SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP)

Volume III: June 26-27

Space Power & Thermal Management

Briefings from the June 24-28, 1991 Meeting
McLean, Virginia

National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Washington, D.C. 20546

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Space Energy Conversion Research and Technology

INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
26 JUNE 1991

Gary L. Bennett
Manager, Advanced Space Power Systems
Propulsion, Power and Energy Division
Office of Aeronautics, Exploration and Technology
NASA Headquarters
AGENDA
POWER AND THERMAL MANAGEMENT
DISCIPLINE REVIEW

WEDNESDAY, JUNE 26, 1991

8:30 AM  ADMINISTRATORS REMARKS  R. Truly
9:30 AM  POWER OVERVIEW (90 min.)  G. Bennett
11:00 AM  PHOTOVOLTAICS (45 min.)  D. Flood
11:45 AM  CHEM. ENERGY CONVERSION (45 min.)  P. Bankston
12:30 PM  LUNCH (60 min.)  All
1:30 PM  THERMAL ENERGY CONVERSION (60 min.)  P. Bankston/ Calogeras
2:30 PM  POWER MANAGEMENT (90 min.)  Bercaw/W. Meador
4:00 PM  THERMAL MANAGEMENT (45 min.)  Swanson
4:45 PM  ADJOURN

THURSDAY, JUNE 27, 1991

FOCUSED TECHNOLOGY:

8:00 AM  SPACE NUCLEAR POWER (60 min.)  J. Sovie
9:00 AM  HIGH CAPACITY POWER (60 min.)  J. Sovie
10:00 AM  SURFACE POWER & TM (45 min.)  J. Bozek
10:45 AM  EARTH-ORBIT PLAT. POWER & TM (45 min.)  R. Cull
11:30 AM  LASER POWER BEAMING (45 min.)  J. Rather
12:15 PM  LUNCH (60 min.)  All
ORDER OF PRESENTATION MATERIAL

- Work Breakdown Structure
- Space Power Technology
- Integrated Technology Plan Process
- Space Power Background
- Technology Needs
- Space Power Reviews and Studies
- Space Power Technology Development
- Coordination and Interfaces
- Budgets
- Summary
- External Review Process

Work Breakdown Structure
FY 90 - 91 PROGRAM CHANGES

PATHFINDER

SURFACE EXPLORATION
- Surface Power
- Planetary Rover
  - Sample Acquisition, Analysis & Preservation
  - Autonomous Lander
  - Photonics

IN-SPACE OPERATIONS
- Space Nuclear Power (SP-100)
  - Autonomous Rendezvous & Docking
  - In-Space Assembly & Construction
  - Cryogenic Fluid Depot
  - Resource Processing Pilot
  - Optical Communications

SURFACE OPERATIONS
- Space Nuclear Power
- Surface Solar Power
- Planetary Rover
  - In Situ Resource Utilization
  - Surface Habitats & Construction

REVISED WORK BREAKDOWN STRUCTURE

SPACE R&T BASE
IN-SPACE TECH. EXPER. PROG.
CSTI PROGRAM
- SCIENCE
- TRANSPORTATION
- OPERATIONS
EXPLORATION TECHNOLOGY
- SPACE TRANSPORTATION
- IN-SPACE OPERATIONS
- SURFACE OPERATIONS
- HUMAN SUPPORT
- LUNAR & MARS SCIENCE
- NUCLEAR PROPULSION
SPACE AUTOMATION & TELEROBOTICS

CIVIL SPACE TECHNOLOGY PROGRAM
- SPACE SCIENCE TECHNOLOGY
- TRANSPORTATION TECHNOLOGY
- OPERATIONS TECHNOLOGY
- SPACE EXPLORATION TECHNOLOGY
- SPACE PLATFORMS TECHNOLOGY
REVISED WORK BREAKDOWN STRUCTURE

- SPACE R&T BASE
  - Aerothermodynamics
  - Space Energy Conversion
  - Propulsion
  - Materials & Structures
  - Space Flight
  - Systems Analysis
  - University Space Research
  - Information and Controls
  - Human Support

- IN-SPACE TECH. EXPER. PROG.

- CSTI PROGRAM
  - SCIENCE
    - Science Sensor
    - High Rate/Capacity Data Systems
    - Precision Segmented Reflectors
  - TRANSPORTATION
    - Earth to Orbit
  - OPERATIONS
    - Telerobotics
    - Artificial Intelligence
    - High Capacity Power
    - Controls/Structures Interaction

- EXPLORATION TECHNOLOGY
  - SPACE TRANSPORTATION
    - Aerobraking
    - Space Based Engines
    - Autonomous Landing
    - Autonomous Rendezvous & Docking
  - IN-SPACE OPERATIONS
    - Cryogenic Fluid Systems
    - In-Space Assembly and Construction
  - SURFACE OPERATIONS
    - Space Nuclear Power
    - In-Situ Resource Utilization
  - HUMAN SUPPORT
    - Regenerative Life Support
    - Radiation Protection
    - Extravehicular Activities Systems (Surface)
    - Exploration Human Factors
  - LUNAR & MARS SCIENCE
    - Sample Acquisition, Analysis & Preservation
    - Planetary Probes & Penetrators
  - NUCLEAR PROPULSION
    - Nuclear Thermal Propulsion
  - INNOVATIVE TECHNOLOGY
    - Exploration Technology Analysis

- SPACE AUTOMATION & TELEROBOTICS

- AEROASSIST FLIGHT EXPERIMENT

- CIVIL SPACE TECHNOLOGY PROGRAM
  - SPACE SCIENCE TECHNOLOGY
    - Science Sensing
    - Observatory Systems
    - Science Information
    - In-Situ Science
    - Technology Flight Expts.
  - TRANSPORTATION TECHNOLOGY
    - ETO Transportation
    - Space Transportation
    - Technology Flight Expts.
  - OPERATIONS TECHNOLOGY
    - Automation & Robotics
    - Infrastructure Operations
    - Info. & Communications
    - Technology Flight Expts.
  - SPACE EXPLORATION TECHNOLOGY
    - Surface Systems
    - Human Support
    - Technology Flight Expts.
  - SPACE PLATFORMS TECHNOLOGY
    - Earth-Orbiting Platforms
    - Space Stations
    - Deep-Space Platforms
    - Technology Flight Expts.
Space Power Technology
OBJECTIVE

Provide the technology to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration.
BASE R&T PROGRAM
SPACE ENERGY CONVERSION R&T

OBJECTIVES

• Programmatic
  Provide the technology base to meet power system requirements for future space missions, including space station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration

• Technical
  >300 W/kg Planar Array Technology
  1 - 4 kg/m² Radiator Specific Mass
  >20% System Efficiency (Thermal-to-Electric)

SCHEDULE

• 1992
  12-panel APSA
  Complete critical technology experiments for liquid sheet radiator (LSR)

• 1993
  5-Ah Li-TiS2 Engineering Model Demo
  Solar Dynamic Heat Receiver Tech Demo
  Prototype Smart Pole (PMAD)

• 1994
  Demonstrate thin 20% InP Cell
  Deliver Bipolar Flight Battery

• 1995
  Complete 100 W/kg Nickel Hydrogen Battery

• 1996
  Demo 600 K PMAD Test Bed

• 1997
  Complete integrated thermal and electrical test of power electronics orbital replacement unit

PARTICIPANTS

• Lewis Research Center
  Lewis Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration

• Jet Propulsion Laboratory
  AMTEC, advanced thermoelectrics, power integrated circuits

• Langley Research Center
  Space-based laser power technology

• Goddard Space Flight Center
  Thermal management for space experiments

FOCUSED TECHNOLOGY PROGRAM
SPACE ENERGY CONVERSION R&T

OBJECTIVES

• Programmatic
  Provide the focused technology to meet power system requirements for lunar and planetary bases, planetary rovers, platforms, Earth-orbiting spacecraft, and deep-space missions

• Technical
  >100 kW space nuclear reactor (7 years full power)
  1300 K Stirling (35% eff) and Thermoelectric (Z = 1.0)
  1000 W/kg RPC with 20,000 h operational life
  PV (30% eff) and Thermoelectric (14% eff) for rovers
  >300 W/kg PV array (rad hard/ULT-resistant)

SCHEDULE

• 1993
  Thermoelectric Multicouple, Z = 85
  Stirling, 1050 K, 25 kW/cylinder, 25% efficient

• 1994
  SP-100 NAT fuel pins fabricated/stored
  600 K radiator demonstration

• 1995
  Restart SP-100 Nuclear Assembly Test (NAT) Site Mfg specs for Z = 1.0 Thermoelectric
  Complete Phase I Development (Laser Beaming)

• 1996
  Complete SP-100 T/E Converter/TEM pump tests
  Stirling, 1050 K, 25 kW/cylinder (35% eff.)
  Demonstrate 300 W/kg orbital/100 W/kg inP converter

• 1997
  Ground demo of 2-kW solar dynamic system
  Complete 5000 h on fuel cell stack
  Complete Phase II Development (Laser Beaming)

• 1999
  Stirling, 1300 K, 25 kW/cylinder (35% eff.)

• 2001
  Complete SP-100 flight-like IAT (lunar outpost)

PARTICIPANTS

• Lewis Research Center
  LEAP subsystems, lead for high capacity power, surface power, mobile systems power, power systems technology for platforms and rovers, FEL power beamng

• Jet Propulsion Laboratory
  Lead for SP-100 GES, power system technology for platforms and rovers, FEL power beamng

• Langley Research Center
  Laser power beaming

• Goddard Space Flight Center
  Thermal management

• Johnson Space Center
  Supporting technology for surface and mobile power

• Marshall Space Flight Center
  Support on FEL power beamng
SPACE ENERGY CONVERSION R&T

MOBILE SURFACE SYSTEMS (POWER)
- System Integration
- Photovoltaic Power Generation
- Energy Storage
- Power Management & Distribution
- Dynamic Isotope Power System (DIPS)
  Ancillary Technology
- Thermal-to-Electric Generators
- Tribology

ROLES & PARTICIPANTS

R&T BASE ELEMENTS
Photovoltaic Energy Conversion
LaRC (advanced cells/modern)
JPL (light-weight arrays)
Chemical Energy Conversion
LaRC (adv. batteries/fuel cells)
JPL (adv. batteries)
Thermal Energy Conversion
LaRC (adv. solar dynamic)
JPL (thermoelectrics/AMTEC)
Power Management
LaRC (PMAD/Materials/Environment)
JPL (PCs technology)
LaRC (power beamng)
Thermal Management
GSCF (sensor thermal control)
LaRC (adv. radiator/electronics cooling)

FOCUSED TECHNOLOGY PROGRAMS
Space nuclear power
JPL (project management)
LaRC (space subsystems)
DOE/SDIO/GEL/ANL/HEDE/etal.
High capacity power
LaRC (project lead/Beaming)
JPL (thermoelectrics)
Surface power & thermal mgmt
LaRC (lead/PV/Storage/EPM/TM)
JPL (PV/Storage/TM) GSCF (TM)
JSC (Storage/TM), LANL (Storage)
Mobile Surface Systems
LaRC (P.
JPL (P.
JSC (P.
Laser Pow. Beaming
MSFC (P.
JPL (Power/PV)
LaRC (PV)
• Heat Pipe Performance

• Solar Array Module Plasma Interaction Experiment (SAMPIE)

• Thermal Energy Storage

• Sodium-Sulfur Battery

Integrated Technology Plan Process
FY'93 ITP IMPLEMENTATION PLAN

• FOR NEAR-TERM NEEDS
  IN '93-'97 COMPLETE THE DELIVER SELECTED HIGH-LEVERAGE ONGOING PROGRAM IMPLEMENT KEY SELECTED NEW TASKS

• FOR END-OF-DECADE NEEDS
  IN '93-'97 BEGIN DELIVER MAJOR NEW SYSTEM CAPABILITIES BEGIN TO PUT CRITICAL R&T TESTBEDS & FACILITIES IN PLACE CONDUCT MAJOR DEMONSTRATIONS-FLIGHT EXPERIMENTS BEGIN SIGNIFICANT USE OF SSF FOR R&T LEVERAGE NASP DEMONSTRATIONS

• FOR LONG-TERM NEEDS
  IN '93-'97 BEGIN SELECTED, LONG-TERM R&T EFFORTS BY 1998 THRU 2003 DELIVER MAJOR NEW SYSTEM CAPABILITIES BEGIN USE OF LUNAR OUTPOST FOR R&T ACHIEVE MARS TECHNOLOGY READINESS

INTEGRATED TECHNOLOGY PL. FOR THE CIVIL SPACE PROGRAM

SPACE R&T BUDGET IMPLICATIONS

![Diagram showing space R&T budget implications]
FLIGHT PROGRAMS FORECAST

- 5-YEAR FORECAST INCLUDES
  '93 THRU '97:
  COMPLETION OF INITIAL SSF
  SOME SHUTTLE IMPROVEMENTS
  INITIAL EOS & E O S D I S
  SELECTED SPACE SCIENCE STARTS
  NLS DEVELOPMENT
  INITIAL SEI ARCHITECTURE SELECTION
  EVOLVING GEO COMMERCIAL COMMSATS
  MINOR UPGRADES OF COMMERCIAL ELVS

- 10-YEAR FORECAST INCLUDES
  '98 THRU '03:
  MULTIPLE NEW STARTS
  TO BE LAUNCHED IN 2003 THRU 2010
  SSF EVOLUTION/INFRASTRUCTURE
  FINAL SHUTTLE ENHANCEMENTS
  ADVANCED LEO EOS PLATFORMS/FULL EOSDIS
  MULTIPLE SPACE SCIENCE STARTS
  NLS OPERATIONS/EVOLUTION
  EVOLVING LAUNCH/OPERATIONS FACILITIES
  INITIAL SEI/LUNAR OUTPOST START
  DSN EVOLUTION (KA-BAND COMMUNICATIONS)
  NEW GEO COMMERCIAL COMMSATS
  NEW COMMERCIAL ELVS

- 20-YEAR FORECAST INCLUDES
  '04 THRU '11:
  MULTIPLE OPTIONS FOR NEW STARTS TO BE LAUNCHED IN 2009 THRU 2020
  SSF MARS EVOLUTION
  BEGINNING OF AMLS/PLS DEVELOPMENT
  MULTIPLE SPACE SCIENCE STARTS
  DSN EVOLUTION (OPTICAL COMM)
  INITIAL MARS HLV DEVELOPMENT
  EVOLVING LUNAR SYSTEMS
  MARS SEI ARCHITECTURE CHOSEN
  LARGE GEO COMMSATS
  NEW COMMERCIAL ELVS

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Space Power Background
ADVANCED TDRSS

PROPULSION, POWER AND ENERGY

TRACKING AND DATA RELAY SATELLITE SYSTEM

WET MASS

TOTAL MASS = 2123 kg

PROPULSION AND POWER DRIVERS ON ATDRSS

IMPROVEMENTS IN PROPULSION AND POWER CAN SIGNIFICANTLY IMPROVE ATDRSS

PROPULSION AND POWER COMPRIS ABOUT ONE-HALF OF THE TOTAL MASS OF ATDRSS
ADVANCED TDRSS

ELECTRICAL SUBSYSTEM MASSES

TOTAL EPS MASS = 422kg

ADVANCED TDRSS

ELECTRICAL POWER SYSTEM MASSES WITH ADVANCED TECHNOLOGIES

ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE 245 kg IN THE ELECTRICAL POWER SYSTEM

PT1-17
- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS 82.67 kg
BATTERY MASS 94.53 kg
PMAD MASS 245.08 kg

- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS

NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS 82.67 kg
BATTERY MASS 94.53 kg
PMAD MASS 245.08 kg

Earth Observing System
POLAR ORBITING PLATFORM WET MASS
ELECTRICAL POWER SYSTEM WEIGHTS

TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

POLAR PLATFORM WEIGHT WITH ADVANCED TECHNOLOGIES

NEW TECHNOLOGIES ALLOW ~32% OF MASS TO BE PAYLOAD

PT1-19
IMPACT OF POWER SYSTEM SPECIFIC MASS ON GEO ORBIT POWER
(25% MASS FRACTION)

COST OF DELIVERING 100 kWe OF USABLE POWER
The Space Energy Conversion R&T Program Supports a Broad Range of Planned and Future NASA/DoD/Commercial Mission Power Requirements, Including

- Earth Observing Systems
- Space Station
- Communications Satellites
- Advanced Tracking and Data Relay Satellite System
- Lunar/Planetary Surface Power
- Planetary Spacecraft
- Electric Propulsion
- Missions to Comets and Asteroids
- Surface Explorers/Rovers
- Penetrators
- Launch and Orbital Transfer Vehicles
Space power technology evolution is and has been a long-term, steady improvement. There will be near-term spinoffs (as in the battery electrolyte for Hubble Space Telescope) as the technology evolves; however, there must be a long-term commitment to supporting the technology if the full benefits are to be realized.

Technology Needs
SPACE ENERGY CONVERSION R&T

TECHNOLOGY NEEDS

- **OSSA**
  
  **HIGHEST PRIORITY**
  - 50 - 100 kWe Ion Propulsion (NEP) [Far-Term Need]
  
  **SECOND HIGHEST PRIORITY**
  - Solar Array/Cells [Near-Term Need]
  - Radiation Hardened Parts/Detectors [Near-Term Need]
  - Long-Life/High-Energy Density Batteries [Near-Term Need]
  
  **THIRD HIGHEST PRIORITY**
  - Mini RTG [Near-Term Need]
  - Thermal Control System [Mid-Term Need]

- **OSF**
  
  **HIGHEST PRIORITY**
  - Advanced Heat Rejection Devices (Heat Pumps/Heat Pipes)
  - High-Efficiency Space Power Systems (PV Concentrator Cells/Solar Dynamic Systems
  - Electromechanical Control Systems/Electrical Actuation (advanced, integrated electric power systems with surge/demand capability

SPACE ENERGY CONVERSION R&T

TECHNOLOGY NEEDS

(Continued)

- **MFPE/SEI**
  
  **HIGHEST PRIORITY**
  - Surface Power (Category 2)
  - Electric Propulsion (Category 3)
SPACE ENERGY CONVERSION R&T

Summary of the 1990 Annual Review by the
Space Systems & Technology Advisory Committee
Aerospace Research & Technology Subcommittee

ESSENTIAL

• Maintain Vigorous Base R&T Program
  - Source of New Ideas and Techniques
  - Training Ground for Next Generation Space Technologists
  - Impacts "World Technology Position"
  - High Probability for Commercial Spin-Off
  - Archival Value

• Develop Long-Range Defendable Strategies
  - Cooperative Programs Wherever Possible
  - Emphasize Commercial Potential Where Obvious

• Promote/Force User Acceptance
  - Space Qualification
  - Tech Transfer Mechanism

PT1-24
High Priority

• Space Nuclear Power
  - Long Lead Time Technology
  - SEI Essential
  - Cooperative Agreements

• Light Weight, Efficient Photovoltaics
  - Growth Space Station
  - First Stages SEI
  - Commercial Spin Off

• Efficient Energy Dense Storage Technology
  - Regenerative Fuel Cells
  - Batteries
  - Thermal Storage
  - Significant Commercial Potential

High Priority (Continued)

• Efficient Energy/Power Dense Power Management and Conditioning
  - Major Contributions to Spacecraft Weight and Volume
  - Significant Commercial Potential
  - Major Uncertainty in Scale Up
SUMMARY RECOMMENDATIONS ON SPACE POWER

Space Power Supplies of the Future Should Include Photovoltaic, Solar Dynamic, and Nuclear Sources. Only Reactor-Generated Power Can Meet Anticipated High-Power Requirements, and NASA should Increase Its Involvement in the SP-100 Program, an Interagency Nuclear Space Power (SP) Research and Demonstration Program Designed to Achieve 100 kW of Space-Based Power.

Further, NASA Should Review Its Most Stressing Missions by Defining Requirements and Evaluating Power System Options Against the Specific Requirements. Optimal Combinations of Power Sources Should be Defined and R&D Programs Initiated on a Time Frame Appropriate With Anticipated Mission Scenarios. For the Nuclear Reactor Power System Option in Particular, It is Important to Introduce it Neither Too Soon Nor Too Late in This Long-Term Scenario.

Much to be Preferred is an Orderly, Properly Paced, Goal-Oriented R&D Program. This Program Should be Coordinated and Made Complementary to all of the Existing Programs and Sponsors... In Short, a National Space Nuclear Power Program is Needed...
CONCLUSIONS AND OBSERVATIONS
ON SPACE POWER

As Energy Requirements for Scientific, Military, and Commercial Missions Increase, There Will be a Need for Larger, More Utility-Like Energy Systems. Desirable Power Supplies Include Photovoltaic, Solar Dynamic, and Nuclear; However, Only Nuclear Reactor Generated Power Can Meet Very High Requirements. The Space Nuclear Power Program has a Start-Stop History. It is Recommended that NASA Increase Its Participation in the SP-100 Program to Ensure That Its Own Future Requirements for High Energy are Met. R&D on Photovoltaic, Solar Dynamic, Stirling Engine, and Other Power Conversion Development Should Continue.

OTHER TECHNOLOGY NEEDS

- IN-SPACE OPERATIONS
- EARTH-TO-ORBIT TRANSPORTATION
- SPACE TRANSPORTATION
- SURFACE SYSTEMS
  (includes surface nuclear power and surface solar power with chemical energy storage)
- HUMANS IN SPACE
- LUNAR AND MARS SCIENCE
- INFORMATION SYSTEMS AND AUTOMATION
**Exploration Initiative**

### Lunar Surface Power System Options

**Strategy:** Early Outpost Power Needs → Later Outpost Power Needs

#### Early Outpost Power Needs

- **Power Generation**
  - Photovoltaic Arrays or Solar Dynamic Modules
  - Low-Moderate Mass/kW
  - Near Term Development
  - Can Be Located Near Outpost
  - Ease of Deployment
- **Daytime Power Only**
- **Power Storage**
  - Batteries
  - Near Term Development
  - High Initial Mass/kW
  - Short Lived Systems
  - Regenerative Fuel Cells
  - Longer Term Development
  - Moderate Mass/kW
  - Short Lived Systems
  - High Spares/Resupply
- **Batteries**
  - Near Term Development
  - High Initial Mass/kW
  - Short Lived Systems
  - High Spares/Resupply

#### Later Outpost Power Needs

- **Nuclear Power**
  - Continuous Day/Night Power
  - No Power Storage Required
  - Low Initial Mass/kW
  - Lowest Spares/Resupply
  - Long Life Systems
  - Minimum Crew Support
- **Dynamic Engine Power Conversion**
- **Power Storage**
  - Batteries
  - Near Term Development
  - High Initial Mass/kW
  - Short Lived Systems
  - Regenerative Fuel Cells
  - Longer Term Development
  - Moderate Mass/kW
  - Short Lived Systems
  - High Spares/Resupply

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**NASA Exploration Initiative**

### SURFACE POWER SYSTEMS

**PHOTOVOLTAIC ARRAY/REGENERATIVE FUEL CELL**

- Initial outpost power source
- 25/12.5 kW day/night capability
- State-of-the-art technology with large experience base
- Low power/mass ratio (1.5-3 W/kg)
- High resupply and sparing mass requirements (1t/year/unit)

**SP-100 NUCLEAR REACTOR**

- Dynamic engine power conversion
- 100 kW day/night capability
- High power/mass ratio (25-60 W/kg)
- Long life, high reliability system (7 year life)

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*Technical Study Group*

PT1-29
The Committee Believes that Nuclear Power Eventually Will be Essential for Lunar and Mars Bases.

At Present, the Only Active Technology Program Applicable to this Need is the SP-100 Thermoelectric Space Reactor, Which has Been Pursued Under a Tri-Agency Program for Several Years. SP-100 Was Initiated in the Absence of a Definite Mission Requirement as a General Purpose Space Reactor Power Source. This Program Should be Redefined in Light of the Requirements of the HEI and Committed to Development; Nuclear Thermionic Research Should Continue to be Pursued as Well.

Consideration Should be Given to Demonstration of the Nuclear Electric Power System as the Power Source for an Electric Propulsion System, Which May Have Application to Science Missions With Large Launch Velocity Requirements. (In Fact, a Number of Outer Planet Missions Have Been Suggested, Including a Jovian System Grand Tour, That Will Require Such Advanced Power Sources.) Here, as With the Nuclear Rocket, Considerations of Safety Must Be Incorporated into Research, Development, and Demonstrations and Factored into Assessments of Overall System Performance. The Nuclear Electric System Might be Demonstrated Within These Constraints by a Mission in Which the System is Launched to a High Orbit, Say 600 Miles, Before It is Operated. The Orbit Could Then be Raised by Nuclear-Electric Propulsion to Geosynchronous Orbit or Beyond.
Principal Recommendations Concerning Space Goals

• A science program, which enjoys highest priority within the civil space program, and is maintained at or above the current fraction of the NASA budget.

• A Mission to Planet Earth (MTPE) focusing on environmental measurements.

• A Mission from Planet Earth (MFPE), with the long-term goal of human exploration of Mars, preceded by a modified Space Station which emphasizes life sciences, an exploration base on the Moon, and robotic precursors to Mars.

• A significantly expanded technology development activity, closely coupled to space mission objectives, with particular attention devoted to engines.

• A robust space transportation system.

On November 2, 1989, the President approved a national space policy that updates and reaffirms U.S. goals and activities in space.

- Strengthen the security of the United States.
- Obtain scientific, technological, and economic benefits.
- Encourage private sector investment.
- Promote international cooperative activities.
- Maintain freedom of space for all activities.
- Expand human presence and activity beyond Earth orbit into the solar system.
SPACE ENERGY CONVERSION R&T

REPORT OF THE SYNTHESIS GROUP RECOMMENDATIONS

SPECIFIC RECOMMENDATIONS ARE PROVIDED FOR THE EFFECTIVE IMPLEMENTATION OF THE SPACE EXPLORATION INITIATIVE

RECOMMENDATION 7

INITIATE A SPACE NUCLEAR POWER TECHNOLOGY DEVELOPMENT PROGRAM BASED ON THE SPACE EXPLORATION INITIATIVE REQUIREMENTS

The Program Must Concentrate on Safe, Reliable Systems to a Megawatt or Greater Level. These Nuclear Power Systems Will Be Required for Use on the Moon Before Use on the Mars Mission.
TRANSPORTATION TO THE MOON REQUIRES POWER FOR ABOUT SEVEN DAYS FOR THE ROUND TRIP PLUS TIME IN LUNAR ORBIT.

TRANSPORTATION TO MARS INVOLVES TRIP TIMES ON THE ORDER OF A YEAR PLUS ORBITAL AND SURFACE OPERATIONS OF UP TO TWO YEARS.

SPACECRAFT WILL BE CONTINUOUSLY ROTATED IN CASES WHERE SOLAR FLUX IS VERY HIGH.

HABITAT POWER MUST HAVE A RELIABILITY >99.5%.

BASE POWER RELIABILITY CAN BE ABOUT 95%.

POWER UNITS SHOULD BE MADE OPERATIONAL
- With a Minimum of Support Activities
- Have Lifetimes Compatible with the Base
- Be Serviceable
- (If Nuclear) Be Refuelable and Disposable

EVOLUTIONARY SYSTEMS DESIGNS ARE PREFERABLE TO SPECIFIC POINT DESIGNS WITHOUT GROWTH POTENTIAL.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Mars Power</th>
<th>Moon Power</th>
<th>Suggested Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
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<tr>
<td>Spacecraft</td>
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<tr>
<td>Piloted</td>
<td>to 20 kw</td>
<td>to 30 kw</td>
<td>Fuel cells (Moon)</td>
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<td>Nuclear/photovoltaics (Mars)</td>
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<td>Cargo</td>
<td>5 kw</td>
<td>5 kw</td>
<td>Fuel cells (Moon)</td>
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<td></td>
<td>Photovoltaics (Mars)</td>
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<tr>
<td>Lander</td>
<td>20 kw</td>
<td>20 kw</td>
<td>Fuel cells (w/wo photovoltaics)</td>
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<tr>
<td>Electric propulsion</td>
<td>to 5 Mw</td>
<td>to 5 Mw</td>
<td>Nuclear</td>
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<td>Nuclear</td>
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<td>Base Power</td>
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<td>to 100 kw</td>
<td>Nuclear</td>
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<td>Next Operational Capability</td>
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<td>to 1 Mw</td>
<td>Nuclear</td>
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<td>Rovers</td>
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<td>Fuel cells (2)</td>
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(1) Depends on final power level
(2) In situ methane and oxygen produced on Mars may substitute for fuel cells.
SPACE ENERGY CONVERSION R&T

REPORT OF THE SYNTHESIS GROUP
SUPPORTING TECHNOLOGIES

- HEAVY LIFT LAUNCH WITH A MINIMUM CAPABILITY OF 150 METRIC TONNES WITH DESIGNED GROWTH TO 250 METRIC TONNES
- NUCLEAR THERMAL PROPULSION
- NUCLEAR ELECTRIC SURFACE POWER TO MEGAWATT LEVELS
  - EXTRAVEHICULAR ACTIVITY SUIT
  - CRYOGENIC TRANSFER AND LONG TERM STORAGE
  - AUTOMATED RENDEZVOUS AND DOCKING OF LARGE MASSES
  - ZERO GRAVITY COUNTERMEASURES
  - RADIATION EFFECTS AND SHIELDING
  - TELEROBOTICS
  - CLOSED LOOP LIFE SUPPORT SYSTEMS
  - HUMAN FACTORS FOR LONG DURATION SPACE MISSIONS
  - LIGHT-WEIGHT STRUCTURAL MATERIALS AND FABRICATION
- NUCLEAR ELECTRIC PROPULSION FOR FOLLOW-ON CARGO MISSIONS
- IN SITU RESOURCE EVALUATION AND PROCESSING

SPACE ENERGY CONVERSION R&T

REPORT OF THE SYNTHESIS GROUP
BASELINE DECISIONS FOR POWER

- FOR MARS, NUCLEAR POWER IS RECOMMENDED OVER PHOTOVOLTAICS DUE TO THE MASS SAVINGS. THE NUCLEAR UNITS WILL BE DEVELOPED TO MARS SPECIFICATIONS, AND THE MOON WILL BE USED TO VALIDATE THE DEPLOYMENT CONCEPT AND DEMONSTRATE SAFE AND RELIABLE OPERATION
  - Power Levels to a Megawatt for Base Power, Including Power for in situ Resource Processing, Refueling Surface Vehicles, and Emergency Habitat Power
  - Designed for Both the Moon and Mars Environments
  - Specific Power >100 W/kg at 1 MW
  - Deployed With a Minimum of Robotic or Human Operations
  - Lifetimes Must Be on the Order of 30 Years

- ADVANCED REGENERATIVE FUEL CELLS COULD PROVIDE POWER FOR LUNAR SPACECRAFT, LANDERS, AND SURFACE VEHICLES, WITH PERFORMANCE GREATER THAN 1 kW-h/kg

- NUCLEAR POWER UNITS (10 TO 100 kW) CAN PROVIDE POWER FOR MARS SPACECRAFT AND LUNAR AND MARS SURFACE HABITATS. THESE SYSTEMS SHOULD HAVE A SPECIFIC POWER >15 W/kg AT 25 kW, RELIABILITY >99.5%, PASSIVE CONVERSION AND NO SINGLE FAILURE POINTS

- ADVANCED SOLAR PHOTOVOLTAIC ARRAYS, WITH SPECIFIC POWERS >200 W/kg, CAN PROVIDE POWER FOR SPACECRAFT AND DAYTIME SURFACE OPERATIONS
SPACE ENERGY CONVERSION R&T

REPORT OF THE SYNTHESIS GROUP
RECOMMENDATIONS FOR DEVELOPMENT PROGRAMS

- THE CURRENT SP-100 AND THERMIonic PROGRAMS SHOULD BE
  RESTRUCTURED TO MEET SPACE EXPLORATION INITIATIVE REQUIREMENTS
  - All Technology Options Should be Considered
  - Technology Down-Selections Should be Based on Demonstrated
    Performance, Safety and Reliability
  - The Benefits Provided by Nuclear Power Systems are Extremely High
    and are Key Enablers for Many Initiative Activities; However, New Efforts
    to Develop Space Applications of Nuclear Power Should be Structured
    to Take Advantage of Lessons Learned From the SP-100 Program

- ADVANCED REGENERATIVE FUEL CELLS CAN BE DEVELOPED BY THE YEAR
  2000. THE COST IS LOW WITH WIDE APPLICATION TO CRITICAL SURFACE
  SYSTEMS SUCH AS LANDERS AND ROVERS

- SOLAR PHOTOVOLTAIC ARRAYS COULD PLAY A WIDE RANGE OF ROLES IN THE
  INITIATIVE. INCREASING THE EFFICIENCY AND DECREASING THE WEIGHT OF
  SOLAR ARRAYS WILL CONTINUE TO PAY HIGH DIVIDENDS FOR BOTH SPACE-
  AND EARTH-BASED APPLICATIONS

- POWER BEAMING FOR SURFACE-TO-SURFACE POWER DISTRIBUTION MAY
  GREATLY REDUCE THE MASS OF ROVERS AND OTHER MOBILE SURFACE
  SYSTEMS, ASSUMING LINE OF SITE CONSTRAINTS CAN BE MET. IF NUCLEAR
  ELECTRIC PROPULSION IS DEVELOPED FOR USE IN THE LUNAR OR MARS CARGO
  VEHICLE, THE ORBITING TRANSFER VEHICLE MAY BE A CONVENIENT POWER
  SOURCE FOR SURFACE OPERATIONS (NOTED NEED TO CONSIDER COSTS)

Space Power Technology Development
SPACE ENERGY CONVERSION R&T

TECHNOLOGY DEVELOPMENT
CHALLENGES/DRIVERS

• Develop power systems for and extend their life in functional environments (LEO, GEO, MOON, PLANETARY)
• Increase power density of power system
• Reduce power system mass
• Increase power system reliability
• Enable power system operation at higher temperatures

AUGMENTATION

• Accelerate development of power system technologies
• Augment R&T areas that are minimally funded
• Initiate mission-focused and advanced technologies
• Transfer maturing technologies to focused thrusts and users

SPACE ENERGY CONVERSION R&T

TECHNOLOGY BENEFITS

• Reduced launch weight
• Increased power for same mass
• Increased lifetime
• Increased reliability
• Reduced costs
• Extended range of power system capabilities
• Reduced volume
TECHNOLOGY DEVELOPMENT APPROACH

- DEVELOP AND EVALUATE HIGH-EFFICIENCY, RADIATION-HARD SOLAR CELLS AND LIGHT-WEIGHT ARRAY SYSTEM COMPONENTS

- DEVELOP ADVANCED HIGH SPECIFIC ENERGY, HIGH ENERGY DENSITY, LONG CYCLE LIFE ENERGY STORAGE SYSTEMS

- DEVELOP IMPROVED THERMAL-TO-ELECTRIC CONVERSION SYSTEMS
  (Advanced thermoelectric materials, AMTEC, solar dynamic, Stirling)

- DEVELOP LIGHT-WEIGHT, SMART, HIGH-TEMPERATURE, COMPACT POWER MANAGEMENT AND CONTROL (PMAC)

- DEVELOP INNOVATIVE, LOW-MASS THERMAL TRANSPORT AND RADIATOR CONCEPTS

- DEVELOP SP-100 SPACE NUCLEAR REACTOR POWER SYSTEM

(Continued)

- DEVELOP LASER POWER BEAMING CAPABILITY

- DEVELOP IMPROVED POWER SYSTEM MATERIALS

- DEVELOP ENVIRONMENTAL INTERACTIONS MODELS AND DESIGN GUIDELINES FOR FUTURE SPACE POWER SYSTEMS
RECENT ACCOMPLISHMENTS

- SUCCESSFUL COMPLETION OF GROUND TESTING OF 130 W/kg ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)

- BOEING APPLICATION OF NASA-SPONSORED MINI-DOME FRESNEL LENS AND PRISMATIC CELL COVER TO ACHIEVE 31% AMO EFFICIENCY

- SUCCESSFUL COMPLETION OF 40,000 LEO CYCLES AT 80% DEPTH OF DISCHARGE (DOD) IN BOILER PLATE NICKEL-HYDROGEN CELLS

- SUCCESSFUL COMPLETION OF >10,000 CYCLES IN BIPOLAR NICKEL-HYDROGEN

- SUCCESSFUL ACHIEVEMENT OF 700 CYCLES AT 50% DOD IN 1-A-h LiTiS2 CELLS

RECENT ACCOMPLISHMENTS (Continued)

- SUCCESSFUL REPRODUCTION OF HIGHER FIGURE-OF-MERIT SILICON-GERMANIUM-GALLIUM-PHOSPHIDE N-TYPE MATERIAL

- DEMONSTRATED FEASIBILITY OF FABRICATION TECHNIQUES FOR SOLAR DYNAMIC CONCENTRATOR ALUMINUM PANELS

- DEMONSTRATED STABILITY OF LIQUID SHEET RADIATOR AT 1-G (VERIFIED ANALYTICAL PREDICTIONS)

- SUCCESSFULLY TESTED SILICON-CARBIDE MOSFET TO 500 C

- DEVELOPED MONTE CARLO MODEL FOR ATOMIC OXYGEN EROSION

- DEMONSTRATED 7X INCREASE IN ATOMIC OXYGEN DURABILITY WITH CVD-DEPOSITED SiO2 ON CARBON/CARBON COMPOSITE RADIATOR SURFACES
SPACE ENERGY CONVERSION R&T

SPACE POWER SYSTEMS

TECHNOLOGY NEEDS
HIGH POWER, HIGH EFFICIENCY,
LOW-MASS ELECTRICAL POWER SYSTEMS AND
THERMAL MANAGEMENT SYSTEMS FOR SPACECRAFT AND PLANETARY BASES

CURRENT PROGRAM S-O-A
COMMERCIAL SOLAR ARRAYS AT -20 W/kg (RIGID) TO -66 W/kg (FLEXIBLE);
NASA/JPL LABORATORY DEMONSTRATION AT 130 W/kg; COMMERCIAL BATTERIES AT -10 Wh/kg;
NASA TECHNOLOGY >20 Wh/kg; THERMOELECTRIC EFFICIENCY <7%; AND POWER MANAGEMENT
AND DISTRIBUTION (PMAD) AT <0.03 W/cm³ (AND <15 W/kg)

AUGMENTED PROGRAM
SOLAR ARRAYS AT 300 W/kg; BATTERIES AT 150 W-h/kg;
STATIC THERMAL-TO-ELECTRIC CONVERSION ≥10%; PMAD AT ≥0.6 W/cm³
(AND 20 W/kg) TO ACHIEVE FACTOR OF TWO REDUCTIONS IN MASS OF
ELECTRIC POWER SYSTEM ON SPACECRAFT

BASE RESEARCH AND TECHNOLOGY PROGRAM
SPACE ENERGY CONVERSION R&T

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<th>SUB-ELEMENT</th>
<th>STATE-OF-THE-ART</th>
<th>OBJECTIVE</th>
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<td>PHOTOVOLTAICS</td>
<td>Comm: 20 W/kg (rigid) to 65 W/kg (flex.)</td>
<td>&gt; 300 W/kg (flex.)</td>
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<td>Demo: 100 W/kg (rigid) to 130 W/kg (flex.)</td>
<td>1000 W/kg (blanket)</td>
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<td>240 W/m²</td>
<td>&gt;0.03 W/cm² (concentrator)</td>
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<tr>
<td>CHEMICAL ENERGY CONVERSION</td>
<td>Comm: 10 Wh/kg</td>
<td>150 Wh/kg (75 % DOD)</td>
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<td>Demo: &gt;20 Wh/kg</td>
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<tr>
<td>THERMAL ENERGY CONVERSION</td>
<td>&lt; 7 % efficiency</td>
<td>&gt; 10 % efficiency</td>
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<tr>
<td>POWER MANAGEMENT</td>
<td>&lt; 0.03 W/cm³</td>
<td>&gt; 0.6 W/cm³</td>
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<tr>
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<td>&lt; 15 W/kg</td>
<td>&gt; 20 W/kg</td>
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<tr>
<td>THERMAL MANAGEMENT</td>
<td>10 kg/m²</td>
<td>1.4 kg/m²</td>
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SPACE POWER SYSTEMS

MISSION SPECIFIC
300 W/m² CONCENTRATORS, 300 W/kg SOLAR ARRAYS
100 W-hr/kg BATTERIES
600K POWER ELECTRONICS AND THERMAL CONTROL
HIGH FREQUENCY POWER
ATOMIC OXYGEN PROTECTIVE COATINGS/ARC PROOF SOLAR ARRAYS
ORBITAL AND PLANETARY SURFACE ENVIRONMENTAL DESIGN GUIDELINES

BREAKTHROUGH
Li/CO₂ FUEL CELLS
BEAMED POWER SYSTEMS
LUNAR REGOLITH STORAGE
1-2 kg/m² RADIATORS/ADVANCED HEAT PIPES
DIAMOND FILM POWER ELECTRONICS

CAPABILITY
PV PERFORMANCE VERIFICATION/FUNDAMENTALS
ELECTROCHEMICAL ADVANCED DIAGNOSTICS/MODELLING
SOLAR DYNAMIC DESIGN/ANALYSIS
HEAT PIPE CODE VALIDATION
SPACE ENVIRONMENTAL SIMULATION FACILITIES

BASE RESEARCH AND TECHNOLOGY PROGRAM
SPACE ENERGY CONVERSION TECHNOLOGY

AUGMENTATION STRATEGY

• HIGH-RISK, INNOVATIVE POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR FUTURE MISSIONS
  - DIAMOND FILM POWER ELECTRONICS
  - Li/CO₂ FUEL CELLS

• MAINTAIN A BALANCE BETWEEN TECHNOLOGY ELEMENTS TO SUPPORT EVOLUTIONARY SPACECRAFT POWER SYSTEM NEEDS
  - PHOTOVOLTAIC ENERGY CONVERSION
  - CHEMICAL/ThERMAL ENERGY CONVERSION
  - POWER/ThERMAl MANAGEMENT

• MAINTAIN SPECIFIC ACTIVITIES TO ENHANCE NASA'S CAPABILITY TO RESPOND TO TECHNOLOGY NEEDS
  - ADVANCED DIAGNOSTICS/MODELLING
  - SPACE ENVIRONMENTAL SIMULATION FACILITIES
FOCUSED TECHNOLOGY PROGRAMS
SPACE ENERGY CONVERSION R&T

AUGMENTATION STRATEGY

- DEVELOP HIGH-RISK, INNOVATIVE POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR THE SPACE EXPLORATION INITIATIVE (SEI) AND OTHER SPACE MISSIONS.

