NASA/TM—2011-216963

Energy Storage Project

Final Report

Carolyn R. Mercer, Amy L. Jankovsky, Concha M. Reid, Thomas B. Miller, and Mark A. Hoberecht
Glenn Research Center, Cleveland, Ohio

January 2011

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Acknowledgments

NASA's Exploration Technology Development Program supported this work, conducted by the Energy Storage Project. Many people contributed to this work. Special thanks to NASA ESMD: Chris Moore and John Warren, NASA ETDP: Frank Peri and Diane Hope, NASA Constellation: David Westheimer, Rob Button, Pat George, Lisa Kohout, Josh Freeh, James Fincannon, Barb McKissock, and Patricia Loyselle, NASA Technical Staff: Ratnakumar Bugga, Judy Jeevarajan, Koroosh Araghi, S.R. Narayan, Bill Bennett, Marshall Smart, Ken Burke, and Ian Jakupca, NASA Management Staff: John Scott, Michelle Manzo, and Subbarao Surampudi, NASA Contractors: Infinity Fuel Cell and Hydrogen, Inc./Bill Smith; Saft, America/Bob Staniewicz; UT Austin/Arumugam Manthiram; PSI/Christopher Lang; NEI Corp/Ganesh Skandan; Lockheed Martin/Justin Golightly; GeorgiaTech/Gleb Yushin; Giner/Robert McDonald; and Yardney Technical Products/Boris Ravdel.

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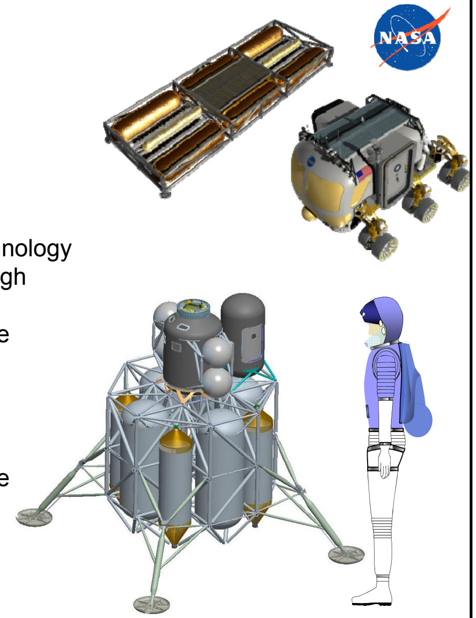
Abstract

NASA's Exploration Technology Development Program funded the Energy Storage Project to develop battery and fuel cell technology to meet the expected energy storage needs of the Constellation Program for human exploration. Technology needs were determined by architecture studies and risk assessments conducted by the Constellation Program, focused on a mission for a long-duration lunar outpost. Critical energy storage needs were identified as batteries for EVA suits, surface mobility systems, and a lander ascent stage; fuel cells for the lander and mobility systems; and a regenerative fuel cell for surface power. To address these needs, the Energy Storage Project developed advanced lithium-ion battery technology, targeting cell-level safety and very high specific energy and energy density. Key accomplishments include the development of silicon composite anodes, lithiated-mixed-metal-oxide cathodes, low-flammability electrolytes, and cell-incorporated safety devices that promise to substantially improve battery performance while providing a high level of safety. The project also developed "non-flow-through" proton-exchange-membrane fuel cell stacks. The primary advantage of this technology set is the reduction of ancillary parts in the balance-of-plant – fewer pumps, separators and related components should result in fewer failure modes and hence a higher probability of achieving very reliable operation, and reduced parasitic power losses enable smaller reactant tanks and therefore systems with lower mass and volume. Key accomplishments include the fabrication and testing of several robust, small-scale non-flow-through fuel cell stacks that have demonstrated proof-of-concept. This report summarizes the project's goals, objectives, technical accomplishments, and risk assessments. A bibliography spanning the life of the project is also included.

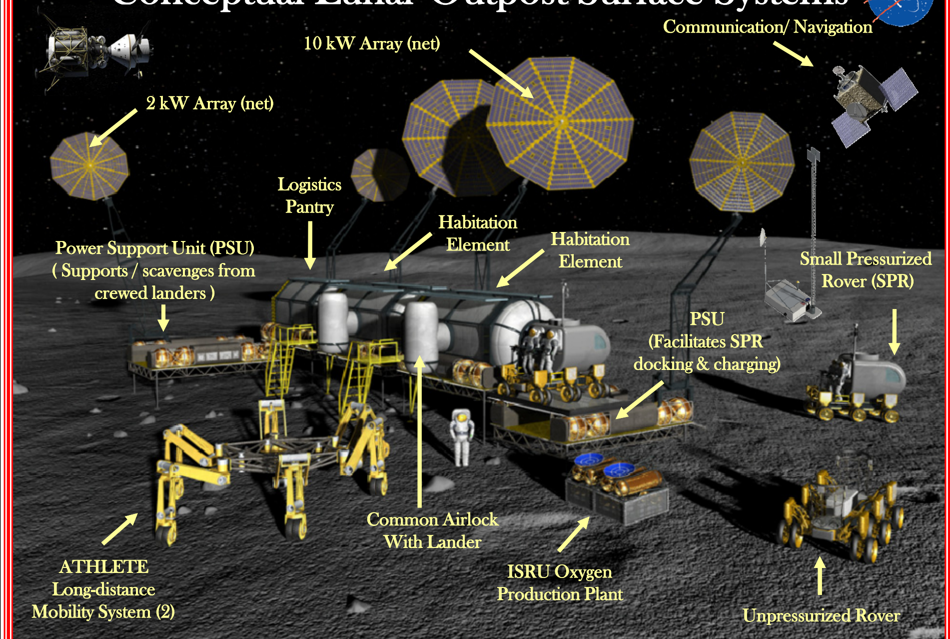
Overview

- Project Goals and Objectives
- Summary of Accomplishments
  - Fuel Cells
    - Prior work in flow-through technology
    - Current work in non-flow-through technology
    - Predicted System Performance
  - Batteries
    - Components
    - Cells
    - Predicted System Performance
- Summary
- Bibliography



Energy Storage Technologies for Altair, EVA, and Lunar Surface Systems

Conceptual Lunar Outpost Surface Systems



Energy Storage Project
Objective and Overall Approach

The Energy Storage Project's objective is to reduce risks associated with the use of Lithium chemistry batteries, fuel cells, and regenerative fuel cells for Altair, Lunar Surface Systems, and EVA.

Our deliverables are:

- Primary fuel cell for Altair Descent Stage (TRL 6 by PDR)
- Regenerative fuel cell for LSS (TRL 6 after CDR)
- Rechargeable battery *cells* for Altair Ascent Stage, EVA Suit 2, and LSS
  EVA and Altair: TRL 6 *cells* by PDR; LSS: TRL 6 *cells* by PDR;
  All: cells early enough for batteries by CDR

We are addressing the top technology development needs for advanced energy storage:

- Human-rating and increased reliability
- Mass/volume reductions
- High performance components and systems

And we are performing systems analyses to ensure the right approaches are being pursued:

- Cost/benefit analyses based on Constellation mission architectures.

Mechanisms to determine Constellation Requirements:

- Cx Technology Prioritization Process
- Risk Identification Workshop (Aug 2007 and Aug 2008)
- Lunar Architecture Team reports
- Exploration Architecture Requirements Document
- Points-of-contact on Lander, Surface Systems, EVA, and Ares I/V projects

Energy Storage Project
Documented Constellation Priorities

Documentation	Project	Criticality	Technology Need
LAT-2 #MOB-5	Mobility	Enabling	**High Specific-Energy-Density Power Systems** – Need lightweight, long-life rechargeable batteries and need reliable micro-fuel cells to reduce mass of the power system by 30% - 50% to extend life of the power system components, and to reduce cost and frequency of maintenance.
LAT-2 #POW-1	Surface Systems	Enabling	**High Specific-Energy-Density PEM Fuel Cell Systems** – Need light weight, long-life (10,000 hr) regenerative fuel cells, 2000 psi electrolyzer, and water separators designed for 1/6 g environment to improve life/reliability, to increase mass to the lunar surface, and to reduce cost.
LAT-2 #EVA-3	EVA	Enabling	**High Specific-Energy-Density EVA Suit PLSS Power** – Need lightweight, high energy density rechargeable batteries and micro-fuel cells to increase useable mass to lunar surface, to increase EVA range and mission flexibility.
LSS TPP – Draft IRMA ID 2380	Surface Systems	Critical	**Regenerative fuel cells** - Meet energy storage requirements for up to 15 days (360 hours) or more (e.g., for a 20 kWe night time power requirement, this means an energy storage requirement of 7,200 kW-hrs of storage capacity (2 orders of magnitude greater than ISS)) Also highly desirable to have 5 year lifetime.
IRMA Risk ID 2527	EVA	5x5	**Required specific energy not achievable with current batteries**
Cx TPP 606	Surface Systems, Orion and ILSM SiG	Critical LS #2	**Regenerative fuel cell** for Lunar Surface Systems
Cx TPP 466	Lander	Critical LT #28	**Low mass, highly reliable fuel cell** for Lunar Lander power generation.
Cx TPP 465 IRMA Risk ID 4796	Lander	Critical LT #27	**Low mass rechargeable battery** to power the Lunar Lander ascent module during ascent from the lunar surface.
Cx TPP 544	EVA	Critical LT #12	**EVA Suit power**
Cx TPP 661	Surface Systems	Highly Desirable LS #11	**High specific energy power for Lunar Rovers**
Ares V Risk #2366 Cx TPP 525	Ares I/V	5x5 Critical LT #16	**Solid Rocket Booster Thrust Vector Control Power Source** require high power, primary batteries

Updated 4/21/08

Energy Storage Technology Development
Mission Requirements Assessment

Lunar Architecture Studies identified regenerative fuel cells and rechargeable batteries as enabling technology, where enabling technologies are defined as having:
"overwhelming agreement that the program cannot proceed without them."

Surface Systems

Surface Power: Maintenance-free operation of **regenerative fuel cells for >10,000 hr using ~2000 psi electrolyzers.** Power level TBD (2 kW modules for current architecture)
Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy, high system efficiency.

Mobility Systems: **Reliable, safe**, secondary batteries and regenerative fuel cells in small mass/volume.
200 W-hr/kg desired; **150 W-hr/kg** may be sufficient.
Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.

EVA

Portable Life Support System (PLSS); and Power, Communications, Avionics, and Informatics (PCAI) Subsystem:
Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lander

Ascent Stage: Rechargeable battery capability for ascent operations and to support emergency lander/surface operations. Nominally 14 kWhr in 67 kg, 45 liter package.
Human-safe, reliable operation; **high energy-density**.

Descent Stage: Functional primary fuel cell with 5.5 kW peak power.
Human-safe reliable operation; high energy-density; architecture compatibility (**operate on residual propellants**).

Fuel Cell Systems

- Goals
- Approach
- Technology Development
- Predicted System Level Performance

Key Performance Parameters for Fuel Cell Technology Development

Customer Need	Performance Parameter	SOA (alkaline)	Current Value* (NFT PEM)	Threshold Value** (@ 3 kW)	Goal** (@ 3 kW)
Altair: 3 kW for 220 hr continuous, 5.5 kW peak. Lunar Surface Systems: TBD kW for 15 days continuous operation. Rover: TBD	System power density				
	Fuel Cell	49 W/kg	44 W/kg	88 W/kg	136 W/kg
	RFC (without tanks)	n/a	n/a	25 W/kg	36 W/kg
	Fuel Cell Stack power density	n/a	51 W/kg	107 W/kg	231 W/kg
	Fuel Cell Balance-of-plant mass	n/a	2 kg	21 kg	9 kg
	MEA efficiency @ 200 mA/cm^2				
	For Fuel Cell	73%	72%	73%	75%
	Individual cell voltage	0.90 V	0.89 V	0.90 V	0.92 V
	For Electrolysis	n/a	83%	84%	85%
	Individual cell voltage	n/a	1.48	1.46	1.44
	For RFC (Round Trip)	n/a	60%	62%	64%
	System efficiency @ 200 mA/cm^2				
	Fuel Cell	71%	64%	71%	74%
	Parasitic penalty	2%	8%	2%	1%
	Regenerative Fuel Cell***	n/a	n/a	43%	54%
	Parasitic penalty	n/a	n/a	10%	5%
	High Pressure penalty	n/a	n/a	20%	10%
Maintenance-free lifetime Altair: 220 hr (primary) Surface: 10,000 hr (RFC)	Maintenance-free operating life				
	Fuel Cell MEA	2500 hr	13,500 hr	5,000 hr	10,000 hr
	Electrolysis MEA	n/a	n/a	5,000 hr	10,000 hr
	Fuel Cell System (for Altair)	2500 hr	n/a	220 hr	220 hr
	Regenerative Fuel Cell System	n/a	n/a	5,000 hr	10,000 hr

*Based on non-flow-through test hardware with 4-cells and heavy end plates, scaled to 3 kW

**Threshold and Goal values based on full-scale (3 kW, 300 cm^2) fuel cell and RFC technology.

***Includes high pressure penalty on electrolysis efficiency 2000 psi

4/5/10

Summary of Fuel Cell and Regenerative Fuel Cell Technology Development since 2006

Flow-Through Fuel Cell Stack Development *(Work stopped)*
- 13,500 hr of MEA testing complete, passing 10,000 hr life goal through use of Pt-black catalysts
- System characterized, strengths and weaknesses documented

Component Development
- Passive components for Flow-Through Balance-of-Plant *(Work stopped)*
  - Water/gas separators, injectors/ejectors, regulators
    - Devices characterized, strengths and weaknesses documented
- Passive thermal management *(Work stopped)*
  - Pyrolitic graphite cooling plates and flat plate heat pipes
    - Tested in Flow-Through and Non-Flow-Through fuel cell stacks, respectively
    - Temperature distribution across any single plate and from plate-to-plate stays within 2-3 °C
    - Devices characterized, strengths and weaknesses documented
- MEAs for fuel cells (*Work continues)*
  - JPL MEAs supplied to Teledyne, Infinity, and Proton
  - 0.89 V at 200 mA/cm^2 exceeds the performance of vendor cells substantially
  - *Work continues*
- MEAs for high pressure electrolyzers (*Work continues)*
  - JPL MEAs supplied to Hamilton Sundstrand
  - *Work continues*

High Pressure Electrolysis (*Work continues only under SBIR)*
- Hamilton-Sundstrand system modified for high pressure operation; tested at JPL
  - Liquid feed system draws significant parasitic power for pumps and water/gas separators
- Novel concepts under study via SBIR (vapor feed, passive liquid feed)

Non-Flow-Through Fuel Cell Stack Development (*Work continues)*
- Water removal mechanism and advanced manufacturing process brought to TRL 4
- Electrochemical hydrogen pump implemented to provide low-power purge and inert concentration

Unitized Regenerative Fuel Cell System (*Work stopped)*
- System characterized, strengths and weaknesses documented

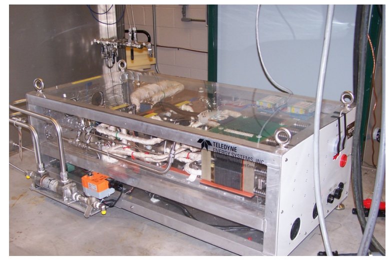
3.2.1 Flow-Through Primary PEMFC Development

