NASA/TM—2015-218902

An Overview of 2014 SBIR Phase II Power, Energy Storage, and Storage

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

December 2015

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Abstract

NASA's Small Business Innovation Research (SBIR) program focuses on technological innovation by investing in the development of innovative concepts and technologies to help NASA mission directorates address critical research and development needs for Agency programs.

This report highlights 21 of the innovative SBIR Phase II projects from 2007 from 2012 that focus on one of NASA Glenn Research Center's six core competencies—Power, Energy Storage, and Conversion. The technologies cover a wide spectrum of applications such as multijunction solar cells, roll-out solar arrays, photovoltaic concentrator blanket assemblies, wide bandgap power semiconductor modules, and indium-gallium nitride high temperature photovoltaic cells. Each article describes an innovation, technical objective, and highlights NASA commercial and industrial applications.

This report provides as an opportunity for NASA engineers, researchers, and program managers to learn how NASA SBIR technologies could help their programs and projects, and lead to collaborations and partnerships between small SBIR companies and NASA that would benefit both.

High-Volume Production of Lightweight Multijunction Solar Cells

Reduces the cost of cells via a 6-inch gallium arsenide (GaAs) epitaxial lift-off and substrate reclaim process

MicroLink Devices, Inc., has transitioned its 6-inch epitaxial lift-off (ELO) solar cell fabrication process into a manufacturing platform capable of sustaining large-volume production. This Phase II project improves the ELO process by reducing cycle time and increasing the yield of large-area devices. In addition, all critical device fabrication processes have transitioned to 6-inch production tool sets designed for volume production. An emphasis on automated cassette-to-cassette and batch processes minimizes operator dependence and cell performance variability. MicroLink Devices established a pilot production line capable of at least 1,500 6-inch wafers per month at greater than 80 percent yield. The company also increased the yield and manufacturability of the 6-inch reclaim process, which is crucial to reducing the cost of the cells.

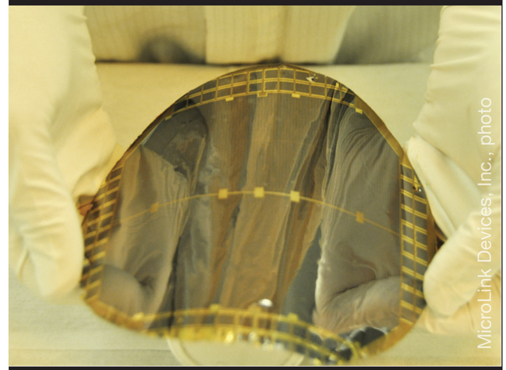
Applications

NASA

- Solar electric propulsion programs

Commercial and Military

- Electric-powered unmanned aerial vehicles (UAVs)
- Commercial and military satellites
- Portable solar electric power chargers



Phase II Objectives

- Improve the manufacturability and reduce the cost of the 6-inch ELO process for fabricating high-efficiency, large-area multijunction solar cells
- Optimize the 6-inch ELO process for high throughput and yield (greater than 80 percent)
- Use automated process tool sets capable of more than 1,500 6-inch wafers per month
- Establish a production-ready 6-inch GaAs substrate reclaim process

Benefits

- Produces lightweight and high specific power multijunction solar cells
- Offers an inexpensive and streamlined manufacturing process

Firm Contact

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Proposal Number: 11-2 X8.04-9001

Active High-Temperature Heat Pipes

For spacecraft nuclear fission systems

Future space transportation and surface power applications require small fission reactors for power generation. To support future NASA science missions, the reactors must have an 8- to 15-year design life. Heat pipes are being examined to transfer the thermal energy from the reactor to the electric conversion systems. Arterial heat pipes are the default design for spacecraft nuclear reactors; however, depriming of the artery due to radiation is a serious potential problem. Grooved and self-venting arterial heat pipes are less susceptible to depriming because the liquid in the grooves is open to the vapor space and the self-venting arterial heat pipe has venting pores in the evaporator to allow trapped vapor to escape. Advanced Cooling Technologies (ACT) examined the tradeoffs between the three types of heat pipe wicks—grooved, self-venting arterial, and sintered arterial—and determined an optimum wick design that is suitable for fission reactor applications.

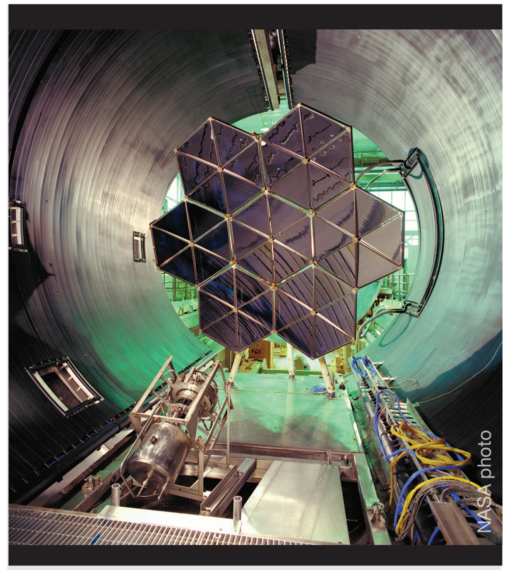
Applications

NASA

- Space fission nuclear reactors that utilize Stirling or thermoelectric converters for power conversion:
  - 1 kWe fission power system with a 15-year design life:
    - The alkali metal heat pipes would be capable of transporting the reactor heat to the Stirling or thermoelectric converters for power generation.
  - Lower temperature radiator heat pipes

Commercial and Military

- Waste heat energy recovery and utilization, specifically for automotive engines and military generator sets:
  - The exhaust heat generated in these applications is considered high-grade heat and would require alkali metal heat pipes for collection and transportation.
  - The high-temperature heat pipes could be used to collect the high-grade exhaust heat and transfer it to either a catalyst converter to reduce the energy needed for vehicle startup or to Stirling engines for electrical energy generation.
- High-temperature solar receivers:
  - Thermochemical reduction processes used to generate alternate energy must be performed at very high temperatures. The high-temperature heat pipes developed could be used to transfer the thermal energy collected by a solar receiver to a reactor to aid in the thermochemical reduction process.



