Materials Needs for Future In-Space Propulsion Systems

Les Johnson, Leslie Alexander, Roy Young and Erin Richardson
NASA George C. Marshall Space Flight Center, Alabama 35812

Kyle Frame
Gray Research, Inc., Huntsville, AL 35806

Abstract

NASA's In-Space Propulsion Technology Project is developing the next generation of in-space propulsion systems in support of robotic exploration missions throughout the solar system. The propulsion technologies being developed are non-traditional and have stressing materials performance requirements. (Chemical Propulsion) Earth-storable chemical bipropellant performance is constrained by temperature limitations of the columbium used in the chamber. Iridium/rhenium (Ir/Re) is now available and has been implemented in initial versions of Earth-Storable rockets with specific impulses (I_{sp}) about 10 seconds higher than columbium rocket chambers. New chamber fabrication methods that improve process and performance of Ir/Re and other promising material systems are needed. (Solar Sail Propulsion) The solar sail is a propellantless propulsion system that gains momentum by reflecting sunlight. The sails need to be very large in area (from 10000 m^2 up to 62500 m^2) yet be very lightweight in order to achieve adequate accelerations for realistic mission times. Lightweight materials that can be manufactured in thicknesses of less than 1 micron and that are not harmed by the space environment are desired. (Aerocapture) Blunt Body Aerocapture uses aerodynamic drag to slow an approaching spacecraft and insert it into a science orbit around any planet or moon with an atmosphere. The spacecraft is enclosed by a rigid aeroshell that protects it from the entry heating and aerodynamic environment. Lightweight, high-temperature structural systems, adhesives, insulators, and ablatives are key components for improving aeroshell efficiencies at heating rates of 1000-2000 W/cm^2 and beyond. Inflatable decelerators in the forms of ballutes and inflatable aeroshells will use flexible polymeric thin film materials, high temperature fabrics, and structural adhesives. The inflatable systems will be tightly packaged during cruise and will be inflated prior to entry interface at the destination. Materials must maintain strength and flexibility while packaged at cold temperatures (-100^{o}C) for up to 10 years and then withstand the high temperatures (500^{o}C) encountered during aerocapture.

Introduction

Future in-space propulsion systems will be quite different from any flown before. This change will be necessitated by the nature of our exploration of the solar system – all the "easy" destinations have been surveyed. Future science and exploration missions will carry more payload, visit more propulsive-intense destinations, survey multiple targets per mission, or some combination thereof. This will drive the propulsion requirements away from today's state-of-the-art (SOA) chemical propulsion systems and toward those with higher performance, or, in some cases, toward non-traditional propulsion technologies such as solar sails and aerocapture.

Advanced Chemical Propulsion Technologies and Systems

Chemical systems have traditionally provided the primary means of spacecraft propulsion. However, today's SOA systems are nearing their theoretical performance limits. Near-term solutions must provide improvements that can not only meet these needs but also offer benefits that can be translated into new science. In response, SOA systems must evolve to meet the ever more demanding missions of the aerospace community.

Increases in earth storable bipropellant rocket performance can be achieved by modifying some combination of the following variables: geometric or mechanical design, thruster operating conditions, or propellant. Changes to operating conditions, e.g. higher chamber pressure or mixture ratio, increase the chamber combustion gas temperature and yield higher wall temperatures. These higher wall temperatures must be addressed through improvements in thermal design. Hence, performance can be significantly impacted by the realization of gains from improved materials properties and manufacturing processes. For chemical systems, the temperature limitations of columbium (niobium) used in the fabrication of traditional thrust chambers place performance constraints on the propulsion system that can be mitigated through alternate material selection. Incorporating high temperature, oxidation resistant combustion chamber materials, such as Iridium/Rhenium (IrRe), into innovative designs can mitigate the impact of higher heat fluxes without compromising engine characteristics or performance.

However, the performance potential for IrRe thrust chambers has not been fully exploited. Advanced IrRe thrust chamber materials offer increases in I_{sp} that approach 10 to 20 seconds over those SOA columbium designs. Further improvements in system performance can be harnessed without compromising risk. To achieve higher I_{sp}, it is possible to operate at higher temperatures -- in the 2800 K range. This requires materials that can be manufactured to withstand the higher combustion temperatures. Analytical and test data suggest that successfully enduring higher temperatures would expand the operating range of existing designs and provide increased margins for chamber pressures and mixture ratios. By modifying mixture ratio and increasing chamber pressure, more aggressive performance targets can be met. This translates directly into kilograms of payload mass.

Factors that affect the operating temperature of IrRe chambers include rhenium purity and porosity. To facilitate technology advancements, investigating in alternative manufacturing processes is key to improving the quality and reducing the cost of fabricating thrust chamber assemblies. Hardware suppliers can now fabricate many propulsion components that can withstand these higher temperatures. Using processes such as electroforming and vacuum plasma spray has the potential to reduce cost, decrease cycle time, and improve both producibility and reliability.

With the current knowledge base, low risk, low cost improvements that capitalize on the significant investments, and the progress made-to-date, addressing component high temperature needs is desirable. The potential for growth in this area will have immediate benefits to flight engines for DoD, NASA and commercial applications. Advanced material engine development can demonstrate the full performance capability of the Ir/Re (or similar) material system and pave the way to higher pressure systems and subsequent high performance storable propellant engines that could be enabling for many mission destinations.

Solar Sail Propulsion Systems

A solar sail is a propellantless propulsion system that gains momentum by reflecting sunlight. Though simple in concept, engineering a solar sail space propulsion system will be challenging. High residual velocities can only be reached by a solar sail if the specific ratio of spacecraft weight and sail size (sail area density) is very small. The sails need to be very large in area (from 10000 m^2 up to 62500 m^2) in order to achieve adequate accelerations for realistic mission times.

The SOA solar sail systems produced for the NASA In-Space Propulsion Technology Program's 20 meter Ground System Demonstrations (GSD), seen in Figure 1, were 2 micron thick Mylar and CP1[1,2]. While Mylar is commercially available in thickness as low as 0.9 micron and is inexpensive, the material is susceptible to solar UV radiation. CP1 is much more tolerant of the space environment; however the variation in material

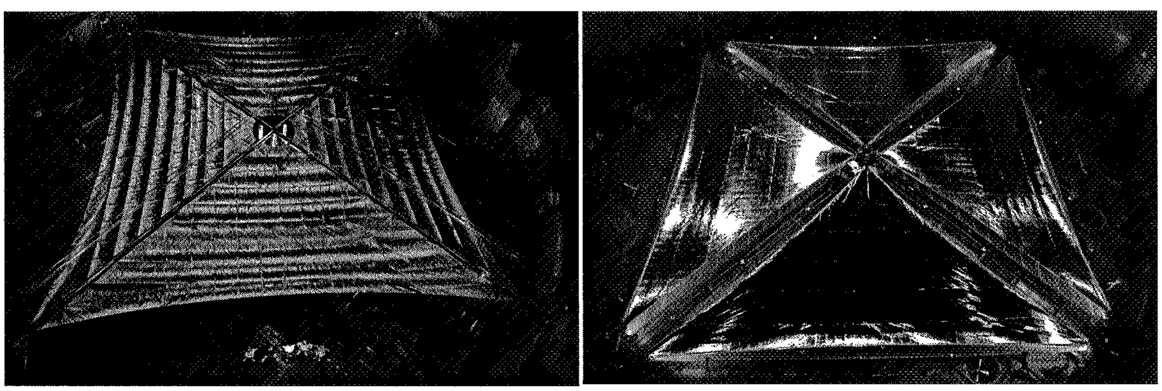


Figure 1: L'Garde (left) and ATK (right) 20 meter GSD in the 33-m diameter Space Power Facility vacuum chamber at the NASA Glenn Research Center's Plum Brook Station.

thickness and material costs may prohibit its use on large solar sails. Lightweight materials that can be manufactured in thicknesses of less than 1 micron and that are not harmed by the space environment are required for future solar sail missions such as Interstellar Probe (ISP)[3] where the required sail areal density is ~ 1g/m^2.

In addition to the sail substrate, innovative coatings that provide the reflective surface and thermal control of the solar sail are also required. Coating processes used on the 20-meter GSD's left many pinholes and variations in the coating thickness, which could result in unwanted radiation exposure of the base substrate. New coatings that reflect better than 89% of the incident sunlight over a broad spectral range and high emissivity backside coatings, including carbon black nanotubes, for temperature control are desired.

Novel concepts to provide lighter sails involve the removal of the heaviest sub-system of a sail as currently conceived, namely the sail substrate. Assuming that a plastic backing is only needed during the manufacturing and assembly phases for handling and the launch phases to prevent the very thin aluminum film from cracking along the fold lines when in the stowed configuration, three solutions have been suggested for the on-orbit removal of that substrate[4]:

1) The mechanical removal of the plastic material, perhaps using a laser beam controlled to a nanometric precision that can ablate the plastic substrate once in orbit
2) The use of a plastic material undergoing photolysis reaction under the effect of the light of the sun
3) Thermally removing the plastic film.

