Conference: International Space Development Conference
Date: May 4-7, 2006
Location: Los Angeles, CA
Session: Solar Power Satellites
Session Chair: John C. Mankins
Title of the Paper: Modular High-Energy Systems for Solar Power Satellites

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Abstract

Modular High-Energy Systems are Stepping Stones to provide capabilities for energy-rich infrastructure located in space to support a variety of exploration scenarios as well as provide a supplemental source of energy during peak demands to ground grid systems. Abundant renewable energy at lunar or other locations could support propellant production and storage in refueling scenarios that enable affordable exploration. Renewable energy platforms in geosynchronous Earth orbits can collect and transmit power to satellites, or to Earth-surface locations. Energy-rich space technologies also enable the use of electric-powered propulsion systems that could efficiently deliver cargo and exploration facilities to remote locations.

A first step to an energy-rich space infrastructure is a 100-kWe class solar-powered platform in Earth orbit. The platform would utilize advanced technologies in solar power collection and generation, power management and distribution, thermal management, electric propulsion, wireless avionics, autonomous in space rendezvous and docking, servicing, and robotic assembly. It would also provide an energy-rich free-flying platform to demonstrate in space a portfolio of technology flight experiments.

This paper summary a preliminary design concept for a 100-kWe solar-powered satellite system to demonstrate in-flight a variety of advanced technologies, each as a separate payload. These technologies include, but are not limited to state-of-the-art solar concentrators, highly efficient multi-junction solar cells, integrated thermal management on the arrays, and innovative deployable structure design and packaging to enable the 100-kW satellite feasible to launch on one existing launch vehicle. Higher voltage arrays and power distribution systems (PDS) reduce or eliminate the need for massive power converters, and could enable direct-drive of high-voltage solar electric thrusters.

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Modular High-Energy Systems for Solar Power Satellites

Presentation to

The 25th Annual International Space Development Conference

Los Angeles, California

May 4-7, 2006

Joe T. Howell, Marshall Space Flight Center

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Neville I. Marzwell, Jet Propulsion Laboratory

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The Affordability Challenge

- One of the central barriers to more ambitious—yet still affordable—space operations in the Earth's neighborhood lies in our inability to affordably preposition consumables (particularly propellants) and needed systems (including spares for in space servicing and maintenance)
- As long as it is not possible to locally repair and refuel high-value (and high-cost) space systems beyond low Earth orbit (LEO) the affordability challenge will not be achievable
- This challenge affects planning for a wide range of potential future missions, but is particularly important for
  - Major, high-value missions such as human exploration activities beyond low Earth orbit;
  - Large-scale defense and/or security focused mission systems; or,
  - Future space industries' (such as larger, multi-payload geostationary Earth orbit (GEO) platforms, space solar power systems, and related concepts)

Notional Example

Operations Costs for Human Lunar Missions

- For example, a large-scale, permanently inhabited lunar base might involve
  - 3-4 human missions to the Moon per year (for crew rotation every 120 days or 90 days, respectively).
  - However, if such a mission scenario were to involve Apollo-era concepts and current-technology expendable space transportation systems, then the total cost per mission due to transportation costs alone (hardware and operations), could range from $2,400M per mission to more than $3,100M per mission (current year dollars).
  - Transportation cost components here are assumed to include the following:
    - » ETO Transport: Assuming Shuttle-derived, expendable systems involving 2 Heavy Lift Launch Vehicles (HLLVs), 1 Crew Launcher at a total cost of $500M to $1,000M per mission. Note that this rough estimate for ETO costs is intended to be comparable to (but lower than) the Space Shuttle at about 3-4 launches per year, plus typical EELV (evolved expendable launch vehicles) costs per launch at the same rate.
    - » In Space Transport: Assuming expendable systems involving at least two in-space stages with individual mass of about 10,000 kg (and a recurring unit per kilogram cost of about $50,000 per kilogram) for a "per mission cost" of about $500M per mission.

Notional Example
Operations Costs for Human Lunar Missions (2)

- Transportation cost components here are assumed to include the following (continued):
  - » Excursion Transport: Assuming expendable systems, involving nominally a descent module and an ascent module with a combined mass of about 10,000 kg to 20,000 kg (and a recurring unit per kilogram cost of approximately $50,000 per kilogram), for a "per mission cost" of about $750M per mission.
  - » Transportation Operations. Assuming incremental improvements on Space Shuttle and International Space Station (ISS) era ground operations concepts,, involving nominally about 20,000 total personnel (with an average cost of about $100,000 per FTE (full time equivalent)), for a "program per year cost" of about $2,000M, and a per mission cost of about $500M per mission at a rate of 4 missions per year, or about to $667M per mission at a rate of 3 missions per year.

- In summary, this scenario would result in an annual cost—for lunar base transportation only—of approximately $7,000M/year (best case, 3 missions/year), to about $11,000M/year (worst case, 4 missions per year).
  - ▪ Additional costs would, of course be incurred for crew transportation systems, supporting infrastructures (such as communications systems), as well as for the wide range of surface systems that would be needed for a lunar base.