Key Accomplishment:

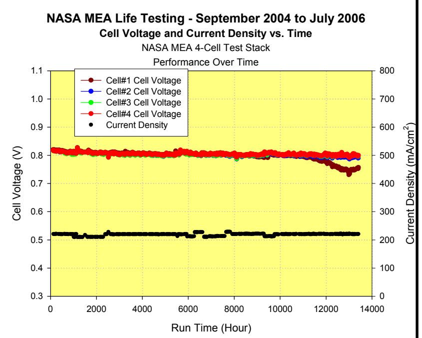
- Initiated testing of Teledyne multi-kW flow-through PEMFC breadboard system
- Achieved several hundred hours of testing through multiple simulated Shuttle load profiles

Significance:

- Passive reactant recirculation and water separator components replace active components; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Initial performance testing has identified limitations and control issues with reactant recirculation system using ejectors and solenoid valves
  - Initial testing has shown performance of membrane water separators to be comparable to active water separators
- Successfully passed 10,000 hr life goal through use of Pt-black catalysts on MEA (13,500 hr)
- Establishes the basis for all future MEA advancements



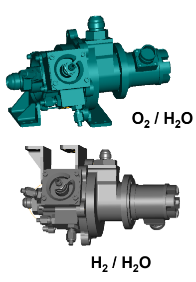
Teledyne multi-kW flow-through PEMFC Breadboard



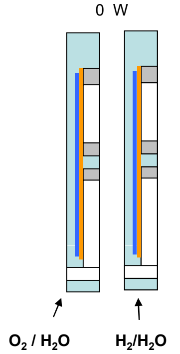
FC Recent Accomplishments: GRC Passive Water/Gas Separators Reduce Mass and Parasitic Power Without Compromising Performance

Water/Gas Separators

Active	Passive
5.67 kg each	0.45 kg each
100 W parasitic loss each	0 W parasitic loss each
================	==============
11 kg	1 kg
200 W	0 W



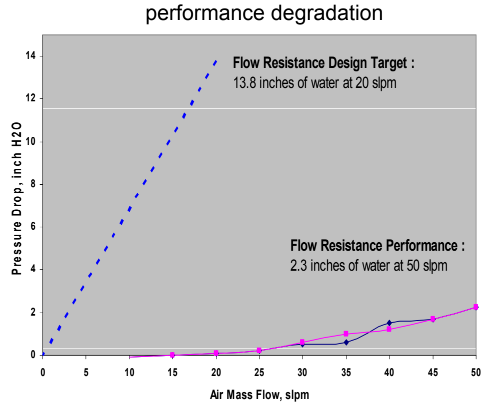
Active Separators

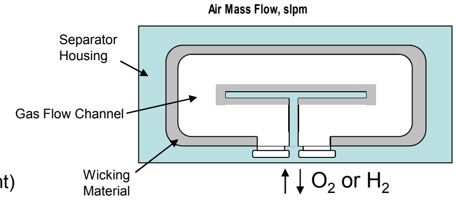


Additional "cells" to fuel cell stack

Passive Separators
Side view (above), top view (right)

Passive Water/Gas Separators: no performance degradation





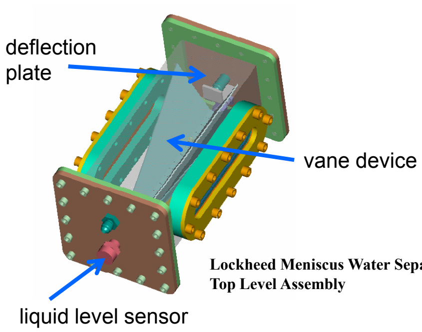
Flow-Through Primary PEMFC Development

Key Accomplishment/Deliverable/Milestone:

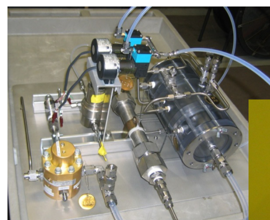
- Completed testing of GRC membrane water separator
- Accepted delivery of Lockheed meniscus water separator

Significance:

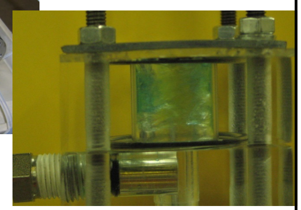
- Passive water separators replace active mechanical water separators; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Testing has shown performance of GRC membrane water separator to be comparable to active water separators
  - Initial assessment of Lockheed meniscus water separator is not promising because of gravity dependency
  - Initial assessment of Texas A&M gas-driven vortex water separator is not promising because of insufficient momentum for consistent operation



Lockheed Meniscus Water Separator Top Level Assembly



Integrated Ejector/Regulator and Integrated Ejector/Regulator/Two-Stage Water Separator System



TAMU Gas-driven water separator demonstration

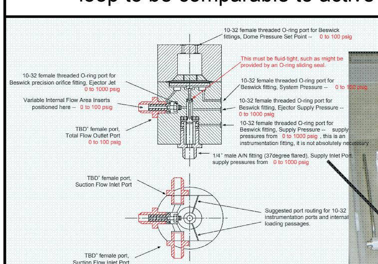
Flow-Through Primary PEMFC Development

Key Accomplishment/Deliverable/Milestone:

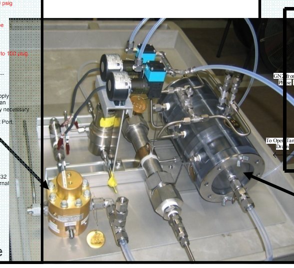
- Completed initial assessment of combined reactant recirculation and water separator concepts at NASA JSC/Texas A&M

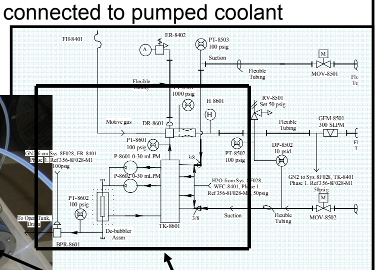
Significance:

- Passive reactant recirculation and water separator components replace active components; reduced mass and volume, lower parasitic power, increased reliability, longer life
  - Initial testing has shown performance of Tescom integrated ejector/ pressure regulator to be comparable to active pumps
  - Initial testing has shown performance of two-stage membrane contactor and de-bubbler (both tubular) to be comparable to active water separators
  - Initial testing has shown gas-driven vortex separator to lack sufficient momentum for consistent operation
  - Initial testing has shown liquid-driven vortex separator connected to pumped coolant loop to be comparable to active water separators



Phase 2 Integrated Ejector and Regulator Package





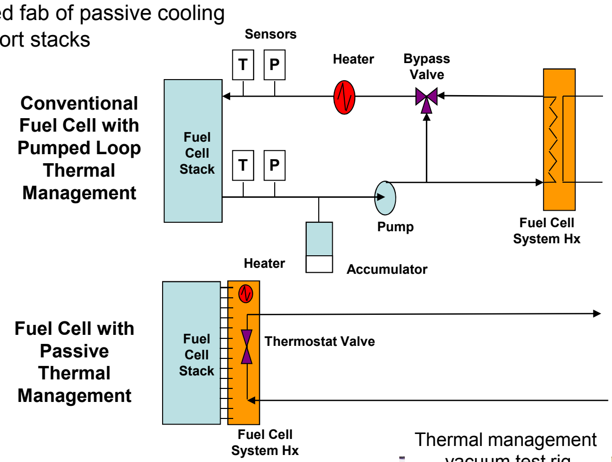
Phase 4, Integrated Ejector, Regulator, and Two-Stage Water Separator System

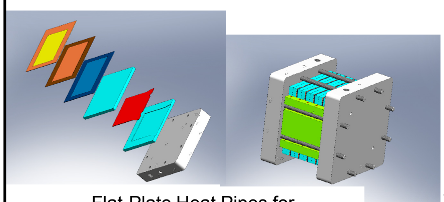
Recent Accomplishments: Fuel Cells

Key accomplishment: Completed fab of passive cooling plates for Teledyne and Infinity short stacks

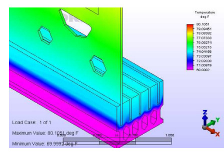
Significance: Passive cooling plates replace active pumped-liquid cooling loop; reduced mass and volume, lower parasitic power, increased reliability, longer life

- Testing has shown pyrolytic graphite cooling plates to have 4x the conductivity of copper
- Testing has shown flat-plate heat pipes to have 30-40x the conductivity of copper



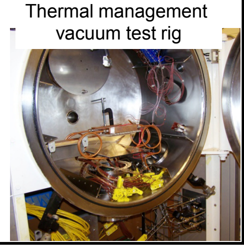


Flat-Plate Heat Pipes for 4-Cell TRL-4 Non-Flow-Through Stack

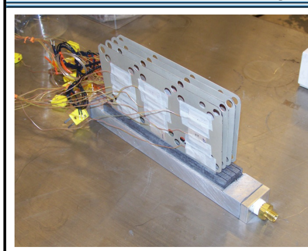


Temperature Distribution Across Pyrolytic Graphite Cooling Plates In 6-Cell Sub-kW Flow-Through Stack

Thermal management vacuum test rig



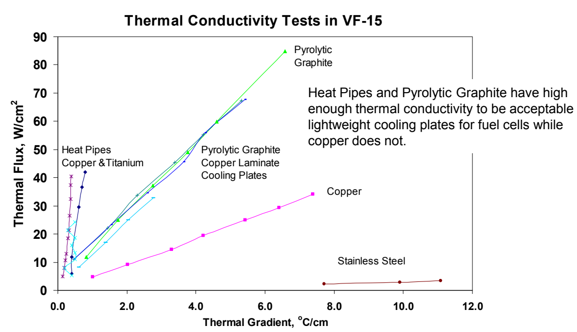
Recent Accomplishments: Passive Cooling Reduces System Mass and Complexity Without Degrading Performance (1/2)

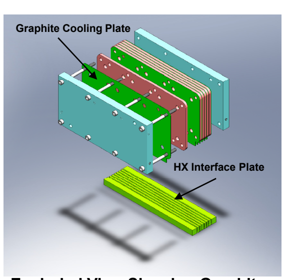


Four Graphite Cooling Plates slid into the HX Interface Plate & Cooling Channel. Pad heaters simulate FC heat.

Testing shows the temperature distribution across any single plate and from plate-to-plate stays <u>within 2-3 °C</u> which is very acceptable.

Temperature control uses a thermostatic valve to modulate the cooling flow through the HX.





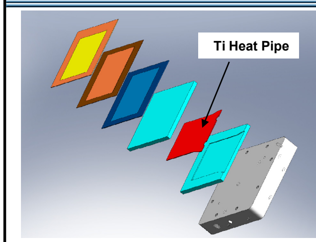
Exploded View Showing Graphite Cooling Plates & HX Interface Plate

The graphite cooling plates, HX Interface Plate, and HX Cooling Channel have been fabricated and delivered to Teledyne Energy Systems for integration into a 6-cell Flow-Thru Stack.

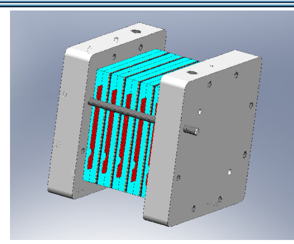
The 6-Cell fuel cell stack has been fully assembled.
The integrated FC stack is to be tested at Teledyne in August 2008.

Simulated fuel cell stack testing with identical graphite cooling plates underway at GRC.

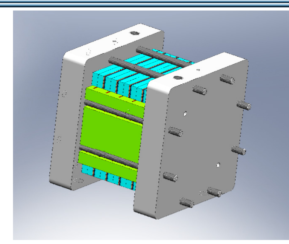
Recent Accomplishments: Passive Cooling (2/2)



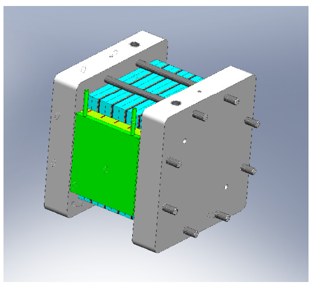
Exploded View Showing Ti Heat Pipe



FC Stack Showing Ti Heat Pipe Edges



FC Stack with HX Interface Plate

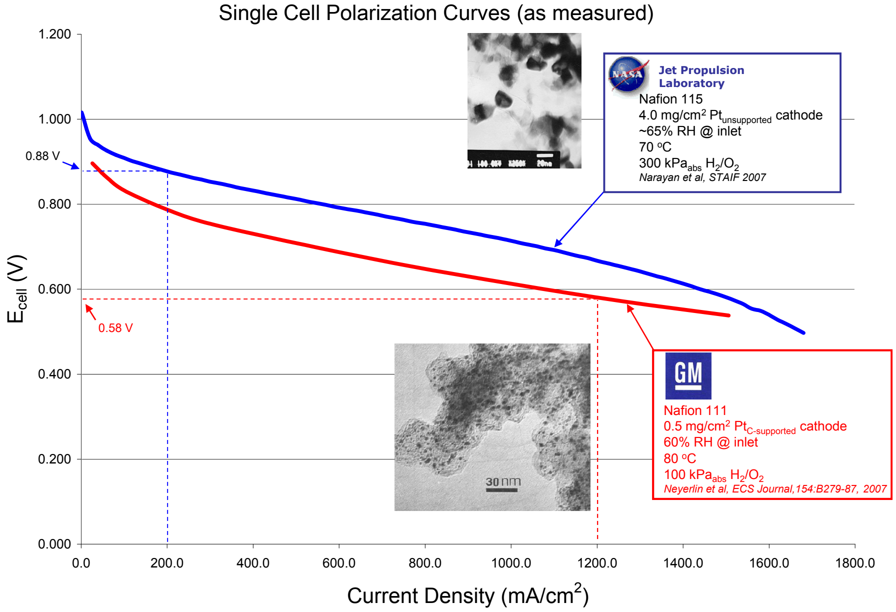


FC Stack Integrated with System HX

- The Ti heat pipes have been fabricated and tested at GRC. Their thermal conductivity ranged from 3500 to 6300 w-m/K. (copper is 400 w-m/K)
- The Ti heat pipes were delivered to Infinity Fuel Cells for integration into the non-flow-through stack
- The HX Interface plate hardware has been fabricated and will be delivered to Infinity for final stack assembly
- The integrated FC stack is to be delivered to GRC by Fall 2008 for testing.
- Preparations are being made for this testing to occur in the GRC Bldg 309 Fuel Cell Laboratory

Milestone Accomplishment: MEA Testing Shows Substantial Improvement Over SOA

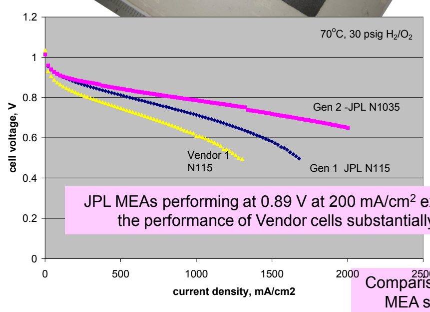
Single Cell Polarization Curves (as measured)



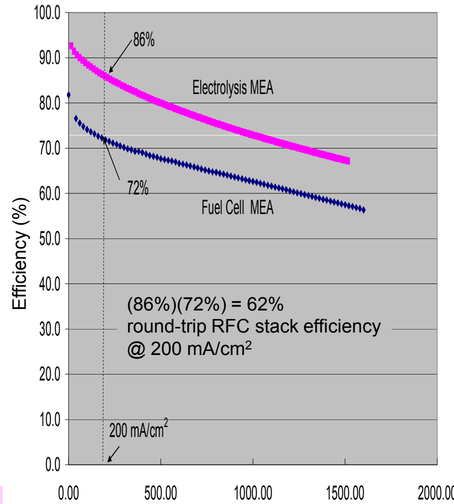
Membrane Electrode Assembly Accomplishments: MEA Performance Exceeds Minimum Success Criteria

- NASA fuel cell and electrolysis MEA performance exceeds best performance of industry vendors

JPL MEAs supplied to
Teledyne, Infinity, and Proton Energy



JPL MEAs performing at 0.89 V at 200 mA/cm^2 exceed the performance of Vendor cells substantially.