Phase II Objectives

- Develop low-mass alkali metal heat pipes for space fission reactors, examining the tradeoffs between grooved, conventional arterial, and self-venting arterial heat pipe wicks
- Demonstrate the feasibility of alkali metal grooved and self-venting heat pipes for a space fission reactor
- Fabricate and test full-length versions of the sintered arterial and self-venting arterial heat pipe wicks for both the Stirling and thermoelectric energy conversion systems

Benefits

- Ensures long design life
- Identifies optimum wick design for fission reactor applications

Firm Contact

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Proposal Number: 11-2 X8.03-9866

Thermal Management System for Long-Lived Venus Landers

For more efficient thermal management on deep space missions

The thermal management system for a long-lived Venus lander is critical for mission success. This project is developing a passive high-temperature thermal management system (HTTMS) for the radioisotope power conversion system that energizes the refrigeration system for Venus missions. The innovation consists of a high-temperature alkali metal variable conductance heat pipe (VCHP) integrated with a two-phase heat collection/transport package from the general purpose heat source (GPHS) stack to the Stirling converter heater head. The HTTMS collects the heat from the GPHS modules and delivers heat, as required, to the Stirling system. The VCHP removes any excess heat when the Stirling system is shut down or in the early stages of a mission powered by a short-life radioisotope. A full-scale HTTMS has been designed and a representative multisegment of the full-scale HTTMS built and tested. This multisegment contains two or three parallel/redundant heat paths from the simulated GPHS stack to the heater head simulator in addition to the VCHP backup cooling system. The full-scale multisegment HTTMS has been integrated and tested with the corresponding full-scale multisegment of the intermediate-temperature thermal management system of the Venus lander.

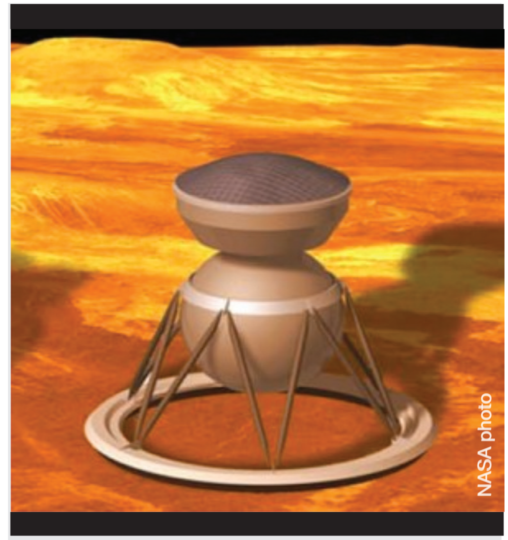
Applications

NASA

- Venus missions:
  - Thermal management for a long-lived Venus lander cooled with a Stirling system
  - High-powered radioisotope systems that require a large number of GPHS modules
  - Smaller systems that use the less-efficient americium-241–based GPHS modules
- Deep space missions powered by alternate radioisotopes
- Missions to other high-temperature locations in the solar system

Commercial and Military

- Pressure-controlled isothermal furnace liners:
  - An isothermal furnace liner is an annular alkali metal heat pipe. Replacing the current heat pipe with a pressure-controlled VCHP will allow much tighter temperature control.
- Fuel cell reformers:
  - In a fuel cell reformer, diesel fuel and air pass through a series of high-temperature reactors to generate hydrogen. The operating temperature of the reactors must be closely controlled to maintain their chemical equilibrium. Alkali metal VCHP heat exchangers can replace the current heat exchanger and control system with a passive system that automatically maintains the output stream from the heat exchanger at a constant temperature.



Phase II Objectives

- Develop an HTTMS for the long-lived Venus lander
- Develop a full-scale design
- Fabricate a single-segment system for 650 °C that can be tested with a Stirling converter
- Fabricate and test a multisegment system operating at 1,000 °C, including tests in the Venus Chamber

Benefits

- Efficiently collects heat from the GPHS modules and delivers it to the Stirling engine
- Allows the Stirling converters and cooling to be shut off during the transit to Venus, saving heater head life
- Allows the use of alternative isotopes with a shorter half-life than plutonium-238

Firm Contact

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Proposal Number: 09-2 S3.03-8061

Optimization of the Roll-Out Solar Array (ROSA) and Mega-ROSA

High-efficiency photovoltaic power production

The Mega-ROSA is a new, highly modularized, and extremely scalable self-deployed solar array that provides immense power level range capability, from 100 kilowatts to several megawatts. Mega-ROSA, an enhancement of NASA's ROSA, will enable extremely high power spacecraft and solar electric propulsion powered missions, including space tug and large-scale planetary science and lunar/asteroid exploration missions. Mega-ROSA/ROSA is adaptable to all photovoltaic and concentrator flexible blanket technologies.

This Phase II project optimized the Mega-ROSA/ROSA technology and deployable structural system. More specifically, the project optimized the elastically deployable slit-tube thin-shell boom structures through advanced composites design, development and analytical modeling, materials design and development, innovative and affordable manufacturing processes, and the development of accurate engineering methodologies to rapidly allow for new material properties and design performance characterizations. The team developed new and innovative structural sections/configurations, such as section closeout and root reinforcement. Finally, the team developed and refined innovative and affordable composite structure fabrication processes.

Applications

NASA

- Solar electric propulsion:
  - Appropriate for NASA missions that require high-efficiency photovoltaic power production through deployment of an ultralightweight and highly modular structural system

Commercial

- Solar electric propulsion
- Low Earth orbit (LEO) surveillance, reconnaissance, communications, commercial mapping, and other critical payload/equipment satellites
- Medium Earth orbit (MEO) satellites and space tugs
- Geosynchronous orbit (GEO) communications and critical payload/equipment satellites
- Fixed-ground and deployable/retractable mobile ground-based systems

Phase II Objectives

- Optimize Mega-ROSA/ROSA solar array materials and structures
- Characterize creep/relaxation phenomena
- Perform analytical modeling
- Optimize the array's manufacturing process

Benefits

- Inexpensive
- Ultralightweight
- Compact stowage volume (< 50 kW/m^3 for very large arrays)
- High strength and stiffness
- Capable of providing power levels from 60 kW to more than 300 kW
- Operates in high-voltage and high- or low-temperature environments
- Radiation tolerant
- Scalable

Firm Contact

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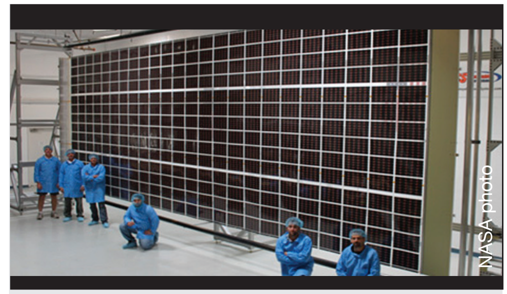
Proposal Number: 11-2 T3.01-9785

Modular Ultra-High-Power Solar Array Architecture

Novel hardware for photovoltaic (PV) power production

Deployable Space Systems (DSS) has developed hardware for the Mega Roll-Out Solar Array (Mega-ROSA), a highly-modularized and scalable solar array that provides immense power level range capability. The Mega-ROSA technology can package much more power into a given launch vehicle envelope than any other solar array, potentially enabling new missions. The stowed package of an ultra-high-power array can fit within the compact stowage volume of a smaller, less expensive, and more readily available launch vehicle.