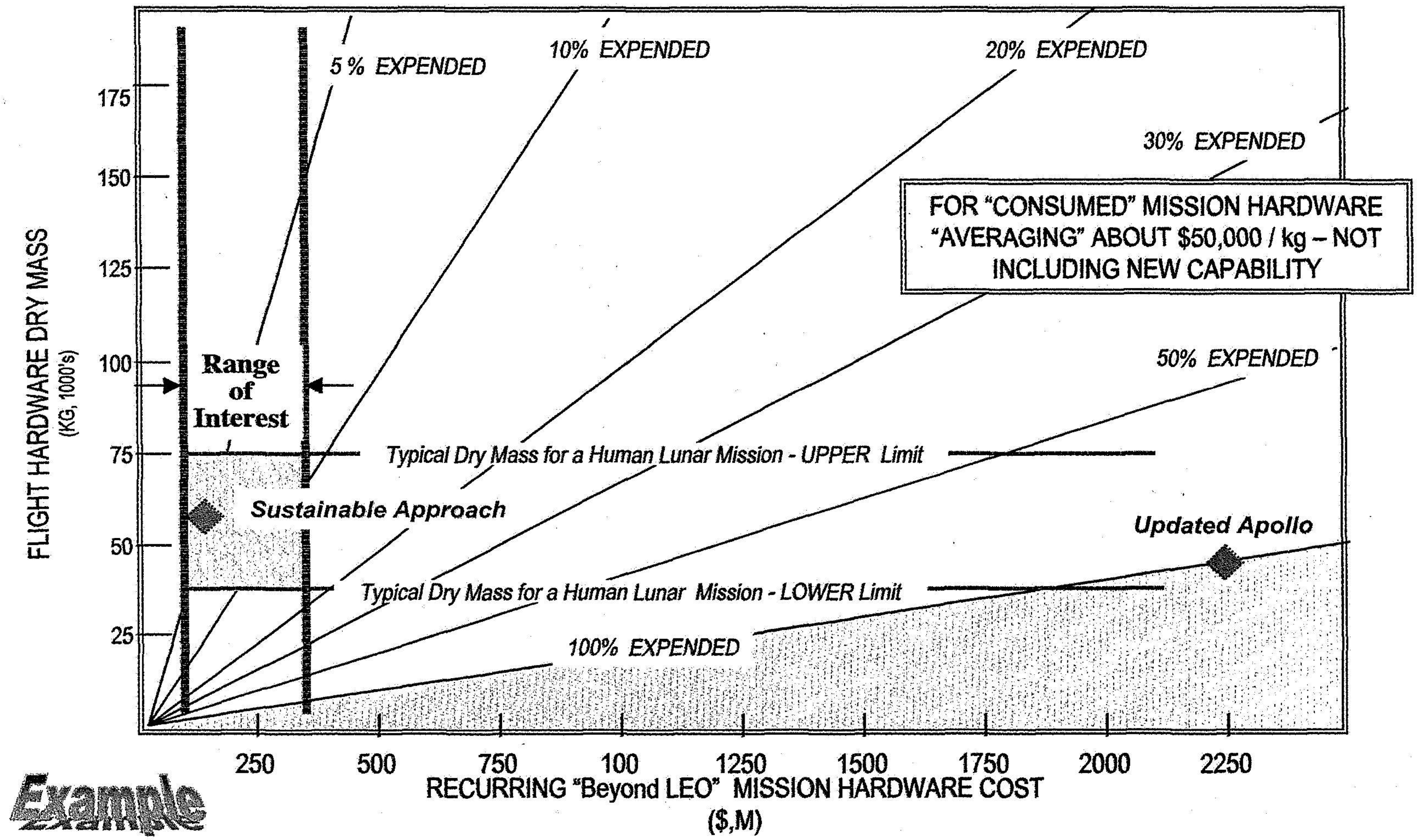
Affordable and Sustainable Ambitious Space Operations Will Require Dramatically Lower Costs

A Potential Solution
Solve ~4 Key Functional Challenges

- Lower cost ETO transport (perhaps by enabling a transition to launchers that are more similar to those used by other government organizations or by commercial sectors; and in the long term by transitioning to reusable launch vehicles);
- Highly-autonomous assembly, maintenance and servicing of modular systems in space and on planetary surfaces (including both robotic and crew-assisted operations),
- Affordable and timely pre-positioning of fuel, systems and other materiel throughout the Earth-Moon system (including to the surface of the Moon); and,
- Reusable, highly reliable and high-energy in-space transportation (and for lunar missions, excursion transportation systems).