(86%)(72%) = 62%
round-trip RFC stack efficiency
@ 200 mA/cm^2

Current density, mA/cm^2
(scale: 0 – 2000 mA/cm^2)

Comparison of JPL's best iridium-doped ruthenium with the latest vendor supplied MEA shows substantially better (30 mV) performance by the NASA material.

Partners: Hamilton Sundstrand, NASA

MEA and Electrolysis Technology: Recent Progress

Objective:

Develop balanced high-pressure (≥ 2,000 psi) electrolysis technology for Exploration missions.
Incorporate advanced membrane-electrode-assemblies (MEAs) with better electrical performance into high-pressure electrolyzers.

Key Accomplishment:

- JPL-developed MEA 86% efficient at 1.48 V
- Hamilton Sundstrand modified existing International Space Station electrolyzer (liquid-feed) for high-pressure operation.
- Testing at JPL showed good voltage performance to 2000 psi H_2 and 1000 psi O_2 with Nafion MEA.

Significance:

- Advanced electrolysis MEAs will deliver more H_2 and O_2 gases with less electrical power input, reducing the required size of a solar array for a regenerative fuel cell system.
- Balanced high-pressure operation permits operation within an architecture having smaller tanks, reducing launch mass and volume requirements.

Future Work:

- Vapor-feed and passive liquid-feed electrolyzers are being investigated to reduce the significant parasitic power draw of the pumps and water/gas separators required for liquid feed systems.

High-pressure electrolyzer in test stand

83 cm^2 MEA with platinum-black catalyst on hydrogen side and iridium oxide catalyst on oxygen side

Recent Accomplishments: Flow-Through vs. Non-Flow-Through PEMFC Down-Select

Background:

Flow-Through PEMFC technology is characterized by recirculating reactants and external product water separation

- Recirculation requires pumps or injectors/ejectors
- Water separation requires motorized centrifugal separators or passive membrane separators

Non-flow-through PEMFC technology is characterized by dead-ended reactants and internal product water removal

- Tank pressure drives reactant feed; no recirculation
- Water separation occurs through internal cell wicking

Selection:

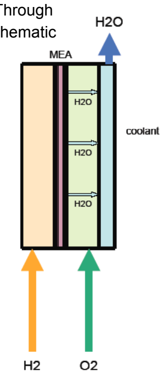
Non-flow-through PEM fuel cell technology selected for further development

Justification:

Flow-through PEMFC technology is at a higher TRL, but non-flow-through technology offers advantages in efficiency, weight, volume, parasitic power, reliability, life, and cost.

derivative of Gemini fuel cell technology

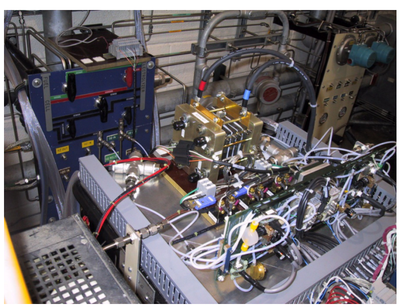
Non-Flow-Through PEMFC Schematic



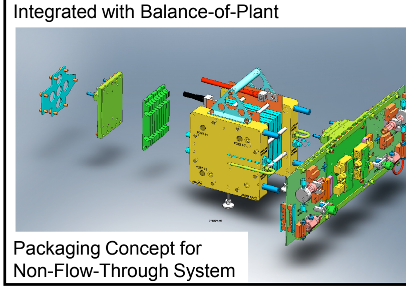
Representative mass allocation for 3 kW fuel cell

	FT	NFT
Stack	16 kg	13 kg
BOP	21 kg	9 kg
Total	37 kg	22 kg

Recent Accomplishments: Non-Flow-Through System Testing Begun



50 cm^2 Lab Stack #1
Integrated with Balance-of-Plant



Packaging Concept for Non-Flow-Through System

Non-flow-through PEMFC technology is characterized by dead-ended reactants and internal product water removal

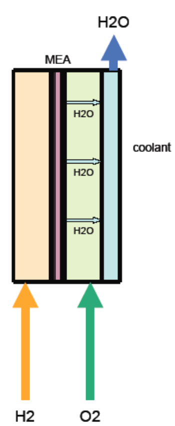
Tank pressure drives reactant feed; no recirculation required

Water separation occurs through internal cell wicking

Components eliminated in NFT system include:

Pumps or injectors/ejectors for recirculation

Motorized centrifugal separators or passive membrane separators for water separation



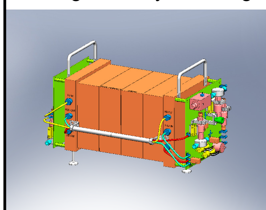
Non-Flow-Through Primary PEMFC Development

Key Accomplishment/Deliverable/Milestone:

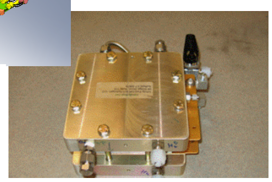
- Completed testing of non-flow-through PEMFC single cell at Phase II SBIR contractor infinity technologies
- Completed 3D modeling of balance-of-plant components at NASA GRC

Significance:

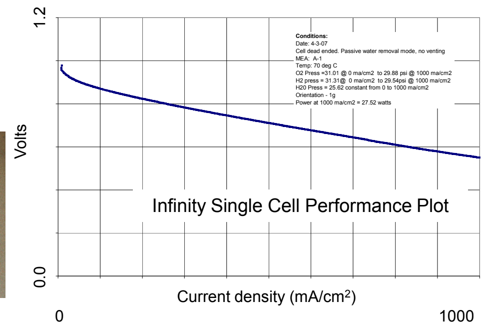
- Successful steady-state operation in dead-ended mode demonstrated; achieved current densities > 1,000 mA/cm^2
- Establishes the basis for future non-flow-through technology advancements
- All ancillary components can be mounted on circuit boards attached to stack end plates, significantly reducing mass and volume of non-flow-through PEMFC systems



3D Packaging Concept Model of Balance-of-Plant Components



Infinity Single Cell Test Article



Infinity Single Cell Performance Plot

WBS 3.2.2 Balance of Plant and System Testing
MS 3.2.2-1 Lab Stack #1 System Testing Complete

PT: Energy Storage
PM: Carolyn Mercer
PI: Mark Hoberecht

Objective:

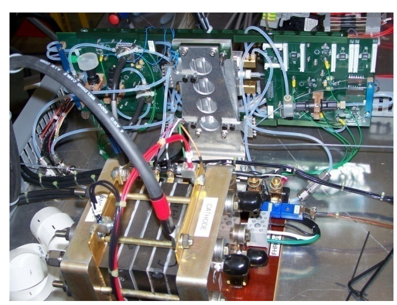
Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Integrate Infinity Lab Stack #1 (4-cell, 50 cm^2) with a GRC-developed balance-of-plant and conduct performance evaluation testing at GRC.

Key Accomplishment/Deliverable/Milestone:

- Partners: Infinity Fuel Cell and Hydrogen, GRC
- 11/30/08 – Infinity Lab Stack #1 System Testing Complete
- The fabrication and testing of this small-area (50 cm^2) short-stack (4 cells) using JPL MEAs with a GRC-developed balance-of-plant is one of several non-flow-through fuel cell system tests used to evaluate the performance of a stack integrated with a balance-of-plant.

Significance:

- The milestone represents the first successful testing at the system level of a non-flow-through fuel cell stack integrated with a balance-of-plant.



Shown: Infinity Lab Stack #1 integrated with GRC balance-of-plant

WBS 3.2.1.1 Baseline Stacks
Milestone 3.2.1.1-1 Lab Stack #2 Unit Delivery

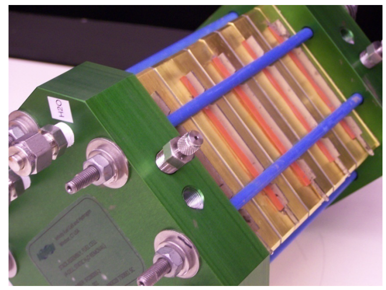
PT: Energy Storage
PM: Carolyn Mercer
PI: Mark Hoberecht

Objective:

Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Incorporate GRC-developed passive flat-plate heat pipe technology and JPL-developed membrane-electrode-assembly (MEA) technology into Infinity fuel cell stacks for performance evaluation.

Key Accomplishment/Deliverable/Milestone:

- Partner: Infinity Fuel Cell and Hydrogen
- 4/30/09 – Lab Stack #2 Unit Delivery from Infinity to GRC
- This small-area (50 cm^2) short-stack (4 cells) delivery is one of several stack deliveries used to evaluate the development progress of non-flow-through fuel cell technology from baseline fuel cell vendor Infinity Fuel Cells and Hydrogen, Inc. This stack also incorporates NASA-developed technology in the form of passive flat-plate heat pipes (GRC) and advanced MEAs (JPL).



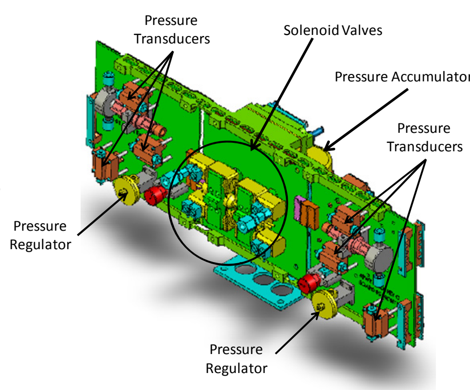
Shown: Infinity Lab Stack #2 with JPL MEAs and GRC flat-plate heat pipes (protruding fins of heat pipes visible behind blue tie rods)

Significance:

- Passive flat-plate heat pipes are an alternative to pumped-liquid cooling loops in fuel cells, and offer the potential of better heat transfer, higher reliability, and lower parasitic power.
- Advanced fuel cell MEAs with better electrical performance will deliver more power from a fixed quantity of hydrogen and oxygen reactants.

Energy Storage Project Recent Accomplishments:
Integrated Balance-of-Plant Components for Fuel Cells

- Integrated balance-of-plant demonstrated in conjunction with the laboratory scale fuel cell stacks
- During this testing, the balance-of-plant ran on a battery source consuming less than 10 W of parasitic power to operate the fuel cell system
- A full-scale (3-kW fuel cell system) balance-of-plant will likely operate on less than 50 W of parasitic power (same number of components, but some components larger)
- A 2-12 kW flow-thru fuel cell system tested at GRC required several hundred watts of parasitic power during operation
- That difference in parasitic power means that Altair would need almost 100 kg less reactants over the course of its 2-3 week mission using a non-flow-through fuel cell system versus a flow-through system



Milestone Accomplishments
3.2.1.1-2 Lab Stack #3 Unit Delivery
3.2.2.2-4 BOP for Lab Stack #3 Complete
3.2.2.2-5 Lab Stack #3 System Testing Complete
3.5-1 Lab Stack #3 MEA Delivery

PT: Energy Storage
PM: Carolyn Mercer
PI: Mark Hoberecht

Objective:

Develop non-flow-through fuel cell technology at baseline stack vendor Infinity Fuel Cells and Hydrogen, Inc. for Exploration missions. Incorporate advanced membrane-electrode-assemblies (MEAs) with better electrical performance into fuel cell stacks. Integrate Infinity Lab Stack #3 (4-cell, 50 cm^2) with a GRC-developed balance-of-plant and conduct performance evaluation testing at GRC.

Key Accomplishment/Deliverable/Milestone:

- Partners: Infinity Fuel Cell and Hydrogen, JPL, GRC
- 3/25/09 – Lab Stack #3 MEA Delivery from JPL to Infinity
- 3/31/09 – Lab Stack #3 Unit Delivery from Infinity to GRC
- 3/31/09 – Balance-of-Plant for Lab Stack #3 Complete
- 4/30/09 – Infinity Lab Stack #3 Testing Complete
- The fabrication and testing of this small-area (50 cm^2) short-stack (4 cells) using JPL MEAs with a GRC-developed balance-of-plant is one of several non-flow-through fuel cell system tests used to evaluate the performance of a stack integrated with a balance-of-plant.

Shown: Infinity Lab Stack #3 and test rig with fuel cell system (stack + balance-of-plant)

Significance:

- System testing of Lab Stack #3 revealed several additional stack design modifications and balance-of-plant procedure adjustments which are both needed to resolve system performance deficiencies.
- These changes will be implemented in subsequent hardware builds and evaluated through additional testing.

Partners: Infinity Fuel Cell and Hydrogen, NASA

Non-Flow-Through Fuel Cell Technology: Recent Progress

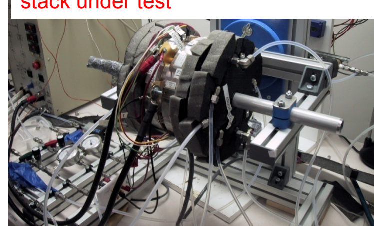
Objective:

Generate data showing performance of a non-flow-through fuel cell stack having a full-size active area.

Key Accomplishments:

- Delivery of 4-cell, 150 cm^2 non-flow-through fuel cell stack incorporating advanced manufacturing process.
- First successful continuous testing of a non-flow-through fuel cell for 100 hr.
- Test data showed successful operation, with performance exceeding all prior small area stacks.
- Innvotive Hydrogen Pump used to increase operation time between purges

Lab-scale non-flow-through fuel cell stack under test

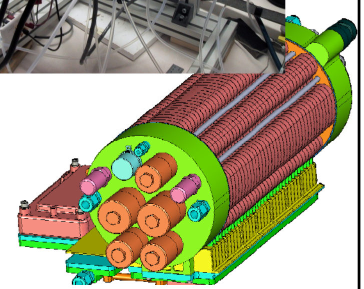


Significance:

- Demonstrates the feasibility of non-flow-through fuel cell technology for Exploration missions
- Eliminates a substantial program risk associated with scale-up of non-flow through fuel cell technology from a laboratory size to the final flight hardware active area.
- Validates the decision to develop non-flow-through fuel cell technology over the previous flow-through technology.
- The 150 cm^2 cell size is optimum for full-size stacks anticipated for 120 VDC Exploration applications such as Altair and Lunar Surface Systems.