EXAMPLES: - SP-100 coupled with advanced conversion and radiators
- High specific energy regenerative fuel cells
- Laser power beaming

- BUILD ON BASE R&T PROGRAM TO FOCUS ON FUTURE SPACECRAFT POWER NEEDS

EXAMPLES: - Chemical/thermal energy conversion tie into high capacity power and surface power, etc.
- Power/thermal management tie into focused power programs

"MISSION PULL"

PROGRESS IN SOLAR ARRAY TECHNOLOGY

- TDRS 30 W/kg
- SAFE 66 W/kg
- APSA 130 W/kg
PHOTOVOLTAIC ENERGY CONVERSION

- **OBJECTIVES**
  
  Provide the technology for photovoltaic arrays with improved conversion efficiency, reduced mass, reduced cost, and increased operating life for advanced space missions

- **PARTICIPANTS**
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

- **AUGMENTATION**
  - Accelerate work on Advanced Photovoltaic Solar Array
  - Development of thin 20% efficient InP solar cell (radiation hard)
  - Accelerate development of thin-film flexible blanket
  - Demonstrate high-temperature blanket
  - Ground test 330 W/m² 1-kWe concentrator array

- **PAYOFF**
  - Lighter weight, longer lived arrays

PROGRESS IN ENERGY STORAGE

**TDRS**

Nickel Cadmium - 10 W-hr/kg

**Space Station and Beyond**

Nickel Hydrogen - 20+ W-hr/kg

**Future Applications**

Lithium Titanium Disulfide - 40+ W-hr/kg
SPACE ENERGY CONVERSION R&T

CHEMICAL ENERGY CONVERSION

• OBJECTIVES
  Provide the technology base for advanced electrochemical energy conversion and storage systems required to support the low to high power needs and cycle life requirements for future space missions

• PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

• AUGMENTATION
  - Accelerate work on sodium sulfur batteries
  - Expand/enhance work of fuel cell catalysts
  - Develop and transfer lithium secondary battery technology
  - Accelerate development of 150 W-h/kg cell
  - Initiate electrochemical capacitor work

• PAYOFF
  Lighter weight, longer lived batteries/More power for same mass
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

- **OBJECTIVES**
  - Develop the technology base to provide advanced high-efficiency, high-temperature, long-life solar dynamic Stirling/Brayton power system
  - Develop new thermoelectric material with significantly higher figure of merit
  - Investigate and demonstrate the feasibility of high-power, long-life alkali metal thermoelectric converter (AMTEC)

- **PARTICIPANTS**
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

- **AUGMENTATION**
  - Accelerate development of static conversion technologies
  - Verify thermal energy storage technologies for lunar base application

- **PAYOFF**
  - Reduction in radioisotope inventory
  - Reduction in transported mass to Moon
SPACE ENERGY CONVERSION R&T

POWER MANAGEMENT

- OBJECTIVES
  - Develop the electrical power systems conditioning, control, and distribution technology for future space missions
  - Development of the capability to model power systems (including environmental interactions)
  - Development of advanced concepts (e.g., power beaming and advanced power management materials)

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Langley Research Center
  - Industry/University Contracts

- AUGMENTATION
  - Brings Power Management up to its level of importance
  - Accelerates work on modular, high-temperature, smart PMAD

- PAYOFF
  - Reliable, fault-tolerant power systems
  - Reduced mass, reduced volume, reduced parts count

SPACE ENERGY CONVERSION R&T

THERMAL MANAGEMENT

- OBJECTIVES
  - Develop the technology base for versatile thermal management systems for next generation of space missions
  - Provide advanced thermal management technology for both high and moderate temperatures, including technology for thermal control of instrument systems

- PARTICIPANTS
  - Goddard Space Flight Center
  - Lewis Research Center
  - Industry/University Contracts

- AUGMENTATION
  - Brings Thermal Management up to its level of importance
  - Provides additional options for thermal management

- PAYOFF
  - Reduction in radiator size and mass
  - Major improvement (≥50%) in sensor cooling
SPACE ENERGY CONVERSION R&T

SPACE NUCLEAR POWER

- OBJECTIVES
  Develop and validate the technologies for safe and reliable space nuclear reactor power systems to support lunar and Mars exploration missions

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - DOE/SDIO/USAF
  - Industry/University Contracts

- AUGMENTATION
  Meets NASA's funding commitments under the MOU so that the SP-100 program can stay on schedule

- PAYOFF
  A flexible power source that can span a range of power levels up to 1 MWe for space and surface bases with improved specific mass and lifetime
SPACE ENERGY CONVERSION R&T

HIGH CAPACITY POWER

• OBJECTIVES
  Develop and demonstrate low-mass, reliable, long-lived power conversion technologies for space nuclear reactor power systems

• PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Industry/University Contracts

• AUGMENTATION
  Allows development and demonstration of 1300 K Stirling conversion system (35% efficient) in time for early SEI use

• PAYOFF
  Provides SP-100 with the conversion technology to scale up to 1 MWe
OBJECTIVES
Develop solar-based power and low-grade heat thermal management technologies to support lunar and Mars surface system operations

PARTICIPANTS
- Lewis Research Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Goddard Space Flight Center
- Los Alamos National Laboratory
- Industry/University Contracts

AUGMENTATION
Allows funding for a solar-based surface power system that will be essential to the first exploration/outpost missions and for backup

PAYOFF
Provides a light-weight, reliable, solar-based power system for lunar and Mars applications
MOBILE SURFACE SYSTEMS (POWER)

- OBJECTIVES
  Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Johnson Space Center
  - Industry/University Contracts

- AUGMENTATION
  Reinstates mobile surface power systems program enabling work on system integration, power generation (PV and nuclear), energy storage, tribolobv, PMAD, small free-piston Stirling engine, convective heat exchangers for Martian surface mobile and/or portable dynamic isotope power systems

- PAYOFF
  Provides mobile power system options that can span the range from <1 kWe to >20 kWe with varying power ratios and usages for a hostile, dusty environment.
MOBILE SURFACE SYSTEMS (POWER)
SPACE ENERGY CONVERSION R&T

OBJECTIVES

- Programmatic
  Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems

- Technical
  Power Generation 14% efficient thermoelectric couple
  Energy Storage >50 W-h/kg battery
  PMAD 30% improvement in operating efficiency

SCHEDULE

- 1994 Recommend primary technology candidates with options
- 1996 Complete lab of bipolar Ni/H2 battery
- 1997 Establish preliminary design of fuel cell
- 1998 Select PMAD's fractional horsepower optimized motor/controller
- 1999 Demonstrate combined Z = 1.4 (14% eff @ 1300 K)
- 2001 Complete performance verification on modified test bed

RESOURCES ($M)

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- Lewis Research Center
  Lead center in all technology elements
- Jet Propulsion Laboratory
  Support in PV cell and array technology
  Innovative PMAD technology
  Support in battery technology
  Thermoelectric technology
- Johnson Space Center
  Supporting verification tests of fuel cells

PARTICIPANTS

TECHNOLOGY NEEDS

Rover and portable extraterrestrial surface systems have been shown to require power levels ranging from <1 kWe to >20 kWe with peak-to-average power ratios >10. Mission durations vary from intermittent to continuous use in a hostile, dusty environment.

PROGRAMMATIC

Original program, Planetary Rover Project, will be terminated in FY 1992. The budget plan allows for restarting the program in FY 1994. The original power subelement of Planetary Rover was limited to improving the performance of thermoelectric materials.

STRATEGIC PROGRAM

The resources under the Strategic budget would permit system studies, focused power generation and energy storage technology, tribology, and PMAD in the relevant environment and duty cycles.
• OBJECTIVES
  Develop and demonstrate the technologies and subsystems for laser power beaming from Earth to Moon

• PARTICIPANTS
  - Jet Propulsion Laboratory
  - Lewis Research Center
  - Marshall Space Flight Center
  - MIT Lincoln Lab/LLNL/Industry/University Contracts

• AUGMENTATION
  Initiates a new thrust to develop the technologies (free electron laser/optics/PV/PMAD) to enable an advanced power supply systems

• PAYOFF
  Provides a revolutionary way to power lunar surface bases and rovers with greatly reduced mass and launches.
PLANETARY ORBITERS (MERCURY ORBITER) MISSIONS TO COMETS (COMET NUCLEUS SAMPLE RETURN TAIL PROBE) MARS ROVER PENETRATORS (GLOBAL NETWORK MISSION)

SPACE ENERGY CONVERSION R&T

SPACECRAFT POWER AND THERMAL MANAGEMENT

- OBJECTIVES
  Develop and demonstrate integrated spacecraft bus technologies for deep space applications

- PARTICIPANTS
  - Jet Propulsion Laboratory
  - Lewis Research Center
  - Goddard Space Flight Center
  - Industry/University Contracts

- AUGMENTATION
  Initiates a new thrust to (1) demonstrate high power density solar array with deployment and LILT resistant; (2) develop advance static or dynamic conversion systems for radioisotope sources; define integration issues/advantages of reactor-powered science spacecraft; (3) develop energy storage for penetrators; (4) develop advanced PMAC and thermal management for deep space missions

- PAYOFF
  Provides high specific power solar arrays and high efficiency converters with advanced PMAC and energy storage to reduce mass and/or increase power of deep space missions
SPACECRAFT POWER AND THERMAL MANAGEMENT

SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
  Develop and demonstrate integrated spacecraft bus technologies for deep space applications including both PV and nuclear power sources.

- **Technical**
  - Assess advantages and issues of reactor power systems
  - Reduce PV array mass by 5X
  - Reduce radioisotope inventory by up to 4X
  - Provide autonomous reconfigurable power system with 2X mass reduction, 75% parts reduction
  - Reduce radiator mass and area by 2X
  - Develop advanced, integrated sensor cooling technology
  - Extend life (2 - 3X) and impact capability of primary batteries

SCHEDULE

- **1994** Select radioisotope power technology
- **1994** Select advanced bus regulator (hybrid components)
- **1996** Demonstrate 300+ W/kg planar PV blanket
- **1997** Design primary battery structure
- **1997** Demonstrate reactor integration, issues and potential advantages
  - Flight test advanced cryo heat pipes
  - Dem adv radioisotope conversion module
  - Dem eng load power converter (hybrid comp)
- **1998** Dem light weight radiator tech & primary batteries
  - Dem low noise instrument power converter using hybrid components
- **1999** Dem integrability of advanced power conversion module with radioisotope power source and 10-year life capability (modeling)

RESOURCES ($M)

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PARTICIPANTS

- Jet Propulsion Laboratory
  Light-weight planar PV array and power integrated circuits (PICs), mission impact assessments; static conversion systems for radioisotope power sources

- Lewis Research Center
  Autonomous PMAC subsystems, dynamic conversion technologies for radioisotope power sources, nuclear reactor analyses, moderate and high temperature radiators, and thin film photovoltaics

- Goddard Space Flight Center
  Low temperature thermal management subsystems

TECHNOLOGY NEEDS

Deep space missions will require reduced radioisotope mass (cost/availability issue) and/or improved performance from photovoltaic arrays (low light/low temperature issue). Inner solar system spacecraft will need high-temperature-resistant arrays. All require lower PMAD mass, battery mass, and radiator mass.

PROGRAMMATIC

The ongoing R&T Base program is generically focused since resources do not permit covering all types of spacecraft. Currently there is no focused technology on assessing, developing, or demonstrating power technologies for deep space missions.

STRATEGIC PROGRAM

The resources under the Strategic budget would focus on increased radioisotope-based system efficiency (reduces fuel requirements and cost). These resources would enable extending the range of photovoltaic capabilities (<1 AU to ~5 AU). In parallel, these resources would enable similar operational environment extensions for the other power system components.
SPACE ENERGY CONVERSION R&T

EARTH ORBIT PLATFORM POWER & THERMAL MANAGEMENT

- OBJECTIVES
  Develop and demonstrate integrated power and thermal management technologies for near-Earth missions.

- PARTICIPANTS
  - Lewis Research Center
  - Jet Propulsion Laboratory
  - Goddard Space Flight Center
  - Industry/University Contracts

- AUGMENTATION
  Initiates a new thrust to develop planar and concentrator arrays immune to the space environment with 100 W-h/kg battery systems, integrated, high-efficiency autonomous PMAC, and integrated thermal management for high-temperature electronics

- PAYOFF
  Provides a 300 W/kg PV blanket; 100 W/kg InP concentrator module, a 100 W-h/kg battery (flight weight), 1 - 2 kg/m2 thermal management system with advanced PMAC integrated system and durable high temperature electronics subsystem
### Program Goals

- Develop the technologies required to apply space nuclear propulsion systems to improve the mission performance for human missions to Mars.

- Identify and develop at least one space nuclear thermal propulsion system and one nuclear electric propulsion system that, alone or in combination with other propulsion systems, meets the propulsion requirements for piloted and cargo missions to Mars (including unmanned precursor missions) and for which technical feasibility issues have been resolved.

### Nuclear Propulsion

#### Nuclear Thermal Propulsion

#### Nuclear Electric Propulsion

The generic nuclear electric propulsion (NEP) system uses a nuclear reactor to produce electrical power which is then used to operate low-thrust electromagnetic thrusters (such as ion thrusters or magnetoplasmadynamic thrusters). The advantage of NEP is that the specific impulse is increased by a factor of at least 10 and perhaps 20 compared to chemical propulsion which can result in a significant reduction (factor of ~2) of the mass into low Earth orbit. Combined with a high-thrust option (either chemical or nuclear thermal propulsion) it can achieve the same transit times as nuclear thermal propulsion.

### Basic Features of a Nuclear Electric Propulsion System

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PT1-55
NEP EVOLUTION POTENTIAL

- NEP MAY EVOLVE FROM kW POWER LEVELS (SP-100) TO MULTI-MW POWER LEVELS
- NEAR TERM NEP TECHNOLOGY MAY BE APPLIED TO UNMANNED PLANETARY MISSIONS (e.g., OUTER PLANETS, ASTEROIDS, COMETS) WHICH HAVE HIGH SCIENTIFIC RETURN AS WELL AS LAYING A FOUNDATION FOR THE NEXT STEP OF EVOLUTION
- HIGHLY ENERGETIC MISSIONS CAN BE PERFORMED WITH NEAR TERM NEP TECHNOLOGY

Characteristics of Nuclear Electric Propulsion

- Powers range from kW to multi-MW
- High specific impulse
- Some systems can operate at range of specific impulses
- Reduces propellant mass
- Decreased startup and replenishment masses
- Long system life
- High level of reusability
- Enhanced flexibility
- Extended launch window
- Same vehicle used for multiple opportunities
- Companionship with surface power systems

### UNMANNED EXPLORATION MISSIONS (POTENTIAL)

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**PROPULSION**
- SCALING TO HIGHER POWER
  - Ion Thrusters/MPD Thrusters
- FACILITY UPGRADES
  - Thermal Management/Pumping
- HIGH-TEMPERATURE POWER PROCESSING

**POWER**
- HIGH-TEMPERATURE, LIGHT-WEIGHT RADIATORS
- HIGH-TEMP, RAD-HARDENED POWER ELECTRONICS
- SYSTEM INTEGRATION, COMPONENT INTERACTION

**KEY ISSUE:** INCREASE SPECIFIC POWER (kW/kg)

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**Coordination and Interfaces**
The following is a list of some of the coordination and interfaces involving the NASA Space Energy Conversion R&T Program:

- Space Technology Interface Group (STIG) (NASA/USAF)
- Interagency Advanced Power Group
- Space Photovoltaic Research & Technology (SPRAT) Conference
- Space Electrochemical Research & Technology (SERT) Conference
- High-Frequency Power Distribution Control Conference
- Radioisotope Power Systems Requirements Workshop
- Aerospace Battery Systems Steering Committee/Battery Workshop/Systems Review
- SP-100 Steering Committee (SDIO/DOE/USAF/NASA)
- SDIO Independent Evaluation Group and Field Support Team
- DoD Advisory/Review Panels (AFSTC Investment Strategy, SPT-21, Thermionic Advisory Team, Thermal Management Steering Committee, Space Power Technology Interdependency Group)
- Program Office/Industry Briefings
  - Earth Observing System (EOS)
  - ATDRSS
- Nuclear Propulsion (DoD/DOE/NASA)
- National Meetings (IECEC, SNPS, etc.)

Budgets
POWER FUNDING TREND

POWER FUNDING TREND
AS % OF TOTAL SPACE R&D FUNDING
### WBS No. 506-41 (CURRENT BUDGET)

**Technology Element: Power R&T**

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Sub-Element Totals ($M): 8.6 8.5 8.9 9.4 9.8 10.3 10.7

**Costs:**

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TOTAL ($M): 12.5 12.8 13.2 13.8 14.6 15.3 16.0

**Basis for Resource Estimates:**

- Maintain current funding levels; adjust for inflation.
- Includes $1M carried over from FY90

### WBS No. 506-41 (“3X” BUDGET)

**Technology Element: Power R&T**

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Sub-Element Totals ($M): 8.6 8.5 12.2 16.1 18.9 20.6 22.2

**Costs:**

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TOTAL ($M): 12.5 12.8 15.8 20.1 23.4 25.6 28.8

**Basis for Resource Estimates:**

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- Insufficient resources to develop an advanced concepts technology program as a separate sub-element program. Advanced concepts will be worked in the existing sub-elements.
- Includes $1M carried over from FY90
WBS No. 506-41 (STRATEGIC BUDGET)

TECHNOLOGY ELEMENT: POWER R&T

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CoF:

- CoF Totals:

| Resources Requirements ($M) | 8.6  | 8.5  | 13.9 | 17.1 | 20.8 | 24.1 | 27.7 |      |      |      |      |      |
| Program Support ($M)        | 1.7  | 1.8  | 1.8  | 2.2  | 2.6  | 3.0  | 3.4  |      |      |      |      |      |
| Special Requirements ($M)   | 2.2  | 2.5  | 2.0  | 2.2  | 2.4  | 2.6  | 2.8  |      |      |      |      |      |
| TOTAL ($M):                 | 12.5 | 12.8 | 17.7 | 21.5 | 25.8 | 29.7 | 33.9 |      |      |      |      |      |

Basis for Resource Estimates:

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Develop advanced concepts program to permit development of innovative technologies that promise revolutionary improvements in performance.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- Includes $1M carried over from FY90

FOCUSED TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION TECHNOLOGY

![Graph showing funding levels from 1991 to 2002]

- CURRENT
- 3X
- STRATEGIC

FISCAL YEAR

PT1-62
### FOCUSED TECHNOLOGY PROGRAMS
**SPACE ENERGY CONVERSION R&T**

#### CURRENT BUDGET

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Basis for Resource Estimates: Maintain current funding levels

#### "3X" BUDGET

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Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-O Platforms to make dramatic reductions in spacecraft mass allocated to power
FOCUSED TECHNOLOGY PROGRAMS
SPACE ENERGY CONVERSION R&T

STRATEGIC BUDGET

<table>
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<th>PROGRAM ELEMENT</th>
<th>FY91</th>
<th>FY92</th>
<th>FY93</th>
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Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-O & SC Platforms/Hi Capacity Pwr to make dramatic reductions in platform/base power mass (or increased power)

CODE RP POWER FUNDING
POWER FUNDS DISTRIBUTION FOR FY 91

![Bar chart showing code RP power funding distribution for FY 91]
CODE RP POWER FUNDING
POWER FUNDS DISTRIBUTION FOR FY 91

LEGEND
- R&T BASE
- CSTI
- EXPLORATION
- PROG SUPPORT

CODE RP POWER FUNDING
POWER FUNDS DISTRIBUTION FOR FY 92

LEGEND
- R&T BASE
- CSTI
- EXPLORATION
- PROG SUPPORT

PT1-65
Summary

SPACE ENERGY CONVERSION R&T

SUMMARY

**TECHNICAL CHALLENGE**
To make a 2X to >10X improvement in the performance of space power systems (specific power/energy, efficiency, lifetime, reliability, etc.)
To enable a wide range of future space missions while holding the power mass fraction at or below today's technology

**APPROACH**
Develop lighter, more efficient primary power sources and energy storage systems with lighter, more reliable, more compact power management & control with innovative thermal management and power distribution.

**PAYOFF**
This technology will enable future missions to provide the same power at greatly reduced mass or more power from the same mass. More importantly, this technology will enable a host of future SEI and other space missions.

**RATIONALE FOR AUGMENTATION**
These resources will allow the base technology to be moved out of the laboratory and demonstrated to a degree that users can take it over. These resources will permit work on new technologies focused on future space missions.

**RELATIONSHIP TO OTHER PROGRAMS**
This work is closely coupled (base + focused) and is well coordinated with other agencies and users.

**TECHNOLOGY CONTRIBUTIONS**
SSF (PV,NiH2,SD, Env.), HST (NiH2), EOS (PV,NiH2, Therm. mgmt), DoD (NiH2), GaAs, USAF (Li primary)
External Review Process

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

EXTERNAL REVIEW APPROACH

OBJECTIVES

"NASA (SHOULD) UTILIZE AN EXPERT, OUTSIDE REVIEW PROCESS, MANAGED FROM HEADQUARTERS, TO ASSIST IN THE ALLOCATION OF TECHNOLOGY FUNDS"

- REVIEW THE PROCESS USED FOR DEVELOPING THE INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

- ASSESS THE TECHNICAL CONTENT OF THE PROPOSED ITP
  - IDENTIFY KEY TECHNOLOGY AREAS THAT NEED TO BE ADDRESSED
  - FIRST-ORDER EVALUATION OF THE ESTIMATES OF "COST FOR ACCOMPLISHMENT"
  - RECOMMEND ADJUSTMENTS IN PRIORITIES AND RESOURCE PLANNING

- ASSESS THE ACCOMMODATION OF USER NEEDS
  - EVALUATE STRATEGIC AND NEAR-TERM TECHNOLOGY PLANS AGAINST TECHNOLOGY NEEDS OF FUTURE MISSIONS
  - RECOMMEND POTENTIAL CHANGES IN THE PHASING OF NEW PROGRAMS TO BETTER MEET TECHNOLOGY NEEDS
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

ITP EXTERNAL REVIEW PLANNING

PRELIMINARY:

DETAILED REVIEW APPROACH

- PROVIDE OVERVIEWS IN PLENARY SESSION PRESENTATIONS
  - MISSION USER TECHNOLOGY NEEDS AND APPLICATIONS
  - EXTERNAL PERSPECTIVES ON SPACE TECHNOLOGY
  - STRATEGIC OVERVIEW OF INTEGRATED TECHNOLOGY PLAN

- REVIEW THRUSTS PLENARY SESSION
  - SCIENCE, EXPLORATION, TRANSPORTATION, PLATFORMS, & OPERATIONS

- CONDUCT IN-DEPTH REVIEWS AGAINST VERTICALLY-INTEGRATED DISCIPLINE RESEARCH AREAS
  - PARALLEL TO 1987 ASEB STUDY APPROACH
  - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH

- CONDUCT SELECTED REVIEWS IN ADDITIONAL SPECIAL TOPIC AREAS
  - RESEARCH AREAS, MANAGEMENT TOPICS
  - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH

- CONDUCT DETAILED REVIEW DISCUSSIONS IN AD HOC SESSIONS, TO BE DETERMINED AT THE MEETING; COORDINATE AND REPORT WORKING GROUP RESULTS THROUGH PLENARY SESSION

- DEVELOP SUMMARY RECOMMENDATIONS IN STEERING COMMITTEE SESSION(S)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

EXTERNAL REVIEW APPROACH

PRODUCT

A FORMAL REVIEW REPORT, TO BE PUBLISHED WITHIN 60 DAYS OF THE END OF THE MEETING

- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING DISCIPLINE AREAS (INCLUDING BOTH BASE AND FOCUSED PROGRAMS)
  - WHAT ARE THE RIGHT RESEARCH ISSUES, ARE THEY BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE AREA (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)

- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING TECHNOLOGY THRUSTS
  - WHAT ARE THE RIGHT MISSION NEEDS, ARE THEY BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE THRUST? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)

- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS FOR THE OVERALL PROGRAM
  - ARE THE RIGHT RESEARCH ISSUES AND MISSION NEEDS BEING ADDRESSED?
  - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
  - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE THRUSTS AND IN THE R&T BASE? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)
SPACE ENERGY CONVERSION R&T

REVIEW QUESTIONS

- Is the program content/approach correct?
- Is the level of investment correct?
- Given the available funding are the priorities correct?
- Is the user interface functioning properly?
- Are the efforts being properly coordinated?
- Are the user needs being met?
- Are the participants correct?
- Is the R&T Base content innovative enough to provide improved capability for future user/mission applications?
- Does the R&T Base activity maintain or enhance NASA's technical capabilities?

Backup Material
SPACE ENERGY CONVERSION BASE R&T

PHOTOVOLTAIC ENERGY CONVERSION

TECHNOLOGY NEEDS

• THE HIGH PERFORMANCE PHOTOVOLTAIC ENERGY CONVERSION PROGRAM WILL DEVELOP TECHNOLOGY THAT CAN SUPPORT A WIDE RANGE OF EARTH ORBITING AND INTERPLANETARY MISSIONS INCLUDING:
  • SPACE STATION
    • REDUCES ARRAY AREA BY ≥1/2
  • EARTH OBTENING SYSTEM
    • LONG LIFE, LIGHT-WEIGHT, RADIATION-HARD ARRAY
  • LUNAR/MARS SURFACE POWER
    • COMPACT, TRANSPORTABLE ARRAYS
  • ELECTRIC PROPULSION
    • LEO-GEO AND INTERPLANETARY
  • COMMUNICATIONS SATELLITES
  • ALL NEAR-EARTH MISSIONS

CHEMICAL ENERGY CONVERSION

TECHNOLOGY NEEDS

• THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING
  • PLANETARY SPACECRAFT
    • RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED
  • SURFACE EXPLORERS/ROVERS
    • RECHARGEABLE LI, NIH2, FUEL CELLS OR ADVANCED CONCEPTS
  • LUNAR/MARS SURFACE POWER
    • REGENERATIVE FUEL CELLS
  • PENETRATORS
    • RECHARGEABLE LITHIUM
  • ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF SHUTTLE EMAs)
  • PENETRATORS
TECHNOLOGY NEEDS

THE THERMAL ENERGY CONVERSION PROGRAM WILL PROVIDE THE ENHANCING AND ENABLING TECHNOLOGIES FOR:

• SPACE STATION
  • LIGHT-WEIGHT, LOWER COST, HIGH PERFORMANCE SOLAR DYNAMIC

• SURFACE EXPLORERS/ROVERS
  • RADIOISOTOPE THERMOELECTRIC GENERATORS OR AMTEC

• LUNAR SURFACE POWER
  • LUNAR MATERIAL FOR THERMAL ENERGY STORAGE

• PROBES AND PENETRATORS
  • RTGs and AMTEC

• DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
  • RTGs, AMTEC, and REACTORS

POWER MANAGEMENT

TECHNOLOGY NEEDS

THE POWER MANAGEMENT TECHNOLOGY PROGRAM WILL SUPPORT TECHNOLOGIES FOR CONDITIONING, DISTRIBUTION AND CONTROL OF ELECTRICAL POWER FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:

• EARTH OBSERVING SYSTEMS
  • INCREASED POWER DENSITY

• SURFACE EXPLORERS/ROVERS
  • REDUCED VOLUME/SMART PMAD/LASER POWER BEAMING

• LUNAR/MARS SURFACE POWER
  • AUTONOMOUS OPERATION OF COMPLEX SYSTEM IN HOSTILE ENVIRONMENT/LASER POWER BEAMING

• PROBES AND PENETRATORS
  • REDUCED VOLUME/INCREASED POWER DENSITY/HOSTILE ENVIRONMENT

• DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
  • REDUCED VOLUME/AUTONOMOUS OPERATION/HOSTILE ENVIRONMENT
TECHNOLOGY NEEDS

- The thermal management program will provide highly advanced thermal management technologies to enable:
  
  - Low mass space radiators
    - Important for all planetary and space missions
  
  - Radiator size reductions for space power electronics
    - Important for all spacecraft and bases
  
  - Thermal control for spacecraft instruments, sensors, and other heat dissipating equipment
    - Important for all spacecraft and bases

SPACE ENERGY CONVERSION R&T

FOCUSED POWER PROGRAMS THAT AFFECT THE BASE

- Space platforms
  - Planar and concentrator arrays immune to space environment
  - Improved battery systems (approaching 150 Wh/kg)
  - Integrated, high-efficiency power management & control that is highly autonomous (goal: 2x reduction in mass)
  - High efficiency (2x - 4x improvement) conversion systems for deep space missions
  - Integrated thermal management/high temperature electron to yield 3x reduction in spacecraft bus mass

- Exploration (surface power/mobile surface power)
  - High-efficiency conversion systems (e.g., Stirling, T/E)
  - High energy density storage (regen. fuel cells/batteries)
  - Thermal management
  - Laser power beaming
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

OSO TECHNOLOGY NEEDS

HIGHEST-PRIORITY

High-Rate Communications
Optical and Millimeter Wave Radio Frequencies
(for space to ground and space to space)

Advanced Data Systems
Advanced Data Storage, Data Compression, and Information Management Systems

Advanced Navigation Techniques
New techniques for cruise, approach, and in-orbit navigation

Mission Operations
Artificial Intelligence, Expert Systems, Neural Networks, Increased Automation in Mission Operations, Testbeds for Advanced Software, Coordination of Distributed Software, and Automated Performance Analysis of Networking Computing Environments

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

OSF TECHNOLOGY NEEDS

HIGHEST-PRIORITY

Program Unique Requirements
Vehicle Health Management
Advanced Turbomachinery (Components/Models)
Combustion Devices
Advanced Heat Rejection Technologies
High Efficiency Space Power Systems
Water Recovery and Management
Advanced Extravehicular Mobility Unit
Electromechanical Control Systems
Crew Training Systems
Characterization of Al-Li Alloys
Cryogen Storage, Handling & Supply
TPS for High-Temp. Applications
Robotic Systems
Orbital Debris Guidance, Navigation & Control
Advanced Avionics Architectures

Industry Driven Technologies
Signal Transmission and Reception
Advanced Avionics Software
Video Technologies
Environmentally Safe Cleaning Solvents, Refng, Foams
Non-Destructive Evaluation
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

MFPE/SEI TECHNOLOGY NEEDS

HIGHEST-PRIORITY

Category 1
- Radiation Protection
- EVA Systems
- Nuclear Thermal Propulsion
- Regenerative Life Support
- Cryo Fluid Mgt, Storage & Transfer
- Micro-G Countermeasures/Air Gravity
- Aerobraking

Category 2
- Auto. Rendezvous & Docking
- Health Maintenance & Care
- In-Space Systems Assembly/Processing
- Surface Systems Construction/Processing
- Cryogenic Space Engines
- In Situ Resource Utilization
- Surface Power

Category 3
- Autonomous Landing
- Human Factors
- Surface System Mobility & Guidance
- Electric Propulsion
- Sample, Acquisition, Analysis & Preservation

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

Space Exploration Initiative Technology Needs

HIGHEST-PRIORITY

Category 1
- Radiation Protection
- EVA Systems
- Nuclear Thermal Propulsion
- Regenerative Life Support
- Cryo Fluid Mgt, Storage & Transfer
- Micro-G Countermeasures/Air Gravity
- Aerobraking

Category 2
- Auto. Rendezvous & Docking
- Health Maintenance & Care
- In-Space Systems Assembly/Processing
- Surface Systems Construction/Processing
- Cryogenic Space Engines
- In Situ Resource Utilization
- Surface Power

Category 3
- Autonomous Landing
- Human Factors
- Surface System Mobility & Guidance
- Electric Propulsion
- Sample, Acquisition, Analysis & Preservation
### Integrated Technology Plan for the Civil Space Program

#### Near Term Need

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<td>Sub-mm &amp; wave Sensing</td>
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<tr>
<td>Long Life Cryo Coatings/Cryo Shielding</td>
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<td>High Energy Detectors</td>
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<td>Sensor Array Electronics</td>
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<td>Vibration Isolation Technology</td>
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<tr>
<td>Efficient/High Refrigerator/Freezer</td>
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<td>Extreme Upper Atmosphere Instrument Platforms</td>
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<th>2ND HIGHEST PRIORITY</th>
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<td>High Frame Rate/Real Video/Data Compression</td>
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<td>2 x 4 Meter 100 K Lightweight PSR Solar Array/Cells</td>
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<td>Automated Biomedical Analyzers</td>
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<td>Radiation-hardened Parts/Components</td>
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<td>Long Life High Energy Density Batteries</td>
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<td>Real-Time Environmental Control System</td>
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<td>Space Qualified Mission Cables</td>
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<td>Fluid Diagnostics</td>
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<th>3RD HIGHEST PRIORITY</th>
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<tbody>
<tr>
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<tr>
<td>K Band Transponders</td>
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<tr>
<td>Ultra High G igabits/terabytes</td>
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<tr>
<td>Very High Power Antennas</td>
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<td>Real Time Radiation Monitoring</td>
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<td>Solid/Liquid Interface Characterization</td>
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<td>High Temperature Materials for Furnaces</td>
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<tr>
<td>Food Portable Gas Chromatographs</td>
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<td>Additive Manufacturing Technology</td>
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#### Mid Term Need

| Long Live Stable Tunable Lasers |
| Solar Probe Mercury Orbit Thermal Project |
| High Value Century-Plus Ontological Data Storage Instrument-specific Technology |

| Auto Sequencing & CAM Generation |
| Auto S/C Monitoring & Fault Recovery |
| 32 GHz TWTA Optical Communications |
| Telescience/Telesurveillance/AI Intelligence |
| Improved EVA Systems (KMU) |
| Combustion Devices |
| Plasma Wave Antenna/Thermal |

#### Far Term Need

| Structures: Large/Controlled/Deployed Antenna Array |
| Precision Inertial S/C Ranging/Positioning |
| 50-100 Megawatt ion Propulsion (MEP) |
| Large Field Arrays |
| Parallel SW Em to Medical/Data Visualization |
| Computational Techniques |

| SIS/3 Tile Heterodyne Receiver |
| SETI Detector Technologies |
| Very Asymmetric Lander Deceleration |
| Radiation Hardening for Crews |
| CAPP-Prototype/Soft/Path Analyzers |
| Human Artifical Gravity Systems |
| X-Ray Optics Technology |
| Advanced Sample Bio-marker Analysis Cap |
| High Resolution Spectrometer |

### Autonomous Rendezvous/Sample Return Landing

- Non Destructive Monitoring Capability
- Low Dose Gyro/Tracker Actuators
- Heat Shield for 16 Inch Earth entry
- Partial Gut/G Medical Care Systems
- Dual Protection/Jupiter’s Rings
- Non Destructive Cosmic Dust Collection
- CE/SS Support Technologies

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**Original Page is of Poor Quality**

PT1-75
SPACE PHOTOVOLTAIC ENERGY CONVERSION

PRESENTED AT THE ITP EXTERNAL REVIEW

McLEAN VIRGINIA
JUNE 26, 1991

DENNIS J. FLOOD
LEWIS RESEARCH CENTER

SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

= OAET

PHOTOVOLTAICS

OBJECTIVES

• Programmatic
  Develop and Demonstrate High Efficiency Lightweight, Long Life, Durable Photovoltaic Cell and Array Technology
• Technical
  ≥300 W/kg Planar Array Technology
  ≥330 W/m² Conc. Arrays
  ≤1% Cell Degradation, 10 Years GEO
  ≥1000 W/kg Flexible Blanket

SCHEDULE (Strategic Budget)

• 1992 12-panel APSA
• 1993 Conc. Array Preliminary Design
• 1994 Demonstrate Thin 20% InP Cell
• 1995 Demonstrate High-Temperature Blanket
• 1996 Demonstrate >10% CIS Flexible Blanket
• 1997 Demonstrate Blanket for 300 W/kg Array
• 1998 Demonstrate 2nd Generation APSA
• 1999 Ground Test 330 W/m² 1 kW Concentrator Array

RESOURCES (M$)

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PARTICIPANTS

• LEWIS RESEARCH CENTER
  Advanced Cell and Blanket Technology

• JPL
  Lightweight Arrays
## Objectives

- **Programmatic**
  - Develop and demonstrate high efficiency lightweight, long life, durable photovoltaic cell and array technology.

- **Technical**
  - ≥300 W/kg planar array technology
  - ≥330 W/m² conc. arrays
  - ≤ 1% cell degradation, 10 years GEO
  - ≥1000 W/kg flexible blanket

## Schedule (Current Budget)

- 1992: LILT Degradation Mechanism/Solution Determined
- 1993: Amorphous silicon radiation damage studies complete
- 1994: Demonstrate low temp. deposition of CIS cells on flexible blanket material
- 1995: Demonstrate >19% InP cell on foreign substrate
- 1996: Fabricate APSA thin film cell flexible blanket
- 1997: Fabricate blanket for 300 W/kg array

## Resources (M$)

<table>
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</tbody>
</table>

## Participants

- **LEWIS Research Center**
  - Advanced cell and blanket technology

- **JPL**
  - Lightweight arrays

## Technology Needs

- **Supports a broad spectrum of planned and future NASA/DOD/Commercial mission power requirements**
  - Space Station
  - EOS
  - Lunar/Mars surface power
  - EP/Orbit transfer, interplanetary to 8 AU
  - COMSATS
  - Brilliant Eyes
  - All Near Earth Missions
SPACE SCIENCE TECHNOLOGY
PHOTOVOLTAICS

TECHNOLOGY CHALLENGES/APPROACH

• TECHNOLOGY DEVELOPMENT CHALLENGES:
  • EXTEND MISSION LIFE
  • REDUCE ARRAY MOMENT OF INERTIA (i.e., MASS & AREA)
  • REDUCE COST

• TECHNOLOGY DEVELOPMENT APPROACH:
  • BASE R&T ON CELLS & ARRAY CONCEPTS
  • FOCUSED DEVELOPMENT OF HIGH EFFICIENCY, LIGHTWEIGHT, CONCENTRATOR ARRAY
  • COORDINATE PLANNING & IMPLEMENTATION WITH PROSPECTIVE USERS, (e.g., SSF, EOS, SEI, DOD, etc.)