Boom materials should combine high strength and stiffness with extremely low density and compactness ratios for stowage within a very tight volume for launch. The 20 meter GSD demonstrated graphite coilable booms (ATK) and inflatable, thermally rigidized booms (L'Garde). Research into thinner graphite protruded rods, possibly incorporating integrated active damping elements to control structural modes, and investigations into other novel composite materials such as carbon fiber reinforced plastic are desired. Several classifications of rigidizable materials have been identified over the last several decades that provide a wide range of performance characteristics[5]. These rigidizable materials, being composite in nature, are compiled of various matrix materials (the materials responsible for the rigidization), reinforcements, and supporting polymer film layers. Investigations into variations and combinations of these materials to provide a wide range of performance characteristics that can be tailored to the solar sail mission environment are also desired.

Aerocapture Systems

The rigid aeroshell is considered the first generation Aerocapture technology. The second generation technology is the inflatable decelerator. The In-Space Propulsion Technology Project has been funding development of three inflatable decelerator systems: the trailing ballute, the afterbody attached ballute, and the forebody attached inflatable aeroshell.

The trailing ballute (Figure 2A) features an inflated toroid that is much larger than the spacecraft it is towed behind and is used similarly to a parachute to slow the vehicle. The toroidal shape was selected to allow the hole in the toroid to "swallow" the spacecraft wake. Approximately 24 hours before the spacecraft interfaces with the planetary atmosphere, the ballute is deployed and allowed to fully inflate. This precludes problems the system would encounter during inflation in the atmosphere. The trailing ballute design allows for easy detachment and minimizes interference with the spacecraft's operation. Trajectory control is simply through drag modulation. When the spacecraft achieves a predetermined deceleration, the ballute is released, allowing the spacecraft to exit the atmosphere. A propulsive periapsis raise maneuver is required to circularize the orbit.

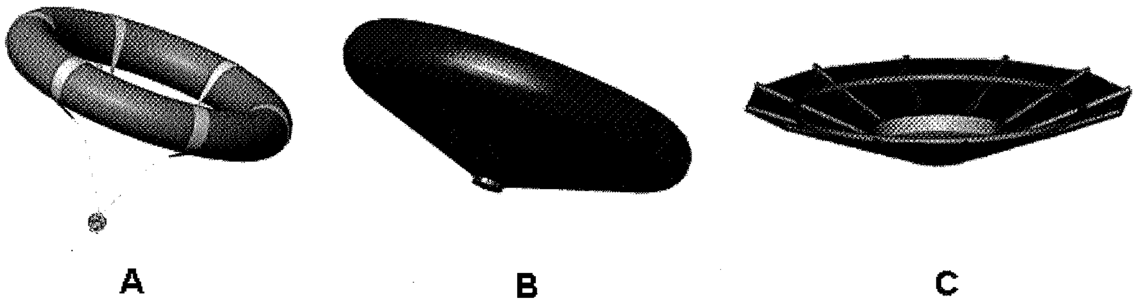


Figure 2: Trailing Ballute (A); Afterbody Attached Ballute (B); Forebody Attached Inflatable Aeroshell (C)

The afterbody attached ballute (Figure 2B) is much like the towed ballute except that the ballute is attached directly to the back of the spacecraft. Again trajectory control is through drag modulation and the ballute is released when a certain deceleration is achieved.

The forebody attached inflatable aeroshell (Figure 2C) is more evolutionary to the rigid aeroshell. The inflatable aeroshell is often referred to as a hybrid system, with a rigid foreshell and an inflated, attached ballute extending from the front of the spacecraft. Trajectory control for the inflatable aeroshell will incorporate lift and drag, like the rigid aeroshell system; therefore the characterization that the system is more evolutionary than the drag-only modulated systems.

Inflatable decelerator systems provide performance advantages over the rigid aeroshell design. One such advantage is that the payload does not need to be enclosed in a rigid aeroshell system during interplanetary cruise. Eliminating the rigid aeroshell allows the spacecraft payload to take full advantage of the volume available in the launch vehicle shroud due to packaging efficiencies enabled by the inflatable systems. Also, with a rigid aeroshell design, the system must fly low into the atmosphere submitting the spacecraft to significant entry heating. With the inflatable decelerator designs, the spacecraft stays higher in the atmosphere where the density is less and heating can be an order of magnitude (or more) lower than with a rigid system, allowing any protection around the payload to be very lightweight. The trailing and attached ballute systems are designed to stay much higher in the atmosphere where heating on the system can be below $5 W/cm^2$. This low heating enables the system design to keep surface temperatures below $500^{o}C$. The inflatable aeroshell may fly deeper into the atmosphere so it will be designed for higher heating rates (on the order of tens of W/cm^2) and slightly higher surface temperatures.

Materials of interest for Aerocapture inflatable decelerators are lightweight, high temperature capable fabrics, fibers, polymers, adhesives. These materials must withstand being tightly stowed during transit through the cold vacuum of space for many years, even decades, without losing ductility or strength. Major materials concerns include polymeric materials becoming creased during stowage leading to weak points that fail during deployment, or structural adhesives becoming embrittled due to exposure to the cold (-100°C) temperatures and ultraviolet radiation of space. Another concern is that the polymeric materials will degrade during transit causing the material to stick to itself and not deploy. Additionally, there is the overarching fear that the maximum temperature exposures will lead to failure of all the materials. Preliminary tests indicate these concerns may not be founded, but much more work needs to be performed to truly retire the risk.

If the above mentioned concerns are in fact problems, there may be options to address them. Some such options could be coatings or other surface treatments to alter the mechanical, physical or optical properties of the materials. Another option involves the additiona of localized thermal protection system materials being applied in high heat flux or high temperature regions. Some novel alternatives include designing material laminates that degrade at a known rate. If structural adhesives cannot be determined to have the necessary mechanical properties at both low and high temperatures, then alternative seaming techniques, such as sewing or mechanical fastening, will need to be investigated.

Summary

While much more mature than just a few years ago, various new in-space propulsions systems and technologies would benefit from materials improvements related to increasing their performance. The highest-priority needs for each propulsion system can best be summarized as follows:

