Title of Presentation: Emerging Propulsion Technologies

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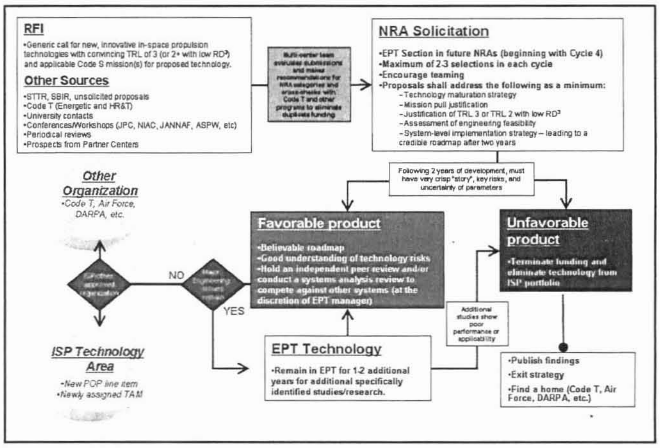
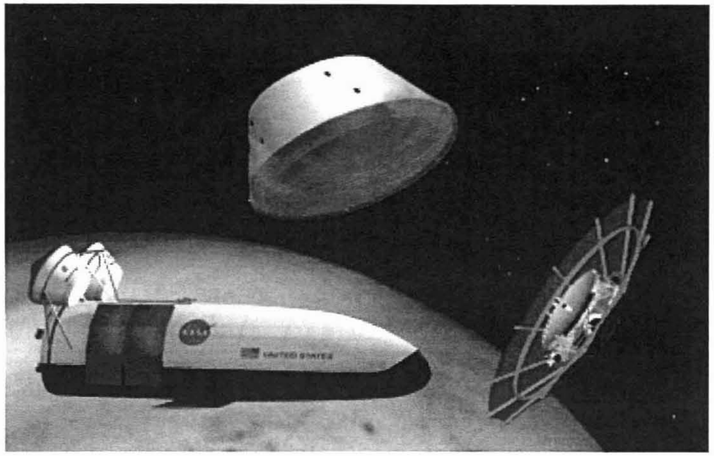
Abstract: The Emerging Propulsion Technologies (EPT) investment area is the newest area within the In-Space Propulsion Technology (ISPT) Project and strives to bridge technologies in the lower Technology Readiness Level (TRL) range (2 to 3) to the mid TRL range (4 to 6). A prioritization process, the Integrated In-Space Transportation Planning (IISTP), was developed and applied in FY01 to establish initial program priorities. The EPT investment area emerged for technologies that scored well in the IISTP but had a low technical maturity level. One particular technology, the Momentum-eXchange Electrodynamic-Reboost (MXER) tether, scored extraordinarily high and had broad applicability in the IISTP. However, its technical maturity was too low for ranking alongside technologies like the ion engine or aerocapture. Thus, MXER tethers assumed top priority at EPT startup in FY03 with an aggressive schedule and adequate budget. It was originally envisioned that future technologies would enter the ISP portfolio through EPT, and EPT developed an EPT/ISP Entrance Process (see above image) for future candidate ISP technologies. EPT has funded the following secondary, candidate ISP technologies at a low level: ultra-lightweight solar sails, general space/near-earth tether development, electrodynamic tether development, advanced electric propulsion, and in-space mechanism development. However, the scope of the ISPT program has focused over time to more closely match SMD needs and technology advancement successes. As a result, the funding for MXER and other EPT technologies is not currently available. Consequently, the MXER tether tasks and other EPT tasks are being phased out and will terminate by November 2006.



Aerocapture Technology Activity Overview

Technology Description

- Aerocapture is a maneuver for orbital insertion of spacecraft around solar system bodies possessing atmospheres.
- Aerocapture relies on the exchange of momentum with an atmosphere to decelerate, resulting in orbital capture.
- Aerocapture permits spacecraft to employ higher trans-planetary velocities, carry less fuel mass and more payload mass.



Proposed aerocapture vehicles including high lift-to-drag bodies, rigid blunt body aeroshells, inflatable systems.

Approach

- Develop aerocapture systems for robotic exploration of the Solar System and validate those systems in relevant environments.
- Raise aerocapture propulsion to TRL 6 through the development of subsystems, operations tools, and system level validation and verification.
- Uncover all risk factors for Aerocapture infusion into science missions and mitigate each risk factor.
- Technical issues include: atmospheric modeling, GN&C, materials selection, aerothermodynamic heating, environmental effects.

Key Actvities:

Applied Research Associates, NASA/LaRC - High-Temperature Structures: Instrumented, 70-degree sphere-cone structures.

Ball Aerospace - Ballute Development: Systems analysis/evaluation/test of inflatable concepts.

Lockheed Martin - Aeroshell Technology: 2-meter-diameter Carbon-Carbon rib-stiffened hot structure.

Lockheed Martin - Inflatable Aeroshell: Flexible TPS test plans and data for inflatable aeroshell.

NASA/ARC - Aeroshell Development: Aerothermal sensitivity analyses, documented TPS qualification plan.

NASA/ARC - Sensors: Thermal Heat Flux and Recession Sensors integrated with and validated in 2 TPS materials.