This Phase II project validated and demonstrated key Mega-ROSA hardware scale-up through the design, development, manufacture, and test of a very large, representative-scale Mega-ROSA engineering development unit (EDU) solar array wing system.



Phase II Objectives

- Validate and demonstrate key Mega-ROSA hardware scale-up
- Design, develop, manufacture, and test a very large, representative-scale Mega-ROSA EDU solar array wing system

Benefits

- Low cost (25-50 percent cost savings, depending on PV and blanket technology)
- High specific power (>200 W/kg to 400 W/kg beginning of life [BOL] at the wing level, depending on PV and blanket technology)
- Compact stowage volume (>50 kW/m^3 for very large arrays)
- Platform simplicity (low parts count and reduced potential failure modes)
- High deployed strength/stiffness (>5 times stiffer and stronger than rigid panel arrays of similar sizes)
- High-voltage operations capability
- Scalable to ultrahigh power (100 kW to several megawatts)
- Unique environment operation (high/low illumination, high/low sun intensity, and high radiation)

Applications

NASA

- PV power production
- High-power spacecraft
- Solar electric propulsion (SEP) spacecraft
- Space tugs
- Large-scale planetary science applications:
  - Mega-ROSA's potential to reduce launch vehicle needs could provide a step function in large NASA SEP/Exploration mission cost savings.

Commercial

DSS has formed a strategic relationship with Orbital Sciences Corporation and Space Systems Loral for this program and the Mega-ROSA technology to help expedite commercialization/technology infusion into their high-power applications, including:

- High-power spacecraft
- Space tugs
- Power stations
- Other large-scale applications
- Low Earth orbit (LEO) surveillance, reconnaissance, communications, mapping, and other critical payload/equipment satellites
- Medium Earth orbit (MEO) satellites and resupply space tugs
- Geosynchronous Earth orbit (GEO) communications satellites

Firm Contact

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Proposal Number: 10-2 X8.04-9339

PV Concentrator Blanket Assembly for Ultralightweight Solar Arrays

Highly affordable, lightweight blanket assembly can be rolled or z-folded

The Flexible Array Concentrator Technology (FACT) is a lightweight, high-performance reflective concentrator assembly that can be used on solar array blankets. FACT replaces alternating rows of solar cells on a solar array blanket, significantly reducing the cost of the array. The modular design is highly scalable for the array system designer, and it exhibits compact stowage, good off-pointing acceptance, and mass/cost savings. The assembly's relatively low concentration ratio, accompanied by a large radiative area, provides for a low cell operating temperature and eliminates many of the thermal problems inherent in designs with a high concentration ratio. Unlike other reflector technologies, the FACT modules function on both z-fold and rolled flexible solar array blankets as well as on rigid array systems.

This Phase II project demonstrated the FACT concentrator flexible blanket technology, with EMCORE Corp. standard third-generation triple junction (ZTJ) photovoltaic (PV) and advanced inverted metamorphic multijunction (IMM) PV, and integrated it onto the ultralightweight Roll-Out Solar Array (ROSA) system. The relevant tests and environments included ambient/hot/cold functional deployments, thermal life cycle, vibration survivability, deployed strength/stiffness, mass properties, thermal balance in vacuum (forward bias), and high-voltage operation (water immersion).

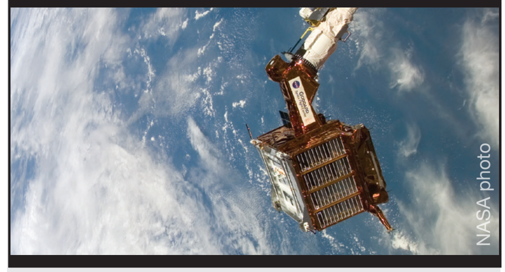
Applications

NASA

- Advanced solar array systems

Commercial

- Low Earth orbit (LEO) surveillance, reconnaissance, communications, commercial mapping, and other critical payload/equipment satellites
- Medium Earth orbit (MEO) satellites and space tugs
- Geosynchronous Earth orbit (GEO) communications and payload/equipment satellites
- Dual-use opportunities for ground and roof-mount applications
- Mobile power production for terrestrial applications



Phase II Objectives

- Demonstrate the technology and integrate it onto the ultralightweight ROSA system
- Conduct detailed design and analysis
- Validate risk mitigation component/breadboard hardware
- Validate multiple FACT flight-like panel assembly hardware coupons
- Validate large functional engineering development unit FACT/ROSA wing assembly hardware

Benefits

- High specific power (>260 W/kg beginning of life [BOL] with ZTJ/NeXt triple-junction and ~400 W/kg BOL with IMM PV when coupled to ROSA array)
- Affordable (>40 percent cost savings when coupled to ROSA array)
- Flexible blanket compatibility and architecture flexibility (accommodates rolled or z-folded blankets)
- Compact stowage volume (>50 kW/m^3)
- High radiation tolerance
- High-voltage operation capability
- Adaptable to standard rigid honeycomb panel arrays

Firm Contact

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Proposal Number: 10-2 S3.03-8462

Lightweight IMM PV Flexible Blanket Assembly

For high-voltage solar electric propulsion missions

Deployable Space Systems (DSS) has developed an inverted metamorphic multijunction (IMM) photovoltaic (PV) integrated modular blanket assembly (IMBA) that can be rolled or z-folded. This IMM PV IMBA technology enables a revolutionary flexible PV blanket assembly that provides high specific power, exceptional stowed packaging efficiency, and high-voltage operation capability. DSS's technology also accommodates standard third-generation triple junction (ZTJ) PV device technologies to provide significantly improved performance over the current state of the art.