Advanced Chemical Propulsion

- High-temperature resistant thrust chamber materials

Solar Sail Propulsion

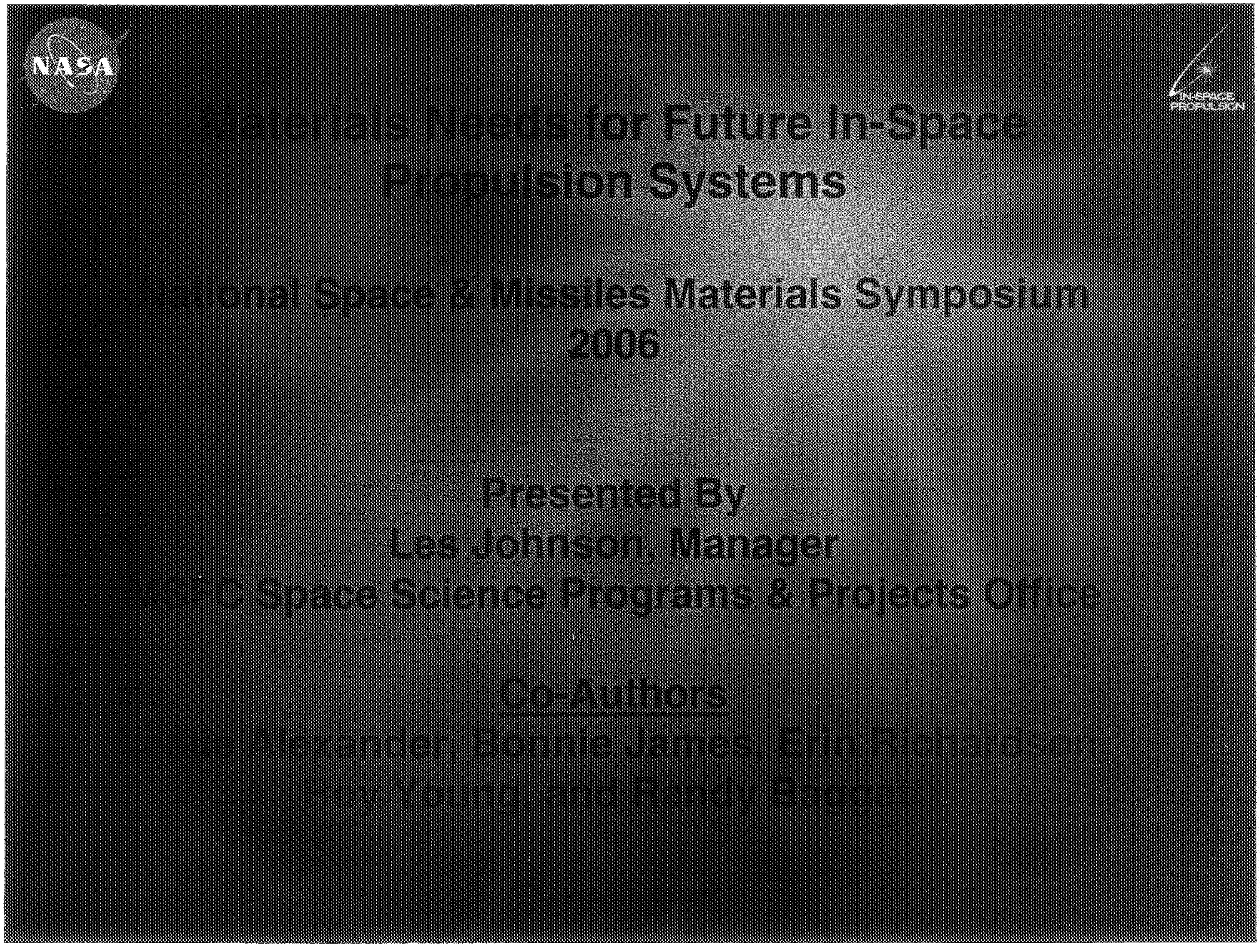
- Light-weight substrates and booms

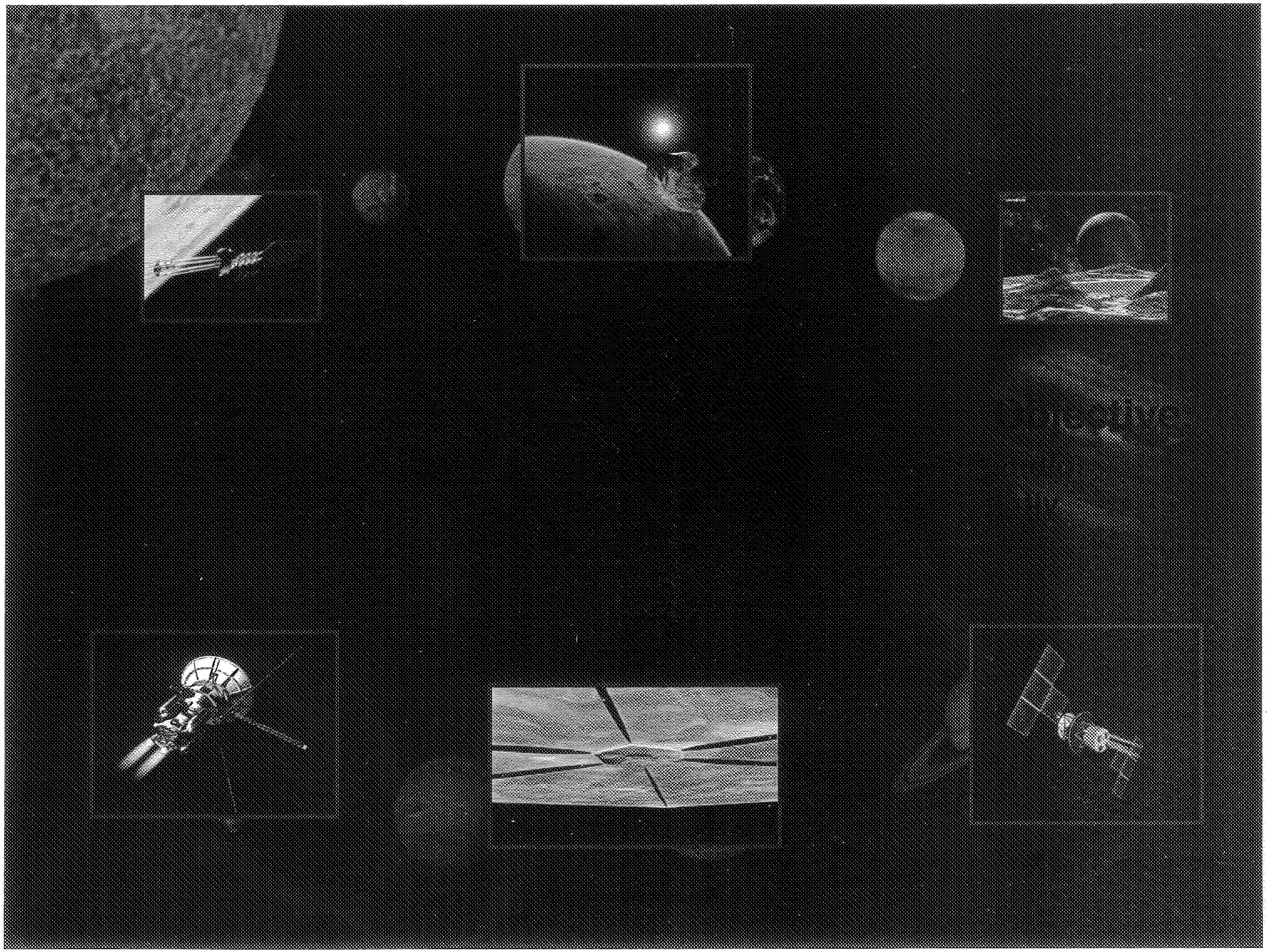
Aerocapture

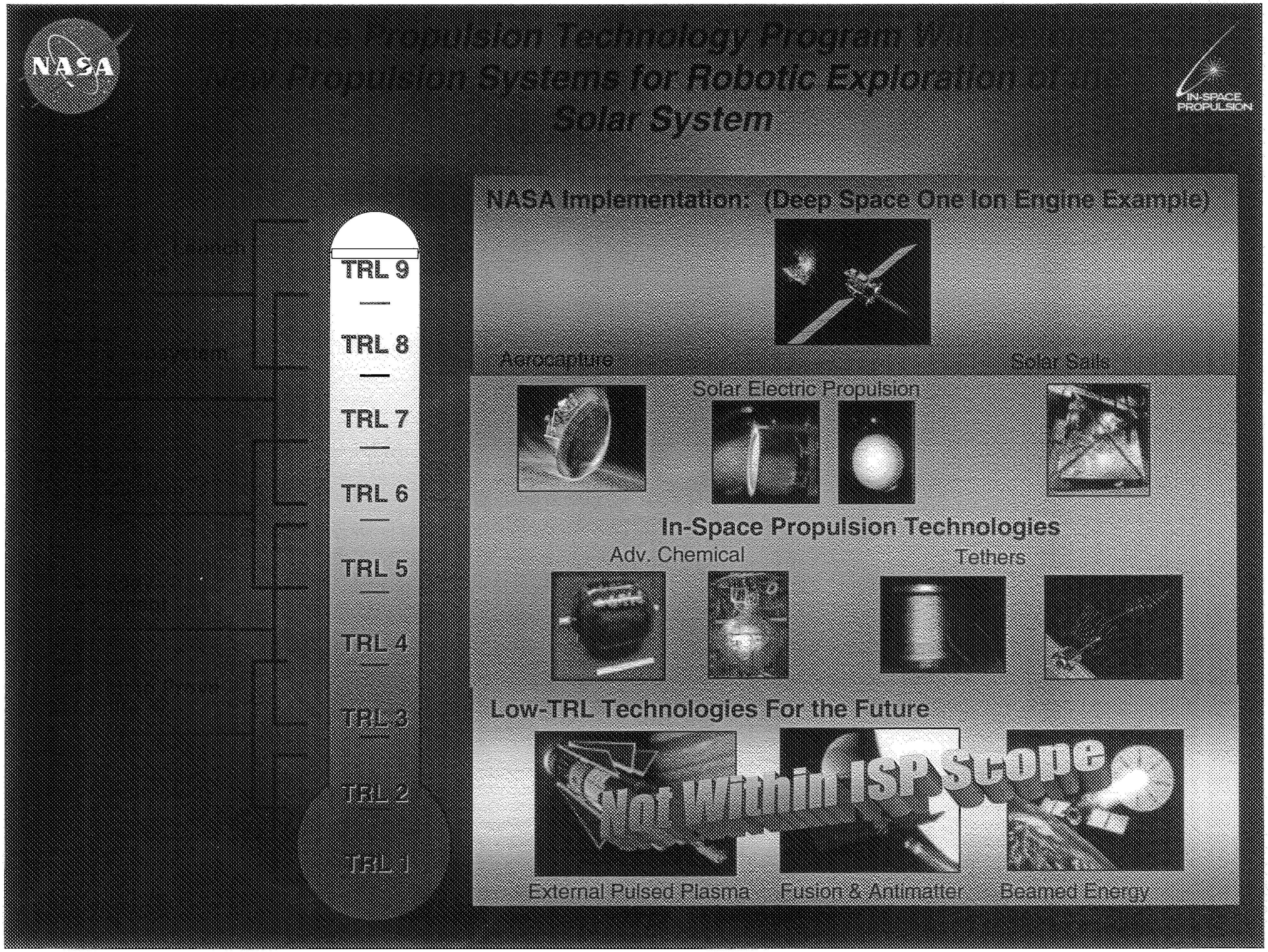
- Storable lightweight, high temperature capable fabrics, fibers, polymers, and adhesives

