A High-Energy Technology Demonstration Platform:

The First Step in A Stepping Stones Approach to Energy-rich Space Infrastructures

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Rocketdyne Propulsion & Power

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Vision for Space Exploration

Excerpts from The President's Vision for U.S. Space Exploration

- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Develop and demonstrate power generation, propulsion, life support, and other key capabilities for long duration, more distant human and robotic missions

Excerpt from Packard Commission Findings

- Apply technology to lower the cost of the system, not just to increase its performance
- Mature technology prior to entering engineering and systems development

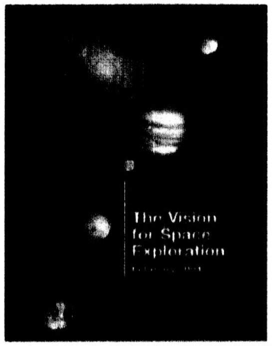
Excerpts from "Vision for Space Exploration" – Sean O'Keefe

Policy Objective (Technology)

"Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration…

National Benefits (Technology)

"The space missions in this plan require advanced systems and capabilities that will accelerate the development of many critical technologies, including power, computing, nanotechnology, biotechnology, communications, networking, robotics, and materials.



Exploration Building Blocks

"To support these missions, a number of key building blocks are necessary. These include new capabilities in propulsion, power, …"

Develop And Demonstrate Advanced Power & Propulsion Technologies

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Solar-Electric Propulsion (SEP)

- **Advantages**
  - Large payload capability: high specific impulse coupled with low inert mass
  - Utilization of available energy source
  - Near-Earth operation: Can operate at lower altitudes where nuclear propulsion would not be desirable
  - Flexibility: Can be used with any electric thruster concept
  - Reusability (LEO refueling; Life extension by replacing solar arrays and propulsion system)

- **Disadvantages**
  - Large solar array area (Launch vehicle packaging, sensitivity to acceleration, Earth escape)
  - Lower solar constant at outer planets

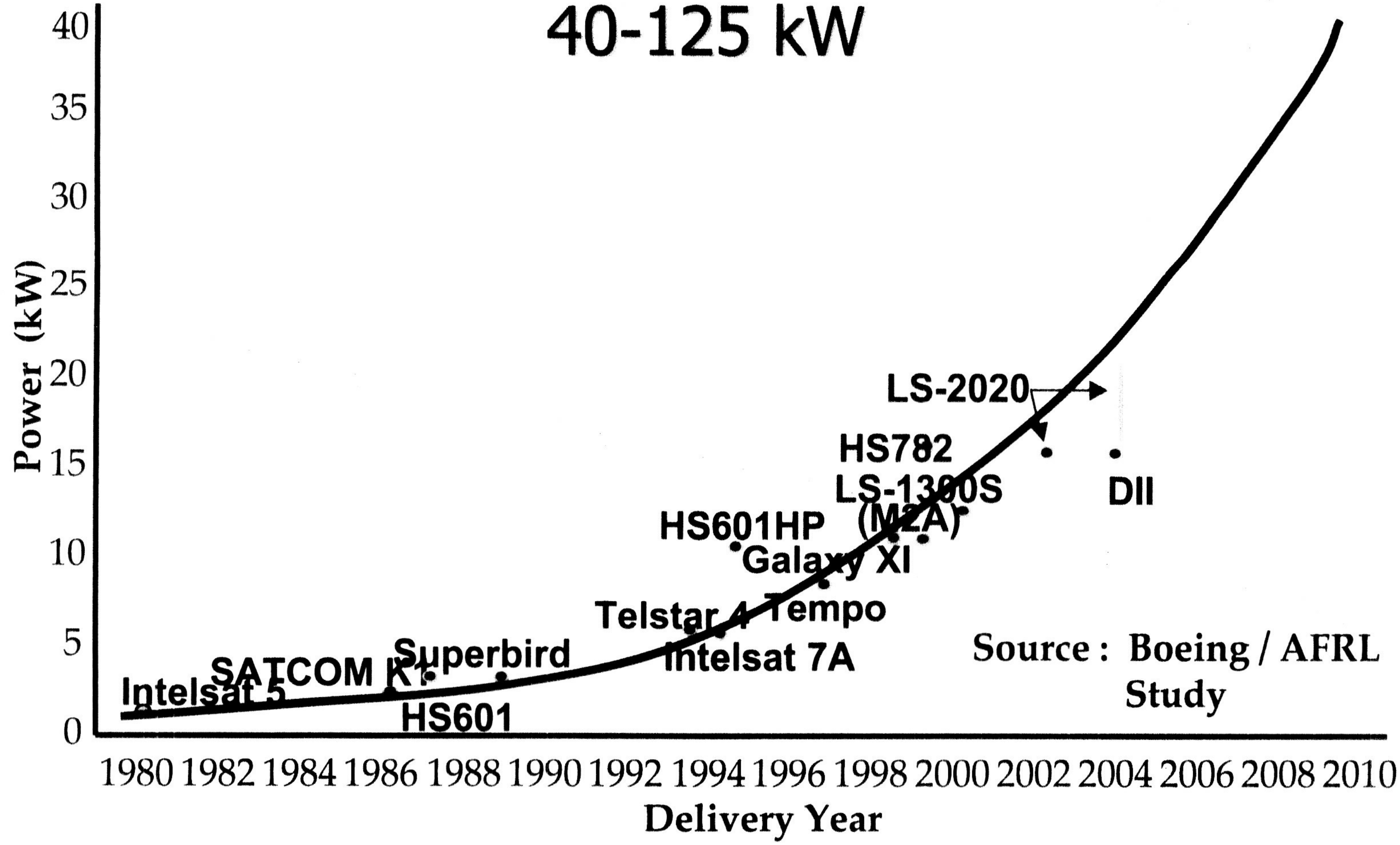
- **Potential SEP Applications for NASA Exploration Initiatives**
  - Unmanned near-Earth / lunar transportation missions for equipment and propellant
  - Exploration missions to inner planets
  - Testing platform for exploration technologies: high-voltage, electric propulsion, advanced thermal