This SBIR project demonstrated prototype, flight-like IMM PV IMBA panel assemblies specifically developed, designed, and optimized for NASA's high-voltage solar array missions.

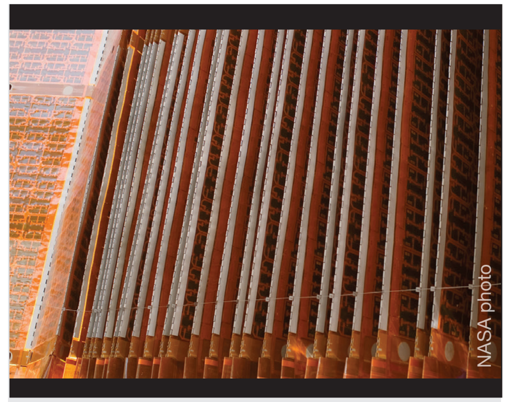
Applications

NASA

- Near- to medium-term NASA Discovery, Flagship Outer-Planets, and New Frontiers–class science missions
- Interplanetary comet rendezvous and solar electric propulsion science missions
- Low Earth orbit (LEO), geosynchronous Earth orbit (GEO), planetary or celestial-body lander, planetary orbiter, and/or deep space applications

Commercial and Military

- Power and energy production for fixed-ground, mobile, and roof-mounted consumer applications
- High-altitude airship applications
- LEO surveillance, reconnaissance, communications, commercial mapping, and other critical payload/equipment satellites
- GEO commercial and Defense Department communications and critical payload/equipment satellites



Phase II Objectives

- Demonstrate and validate prototype IMM PV IMBA panel assemblies specifically developed, designed, and optimized for NASA's high-voltage solar array missions
- Develop scalable analytical models and correlate with test results to validate IMM PV IMBA prototype hardware
- Develop technology and manufacture infrastructure

Benefits

- High-voltage operability
- High specific power (>1,000 W/kg beginning of life [BOL] at the blanket subsystem level; >500 W/kg BOL at the array level)
- Compact stowage volume (>50 kW/m^3)
- Rollable or z-foldable for stowage
- Flexible and durable
- Adaptable to all existing industry flexible blanket solar array products

Firm Contact

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Proposal Number: 09-2 S3.03-8863

Advanced Passive Liquid Feed PEM Electrolyzer

Reduces system weight while offering high operational efficiency

Proton Exchange Membrane (PEM) water electrolyzers have undergone continuous development for commercial, military, and space applications since the 1970s. Unfortunately, conventional technology requires a complex balance of plant components that add weight to the overall system package. This SBIR project is developing a high-pressure electrochemical cell architecture that uses novel water management technology to generate a passive liquid feed electrolyzer capable of operating at 2,000 psi and scalable to higher pressures. This new technology can substantially reduce system weight while offering high system operational efficiency and enhanced current density capability.


Department of Energy photo

Applications

NASA

- Energy storage
- High energy density systems for long-term space travel as well as lunar and Mars bases:
  - Oxygen produced at high pressure can be used to meet life support needs, including recharge of the extravehicular mobility unit (EMU).
- Hydrogen recovery systems:
  - Substantial savings are possible due to hydrogen loss resulting from cryogenic boil-off.

Commercial and Military

Successful development of efficient, high-pressure water electrolysis systems is critically important in meeting developing needs in the hydrogen economy:

- Refineries
- Ammonia production
- Chemical plants
- Vehicle refueling applications (require higher pressures, up to 12,000 psi)

Phase II Objectives

- Evaluate and develop critical aspects of the advanced passive liquid cathode feed PEM electrolyzer
- Increase technical readiness level of the design
- Compare four water feed approaches
- Conduct data analysis and system modeling
- Design/Develop system and stack
- Test short stack performance and endurance

Benefits

- Reduces system weight
- Offers high operational efficiency
- Enhances current density capability

Firm Contact

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Proposal Number: 10-2 X8.01-8730

Thin, Flexible IMM Solar Array

Offering higher efficiencies and lower mass and flexibility

NASA needs solar arrays that are thin, flexible, and highly efficient; package compactly for launch; and deploy into large, structurally stable high-power generators. Inverted metamorphic multijunction (IMM) solar cells can enable these arrays, but integration of this thin crystalline cell technology presents certain challenges. The Thin Hybrid Interconnected Solar Array (THINS) technology allows robust and reliable integration of IMM cells into a flexible blanket comprising standardized modules engineered for easy production. The modules support the IMM cell by using multifunctional materials for structural stability, shielding, coefficient of thermal expansion (CTE) stress relief, and integrated thermal and electrical functions. The design approach includes total encapsulation, which benefits high voltage as well as electrostatic performance.

In Phase I of this project, the THINS design was refined for enhanced environmental durability and integration into a large deployment structure such as Mega Roll-Out Solar Array (Mega-ROSA) or MegaFlex. Phase II advanced the THINS technology, incorporating advanced IMM solar cells into THINS modules and then integrating these modules into the MegaFlex deployable structure where it underwent environmental testing, including launch vibration, thermal vacuum deployment, and electrostatic discharge/plasma testing. The THINS technology is further enhanced by automated manufacturing activities being performed under a Phase II SBIR with NASA, focusing on reducing manufacturing costs and scale-up. This technology is expected to provide tens to hundreds of kilowatts to enable outer planetary missions, allow improved solar electric propulsion performance during cruise, and provide significant power (i.e., hundreds of watts) despite the minimal sunlight available at the asteroid belt, Jupiter, and beyond.

