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High-Voltage High-Energy Stretched Lens Array Square-Rigger (SLASR) for Direct-Drive Solar Electric Propulsion

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Direct-Drive Solar Electric Propulsion (SEP)

- When the output of a high-performance, high-voltage solar photovoltaic array (e.g., Stretched Lens Array) is directly connected to an electric thruster (e.g., Hall-effect thruster) with minimal power distribution system in between, a very fuel-efficient and cost-effective reusable SEP space tug becomes possible.

- As shown in the following two slides, such an SEP space tug could deliver 110 metric tons of cargo to the lunar surface at savings of more than $3 billion compared to conventional chemical propulsion transport.

- The critical enabling technology for such SEP space tugs is the high-performance, high-voltage solar array, which must provide unprecedented performance metrics compared to today's state of the art arrays.

- The Stretched Lens Array (SLA) offers these required performance metrics, and ground tests and flight tests to validate SLA for SEP are critical to near-term availability of this important technology for space exploration.
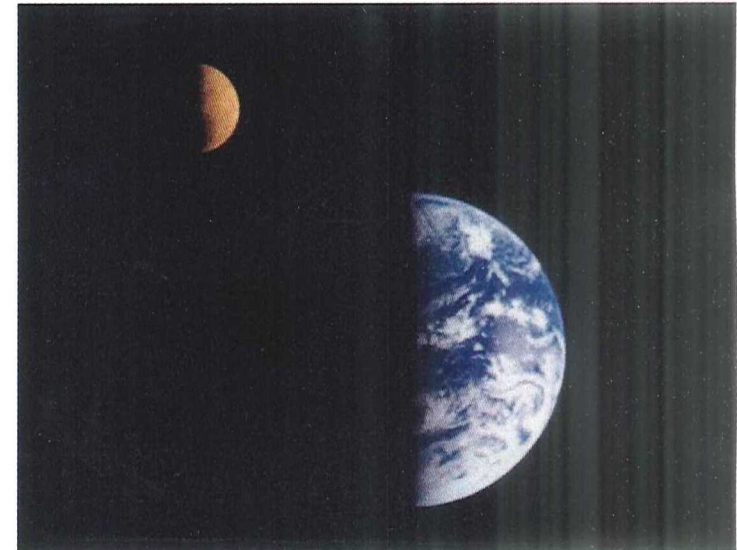
600 kW SLASR-Powered SEP Tug Mission

◆ **SLASR-Powered SEP Tug**
  - **Nominal 600 kW SLASR Array (Approx. 2,000 sq.m. Total)**
  - **Hall-Effect Thrusters**
  - **600 Volt Direct Drive System**
  - **22 MT to Lunar Surface Each Trip**
  - **1 Year Max Round-Trip Time**
  - **Reusable Tug (5 Round Trips)**
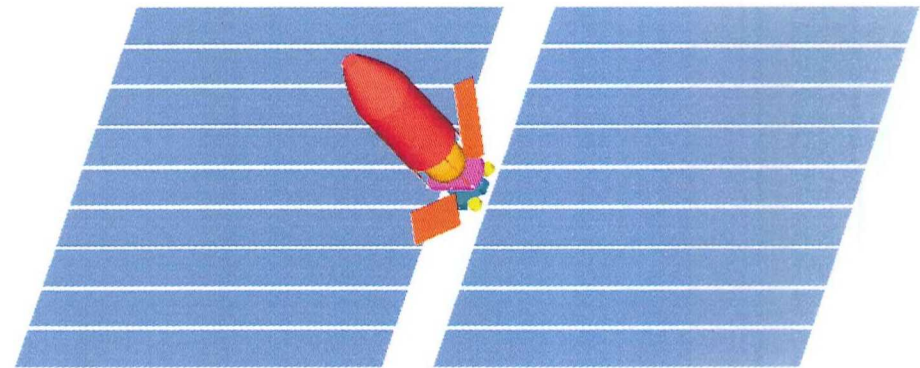
◆ **Reusable Lunar Tug Mission**
  - **Five Round-Trips (One per Year) from LEO (400 km) to LLO, with On-Board Chemically Fueled Lander Delivering Cargo to Lunar Surface**
  - **First LEO Launch Contains Tug, Xenon, Lander with Chemical Fuel, and Cargo**
  - **Subsequent LEO Launches Provide New Xenon, Lander with Fuel, and Cargo, Which Dock with Tug in LEO for Next Trip**
 - **28 Degree Inclination Near Earth with Plane Changes Near Moon**

600 kW SLASR-Powered Lunar SEP Tug Offers Huge Savings

Conventional Chemical Cargo Transport		Reusable SLA-Powered SEP Cargo Transport	
Item	**Mass**	**Item**	**Mass**
LEO-to-LLO Vehicle (Expendable)	10 MT	LEO-to-LLO Vehicle (Reusable)	10 MT
Cargo	22 MT	Cargo	22 MT
LLO-to-Lunar Surface Fuel	15 MT	LLO-to-Lunar Surface Fuel	15 MT
LEO-to-LLO Fuel	80 MT	LEO-to-LLO Propellant (Xenon)	23 MT
Total Launch Mass	127 MT	Total Launch Mass (First Launch w/Vehicle)	70 MT
		Total Launch Mass (Subsequent Launches)	60 MT
Total LEO Launch Mass for Five Deliveries Over Five Years (110 MT Total Cargo)	635 MT	Total LEO Launch Mass for Five Deliveries Over Five Years (110 MT Total Cargo)	310 MT
Launch Costs Using Shuttle-Derived Heavy	**$ 6,350 Million**	Launch Costs Using Shuttle-Derived Heavy	**$ 3,100 Million**
($10 M/MT from ATK: safesimplesoon.com)		($10 M/MT from ATK: safesimplesoon.com)	

- ◆ **SEP Offers Over $3 Billion in Savings Just in Launch Costs per Tug**
- ◆ **SEP Offers Additional Savings of 4 Fewer LEO-to-LLO Transfer Vehicles**
- ◆ **More than 5 Round-Trips May Be Practical for SEP Tug (More Savings)**
- ◆ **For 70-MT-Class Shuttle-Derived Launch Vehicles, SEP Approach Will Require Half as Many Launches as Chemical Approach, and, as ATK Accurately States, " Fewer Launches + Fewer Payloads + Fewer In - Space Assemblies = Higher Mission Reliability "**