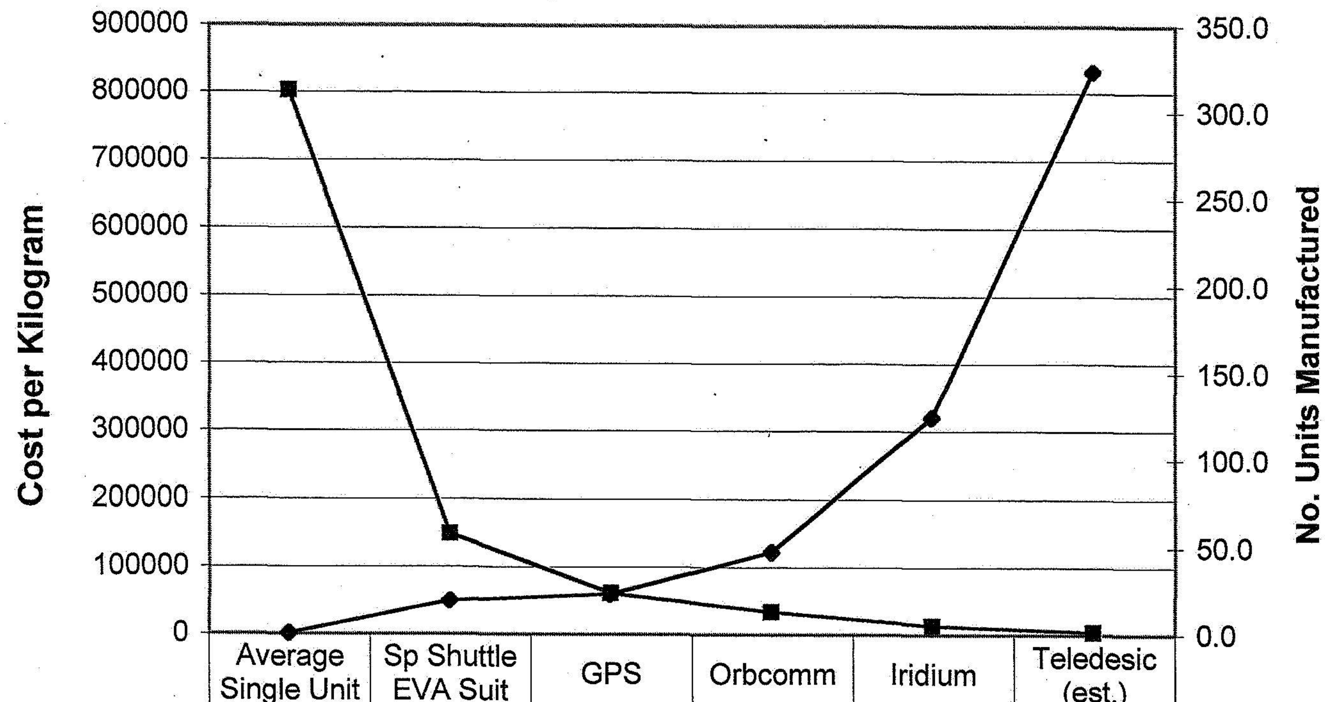
Why Reusable Systems? — Cost per Mission Improvement

Parametric Comparison of "Levels of Expendability"



Reusable Space Systems critical to reducing excessive 'expendable hardware" costs of Apollo-derived architectures.

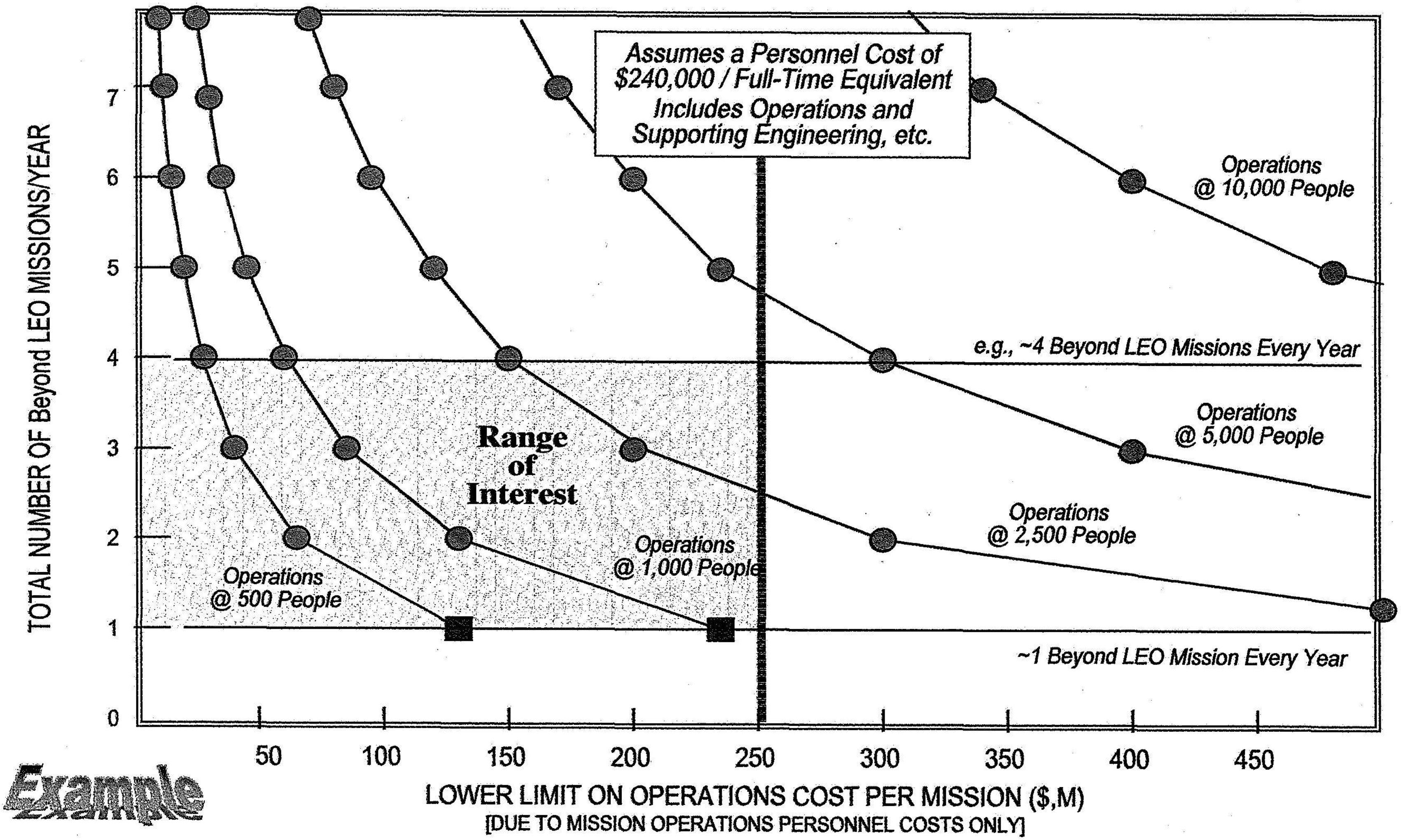
Why Modular Systems?
"No. of Units Manufactured" & Specific Cost ($/kg)*



