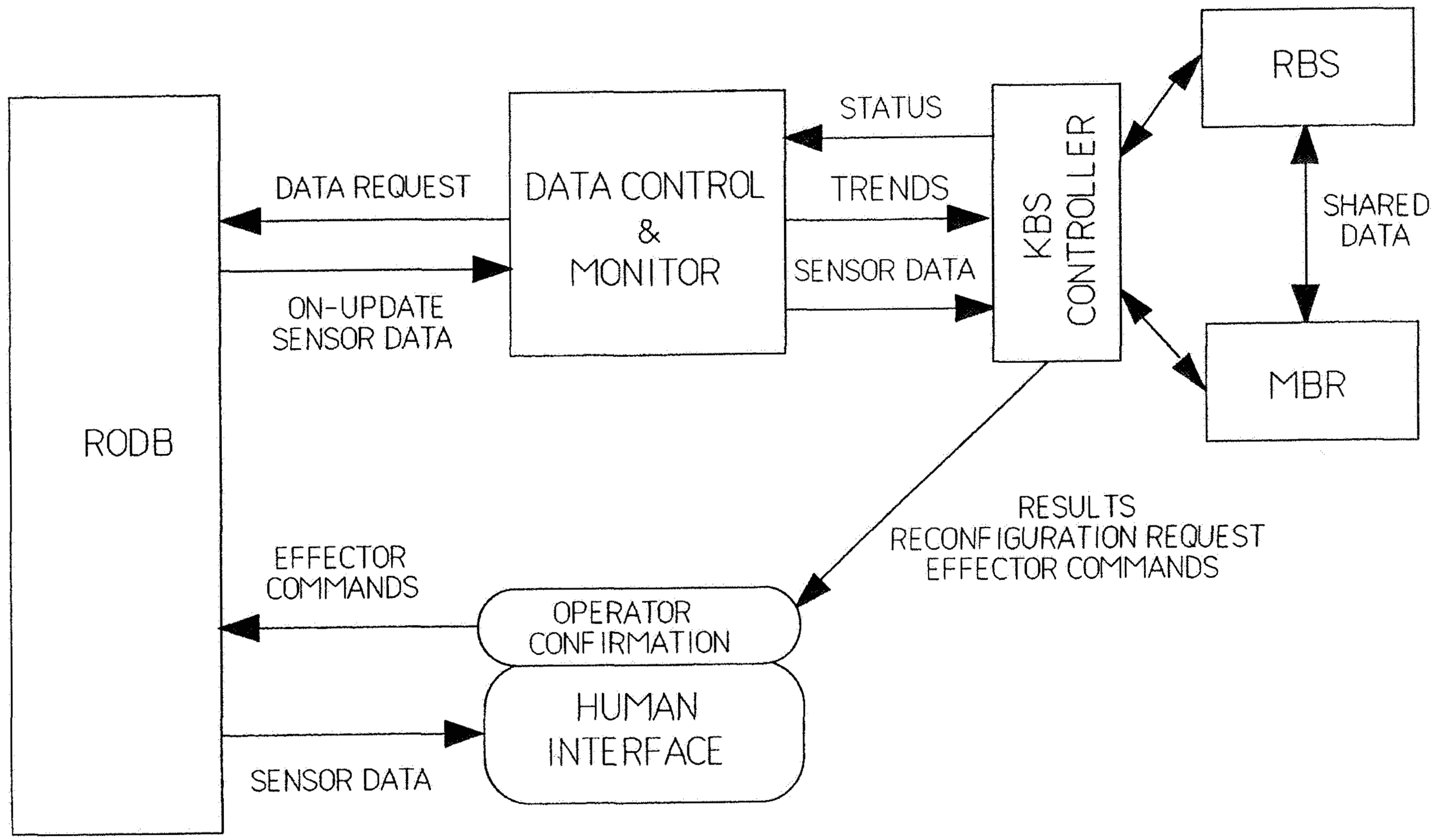
- The Application Interface Services allow external applications to tie into the RODB-like software.

- The Transaction Manager tracks the on-update and cyclic data requests received from the Application Interface Services.

- The RODB Interface Services act as the interface to the sensor objects. The Application Interface Services can ask the Interface Services for an on-demand data request, which is a one-shot data request. This service allows external programs to request certain sensors one time and not see them again. Note that the Interface Services can access sensor data from any other subsystem and can be portrayed in a three-dimensional schematic coming out of the page and connecting to the other subsystem's Local Device Mgr.