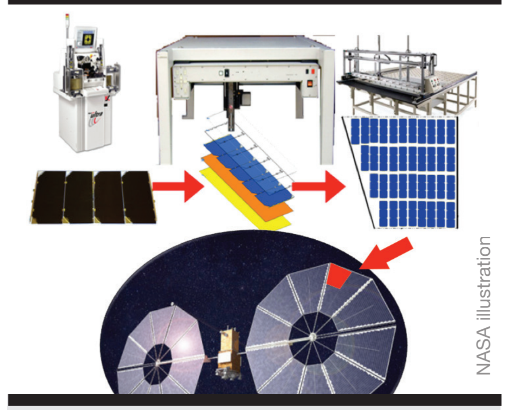
Applications

NASA

- Solar electric propulsion (SEP)
- Electric and magnetic field instruments used on NASA science spacecraft:
  - Time History of Events and Macroscale Interactions during Substorms (THEMIS)
  - Magnetospheric Multiscale (MMS) mission
  - Mars Atmosphere and Volatile Evolution (MAVEN) space probe
  - Direct-drive SEP approaches

Commercial

- Commercial spacecraft



Phase II Objectives

- Fabricate and performance test a full-scale module
- Test module coupons in the most stressing simulated space environments
- Develop and fabricate a deployment demonstration of a THINS MegaFlex array containing a complete photovoltaic array blanket comprising THINS modules with some active cells
- Demonstrate full-scale deployment at ambient, hot, and cold temperatures

Benefits

- Designed for manufacturability using mature semiconductor industry standard equipment and processes
- Fits tens of kilowatts in a compact stowage envelope
- Improves process control
- Enables smaller, more economical launch vehicles
- Uses total encapsulation and continuity of cover glass materials to create a continuous grounded, shielded enclosure

Firm Contact

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Proposal Number: 10-2 X8.04-9431

High Radiation Resistance IMM Solar Cell

For efficient, lightweight, radiation-resistant solar power

Due to high launch costs, weight reduction is a key driver for the development of new solar cell technologies suitable for space applications. This project is developing a unique triple-junction inverted metamorphic multijunction (IMM) technology that enables the manufacture of very lightweight, low-cost InGaAsP-based multijunction solar cells. This IMM technology consists of indium (In) and phosphorous (P) solar cell active materials, which are designed to improve the radiation-resistant properties of the triple-junction solar cell while maintaining high efficiency. The intrinsic radiation hardness of InP materials makes them of great interest for building solar cells suitable for deployment in harsh radiation environments, such as medium Earth orbit and missions to the outer planets. NASA Glenn's recently developed epitaxial lift-off (ELO) process also will be applied to this new structure, which will enable the fabrication of the IMM structure without the substrate.

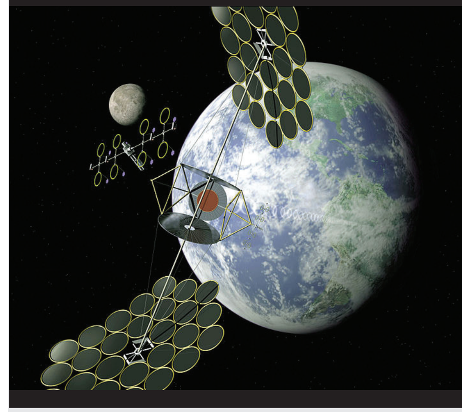
Applications

NASA

- Medium Earth orbit missions
- Outer planet missions
- Satellite power systems

Commercial

- Concentrator photovoltaic (CPV) systems to provide terrestrial solar power



NASA photo

Phase II Objectives

- Reduce efficiency degradation to less than 10 percent
- Develop solar cells with efficiency greater than 30 percent
- Maintain high end-of-life performance

Benefits

- Suitable for harsh environments
- Reduces or eliminates the heavy cover glass materials as required on conventional gallium-arsenide (GaAs)-based cells
- Uses the quaternary InGaAsP subcell rather than the GaAs subcell, allowing the use of a set of bandgaps that better match the solar spectrum
- Reuses multiple times, and ultimately recycles, the GaAs substrate on which the solar cell is grown via the ELO process

Firm Contact

MicroLink Devices, Inc.
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Proposal Number: 09-2 S3.03-8143

High-Temperature, Wirebondless, Ultracompact Wide Bandgap Power Semiconductor Modules

For space and commercial power systems

Silicon carbide (SiC) and other wide bandgap semiconductors offer great promise of high power rating, high operating temperature, simple thermal management, and ultrahigh power density for both space and commercial power electronic systems. However, this great potential is seriously limited by the lack of reliable high-temperature device packaging technology.

This Phase II project developed an ultracompact hybrid power module packaging technology based on the use of double lead frames and direct lead frame-to-chip transient liquid phase (TLP) bonding that allows device operation up to 450 °C. The new power module will have a very small form factor with 3–5X reduction in size and weight from the prior art, and it will be capable of operating from 450 °C to –125 °C. This technology will have a profound impact on power electronics and energy conversion technologies and help to conserve energy and the environment as well as reduce the nation's dependence on fossil fuels.

Applications

NASA

- Wide operating temperature power semiconductors for space power systems and science missions:
  - Spacecraft orbiting Earth, Venus, Europa, and Titan
  - Lunar Quest Program

Commercial

- Power electronics, along with computer and microprocessor technology:
  - Automobiles, electric utilities, pollution controls, communications, computer systems, consumer electronics, and factory automation
- Hybrid electric vehicles
- Renewable energy conversion
- Power supplies

Phase II Objective

- Develop an ultracompact hybrid power module packaging technology based on the use of double lead frames and direct lead frame-to-chip TLP bonding

Benefits

- Device operation up to 450 °C
- Very high current-carrying capability
- Low package parasitic impedance
- Low thermomechanical stress at high temperatures
- Double-side cooling
- Modularity for easy system-level integration

Firm Contact

Advanced Power Electronics Corp. (ApECOR)
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Orlando, FL 32826–2930
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Proposal Number: 09-2 S3.05-8550

Mesoporous Silicon-Based Anodes

For high-capacity, high-performance lithium-ion batteries

A new high-capacity anode composite based on mesoporous silicon is being developed. With a structure that resembles a pseudo one-dimensional phase, the active anode material will accommodate significant volume changes expected upon alloying and dealloying with lithium (Li). The mesoporosity is created without the aid of a surfactant template using a novel, high-volume synthetic process. The anode composite based on this material is designed to have a reversible Li-ion capacity exceeding 600 mAh/g—or nearly twice that obtainable with graphite anodes—and much higher capacities could be attainable. Phase I successfully demonstrated the synthesis of this new meso-silicon (Si) material as well as its high electrochemical activity and rechargeability. Phase II expanded the investigation of the development of mesoporous Si-based Li-ion anodes. The optimum anode was evaluated in Li-ion cells containing 4-V oxide cathodes.

