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 transplanetary velocities, carry less fuel mass and more payload mass.

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 Activities:

- Ball Aerospace - Ballute Development: Systems analysis/evaluation/test of inflatable concepts.
- Lockheed Martin - Inflatable Aeroshell: Flexible TPS test plans and data for inflatable aeroshell.
- NASA/ARC - Aeroshell Development: Aerothermal sensitivity analyses, documented TPS qualification plan.
Emerging Propulsion Technologies

In Space Propulsion Technology Project
NASA Marshall Space Flight Center
Dr. Andrew S. Keys
Earth Science Technology Conference 2006
June 27-29, 2006
Outline

• In-Space Propulsion Technology Project Prioritization Process

• Emerging Propulsion Technologies

• Emerging Propulsion Technologies ISPT Entrance Process

• Momentum eXchange Electrodynamical 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

Systems Concepts Developed
- Architecture
- Safety/Reliability
- Cost, Trip Time, etc.

Technology Options Identified

Systems Concepts Compared
- Feasibility
- Identification of Technology Drivers
- Recommended approaches

Technologies Prioritized (scoring process)

<table>
<thead>
<tr>
<th>High Priority</th>
<th>Medium Priority</th>
<th>Low Priority</th>
<th>High Payoff/High Risk</th>
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<tbody>
<tr>
<td>Aerocapture</td>
<td>Advanced Chemical</td>
<td>Solar Thermal</td>
<td>Solar Sails 1 g/m²</td>
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<tr>
<td>NGI (5/10 kW)</td>
<td>SEP Hall</td>
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<tr>
<td>Solar Sails</td>
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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 (RD³), 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

RFI
• Generic call for new, innovative in-space propulsion technologies with convincing TRL of 3 (or 2+ with low RD³) and applicable SMD mission(s) for proposed technology.

Other Sources
• STTR, SBIR, unsolicited proposals
• ESMD (Energetic and HR&T)
• University contacts
• Conferences/Workshops (JPC, NIAC, JANNAF, ASPW, etc)
• Periodical reviews
• Prospects from Partner Centers

Multi-center team evaluates submissions and makes recommendations for NRA categories and cross-checks with ESMD and other programs to eliminate duplicate funding

NRA Solicitation
• EPT Section in future NRAs (beginning with Cycle 4)
• Maximum of 2-3 selections in each cycle
• Encourage teaming
• Proposals shall address the following as a minimum:
  - Technology maturation strategy
  - Mission pull justification
  - Justification of TRL 3 or TRL 2 with low RD³
  - Assessment of engineering feasibility
  - System-level implementation strategy – leading to a credible roadmap after two years

Following 2 years of development, must have very crisp “story”, key risks, and uncertainty of parameters

Favorable result
• Believable roadmap
• Good understanding of technology risks
• Hold an independent peer review and/or conduct a systems analysis review to compete against other systems (at the discretion of EPT manager)

Unfavorable result
• Terminate funding and eliminate technology from ISP portfolio

EPT Technology
• Remain in EPT for 1-2 additional years for additional specifically identified studies/research.

Unfavorable result
• Publish findings
• Exit strategy
• Find a home (ESMD, Air Force, DARPA, etc.)

Additional studies show poor performance or applicability

Other Organization
• ESMD, Air Force, DARPA, etc.

ISP/other approved organization

Major Engineering Issues remain

YES

ISPT Technology Area
• New POP line item
• Newly assigned TAM

No
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

Power Nodes to store energy for electrodynamic reboost

- Tracking solar arrays to recharge flywheels
- Hybrid High-strength tether interwoven with aluminum conductor

Tether Deployer Node carrying both tapered and hybrid tethers

- Payload accommodation assembly

- Multiple control stations driving current through the tether

- Catch mechanism on one end capturing & releasing prospective payloads
MXER Tether Propulsion

- MXER in elliptical orbit about Earth
- Payload LEO orbit
- MXER orbit after catch
- MXER orbit after throw
- Payload orbit after being thrown by MXER

National Aeronautics and Space Administration
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 gimbaled 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

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

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

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 tangible, industry capabilities 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 (jxB) 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

Electromagnetic pump
- Pressure rise produced as a function of input current (solid lines represent theoretical bounds)
For additional information on the Emerging Propulsion Technologies within the In-Space Propulsion Technology Program, please contact:

Dr. Andrew Keys
EPT Technology Area Manager (acting)
Phone: 256-544-8083
andrew.s.keys@nasa.gov

Mr. Kirk Sorensen
EPT Lead Systems Engineer
Phone: 256-544-4109
kirk.f.sorensen@nasa.gov

Mr. Kyle Frame
EPT Technical and Programmatic Support
Phone: 256-544-3259
kyle.l.frame@nasa.gov
Backup Slides
Emerging Propulsion Technologies
Manager: Andrew S. Keys (acting), NASA/Marshall Space Flight Center

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/transfered 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