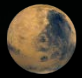
National Aeronautics and Space Administration

The NASA Advanced Space Power Systems Project

Space Power Workshop | Huntington Beach, CA | May 11-14, 2015



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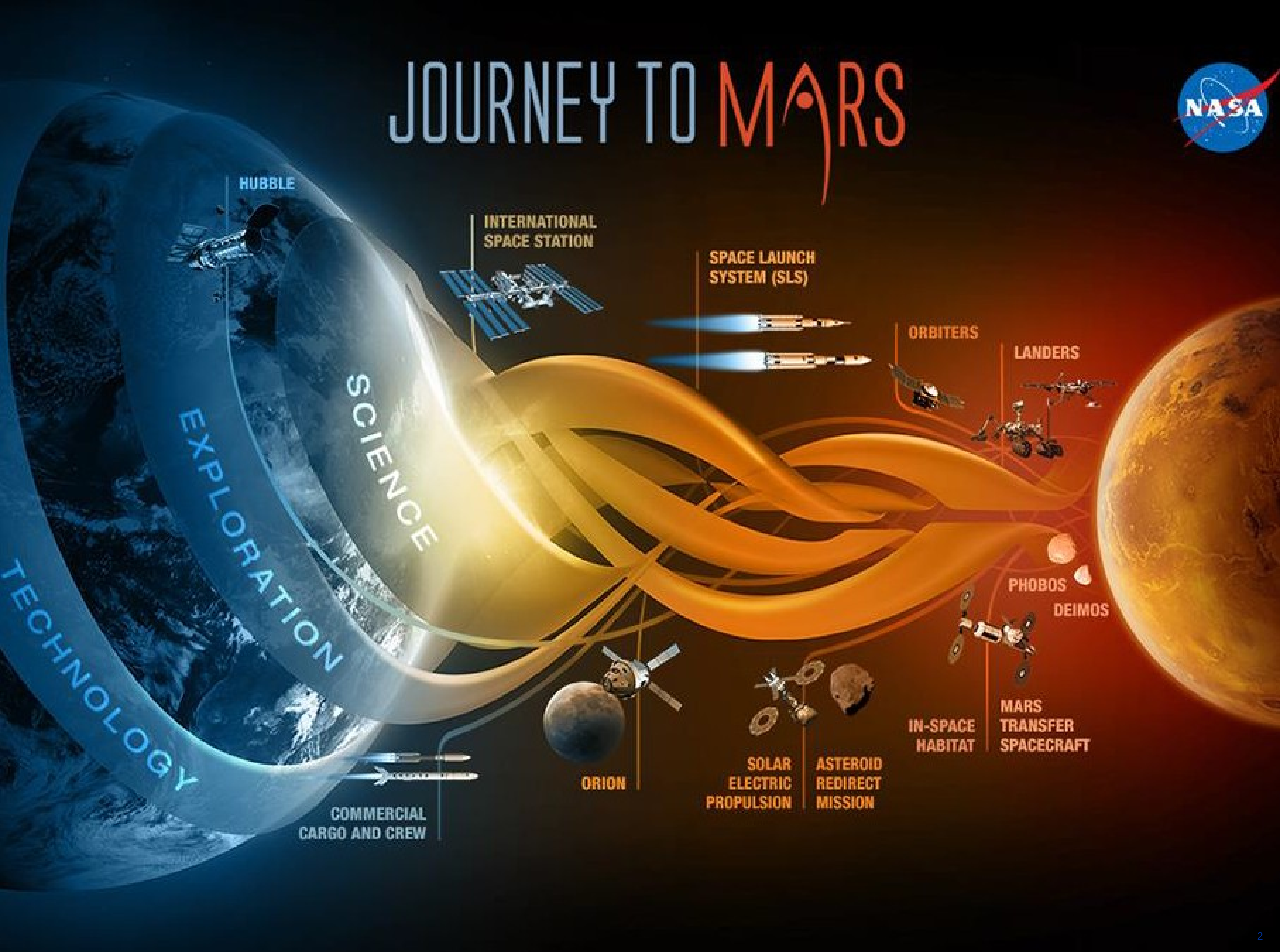
JOURNEY TO MARS
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INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
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PHOBOS
DEIMOS
MARS TRANSFER SPACECRAFT
IN-SPACE HABITAT
ASTEROID REDIRECT MISSION
SOLAR ELECTRIC PROPULSION
ORION
COMMERCIAL CARGO AND CREW