• *Future Work:*

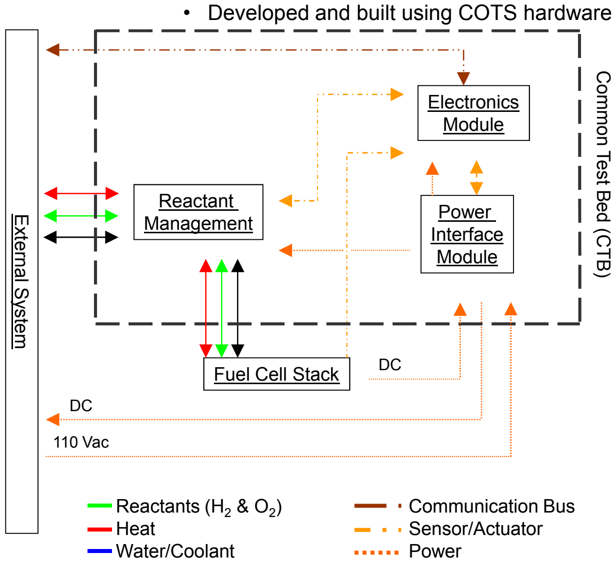
- Build ¼-scale breadboard, then 3-kW Engineering Model

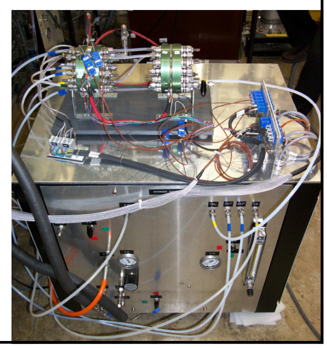


Schematic image of future 3 kW non-flow-through fuel cell stack

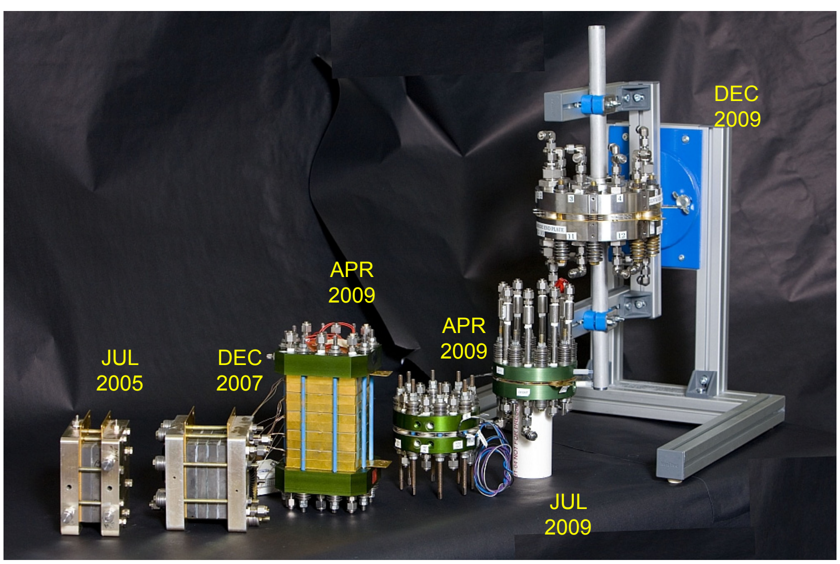
Non-Flow-Through Fuel Cell: Common Test Bed

- Configurable to test stacks provided by multiple vendors
- Capable of testing total output power of 1 kWe
- Capable of testing stacks up to 40 cells
- Capable of conducting un-attended life testing
- Developed and built using COTS hardware





Infinity Non-Flow-Through Fuel Cell Stack Progression



Johnson Space Center
UTC Power

Shuttle
"Active BOP"
Alkaline

Glenn Research Center
TELEDYNE ENERGY SYSTEMS, INC

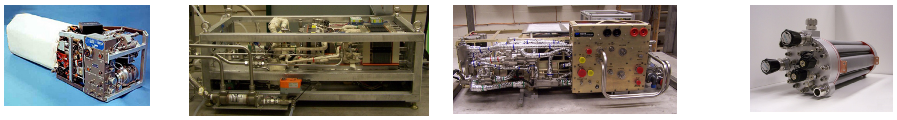
"Active BOP"
PEM

Glenn Research Center
TELEDYNE ENERGY SYSTEMS, INC.

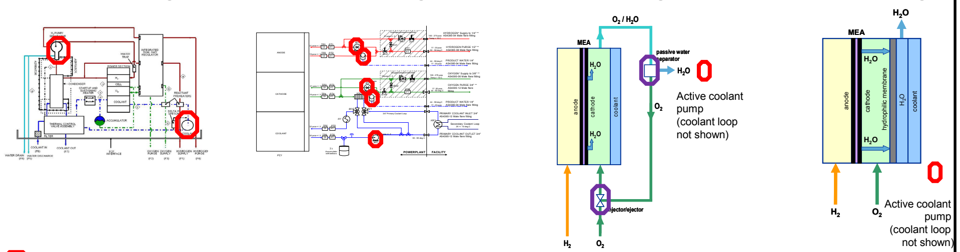
"Passive BOP"
PEM

Glenn Research Center
Infinity

"Passive BOP"
PEM



Flow-Through | Flow-Through | Flow-Through | *Non*-Flow-Through

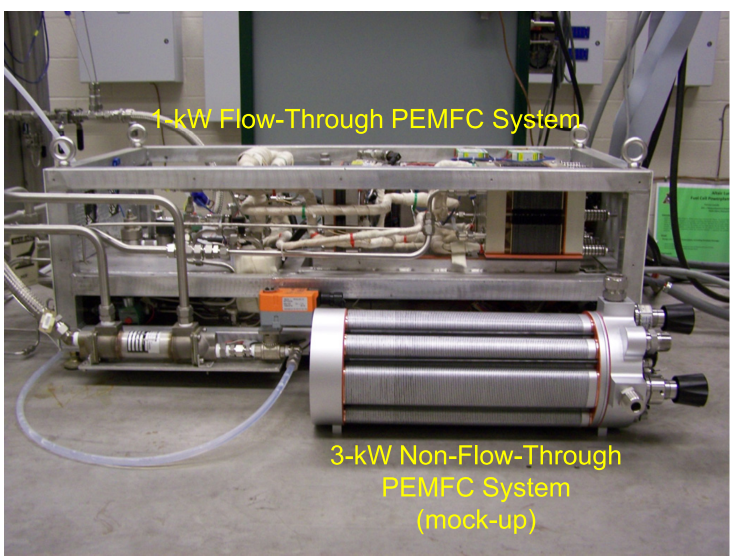


= Active Mechanical Component (pump, active water separator)

= Passive Mechanical Component (injector/ejector, passive water separator)

Fuel Cell Technology Progression to Simpler Balance-of-Plant

PEMFC System Comparison (cont'd)



Fuel Cell Predicted Performance

- **Test data shows** that even with existing heavy endplates, power density of current hardware nearly matches that of SOA Shuttle alkaline flight hardware:
  - 59 kg **non-flow-through** stack (endplates 17 kg) + 10 kg BoP @ 3 kW = **44 W/kg**
  - SOA **Shuttle** alkaline @ 6 kW = **49 W/kg**
- Note: KPP threshold and goal power density values are based on 300 cm^2 hardware (for 30 V systems), which is more mass efficient than smaller 150 cm^2 hardware (for 120 V systems). Our current expectations for 3 kW performance are based on test results from 4-cell stacks, and assume a 4-screen design, 4 kg flightweight endplates, and a 10 kg BOP. **The expected 3 kW performance ranges from:**
  - 66 W/kg for the stack and **54 W/kg** for the system, assuming a 4-chamber cell (separate cavities for coolant and product water); to
  - 125 W/kg for the stack and **88 W/kg** for the system, assuming a 3-chamber cell (combined water/coolant cavity) and additional mass optimization.
- Next steps are to build successively taller stacks to move toward 1/4 scale breadboard (40 cells, 1 kW, 150 cm^2) while retaining the excellent power density
- Voltage, lifetime, and some mass KPP's not specifically addressed in current fiscal year
  - Optimization for voltage not in current year scope, although some conductive coatings will be investigated
  - Lifetime testing not in current year scope
  - Mass optimization not in current year scope, although replacing metallic porous plate with Supor membrane for mass reduction will be investigated

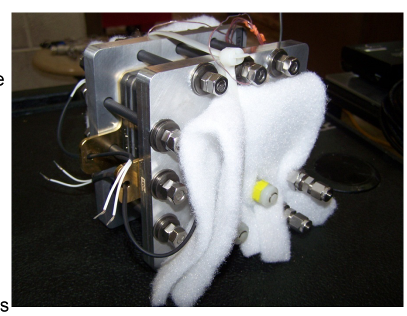
WBS 3.2.1.2 Alternative Stacks
Milestone 3.2.1.2-1 SBIR Stack Delivery

PT: Energy Storage
PM: Carolyn Mercer
PI: Mark Hoberecht

Objective:
Develop non-flow-through fuel cell technology at alternative stack vendor ElectroChem, Inc. for Exploration missions. Integrate this ElectroChem stack with a GRC-developed balance-of-plant and deliver to JSC for performance evaluation testing.

Key Accomplishment/Deliverable/Milestone:
- Partners: ElectroChem, GRC, JSC
- 4/30/09 – ElectroChem Alternative Stack Delivery to GRC
- This small-area (50 cm^2) short-stack (4 cells) delivery will be used to evaluate the development progress of non-flow-through fuel cell technology from alternative fuel cell vendor ElectroChem, Inc.

Significance:
- Several fuel cell stack vendors are developing non-flow-through fuel cell technology as an alternative to the baseline stack technology under development. This approach increases competition and reduces risk.



Shown: ElectroChem alternative non-flow-through fuel cell stack (4-cell short stack)

3.4 Regenerative Fuel Cell Technology Development

Key Accomplishment/Deliverable/Milestone:

- Completed testing of single-cell unitized regenerative fuel cell (URFC) system in NASA GRC test facility
- Accepted delivery of 10-cell URFC stack from Proton Energy Systems

Significance:

- URFC performs both fuel cell and electrolysis functions in a single stack; reduced RFC stack mass and volume, but higher system mass and volume due to lower efficiency in both fuel cell and electrolysis operating modes

Plans for FY'08 and beyond:

- Conduct performance testing of 10-cell URFC system in NASA GRC test facility
- Perform study/design of reactant management integration hardware required for RFC system with separate fuel cell and electrolysis stacks

URFC System

Batteries

- Goals
- Approach
- Component Development
- Cell Development
- Predicted Cell Level Performance

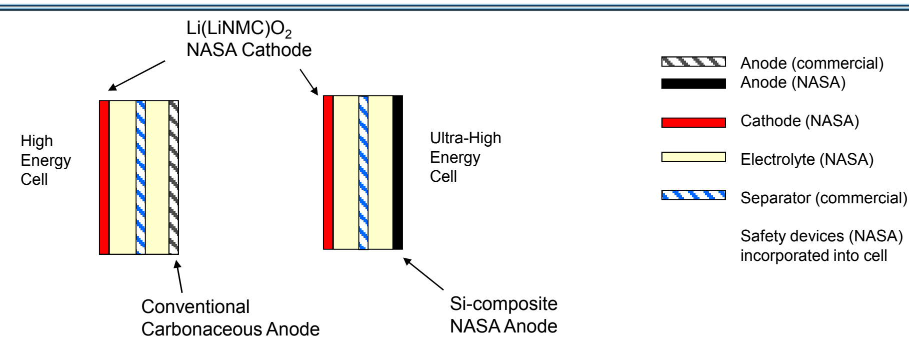
Key Performance Parameters for Battery Technology Development

Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a small reduction in performance using safer electrolytes and cathode coatings	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or flame***	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or flame***
Specific energy Lander: 150-210 Wh/kg 10 cycles Rover: 160-200 Wh/kg 2000 cycles EVA: 270Wh/kg 100 cycles	**Battery-level** specific energy* [Wh/kg]	90 Wh/kg at C/10 & 30 °C 83 Wh/kg at C/10 & 0 °C (MER rovers)	160 at C/10 & 30 °C (HE) 170 at C/10 & 30 °C (UHE) 80 Wh/kg at C/10 & 0 °C (predicted)	**135** Wh/kg at C/10 & 0°C "High-Energy"** **150** Wh/kg at C/10 & 0°C "Ultra-High Energy"**	**150** Wh/kg at C/10 & 0°C "High-Energy" **220** Wh/kg at C/10 & 0°C "Ultra-High Energy"
	Cell-level specific energy [Wh/kg]	130 Wh/kg at C/10 & 30 °C 118 Wh/kg at C/10 & 0 °C	199 at C/10 & 23 °C (HE) 213 at C/10 & 23 °C (UHE) 100 Wh/kg at C/10 & 0 °C (predicted)	**165** Wh/kg at C/10 & 0°C "High-Energy" **180** Wh/kg at C/10 & 0°C "Ultra-High Energy"	**180** Wh/kg at C/10 & 0°C "High-Energy" **260** Wh/kg at C/10 & 0°C "Ultra-High Energy"
	Cathode-level specific capacity [mAh/g]	180 mAh/g	252 mAh/g at C/10 & 25 °C 190 mAh/g at C/10 & 0 °C	**260** mAh/g at C/10 & 0°C	**280** mAh/g at C/10 & 0°C
	Anode-level specific capacity [mAh/g]	280 mAh/g (MCMB)	330 @ C/10 & 0 °C (HE) 1200 mAh/g @ C/10 & 0 °C for 10 cycles (UHE)	**600** mAh/g at C/10 & 0°C "Ultra-High Energy"	**1000** mAh/g at C/10 0°C "Ultra-High Energy"
Energy density Lander: 311 Wh/l Rover: TBD EVA: 400 Wh/l	**Battery-level** energy density	250 Wh/l	n/a	**270** Wh/l "High-Energy" **360** Wh/l "Ultra-High"	**320** Wh/l "High-Energy" **420** Wh/l "Ultra-High"
	Cell-level energy density	320 Wh/l	n/a	**385** Wh/l "High-Energy" **460** Wh/l "Ultra-High"	**390** Wh/l "High-Energy" **530** Wh/l "Ultra-High"
Operating environment 0 to 30 °C, Vacuum	Operating Temperature	-20 to 40 °C	0 to 30 °C	**0** to **30 °C**	**0** to **30 °C**

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.
* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 V/cell, and at 0 °C operating conditions
** "High-Energy" = mixed metal oxide cathode with graphite anode
** "Ultra-High Energy" = mixed metal oxide cathode with Silicon composite anode
*** Over-temperature up to 110 °C; reversal 150% excess discharge @ 1C; pass external and simulated internal short tests; overcharge 100% @ 1C for Goal and 80% @ C/5 for Threshold Value.