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NASA

Emerging Propulsion Technologies

In Space Propulsion Technology Project

NASA Marshall Space Flight Center

Dr. Andrew S. Keys

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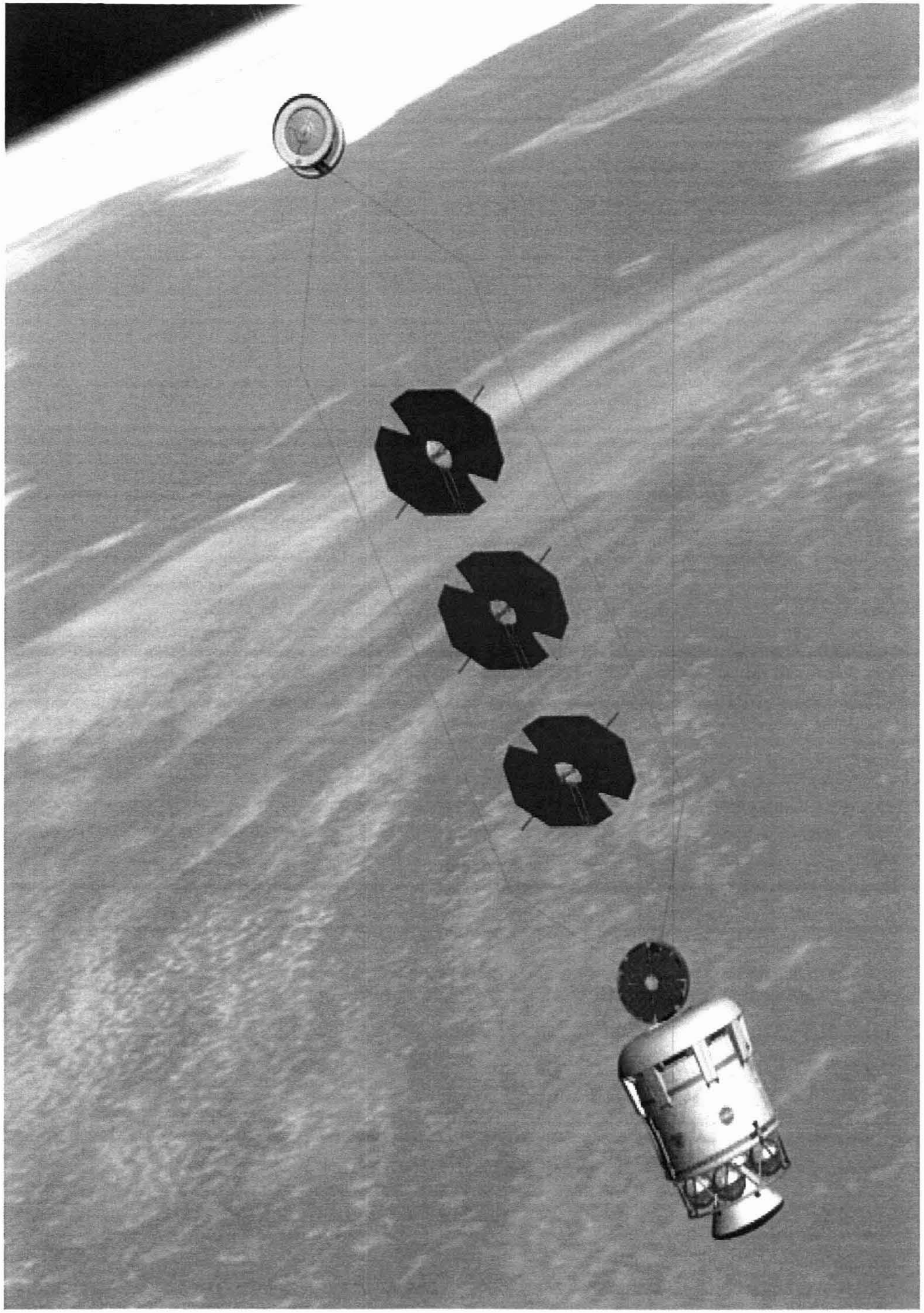


Outline

- In-Space Propulsion Technology Project Prioritization Process
- Emerging Propulsion Technologies
- Emerging Propulsion Technologies ISPT Entrance Process
- Momentum eXchange Electrodynamic Reboost (MXER) Tether
- Emerging Technologies
- Additional Technology Subject of Interest

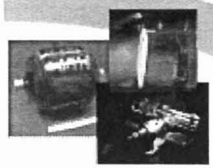
In-Space Propulsion Technology Project Prioritization Process

Requirements/Goals Established

- Space Science
- Earth Science
- Exploration and Development

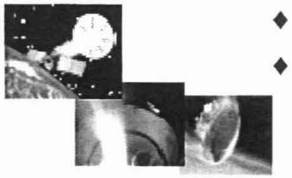
Requirements provided by NASA Enterprise customers

Technology Options Identified



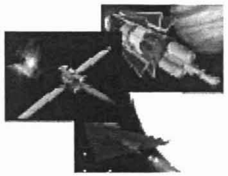
Systems Concepts Developed

- Architecture
- Safety/Reliability
- Cost, Trip Time, etc.



Systems Concepts Compared

- Feasibility
- Identification of Technology Drivers
- Recommended approaches



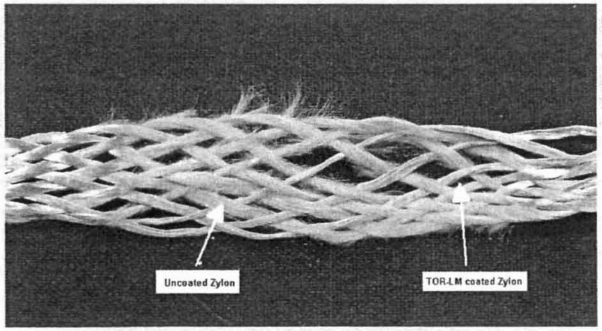
Technologies Prioritized (scoring process)

High Priority	Medium Priority	Low Priority	High Payoff/High Risk
Aerocapture	Advanced Chemical	Solar Thermal	Solar Sails 1 g/m2
NGI (5/10 kW)	SEP Hall		Momentum Exchange Tethers
Solar Sails			

Cross-Enterprise In-Space Propulsion Priorities

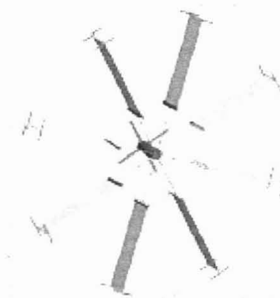
Emerging Propulsion Technologies

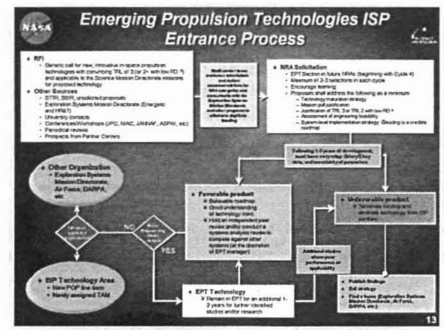
- Very broad & unique technology portfolio that acts a "gateway" for new technologies to enter the ISPT portfolio.
- Focus on development and implementation of innovative, highly beneficial propulsion systems and subsystems.
- Technologies are generally near Technology Readiness Level (TRL) of 3, possess a low Research & Development Degree of Difficulty (RD^3), and are attractive to the Science Mission Directorate.
- Development time period can be longer than other ISPT technologies.
- The EPT area targets "high-risk, high-payoff" technologies that have potential for enabling revolutionary science.
- Ideally, successful EPT investments are promoted to become a full ISPT technology area.
- The Momentum-eXchange/Electrodynamic Reboost (MXER) Tether is the current, primary investment. Additional, secondary investments have included:
  - Ultra-light Solar Sails (<1g/m2)
  - Advanced Electric Propulsion
    - Pulsed Inductive Thruster
    - Plasmoid Thruster
  - Space tethers
  - Gimballing joint mechanism