SPACE ENEF TECHNOLOGY
SPACE ENERGY CONVERSION

PHOTOVOLTAIC ENERGY CONVERSION
TECHNOLOGY BENEFITS

• 3X HIGHER SPECIFIC POWER
  +30 W/KG SOA TO >300 W/KG ADV. PLANAR

• 10X HIGHER POWER DENSITY
  +110 W/SQM TO >330 W/SQM

• 20X BETTER RADIATION RESISTANCE
  +>20% TO <1%, 10 yrs GEO
SPACE SCIENCE TECHNOLOGY
PHOTOVOLTAICS

STATE-OF-THE-ART ASSESSMENT

CURRENT:
- BODY MOUNTED OR DEPLOYABLE RIGID
- DEPLOYABLE FLEXIBLE ARRAYS
- NO CONCENTRATOR ARRAYS

• Si PLANAR CELLS
  - 110 W/m², 25 - 40 W/kg
  - 25% - 40% DEGRADATION, 7 YEARS GEO
    (2 mil Si CELL @ 15% DEGRADATION)

• GaAs PLANAR CELLS
  - ≥170 W/m², 25 - 40 W/kg
  - 15% DEGRADATION, 10 YEARS GEO

• OAET/APSA (ADVANCED PHOTOVOLTAIC SOLAR ARRAY)
  - 2 mil Si CELL
  - 110 W/m², 130 W/kg
  - 20% DEGRADATION, 10 YEARS GEO

SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

OAET
HIGH PERFORMANCE PHOTOVOLTAIC SOLAR ARRAYS

CURRENT PROGRAM

• ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)
  - COMPLETE FABRICATION AND VERIFICATION OF 12 PANEL LIGHTWEIGHT PROTOTYPE ARRAY WING
  - DEVELOP DESIGN MODIFICATIONS FOR RETRACTION AND RELATCHING
  - DEVELOP ALTERNATIVE CIRCUIT DESIGNS FOR SHADOWING AND CELL BREAKAGE

• RADIATION EFFECTS ON LIGHTWEIGHT BLANKET COMPONENTS
  - DETERMINE PROTON AND ELECTRON DAMAGE EQUIVALENCE FOR GaAs/Ge SOLAR CELLS
  - CALCULATE GaAs/Ge CELL BEHAVIOR FOR POTENTIAL MISSION APPLICATIONS

• LOW INTENSITY, LOW TEMPERATURE (LILT) EFFECTS
  - DETERMINE MECHANISM FOR LILT DEGRADATION IN SILICON
  - DETERMINE METHOD(S) FOR AVOIDING LILT DEGRADATION
SPACE ENERGY TECHNOLOGY
PHOTOVOLTAIC ENERGY CONVERSION

CURRENT PROGRAM

- PERFORMANCE VERIFICATION AND CELL FUNDAMENTALS
  - HIGH ALTITUDE AND LABORATORY SIMULATOR CELL MEASUREMENTS
  - THERMAL CYCLING
  - RADIATION DAMAGE STUDIES

- HETEROEPITAXIAL InP SOLAR CELLS
  - DEVELOP ≥ 19%, RADIATION RESISTANT InP CELL ON LOW COST, LIGHTWEIGHT SUBSTRATE

- CONCENTRATOR ARRAY TECHNOLOGY
  - DEMONSTRATE KEY COMPONENT TECHNOLOGY FOR ≥ 300 W/m² ARRAY
  - COMPLETE TESTS OF PASP-PLUS FLIGHT HARDWARE

- THIN FILM CELL R&T
  - DEMONSTRATE CIS TECHNOLOGY FOR 1000 W/kg FLEXIBLE SOLAR BLANKET

- SELECTIVE EMITTER/PV CONVERTER R&T
  - DEMONSTRATE KEY TECHNOLOGIES FOR ≥ 20% DIRECT THERMAL-TO-ELECTRIC CONVERSION

- HIGH EFFICIENCY InP CELLS
  - DEMONSTRATE ≥ 20% EFFICIENT PLANAR CELL
### InP on Foreign Substrate Performance Objectives

<table>
<thead>
<tr>
<th>Performance Requirement</th>
<th>Current SOA (10% GEO)</th>
<th>Development Goals</th>
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<tbody>
<tr>
<td>Cell Efficiency</td>
<td>10%</td>
<td>≥ 19%</td>
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<tr>
<td>Degradation (10 Years GEO)</td>
<td>4%</td>
<td>&lt; 1%</td>
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<table>
<thead>
<tr>
<th>Array Specific Power (W/kg)</th>
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<tr>
<td>BOL</td>
<td>96</td>
<td>390</td>
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<tr>
<td>10 Years GEO</td>
<td>92</td>
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<table>
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<th>Array Specific Area (W/m²)</th>
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<tr>
<td>BOL</td>
<td>82</td>
<td>160</td>
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<tr>
<td>10 Years GEO</td>
<td>79</td>
<td>158</td>
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</table>

### Approximate Need Date

- 1995

### Space Science Technology

#### Photonics

### CIS Blanket Performance Objective

<table>
<thead>
<tr>
<th>Performance Requirement</th>
<th>Present SOA (11% Rigid Substrate)</th>
<th>Development Goals (Flexible Substrate)</th>
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<tbody>
<tr>
<td>Cell Efficiency</td>
<td>11% *</td>
<td>≥ 11%</td>
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<tr>
<td>Degradation (10 Years GEO)</td>
<td>5% (Estimated)</td>
<td>≤ 1%</td>
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<th>Blanket Specific Power (W/kg)</th>
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<tbody>
<tr>
<td>BOL</td>
<td>24 W/kg *</td>
<td>≥ 1000 W/kg *</td>
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<tr>
<td>10 Years GEO</td>
<td>23 W/kg *</td>
<td>≥ 990 W/kg *</td>
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<table>
<thead>
<tr>
<th>Blanket Specific Area (W/m²)</th>
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<tr>
<td>BOL</td>
<td>135 W/m² *</td>
<td>135 W/m² *</td>
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<tr>
<td>10 Years GEO</td>
<td>110 W/m² *</td>
<td>133 W/m² *</td>
</tr>
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</table>

### Approximate Need Date

- 1996

* Estimated from terrestrial measurement (no space calibrated standard available)
### SPACE ENERGY TECHNOLOGY

**SPACE ENERGY CONVERSION**

### CONCENTRATOR ARRAY TECHNOLOGY PERFORMANCE OBJECTIVES

**MINI-DOME FRESNEL LENS CONCENTRATOR ARRAY**

<table>
<thead>
<tr>
<th>PERFORMANCE REQUIREMENT</th>
<th>SOA REFLECTIVE CONCENTRATOR SYSTEMS</th>
<th>DEVELOPMENT GOALS MINI-DOME TECHNOLOGY</th>
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<tbody>
<tr>
<td>CONCENTRATOR ELEMENT EFFICIENCY</td>
<td>80 - 90%</td>
<td>&gt; 95%</td>
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<td>CONCENTRATOR ELEMENT MATERIAL</td>
<td>METALLIC REFLECTORS</td>
<td>POLYMERIC MATERIALS</td>
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<tr>
<td>PHOTOVOLTAIC CELL EFFICIENCY</td>
<td>18 - 20%</td>
<td>30%</td>
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<tr>
<td>ARRAY LIFETIME</td>
<td>10 YEARS (GEO)</td>
<td>10 YEARS (GEO)</td>
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<tr>
<td>COST</td>
<td>HIGH</td>
<td>LOW *</td>
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<tr>
<td>ARRAY SPECIFIC POWER (W/kg)</td>
<td>25 - 40</td>
<td>&gt; 100</td>
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<tr>
<td>ARRAY SPECIFIC AREA (W/m²)</td>
<td>150 - 180</td>
<td>&gt; 330</td>
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<tr>
<td>APPROXIMATE NEED DATE</td>
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* TAKES ADVANTAGE OF AUTOMATED, LOW-COST FABRICATION AND ASSEMBLY TECHNIQUES

### SPACE SCIENCE TECHNOLOGY

**PHOTOVOLTAICS**

### THIN InP SOLAR CELLS PERFORMANCE OBJECTIVE

<table>
<thead>
<tr>
<th>PERFORMANCE REQUIREMENT</th>
<th>PRESENT SC.</th>
<th>DEVELOPMENT GOALS</th>
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<tbody>
<tr>
<td>CELL EFFICIENCY</td>
<td>19.1%</td>
<td>&gt; 20%</td>
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<tr>
<td>CELL THICKNESS (MICROMETER)</td>
<td>380</td>
<td>10</td>
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<tr>
<td>CELL DEGRADATION</td>
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<tr>
<td>10 YEARS GEO</td>
<td>7.5%</td>
<td>&lt;1%</td>
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<tr>
<td>BLANKET SPECIFIC POWER (W/kg)</td>
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<tr>
<td>BOL</td>
<td>85</td>
<td>425</td>
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<tr>
<td>10 YEARS GEO</td>
<td>79</td>
<td>421</td>
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<tr>
<td>BLANKET SPECIFIC AREA (W/m²)</td>
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<tr>
<td>BOL</td>
<td>173</td>
<td>180</td>
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<tr>
<td>10 YEARS GEO</td>
<td>160</td>
<td>178</td>
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<td>APPROXIMATE NEED DATE</td>
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<td>1994</td>
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</table>

PT2-8
SPACE SCIENCE TECHNOLOGY
PHOTOVOLTAICS

OTHER DEVELOPMENT EFFORTS

SDIO SUPER ARRAY (SURVIVABLE)
• 15 x CONCENTRATION
• 20% GaAs CELLS
• 15 W/kg
• ≥ 200 W/m²

SPACE STATION FREEDOM ARRAY
• 8 x 8, 8 mil Si CELLS
• 110 W/m²
• 40 W/kg
(NO LEO RADIATION DAMAGE)

ADVANCED TDRSS ARRAY
• Si CELL TECHNOLOGY TBD
• 110 W/m²
• 35 W/kg

AIR FORCE MULTIBANDGAP
CELL DEVELOPMENT
• GaAs/Ge
• GaAs/CIS
• AlGaAs/Ge
• FY91 NEW START (~ 1 $M)
• 30% GOAL
• CELL COST NOT A CONCERN

VARIABLE BLACK PROGRAMS

SPACE ENERGY TECHNOLOGY
PHOTOVOLTAIC ENERGY CONVERSION

AUGMENTED PROGRAM

CONCENTRATOR ARRAY TECHNOLOGY
DEMONSTRATE 1 kW CONCENTRATOR ARRAY AT
> 330 W/M, 100 W/kg

THIN FILM EFFICIENCY InP CELLS
DEMONSTRATE THIN (≤ 100 microns) PLANAR InP
CELLS WITH ≥ 20% EFFICIENCY
INITIATE PRE-PILOT PRODUCTION
SPACE ENERGY TECHNOLOGY
PHOTOVOLTAIC ENERGY CONVERSION

ROADMAP/SCHEDULE

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<td>CONCENTRATOR ARRAY</td>
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<tr>
<td>CIS BLANKET</td>
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<td>20% InP THIN CELL</td>
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R&T BASE: PHOTOVOLTAIC ENERGY CONVERSION

TECHNICAL CHALLENGE:

- SOLAR ARRAYS WITH EXTENDED LIFE, LIGHTER WEIGHT, SMALLER AREA, REDUCED MISSION COST

APPROACH:

- ADVANCED CELLS, BLANKETS, ARRAY SYSTEM COMPONENTS
- INTEGRATED ARRAY SYSTEM HARDWARE

PAYOFF:

- 10X INCREASE IN ARRAY SPECIFIC POWER
- RADIATION HARD ARRAYS
- 3X INCREASE IN POWER DENSITY

RATIONALE FOR AUGMENTATION:

- ALTERNATE/ENABLING TECHNOLOGY FOR MANY FUTURE MISSIONS
- AVAILABLE FOR NEAR, MID TERM
- RESTORES CRITICAL PARTICIPATION BY VENDORS
  - U.S. COMPETITIVE POSITION ERODING

RELATIONSHIP TO FOCUSED ACTIVITIES AND OTHER PROGRAMS:

- JOINT ACTIVITIES, MOUs WITH A/F, SDIO, SERI, RAE

TECHNOLOGY CONTRIBUTIONS:

- OAST1 - BASELINE FOR SSF
- SILICON CELLS FOR SSF, VIRTUALLY ALL U.S. CIVIL, DOD MISSIONS
- PIONEERED GaAs CELLS - MANTECH FUNDED BY AIR FORCE
TECHNICAL CHALLENGE:
- Solar arrays with extended life, lighter weight, smaller area, reduced mission cost

APPROACH:
- Advanced cells, blankets, array system components
- Integrated array system hardware

PAYOFF:
- 10x increase in array specific power
- Radiation hard arrays
- 3x increase in power density

RATIONALE FOR AUGMENTATION:
- Alternate/enabling technology for many future missions
- Available for near, mid term
- Restores critical participation by vendors
  - U.S. competitive position eroding

RELATIONSHIP TO FOCUSED ACTIVITIES AND OTHER PROGRAMS:
- Joint activities, MOU's with A/F, SDIO, SERI, RAE

TECHNOLOGY CONTRIBUTIONS:
- OAST 1 - baseline for SSF
- Silicon cells for SSF, virtually all U.S. civil, DOD missions
- Pioneered GaAs cells - MANTECH funded by Air Force

SPACE ENERGY CONVERSION
- Two distinct technology paths

300 WATTS/KG
300 WATTS/SQ.M
OAST 1/SSF
MCC/SUPER
SOA RIGID PLANAR/SI
300 WATTS/KG
300 WATTS/SQ.M
OAST 1/SSF
MCC/SUPER
SOA RIGID PLANAR/SI
MDL conc. GaAs or InP
APSA 2 MIL SI
OAST 1/SSF
MCC/SUPER
SOA RIGID PLANAR/SI
MDL conc. GaAs or InP
APSA 2 MIL SI
SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

**Photovoltaic Energy Conversion**

- **Agency Program Has Two Major Technology Subareas:**
  - Advanced Array Technology
  - Advanced Solar Cell Technology

- **Advanced Array Technology Consists of One Major Effort:**
  - APSA and Related Technology Issues (LILT Effects, Radiation Damage, Thin Cells, etc.)

- **Advanced Solar Cell Technology Consists of a "Million Pieces"**
  - Single Crystal Cells (InP, GaAs, AlGaAs, InGaAs, MBG's, etc.); Thin Film Cells (CIS, a-Si) Flexible Substrates, Alternate Single Crystal Substrates; Concentrator Cells & Optics; Thermal Cycling Tests; Flight Tests (UOSAT, PASP-PLUS, APEX); Cell Measurement and Calibration, etc, etc

---

**Even the SoA Has**

- Few Array Designs (Costly, Stick with What's Flown...)
- Many Silicon Solar Cell Types
  - 10 Ohm-Cm, 2 Ohm-Cm, BSF, BSR, BSFR, Textured, 2x4CM, 4x2CM, 2x6CM, 6x6CM, 8x8CM, Backside Grids, 2Mil, 8Mil, 12Mil, etc, etc

**Why?**

- Because missions fly in different environments with different performance requirements
- No one Si cell, even on the same array design, gives optimum performance for all missions

- A "Catalog" of advanced solar cells is similarly needed to optimize future missions
  - Advanced "optimum" cells are made from different materials, different configurations

**Reason for All This? The User Community**
THE BOTTOM LINE:

- BASE R&T FUNDING AT LEAST ONE-THIRD LESS (REAL DOLLARS) THAN DECADE AGO

CAUSE:

- CONSTRAINED POWER R&T BUDGET W/LARGE EFFORTS TO DEVELOP ALTERNATE TECHNOLOGIES
  - GROWTH SPACE STATION/SOLAR DYNAMICS
  - LUNAR BASE/SP-100
  - NEP NEXT?

EFFECT:

- LARGE INVESTMENTS IN ALTERNATE SYSTEMS FOR FAR TERM (BEYOND 2000) HAVE ERODED AGENCY'S ABILITY TO HAVE IMPACT ON NEAR AND MID TERM MISSIONS

CONSEQUENCE:

- REDUCED FUNDING PUSHES NEAR AND MID TERM PV TECHNOLOGY TO FAR TERM
  - VENDORS DROP OUT
  - USER COMMUNITY CAN'T WAIT
  - MISSION CAPABILITIES COMPROMISED
INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

CHEMICAL ENERGY CONVERSION AND STORAGE
TECHNOLOGY PROJECT SUMMARY

SPACE ENERGY CONVERSION
PROGRAM AREA OF THE
R&T BASE PROGRAM

June 26, 1991

P. Bankston and M. Warshay

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OBJECTIVES

- **Programmatic**
  - Develop and Demonstrate Advanced Rechargeable Battery and Fuel Cell Technologies for Space Applications

- **Technical**
  - Specific Energy: 100-200 Wh/Kg
  - Energy Density: 150-300 Wh/l
  - Operational Life: 10 years

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<td>1996</td>
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<tr>
<td>1997</td>
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PARTICIPANTS

- Lewis Research Center
  - Responsibility includes advanced batteries and fuel cells
- Jet Propulsion Laboratory
  - Responsibility includes advanced batteries

SCHEDULE

- 1993: 5 Ah Engineering Model LiTIS₂ Cell
- 1994: Deliver Bipolar Flight Battery
- 1995: Demonstrate 1000 Cycles at 50% DOD and 100 Wh/Kg for LiTIS₂ Cells Complete 100 Wh/Kg Nickel-Hydrogen Battery
- 1996: Bi-functional Catalyst Technology Developed
- 1997: Design for 150 Wh/Kg Battery
THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING EARTH ORBITAL, PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING:

- PLANETARY SPACECRAFT
  - RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED CONCEPTS
- SURFACE EXPLORERS/ROVERS
  - RECHARGEABLE LI, NIH2, FUEL CELLS OR ADVANCED CONCEPTS
- LUNAR/MARS SURFACE POWER
  - REGENERATIVE FUEL CELLS
- PROBES AND PENETRATORS
  - RECHARGEABLE LITHIUM
- ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF/SHUTTLE/EVs)
- MARS AND VENUS MISSION POWER
  - LICO2 SYSTEM
- EMA's FOR SHUTTLE
  - BI-POLAR NIH2 WITH ELECTROCHEMICAL CAPACITORS

TECHNOLOGY CHALLENGES

- REDUCE BATTERY WEIGHT (2-3 TIMES LESS THAN Ni-Cd)
- REDUCE BATTERY VOLUME (2-3 TIMES)
- INCREASE OPERATIONAL LIFE (10 YEARS)
- DEVELOP A BATTERY FOR HIGH VOLTAGE, HIGH POWER, AND PULSE APPLICATIONS
- EXTEND ACTIVE STORAGE/CHARGE RETENTION (5 YEARS)
- STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS
- IDENTIFY ADVANCED CONCEPTS CAPABLE OF FURTHER ENERGY STORAGE IMPROVEMENTS BY FACTORS OF 3-5 BEYOND SOA
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

TECHNOLOGY BENEFITS

• MASS REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED; AND INCREASE IN PAYLOAD CAPABILITY

• 2-3 TIMES SAVING IN ENERGY STORAGE VOLUME ENABLES REDUCTIONS IN SYSTEM ENVELOPE

• INCREASE OF OPERATION LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS

• HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS

• STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS

MASS COST ADVANTAGE

PT3-3
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

STATE OF THE ART ASSESSMENT

- SOA RECHARGEABLE BATTERIES ARE ACCEPTABLE, BUT POSSESS LOW SPECIFIC ENERGY (30 Wh/Kg, Ni-Cd; 55 Wh/Kg, NiH2) AND ENERGY DENSITY.
- 10 YEAR OPERATIONAL LIFE WHILE CYCLING DEMONSTRATED FOR SOME; MANY YEARS ON STAND (CRUISE) GENERALLY NOT DEMONSTRATED
- SOA RECHARGEABLE BATTERIES TYPICALLY HAVE POOR CHARGE RETENTION CHARACTERISTICS
- NO HIGH VOLTAGE, HIGH POWER SPACE BATTERY YET DEVELOPED
- STABLE, HIGH PERFORMANCE CATALYSTS ESSENTIAL TO REGENERATIVE FUEL CELL UTILIZATION IN SPACE

<table>
<thead>
<tr>
<th>PERFORMANCE CHARACTERISTIC</th>
<th>SOA BATTERIES</th>
<th>ADVANCED BATTERIES</th>
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<tbody>
<tr>
<td></td>
<td>NiCd</td>
<td>NiH2</td>
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<tr>
<td>SPECIFIC ENERGY (Wh/Kg)</td>
<td>30</td>
<td>55</td>
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<tr>
<td>ENERGY DENSITY (Wh/An)</td>
<td>80</td>
<td>60</td>
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<tr>
<td>MASS PERFORMANCE (Kg/Kw)</td>
<td>65</td>
<td>35</td>
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<tr>
<td>CAPACITY (Ah)</td>
<td>5-50</td>
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<td>OPERATING TEMPERATURE (°C)</td>
<td>-10-35</td>
<td>-10-35</td>
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<tr>
<td>CYCLE LIFE (# Cycles @ 70% DOD)</td>
<td>1000</td>
<td>40,000</td>
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<tr>
<td>MINIMUM LIFE TIME (Years)</td>
<td>10</td>
<td>10</td>
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* On a battery (10 cell pack) level.
SPACE ENERGY CONVERSION BASE R&T
CHEMICAL ENERGY CONVERSION & STORAGE

RECENT MAJOR ACCOMPLISHMENTS

• IPV NiH₂
  • 40,000 LEO CYCLES AT 80% DOD IN BOILERPLATE CELLS
  • LIGHTWEIGHT COMPONENT TECHNOLOGY DEMONSTRATED FOR
    5800 CYCLES ON SUBSCALE LEVEL
  • 90% NI ELECTRODE SUBSTRATE POROSITY ACHIEVED (vs. 83%
    SOA)
• BIPOLAR NiH₂
  • OVER 10,000 CYCLES ACHIEVED IN ON-GOING TESTS
• LI-TiS₂
  • 700 CYCLES ACHIEVED AT 50% DOD IN 1 Ah CELLS
• ADVANCED RECHARGEABLE BATTERY CONCEPTS
  • CONFIRMED CYCLEABILITY OF NaNiCl₂ CELL; SELECTED FOR
    TECHNOLOGY DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T
CHEMICAL ENERGY CONVERSION & STORAGE

CURRENT PROGRAM

• DEVELOP GEO NICKEL HYDROGEN (Ni/H₂) BATTERIES WITH
  INCREASED ENERGY DENSITY (100 Whr/Kg) AND RELIABILITY BY 1995
  • INTERIM 60 Whr/Kg (80% DOD) BY 1993
  • LIGHTWEIGHT COMPONENT TECHNOLOGY
  • HIGH PERFORMANCE NICKEL ELECTRODE DEVELOPMENT
• DEVELOP BIPOLAR Ni/H₂ BATTERY FOR HIGH VOLTAGE, HIGH POWER,
  HIGH CURRENT, AND PULSE APPLICATIONS BY 1994
  • IN-HOUSE AND CONTRACT CYCLE LIFE TESTING
  • FABRICATE AND TEST ADVANCED BOILERPLATE BATTERY IN
    1992
• DEVELOP ADVANCED SODIUM SULFUR (Na/S) BATTERIES AS VIABLE
  NASA FLIGHT SYSTEMS
  • MANAGEMENT OF $5M IN-STEP FLIGHT EXPERIMENT
  • INITIATE TECHNOLOGY DEVELOPMENT IN 1993
• DEVELOP STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS
  • COMPLETE EVALUATION OF LeRC LONG-LIFE CATALYSTS IN
    SOA PEM FUEL CELL IN 1993
  • CATALYST/SUPPORT TECHNOLOGY FOR REGENERATIVE FUEL
    CELL SYSTEM
  • BI-FUNCTIONAL CATALYST TECHNOLOGY
SIZE AND VOLUME COMPARISON OF 1.4 kWhr BIPOLAR AND IPV NICKEL HYDROGEN SYSTEMS

BIPOLAR BATTERY
2 X 100 CELLS (-130 VOLTS)

IPV BATTERY
21 CELLS (-20 VOLTS)

BIPOLAR DESIGN REPRESENTS
-10% VOLUME REDUCTION
COMPAPE TO IPV

ORIGINAL PAGE IS OF POOR QUALITY

PT3-6
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

= LeRC

STRATEGIC PROGRAM

- IPV NICKEL HYDROGEN - DEVELOP COMMERCIAL MANUFACTURING CAPABILITY

- SODIUM SULFUR - ACCELERATED PROGRAM
  - TIMELY
    - BETTER PHASING
    - TIMELY PRODUCTION, MANUFACTURING CAPABILITY

- FUEL CELLS - CATALYST LIFE TEST, AND HALF CELL TEST
  ENHANCE IN-HOUSE FUEL CELL TESTING CAPABILITY

- ELECTROCHEMICAL CAPACITORS - INITIATE ELECTROCHEMICAL CAPACITOR DEVELOPMENT PROGRAM

ROADMAP/SCHEDULE

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<td>GEO LIGHTWEIGHT IPV</td>
<td>HIGH BP, ENERGY</td>
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<td>65 W/kg</td>
<td>FLIGHT CELL VERIFICATION</td>
<td>MANUFACTURER CAPABILITY IN PLACE</td>
<td>MOVE TO FOCUSED PROGRAM</td>
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<td>BIPOLAR</td>
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<td>LITHIUM CARBON DIOXIDE</td>
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PT3-7
CURRENT PROGRAM

- DEMO FEASIBILITY OF AMBIENT TEMPERATURE Li-TiS₂ CELL TECHNOLOGY (100 Wh/Kg) BY 1995
  - IDENTIFY STABLE ELECTROLYTES
  - EVALUATE ALTERNATE LI ANODE MATERIALS
  - DEVELOP OVERCHARGE CONCEPTS
  - DEFINE DESIGN REQUIREMENTS
  - DEVELOP 5 Ah CELLS
  - ASSESS SAFETY

- DEVELOP ADVANCED BATTERY SYSTEMS CAPABLE OF >150 Wh/Kg
  - SODIUM/METAL HALIDES
  - LITHIUM/POLYMER ELECTROLYTE/INSERTION CATHODES
    - SELECT CANDIDATE SYSTEM
    - DEMONSTRATE CYCLE LIFE
    - DEVELOP ENGINEERING MODEL CELL
    - DEMONSTRATE TECHNOLOGY

RECHARGEABLE LITHIUM CELL PROGRAM

SCALE UP OF Li-TiS₂ CELL TECHNOLOGY

**CELL DESIGN**

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<th>COMPONENT</th>
<th>150 mAh CELL</th>
<th>1 Ah CELL</th>
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<tr>
<td>Li ANODE</td>
<td>1.5 Ah</td>
<td>6 Ah</td>
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<tr>
<td></td>
<td>(1&quot; x 4.5&quot; x 0.02&quot;)</td>
<td>(1.6&quot; x 10&quot; x 0.02&quot;)</td>
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<td>TiS₂ CATHODE</td>
<td>150 mAh</td>
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<td>EC/2-MeTHF, 6 c.c.</td>
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SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

= JPL

STRATEGIC PROGRAM

- DEVELOP AND TRANSFER TECHNOLOGY TO INDUSTRY FOR 30 Ah, 30 V, LI-TIS₂ CELL BY 1996

ACTIVITIES

- ISSUE CONTRACT TO INDUSTRY
- DEVELOP PROTOTYPE 30 Ah CELL
- COMPLETE SAFETY, LIFE AND PERFORMANCE TESTS
- ACCELERATE 150 Whr/Kg CELL DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

= JPL

ROADMAP/SCHEDULE

KEY ACTIVITIES

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DEVELOPMENT OF

Characterization of Na/MC₁₂ System

Define Design Requirements

Develop Eng. Model Cell

Performance Tests

Safety Tests

Characterization of Li/Polymer System

Select Promising Option

Provide Additional Options

Continuing Research

Continuing Research

PT3-9
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

= OAET

RESOURCE REQUIREMENTS

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SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

= OAET

RELATIONSHIP TO FOCUSSED PROGRAM

L&RC

MANAGE:
- NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- EXPLORATION REGENERATIVE FUEL CELL (RFC) TECHNOLOGY DEVELOPMENT PROGRAM (SOLAR SURFACE POWER)

SUPPORT:
- EXPLORATION SOLAR SURFACE POWER PROGRAM
- SPACE STATION, HST, EOS, AND ADVANCED TDRSS NICKEL HYDROGEN BATTERY PROGRAMS

JPL

- SUPPORT NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- R&T BASE TAKES LI-TiS2 BATTERY DEVELOPMENT TO "GENERIC" CELL COMPONENT AND DESIGN DEMONSTRATION
- SPACECRAFT PLATFORMS PROGRAM ADDRESSES LI-TiS2 CELL AND BATTERY DEVELOPMENT WITH APPLICATIONS FOCUS
- ADVANCED RECHARGEABLE BATTERY CONCEPTS NOT ADDRESSED IN FOCUSSED PROGRAM

PT3-10
SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

RELATED TECHNOLOGY AREAS/EFFORTS

• PRIMARY LITHIUM BATTERY DEVELOPMENT FOR CENTAUR - AIR FORCE PROGRAM MANAGED BY JPL
• LABCOM, NSWC, AND AIR FORCE ARE DEVELOPING (AMBIENT) RECHARGEABLE LI BATTERIES FOR DEFENSE APPLICATIONS - (USUALLY FOR LIMITED CYCLE LIFE - 50 CYCLES)
• DOE LABS ARE WORKING PROGRAMS TO DEVELOP LI-POLYMER AND SODIUM METAL CHLORIDE BATTERIES FOR TRANSPORTATION; ALSO NI-METAL HYDRIDE FOR DEFENSE SPACE (JPL INVOLVED)
• AIR FORCE IS DEVELOPING Na-S BATTERY FOR DEFENSE SPACE APPLICATIONS
• SSF, HST, EOS, AND ADVANCED TDRSS NI-H₂ BATTERY PROGRAMS SUPPORTED BY LeRC
• EMA APPLICATIONS STUDY UTILIZING BIPOLAR NI-H₂ BATTERY
• DARPA UNMANNED UNDERSEA VEHICLE BATTERY POWER PROGRAM MANAGED BY LeRC
• DARPA UNMANNED UNDERSEA VEHICLE FUEL CELL POWER PROGRAM MANAGED BY LeRC
• LeRC COORDINATING WITH DOE PEM FUEL CELL PROGRAM (PASSENGER CAR APPLICATION)

JPL

CENTAUR Li-SOCl₂ BATTERY

ALLIANT VERSION

FEATURES

- WEIGHT: 75 lb, 34 kg
  (1/2 OF EXITING SILVER-ZINC BATTERY)
- LOW TEMPERATURE LIFE: 6 yrs @ 0°F
- AMBIENT TEMPERATURE LIFE: 1 yr @ 40-90°F
  (10 TIMES EXITING SILVER-ZINC BATTERY)
- CURRENT:
  • CONTINUOUS > 40 A
  • SHORT TERM > 75 A

YARDNEY VERSION

3.4 V - 250 AH CELL

QUALIFICATION OF DESIGN AND MCD 9/91

STATUS

28 V - 250 AH BATTERY

PT3-11
IPV NICKEL HYDROGEN CELL TESTING
SPACE STATION FREEDOM SUPPORT

- LEO life tests 40% DOD
- 39 Flightweight cells on test
- 50 Ah and 65 Ah capacity
- 3 Commercial vendors
- 10 °C and -5 °C temperatures
- 35% Depth-of-discharge
- 26% and 31% KOH comparison
- Cell design variations

Space Station Freedom Ni-H₂ Cells

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

SUMMARY

- TECHNICAL CHALLENGE: INCREASE PAYLOAD BY REDUCING BATTERY SYSTEM WEIGHT (2X-4X) AND VOLUME WITH OPERATIONAL LIFE BEYOND 10 YEARS. ALSO, PROVIDE HIGH VOLTAGE, PULSE POWER CAPABILITY.

- APPROACH: DEVELOP ADVANCED NICKEL-HYDROGEN BATTERY TECHNOLOGY FOR (2X-3X) STORAGE IMPROVEMENT FOR LARGER SYSTEMS (>1kW), AND U-TET FOR 2X-3X IMPROVEMENT IN SMALLER (<1kW) SYSTEMS. DEVELOP RECHARGEABLE SODIUM SYSTEMS FOR 3X-5X IMPROVEMENTS IN LONG TERM. CONDUCT FUEL CELL CATALYST RESEARCH AND DEVELOP ADVANCED CONCEPTS.

- PAYOFF:
  - MASS AND VOLUME REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED
  - INCREASE OF OPERATIONAL LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS
  - HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS
  - STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS

- RATIONALE FOR AUGMENTATION:
  - ACCELERATE TECHNOLOGY DEVELOPMENT FOR TIMELY TRANSFER TO USER (e.g., Na-S IN PHASE WITH FLIGHT EXPERIMENT, RFC CATALYST FOR EXPLORATION, LITSF FOR PLATFORMS)
  - INITIATE NEW TECHNOLOGY DEVELOPMENT (e.g., ELECTROCHEMICAL CAPACITOR, POLYMER BATTERY)

- RELATIONSHIP TO FOCUSED ACTIVITIES AND OTHER PROGRAMS:
  - PROGRAM DESIGNED TO SUPPORT VIRTUALLY ALL FOCUSED TECHNOLOGY PROGRAMS
  - JPL AND JPL PROVIDE PROGRAM MANAGEMENT, TRANSFER TECHNOLOGY, AND COORDINATE WITH OTHER NASA CODES, DOD, AND DOE

- TECHNOLOGY CONTRIBUTIONS:
  - LEO IPV NICKEL HYDROGEN BATTERY TECHNOLOGY TRANSFERRED TO NASA (HST AND SSF), MILITARY AND INDUSTRY APPLICATIONS
  - LITHIUM THIONY/CHLORIDE (PRIMARY) BATTERY TECHNOLOGY TRANSFERRED TO AIR FORCE FOR CENTAUR
SPACE ENERGY CONVERSION R&T PROGRAM

506-41

THERMAL ENERGY CONVERSION SUBELEMENT

506-41-31

PRESENTED AT THE ITP EXTERNAL REVIEW

June 26, 1991

Power Technology Division of the Aerospace Technology Directorate
NASA Lewis Research Center
Cleveland, Ohio 44135

WHAT WE WILL DISCUSS

• PROGRAM OVERVIEW
• MISSIONS AND BENEFITS
• CURRENT PROGRAM DESCRIPTION
• STRATEGIC PROGRAM DESCRIPTION
• ROADMAP/SCHEDULE/RESOURCES
• RELATED DEVELOPMENT EFFORTS
• SUMMARY
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

OBJECTIVES

- **Programmatic**
  Develop and Demonstrate High-Efficiency Solar Dynamic, Thermoelectric, Brayton/Stirling, and Alkali Metal Thermoelectric Conversion (AMTEC) Technologies

- **Technical**
  System Efficiency - > 20%
  Specific Power - 12 W/kg (TE)
  16 - 20 W/kg (SD)
  15 W/kg (AMTEC)

SCHEDULE

- 1993 Demonstrate Technical Feasibility of Solar Dynamic Heat Receiver Technologies
- 1994 15% Efficiency, 3000-Hour AMTEC Complete Critical Technology Experiments to Utilize Lunar in-situ Materials for TES
- 1995 Identify Advanced Thermoelectric Material with Z = 1.4 E-03/K
- 1996 Complete Critical Technology Experiment for Advanced Sensible Heat Receiver
- 1997 Prototype Static Conversion Module Design

RESOURCES ($M)

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PARTICIPANTS

- Lewis Research Center
  Responsibility includes advanced solar dynamic systems, Brayton/Stirling technologies

- Jet Propulsion Laboratory
  Responsibility includes advanced thermoelectrics and AMTEC

SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS

QUALITATIVE BENEFITS
- More Flexibility
- Long Life Components
- Less Drag
- Lower Mass
- Lower Recurring Costs
- Less Aggregate EVA

QUANTITATIVE BENEFITS

![Graph showing cost comparison between photovoltaic and solar dynamic systems](Image)

Notes:
5. Data change between 1990 and 1995 due to internal budget reallocations.
6. Data based on current, 1995-1999 data as at 1990-1994 data, to reflect current cost configuration. Data over data were outline in the current year's budget plan.
THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

QUALITATIVE BENEFITS
- LONGER MISSION LIFE
  - LOWER AMORTIZED COSTS
- LESS SUSCEPTIBILITY TO RADIATION EFFECTS
  - OPERATIONAL FLEXIBILITY

SMALL SATELLITES
COMMUNICATIONS, EARTH OBSERVING

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- SURFACE POWER -

QUALITATIVE BENEFITS
- PROVIDES PROCESS HEAT PLUS ELECTRICAL POWER
- USES IN-SITU MATERIALS FOR TES
- LONG LIFE COMPONENTS

QUANTITATIVE BENEFITS
COMPARISON OF ALTERNATE SOLAR POWER SYSTEMS FOR LUNAR BASE

LUNAR BASE SD POWER SYSTEM & OXYGEN PROCESS PLANT
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

CURRENT PROGRAM DESCRIPTION

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

SPACE STATION FREEDOM SOLAR DYNAMIC POWER MODULE COMPONENTS

SOLAR DYNAMIC TECHNOLOGY PERFORMANCE GOALS

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<th>CURRENT SOA</th>
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<td>- SPECIFIC POWER</td>
<td>5 - 8 W/kg</td>
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<td>- CONCENTRATOR</td>
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<tr>
<td>- MASS</td>
<td>4 kg/sq. m.</td>
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<td>- ACCURACY</td>
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<td>- RECEIVER</td>
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<td>- MASS</td>
<td>50 kg/kW</td>
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<td>- SPECIFIC POWER</td>
<td>1 - 3 W/kg</td>
<td>5 - 10 W/kg</td>
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OBJECTIVES

• IDENTIFY INNOVATIVE COMPONENT & SYSTEM CONCEPTS
• IDENTIFY CRITICAL TECHNOLOGIES
• PROVIDE SPACECRAFT AND SUBSYSTEM INTERFACE REQUIREMENTS

MILESTONES

1992 COMPLETE CONCEPTUAL DESIGN OF 5 kW HYBRID (PV/SD) SPACECRAFT
1993 DEFINE SUBSYSTEM REQUIREMENTS FOR ADVANCED SENSIBLE HEAT RECEIVER

OBJECTIVES

DEVELOP FABRICATION PROCESS TECHNOLOGY FOR:

• ACCURATE SURFACE CONTOURS (1 MILLIRADIAN)
• HIGH SPECULAR REFLECTION (90%)
• LOW SPECIFIC MASS (1-2 kg/m²)
• HIGH CONCENTRATION RATIO (2000-5000)

REFLECTOR RESEARCH OBJECTIVES

HIGHLY SPECULAR ALL ALUMINUM REFLECTOR PANEL

MILESTONES

1992 COMPLETE DEVELOPMENT OF ALL METAL FABRICATION TECHNIQUES
ADVANCED RECEIVERS

OBJECTIVES
DEVELOP HEAT RECEIVER TECHNOLOGIES THAT REDUCE THE MASS OF AVAILABLE TECHNOLOGY RECEIVERS BY AT LEAST A FACTOR OF 2

BRAYTON SOLAR RECEIVER

MILESTONES
1991 - COMPLETE INVESTIGATION OF A 0.5 kWe BENCH TOP PROTOTYPE OF DIRECT FLUID ABSORPTION RECEIVER
1993 - COMPLETE TECHNOLOGY FEASIBILITY EXPERIMENTS FOR BRAYTON CYCLE HEAT RECEIVER
1995 - COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS FOR SENSIBLE HEAT RECEIVER

THERMAL ENERGY STORAGE

OBJECTIVES
• DEVELOP 3-D CODE FOR PREDICTING VOID FORMATION/MIGRATION IN TES MEDIA UNDER MICRO-GRAVITY CONDITIONS
• DEVELOP TECHNOLOGIES FOR UTILIZING LUNAR IN-SITU MATERIALS FOR TES

Regolith Thermal Energy Storage

MILESTONES
1993 COMPLETE MODS TO THE NORVEX CODE TO COVER WEDGE GEOMETRY AND NON-WETTING MEDIA
1994 COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS OF LUNAR TES CONCEPT
MAJOR ACCOMPLISHMENTS

DESIGN & ANALYSIS
- COMPARED PV AND SD POWER SYSTEMS (7 TO 35 kW RANGE) FOR AVAILABLE, NEAR TERM, & FAR TERM TECHNOLOGIES
- IDENTIFIED ENABLING TECHNOLOGIES FOR POTENTIAL LUNAR SURFACE POWER APPLICATIONS

ADVANCED CONCENTRATORS
- SELECTED SPLINED RADIAL PANELS & HINGED PETAL DEPLOYMENT CONCEPTS
- DEVELOPED FABRICATION PROCESSES FOR ALL METAL MIRROR SECTORS
  - STRETCH-FORM PANELS
  - SPRAY & SPIN COATED SURFACE LEVELIZING LAYERS
  - MICROSEET GLASS FORMING & BONDING

ADVANCED RECEIVERS
- DESIGNED RECEIVERS FOR BRAYTON & STIRLING CONVERSION UNITS
- COMPLETED TES CRITICAL TECHNOLOGY EXPERIMENTS
  - UNIFORM FLUX WILL PRECLUDE THERMAL RATCHETING

THERMAL ENERGY STORAGE
- GERMANIUM & BORON NITRIDE ARE VIABLE TES MATERIALS
  - NO DEGRADATION AFTER 1000 CYCLES
- COMPLETED NORVEX CODE FOR LARGE VOLUME CHANGE TES MEDIA

STRATEGIC PROGRAM* DESCRIPTION

* CONTAINS ALL ELEMENTS AND ASPECTS OF CURRENT PROGRAM PLUS:

- CONDUCT EXPERIMENTS TO DEMONSTRATE TECHNOLOGY READINESS OF CRITICAL SD COMPONENTS FOR LUNAR BASE APPLICATION
  - 10 kW DIRECT ABSORPTION RECEIVER IN SANDIA ON-SUN FACILITY
  - REDUCED SCALE TES SUBSYSTEM IN RELEVANT ENVIRONMENT
**Solar Dynamic Roadmap/Schedule**

**Key Activities**

<table>
<thead>
<tr>
<th>STRATEGIC R&amp;T PROGRAM</th>
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<tbody>
<tr>
<td>- Verification of technical readiness by test of 10 kW direct-absorption receiver</td>
</tr>
<tr>
<td>- Verification of technical readiness by test of reduced scale TES subsystem</td>
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**Current R&T Program**

- Advanced Concentrator/Receiver/TES Technology Development

**Resources ($K)**

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</table>

**Related Efforts**

- In-Step Test Flight Experiments
- CSTI High Capacity Power Project
- DOD/AF Space Power Programs
- DOE Terrestrial Solar Power Program
SPACE ENERGY CONVERSION BASE R&T

THERMAL ENERGY CONVERSION

SUMMARY

- TECHNICAL CHALLENGE:
  DEVELOP HIGH EFFICIENCY, STATIC THERMAL-TO-ELECTRIC CONVERSION TECHNOLOGIES TO REDUCE THE MASS AND FUEL INVENTORY IN RADIOISOTOPE BASED SPACE POWER SYSTEMS. IMPROVE THE EFFICIENCY, RELIABILITY AND LIFE, AND REDUCE THE MASS OF SPACE SOLAR DYNAMIC POWER SYSTEMS.