Roger Boyer
8-6-91

KBS FUNCTIONAL ARCHITECTURE



Space Station Freedom — McDonnell Douglas • GE • Honeywell • IBM • Lockheed

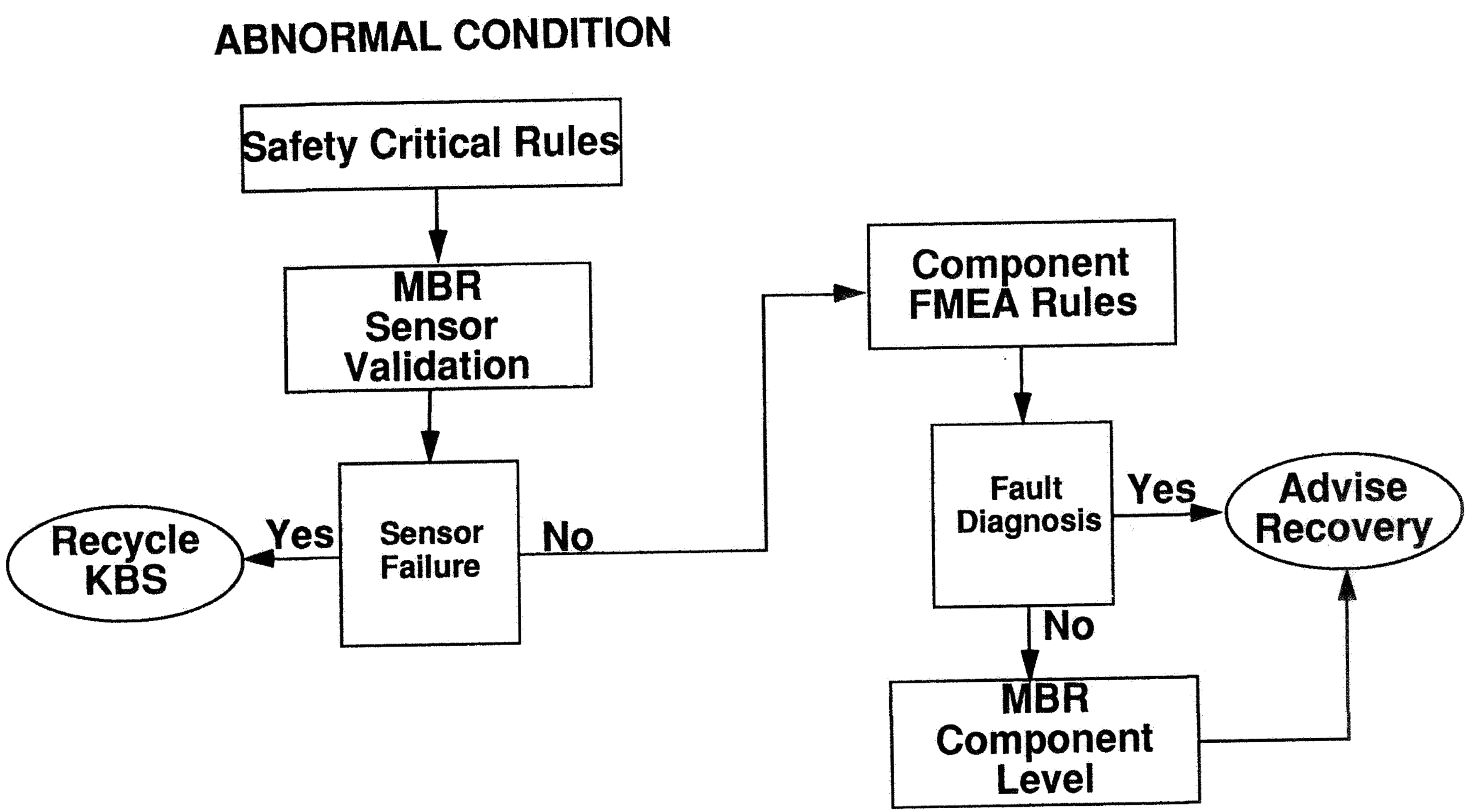
Roger Boyer
8-8-91

KBS FUNCTIONAL ARCHITECTURE

- The KBS receives sensor data from the RODB-like software, performs a trending analysis on selected sensors, and sends the data (both quantitative and qualitative data) to the KBS controller. The controller manages the order in which data is provided to the various sets of rules and model based reasoning applications, which are discussed further on the following slide. Once a fault has been detected and isolated, a message is sent to the human interface for confirmation of the recommended recovery action.