Introduction

- Paper summarizes results from recent advanced concepts study on a 100kW solar-powered spacecraft
- Platform to flight-test advanced high-energy technologies
- Near-term technologies used (suitable for 2008 manufacturing start)
- Modular technology approach, where possible
- Single-bus design
- Three-year mission lifetime (LEO, then transit to 15,000 km orbit)
- 100kW operation limited to periods of insolation

Spacecraft Power Growth

Future power requirements for near-Earth space-based applications and electric propulsion are 40-125 kW



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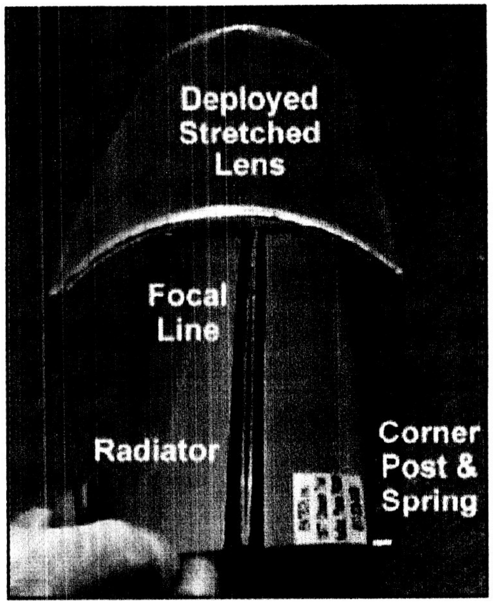
Solar Power Generation

Near-Term PV Technologies

- Triple-junction improvements: >30% efficiency by 2008
- Quadruple-junction cell: mid 30's % efficiency by 2008



ENTECH Stretched Lens Arrays

- Quadruple-junction solar cells
- Lightweight line-focus lens
- 8.5x concentration
- Passive thermal design
- SLA provides modularity

