



2014 Overview of NASA GRC Electrochemical Power and Energy Storage Technology

Interagency Advanced Power Group
Chemical Working Group Meeting
Sandia National Laboratory
Albuquerque, New Mexico
September 11-12, 2014

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Great News!

Dr. Richard Baldwin, former IAPG CWG Chair and NASA representative to the IAPG CWG retired in late 2013 with over 25 years of NASA service.



We wish him luck in his retirement!



NASA GRC Electrochemical Technology Activities

- Mission Programs/Projects
 - International Space Station (ISS)
- Demonstrations
 - Advanced Exploration Systems Modular Power Systems Project
- Research Programs/Projects
 - Enabling Electric Aviation with Ultra High Energy Lithium Metal Batteries
 - Advanced Space Power Systems Project
 - SBIR/STTRs



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ISS Lithium-ion Battery Replacements

POC: Penni Dalton, ISS Battery Subsystem Manager, NASA GRC (216) 433-5223

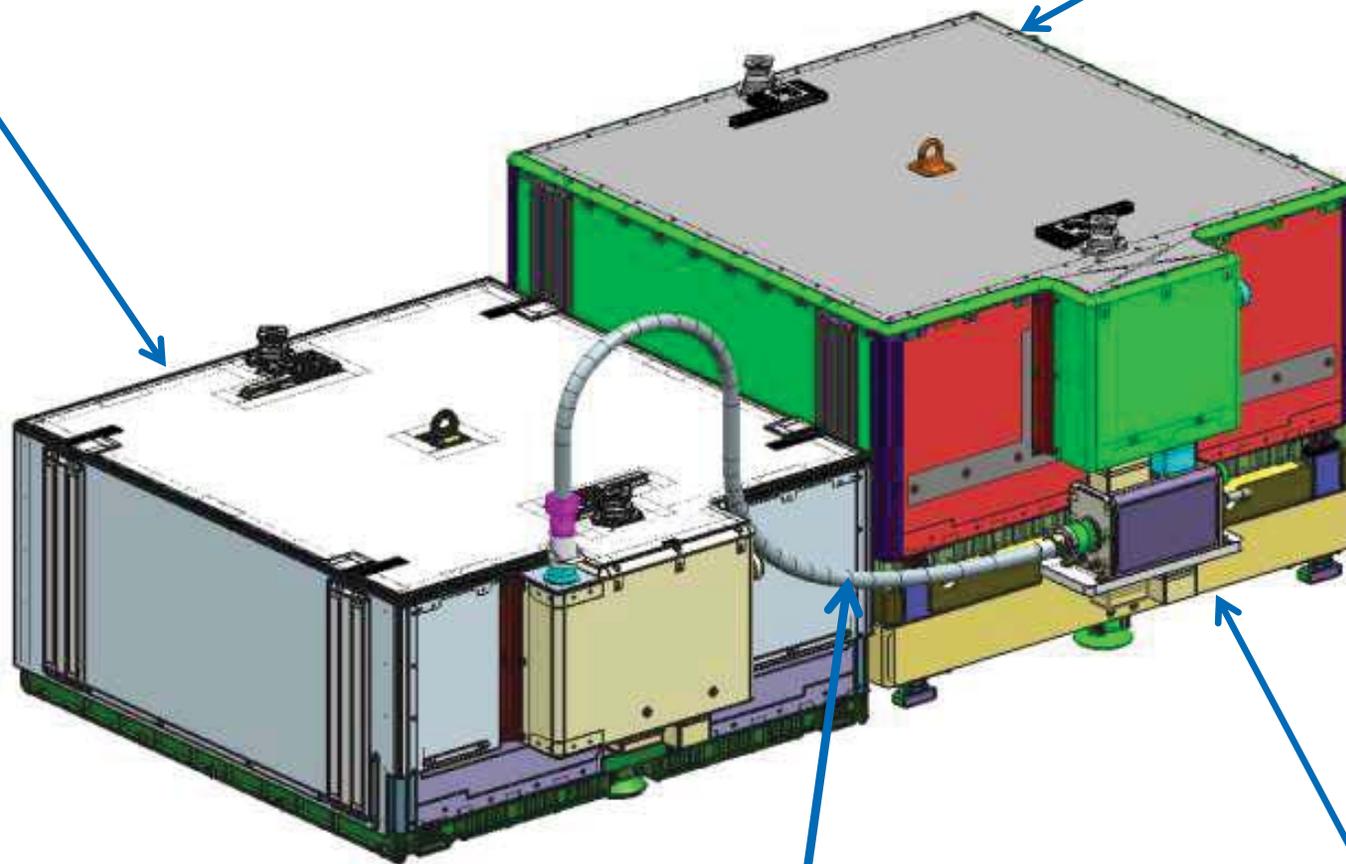
- Development of Li-ion batteries
- One Li-ion battery to replace two Nickel-Hydrogen Orbital Replacement Units (ORUs)
 - ISS battery consists of 2 NiH₂ ORUs in series
 - 76 81 Ah NiH₂ cells in series
 - Li-ion battery to replace two NiH₂ ORUs
 - 30 134 Ah Li-ion cells in series
 - 9 Ni-H₂ ORUs returned to carrier, to be burned up upon reentry
 - Second ORU slot to be covered by an Adapter Plate (AP) to make the series connection
 - 3 Ni-H₂ ORU stored on top of the AP
- First Launch of 6 Li-ion batteries scheduled for no earlier than Dec 2016 on Japanese HTV; One launch per year through 2019
- Boeing is the Prime integrator
 - 27 Battery ORUs (3 spares), 25 Adapter Plates (2 spares), 3 Status Charging Units (ground chargers)
- Aerojet Rocketdyne is the battery integrator
- GS Yuasa is the cell manufacturer



IEA Li-ion Battery/Adaptor Plate Arrangements

Li-ion Battery ORU

NiH₂ Battery ORU
Long term storage



Data Link Cable

Adaptor Plate ORU



ISS Lithium-ion Battery Replacements

- Delta ORU CDR, October 2013
- System CDR completed November 2013
- Adapter Plate Production Readiness Review, November 2013
- ORU Flight Production Readiness Review, July 2014
- ORU Li-ion venting analysis to EVA Board and Safety Review Panel, July 2014
- EM02 delivery to ISS Power Laboratory for test, September 2014
- Annual configuration management and production line audit at GS Yuasa, Kyoto Japan, September 2013 and 2014
- Cell destructive physical analysis, Lot 4, April and Lot 5, August 2014
- Qualification Units in assembly, Qualification testing to be complete February 2015
- Cell Life testing
 - LEO cycling, ~20% DOD
 - Constant current charge with stepped taper
 - Constant power discharge
 - 6 month 92 minute contingency discharge/1 year full discharge
 - Crane, GS Yuasa LSE134-101
 - Implemented improved terminal connection procedure, per Yuasa instructions, June 2014
 - Implemented 16 step charge profile, June/July 2014
 - 1P10S Lot1 cells: 12,120 cycles completed
 - 1P2S Lot 2 cells: 6,760 cycles completed
 - 1P2S Lot 3 cells: 960 cycles completed
 - GRC, GS Yuasa LNF51
 - 1P10S : 17,300 cycles completed



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AES Modular Power Systems Modular Battery FY14 Overview



AMPS Modular Battery FY14 Objectives

- Develop a 28 V battery pack compatible with the Portable Life Support System (PLSS) 2.0 assembly (advanced spacesuit life support testbed)
- Demonstrate a battery architecture that meets the immediate testbed needs and has a path forward to next generation extravehicular activities systems
- Support vacuum testing of PLSS 2.0 hardware in the testbed

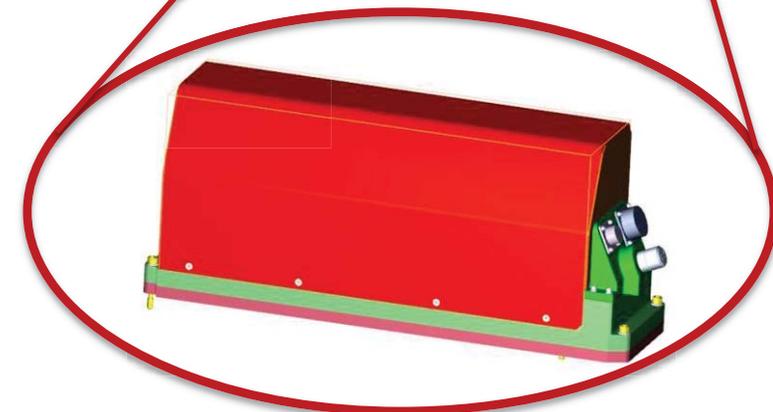
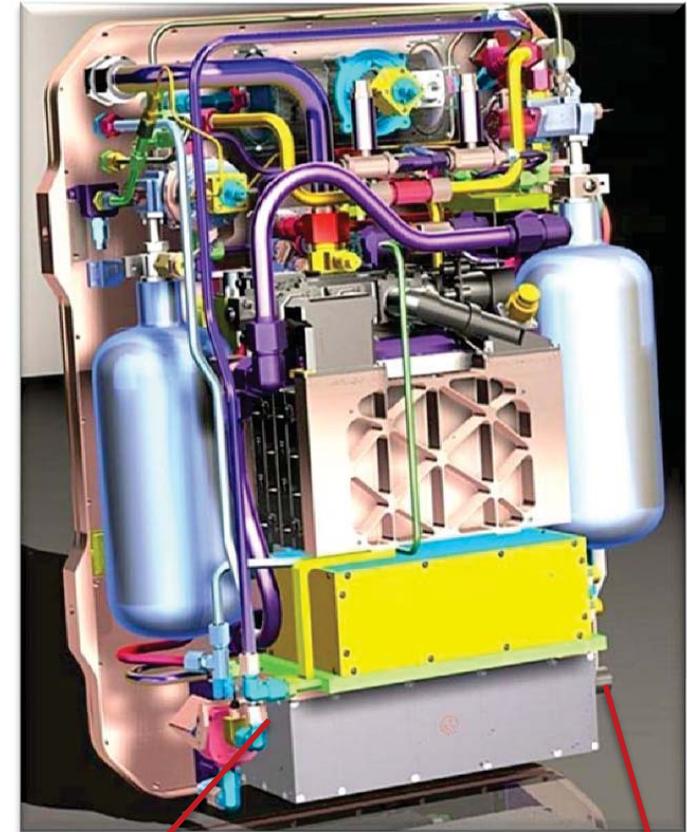
FY14 Accomplishments