	Average Single Unit	Sp Shuttle EVA Suit	GPS	Orbcomm	Iridium	Teledesic (est.)
Price/kg-Dry	803220	150000	62238	34722	14464	5513
No. Units Made	1.0	20.0	24	48.0	125.0	324.0

***100-10,000 kg class Space Systems**

Why Autonomous / Intelligent Systems?
Parametric Comparison of "Impact of Staffing"

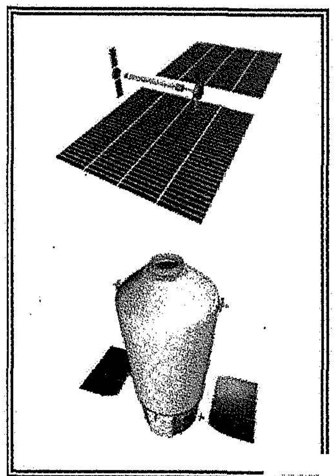


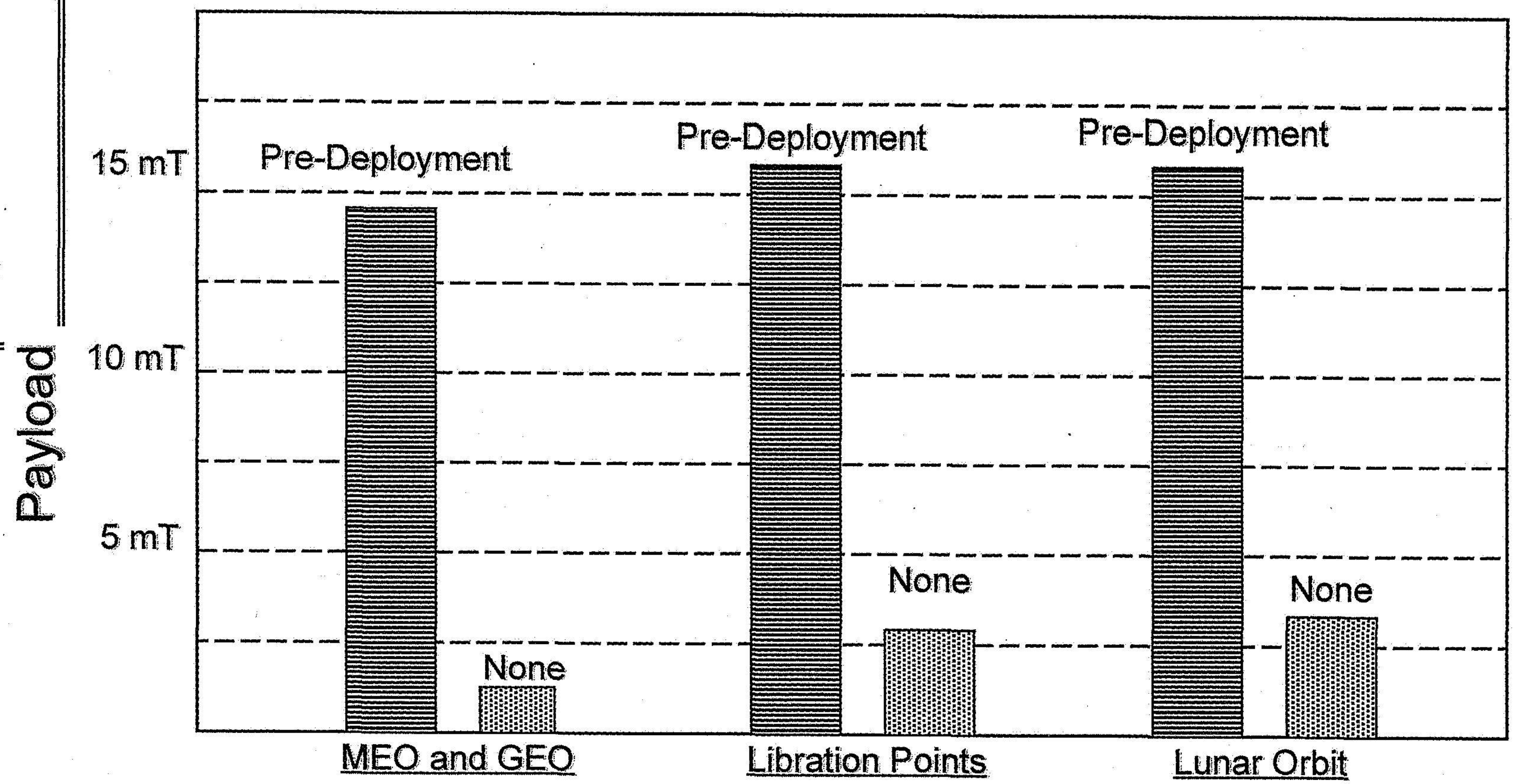
Example

Intelligent systems critical to low recurring operations costs.