Advanced Space Power Systems Technologies: Challenges for human space exploration

Batteries for Extravehicular Actitvies

- >265 Wh/kg, >550 Wh/liter, 200 cycles, human safety rating

Batteries for Landers

- >200 Wh/kg, 10 cycles, human safety rating

Batteries for Rovers

- >200 Wh/kg, 200 cycles, human safety rating

Fuel Cells for Landers and Mobility Systems

- >220 hours maintenance free operation, >100 W/kg, >73% η, Operable on residual propellants

Regenerative Fuel Cells for Surface Power

- >10,000 hours maintenance free operation, >30 W/kg, >50% η

Key Performance Parameters for Battery Technology Development

Mission Need	Performance Parameter	State-of-the-Art (Aerospace Custom)[1]	State-of-the-Arts COTS-Based	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	Instrumentation/ controllers used to prevent unsafe conditions. Cells have built0in safety devices (PTC, CID) .Electrolyte is flammable	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or thermal runaway[2]	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or thermal runaway[2]
Specific energy 250 Wh/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)	90-130 Wh/kg at C/10 and 20°C	**168** Wh/kg at C/10 & 10°C.[3]	**225** Wh/kg at C/10 & 10°C.[3]
	Cell-level specific energy* [Wh/kg]	130 Wh/kg at C/10 & 20°C 118 Wh/kg at C/10 & 0°C	180-210 Wh/kg at C/10 & 20°C	**210** Wh/kg at C/10 & 10°C; 200 cycles	**265** Wh/kg at C/10 & 10°C; 100 cycles
	Cathode-level specific capacity [mAh/g]	165-170 mAh/g at C/10 & 30°C (1000 cycles)	170 mAh/g at C/10 & 20°C (500 Cycles)	**250** mAh/g at C/10 & 10°C to 2.5V, 1.5 g/cc; 150 cycles	**270** mAh/g at C/10, 10°C to 2.5 V, 1.5 g/cc; 150 cycles; 7.5 mg/cm^2
	Anode-level specific capacity [mAh/g]	280 mAh/g (MCMB) (1000 cycles)	300-330 mAh/g (graphite) (500 cycles)	**1000** mAh/g at C/10 &10°C to 1.0V, 7.5 mAh/cm^2; 150 cycles	**1200** mAh/g at C/10, 10°C to 1.0V, 7.5 mAh/cm^2; 150 cycles
Energy density 540 - 700 Wh/l	**Battery-level** energy density*	250 Wh/l	300Wh/l	**430 Wh/l**	**450 Wh/l**
	Cell-level energy density*	320 Wh/l	400 Wh/l	**500 Wh/l**	**550 Wh/l**
Operating environment	Operating Temperature	-20°C to +40°C	-10°C to 40°C	**10°C to 30°C**	**10°C to 30°C**

Notes
1) The State of Art Aerospace batteries represent the mature systems (at TRL 9) that have been in mission use (e.g., Yardney and SAFT Batteries). The SOA COTS based batteries, on the other hand are at a lower TRL (5), except for the Sony hard carbon cells with low specific energies (in ABSL batteries).
2) Over-temperature up to 110°C; reversal with 150% excess discharge @ 1C; external short tests; overcharge a charged cell @ C/5 for 5 hours to 12 V max.
3) The Battery-level specific energies are projected only for the high energy systems being developed here (only cell level demonstration)