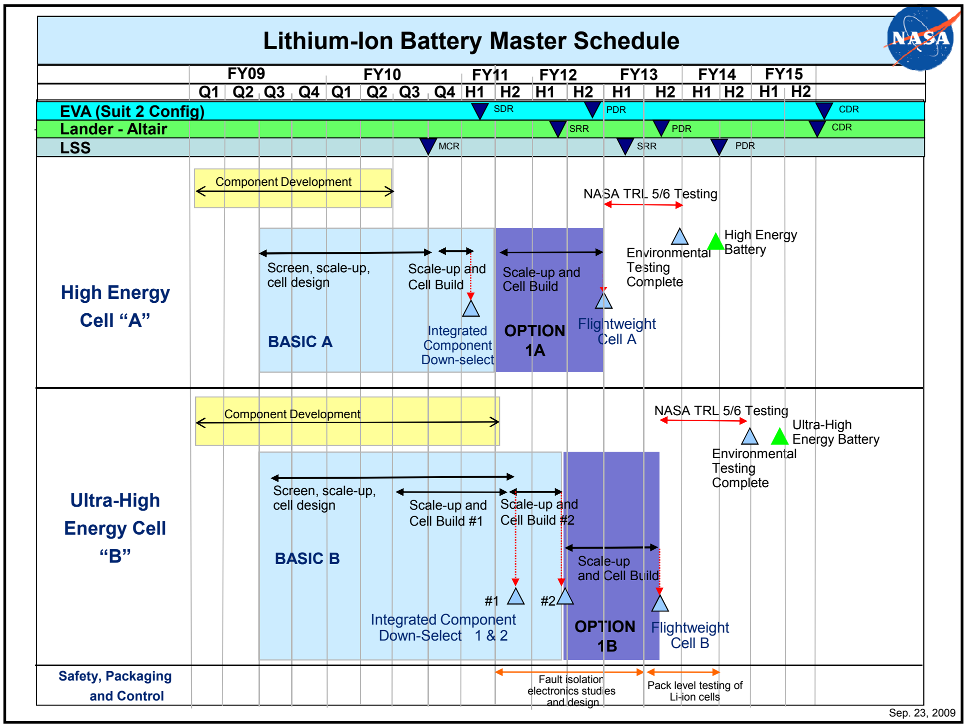
Revised 4/8/10

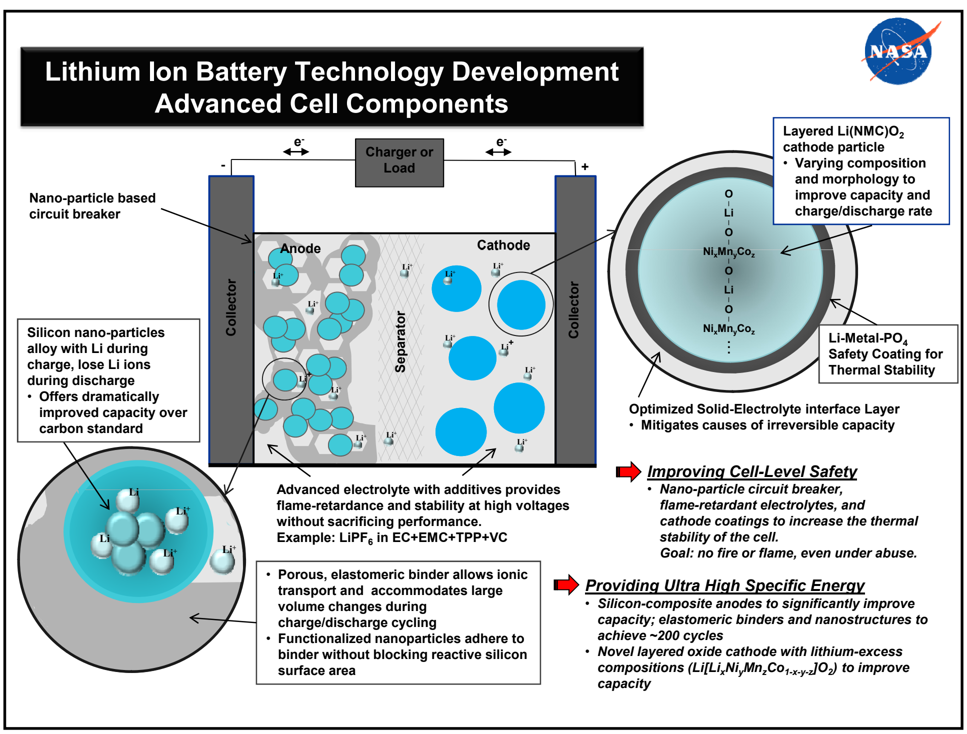
Energy Storage Project Cell Development for Batteries



"High Energy" Cell
Baseline for EVA and Rover
Lithiated-mixed-metal-oxide cathode/Graphite anode
$Li(LiNMC)O_2$/Conventional carbonaceous anode
150 Wh/kg (100% DOD) @ battery-level 0 °C C/10
80% capacity retention at ~**2000** cycles

"Ultra-High Energy" Cell
Upgrade for EVA and Altair, possibly Rover
Lithiated-mixed-metal-oxide cathode/Silicon composite anode
$Li(LiNMC)O_2$/silicon composite
220 Wh/kg (100% DOD) @ battery-level 0 °C C/10
80% capacity retention at ~**200** cycles

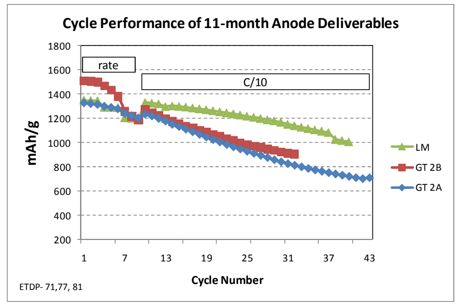

Lithium-Ion Battery Master Schedule
FY09
FY10
FY11
FY12
FY13
FY14
FY15
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 H1 H2 H1 H2 H1 H2 H1 H2 H1 H2
EVA (Suit 2 Config)
Lander - Altair
LSS
SDR
PDR
CDR
SRR
MCR
Component Development
NASA TRL 5/6 Testing
High Energy Battery
Environmental Testing Complete
Screen, scale-up, cell design
Scale-up and Cell Build
Integrated Component Down-select
BASIC A
OPTION 1A
Flightweight Cell A
High Energy Cell "A"
Ultra-High Energy Battery
Screen, scale-up, cell design
Scale-up and Cell Build #1
Scale-up and Cell Build #2
Scale-up and Cell Build
BASIC B
Integrated Component Down-Select 1 & 2
OPTION 1B
Flightweight Cell B
Ultra-High Energy Cell "B"
Safety, Packaging and Control
Fault isolation electronics studies and design
Pack level testing of Li-ion cells
Sep. 23, 2009


Lithium Ion Battery Technology Development
Advanced Cell Components
Charger or Load
Nano-particle based circuit breaker
Anode
Cathode
Collector
Separator
Silicon nano-particles alloy with Li during charge, lose Li ions during discharge
• Offers dramatically improved capacity over carbon standard
Layered Li(NMC)O2 cathode particle
• Varying composition and morphology to improve capacity and charge/discharge rate
Li-Metal-PO4 Safety Coating for Thermal Stability
Optimized Solid-Electrolyte interface Layer
• Mitigates causes of irreversible capacity
Advanced electrolyte with additives provides flame-retardance and stability at high voltages without sacrificing performance.
Example: LiPF6 in EC+EMC+TPP+VC
• Porous, elastomeric binder allows ionic transport and accommodates large volume changes during charge/discharge cycling
• Functionalized nanoparticles adhere to binder without blocking reactive silicon surface area
Improving Cell-Level Safety
• Nano-particle circuit breaker, flame-retardant electrolytes, and cathode coatings to increase the thermal stability of the cell.
Goal: no fire or flame, even under abuse.
Providing Ultra High Specific Energy
• Silicon-composite anodes to significantly improve capacity; elastomeric binders and nanostructures to achieve ~200 cycles
• Novel layered oxide cathode with lithium-excess compositions (Li[LixNiyMnzCo1-x-y-z]O2) to improve capacity

Anode Development

Led by William Bennett, ASRC at NASA GRC

- **Develop silicon-based carbon composite materials**
  - **Much higher theoretical capacity than carbonaceous materials**
- **Development focus on:**
  - **Decreasing irreversible capacity loss**
  - **Increasing cycling stability by reducing impact of volume expansion**
  - **Improving cycle life**
- **Anode Development at:**
  - **Georgia Tech Research Institute**
  - **Lockheed Martin**
  - **Glenn Research Center**



Silicon-based anodes: Specific capacity vs. cycles for three materials at C/10 and 23 °C in coin cell half cell.

Anode Development

NASA Contract # NNC08CB02C

Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**

COTR: **Concha Reid, NASA GRC**

"Advanced Nanostructured Silicon Composite Anode Program"

PI: Dr. Justin Golightly, Lockheed Martin

Objective:

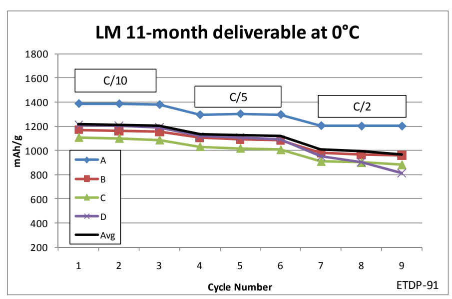
To develop an optimized silicon nanoparticle anode with a novel elastomeric binder that will mitigate capacity fade and enable long cycle.

***Approach*:**

- Functionalize nanoparticles to covalently adhere with binder
- Optimize binder to manage volume changes during cycling
- Optimize anode properties to meet capacity, temperature and life requirements

***Accomplishments*:**

- Anode exceeded 1000 mAh/g when tested in a full cell with an NMC cathode (NEI-D) at room temperature. Performance has stayed good through all 5 cycles to date.
- Anode samples demonstrated >1000 mAh/g at C/10 for 40 cycles at room temperature in half cell testing.
- The KPP goal for the anode specific capacity of 1000 mAh/g at C/10 and 0 °C has been demonstrated over more than 10 cycles.
- Anode tested in a full cell with Saft's NCA cathode and tested for 230 cycles at 40% depth of discharge. Long-term cycling stability was demonstrated with this electrode pair, but capacity imbalance between electrodes limited performance.



Preliminary results for unoptimized materials are shown. Materials were tested at NASA in coin cell half cells.

Challenge:

Anode specific capacity fade rates are still too high to meet the goal of 200 cycles at the cell level.

Anode Development

NASA Contract # NNC08CB01C

Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**
COTR: **Richard Baldwin, NASA GRC**

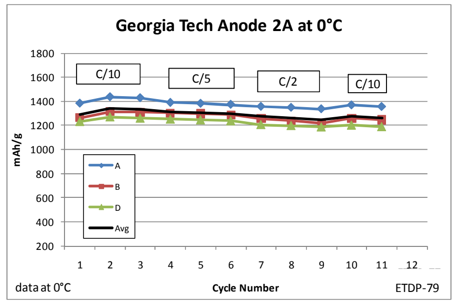
“Design of Resilient Silicon Anodes”

Dr. Gleb Yushin & Dr. Tom Fuller, Georgia Institute of Technology
Dr. Igor Luzinov, Clemson University

Objective:
To address the NASA “ultra-high energy cell” performance metrics, develop a practical silicon-based anode cell component with demonstrated high capacity and cycle life.

Approach:
Optimize a (nano)silicon-based anode structure by utilizing a novel elastic epoxidized polybutadiene (EPB) binder so as to permit sufficient elastic deformations during detrimental volume changes associated with lithium-silicon alloying and de-alloying.

Accomplishments:
- Anode samples demonstrated >1000 mAh/g at C/10 for 10 cycles at room temperature in half cell testing.



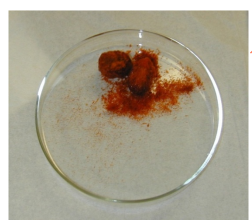
Preliminary results for unoptimized materials are shown. Materials were tested at NASA in coin cell half cells.

Challenge:

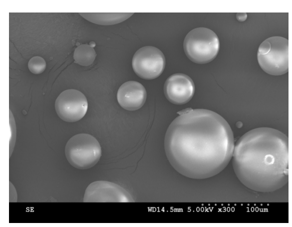
Anode specific capacity fade rates are still too high to meet the goal of 200 cycles at the cell level.

GRC In-House Anode Synthesis

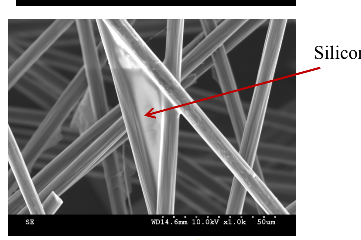
PI: Jim Woodworth, NPP,NASA GRC



Resorcinol Formaldehyde (RF) Gels
- Resorcinol- formaldehyde resin formed in water
- Formed into monoliths
- Formed into microspheres
- Silicon or other materials may be added to the material
- Materials are freeze dried and pyrolyzed to form the carbonaceous anode material



Silicon Sputter Coated Carbon Fiber Paper
- Apply Si to an active support material that is also capable of acting as a current collector
- 50 nm Si Coating

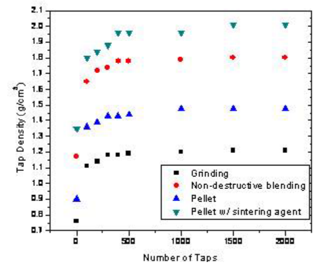


Silicon Sputter Coated Copper
- 50 nm Si coating
- Used to study lithiation of silicon

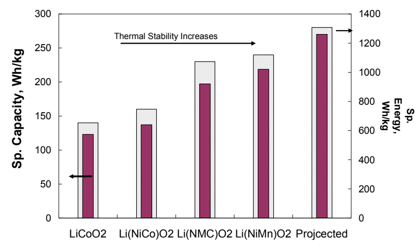
Cathode Development

Led by Kumar Bugga, NASA JPL

- **Develop Li(NMC) materials**
  - **Offer enhanced thermal stability over conventional cobaltate cathodes**
  - **High voltage materials**
- **Development focus on:**
  - **Increasing specific capacity**
  - **Improving rate capability**
  - **Stabilizing materials for higher voltage operation**
  - **Reducing irreversible capacity loss**
  - **Increasing tap density**
- **Cathode Development at:**
  - **University of Texas at Austin**
  - **NEI Corporation**
  - **JPL**



Synthesis methods affect tap density



Adding transition metals improves thermal stability

Cathode Development

NASA Contract # NNC09CA08C

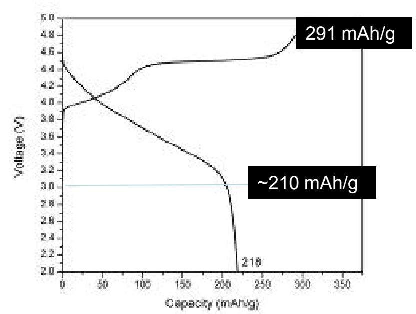
Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**
COTR: **Richard Baldwin, NASA GRC**
TM: **Kumar Bugga, NASA JPL**

"Development of High Capacity Layered Oxide Cathodes"
PI: Dr. Arumugam Manthiram, University of Texas at Austin

***Objective*:**
Develop $LiNMCO_2$ cathode materials with high capacity and low irreversible capacity (IRC) loss.

***Approach*:**
- Vary composition of base material to maximize discharge capacity with low IRC loss.
- Modify cathode surface with metal oxide coatings to increase capacity and decrease the IRC.
- Dope samples with titanium to increase capacity.

