

## **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 Battery and Fuel Cell Development for NASA's Exploration Missions

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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



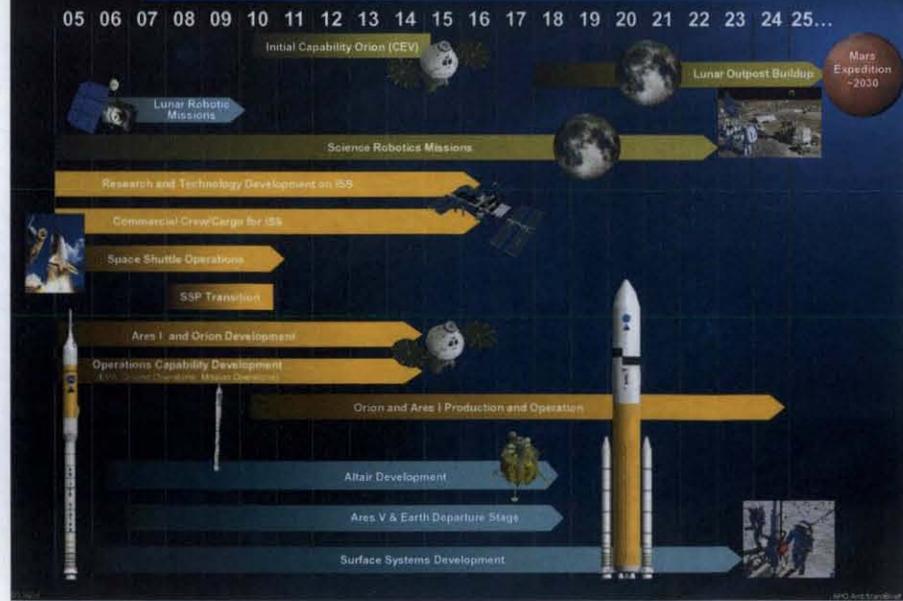
- ♦ Safely fly the Space Shuttle until 2010
- ♦ Complete the International Space Station (ISS)
- ♦ Develop a balanced program of science, exploration, and aeronautics
- ♦ Develop and fly the Orion Crew Exploration Vehicle (CEV)
- ♦ Land on the Moon no later than 2020
- ♦ Promote international and commercial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

**Ames**

- Lead Thermal Protection System ADP
- Aero-Aerothermal database
- Ares Abort simulations
- Simulations and GN&C support

**Glenn**

- Lead Service Module and Spacecraft Adapter integration
- Flight Test Article "Pathfinder" fabrication
- Ares I-1 upper stage simulator lead
- Ares power, TVC and sensors lead
- J-2X altitude/inspace testing
- SE&I Support
- EVM, DevOps, Communications, Operations, and Informatics Lead

**Goddard**

- Communications Support

**Dryden**

- Lead Abort Flight Test Integration/Operations
- Abort Test Booster procurement
- Flight Test Article Development/Integration

**JPL**

- Thermal Protection System support

**Johnson**

- Home for Program
- Home for Projects: Orion, Mission Ops, EVA, Lunar Lander
- Lead Crew Module integration
- Orion Spacecraft Integration
- GFE projects management
- Flight Test Program

**Stennis**

- Rocket Propulsion Testing for Ares

**Marshall**

- Home for Ares Project
- Ares I and V development and integration lead
- LAS and SM SE&I Support

**Langley**

- Lead Launch Abort System Integration
- Lead landing system ADP
- Ares I-1 vehicle integration
- Ares aerodynamics lead
- SE&I Support

**Kennedy**

- Home for Ground Ops Project
- Ground processing
- Launch operations
- Recovery operations

## 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

**LOCKHEED MARTIN**

**Launch Abort System (LAS)**  
140 volt Li-ion Battery – Quallion/Sanyo

**Crew Module (CM)**

**Service Module (SM)**

**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

Lockheed Martin /Hamilton Sundstrand

## 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)

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

**BOEING**  
Instrument Unit Avionics Contractor

## 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

**Ascent Module: Baseline Primary LiMnO<sub>2</sub> 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



**Ascent Module**

**Airlock**

**Descent Module**

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

## 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: 706.9 kg (dry), 963.4 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 H<sub>2</sub>/O<sub>2</sub> 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



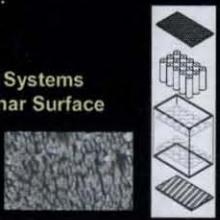

**Project Objective:** Reduce risks associated with the use of batteries, fuel cells, and regenerative fuel cells for *Altair*, Lunar Surface Systems, and EVA.