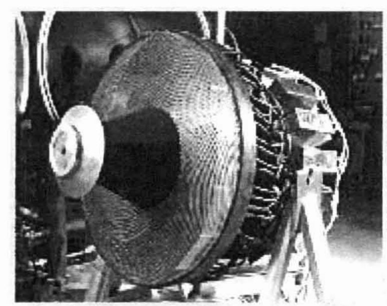


Emerging Propulsion Technologies ISPT Entrance Process

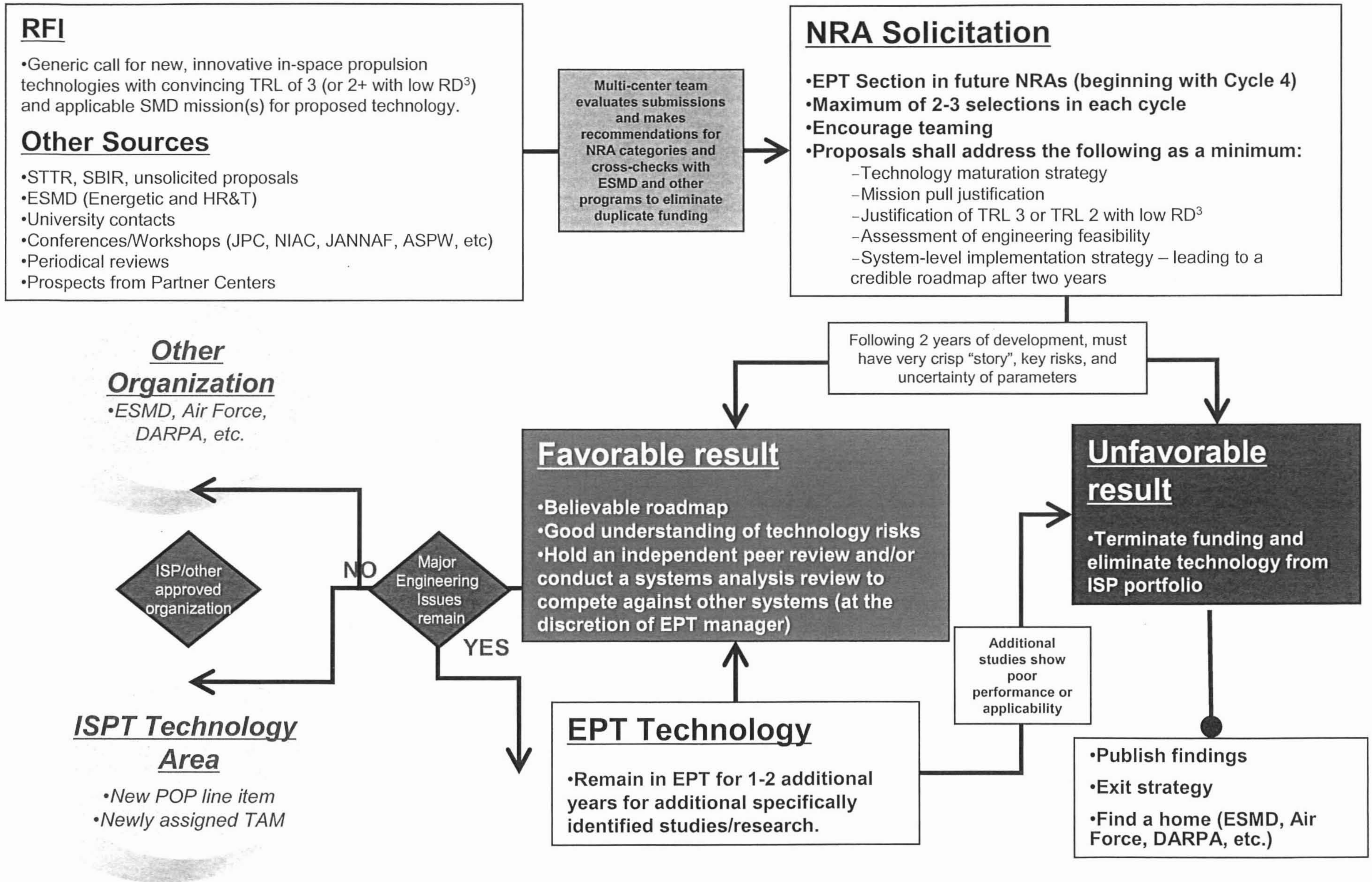
- **Initial request for information or acquire concepts and designs from other areas (conferences, workshops, etc.).**
- **Multi-center NASA team evaluates concepts and recommends general funding areas.**
- **Possible NRA solicitation in recommended areas.**
- **Concept development for 1-3 years:**
  - Complete understanding of key risks
  - Develop concise, crisp story of unique benefits & applications
  - Identify uncertainty of parameters
- **Evaluation of concept development**
  - Favorable results (met or exceeded predefined criteria)
  - Unfavorable results (did not meet the predefined criteria)
    - Publish findings
    - Actively seek investment retargeting
    - Additional studies required (specific tests, studies, or evaluations done on pivotal or critical unresolved issue/question)
- **Promotion into ISPT as a stand-alone technology area** ***or offered to another organization (Air Force, other NASA area, DARPA, etc.)***





