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An Overview of SBIR Phase 2 In-Space Propulsion and Cryogenic Fluids Management

Hung D. Nguyen and Gynelle C. Steele
Glenn Research Center, Cleveland, Ohio

July 2015

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Space Administration

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An Overview of SBIR Phase 2
In-Space Propulsion and Cryogenic Fluids Management

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Abstract

Technological innovation is the overall focus of NASA's Small Business Innovation Research (SBIR) program. The program invests in the development of innovative concepts and technologies to help NASA's mission directorates address critical research and development needs for agency projects.

This report highlights innovative SBIR Phase II projects from 2007-2012 specifically addressing Areas in In-Space Propulsion and Cryogenic Fluids Management which is one of six core competencies at NASA Glenn Research Center. There are nineteen technologies featured with emphasis on a wide spectrum of applications such as high-performance Hall thruster support system, thruster discharge power converter, high-performance combustion chamber, ion thruster design tool, green liquid monopropellant thruster, and much more. Each article in this booklet describes an innovation, technical objective, and highlights NASA commercial and industrial applications.

This report serves as an opportunity for NASA personnel including engineers, researchers, and program managers to learn of NASA SBIR's capabilities that might be crosscutting into this technology area. As the result, it would cause collaborations and partnerships between the small companies and NASA Programs and Projects resulting in benefit to both SBIR companies and NASA.

Low-Cost, High-Performance Hall Thruster Support System

Power processing unit (PPU) for Hall thrusters

Colorado Power Electronics (CPE) has built an innovative modular PPU for Hall thrusters, including discharge, magnet, heater and keeper supplies, and an interface module. This high-performance PPU offers resonant circuit topologies, magnetics design, modularity, and a stable and sustained operation during severe Hall effect thruster current oscillations. Laboratory testing has demonstrated discharge module efficiency of 96 percent, which is considerably higher than current state of the art.

The Phase II project developed an engineering model high-voltage Hall accelerator (HiVHAC) PPU that includes a digital control interface unit (DCIU). This will position CPE to manufacture a qualification model PPU as a Phase III project. The prototype digitally controlled flow controller with a PC interface developed in Phase I served as the foundation for a combination DCIU-flow module added to the PPU in Phase II. Thermal and vibration finite element analysis was performed on the reduced-mass chassis, and then a test brassboard PPU was built and tested. Additionally, the control loops of the PPU were analyzed and a stress analysis performed. The team designed and built an engineering model flight-like PPU that includes flight-like wire harnessing schemes, electromagnetic interference filtering, enhanced modularity, and the new DCIU-flow module.

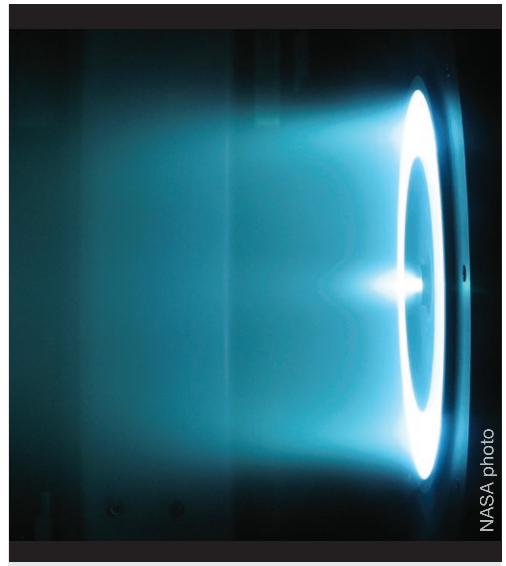
Applications

NASA

- PPU for Hall thrusters
- PPU for ion thrusters

Commercial

- Space-rated piezoelectric driver
- Resonant converters for high-power Hall thrusters


NASA photo

Phase II Objectives

- Develop an engineering model flight-like HiVHAC PPU
- Develop and integrate a DCIU that controls the PPU and xenon feed system
- Refine electrical and mechanical PPU design
- Improve manufacturability
- Develop electrical, thermal, and structural models

Benefits

- Offers discharge module efficiency of 96 percent
- Provides sustained operation during severe Hall effect thruster current oscillations
- Can operate a Hall thruster at a wide range of voltages

Firm Contact

Colorado Power Electronics
Bryce Hesterman
bryce.hesterman@c-pwr.com
120 Commerce Drive, Unit 3
Fort Collins, CO 80524–4731
Phone: 970–482–0191

Proposal Number: 09-2 S3.04-8077

Low-Mass, Low-Power Hall Thruster System

For radioisotope electric propulsion (REP)

NASA is developing an electric propulsion system capable of producing 20 mN thrust with input power up to 1,000 W and specific impulse ranging from 1,600 to 3,500 seconds. The key technical challenge is the target mass of 1 kg for the thruster and 2 kg for the power processing unit (PPU). In Phase I, Busek Company, Inc., developed an overall subsystem design for the thruster/cathode, PPU, and xenon feed system. This project demonstrated the feasibility of a low-mass power processing architecture that replaces four of the DC–DC converters of a typical PPU with a single multifunctional converter and a low-mass Hall thruster design employing permanent magnets.

In Phase II, the team developed an engineering prototype model of its low-mass BHT-600 Hall thruster system, with the primary focus on the low-mass PPU and thruster. The goal was to develop an electric propulsion thruster with the appropriate specific impulse and propellant throughput to enable radioisotope electric propulsion (REP). This is important because REP offers the benefits of nuclear electric propulsion without the need for an excessively large spacecraft and power system.

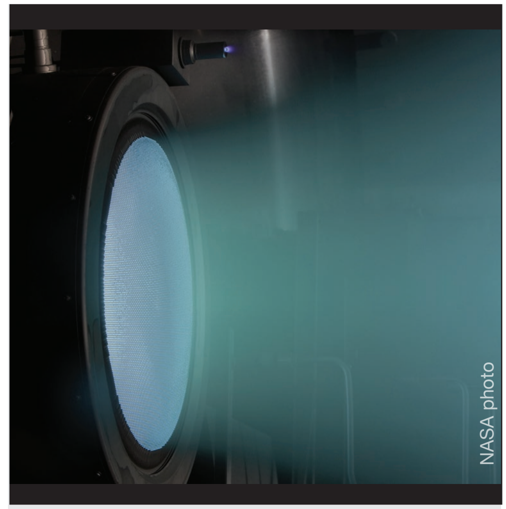
Applications

NASA

- Orbiters around Pluto, Neptune, and Uranus
- Rendezvous and Centaurs, Kuiper belt objects, and primitive bodies in the outer solar system
- Extensive surveys of major asteroid groups