Quadruple-Junction Cells Selected, Triple-Junction Backup

Low-Risk SLA Design Uses Off-the-Shelf Space-Qualified Materials

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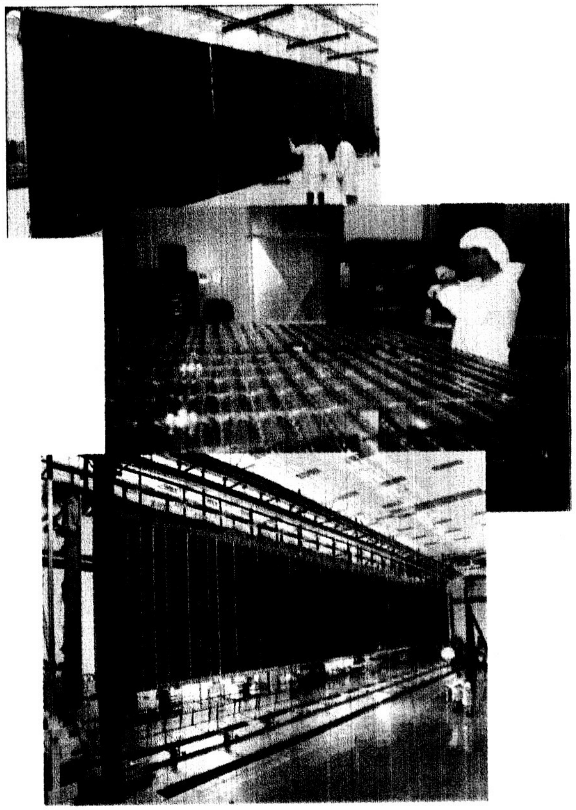
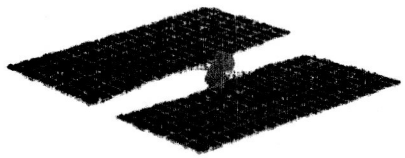
Solar Panel Architecture Trades



- Rigid Panel
  - Solar cells mounted to folded rigid panels
  - Minimal development effort for flight qualification
  - Large panel areas result in significant stowed volume requirements
- Concentrator SLA PV System
  - Concentrator design replaces expensive cells with cheaper optics
  - High efficiency with lightweight optics, flight heritage
  - Rad hard benefits, facilitates higher-voltage strings
  - Not flight-qualified
- Telescoping Mast Design (Flexible Array)
  - Cells mounted to folded rectangular flexible blankets
  - High power/stowed volume, basic ISS design
  - High aspect ratio with large moment of inertia
- Square Rigger Folded Design (Flexible Array)
  - Cells mounted to folded rectangular flexible blankets
  - High power/stowed volume, lower aspect ratio
  - In development, not flight qualified



Square Rigger with SLA is lowest mass, smallest area, lowest cost

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Mission Description

- ELV Launch from KSC to Circular ISS Orbit
  - 407 km at 51.6° inclination
  - 2 years station-keeping at LEO
- Raise Orbit to ~15,000 km Using Hall-Effect Thrusters
  - ~3 months to transition to higher orbit
    - » Slow transition through inner Van Allen belt
    - » Verify high-voltage operation in high radiation environment
  - 6 months station-keeping at MEO
    - » Map spacecraft performance to LEO baseline
    - » Payload operation
- Spiral Out to Earth Escape at End-of-Life
  - 906,378 km at 51.6° inclination
  - Estimated 3 month transition

3-Year Mission Life Allows LEO and MEO Performance Demonstration

Solar Array Sizing

- 100 kW EOL at GEO will require ~ 300 m^2
- Two 150 m^2 SLASR wings
  - Each 10 m x 15 m Wing Has 12 Bays (2.5 m x 5.0 m)
  - Mass of Each Wing ~160 kg
- EOL performance at GEO
  - 340 W/m^2 Areal Power Density
  - 330 W/kg Specific Power