- Identified modular mil spec BB-2590 lithium-ion battery packs with integrated battery management system (BMS) as candidates for the battery
- Cycled and vacuum tested packs and assessed their suitability for the application
- Designed a master BMS to monitor individual BB-2590 BMS's
- Designed separate charger and balancing system for the integrated battery
- Developed software interfaces to read BMS outputs and provide a graphical user interface for battery charging and discharging operations
- Designed, built, and currently testing integrated battery system
 - Final battery assembly contains three BB-2590 packs in parallel

FY15 Plans

- Explore the use of pouch cells in BB-2590 packs to enable a more lightweight 28 V battery
- Investigate the feasibility of a distributed battery architecture on the spacesuit to allow for more battery power than is possible within the confined volume of the backpack

POC: Larry Trase, AMPS 28V Battery Lead, NASA GRC (216) 433-5347





AES Modular Power Systems Modular Fuel Cells FY14 Overview



AMPS Modular Fuel Cells Objectives

- Advance the development of Non-Flow-Through fuel cell technology into modular packages for exploration vehicles to reduce mass and volume while increasing system reliability for extended hours of maintenance-free operation
- Demonstrate advantages of Non-Flow-Through (NFT) fuel cell technology over conventional Passive Flow Through (PFT) fuel technology

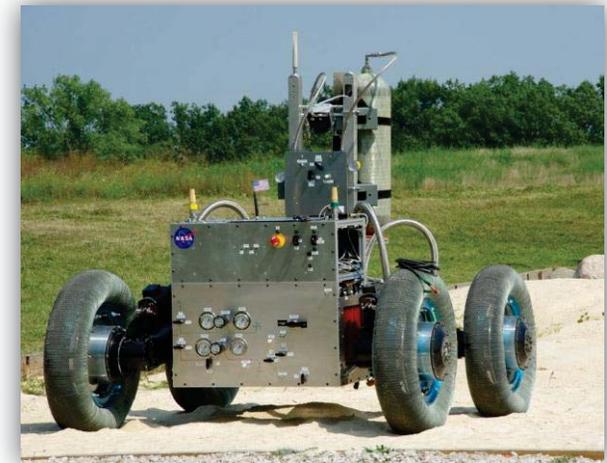
FY14 Accomplishments

- After operationally validating a 1-kW Block I NFT Fuel Cell within a modular package, the fuel cell experienced a failure during startup testing on the SCARAB rover
- After a failure investigation was completed, it was found that the sealing method for the Block I fuel cell was insufficient to allow reliable operation of the fuel cell
- A Block II fuel cell is currently being built with a proven sealing method that has successfully been implemented in the past



FY15 Plans

- The Block II fuel cell will be demonstrated in the modular package originally built for the Block I fuel cell in order to validate the lessons learned from FY14
- A conceptual study of utilizing a modular decoupled regenerative fuel cell system for the RESOLVE rover will be completed
- The Block II fuel cell modular power system will be demonstrated as a modular decoupled regenerative fuel cell with the RESOLVE rover as a mission target
 - A benchtop system will demonstrate the ability to meet RESOLVE mission profile
 - The SCARAB rover will demonstrate the ability to provide a mobile power platform with a regenerative fuel cell systems



POC: Monica Guzik, AMPS Fuel Cell Lead, NASA GRC (216) 433-3317



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Enabling Electric Aviation with Ultra High Energy Lithium Metal Batteries

- **Goal:** *Develop a predictive tool to screen and design novel electrolytes for development of ultra high energy batteries*
- **Funding:** *\$275k plus \$75k option awarded for 18-month performance period from Sept 2013 – Feb 2015*
- **Status:**
 - Determined transport properties (computation/experiment) of additional new ionic liquids (ILs)
 - Determined electrochemical window of ILs (computation/experiment)
 - Determined differential capacitance of ILs on electrode with applied voltages (computation/experiment)
 - Built and cycled coin cells with new additional ILs
 - Evaluating the ILs in Li/O₂ systems using lab cells

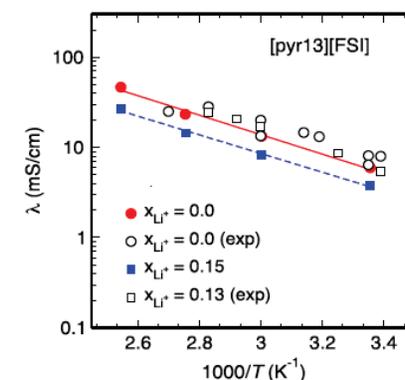


Figure 1: Simulation and experimental results for ionic conductivity of [pyr13][FSI]

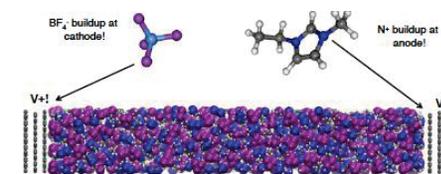


Figure 3: Molecular structure of electrochemical interface with [EMIM][BF₄]

POC: Dr. James Wu, NASA GRC, (216) 433-5231



		FY13	FY14	FY15
Batteries	Total \$K	1708	865	
	FTE	3.5	2.5	
Fuel Cells	Total \$K	3725	1549	
	FTE	4.5	1.5	
PV	Total \$K	2165	1477	
	FTE	2.5	2.0	

Purpose/Goals/Objectives/Issues

Purpose/Goals:

- (1) Improve the specific energy of batteries to increase EVA mission duration
- (2) Increase the reliability of regenerative fuel cell systems
- (3) Reduce cost of very large solar arrays to enable affordable deep space exploration

Objectives:

- (1) Demonstrate lithium ion cells that meet EVA goals.
- (2) Demonstrate 1-kW non-flow-through fuel cell, 1-kW electrolyzer, with associated MEAs and BOP that meet vehicle requirements (such as Altair)
- (3) Identify innovative PV technologies and demonstrate performance leading to 50% cost savings in a 300 kW array

Technical Approach/Benefits/Outcomes

Develop advanced components and integrate them into power systems

Batteries: advanced silicon composite anodes, high voltage cathode (NMC), and non-flammable, electrolytes that are stable to 5V

Regenerative Fuel Cells: develop non-flow-through fuel cells, high efficiency MEAs and BOP components, and highly reliable electrolyzers

PV arrays: reduce cost of cells, interconnects, coverglasses, blankets, strings, and modules

Benefit/Outcome: Increasing available power and system reliability while reducing mass and cost

Milestones:

	Date
2 nd 1kW Non-Flow-Through Fuel Cell Assessed	Feb '14
Electrolysis Concept Selected	Mar '14
3kW NFT Fuel Cell Stack Delivered	Dec '13
Battery Cell Assessment	Oct '13

Products:

	Date
Bench-Top RFC Components Built	Sep '14
Electrolyzer Evaluation Testing Complete	Sep '14
PV Technology Demonstration	Aug '14
Li-Ion Evaluation Cells Built	Aug '14
100W RFC System Testing Complete	Oct '14

High Energy Li-ion Battery Cells



- **OBJECTIVE:** Demonstrate safe, high energy Li-ion battery cells scaled to large format size that have a capacity in excess of 210 Wh/kg with 80% capacity retention after 100 cycles at 10°C.
- **APPROACH:** Develop advanced, high energy anode and cathode components through a competitive procurement and down-select process, integrate into cells with flame retardant electrolytes and build into commercial-grade cells in partnership with battery vendors.
- **IMPACT:**



Safe, large format battery cells with specific energy greater than 210 Wh/kg offer alternative battery pack design options to small format commercial battery cells with a potential infusion path to future battery pack builds for EVA spacesuit application through the AES AMPS Project.

- **FY2014 MAJOR ACCOMPLISHMENTS:**
 - ✓ Redesigned baseline 50 Ah, NCA (nickel-cobalt-aluminum) - C(carbon) cells achieved 200 Wh/kg (22% increase) with >90% capacity retention after 100 cycles.
 - ✓ NCA – Si (silicon) large format cell design has been completed and sent to Saft America for production. The projected specific energy is 225 Wh/kg at 10°C.
 - ✓ Scaled-up UT Austin nickel-manganese-cobalt (NMC) high voltage cathode material to enable building and testing of larger cells. Coated NMC cathodes are predicted to provide a 20% increase in specific energy over NCA cathodes.



Space Power Systems: Key Milestone Report MS #4.2.5 100-W RFC Demonstration

Objective:

Complete demonstration of 100-W RFC system using passive technology (non-flow-through fuel cell and static-feed electrolyzer)

Key Deliverable:

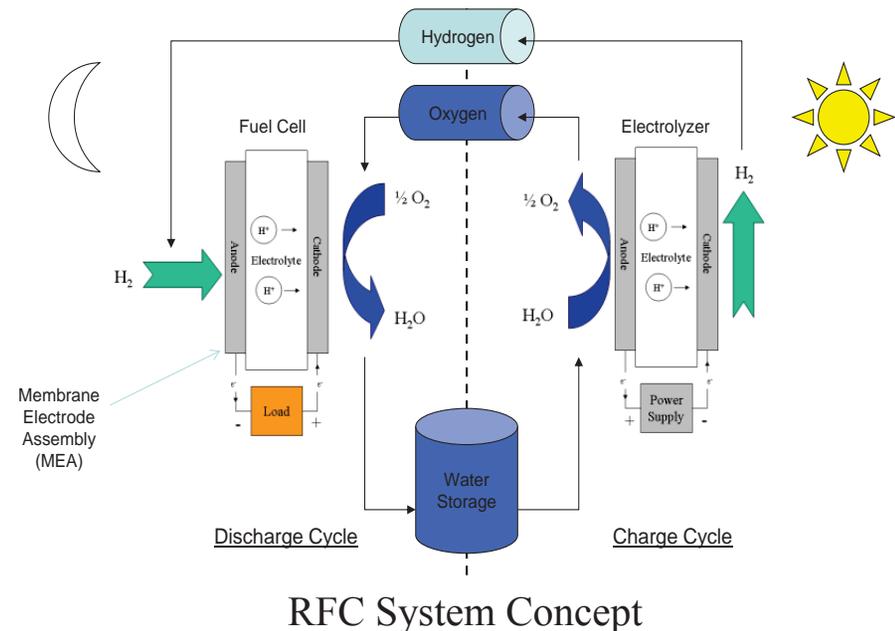
Assessment of passive RFC technology development

Description:

- 7-cell non-flow-through fuel cell stack.
- 5-cell static-feed electrolysis stack.
- Bench-top RFC “system” comprised of test stations for fuel cell and electrolysis subsystems, along with balance-of-plant for reactant management subsystem.
- Initial testing will focus on assessment of round-trip electrical efficiency and passive reactant management concepts.