Commercial

- Low-power electric propulsion systems
- Low-power Hall effect thruster systems
- Commercial satellite manufacturers:
  - Primary propulsion on low Earth orbit spacecraft
  - Station keeping on geostationary satellites



Phase II Objectives

- Develop a low-mass BHT-600 Hall thruster system, with the primary focus on the low-mass PPU and thruster
- Design, fabricate, and demonstrate an engineering model version of a low-mass (2 kg) PPU and a low-mass (1 kg) version of the BHT-600 thruster
- Conduct an integrated system test and deliver a prototype PPU and thruster system

Benefits

- Low mass
- Low power

Firm Contact

Busek Company, Inc.
Bruce Pote
bpote@busek.com
11 Tech Circle
Natick, MA 01760–1023
Phone: 508–655–5565

Proposal Number: 09-2 S3.04-8131

High-Efficiency Hall Thruster Discharge Power Converter

For use in high-voltage Hall accelerator thrusters and other electric propulsion devices

Busek Company, Inc., is designing, building, and testing a new printed circuit board converter. The new converter consists of two series or parallel boards (slices) intended to power a high-voltage Hall accelerator (HiVHAC) thruster or other similarly sized electric propulsion devices. The converter accepts 80- to 160-V input and generates 200- to 700-V isolated output while delivering continually adjustable 300-W to 3.5-kW power. Busek built and demonstrated one board that achieved nearly 94 percent efficiency the first time it was turned on, with projected efficiency exceeding 97 percent following timing software optimization. The board has a projected specific mass of 1.2 kg/kW, achieved through high-frequency switching.

In Phase II, Busek optimized to exceed 97 percent efficiency and built a second prototype in a form factor more appropriate for flight. This converter then was integrated with a set of upgraded existing boards for powering magnets and the cathode. The program culminated with integrating the entire power processing unit and testing it on a Busek thruster and on NASA's HiVHAC thruster.

Applications

NASA

- Lunar and Mars exploration
- Vesta–Ceres rendezvous (Dawn Mission)
- Comet 22P/Kopff rendezvous
- Asteroid 4660 Nereus sample return mission

Commercial

- Department of Defense space assets
- Defense Advanced Research Projects Agency Fast Access Spacecraft Testbed Program:
  - All-electric, high-power space tug and geosynchronous Earth orbit servicing vehicle
- Commercial satellite manufacturers:
  - Satellite servicing
  - Orbit maintenance
  - Orbit raising and lowering
  - Inclination changes
  - Repositioning

Phase II Objectives

- Demonstrate very high efficiency, low mass modular power processing unit (PPU) with input and output voltages appropriate for deep-space missions and NASA's HiVHAC thruster
- Integrate new with existing converters operating at different input voltages
- Complete existing breadboard and build next version with the correct form factor
- Convert existing boards for magnets, cathode, etc.
- Integrate new and existing boards
- Test PPU on BHT-1500 thruster at Busek and on HiVHAC thruster at NASA Glenn

Benefits

- High efficiency Hall thruster
- Low mass

Firm Contact

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Thomas Jaquish
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Phone: 508–655–5565

Proposal Number: 09-2 S3.04-8809

Silicon Carbide (SiC) Power Processing Unit (PPU) for Hall Effect Thrusters

A high-efficiency, radiation-hardened power supply

Arkansas Power Electronics International (APEI), Inc., is developing a high-efficiency, radiation-hardened 3.8-kW SiC power supply for the PPU of Hall effect thrusters. This project specifically targets the design of a PPU for the high-voltage Hall accelerator (HiVHAC) thruster, with target specifications of 80- to 160-V input, 200- to 700-V/5A output, efficiency greater than 96 percent, and peak power density in excess of 2.5 kW/kg. The PPU under development uses SiC junction field-effect transistor power switches, components that APEI, Inc., has irradiated under total ionizing dose conditions to greater than 3 MRad with little to no change in device performance.

Applications

NASA

- Satellite and spacecraft power management systems
- Satellite and spacecraft motors and actuators:
  - Opening and rotating solar array panels, controlling robotic arms, aligning communications arrays, pointing cameras and instruments, etc.
- Extreme environment exploratory vehicles

Commercial

- High-voltage hybrid electric vehicle battery packs
- Photovoltaic energy systems
- Energy exploration
- Industrial motor drives
- Electric vehicle motor drives
- Military systems

Phase II Objectives

- Determine the overall system requirements for the PPU power converter
- Develop the electrical design of the radiation-hardened SiC-based PPU power supply
- Fabricate and test PPU power supply prototype

Benefits

- More efficient than silicon
- Lower weight and volume
- Operates in high-temperature environments

Firm Contact

APEI, Inc.
Bradley Reese
breese@apei.net
535 W. Research Center Blvd.
Fayetteville, AR 72701–7175
Phone: 479–443–5759 ext. 8250

Proposal Number: 09-2 S3.04-8940

Unibody Composite Pressurized Structure (UCPS) for In-Space Propulsion

Single, all-composite structure reduces spacecraft mass and cost

Microcosm, Inc., in conjunction with the Scorpius Space Launch Company, is developing a UCPS for in-space propulsion. This innovative approach constitutes a clean break from traditional spacecraft design by combining what were traditionally separate primary and secondary support structures and metal propellant tanks into a single unit. The all-composite construction is stronger, significantly lighter, more robust and reliable, and capable of supporting much higher pressures and smaller volume than previous approaches. The single, all-composite structure includes linerless high-pressure propellant tank(s), composite bosses, flanges, longitudinal and circumferential stringers with integral shelves, holding mechanisms, and attach features to support all of the spacecraft equipment. These features will replace the separate mission-critical primary support structure, tanks, struts, straps, braces, clamps, and brackets traditionally required to hold subsystem parts in place. The new structure has nearly 0 coefficient of thermal expansion over a temperature range from cryogenic to more than 100 °C.

The Phase II project refined the design of the UCPS integrated with a bladder; continued materials compatibility testing with hydrazine; fabricated two UCPS as positive expulsion tank (PET) structures; and completed expulsion, qualification, and burst testing on one of them.