Spacecraft Requires 300 m^2 of SLASR Area

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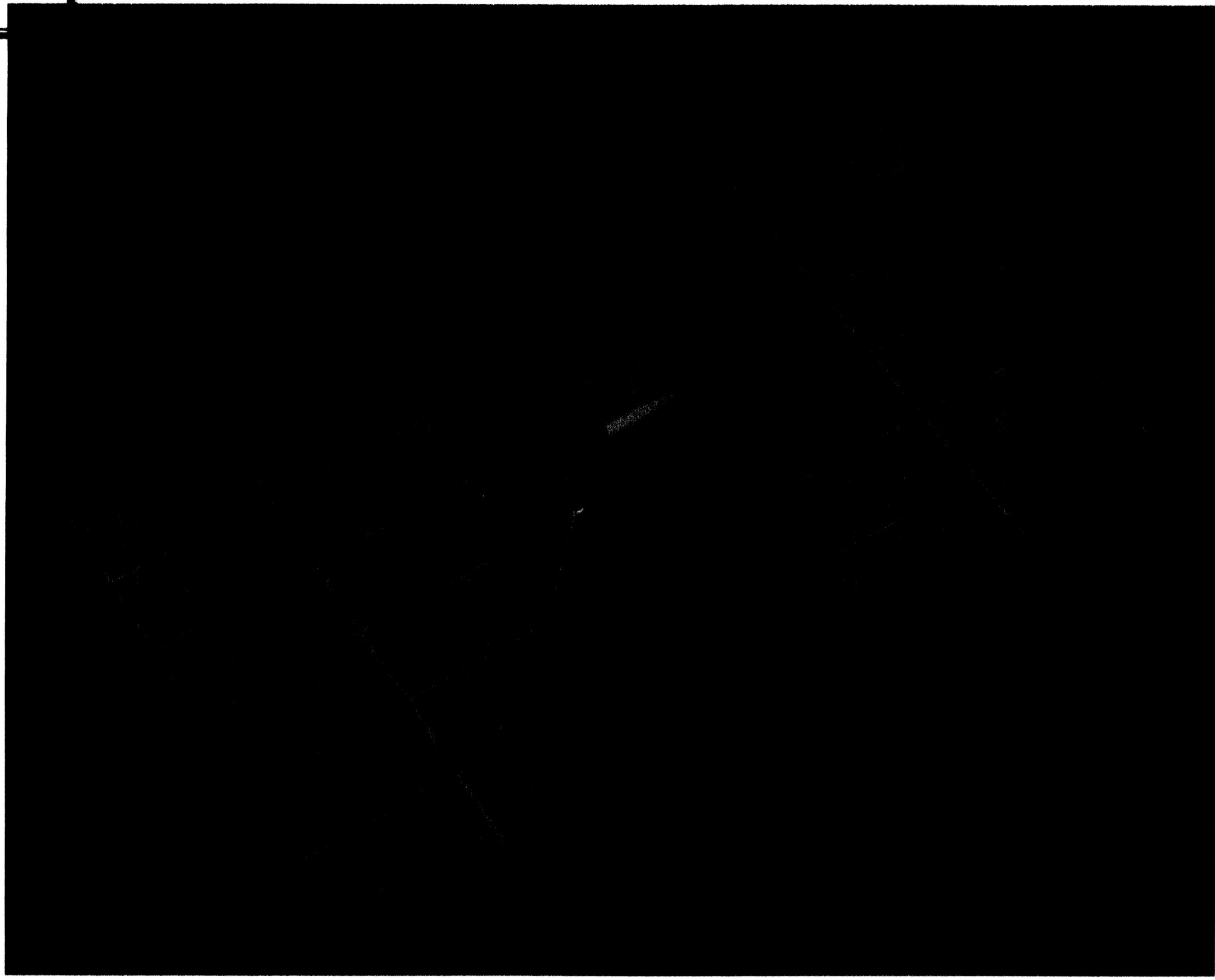
Spacecraft with SLASR Solar Wings



wings

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Electric Thruster Trades

Electric Thruster Concept	Complexity	Robustness / Flexibility	Relative Cost
Ion Engine	• Sophisticated design • Many components • Close tolerances • > 16 thrusters for 100 kW	• Demonstrated long life (> 25,000 hours) • Lower power per unit • Limited throttling capability	High
Hall Thruster	• Simple design • Few parts • Simpler PPU • 2 thrusters for 100 kW	• Rugged thruster • Throttle capability (> 4 to 1) • Capable of using alternate propellants	Low
MPD / LFA	• Simple thruster design • More complex propellant feed system	• Electrode durability unproven • Better suited for very high power levels	Low to Moderate
VASIMR	• Elaborate design • Many components • Requires cryo storage (hydrogen)	• Unknown reliability • Variable Isp and thrust • Better suited for very high power levels	High

Hall Thruster Has Simple Design and Low Cost

Hall Thruster Offers Lowest Trip Time and Best Operability

Power Management and Distribution

- Architecture #1 : 300-volt spacecraft bus
  - Power conditioning required at Hall thrusters to elevate voltage
- Architecture #2: 600-volt spacecraft bus
  - Direct drive capability for Hall thruster
  - Potential mass / cost / efficiency savings
- Required Technology Advancements For High-Voltage PMAD
  - 300 to 600 volt PMAD bus is higher voltage than current spacecraft
    - Development of corona detection, mitigation, extinction techniques for high voltage panels
    - Requires technology development and qualification of new hardware
  - High voltage electronics currently in development (TRL 5)
    - Silicon carbide devices for high voltage levels
    - Wire insulation understood and workable
    - Corona mitigation feasible
    - Suitable transformers and resistors have been identified