Background: Mini-Dome Lens Array on PASP-Plus and SCARLET Array on Deep Space 1

720 ENTECH Lenses on
2.5 kW SCARLET Solar Array
on NASA/JPL Deep Space 1
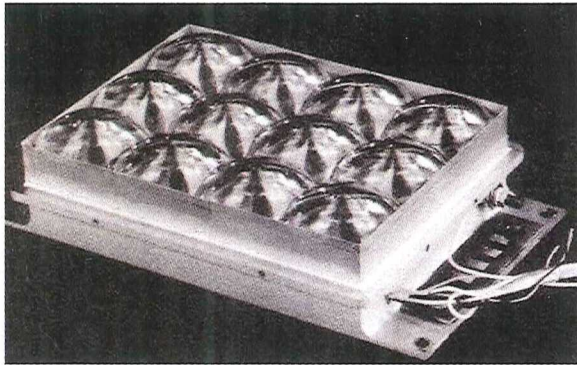
Mini-Dome Lens Array Flew on PASP-Plus Flight Experiment in 1994-95 and Performed Very Well in High-Radiation Elliptical Orbit
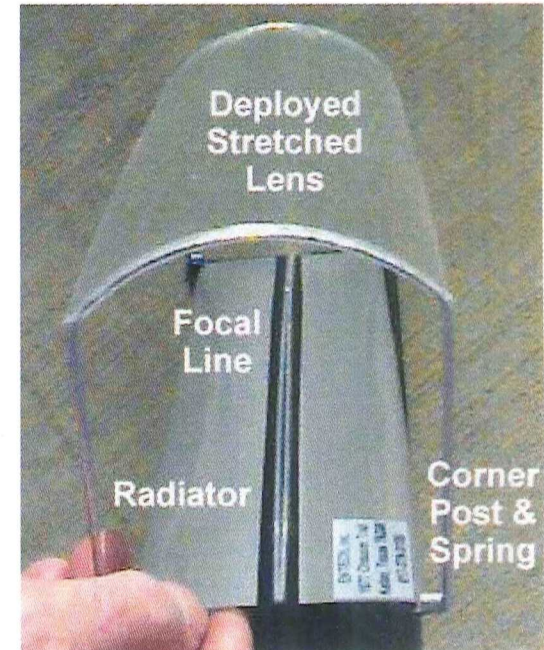
SCARLET Array Flew on Deep Space 1 in 1998-2001 and Performed Flawlessly for 38 Month Extended Mission
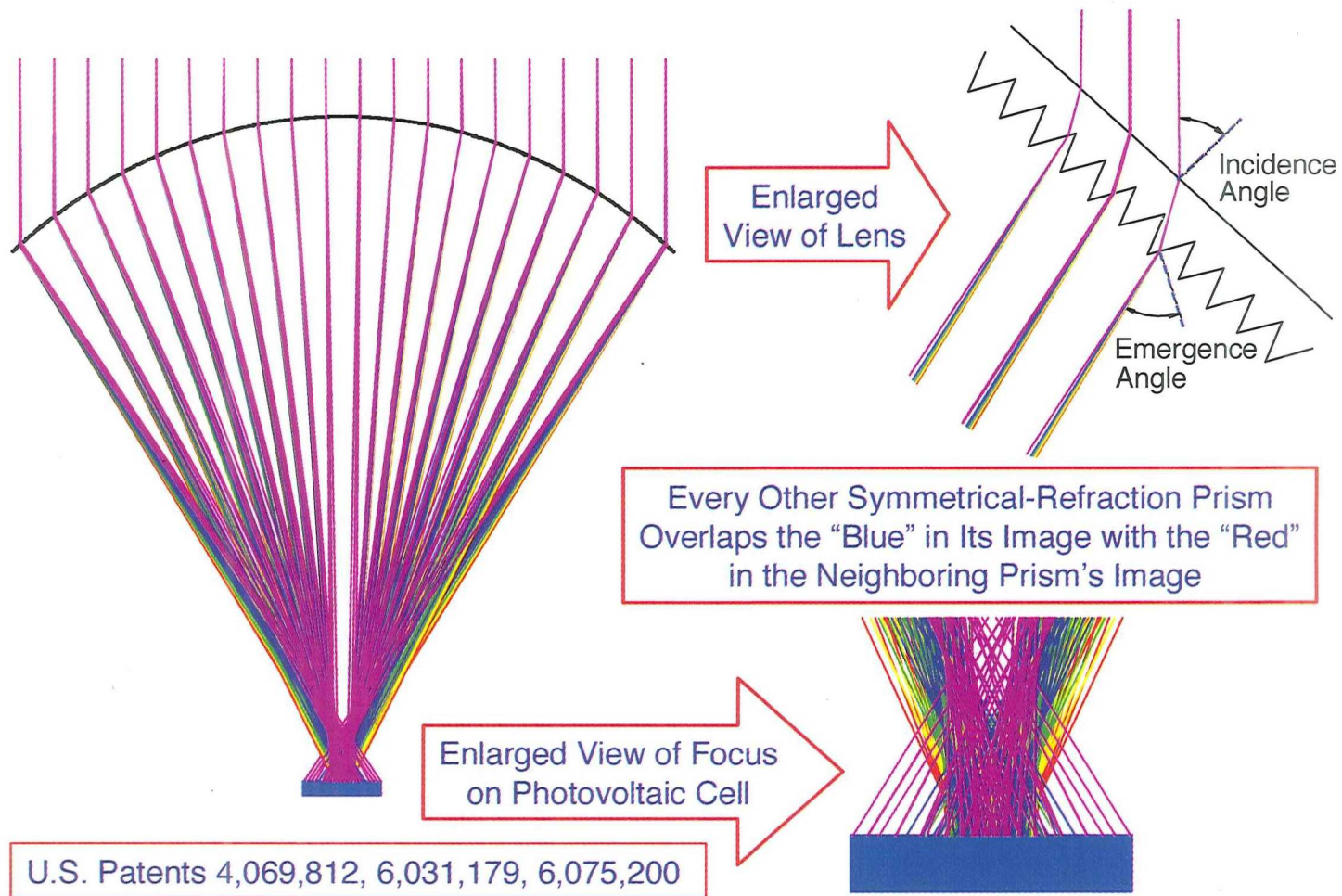
Stretched Lens Array (SLA) Approach
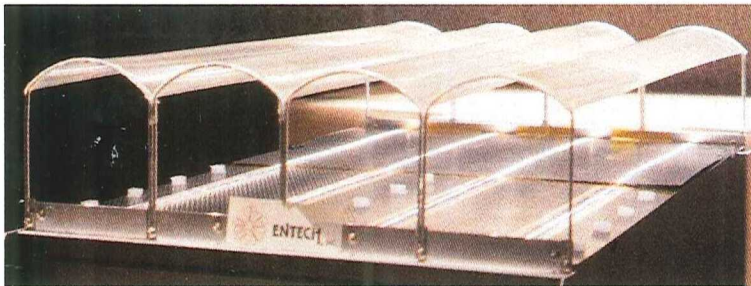