Roger Boyer
8-6-91

KBS LOGIC FLOW



Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed

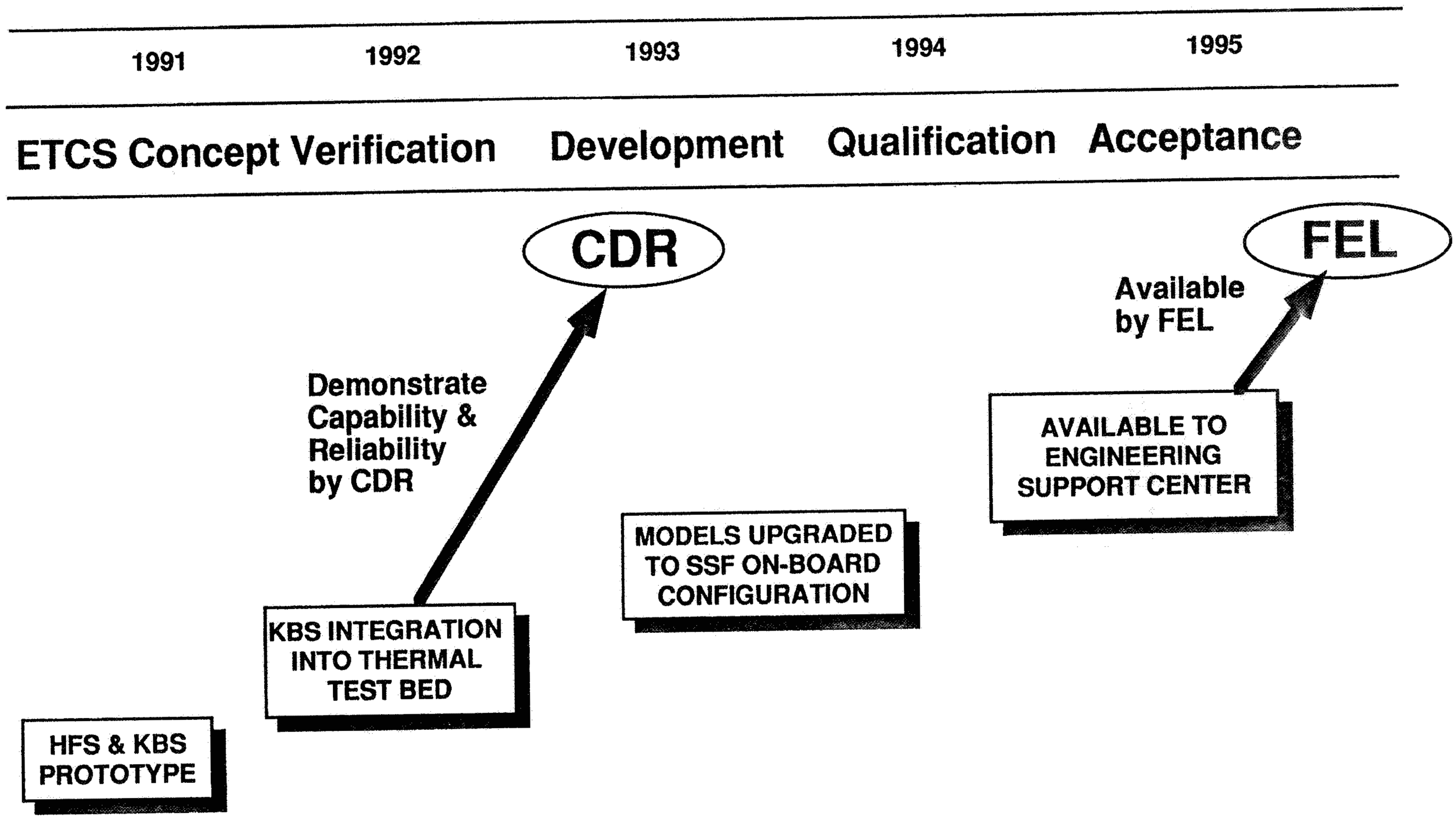
Roger Boyer
8-8-91

KBS LOGIC FLOW

- Incoming ETCS sensor data is compared to an expected range of values. If the range is exceeded for any sensor, the complete set of sensor values are sent to the KBS controller. The KBS controller manages the evaluation of incoming sensor data. The safety critical rules are checked first along with sensor validation. If the sensor is determined to be invalid, then it is flagged as such and the KBS continues its monitoring. However, if the sensor is determined to be valid and not indicative of a safety critical fault, then the Failure Mode & Effects Analysis (FMEA) rules are checked. If the event is not determined to be of those identified in the ETCS FMEA, then it is considered to be a novel fault and must be evaluated by the component model based reasoner of the KBS. When either a safety critical event, FMEA fault, or a novel fault is identified, a message identifying the fault is sent to the human interface along with the recommended recovery action.