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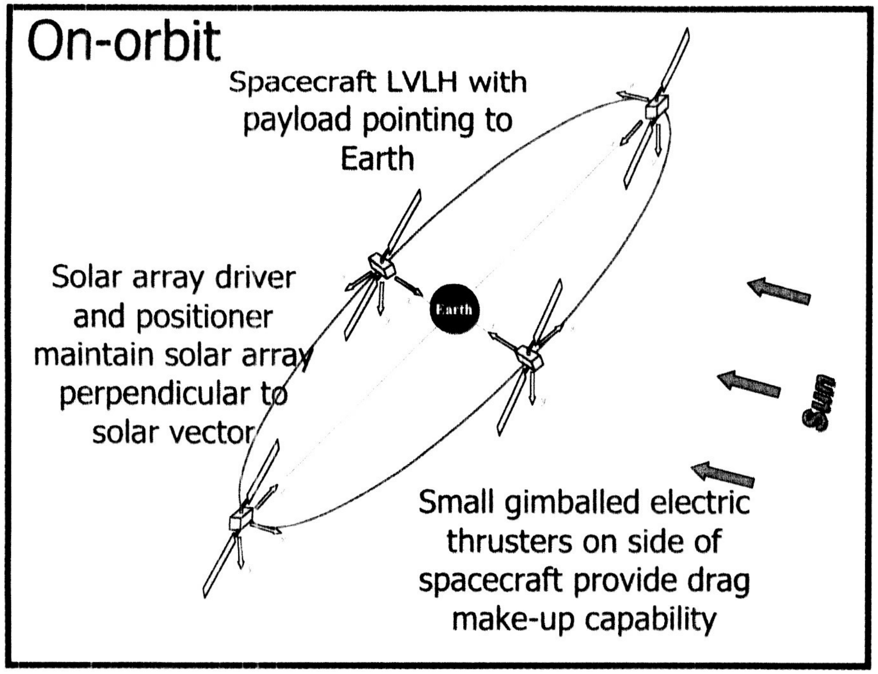
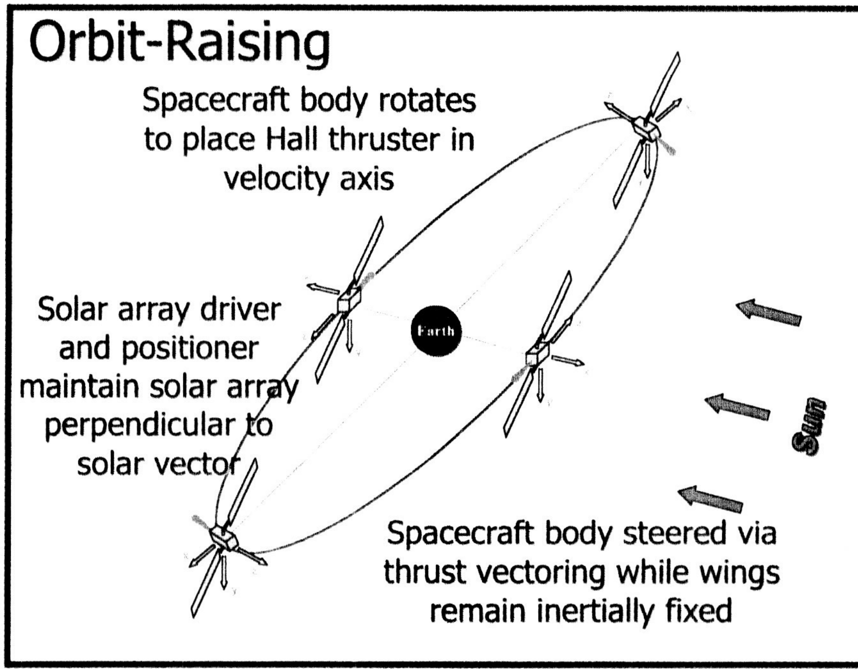
Attitude Control Subsystem (ACS)

- 4 reaction wheels, star trackers, redundant control processor
- Gimbaled Hall thruster platform for thrust vectoring and momentum management
- Small electric thrusters and their gimbaled platforms on side of spacecraft for drag makeup and momentum management
- 2-axis steering mechanism for large solar panels
- Thrust vector control during orbit raising by steering entire bus