References

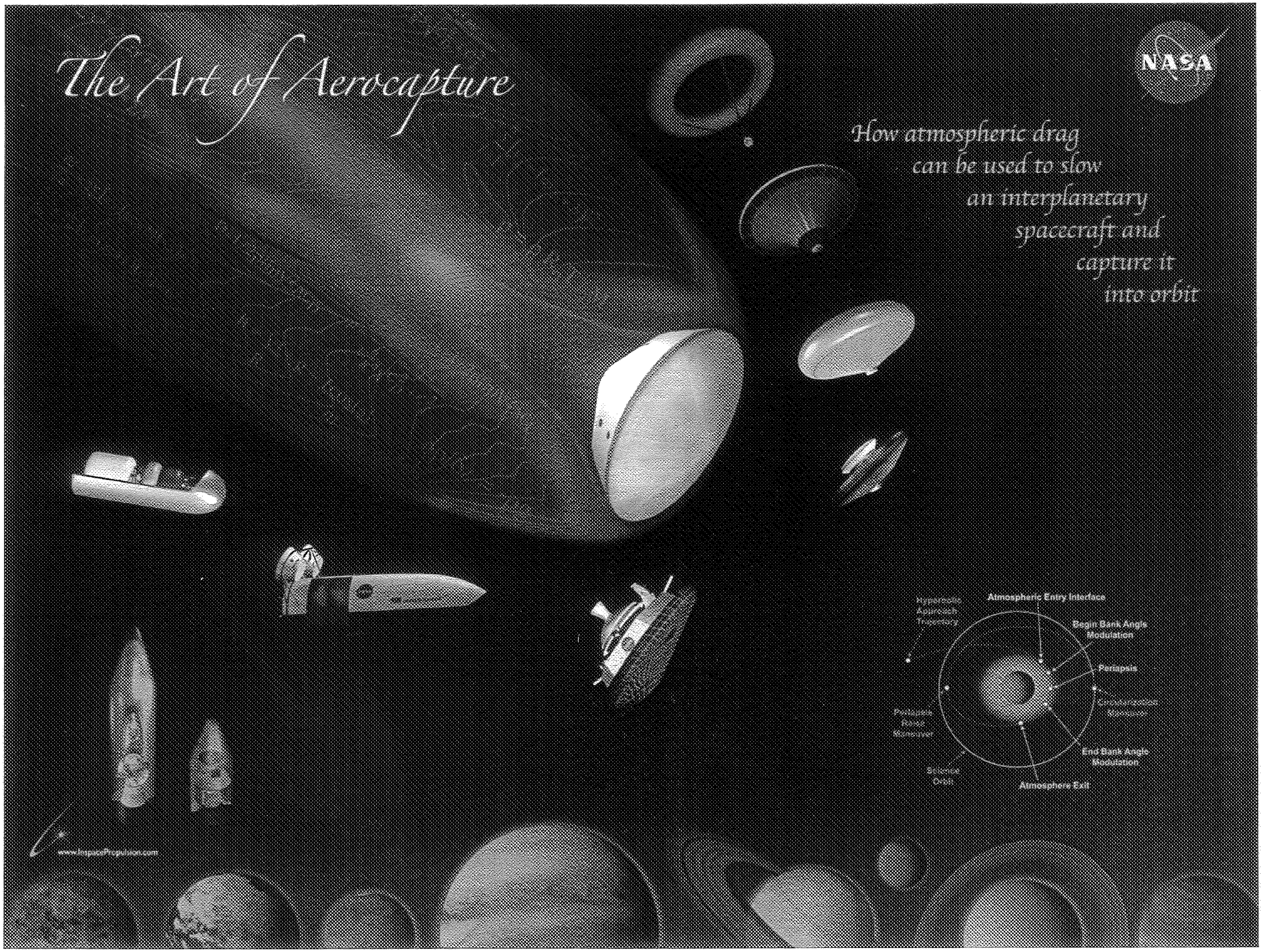
[1] Murphy, D.M., "Validation of a Scalable Solar Sailcraft," *53rd Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Conference,* December; 2005.
[2] Lichodziejewski, D., Derbès, B., Galena, D., Friese, D., "Vacuum Deployment and Testing of a 4-Quadrant Scalable Inflatable Rigidizable Solar Sail System," AIAA 2005-3927, *Joint Propulsion Conference*, July, 2005.
[3] Sauer, C. G., "Solar sail trajectories for solar polar and interstellar probe missions," AAS 99-336, *AAS/AIAA Astrodynamics Specialist Conference,* August, 1999.
[4] Scaglione, S., Vulpetti, G., "The Aurora Project: Removal Of Plastic Substrate to Obtain an All-Metal Solar Sail," *Acta Astronautica*, Vol. 44, Nos. 2-4, pp. 147-150, 1999.
[5] Cadogan, D. P., Scarborough, S. E., "Rigidizable Materials for use in Gossamer Space Inflatable Structures," AIAA 2001-1417, *42nd Structures, Structural Dynamics, and Materials Conference & Exhibit*, April, 2001.


Materials Needs for Future In-Space Propulsion Systems
National Space & Missiles Materials Symposium 2006
Presented By
Les Johnson, Manager
MSFC Space Science Programs & Projects Office
Co-Authors
Alexander, Bonnie James, Erin Richardson
Roy Young, and Randy Baggett
IN-SPACE PROPULSION