- APPROACH:
  DEVELOP ADVANCED THERMOELECTRIC MATERIALS, AND AMTEC, FOR STATIC, RADIOISOTOPE-BASED POWER SYSTEMS. INVESTIGATE OTHER STATIC CONVERSION CONCEPTS AS WARRANTED. FOR SOLAR DYNAMIC SYSTEMS, FOCUS ON FABRICATION PROCESSES FOR CONCENTRATORS, HEAT PIPE RECEIVER CONCEPTS, AND UTILIZATION OF IN-SITU MATERIALS FOR TES.

- PAYOFF:
  HIGH EFFICIENCY STATIC CONVERSION COULD REDUCE RADIOISOTOPE FUEL INVENTORY BY FACTORS OF 2-5, THUS SIGNIFICANTLY REDUCING FUEL COSTS, AND REDUCING MASS AND VOLUME. FOR SOLAR DYNAMIC, REDUCED ORBITAL SYSTEM MASS BY 50% AND TRANSPORTED LUNAR MASS BY FACTORS OF 2-5 ARE THE PAYOFFS.

- RATIONALE FOR AUGMENTATION:
  ENABLES TRANSFER OF STATIC CONVERSION TECHNOLOGY INDUSTRY. EXPANDS CURRENT SOLAR DYNAMIC PROGRAM TO INCLUDE VERIFICATION OF LUNAR BASE RECEIVER, LUNAR BASE TECHNOLOGIES.

- TECHNOLOGY CONTRIBUTIONS:
  THERMOELECTRIC MATERIALS MODELING CAPABILITIES UTILIZED IN HIGH CAPACITY POWER/SP-100 PROGRAMS. ALL-METAL SOLAR CONCENTRATOR TECHNOLOGIES INCORPORATED BY SSF PROGRAM IN FY'90.
## Objectives

**Programmatic**
- Develop and demonstrate reliable, lightweight, efficient components and systems for the management and distribution of electrical power for a broad spectrum of space systems

**Technical**
- Utilize power for space, exploration power, integrated circuits (PIC), advanced power materials, environmental interaction models/guidelines, high-temperature power electronics

## Schedule

- 1993: Sample Shuttle Experiment Launch
  - Demonstrate 200°C baseplate inverter

- 1994: Complete Technology Demonstration Facility

- 1995: Prototype Smart Pole PIC
  - 1st IC Synch. Rectifier Prototype

- 1996: EPSAT based Interactions Codes Done
  - 300°C components complete
    - Advanced Synch. Rectifier PIC

  - Demonstrate high thermal conductivity
    - Graphite-Fluoride Circuit Board
    - Utility Power Demonstration

## Resources ($M)

<table>
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<th>Baseline</th>
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## Participants

- **Lewis Research Center**
  - Responsibilities: Electrical Power Management
    - Power Materials
    - Space Environment

- **Jet Propulsion Laboratory**
  - Responsibilities: Power Integration Technology
POWER MANAGEMENT AND DISTRIBUTION
PERFORMS ALL POWER SYSTEM FUNCTIONS OTHER THAN GENERATION AND STORAGE

POWER MANAGEMENT TECHNOLOGY NEEDS

- ADVANCED POWER MANAGEMENT TECHNOLOGY FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:
  
  - LUNAR AND MARS BASES
    - COMPLEX, EVOLUTIONARY SYSTEMS COMPARABLE TO TERRESTRIAL UTILITIES
    - SURVIVE UNIQUE, HOSTILE ENVIRONMENTS, INCLUDING HIGH TEMPERATURES & CHARGED DUST, CORROSIVE ATMOSPHERE & GEOTAIL
    - AUTONOMOUS OPERATION
  
  - ADVANCED SCIENCE MISSIONS: EOS PLATFORMS, PLANETARY SPACECRAFT, ETC.
    - RELIABLE, LIGHTWEIGHT SPACECRAFT POWER
      - REDUCED PARTS COUNT (75%)
      - REDUCED VOLUME (40%)
      - REDUCED MASS (50%)
    - EOS PLATFORMS: HIGH POWER & DURABLE PV BLANKETS
    - SOLAR PROBE AND MDO: VERY HIGH TEMPERATURE OPERATION
  
  - LAUNCH AND ORBITAL TRANSFER VEHICLES
    - REPLACEMENT OF HYDRAULICS WITH ELECTRICAL ACTUATORS
    - LIGHTWEIGHT INTEGRATED POWER SYSTEM
    - VEHICLE HEALTH MANAGEMENT
    - STS EVOLUTION
    - NUCLEAR ELECTRIC PROPULSION - LIGHTWEIGHT ELECTRICAL SUBSYSTEM
  
  - ENVIRONMENTALLY COMPATIBLE POWER SYSTEM
    - PV
    - NUCLEAR & SOLAR DYNAMIC
BASE R&T: SPACE ENERGY CONVERSION  POWER MANAGEMENT

PROGRAM ELEMENT INTERACTIONS

POWER MATERIALS

ENVIRONMENTAL INTERACTIONS

LeRC ELECTRICAL
- LUNAR/MARS BASES
- ETO & OTV VEHICLES
- EOS
- 5 kW - 20 MW
- AC & DC

JPL ELECTRICAL
- SPACECRAFT / PLANETARY
- PROBES
- PENETRATORS
- ROVERS
- 0.1 - 10 kW
- DC

OTHER POWER PROGRAMS
- PV
- SD
- NUCLEAR
- THERMAL MANAGEMENT
- RADIATORS
- STORAGE

TECHNOLOGY DEVELOPMENT CHALLENGE

POWER MANAGEMENT IS CHARACTERIZED BY:

COMPLEX ISSUES
- ELEMENT OF ALL SPACE SYSTEMS
  - DIVERSE REQUIREMENTS
- UNIQUE, HOSTILE ENVIRONMENTS
- REQUIRES MULTIPLE TECHNOLOGIES
  - MATERIALS
  - COMPONENTS
  - SYSTEM
- NEW MISSIONS

COMPLEX INFRASTRUCTURE
- BROAD R&D BASE
  - NASA
  - OTHER AGENCIES
  - INDUSTRY
  - OTHER NATIONS
- EXTENSIVE VENDOR BASE
  - SPACE
  - AERONAUTICS & MILITARY
  - COMMERCIAL
- SPACE IS MINOR MARKET

POWER MANAGEMENT MUST MAKE SIGNIFICANT IMPACT ON NASA PROGRAMS WITH LIMITED BUDGET AND STAFFING
TECHNOLOGY DEVELOPMENT APPROACH

- IDENTIFY CRITICAL ISSUES AND BENEFITS THROUGH PMAD SYSTEMS ANALYSIS
- AUGMENT RESOURCES THROUGH SPECIFIC TASK ASSIGNMENTS ON RELEVANT SUBJECTS
- LEVERAGE OTHER R&D EFFORTS AND COMMERCIAL DEVELOPMENTS THROUGH SPECIFIC PROJECT EFFORTS
- MAINTAIN CLOSE COMMUNICATIONS WITH TECHNOLOGY AND USER GROUPS IN NASA, OTHER AGENCIES AND INDUSTRY
Earth Observing System

POLAR ORBITING PLATFORM WET MASS

TOTAL WEIGHT IS 29715 lbs (13507 kg)

Earth Observing System

ELECTRICAL POWER SYSTEM WEIGHTS

TOTAL EPS WEIGHT IS 3284.8 lbs (1484 kg)
SPACE STATION FREEDOM

- PERMANENTLY MANNED, MULTI-PURPOSE, SPACE BASED FACILITY
- POWER HALF THE COST OF SSF
  - WP - 1
  - WP - 2
  - WP - 4
- POWER CONDITIONING, CONTROL AND DISTRIBUTION (PCC&D) MASS > GENERATION & STORAGE MASS
- BALANCE OF SYSTEM IS 2/3 OF POWER SYSTEM MASS
- MAJOR DISPUTES OVER POWER DISTRIBUTION CONVENTIONS
  - HIGH VOLTAGE DC
  - 400 Hz AC
  - 20 kHz AC
  - "WILD FREQUENCY" AC
- DIFFERENT CONCEPTS
  - EXTENSION OF SPACECRAFT TECHNOLOGY
  - SPACE POWER UTILITY

MASS ANALYSIS

- 30350 kg total BOS mass
- 80 kg (1%) SYSTEM CONTROL
- 740 kg (2%) GENERATION
- 583 kg (2%) PC&C
- 6177 kg (20%) MECHANICAL
- 5500 kg (18%) LOAD
- 8230 kg STORAGE

POWER PROCESSING, CONTROLS, AND DISTRIBUTION
STATE-OF-THE-ART
25-100 kg/kWe

PILOTED MARS NEP VEHICLE
TOTAL
5-10 kg/kWe
OTHER DEVELOPMENT EFFORTS

POWER INTEGRATION TECHNOLOGY
- SOLID STATE POWER SWITCH HYBRID FOR THE CRAFT AND CASSINI SPACECRAFT
  - HIGH RELIABILITY
  - 90 WATT DELIVERED TO LOAD
- SMART POLE HYBRID FOR 15 HP ELECTRICAL ACTUATOR
  - AIR FORCE PROGRAM 1988 - 1990
- SMART POLE HYBRID FOR PV POWER CONDITIONING
  - DOE FUNDED: AUGUST 1991 START

SPACE ENVIRONMENT
- EPSAT ENGINEERING CODE
  - SDIO SPONSORED
  - EMPHASIS ON MILITARY PLATFORMS
  - SURVIVABILITY KEY GOAL
  - COMPLETE IN FY 1992
- ENVIRONMENT WORKBENCH
  - EPSAT DERIVATIVE
  - SSF FUNDED, MINIMALLY
  - SPACE STATION SPECIFIC
  - COMPLETION REQUIRES LARGE INCREASE IN SSF FUNDING

PLASMA EFFECTS IDENTIFIED AS CRITICAL FOR SSF
MOTIVATED ENGINEERING CHANGE
- ARRAY "FLOATS" WITH 90% OF AREA BELOW PLASMA POTENTIAL
  - SSF USES NEGATIVE GROUNDING
  - SUBJECTS MODULE SURFACES TO 140 eV IONS
  - ANODIZED AL SPUTTERS, BREAKS DOWN
- SSF ELECTRICAL GROUNDING TIGER TEAM CONVENED
  - CONFIRMED EFFECTS
  - EVALUATED GROUNDING CHANGES OR OTHER WAYS TO REDUCE SSF FLOATING POTENTIAL
  - EPSAT-BASED CODE (EBW) MADE DESIGN TRADES EASY
  - RECOMMENDED PLASMA CONTACTOR TO CONTROL POTENTIALS
  - CONSIDERING ARRAY REDESIGN TO REDUCE ELECTRON CURRENT COLLECTION - LeRC NASCAP/LEO MODELING RESULT
OTHER DEVELOPMENT EFFORTS (con'td)

ELECTRICAL COMPONENTS AND SYSTEMS

- SYSTEMS DIAGNOSTICS, RADIATION TOLERANT SWITCHES AND HIGH TEMPERATURE MAGNETICS
  - CSTI - HIGH CAPACITY POWER
- STIRLING LINEAR ALTERNATOR - PC&C
  - CSTI - HIGH CAPACITY POWER
- NASA WIRING STUDY (KAPTON REPLACEMENT)
  - CODE - Q
- HIGH FREQUENCY LINK AND ELECTRIC ACTUATORS
  - ALS AND CODES R-M BRIDGING TECHNOLOGY
  - NLS AND SHUTTLE UPGRADES
- MORE ELECTRIC AIRPLANE
  - CODE RP & DOD
- AUTONOMOUS POWER SYSTEM & EXPERT SYSTEMS
  - CSTI - ARTIFICIAL INTELLIGENCE
- SYSTEMS ANALYSIS (SCIENCE)
  - CODE RS
- MULTI-MEGAWATT INVERTER TECHNOLOGY
  - USAF
- SPACE BASED TESTBED (SC-2000)
  - CODE C

POWER MATERIALS

- SPACE POWER MATERIALS TECHNOLOGY
  - CODE RP
- HIGH EMITTANCE RADIATOR SURFACES FOR SP-100
  - CODE RP
- DIAMOND THIN FILMS
  - SDIO
- PV ARRAY ATOMIC OXYGEN PROTECTION
  - SSF: ARRAY PROTECTION SYSTEM ADOPTED
- PV POWER MODULE RADIATOR SURFACE LEO DURABILITY
  - SSF: RECOMMENDED MODIFICATIONS ADOPTED
- SPACE STATION FREEDOM ARRAY MATERIALS EROSION FLIGHT EXPERIMENT ON EOIM III
  - SSF
- PV ARRAY FLEXIBLE CIRCUIT CARRIER KAPTON PYROLYZATION
  - SSF
OTHER DEVELOPMENT EFFORTS (con'td)

- LEO ENVIRONMENTALLY DURABLE MATERIALS
  - CODE RM
- NASA ATOMIC OXYGEN EFFECTS TEST PROGRAM
  - CODE RM
- LDEF POST RETRIEVAL ANALYSIS
  - CODE RM
- PARA-TO-ORTHO HYDROGEN CONVERSION CATALYTIC SURFACES
  - NASP
- DIAMOND-LIKE FILMS FOR OPHTHALMIC LENS PROTECTION
  - TECHNICAL UTILIZATION
- OXYGEN DIFFUSION BARRIER COATINGS FOR BEVERAGE CONTAINERS
  - EASTMAN CHEMICAL CO.

SPINOFF APPLICATIONS OF
FLEXIBLE ATOMIC OXYGEN PROTECTIVE COATINGS
POWER MANAGEMENT

DEVELOPMENT OF TECHNOLOGY INFRASTRUCTURE
FOR NASA MISSIONS

NASA—LeRC
POWER TRANSISTOR TECHNOLOGY TRANSFER

BENEFITS TO NASA
• CRITICAL TRANSISTORS ARE NOW COMMERCIALLY AVAILABLE AT LOW COST
• INDUSTRIAL APPLICATIONS WILL DEMONSTRATE RELIABILITY
• DESIGNER ACCEPTANCE IS DEVELOPED FOR USE IN SPACE POWER APPLICATIONS

WESTINGHOUSE
(PROJECTED)
• INVESTMENT 2 (MILLION)
• SALES 540 (THOUSAND) PER YEAR

WESTINGHOUSE
• INVESTMENT 1 (MILLION)
• SALES 200 (THOUSAND) PER YEAR

1974-78 1978-81 1981-84

• NASA MINOR PLAYER IN POWER AND CONTROL ELECTRONICS INDUSTRIES
• REQUIRED TECHNOLOGY ONLY AVAILABLE IF THERE IS AN INDUSTRIAL BASE
• OAET CAN IMPACT BASE THROUGH JUDICIOUS SEED PROJECTS
• D60T AND OTHER POWER TRANSISTORS NOW IN WIDE USE BY NASA, DoD AND INDUSTRY
• MCT NOW ENTERING PRODUCTION AFTER JOINT SPONSORSHIP BY NASA, DoD AND EPRI

BASE R&T: SPACE ENERGY CONVERSION
POWER MANAGEMENT

TECHNOLOGY CHALLENGES

SPACECRAFT POWER MANAGEMENT

• ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ATDRSS, ETC.
• OBJECTIVE: EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

POWER FOR ADVERSE ENVIRONMENTS

• LUNAR/MARS BASES, SELF-INDUCED ENVIRONMENTS
• OBJECTIVE: DEVELOP HIGH TEMPERATURE, RADIATION TOLERANT POWER ELECTRONICS AND RESOLVE OTHER ENVIRONMENTAL HAZARDS

UTILITY POWER

• MANNED SYSTEMS, SPACE EXPLORATION INITIATIVE
• OBJECTIVE: PROVIDE SPACE SYSTEMS WITH THE SAFETY, FLEXIBILITY, MAINTAINABILITY AND USER TRANSPARENCY NOW FOUND ONLY IN TERRESTRIAL POWER UTILITIES
BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

SPACECRAFT POWER MANAGEMENT

OBJECTIVE:

EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

• ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ADRSS, ETC.

APPROACH/BENEFITS:

• POWER INTEGRATED CIRCUITS
  - REDUCE PARTS COUNT BY 75% (INCREASED RELIABILITY)
  - REDUCE WEIGHT BY 50%
  - REDUCE VOLUME BY 40%
  - INCREASED POWER DENSITY (X10) AND INCREASE EFFICIENCY

• INTERCALATED GRAPHITE ELECTRONIC ENCLOSURES
  - EQUIVALENT TO METAL BOXES FOR EMI SHIELDING AND STRENGTH
  - 1/2 - 1/4 WEIGHT OF METAL - STRUCTURES/MECHANISMS 20% OF POWER SYSTEM MASS

• EOS: ATOMIC OXYGEN PROTECTIVE COATINGS FOR SOLAR ARRAYS IN LEO
  - KAPTON SUBSTRATE MASS LOSS < 50% OVER 15 YEARS

CONVENTIONAL SPACECRAFT POWER

SYSTEM DRIVERS

• DEDICATION MISSION
• MINIMUM MASS
• HIGH RELIABILITY
  - MINIMAL ON-ORBIT REPAIR

MULTIPLE, INCOMPATIBLE, "STANDARD" BUSES

- GENERATION: SOLAR ARRAY OR RTG
- STORAGE: BATTERIES
- POWER CONDITIONING CONTROL AND DISTRIBUTION
  - SINGLE/DUAL BUS
  - FULL, SUNLIGHT OR UNREGULATED
  - SHUNT OR PEAK POWER TRACKER
  - 28-50 VDC

PT5-11
STATE OF THE ART ASSESSMENT

- GENERAL ASSESSMENT: CURRENT GENERIC POWER MODULES ARE OF VERY LIMITED UTILITY (e.g. low power, simple functions), LOW AVERAGE EFFICIENCIES, WILL NOT MEET SPACE APPLICATION REQUIREMENTS.

- DETAILED ASSESSMENT:
  - CURRENT HYBRID MODULES ARE DRIVEN BY THE AUTOMOBILE INDUSTRY FIRST, PC INDUSTRY SECOND
  - CURRENT, MULTI-FUNCTION or SMART, HYBRID MODULES ARE LIMITED IN POWER DELIVERY (e.g. 30 WATTS DISSIPATION)
  - HYBRID TECHNOLOGY IS NOT READY TO SUPPORT THE THERMAL NEEDS OF A SPACE BOUND DEVICE
  - MONOLITHIC TECHNOLOGY FOR POWER INTEGRATED CIRCUITS IS LIMITED TO LOW POWER (1 TO 3 WATTS)
  - MONOLITHIC PROCESSING OF POWER INTEGRATED CIRCUITS, INTEGRATING HIGH POWER AND CONTROL FUNCTIONS, IS NOT A MATURE TECHNOLOGY
INTERCALATED GRAPHITE COMPOSITE EMI SHIELDS

METALLIC SHIELDING -- COMPOSITE WEIGHT

AT LEAST 80 dB SHIELDING/MM THICKNESS

80 PERCENT REDUCTION IN SHIELD MASS
16 PERCENT REDUCTION IN POWER SYSTEM MASS
UP TO 40 PERCENT PAYLOAD INCREASE

COMPARSED TO STANDS \textsuperscript{7} ALUMINUM EMI COVERS

PT5-13
ATOMIC OXYGEN PROTECTIVE COATINGS FOR LOW EARTH ORBIT POWER SYSTEM SURFACES

ATOMIC OXYGEN ATTACK
- Occurs at defects in coating
- Results in large area of damage
- Optical then mechanical degradation

RECOMBINATIVE PROTECTIVE COATINGS
- Coating catalyses $O_2 \rightarrow O$ reaction
- Limits undercutting damage

50% REDUCTION IN SOLAR ARRAY BLANKET MASS

BASE R&T: SPACE ENERGY CONVERSION POWER MANAGEMENT

POWER FOR ADVERSE ENVIRONMENTS

OBJECTIVE:
- Develop high temperature, radiation tolerant power electronics and resolve other environmental hazards
  - Lunar/Mars bases
  - Self-induced environments

APPROACH/BENEFITS:
- Develop radiation-hard, high-temperature power electronics: materials, devices and systems
  - Allow operation on lunar surface without need for insulated enclosures and heat pumps
  - Reduce size and mass of low temperature radiator by factor of 2 or more
  - Enable nuclear and SD power systems
- Model interactions between power systems and various space plasmas and gases
  - Avoid disabling electrical discharges and system degradation
  - Provide environmental guidance to system designers
- Avoid damage and system degradation due to lunar and Mars dust
  - Wind and other abrasion
  - Shadowing of solar energy collections and radiator surfaces

PT5-14
HIGH TEMPERATURE ELECTRONICS PROGRAM

GOALS
- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST

TECHNOLOGICAL DEVELOPMENTS
- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS
- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT

POWER TECHNOLOGY DIVISION
AEROSPACE TECHNOLOGY DIRECTORATE

200°C-BASEPLATE ELECTRONICS
SURVIVES SEVERE ENVIRONMENTS AND LIGHTENS RADIATORS

GOAL: BUILD & TEST ASSEMBLY
- ACHIEVABLE (100°C > SOA)
- UNCOVERS MISSING TECHNOLOGY
- EXCEEDS LUNAR TEMPERATURE (130°C)
- REDUCES RADIATOR AREA > 2
- BROAD SPINOFFS

H. T. TEST LAB

POWER TECHNOLOGY DIVISION
AEROSPACE TECHNOLOGY DIRECTORATE

200°C-BASEPLATE ELECTRONICS
SURVIVES SEVERE ENVIRONMENTS AND LIGHTENS RADIATORS

GOAL: BUILD & TEST ASSEMBLY
- ACHIEVABLE (100°C > SOA)
- UNCOVERS MISSING TECHNOLOGY
- EXCEEDS LUNAR TEMPERATURE (130°C)
- REDUCES RADIATOR AREA > 2
- BROAD SPINOFFS

H. T. TEST LAB
SILICON CARBIDE TECHNOLOGY FOR HIGH TEMPERATURE ELECTRONIC SWITCHES

Goal:
Develop and demonstrate a high temperature and radiation resistant SiC MOSFET power switch

Recently fabricated 6H-SiC grown junction light emitting diode operating at 600 °C

Accomplishments
• Demonstrated high quality 6H-SiC epitaxial film growth processes
• Demonstrated capability to dope 6H-SiC films p-type with aluminum
• Fabricated prototype 6H-SiC MOSFET and successfully tested to 500 °C

GRAPHITE FLOURIDE HIGH THERMAL CONDUCTIVITY PRINTED CIRCUIT BOARDS

<table>
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<th>Graphite Fluoride (GF-123)</th>
<th>Fiber glass (S Glass)</th>
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<tbody>
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<td>Electrical resistivity</td>
<td>2.5 x 10⁻⁴</td>
<td>10¹¹</td>
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<tr>
<td>(Ω cm)</td>
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<td>10¹⁴</td>
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<td>11</td>
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<td>Young modulus (Msi)</td>
<td>105</td>
<td>25</td>
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<tr>
<td>Strength (Ksi)</td>
<td>300</td>
<td>40</td>
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<tr>
<td>Longitudinal tensile</td>
<td>500</td>
<td>500</td>
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<tr>
<td>Temperature expansion</td>
<td>-1</td>
<td>8</td>
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<tr>
<td>(CTE) (ppm/K)</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.18</td>
<td>2.5</td>
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</table>

Thermal conductivity of various materials:
- Epoxy
- Kapton
- Glass
- Quartz
- Graphite fluoride
- Stainless steel 304
- Copper
CVD DIAMOND FILMS FOR HIGH POWER ELECTRONICS

SYNTHESIS

CHARACTERIZATION

& MODELLING

OF CVD DIAMOND

WILL ENABLE:

- More Efficient Heat Spreaders
- Lower Device Operating Temperatures
- Increased Device Reliability/Lifetime
- Increased Specific Power
- Elaborate Device Geometries

Space Environment Activity

SAMPLE Shuttle Flight Experiment

1. Serve as principal investigator and project scientist of approved Shuttle flight experiment.
2. Obtained approval for phase C/D flight experiment development.
3. Performing ground tests in plasma interactions facility at LeRC.
4. SAMPLE will space test SSF, APSA, "arc-free," and "electron current choking" designs.

FIGURE: SAMPLE on Hitchhiker pallet in Shuttle bay.

PT5-17
EPSAT
Environment - Power System Analysis Tool

System Design Tool For Large Space Based Power Systems
- System Analysis Of Complex Systems
- Incorporate Many Analysis Models
- Changeable As System Concepts Evolve

Technology Transfer
Scientists and Engineers → Power System Design Engineers

EPSAT Performs Multi-Step Analysis By Connecting Output To Input

ORBIT
SYSTEM DEFINITION
SYSTEM GEN. ENVIRON.
NATURAL ENVIRONMENT
ANALYSIS OR TRADE OFF STUDY
EPSAT - A FOUNDATION FOR SEI

- EPSAT DEVELOPED UNDER SDIO FUNDING
  - COMPLETE FOR SDIO ENVIRONMENTS
  - CONSIDERED A MAJOR SUCCESS, AND HAS BEEN EMBRACED BY LARGE COMMUNITY OF MILITARY SPACECRAFT DESIGNERS & ENGINEERS
  - A VERSION CALLED ENVIRONMENTS WORKBENCH IS UNDER DEVELOPMENT FOR SPACE STATION DESIGNERS

- NEW NASA MISSIONS DEMAND NEW ENVIRONMENT AND EFFECTS MODULES AND VALIDATION THEREOF
  - LUNAR/MARS BASES
  - NEP/NTP

LUNAR ENVIRONMENTAL INTERACTIONS WITH POWER SYSTEMS

PREDICTED LUNAR DUST ACCUMULATION AFTER MULTIPLE MISSIONS WITH 26,800-N LAUNCH VEHICLE

DUST ACCUMULATION PREDICTED TO:
- OCCUR BY SEVERAL MECHANISMS
- BE SIGNIFICANT WITH TIME, DISTANCE
- DRAMATICALLY REDUCE PV PERFORMANCE
- REDUCE RADIATOR PERFORMANCE

THEORETICAL APPROACH

EXPERIMENTAL APPROACH
DURABILITY OF MARTIAN SURFACE POWER SYSTEMS

THEORETICAL PREDICTIONS

\[ C + CO_2 \rightarrow 2 CO \]

![Graph showing the reaction of \( C + CO_2 \rightarrow 2 CO \)]

EXPERIMENTAL VERIFICATION

Martian Atmospheric Chemistry Simulator (MACS)

- Dust Accumulation
- Aeolian Effects
- Chemical Degradation
- Component Testing
- Thermal Cycling
- Radiation Damage
- Paschen Breakdown
- Abatement Techniques

UTILITY POWER FOR SPACE EXPLORATION

- Combines spacecraft & terrestrial attributes
- Space infrastructure requires commonality with diversity
- Requirements and approach need to be defined
- Spacecraft designs inappropriate

SBOTV PLATFORM

AL\S

SHUTTLE II
EXPLORATION MISSIONS

NEW SYSTEMS

- LUNAR/MARS BASE
- SPACE STATIONS
- ROVERS

- ADVANCED LAUNCH SYSTEMS
- TRANSFER VEHICLES (CHEMICAL)
- TRANSFER VEHICLES (NUCLEAR)

NEW TECHNOLOGIES

- NUCLEAR REACTOR
- SOLAR DYNAMIC
- CONVERSION
  - BRAYTON
  - STIRLING
  - RANKINE
- REGEN-FUEL CELL
- FLYWHEEL

CHANGED LOADS

- 1 kW TO > MW
- CONNECTABLE LOADS
  - DIVERSE (SOME LARGE) & > 100
  - >> GEN. CAPACITY
  - LOAD SCHEDULING
- SYSTEM INTERCONNECT
- MOTOR & ELECTRICAL ACTUATOR
  - HIGH REACTIVITY
  - HIGH PEAK POWER
  - REVERSE POWER FLOW

FUTURE POWER SYSTEMS WILL BE VERY DIFFERENT FROM TODAY'S SPACECRAFT SYSTEMS
DEDICATED vs UTILITY POWER SYSTEMS

### REQUIREMENTS

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<tr>
<th>CHARACTERISTIC</th>
<th>DEDICATED</th>
<th>UTILITY</th>
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<tbody>
<tr>
<td>Source Capacity</td>
<td>1-10 kW</td>
<td>kW-MW</td>
</tr>
<tr>
<td>Source Number</td>
<td>1-2</td>
<td>Multiple</td>
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<tr>
<td>Growth</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Fixed</td>
<td>Extendible</td>
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<tr>
<td>Repairable</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Load/Source Cap.</td>
<td>&gt;1</td>
<td>&gt;&gt;1</td>
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<tr>
<td>Physical Size</td>
<td>Small</td>
<td>Large</td>
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<tr>
<td>Flexibility</td>
<td>Loads fixed</td>
<td>Loads vary</td>
</tr>
<tr>
<td>Manned</td>
<td>No</td>
<td>Yes</td>
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### APPROACH

**DEDICATED**
- FOCUS ON MEETING
  - MISSION SPECIFIC REQUIREMENTS
  - ADAPT EXISTING SPACECRAFT BUS

**UTILITY**
- FOCUS ON MAJOR SYSTEM ELEMENTS
  - GENERAL REQUIREMENTS
  - FUNCTIONS
  - MUTUAL COMPATIBILITY
  - COMBINE MODULAR ELEMENTS
  - INCLUDE REQUIREMENTS FOR
    - REPAIRS
    - USER TRANSPARENCY
    - EVOLUTIONARY DEVELOPMENT

**UTILITY APPROACH** INCREASES DDT&E COSTS BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.

BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

SPACE UTILITY SYSTEMS
AC versus DC

- **SPACE SYSTEMS - BASED ON DC**
- **TERRESTRIAL & AIRCRAFT - BASED ON AC**
  - HEAVY
  - HIGH FREQUENCY AC DEVELOPED TO REDUCE MASS

- **SSF FREQUENCY SELECTION**
  - EXTENSIVE TRADE STUDIES
  - DC AND 20 kHz AC TESTBEDS (25 kW)
  - TECHNOLOGY READINESS
  - SELECTED DC (FY91 BUDGET RESTRICTIONS)
    - LOWER DEVELOPMENT COST, LOWER PERFORMANCE
    - HIGHER TRANSPORTATION COSTS

- **DATA BASE FOR SPACE EXPLORATION**
AC versus DC POWER CONDITIONING

- AC TRADES UP-STREAM COMPLEXITY FOR DOWN-STREAM SIMPLICITY
  - e.g. INVERTER + TRANSFORMERS vs. DIRECT COUPLE + DC-DC CONVERTER

- DC ATTRACTIVE FOR SPACECRAFT POWER
  - DIRECT-COUPLED SOLAR ARRAY
  - SIMPLE DISTRIBUTION & LOAD STRUCTURE (DOWN STREAM)

- AC ATTRACTIVE FOR SPACE UTILITY
  - COMPLEX DISTRIBUTION
  - HIGH FANOUT

### SUBSYSTEM CAPACITIES & MASSES
(SSF EXAMPLE)

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>CAPACITY (kW)</th>
<th>MASS (kg)</th>
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<tbody>
<tr>
<td>GENERATION PC&amp;C</td>
<td>8 x 9.775</td>
<td>1740</td>
</tr>
<tr>
<td>STORAGE PC&amp;C</td>
<td>8 x 12.5</td>
<td>1950</td>
</tr>
<tr>
<td>INTERCONNECT</td>
<td>8 x 12.5</td>
<td>740</td>
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<tr>
<td>PRIMARY DISTRIBUTION</td>
<td>8 x 12.5</td>
<td>583</td>
</tr>
<tr>
<td>SECONDARY</td>
<td>32 x 12.5</td>
<td>6177</td>
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<tr>
<td>LOADS PC&amp;C</td>
<td>&lt; 2000</td>
<td>5500</td>
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BASE R&T: SPACE ENERGY CONVERSION
POWER MANAGEMENT

ADVANCED PMAD FOR GROWTH STATION
MASS DISTRIBUTION AND SAVINGS

HIGH FREQUENCY AC AND HIGH TEMPERATURE PMAD COMPONENTS
• LIGHTER PMAD
• HIGHER EFFICIENCY
• REDUCED ARRAYS & BATTERIES
• REDUCED RADIATORS & THERMAL SYSTEMS

PRESENT POWER SYSTEM MASSES

HIGH FREQUENCY LINK, INDUCTION MOTOR DRIVE SYSTEM
PRINCIPLES/BENEFITS
OF NEW MOTOR DRIVE

- DEMO 5hp INDUCTION MOTOR DRIVE
  - PULSE POPULATION MODULATION
    FROM HIGH FREQUENCY LINK
  - FIELD ORIENTED CONTROL
- MAX TORQUE AND EFFICIENCY AT ANY SPEED
- MINIMIZES STRESS ON ELECTRICAL COMPONENTS
- MINIMIZES EMI/EMC

PAYOFFS FOR LAUNCH VEHICLES AND AIRCRAFT:
- OPERABILITY—LAUNCH ON DEMAND
- REDUCE MAN TESTS, COSTS
- ELIMINATE HYDRAULICS, APU’S, CARTS
- REDUCE WEIGHT, ENERGY

POWER TECHNOLOGY DIVISION

PT5-24
POWER TECHNOLOGY DIVISION

LeRC IN-HOUSE EMA
(ELV/ATLAS)

- Joint NASA-General Dynamics exchange program
- 20 Hp nominal, 30 Hp peak induction motor drive system
- BIT (Built-in-Test) capability
  - Phase voltage and current testing
- DSP Control scheme
- Optically coupled, closed loop field oriented control
- Schedule

<table>
<thead>
<tr>
<th>System Design</th>
<th>FY '91</th>
<th>FY '92</th>
<th>FY '93</th>
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<td>System Build-up</td>
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<tr>
<td>System Testing</td>
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BASE R&T: SPACE ENERGY CONVERSION     POWER MANAGEMENT

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE

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<tbody>
<tr>
<td>TECH. DEMO</td>
<td>UTILITY POWER DEMONSTRATION *</td>
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</table>

200°C PMAD

1 kg/kW PMAD

PMAD SYSTEM STUDIES

COMPONENTS

AKGaAs SWITCH *

SYSTEM DESIGN

PMAD BREADBOARD

PASSIVE COMPONENTS

SiC/DIAMOND POWER SWITCH *

STRATEGIC ONLY

* REDUCED SCOPE & SCHEDULE IN BASELINE

PTS-25
POWER MANAGEMENT AND DISTRIBUTION BASE R&T

POWER INTEGRATION TECHNOLOGY

ROADMAP/SCHEDULE

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<tr>
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<td>Power Switch Hybrid</td>
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<tr>
<td>Current</td>
<td>HYBRID SWITCH</td>
<td>SMART PROTOTYPE</td>
<td>SMART HYBRID MODULE</td>
<td>MONOLITHIC SMARTS</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Augmented</td>
<td>SMART PROTOTYPE</td>
<td>SMART HYBRID MODULE</td>
<td>MONOLITHIC SMARTS</td>
<td>INTEGRATED SMART POLE</td>
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<tr>
<td>Synchronous Rectification</td>
<td>Prototype</td>
<td>Advanced Prototype</td>
<td>SMART Prototype</td>
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<tr>
<td>Current</td>
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<td>Advanced Prototype</td>
<td>SMART Prototype</td>
<td>INTEGRATED SMART SYNCH. RECT.</td>
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<td></td>
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<td></td>
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<tr>
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</table>

JUNE 26, 1991

POWER MANAGEMENT

ACCOMPLISHMENTS - TRANSFERRED TECHNOLOGY

POWER INTEGRATION

- ELECTRONIC SWITCHING (REMOTE POWER CONTROLLER) ADOPTED FOR CRAFT

ELECTRICAL COMPONENTS AND SYSTEMS

- DEVELOPED FIRST LARGE POWER TRANSISTOR (DGQ) - NOW IN WIDE USE IN DOD AND INDUSTRY
- 150 VDC REMOTE POWER CONTROLLER ADOPTED FOR SSF
- "ROLL RING" ROTARY POWER TRANSFER DEVICE ADOPTED FOR SSF
- HIGH FREQUENCY PMAD ADOPTED FOR SSF (LATER CHANGED TO PC)
- PULSE DENSITY MODULATED DRIVE AND INDUCTION MOTORS ADOPTED FOR ALS TVC AND PRIME CANDIDATE FOR NLS ACTUATORS
- MOSFET CONTROLLED THYRISTOR (MCT) NOW IN PRODUCTION
- FIBER OPTIC CURRENT METER TO BE PRODUCED BY 3M FOR POWER INDUSTRY APPLICATION

ENVIRONMENTAL INTERACTIONS

- NASCAP IN WIDE USE FOR DESIGN OF GEO SPACECRAFT
- EPSAT IN USE FOR SDIO MISSIONS
- SSF ARRAY DESIGNS BASED ON SAMPE AND L&RC TESTS
- REVISED "GROUNDING" FOR SSF

POWER MATERIALS

- ATOMIC OXYGEN PROTECTION COATING USED ON SSF ARRAYS
- COATING ALSO BEING EVALUATED FOR BEVERAGE INDUSTRY
- Z93 COATING USED ON SSF RADIATORS
- DIAMOND-LIKE FILMS TO BE USED FOR FACE SHIELDS, HELICOPTER WIND SHIELDS & EYE GLASSES

PT5-27
TECHNICAL CHALLENGE: FOR ALL MISSIONS, PMAD INTEGRATES POWER SUBSYSTEM WITH THE TOTAL SYSTEM AND SATISFY ITS REQUIREMENTS. NEW TECHNOLOGY IS REQUIRED TO:
- MEET EMERGING NEEDS OF NEW MISSIONS: BASES, ROVERS, PLATFORMS, VEHICLES
- REDUCE PMAD MASS AND COST (NOW 1/2 - 1/4 THOSE OF POWER SYSTEM)
- INCREASE SYSTEM SAFETY, LIFE, FLEXIBILITY AND USABILITY

APPROACH: MUST ADDRESS EXTREMELY COMPLEX SET OF ISSUES, MULTIPLE TECHNOLOGIES AND A MASSIVE COMMERCIAL INFRASTRUCTURE
- FOUR INTERLINKED RESEARCH GROUPS WITH DIFFERENT SPECIALTIES
- SYSTEM ANALYSIS TO IDENTIFY ISSUES AND QUANTIFY BENEFITS
- COMMERCIAL DEVELOPMENT & MARKET SERVE AS PROGRAM AMPURERS

PAYOFF: IMPACTS ALL MISSIONS, EITHER ENABLING OR ENHANCING
- SIGNIFICANTLY REDUCED MASS AND COST
- GREATER SAFETY, RELIABILITY AND LIFETIME
- FLEXIBLE AND USER FRIENDLY POWER SYSTEMS
- CONFIDENT SYSTEM DEVELOPMENT

FUNDING AUGMENTATION NEEDED TO ASSURE THAT ALL CRITICAL ISSUES ARE ADDRESSED AND TECHNOLOGY INFRASTRUCTURE IS AVAILABLE WHEN NEEDED

PMAD PROGRAM IMPACTS ALL FOCUS THRUSTS AND 12 THRUST ELEMENTS
- STRONG SYNERGISM WITH AERONAUTICS, DoD PROGRAMS AND COMMERCIAL APPLICATIONS
INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
-JUNE 26, 1991-

BASE R & T PROGRAM
THERMAL MANAGEMENT
(506-41-51)

T. D. SWANSON
GOO D ARD SPACE FLIGHT CENTER

BASE R & T PROGRAM
SPACE ENERGY CONVERSION R & T

OBJECTIVES

- PROGRAMATIC
  DEVELOP ADVANCED ORBITAL AND PLANETARY THERMAL CONTROL TECHNOLOGIES WITH LOW MASS, HIGH RELIABILITY, AND LONG LIFE

- TECHNICAL
  HEAT PUMPS 7 KG/KW
  RADIATOR MASS 1 - 4 KG/M2
  CRYOGENIC HEAT PIPES 3X
  POWER ELECTRONICS 1/20

SCHEDULE

- 1992 DEMONSTRATE LIQUID SHEET RADIATOR
- 1995 DEMONSTRATE 2X SOA IMPROVEMENT IN CRYOGENIC HEAT PIPES
- 1996 DEMONSTRATE ADVANCED HEAT PUMPS (3X SOA) SUITABLE FOR MICRO G
- 1997 COMPLETE INTEGRATED TEST FOR POWER ELECTRONICS RADIATOR
- 1998 VALIDATE ANALYTICAL MODELS FOR HEAT PUMPS AND HEAT PIPES

RESOURCES

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<th>YEAR</th>
<th>CURRENT</th>
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<td>$1.0M</td>
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</tr>
<tr>
<td>1994</td>
<td>$1.1M</td>
<td>$1.4M</td>
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<td>1995</td>
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<td>1999</td>
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PARTICIPANTS

- GODDARD SPACE FLIGHT CENTER
  RESPONSIBILITY INCLUDES THERMAL CONTROL OF INSTRUMENTATION, SENSORS, AND OTHER HEAT DISSIPATING EQUIPMENT

- LEWIS RESEARCH CENTER
  RESPONSIBILITY INCLUDES ADVANCED RADIATOR CONCEPTS AND ADVANCED POWER ELECTRONICS COOLING
PROGRAM SCOPE

THE THERMAL MANAGEMENT BASE R & T PROGRAM WILL SUPPORT FUTURE ORBITAL, DEEP SPACE, AND PLANETARY MISSIONS BY DEVELOPING A BROAD, GENERIC TECHNOLOGY BASE IN NEW THERMAL CONTROL SYSTEMS AND COMPONENTS.