ACS Accommodates Hall Thrusters and Gimbaled Solar Arrays

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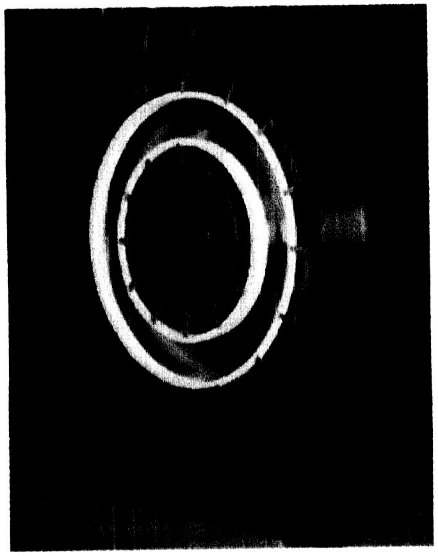
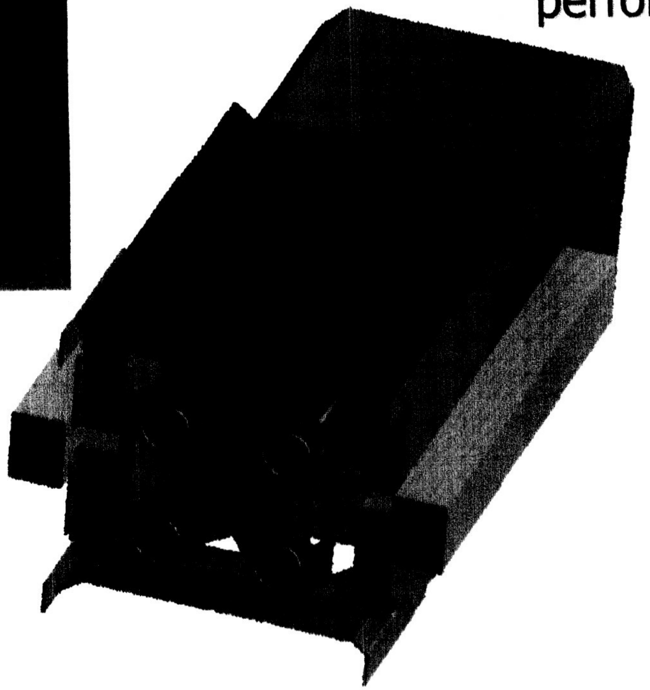
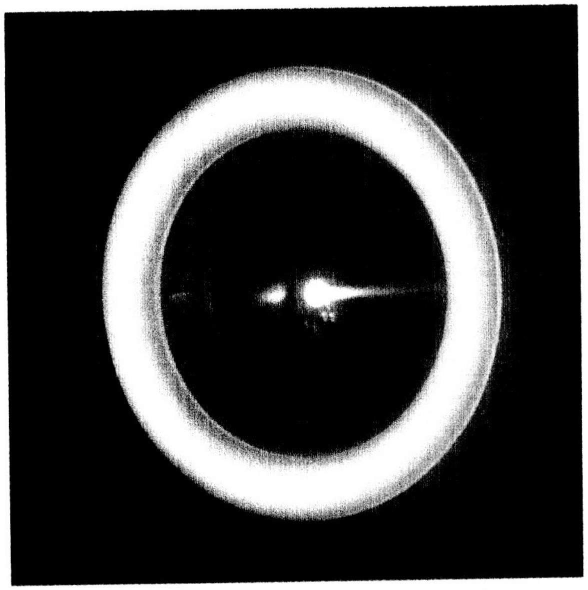
Propulsion Subsystem

Hall-Effect Thrusters Mounted on Gimballed Plate

- Diagonally-mounted primary thrusters
- Fully redundant set of thrusters
- Provides 2-engine capability
  - » 4-engine capability at reduced performance