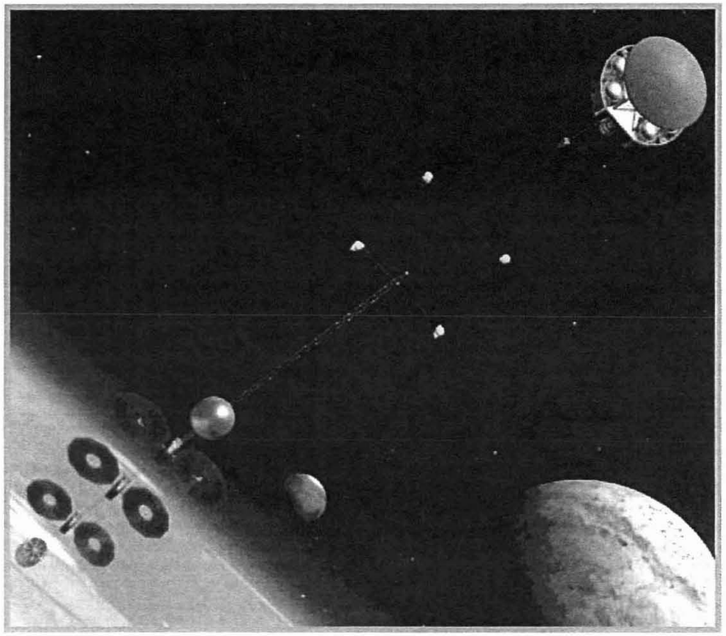


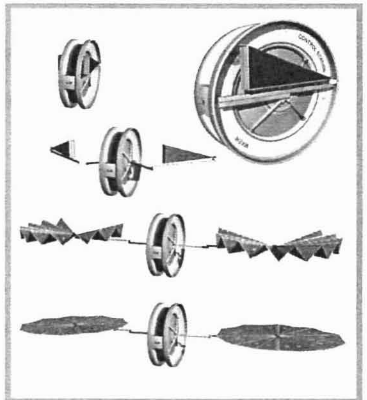
Emerging Propulsion Technologies ISPT Entrance Process Flowchart

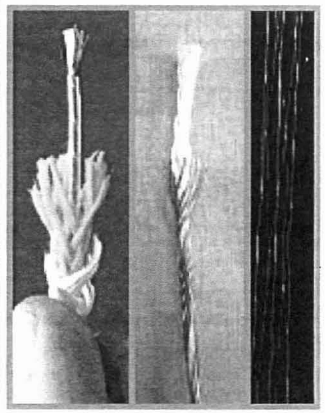


Momentum eXchange Electrodynamic Reboost (MXER) Tether

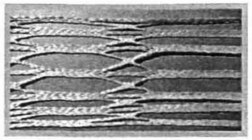
- **The MXER Tether is a reusable, *propellantless*, in-space “upper stage” for sending payloads from LEO to GTO and beyond.**
  - Long, rotating cable operating in an elliptical orbit.
  - Restores orbital energy by using electrodynamic tether
  - Development time: ~10-15 years
- **Potential benefits to payloads using MXER**
  - Increase in Isp while maintaining reasonable trip time
  - Lowers overall mission cost and/or enables larger payloads
  - Capable of ~75% Earth escape Delta-V
  - Interplanetary mission enhancer
  - Useable by essentially all missions beyond LEO
  - A spiral development for future generations
    - Readily scales up or down
    - Future transportation to and from Lunar surface
- **MXER generates launch vehicles savings**
  - Increase in payload size and capability
  - Savings provided by MXER after only a few uses and significantly accumulate with more missions
  - High equivalent Isp without long durations in radiation belts





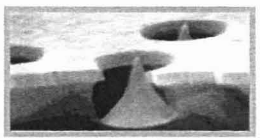


Single Launch MXER Tether Concept

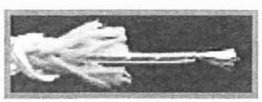


- ♦ Strength tether in a multi-strand configuration

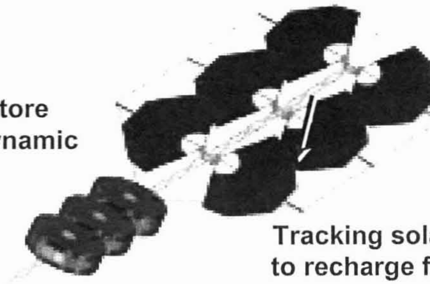
- ♦ Passive anode on each end collecting electrons

