Battery and Fuel Cell Development for NASA's Constellation Missions

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NASA's return to the moon will require advanced battery, fuel cell and regenerative fuel cell energy storage systems. This paper will provide an overview of the planned energy storage systems for the Orion Spacecraft and the Aries rockets that will be used in the return journey to the Moon. Technology development goals and approaches to provide batteries and fuel cells for the Altair Lunar Lander, the new space suit under development for extravehicular activities (EVA) on the Lunar surface, and the Lunar Surface Systems operations will also be discussed.

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Glenn Research Center
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21st Space Photovoltaic Research and Technology Conference (SPRAT)
October 7, 2009

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- Introduction
- Constellation Projects
  - *Ares I* — Crew Launch Vehicle (CLV)
  - *Orion* — Crew Exploration Vehicle (CEV)
  - *Altair* — Lunar Lander
  - *Ares V* — Cargo Launch Vehicle
  - *Extra Vehicular Activity (EVA) Suits*
  - *Lunar Surface Systems*
- Technology Development
  - *Exploration Technology Development Program – Energy Storage Project*
    - *Li-ion Batteries*
    - *PEM Fuel Cells*
    - *PEM Regenerative Fuel Cells*
- NESC Battery Working Group

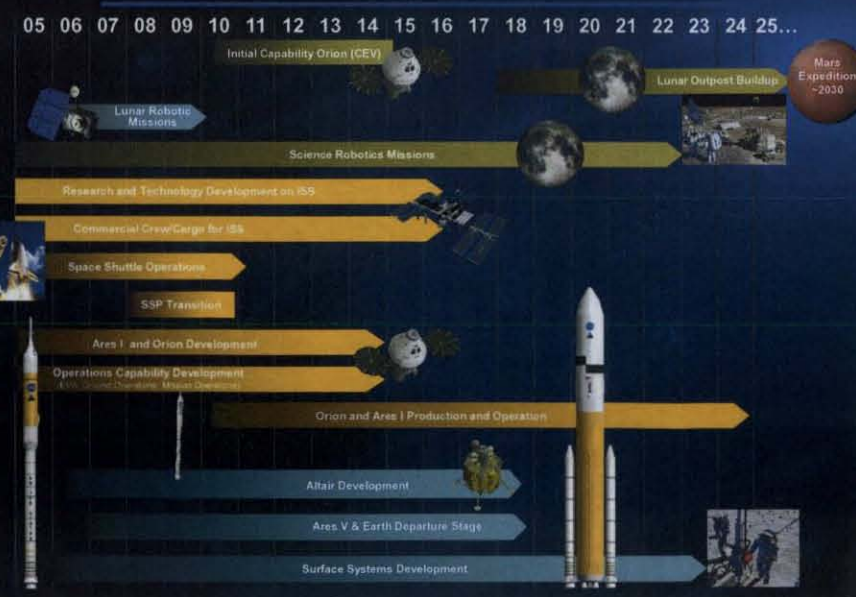
U.S. Space Exploration Policy

- Safely fly the Space Shuttle until 2010
- Complete the International Space Station (ISS)
- Develop a balanced program of science, exploration, and aeronautics
- Develop and fly the Orion Crew Exploration Vehicle (CEV)
- Land on the Moon no later than 2020
- Promote international and commercial participation in exploration

"The next steps in returning to the Moon and moving onward to Mars, the near-Earth asteroids, and beyond, are crucial in deciding the course of future space exploration. We must understand that these steps are incremental, cumulative, and incredibly powerful in their ultimate effect."

*– NASA Administrator Michael Griffin
October 24, 2006*

NASA's Exploration Roadmap



Constellation Leverages Unique Skills and Capabilities Throughout NASA Centers

NASA Exploration Mission Energy Storage Systems

Near-term

- Orion (Crew Exploration Vehicle, CEV)
- Ares I (Crew Launch Vehicle, CLV)
- Ares V (Cargo Launch Vehicle, CaLV)

Lithium-ion baselined for Ares I and Orion

Far-term

- Ares V (Cargo Launch Vehicle, CaLV) - EDS
- Precursor and Robotics Program (LPRP)
- Lunar Surface Access Module (Altair)
- Rovers, Habitats and EVA

Battery, fuel cell, regenerative fuel cell energy storage technologies under development

Orion - Crew Exploration Vehicle Li-Ion Battery

- Operational Requirements
  - 120 Volt system
  - 6000 LEO Cycles at 20%DOD, 14 cycles at 100% DOD
  - Mission length – 235 days
  - 50-68°F – Operating range, excursions 30 day cumulative to 104°F