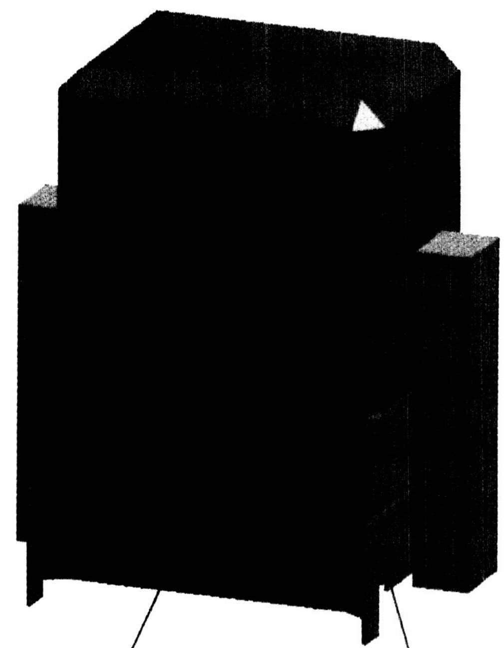




Electric Thrusters Provide Main Engine Capability

Thermal Control Subsystem

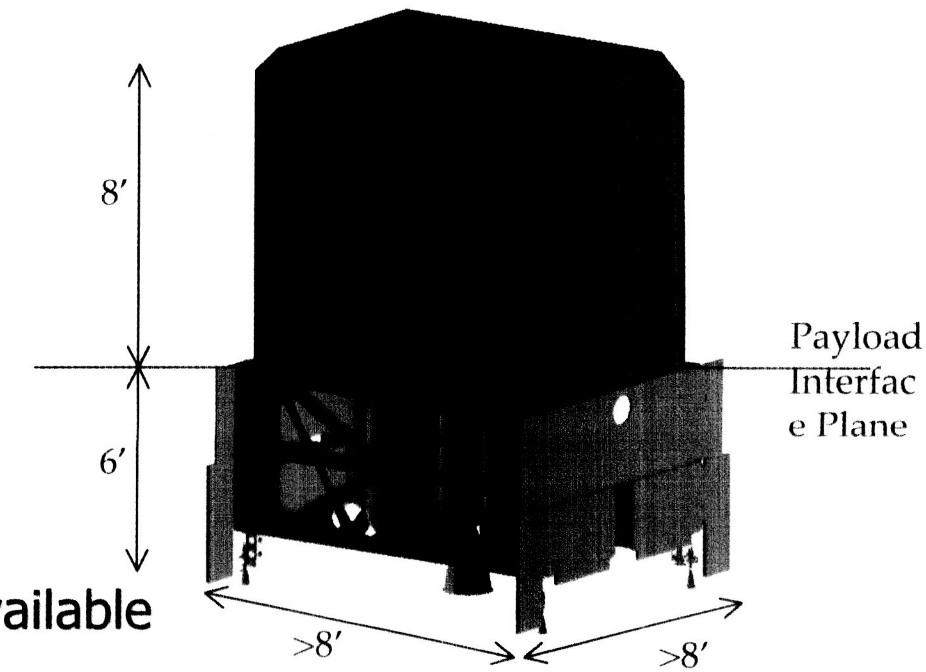
- High-Temperature Parasitic Load Radiator Required to Dissipate Shunted Power
  - Up to 110 kW when payload / thrusters not operating
  - Radiator operating temperature is 1,000°F to minimize area
  - Radiator located on sun-facing side
- Avionics Radiators Accommodate PMAD
  - ~5 to 6.7 kW heat rejection capability
  - Radiator operating temperature ~ 45°C
  - Fixed radiators located on solar array sides and dark side (non-sun) to handle 1.5 kW
  - Deployable radiators mounted at S/C non-sun corners will supplement fixed radiators



Large Spacecraft Bus Can Accommodate Additional Radiators

Payload Envelope

- Modular Payload Interface
  - 4 bolts
  - 6 connectors
- Volume
  - Fairing diameter
    - » 12 to 15 feet
  - Fairing length
    - » 14 to 23 feet cylindrical
    - » 11 to 17 feet conical
  - Additional payload volume available
- Mass
  - Payload weight budget is 2,150 kilograms
  - Potential mass increase based on structural analysis / redesign



Large Payload Envelope (Mass and Volume) Is Available

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Spacecraft Mass

Subsystem	Mass (Kg)
C&DH / ACS	120
Electric Propulsion	510
Power (Solar Panels)	400
Power (Electronics)	875
Power (Batteries)	100
Structures / Thermal	525
Wiring	135
Payload	2,150
Propellant	1,920
LV Adapter	115
Margin	150
Total	**7,000**

Technology Demonstration Spacecraft Launch Mass ~ 7,000 kg (15,400 lb_m)

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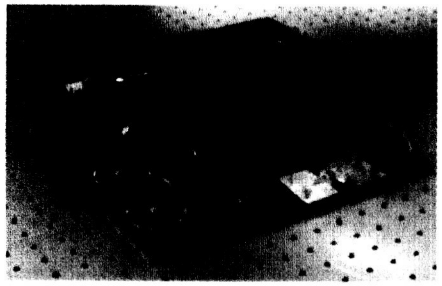
Technology Payload Candidates