Lithium-Ion Batteries – Component Development

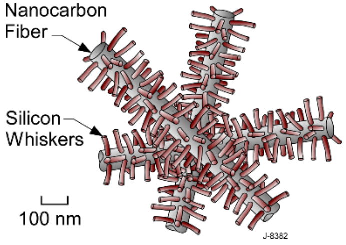
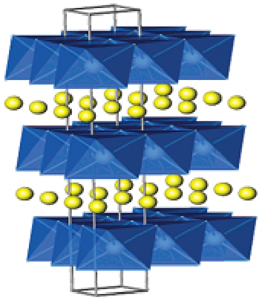


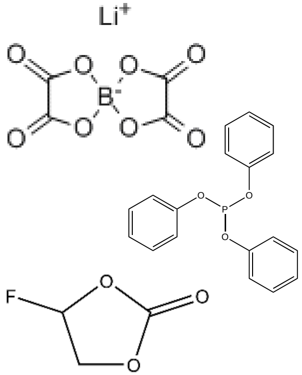
Image: Physical Science

- **Silicon alloy anode** - Physical Sciences, Inc.
  - Carbon nanofibers with silicon whiskers
  - Practical anode loading >4 mg/cm^2
    - Initial capacity >1000 mAh/g
    - Rate capability C/10 to C/1
    - 50 cycles in 35 Ah cells
    - Scalable production process

We also assessed NMC cathode materials from BASF and Toda (coated and uncoated), and Si anode materials from 3M.



- **High capacity, high voltage lithiated-mixed-metal-oxide cathode** – NASA/UT Austin
  - $Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O_2$
  - $AlPO_4$ coating (1-2 w%) – Physical Sciences
  - Practical tap density 1.6 g/cc
    - Initial capacity >250 mAh/kg (uncoated)
    - Initial capacity >180 mAh/kg (coated)
    - 100 cycles in half-cells
    - Scalable production process – scaled-up the synthesis to ~2 kg