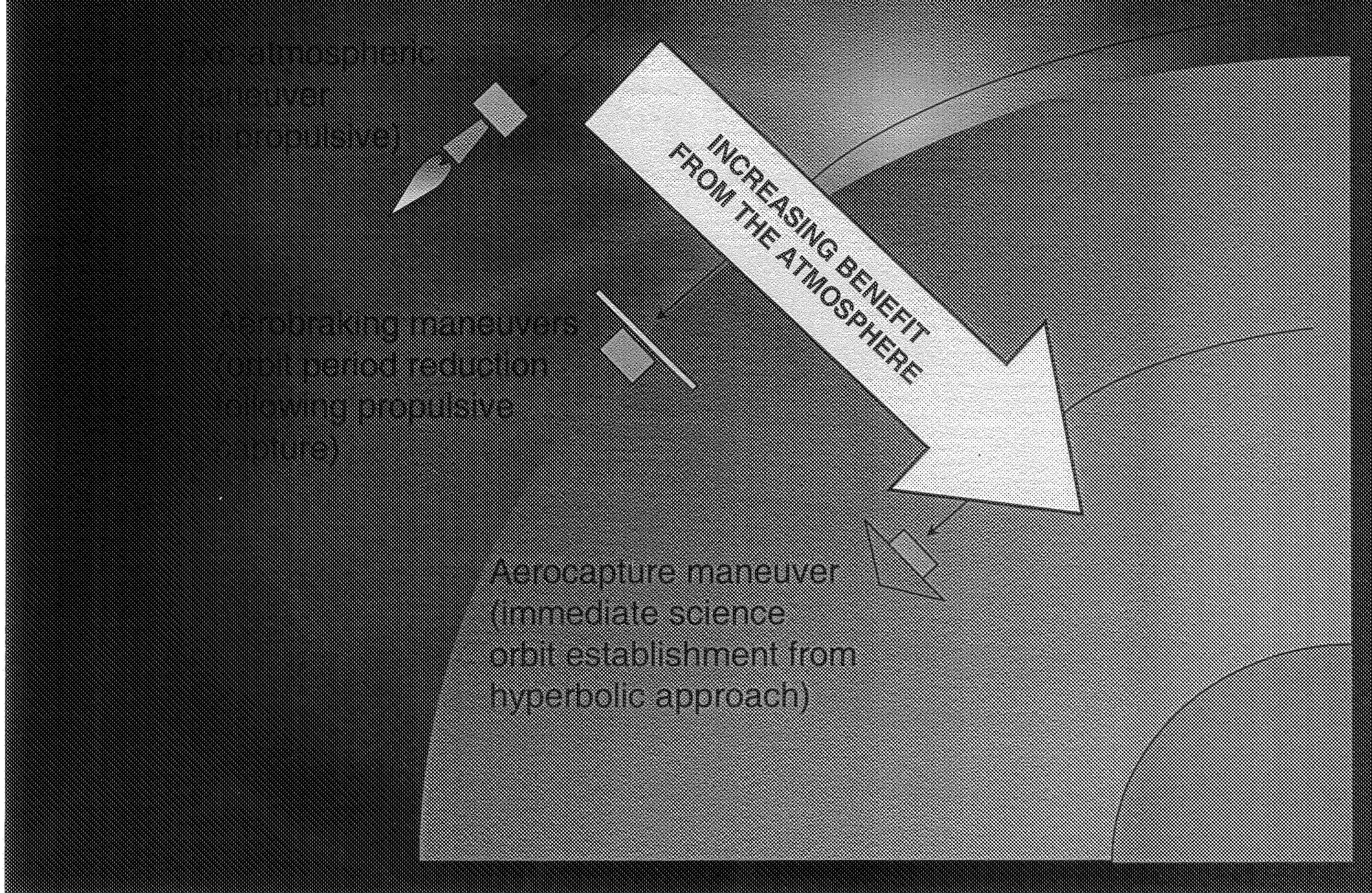




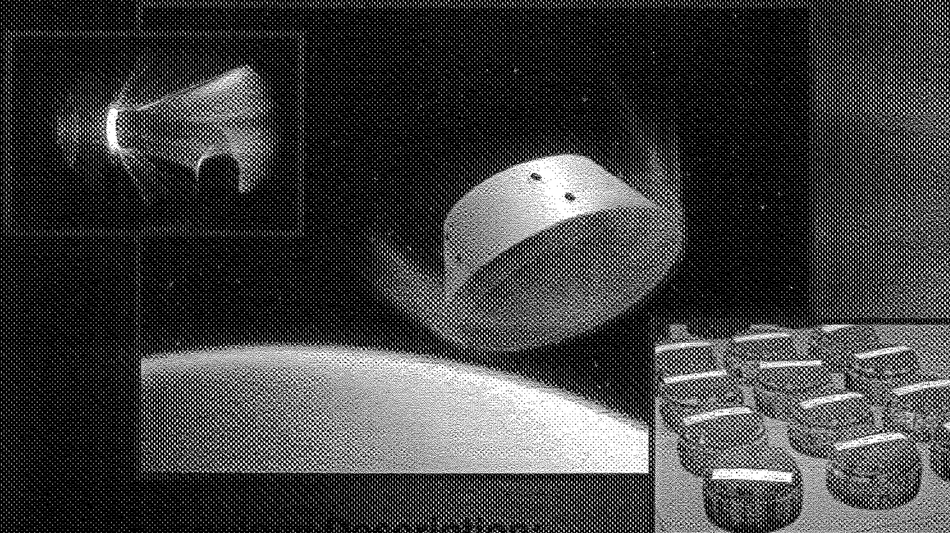
Propulsion Technology Program
Propulsion Systems for Robotic Exploration
Solar System
NASA
IN-SPACE PROPULSION
NASA Implementation: (Deep Space One Ion Engine Example)
TRL 9
TRL 8
TRL 7
TRL 6
TRL 5
TRL 4
TRL 3
TRL 2
TRL 1
Aerocapture
Solar Electric Propulsion
Solar Sails
In-Space Propulsion Technologies
Adv. Chemical
Tethers
Low-TRL Technologies For the Future
Not Within ISP Scope
External Pulsed Plasma
Fusion & Antimatter
Beamed Energy

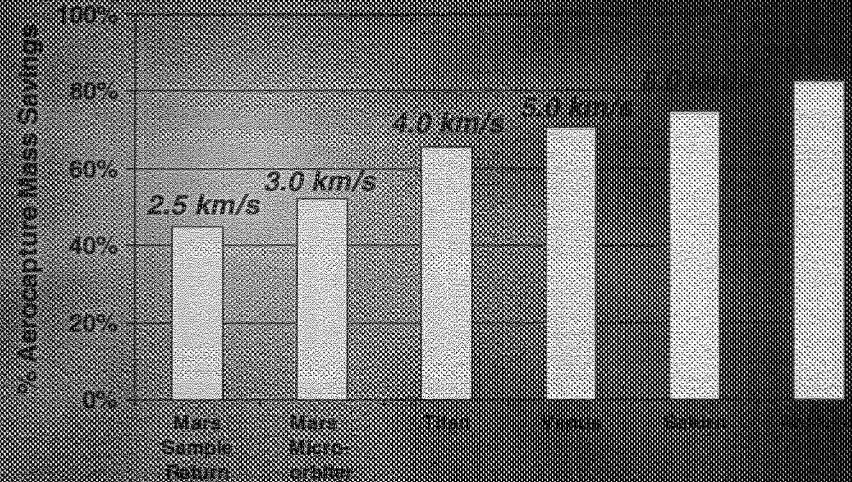

The Art of Aerocapture
NASA
How atmospheric drag can be used to slow an interplanetary spacecraft and capture it into orbit
Atmospheric Entry Interface
Begin Bank Angle Modulation
Periapsis
End Bank Angle Modulation
Atmosphere Exit
www.InspacePropulsion.com

Basics of Orbit Capture



Aerocapture





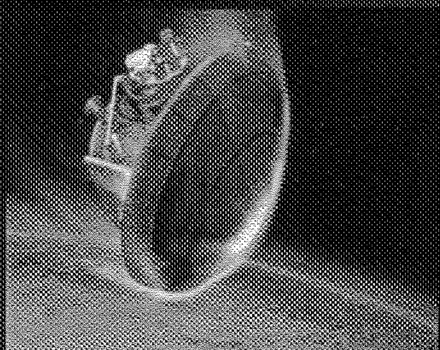
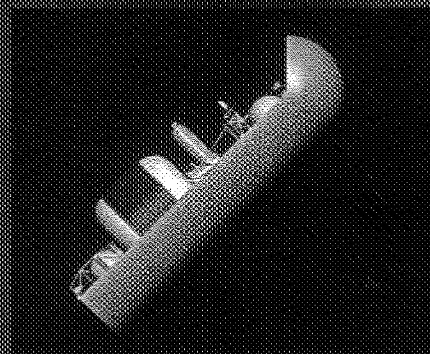
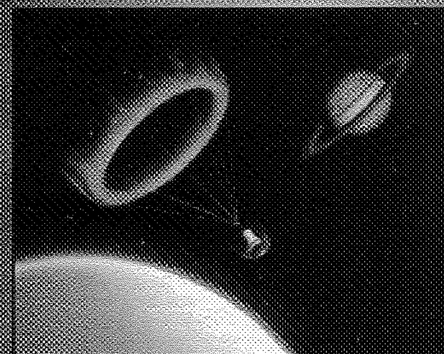
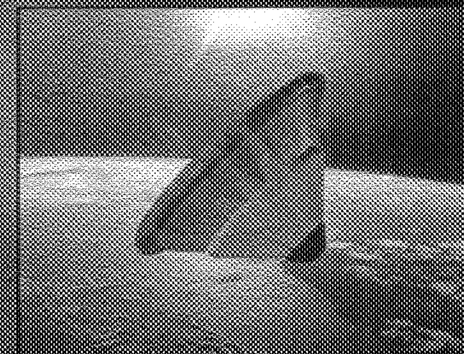
All values are compared to the mass of an all-propulsive ... Equivalent ΔV from Aerocapture noted above each column

... Description:

... technology uses the atmospheres of ... to reduce the speed of a vehicle ... quick, near-propellantless orbit capture. ... is used as a brake, transferring the ... associated with the vehicle's high speed into ...

- **Technology Area Status**
  - Four awards developing advanced TPS ... structures and adhesives to enable a ... aeroshell with integrated TPS – hardware development and tests are underway
  - Trade Studies, conceptual design ... development and testing in the areas of ... aerodynamic ...

Aerocapture Technology Alternatives

[illegible] Maturity)		(Lower Maturity)	
[illegible] Designs	Slender Body Designs	Trailing Ballutes	Attached Ballutes
			
[illegible]	• Low to moderate maturity • Provides increased tolerance for navigation and atmospheric uncertainties • Provides increased volume and improved packaging advantages for larger spacecraft	• Low maturity • Applicable to all size and shape payloads • May have performance advantages over Blunt Body, such as not having the payload enclosed during interplanetary cruise	• Low to moderate maturity for Earth and Mars • Developed and launched in 1996 by Soviet Union as part of Mars [illegible] mission. Launch vehicle failure. • Investigating [illegible]

Rigid Body Aerocapture
Materials Challenges

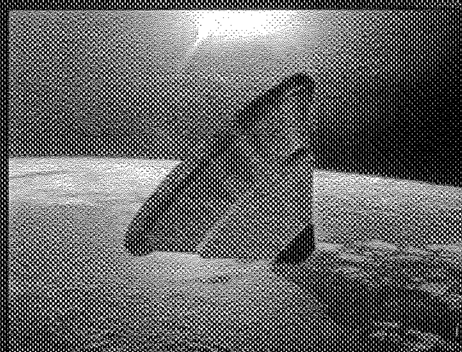
...emely high flow velocities
...t in rich variety of
...thermodynamic phenomena
...h drive material challenges.
...y include:

- ...plex Shock Waves
- ...onic, Transonic,
- ...ic and Hypersonic Flows
- ...Equilibrium Gas Chemistry
- ...ective and Radiative Heat-
...