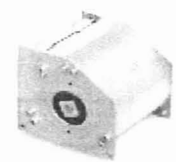


- ♦ Active cathodes on each end emitting electrons

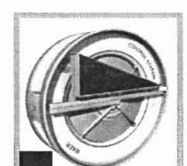


- ♦ Insulated aluminum fibers integrated into strength tether

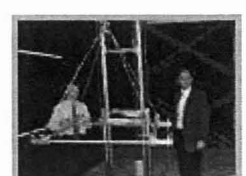




- ♦ Payload accommodation assembly

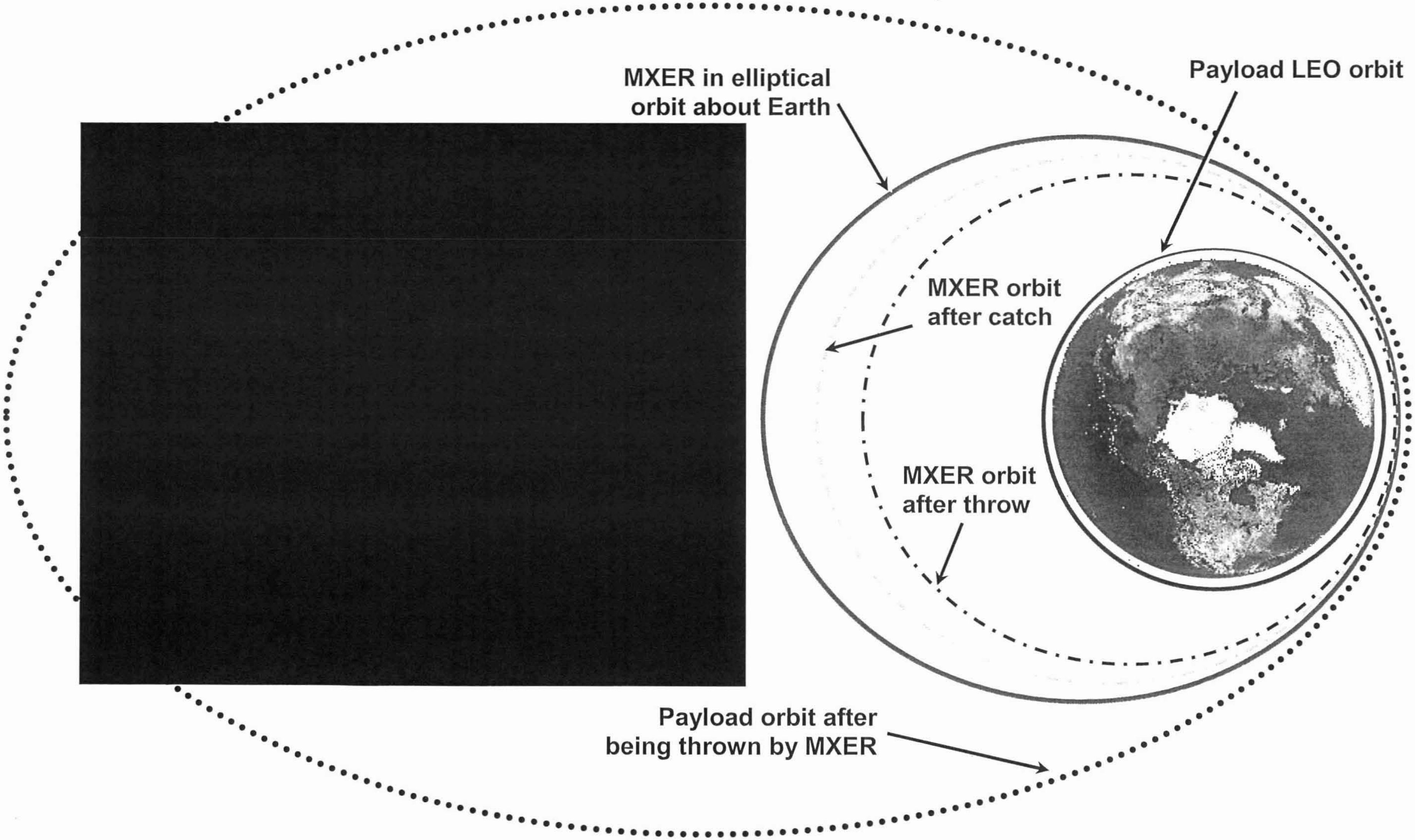


- ♦ Multiple control stations driving current through the tether



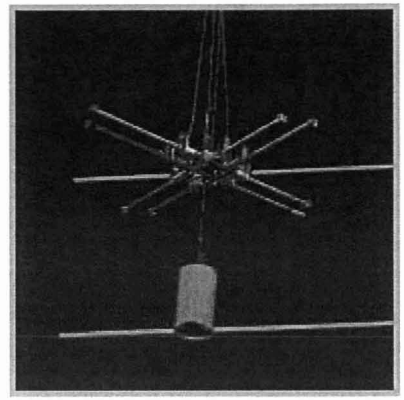
- ♦ Catch mechanism on one end capturing & releasing prospective payloads

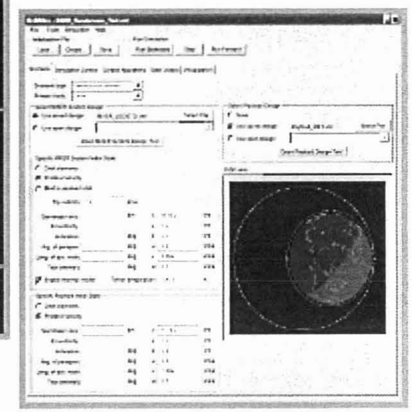
MXER Tether Propulsion



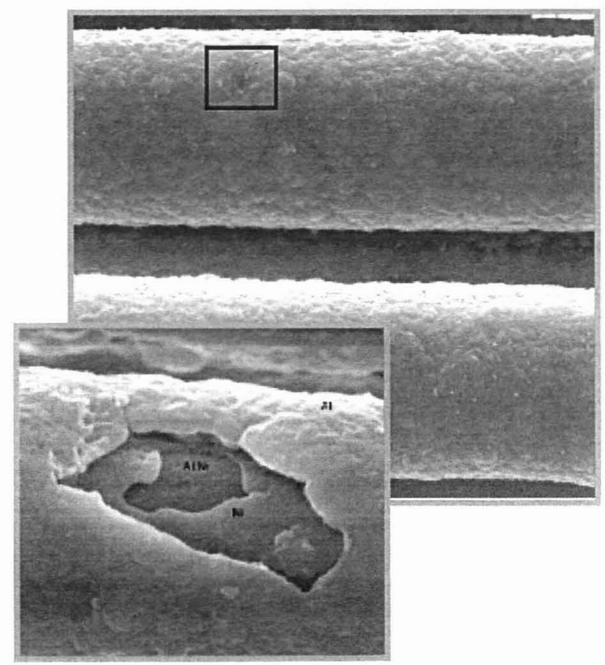
Progress on MXER Subsystems

- **Catch Mechanism** (Tennessee Tech & Lockheed Martin)
  - Nearly 100 capture concepts proposed and initially analyzed
  - Three concepts were selected for manufacturing
    - QuadTrap
    - PatTrap
    - Umbrella
  - Several hundred catch attempts were made with the QuadTrap
    - >90% catch capture



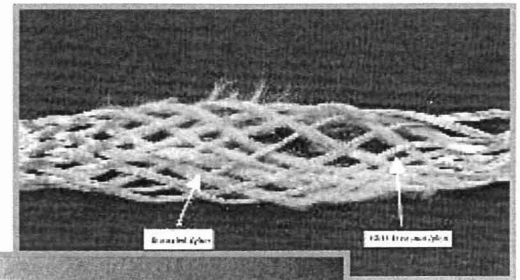


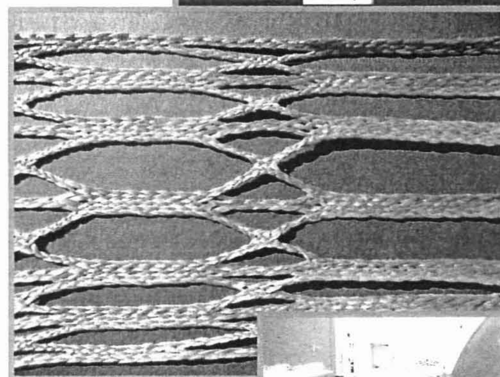
- **Propagator/Predictor Code** (Tennessee Tech & Tethers Unlimited)
  - Developed an extremely fast tether propagation algorithm
  - Achieved accuracy within three meters
  - Concluded that addition of a laser ranging system between the deployer reel and the tether tip could allow the tether to adjust its length slightly and exceed the required accuracy while accounting for all external and internal forces acting upon the tether.
- **Electrodynamic Tether** (Triton Systems)
  - Multiple coatings on polymers have been analyzed for use as a conductive tether