Applications

NASA

- Science mission directorate spacecraft
- High-pressure liquid and gaseous propellants for chemical and electric propulsion systems

Commercial

- Aerospace
- Automotive
- Electrical
- Medical

Phase II Objectives

- Refine the system objectives and requirements for next-generation propulsion systems and how the PET can best meet current and future needs
- Refine the design for the new UCPS structure employing the unibody integrated tank/structure approach that includes a bladder as a PET
- Conduct more extensive materials compatibility tests with UCPS structural material and hydrazine
- Fabricate and test a transparent bottle plus bladder to characterize bladder mechanics
- Fabricate and conduct water-only qualification tests of the PET

Benefits

- Allows much higher pressure chemical propulsion systems (in excess of 2,000 psi) with less tank mass
- Uses all-composite structure combined with high-pressure, low-volume tanks

Firm Contact

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Hawthorne, CA 90250–6708
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Proposal Number: 09-2 S3.04-9659

Low-Cost, High-Performance Combustion Chamber

For use with cryogenic liquid oxygen/methane (LOX/CH_4) propellant

Ultramet designed and fabricated a lightweight, high-temperature combustion chamber for use with cryogenic LOX/CH_4 propellants that can deliver a specific impulse of ~355 seconds. This increase over the current 320-second baseline of nitrogen tetroxide/monomethylhydrazine (NTO/MMH) will result in a propellant mass decrease of 55 lb_m for a typical lunar mission. The material system was based on Ultramet's proven oxide-iridium/rhenium architecture, which has been hot-fire tested with stoichiometric oxygen/hydrogen for hours. Instead of rhenium, however, the structural material was a niobium or tantalum alloy that has excellent yield strength at both ambient and elevated temperatures.

Phase I demonstrated alloys with yield strength-to-weight ratios more than three times that of rhenium, which will significantly reduce chamber weight. The starting materials were also two orders of magnitude less expensive than rhenium and were less expensive than the C103 niobium alloy commonly used in low-performance engines.

Phase II focused on the design, fabrication, and hot-fire testing of a 12-lb_f thrust class chamber with LOX/CH_4, and a 100-lb_f chamber for LOX/CH_4. A 5-lb_f chamber for NTO/MMH also was designed and fabricated.

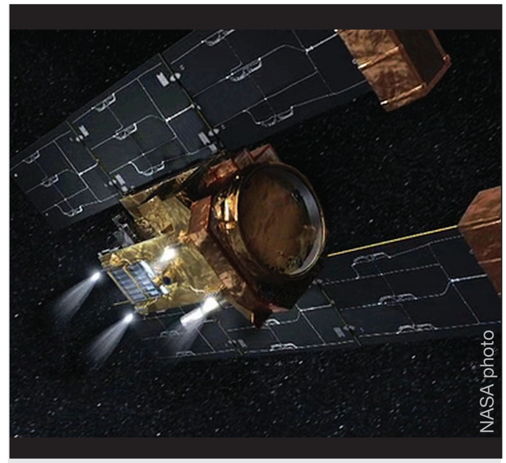
Applications

NASA

- Reaction control systems for lunar or Martian ascent/descent vehicles
- Lunar or Martian sample return vehicles
- Main engines for interplanetary spacecraft and spacecraft being placed into geostationary orbit
- Apogee topping engines and attitude control systems for Earth-orbiting satellites
- Launch vehicles for attitude control

Commercial

- Apogee topping engines for commercial satellites
- Attitude control thrusters for launch vehicles
- Primary propulsion as well as divert and attitude control system functions for ballistic missile defense and tactical missiles
- Drop-in replacements for iridium/rhenium engines currently being manufactured and flown



Phase II Objectives

- Optimize the alloy composition and deposition conditions and perform extensive mechanical characterization of the resulting alloys
- Design and fabricate a flight-weight 12-lb_f combustion chamber for hot-fire testing
- Perform hot-fire testing of the 12-lb_f chamber with LOX/CH_4
- Design and fabricate a high-performance 100-lb_f combustion chamber for use with LOX/CH_4
- Design and fabricate a 5-lb_f chamber for use with NTO/MMH

Benefits

- Reduces combustion chamber weight
- Lowers costs of materials
- Increases yield strength at ambient and elevated temperatures

Firm Contact

Ultramet
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12173 Montague Street
Pacoima CA 91331–2210
Phone: 818–899–0236

Proposal Number: 09-2 X10.01-8636

Wrapped Multilayer Insulation

Thermal insulation for cryogenic piping

New NASA vehicles, such as Earth Departure Stage (EDS), Orion, landers, and orbiting fuel depots, need improved cryogenic propellant transfer and storage for long-duration missions. Current cryogen feed line multilayer insulation (MLI) performance is 10 times worse per area than tank MLI insulation. During each launch, cryogenic piping loses approximately 150,000 gallons (equivalent to $300,000) in boil-off during transfer, chill down, and ground hold. Quest Product Development Corp., teaming with Ball Aerospace, developed an innovative advanced insulation system, Wrapped MLI (wMLI), to provide improved thermal insulation for cryogenic feed lines.

wMLI is high-performance multilayer insulation designed for cryogenic piping. It uses Quest's innovative discrete-spacer technology to control layer spacing/density and reduce heat leak. The Phase I project successfully designed, built, and tested a wMLI prototype with a measured heat leak 3.6X lower than spiral-wrapped conventional MLI widely used for piping insulation. A wMLI prototype had a heat leak of 7.3 W/m^2, or 27 percent of the heat leak of conventional MLI (26.7 W/m^2).

The Phase II project is further developing wMLI technology with custom, molded polymer spacers and advancing the product toward commercialization via a rigorous testing program, including developing advanced vacuum-insulated pipe for ground support equipment.

Applications

NASA

- New NASA vehicles
- Orbiting fuel depots
- Vacuum-insulated pipe used to transfer cryogens

Commercial

- Food, research, medical, and industrial applications:
  - Transfers of cryogenic liquid into and from cryogenic dewars for liquid nitrogen (LN_2), hydrogen (LHe), and oxygen (LOX)
- Industrial:
  - Handling LN_2, LOX, and liquefied natural gas (LNG)
  - Handling piping, automatic filling equipment, dewar manifolds, and gas panels
- LNG:
  - High-performance insulated cryogenic transfer piping to reduce LNG losses from vaporization during liquid transfer
- LN_2 equipment:
  - Semiconductor, electronics, and aerospace environmental temperature testing
  - Special effects (fogging), biological freezing applications, inerting of food and beverage containers, container pressurization, and food freezing

Phase II Objectives

- Design and develop a custom, molded polymer spacer
- Further develop assembly and installation processes
- Develop and test wMLI for three different piping diameters
- Conduct testing to optimize spacer and wrap geometries
- Perform thermal testing on 12 different wMLI test configurations
- Perform thermal testing on advanced "clam-shell" netting MLI
- Design, develop, and test MLI in a vacuum-insulated pipe prototype for use in ground support equipment

Benefits

- Low heat leak (3.6X less than conventional MLI)
- Easy assembly
- Few layers
- Low cost
- Less mass

Firm Contact

Quest Product Development Corporation
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Arvada, CO 80007–7570
Phone: 303–670–5088 ext. 12

Proposal Number: 09-2 X8.01-8258

High-Power, High-Thrust Ion Thruster (HPHTion)

For near-Earth applications

Advances in high-power photovoltaic technology have enabled the possibility of reasonably sized, high–specific power solar arrays. At high specific powers, power levels ranging from 50 to several hundred kilowatts are feasible. Ion thrusters offer long life and overall high efficiency (typically >70 percent efficiency). In Phase I, the team at ElectroDynamic Applications, Inc., built a 25-kW, 50-cm ion thruster discharge chamber and fabricated a laboratory model. This was in response to the need for a single, high-powered engine to fill the gulf between the 7-kW NASA's Evolutionary Xenon Thruster (NEXT) system and a notional 25-kW engine.