Applications

NASA

- Power for landers, rovers, and extravehicular activities (EVAs)
- Space-related applications in Moon and other planetary habitats

Commercial

The new anodes will result in high-performance Li-ion batteries suitable for the following commercial applications:

- Electric vehicle propulsion
- Portable consumer products:
    - Cellular phones
    - Portable power tools
    - Cameras
    - Laptop computers

Phase II Objectives

- Expand the investigation of the development of a mesoporous, Si-based Li-ion anode
- Evaluate the optimum anode in Li-ion cells containing 4-V oxide cathodes

Benefits

- Reversible Li-ion capacity exceeding 600 mAh/g (nearly twice that obtainable with graphite anodes)
- Nonflammable
- Subambient temperature operation

Firm Contact

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Phone: 781–769–9450

Proposal Number: 09-2 X7.01-8568

Autonomous Instrumentation and Control Maintenance and Health Monitoring System

For fission surface power (FSP)

The primary goal of this project is to design and develop an autonomous instrumentation and control (I&C) health monitoring system for space nuclear power applications. The system will be able to detect anomalies based on analytical modeling techniques that use data from existing sensors in the power generator.

This Phase II project is extending the software and algorithm design into a fully functional software module for the health monitoring system. In designing and building the system, Analysis and Measurement Services Corp. (AMS) worked with NASA to determine the specific number and types of sensors, sensor interfaces, and data transfer protocols to be used. Researchers used data collected at the AMS labs and NASA historical test loop data to perform final validation testing of the developed health monitoring system. This autonomous I&C and health monitoring technology can be applied to a wide range of applications, including other space applications, propulsions systems, and next-generation designs of nuclear reactors.

Phase II Objectives

- Design and develop the prototype health monitoring system:
  - Establish software and hardware requirements
  - Design and build software modules and hardware
  - Integrate software and hardware components into a complete, self-contained prototype system
- Demonstrate functionality of the system:
  - Test integrated system on the AMS test loop
  - Test system on simulated or historical data from FSP test loop and operational FSP test loop

Applications

NASA

- Space nuclear reactors
- Nonnuclear test systems used for component- and system-level validation
- Aircraft structural and system health monitoring
- Chemical propulsion systems
- Ground test facilities for liquid fuel rocket motor testing and development

Commercial

- Nuclear power utilities for health monitoring
- Small modular reactors for autonomous health monitoring systems
- Aircraft structural and system health monitoring
- Chemical propulsion systems

Benefits

- Detects system anomalies using analytical modeling techniques
- Provides online calibration monitoring
- Provides sensor validation and fault detection capabilities
- Enables automated diagnosis of sensor and process anomalies

Firm Contact

Analysis and Measurement Services Corp.
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Proposal Number: 09-2 X7.02-8908

High-Speed Neutron and Gamma Flux Sensor

For monitoring surface nuclear reactors

NASA needs compact nuclear reactors to power future bases on the Moon and Mars. These reactors require robust automatic control systems using low-mass, rapid-response, in–core reactor power monitoring sensors and radiation-tolerant sensor interrogation systems that do not yet exist. Luna Innovations developed a new type of fiber optic miniature sensor of neutron flux and gamma flux that will have significantly faster response than recently developed fiber optic radiation sensors. Luna has optimized the sensor design and the interrogation system for high-temperature, in-core monitoring of both gamma flux and neutron flux with internal thermal compensation and *in situ* thermal calibration. Luna is delivering a lightweight sensor interrogation system, using experimentally verified radiation-hardened components wherever possible, including an analog output signal for interfacing with standard reactor control electronics. While the sensor development was focused on nuclear space power needs, the sensors also can be directly used for monitoring terrestrial nuclear power reactors.

Applications

NASA

- Lunar surface power reactors
- Mars surface power reactors
- Nuclear thermal propulsion for Mars manned missions

Commercial

- Nuclear power plants
- Nuclear waste storage facilities
- Monitoring spent fuel

Phase II Objectives

- Demonstrate the feasibility of fiber optic gamma thermometer sensors
- Continue development of the novel fiber optic neutron flux sensors
- Develop a strategy for the sensor interrogation system to operate in space radiation

Benefits

The new sensors will maintain the advantages of current fiber optic reactor sensor technology, including:

- Small size for in-core sensor distributions
- High-temperature performance (>600 °C)
- High-speed performance
- Immunity to electrical noise in the presence of ionizing radiation

Firm Contact

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Proposal Number: 09-2 X7.02-9116

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

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Proposal Number: 09-2 X8.01-8258

High-Performance Elastically Self-Deployed Roll-Out Solar Array

Lightweight, compact, flexible solar arrays

Deployable Space Systems has developed an ultralightweight elastically self-deployable Roll-Out Solar Array (ROSA) structural platform. When combined with ultrathin 33 percent inverted metamorphic multijunction (IMM) photovoltaic (PV) or 29.5 percent standard third-generation triple-junction (ZTJ) PV solar cell, flexible blanket technologies can produce a near-term and low-risk solar array system that provides revolutionary performance. ROSA's predicted performance metrics are significant improvements over current state of the art, and in many cases they are mission-enabling for future applications. The ROSA technology innovation is applicable to practically all NASA and non-NASA missions as a direct replacement for current solar array technologies.

The Phase II project was uniquely structured to develop a feasible scaled-up ROSA system specifically configured for NASA's outer-planets missions. This project will rapidly enable the ROSA technology for commercial infusion into future programs.

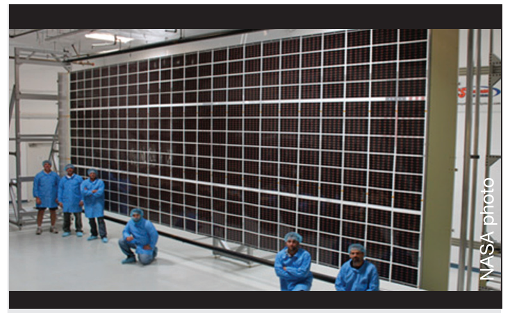
Applications

NASA

- Direct replacement for standard solar array technologies in space
- Low Earth orbit (LEO), geosynchronous Earth orbit (GEO), interplanetary, deep space, outer planets, lunar surface, and planetary lander missions

Commercial and Military

- Direct replacement for terrestrial solar array technologies
- LEO, GEO, medium Earth orbit (MEO), fixed-terrestrial, and mobile-terrestrial applications:
    - Operational responsive space, nanosatellite, military satellite communications systems, space-based radar, solar electric tugs, military space and/or terrestrial applications, and Army mobile power applications