Pre-Deployment of Logistics/Propellants

Parametric Comparison of Major Options

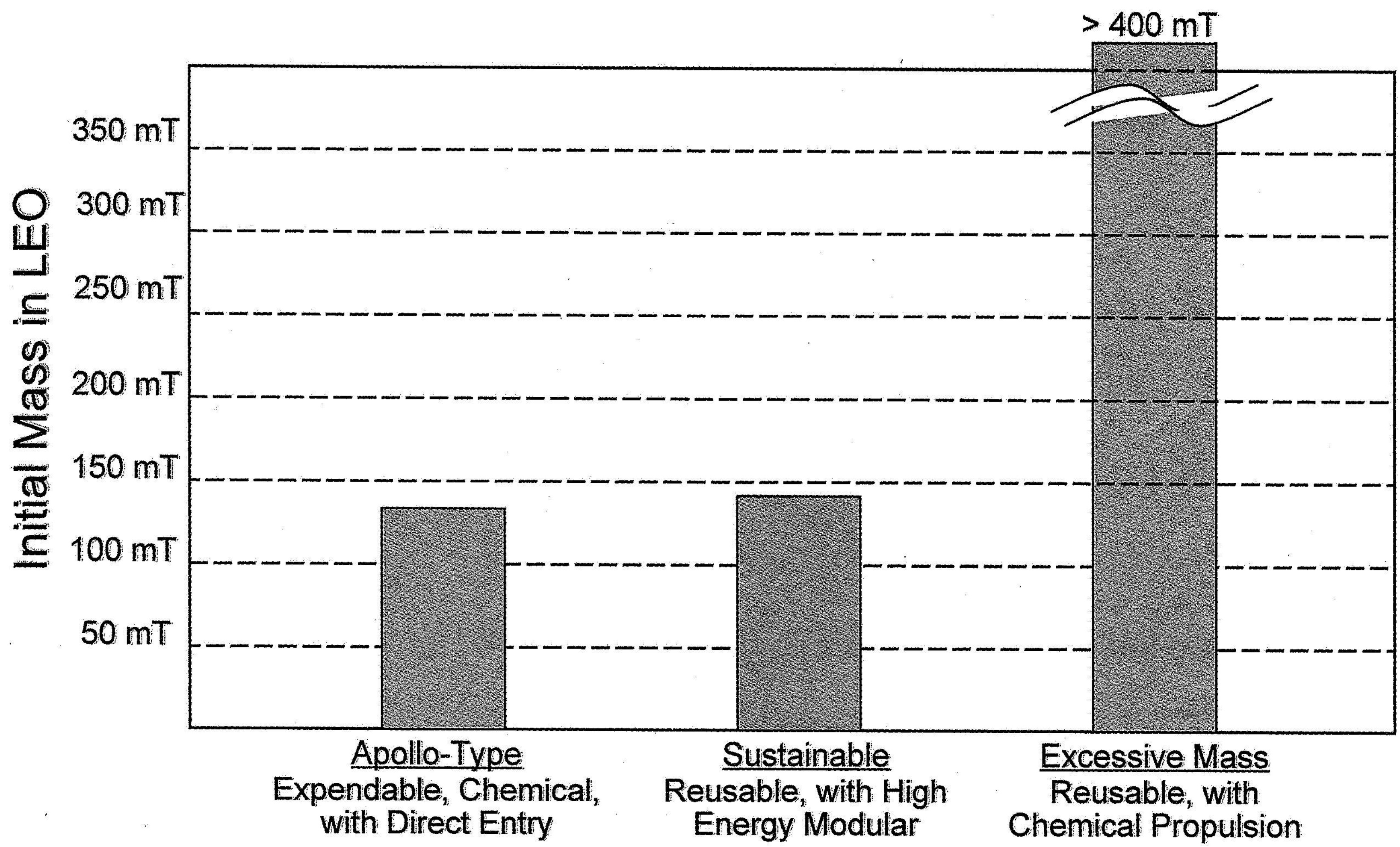




Pre-Deployment of Logistics/Propellants critical to "Timely-Payload Delivery" performance for reusable architectures.

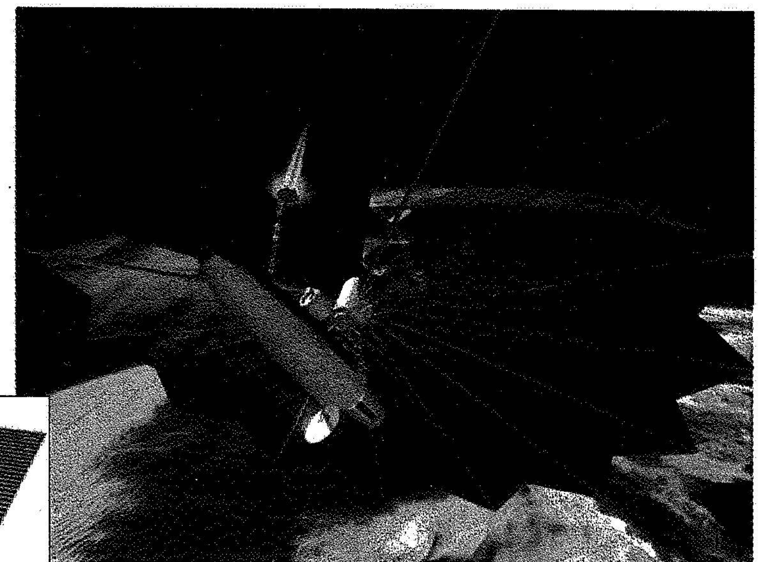
Why Refueling and High Energy Systems are BOTH Required