Accomplishments
- Surface modified samples demonstrate higher capacity, lower irreversible capacity loss, and more stable cyclability after 25 cycles as compared to unmodified cathode sample.
- Tap density increased to 1.6 g/cc to accommodate Saft's manufacturing process, but specific capacity degraded (down to ~210 mAh/g from 252 at 3.0 V)



Preliminary results of high tap density material in coin cell half cell. 1st cycle data shown. The discharge capacity is slightly lower than anticipated, but increases after a few cycles to ~ 230 mAh/g at C/10.

Challenge:

0 °C capacity is very poor (~30% reduction). Even at room temperature, the specific capacity remains below 260 mAh/g.
High first cycle irreversible capacity loss.(~30% at room temperature).

Project: ETDP Energy Storage Project – Space-rated Lithium-ion Batteries
COTR: Concha Reid, NASA GRC
TM: Will West, NASA JPL

Cathode Development

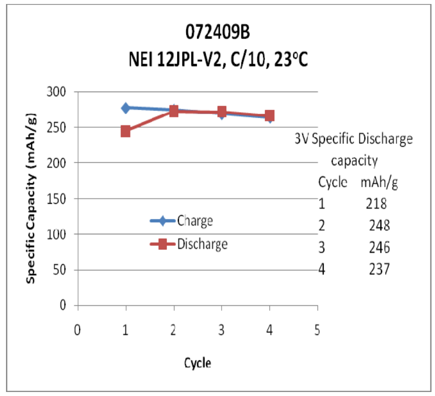
NASA Contract # NNC09CA07C

"Mixed Metal Composite Oxides for High Energy Li-ion Batteries"
PI: Dr. Nader Hagh, NEI Corporation

***Objective*:**
Develop a LiNMC cathode material with a unique structure, composition, and a fine-grained particle morphology. Synthesize materials using a scalable and low cost process.

***Approach*:**
- Understand ordering and produce a highly ordered structure
- Ultra fine particle crystallization using solid state reactions
- Structure refinement

***Accomplishments*:**
- Produced several variants of $LiNMCO_2$ cathode materials
- Demonstrated stability over a wide operating voltage window (4.8 to 2.5 V).
- Successfully synthesized powders with tap densities above 2.0 g/cc.



Preliminary results of unoptimized materials are shown. Materials were tested at NASA in coin cell half cells.

Challenge:

0 °C performance is very poor (~40% reduction).
High first cycle irreversible capacity loss.(~24% at R.T.)

Electrolyte Development

Led by Marshall Smart, NASA JPL

- **Develop advanced electrolytes with additives:**
  - **Non-flammable electrolytes and flame retardant additives**
  - **Stable at potentials up to 5 V**
  - **Compatible with the NASA chemistries**
- **Development focus on:**
  - **Reducing flammability**
  - **Stabilizing materials for higher voltage operation**
  - **Compatibility with mixed-metal-oxide cathodes and silicon composite anodes**
- **Electrolyte Development at:**
  - **JPL**
  - **Yardney Technical Products/University of Rhode Island**

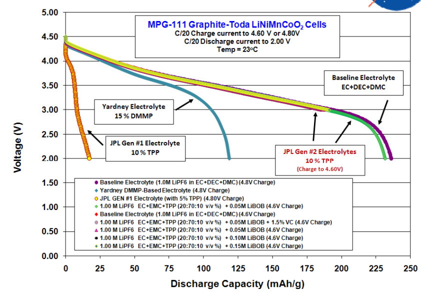
JPL In-House Electrolyte Development

Led by Marshall Smart, NASA JPL

***Objective*:**
- To develop flame retardant electrolytes for Li-ion cells that are stable up to 5.0 V.

***Approach*:**
- Determine best formulation for low-flammability that is consistent with high-voltage mixed-metal-oxide cathodes, and with graphite and silicon composite anodes:
    - Vary concentration of triphenyl phosphate additives
    - Test both linear and cyclic fluorinated carbonates as non-flammable solvents.

***Accomplishments*:**
- JPL Gen #1 Electrolyte has <50% heat release, <25% pressure rise, and >33% faster flame extinction compared to Saft electrolyte, but showed poor compatibility with NMC cathodes.
- JPL Gen #2 electrolytes (containing LiBOB) now shows good performance with graphite/NMC electrodes, and has lower flammability because of increased TPP content (10%).



Comparable performance was obtained with the JPL Gen #2 electrolytes (containing LiBOB) compared with the baseline solution.

Description	Electrolyte	Percentage Flame Retardant Additive (%)	SET, S	Standard Deviation
Yardney/URI GEN # 2 Electrolyte	1.0M (95% LiPF6+ 5% LiBOB) in EC/EMC/DMMP (3/5.5/1.5)	15% DMMP	1.8	1.5
JPL Electrolyte	1.0M LiPF6 in EC/EMC/TPP (2/6.5/1.5) + 2% VC	15% TPP	3.78	1.2
JPL Electrolyte	1.0M LiPF6 in EC/EMC/TPP (2/7/1) + 2% VC	10% TPP	9.57	0.9
JPL GEN # 1 Electrolyte	1.0M LiPF6 in EC/EMC/TPP (2/7.5/0.5) + 2% VC	5% TPP	22.45	2.3
"Baseline" Electrolyte	1.0M LiPF6 in EC/EMC (3:7)	None	33.4	3.4
Yardney/URI GEN # 1 Electrolyte	1.0M (95% LiPF6+ 5% LiBOB) in EC/EMC/DMMP (3/5/2)	20% DMMP	0.4	0.4

Self-extinguishing time (SET) flammability tests show excellent flame retardance in JPL and Yardney/URI electrolytes.

Electrolyte Development

NASA Contract # NNC09CA06C

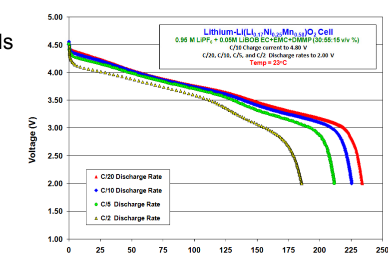
Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**
COTR: **Richard Baldwin, NASA GRC**
TM: **Marshall Smart, NASA JPL**

"Flame Retardant, Electrochemically Stable Electrolyte for Lithium-Ion Batteries"
PI: Dr. Boris Ravdel, Yardney Technical Products
Collaborator: Dr. Brett Lucht, University of Rhode Island (URI)

***Objective*:**
- To develop flame retardant electrolytes for Li-ion cells
- that are stable up to 5.0 V.

***Approach*:**
- Characterize electrochemical stability of baseline electrolyte solution at and above 5 V
- Examine flame retardant properties of baseline electrolyte with additives
- Characterize effect of additives on electrochemical
- stability
- Analyze performance of cells containing the developed electrolytes

***Accomplishments*:**
- Flame retardant electrolytes were formulated
- Tests performed on 12 Ah cells made with developed electrolyte formulations



Rate capability at 23 °C of electrolyte with lowest Self-extinguishing time (left): 0.95 M $LiPF_6$ + 0.05M LiBOB EC+EMC+DMMP (30:55:15 wt %) developed by Yardney Technical Products

(effort completed December 2009)

Separators and Safety Components

Separators

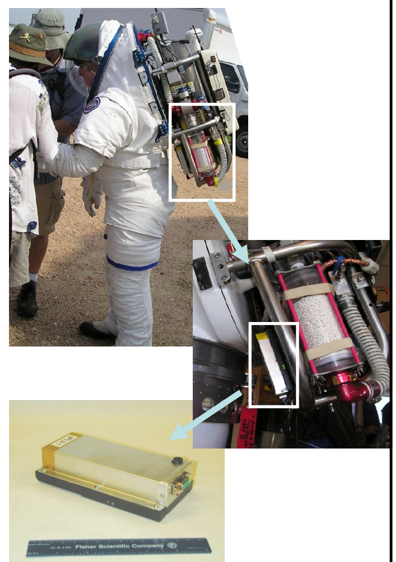
Led by Richard Baldwin, NASA GRC

- Separators with improved safety
- Shutdown separators
- Optimized for ETDP chemistry

Safety Component Development

Led by Judy Jeevarajan, NASA JSC

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
- Functional components
- Safety Component Development at:
  - Physical Sciences, Inc.
  - Giner



Safety Component Development
NASA Contract # NNC09CA04C

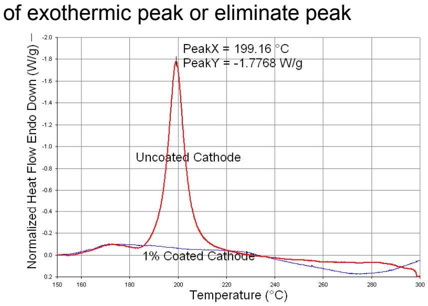
Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**
COTR: **Judy Jeevarajan, NASA JSC**

"Metal Phosphate Coating for Improved Cathode Safety"
PI: Dr. Christopher Lang, Physical Sciences Corporation

***Objective*:**
•Coat metal oxide cathodes with lithium metal phosphate coatings to improve thermal stability.

***Approach*:**
•Coat $LiCoO_2$ cathodes using 1 and 2% lithium metal phosphate solutions
•Optimize coatings to increase onset temperature of exothermic peak or eliminate peak

***Accomplishments*:**
- Demonstrated no loss in discharge capacity for uncoated cathode compared to cathode with ~1.5% $LiCoPO_4$ coating (results reported for 1 cycle)
- Demonstrated robust adhesion of coating in half cells for 200 cycles, cycling at C-rate with capacity retention of ~90 of 1st cycle capacity
- Demonstrated to reduce exotherms without reducing performance on high voltage cathodes (Toda).



Preliminary results show complete suppression of exotherm with coated $LiCoO_2$ cathode.

Next step:

Determine compatibility with MPG-111/NMC full cell.

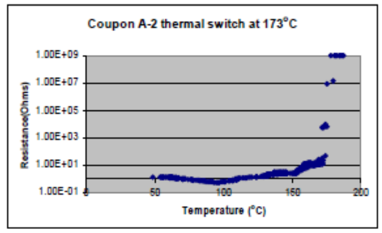
Safety Component Development
NASA Contract # NNC09CA05C

Project: **ETDP Energy Storage Project – Space-rated Lithium-ion Batteries**
COTR: **Judy Jeevarajan, NASA JSC**

"Control of Internal and External Short Circuits in Lithium-Ion Batteries"
PI: Dr. Robert McDonald, Giner Incorporated

***Objective*:**
To develop the compositions and fabrication methods for integration of a Composite Thermal Switch into Li-ion cells.

***Approach*:**
•Optimize a switch temperature for safe handling of short circuits in Li- ion cells (switch activation causes a resistance increase at surface of coated electrode).
•Build Li-ion cells to demonstrate the concept and effect using externally applied heat and hard shorts.
•Perform electrochemical testing to confirm that safety improvements do not compromise performance.



Prior work for Li primary cells. Activation of switch at ~173 °C yields >10^8 fold increase in resistance.

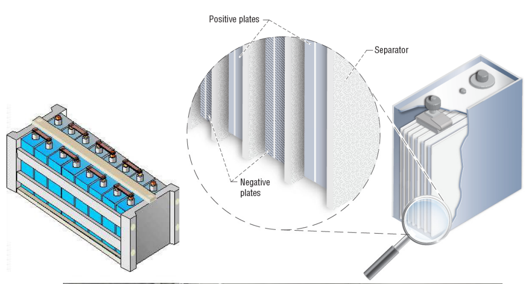
***Accomplishments*:**
- Switch coated on both copper and aluminum substrates
- Coatings deposited in different thicknesses to compare switch behavior as a function of temperature
- Non-uniform switching behavior and resistance observed on samples

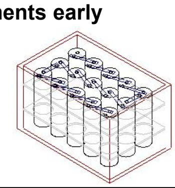
Challenge:

Repeatable, consistent switching behavior.

Cell Development
Led by Tom Miller, NASA GRC

- **Assess NASA-developed components**
  - **Build and test electrodes and screening cells**
  - **Provide manufacturing perspective from the start**
- **Scale-up NASA-developed components**
  - **Transition components from the lab to the manufacturing floor**
- **Build and test evaluation cells (10 Ah):**
  - **Determine component interactions**
  - **Determine cell-level performance**
- **Design flightweight cells (35 Ah)**
  - **Identify high risk elements early**



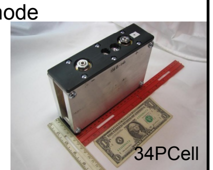


Cell Development
NASA Contract # NNC09BA04B

Project: ETDP Energy Storage Project – Space-rated Lithium-ion Batteries
COTR: Tom Miller, NASA GRC

"Advanced Lithium-Based Chemistry Cell Development"
PI: Dr. Bob Staniewicz, Saft America

Component screening:
UT Austin increased the tap density of their cathode to provide manufacturability;
Saft modified their electrode processing to be compatible with Giner's thermal switch;
Georgia Tech will modify their binder additives to be compatible with Saft's anode manufacturing process.
Toda-9100 identified as baseline cathode.



Baseline cells: graphite anode (MPG-111), nickel-cobalt cathode (NCA)
DD cells (10 Ah, cylindrical): fabricated and under test.
34P cells(45 Ah, prismatic): fabricated, activated, and delivered.

Flightweight cells (35 Ah, prismatic): PDR held May, 2010
Flightweight cell design predicted to meet 185 Wh/kg at 25 °C, and possibly 194 Wh/kg (using a proposed design change in the bussing configuration). 0 °C predictions below current baseline.