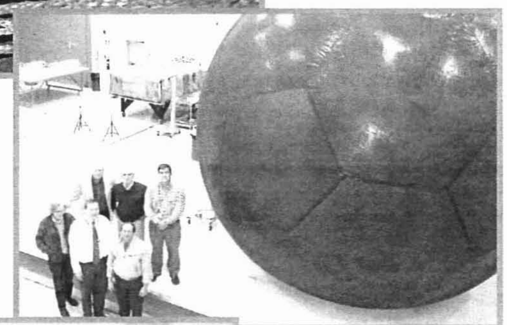


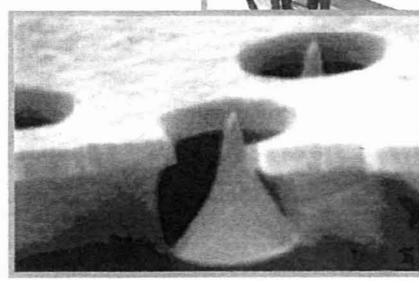
Progress on MXER Subsystems

- **Strength Tether** (Lockheed Martin & Tethers Unlimited)
  - Produced numerous tether hardware samples & test data
  - Performed independent, preliminary testing on supplied samples
    - Atomic Oxygen
    - Ultraviolet radiation
  - Developed multi-strand tether manufacturing process
    - Yarn plying/twisting
    - Bobbin winding
    - Braiding
    - Braider splicing
    - Spooling
- **Plasma Contactors** (MSFC, Jet Propulsion Laboratory & SRS Technologies)
  - Initial analysis performed to evaluate use of anode concepts
    - Bare wire anode
    - Grid-sphere anode
  - Testing of Field Emitter Array Cathodes (FEAC) in MXER environment
  - Alternative method for ED operations without using plasma contactors has been analyzed and seem feasible



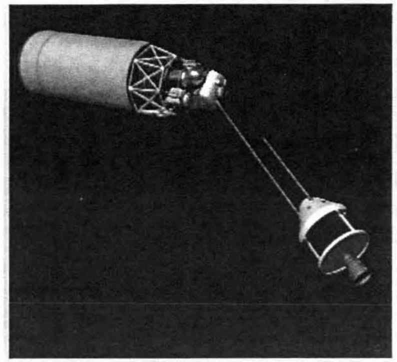




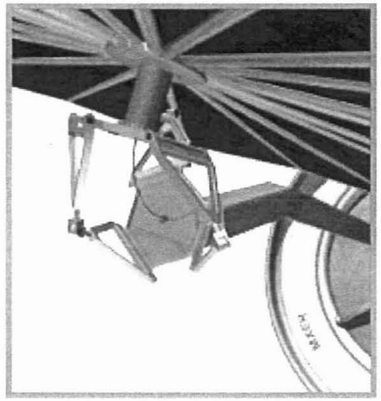


Emerging Technologies

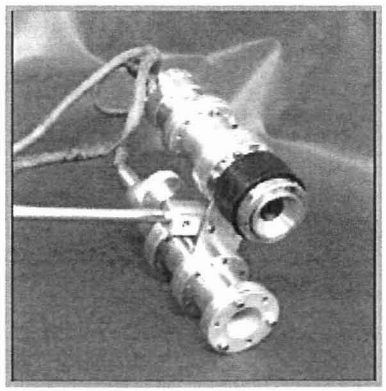
- **Unique boom-rendezvous concept**
  - Method for “mating” two large space assets via a tether imbedded in a bi-stem boom



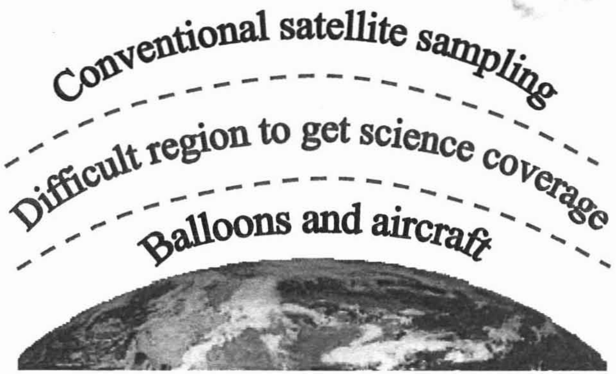
- **“Canfield” Joint (changes spacecraft operations)**
  - Provides tracking and pointing with no slip rings
  - Continuous solar array tracking of Sun
  - Communications tracking (independent of spacecraft)
  - Instrument platforms with complete independent control and total connectivity (power, fluids, optics)
  - Mounting of RCS thruster with flexible feedlines would point and fire essentially anywhere in a hemisphere (2π steradian)
    - This pointing flexibility means that just one gimballed thruster like this could replace a large number of body-mounted thrusters, as well as eliminating cosine losses.



- **Solid Expellant Plasma Source/Contactor (SOLEX)**
  - A new plasma contactor with significant benefits over a traditional hollow cathode
  - May also provide methods for operating electrodynamic tethers beyond the ionosphere



Electrodynamic (ED) Tethers



Mission Applications

- Near Earth Propulsion
  - 'Propellantless'
  - Large inclination changes
  - Rotating area coverage (multiple sensors)
  - Upper atmosphere sampling
- Unique power supply
- End-of-life disposal
- Unprecedented science coverage

Technology Description

- Ability to provide 'propellantless' propulsion and passive stability to any space asset.
- Theoretically limited to ~100-1000 km above the Earth (relatively strong ionosphere and magnetic field).
- The tether will act as a "tug" to the space asset.
- Can be used to lower an orbit more quickly than natural drag, which could aid in disposing of "space trash."
- Operates on same physics behind any electric motor – a wire moving through a magnetic field applies a body force to the wire
  - Collects electrons from the ionosphere and flows the current through a conductive portion of the tether.
  - Creates thrust by driving current against the natural electron flow and create thrust

Tether Benefits for Earth Science

- Continuous sampling of upper atmosphere with wide coverage of areas not normally possible
- Single science instrument packages providing coverage equal to multiple launches/instruments
- No propellant-limited missions
- Upper atmosphere maneuverability with multiple sensors while providing coverage areas with time history data
- Simple formation flying
- Advanced communications antenna and/or microwave receivers
- Provide required de-orbit mechanism after mission is complete (passive & low mass)

Emerging Propulsion Technologies Summary

- Looking for the "unplowed ground" that houses the potential high-payoff technologies
- High standards for SMD "customer" benefit-to-risk ratio
- Clearly defined evaluation procedure and criteria
- Accomplishing meaningful technology hardware tasks
- Small budget – potentially largest payoff - very *disruptive!*
- Gateway to ISPT portfolio
- Immediate spin-offs of MXER tether investments to science community & other non-propulsion related areas
- Small-team and results oriented
- Supporting <u>tangible, industry capabilities</u> that are readily available