Phase II Objectives

- Establish technology validation and demonstrate technology readiness level (TRL) 5–6 of an optimized and scaled-up ROSA solar array with thin IMM PV and ZTJ PV
- Validate technology through requirements definition, detailed design and development, analytical modeling, hardware risk mitigation, and build/test of a very large (10 kW size) ROSA engineering development unit wing system
- Correlate analytical models with test results

Benefits

- High specific power (up to 400 W/kg beginning of life [BOL] with IMM and ~200 W/kg with ZTJ)
- Lightweight
- High deployed strength and stiffness
- Compact stowage volume (>50 kW/m^3 BOL)
- Reliable
- Affordable

Firm Contact

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Proposal Number: 08-2 S3.03-8644

InGaN High-Temperature Photovoltaic Cells

For high-temperature, high-radiation environments

This Phase II project developed Indium-Gallium-Nitride (InGaN) photovoltaic cells for high-temperature and high-radiation environments. The project included theoretical and experimental refinement of device structures produced in Phase I as well as modeling and optimization of solar cell device processing. The devices have been tested under concentrated air mass zero (AM0) sunlight, at temperatures from 100 °C to 250 °C, and after exposure to ionizing radiation. The results are expected to further verify that InGaN can be used for high-temperature and high-radiation solar cells.

The large commercial solar cell market could benefit from the hybridization of InGaN materials to existing solar cell technology, which would significantly increase cell efficiency without relying on highly toxic compounds. In addition, further development of this technology to even lower bandgap materials for space applications would extend lifetimes of satellite solar cell arrays due to increased radiation hardness. This could be of importance to the Department of Defense (DoD) and commercial satellite manufacturers.

Applications

NASA

- Missions near the Sun:
  - Solar Orbiter
  - Solar Sentinels in the Living with a Star (LWS) Program
- Missions in high-radiation environments

Commercial and Military

- Terrestrial DoD applications

Phase II Objectives

- Refine single-junction device structures
- Optimize the processing of single-junction devices
- Demonstrate two-junction devices
- Verify the stability of InGaN solar cells at high temperatures and high radiation environments

Benefits

- Remains stable in high-temperature and high-radiation environments
- Extends lifetime of satellite solar cell arrays

Firm Contact

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Phone: 713–748–7926

Proposal Number: 08-2 S3.03-9731

Titanium Heat Pipe Thermal Plane

For thermal management of fuel cells

This Phase II project is completing the development of a titanium heat pipe thermal plane for thermal management of fuel cells for space applications as well as commercial applications. Modern electronic components are small in size and generate heat fluxes that cannot be handled by pure conduction or direct forced convection cooling technologies. This planar heat pipe can be integrated with a printed circuit board (PCB), allowing it to stay at near-uniform temperature. As a result, several components can be cooled utilizing a single cooling device located at the edge of the PCB.

In Phase I, three thermal plane units were produced and thermally tested. One unit was shipped to NASA Glenn, and one unit is currently in a "burn-in" setup for noncondensable gas (NCG) generation prevention. NCG generation still remains the most important issue to be resolved before the heat pipe will be ready for production. Another limiting factor for wide commercial application of the titanium heat pipes is their high manufacturing cost. These issues have been addressed in the Phase II project.

Phase II involved requirements review, thermal plane design, alternative materials development, design optimization, and NCG abatement. Researchers also are establishing all necessary steps for production of this heat pipe.

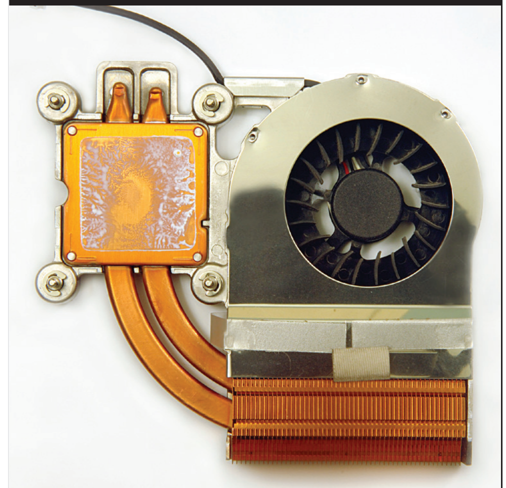
Applications

NASA

- Passive fuel cell or electrolysis cell heat removal/thermal control
- Spacecraft onboard electronics cooling
- Isothermal panels for heat radiation into space
- Radiator demonstration unit (RDU) panels

Commercial

- Electronics cooling



Phase II Objectives

Develop titanium heat pipe thermal plane with the following parameters:

- Heat pipe thickness: 0.045±0.005 inches
- Bulk density: ≤ 3 g/cm^3
- Effective thermal conductivity: ≥ 2,000 W/m·K
- Electrical resistivity: ≤ 0.2 Ω·cm
- Operation against gravity: ≥ 6 inches
- Operating temperature range: +20 °C to +90 °C
- Maximum heat flux: ≥ 0.5 W/cm^2
- Evaporator area: ≥ 150 cm^2
- Condenser area: ≤ 9 cm^2
- Life cycle: ≥ 10 years
- Manufacturing cost: ≤ $1,000 each
- Compression strength: ≥ 400 psi

Benefits

- High thermal conductivity
- Low effective density
- Coefficient of thermal expansion (CTE) match with titanium round heat pipes

Firm Contact

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Lancaster, PA 17601–4275
Phone: 717–519–3133

Proposal Number: 08-2 X6.01-8889

Advanced Cathode Electrolyzer

Based on proton exchange membrane (PEM) electrolysis technology

This Phase II project developed a static, cathode-fed, 2,000 psi, balanced-pressure Advanced Cathode Electrolyzer (ACE) based on PEM electrolysis technology. It electrolyzes water vapor supplied to the hydrogen-evolving electrode and eliminates the need to circulate hydrogen and water on the cathode side of the cell. Infinity Fuel Cell and Hydrogen's proprietary cell-sealing technology is applied to electrolysis to minimize high-pressure seals. In addition, innovative passive current-control techniques are used to eliminate potential hydrogen gas in feedwater chambers. ACE produces hydrogen and oxygen that is free of liquid water droplets without using dynamic product gas/liquid water phase separation or other motorized equipment.