<table>
<tr><th></th><th><u>Basic</u>
(34 months)</th><th><u>Option 1</u>
Flightweight Cell Fabrication (18 months)</th></tr>
<tr><td>High Energy Cell</td><td rowspan="2">• Component screening and evaluation for manufacturing suitability
• Component material scale-up
• Electrode optimization
• Fabrication and delivery of evaluation screening cells
• Flightweight cell design</td><td>Fabrication and delivery of 12-48 (TBR) High Energy, ~35 Ah (TBR) flightweight cells that incorporate cell-level safety components.</td></tr>
<tr><td>Ultra High Energy Cell</td><td>Fabrication and delivery of 12-48 (TBR) Ultra High Energy, ~35 Ah (TBR) flightweight cells that incorporate cell-level safety components.</td></tr>
</table>

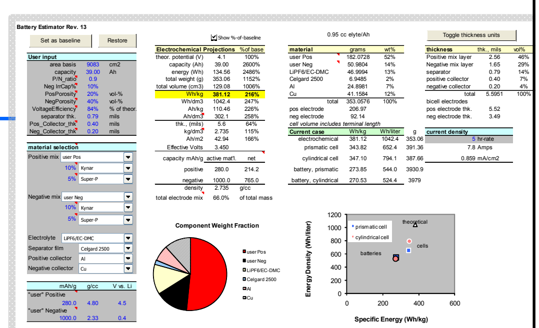
Cell Development

Objective:

Develop a cell/battery design tool to aid in component materials assessments

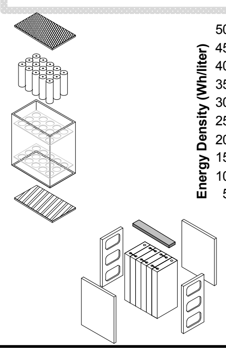
Key Accomplishment:

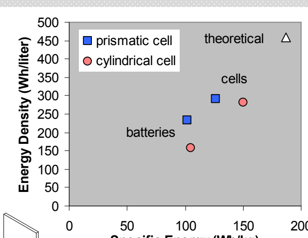
- Spread sheet developed that projects cell/battery level characteristics based on component level materials
  - Based on standard design configuration
  - Configured to rapidly perform what-if? analyses



Significance:

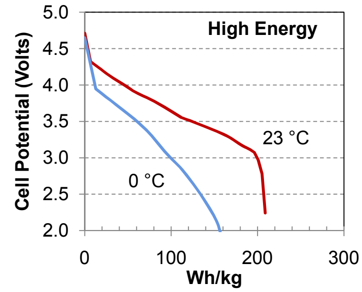
- Aids in quantifying impact of incremental improvements in battery design materials
- Allows identification of critical factors which control cell/battery energy density and specific energy
- Provide engineering-accuracy forecasts of size and mass for cells and batteries
- Rate performance can be estimated from laboratory data for electrodes under relevant conditions

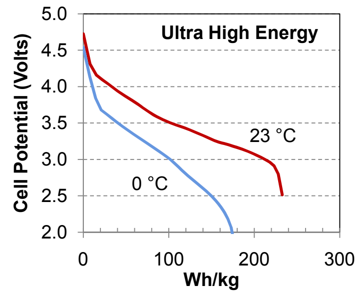




Cell-Level Specific Energy Prediction Results – Using Current Component Data

- **Projected discharge profiles for cells using electrode voltage data**
  - Based on electrode data at 23 and 0 °C
  - Representative of fresh cell without many cycles
- **Cathode low-temperature performance produces very low specific energy at 0 °C**
  - Lower than SOA at 0 °C
  - Specific energy at room temperature represents improvement over SOA



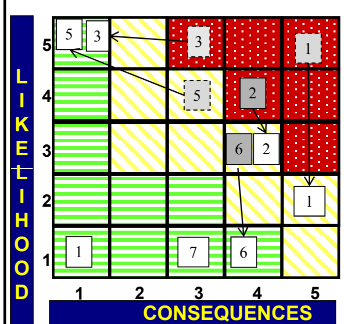


	KPP at 0 °C		model at 3 V cutoff	
	threshold	goal	23 °C	0 °C
Baseline		150	173	156
HE	165	180	199	100
UHE	180	260	213	100

Baseline electrodes = MPG-111 and NCA
HE electrodes = MPG-111 and $Li(LiNMC)O_2$
UHE electrodes = Si-composite and $Li(LiNMC)O_2$

- **Expected performance should improve with further component development**

Energy Storage Risk Assessment: Overall Project - Closed Risks Summary Since December 2007 Major Re-plan



Explanation of risk closure before becoming "green":

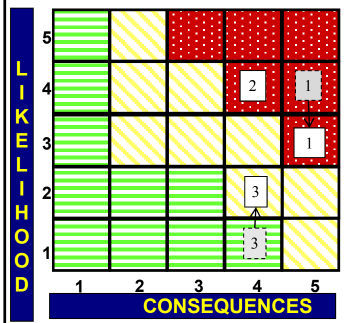
1. Constellation accepted late delivery of regenerative fuel cell so this project closed it as an Energy Storage risk.

2. Battery performance risk split into more detailed technical risks.

Risk ID and Open Date	Risk Title	Risk Statement	Mitigation
ES-01 12/2007 1 ⬇	Resources for FC and RFC	Given that there is insufficient money to develop fuel cells and regenerative fuel cell technology in the timeframe required for LSS, there is a possibility that hardware will not be ready in time, resulting is a schedule slip for LSS.	Stopped "flow-through" fuel cell work, and accepted late delivery of regenerative fuel cell.
ES-02 12/2007 2 ⬇	Battery Performance	Given that there is a gap between the stated customer requirements and our performance goals, there is a possibility that our technology will not be responsive to Cx needs, resulting in an inability to meet the mision.	Reformulated our goals to meet Cx needs.
ES-05 12/2007 3	Electrolysis work starts late	Thie only work done on high pressure electrolysis is done via SBIR and IPP.	Accept.
ES-06 1/2008 4 ⬇	Schedule for batteries	Given the aggressive performance and safety goals needed for EVA Suit 2 and Altair Ascent stage batteries, there is a possibility that we can not develop TRL 6 batteries in time for their PDR resulting in a schedule slip for EVA and Altair.	Negotiated with EVA and Altair to deliver cells instead of batteries.
ES-07 1/2008 5 ⬇	Commonality of EVA and Altair requirements	Given that EVA may require a unique cell package to fully optimize its battery design, there is a possibility that building only one cell design will not be optimal for both EVA and Altair, resulting in a loss of specific energy and/or energy density for one or the other.	A conformal cell configuration unique to the EVA geometry may improve specific capacity and energy density for EVA, but this configuration would not be optimum for Altair. The existing budget and schedule can only support one cell configuration. Accept.
ES-08 7/2008 6 ⬇	Funds availability	Given that there will be a continuing resolution in FY09, there is a possibility that insufficient procurement funds will be available to start the new battery contracts, resulting in a schedule slip for delivering cells to EVA and Altair.	Requested early funds from ETDPO, negotiated with procurement to allow partial initial funding, apply FY08 funds to these contracts.
ES-11 7/2008 7 ➡	No bidders or high bidding on battery contracts	Given that we have very aggressive battery goals and need to contract out much of the work, there is a possibility that no one will bid or that the bids will come in much more expensive than we can afford, resulting in an inability to pursue the direction we have chosen to meet the EVA and Altair performance goals.	Announced solicitations at Space Power Workshop, held WebEx bidders conference. Negotiate contracts as necessary.
ES-09 7/2008 8 ➡	Technology infusion into Cx	Given that new technology is being developed for both batteries and fuel cells, there is a possibility that prime and subcontractors for Cx will be unfamiliar with our work and therefore uncomfortable with it, resulting in the selection of less capable technology for flight hardware.	Formed Fuel Cell Working Group and contracting for Battery Industry Partner.

2010

Energy Storage Risk Assessment: Overall Project – Open Risks Summary Since December 2007 Major Re-plan



1. Li-ion chemistry selected.
2. Primary fuel cell risk lowered; electrolysis still at low TRL.
3. Management structure of the SBIR program in flux.

Rank/ ID	Description	Likelihood, Consequence Mitigation	Risk Mgmt Approach
1 ES-04 ⬇	Battery safety: chemistries may pose unacceptable risks to the crew.	Less likely with lithium ion chemistry than with lithium metals. Potential consequence is spontaneous ignition causing loss of crew. (3, 5)	Address electrolyte flammability. Include safety goals in NRA and RFP. Develop fault isolation electronics. Carry "high energy" cell as fall back.
2 ES-03 ➡	Regenerative fuel cell life: 10,000 hr reliable operation may not be achieved.	Highly likely that new system design will have unforseen problems that could limit life goal. (4, 4)	Develop non-flow-through technology to eliminate balance-of-plant components (including the highest-failure-rate components) for both primary and regenerative fuel cell systems. Build fuel cell systems out of modular units to prevent single-point failures. Leverage SBIR/IBR for innovation.
3 ES-10 ⬆	IPP/SBIR electrolysis funding not stable	IPP/SBIR funding likely to remain steady in FY09 and FY10. If not, high pressure electrolysis will not be ready for integration further impacting LSS schedule. (1, 4)	Focus SBIR solicitations on Energy Storage needs.

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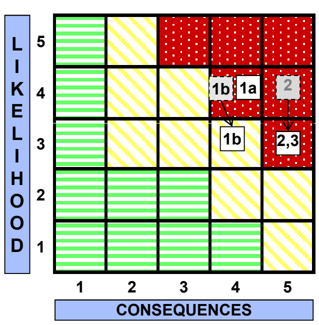
Energy Storage Risk Assessment: Batteries Status of Risks as Reported at Last TCR

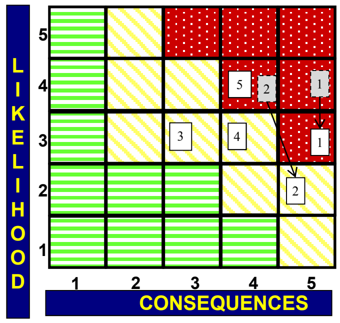


1. EVA and Altair have detailed power lists, although still subject to change. LSS working on power profiles.
2. Materials now selected; scale-up not yet begun
3. Integration not yet begun.

Rank/ Trend	Description	Likelihood/Consequences	Risk Mgt. Approach
1 ES-13a ES-13b ⬇	There is uncertainty of the load profile and energy requirements within the Constellation Program. 1a) LSS 1B) EVA and Altair	Trade studies based on limited program requirements may miss the key drivers associated with the energy storage technical focus. Impact: Although there are iterative cycles to continuously review updated requirements, there are potential schedule impacts if significant re-work is necessary.	Define the power load profiles and mission requirements as early as possible.
2 ES-14 ➡	Scale-up of critical materials to meet performance goals may not be compatible with existing manufacturing techniques or may require multiple re-qualifications.	The aerospace lithium-ion battery market is small in comparison with the commercial market sector and the commercial market drives the manufacturing process. Impact: There is a risk that once the lithium-ion cell design has been baselined, the suppliers may alter their manufacturing process and impact performance or necessitate re-qualification of the lithium-ion cell.	Contract with Industry Partner to evaluate advanced materials for their manufacturability. Factor results into component downselection decisions. Once baselined for flight, maintain government control/oversight/manufacturing of critical materials.
3 ES-15 ➡	Poor integrated cell performance due to potential incompatibility of the best selected cathodes, anodes, electrolytes, separators, and their associated unique manufacturing processes to function together as a complete lithium-ion cell design.	Prelim assessment = 3 / 5; Individual development of advanced components for lithium-ion cells may fail to meet all of the enhanced performance metrics for human-rated batteries. Impact: Additional interactive investigations with added costs will need to be conducted to meet the compatibility issues and safety for human-rating.	Integrate candidate materials together in a laboratory to screen for compatibility and guide selection of best components. Manufacture evaluation cells with different combinations of candidate component materials and conduct performance, safety and abuse testing to determine the best performing chemistries.

2010

Energy Storage Risk Assessment: Fuel Cells
Status of Risks as Reported at Last TCR



1. Non-flow-through stacks built and tested, initial feasibility demonstrated.
2. NFT BOP built and tested, initial feasibility demonstrated.
3. Initial electrolysis work promising, but too early to reduce likelihood a level.
4. Same
5. Same

Rank WBS Trend	Description	Likelihood, Consequence Mitigation	Risk Mgmt Approach
1 ES-12 ↓	Non-Flow-Through stack development may not be successful.	If Non-Flow-Through stack development is not successful, mass/vol and reliability requirements won't be met for Lander & LSS.	Non-flow-through stack being developed by experienced vendor personnel team (Gemini, Shuttle fuel cell experience); several leading fuel cell SBIR vendors developing back-up stacks.
2 ES-12 ↓	Non-Flow-Through balance-of-plant development may not be successful.	If Non-Flow-Through balance-of-plant development is not successful, mass/vol and reliability requirements won't be met for Lander & LSS.	Non-flow-through balance-of-plant being developed in-house at NASA by experienced fuel cell team; system integration and testing planned at each succeeding technology readiness level.
3 →	High-pressure electrolysis for RFC may not be successful.	If high-pressure electrolysis is not successful, lower pressure electrolysis will be required with mass/vol and parasitic power penalties.	Two parallel development approaches (IPP & SBIR) with leading high-pressure electrolysis vendors. Down-select to follow, leading to TRL 5 & 6.
4 →	RFC integration of fuel cell and electrolysis technologies may not be successful.	If necessary integration hardware doesn't work, RFC won't be available for LSS.	Perform reactant management study/design, followed by hardware development, integration, and testing.
5 ES-03 →	10,000 hr. life for primary fuel cells and RFCs may not be achievable.	If 10,000 hr. system life is not achievable, extra redundancy or premature system maintenance or replacement will be required.	Stress long life at component and subsystem levels; perform system life testing at TRL-5 for early awareness of issues; perform at TRL-6 in parallel with system qualification.

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Baselined 10/09/09
Updated 3/23/2010
Revised 4/28/2010 (format only)