Significance:

- System integration of non-flow-through fuel cell and static-feed electrolyzer technologies is a necessary precursor to further RFC “system” technology advancement:
 - This 100-W bench-top RFC demonstration will identify parameters requiring further development for fuel cell, electrolysis, and reactant management subsystems.
- This passive RFC design is targeting 10,000 hours of reliable energy storage for space applications.
- RFC subsystems have synergy with ECLSS/ISRU systems.





Alignment of NASA SBIR/STTR Topics

- NASA SBIR topics are aligned with one of four Mission Directorates
 - Solicitations focus on technology gaps specific to the particular mission directorate
- Subtopics in FY14 solicitation with focus on electrochemical technologies led by NASA Glenn Research Center:
 - Human Exploration and Operations Mission Directorate
 - X8.01 Solid Oxide Fuel Cells and Electrolyzers
 - Space Technology Mission Directorate
 - Z1.02 Advanced Space Battery Technology
 - Science Mission Directorate
 - S3.03 Power Electronics and Management, and Energy Storage
- STTR topics correspond to current highest priority technology thrusts at the NASA Center
 - No electrochemical power technologies sought in the 2014 STTR solicitation

As internal research and technology dollars shrink, SBIRs and STTRs offer opportunities to leverage technologies that are directly applicable to missions for potential mission infusion



Battery SBIRs and STTRs

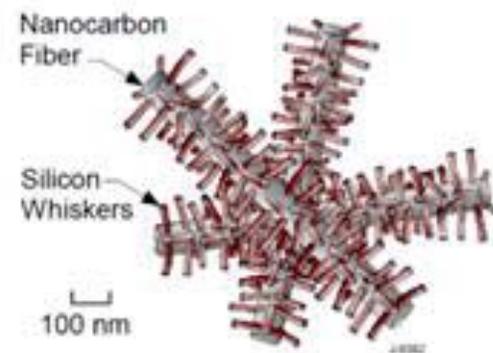
2014 Phase I SBIRs – Funding of up to \$125K for 6 months

- Z1.02-8653 - Multifunctional Electrolytes for Abuse-Tolerant 5V Li-Ion Space Batteries - PolyK Technologies, LLC
- Z1.02-8803 - High Energy Density Solid State Li-Ion Battery with Enhanced Safety - NEI Corporation
- Z1.02-8848 - Advancing High Energy Lithium-Sulfur Batteries - Yardney Technical Products, Inc.
- Z1.02-9269 - Rechargeable Lithium Metal Cell - Physical Sciences, Inc.
- Z1.02-9473 - Ultra High Energy Solid-State Batteries for Next Generation Space Power - Solid Power, Inc.
- Z1.02-9486 - Highly Conductive Polymer Electrolyte Impregnated 3d Li-Metal Negative Electrode - Xerion Advanced Battery
- Z1.02-9604 - High Performance Lithium Sulfur Battery with Novel Separator Membrane for Space Applications – Bettergy Corporation
- Z1.02-9938 - Li Metal Protection for High Energy Space Batteries - Nohms Technologies

- S3.03-9142 - High Energy Density Lithium Battery System with an Integrated Low Cost Heater Sub-System for Missions on Titan - American Energy Technologies Company
- S3.03-9514 - All-Solid, High-Performance Li-ion Batteries for NASA's Future Science Missions - TH Chem, Inc.

2012 Phase II SBIR – Funding of up to \$750K for 24 months

- H8.02-9413 Storagenergy Technologies – Advanced Li/S Batteries Based on Novel Composite Cathode and Electrolyte System



Courtesy: Physical Sciences, Inc.



PI: TC Chen

TH Chem, Inc. - Albuquerque, NM

Identification and Significance of Innovation

The state-of-the-art Li-ion battery technology is based on processing of lithium transition metal oxides, and graphite powder, and use of liquid organic electrolytes. It has shown limited room for further performance improvements in terms of energy density, cycle and calendar life, abuse tolerance and cost. This has heavily hindered the advancements of NASA's future space missions that need rechargeable batteries with higher energy density, longer life, and excellent abuse tolerance. In the commercial sector of electrical vehicles (EVs) and hybrid electric vehicles (HEVs), there are also urgent needs for rechargeable batteries with significantly higher performance characteristics that appear beyond the potential of current Li-ion system. TH Chem, Inc. (THC) proposes to team with New Mexico Institute of Mining and Technology (NMT) to develop a new, all-solid-state Li-ion technology for NASA's future space missions.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 5)

Technical Objectives and Work Plan

The new battery system is based on development of a novel, all-solid-state, 3-dimensional (D) battery design that exploits the full potentials of the electrode and electrolyte materials for significantly higher energy density (>250 Wh/kg), longer cycle life (>50,000 cycles), extended operation temperatures and radiation tolerance. In Phase I, THC will demonstrate the feasibility of the new battery technology by preparation of the proposed all-solid-state 3-D batteries via processing of electrode and electrolyte precursors, followed by electrochemical evaluation of the test cells. The concept of the new electrochemical system will be demonstrated. THC and its team have extensive experience in advanced rechargeable battery chemistries and technologies.

BATTERY PERFORMANCE CHARACTERISTICS COMPARISON

	Current Li-ion	THC's All-Solid, 3-D Li-ion
Energy Density (Wh/Kg)	~ 150	~ 250
Power Density (W/Kg)	Low	Moderate
Cycle Life	~ 1000	~ 50,000
Operation Temperature (°C)	-20 to +60	-20 to +500
Radiation Tolerance	No	Yes

NASA Applications

The new battery technology will provide more stored energy and power for improved performance of NASA's power systems in robotic and human exploration missions, satellites, spacecraft, and probes.

Non-NASA Applications

New battery technologies with improved performance characteristics have extensive applications in commercial products including electric vehicles, laptop computers, video cameras, sensors, portable tools and other consumer products.

Firm Contacts TC Chen
 TH Chem, Inc.
 9008 Cascajo NE
 Albuquerque, NM, 87111-2202
 PHONE: (505) 610-6027

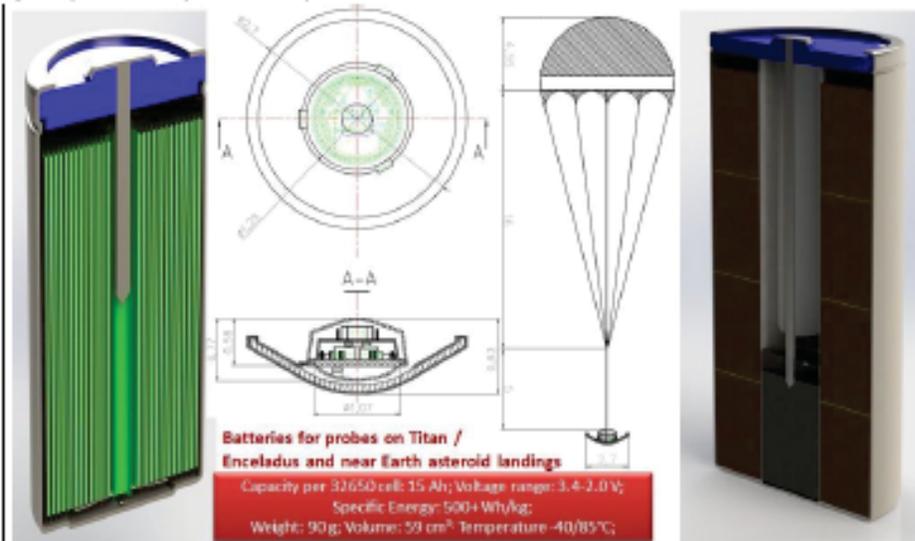
S3.03-9142 - High Energy Density Lithium Battery System with an Integrated Low Cost Heater Sub-System for Missions on Titan.

PI: Igor Barsukov

American Energy Technologies Company - Arlington Heights, IL

Identification and Significance of Innovation

The opportunity presented to NASA with this project is to conduct a thorough feasibility study into the development of a Li/CFx battery. We describe a rationale for the development of AETC battery over the incumbent Li/SO2 battery which powered the Huygens probe that parachuted on the surface of Titan in Jan. 2005 as part of the joint ESA/NASA(JPL) Cassini-Huygens mission. We analyze the Huygens probe and propose how AETC's battery can help radically improve its design. The second source of opportunity for NASA with this project is to address concerns with the application of Radioactive Heating Units as heat sources. According to the DOE in 2005 the U.S. government owned 87lbs of 238PuO2, of which roughly 36lbs remain earmarked for NASA. A tangible opportunity exists with AETC's 500+Wh/kg Li/CFx battery to dedicate a portion of its energy for the operation of a built-in heater subsystem. As a result, in Huygens-type probe the number of RHUs could be reduced from 35 to less than 20.



Estimated TRL at beginning and end of contract: (Begin: 3 End: 5)

Technical Objectives and Work Plan

The objective of the project is to help enhance technological superiority of NASA's deep space exploration systems by developing and commercializing a Lithium/Carbon Monofluoride battery system as a primary power source for the on-board DC power modules in parachutable probes and landers. The key components of the work plan are enumerated: AETC will design, manufacture and test batches of 32650 cells of spirally wound configuration; we will undertake a feasibility study of Li/CFx molded cathode cell design. The key novelty of this design will be a transition from conventional thin film pasted electrodes to compression molded cathodes of engineered porosity? akin the design of primary alkaline cells. CFx will be then diluted with an engineered amount of MnO2 and tested for how it can support discharges with 1.65A (Huygens load profile); optimization of cell performance will then ensure by developing and manufacturing, the unique additive materials to include new forms of conductive carbon; further AETC will develop an integrated heater subsystem by performing significant calculations, modeling & system design engineering work in order to develop a "smart" network of resistive heaters which will be powered by a fraction of energy taken from the excess energy budget of the Li/CFx battery; Lastly, in working with Lockheed Martin, AETC will develop initial system integration designs for a NASA lander platform. The asteroid explorer program, OSIRIS-REx is under consideration.