Lens Stowed Against Radiator

Flexible Silicone Lens Folds Flat Against
Radiator Sheet (Containing Solar Cells)
for Compact Launch, and Deploys on
Orbit Using Lengthwise Tensioning to
Support Arched Lens in Proper Position

Deployed
Stretched
Lens

Focal
Line

Radiator

Corner
Post &
Spring

Unique Lens Provides High Optical Performance, Color-Mixing, and Unparalleled Error Tolerance

Enlarged View of Lens

Incidence Angle

Emergence Angle

Every Other Symmetrical-Refraction Prism Overlaps the "Blue" in Its Image with the "Red" in the Neighboring Prism's Image

Enlarged View of Focus on Photovoltaic Cell

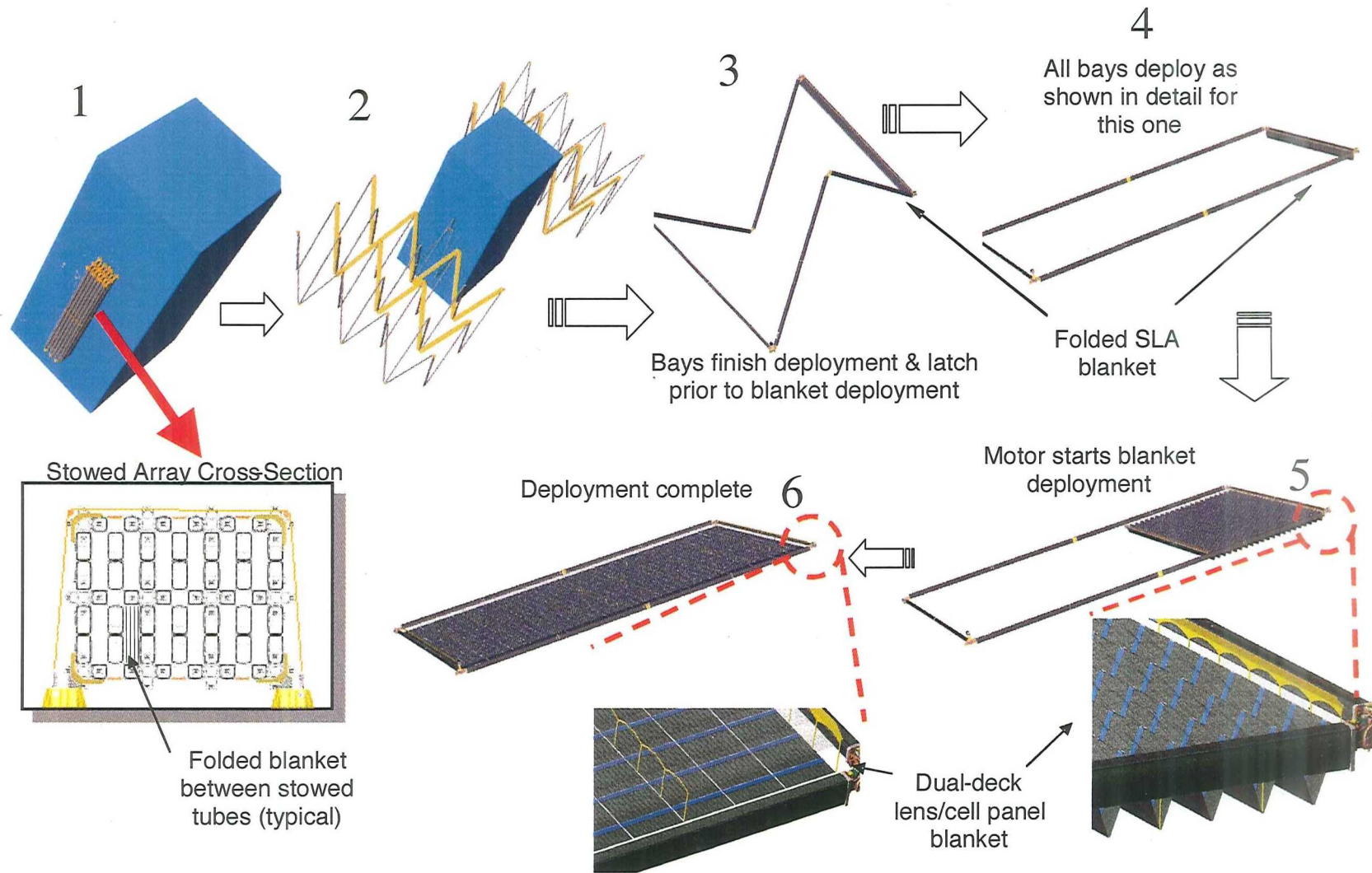U.S. Patents 4,069,812, 6,031,179, 6,075,200

Two Versions of Stretched Lens Array (SLA)

Flexible-Blanket Version (Above) of SLA Uses End Tensioning to Deploy and Support Lenses and Radiator Blankets


Stretched Lens Array (SLA) Prototype Wing (Comprising 4 Rigid Panels, Each 0.5 m x 1.0 m) November 2002

Rigid-Panel Version (Above) of SLA Uses Pop-Up Lenses on Lightweight Honeycomb Panels

Stretched Lens Array SquareRigger (SLASR)

1

2

3

4

All bays deploy as shown in detail for this one

Bays finish deployment & latch prior to blanket deployment

Folded SLA blanket

Stowed Array Cross-Section

Folded blanket between stowed tubes (typical)