**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

Li(LiNMnCO<sub>2</sub>)  
•NASA Cathode

Conventional Carbonaceous Anode

Lithiated-mixed-metal-oxide cathode - Li(LiNMnCO<sub>2</sub>)

Conventional carbonaceous anode

180 Wh/kg @ cell level  
150 Wh/kg @ battery-level  
At 0°C C/10

~2000 cycles to 80% of original capacity at 100% DOD

#### Ultra-High Energy Cell

Li(LiNMnCO<sub>2</sub>)  
•NASA Cathode

Si-composite NASA Anode

Lithiated-mixed-metal-oxide cathode /Li(LiNMnCO<sub>2</sub>)

Silicon composite anode

260 Wh/kg @ cell level  
220 Wh/kg @ battery-level  
At 0°C C/10

~200 cycles to 80% of original capacity at 100% DOD

- Anode (commercial)
- Anode (NASA)
- Cathode (NASA)
- Electrolyte (NASA)
- Separator (commercial)
- Safety devices (NASA)  
Incorporated into NASA anode/cathode

## Key Performance Parameters for Battery Technology Development



Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
<b>Safe, reliable operation</b>	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
<b>Specific energy</b> Lander: 150 - 210 Wh/kg 10 cycles  Rover: 160 - 200 Wh/kg  EVA: 270Wh/kg 100 cycles	<b>Battery-level specific energy*</b>	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"
	<b>Cell-level specific energy</b>	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"
	<b>Cathode-level specific capacity</b> Li(LiNiMn)O <sub>2</sub>	180 mAh/g	Li(Li <sub>0.5</sub> Ni <sub>0.25</sub> Mn <sub>0.25</sub> )O <sub>2</sub> : 240 mAh/g at C/10 & 25°C Li(Li <sub>0.5</sub> Ni <sub>0.15</sub> Mn <sub>0.35</sub> Co <sub>0.15</sub> )O <sub>2</sub> : 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
	<b>Anode-level specific capacity</b>	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)
<b>Energy density</b> Lander: 311 Wh/l Rover: TBD EVA: 400 Wh/l	<b>Battery-level energy density</b>	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"
	<b>Cell-level energy density</b>	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"
<b>Operating environment</b> 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



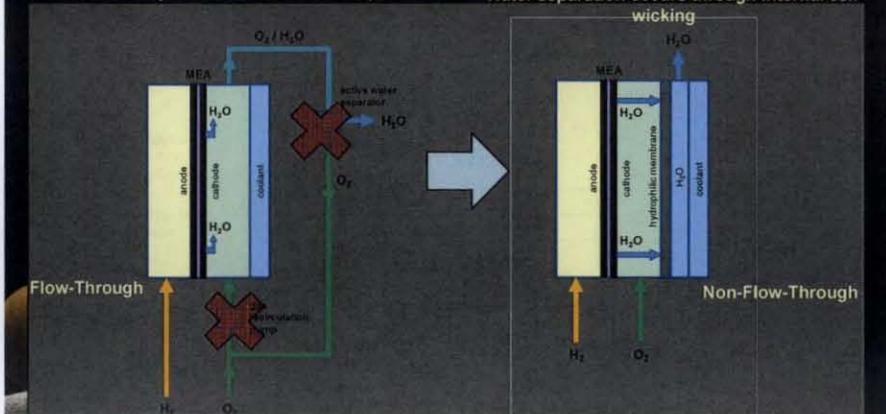
Develop "non-flow-through" proton exchange membrane fuel cell technology for a system improvement in weight, volume, reliability, and parasitic power over "flow-through" technology

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

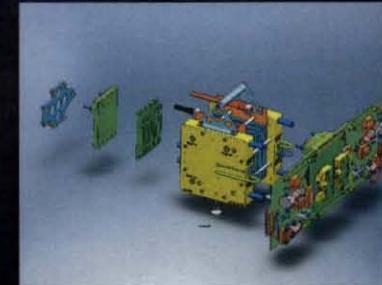
- Tank pressure drives reactant feed; no recirculation
- Water separation occurs through internal cell



## 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 RFC (without tanks)	49 W/kg n/a	n/a n/a	88 W/kg 25 W/kg	136 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/cm <sup>2</sup> For Fuel Cell	73%	72%	73%	75%
	Individual cell voltage For Electrolysis	0.90V	0.89V	0.90V	0.92V
	Individual cell voltage For RFC (Round Trip)	n/a	1.48	1.46	1.44
Rover: TBD  *Based on limited small-scale testing.  **Threshold and Goal values based on full-scale (3 kW) fuel cell and RFC technology.  ***Teledyne passive flow through with latest MEA.  ****Includes high pressure penalty on electrolysis efficiency 2000 psi	System efficiency @ 200 mA/cm <sup>2</sup> Fuel Cell	71%	65%***	71%	74%
	Parasitic penalty	2%	10%	2%	1%
	Regenerative Fuel Cell**** Parasitic penalty	n/a	n/a	43%	54%
	High Pressure penalty	n/a	n/a	10%	5%
Maintenance-free lifetime Altair: 220 hours (primary) Surface: 10,000 hours (RFC)	Maintenance-free operating life Fuel Cell MEA	2500 hrs	13,500 hrs	5,000 hrs	10,000 hrs
	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<sub>2</sub> 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