COR: Thomas Miller, NASA GRC, 216-433-6300

NASA Applications

The proposed development of ultra-high energy density, inherently safe and efficient advanced battery system is geared towards benefiting several groups of applications within NASA. They include the next generation safe batteries for power systems on lunar rovers, ascent systems, EVA suits, re-entry vehicles, etc. Non-Government space programs (i.e. commercial space exploration) will likely also use the battery platform in order to replace banks of lithium-ion batteries on reentry vehicles.

Non-NASA Applications

Applications on Earth for this technology include: medical batteries; power sources for remote unmanned sensors; batteries for Army Missions; consumer electronics; and in the PC computer world: CMOS backup battery; high-end computer redundant array of independent disks (RAID) disk controllers, etc.

Firm Contacts

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NON-PROPRIETARY DATA

PI: Nanyan Zhang

PolyK Technologies, LLC - State College, PA

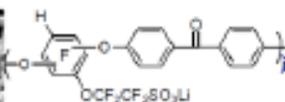
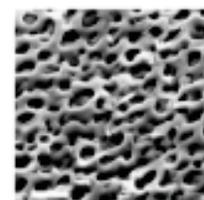
Identification and Significance of Innovation

The key innovation of this SBIR project is a multifunctional electrolyte that will enable the use of 5 V abuse-tolerant cathodes to achieve high energy density and high reliability. The non-flammability of the ionic liquid electrolyte, the superior low and high temperature performance, and the abuse-tolerant nature of the high voltage cathode, will ensure a high reliability lithium ion battery with significantly improved energy density for NASA space missions. The safety of lithium ion battery has been a serious issue limiting the use of large size battery in more applications due to the flammable carbonate solvents and the un-controlled oxidization of the cathode under abuse conditions. This SBIR Phase I project will develop a patent-pending multifunctional electrolyte that is electrochemically stable at 5 V vs Li/Li for many charge-discharge cycles to enable the adoption of the abuse-tolerant 5 V cathodes in large size batteries.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

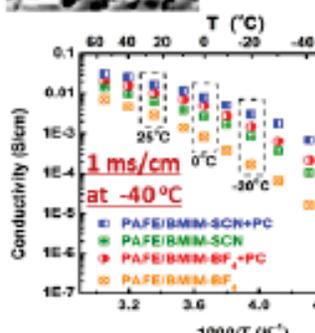
The Phase I project will evaluate the performance of the multifunctional electrolytes in coin cells made with LiCoPO₄ cathode. Compatibility of the ionomer/ionic liquid electrolyte with the 5 V cathode will be thoroughly examined to demonstrate the feasibility of the abuse-tolerant 5 V high energy density lithium ion battery technology. Various abuse tests will be performed such as overcharging, short circuit, crush, nail penetration and high temperature exposure. Low temperature test of the coin cell will be performed at <-40 degree celsius. Systematic cycling test will also be performed to meet the NASA requirement of 1,000 charge-discharge cycles. In addition, the feasibility to use lithium metal anode will also be examined to further improve the energy density of the lithium ion battery.



- 0.3~0.5 um pores
- ~47% porosity

Multifunctional Electrolyte

- PAFE ionomer electrochemically stable at 5 V vs. Li/Li⁺ → enable abuse-tolerant 5 V high energy density cathode LiCoPO₄
- Non-flammable ionic liquid with superior low temperature conductivity
- High thermal & mechanical stability



Impacts to NASA Missions

- Improve energy efficiency & size reduction
- High reliability with nonflammable electrolyte and abuse-tolerant cathode

NASA Applications

Breakthrough battery cell technologies that far exceed the specific energy and energy density of current state-of-the-art lithium-ion cell technologies are required to achieve NASA's far-term energy storage goals for human and robotic missions. The high-voltage abuse-tolerant lithium ion batteries to be developed in this project will have the critical reliability, safety, high energy density, and long lifetime for mission critical NASA space applications.

Non-NASA Applications

The high energy density and abuse-tolerant lithium ion batteries have numerous applications in military, consumer electronics, energy industry, and transportation industry, such as soldier power, auxiliary power such as in a silent watch application, cellular phones, laptop computers, power tools and transportation in an electric, hybrid electric vehicle or in aviation.

Firm Contacts

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COR: Brianne DeMattia, NASA GRC, 216-433-2511

NON-PROPRIETARY DATA

PI: Nader Hagh
NEI Corporation - Piscataway, NJ

Identification and Significance of Innovation

While rechargeable Li-ion batteries are attractive energy storage systems due to their high energy and power densities, the unfavorable side reactions between the electrodes and the liquid electrolyte adversely impact the performance as well as safety. Thus there is a need for a safe, stable and non-flammable electrolyte. The proposed program will eliminate the flammability issues of Li-ion batteries, thereby leading to a safer device with high thermal and mechanical stability. The primary objective of the Phase I is to demonstrate that the recently invented solid electrolyte can be formulated into a usable form in a practical Li-ion battery, and that traditional challenges associated with the use of a solid electrolyte can be overcome. A successful Phase I program will lay the foundation for prototype cell and cell-pack demonstration in Phase II, where Li-ion cells will be designed, assembled, and tested to meet the requirements of NASA for safety, cycle life and energy density.

Estimated TRL at beginning and end of contract: (Begin: 1 End: 3)

Technical Objectives and Work Plan

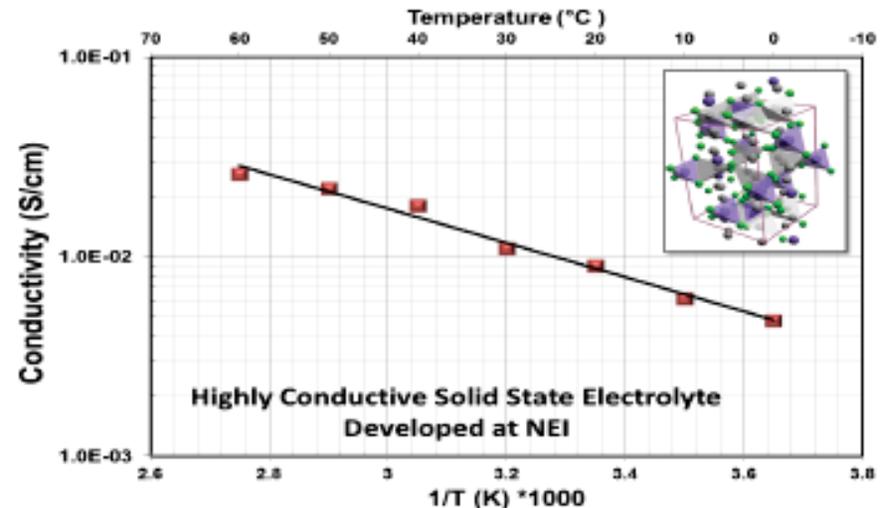
The primary goal of the Phase I program is to advance the state of the art of solid electrolyte system by demonstrating that the key challenges associated with this system can indeed be overcome, thereby leading to a practical, safe, and reliable energy storage system with high energy density.

Technical Objectives:

- (i) To fabricate an all solid state electrolyte with unique structure that utilizes the organic component to produce a unique morphology and a highly conductive and flexible network, along with structural characterization, and
- (ii) To demonstrate proof of concept for all solid state electrolyte capable of reversible and stable cycling with cell level energy density of greater than 500Wh/kg (gravimetric) and 2700 Wh/l (volumetric), while maintaining 80% of initial capacity after 500 cycles under full depth of discharge.

Work Plan:

- Prepare and synthesize of suitable cathode particles for solid state system;
- Synthesize of solid state electrolyte;
- Incorporate organic component into solid electrolyte;
- Characterize the structure of the cathode and composite solid electrolyte;
- Determine ionic conductivity and Li transference number for electrode and solid electrolyte sheets;
- Perform electrochemical cell testing using metallic anode;



NASA Applications

Safe and reliable high energy density storage devices with wide temperature of operation are required for Altair-lunar lander, extravehicular activities (EVA space suits), rovers for missions to outer planet, moon and asteroids, NASA's James Webb Space Telescope (JWST), and International X-ray Observatory (IXO).

Non-NASA Applications

The non-NASA applications include laptops, mobile phones, PDAs, portable TVs, radios, camcorders, electric razors, digital cameras, energy storage for renewable power generation (e.g., solar panels and wind turbines), electric bikes, automotives, and a wide range of military and aerospace applications such as power for sensors, and army soldier conformal batteries.

Firm Contacts

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201 Circle Drive North, Suite 102/103
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FAX: (732) 868-3143

PI: Joseph Gnanaraj
 Yardney Technical Products, Inc. - East Greenwich, RI

Identification and Significance of Innovation

Lithium-Ion batteries have been a main source of energy for many aerospace applications over the past decade. Future space missions are facing a number of challenging requirements, including significant increase in specific energy, approaching 500 Wh/kg, and energy density of 700 Wh/l at cell level. Compared to state-of-the-art technology today, a reduction in mass and volume are necessary, along with improvements for functioning in harsh space environments and an increase in reliability. Yardney Technical Products, Inc., a world leader in cutting-edge battery technology, in collaboration with Purdue University, proposes developing lithium-sulfur battery technology. This will have a cathode based on a novel, sulfur mesoporous carbon composite. In addition, the proposed Phase I research will include lithium dendrite suppressive electrolyte for a significant improvement in safety.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

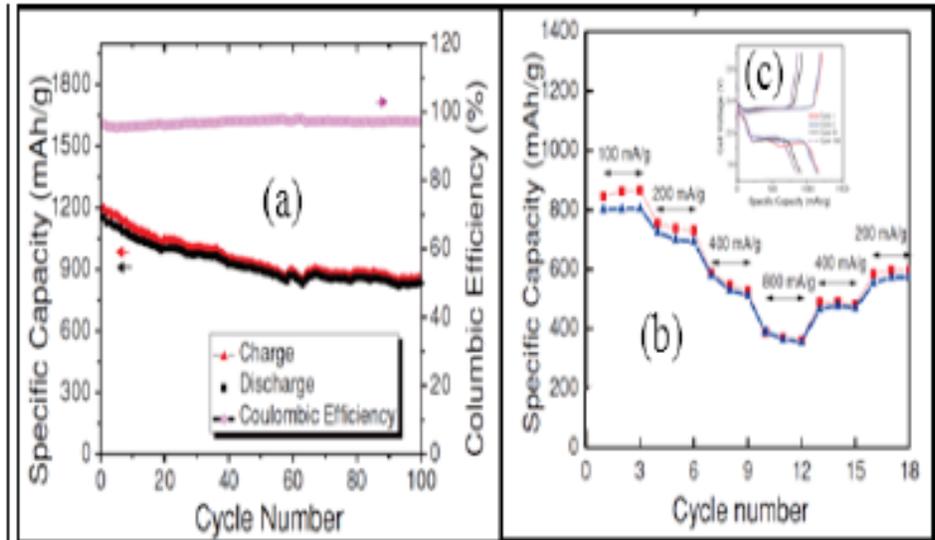
Technical Objectives and Work Plan

Technical Objectives

1. Synthesize highly efficient high capacity sulfur cathode.
2. Develop safe nonflammable dendrite-suppressing electrolyte system
3. Manufacture lithium sulfur cell that has excellent cycleability and Coulombic efficiency.