Roger Boyer
8-6-91

TCSAP INTEGRATION INTO BASELINE



Space Station Freedom — McDonnell Douglas • GE • Honeywell • IBM • Lockheed

Roger Boyer
8-8-91

TCSAP INTEGRATION INTO BASELINE

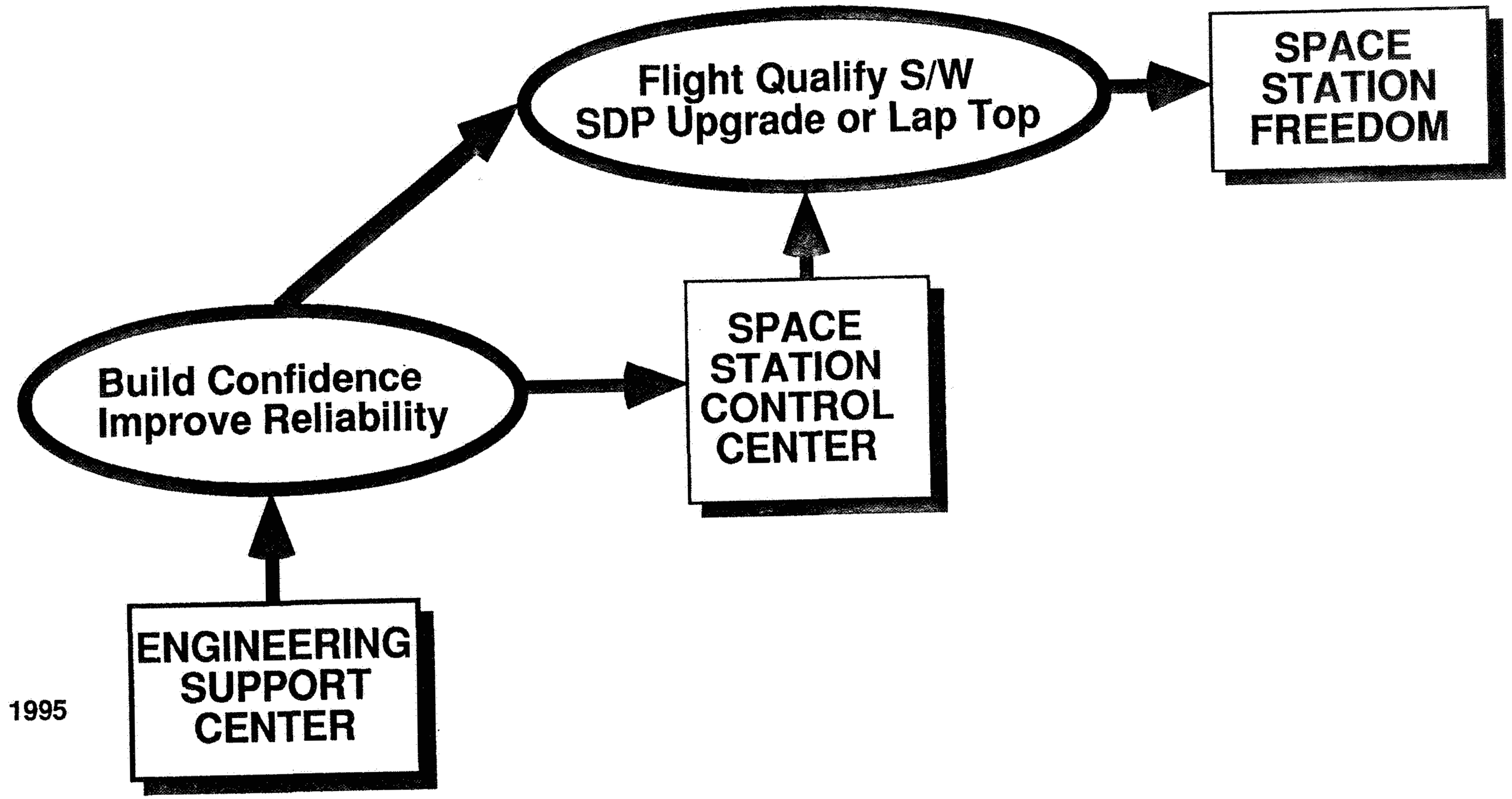
- This slide shows a comparison between the major phases of the ETCS Verification program and the TCS Automation Project milestones. The top bar gives a general idea of the time frame in fiscal years. The ETCS design is currently in the concept verification phase until the end of FY92. The TCS Critical Design Review (CDR) is scheduled for January 1993 and First Element Launch (FEL) is scheduled for December 1995.