•Materials challenges include:

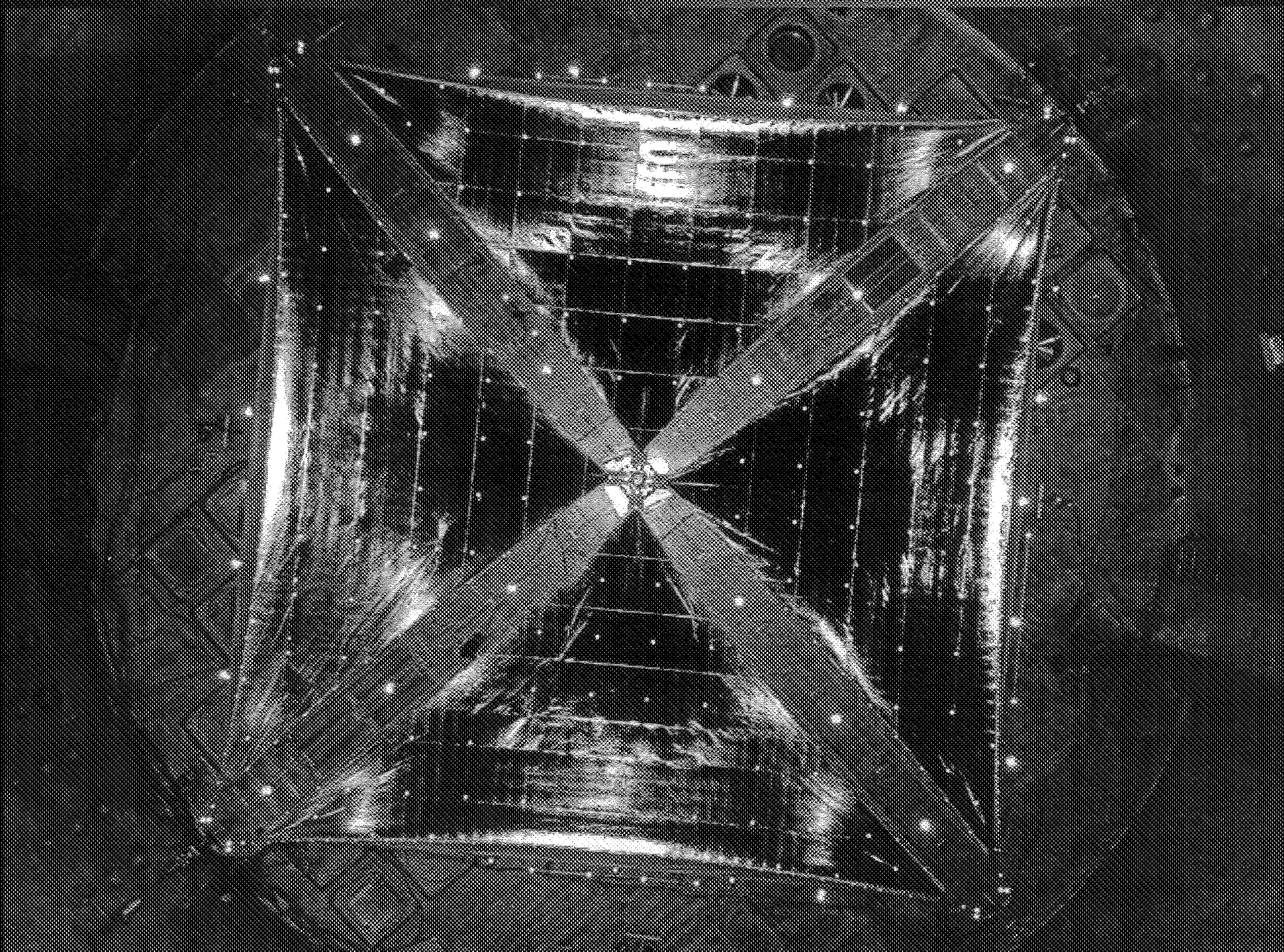
- Lightweight, high-temperature structures, adhesives, insulators, and ablatives operating with heating rates of 1000 - 2000 W/cm2 and beyond.
- Minimize Heat Flux
- Very Thin Materials
- Significant Tensile Strength ... Temperatures
- High Emissiv...
...

Inflatable Body Aerocapture
Materials Challenges



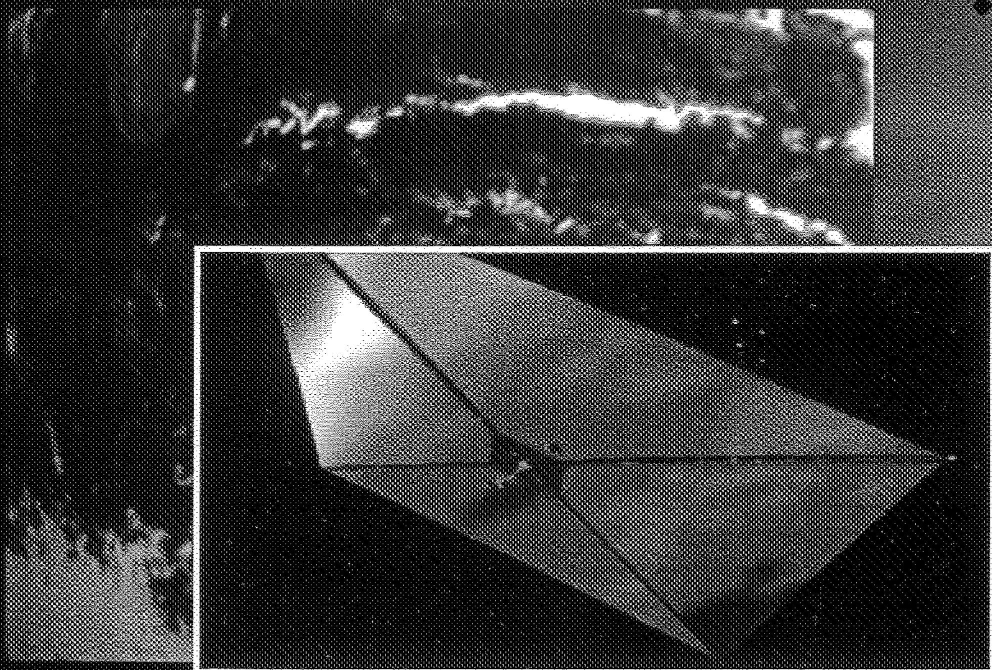
- **Materials challenges include:**
  - Survive being tightly-packaged for years during mission cruise and then being quickly inflated
  - Maintain strength and flexibility at [illegible] during cruise and then withstand 500 [illegible] during aerocapture

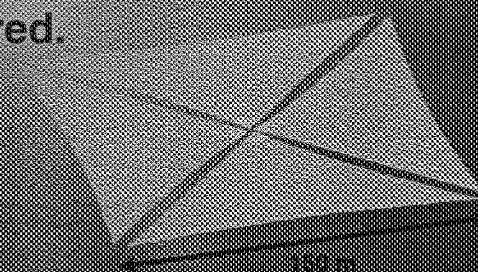
Solar Sail Propulsion

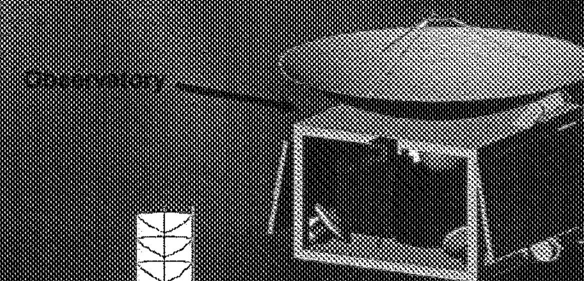


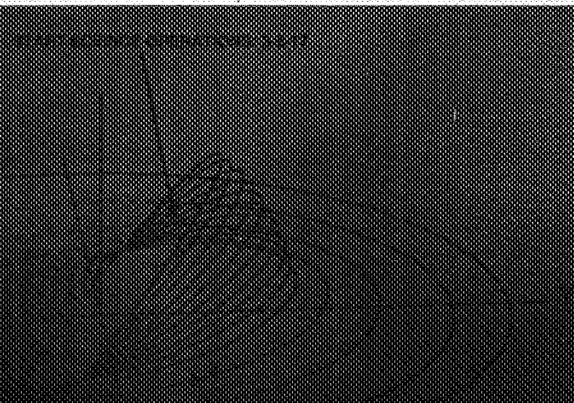
Solar Sails

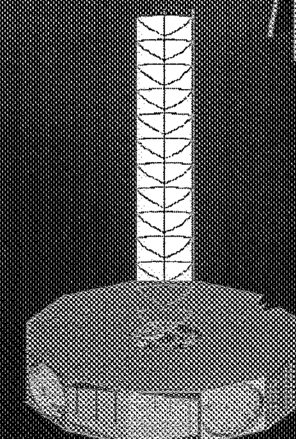
- Solar sails use photon "pressure" force on thin, lightweight reflective sheet to produce thrust. Sails open up new regions of the solar system to accessibility for important science missions, with no propellant required.