Yardney - battery manufacturer

Crew Module
- 32 cells, 30AH NCP25-1 (Mars Lander Cells)
- 4 batteries
- Target mass 88 lbs
- Volume allocation 13.6 in. width, 17.6 in length, and 13.4 in height

Service Module
- 32 cells, 7 AH
- 2 batteries
- Target mass 35 lbs
- Volume allocation - 12.4 in width, 16.8 in length, and 11 in height

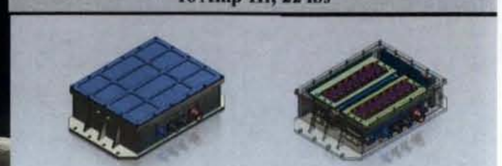
Ares I Upper Stage Batteries

- Upper Stage – (Single Failure Tolerant)
  - Instrument Unit (IU):
    - Two Power Busses (1 kW average per Bus)
      - Two 16 A-Hr Li-Ion Batteries for EPS
  - Aft Skirt:
    - Two Power Busses (3.4 kW average per Bus)
      - Two 16 A-Hr Li-Ion Batteries
  - Flight (Range) Safety System: Silver Zinc Batteries (heritage)
- Interstage
  - Three Power Busses (500 W average per Bus)
  - 3 16AH Li-Ion Batteries
- First Stage:
  - 55 A-Hr Silver-Zinc Batteries (heritage)

BOEING

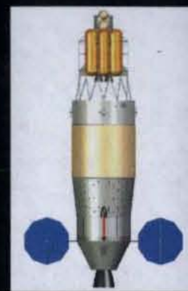
Instrument Unit Avionics Contractor

Common US Battery Line Replaceable Unit Concept
16 Amp-Hr, 22 lbs



Ares V Electrical Power

- **Earth Departure Stage (EDS)**
  - **Design Drivers:**
    - Electrical Power for Earth orbit loiter
    - Electrical power transfer to *Altair* Lunar Lander
      - Launch through trans-lunar injection (TLI) burn
  - **Design Alternatives:**
    - **Solar Array & Lithium-Ion Battery**
      - Provides for indefinite loiter times
      - Lower heat rejection requirements
      - Opportunity for commonality with Orion systems
    - **Primary Fuel Cell**
      - Opportunity for commonality with Lander systems
      - Performance not impacted by vehicle attitude during loiter
      - No significant mechanisms required
      - TLI loads should not be an issue



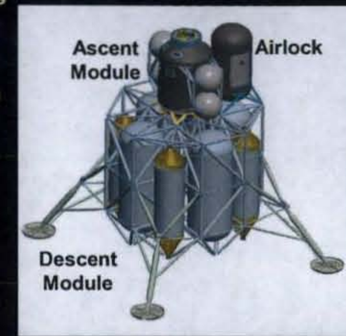
- **Core Stage Systems**
  - Batteries & Power Distribution Units – Common with Ares I
  - Flight (Range) Safety System Batteries

- **Solid Rocket Booster (SRB)**
  - Thrust Vector Control: electro-hydrostatic actuators (EHAs) under consideration
  - May require high-voltage battery

Altair Energy Storage Requirements

Descent Module: Baseline – Primary PEM Fuel Cell

- **3 kW nominal, 6 kW peak, 220 hours continuous**
  - **Sortie: Power Lander for 9 days continuous (7 days surface)**
  - **Outpost: 3 days continuous power (1 day on surface)**
- **Should operate until all residual propellants converted to water/power**
- **Must operate with expected fuel and oxidant contamination levels of residual lander propellants.**
- **Must remove dissolved gases from water by-product during all phases of the mission, including in 0-g.**
- **Human-safe operation from 0 – 30°C and 0 – 1 G**



Lunar Design Analysis Cycle-3 (LDAC) design
Assumes no single-point failures, and 2-string redundancy on battery to minimize LOC.
Baselines primary battery

Ascent Module: Baseline Primary $LiMnO_2$ Battery

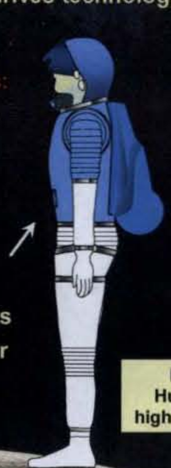
- **Baseline battery 121.6 kg, 22.7 kW-hour sized for an ascent underburn**
- **Human-safe operation from 0 – 30°C and 0 – 1 G.**

Lunar Extravehicular Activity Suit

Greatly increased electronic capability (HDTV, communications node, displays, etc…) drives need for high energy batteries in small, low-mass package. Very high specific energy and energy density with 8-hour, human-safe operation drives technology development.