Reduced Initial Mass in LEO

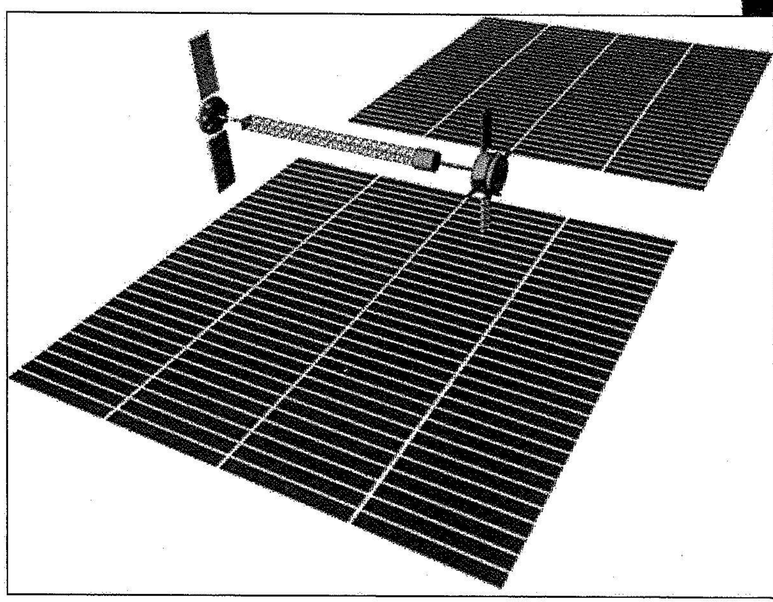


High-energy electric propulsion critical to reducing excessive propellant mass of reusable architectures.