The Phase II project matured the laboratory model into a protoengineering model ion thruster. This involved the evolution of the discharge chamber to a high-performance thruster by performance testing and characterization via simulated and full beam extraction testing. Through such testing, the team optimized the design and built a protoengineering model thruster. Coupled with gridded ion thruster technology, this technology can enable a wide range of missions, including ambitious near-Earth NASA missions, Department of Defense missions, and commercial satellite activities.

Applications

NASA

- Cargo propulsion requirements with power levels extending from 30 kW to 300 kW
- Space science endeavors

Commercial

- Satellites
- Orbit transfer needs
- Propulsion systems

NASA photo

Phase II Objectives

- Evaluate prototype discharge chamber with simulated beam extraction
- Characterize performance of discharge chamber with full beam extraction
- Design and fabricate stainless steel protoengineering model
- Complete performance characterization of protoengineering model

Benefits

- Long life
- High thrust-to-power ratio (~50 mN/kW)
- Low system complexity

Firm Contact

ElectroDynamic Applications, Inc.
Peter Y. Peterson
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3600 Green Court, Suite 300
Ann Arbor, MI 48105–1570
Phone: 734–734–1434

Proposal Number: 09-2 T3.01-9881

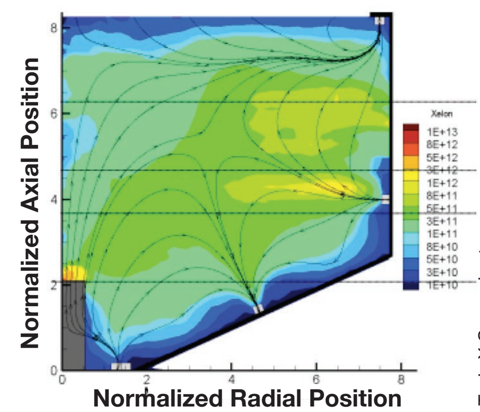
Next-Generation Ion Thruster Design Tool

To support future space missions

Computational tools that accurately predict the performance of electric propulsion devices are highly desirable and beneficial to NASA and the broader electric propulsion community. The current state of the art in electric propulsion modeling relies heavily on empirical data and numerous computational "knobs."

In Phase I of this project, Tech-X Corporation developed the most detailed ion engine discharge chamber model that currently exists. This kinetic model simulates all particles in the discharge chamber along with a physically correct simulation of the electric fields. In addition, kinetic erosion models are included for modeling the ion-impingement effects on thruster component erosion.

In Phase II, Tech-X developed a user-friendly computer program for NASA and other governmental and industry customers. Tech-X has implemented a number of advanced numerical routines to bring the computational time down to a commercially acceptable level. NASA now has a highly sophisticated, user-friendly ion engine discharge chamber modeling tool.



Tech-X Corp. chart

Phase II Objectives

- Reduce computational time of new modeling tool
- Make new modeling tool user friendly and commercially attractive

Benefits

- Reduces time and expense in designing new/different sizes of ion engines
- Analyzes existing ion engine performance
- Extends the operating range of the NEXT ion engine to higher power levels

Applications

NASA

- 40-cm-diameter NASA's Evolutionary Xenon Thruster (NEXT)
- Hall thrusters, such as the high-voltage Hall accelerator (HiVHAC) thruster

Commercial

- Electric propulsion
- Military and commercial satellites:
  - Satellite station keeping
  - Orbit-changing maneuvers in space
- Ion source and plasma processing

Firm Contact

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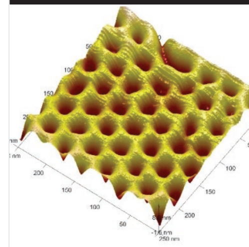
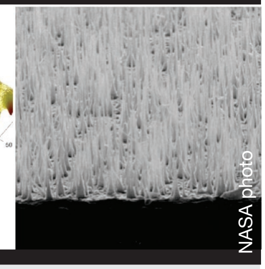
5621 Arapahoe Avenue
Boulder, CO 80303–1379
Phone: 303–996–7527

Proposal Number: 09-2 T3.01-9893

Nanowire Photovoltaic Devices





For ultrahigh-efficiency, radiation-tolerant space solar cells

Firefly Technologies, in collaboration with the Rochester Institute of Technology and the University of Wisconsin–Madison, developed synthesis methods for highly strained nanowires. Two synthesis routes resulted in successful nanowire epitaxy: direct nucleation and growth on the substrate and a novel selective-epitaxy route based on nanolithography using diblock copolymers. The indium-arsenide (InAs) nanowires are implemented *in situ* within the epitaxy environment—a significant innovation relative to conventional semiconductor nanowire generation using *ex situ* gold nanoparticles. The introduction of these nanoscale features may enable an intermediate band solar cell while simultaneously increasing the effective absorption volume that can otherwise limit short-circuit current generated by thin quantized layers. The use of nanowires for photovoltaics decouples the absorption process from the current extraction process by virtue of the high aspect ratio.

While no functional solar cells resulted from this effort, considerable fundamental understanding of the nanowire epitaxy kinetics and nanopatterning process was developed. This approach could, in principle, be an enabling technology for heterointegration of dissimilar materials. The technology also is applicable to virtual substrates. Incorporating nanowires onto a recrystallized germanium/metal foil substrate would potentially solve the problem of grain boundary shunting of generated carriers by restricting the cross-sectional area of the nanowire (tens of nanometers in diameter) to sizes smaller than the recrystallized grains (0.5 to 1 μm^2).