Top 10 Battery Lower-Level Risks

ID	Category	Rank & Trend	Trend	Open Date	Risk Title	Risk Statement	Likelihood	Consequence	Affinity Group	Owner / Initiator	Approach (M,W,A,R)	Status/Context	Mitigation 1 Mitigation	est. Start	est. End
ES_B_C_5	Cathodes	23	⇨	3/23/10	Interim Cathode Performance Lower than Expected in UHE Cells	Given that the **UHE** specific capacity performance of cathodes achieved so far is less than our goals; there is a possibility that the battery-level Specific Energy goals may not be obtained.	5	4			M	1-yr deliverables are showing improvements, however cell-level predictions are not showing that we can currently make performance goals, even at room temperature.	Saft on contract to recommend cell level design improvements that could accommodate some shortfalls in cathode performance. E.g. thinner substrates, lower density electrolyte,		
ES_B_C_4	Cathodes	20	⇩	10/9/09	Interim Cathode Performance Lower than Expected in HE Cells	Given that the **HE** specific capacity performance of cathodes achieved so far is less than our goals; there is a possibility that the battery-level Specific Energy goals may not be obtained.	5	3			M	Cell-level predictions are showing that we can meet performance theoretically *when operating at* ***room temperature***, so there is a possibility that we can handle the lower cathode performance. KPP goal is for 0 deg. operation, however. 1-yr deliverables are showing improvements.	Saft on contract to recommend cell level design improvements that could accommodate some shortfalls in cathode performance. E.g. thinner substrates, lower density electrolyte,		
ES_B_E_6	Electrolytes	19	⇨	10/9/09	Competing Electrolyte Requirements	Given that electrolytes that meet safety requirements may not possess the physical properties to ensure good rate capability (adequate conductivity) and compatibility (wettability); there is a possibility that we may not succeed in simultaneously meeting our safety and performance goals.	3	4			M	Trades are being conducted.	Working with EC formulations to reduce viscosity.		
ES_B_UHE_2	UHE Cell	19	⇨	10/9/09	Cycle Life Testing not within Schedule	Given that there is insufficient schedule to demonstrate 2000 cycles; there is a possibility that we will not be able to meet the end-of-life goals.	3	4			A	Need to correlate test data at C/2 and C/10.	Mitigate. Look at charge and discharge voltages, internal resistance, etc., monitor trends and try to predict what the performance will be at 2000 cycles.		
ES_B_A_4	Anodes	18	⇨	10/9/09	Anode Particle Expansion	Given that volume expansion occurs during cycling and that this affects the mechanical integrity of the electrode; there is a possibility that cycle life goals may not be achieved.	4	3			M	230 cycles achieved with ***limited*** depth of discharge.	Look at hard coatings and rubber binders to force the anode into its structure or to accommodate for the expansion during year 2 of the component development contracts. Saft will work issue as well as they form electrodes from the anode mat'ls and test for		
ES_B_C_8	Cathodes	18	⇨	10/9/09	Cathode Rate Capability Inherently Low	Given that the chosen cathode materials have inherently low rate capability; there is a possibility that we may not meet our rate goals.	4	3			M	Poor power performance may result.	Work on keeping particle size uniform and small. Consider directly working with nano-experts. Consider hybrid cathodes.		
ES_B_HE&UHE_1	HE & UHE Cells	18	⇧	10/9/09	Uncertainties due to New Cell Design	Given that we are using a new cell design; there is a risk that cell-level issues show up late in the program, causing delays in schedule and more budget required.	4	3			M	The likelihood of developing a new cell with a novel design and all these new components is lower than we'd like.	Provide cells in prismatic format prior to CDR for evaluation at NASA centers. Provide pathfinder cells in flight design process. Consider add'l testing with either 34P's or DD's to understand the cell design variations versus component variations.		
ES_B_HE&UHE_2	HE & UHE Cells	18	⇨	10/9/09	Unknown Schedule Needs for Component Scale-Up	Given that the Saft schedule includes a critical path to scale-up materials, and the required time is unknown; there is a possibility that there will be delays in the delivery of flight cells, resulting in schedule delays and budget overruns.	4	3			M	May consider staggering future deliveries as was done for 6-month NRA materials to provide a few more months in the schedule, but this diminishes NASA's ability to compare materials against one another and in different combinations	Ask Saft to assess the risk now that the first batch of deliveries has been received. Formulate and consider options if the risk is still high, in comparison with the other cell-buildup tasks. Ask Saft for an update - are the scale-up durations still unknown and is there a critical		
ES_B_E_3	Electrolytes	17	⇨	10/9/09	Electrolyte Atomization	Given that electrolytes may atomize during abuse conditions; there is a possibiliy that we won't be able to achieve the flame-retardant goals.	2	5			A	More aggressive flame tests reveal that the flame-retardant additive is currently insufficient. May be out of scope after KPP's are revised. Action for JSC safety to confirm.	Accept for now. Reconsider after Safety KPP's are better defined.		
ES_B_A_2	Anodes	15	⇨	10/9/09	Anode Expansion and Contraction	Given that anode expansion and contraction due to electrochemical cycling may pose design challenges for the cell/battery system; there is a possibility that the final cell design may require increased mass, volume, increased amounts of electrolyte material and other unknowns, resulting in schedule delays and budget overruns.	3	3			M	The silicon expands 300% by volume during a charge at maximum theoretical capacity.	Explore physical optimization of the cast electrode structure.		

Baselined October, 2009
Updated March 29, 2010
Revised April 28, 2010 (format only)

Top 10 Fuel Cell & RFC Lower-Level Risks

ID	Category	Rank & Trend	Trend	Open Date	Risk Title	Risk Statement	Likelihood	Consequence	Affinity Group	Owner / Initiator	Approach	Status/Context	Mitigation 1: Mitigation	est. Start	est. End
ES_FC_System_2	NFTFC System	20	⇨	10/9/09	NFTFC Life Testing	Given that subsystems, components and the integrated Fuel Cell power plant will not be tested for 10,000 hours; there is the possibilty that failures may occur, resulting in design changes in later development (post-TRL6) programs.	5	3			M	Some failure mechanisms are not measureable until after a certain number of hours. Schedule is not long enough to accommodate full system tests for 10,000 hours. Accelerated testing not always reliable for Fuel Cells because failure modes are not always linear w.r.t. current density, temp, etc.	Look for funding opportunities (overguideline) to perform life testing at component, subsystem and system level whenever possible. Rely on Cx customers to perform lifetime and qualification testing as they need it. Begin lifetime testing on quarter-scale breadboard and continue on until Tech. Infusion required date.		
ES_FC_BOP_1	NFTFC BOP	19	⇨	10/9/09	NFTFC BOP Component Reliability & Maintainability	Given that BOP components may lack sufficient reliabiltiy; there is a possibility that the 10,000 hour, lifetime/maintenance-free lifetime requirement will not be met.	3	4			M	Possible sources of failure: corona, tin whiskers, sensors, instrumentation, regulators. No redundancy is currently planned. These issues are common to all space-based electronics and are not unique to Fuel Cell BOP's.	Involve S&QA prior to vacuum testing to make sure proper design techniques are employed, ensure proper clauses are used in component SOW's and supplier spec's. Use redundancy and fault		
ES_FC_E_1	Electrolysis	19	⇨	10/9/09	Vendor Cooperation for Electrolysis Optimization	Given that technology advancements are being developed independently at different vendors(components with intellectual property restrictions); there is a possibility that issues will arise regarding integration and communication of all required details, resulting in the inability to optimize the electrolysis concept.	3	4				SBIR developers - find ways to combine the best of the best into a NASA designed system	Continue to encourage vendors to work with each other and exchange information while protecting intellectual property rights.		
ES_FC_E_3	Electrolysis	19	⇨	10/9/09	Electrolysis Stack Component Reliability & Maintainabiliy	Given that stack components may lack sufficient reliabiltiy; there is a possibility that the 10,000 hour, lifetime/maintenance-free lifetime requirement will not be met.	3	4				Material compatibility and breakdown issues over a long period of time can cause degradation which will manifest itself as loss in voltage which will ultimately affect life. MEA degradation results in lower voltage performance which will	Evaluating other material choices (Niobium, etc) for components. Performing durability tests to watch for problems. Perform MEA life		
ES_FC_E_4	Electrolysis	19	⇨	10/9/09	Electrolysis BOP Component Reliability & Maintainability	Given that BOP components may lack sufficient reliabiltiy; there is a possibiltiy that the 10,000 hour, lifetime/maintenance-free lifetime requirement will not be met.	3	4				Possible sources of failure: corona, tin whiskers, sensors, instrumentation, regulators. No redundancy is currently planned. These issues are common to all space-based electronics and are not unique to Fuel Cell BOP's.	Involve S&QA prior to vacuum testing to make sure proper design techniques are employed, ensure proper clauses are used in component SOW's and supplier spec's. Use redundancy and fault tolerant design approches.		
ES_FC_RFC_1	RFC	19	⇨	10/9/09	LSS Reactant Management & Storage	Given that temperature extremes on the surface of the moon may cause water to condense in reactant tanks; there is a possibility that the design will be required to incorporate means to dry and store the reactants, resulting in increased design complexity.	3	4			A	Trade off to store warm and wet, or cold and dry	Accept. Not within scope of our program to perform this trade. Will monitor system architecture and will advise/adjust accordingly.		
ES_FC_Stack_1	NFTFC Stack	19	⇨	10/9/09	Novel Fuel Cell Technology	Given that Non Flow-Through FC technology is novel and a significant departure from existing space-qualified flow-through fuel cell technology; there is a possibility that TRL-6 may not be achieved within cost and schedule constraints.	3	4	c, s		M	Currently three alternate stack developers: Proton, Electrochem and Teledyne (funded through IPP, SBIR and some program fundijng), but we are not able to pursue these as agressively.	Employ parallel paths as best as we can given the program funding and schedule limitations. Continue to examine possible alternative approaches.		
ES_FC_Stack_2	NFTFC Stack	19	⇨	10/9/09	NFTFC Stack Water Management Robustness	Given that the Non-flow-through technology water management approach is not robust; there is a possibility that reliable operation will not be achieved.	3	4			M	Sintered porous metal plate currently being considered for water management, but nonuniformities in the material lead to control issues, affecting BOP design and causing loss of reactants (increases system mass/volume).	Looking at PES (polyethersulfone) material as an alternative. Also looking into quality control of manufacturing of sintered porous materials.		
ES_FC_Stack_6	NFTFC Stack	19	⇨	10/9/09	NFTFC Stack Component Reliability & Maintainabiliy	Given that stack components may lack sufficient reliabiltiy; there is a possibility that the 10,000 hour, lifetime/maintenance-free lifetime requirement will not be met.	3	4			M	Material compatibility and breakdown issues over a long period of time can cause degradation which will manifest itself as loss in voltage which will ultimately affect life. MEA degradation results in lower voltage performance which limits life. Failure mechanisms are not well-known and the program does not have sufficient calendar time to perform the life testing required. Consequence is 5 for LSS, but 1 for Altair.	Evaluating other material choices (Niobium, etc) for components. Performing durability tests to watch for problems. Perform MEA life tests.		
ES_FC_System_1	NFTFC System	19	⇨	10/9/09	Reactant Purity	Given that the NFTFC may be required to operate with propellant-grade and contaminated fuels; there is a possibiltiy that performance/operability issues will occur.	3	4			M	The use of propellant-grade reactants, which can contain up to 60% helium, and other impurties can lead to operability and performance issues.	Inert concentrator options include H2 pump and cascading stack design.		

TRL Status

Technology	TRL at end of FY10	Needed to reach TRL 6			Comments
		Technical	Budget (ROM)	Schedule (ROM)	
Non-Flow-Through Fuel Cell System	4		$19M	3 Years	
High Pressure (2000 psi) electrolyzer	2/3		$21M	5 Years	
Regenerative Fuel Cell System	2				
"High Energy" lithium-ion battery cell	2/3	Component development	$17M*	3-4 Years	Operation at 0 °C limits performance
"Ultra High Energy" lithium-ion battery cell	2/3	Component development	$19M*	6 Years	Cycle life and operation at 0 °C limits performance

*****Some synergy will allow for cost savings if both High Energy and Ultra-High Energy battery cells are pursued concurrently. These estimates assume a stand-alone task.*

Lessons Learned

1. It is better to try to develop technologies with aggressive goals, aggressive schedules, and no budget margin than not to try, even if the risks are very high.
   - Although we have not met our technical goals for battery components, we made substantial progress and are now positioned to support nearer-term demos.
   - Further development is required, and will continue to be high risk.

2. Down-selecting technologies before TRL-4 is extremely risky – we got lucky on this one for fuel cells.
   - A serious technology development program supporting serious program schedules should not take this risk.
   - It is a testament to the skill of our technical staff that this decision could be made without adequate data on the lower-TRL system.

3. Working closely with Cx and industry at the very beginning had us on a path to cross the “valley-of-death” for technology infusion.
   - Priorities set by EVA, LSS and Altair were essential to keep the technology focused.
   - Feedback provided by Saft, America ensured a sharper focus on manufacturability early on.
   - Close collaboration with Infinity Hydrogen led to success.

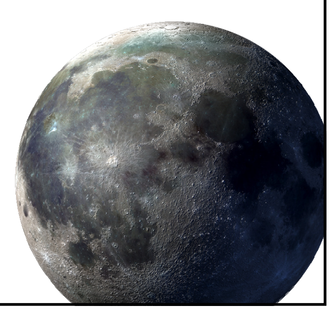
Summary

Energy storage technologies were considered critically important for NASA’s Constellation Program.

- Advanced batteries are critical
  - Reduces mass/volume and extends mission duration for EVA,
  - Extends range and/or functionality of robots/mobility systems,
  - Reduces mass or adds functionality for landers
- Advanced fuel cells are critical for vehicle power
  - Recent advances make NASA-developed technology extremely attractive for reliability and system mass/volume
  - Provides water for life support
- Advanced regenerative fuel cells are critical
  - Provides surface power during the lunar night

Substantial technical progress was made under the Energy Storage Project

- Advancements made in Lithium Ion components
  - Li(NMC) cathodes show improved specific capacity at C/10,
  - Silicon-composite anodes show improved cycle life,
  - Electrolytes show compatibility with high-voltage cathodes and improved self-extinguishing times,
  - Cathode coating shows improved thermal stability.
- Advancements made in PEM fuel cells
  - “Non-flow-through” stack technology demonstrated to TRL-4
  - Flat-plate heat-pipes demonstrated to be effective for thermal management



Energy Storage Project Final Report
List of Acronyms

BOP	Balance of Plant
C	Charge/Discharge Rate
CDR	Critical Design Review
Cx	Constellation Program
DOD	Depth of Discharge
ETDP	Exploration Technology Development Program
EVA	Extra Vehicular Activity
FC	Fuel Cell
FT	Flow Through
GEN	Generation
GRC	Glenn Research Center
HE	High Energy
HX	Heat Exchanger
IPP	Innovative Partnership Program
IRC	Irreversible Capacity
ISRU	In-Situ Resource Utilization
JPL	Joint Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAT	Lunar Architecture Team
LS	Lunar Surface
LSS	Lunar Surface Systems
LT	Launch Technology
MEA	Membrane Electrode Assembly
NFT	Non-Flow Through
NMC	Ni-Mn-Co
NTR	New Technology Report
PDR	Preliminary Design Review
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Principal Investigator
PLSS	Portable Life Support System
PSU	Power Supply Unit
RFC	Regenerative Fuel Cell
R.T.	Room Temperature
SBIR	Small Business Innovative Research
SPR	Small Pressurized Rover
TAMU	Texas A&M University
TBD	To Be Determined
TBR	To Be Reviewed
TCR	Technical Content Review
TPP	Technology Prioritization Process
TRL	Technology Readiness Level
UHE	Ultra-High Energy
URFC	Unitized Regenerative Fuel Cell

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REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-01-2011

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Energy Storage Project
Final Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mercer, Carolyn, R.; Jankovsky, Amy, L.; Reid, Concha, M.; Miller, Thomas, B.; Hoberecht, Mark, A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 038957.01.01.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17568

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-216963

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 20 and 44
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
NASA's Exploration Technology Development Program funded the Energy Storage Project to develop battery and fuel cell technology to meet the expected energy storage needs of the Constellation Program for human exploration. Technology needs were determined by architecture studies and risk assessments conducted by the Constellation Program, focused on a mission for a long-duration lunar outpost. Critical energy storage needs were identified as batteries for EVA suits, surface mobility systems, and a lander ascent stage; fuel cells for the lander and mobility systems; and a regenerative fuel cell for surface power. To address these needs, the Energy Storage Project developed advanced lithium-ion battery technology, targeting cell-level safety and very high specific energy and energy density. Key accomplishments include the development of silicon composite anodes, lithiated-mixed-metal-oxide cathodes, low-flammability electrolytes, and cell-incorporated safety devices that promise to substantially improve battery performance while providing a high level of safety. The project also developed "non-flow-through" proton-exchange-membrane fuel cell stacks. The primary advantage of this technology set is the reduction of ancillary parts in the balance-of-plant--fewer pumps, separators and related components should result in fewer failure modes and hence a higher probability of achieving very reliable operation, and reduced parasitic power losses enable smaller reactant tanks and therefore systems with lower mass and volume. Key accomplishments include the fabrication and testing of several robust, small-scale non-flow-through fuel cell stacks that have demonstrated proof-of-concept. This report summarizes the project's goals, objectives, technical accomplishments, and risk assessments. A bibliography spanning the life of the project is also included.

15. SUBJECT TERMS
Lithium batteries; Electric batteries; Storage batteries; Fuel cells; Hydrogen oxygen fuel cells; Regenerative fuel cells; Electrochemical cells; Energy storage

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	54	443-757-5802