Additional Technology Subject of Interest

MSFC Propulsion Research Center

Dr. Andrew S. Keys

Manager (acting), Emerging Propulsion Technologies

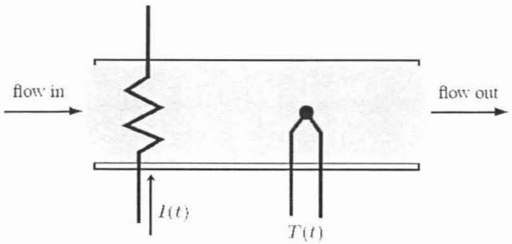
NASA, Marshall Space Flight Center

Liquid Metal Propellant Feed Systems for Electric Propulsion

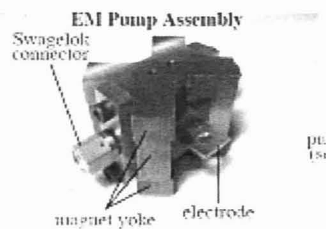
Kurt Polzin and Thomas Markusic (NASA-MSFC)

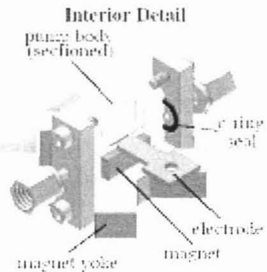
Motivation

- Recent work reveals significant potential advantages to operating electric propulsion systems using a liquid metal propellant
  - Bismuth for Hall thrusters – greater I_{sp} and thrust efficiency than xenon Hall thrusters (applicable for science missions)
  - Lithium for MPD thrusters – lower erosion rates, efficient operation at lower power levels than argon-fed MPD thrusters
- MSFC has partnered with other institutions to advance the TRL of these systems, with MSFC developing liquid metal propellant feed components and systems
  - Busek Co: Bismuth-fed SPT geometry thruster (*presently ongoing*)
  - JPL: Very High I_{sp} Thruster with Anode Layer (VHITAL) program
  - Princeton: Lithium-fed Lorentz Force Accelerator (ALFA[2])

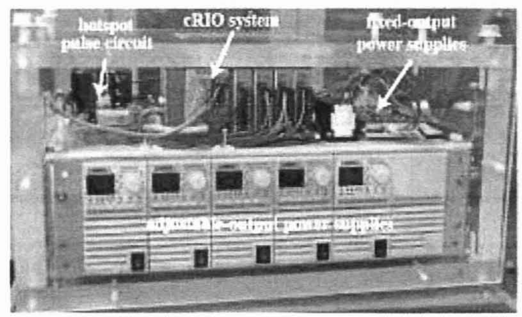


'Hotspot' Flow Sensor (bismuth)
- MSFC-original design
- Thermally 'tag' conducting fluid upstream via Joule heating
- Measures thermal feature downstream
- Computes velocity using time-of-flight





Electromagnetic Pump
- Lorentz (**j**x**B**) acceleration
- Insulating bodies (macor & aluminum nitride) successfully mated to steel tubing
- Successful operation with bismuth & lithium



Bismuth propellant feed control system
- Fully-independent, NI-cRIO real-time control
- Remote PC runs user interface for issuing commands and monitoring system operation

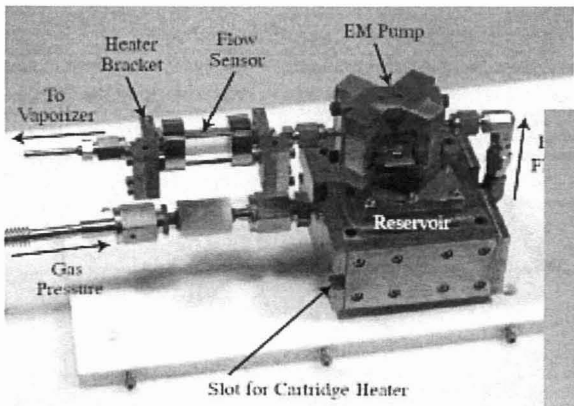
Liquid Metal Propellant Feed Systems for Electric Propulsion

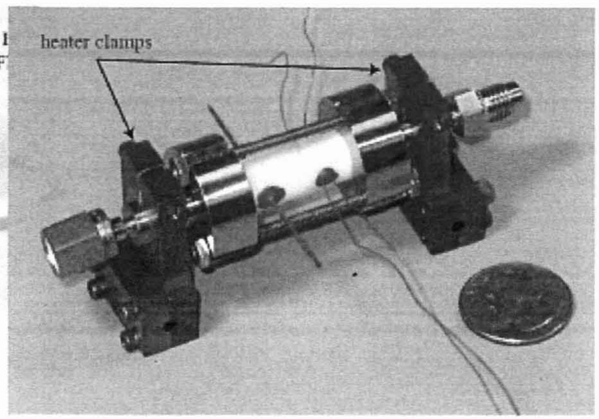
Kurt Polzin and Thomas Markusic (NASA-MSFC)

Hardware Development Summary

- Implemented electromagnetic pumps for pushing propellants
- Used two different flow sensors tailored to the propellant properties
  - Invented 'hotspot' flow sensor for bismuth
  - Implemented back-EMF flow sensor for lithium
- Developed fully integrated control system for VHITAL feed system
- Presently developing a fully integrated control system capable of vacuum operation