Work Plan

Synthesis and characterization of sulfur-carbon composite cathode with high reversible energy density (>50% S content)
 Manufacture 100-200 mAh Li-S cells with improved safety characteristics
 Perform electrochemical evaluation of new Li-S cells



NASA Applications

Li-S batteries find various applications in NASA's deep space missions where areas of emphasis include weight and volume performance improvements and safety advancements in human-rated systems. Possible applications include extravehicular activities, landers and rovers.

Non-NASA Applications

The proposed Li-S battery may be used on military applications such as Small/Micro Unmanned Aerial Vehicles where light-weight, high-energy power sources are needed. Value can be found in electrically powered weight/volume sensitive applications, i.e., portable consumer electronics, power tools, telecommunications and hybrid electric vehicles, applications where dense energy/safety are paramount.

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COR: Dr. Patricia Loyselle, NASA GRC (216) 433-2180

NON-PROPRIETARY DATA

PI: Christopher Lang
Physical Sciences, Inc. - Andover, MA

Identification and Significance of Innovation

PSI proposes to develop a rechargeable lithium metal cell with energy density >400Wh/kg. During Phase I, PSI will build pouch cells demonstrating the cycling efficiency of its lithium metal cell design. A specialized electrolyte will be developed that maximizes the cycle life and offers comparable performance to conventional electrolytes designed for graphite cells. A composite separator tailored to efficiently operate with the electrolyte will be used to provide a reduced diffusion distance between the anode and cathode. Phase I testing will demonstrate each component can be scaled to allow the construction of Ah pouch cells. Phase II will focus on building multi amp hour cells that achieve the targeted energy density, 400Wh/kg.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

Work Plan:

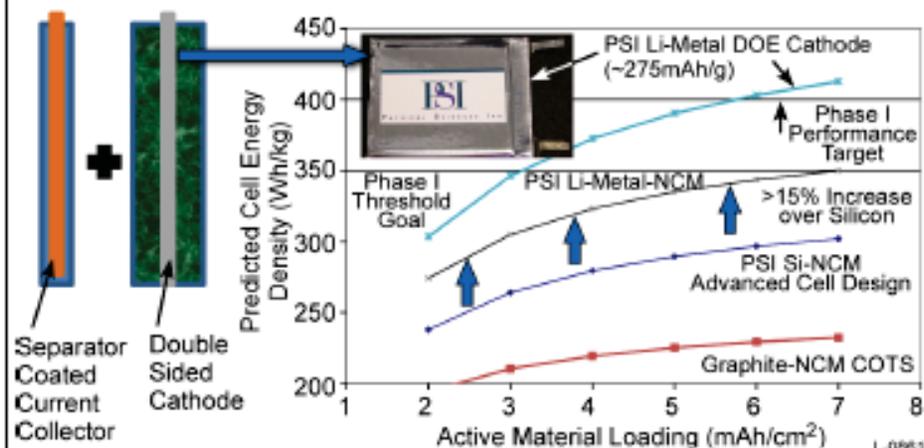
During the proposed Phase I PSI will:

- Construct and test lithium metal pouch cells.
- Develop a customized electrolyte for use in the cell.
- Develop a composite separator.
- Construct and measure the performance of Ah sized cells.
- Scale-up the relevant preparation techniques.

Technical Objectives:

- Construct pouch sized lithium metal cells and demonstrate the ability to achieve 80% capacity retention over 50 cycles.
- Develop an electrolyte that supports >98% of the C/2 discharge capacity achieved with a carbonate electrolyte.
- Develop a composite separator of <10 microns that supports >98% of the C/2 discharge capacity achieved with a conventional separator.
- Produce 1Ah pouch sized lithium metal cells that will enable energy densities of >400Wh/kg to be achieved on further scale-up.

The PSI Lithium Metal Technology together with Advanced DOE Cathodes Increases the Energy Density >70% Over COTS Graphite-NCM Cells while Eliminating Anode Production and Processing Costs and Simplifying Construction



NASA Applications

The proposed cell technology could be utilized in all NASA battery applications. In particular the rechargeable lithium metal cell technology could be used in any mission or application that requires low mass and low volume. The absence of an intercalation component on the negative electrode allows for higher discharge rate capabilities. Applications include EVA suits, landers, rovers, habitats, vehicle power, and power for payloads.

Non-NASA Applications

The initial market for the proposed technology is military aerospace applications where space is limited and battery energy density is critical. The technology would be well suited to powering microdevices, such as remote sensing devices. The system may be used in emergency power generators and as a replacement for current power sources employing primary and thermal batteries.

Firm Contacts

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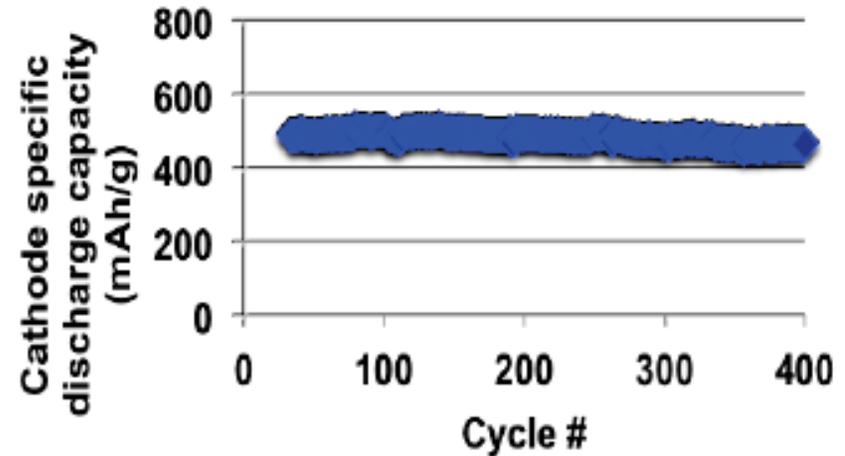


PI: Joshua Buettner-Garrett
Soild Power, Inc. - Louisville, CO

Identification and Significance of Innovation

All solid-state rechargeable battery:

- 1) Highest capacity of any known cathode, >700 mAh/g based on total cathode mass including electrolyte
- 2) Projected cell-level specific energy >600 Wh/kg and energy density >900 Wh/L
- 3) Made up of Earth -abundant materials
- 4) No self-discharge
- 5) Inherently safe
- 6) Considerable high temp. stability (>150C)
- 7) Long-term stable cycling with lithium metal anode using the proposed modified ceramic separator



Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

- Task 1: Demonstrate and refine process for depositing ceramic electrolyte layers that prevent Li dendrite growth
- Task 2: Minimize separator thickness while maintaining reliable operation
- Task 3: Demonstrate high energy density cell stacks in coin cells in preparation for larger Phase II prototypes

NASA Applications

Broadly speaking, the proposed safe, ultra high energy and low cost could see use in a broad array of NASA missions including:

- 1) exploration vehicles
- 2) extra-vehicular activity (EVA) equipment
- 3) landers and rovers
- 4) human habitat systems
- 5) planetary orbiters.

If successful, the proposed technology will increase each NASA application's

Non-NASA Applications

Potential to impact virtually every sector of the \$20+BN rechargeable battery market. Potential Non-NASA applications include:

- 1) Commercial and military satellites
- 2) Commercial and military aircraft
- 3) Military power (e.g., UAVs, ground vehicles, portable power, etc.)
- 4) Electric vehicles

Firm Contacts

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PI: Thuy Dang

Xerion Advanced Battery - Champaign, IL

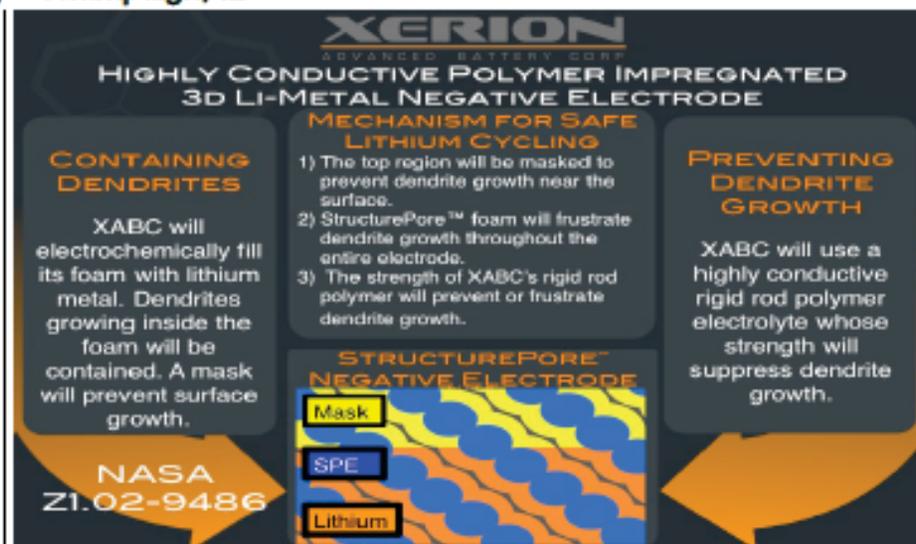
Identification and Significance of Innovation

XABC proposes a novel anode with three unique features, each designed to 1) control or 2) prevent dendrite growth. The first feature is a 95% porous electrode architecture called StructurePore™ whose internal structures are conformal coated with lithium metal. The continuous nature of the foam will contain dendrites as they form. The second feature is a five micron mask that, when applied to the surface of the 3d foam, prevents electrodeposition of lithium metal near the surface of the electrode, hence preventing growth of lithium dendrites near the surface. The third feature is a novel, highly conductive ionic fluid rigid-rod polymer composite expected to achieve $8.3 \times 10^{-3} \text{ S/cm}^2$. Rigid-rod polymers have a tensile modulus that is 37x - 62x stronger than polyethylene. This strength may physically deter or prevent the growth of lithium dendrites. XABC believes that the novel combination of these three features will enable stable cycling of lithium metal cell.