Deployment complete

6

Motor starts blanket deployment

5

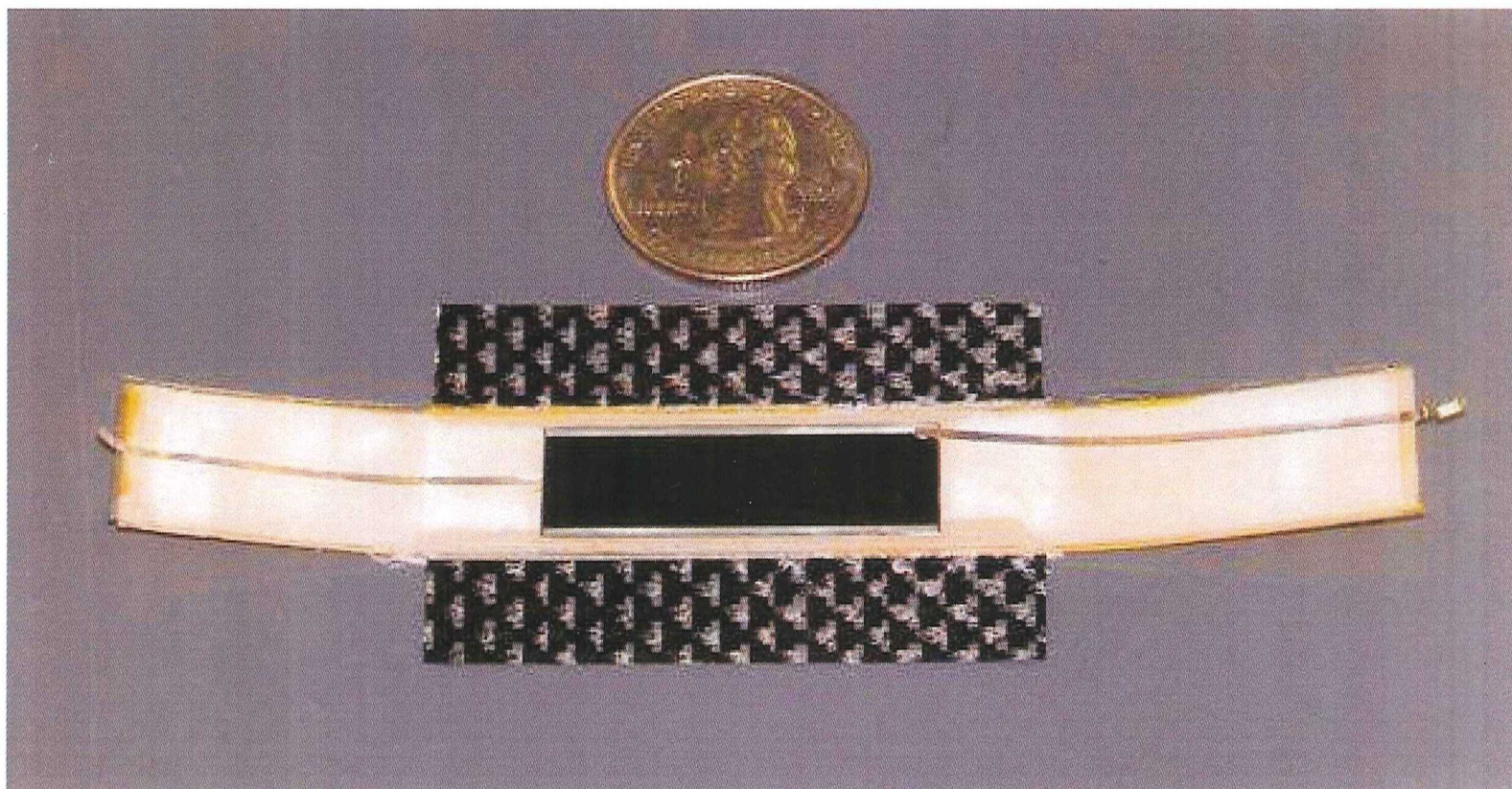Dual-deck lens/cell panel blanket

Prototype Stretched Lens Array SquareRigger (SLASR) Hardware

Prototype Hardware Shows That the SLASR Approach Provides Excellent Deployment, Support, and Alignment of Lenses and Radiators Containing Solar Cell Receivers
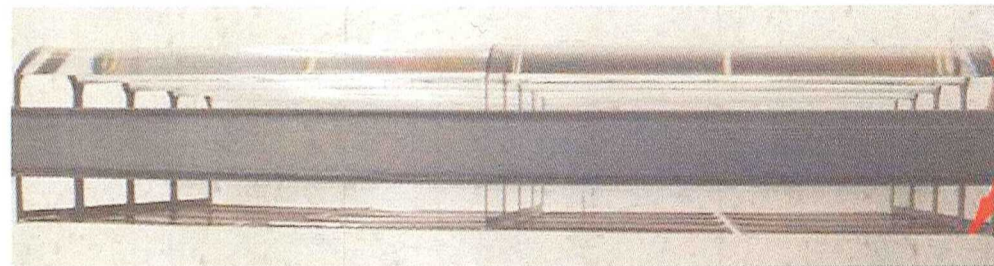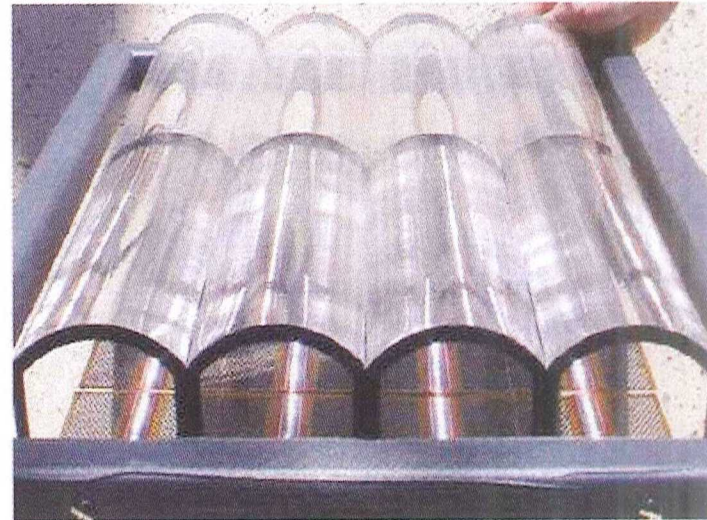
Gossamer Lens and Cell Blankets