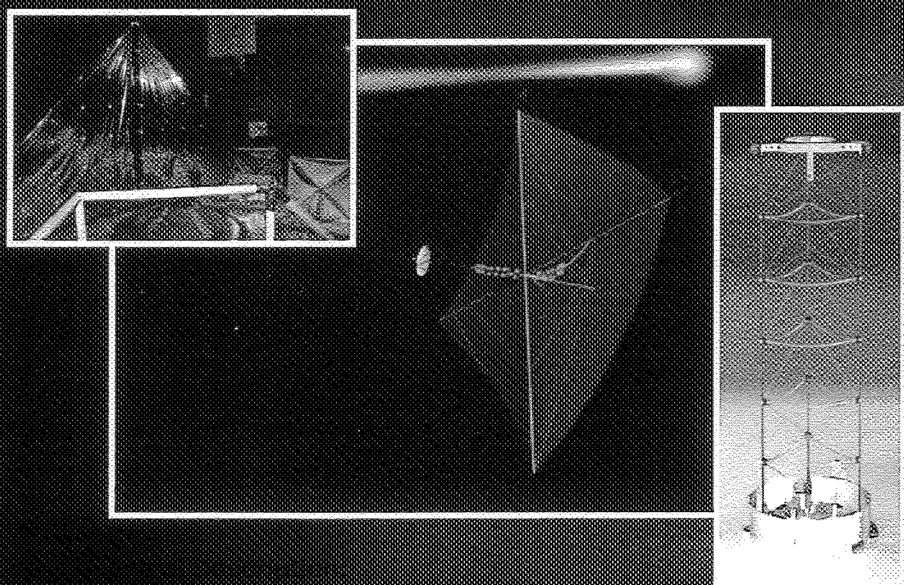


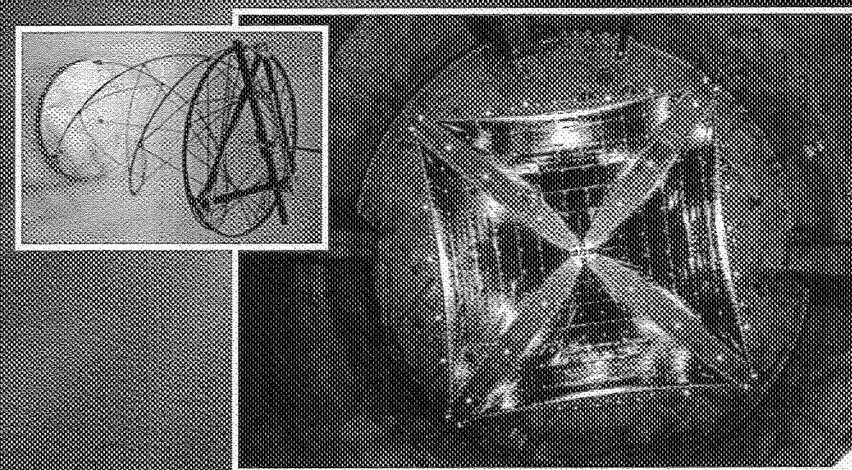






Solar Sails



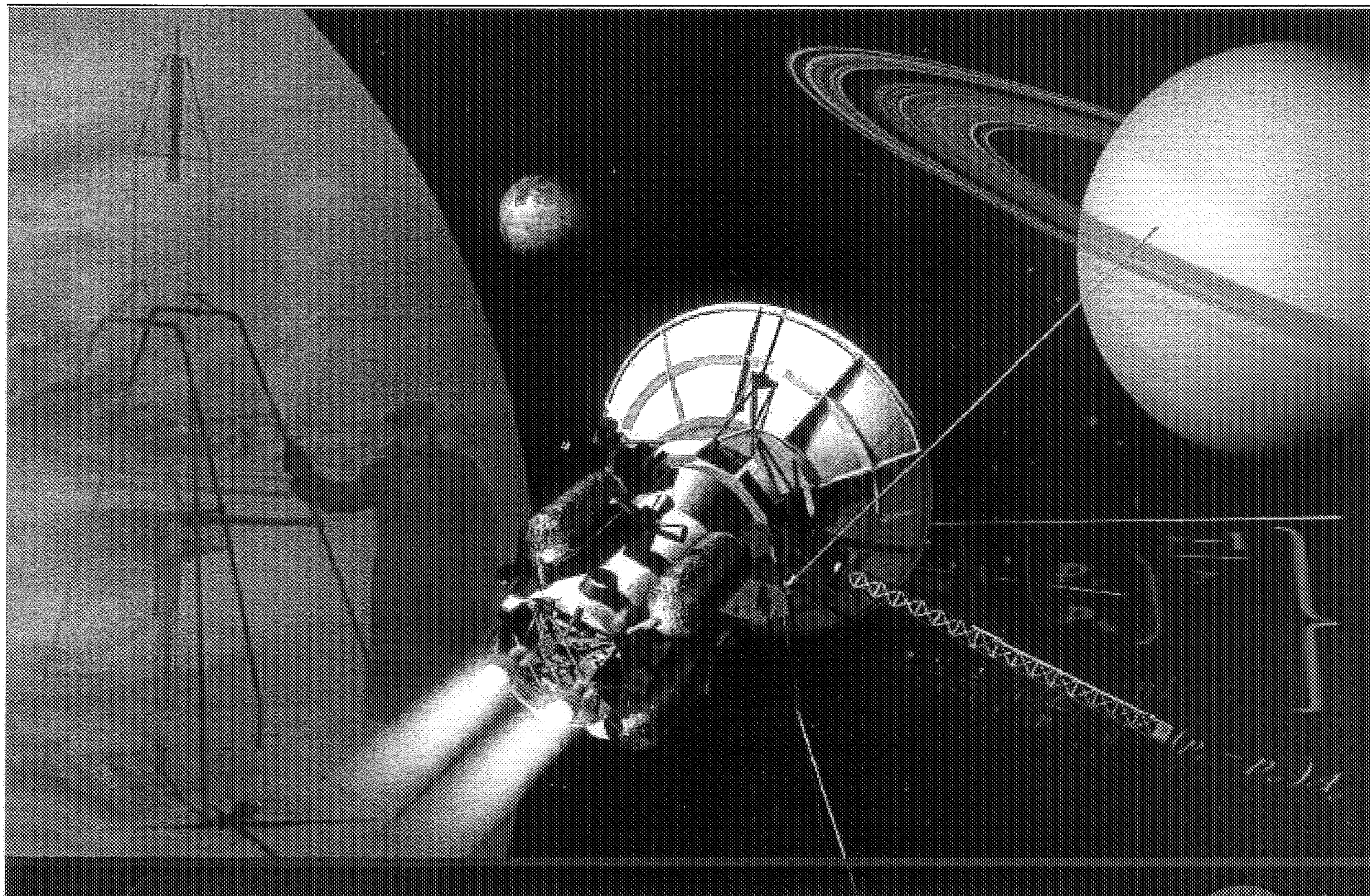


- **Technology Area Status:**
  - Two parallel awards to design, fabricate, and test competing sail concepts for system level ground demonstration
    - 10 m system ground demonstrators were developed and tested in 2004
    - 20 m system ground demonstrators designed, fabricated, and tested under thermal vacuum conditions
  - Multiple awards to develop high fidelity computational models and diagnostics
  - Multiple awards to ... optical properties ... structures

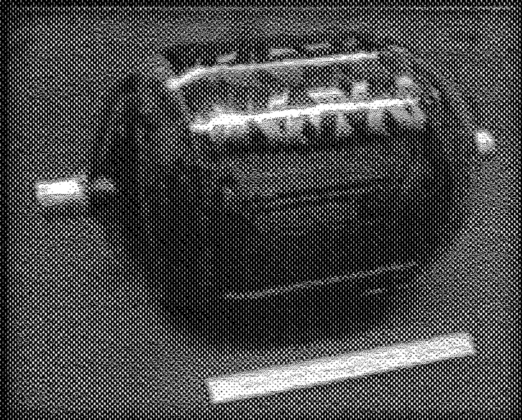
Solar Sails
Materials Challenges

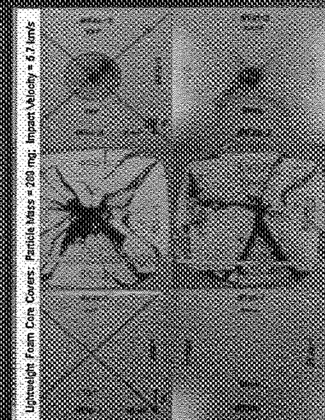
Materials challenges include:

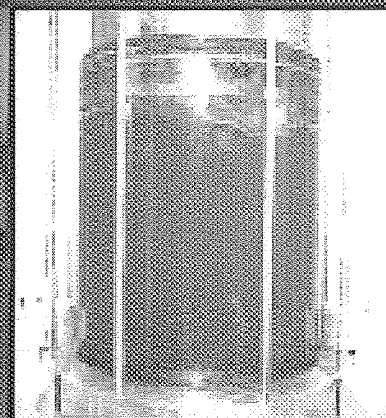
- [illegible] ufacturable in sizes from 10000 m² to [illegible]
- [illegible] perature Tolerance 70 - 2000 °K
  [illegible] 0.25 AU)
- [illegible] issivity 0.4 - 0.9
- [illegible] Tensile Strength (2 500 °K) 2205 MPa
- [illegible] Gamma and UV Radiation Tolerance
- Low Coefficient of Thermal Expans[illegible]
  3 x 10-6 (per °C)
- Sail Fabric Areal Density 0.5 g/m[illegible]
- Fabric Thickness < 0.35 m
  (polyimide [illegible] = 1.4 gm/m[illegible])
- Sail Structure Areal Density 0.5 g/m[illegible]

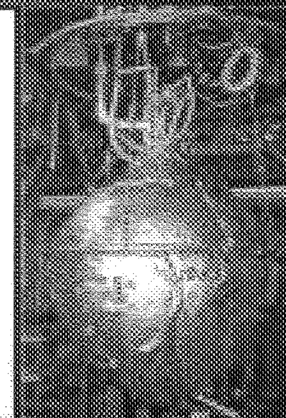

ADVANCED CHEMICAL PROPULSION
Advanced Propellants • Lightweight & Optimized Components
IN-SPACE PROPULSION
NASA