Applications

NASA

- Space-based applications
- Virtual substrates

Commercial

- Space-based power generation
- Photovoltaics:
    - Integration of III-V nanostructures on low-cost silicon substrates

Phase II Objectives

- Demonstrate controllable gallium-arsenide (GaAS)-embedded InAs nanowire growth and characterization
- Demonstrate improved cell performance from nanowire-infused cells compared to standard GaAs cells

Benefits

- Offers solar cell efficiency of more than 40 percent
- Reduces costs in terms of photovoltaic array size, array weight, and launch costs
- Enables more optimal bandgap and material combinations for novel devices

Firm Contact

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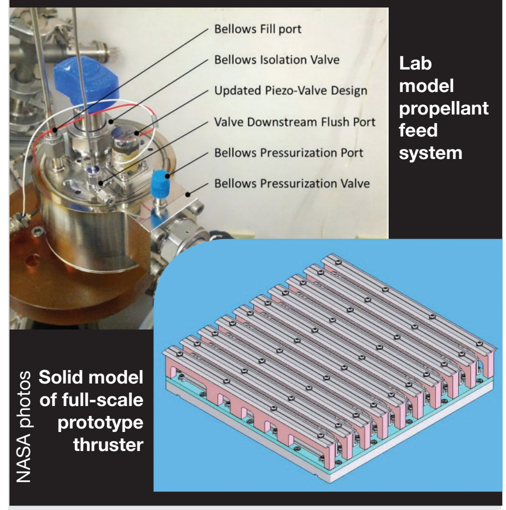
Proposal Number: 09-2 T3.01-9972

20-mN Variable Specific Impulse (Isp) Colloid Thruster

For colloid-based, multimode propulsion using ionic liquids

Busek Company, Inc., has designed and manufactured an electrospray emitter capable of generating 20 mN in a compact package (7x7x1.7 in). The thruster consists of nine porous-surface emitters operating in parallel from a common propellant supply. Each emitter is capable of supporting over 70,000 electrospray emission sites with the plume from each emitter being accelerated through a single aperture, eliminating the need for individual emission site alignment to an extraction grid. The total number of emission sites during operation is expected to approach 700,000.

This Phase II project optimized and characterized the thruster fabricated during the Phase I effort. Additional porous emitters also were fabricated for full-scale testing. Propellant is supplied to the thruster via existing feed-system and microvalve technology previously developed by Busek, under the NASA Space Technology 7's Disturbance Reduction System (ST7-DRS) mission and via follow-on electric propulsion programs. This project investigated methods for extending thruster life beyond the previously demonstrated 450 hours. The life-extending capabilities will be demonstrated on a subscale version of the thruster.



Lab model propellant feed system

Solid model of full-scale prototype thruster

Applications

NASA

- Missions requiring exceptional thrust/power where power is limited
- Missions benefiting from variable Isp (200 to 2,000+ s) and variable thrust (10x throttling)

Commercial

- Colloid-based multimode propulsion using ionic liquids, where there is a lack of suitable thrusters at the millinewton level or greater
- Replacement for lower thrust plasma-based electric propulsion devices, which suffer from decreased efficiency at low power due to unfavorable surface-to-volume scaling
- Spacecraft requiring both dwell/station keeping and rapid maneuvers from a single propulsion system

Phase II Objectives

- Validate Busek's concept for scaling electrospray thrust to the 20-mN level through self-organized electrospray emission from porous surfaces
- Develop a thruster package that is compact, robust, and does not require complicated manufacturing techniques
- Optimize the design for best performance and improve the total impulse achievable through increased thruster lifetime

Benefits

- Offers a compact, robust package
- Potential future use of shared propellant tanks for high-thrust chemical propulsion as well as high Isp electric propulsion
- Enables new classes of missions benefiting from variable Isp of 200 to 5,000+ s and variable thrusts up to and exceeding 20 mN

Firm Contact

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Proposal Number: 10-2 S3.04-8878

Green Liquid Monopropellant Thruster

For in-space propulsion in challenging environmental conditions

Physical Sciences, Inc. (PSI), and Orbital Technologies Corporation (ORBITEC) are developing a unique chemical propulsion system for next-generation NASA science spacecraft and missions. The system is compact, lightweight, and can operate with high reliability over extended periods of time and under a wide range of thermal environments. The system uses a new storable, low-toxicity liquid monopropellant as its working fluid. In Phase I, the team demonstrated experimentally the critical ignition and combustion processes for the propellant and used the data to develop thruster design concepts.

In Phase II, the team developed and demonstrated in the laboratory a proof-of-concept prototype thruster. A Phase III project is envisioned to develop a full-scale protoflight propulsion system applicable to a class of NASA missions.

Applications

NASA

This technology is ideal for propulsion systems in challenging environmental conditions, with long operational life, and with high duty cycles:

- Missions to other planets, their moons, and other small bodies:
  - Sampling their atmospheres
  - Descent and landing on their surfaces
  - Returning soil samples from their surfaces in ascent modules
  - Rendezvous and docking with orbiting mother ships
- Missions to the Earth's Moon, Venus, Mars and its moons, the moons of Jupiter, and asteroids

Military

- Air Force:
  - Liquid thrusters for in-space propulsion
- National Reconnaissance Organization:
  - Fast-response, long-life maneuvering propulsion systems
- Army:
  - Green monopropellant–based, high-pressure gas generators for pressurizing gelled propellants
- Other Department of Defense:
  - Liquid engines for propelling highly maneuverable, throttleable tactical missiles


NASA photo

Phase II Objectives

- Demonstrate operation of a prototype liquid monopropellant thruster incorporating the new fast-response, high-reliability, and long-life ignition system
- Develop ignition system designs to optimize performance
- Develop a modular, small-scale test thruster incorporating the ignition system to allow rapid changeability of components representative of different ignition/combustor designs
- Characterize the operation and performance of the small-scale thruster to demonstrate propulsive performance and ignition system start/stop/restart
- Develop functional prototype of a large-scale thruster and demonstrate its operation
- Develop complete propulsion system design incorporating the proposed in-space thruster technology

Benefits

- Compact and lightweight
- Can operate reliably over extended periods of time and under a wide range of thermal environments

Firm Contact

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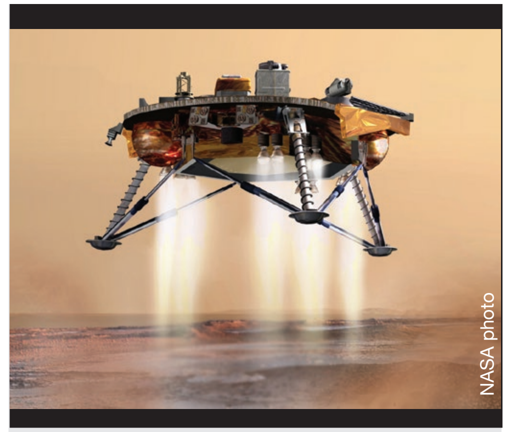
Improved Rhenium Thrust Chambers



Reduces chamber fabrication costs by 30 percent or more

Radiation-cooled bipropellant thrust chambers are being considered for ascent/descent engines and reaction control systems on various NASA missions and spacecraft, such as the Mars Sample Return and Orion Multi-Purpose Crew Vehicle (MPCV). Currently, iridium (Ir)-lined rhenium (Re) combustion chambers are the state of the art for in-space engines. NASA's Advanced Materials Bipropellant Rocket (AMBR) engine, a 150-lb_f Ir-Re chamber produced by Plasma Processes and Aerojet Rocketdyne, recently set a hydrazine specific impulse record of 333.5 seconds.