Large Solar Electric Propulsion (SEP) Vehicles
Conventional Concepts

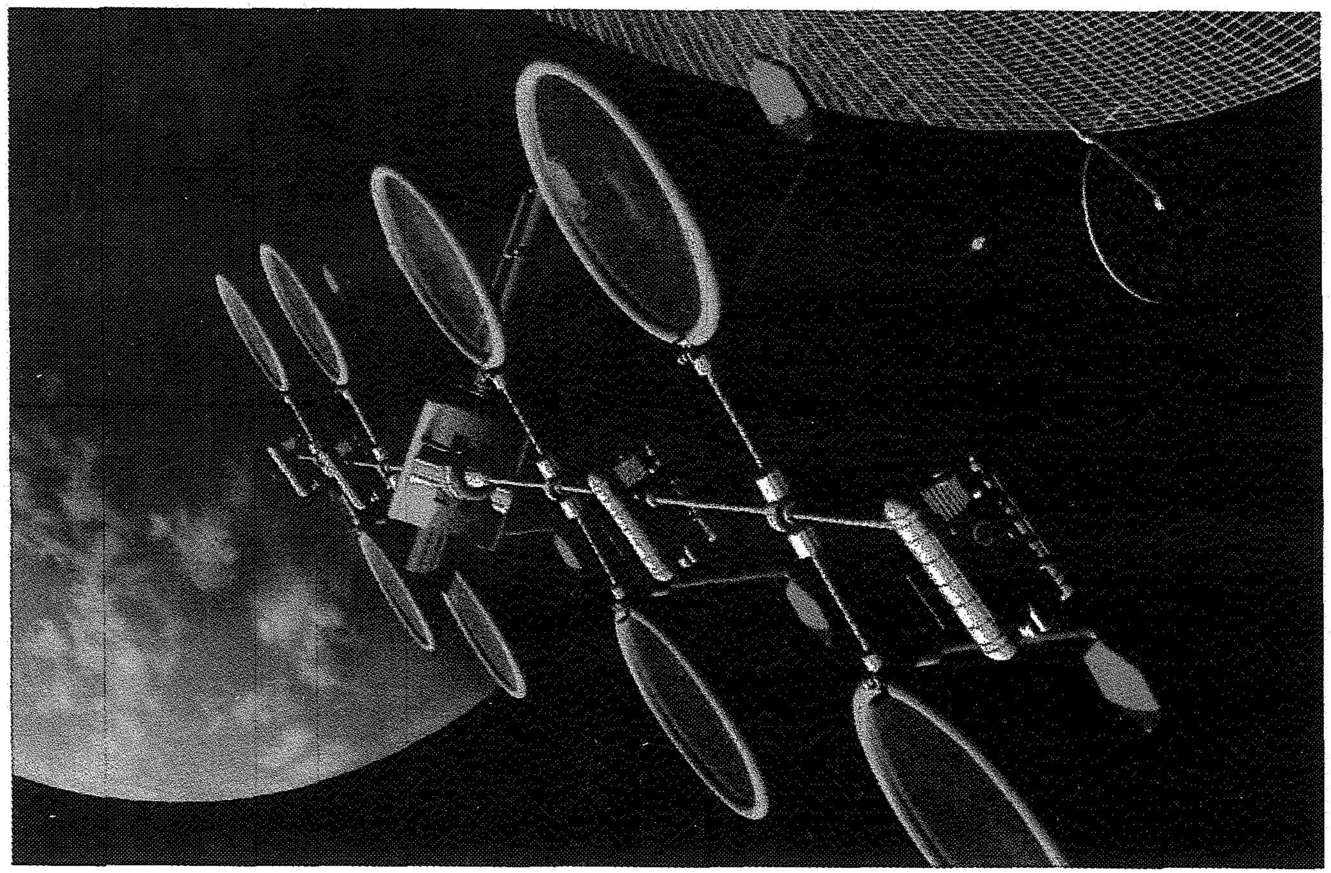


Thin Film "Bat-Wing" Array



Monolithic Square Array

Large Solar Electric Propulsion (SEP) Vehicles
Alternative: Modular High-Energy Systems



Key Technology Challenges

- Tele-supervised (and eventually autonomous) highly resilient deep space systems operations (in this case, 'deep space' operations includes all ambitious mission operations beyond LEO)
- **Self-adaptive modular systems**
- **Space assembly**, maintenance and servicing (from the system level, down to the subsystem level)
- **Highly fuel-efficient, high reliability, re-startable propulsion, such as high-power electric propulsion for cargo** and cryogenic engines for time critical mission (such as those involving astronaut crews).
- High-energy propellants for long-duration missions (particularly cryogenic propellants such as liquid oxygen, liquid hydrogen, etc.)
- Long-term storage and management, as well as the highly reliable and low-loss transfer (including transfer in micro-gravity) of cryogenic propellants.
- **High-power, but low-mass space power generation and management systems**

Potential Benefits of Modular High-Energy & Depot Systems

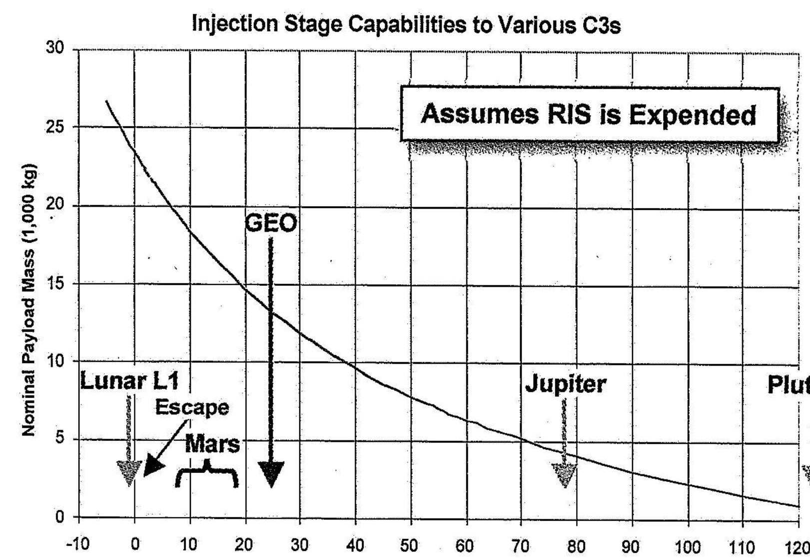
Examples

- What capabilities can the Reusable / Refueled Vehicles and SEPs "Freighters" provide to other potential missions?

<u>Reusable Injection Stage Specs*</u>
Dry Mass = 5,240 kg (no landing gear)
Propellant Capacity = 29,217 kg
Isp = 460 s
Propulsive Capture for LEO Return
Starting/Return Orbit: LEO, 500 km, 28.5°

<u>SEP Stage Specs*</u>
Dry Mass = 10,000 kg (Xe tankage not included)
Propellant Capacity = 19,151 kg
Isp = 3,000 s
Max. Power = 500 kW
Starting/Return Orbit: LEO, 500 km, 28.5°

	Mission	Max Payload Capability w/ No Refueling	Max Payload Capability w/ Refueling
Reusable Injection Stage(1)	DoD Mid-Inclination Orbit	178 kg	13,561 kg
	GEO Payload Deployment	793 kg	13,993 kg
	Lunar L1 Halo Orbit	2,793 kg	15,437 kg
	Lunar Orbit	2,805 kg	15,445 kg
	GPS Orbit	3,254 kg	15,778 kg
	GEO Transfer Orbit	28,135 kg	N/A
	Lunar Surface Cargo Delivery(2)	15,733 kg	27,775 kg
	Trans-Mars Injection(3)	17,794 kg	-
SEP Stage(4)	Lunar Orbit	33,015 kg	36,438 kg
	Lunar L1	44,170 kg	46,971 kg
	GEO Payload Deployment	46,259 kg	48,967 kg