Fully Encapsulated SLASR Receiver Sample

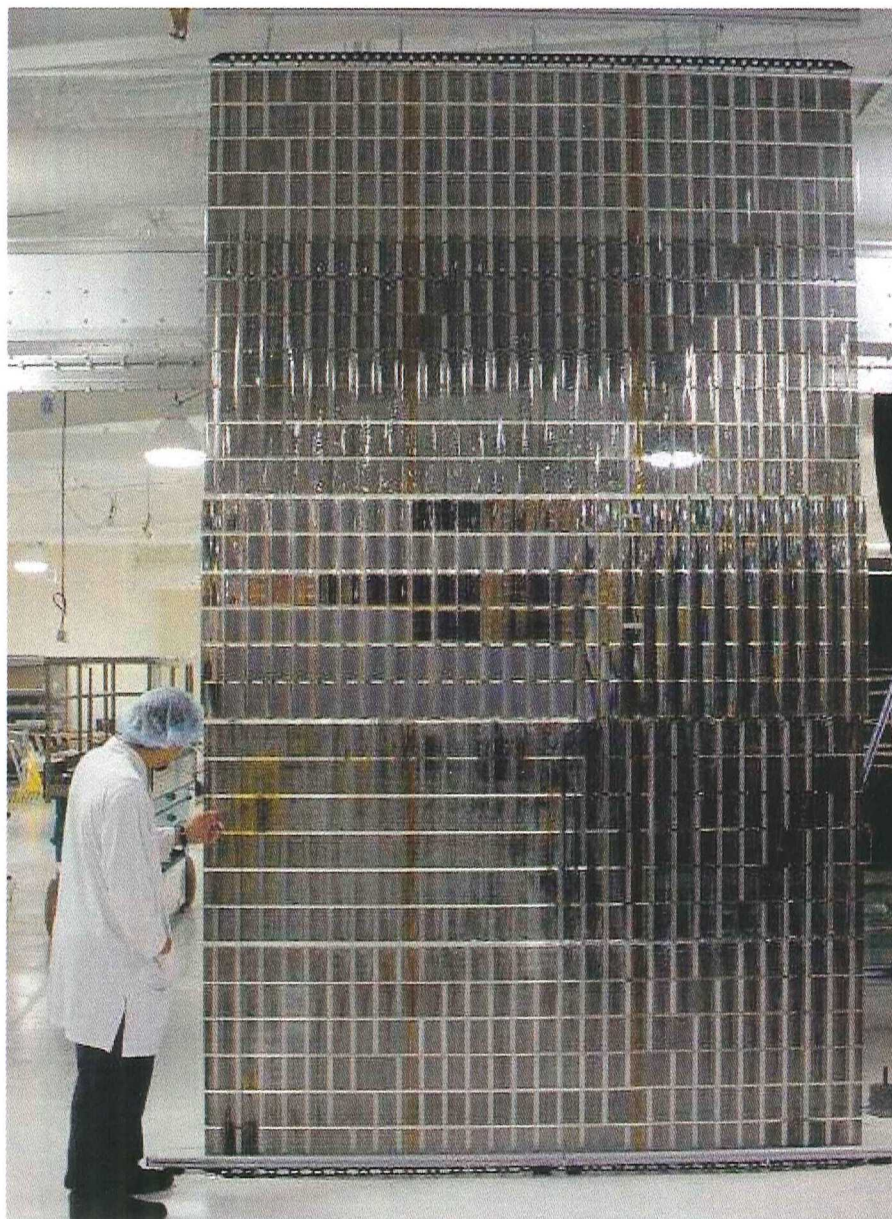# Relocation of 1 kW *SunLine* Array with 600-Volt Photovoltaic Receiver Circuits from Hawaii to ENTECH

NASA SunLine at ENTECH July 25, 2005
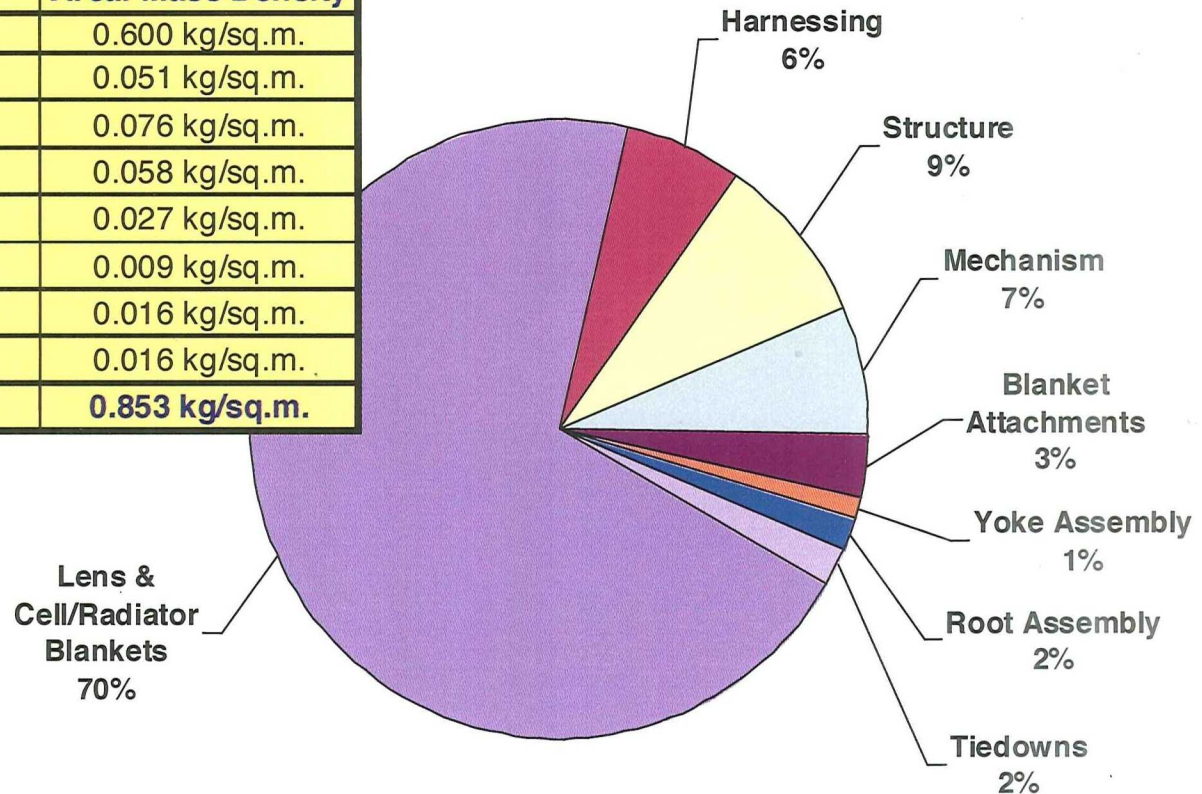
Each 26X Concentrator Uses ENTECH Color-Mixing Lens

Over Boeing Triple-Junction Solar Cells

Full-Scale SLASR Bay.