CURRENT THERMAL MANAGEMENT SITUATION

THERMAL CONTROL TECHNOLOGY IS CURRENTLY EXPERIENCING A MAJOR GROWTH IN REQUIREMENTS. THIS IS DRIVEN BY MAJOR INCREASES IN SPACECRAFT:

• PHYSICAL SIZE
• POWER LEVEL
• COMPLEXITY

EVOLUTION OF TECHNOLOGY FROM DISCRETE TO CENTRAL THERMAL CONTROL

IMPLICATIONS INCLUDE:

• NOW ENABLING TECHNOLOGY (EOS PLATFORM)
• GREATER RISK; FAILURE NOT GRADUAL, MAY CAUSE LOSS OF SPACECRAFT
GROWTH IN SIZE

POWER IN = HEAT REJECTED

GROWTH IN COMPLEXITY
BUILDINGS/SPACECRAFT ANALOGY

1800's
Fireplace and Windows

Early-Mid 1900's
Furnace and Windows

Today
Central, multi-zone heating and cooling

1960's and 1970's
MLI and heaters

1980's
Pumped single phase and heat pipes

1990's
Two-phase central thermal bus
DOD PREDICTIONS

<table>
<thead>
<tr>
<th>YEAR</th>
<th>BASELINE (KG)</th>
<th>CURRENT (KG)</th>
<th>PROJECTED (KG)</th>
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<tr>
<td>1975</td>
<td>940</td>
<td>1300</td>
<td>1950</td>
</tr>
<tr>
<td>1990</td>
<td>1350</td>
<td>3750</td>
<td>15000</td>
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<tr>
<td>2000</td>
<td>180</td>
<td>1350</td>
<td>7000</td>
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<tr>
<td>THERMAL DISSIPATION (W)</td>
<td>670</td>
<td>2400</td>
<td>8000</td>
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</table>
DOD PREDICTIONS

APPROACH

PROGRAMMATIC ELEMENTS FOR ACCOMPLISHING THIS EFFORT INCLUDE THE FOLLOWING:

- MISSION FOCUSED SYSTEMS LEVEL ANALYSIS STUDY TO IDENTIFY NEEDS
- MULTI-CENTER PARTICIPATION
- LEVERAGE WITH DOD, DOE AND OTHER NASA EFFORTS (SBIR, IN-STEP EXPERIMENTS, PROJECT SUPPORTED WORK)
- TRANSITION FROM OAET SUPPORT TO PROJECT SUPPORT AS TECHNOLOGY MATURES
- 10 TO 15 YEAR LEAD TIME NEEDED
- PURSUE MULTIPLE TECHNOLOGY OPTIONS (FOR STRATEGIC LEVEL OF FUNDING)
TECHNOLOGY NEEDS

ANALYSIS OF FUTURE MISSIONS, SUCH AS SECOND GENERATION EOS PLATFORMS, LUNAR BASE, MARS MISSION, AND CRAFT/CASSINI, INDICATE THE FOLLOWING FUTURE REQUIREMENTS:

- GREATER POWER LEVELS
- MORE HEAT LOAD SOURCES
- HEAT LOADS BURIED WITHIN BODY OF THE SPACECRAFT WITH NO VIEW TO SPACE
- CONFLICT BETWEEN RADIATOR VIEWS AND INSTRUMENT VIEWS
- GREATER TRANSPORT LENGTHS
- TIGHTER TEMPERATURE CONTROL
- INCREASED CRYOGENIC TEMPERATURE CONTROL
- HIGHER RELIABILITY
- LOWER WEIGHT

TECHNOLOGY OPTIONS

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<thead>
<tr>
<th>TECHNOLOGY</th>
<th>HARDWARE/SOFTWARE NEEDED</th>
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<tr>
<td>CENTRAL TWO-PHASE BUS</td>
<td>- HEAT PUMPS</td>
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<tr>
<td></td>
<td>- ANALYTICAL MODEL OF FLUIDS IN MICRO-GRavity</td>
</tr>
<tr>
<td></td>
<td>- LONG LIFE MECHANICAL PUMPS FOR AMMONIA</td>
</tr>
<tr>
<td></td>
<td>- PUMP CONTROLLER</td>
</tr>
<tr>
<td></td>
<td>- UNDERSTANDING OF NON-CONDENSABLE GAS ISSUE</td>
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<tr>
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<td>- LIGHT WEIGHT MATERIALS</td>
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<tr>
<td>REDUCED RADIATOR AREA/WEIGHT</td>
<td>- COMPOSITE RADIATORS</td>
</tr>
<tr>
<td></td>
<td>- INNOVATIVE CONCEPTS</td>
</tr>
<tr>
<td></td>
<td>- HEAT PUMPS</td>
</tr>
<tr>
<td></td>
<td>- ELIMINATE NEED FOR EXTERNAL POWER ELECTRONICS RADIATOR</td>
</tr>
<tr>
<td></td>
<td>- LIQUID METAL MICRO HEAT PIPE</td>
</tr>
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<td>- DIRECT IMMERSION HEAT PIPE</td>
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HEAT PUMP TWO-PHASE BUS CONCEPT
-INCREASE REJECTION TEMPERATURE/COOL PAYLOAD-

COMPRESSOR

RADIATORS

HEAT PUMP

CAPILLARY HEAT EXCHANGER

PAYLOAD

CAPILLARY HEAT EXCHANGER

PAYLOAD

HEAT PUMP

CAPILLARY HEAT EXCHANGER

EXPANDER

DIRECT IMMERSION HEAT PIPE

CONTAINMENT BOX

HEAT SINK

VAPOR SPACE

WICK

BOARD

ELECTRONIC COMPONENTS

HEAT PIPE WORKING FLUID

PT6-7
LIQUID METAL MICRO HEAT PIPE FINS

SILICON SHEETS

LIQUID METAL MICRO HEATPIPES

SECTION A – A

LIQUID DROPLET AND LIQUID SHEET RADIATOR

RADIATIVE "FINS" AND "HEATPIPES" OF CONVENTIONAL RADIATORS REPLACED BY STREAMS OF DROPLETS OR A LIQUID SHEET
# TECHNOLOGY OPTIONS

(Continued)

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>HARDWARE/SOFTWARE NEEDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW TEMPERATURE THERMAL CONTROL</td>
<td>• CRYOGENIC HEAT PIPES</td>
</tr>
<tr>
<td></td>
<td>• ANALYTICAL MODEL</td>
</tr>
<tr>
<td></td>
<td>• CRYOGENIC TWO-PHASE BUS</td>
</tr>
<tr>
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<td>• THERMAL SWITCH</td>
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<td>HIGH TEMPERATURE THERMAL CONTROL</td>
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<td>• ANALYTICAL MODEL</td>
</tr>
<tr>
<td></td>
<td>• MATERIALS</td>
</tr>
</tbody>
</table>

## CRYOGENIC HEAT PIPE APPLICATION

### INDIVIDUALLY COOLED SENSORS

![Diagram of individually cooled sensors](PT6-9)

- THREE SENSORS, 12 CRYOCOOLERS

### CENTRAL BANK OF CRYOCOOLERS

![Diagram of central bank of cryocoolers](PT6-9)

- THREE SENSORS, 2 TO 6 CRYOCOOLERS
TECHNOLOGY PAYOFF

- ENABLE CERTAIN MISSIONS
  - LUNAR BASE (LOW TEMPERATURE (<300 K) HEAT REJECTION)
  - ADVANCED ORBITAL PLATFORMS

- ENHANCE SCIENCE RETURN
  - LOWER WEIGHT FOR SUBSYSTEMS MEANS MORE WEIGHT AVAILABLE FOR SCIENCE PAYLOAD
  - LONGER LIFE/MORE RELIABLE THERMAL CONTROL WILL ALLOW LONGER MISSIONS

- ENABLE LARGER/MORE COMPLEX COMMERCIAL SATELLITES

STATE OF THE ART VS. GOALS

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>STATE OF THE ART</th>
<th>GOAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAT PUMP</td>
<td>24 KG/KW</td>
<td>8 KG/KW</td>
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<tr>
<td>CRYO HEAT PIPE</td>
<td>10 W-m @ 70 K</td>
<td>20 W-m @ 70 K</td>
</tr>
<tr>
<td>LIGHTWEIGHT RADIATOR</td>
<td>9 KG/M2</td>
<td>1-4 KG/M2</td>
</tr>
<tr>
<td>ANALYTICAL MODELS FOR ENGG.</td>
<td>N/A</td>
<td>VERIFIED BY MICRO-GRAVITY DATA</td>
</tr>
<tr>
<td>MECHANICAL PUMP</td>
<td>500 HOURS LIFE</td>
<td>80,000 HOURS LIFE</td>
</tr>
</tbody>
</table>

PT6-10
PROGRAM DESCRIPTION
-RECENT ACCOMPLISHMENTS-

- OAET
- OXYGEN AND NITROGEN CRYOGENIC HEAT PIPES
  - FABRICATED AND TESTED, GOOD CORRELATION TO MODEL

- CRYOGENIC HEAT PIPE FLIGHT EXPERIMENT
  - UNDERGOING PERFORMANCE TESTING, OCTOBER 1992 MANIFEST, JOINT EXPERIMENT WITH AIR FORCE (WRIGHT LABORATORY)

- HEAT PUMPS
  - COMPLETED SYSTEM LEVEL STUDY, INITIATED COMPONENT LEVEL CONCEPTUAL DESIGN AND SPECIFICATION (LEVERAGED EFFORT WITH NIST)

- LIGHTWEIGHT MATERIALS
  - COMPLETED SOA SURVEY, IDENTIFIED SEVERAL PROMISING CANDIDATES

- TWO-PHASE LOOPS
  - INITIATED INNOVATIVE CONTROLLER STUDY AND TEST

PROGRAM DESCRIPTION
-CURRENT AND STRATEGIC-

- OAET

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>ESTIMATE</th>
<th>SCHEDULE</th>
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<tbody>
<tr>
<td>HEAT PUMPS</td>
<td></td>
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<tr>
<td>DEVELOP TWO (ONE) BASIC DESIGN CONCEPTS</td>
<td></td>
<td>1994</td>
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<tr>
<td>3X SOA (2X SOA) IMPROVEMENT SPECIFIC WEIGHT</td>
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<td>1996/1997</td>
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<tr>
<td>DESIGN LIGHT EXPERIMENT</td>
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<td>1999/2001</td>
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<tr>
<td>CRYOGENIC HEAT PIPES</td>
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<td>1995</td>
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<tr>
<td>50% (35%) IMPROVEMENT OVER SOA</td>
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<td>DESIGN FLIGHT EXPERIMENT</td>
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<tr>
<td>LIGHTWEIGHT RADIATORS</td>
<td>IDENTIFY INNOVATIVE CONCEPTS</td>
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<tr>
<td>CONSTRUCT MICRO HEAT PIPE FINS</td>
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<td>DEMONSTRATE 1-4 KG/M2 (3-5 KG/M2) RADIATOR</td>
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NOTE: ITALICS REFERS TO REDUCTION IN SCOPE/PERFORMANCE IF STRATEGIC FUNDING LEVEL IS NOT APPROVED
### PROGRAM DESCRIPTION-CONTINUED

- CURRENT AND STRATEGIC -

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<td>• 20:1 REDUCTION IN SIZE AND WEIGHT OF RADIATOR</td>
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<td>• GROUND TEST</td>
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<td>CODE VALIDATION</td>
<td>• WATER HEAT PIPE</td>
<td>• 1994/1997</td>
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<td>• LIQUID METAL HEAT PIPE</td>
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<td>LIGHTWEIGHT MATERIALS</td>
<td>• 35% (20%) REDUCTION IN WEIGHT OF COMPONENTS</td>
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<td>• CRYOGENIC HEAT PIPES</td>
<td>• 1996/1998</td>
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<tr>
<td></td>
<td>• HEAT PUMPS</td>
<td>• 1999/2002</td>
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### RESOURCE REQUIREMENTS

($M$)

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<td>1.9</td>
<td>2.3</td>
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RELATIONSHIP OF R & T BASE TO FOCUSED PROGRAM

OAET

FOCUSED PROGRAM ENHANCES BASE PROGRAM BY;

- PROVIDING MORE TECHNICAL OPTIONS FOR A GIVEN COMPONENT
- PROVIDING MORE SPECIFIC DESIGN AND ANALYSIS OF ISSUES FOR A GIVEN MISSION CLASS
- IMPROVING PERFORMANCE MARGIN
- ACCELERATING DEVELOPMENT SCHEDULE

RELATED TECHNOLOGY EFFORTS

OAET

NASA
- EOS AND SPACE STATION PROJECTS
  -40 C TWO-PHASE THERMAL BUS CONCEPTS
- IN-STEP
  -GREGORIG GROOVE HEAT EXCHANGER
  -LIQUID MOTION IN A TANK
- SBIR
  -MECHANICAL/CHEMICAL HEAT PUMP
  -SINTERED WICK CRYOGENIC HEAT PIPE
  -LONG LIFE MECHANICAL PUMP
  -COMPOSITE RADIATOR

AIR FORCE
- JOINT CRYOGENIC HEAT PIPE EXPERIMENT WITH NASA/GSFC
- HIGH TEMPERATURE HEAT PIPE
- ANALYTICAL MODEL FOR HEATPIPES
- CAPILLARY PUMPED LOOPS

DOE
- ADVANCED HEAT ENGINES (STIRLING, ABSORPTION)
-SUMMARY-

R&T BASE: THERMAL MANAGEMENT

• TECHNICAL CHALLENGES: MICRO G PERFORMANCE, COST, LIFETIME

• APPROACH: FOCUS ON HEAT PUMPS, CRYOGENIC HEAT PIPES, INNOVATIVE RADIATORS, 20:1 REDUCTION FOR POWER ELECTRONICS RADIATOR, AND ANALYTICAL MODELS

• PAYOFF: ENABLE LUNAR BASE (300 K WASTE HEAT REJECTION), MAJOR IMPROVEMENT IN SENSOR COOLING, 50% OR MORE REDUCTION IN RADIATOR SIZE AND SPECIFIC MASS, AND BETTER ANALYTICAL MODELS

• AUGMENTATION RATIONALE: EXPAND BASE PROGRAM TO INCLUDE MULTIPLE OPTIONS, ADDRESS PROBLEMS NOT ADDRESSED IN BASE

• RELATIONSHIP TO OTHER PROGRAMS: BASE PROGRAM PROVIDES GENERIC FOUNDATION FOR MORE MISSION SPECIFIC FOCUSED EFFORT, SIGNIFICANT INTERACTION WITH AIR FORCE

• TECHNOLOGY CONTRIBUTIONS: CODE R FUNDED CAPILLARY PUMPED LOOP TECHNOLOGY NOW BASELINED FOR EOS PLATFORM - ENABLING TO THIS MISSION
SPACE NUCLEAR POWER
(SP-100)

BY

R. J. SOVIE
DEPUTY CHIEF, POWER TECHNOLOGY DIVISION
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW
JUNE 27 1991

WHAT WE WILL DISCUSS

• OBJECTIVES/BENEFITS
• SP-100 BACKGROUND
• SCALING
• SP-100 GROUND ENGINEERING SYSTEM STORY
  - TECHNICAL CONTENT
  - PROGRAMMATICS
  - SP-100 REVIEW GROUP
  - PRESENT SCHEDULE
• TECHNICAL PROGRESS
• CONCLUDING REMARKS
OBJECTIVES

- Programmatic
  Develop and Validate Technologies for Safe and Reliable Nuclear Power Systems to Support Lunar Outpost and Mars Exploration Missions

- Technical
  Power Level: 100+ kilowatts (nominal)
  Specific Mass: 30-50 kilograms per kilowatt
  Operations: Space- and Surface based
  Life Time: 7 years at full power

SCHEDULE

- 1993 Thermoelectric Cell Fabricated and Tested in Relevant Thermal Environment
- 1994 NAT Fuel Pins Fabricated & in Storage
- 1995 Restart Nuclear Assembly Test Site
- 1996 Thermoelectric Converter/Electromagnetic Pump Subsystem Performance Testing Complete
- 2001 Complete Flight-Like Integrated Assembly Test and Nuclear Assembly Test for Lunar Outpost Nuclear Power Systems

RESOURCES*

<table>
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<tr>
<th>CURRENT</th>
<th>STRATEGIC/SX</th>
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<td>1996</td>
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<td>1997</td>
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</table>

*Note: This Element Provides NASA's Contribution To The Ongoing NASA, DoD, DoE, SP-100 Program. Resources Shown are NASA's Contribution Only.

PARTICIPANTS

- Jet Propulsion Laboratory
  Lead for SP-100 Ground Engineering System Project, Responsible for Component Technologies, Project Management
- Lewis Research Center
  Space Subsystems, Materials
- Los Alamos National Laboratory
  Lead for Reactor Systems/Fuel Development
- Contractors
  General Electric

EXPLORATION TECHNOLOGY

SPACE NUCLEAR POWER

SP-100

- SP-100
  - NATIONAL PROGRAM
  - DOE/NASA/DOD

TO DEVELOP SPACE REACTOR POWER SYSTEMS AT THE 10 kWe to 1 MWe POWER LEVELS FOR USE IN FUTURE MILITARY AND CIVILIAN SPACE MISSIONS
## ADVANCED TECHNOLOGY GOALS

<table>
<thead>
<tr>
<th>Technology</th>
<th>LEO</th>
<th>MARS</th>
<th>LUNAR</th>
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</thead>
<tbody>
<tr>
<td>Photovoltaics - 300 W/kg Arrays</td>
<td>16</td>
<td>NA</td>
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<tr>
<td>Batteries - 100 W-hr/kg</td>
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<td>8</td>
<td>3</td>
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<tr>
<td>Regen. Fuel Cells - 1000 W-hr/kg</td>
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<tr>
<td>Advanced Solar Dynamics</td>
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<td>Nuclear Reactor Power Systems</td>
<td>25 - 40</td>
<td>←25 - 65→</td>
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<tr>
<td>Rovers, Vehicles</td>
<td>←5 - 10→</td>
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</tbody>
</table>

### SURFACE POWER SYSTEM MASS DRIVERS

- **Space Station**
  - ~ 60 min. light/30 min. dark

- **Lunar**
  - ~ 14 day day/night cycle

- **Mars**
  - ~ 12 hr day/night cycle

**Storage**

- Batteries
- Regenerative Fuel Cells
- Nuclear
MASS SAVINGS IN LEO
ADV. SOLAR vs SPACE STATION SOLAR
NUCLEAR vs ADV. SOLAR

MASS SAVINGS
(kg)

2,000,000

1,800,000

1,200,000

900,000

400,000

POWER, (kWe)

100

20

10

500

100

MASS SAVINGS BENEFITS

NASA

LeRC

MASS SAVINGS (MT)

HLV's

Billions of Dollars

0

1

2

3

4

5

6

7

8

9

10

0 100 200 300 400 500 600 700 800 900 1000

0 100 200 300 400 500 600 700 800 900 1000

PT7-4
SPACE NUCLEAR POWER
SP-100

PROVIDES TECHNOLOGY FOR:

SPACE EXPLORATION
LUNAR, MARS SURFACE POWER
NEP PRECURSOR MISSIONS

SCIENCE
1 - 100 kWe NEP

TRANSPORTATION
1 - 40 MWe NEP CARGO, MANNED, & MARS TRANSFER VEHICLES

SPACE NUCLEAR POWER
SP-100 KEY REQUIREMENTS

• SCALABLE: 10's TO 100's OF kWe
• LIFETIME: 7 YEARS FULL POWER - 10 YEAR LIFE (15)
• SAFE FOR ALL MISSION PHASES
• RADIATION SHIELDED TO PROTECT PAYLOAD
• SURVIVABLE
• SPACE SHUTTLE AND ELV COMPATIBLE
• ~ 25 W/kg AT 100 kWe (80 W/kg)
SP-100 BACKGROUND

PHASE I - CONCEPT SELECTION - 1983

PHASE II - TECHNOLOGY DEVELOPMENT AND VALIDATION

PHASE III - FLIGHT DEMONSTRATION (FSQ)
SP-100 PHASE I PROGRAM

- MISSION ANALYSIS AND REQUIREMENTS
- SYSTEM DEFINITION
- TECHNOLOGY DEVELOPMENT
- SAFETY ANALYSIS

1985 CONCEPT RECOMMENDATION
- MEET MISSION REQUIREMENTS
- SAFE AND TECHNICALLY FEASIBLE
- MANAGEABLE COST AND SCHEDULE

PHASE II GROUND ENGINEERING SYSTEM (GES)

SP-100 PHASE I

- 50 ORIGINAL CONCEPTS
- 4 FINAL CONTENDERS
  - LIQUID METAL COOLED REACTOR (LMR)
  - THERMEOLECTRICS
  - BRAYTON
  - STIRLING
  - IN-CORE THERMIONICS SYSTEM
AT END OF PHASE I

- **SP-100 GROUND ENGINEERING SYSTEM**
  - LITHIUM COOLED REACTOR
  - TE CONVERSION
    - UN FUEL PWC-11 CLAD
    - 300 kW -→ 100 kW

- **ADVANCED TECHNOLOGY PROGRAM (CSTI - HIGH CAPACITY POWER)**
  - ADVANCED STATIC CONVERSION
  - DYNAMIC CONVERSION
  - RADIATORS
    - GROWTH
    - FALBACK POSITIONS

- **THERMIONICS TECHNOLOGY PROGRAM**
  - ADDRESS UNRESOLVED FEASIBILITY ISSUES

---

**Simplified System Diagram**

*Subsystems:*
- Reactor
- Shield
- Heat Transport
- Reactor Inst. & Control
- Power Conversion S/S
- Heat Injection
- Power Conditioning
- Structural/Mechanical

---

PT7-8
SCALING

Design Scalability

10 kW LOW POWER MILITARY MISSION: \( \sim 1500 \text{ kg} \) \( \sim 2 \text{ W/kg} \)

30 kW ELECTRIC PROPULSION: \( \sim 2200 \text{ kg} \) \( \sim 14 \text{ W/kg} \)

100 kW GENERIC FLIGHT SYSTEM: \( \sim 4600 \text{ kg} \) \( \sim 2.2 \text{ W/kg} \)

1000 kW STEELING CONVERSION CFS REACTOR: \( \sim 157,000 \text{ kg} \) \( \sim 66 \text{ W/kg} \)

SP-100 Technologies Applicable Over Wide Power Range

\( 76 \sim 23,000 \text{ kg} \)

PT7-9
MASS SENSITIVITY TO T/E TECHNOLOGY STATUS

System Mass Kg vs Power Output (kWe)

Baseline Technology (Z = .85)
Year 2000 Technology (Z = 1.4)

POWER TECHNOLOGY DIVISION
SPACE NUCLEAR POWER
High Capacity Power

• Free piston Stirling converters
• Advanced thermal management
• Power management & distribution
• Environmental interactions
• Thermoelectrics
• Materials development

PT7-10
SMALL REACTORS FOR PLANETARY EXPLORATION

ACCESS USE OF SMALL REACTOR POWER SYSTEMS FOR NASA PLANETARY EXPLORATION MISSIONS

PTT-11

CASUAL INREFERENCE MISSION

11 kWs REACTOR FOR SCIENCE ALTERNATIVE FOR ATOMIC TRIP, TIME INCREASE SET TO 1 YEAR

25 kWs REACTOR FOR ELECTRIC PROPULSION & SCIENCE

EQUAL OR REDUCED TRIP TIME

ENHANCED SCIENCE

INCREASED LAUNCH WINDOWS

SP-100 TECHNOLOGY ATTRACTIVE FOR SMALL REACTOR

SP-100 TECHNOLOGY ATTRACTIVE FOR LOW POWER REQUIREMENTS

WIDE VARIETY OF ALTERNATIVE TECHNOLOGY CONCEPTS STUDIED

SP-100 TECHNOLOGY AMONG THE MOST ATTRACTION

REACTOR MASS IS SMALL FRACTION OF TOTAL SYSTEM MASS

SMALL REACTOR CAN PROVIDE AGENCY WITH ALTERNATIVE TO RTG'S

TECHNOLOGY IN NATIONAL SP-100 PROGRAM DIRECTLY APPLICABLE TO LOW POWER NEEDS
SP-100 APPLICABILITY TO
LARGE SCALE NEP
5 - 50 MWe

MAJOR PARAMETERS CONSIDERED AND APPROACH USED

POWER RANGE CONSIDERED: 200 kWt TO 200 MWt
REACTOR LIFETIME: 10 YEAR BASELINE; LONGER LIFETIMES ARE FEASIBLE
FUEL/BURNUP: UN / ≤ 10 ATOM %
COOLANT: LITHIUM OR OTHER LIQUID METAL FOR PRIMARY HEAT TRANSPORT; - 1350K SECONDARY LOOP CAN BE LIQUID METAL, GAS, HEAT PIPES OR TBD
STRUCTURES: REFRACTORY METAL; CAN USE HIGH TEMPERATURE ALLOYS SUCH AS 617 DEPENDING ON MISSION AND EXTERNAL ATMOSPHERE
COROPT-S CODE CAPABILITIES

0 SP-100 NUCLEAR SUBSYSTEMS OPTIMIZATION CODE

0 USES FIRST PRINCIPLES TO SIZE REACTOR, SHIELD, PRIMARY HEAT TRANSPORT SYSTEM AND REACTOR I&C SUBSYSTEMS

0 DEMONSTRATED CAPABILITY TO SCALE SP-100 CONCEPT FOR A WIDE RANGE OF REQUIREMENTS AND CONCEPTS

TYPICAL OPTIMIZED PARAMETERS

CORE HEIGHT
PIN DIAMETER
PIN P/D RATIO
CLADDING THICKNESS
PLENUM LENGTH
REFLECTOR THICKNESS
FUEL PELLET/CLADDING GAP

CONSTRAINTS

PEAK BURNUP
F.G. PRESSURE STRAIN
FCH1+FG PRESSURE STRAIN
MAX FUEL TEMP
REACTOR AP
REFLECTOR WORTH

O SIZES AND PROVIDES MASS ESTIMATES IN SENSITIVITY OR OPTIMIZATION MODE

CORE CROSS SECTION SCHEMATIC

10MW
Number of full assemblies = 43
Number of partial assemblies = 12
Assembly pitch = 5.18 cm
Vessel outer radius = 21.6 cm
Reflector outer radius = 29.4 cm

50MW
Number of full assemblies = 75
Number of partial assemblies = 12
Assembly pitch = 8.09 cm
Vessel outer radius = 40.9 cm
Reflector outer radius = 56.4 cm

Core Zone 1
Bypass Coolant
Core Zone 2
Vessel
Core Zone 3
Radial Reflector

1/8 SCALE
DEVELOPMENT NEEDS

- NO TECHNOLOGY DEVELOPMENT ITEMS BEYOND GES

- KEY FEATURE TESTS NEEDED
  - CRITICAL EXPERIMENT
  - SLIDING REFLECTOR
  - SCALED-UP CONTROL DRIVE
  - SCALED-UP PUMP
  - FLOW TEST
  - Li7H NUCLEAR HEATING TEST
  - EXTEND FUEL AND MATERIALS IRRADIATION DATA BASE
SDIO IEG STUDY

- SP-100 TECHNOLOGY FOR MMWe APPLICATIONS
- CHANGE CLAD → INCREASE TEMPERATURE
- PERFORMANCE EQUIVALENT TO PROPOSED LMC REACTOR SPECIFICALLY PROPOSED FOR ADVANCED CONVERSION

EXPLORATION TECHNOLOGY

SP-100 GROUND ENGINEERING

SYSTEM STORY
SP-100 GES PROJECT

PHASE II PROGRAM OBJECTIVE

- DEVELOP AND DEMONSTRATE BY 1992 THAT THE TECHNOLOGY IS READY
  FOR FLIGHT APPLICATION OF 10 TO 1000 kW_e SPACE REACTOR POWER
  SYSTEMS FOR FUTURE MILITARY AND CIVILIAN SPACE MISSIONS.

THE SP-100 GES PROGRAM

OBJECTIVE

- CONDUCT THE ENGINEERING DEVELOPMENT AND GROUND SYSTEM TESTING OF A
  REACTOR SPACE POWER SYSTEM FOR POWER LEVELS OVER THE RANGE OF 10's TO
  100's OF KILOWATTS ELECTRIC.

SCOPE

- SUBSYSTEM TECHNOLOGY OF THE COMPLETE POWER SYSTEM (DEMONSTRATE
  COMPONENT LIFETIME)
  - REACTOR AND SHIELD
  - THERMOELECTRIC POWER CONVERTER
  - HEAT TRANSPORT
  - HEAT REJECTION
  - INSTRUMENTATION AND CONTROL
  - POWER CONDITIONING, CONTROL, AND DISTRIBUTION
  - STRUCTURAL

- TWO MAJOR PERFORMANCE TESTS (DEMONSTRATION SYSTEM PERFORMANCE)
  - NUCLEAR ASSEMBLY TEST (NAT)
  - INTEGRATED ASSEMBLY TEST (IAT)

- SYSTEM EFFORTS
  - MANAGEMENT
  - SYSTEM DESIGN
  - RELIABILITY AND QUALITY ASSURANCE
  - SAFETY
  - SYSTEM STUDIES (SCALEABILITY, MAINTAINABILITY)
ENERGY CONVERSION ASSEMBLY SEGMENT

SP-100 SYSTEM INTEGRATED ASSEMBLY TEST (IAT)
BASELINE COSTS (M$)

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- PROGRAM SCOPE/SCHEDULE ADJUSTMENTS HAVE BEEN REQUIRED AS RESULT OF CONTINUED BUDGET SHORTFALLS

GENERALLY - STRETCH NAT
- STRETCH/ELIMINATE SPACE SUBSYSTEMS EFFORTS
- INCREASE OVERALL BUDGET

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<th>88</th>
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SP-100
PROGRAM REVIEW GROUP
1989 - 90
There is a clear need for Space Reactor Power
- Enabling for NASA Space Exploration Initiative (earliest projected NASA application)
- Enhancing for SDIO and USAF mission (USAF evaluating future role of space reactor power)

Top level SP-100 requirements are still appropriate
- Power range (10's to 100's kWe)
- Lifetime (7 years full power)

Decision to select thermoelectric conversion still appropriate
SP-100 PROGRAM REVIEW
GROUP FINDINGS

(continued)

- Significant progress has been made by the SP-100 Program
  - Hardware being fabricated
  - Major advancements in thermoelectrics and fuel rod construction
  - Technical areas of concern in reactor and converter being addressed
  - Funding shortfalls are the principal threat to balanced technical progress

(continued)

- There is a major deficiency in the current program
  - Development effort is limited to reactor and converter
  - Key overall system development not being addressed
  - Key technical areas in non-nuclear space subsystems not being addressed (e.g., heat rejection)
1991 REDIRECTED FLIGHT SYSTEM QUALIFICATION

- RE-ORIENT TO COMPONENT DEVELOPMENT FOCUS
- DELAY NAT
- DEMONSTRATE EARLY COMPLETION OF NUCLEAR AND SPACE TECHNOLOGY READINESS - 98
- EARLY CONVERTER/PUMP ASSEMBLY TEST - 96
- REDESIGN OF NUCLEAR ASSEMBLY UPDATE
- LEAST SENSITIVE TO FUNDING DISRUPTIONS
### SP-100 FLIGHT SYSTEM QUALIFICATION PROGRAM SUMMARY SCHEDULE

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### SP-100 GES PROGRAM STATUS & OPTIONS

**LeRC**

- **GES PROGRAM**
  - THRU FY90 $320M HAS BEEN SPENT -
    - ~ $240M FOR NUCLEAR SUBSYSTEM
    - ~ $ 80M FOR SPACE (NON-NUCLEAR) SUBSYSTEM

- **CURRENT FSO PROGRAM**
  - WITH EXPECTED (PLANNED) ANNUAL FUNDING RATE A TRL 6
  - CAN BE ACHIEVED IN 2001 WITH TOTAL FUNDING OF $1284M THRU FY2001
    - $1064M FOR NUCLEAR SUBSYSTEM
    - $ 220M FOR SPACE (NON-NUCLEAR) SUBSYSTEM

- **OPTIONAL ACCELERATED PROGRAM**
  - CAN ACHIEVE A TRL 6 BY 1997 FOR $1145M

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FSQ PROGRAM COST

ACTUALS TO DATE
ORIGINAL COST PLAN
GROUND DEMONSTRATION PROGRAM
QUALIFICATION COST PLAN

FISCAL YEARS


$M

TECHNICAL PROGRESS
**GFS Design Options**

**New Features**

**HEAT TRANSPORT**
- Smaller pumps
- Improved thaw

**SHIELD**
- S.S. vessel
- Less tungsten

**POWER CONVERSION**
- No design changes

**PCC&D**
- Advanced packaging

**STRUCTURE**
- Electronics integrated in mission module

**REACTOR**
- 3 safety rods
- Sliding reflector control
- Optimized fuel pin
- Axial reflector
- Optimized hex core structure

**RI&C**
- Neutron monitor

**HEAT REJECTION**
- C-C armored heat pipes
- Double duct
- Aft folding radiator

---

**FIVE CANDIDATE THAW SYSTEMS**

- Auxiliary Coolant Loop/Nak Trace Line/Sequential Thaw (ACT)
- Auxiliary Coolant Loop/Bleed Tube
- Bleed Tube Thaw Concept
- Heat Pipe Thaw Concept
- Sequenced Electrical Heater Concept
SP-100 GES PROGRESS

• GENERIC REFERENCE FLIGHT SYSTEM DESIGN
• SUBSYSTEM AND COMPONENT SPECIFICATIONS
• MATERIALS, PROCESS AND FABRICATION SPECIFICATIONS
• VALIDATION PLAN
• EIS, FONSI, ETC., FOR FACILITY

Nuclear Assembly Test Progress

Conceptual Design
- Prototypicality
- Functions
- Sizing
- Concept Arrangement

Preliminary Design
- NPDR
- Preliminary Component Design Review

Final Design
- NFDR
- Final Component Design Review

Mfg. and Assembly
- Materials
- Components Manufacture
- Assembly
- Test
- Ship

Installation and Test
Containment Building
Vacuum Vessel
Dump Heat Exchanger
Control Room & Auxiliaries
Reactor

SP-100 Key Technologies

- BARRIER CLADDING
- UN FUEL
- AUTONOMOUS CONTROL
- MULTIPLEXER
- LiH SHEILD
- CONTROL DRIVES AND BEARINGS
- REFRACTORY MATERIALS
- SAFETY

- T/E MATERIAL
- ELECTRICAL INSULATOR
- COMPLIANT PAD
- CELL ELECTRODES
- CELL PERFORMANCE/PRODUCTION
- SYSTEM THAW

- HEAT PIPE PERFORMANCE/ PRODUCTION
- FLEXIBLE JOINT

- TEM PUMP
- GAS SEPARATOR
SP-100 Uranium Nitride Fuel

- Process Developed at Los Alamos National Laboratory
- Meets Exacting GE Specifications
  - Chemistry
  - Dimensions
  - Density
  - Microstructure
  - Quality Assurance
- Pellet Production for Nuclear Assembly Test
  Nearing Completion
UN Fuel Manufacturing at Los Alamos

SP-100 Uranium Nitride Fuel
**NAT FUEL PRODUCTION**  
(LANL Status)

- Total NAT fuel pellets required
  
  49,000 - 97% enriched  
  
  ~6600 - 89 or 93% enriched (depends on GFS updated design)