- During 1991, a prototype HFS and KBS was developed. During 1992, TCSAP will integrate the KBS into the ETCS test bed to demonstrate its capability and reliability prior to CDR. The next step is to modify the models to represent the on-board configuration, enhance the model based reasoning capability, and make both the HFS and KBS available for the ESC by FEL. Note that the ETCS will not be activated until MB-5.

- The point of this slide is to show that TCSAP is in sync with the ETCS baseline schedule, thus allowing the SSF program the opportunity to use the KBS in the ESC by the time the ETCS is activated.

Roger Boyer
8-6-91

TCSAP GROWTH & EVOLUTION



Space Station Freedom — McDonnell Douglas • GE • Honeywell • IBM • Lockheed

Roger Boyer
8-8-91

TCSAP GROWTH & EVOLUTION

- This slide provides two possible approaches for placing the TCSAP software on-board SSF. The first approach is to migrate it directly to the station from the ESC. The second approach is to migrate it from the ESC to the control center, then to on-board.
- Given that its in the ESC by FEL and it still hasn't proven itself to the SSF program, man tended FDIR would be used to build its confidence. As the operating experience database of the on-board ETCS grows, so will the reliability of the KBS to perform FDIR. Selected portions (e.g., FMEA rules) or all of the KBS may be loaded onto lap top computers that can be carried up and plugged into the space station. Another alternative is to upgrade the SDPs as time, money, and incentive lends itself.
- The point of this slide is to show that TCSAP's KBS can be migrated to on-board.

Roger Boyer
8-6-91

TCSAP RELATIONSHIPS

- CREW AND GROUND TRAINING
- ETCS PROCEDURES DEVELOPMENT
- FAILURE ENVIRONMENT ANALYSIS TOOL (FEAT)
- GROUND TEST RESULTS ANALYSIS

Roger Boyer
8-8-91

TCSAP RELATIONSHIPS

- The TCSAP HFS can be used for a variety of other uses within the SSF program. For example, crew and ground training can be enhanced with a HFS of the ETCS. The HFS can provide sensor data representing the ETCS under both normal and abnormal conditions. During the development of the ETCS operating procedures, the HFS can be used to evaluate alternative operator actions or procedure steps. The Failure Environment Analysis Tool (FEAT) will be using the ETCS as the prototype system. Due to the closeness of the HFS to the ETCS testbed, it can also be used to assist in ground test results analyses.

- The KBS can serve as a knowledge database for thermal applications and can enhance ETCS training. It can be expanded to include such features as predictive maintenance.

SUMMARY

- ETCS ISSUES
- FDIR CONFIDENCE
- BENEFITS OF TCS ADVANCED AUTOMATION
- DESCRIBED THE TECHNICAL APPROACH
- DEMONSTRATE THE INTEGRATION OF THE KBS INTO THE ETCS THERMAL TESTBED
- BE THERE FOR FIRST ELEMENT LAUNCH!

Roger Boyer
8-8-91

SUMMARY

- In summary, I've identified some of the issues associated with the ETCS and discussed the confidence in the ETCS FDIR. The benefits of the TCSAP software include using the HFS for enhancing training and the KBS for FDIR.

- The technical approach taken by this project was to use a high fidelity simulator of the ETCS and a RODB-like software to test the KBS software. This approach provides a cost effective method for testing the KBS and knowledge acquisition of the ETCS.

- By CDR, TCSAP will have demonstrated its capability and reliability to the SSF program through the integration of the KBS into the ETCS thermal testbed. By FEL, the TCSAP KBS will be available to the ESC for ground operations.

Roger Boyer
8-6-91