To withstand the high loads during terrestrial launch, Re chambers with improved mechanical properties are needed. Recent electrochemical forming (EL-Form™) results have shown considerable promise for improving Re's mechanical properties by producing a multilayered deposit composed of a tailored microstructure (i.e., Engineered Re).

The Engineered Re processing techniques were optimized, and detailed characterization and mechanical properties tests were performed. The most promising techniques were selected and used to produce an Engineered Re AMBR-sized combustion chamber for testing at Aerojet Rocketdyne.

Applications

NASA

- Ascent/descent engines and reaction control systems for missions:
  - Mars Sample Return
  - Orion MPCV
- In-space propulsion components for:
  - Apogee insertion
  - Attitude control
  - Orbit maintenance
  - Repositioning of satellites/spacecraft
  - Reaction control systems
  - Descent/Ascent engines
  - Nuclear power/propulsion
  - Microgravity containment crucibles and cartridges

Commercial

- Defense
- Material research and development
- Nuclear power
- Aerospace
- Propulsion
- Automotive
- Electronics
- Crystal growth
- Medical
- Net-shaped fabrication of refractory and platinum group metals for:
  - Rocket nozzles
  - Crucibles
  - Heat pipes
  - Propulsion subcomponents
- Advanced coating systems for:
  - X-ray targets
  - Sputtering targets
  - Turbines
  - Rocket engines
  - Wear and thermal/electrical insulation

EL-Form is a registered trademark of Plasma Processes, LLC.

Phase II Objectives

- Optimize the Engineered Re processing techniques to produce an AMBR-sized chamber that has room temperature yield strength of 40 ksi and 10 percent elongation
- Perform detailed characterization of the pinning layers and tailor the architecture of the Engineered Re to achieve the desired properties
- Perform extensive materials properties testing and select the most promising Engineered Re fabrication method
- Optimize the multicomponent processing technique to produce Engineered Re deposits on multiple AMBR-sized mandrels
- Demonstrate repeatability of the optimized Engineered Re fabrication technique
- Produce an AMBR-sized combustion chamber that incorporates the Engineered Re structure and test

Benefits

- Reduces chamber fabrication costs by 30 percent or more

Firm Contact

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Proposal Number: 10-2 S3.04-9213

Nontoxic Hydroxylammonium Nitrate (HAN) Monopropellant Propulsion

To replace hydrazine with a green monopropellant

Nontoxic monopropellants have been developed that provide better performance than toxic hydrazine. Formulations based on HAN have superior performance as compared to hydrazine with enhanced specific impulse (Isp), higher density and volumetric impulse, lower melting point, and much lower toxicity. However, HAN-based monopropellants require higher chamber temperatures (2,083 K vs. 883 K) to combust. Current hydrazine-based combustion chamber technology (Inconel® or niobium C103 and silicide coating) and catalyst (Shell 405) are inadequate. In Phase I, state-of-the-art iridium-lined rhenium chambers and innovative new foam catalysts were demonstrated in pulse and 10-second firings. Phase II developed and tested a flight-weight thruster for an environmentally green monopropellant.

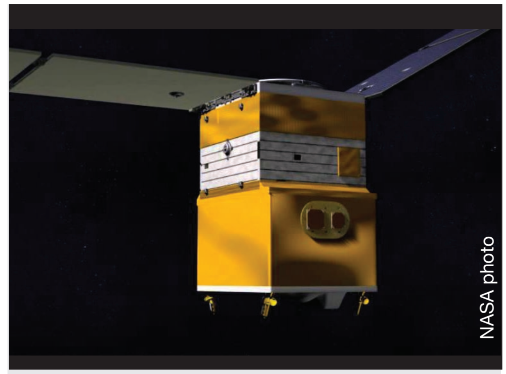
Applications

NASA

- Mars Ascent Vehicle
- Lunar landers
- Reaction control systems
- In-space propulsion:
    - Attitude control
    - Orbit maintenance
    - Repositioning of satellites/spacecraft
    - Descent/Ascent engines
- Nuclear power/propulsion
- Microgravity containment crucibles and cartridges

Commercial

- Rocket nozzles for satellites and military
- Crucibles, heat pipes, propulsion subcomponents, X-ray targets, sputtering targets, turbines, rotors, furnaces, power generation, jet engine restarters, catalysts, etc.


NASA photo

Phase II Objectives

- Develop a nontoxic HAN-based monopropellant thruster to replace hydrazine
- Pursue improvements to Phase I foam catalyst and injector
- Demonstrate ignition of nontoxic AF-M315E with Phase II design
- Test life and response time of the thrust chamber assembly
- Analyze posttest thruster and catalyst
- Fabricate multiple thrust chambers for commercial partners
- Commercialize green thruster

Benefits

- Enhanced Isp of 261 seconds (12 percent greater than hydrazine)
- Higher density and volumetric impulse (60 percent greater density impulse than hydrazine)
- Lower melting point than hydrazine
- Low toxicity (no self-contained breathing apparatus required)

Firm Contact

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Proposal Number: 10-2 X2.02-9554

Inconel is a registered trademark of Special Metals Corp.

Extreme-Environment Silicon-Carbide (SiC) Wireless Sensor Suite

For real-time monitoring of nuclear thermal propulsion (NTP) engines

A number of critical telemetry measurements must be monitored under continuous field operation, including temperature data across the reactor chamber and the nozzle, pressure data, neutron flux density, and flow rate of the propellant. Real-time monitoring of these data in nuclear thermal engines would greatly improve operational safety and performance, reduce operational costs, and significantly impact maintenance costs and reliability. Even though some extreme-environment sensors have become available recently, it is still impossible to directly and accurately measure the critical operational parameters of NTP engines due to the lack of extreme-environment electronics for those sensors. Data from extreme-environment sensors is delivered via wire-line to an external actively cooled electronics box, where it is processed. This approach presents significant drawbacks, such as the need for complex shielded wiring harnesses that not only are heavy but also limit sensor location and signal quality (i.e., signal-to-noise ratio). Additionally, these systems suffer from reliability issues due to wiring connections.