- Total NAT fuel pellets currently fabricated
  
  44,400 - 97%  
  
  zero - 89 or 93% (93% enrichment feedstock available)

- Total fuel pellets requiring resintering
  
  44,400 - 97%

- Fuel pellets currently resintered
  
  9700 - 97%

---

**SP-100 Materials Technology**

- **Demonstrated Fabricability of Re Lined Nb-12r (Barrier) Fuel Cladding**

- **Demonstrated High Creep Strength of Barrier Cladding**

- **Demonstrated Effectiveness of Chemistry Control and/or Heat Treatment**
  
  Preventing Li Attack of Nb-12r Welds

- **Demonstrated High Temperature Strength of Controlled Chemistry Nb-12r**

- **Demonstrated Dynamic Friction Properties of ZrC and HfC Hardfacings**
  
  Under High Temperature (1600°K) High Vacuum (10⁻⁴ Torr) Conditions
22 TUBES OF QUALIFICATION BATCH 1 IN THE VACUUM HEAT TREAT FURNACE AFTER BEING DRAWN TO FINAL SIZE

Fuel Pin Supporting Data

Operating Range

- LITERATURE
- SP-100 TEST
- COMPLETED TEST
Materials Test Loop

Gas Separator/Accumulator Test

ORIGINAL PAGE IS OF POOR QUALITY
SP-100 Full Scale Hydraulic Flow Test

- Measured Overall Pressure Drop
- Measured Coolant Flow Distribution Within Reactor Core
- Verified Orifice Sizing Predictions
- Investigated Reactor Hydraulic Characteristics:
  - Entrance to Annulus Losses
  - Annulus to Core Entrance Losses
  - Exit Plenum to Reactor Outlet Losses
  - Effects of Inlet Pipe Blockage on Coolant Distribution
- Tests Complete

Control Drive Development

Key Feature Test
- SRDA SCRAM Shutdown
- RCDA Operation and SCRAM
- Safety Rod Separation Joint

Component Tests
- Electromagnetic Coils
- Actuator Bearings
- Motor, Clutch Brake and Position Sensor
- Spherical Self-Align. Bearings
- Safety Rod Slider Bearings

Sub-assembly Test
- Drive Motor
- Drive Actuator
- Hinged Reflector
- Safety Rod Driveline

Prototype Tests
- SRDA (2)
- RCDA (2)

Endurance Tests
- SRDA (2)
- RCDA (2)
High Temperature Tribology

Control Drive Self-Aligning Bearing Test
Control Drive Clutch/Resolver Test

Multiplexer Development

**Gamma:**
- No JFET Damage
- 50°C
- Dose Acceleration 15:1

**Neutron:**
- 40% JFET Damage
- 50°C
- Dose Acceleration 120:1

Acceptable Performance Expected at Lower Dose Rates & Higher Temperatures

PT7-36
SPACE SUBSYSTEM
TECHNICAL CHALLENGES

HEAT TRANSPORT SUBSYSTEM
• TE-EM PUMP MASS AND EFFICIENCY
• TEM PUMP TE CELL

POWER CONVERSION SUBSYSTEM
• HIGH VOLTAGE INSULATOR
• COMPLIANT PAD
• ELECTRODES
• TE CELL ASSEMBLY
• IMPROVED SiGe

HEAT REJECTION SUBSYSTEM
• HEAT PIPE
• RADIATOR DUCT THAW

TECHNOLOGY CHALLENGES

RTG
HEAT SOURCE

SILICON ALLOY ELECTRODE
1000°C

n⁺ SiGe

p⁺ SiGe

300°C

TUNGSTEN ELECTRODES

SP-100
HEAT EXCHANGER, 1100°C

TUNGSTEN GRAPHITE ELECTRODE

INSULATOR

COMPLIANT PAD

N P

8-COUPLE T/E MODULE

P N P

COLD-SIDE HEAT EXCHANGER, 600°C

PT7-37
Power Converter Cell Configuration

- Accelerated Life Tests Have Demonstrated Substantial Performance and Life Margins
  - High Temperatures (Up to 1670 °K)
  - High Voltage Gradient (4 kV/cm)
  - Long Times (Up to One Year)

- Compatibility With Li Cooled Systems
  Proven by Analysis and Test

- Mechanistic Degradation Models
  Developed and Validated

Essential Technology Demonstrated

SPAC 02980 02-00

PT7-38
Compliant Pad

Face-sheet

Fabricability Demonstrated
- Facesheet Materials/Thickness
- Filament Diameters/Density
- Pad Thickness

Bond Strength Demonstrated

Compliance Demonstrated

Design Optimization Proceeding

Filament Bundles

Space Subsystems
Cell Assembly

Cell Development Road Map

PD-1 ASSEMBLY VERIFICATION

PD-1 PERFORMANCE VERIFICATION

PD-2

TA

DEV

TCA

March 1989

Verified Fabrication and Assembly Processes

March 1991

Test at Full Prototypic Hot Side Temperature

October 1992

Prototypic Configuration

Prototypic Configuration and Operating Conditions

Prototypic Pump Test

September 1989

Verified Predictability of Performance

Demonstrated Structural Integrity

Lessons Learned for PD-2

Verified Performance

Demonstration of Technology Features of GFS Design

Cell Life Tests

Array Life Tests

Hot Side Temperature Limited by Braze
First Generation Cell In-Gradient Test

Potassium Heat Pipe Development
O POTASSIUM HEAT PIPE ACCOMPLISHMENTS

- DEVELOPMENT OF ETCHED TITANIUM FOIL WICKS (PREFERRED TECHNOLOGY)
- DEVELOPMENT OF SINTERED TITANIUM WICKS
- DEMONSTRATED PERFORMANCE OF NB1Zr HEAT PIPES WITH FOIL WICKS
- PRELIMINARY DEMONSTRATION OF RADIATOR THAW CONCEPT, DUCT WITH BLEED HOLES
TEMP Pump Magnetic Bench Test

EXPLORATION TECHNOLOGY

SPACE NUCLEAR POWER - SP-100

SUMMARY

- IMPACT:
  - PROVIDES ENABLING TECHNOLOGY FOR LUNAR/MARS BASES
  - POWER SOURCE FOR 1 - 100 kW \( e \) NEP FOR EARLY 21st CENTURY SCIENCE MISSIONS
  - REACTOR TECHNOLOGY FOR MMW \( e \) NEP SYSTEMS FOR MARS CARGO AND PILOTED SPACE EXPLORATION MISSIONS

- USER COORDINATION:
  - SEI TECHNOLOGY REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH CODE RZ
    (NUCLEAR POWER IDENTIFIED AS A HIGH PRIORITY AND ENABLING BY CODE RZ)
  - PLANETARY SCIENCE REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH OSSA AND WITH JPL
    (NUCLEAR POWER RATED AS A HIGH PRIORITY BY OSSA IS ENABLING FOR MANY MISSIONS)

- MAJOR TECHNICAL PROGRAMMATIC ISSUES:
  - GENERIC TECHNOLOGY DEVELOPMENT - MEETS ALL POTENTIAL USER NEEDS
  - ABSENCE OF SPECIFIC APPROVED PROGRAM USING NUCLEAR POWER CONFUSES FIRM TECHNOLOGY READINESS REQUIREMENT DATE

PT7-42
CONCLUDING REMARKS

- SP-100 IS THE NATIONAL NUCLEAR SPACE POWER PROGRAM
  - NATIONAL LEVERAGE

- PROVIDES A WIDE RANGE OF OPTIONS
  - FEW kW's  ——  MMW's

- MAJOR IMPACT ON EXPLORATION MISSION

- EXCELLENT TECHNICAL PROGRESS
  - FUNDING DIFFICULTIES

- FULL-UP PROGRAM
  - DEMONSTRATES USER SUPPORT/LEVERAGE
  - TECHNICAL SUCCESS
HIGH CAPACITY POWER

WHAT WE WILL DISCUSS

• OBJECTIVES/BENEFITS

• MAJOR MILESTONES/SCHEDULE/BUDGET
  - BASELINE

• TECHNICAL PROGRESS

• FULL-UP PROGRAM

• Δ WITH AUGMENTED PROGRAM

• ISSUES/CONCERNS

• CONCLUDING REMARKS
CSTI HIGH CAPACITY POWER

- PROVIDE FOR INCREASED POWER, RELIABILITY AND LIFETIME FOR NUCLEAR SPACE POWER SYSTEMS USING THE SP-100 REACTOR, THROUGH ADVANCED TECHNOLOGY DEVELOPMENT IN STATIC AND DYNAMIC ENERGY CONVERSION SYSTEMS, THERMAL AND POWER MANAGEMENT SYSTEMS AND MATERIALS

OBJECTIVES

- Programmatic
  Develop and Demonstrate Low Mass, Reliable Long-Lived Power Conversion Technology for Space Nuclear Reactor Power Systems
- Technical
  Temperature - 1050K Stirling
  - 1300K Stirling and Thermoelectric
  Power - Stirling at 25 kW/Cyl - 50 kW Modules
  Lifetime - > 7 years

SCHEDULE

- 1992 - EOIM-3, STS-46 Flight Experiment
- 1993 - Thermoelectric Multicouple, Z = 0.85
- 1993 - Stirling, 1050K, 25 kW/Cylinder, 25% eff.
- 1993 - H2O Heat Pipe/Radiator Module Demo
- 1994 - 600K Radiator Segment Demo
- 1995 - Mfg. Specs. for Z = 1.0 Thermoelectric
- 1996 - Stirling, 1050K, 25 kW/Cylinder, 30% eff.
- 1997 - Endurance Test, 1050K Stirling
- 1999 - Stirling, 1300K, 25 kW/Cylinder, 75% eff.

RESOURCES ($M)

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PARTICIPANTS

- Lewis Research Center
  Responsibility for Project Lead
- Jet Propulsion Laboratory
  Responsibility for Thermoelectrics

*Note: This Element is Integrated With Development of the SP-100 Space Nuclear Reactor Program
POWER TECHNOLOGY DIVISION

SPACE NUCLEAR POWER
High Capacity Power

- Free piston Stirling converters
- Advanced thermal management
- Power management & distribution
- Environmental interactions
- Thermoelectrics
- Materials development

HIGH CAPACITY POWER

WHY NUCLEAR STIRLING?

NUCLEAR-STIRLING IS AN ENABLING TECHNOLOGY PROVIDING LOW MASS, HIGH SPECIFIC POWER ELECTRICAL GENERATING SYSTEMS FOR THE MOON AND MARS

LUNAR BASE POWER SYSTEM IMLEO COMPARISON

- SAVES 1300 HLLVs vs SOA SOLAR PV
- SAVES 15 HLLVs vs ADVANCED SOLAR PV
- REQUIRES ONLY 1 LTV TO LUNAR SURFACE

550 kWe NUCLEAR-STIRLING LUNAR POWER SYSTEM

PT8-3
MISSION APPLICATION

- HIGH CAPACITY POWER PROGRAM
  - SUPPORTS LUNAR/MARS BASE
  - NEP SCIENCE, CARGO
  - DYNAMIC SYSTEMS FOR SPACE PLATFORMS, DIPS
  - HEAT REJECTION FOR ALL APPLICATIONS

- PROVIDE GROWTH AND BACK-UP FOR SP-100
  - IMPROVED MATERIALS
  - LOWER TEMPERATURE
  - INCREASED LIFETIME

HIGH CAPACITY POWER

HIGH CAPACITY POWER BASELINE PROGRAM
MAJOR MILESTONES

- FREE-PISTON STIRLING
  - 1050 K, 25 kWe/CYLINDER, 30% EFF, 7 YEAR LIFE
    (PRESENT - 650 K, 12.5 kWe/CYLINDER, 20% EFF, 1000 HR. LIFE)

- THERMOELECTRICS
  - \( Z = 0.85 \times 10^{-3} \text{K}^{-1} \) MULTICOUPLES/CONDUCTIVELY COUPLED
    (PRESENT - \( Z = 0.67 \times 10^{-3} \text{K}^{-1} \) MULTICOUPLES/RADIATIVELY COUPLED)

- THERMAL MANAGEMENT
  - 500 - 550 K RADIATOR SEGMENT TEST - STIRLING COLD END
    (PRESENT - PAPER DESIGNS, COMPONENT PRODUCED, NO RADIATOR TESTS)

- POWER MANAGEMENT
  - RAD HARD, HIGH TEMP SEMICONDUCTOR AND MAGNETICS COMPONENTS
    (PRESENT - RADIATION DEGRADES SEMICONDUCTORS, HIGH TEMPERATURE DEGRADES MAGNETS)

- SYSTEM DIAGNOSTICS
  - FIBER OPTIC POWER SENSOR FLIGHT QUALIFIED
    (PRESENT - POWER SENSORS EMI SENSITIVE, FIBER OPTIC CURRENT SENSOR BREAKTHROUGH)

- ENVIRONMENTAL INTERACTIONS
  - MODELS/EXPERIMENTS DEMONSTRATING LUNAR/MARTIAN/SPACE PLASMAS
    COMPATIBILITY OF SPACE POWER SYSTEMS
    (PRESENT - NO MODELS AVAILABLE - INITIAL EXPERIMENTS ON MARS ENVIRONMENT BEGINNING)
HIGH CAPACITY POWER - BASELINE PROGRAM SCHEDULE

MATERIALS
- DEVELOPMENT
- REFRACTOR COMPOSITE DEVELOPMENT FOR STIRLING STRUCTURES
- COMPOSITE DEVELOPMENT FOR RADIATORS
- CONTRACT AWARD: HEAT PIPE
- 5 km^2 COMMON DEMO
- 5 km^2 SYSTEM DEMO
- 450k WHEAT PIPE DEMO
- 60k RAD SLS TESTS
- 450k 600k RAD FOR SYSTEM TESTS

THERMAL MANAGEMENT
- DEVELOPMENT
- STIRLING DEVELOPMENT
- PRELIM DESIGN COMPONENT TEST: ENGINE COMPLETED
- 100k DIRECT COMP DEVELOPMENT
- 550C 100k TEST
- 1050C 100k SYSTEM TEST
- 1500k 100k ENDURANCE TEST

POWER CONVERSION
- DEVELOPMENT
- THEORETICAL MODELS DEVELOPED FOR DESIGN AND LOSS UNDERSTANDING OF FPSE
- FY
- 80 90 91 92 93 94 95 96 97
- CRITICAL MATERIALS TEST
- TE DEVELOPMENT
- Z x 0.5 DEMO
- Z x 1.0 DEMO

POWER MANAGEMENT
- COMMERCIAL ADVANCED COMPONENTS
- RADIATION TESTING SOA COMPONENTS
- MW DEMO SOA COMPLETE
- RAD HARD SWITCH DEMO
- RAD HARD CIRCUIT DEVELOP

SYSTEM DIAGNOSTICS
- SENSORS, SYSTEMS
- OPTICAL CURRENT SENSORS
- OPTICAL VOLTAGE SENSORS
- OPTIC SYSTEM DEVELOP

ENVIRONMENTAL INTERACTIONS
- THEORETICAL MODEL DEVELOPMENT
- DEVELOPMENT OF MODELS TO PREDICT ENVIRONMENTAL EFFECTS AND GUIDE DESIGN

Figure 7

HIGH CAPACITY POWER
GROSS FUNDING HISTORY/PROJECTIONS
NASA SP-100 ATP - HIGH CAPACITY POWER

HIGH CAPACITY POWER Baseline

MILLIONS OF DOLLARS

30
25
20
15
10
5

0

DARPA NASA ATP CSTI

85 86 87 88 89 90 91 92 93 94 95 96 97 98 99

PROJECT YEARS

FISCAL YEAR
HIGH CAPACITY POWER

ADVANCED STIRLING

MAJOR OBJECTIVE:

DEMONSTRATE THE PERFORMANCE, SPECIFIC POWER, LIFETIME, RELIABILITY, OF A 25 kWe/PISTON, 1300 K, T_R = 2, FPSE FOR LUNAR BASE APPLICATION

- DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS
  (Heat Transport, Power Conversion, Heat Rejection, PMAD)

- INTEGRATE SUB-SYSTEMS/DEMONSTRATE SYSTEM OPERATION

CSTI HIGH CAPACITY POWER

SSPC SUPPORTING R&T

OBJECTIVE:

- TO ESTABLISH A STRONG FPSE TECHNOLOGY BASE

ACTIVITIES:

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<td>1.5 kWe SOLAR DYNAMIC DESIGN</td>
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ANALYSIS

- CODE DEVELOPMENT
  - FAST, GUMPS, CFD
- LOSS UNDERSTANDING
  - CONTRACTS (3)
  - GRANTS (8)
  - ANNUAL WORKSHOP
- PARTICIPANTS
  - U OF MINNESOTA (3)
  - CLEVELAND STATE (2)
  - MIT
  - U OF PITTSBURGH
  - CASE WESTERN RESERVE
  - SUNPOWER
  - NASA-L&RC

COMPONENT TECHNOLOGY

- MAGNETICS
- LINEAR ALTERNATORS
- CONTROLS
- LOAD INTERACTION
- HEAT PIPES
- HEAT EXCHANGERS
- MATERIALS/JOINING
- MAGNETIC BEARINGS
- HIGH TEMPERATURE INSTRUMENTATION

"Notice all the computations, theoretical scribbings and lab equipment, Norm. ... Yes, curiosity killed these cats"
FREE-PISTON STIRLING ENGINES

KEY PROGRAM ELEMENTS

SCALING: 12.5 → 25 kWe/P
SPECIFIC MASS: 9 kg/kWe < 6 kg/kWe
EFFICIENCY: 20 → 30 (35)
LIFETIME: ≥ 7 YEARS
OPERATING TEMPERATURE: 650 K → 1050 K (1300 K)

APPROACH

COMPONENT DEV. TESTING → SUB-SYSTEMS → SYSTEM TESTS
STRONG AS SUPPORTING ANALYSIS

HIGH CAPACITY POWER

STIRLING DEVELOPMENT

BASELINE PROGRAM

PISTON HYDRODYNAMIC BEARING
DISPLACER HYDRODYNAMIC BEARINGS
ALTERNATOR MATERIALS SUBSTITUTION
REGENERATOR MATRIX CONFIGURATION

LOSS UNDERSTANDING AND REDUCTION
CODE DEV AND VALIDATION
DYNAMIC BALANCING
LOSS SENSITIVITY AND PERFORMANCE IMPROVEMENTS

Figure 1

PT8-7
SUCCESSFUL DEMONSTRATION OF:

- 12.5 kW$_e$/PISTON
- $T_R = 2$
- NON-CONTACTING GAS BEARINGS (HYDROSTATIC & HYDRODYNAMIC)
- STABLE OPERATION WITH CENTERING PORTS REDUCED FROM 6 TO 2
- RADIAL CLEARANCE INCREASED FROM 2 mils TO 5 mils
  - PREDICTED POWER LOSS
  - NO CHANGE IN EFFICIENCY
- VALIDATED DESIGN CODES
- DEMONSTRATED LINEAR ALTERNATOR EFFICIENCY $> 90\%$ AT 325 K
LINEAR ALTERNATOR TECHNICAL PROGRESS

- LINEAR ALTERNATOR DYNAMOMETER QUANTIFIED EDDY CURRENT LOSSES
- VERIFIED IMPROVED PERFORMANCE WITH NON-MAGNETIC SUPPORT STRUCTURE
- LINEAR ALTERNATOR "SHAKE AND BAKE" TEST RIG VALIDATES INSULATION AND STRUCTURAL INTEGRITY

HIGH TEMPERATURE MAGNETICS TECHNICAL PROGRESS

- 5 COMMERCIAL MATERIALS EVALUATED
- SAMARIUM₂ COBALT₁₇ CHOSEN FOR 525K
- DEFINES DESIGN MARGINS ON TEMPERATURE AND CURRENT
- STABILITY - CYCLING AND LIFETIME UNDER INVESTIGATION
FREE-PISTON STIRLING ENGINE
ADVANCED HEAT EXCHANGER TESTS

- Measured heat pipe temperature drops agree with the analytical predictions
- Operated with heat pipe temperature as high as 1050K
- Heater metal and gas temperature profiles are being studied to better understand heat flux distribution
- Heat exchangers will be characterized with heat pipes operating with gravity and against gravity

HIGH CAPACITY POWER

WE HAVE DEMONSTRATED

12.5 kWe/PISTON

Efficiency = 20%

TR = 2.0

TH = 650 K

TC = 325 K

DATA, ANALYSIS PROVIDE CONFIDENCE TO PROCEED TO THE NEXT GENERATION ENGINE
STIRLING SPACE POWER CONVERTER PROGRAM
PHASE TWO 1050K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

OBJECTIVE:
TO PROVIDE A LOW-COST, LOW-RISK AND SHORT SCHEDULE APPROACH TO DEVELOP ALL COMPONENT TECHNOLOGIES FOR THE 25 kWe 1050 K SUPERALLOY STIRLING SPACE POWER CONVERTER

PROGRAM GOALS:

END OF LIFE POWER - 25 kWe
EFFICIENCY - > 25% @ Tr = 2.0
LIFE (DESIGN) - 60,000 HOURS
VIBRATION - < .04 mm (OPPOSED PISTON)
BEARINGS - NON CONTACTING (GAS FILM)
SPECIFIC MASS - < 6 kg/kWe
HOT END - HEAT PIPE

STIRLING SPACE POWER CONVERTER PROGRAM
PHASE TWO
1050 K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

FIRST MOTORIZING TEST OF COLD END

- 12.5 kWe DESIGN
- MOTORED AT 70 Hz (4/15/91)
- "NEW" HYDROSTATIC BEARING SYSTEM
- NO RUBS
- START OF MTI/CTPC TEST PROGRAM

PT8-12
HIGH CAPACITY POWER

WILL IT REALLY WORK IN SPACE?

STIRLING MACHINES (CRYOCOOKERS) HAVE ALREADY FLOWN IN SPACE

- 7 FLIGHTS HAVE BEEN IDENTIFIED (6 USA/1 USSR)
- DEMONSTRATED OPERATION FROM HOURS TO 6 YEARS
- KINETIC STIRLING TECHNOLOGY
  * STIRLING CRYOCOOKER PROTOTYPES DESIGNED FOR TERRESTRIAL APPLICATION

PLANNED LONG-LIFE CRYOCOOKER MISSIONS - FREE-PISTON STIRLING TECHNOLOGY

- 7 FLIGHTS PLANNED WITH FLEXURE BEARING SYSTEM
  - ALONG TRACK SCANNING RADIOMETER - 1991
  - IMPROVED STRATOSPHERIC AND MESOSPHERIC SOUNDER - 1991
  - HIGH TEMPERATURE SUPERCONDUCTIVITY EXPERIMENT - 1992
  - X-RAY SPECTROMETER - 1996
  - EARTH OBSERVING SYSTEM INSTRUMENTS - '96, '97, '98

- 1 FLIGHT PLANNED WITH GAS BEARING SYSTEM
  - SDI/SPAS EXPERIMENT 1994

  * TO DEMONSTRATE THAT FREE-PISTON STIRLING CRYOCOOKERS WITH GAS BEARINGS CAN SURVIVE LAUNCH ENVIRONMENTS
HIGH CAPACITY POWER

CODE DEVELOPMENT PROGRESS

- IMPROVED UNDERSTANDING OF FLUID FLOW AND HEAT TRANSFER IN HEATERS, COOLERS, AND GAS SPRINGS WITH OSCILLATING FLOW

- MULTI-DIMENSIONAL CODES → INSTANTANEOUS HEAT TRANSFER AND FLUID FRICTION COEFFICIENTS FOR 1-D DESIGN CODES

IMPROVED UNDERSTANDING OF FLUID FLOW AND HEAT TRANSFER IN HEATERS, COOLERS, AND GAS SPRINGS WITH OSCILLATING FLOW

MULTI-D CODES & TEST RIGS

1-D CODES

WORKSHOPS

MULTI-D CODES

ICOMP, MIT
U. of Minnesota, CSU
Gideon, U. of Pittsburgh
Ohio University, Argonne

STIRLING ENGINES

HFAST
GLIMPS
SAUCE
MARWEISS
NASA

GOVT.
INDUSTRY
ACADEME

MINNESOTA

Oscillating-flow Rigs

OHIO U.

MIT

PT8-14
GOVERNMENT IN-HOUSE TEST FACILITIES
SPACE POWER RESEARCH ENGINE
STIRLING RE 1000 HEAT PIPE TEST
LINEAR ALTERNATOR RESEARCH
ATOMIC OXYGEN TEST
125 TON VACUUM HOT PRESS
HIGH TEMPERATURE VACUUM CREEP TEST
HEAT PIPE TEST
HI-TEMP CALORIMETRIC VACUUM EMISSOMETER

INDUSTRY/UNIVERSITY TEST FACILITIES
MTI MANUFACTURING U. OF PGH. HIGH TEMPERATURE MAGNETIC TEST CWRU ATOMIC OXYGEN TEST
MTI FREE-PISTON STIRLING OHIO STATE UNIVERSITY MATERIAL TEST REACTOR SUNPOWER OSCILLATING/STEADY-STATE FLOW TEST
MTI LINEAR ALTERNATOR DEVELOPMENT UNIVERSITY OF CINCINNATI GAMMA TEST
MATERIALS STUDIES FOR THE STIRLING SPACE POWER CONVERTER

EFFECT OF Na ON MECHANICAL PROPERTIES
- THERMACORE
- ETEC
- MTI

1050K RATIO
LIFETIME
FREQUENCY

FATIGUE/CREEP
LIQUID METAL COMPATIBILITY

WELD MIC-F/CRAKING
EDM SURFACE MICROCRACKING
- MEFEM
- SPEEDRING
- M1I

FABRICATION/JOINING

BRAZE COMPATIBILITY
WICK MATERIALS
JOINING TO HEAT SOURCE
- THERMACORE
- ALLIED SIGNAL
- WALLCOL
- M1I

CHOICE OF HEATER HEAD ALLOY
FABRICATION OF HEATER HEAD

REFLUX BOILER vs HEAT PIPE
FILLING PROCEDURES
COATINGS
- THERMACORE
- ETEC
- MTI

PT8-16
SODIUM HEAT PIPE FATIGUE TESTS
THERMACORE MTI

- SIMULATES STARFISH HEATER LOADINGS AND ENVIRONMENT
- SODIUM HEAT PIPE
- INCONEL 718 (CTPC MATERIAL)
- EVALUATES CORROSION EFFECTS
- EVALUATES CREEP AND HIGH CYCLE FATIGUE

- 4 HEAT PIPES FABRICATED
  1 CH APART FOR O2 TEST
  1.15C 100 PPM
  MILD STEEL 200 PPM
  3 INSTALLED IN FATIGUE TEST RIG

- ETEC PUMPED LOOP IDENTIFIED AS SUITABLE FILL TECHNIQUE

BASE TEST SYSTEMS CAN BE EASILY UPGRADED TO TEST REFRACTORY METALS

From superalloys base test system
To refractory metal upgrade of base test system
HIGH CAPACITY POWER

STIRLING MATERIALS PROGRESS

• CERAMIC COATINGS - MAGNET INSULATORS
• NON-MAGNETIC ALTERNATOR SUPPORT STRUCTURES
• REFRACTORY MATERIALS - 1300 K CONVERTER
• STEM AND EDM TECHNIQUES - HOT END MATERIALS
• TRANSIENT LIQUID PHASE DIFFUSION BONDING
  EB WELDING } UDIMET 720
• LOW OXYGEN FILL TECHNIQUES - Na HEAT PIPES
• VISCOPLASTIC/INELASTIC ANALYSIS & TESTING - LONG LIFE DESIGN

HIGH CAPACITY POWER

STIRLING SYSTEMS PROGRESS

• LUNAR BASE REFRACTORY STIRLING-NUCLEAR INTERFACE CONCEPTS
• SYSTEM RESPONSE TRANSIENTS
• MULTIPLE CONVERTER INTEGRATION & INTERACTION
HIGH CAPACITY POWER

SPIN-MOTOR FOR PISTON-CYLINDER
HYDRODYNAMIC GAS BEARING
(DEMONSTRATED ON SPRE)

SCHEMATIC SHOWING PISTON SPIN-MOTOR FOR
PISTON-CYLINDER HYDRODYNAMIC GAS BEARING
CONCEPT FOR A FREE PISTON STIRLING ENGINE

HIGH CAPACITY POWER

NON-CONTACTING BEARINGS TECHNOLOGY PROGRESS

- HYDROSTATIC BEARING LOSSES REDUCED 50%
- HYDRODYNAMIC BEARING DEMONSTRATED
- "NEW" HIGH STIFFNESS, ULTRA STABLE HYDRODYNAMIC BEARING IDENTIFIED
- MAGNETIC BEARINGS VIABLE FOR HIGH POWER CONVERTERS
- OTHER NON-CONTACTING BEARINGS UNDER INVESTIGATION
REFERENCE ENGINE DESIGN GUIDING EFFORT

- NEW "RELATIVE DISPLACER" DESIGN REDUCES COMPLEXITY, IMPROVES MANUFACTURABILITY AND RELIABILITY, IMPROVES POWER AND EFFICIENCY (+2% POINTS)

RSSE RELATIVE DISPLACER GAS SPRING CONFIGURATION

- REDUCED COMPLEXITY OF DISPLACER DRIVE
- IMPROVED MANUFACTURABILITY
- IMPROVED RELIABILITY
- ACCEPTS MAGNETIC BEARINGS
- INCREASED POWER DENSITY
- APPROACHES 30% EFFICIENCY
ADVANCED THERMOELECTRICS

MAJOR OBJECTIVES:

DEVELOP SiGe/GaP n-LEG AND p-LEG TO PRODUCE THE Z = .85 x 10^{-3} K^{-1}
SPECIFIED FOR THE SP-100 REACTOR SYSTEM

- OPTIMIZE DOPANTS. ADD SCATTERING CENTERS
- DETERMINE MANUFACTURING SPECIFICATIONS
- PROCURE AND TEST MODULES/MULTICOUPLES FOR ACCELERATED LIFETIME MEASUREMENTS

THERMOELECTRIC DEVELOPMENT

Figure 6

PT8-21
ADVANCED THERMOELECTRICS - BASELINE PROGRAM

THERMOELECTRICS GOALS:

- REPRODUCIBLY OBTAIN n-TYPE SiGe/GaP with $Z = 0.9 \cdot 1.0 \times 10^{-3} \text{ K}^{-1}$
  - ADD INERT SCATTERING CENTERS TO INCREASE $Z$ TO $1.1 \cdot 1.2 \times 10^{-3} \text{ K}^{-1}$
- INCREASE $Z$ OF p-LEG TO $0.70 \cdot 0.75 \times 10^{-3} \text{ K}^{-1}$ WITH SCATTERING CENTERS
  - RESULTS IN COMBINED $Z$ TO $0.85 \cdot 0.90 \times 10^{-3} \text{ K}^{-1}$ BETWEEN 600 - 1000 °C

PRESENT STATUS

N-LEG: 9 SAMPLES $Z$ BETWEEN 0.85 AND $1.0 \times 10^{-3} \text{ K}^{-1}$
- CANNOT FABRICATE HIGHEST $Z$ SAMPLES AT WILL
- CAN FABRICATE HEAVILY OVERDOPED SAMPLES, MUST REDUCE CARRIER CONCENTRATION

P-LEG: INCREASED $Z$ BY 10-15% ($0.6 \times 10^{-3} \text{ K}^{-1}$) BY OPTIMIZING BORON CONTENT
- SMALL INERT PARTICLES BEING ADDED TO REDUCE THERMAL CONDUCTIVITY
- MODEL PREDICTS $Z$ INCREASE OF 40% POSSIBLE WITH PARTICULATE SCATTERING

IMPROVED n-TYPE SiGe/GaP

<table>
<thead>
<tr>
<th>$Z$ ($10^{-3} \text{ K}^{-1}$)</th>
</tr>
</thead>
</table>
| TN 106
| TN 373
| TN 428
| TN 660
| TN 681
| TN 709
| TN 711
| TN 715
| TN 716

8TH SYMPOSIUM ON SPACE NUCLEAR POWER SYSTEMS

PT8-23

ORIGINAL PAGE IS OF POOR QUALITY
Z FOR p-TYPE SiGe

![Graph showing Z as a function of temperature for different samples and a goal line.]

OVERALL T/E IMPROVEMENT

- SP-100 GOAL OF $Z_{np} = 0.85$ (B.O.L.) IN SIGHT

JPL
Los Alamos

PT8-24
MAJOR OBJECTIVES:

DEVELOP AND DEMONSTRATE ADVANCED THERMAL MANAGEMENT CONCEPTS FOR BOTH THERMOELECTRIC AND STIRLING CONVERSION SYSTEMS

STIRLING - RADIATOR AT 475 - 600 K, 5 kg/m², 10 YEAR LIFETIME, .99 RELIABILITY
- HOT SIDE HEAT EXCHANGERS AND PUMPS
  - Low Mass, High Performance, Superalloy and Refractory
- COLD SIDE HEAT EXCHANGERS AND PUMPS
  - Low Mass, High Performance

THERMOELECTRIC - RADIATOR AT 800 - 900 K, 5 kg/m², 10 YEAR LIFETIME, .99 RELIABILITY

DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS (Heat Pipes, Pumps, Heat Exchangers)


ADVANCED RADIATOR SEGMENT DEVELOPMENT

- TECHNOLOGY —> COMPONENT —> SUBSYSTEM —> RADIATOR SEGMENT
  - 875 K HEAT PIPE WITH FINS FOR THERMOELECTRIC
  - 600 K LiNaK PUMPED LOOP FOR STIRLING

- SURFACE MORPHOLOGY
  - EMISSIVITY > .85 WITH SURFACE TREATMENT, NO COATINGS

- MATERIALS DEVELOPMENT
  - Cu/Gr COMPOSITE TO REPLACE Be FINS WITHOUT MASS PENALTY

- HEAT PIPE/RADIATOR DESIGN CODES AND CORRELATION
  - ANALYSIS, AUDITS, TRANSIENT BEHAVIOR
  - TESTING
HIGH CAPACITY POWER

THERMAL MANAGEMENT
BASELINE BUDGET

Advanced Radiator Concepts Contractors
SPI, RI

Feasibility Demonstrations

PHASE III
ARC
COMPL.

(Components)

PHASE IV CONTRACTS
475-500 K CONCEPT DEMO
500 K CONCEPT DEMO

(Subsystem)

475-500 K RAD SEG. FAB

475-500 K SEGMENT DEMO

1056K Stirling System Test

HIGH CONDUCTIVITY COMPOSITE FIN DEVELOPMENT
LeRC, ASI, SAIC

DOE/PHL
FABRIC-FOR-HP

H₂O HEAT PIPE

Figure 9
HIGH CAPACITY POWER

ROCKWELL ACCOMPLISHMENTS

• DEMONSTRATED CARBON-CARBON COMPOSITE INTEGRATED TUBE-FIN MANUFACTURING TECHNOLOGY

• IDENTIFIED Nb AND Ti AS LINER OR COATING MATERIALS TO CONTAIN WORKING FLUID

• IDENTIFIED BRAZE MATERIALS AND Re PRECOAT FOR JOINING LINERS TO TUBES (PERFORMED INITIAL BRAZING AND COATING EXPERIMENTS)

• INITIATED TWO ALTERNATIVE METAL FOIL LINER FABRICATION SUBCONTRACTS
LOW TEMPERATURE Li-NaK RADIATOR
EXPERIMENTAL TEST SECTION
Operated In Li-NaK Loop

SPI ACCOMPLISHMENTS

• COMPLETE Li/NaK LOOP GROUND TEST FACILITY

• PERFORMED Li/NaK FLOW TESTS IN BOTH Li THAW AND Li FREEZE MODES

• DEVELOPED 2-D COMPUTER SIMULATION OF Li/NaK FREEZE/THAW WITH VIDEO GRAPHIC OUTPUT

• PERFORMED LONG TERM (3000 hr) HIGH TEMPERATURE Li/NaK CAPSULE TO VERIFY MIXTURE STABILITY

• FABRICATED OIL-WATER FLOW VISUALIZATION LOOP SIMULATOR

FIGURE 1

HIGH CAPACITY POWER

NASA

PT8-28
PNL ACCOMPLISHMENTS

- DESIGNED AND FABRICATED ULTRA-LIGHT HEAT PIPES WITH METAL FOIL LINERS AND HIGH STRENGTH WOVEN CERAMIC FIBER MANTLE

- TESTED FABRIC-FOIL HEAT PIPE WITH H₂O FLUID AND DELIVERED PROTOTYPE TO LeRC FOR MORE EXTENSIVE TESTING

HEAT PIPE CODES

DEVELOPED STEADY STATE DESIGN CODE
- VALIDATED WITH SP-100 HEAT PIPE DATA
- INCORPORATED IN HEPSPARC RADIATOR DESIGN CODE
- IMPROVED VAPOR FLOW ALGORITHM
- WILL BE USED FOR HEAT PIPE DESIGN & AUDITS

TRANSIENT CODES
- JOINT EFFORT (NASA, AIR FORCE, WSU, UCLA, UNM)
- MODELS SP-100 HEAT PIPE START-UP FROM FROZEN STATE
- VAPOR FLOW REGIONS COMPLETED AND VALIDATED
- COMPLETED EXPERIMENTS FOR CODE VALIDATION
NASA LeRC HEAT PIPE LABORATORY

- OPERATED WATER, LIQUID METAL HEAT PIPES
- FACILITY DATA ACQUISITION SYSTEM CHECK-OUT COMPLETE
- SIMULATE STIRLING AND THERMOELECTRIC RADIATOR OPERATING CONDITIONS
- INITIATING TESTS ON PNL FIBER-FABRIC HEAT PIPE
  - FUTURE TEST ON CONTRACTOR HEAT PIPES
FABRICATION OF Gr/Cu COMPOSITES AT LERG
COPPER-COATED 9100 GRAPHITE YARNS

YARNS WOUND 8 ARC-SPRAYED
Gr/Cu MONOTAPES CUT TO SIZE

Gr/Cu COMPOSITE

GRAPHITE/COPPER COMPOSITE
SUBSCALE DEMONSTRATION RADIATOR PIN

• SIX DIFFERENT TYPES OF C-C COMPOSITES EVALUATED
  - UNTREATED THERMAL EMITTANCE .45-.82 AT 800 K
  - AFTER A/O BEAM TEXTURING THERMAL EMITTANCE .85-.9 AT 800 K
  - PEAK EMITTANCE REACHED AT A/O EFFECTIVE FLUENCE OF 4 X 10^15
  - CVD SiO2 COATINGS ON C-C ARE BENEFICIAL
  - COATINGS ON UNTREATED C-C INCREASE EMITTANCE FROM .67 TO .82 AT 800 K
  - COATING PREVENTS MASS LOSS AND PRESERVES EMITTANCE IN A/O ENVIRONMENT

• APPLICABLE TO SP-100 AND SOLAR DYNAMIC SYSTEM C-C HEAT PIPE RADIATORS (600-860 K)

PT8-31

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HIGH CAPACITY POWER

ADVANCED MATERIALS

MAJOR OBJECTIVES:

DEVELOP MATERIALS WITH SIGNIFICANTLY ENHANCED CHARACTERISTICS COMPARED TO SOA RADIATOR AND REFRACTORY MATERIALS

- RADIATOR FIN MATERIALS TO REPLACE Be WITH NO MASS PENALTY

- REFRACTORY MATERIAL/COMPOSITE WITH FACTORS 2 TO 10 IMPROVEMENT IN CREEP STRENGTH COMPARED TO Nb-1Zr

- DEVELOP DATA BASE TO QUALIFY ALL MATERIALS AT DESIGN CONDITIONS (PWC-11, IN 718, IN 720, Cu/Gr, W/Nb, MoHfC/Nb)

HIGH CAPACITY POWER

ADVANCED MATERIALS

MAJOR PROJECT ELEMENTS

- DEVELOPMENT OF PWC-11
  - SPECIFICATION, FABRICATION, TESTING, APPLICATION (WELDING/JOINING)

- DEVELOPMENT OF WIRE REINFORCED REFRACTORY COMPOSITES
  - WIRE CHARACTERIZATION, COMPOSITE FABRICATION, TESTING, APPLICATIONS

- MATERIAL SELECTION AND COMPATIBILITY DETERMINATION FOR SUPERALL STIRLING DESIGNS AND REFRACTORY STIRLING DESIGNS
PWC-11 Alternate for Nb-1Zr

Aging at 1350-1400 K does not overage precipitate particle. After 35,000 h, precipitate (Zr,Nb)C still effective strengthener.