Applications

NASA

- Lunar and planetary fixed-base energy storage
- Recharge of lunar rovers and portable power fuel cells
- Generation of oxygen for crew life support

Commercial

- Recharge of fuel cells for telecommunications backup power
- Remote off-grid power
- Undersea fuel cell systems
- Aircraft and airship energy storage systems

Phase II Objectives

- Prove the concept of a gravity-independent primary cathode vapor feed electrolysis cell
- Define and assess the benefits of ACE technology when incorporated into a complete system

Benefits

- Eliminates the need to circulate hydrogen and water on the cathode side of the cell
- Minimizes high-pressure seals
- Eliminates potential hydrogen gas in feedwater chambers

Firm Contact

Infinity Fuel Cell and Hydrogen, Inc.
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Proposal Number: 08-2 X6.01-9321

SiLix-C Nanocomposites

For high energy density Li-ion battery anodes

For this Phase II project, Superior Graphite Co., in collaboration with the Georgia Institute of Technology and Streamline Nanotechnologies, Inc., developed, explored the properties of, and demonstrated the enhanced capabilities of novel nanostructured SiLix-C anodes. These anodes can retain high capacity at a rapid 2-hour discharge rate and at 0 °C when used in Li-ion batteries.

In Phase I, these advanced anode materials had specific capacity in excess of 1,000 mAh/g, minimal irreversible capacity losses, and stable performance for 20 cycles at C/1. The goals in Phase II were to develop and apply a variety of novel nanomaterials, fine-tune the properties of composite particles at the nanoscale, optimize the composition of the anodes, and select appropriate binder and electrolytes. In order to achieve a breakthrough in power characteristics of Li-ion batteries, the team developed new nanostructured SiLix-C anode materials to offer up to 1,200 mAh/g at C/2 at 0 °C.

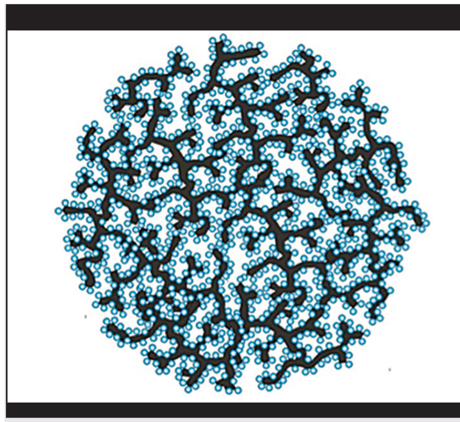
Applications

NASA

- Ascent module of the Altair Lunar Lander
- Lunar extravehicular activity (EVA) suit and integrated portable life support systems
- Lunar surface systems and mobility systems
- Uninterruptable power systems (UPS) for Orion spacecraft, the International Space Station (ISS), and other spaceflight vehicles

Commercial and Military

- Power sources for hybrid electric and electric vehicles (HEV and EV)
- Portable consumer electronics
- Handheld military equipment, exploration robots, and drones



NASA illustration

Phase II Objectives

- Identify ideal combination of binder and electrolyte material to maximize performance for silicon-carbon (SiC) nanocomposite powder at 0 °C using a charge/discharge rate of C/2
- Identify and adjust optimum parameters of SiC nanocomposite powder, such as particle size, thickness, and morphology of the carbon coating; porosity of the adaptive carbon matrix; size of Si crystals; and Si content
- Determine origin of irreversible capacity loss
- Plan and build small pilot plant
- Optimize synthesis process of SiC nanocomposite powders to maximize uniformity and reproducibility
- Develop an anode-based on the novel SiC nanocomposite powder that offers 1,200 mAh/g at C/2 at 0 °C and a long cycle life

Benefits

- High energy density
- Dramatically improved capacity
- Cycling performance

Firm Contact

Superior Graphite Co.
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Proposal Number: 08-2 X6.02-8492

Advanced Radiative Emitters

For radioisotope thermophotovoltaic (RTPV) power systems

Radioisotope power systems (RPS) are critical for future space and planetary exploration missions. Small improvements in RPS performance, weight, size, and reliability can have a dramatic effect on the scientific capability of the vehicle and the overall mission costs. RTPV energy converters are a particular type of RPS that directly convert the heat produced by a general purpose heat source to electrical power using a specialized photovoltaic (PV) cell. A key element in an RTPV system is the radiative emitter that converts thermal energy into radiative energy to illuminate the PV cell.

In this project, Creare and the Massachusetts Institute of Technology have advanced the development of a two-dimensional photonic crystal radiative emitter optimized for RTPV systems. The technology provides high emittance matched to the bandgap of the PV cell with low emittance elsewhere, providing high system efficiency. In Phase I, the team designed, fabricated, and tested prototype emitters. In Phase II, they improved and scaled up the fabrication processes. They also fabricated larger, improved test samples to be fully characterized for high-temperature emittance and durability. The project also assessed the impact of this new emitter on the overall RTPV system design and performance.

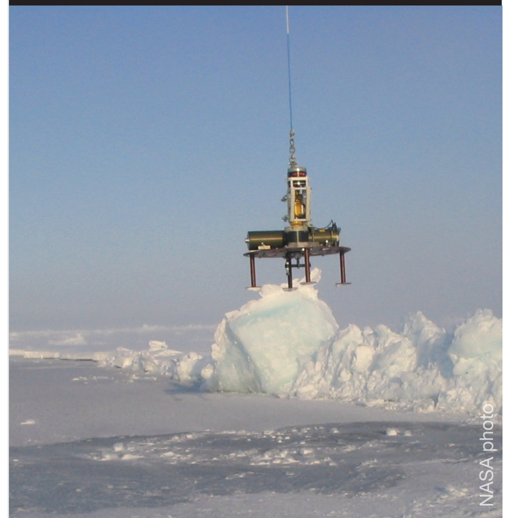
Applications

NASA

- Deep space power systems
- Exploration of the outer solar system for both spacecraft and rovers

Commercial and Military

- Military sensing
- Power for deep sea monitoring instruments
- Monitoring stations in remote locations



Phase II Objectives

- Develop an improved design of the photonic crystal for RTPV applications
- Improve high-temperature stability
- Match performance to current RTPV operating constraints
- Develop and demonstrate techniques for fabricating larger photonic crystals
- Quantify the advantages that the fabricated crystals provide to overall system efficiency

Benefits

- High mass-specific power
- High system efficiency

Firm Contact

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Proposal Number: 08-2 T3.01-9974