Estimated TRL at beginning and end of contract: (Begin: 6 End: 7)

Technical Objectives and Work Plan

1)Develop Polymer - XABC will develop a strong (280 GPa modulus), rigid rod ionic liquid polymer composite expected to achieve a conductivity of $8.3 \times 10^{-3} \text{ S/cm}^2$. 2)Quantify How Dendrites Grow in Masked StructurePore foam(tm) - XABC will determine the degree to which dendrite growth is frustrated by a masked StructurePore(tm) foam. 3)Measure the Polymer's Effects on Dendrite Growth. *Work Plan* 1)Dendrite Analysis of StructurePore(tm) foam - XABC will use SEM and non-destructive 3d XRay CT to determine the degree to which StructurePore(tm) foam hinders dendrite growth. 2)Monomer Synthesis - XABC will synthesize required monomers for polymer synthesis. 3)Polymer Synthesis - XABC will synthesize required polymers for film fabrication.4)Doping - XABC will study the effect of two dopants, to include an ionic-liquid, and measure their effect on conductivity.5)Film Fabrication - XABC will cast films of the doped polymers. 6)Characterization - XABC will characterize the films via Electrochemical Impedance Spectroscopy (EIS) and mechanical testing on an Instron tester.7)Dendrite Analysis of Polymer Film - XABC will use SEM and non-destructive 3d XRay CT to determine the degree to which the polymer film hinders dendrite growth. This test will be conducted in a coin cell with commercial cathode and lithium metal anode. 8)Polymer Downselect - XABC will choose the best doped polymer system.



NASA Applications

A secondary battery with a net energy density greater than 500 Wh/kg. Given design constraints, an energy dense battery would be smaller and allow for the deployment of larger, more complex sensors. More importantly, the use of a strong solid electrolyte would significantly increase the safety of the battery, allowing it to be deployed as a critical component. Such a cell would also reduce operational risk when deployed on probes, rovers and the like.

Non-NASA Applications

XABC will focus on applications of high desirability in three of the following potential market segments: 1) Military, DoD and NASA applications where enhanced performance at a much lower weight is highly desirable. 2) Portable electronic devices especially in the rapidly growing mobility market for laptops and phones. 3) Automotive application for electric and hybrid vehicles.

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Z1.02-9604 - High performance lithium sulfur battery with novel separator membrane for space applications

PI: Lin-Feng Li
Bettergy Corp. - Peekskill, NY

Identification and Significance of Innovation

Current state-of-the-art lithium ion batteries cannot meet the power source requirement for the future NASA human and robotic mission. The battery with extremely high specific energy (>500 Wh/kg) and long cycle life are urgently sought after in order to reduce the payload weight. New out-of-box battery chemistries and components need to be developed.



Estimated TRL at beginning and end of contract: (Begin: 1 End: 3)

Technical Objectives and Work Plan

The objective of this proposal is to develop and commercialize this novel ion selective membrane, ultimately high specific energy and long cycle life lithium sulfur battery for space and commercial applications.

In the Phase I program, this novel ion selective membrane will be developed and tested along with lithium sulfide based cathode material to develop high specific energy, long life lithium sulfur battery.

NASA Applications

It can provide high energy density, safe lithium Sulfur battery for future space mission.

Non-NASA Applications

Provide high energy density, safe lithium Sulfur battery for future space mission;
It can be used to replace low energy density primary lithium battery for military applications, such as UAV;
It can be used as the power source for portable electronics and electric vehicles.

Firm Contacts

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COR: Dr. James Wu, NASA GRC, (216) 433-5231

NON-PROPRIETARY DATA



PI: Surya Moganty
 Nohms Technologies - Rochester, NY

Identification and Significance of Innovation

NOHMs Technologies proposes to develop a novel ionic liquid electrolyte formulation developed for the Lithium-Sulfur chemistry that can protect the lithium metal and has demonstrated superior performance and safety characteristics with the potential to offer 600 Wh/kg on the cell level. NOHMs will provide full cell data and analysis to demonstrate the feasibility of our system to meet NASA's 'Far Term Mission' specific energy and energy density goals. The battery technology under development by NOHMs is capable of delivering batteries with specific energies that are three times higher than today's state of the art Li-ion battery systems. For NASA missions, this can be translated into increased operational range, functionality, or payload capabilities and significantly reduced operational cost. NASA applications.

	Specific Energy (Wh/kg)	Energy Density (Wh/l)	Cycle Life
Lander	210	130-500	10
Rover	200	180	2000
EVA	270	250	100
Near Term Missions	265	675	250
Far Term Missions	500	700	250
NOHMs Li-S (now)	350	400	500
Phase I Objective	600	675	500

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

The primary objective of this Phase I research and development is to increase the safety and energy densities of NOHMs Technologies high energy density Li-S batteries to meet NASA's requirements for Near-Term and Far-Term Space Missions. We propose to achieve this goal using NOHMs Technologies proven nanostructured sulfur-carbon (S@C) composites to increase the energy density and to develop ionic liquid electrolytes to provide protection for the Li-metal. The work plan for this SBIR Phase I proposal includes synthesizing and characterizing ionic liquid electrolytes, making poly(ionic) membranes and assessing the Li-metal protection and testing the membranes and electrolytes with full pouch cell studies for high energy, safe operation and long cycle life.

NASA Applications

Advanced batteries with 2-3X improved performance are required for future space missions. These uses include batteries for astronaut equipment and EVA suits, crew exploration vehicles, in-space habitats, surface habitats, humanoid robots, landers, ISRU, ISS astronaut equipment, life support systems, and photovoltaic energy storage. Successfully deployed safe lithium-sulfur batteries would result in significant mass and volume savings and operational flexibility.

Non-NASA Applications

High energy, safe Lithium-Sulfur (Li-S) batteries are needed in the consumer, automotive vehicles and grid energy storage market. Li-Sulfur batteries have a theoretical storage capacity of 2.3 kW/kg and offer one of the highest theoretical energy densities among rechargeable batteries and can yield a dramatic 3-4x reduction in weight, size, and cost to present day Li-ion batteries.

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PI: Yiyun Yang

Storagenergy Technologies, Inc. - Salt Lake City, UT

Identification and Significance of Innovation

Energy storage devices in many aerospace applications are facing unique challenges. Most of such applications depend on high-performance, highly specialized batteries. NASA desires high specific energy batteries that are safe for human exploration missions. Since none exist today, they must be developed. Rechargeable lithium-sulfur (Li-S) batteries offer great potential as high energy power supplies for NASA. Its theoretical specific energy of 2600 Wh/kg is one of the highest known using non-gaseous constituents. The materials themselves are light, energetic, inexpensive and readily available. It is highly desirable to develop new sulfur composite materials, novel electrode/cell configurations, and efficient electrolyte that can overcome these problems, therefore advance the Li-S technology close to commercialization.

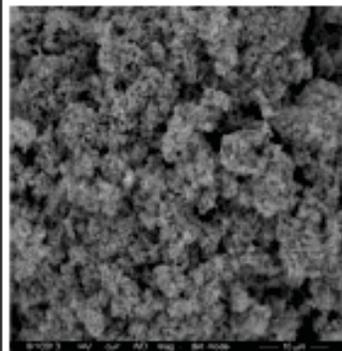
Estimated TRL at beginning and end of contract: (Begin: 3 End: 5)

Technical Objectives and Work Plan

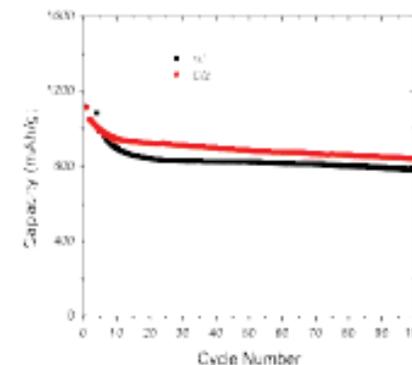
The overall objective of Phase II is to develop a low-cost, high energy density, and long cycle life Li-S batteries. The target cell performance goals are as follows: (1) cost \$100/kWh, (2) discharge capacity > 1,000 mAh/g of sulfur (600 mAh/g of the whole cathode), (3) energy density of packaged cell > 500 Wh/kg, and (4) cycle life > 1,000 cycles with less than 20 % capacity loss.

We will initially focus on optimizing the cathode components, carbon coated separator as well as novel electrolyte. We will then incorporate high energy density cathode materials and evaluate the Ahr/kg capacity performance and Whr/kg energy density of test cells. In parallel, scale-up big size cells will be designed and prototype batteries will be assembled and evaluated.

Microstructure of S/C nanocomposites



Cell performance using S/C nanocomposites



NASA Applications

The proposed Li sulfur battery systems will enable power and energy storage for future science and exploration missions such as: missions using electric propulsion, robotic missions, lunar exploration missions to NEO and MARS, crewed habitats, astronaut equipment, robotic surface missions to Venus and Europa, polar Mars missions and Moon missions, and distributed constellations of micro-spacecraft.

Non-NASA Applications

The Li sulfur battery system also offers benefits to other national needs. This includes national defense systems such as unmanned aerial vehicles, unmanned underwater vehicles (AUV's), and soldier portable power systems. Benefits to the terrestrial energy sector include: all-electric and hybrid cars, grid-scale energy storage systems, smart grid, and remote, off-grid power systems.