Mass Breakdown for 100 kW Stretched Lens Array SquareRigger (SLASR) for Current Technology and Normal GEO Radiation Shielding

Element	Areal Mass Density
Lens & Cell/Radiator Blankets	0.600 kg/sq.m.
Harnessing	0.051 kg/sq.m.
Structure	0.076 kg/sq.m.
Mechanism	0.058 kg/sq.m.
Blanket Attachments	0.027 kg/sq.m.
Yoke Assembly	0.009 kg/sq.m.
Root Assembly	0.016 kg/sq.m.
Tiedowns	0.016 kg/sq.m.
Total	**0.853 kg/sq.m.**

Note that the Lens & Cell/Radiator Blankets Comprise 70% of Total Mass

Harnessing 6%

Structure 9%

Mechanism 7%

Blanket Attachments 3%

Yoke Assembly 1%

Root Assembly 2%

Tiedowns 2%

Lens & Cell/Radiator Blankets 70%

This mass breakdown is for a near-term 100 kW SLASR with today's 30% efficient cells and today's lens and radiator thicknesses

Key SLASR Performance Parameters.

| Parameter	Value for SLASR	Measurement or Model
Lens Transmittance	92%	Measurement
Cell Efficiency @25C	30%	Measurement
Net Lens/Cell Efficiency @25C	27.6%	Measurement (NASA Lear Jet Confirmed)
Cell Temperature on GEO	71C	Model (Validated on SCARLET)
Cell Temperature Knockdown Factor	91%	Measurement (Cell Temperature Coefficients)
Input Irradiance to SLA Lens	1,366 W/sq.m.	Measurement (International Standard)
SLA SquareRigger Gross Areal Power Density	343 W/sq.m.	Model
Wiring/Mismatch/Packing Knockdown Factor	90%	Model
SLA SquareRigger Net Areal Power Density	**309 W/sq.m.**	Model
SLA SquareRigger Wing Mass Density	0.853 kg/sq.m.	Model (Based on Prototype)
SLA SquareRigger Net Specific Power	**362 W/kg**	Model
SLA SquareRigger Stowed Power Density	**80 kW/cu.m.**	Model (Based on Prototype)

Stretched Lens Array SquareRigger (SLASR) Offers Spectacular Performance Metrics

Time Frame	< 5 Years	5-10 Years
Power Capability (kW)	100	1,000
BOL Specific Power (W/kg)	330	500
Stowed Power (kW/m^3)	80	120
Voltage	1,000	TBD
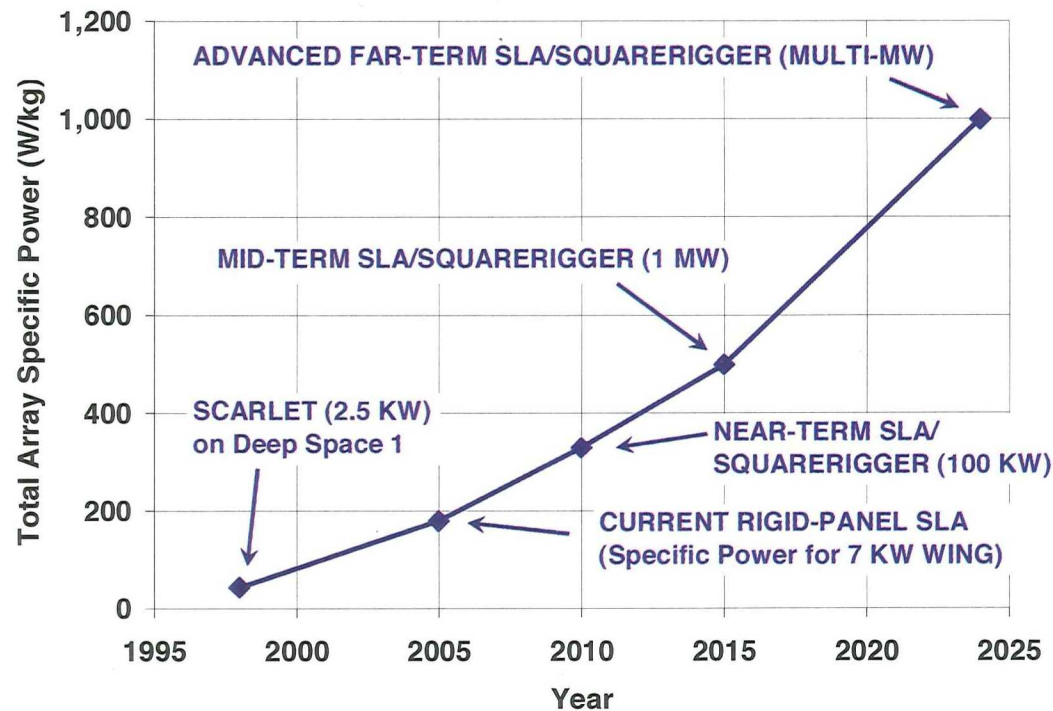
SLASR Optimization for a Solar Electric Propulsion (SEP) Space Tug Mission with 7 Annual Trips from Low Earth Orbit to Low Lunar Orbit