Preliminary Battery Requirements:

Human-safe operation
~ 1155 W-Hr energy
8 hours continuous operation
~ 144 W average power
233 W max power
Current mass allocation: 5 kg
Current volume allocation: 3 liters
100 cycles (operation every other day for six months)



Prioritized mission requirements: Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lunar Surface Systems

Scenario-Based Planning:

Rechargeable batteries and/or regenerative fuel cells for power & support unit, portable utility pallet, and/or mobility systems

- Power & Support Unit
  - Mass: PSU 2,867 kg / SSU 680 kg
  - Energy storage: 720 kWh Regenerative Fuel Cells
  - Power generation: 11.2 kW net, 9 meter solar array
  - Power consumables storage: 337 kg oxygen, 43 kg hydrogen; 450 kg water x 2 (power and scavenge)
- Crew Mobility Chassis Specifications
  - 969 kg dry vehicle mass, >100 km range, upgradable with PUPs
  - 0-5 kph low gear, 0-20 kph high gear
  - 20 kWh onboard energy storage (Li-ion battery)
  - 5.9 kW peak power, 1.15 kW average power and 125 W standby power.
  - Nominal drive time is 87 hours and stand-by time is 800 hours.
- Portable Utility Pallet
  - Logistics: 25 kg Oxygen, 90 kg Water, 90 kg Wastewater
  - Power Generation: 4.4-kW, 5.5-meter Orion-class array
  - Energy Storage: 10 kWh (Li-ion batteries)
  - Mass: 708.9 kg (dry), 903.4 kg (wet)

Lunar Surface Systems

Potential Requirements

- Modular power system
- ~20-40 kW lunar daytime power level
- ~10-20 kW lunar nighttime power level
- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 5-10 year calendar life
- 100 -1000+ discharge/recharge cycles
- Thermal, dust, launch/landing, vacuum environments
- Reliable, human-rated operation in thermal, dust, launch/landing, vacuum environments
- Autonomous control and operation
- Human-rated
- Low mass and volume
- Little or no maintenance needs

Preliminary Fuel Cell /Regenerative Fuel Cell Design Parameters

- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 100 -1000+ discharge/recharge cycles
- Compatible with $H2/O2$ tanks at 2000 psi

Preliminary Battery Design Parameters

- 10-hour discharge and 10-hour charge
- 2000 discharge/recharge cycles
- Temperature controlled to 0 – 30°C
- 5 year calendar life

Exploration Technology Development Program Energy Storage Project

Project Objective: Reduce risks associated with the use of batteries, fuel cells, and regenerative fuel cells for *Altair, Lunar Surface Systems, and EVA.*

Project TRL-6 Deliverables:

- **Primary fuel cell** for *Altair* Descent Stage
- **Regenerative fuel cell** for Lunar Surface Power Units and Mobility Systems
- **Rechargeable battery cells** for *Altair* Ascent Stage, EVA Suit 2, Lunar Surface Mobility Systems

Lithium-based Battery Technology:
Develop Lithium-based cells for human-rated, reliable operation with very high specific energy.

Fuel cell technology:
Develop proton-exchange-membrane stack and balance-of-plant technology to increase system lifetimes and reduce mass, volume and parasitic power.

Regenerative fuel cell technology:
Develop balanced high-pressure electrolyzers and thermal management and reactant processing technologies for integrated electrolyzer/fuel cell.

Li-Ion Battery Development

Objectives: Develop Flight Qualified, Human-Rated Li-Ion cells with increased reliability and mass and volume reductions

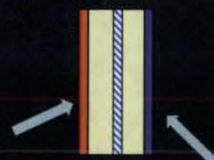
Approach:

- Identify chemistries most likely to meet overall NASA goals and requirements within allotted development timeframe
  - "High energy" and "ultra high energy" cells targeted to meet customer requirements.
- Utilize in-house and NRA Contracts to support component development
  - Develop components to increase specific energy (anode, cathode, electrolyte)
  - Develop low-flammability electrolytes, additives that reduce flammability, battery separators and functional components to improve human-safety;
  - Charge methodology
- Engage industry partner - multi year contract
  - Provide recommendations for component development / help screen components
  - Scale-up components (core)
  - Manufacture evaluation and screening cells
  - Design and optionally manufacture flightweight cells that address NASA's goals
- Complete TRL 5 and 6 testing at NASA
- Leverage outside efforts
  - Utilize SBIR/IPP efforts
  - Leverage work at DoE and other government agencies

Cell development TRL definitions
TRL 4: Advanced cell components integrated into a flight design cell
TRL 5: Performance testing on integrated cell shows goals met
TRL 6: Environmental testing on cell (vibration, thermal) shows robust performance