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NON-PROPRIETARY DATA



Fuel Cell SBIRs

2014 Phase I SBIRs – Funding of up to \$125K for 6 months

- H8.01-8950 – NexTech Materials, Ltd. – High Efficiency Direct Methanol Solid Oxide Fuel Cell System
- H8.01-9586 – MO-SCI Corporation – Development of Hermetic Sealing Glasses for Solid Oxide Fuel Cells
- H8.01-9741 – Yanhai Power, LLC – Fabrication of T-SOFC via Freeze Cast Methods for Space and Portable Applications
- H8.01-9874 – Paragon Space Development Corporation – Integrated Electrolysis and Sabatier System for Internal Reforming Regenerative Fuel Cells

Phase II SBIRs – Funding of up to \$750K for 24 months

- 2010
 - X8.01-8730 Sustainable Innovations, LLC - Advanced Passive Liquid Feed PEM Electrolyzer
- 2012
 - X8.01-9759 ITN Energy Systems, Inc. - Advanced Manufacturing of Intermediate Temperature Direct Methane Oxidation Membrane Electrode



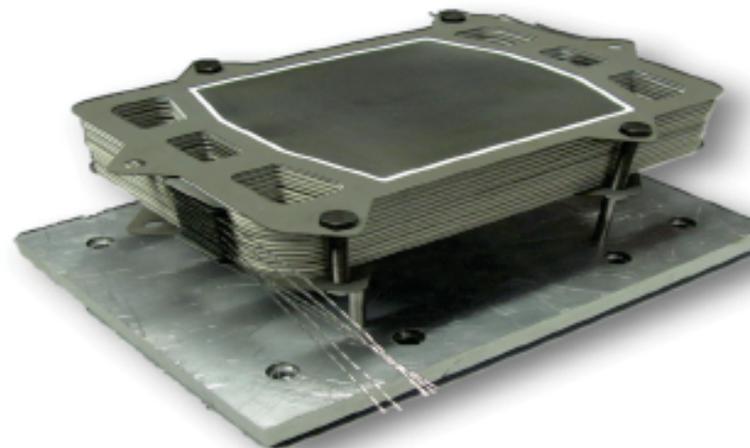
Non-flow through Fuel Cell

PI: Scott Swartz

NexTech Materials, Ltd. - Lewis Center, OH

Identification and Significance of Innovation

NASA has a defined need for energy dense and highly efficient power systems for future space missions. Compared to other fuel cell technologies, solid oxide fuel cell (SOFC) based systems are better suited to meeting NASA's efficiency targets while operating directly on methane and oxygen reactants. NASA has established an aggressive set of requirements that presents a tremendous challenge to traditional SOFC technologies. NexTech Materials has established SOFC technology that offers high power density with direct internal fuel reforming and high single-pass fuel utilization, making it uniquely suited for achieving NASA's performance and efficiency requirements. In this project, NexTech will leverage its experience developing lightweight, energy dense SOFC systems for the U.S. military to develop an SOFC system that meets NASA's power system requirements.



Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

Technical Objectives:

- Establish/refine process model to predict stack operating conditions to define parameters that enable 70 percent electrical efficiency to be achieved in the stack operating with methane and oxygen.
- Complete a comprehensive design of a high efficiency, 2-kW scale SOFC stack
- Evaluate alternative stack repeat unit designs with potential for improving stack performance, efficiency, size and weight.
- Evaluate alternative stack repeat unit designs with potential for improving stack performance, efficiency, size and weight.
- Analyze the requirements for start-up of the SOFC system, establish a preliminary start-up protocol and estimate the minimum start-up time.
- Perform short-stack testing to validate stack design/modeling assumptions, to demonstrate targeted stack performance and thermal cycling capability.

Work Plan:

- Task 1. SOFC Process Modeling and System Design
- Task 2. Stack Design and Modeling
- Task 3. Stack Validation Testing
- Task 4. Project Management

NASA Applications

Solid oxide fuel cells have promise to meet some of NASA's emerging power generation system needs. An SOFC power system using the same reactants as the propulsion system (cryogenically stored oxygen and methane) can provide exceptional energy density. Lunar landers or other exploration vehicles are an ideal application of this technology. SOFC systems also may find uses on the moon or on Mars for generating power from hydrocarbons produced from In-Situ Resource Utilization technologies.

Non-NASA Applications

The technology is directly applicable to unmanned underwater vehicle applications of interest to the Navy. The technology also can be adapted for other military power applications, such as gen-sets, auxiliary power units and unmanned aerial vehicles. The internal reforming SOFC technology to be developed in this project is directly applicable to residential micro-combined heat and power systems.

Firm Contacts

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NON-PROPRIETARY DATA

PI: Cheol-Woon Kim
MO-SCI Corporation - Rolla, MO

Identification and Significance of Innovation

*Produce "Hermetic Sealing Glasses" for NASA SOFC/SOE seals with the goal of zero or minimal leak rates.

- 1) Ceramic cell-to-steel interconnect
- 2) Ceramic cell-to-ceramic interconnect
- 3) Capable of thermal cycling (e.g., RT-850°C) under SOFC operational conditions (e.g., methane/oxygen)
- 4) Thermally and chemically stable

*Utilize rigid glass-ceramic and/or compliant (viscous) glass seals.

*MO-SCI Corp./Missouri S&T have experience.

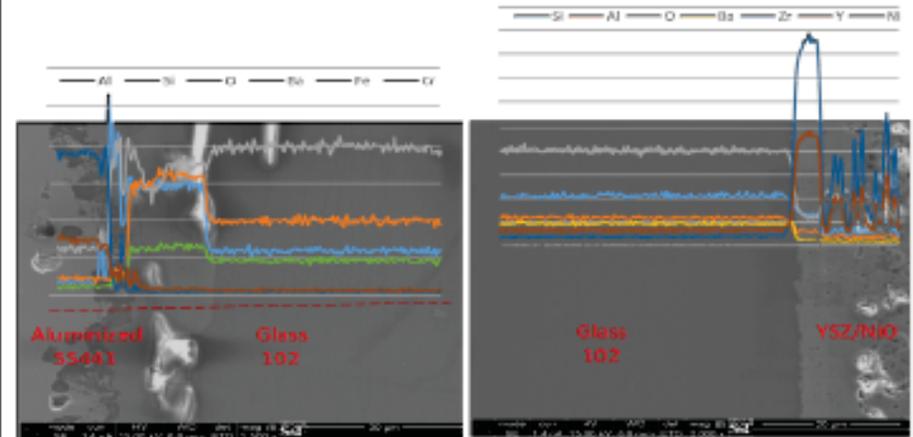


Figure 1. SEM micrographs and EDS line-scans of a G102 (viscous glass) sandwich seal with aluminumized 441 stainless steel and a NiO/YSZ bilayer held at 800°C in air for 2280 hours. Excellent wetting and bonding; homogeneous glass.

Estimated TRL at beginning and end of contract: (Begin: 4 End: 5)

Technical Objectives and Work Plan

- 1) Identify specific SOFC materials of interest to NASA for sealing and determine specific operational conditions.
- 2) Test G27 (glass-ceramic seal) and/or G102 (viscous glass seal) with NASA-specified materials and conditions.
- 3) Refine and optimize the glass compositions and processing parameters with the requisite thermal and physical properties.
- 4) Evaluate long-term (e.g., >500 hrs at 650-850°C) thermal and chemical stability.
- 5) Conduct hermetic and thermal cycle tests (e.g., RT-850°C).

NASA Applications

Provide new reliable, thermally stable, hermetic sealing materials critical for the development of SOFCs/SOEs as a high-efficiency power system/a life support system, respectively.

Non-NASA Applications

Assist the nation's SOFCs program in meeting its cost and performance targets by ensuring that SOFC seals can achieve reliable operation over an extended operating life.

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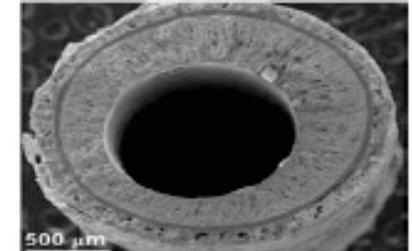
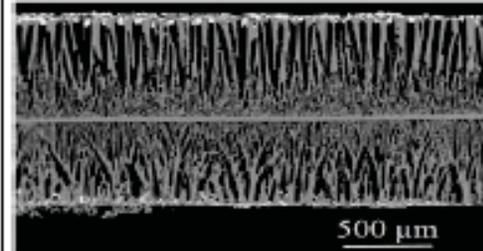
COR: Dr. Serene Farmer, NASA GRC, 216-433-3289

NON-PROPRIETARY DATA

PI: Joshua Persky
Yanhai Power LLC - Immo, SC

Identification and Significance of Innovation

Human occupied vehicles such as the International Space Station and autonomous vehicles such as rovers and landers may benefit from the fuel flexibility and the high energy density of SOFC compared to batteries and PEM systems. Fuel systems greater than 1kw are traditionally planar and exhibit high volumetric power density; however, due to large sealing areas, have poor cycling characteristics. We recently demonstrated 250 cycles on a Tubular SOFC system. Hot zones designed around T-SOFC have a lower packing density, but significantly better cycle life and start times making them an ideal solution. By increasing the power density of T-SOFCs, overall hot zone and system volumetric power densities can be greatly improved. Extending the methodology of freeze casting to T-SOFC will provide NASA a system with the micro structural advantages of their planar counterpart but with the rapid thermal cycling capacity of traditional extruded SOFCs.



Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

A key barrier to the use of the SOFC generators as a power system for NASA applications is the use of logistical fuels and oxidants. The use of pure oxygen specifically presents a challenge. At the standard SOFC operation temperature (600-900 C) metallic frames used to support planar stacks will quickly degrade leading to leaks and eventually stack failures. The use of a tubular geometry allows the oxygen to be separated from all metallic surfaces.

The primary technical objective of the Phase I program is a demonstration of single cell freeze cast T-SOFC operating on methane and oxygen. Cells development of TRL 4/5 is expected at the conclusion. The first technical objective of the Phase I program is the adaptation of the freeze cast structure to current production technique for tubular SOFC to produce cells suitable for NASA's missions, operating on methane/oxygen. The T-SOFC cell is the key component driving the SOFC power system performance and a production technique must be proven first in order to develop the system. A second technical objective in Phase I is to demonstrate the T-SOFC cell electrochemical performance in a representative methane/oxygen environment. The final technical objective of the Phase I program will be to develop a conceptual design of T-SOFC power system operating on methane/oxygen. The conceptual design will consider reforming needs, thermal management and have a projected power output of 2.5kW.

NASA Applications

Increasing the power density of T-SOFCs is a vital step in achieving NASA's objective. Specifically, cells developed during this program can be further used in the following systems:

- Energy storage and maintenance for the international space station
- High altitude balloons
- High altitude aircraft
- Energy storage for future missions and settlement on the moon and Mars

Non-NASA Applications

This unique fuel cell microstructure can be leveraged across all SOFC developments, improving both system power density and reducing cost and used for electrolysis of water and or carbon dioxide leading to a host of applications such as: CO2 conversion, Hydrogen or Oxygen production, and the production of metals from oxide salt mixtures.