Advanced Chemical Propulsion









/ Technology Status

of transportation for space payloads

chemical rocket systems are at or near

performance limits

systems: solid, storable liquid, and

liquid propellants, as well as hybrid

monopropellants, and cold gas rockets

Benefits

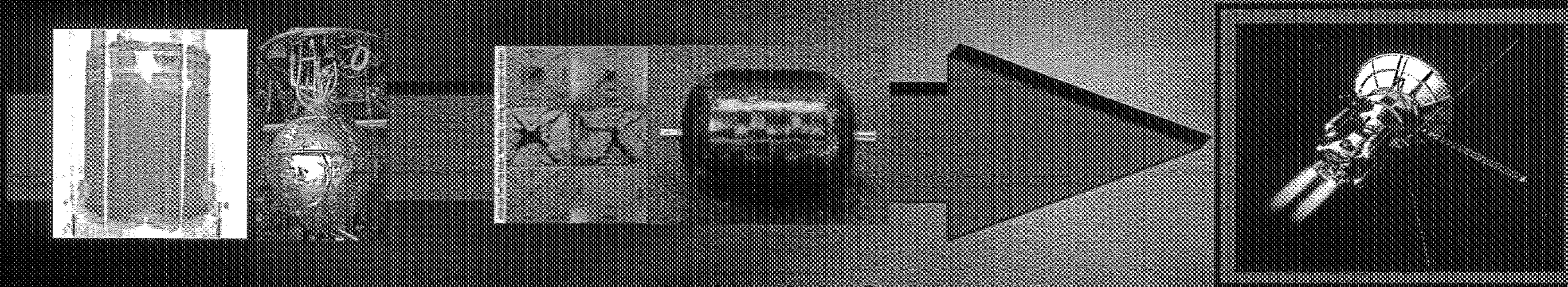
- Reduced cost
- Reduced propulsion system mass
- Increased payload mass fraction
- Improved propellant performance and safety
- Improved overall efficiency for thermal control, propellant management, and meteoroid shielding systems

Objectives

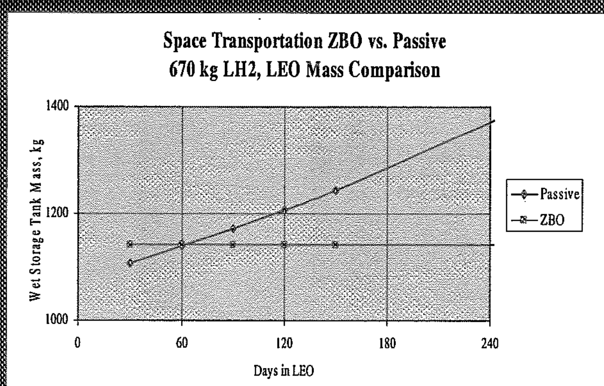
Lightweight & Optimized

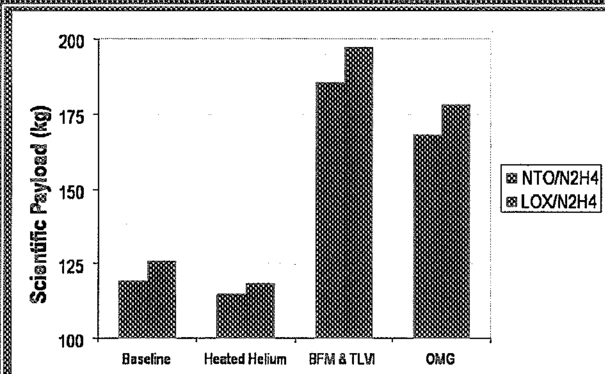
Advanced Chemical Propulsion

IN-SPACE PROPULSION

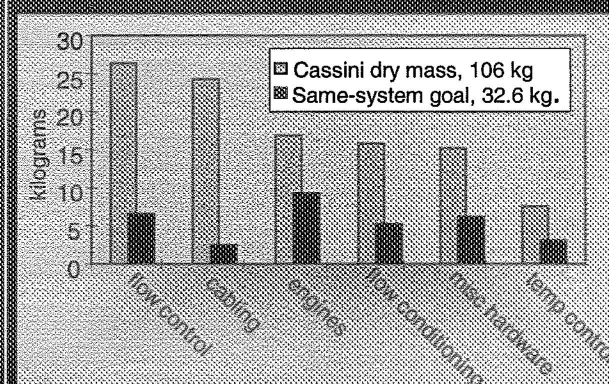


- ... Propellants: ... chemical propulsion ... that offer significantly ... performance and ... technologies that ... long-term storage ... in low g
- Lightweight Components: Optimized component, material and manufacturing technology to reduce the mass of cross-cutting propulsion components: feed system components, tanks, etc.



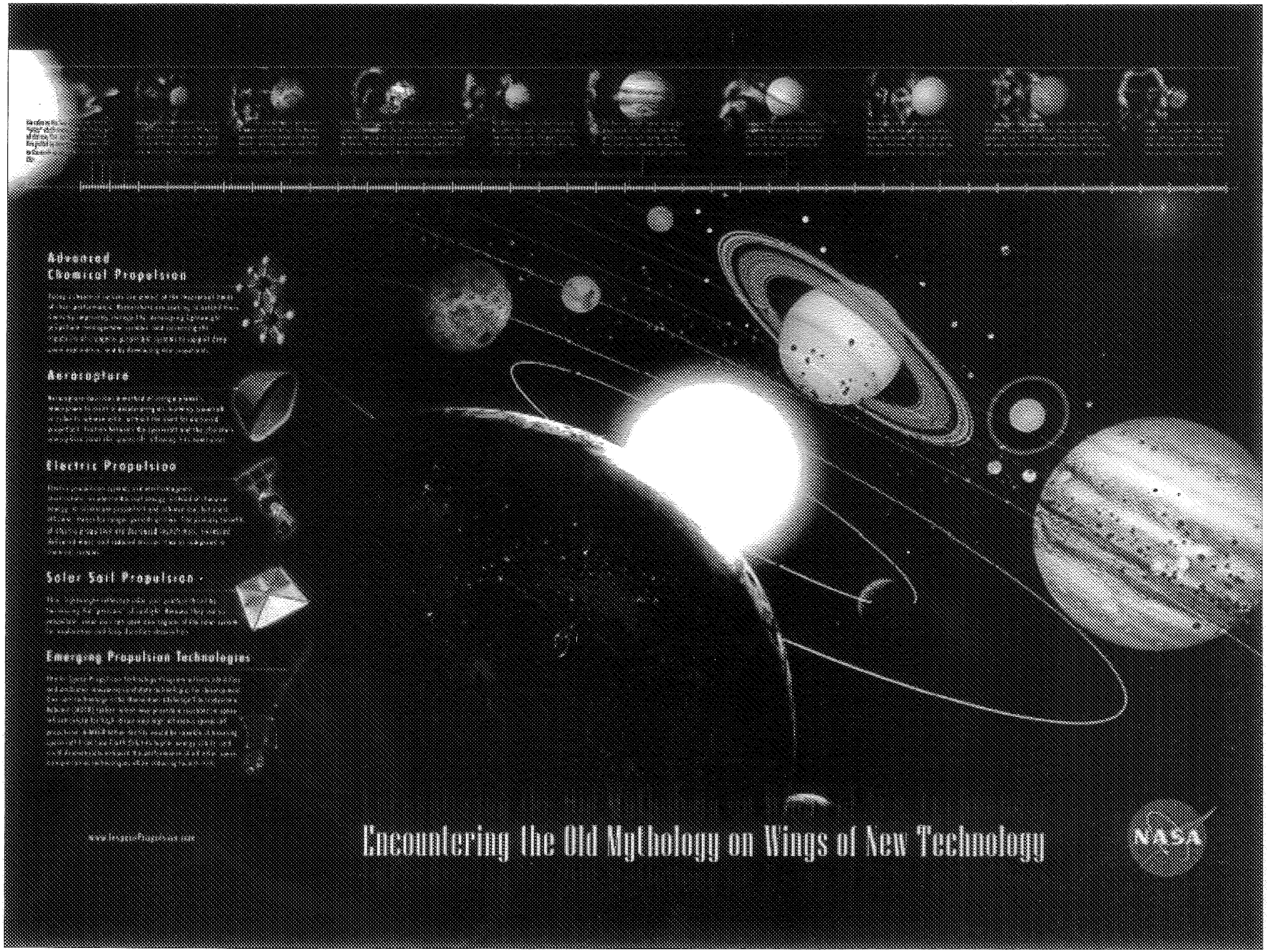


Active mixture ratio control results in a 56% increase in science payload



Advanced Chemical Propulsion Materials Challenges

- **Materials challenges include:**
  - Survive being tightly-packaged for years during mission cruise and then being quickly inflated
  - Maintain strength and flexibility at [illegible] during cruise and then withstand 500 [illegible] during aerocapture


Advanced Chemical Propulsion
Aerocapture
Electric Propulsion
Solar Sail Propulsion
Emerging Propulsion Technologies
Encountering the Old Mythology on Wings of New Technology
NASA