Energy Storage Project Cell Development for Batteries

High Energy Cell	Ultra-High Energy Cell
Lithiated-mixed-metal-oxide cathode - $Li(LiNMnC)O_2$	Lithiated-mixed-metal-oxide cathode /$Li(LiNMnC)O_2$
Conventional carbonaceous anode	Silicon composite anode
180 Wh/kg @ cell level 150 Wh/kg @ battery-level At 0°C C/10	260 Wh/kg @ cell level 220 Wh/kg @ battery-level At 0°C C/10
~2000 cycles to 80% of original capacity at 100% DOD	~200 cycles to 80% of original capacity at 100% DOD



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 moderate reduction in the performance with flame retardants and non-flammable electrolytes	Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and external short circuit with no fire or flame
Specific energy Lander: 150 – 210 Wh/kg 10 cycles Rover: 160 – 200 Wh/kg EVA: 270Wh/kg 100 cycles	**Battery-level** specific energy*	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	130 Wh/kg at C/10 & 30°C 120 Wh/kg at C/10 & 0°C	**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	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	150 Wh/kg at C/10 & 0°C	**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 $Li(LiNiMn)O_2$	180 mAh/g	$Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$: 240 mAh/g at C/10 & 25°C $Li(Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13})O_2$: 250 mAh/g at C/10 & 25°C 200 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	280 mAh/g (MCMB)	350 mAh/g (MPG-111) 450 mAh/g Si composite	**600** mAh/g at C/10 & 0°C (with Si composite)	**1000** mAh/g at C/10 0°C (with Si composite)
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°C to 30°C, Vacuum	Operating temperature	-20°C to +40°C	-50°C to +40°C	**0°C to 30°C**	**0°C 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 3.000 volts/cell, and at 0°C operating conditions**
**** "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode**
"Ultra-High Energy" = Exploration Technology Development Program cathode with Silicon composite anode

Revised 5/19/09

PEM Fuel Cell Development

Objectives:

- Increase system lifetimes and reduce system mass, volume and parasitic power for primary and regenerative proton exchange membrane (PEM) fuel cells, and
- Enable the use of regenerative PEM fuel cells including the use of high pressure (>2000 psi) reactants to reduce tankage mass and volume.

- Focus is exclusively on Proton Exchange Membrane fuel cells and regenerative fuel cell systems

- Technical Approach is to develop:
  - "Non-flow-through" proton exchange membrane stack and customized balance-of-plant technology;
  - Advanced membrane-electrode-assemblies (MEAs) for both fuel cells and electrolyzers,
  - Balanced high-pressure electrolyzers; and
  - Thermal and reactant management technologies for electrolyzer/fuel-cell integration into regenerative fuel cell systems.

Fuel Cell Technical Approach

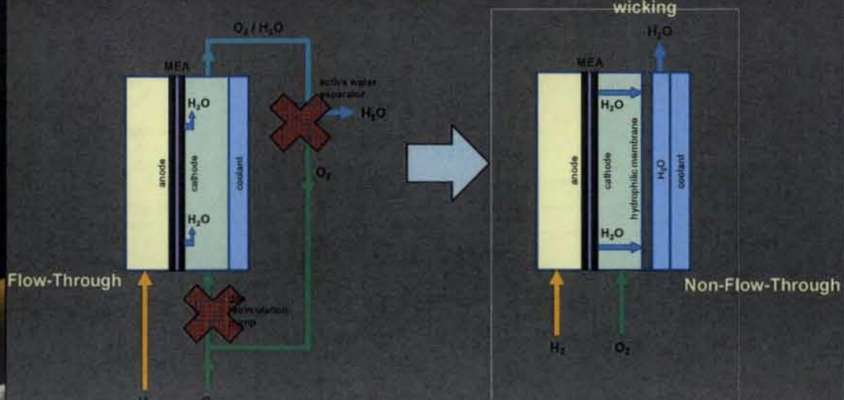
Develop "non-flow-through" proton exchange membrane fuel cell technology for a system improvement in weight, volume, reliability, and parasitic power over "flow-through" technology

Flow-Through components eliminated in Non-Flow-Through system include:

- Pumps or injectors/ejectors for recirculation
- Motorized or passive external water separators

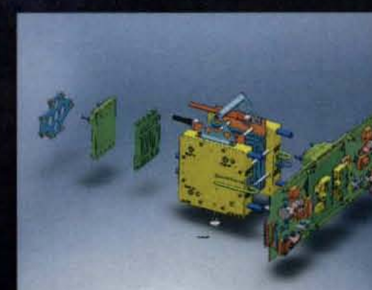
Non-Flow-Through PEMFC technology characterized by dead-ended reactants and internal product water