Firm Contacts

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NON-PROPRIETARY DATA COR: Dr. Serene Farmer, NASA GRC, 216-433-3289

PI: Christine Iacomini, Ph.D.

Paragon Space Development Corporation - Tucson, AZ

Identification and Significance of Innovation

Paragon Space Development Corporation® will advance our Solid Oxide Electrolysis/embedded Sabatier reactor (SOE/ESR) system to generate power from its oxygen (O₂) and methane (CH₄) products. Our SOE/ESR technology provides a carbon deposition resistant system capable of internally steam reforming CH₄ and generating power. Minimal start-up water is required; operations are sustained by recycling water from the affluent using Paragon's spaceflight-qualified humidity control membrane technology. The system is gravity-independent and compact with no moving parts. Leak-tight operations are improved by employing a 3D glass seal approach. The system will survive hundreds of high pressure differential thermal cycles. The innovation simplifies operations, lowers hardware complexity, and increases reliability. It can perform multiple functions without modifications, making it deployable on various missions: from ISRU on the Moon and Mars to life support systems of space crafts and habitats.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)

Technical Objectives and Work Plan

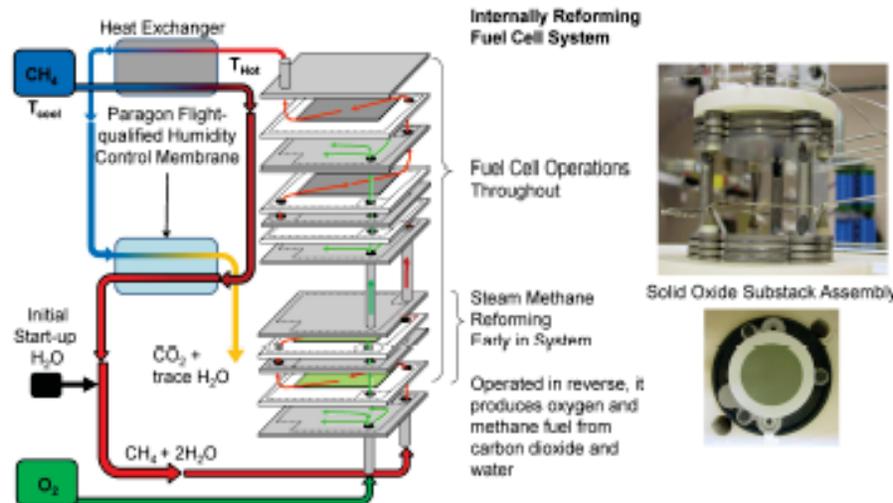
The overall objective is to develop a regenerative CH₄ fuel cell system. Our Phase I effort includes laboratory tests to confirm simultaneous internal CH₄ steam reforming and fuel cell operation without carbon deposition. Tests will also determine the feasibility of employing new sealing features at high differential pressure and multiple thermal cycles.

Specifically the objectives of this Phase 1 effort are:

- 1) Confirm system and test requirements that map to an ISRU end-use and allow assessment of technology feasibility.
- 2) Incorporate features that will improve the SOE/ESR sealing endurance.
- 3) Demonstrate new seals that survive 20 thermal cycles.
- 4) Demonstrate a SOE/ESR cell operated as a fuel cell with CH₄ fuel and pure O₂ via internal steam reforming.
- 5) Evaluate the impact of CH₄/H₂O flow rate and mixture on performance and fuel utilization.
- 6) Estimate sizing and operation for a 1 kW regenerative fuel cell system.

This will be achieved by the following work plan:

- 1) Draft a concept of operations and subsequent test requirements specific to the Phase I scope.
- 2) Incorporate new sealing features into current SOE/ESR cell seal design.
- 3) Manufacture test articles, finalize test procedures, and ready the test bed.
- 4) Perform tests, reduce data, and analyze results to assess system feasibility.



NASA Applications

The SOE/ESR Internal Reforming Fuel Cell system can produce O₂ and CH₄ from both lunar and Martian resources; then use those products to produce power when solar power is not available or as auxiliary power. Smaller units can be dedicated fuel cells in rovers or habitats fueled by larger in situ O₂ and CH₄ production plants. For life support, it can regenerate 100% of crew O₂ needs from crew-produced CO₂ and H₂O vapor. CH₄ by-products can be used for spacecraft or habitat auxiliary power.

Non-NASA Applications

The SOE/ESR Internal Reforming Fuel Cell system can be used in underwater research facilities, submarines, emergency bunkers, and commercial and civil space vehicles. Powered by easily storable, self-generated CH₄ fuel, it extends operations in remote locations. It also provides relief power during high energy-use periods of the day, making its own fuel during low energy-use periods.

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ITN Energy Systems, Inc. - Littleton, CO

Identification and Significance of Innovation

The proposed innovation builds on the successes of the Phase I program by integrating our direct oxidation MEA into a monolithic solid oxide fuel cell stack capable of long-term operation on methane. This innovation enables durable, cycle-able and simple SOFC systems to meet the needs for NASA and commercial customers. ITN's Phase II strategy addresses the technical hurdles that limit the long-term durability and thermal cycling of state-of-the-art SOFCs operating on methane fuel, including

- ?Component CTE matching
- ?Mass reduction
- ?Stack sealing
- ?Reducing anode degradation and stack operating temperatures.

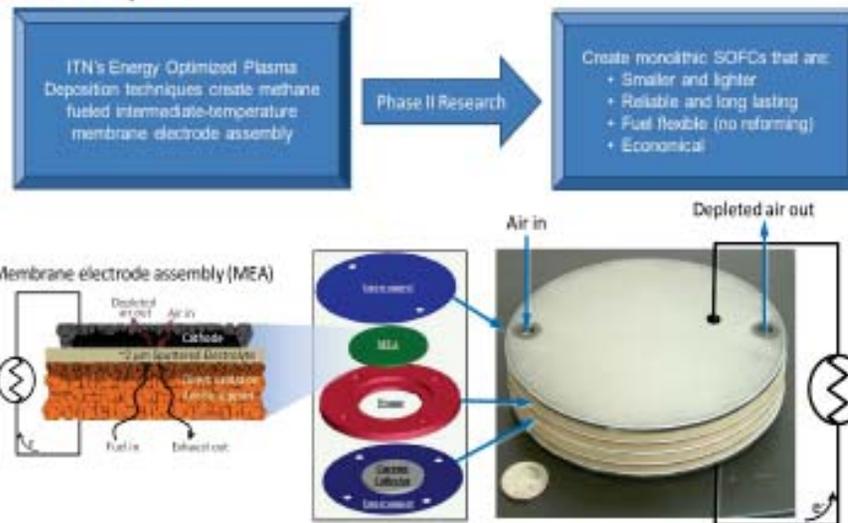
With this innovation, we project that the proposed SOFC stack will be capable of operating without degradation for more than the targeted 2500 hours and will operate without power density degradation after 50 start-up and shut-down cycles.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

The technical objectives of this research are designed to build on the success of the phase I program to create the next generation SOFC by building on the developments of phase I to create a durable, direct-oxidation MEA and incorporate it into our monolithic SOFC stack. The specific technical objectives are listed below:

- ?Fabricate durable, anodes capable of the direct oxidation of methane or syngas fuels without coke formation (500 mW/cm²)
- ?High rate (11 ?/s) sputtering of YSZ electrolytes directly on ITN's large area, direct oxidation anodes.
- ?Demonstrate long-term durability and the ability to withstand thermal cycling.
- ?Incorporate large-area MEAs into a durable monolithic 1-3 kW stack



NASA Applications

NASA needs efficient and reliable methods for both portable and stationary electricity and heat generation, with the greatest possible flexibility. ITN's proposed SOFC provides the solution, allowing for systems capable of generating electricity from a variety of fuels such as syngas, methane, hydrogen or hydrocarbon fuels. Potential NASA customers are the International Space Station or the Human Exploration and Operations Mission Directorate or other long-term missions

Non-NASA Applications

Applications include residential/ commercial buildings, transportation, military, emergency services, and other off-grid power applications. Because it can operate directly on natural gas (which is primarily methane) with minimal processing and tolerate a wider range of operating conditions than current SOFCs, fuel is widely available without investment in fuel delivery infrastructure.

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NON-PROPRIETARY DATA

NASA SBIR/STTR Technologies
Advanced Passive Liquid Feed PEM Electrolyzer
 Sustainable Innovations
 Glastonbury, CT
 Proposal No.: X8 . 01 - 8730

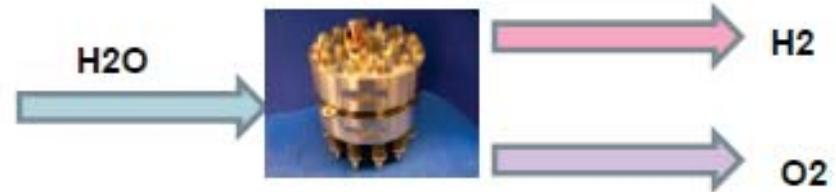


Identification and Significance of Innovation

- Permits Efficient Generation Of Hydrogen And Oxygen From Water With Minimal Balance Of Plant
- No Moving Parts
- Utilizes Innovative Water Transport Materials And Technology

Estimated TRL (1 – 9) at beginning and end of contract: Beginning At 2 Ending At 4

Scientific Principle



Technical Objectives and Work Plan

Develop And Demonstrate The Fundamental Technology For An Efficient Advanced Passive Liquid Feed PEM Electrolyzer Capable Of Operation At 2,000 Psi With No Moving Parts And Minimal Balance Of Plant.

1. Develop And Advanced Water Transport Media.
2. Integrate Media Into A High Pressure Cell Architecture.
3. Evaluate Performance Of This Cell Architecture To Confirm Design Approach.

NASA and Non-NASA Applications

- **NASA:** Facilitates Efficient Energy Storage Using PEM Electrolyzers And Fuel Cells Based On The Hydrogen/Oxygen Cycle. Supports Renewables Energy Storage For Space Travel And Bases.
- **Civilian:** Facilitates Hydrogen Economy Through Efficient Generation Of Hydrogen To Serve As A Vehicular Fuel.
- **Civilian:** Supports Low-cost Designs For Electrolyzers That Generate Hydrogen As An Industrial Gas.

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NON-PROPRIETARY DATA



Thanks for your attention!