Fully-assembled bismuth propellant feed system

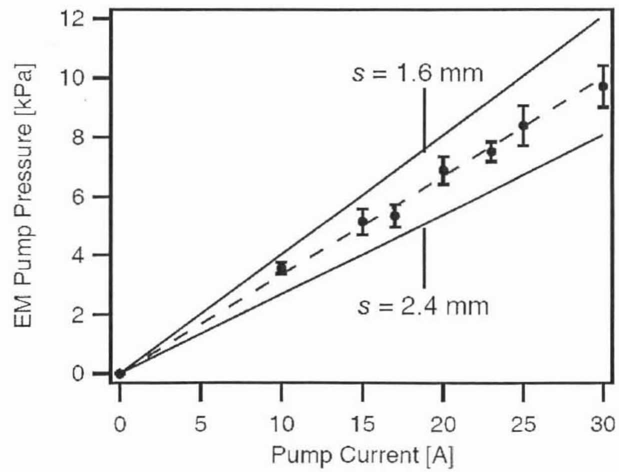


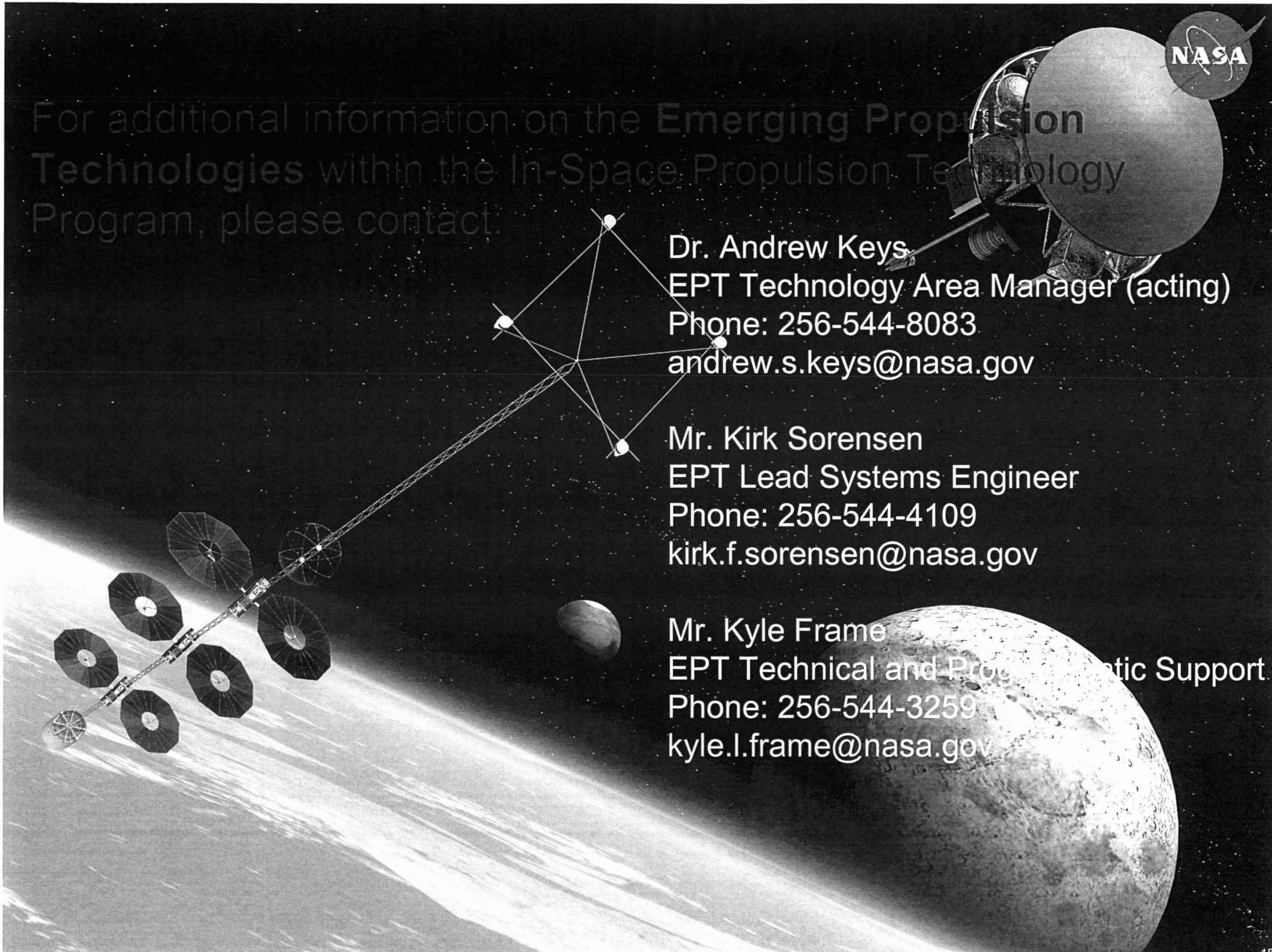


Hotspot Flow Sensor Assembly

Electromagnetic pump

- Pressure rise produced as a function of input current (solid lines represent theoretical bounds)

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Emerging Propulsion Technologies

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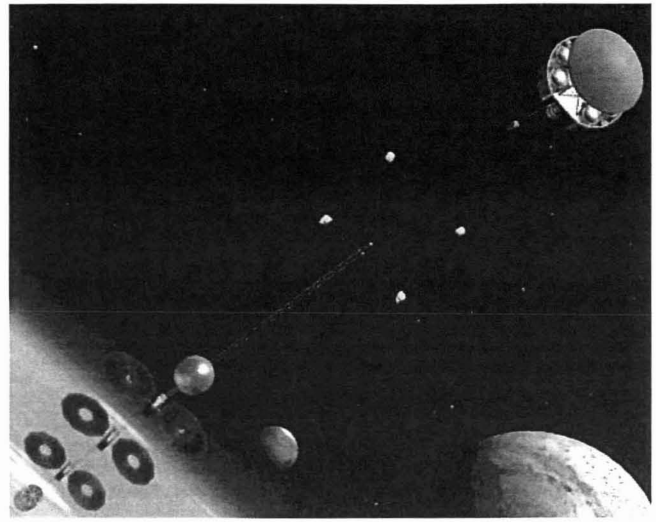
Technology Description

- Newest area of In-Space that bridges technologies in the lower TRL range (2 & 3) to the mid TRL range (4 to 6). MXER tether was originally the top priority with an aggressive schedule. However, the MXER Tether tasks are being phased out and will terminate by November 2006. EPT is also home to secondary, candidate ISP technologies:
  - Solar sail/aerocapture combination
  - Advanced electric concepts (FRC, PIT, etc.)
  - External Pulsed Plasma Propulsion
  - ED or other tether applications
  - Advanced mechanisms for in-space applications



Current Activities (MXER)

- Lightweight Catch Mechanism
  - Lightweight with large capture area that offers acceptable catch probability for a target payload
- Propagator Code
  - Design code that will later be developed/transferred into a propagator/predictor code to track a MXER tether.
- Survivable Strength Tether
  - Development of coatings and/or fibers that will protected from the harsh space environment.

Key Milestones

- June 2006: Final Review for Tethers Unlimited SBIR/STTR contracts
- June 2006: Final Review for Lockheed Martin tasks (catch mechanism/strength tether)
- June 2006: Orbitec STTR Final Review
- October 2006: Final Review for Tethers Unlimited tasks (strength tether/propagator code)
- November 2006: Triton Systems SBIR Final Review