In this Phase II project, Arkansas Power Electronics International (APEI), Inc., delivered a set of SiC-based integrated wireless sensor-transmitter suites for extreme-temperature operation (450 °C) in NTP engines. These sensor suites allow for real-time monitoring of critical engine components, reducing the risk of catastrophic failure and decreasing the inherent risk associated with NTP operation. The final wireless sensor systems are fully integrated into an autonomous drop-in solution for advanced sensing systems, including wireless energy harvesting.

Applications

NASA

- Health monitoring systems of NASA space exploration vehicles:
  - Spacecraft
  - Rockets
  - Aircraft

Commercial

- Health monitoring of turbine engines for both military and commercial aircraft:
  - This technology enables nearly continuous onboard situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot.
- Power generation, including both nuclear power generation and gas turbine power generation:
  - By introducing high-temperature sensors and wireless transmitters into the gas turbine units (specifically within the blades where temperatures range from 450 to 1,200 °C), very accurate turbine conditions can be determined in real time.

Phase II Objectives

- Develop an integrated SiC wireless sensor suite capable of *in situ* measurements of critical characteristics of NTP engine
- Compose SiC wireless sensor suite of:
  - Extreme-environment sensors
  - Dedicated high-temperature (450 °C) SiC electronics that provide power and signal conditioning capabilities as well as radio frequency modulation and wireless data transmission capabilities
  - An onboard energy harvesting system as a power source

Benefits

- Allows for real-time monitoring of critical engine components
- Reduces the risk of catastrophic failure
- Decreases risk associated with NTP operation
- Eliminates (or reduces) the need for thermal shielding and active cooling systems, reducing the size, weight, and the complexity of control systems

Firm Contact

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Proposal Number: 10-2 X2.03-9748

Data Concentrator

For modular and distributed control of propulsion systems

Orbital Research, Inc., developed, built, and tested three high-temperature components for use in the design of a data concentrator module in distributed turbine engine control. The concentrator receives analog and digital signals related to turbine engine control and communicates with a full authority digital engine control (FADEC) or high-level command processor. This data concentrator follows the Distributed Engine Controls Working Group (DECWG) roadmap for turbine engine distributed controls communication development that operates at temperatures at least up to 225 °C.

In Phase I, Orbital Research developed detailed specifications for each component needed for the system and defined the total system specifications. This entailed a combination of system design, compiling existing component specifications, laboratory testing, and simulation. The results showed the feasibility of the data concentrator.

Phase II of this project focused on three key objectives. The first objective was to update the data concentrator design modifications from DECWG and prime contractors. Secondly, the project defined requirements for the three new high-temperature, application-specific integrated circuits (ASICs): one-time programmable (OTP), transient voltage suppression (TVS), and 3.3V. Finally, the project validated each design by testing over temperature and under load.

Applications

NASA

- NASA space programs will benefit from the development of the high-temperature electronic (HTE) component chips, data concentrator, and multichip modules.

Commercial

- Next-generation military and civilian aircraft turbine engines:
  - Rotorcraft
  - Unmanned aircraft systems
  - Land vehicles
- Downhole drilling and geothermal drilling controls
- Ground testing rocket and turbine engines
- Prognostic/Integrated system health management (PHM/ ISHM)
- Chemical, nuclear, refinery, and process plant instrumentation
- Powertrain controls for gas or diesel internal combustion engines (e.g., improved waste gate turbobooster)

Phase II Objectives

- Update data concentrator modifications from DECWG and prime contractor
- Define requirements for the OTP, TVS, and 3.3V linear regulator
- Validate each design by testing over temperature and under load

Benefits

- Enables replacement of the large bundles of noise-sensitive analog cable interfaces between sensors/ actuators and the FADEC with a digital data bus, thus reducing weight
- Optimizes actuator performance through closed-loop control
- Lowers maintenance costs through condition-based maintenance (CBM) and PHM capabilities
- Lowers costs for FADEC upgrades

Firm Contact

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Proposal Number: 10-2 A2.07-8712

Magnesium Hall Thruster


Busek Co., Inc. photo

For solar system exploration

This Phase II project is developing a magnesium (Mg) Hall effect thruster system that would open the door for *in situ* resource utilization (ISRU)-based solar system exploration. Magnesium is light and easy to ionize. For a Mars–Earth transfer, the propellant mass savings with respect to a xenon Hall effect thruster (HET) system are enormous. Magnesium also can be combusted in a rocket with carbon dioxide (CO_2) or water (H_2O), enabling a multimode propulsion system with propellant sharing and ISRU. In the near term, CO_2 and H_2O would be collected *in situ* on Mars or the moon. In the far term, Mg itself would be collected from Martian and lunar regolith.

In Phase I, an integrated, medium-power (1- to 3-kW) Mg HET system was developed and tested. Controlled, steady operation at constant voltage and power was demonstrated. Preliminary measurements indicate a specific impulse (Isp) greater than 4,000 s was achieved at a discharge potential of 400 V. The feasibility of delivering fluidized Mg powder to a medium- or high-power thruster also was demonstrated.

Phase II of the project evaluated the performance of an integrated, high-power Mg Hall thruster system in a relevant space environment. Researchers improved the medium power thruster system and characterized it in detail. Researchers also designed and built a high-power (8- to 20-kW) Mg HET. A fluidized powder feed system supporting the high-power thruster was built and delivered to Busek Company, Inc.

Applications

NASA

- NASA Flagship, Frontier, and Discovery class missions:
  - Extremely high Isp at voltages typical of low-cost, flight-qualified power processors
- Missions to asteroids, comets, and the outer planets
- Sample return missions
- Lunar and Martian missions
- Manned missions for transporting fuel and cargo
- *In situ* propellant use at the Moon and Mars
- Multimode Mg-based propulsion system:
  - Featuring a Mg rocket and a Hall thruster with full or partial propellant sharing

Commercial

- Satellite orbit maintenance, orbit raising, and repositioning
- One-half of a multimode propulsion system that also contains a Mg-based rocket

Phase II Objectives

- Evaluate the performance of an integrated, laboratory model Mg Hall thruster system in a relevant space environment
- Develop a Mg Hall thruster system
- Achieve Isp of 4,000 to 6,000 s from commercial orbital transportation services–derived 400- to 600-V power processing unit (PPU)

Benefits

- Higher Isp and less life-limiting erosion than a xenon HET:
  - Isp for a high-efficiency Mg Hall thruster driven by a 400-V PPU may exceed 5,000 s
- Low propellant cost and low-pressure propellant storage
- System efficiency in excess of 50 percent

Firm Contact

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Proposal Number: 10-2 T3.01-9872

Thin Aerogel as a Spacer in Multilayer Insulation

For cryogenic space applications

Cryogenic fluid management is a critical technical area that is needed for future space exploration. A key challenge is the storability of liquid hydrogen (LH_2), liquid methane (LCH_4), and liquid oxygen (LOX) propellants for long-duration missions. The storage tanks must be well-insulated to prevent overpressurization and venting, which can lead to unacceptable propellant losses for long-duration missions to Mars and beyond.