Assumption: Total SquareRigger Array Mass = Blanket Mass/0.70 (Reference: ABLE's 100 kW SLA SquareRigger Design Study)
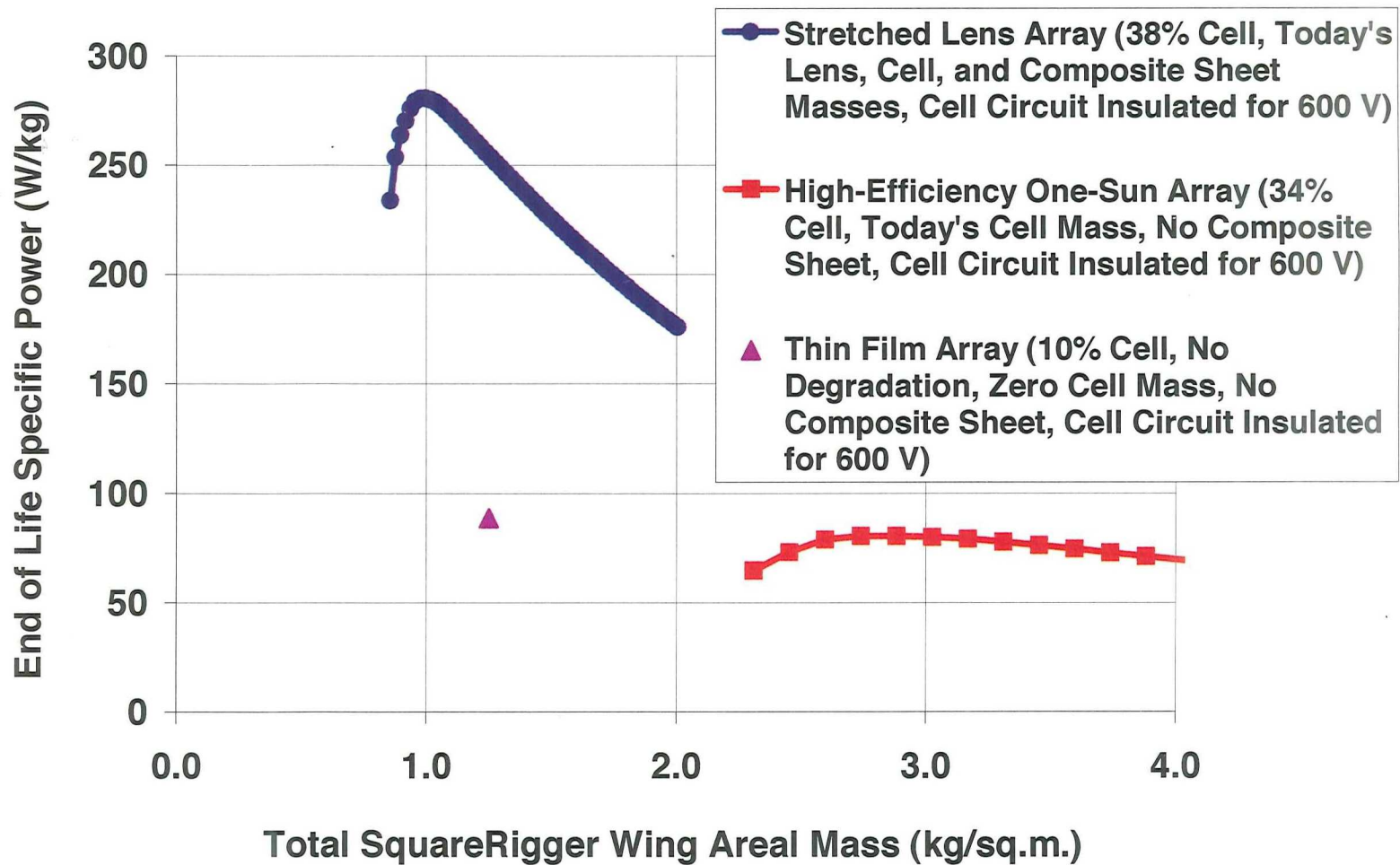
# SLASR Advantages for Solar Electric Propulsion Missions

SLASR's Advantages for SEP Missions Include a Set of Unprecedented Performance Metrics and Features:

- Areal Power Density = 300-400 W/m^2

- Specific Power = 300-500 W/kg for Full 100 kW Solar Array

- Stowed Power = 80-120 kW/m^3 for 100 kW Solar Array

- Scalable Array Capacity = 100's of W's to 100's of kW's

- Super-Insulated Small Cell Circuit = High-Voltage Operation

- Super-Shielded Small Cell Circuit = Radiation Hardness

- 85% Cell Area Savings = 75% Lower Array Cost per Watt

- Modular, Scalable, & Mass-Producible at MW's per Year Using Existing Processes and Capabilities