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



Integrated Balance-of-Plant

- 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 only 10 watts of parasitic power to operate the fuel cell system
- A full-scale (3-kw fuel cell system) balance-of-plant will likely operate on only 50 watts or less of parasitic power (same number of components, but some components larger)
- A 2-12 kW flow-thru fuel cell system tested at GRC required over 1000 watts of parasitic power during operation
- That difference in parasitic power means that Altair would need 100-200 kg less reactants over the course of its 2-3 week mission using a non-flow-through fuel cell system vs. a flow-through system



National Aeronautics and Space Administration

Key Performance Parameters for Fuel Cell Technology Development

Customer Need	Performance Parameter	SOA (alkaline)	Current Value* (PEM)	Threshold Value** (@ 3 kW)	Goal** (@ 3 kW)
Altair: 3 kW for 220 hours continuous, 5.5 kW peak.	System power density				
	Fuel Cell	49 W/kg	n/a	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	n/a	107 W/kg	231 W/kg
	Fuel Cell Balance-of-plant mass	n/a	n/a	21 kg	9 kg
Lunar Surface Systems: TBD kW for 15 days continuous operation	MEA efficiency @ 200 mA/cm²				
	For Fuel Cell	73%	72%	73%	75%
	Individual cell voltage	0.90V	0.89V	0.90V	0.92V
Rover: TBD	For Electrolysis	n/a	86%	84%	85%
*Based on limited small-scale testing.	Individual cell voltage	n/a	1.48	1.46	1.44
**Threshold and Goal values based on full-scale (3 kW) fuel cell and RFC technology.	For RFC (Round Trip)	n/a	62%	62%	64%
	System efficiency @ 200 mA/cm²				
***Teledyne passive flow through with latest MEA	Fuel Cell	71%	65%***	71%	74%
	Parasitic penalty	2%	10%	2%	1%
****Includes high pressure penalty on electrolysis efficiency 2000 psi	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	Maintenance-free operating life				
Altair: 220 hours (primary)	Fuel Cell MEA	2500 hrs	13,500 hrs	5,000 hrs	10,000 hrs
Surface: 10,000 hours (RFC)	Electrolysis MEA	n/a	n/a	5,000 hrs	10,000 hrs
	Fuel Cell System (for Altair)	2500 hrs	n/a	220 hrs	220 hrs
	Regenerative Fuel Cell System	n/a	n/a	5,000 hrs	10,000 hrs

5/22/08

NASA Engineering and Safety Center (NESC)
NASA Aerospace Flight Battery Systems Working Group

Addresses critical battery-related performance / manufacturing issues for NASA and the aerospace community

Objectives

- Develop/maintain/provide tools for the validation of aerospace battery technologies
- Accelerate technology readiness and provide infusion paths for emerging technologies
- Enable implementation of critical risk-mitigating test programs
- Disseminate validation/assessment tools, quality assurance and information to the NASA and aerospace battery communities
- Provide problem resolution expertise and capabilities

Working Group Makeup

- NASA Center members on core teams responsible for task implementation
- Partner agencies provide consultation and support for planning/reviewing activities

NASA Engineering and Safety Center (NESC)
NASA Aerospace Flight Battery Systems Working Group

Binding Procurements – guidelines related to requirements for the battery system that should be considered at the time of contract award

Wet Life of Ni-H_2 Batteries – issues/strategies for effective storage and impact of long-term storage on performance and life

Generic Guidelines for Lithium-ion Safety, Handling and Qualification – Standardized approaches developed and risk assessments

- Lithium-ion Performance Assessment – survey of manufacturers and capabilities to meet mission needs. Guidelines document generated
- Conditions Required for using Pouch Cells in Aerospace Missions – focus on corrosion, thermal excursions and long-term performance issues. Document defining requirements to maintain performance and life
- High Voltage Risk Assessment – focus on safety and abuse tolerance of battery module assemblies. Recommendations of features required for safe implementation
- Procedure for Determination of Safe Charge Rates – evaluation of various cell chemistries and recommendation of safe operating regimes for specific cell designs

Lithium-ion Battery Source Material Availability – provide additional support for the governmental Title 3 effort aimed at ensuring a constant supply of source material

NASA Aerospace Battery Workshop – government-industry forum focused on battery industry developments and issues (held annually in the Fall)

Concluding Remarks

NASA GRC supports the development of electrochemical systems for NASA's upcoming Exploration Missions - from fundamental technology development for EVA, Altair and Lunar Surface Systems through flight hardware development for Ares and Orion Flight Programs