---

PWC-11 Precipitate Characterization

<table>
<thead>
<tr>
<th>Size</th>
<th>AS-Rolled</th>
<th>Heat Treated</th>
<th>Tested</th>
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<tbody>
<tr>
<td>1-10 μm</td>
<td>hcp</td>
<td>lcc</td>
<td>lcc</td>
</tr>
<tr>
<td>0.5-10 μm</td>
<td>Nb₃C</td>
<td>(Zr,Nb)C</td>
<td></td>
</tr>
<tr>
<td>0.1-0.15 μm</td>
<td>Nb₃C</td>
<td>lcc</td>
<td>(Zr,Nb)C</td>
</tr>
</tbody>
</table>

- Nb₃C transforms to stable (Zr,Nb)C particle.
- Aging at 1350-1400 K does not overage precipitate particle.
- After 35,000 h, precipitate (Zr,Nb)C still effective strengthener.

---

Creep Curves for Nb-1Zr & PWC-11 (0.06C)

ANN: 1755K/1h + 1475K/2h
TEST: 1350K/10MPa
VAC: 10-7Pa

---

MATERIALS DIVISION

NASA Lewis Research Center

---

PT8-33
Creep Curves for Nb–1% Zr and PWC–11

- Nb–1% Zr:
  - 1350K/34.5 MPa
  - 10^{-7} Pa

- PWC–11:
  - 0.06C
  - 0.1C

Time in hours:

- 1000, 2000, 3000, 4000, 5000, 6000

Comparison of Creep Strength/Density Ratios of W/Unalloyed Nb Composites With Conventional Nb Alloys
## HIGH CAPACITY POWER

**REFRACTORY MATERIAL CANDIDATES FOR 1300K STIRLING**

<table>
<thead>
<tr>
<th>BASE MATERIAL</th>
<th>MP (K)</th>
<th>( \rho ) (g/cc)</th>
<th>ALLOY NAME</th>
<th>COMPOSITION (wt%)</th>
<th>JOINABILITY</th>
<th>FABRICABILITY</th>
<th>ALLOY AVAILABILITY</th>
<th>DATA AVAILABILITY</th>
<th>VACUUM (torr)</th>
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<tbody>
<tr>
<td>W</td>
<td>3680</td>
<td>19.3</td>
<td>W-25Re-HfC</td>
<td>24.26% Re, 1% HfC</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>10^-6</td>
</tr>
<tr>
<td>Ta</td>
<td>3270</td>
<td>16.6</td>
<td>ASTAR-611C</td>
<td>8% W, 1% Re, 1% HfC</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>5</td>
<td>10^-6</td>
</tr>
<tr>
<td>Mo</td>
<td>2880</td>
<td>10.2</td>
<td>TZM</td>
<td>0.008% Zr, 0.5% Ti</td>
<td>2</td>
<td>8</td>
<td>10</td>
<td>4</td>
<td>10^-6</td>
</tr>
<tr>
<td>Mo/Re</td>
<td>2780</td>
<td>15.5</td>
<td>Mo-47.5 Re</td>
<td>47.5% Re, bal Mo</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>10^-6</td>
</tr>
<tr>
<td>Nb</td>
<td>2740</td>
<td>8.6</td>
<td>FS-85</td>
<td>11% W, 28% Ta, 1% Zr</td>
<td>8</td>
<td>8</td>
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</tr>
<tr>
<td>B-88</td>
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<td></td>
<td></td>
<td>27% W, 2% HfC</td>
<td>7</td>
<td>7</td>
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<td>10^-6</td>
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<tr>
<td>C-103</td>
<td></td>
<td></td>
<td></td>
<td>10% Hf, 1% Ti, 0.7% Zr</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>10^-6</td>
</tr>
<tr>
<td>PWC-11</td>
<td></td>
<td></td>
<td></td>
<td>1% Zr, 0.1% C</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>10^-6</td>
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<tr>
<td>Nb-12Zr</td>
<td></td>
<td></td>
<td></td>
<td>1% Zr</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>10^-6</td>
</tr>
</tbody>
</table>

### HIGH CAPACITY POWER

**POWER MANAGEMENT/SYSTEM DIAGNOSTICS**

**MAJOR OBJECTIVES:**

- **DEVELOP PMAD ARCHITECTURE TO ENABLE USE OF FPSC's IN FUTURE MISSIONS**
  - CONTROL STABILITY, LOW MASS (1 kg/kWe), RELIABILITY (.99)
- TEST POWER SWITCHES IN HIGH TEMPERATURE (425K), HIGH RADIATION (10^{15} n/cm, .5 Mrad gamma), ENVIRONMENTS
- DEVELOP DIAGNOSTIC SENSORS AND SYSTEMS TO MONITOR NUCLEAR SYSTEM PERFORMANCE WITH EMI IMMUNITY AND SAFETY UNDER EXCESS CURRENT AND INSULATION BREAKDOWN CONDITIONS
TECHNICAL HIGHLIGHTS

PMAD

• SET-UP TEST LABORATORY TO DEVELOP CONTROL TECHNIQUES FOR MULTIPLE FREE-PISTON STIRLING CONVERSION SYSTEMS

• QUALIFIED HIGH TEMPERATURE (525K) MAGNETIC MATERIALS FOR FPSE LINEAR ALTERNATOR - Sm2Co17

• IRRADIATED COMMERCIAL SEMI-CONDUCTOR POWER SWITCHES TO SP-100 SPECIFICATIONS - ALL DEGRADED

• BEGAN DEVELOPMENT OF SiC SWITCHES TO MEET REQUIREMENTS

SYSTEM DIAGNOSTICS

• FIBER OPTIC CURRENT SENSOR COMPLETE (IR&D 100 AWARD)

• FIBER OPTIC VOLTAGE SENSOR NEAR COMPLETION
SPACE ENVIRONMENTAL EFFECTS

MAJOR OBJECTIVES:

DEVELOP CODES AND EXPERIMENTAL CORRELATIONS TO PREDICT BEHAVIOR OF HIGH POWER SYSTEMS UNDER RELEVANT ENVIRONMENTS

- EPSAT CODE EXTENDED TO LUNAR AND MARS ENVIRONMENTS
  (Atomic Oxygen, Meteoroids, Space Plasma, Ion Effluents)

ENSURE SAFETY AND LONG-LIFE OPERATION OF HIGH POWER SYSTEMS

TECHNICAL HIGHLIGHTS - ENVIRONMENTAL EFFECTS

- MEASURED ATOMIC OXYGEN IONIZED SPUTTERING YIELDS TO CORRELATE WITH SP-100 MATERIALS AND DESIGNS

- MEASURED AND MODELED CURRENTS THROUGH CABLE INSULATION PINHOLES

- MEASURED DIELECTRIC BREAKDOWN POTENTIAL BETWEEN SPACE PLASMA AND SPACECRAFT
### BUDGETS, $ M

<table>
<thead>
<tr>
<th>YEAR</th>
<th>BASELINE</th>
<th>AUGMENTED</th>
<th>FULL-UP</th>
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<tbody>
<tr>
<td>1991</td>
<td>10.4</td>
<td>10.4</td>
<td>10.4</td>
</tr>
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HIGH CAPACITY POWER
GROSS FUNDING HISTORY/PROJECTIONS
NASA SP-100 ATP - HIGH CAPACITY POWER

EXPLORATION TECHNOLOGY
SURFACE SYSTEMS/OPERATIONS

CURRENT PROGRAM

- 1050K SUPERALLOY STIRLING DEMONSTRATION- 25% EFF., 6 kg/kWe, 25 kWe - 1994
  - 30% IN 1996
  - 1 YEAR OPERATION IN 1997
- 450K WATER HEAT PIPE DEMONSTRATION < 5kg/m² - 1992
  - 525K RADIATOR SEGMENT DEMO IN 1994
- THERMOELECTRIC MATERIAL (SiGe/GaP) Z = 1.0 X 10⁻³ K⁻¹ DEMONSTRATED - 1994
- RADIATION HARD CIRCUITS DEVELOPED - 1995
- OPTIC POWER SENSING SYSTEM DEVELOPED - 1995
- ATOMIC OXYGEN, CO₂ ION, AND CO TESTING OF MATERIALS FOR MARTIAN SURFACE - 1997
STIRLING DEVELOPMENT
FULL-UP BUDGET

- PISTON HYDRODYNAMIC BEARING
- DISPLACER BEARING (HYDROSTATIC)
- ALTERNATOR MATERIALS SUBSTITUTION
- REGENERATOR MATRIX CONFIGURATION

LIFE DEMO
CTPC
10/96
MTI 12.5 KW 650 K/325 K
10/96
MTI 12.5 KW 525 K
2/91
CTPC
MTI 12.5 KW 525 K
- ALTERNATOR
- BEARINGS
- SEALS
2/92
CTPC
MTI 12.5 KW 525 K
- 525 K COLD END TEST
MTI 12.5 KW 525 K
- ALTERNATOR
- BEARINGS
- SEALS
5/93
SSPC
MTI 25 KW 1050 K/525 K
- 25 KW HEATER
- 525 K ALTERNATOR
- HIGH-STRENGTH SUPERALLOY (U-720)

PLANT GOALS
End of life power: 25 kW
Efficiency: > 25%
Life (design): > 60,000 hrs
Vibration (peak-to-peak): < 0.04 mm
Bearings - Non-Contacting
Specific mass: < 8 kg/kW

EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

FULL-UP BUDGET PROGRAM

- FULL-UP PROGRAM CONTAINS ALL ELEMENTS AND COF NECESSARY TO COMPLETE A 1300K FREE-PISTON STIRLING TEST IN 1997, PROVIDES SIGNIFICANT PROGRESS IN RADIATORS, MATERIALS, PMAD, ENVIRONMENTAL INTERACTIONS
  - 30% EFFICIENCY, 6 kg/kWe, 25 kWe REFRACTORY POWER CONVERTER
  - MULTIPLE STIRLING SYSTEM TESTS FOR POWER SYSTEM PHASING AND CONTROL
  - 5 kg/m², 600K RADIATOR
  - FACILITIES TO PERFORM POWER CONVERSION/RADIATOR SYSTEM TESTS
  - ENDURANCE TESTS AND ACCELERATED LIFETIME MODELS/TECHNIQUES TO ASSURE 10 - 15 YEAR LIFE
  - 875K RADIATOR SEGMENT TESTS FOR THERMOELECTRICS
  - MATERIALS DATA BASE AND APPLICATION OF SUPERALLOYS, PWC-11, REFRACTORY COMPOSITES AND RADIATOR MATERIALS TO SYSTEM TESTS

PT9-40
STIRLING DEVELOPMENT
AUGMENTED BUDGET

- Piston Hydrodynamic Bearing
- Displacer Bearing (Hydrodynamic, Hydrostatic)
- Alternator Materials Substitution
- Regenerator matrix configuration

FIG.

EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER
∆ AUGMENTED PROGRAM

ELIMINATES THE FOLLOWING:

- Hardware and facilities for 1300K Stirling system test
- Double-ended Stirling endurance tests at 1050K and 1300K
- Multiple Stirling system test
- Basic understanding, code development and correlation to reduce program risk
- Thermal management development for 1300K Stirling system test
- Advanced PMAD and diagnostic full system development
- Modelling development for Lunar and Mars environments, ion thruster effluents
- Detailed material data base and application development for advanced alloys and composites
- Facility development for refractory testing at simulated Mars conditions

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PT8-41

ORIGINAL PAGE IS OF POOR QUALITY
HIGH CAPACITY POWER

THERMAL MANAGEMENT
BASELINE BUDGET

Advanced
Radiator
Concepts
SPI, RI

Feasibility Demonstrations
PHASE IV CONTRACTS
875 K CONCEPT DEMO
600 K CONCEPT DEMO

475-500 K RAD
SEG. FAB

HIGH CONDUCTIVITY COMPOSITE FIN DEVELOPMENT
LeRC, ASI, SAIC

DOE/NHL
FABRIC-TO-LYP
H₂O HEAT PIPE

TO SP-100 FSQ

THERMAL MANAGEMENT
FULL-UP BUDGET

800 - 850 K RADIATOR SEGMENT DEMO

1100 K PUMP DEVELOPMENT
1150 K HEAT EXCHANGER DEVELOP

1360 K PUMP DEVELOPMENT
1390 K HEAT EXCHANGER DEVELOP

475 - 500 K RADIATOR SEGMENT DEMO

1050 K STIRLING SYSTEM TEST
(STERLING PORTION BASELINE FUNDED)

600 K RADIATOR SEGMENT DEMO

500 - 600 K PUMP DEVELOPMENT
STIRLING COLD SIDE LOOP DEVELOP

1300 K STIRLING SYSTEM TEST

Figure 9

JAW90-004 4

PT8-42
THERMAL MANAGEMENT
AUGMENTED BUDGET

800 - 850 K RADIATOR SEGMENT DEMO

TO SP-100 FSQ

1100 K PUMP DEVELOPMENT
1150 K HEAT EXCHANGER DEVELOP

1360 K PUMP DEVELOPMENT
1390 K HEAT EXCHANGER DEVELOP

475 - 500 K RADIATOR SEGMENT DEMO

1059 K STIRLING SYSTEM TEST

(STIRLING PORTION BASELINE FUNDED)

500 - 600 K PUMP DEVELOPMENT
STIRLING COLD SIDE LOOP DEVELOP

600 K RADIATOR SEGMENT DEMO

92 93 94 95 96 97 98 99 00

EXPLORATION TECHNOLOGY=

HIGH CAPACITY POWER
PMAD/SYSTEM DIAGNOSTICS

FULL-UP BUDGET

PMAD  •  RADIATION-HARD CIRCUITS DEVELOPED AND DEMONSTRATED AT SYSTEM OPERATING CONDITIONS

• SOFT MAGNETIC MATERIALS COMPLETELY CHARACTERIZED FOR USE IN HIGH POWER, HIGH TEMPERATURE, SPACE POWER APPLICATIONS
  • COMPONENTS (TRANSFORMERS) DESIGNED AND TESTED IN RELEVANT ENvironments

DIAGNOSTICS  •  DEVELOP EXTENDED RANGE OF OPERATION FOR POWER SENSORS (TEMPERATURE AND VIBRATION)

• SENSORS MODIFIED FOR PRODUCTION / THEN FLIGHT QUALIFIED
PMAD/SYSTEM DIAGNOSTICS

AUGMENTED BUDGET

PMAD
- RADIATION-HARD DEVELOPMENTS RESTRICTED TO SWITCHES, NOT CIRCUITS
- LESS SOFT MAGNETIC MATERIALS CHARACTERIZED, NO COMPONENTS TESTED

DIAGNOSTICS
- RESTRICTED RANGE OF TEMPERATURE AND VIBRATION OPERATION
- MAY NOT FULLY QUALIFY FOR FLIGHT, NOT PRODUCTION ITEMS

ENVIRONMENTAL INTERACTIONS

BASELINE
- ATOMIC OXYGEN, CO₂ ION, AND CO TESTING OF POWER SYSTEM MATERIALS FOR MARTIAN SURFACE APPLICATIONS

AUGMENTATION
- TESTING FOR PASCHEN BREAKDOWN OF HIGH VOLTAGE POWER SYSTEM GEOMETRIES IN LUNAR AND MARTIAN LOCAL ATMOSPHERIC CONDITIONS (AND DUST)

FULL-UP
- EPSAT - BASED MODELLING OF POWER SYSTEM INTERACTIONS WITH ION THRUSTER EFFlUENTS, ETC.
- MODEL/CORRELATION OF SYSTEM BEHAVIOR FOR LUNAR AND MARTIAN ENVIRONMENTS
RELATED EFFORTS

- JPL BASE R&T EFFORT ON SILICIDE THERMOELECTRICS WITH POTENTIAL ORDER OF MAGNITUDE IMPROVEMENT IN Z
- DOE SOLAR STIRLING DEVELOPMENT - 1050K, 25 kW/CYLINDER
- GE SP-100 CONTRACT FOR THERMOELECTRIC MODULES (Z = .85) AND SPACE RADIATORS
- DOD DEVELOPMENT OF SURVIVABLE SPACE RADIATOR TECHNOLOGY
  - CODE DEVELOPMENT
- DOD DEVELOPMENT OF RADIATION HARD SENSOR TECHNOLOGY
- DOD DEVELOPMENT OF EARTH ORBITAL ENVIRONMENTAL INTERACTIONS MODELS/EXPERIMENTS - EPSAT

FOCUSED TECHNOLOGY: HIgH CAPACITY POWER

SUMMARY

- IMPACT:
  - Advanced conversion (Stirling/Thermoelectric) coupled to an SP-100 reactor will provide the enabling technology for the development of lunar and Mars surface power systems

- USER COORDINATION:
  - SEI technology requirement for Surface Systems and NEP being developed co-operatively with RP, RZ, JSC
  - Planetary science requirements being developed with OSSA and with JPL

- OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
  - Significant progress in all areas including Conversion Systems, Thermal Management, PMAD, Space Environment, and Materials Development
  - Stirling cold end component test successful at 525 K
  - Some program elements have been delayed by complex component fabrication issues and subscale feasibility test delays - major out-year milestones not yet delayed

- MAJOR TECHNICAL/PROGRAMMATIC ISSUES
  - Lack of clear user commitment has delayed nuclear heat source development
  - Development/qualification of seven-year lifetime systems and technology to facilitate fifteen to twenty year overall lifetime
HIGH CAPACITY POWER

CONCLUDING REMARKS

• HIGH CAPACITY POWER
  - BROAD-BASED PROGRAM
  - KEY ELEMENTS
  - SIGNIFICANT PROGRESS TO DATE

• CURRENT PROGRAM MEETS MANY KEY MILESTONES

• STRATEGIC PROGRAM NECESSARY TO BRING ALL PROGRAM ELEMENTS TO FRUITION

• AUGMENTED PROGRAM PROVIDES EARLY 1050K STIRLING ENDURANCE TEST, PLUS DESIGN, FAB, AND TEST OF A 1300K REFRACTORY STIRLING AND SELECTED CRITICAL SUBSYSTEMS
SURFACE POWER AND THERMAL MANAGEMENT

BY

JOHN M. BOZEK
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW
JUNE 27, 1991

OBJECTIVES

- Programmatic
  Develop Solar-Based Power and Low-Grade Heat Thermal Management Technologies to Support Lunar and Mars Surface System Operations

- Technical
  Power System - 25 kWe @ 3 We/kg (Lunar), 8 We/kg (Mars)
  Fuel Cell Life - 20,000 hrs operational life
  RFC Energy Density - 500 to 1000 W-kg/kg
  Thermal Ops. - 60K to 400K with Long Life
  Photovoltaics - > 300 W/kg (AMO)
  Electrical - ≤ 55 kg/kWe

SCHEDULE

- 1993 Select RFC PEM Membrane(s)
- 1994 Complete Thermal Model for RFC
- 1995 Full Area Fuel Cell
  - PV Cell Choice
  - 50% Improvement in Cryo Heat Pipes
- 1996 300% Heat Pump Improvement
  - Stable Electrical Transmission
  - Fuel Cell Stacks Fabricated
- 1997 5,000 hrs on Fuel Cell Stack w/SOA Electrolyzer
  - PV Cell/Structure Integrated
- 1998 1 yr Life Test on EPM Board
  - Ground Verification of RFC/TPM
  - TPM Flight Experiment Design
- 1999 Complete RFC B-B Test (Adv. FL/EL/Tanks)
- 2000 Board-Board Performance of TDA/C
  - 3 W/kg, 20,000 hr Lunar Power System Reference Design

RESOURCES

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POTENTIAL PARTICIPANTS

- Lewis Research Center
  Lead, Analyze, Energy Storage, PEM, Thermal Mgt., PV
- Jet Propulsion Laboratory
  Supporting PV Arrays, Energy Storage, Analyze, Thermal Mgt.
- Johnson Space Center
  Supporting Energy Storage & Thermal Mgt.
- Goddard Space Flight Center
  Supporting Low-Temperature Thermal Mgt.
- Los Alamos National Laboratory
  Supporting Energy Storage Component Testing
EXPLORATION TECHNOLOGY

SURFACE POWER AND THERMAL MANAGEMENT

WHAT IS IT?

FOCUSED TECHNOLOGY PROJECT (ELEMENT OF EXPLORATION TECHNOLOGY PROGRAM)

FOCUSED ON EXTRATERRESTRIAL SURFACES (LUNAR & MARS)

FOCUSED ON SOLAR-BASED POWER (REGENERATIVE)

FOCUSED ON ENERGY STORAGE (REGENERATIVE FUEL CELLS)

FOCUSED ON POWER GENERATION (PHOTOVOLTAICS)

FOCUSED ON ELECTRICAL POWER MANAGEMENT (TEMP. & POWER)

FOCUSED ON THERMAL POWER MANAGEMENT (3 R'S)

FOCUSED HARDWARE THAT IS SCALABLE TO NEEDS (TEST BEDS)

PROJECT SUPPORTS EXPLORATION PROGRAM

THRU

FOCUSED TECHNOLOGY VERIFICATION

OF

ALL SOLAR-BASED POWER SYSTEM TECHNOLOGIES

AND

LOW-GRADE THERMAL MANAGEMENT TECHNOLOGIES
EXPLORATION TECHNOLOGY -

SURFACE POWER AND THERMAL MANAGEMENT

OBJECTIVE

DEVELOP SOLAR-BASED POWER AND THERMAL MANAGEMENT TECHNOLOGY TO A LEVEL OF READINESS SUFFICIENT TO ENABLE OR ENHANCE EXTRATERRESTRIAL SURFACE MISSIONS IN THE 21st CENTURY
SURFACE POWER AND THERMAL MANAGEMENT

GOALS

POWER SYSTEM

- 0.1 W/kg → LUNAR → 3 W/kg
- 2.0 W/kg → MARS → 8 W/kg
- 30 to 90 DAYS → LUNAR/MARS → UP to 5 YEARS

THERMAL MANAGEMENT

- 21 kg/kWt → LUNAR → 7 kg/kWt
- 6 kg/Wt → HEAT PUMPS → 0.3 kg/Wt
- 17 kg/Wt → 160 K HEAT PIPES → 5 kg/Wt
- 400 K HEAT PIPES → 80 K HEAT PIPES → 5 kg/Wt
  → SIPHONS
  → STORAGE
  → HEAT PIPES, PUMPS
  → OTHER
EXPLORATION TECHNOLOGY

SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY CHALLENGE

• COMPATIBLE TECHNOLOGIES FOR INTEGRATED SYSTEM
• LONG LIFE RFC WITHOUT SACRIFICING PERFORMANCE
• HIGH POWER DENSITY, ROBUST PHOTOVOLTAICS
• LOW MASS, RELIABLE, ENVIRONMENTALLY COMPATIBLE ELECTRICAL SUBSYSTEM
• LOW MASS, LONG LIFE, HIGH PERFORMANCE THERMAL REJECTION, RETENTION, AND REDISTRIBUTION

STRATEGIC PROGRAM ELEMENT

• SYSTEM INTEGRATION
  - TRADE STUDIES: INNOVATIVE TECHNOLOGY FEASIBILITY
  - REFERENCE DESIGNS [3 W/kg (Lunar); 8 W/kg (Mars)]

• ENERGY STORAGE (RFC's)
  - FUEL CELLS [Life/Efficiency]
  - ELECTROLYZERS [Life/Efficiency]
  - REACTANT STORAGE [Life/Mass/Volume]
  - TEST BEDDED SUBSYSTEM [Life/Performance]

• POWER GENERATION (PV's)
  - CELLS [Life/Efficiency]
  - BLANKET [Mass]
  - STRUCTURE [Deployment]
  - SCALABLE ARRAY PERFORMANCE [AMOVacuum/Thermal]

• ELECTRICAL MANAGEMENT
  - INTEGRATION OF POWER SUBSYSTEMS [Mass, Temp., Efficiency, Reliability]
  - TRANSMISSION, DISTRIBUTION AND CONTROL [Mass, Temp., Autonomy, Environment]
  - TEST BEDDED SUBSYSTEM

• THERMAL MANAGEMENT
  - MODELING [Requirements]
  - COMPONENTS [Rejection, Retention, Redistribution]
  - TEST BEDDED SUBSYSTEM [RFC, EPM/T&D, Science]
  - FLIGHT EXPERIMENT WHERE NECESSARY

ITP-JMB91-002.11

PT9-5
EXPLORATION TECHNOLOGY

SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY PLAN

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| SCALABLE TEST BEDDED HARDWARE |      |      |      |      |      |      |      |

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IMPACT:
- PROVIDES FOR EARLY DEPLOYMENT OF NEEDED POWER FOR LUNAR BASE
- MEETS MASS, VOLUME AND OPERATIONAL CONSTRAINTS
- SYNERGISTIC WITH MARS MISSION

USER COORDINATION:
- CODE RZ: OAET/SPACE EXPLORATION: PSS/JSC
- CODE M: OFFICE OF SPACE FLIGHT (OSF)
- CODE S: OFFICE OF SPACE SCIENCE AND APPLICATION (OSSA)

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
- CRITICAL SYSTEM ELEMENTS IDENTIFIED
- PEM FUEL CELL LIFE (>1000 HOURS)
- RETRENCH TO BASE R&T IN FY92
- SYNERGISTIC PROGRAMS ADVANCING TECHNOLOGY OUTSIDE AGENCY

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:
- REQUIREMENTS EVOLVING
- NUCLEAR (REACTOR/DIPS) AVAILABILITY

PT9-6
TECHNOLOGY BACK-UP

SURFACE POWER AND THERMAL MANAGEMENT

REGENERATIVE FUEL CELL vs BATTERIES

MASS COMPARISON

ENERGY DENSITY, Watt-Hour/AG

CRYO RFC
GAS RFC
ADV. BATTERY
NEAR TERM BATTERY
SOA BATTERY

CHARGE TIME = DISCHARGE TIME, Hours

DISCHARGE = CHARGE TIME
< 1 HOUR
> 1 HOUR but < 10 HOURS
> 10 HOURS but <100 HOURS
> 100 HOURS

TECHNOLOGY OF CHOICE *
BATTERIES
BATTERIES or GAS RFC
GAS RFC or CRYO RFC
CRYO RFC

* CHOICE BASED ON MASS OF ENERGY STORAGE SYSTEM ONLY
SURFACE POWER AND THERMAL MANAGEMENT
SURFACE POWER AND THERMAL MANAGEMENT

PMAD ELEMENTS
(EPM and TD&C)

EPM: 110 kg/kW → 55 kg/kW
TD&C: MISSION DEPENDENT
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

SPACE PLATFORMS FOCUSED TECHNOLOGY PROGRAM
POWER AND THERMAL MANAGEMENT

PRESENTATION TO:
THE ITP EXTERNAL EXPERT REVIEW TEAM

RONALD C. CULL

JUNE 27, 1991

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

AGENDA

THE PROBLEM
HOW ADDRESSED
MARKET SURVEY
WHAT'S NEEDED
WHAT IMPACT
HOW DO WE GET THERE
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

THE PROBLEM

• ENERGY IS CRUCIAL FOR ALL ACTIVITIES IN SPACE
  - ELECTRICAL POWER
  - THERMAL MANAGEMENT

• EXTREMELY COSTLY
  - $600 - 800/kW hr.

• NEW MISSIONS REQUIRE CONSIDERABLY MORE
  - SSF
  - EOS
  - ADTRSS

POSSIBLE SOLUTIONS

• CUT BACK MISSION RETURNS
  - TIME AVAILABLE
  - QUANTITY
  - QUALITY
  - LIFETIME

• MAKE USER MORE EFFICIENT
  - HIGHER EFFICIENCY LOADS
  - LOAD SCHEDULING AND MANAGEMENT

• IMPROVE TECHNOLOGY
  - MASS
  - EFFICIENCY
  - COST
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

SPACE PLATFORM
BACKBONE FOR ACTIVITIES IN SPACE

POWER & PROPULSION

OTHER

SPACE PLATFORM

PAYLOAD

LOAD MANAGEMENT IMPACT
(SSF EXAMPLE)

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>CAPACITY (KW)</th>
<th>MASS (kg)</th>
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<tbody>
<tr>
<td>GENERATION PC&amp;C</td>
<td>8 x 9.375 75</td>
<td>1740</td>
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<td>STORAGE PC&amp;C</td>
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<td>INTERCONNECT</td>
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<tr>
<td>LOADS PC&amp;C</td>
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% OF PCC&D MASS

PT10-3
PHILOSOPHY

- SCOPE OF NEAR EARTH SPACE ACTIVITIES DETERMINED BY FEDERAL BUDGET REALITIES

- TECHNOLOGY CAN BROADEN SCOPE WITHIN CONSTANT BUDGET
  - NUMBER OF MISSIONS
  - LIFE OF MISSIONS
  - QUALITY OF MISSIONS

- PLATFORM TECHNOLOGY THRUSTS SHOULD FOCUS ON BROADENING SCOPE
  - TOWARD LONG LIFE
  - TOWARD IMPROVED PERFORMANCE
  - TOWARD LOW COST

PHILOSOPHY (CONT.)

- MANY TECHNOLOGIES CURRENTLY UNDER DEVELOPMENT
  - LEVEL OF EFFORT INADEQUATE FOR TIMELY DEVELOPMENT
  - UNFOCUSED

- SPACE PLATFORM TECHNOLOGY PROGRAM SHOULD FOCUS ON THOSE TECHNOLOGIES THAT:
  - MAKE SIGNIFICANT IMPACT
  - BROADLY APPLICABLE
  - CAN BE READY IN TIME
PROGRAM FORMULATION

- IDENTIFY MARKET (USERS)
- DEFINE POWER AND THERMAL REQUIREMENTS
  - MISSION DOMAINS
  - MISSION UNIQUE
- ASSESS TECHNOLOGY IMPACT
- IDENTIFY CRITICAL TECHNOLOGY
- OUTLINE TECHNOLOGY DEVELOPMENT PLANS
  - INTEGRATED OBJECTIVES
  - ROADMAPS
  - FUNDING REQUIREMENTS
  - MILESTONES & DELIVERABLES

MARKET

- APPLICATIONS
  - EARTH OBSERVING (EOS)
  - ADVANCED COMMUNICATIONS (ATDRSS)
  - ADVANCED SPACE STATIONS (SSF)

- MISSIONS
  - MANNED/UNMANNED
  - CIVIL/COMMERCIAL

- ORBIT REQUIREMENTS
  - LEO → GEO
  - EQUATIONAL → POLAR

- POWER LEVELS
  - 10's W → 10's kW
SYSTEM REQUIREMENTS

- NEED TO SIGNIFICANTLY IMPROVE NEW SYSTEM DRIVERS
  - LIFE
  - RELIABILITY
  - MAINTAINABILITY
  - ADAPTABILITY

- WHILE MAINTAINING/IMPROVING TRADITIONAL DRIVERS
  - MASS
  - EFFICIENCY
  - COST

- BY IMPROVING TECHNOLOGY

- BY ADDING ATTRIBUTES
  - RECONFIGURABLE
  - SERVICEABLE
  - FAULT TOLERANT
  - AUTONOMOUS
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

DEDICATED vs UTILITY POWER SYSTEMS

REQUIREMENTS

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<th>CHARACTERISTIC</th>
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<th>UTILITY</th>
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<td>Source Capacity</td>
<td>1-10 kW</td>
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<tr>
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<tr>
<td>Manned</td>
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APPROACH

DEDICATED

- FOCUS ON MEETING
- MISSION SPECIFIC REQUIREMENTS
- ADAPT EXISTING SPACECRAFT BUS

UTILITY

- FOCUS ON MAJOR SYSTEM ELEMENTS
- GENERAL REQUIREMENTS
- FUNCTIONS
- MUTUAL COMPATIBILITY
- COMBINE MODULAR ELEMENTS
-INCLUDE REQUIREMENTS FOR
- REPAIRS
- USER TRANSPARENCY
- EVOLUTIONARY DEVELOPMENT

UTILITY APPROACH INCREASES DDT&E COSTS BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

TECHNOLOGY ASSESSMENT

LIFE

LONGEVITY

OBsolescence

SYSTEM COST

DISCRETE DESIGN

UNIVERSAL DESIGN

VALIDATED, ROBUST, COST EFFECTIVE, LONG LIFE SYSTEMS

PERFORMANCE

WEIGHT

EFFICIENCY

TESTING/DEMO

GROUND

IN-SPACE

PT10-7
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

PLAN

- FOCUS ON MISSIONS
- USE BASE PROGRAM TECHNOLOGY
- ENHANCE TECHNOLOGY DEVELOPMENT
  - TIMELINESS
  - DEVELOPMENT LEVEL
- DEMONSTRATE AT SYSTEMS LEVEL
- MOVE INTO FLIGHT PROGRAM

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

SPACE RESEARCH AND TECHNOLOGY GOAL

TO ENSURE THE EFFECTIVE TRANSFER OF TECHNOLOGY TO MISSION APPLICATIONS BY CONDUCTING FOCUSED TECHNOLOGY PROGRAMS, WITH NEGOTIATED AND COORDINATED USER HAND-OFF AGREEMENTS WITH THE OTHER PROGRAM OFFICES IN NASA.
# SPACE PLATFORMS TECHNOLOGY PROGRAM

## EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

### OAET

#### POWER AND THERMAL MANAGEMENT

## OBJECTIVES

- **Programmatic**
  - Develop and demonstrate integrated power and thermal management technologies for near earth missions.

- **Technical**
  - Reduce array area by 30% with 3X increased rad. tolerance
  - 3X increase in battery energy density
  - 2X reduction in PMAD system mass
  - 2X reduction in radiator mass and area
  - Extend lifetimes to 15-30 years

## SCHEDULE

<table>
<thead>
<tr>
<th>Year</th>
<th>Objective</th>
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<tbody>
<tr>
<td>1996</td>
<td>Demonstrate 300 W/kg planar PV, 100 W/kg InP concentrator module</td>
</tr>
<tr>
<td>1996</td>
<td>Ground test cryogenic capillary pumped loop</td>
</tr>
<tr>
<td>1997</td>
<td>Demonstrate advanced PMAD integrated avionics system</td>
</tr>
<tr>
<td>1997</td>
<td>Ground demo, integrated 2 kW solar dynamic system</td>
</tr>
<tr>
<td>1998</td>
<td>Demonstrate 1-2 kg/m² thermal management system</td>
</tr>
<tr>
<td>1998</td>
<td>Complete advanced EPSAT</td>
</tr>
<tr>
<td>1999</td>
<td>Demonstrate flight weight 100 Wh/kg battery</td>
</tr>
<tr>
<td>2000</td>
<td>Demonstrate durable high temp. electronics subsystem (200-600 °C)</td>
</tr>
</tbody>
</table>

## RESOURCES

<table>
<thead>
<tr>
<th>Year</th>
<th>Current</th>
<th>Strategic</th>
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<tbody>
<tr>
<td>1991</td>
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<td>---</td>
</tr>
<tr>
<td>1992</td>
<td>---</td>
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</tr>
<tr>
<td>1993</td>
<td>---</td>
<td>$ 5.1 M</td>
</tr>
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<td>1994</td>
<td>---</td>
<td>$ 10.2 M</td>
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<td>1995</td>
<td>---</td>
<td>$ 13.5 M</td>
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<tr>
<td>1996</td>
<td>---</td>
<td>$ 14.3 M</td>
</tr>
<tr>
<td>1997</td>
<td>---</td>
<td>$ 14.7 M</td>
</tr>
</tbody>
</table>

*Includes both Earth Orbiting Platforms and Space Stations

## PARTICIPANTS

- **Goddard**
  - Responsibility includes cryogenic bus technology and low temperature thermal management subsystems

- **JPL**
  - Responsibility includes lightweight planar PV and lithium battery technology and integrated PICs

- **LeRC**
  - Responsibility includes concentrator PV, InP cells, lightweight Ni/H2 and Na/S, batteries moderate and high temperature radiators, integrated autonomous PMAD and high temperature electronics, solar dynamic system

---

# SPACE PLATFORMS TECHNOLOGY PROGRAM

## EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

### OAET

#### POWER AND THERMAL MANAGEMENT

## OBJECTIVE

**PROVIDE THE TECHNOLOGY TO MEET POWER SYSTEM REQUIREMENTS FOR FUTURE NEAR EARTH SPACE MISSIONS, INCLUDING GROWTH SPACE STATIONS AND EARTH ORBITING SPACECRAFT.**

## TECHNOLOGY AREAS:

- PHOTOVOLTAIC ENERGY CONVERSION (CELLS/ARRAYS)
- THERMAL ENERGY CONVERSION (SOLAR DYNAMIC)
- CHEMICAL ENERGY STORAGE (BATTERIES)
- POWER MANAGEMENT AND DISTRIBUTION
- THERMAL MANAGEMENT AND DISTRIBUTION
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

POWER AND THERMAL SUBSYSTEMS
(ENERGY FLOW)

SOURCE

RADIATOR

TMAD

PMAD

USER (LOAD)

STORAGE

APPLICATIONS INVESTIGATED

EOS
TDRSS
SSF
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

TRACKING AND DATA RELAY SATELLITE SYSTEM
WET MASS

TOTAL MASS = 2123 kg

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

PROPULSION AND POWER DRIVERS ON ATDRSS

IMPROVEMENTS IN PROPULSION AND POWER CAN
SIGNIFICANTLY IMPROVE ATDRSS

PROPULSION AND POWER COM普RIS ABOUT ONE-HALF OF THE TOTAL MASS
OF ATDRSS

A 2X IMPROVEMENT IN
PROPULSION AND POWER
WOULD DOUBLE THE
PAYLOAD ON ATDRSS
ELECTRICAL POWER SYSTEM WEIGHTS

TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

PHOTOVOLTAIC ENERGY CONVERSION

OBJECTIVE

PROVIDE THE TECHNOLOGY FOR PHOTOVOLTAIC ARRAYS WITH IMPROVED CONVERSION EFFICIENCY, REDUCED MASS, REDUCED COST, AND INCREASED OPERATING LIFE FOR ADVANCED SPACE MISSIONS

SPECIFIC LONG-RANGE GOALS ARE TO DEVELOP THE TECHNOLOGY BASE FOR PHOTOVOLTAIC ARRAYS WITH SPECIFIC POWER OF 300 W/kg WITH SUBSTANTIAL REDUCTIONS IN SIZE, COST, AND INCREASES IN END-OF-LIFE POWER CAPABILITY

TECHNOLOGY AREAS

- ADVANCED PHOTOVOLTAIC CELL TECHNOLOGY
- HIGH-CURRENT ARRAYS
- HIGH-POWER ARRAYS
OBJECTIVE

TO DEVELOP AN ULTRA-LIGHT-WEIGHT, HIGH PERFORMANCE, ADVANCED DEPLOYABLE PHOTOVOLTAIC ARRAY DESIGN THAT WILL BE SUITABLE FOR A BROAD RANGE OF LONG-TERM NASA AND U.S. COMMERCIAL SPACE APPLICATIONS FOR THE PERIOD BEYOND 1990

NEAR-TERM SPECIFIC POWER: 130 W/kg*
LONG-TERM SPECIFIC POWER: 300 W/kg*

*BOL ARRAY POWER FOR GEO
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

APSA ARRAY FOR EOS
- Thin silicon cells, 13.5% eff
- Retractable
- Carbon-loaded Kapton blanket
- Graphite/epoxy structure
- Fiberglass boom
- Aluminum canister

Power and Thermal Management

Performance
Without Solar Array Drive Assembly (SADA)
- Specific Power = 96 W/kg
- Power Density = 94 W/m²

With SADA/Boom (27 kg allocation)
- Specific Power = 84 W/kg
- Power Density = 94 W/m²

Electrical Power System Weights

Advanced Photovoltaic Solar Array (APSA)
Saves 297.3 kg (654 lb)

PT10-14
ADVANCED PHOTOVOLTAIC SOLAR ARRAY

- GOAL: 10X IMPROVEMENT IN PHOTOVOLTAIC ARRAY DESIGN
  - ACHIEVED NEAR-TERM GOAL OF 130 W/kg
  - WORKING TOWARD LONG-TERM GOAL OF 300 W/kg

- LABORATORY VERIFICATION WITH PROTOTYPE BLANKET ASSEMBLY AND LIGHT-WEIGHT MAST SYSTEM
  - 2X IMPROVEMENT OVER SAFE ARRAY AND 3X-4X IMPROVEMENT OVER CURRENT RIGID-PANEL ARRAYS

- PLAN TO COMPLETE PROTOTYPE COMPONENTS AND CONDUCT FUNCTIONAL TESTS

ACTIVE INVOLVEMENT OF USERS WILL ENSURE TIMELY COMPLETION TO MEET LAUNCH DATES

EVOLUTION OF PLANAR ARRAY SPECIFIC POWER
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

CONCENTRATOR TECHNOLOGY

LeRC
MINI-DOME FRESNEL LENS
CONCENTRATOR ELEMENT

POWER AND THERMAL MANAGEMENT

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

EVOLUTION OF ARRAY POWER DENSITY

POWER DENSITY W/M²

EOS  AP3A  InP  30% CONC.
2 MIL SI  CONC.