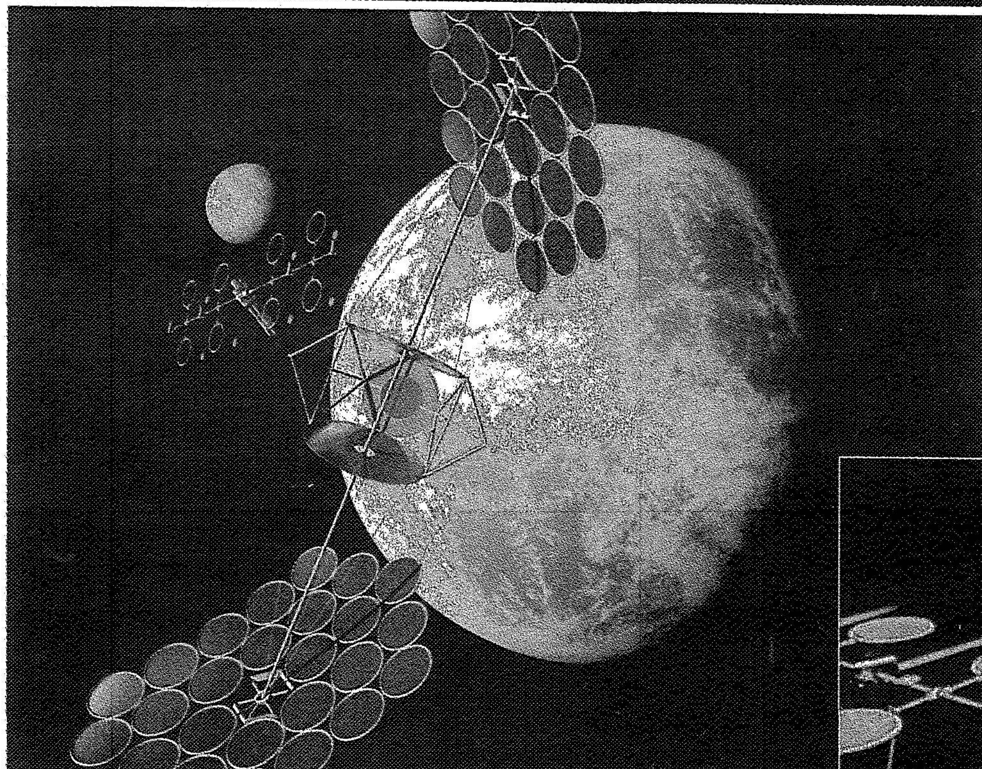


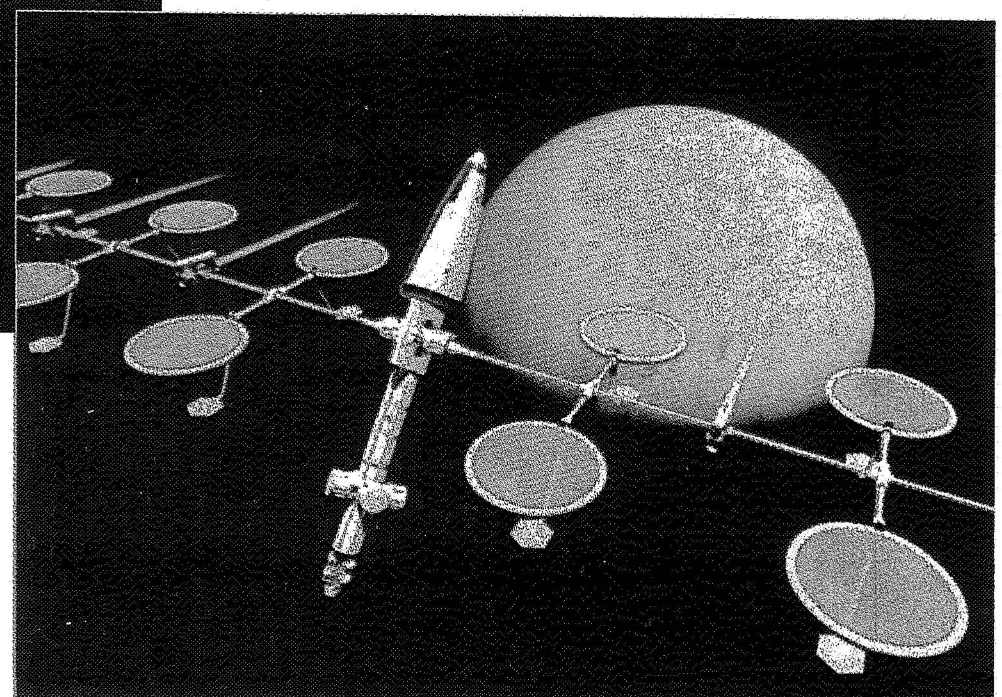
<u>Notes:</u>
1. **RIS returns to LEO via propulsive capture**
2. **SEP delivers RIS and payload to lunar orbit. RIS is expended on lunar surface.**
3. **Mars/Deep Space missions assume RIS is expended**
4. **SEP Stage outbound trip times limited to no longer than 270 days**

****Element Specs consistent with Space-based XTV / LEO Propulsive Capture / LOR Architecture***

Notional Modular High-Energy Systems Applications

Transporting Large Space Systems to GEO and Beyond





Conclusions

- Future ambitious space operations--particularly beyond LEO--must be much more affordable, if they are to be sustainable
- Modular Self-Adaptive High-Energy systems represent one important alternative approach in realizing the goal of dramatically reduced space operations costs
- Key technology challenges must be addressed, however, before such advanced systems concepts could be used in space applications
- Nearer term, large scale technology flight demonstrations are possible in the next 5 years to test both component technologies and systems level functionality