A notional Solar Electric Propulsion (SEP) System – an Earth-Moon System "Solar Clipper" – in operation, transporting large space systems to GEO
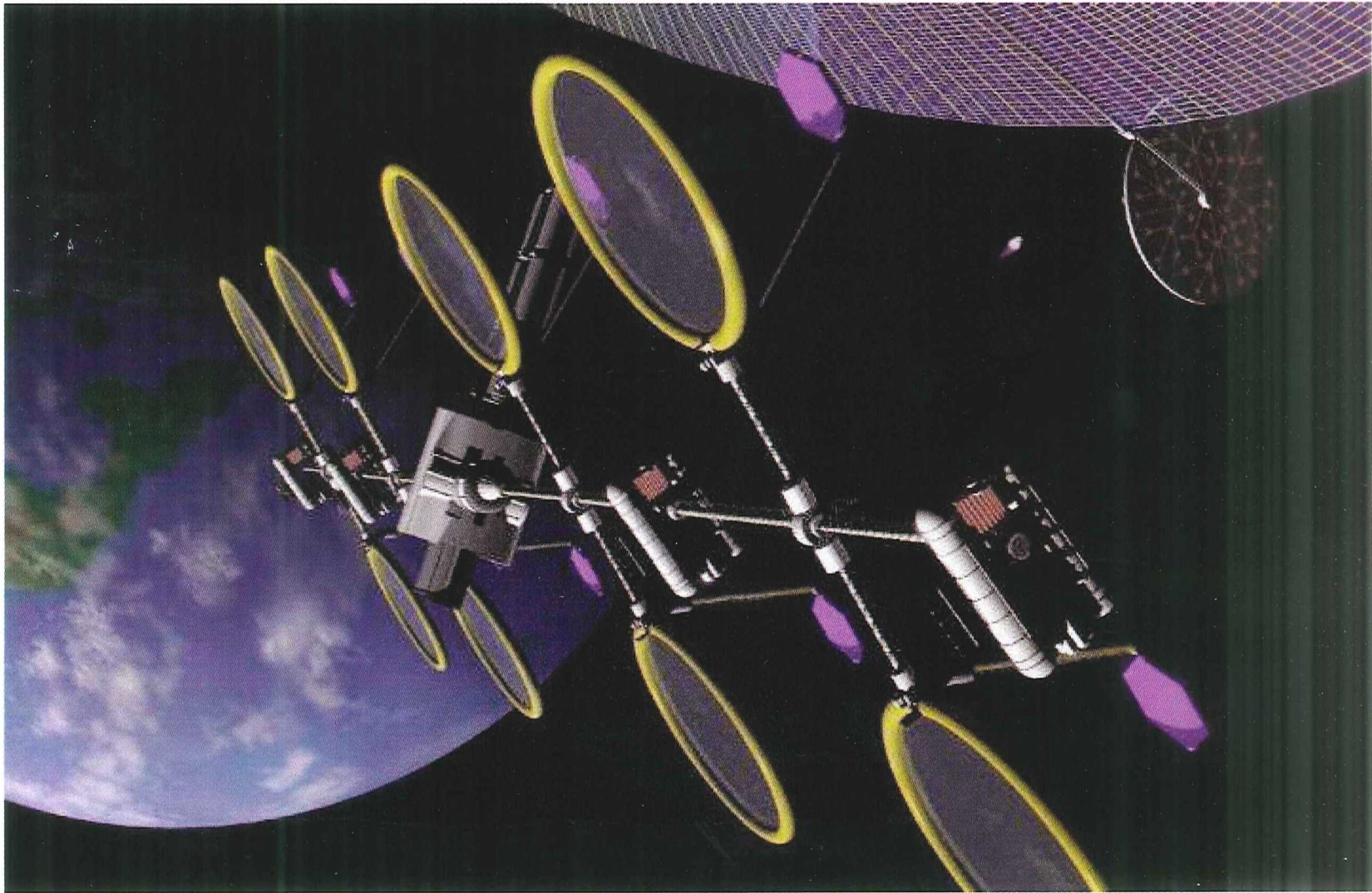
Another notional Solar Electric Propulsion (SEP) System – an Earth-Mars
"Solar Clipper" – transporting large exploration mission systems and cargo to Mars orbit.
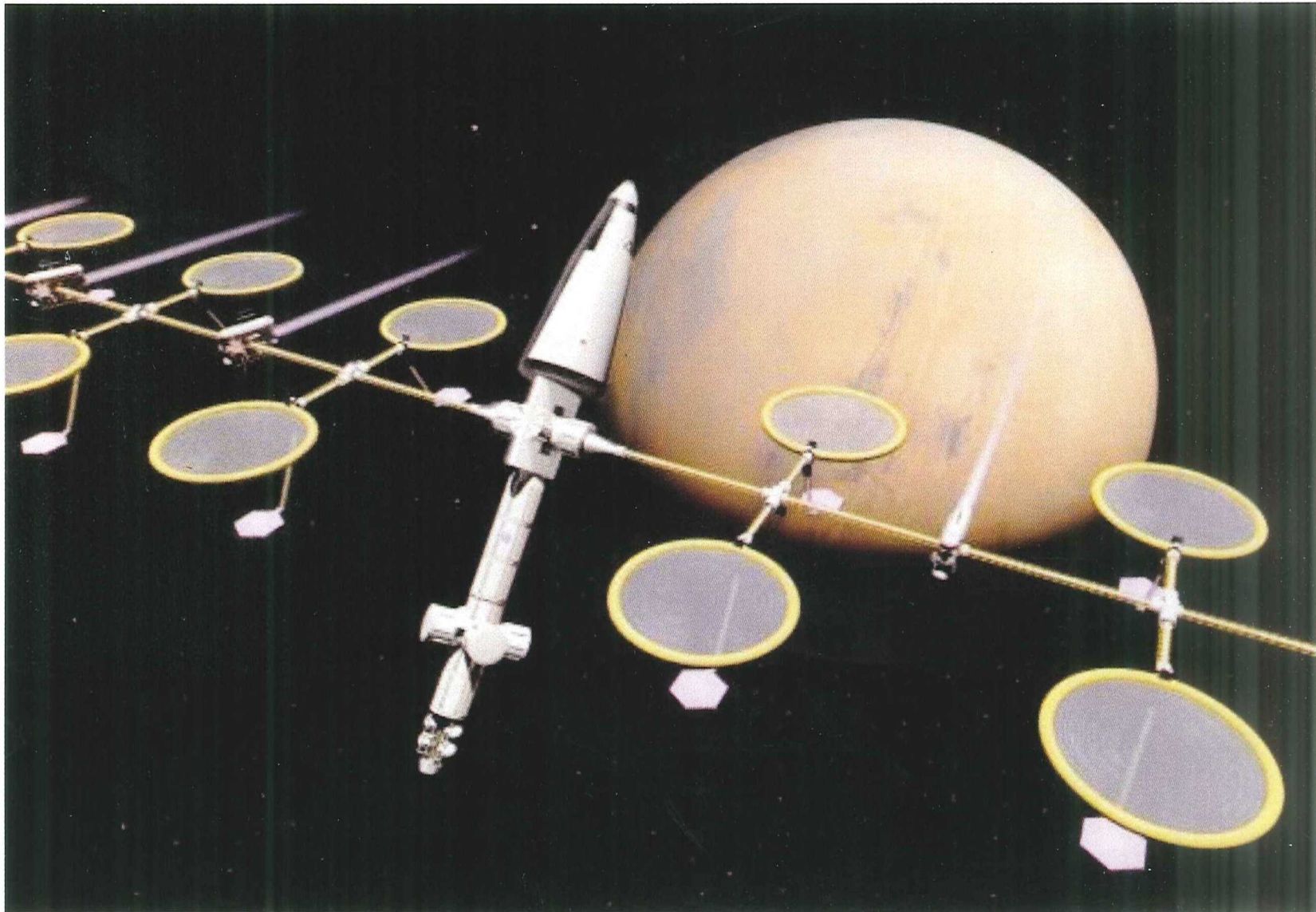
Conclusions

- Solar electric propulsion using direct-drive, high-voltage, high-performance solar arrays offers substantial benefits for delivering cargo in support of exploration missions to the Moon, and later to Mars.

- A single 600 kW reusable space tug could save over **_$3 billion_** in launch costs alone in delivering 110 metric tons of cargo to the Moon.

- The critical enabling technology for such SEP space tug missions is the high-performance, ultra-light, radiation-durable, scalable, cost-effective, high-voltage solar array.

- The Stretched Lens Array (SLA) offers the portfolio of attributes and performance metrics needed for SEP space tug missions.

- Ground tests and later flight tests are critical to validate the SLASR technology for direct-drive SEP missions.

- Initial ground tests are underway and additional ground tests are planned for the next 2-3 years to support the development of SLA for direct-drive SEP missions.