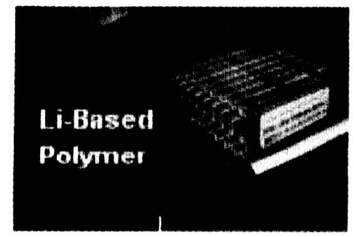
In-Space Optical Data Transmission

- LASER Communications – numerous NASA, ESA & AFRL efforts
- High-power transmitter provides larger ground footprint



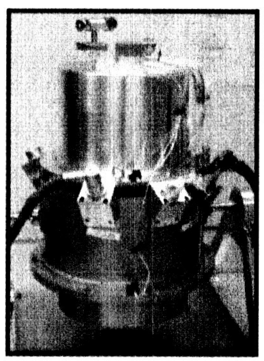
Advanced Batteries

- Advanced batteries increase energy density (specific energy) and permit greater depth of discharge (DOD)
- Available technologies
  - » Lithium ion
  - » Lithium polymer



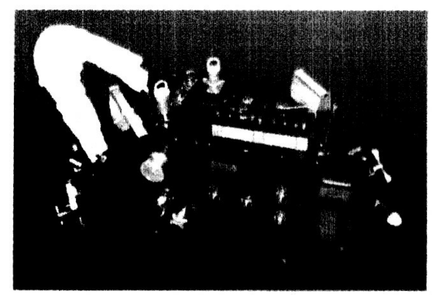
Energy Storage - Flywheels

- Store energy more efficiently than rechargeable chemical batteries
- Provide pointing control authority

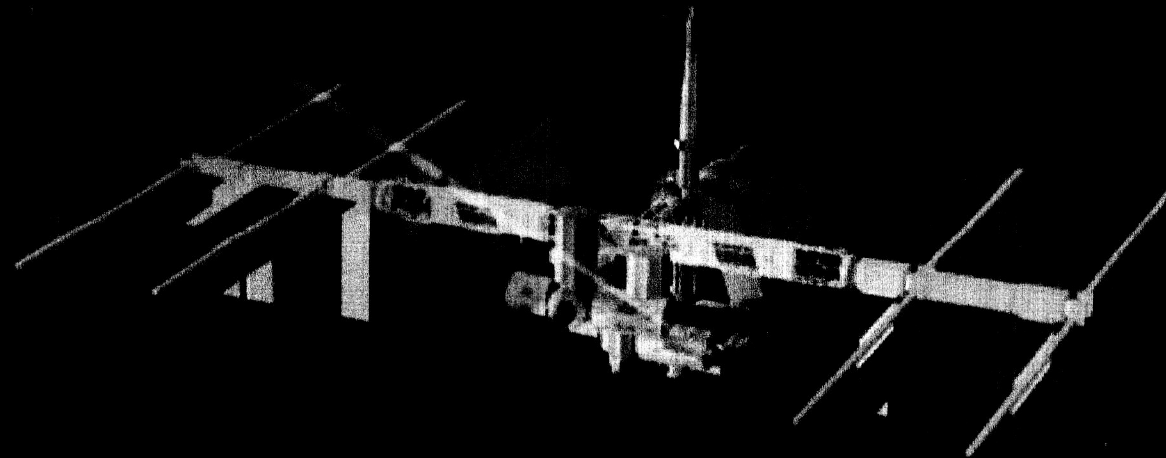


On-orbit Propellant Storage

- Reusable in-space transportation requires long-term cryogen storage
- Demonstrate cryogen thermal control



Laser Power Beaming Experiment From ISS to Technology Demonstrator



- ISS JEM-EF site 1 utilized for laser unit
- 3-5 kWe power provides ~ 1 kWe beamed energy to co-orbiting satellite
- Tech. demonstrator orbits 10-20 km ahead of ISS
- Tuned PV-array for laser-power reception on tech. demonstrator
- Beam is targeted from ISS using infrared sensors on ISS and edge heating of target PV-array

Summary

- Spacecraft Design Includes Advanced Technologies
  - Power subsystem sized to satisfy all near-term spacecraft power needs
  - Spacecraft bus provides testbed for maturing technologies
  - No insurmountable technical hurdles
- Space Solar Power Primary Payload Options
  - Large envelope with standard interfaces reserved for high-power payload
- Modular Spacecraft Design
  - Provides upgrade opportunities
  - Capability for mission tailoring
  - Bus qualified for most launch vehicles
- Spacecraft Compatible with Medium ELV Performance
  - Mass capability to ISS orbit
  - Fairing capability for large payloads on this bus