BEGINNING OF LIFE

END OF LIFE
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

Project Overview and Resources

<table>
<thead>
<tr>
<th>Technology Program:</th>
<th>Space Platforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Area:</td>
<td>Earth Orbiting Platforms</td>
</tr>
<tr>
<td>Technology Element:</td>
<td>Power</td>
</tr>
<tr>
<td>Technology Sub-Element:</td>
<td>Power Generation (Photovoltaic)</td>
</tr>
</tbody>
</table>

Milestones:
- 1996 300 w/kg planar blanket fabricated
- 1996 100 w/kg InP concentrator panel demo
- 1998 Demo thin film cell array > 300 w/kg
- 1998 Demo 50 w InP concentrator module through environmental testing

<table>
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SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

CHEMICAL ENERGY CONVERSION

OBJECTIVES

PROVIDE THE TECHNOLOGY BASE FOR ADVANCED ELECTROCHEMICAL ENERGY CONVERSION AND STORAGE SYSTEMS REQUIRED TO SUPPORT THE LOW TO HIGH POWER NEEDS OF FUTURE MANNED AND UNMANNED SPACE APPLICATIONS, THE CYCLE LIFE REQUIREMENTS OF LOW-EARTH-ORBIT (LEO) SYSTEMS

TECHNOLOGY AREAS

- SECONDARY BATTERIES
- ADVANCED ELECTROCHEMICAL ENERGY STORAGE

PT10-17
PROGRESS IN ENERGY STORAGE

EOS Nickel-Hydrogen
(10 W-hr/Kg)

Advanced Nickel-Hydrogen
(24 W-hr/Kg)

Future Applications
Chemical Energy Storage
(>40 W-hr/Kg)

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

LIGHT-WEIGHT NiH₂ CELLS NEAR-TERM ADVANCEMENT OF
PROVEN TECHNOLOGY

OBJECTIVES
- IMPROVED SPECIFIC ENERGY CELLS
- IMPROVED SPECIFIC VOLUME CELLS

APPROACH
- COMPUTER-AIDED DESIGN OPTIMIZATION
- TECHNOLOGY DEVELOPMENT
  - LIGHT-WEIGHT NICKEL ELECTRODE
  - OPTIMIZATION OF KOH CONCENTRATION
- VERIFICATION TESTING VIA BOILER PLATE AND FLIGHT-WEIGHT CELLS
LIGHT-WEIGHT NiH₂ CELLS NEAR-TERM ADVANCEMENT OF PROVEN TECHNOLOGY
(Continued)

GOALS

- 2.0 x SOA SPECIFIC ENERGY
- 1.2 x SOA SPECIFIC VOLUME
- ENHANCED LEO AND GEO MISSIONS, SUCH AS:
  - SSF PLATFORMS
  - SPACE TELESCOPE
  - COMMUNICATION SATELLITES

ADVANCED BATTERY TECHNOLOGY CAN SAVE ~227 kg (~500 lb)
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

---

POWER AND THERMAL MANAGEMENT

Project Overview and Resources

<table>
<thead>
<tr>
<th>Technology Program</th>
<th>Space Platforms</th>
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<td>Technology Element</td>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Technology Sub-Element</td>
<td>Energy Storage</td>
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</tr>
</tbody>
</table>

Milestones:

- 1995: Demo 100 Wh/kg boilerplate cells to 1000+ cycles (GEO) (LJ and NH2)
- 1997: Define engineering model components for 150 Wh/kg battery
- 1999: Demo 100 Wh/kg lightweight battery
- 2000: Demo 150 Wh/kg (engineering model)

<table>
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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

---

POWER AND THERMAL MANAGEMENT

THERMAL ENERGY CONVERSION

OBJECTIVES

- DEVELOP THE TECHNOLOGY BASE TO PROVIDE ADVANCED HIGH-EFFICIENCY, HIGH-TEMPERATURE (1050 - 1400 K), LONG-LIFE SOLAR DYNAMIC STIRLING/BRAYTON POWER SYSTEM FOR A WIDE RANGE OF NASA AND COMMERCIAL SPACE POWER NEEDS

TECHNOLOGY AREAS

- HIGH-TEMPERATURE SOLAR DYNAMICS

PT10-20
SPACE STATION FREEDOM

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

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

TECHNOLOGY ISSUES

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
  - NONE
- CONTROLS
  - PARALLEL OPERATION
  - LOAD FOLLOWING
SOLAR DYNAMICS 2 kW GROUND TEST EXPERIMENT

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>FISCAL YEAR</th>
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<tbody>
<tr>
<td>1. PROCUREMENT</td>
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<tr>
<td>2. SYSTEM DESIGN &amp; INTEGRATION</td>
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<td>3. CONCENTRATOR</td>
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<td>- ENGR. DEVELOPMENT</td>
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<td>- FABRICATION</td>
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<td>- ENGR. DEVELOPMENT</td>
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<td>- FABRICATION</td>
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<tr>
<td>7. INTEGRATED SUBSYSTEMS TESTS</td>
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<tr>
<td>8. SYSTEM INTERACTION TESTS</td>
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</table>

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

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<td>Power</td>
</tr>
<tr>
<td>Technology Sub-Element:</td>
<td>Power Generation (Solar Dynamic)</td>
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</table>

Milestones:

1994 Select Brayton or Stirling PCU
1995 Demo 30% efficient concentrator cascade cell
1997 Demo 300 W/m² refractive concentrator PV module (750 W)
1997 Ground demo 2 kW advanced solar dynamic system
1999 Identify system level SD issues

R&D Resources:

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POWER MANAGEMENT

OBJECTIVES

- Develop the electrical power systems conditioning, control, and distribution technology needed for Earth orbital space missions

TECHNOLOGY AREAS

- High-voltage, high-power systems
- High-density power systems
- Fault tolerant/power integrated circuits

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

HIGH POWER LIGHT-WEIGHT ELECTRICAL COMPONENTS

POWER INTEGRATED CIRCUITS

EXTREMELY RELIABLE FAULT TOLERANT POWER CIRCUITS

AUTONOMOUS POWER SYSTEMS

POWER MANAGEMENT & DISTRIBUTION

ORIGINAL PAGE IS OF POOR QUALITY
**SPACE PLATFORMS TECHNOLOGY PROGRAM**

**EARTH ORBITING PLATFORMS**

(INCLUDES SPACE STATIONS)

**POWER AND THERMAL MANAGEMENT**

---

### EXISTING BATTERY ELECTRONICS

**ASSEMBLY**  
**MASS (LBS.)**

- 2ea BCR: 26 lbs
- 2ea BDR: 52 lbs
- 2ea BIM: 6 lbs

**TOTAL PER POWER ORU: 84 lbs**

---

### ADVANCED BATTERY ELECTRONICS

**ASSEMBLY**  
**MASS (LBS.)**

- 2ea BDC: 34 lbs

---

**SIGNIFICANCE**

EOS POWER SYSTEM MASS SAVINGS  
50lbs PER POWER ORU OR 200lbs PER PLATFORM.

---

### SPACE PLATFORMS TECHNOLOGY PROGRAM

**EARTH ORBITING PLATFORMS**

(INCLUDES SPACE STATIONS)

**POWER AND THERMAL MANAGEMENT**

---

**POWER SUBSYSTEM BLOCK DIAGRAM**

---

**FAULT TOLERANCE SAVINGS**

REDUCE NUMBER OF POWER BUSES FROM THREE TO TWO

- 2 LPCs: 4.4 lbs
- 3 RPCs: 2.3 lbs
- 1 PCU: 6.5 lbs
- 15 RBIs: 30.0 lbs
- ORU HARNESS: 16.0 lbs

**TOTAL SAVINGS 59.2 lbs (27 kgs)**

---

**NOTE:** ORU #2 MAY BE ABLE TO BE ELIMINATED ENTIRELY, DEPENDING ON THERMAL CONSIDERATIONS. IF ORU IS ELIMINATED ENTIRELY, THE WEIGHT SAVINGS WOULD BE 210 lbs (95 kgs)

---

PT10-24
Goal: Achieve high density power technologies of 10 W/in.³ by year 2000

State of the art discretes: volume/mass intensive

Impact:
- 80% mass reduction
- 80% volume reduction
- 89% parts reduction
- 50% loss reduction

Plan: Hold power system to 20% of total system

High frequency power technology
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

HIGH TEMPERATURE POWER TECHNOLOGY

GOALS
- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST

TECHNOLOGICAL DEVELOPMENTS
- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS
- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

CVD DIAMOND FILMS FOR HIGH POWER ELECTRONICS

SYNTHESIS

CHARACTERIZATION

& MODELLING

OF CVD DIAMOND

WILL ENABLE:
- More Efficient Heat Spreaders
- Lower Device Operating Temperatures
- Increased Device Reliability/Lifetime
- Increased Specific Power
- Elaborate Device Geometries
Efficient, High Temperature Power for Growth Station

Present Power System Masses

Fault Tolerant AC and Advanced PMAD Components

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE

RADIATION HARD HIGH TEMPERATURE POWER ELECTRONICS

300°C POWER ELECTRONICS

SPACE POWER UTILITY


- TECH. DEMO
- UTILITY POWER DEMONSTRATION

- 200°C PMAD
- PMAD SYSTEM STUDIES

- COMPONENTS
- SiC/DIAMOND POWER SWITCH

STRATEGIC ONLY

REDUCED SCOPE & SCHEDULE IN BASELINE
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Management & Control (Solar Dynamic)

Milestones:
1994 Select PMAD architecture
1996 Demo prototype PMAD brassboard
1997 Demo mixed source operation
1998 Complete PMAD tested
1999 Demo autonomous control, fault tolerance, and reconfiguration

R&D Resources:

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SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Management & Control (Photovoltaic)

Milestones:
1994 Select PMAC architectures; demo GIC EMI shielded electronics box
1995 Demo smart, long life components (PIC and other)
1996 Demo monolithic circuits
1997 Demo fault tolerant PMAC breadboard
1998 Demo 200-600 C components/circuits
1999 Advanced EPSAT code
1999 Demo smart power backbone avionics system

R&D Resources:

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PT10-28
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

THERMAL MANAGEMENT

OBJECTIVES

- Develop the thermal management technology for advanced high capacity and high performance thermal management systems for future NASA space missions.

- Enhance the understanding of fluid behavior and dynamics in a reduced gravity environment to establish reliable predictive models and data bases for the development of advanced space systems. Interests include two-phase flow regime, liquid/vapor interfaces and flow boiling.

- Develop, analyze, and test various thermal energy management concepts and components for application to future spacecraft and space facilities.

TECHNOLOGY AREAS

- Film condensation, flow boiling and two-phase regimes
- Heat pipes
- Advanced radiators
- Heat pumps

THE THERMAL MANAGEMENT SUB-ELEMENT WILL SUPPORT THE PLATFORM POWER AND THERMAL MANAGEMENT BY PURSUING AN INTEGRATED PROGRAM WHICH FOCUSES ON THE FOLLOWING ACTIVITIES:

- Modular heat pumps (100 W to 1 kW)
- Cryogenic heat pipes (60 - 80 K range)
- Lightweight materials
- Mini capillary pumped loops (<500 W)
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

THE THERMAL MANAGEMENT TECHNOLOGIES DEVELOPED IN THIS ACTIVITY WILL PROVIDE THE FOLLOWING BENEFITS:

- **HEAT PUMPS** - AS AN INTERMEDIARY BETWEEN A CENTRAL THERMAL BUS AND A LOAD, A HEAT PUMP COULD ALLOW INDEPENDENT TEMPERATURE CONTROL. THE SECOND, LOWER TEMPERATURE BUS, WOULD NOT BE NEEDED. ALTERNATIVELY, LOWER TEMPERATURES ARE POSSIBLE.

- **CRYOGENIC HEATS PIPES** - THESE COULD SERVE AS AN INTERFACE BETWEEN CRYOGENIC SENSORS AND A CENTRAL BANK OF CRYOCOOLERS. THE NUMBER OF SUCH COOLERS NEEDED WOULD THUS BE REDUCED, AND THEIR ASSOCIATED VIBRATION AND EMI SEPARATED FROM THE SENSORS.

- **LIGHT-WEIGHT MATERIALS** - WEIGHT REDUCTION

- **MINI CAPILLARY PUMPED LOOPS** - COULD PROVIDE INDEPENDENT COOLING FOR INSTRUMENTS

---

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

**Project Overview and Resources**

<table>
<thead>
<tr>
<th>Technology Program:</th>
<th>Space Platforms</th>
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<tr>
<td>Technology Area:</td>
<td>Earth Orbiting Platforms</td>
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<td>Technology Element:</td>
<td>Power</td>
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<tr>
<td>Technology Sub-Element:</td>
<td>Thermal Management (Photovoltaic)</td>
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**Milestones:**

- **1994**  Demo mini CPL thermal control loop
- **1995**  Demo 50% improvement (wall-meter basis) in advanced cryoheat pipes on ground
- **1995**  Demo 33% weight reduction in thermal components by using lightweight materials
- **1996**  Demo advanced heat pump designs suitable for microgravity applications, with goal of 3x current performance factor
- **1996**  Design cryo CPL thermal control loop
- **1997**  Flight test advanced cryo heat pipes
- **1997**  Demo ground test of advanced cryo CPL
- **1998**  Validate cryo heat pipe models
- **1998**  Flight test advanced heat pumps
- **1999**  Validate heat pump models
- **2000**  Flight test cryo CPL thermal control loop

**R&D Resources:**

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PT10-30
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Thermal Management (Solar Dynamic)

Milestones:

- 1994: Demo mini CPL thermal control loop
- 1995: Demo 50% improvement for advanced cryoheat pipes in ground test
- 1995: Demo 33% weight reduction for thermal components made from lightweight materials
- 1996: Demo advanced heat pump (for 500 W 5 kW range), 3X performance improvement
- 1997: Flight test cryoheat pipes
- 1997: Demo ground test of cryo CPL ground loop
- 1998: Validate cryo heat pipe models
- 1998: Flight test of advanced heat pumps
- 1999: Validate heat pump models
- 2000: Flight test of cryo CPL thermal loop

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SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS WITH ADVANCED TECHNOLOGIES

ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE 645 kg (1420 lb) IN THE ELECTRICAL POWER SYSTEM
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

POLAR PLATFORM WEIGHT WITH
ADVANCED TECHNOLOGIES

NEW TECHNOLOGIES SAVE 850 Kg (1870 lbs.)
ALLOWS ~32% OF MASS TO BE PAYLOAD

SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

TDRSS

- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS 82.67 kg
BATTERY MASS 94.53 kg
PMAD MASS 245.08 kg

- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS

PT10-32
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

Milestones:

1997
(2) Demo 300 W/sq. m PV concentrator module (>50 W)
(2) Ground demo, integrated 2 kW solar dynamic system
(2) Demo advanced heat pump designs suitable for micro gravity
(2) Demo prototype PMAD brassboard
(1) Complete enhanced EPSAT environmental interaction model (LEO, GEO, MEO, POLAR); ground test cryo CPL
(1) Demo 300 W/GPV focusing tower; 100 W/GPV tower concentrator module
(1) Demo 100 Wh/kg battery plates cells to 1000 cycles (GEO); complete design of cryo CPL for sensors
(1) Demo 25% reduction in weight of thermal components
(1) Demo G/C shielded electronics box
(1) Demo ground test of advanced cryo CPL
(1) Demo advanced PMAC integrated avionics system; validate heat pump models
(1) Demo 1-2 kg/sq. m thermal management system
(2) 2 kW solar dynamic
(2) Complete advanced EPSAT
(2) Demo SSF power T&D facility
(1) Demo 100 Wh/kg battery (flightweight)
2000
(1) Demo durable high temperature electronics subsystem (200-500 C)
(1) Flight test cryo CPL

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SPACETECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

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<th>694-11 SPACE PLATFORM TECHNOLOGY - EARTH ORBITING PLATFORMS</th>
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PT10-33
SPACE PLATFORMS TECHNOLOGY PROGRAM
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

CONCLUSIONS

- THERE ARE BASE TECHNOLOGIES THAT COULD BE MADE AVAILABLE FOR ORBITING PLATFORMS
  - ADVANCED PHOTOVOLTAIC SOLAR ARRAY (PLANAR AND CONCENTRATOR)
  - IMPROVED BATTERIES (NIH AND SODIUM)
  - SOLAR DYNAMIC SYSTEMS
  - IMPROVED PMAD
  - IMPROVED TMAD

- CODE RP IS CONTINUING TO SUPPORT ADVANCES IN POWER TECHNOLOGIES, INCLUDING:
  - HIGH EFFICIENCY, LIGHT-WEIGHT, RADIATION RESISTANT CELLS
  - ADVANCED CHEMICAL ENERGY STORAGE (NICKEL-HYDROGEN, BIPOLAR NICKEL-HYDROGEN)
  - POWER INTEGRATED CIRCUITS AND FAULT-TOLERANT AUTONOMOUS PMAD

- THESE TECHNOLOGIES CAN BE USED TO ACCOMPLISH SOME COMBINATION OF THE FOLLOWING:
  - REDUCE TOTAL MASS, OR
  - INCREASE PAYLOAD MASS
  - INCREASE POWER AVAILABLE BY UP TO 2x

FOCUSED TECHNOLOGY: EARTH ORBITING PLATFORM
POWER AND THERMAL MANAGEMENT

SUMMARY

- Enable exploitation of earth orbiting space by significant (> 2) improvements in mission critical power and thermal capacities
  - Wide range of users and missions: Unmanned/manned - Civil, Commercial, Operating requirements: LEO → GEO, EQUATORIAL → POLAR
  - Power levels: 10’s W → 10’s kW

USER COORDINATION:
- Four element effort: (e.g., presently applied to EOS, ATDRSS, SSF)
  - Determining requirements of planned and proposed missions
  - Assessing impact of upgrade to base technologies
  - Addressing modification and adaptation of technology for mission unique requirements
  - Reviewing with program and project managers

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
- Basic understanding and development of technology progressing in all areas under base program
- No lack of technology

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:
- Absence of focused effort to bring about:
  - Coordination with broad user and mission base
  - Coordination of multiple disciplines at system level
  - Timely development to level of implementation for flight
- Lack of means to get technology used
## Thermal Management

### Milestones / Schedule

<table>
<thead>
<tr>
<th>Milestone Description</th>
<th>Year</th>
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<td>Demonstrate mini-capillary pumped loops</td>
<td>1994</td>
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<tr>
<td>Demonstrate 3x-3x SOA for cryogenic heat pipes</td>
<td>1995</td>
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<tr>
<td>Demonstrate 50% weight reduction for thermal components</td>
<td>1995</td>
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<tr>
<td>Develop several advanced heat pump designs, goal of 3x SOA</td>
<td>1996</td>
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<tr>
<td>Flight test advanced cryogenic heat pipes</td>
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<td>Validate cryogenic heat pipe models</td>
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<tr>
<td>Validate heat pump models</td>
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Project SELENE

SpacE Laser Electric ENergy

John D. G. Rather

NASA

"SELENE" is the ancient Greek name for the moon
# TRANSPORTATION COSTS WITH MAXIMUM PAYLOADS

(1991 $ PER POUND)

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<td>25,000</td>
<td>10,000</td>
<td>34,000</td>
<td>10,000</td>
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<td>National Launch Systems (NLS)</td>
<td>$3,000</td>
<td>50,000</td>
<td>22,700</td>
<td>10,000</td>
<td>34,000</td>
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<tr>
<td></td>
<td>$1,200</td>
<td>150,000</td>
<td>13,600</td>
<td>10,000</td>
<td>25,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

*Use of IUS with 500lb payload results in high $/lb relative to other options which assume a new upper stage with 10,000lb payload.

---

## High-Power Space Applications

- Electric propulsion for economical orbit raising (LEO to GEO, LEO to LLO, etc.)
- Power for lunar base
- Life support for large, manned space stations
- Industrial processes
- K-Band traffic monitoring and identification
  - Air traffic monitoring and identification
  - Ship traffic monitoring and identification
  - Clear air turbulence mapping
  - Defense
- Direct-broadcast TV transmission
- Advanced remote sensing
Comparison of costs of candidate lunar surface power architectures

- New optical technologies: The Key to implementation

* Costs include estimated transportation costs in 1990 dollars

Refs:
(1) – NASA Lewis Research Center
(2) – NASA Pathfinder Program Plan
BASIC ELEMENTS OF A COMPTON - REGIME FREE ELECTRON LASER

WIGGLER MAGNET ARRAY

rf ELECTRON ACCELERATOR

\[ \lambda_s = \frac{\lambda_w}{2\gamma^2 (1 + \frac{K^2}{2})} \]
\[ K = \frac{e \lambda_w B}{2\pi mc^2} \]

TYPICAL MAGNETIC SWITCH OPERATION

REFERENCE: SCIENCE RESEARCH LABORATORY
Copper laser corridors provide more than 8 kW of average power in around-the-clock operations.
SNOMAD-V NONLINEAR MAGNETIC COMPRESSOR AND
1 MeV HIGH GRADIENT ACCELERATOR SECTION
LOCATION OF GROUND SITES DEPENDS PRIMARILY UPON AVERAGE ANNUAL NUMBER OF CLEAR DAYS.

ATMOSPHERIC TRANSMITTANCE TO SPACE

LASERS LOCATED AT 2KM ELEVATION ABOVE SEA LEVEL
Turbulence coherence length as a function of wavelength and zenith angle

- Hand calc. with Fried module
- Correlates well with ESP4-SWL
- Maui site
- 3-km altitude

Range of interest
COOLED DEFORMABLE MIRRORS

UTOS HICLAS

ACTUATORS: 69
STROKE: 30 μm
ACTIVE AREA: 16 cm DIAMETER
SURFACE FIGURE: \(0.1 \lambda \text{rms}(\lambda = 0.633 \mu m)\)

ITEK LCDM

241 (+ Two Guard Bands)
4 μm
16 cm DIAMETER
\(-0.02 \lambda \text{rms}(\lambda = 0.633 \mu m)\)
LACE Data 30 November 1990

SMC 182, Samples 180-184
SMC 181, Samples 160-164

Uncompensated
Compensated

SWAT/RME LASER RELAY EXPERIMENT
BASELINE RESULTS
STREHL RATIOS FOR
VARIOUS POWERS AND DIAMETERS
WITH TWO REALIZATIONS OF KOLMOGOROV FLUCTUATIONS

\[ P \propto D^{1.5} \]

- 0.32, 0.52
- 0.45
- 0.73

POWER (MW)

STREHL RATIO

DIAMETER (m)
**EDGE SENSORS**

**LONG-THROW ACTUATORS**

**SEGMENT**

**CLUSTER OF SEGMENTS**

**FULL APERTURE**

- Distance: >2.5 cm
- Distance: >50-100 cm
- Distance: >10 m
PAMELA — A Lower Cost Approach

CONVENTIONAL TELESCOPE WITH ADAPTIVE OPTICS

<table>
<thead>
<tr>
<th>CONVENTIONAL ADAPTIVE OPTICS</th>
<th>PAMELA</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIMARY</td>
<td></td>
</tr>
<tr>
<td>SECONDARY</td>
<td></td>
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<tr>
<td>SUPPORT STRUCTURE</td>
<td></td>
</tr>
<tr>
<td>WAVEFRONT SENSOR</td>
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<tr>
<td>RECONSTRUCTOR</td>
<td></td>
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<td>CONTROL PROCESSOR</td>
<td></td>
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<tr>
<td>COMPENSATION MIRROR</td>
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<tr>
<td>HIGHEST COST</td>
<td>LOW COST</td>
</tr>
<tr>
<td>HEXAGONICAL OR LINE SEGMENTS</td>
<td>MASS PRODUCED SEGMENTS</td>
</tr>
<tr>
<td>NOT REQUIRED</td>
<td></td>
</tr>
<tr>
<td>ON ARRAY 3 ROW ON SEGMENT</td>
<td></td>
</tr>
<tr>
<td>ACTUATING ONLY</td>
<td></td>
</tr>
</tbody>
</table>

Computer map of prototype dish surface as measured following the initial polishing of the panels. Approximate boundaries of the panels are drawn, and approximate half-wave contours are shown. Positive heights above a

hexagon grid are isolated by the digits 0-9, negative heights by the

letters A-F. 32 13 cm (0.06 inch) steps. If a given pixel does not fall within 2 / 4 unit of an integer value, a blank is printed. The panels to the left of the heavy jagged line had "scrubbers" attached to them; those on the right did not. These panels are shown "coming" of the undeformed panels as compared with the stretched areas. The RMS surface errors for the two areas are 30 µm and 60 µm respectively, and the mean value is 50 µm.

PT11-16

ORIGINAL PAGE IS OF POOR QUALITY
TTPM FUNCTIONAL BLOCK DIAGRAM

BEAM INCIDENT ON ONE ELEMENT

ONE OPTICAL MEASUREMENT PER SEGMENT

TILT SENSING WAVEFRONT MONITOR (SINGLE CHANNEL)

EDGE SENSOR SIGNALS CONTROL AVERAGE PHASE

SEGMENT ACTUATOR ELECTRONICS

SIGNAL CONDITIONING ELECTRONICS

SEGMENT SIGNAL

ACTUATOR

SUBSYSTEM CONTAINED ON EACH SEGMENT

MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SEGMENT SIZE
CONSTRAINTS AFFECTING SEGMENT SIZE

WHAT DETERMINES THE PHASED ARRAY ELEMENT SIZE?

• UPPER LIMIT
  - SCALE SIZE OF OPTICAL DISTURBANCES
  - VIBRATION-INDUCED DISTURBANCES
  - ATMOSPHERIC DISTURBANCE SCALE
  - THERMAL INERTIA

• LOWER LIMIT
  - SEGMENT FABRICATION COSTS
  - ACTUATOR STROKE
  - SYSTEM WEIGHT
  - SYSTEM COMPLEXITY

SEGMENT DESIGN ISSUES

OPTIMIZED MINIMUM OVERALL SYSTEM WEIGHT AND COST

PT11-18
ARRANGEMENT OF SENSING COILS ON SEGMENT EDGE

MIRROR SURFACE

PRIMARY COIL

RELATIVE POSITION OF SECONDARY COIL WHICH IS DEPOSITED ON OPPOSITE FACE OF ADJACENT SEGMENT
Edge-Matching Sensor Circuit Diagram

Rotor Coils

L₁  ||  L₂

Direction of Travel

L₃  ||  L₄

Stator Coils

Oscillator

Phase Detector

V_OUT

PT11-20
LEGEND

- MAGNET
- VANADIUM
- ALUMINUM
- COMPOSITE
- Be Cu

SCALE

REAR SURFACE OF SEGMENT
CENTRAL POLE PIECE
FLEXURE
BUSHING

COIL WINDING
BACK-UP STRUCTURE
WHITE LIGHT FRINGES

**STEPS IN RAPID CONVERGENCE ALGORITHM**

- Edge match all segments
- Measure tilts of all segments
- Apply and fix segment tilts while edge matching
- Compute pistons of all reference segments at center of each cluster by integrating tilts along specified pathways (relative to master segment)
- Adjust and fix pistons of reference segments at center of each cluster
- Pistons of remaining segments within each cluster are adjusted by edge matching to reference segment

REFERENCE SEGMENTS
DEFINES CLUSTERS
POSSIBLE PATHWAYS OF PISTON COMPUTATION

Fringe spacing \(d = 0.25\mu\)
SURFACE SETTING ALGORITHMS
STEP FUNCTION RESPONSE (CONVERGENCE TIME)

- S.O.R. (5 SIDES) \( (\times \sqrt{N}) \)
- Jacobi or least squares \( (\times N) \)
- Inner (3 SIDES) \( (\times \sqrt{N}) \)
- (3 SIDES) \( (\times N) \)

WAVEFRONT ERROR

STREHL RATIO (%)

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35

0.06 \( \lambda \) (Theoretical Value)

OCCURRENCES

0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0 100.0

PT11-23
The integrated control concept is scalable

- Simple sensor arrays
  - CCDs
  - Quad cell witness plate
- Linear distribution of sensor data to segments
- "Smart" self-processing segments
- Long stroke actuators
- Only parallel processing required

### Strehl ratio

![Graph showing Strehl ratio vs. Power in main beam (\%)]

\[ S = \exp \left\{ (-2\pi \Delta \lambda / \lambda) \right\} \]

<table>
<thead>
<tr>
<th>$\Delta \lambda / \lambda$</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.91</td>
</tr>
<tr>
<td>0.10</td>
<td>0.67</td>
</tr>
<tr>
<td>0.15</td>
<td>0.41</td>
</tr>
<tr>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>0.25</td>
<td>0.08</td>
</tr>
</tbody>
</table>

PT11-24
The function $1 - J_0(x) - J_1(x)$ representing the fraction of the total energy contained within circles of prescribed radii in the FRAUNHOFER diffraction pattern of a circular aperture.
DIFFRACTION PATTERN FROM A SINGLE HEXAGONAL MIRROR

Single hexagon diffraction pattern at 10 micron wavelength (1.8-meter hexagons)
36-hexagon diffraction pattern at 10-micron wavelength (1.8-meter hexagon—10-meter full aperture)

Effect of segmentation on aperture performance

- Strehl does not depend on segment number
- Strehl degradation depends on percentage area of gaps to total area:
  - Gap 1% of segment area → Strehl = 96%
  - Gap 0.65% of segment area (Keck design) → Strehl = 97.4%
- Variation in diffraction pattern at levels of $10^{-5}$ of peak and less and are present only many airy diameters away
- Details of energy distribution within the central lobe are unaffected by segmentation

Imaging performance is not affected by segmentation
PAMELA Ground-based Laser Beam Director

ORIGINAL PAGE IS OF POOR QUALITY
Technological goals of PAMELA-Type Optical System

- Very large apertures (>10 m)
- Fast primary optic for a compact, lightweight telescope
- Compensation for internal optical aberrations
- Compensation for atmospheric turbulence
- Control architecture scalable to very large numbers of segments
- Elimination of the requirement to reconstruct wavefront phase from gradient measurements
- Large adaptive optics closed-loop bandwidth
- Diffraction-limited beam quality
- Identical intelligent mirror segments
- Identical wavefront sensor modules
- Economical fabrication through mass-production methods
Laserpath is a ground-based laser-driven space power and propulsion concept

A Laserpath manned lunar shuttle (MLS) departing for the moon

Because laserpath can exploit the high specific impulse of plasma thrusters, it requires little propellant mass
Laserpath's power supply mass is low in comparison with nuclear or solar vehicles for three reasons:

- The prime power source is not on board
- Monochromatic laser light is converted to electric power with high efficiency
- Pulse repetition rate matching of laser and plasma thrusters reduces need for on board power conditioning equipment

Shuttle rendezvous with tugboat in LEO. Residual shuttle main tank fuel is transferred to tug. Tug then boosts main tank or full shuttle payload to GEO

- \( I_{sp} = 1,500 \ \text{seconds} \)
- \( \Delta V = 5,630 \ \text{meters/sec (each way)} \)
- Tug spacecraft dry mass \( = 4,400 \ \text{kg} \)
- Available fuel mass \( = 3,640 \ \text{kg}^* \)
- Main tank dry mass (or alt. payload) \( = 32,300 \ \text{kg} \)
- Total required energy \( = 4,500 \ \text{GJ} \)
- Minimum one way mission duration \( = 5.2 \ \text{days} \)
- Minimum required laser power \( = 10.2 \ \text{MW} \)

* 520 kg \( \text{H}_2 \), 120 kg LOX
ADAPTIVE OPTICS ERROR BUDGET

\[ \lambda = 1\mu m, \ r_n = 9.6 \text{ cm AND } \theta_n = 15 \mu \text{rad AT ZENITH,} \]
ACTUATOR SPACING 10 cm, BANDWIDTH 100 Hz, WIND 6 m/s,
RETRO ARRAY AT MEAN POINT-AHEAD LOCATION

BASELINE SELENE POWER SYSTEM
REPRESENTATIVE POWER BUDGET

<table>
<thead>
<tr>
<th>Component</th>
<th>Power</th>
<th>Eff.</th>
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</thead>
<tbody>
<tr>
<td>EARTH SITE POWER INPUT</td>
<td>110 MW</td>
<td>0.1x</td>
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<tr>
<td>LASER EFFICIENCY</td>
<td></td>
<td></td>
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<tr>
<td>LASER OUTPUT</td>
<td>11 MW</td>
<td>0.9</td>
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<tr>
<td>OPTICS TRANSMISSION</td>
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<td></td>
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<tr>
<td>POWER OUT OF APERTURE</td>
<td>10 MW</td>
<td>0.9</td>
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<tr>
<td>ATMOSPHERIC TRANSMISSION</td>
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<tr>
<td>ATMOSPHERIC COMPENSATION</td>
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<td>0.5</td>
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<tr>
<td>COLLECTOR GEOM. EFFICIENCY</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>ARRAY ELECTRICAL EFFICIENCY</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>NET PV ARRAY ELECTRICAL POWER OUTPUT TO USER</td>
<td>2 MW</td>
<td></td>
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A MINIMUM OF 3 EARTH STATIONS IS REQUIRED TO PROVIDE CONTINUOUS 1+ MEGAWATT ELECTRICAL POWER TO USERS ON MOON

PT11-32
LUNAR STATION

- RADIUS OF UNCORRECTED BEAM
  - 5000 m
  - INTENSITY: 0.4 W/m²
- COLLECTOR ARRAY
  - 80 m
- DIFFRACTION LIMITED
  - BEAM DIAMETER
  - ATLAS: 50 m
  - BEAM INTENSITY: 4 kW/m²

POWER CONDITIONING

LOAD
(1 MW)

STORAGE

FOR GROUND LASER OUTAGES (Clouds)

DIFFRACTION LIMITED POWER COLLECTED

80% DIFFRACTION BEACON PROBE (Laser or Reflector)

- 70% POWER

- 70% BEAM DIAMETER

PROJECT SELENE

KEY ACTIVITIES

| Phases | Description                                                                 | FY81 | FY82 | FY83 | FY84 | FY85 | FY86 | FY87 | FY88 | FY89 | FY90 | FY91 | FY92 | FY93 | FY94 | FY95 | FY96 | FY97 | FY98 | FY99 | FY2000 |
|--------|------------------------------------------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| V      | PV Array / Power Conditioning                                                 | $1.5M| $2.0M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M|
| V      | Photovoltaic Research                                                        | $0.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M| $1.5M|
| V      | Decision Points on "Initial Technologies" - TRL 3/4                         |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| V      | Studies / Advanced Concepts                                                   |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| V      | Total Feasibility Studies                                                     |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| V      | Studies Total                                                                |       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| V      | Approx. $20M                                                                  | $20M |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

Initial Tests - TRL 5/6

Annual Funding:

- $0.5M (FY81)
- $13.5M (FY82)
- $49.5M (FY83)
- $73.0M (FY84)
- $81.5M (FY85)
- $35.0M (FY86)
- $5.0M (FY87)

FISCAL YEAR

PT11-33
LASER POWER BEAMING -- PROJECTION OF EXPENDITURES

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<tr>
<th>Technology Area</th>
<th>'93</th>
<th>'94</th>
<th>'95</th>
<th>'96</th>
<th>'97</th>
<th>'98</th>
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<tbody>
<tr>
<td>Free Electron Laser Option I - RF FEL</td>
<td>1.0M</td>
<td>1.0M</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(Industry) Track parallel DoD RF FEL and generate alternate NASA Concept. This work will terminate in mid-'94 if Option II succeeds.</td>
<td></td>
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<tr>
<td>Free Electron Laser Option II - Induction FEL</td>
<td>3.5M</td>
<td>10.5M</td>
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<tr>
<td>(Industry) Build and test new high gradient induction accelerator. (LLNL) Model FEL.</td>
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<tr>
<td>Option II (Cont'd)</td>
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<td>25M</td>
<td>25M</td>
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<tr>
<td>Decision point for initial technologies (TRL 3/4)</td>
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<tr>
<td>(Industry/MSFC) Construct/ Test Induction FEL</td>
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<tr>
<td>Option II (Cont'd)</td>
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<tr>
<td>Technology/Subsystem ready for integration (TRL 4/5)</td>
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<tr>
<td>Optical Beam Expander - Option I Monolithic Primary/ Membrane AO</td>
<td>3M</td>
<td>10M</td>
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<td>(MIT Lincoln Lab) Track Parallel DoD optics and generate alternate NASA Concept. This work will terminate in mid-'94 if option II succeeds.</td>
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<tr>
<td>Optical Beam Expander Option II - Segmented Primary AO</td>
<td>3.3M</td>
<td>2.5M</td>
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<tr>
<td>(JPL/LLNL/MSFC/Industry) Design and test mass-producible precision segments. Design beam expander and control system</td>
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<tr>
<td>Optical Beam Expander Option III - Segmented Primary AO</td>
<td>9.5M</td>
<td>25M</td>
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<tr>
<td>Photovoltaic Research PV Array + Power Conditioning</td>
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<td>1.5M</td>
<td>1.5M</td>
<td>2.0M</td>
<td>1.5M</td>
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<tr>
<td>(JPL/LLNL/Industry) Develop efficient PV power converter. (Initial Demonstration (TRL 5/6))</td>
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<tr>
<td>Testbed/Site Integration and Operation</td>
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<td>15M</td>
<td>25M</td>
<td>20M</td>
<td>TBD</td>
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<tr>
<td>(MSFC/JPL/Lincoln Lab) Integrate Laser Beam Expander and PV Array and Test.</td>
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<tr>
<td>Advanced Concepts</td>
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<td>5M</td>
<td>5M</td>
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<tr>
<td>(NASA Centers/WPO) Applications/Mission Studies</td>
<td></td>
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Annual Funding

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<th>'94</th>
<th>'95</th>
<th>'96</th>
<th>'97</th>
<th>'98</th>
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<td>49.5M</td>
<td>73M</td>
<td>61.5M</td>
<td>35M</td>
<td>5M</td>
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LASER POWER BEAMING POWER AND PROPULSION FLIGHT DEMONSTRATION

- LASER-ELECTRIC PROPULSION VEHICLE FLIGHT FROM LOW EARTH ORBIT (LEO) TO LOW LUNAR ORBIT (LLO)

- MISSION WOULD DEMONSTRATE/INVESTIGATE:
  - LASER POWER TRANSMISSION THROUGH ATMOSPHERE
  - TRACKING OF REMOTE TARGET BY TRANSMITTER AND RECEIVER
  - POWER CONVERSION BY PHOTOVOLTAIC ARRAY
  - RADIATION IMPACTS TO PV ARRAYS DUE TO TRANSFER THROUGH VAN ALLEN BELTS
  - ELECTRIC PROPULSION SYSTEM AS MISSION POWER LOAD
  - INTERACTIONS BETWEEN ELECTRIC PROPULSION SYSTEM AND PV ARRAYS

- OTHER FEATURES OF THE DEMO MISSION:
  - OPERATE AT MODEST POWERS (10's OF KW TO MW)
  - INITIAL DEMO FROM LEO TO HIGH EARTH ORBIT (GEO?) TO INVESTIGATE VAN ALLEN BELT IMPACTS CAN BE DONE WITH FIRST GENERATION SMALL TRANSMITTER MIRROR.
  - SECOND GENERATION LARGER TRANSMITTER USED FOR TRANSFER TO LLO