Aspen Aerogels had validated the key process step to enable the fabrication of thin, low-density aerogel materials. The multilayer aerogel insulation (MLAI) system prototypes were prepared using sheets of aerogel materials with superior thermal performance exceeding current state-of-the-art insulation for space applications. The exceptional properties of this system include a new break-through in high-vacuum cryogenic thermal insulation, providing a durable material with excellent thermal performance at a reduced cost when compared to longstanding state-of-the-art multilayer insulation systems. During the Phase II project, further refinement and qualification/system-level testing of the MLAI system will be performed for use in cryogenic storage applications.

Aspen has been in discussions with United Launch Alliance, LLC; NASA's Kennedy Space Center; and Yetispace, Inc., to test the MLAI system on real-world tanks such as Vibro-Acoustic Test Article (VATA) or the Cryogenic Orbital Testbed (CRYOTE).

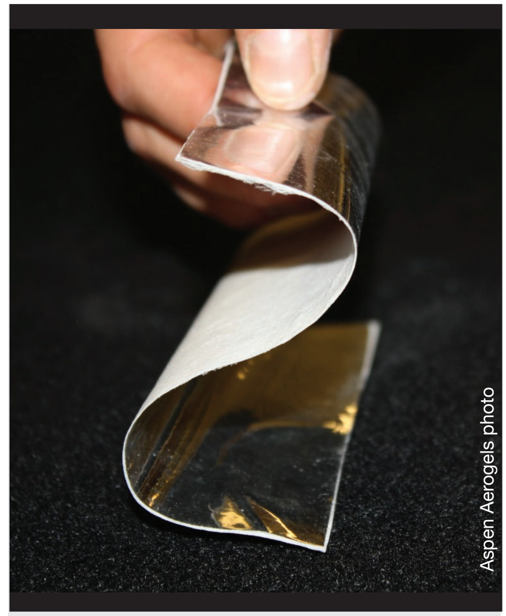
Applications

NASA

- Insulation for cryotanks and cryogen transfer pipelines for ground processing
- Cryogen storage insulation for in-space applications
- Satellite thermal management
- Extravehicular activity (EVA) suits
- Internal insulation on future generations of reusable launch vehicles

Commercial

- Durable and reliable insulation systems for any cryogenic, high-vacuum, or thin and flexible applications:
  - Appliances
  - Airliner fuselage
  - Liquid natural gas fuel storage tanks and transfer lines
  - Apparel



Aspen Aerogels photo

Phase II Objectives

- Refine low-density and thin aerogel formulations
- Optimize thin aerogel scale-up process and MLAI system fabrication
- Assess MLAI prototype performance:
  - Cryostat 500 (size 8-in diameter) testing
- Large-scale testing of optimum MLAI system:
  - Cryostat 100 (2 x 4-ft size)
  - System-level testing at Ball Aerospace & Technologies Corp.

Benefits

- More durable and robust multilayer insulation system that is easy to install
- Improved process for manufacturing thin, low-density aerogel materials
- Superior thermal insulation for cryogenic applications

Firm Contact

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Proposal Number: 11-2 X10.01-9295

Iodine Hall Thruster

For space exploration

Iodine enables dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers. The demonstrated throttling ability of iodine is important for a singular thruster that might be called upon to propel a spacecraft from Earth to Mars or Venus. The ability to throttle efficiently is even more important for missions beyond Mars.

In the Phase I project, Busek Company, Inc., tested an existing Hall thruster, the BHT-8000, on iodine propellant. The thruster was fed by a high-flow iodine feed system and supported by an existing Busek hollow cathode flowing xenon gas. The Phase I propellant feed system was evolved from a previously demonstrated laboratory feed system. Throttling of the thruster between 2 and 11 kW at 200 to 600 V was demonstrated. Testing showed that the efficiency of iodine fueled BHT-8000 is the same as with xenon, with iodine delivering a slightly higher thrust-to-power (T/P) ratio.

In Phase II, a complete iodine-fueled system was developed, including the thruster, hollow cathode, and iodine propellant feed system. The nominal power of the Phase II system is 8 kW; however, it can be deeply throttled as well as clustered to much higher power levels. The technology also can be scaled to greater than 100 kW per thruster to support megawatt-class missions. The target thruster efficiency for the full-scale system is 65 percent at high specific impulse (Isp) (~3,000 s) and 60 percent at high thrust (Isp ~2,000 s).

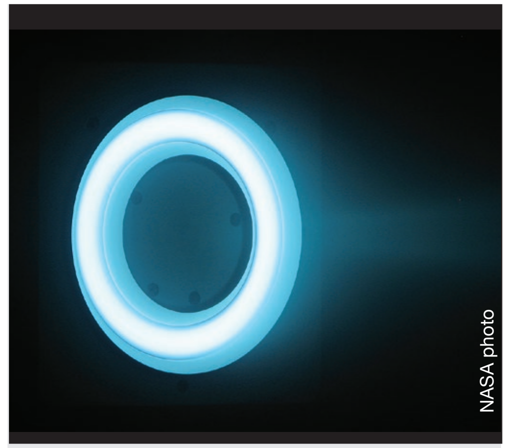
Applications

NASA

- Orbit raising and interplanetary transfers:
  - Exploration and science missions to near-Earth objects, asteroids, comets, and planets
- Reboosting the International Space Station (ISS), which is currently accomplished by chemical propulsion

Commercial

- Orbiting spacecraft:
  - Orbit raising
  - Orbit circularization
  - Inclination changes
  - Station keeping
  - Repositioning
- High-power electric upper stage for a commercial launch vehicle



NASA photo

Phase II Objectives

- Design and build fully integrated high-power iodine thruster system consisting of a thruster, cathode, and propellant feed system
- Measure performance of integrated system
- Assess materials compatibility requirements and system issues
- Collect data to assess spacecraft interactions

Benefits

- High-purity iodine is available commercially in large quantities and at much lower cost than xenon.
- Iodine stores at two to three times greater density than xenon and at approximately one-thousandth of the pressure and may be stored in low-mass, low-cost propellant tanks.
- Passive, long-term storage of a fully fueled system is feasible, including storage in conformal tanks that may be used to shield internal components against some types of space radiation.

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