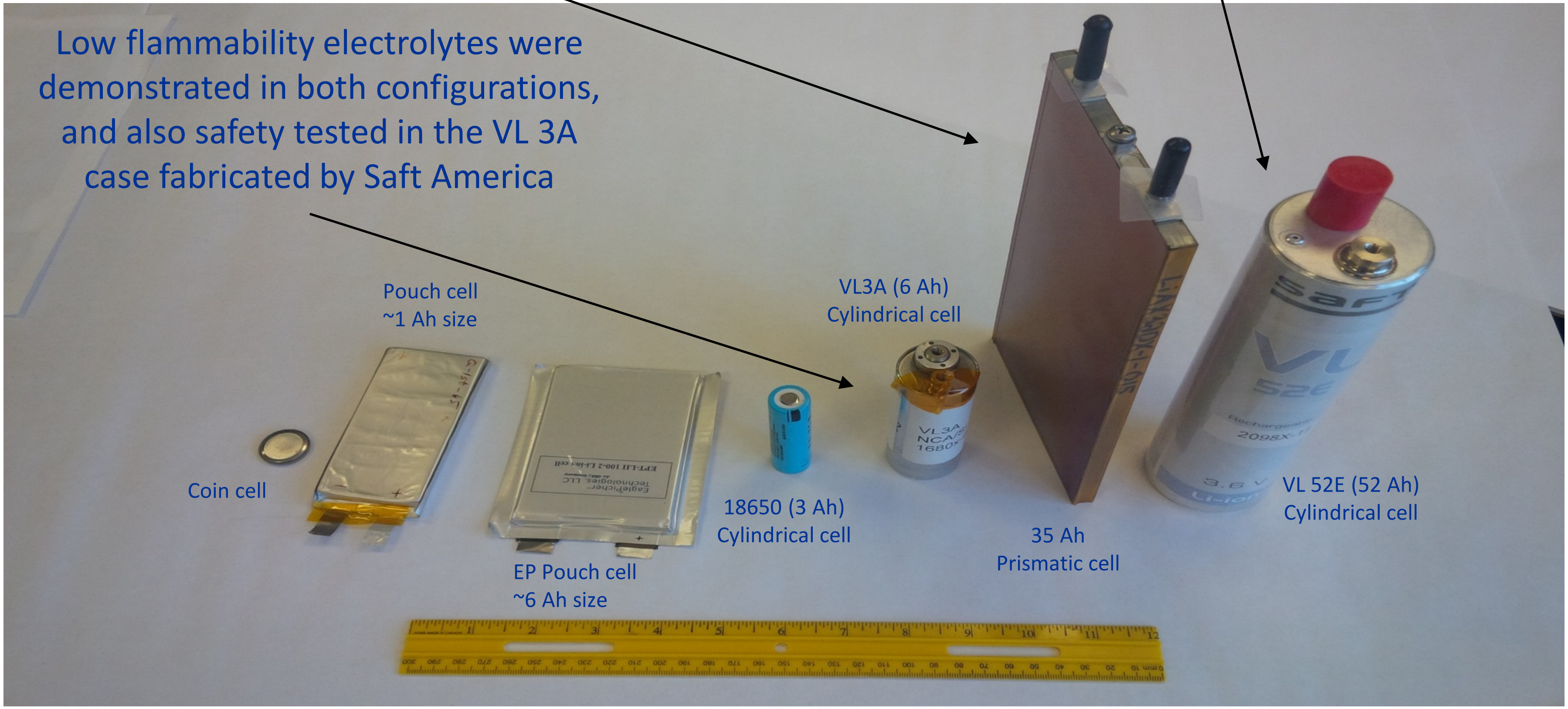
- **Low-flammability, high voltage electrolyte** – NASA JPL
  - Triphenylphosphate (TPP) flame retardant additive (FRA) with LiBOB for high voltage compatibility
  - Fluoroethylene carbonate for compatibility with Silicon anodes
  - 5v%, 10v%, and 15v% FRA show enhanced flame retardance at the component level (reduced self-extinguishing time from flame test)
  - 5v% and 10v% FRA incorporated into conventional Li-ion cells with 4V NCA cathodes showed impressive cycle life – better than baseline cells
  - 10v% FRA incorporated into 6 Ah cells for safety and abuse testing

Lithium-Ion Batteries – Cell Formats

Components developed under NASA's Advanced Space Power Systems Project were scaled-up and fabricated into in the large format cells shown below.

PSI silicon anode in 35 Ah prismatic case fabricated by Yardney Technical Products

NMC cathode (against commercial anode) and 3M Anode (against commercial cathode) in VL 52E fabricated by Saft America.

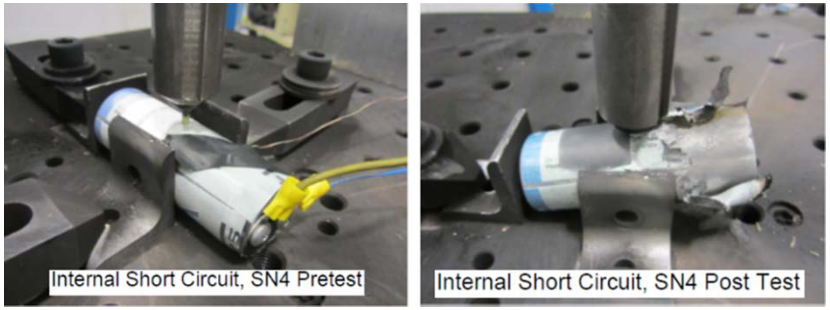


Note: Capacity (Ah) values shown are nominal; exact value is dependent on the components used within the cell.

Lithium-Ion Batteries – Cell Safety Testing

Overcharge Post-Test Results for S/N: 1429x-15. Venting and fire during overcharge test.

Overcharge Post-Test Results for S/N: 1429x-40. Venting on the non-terminal end of the cell.



Internal Short Circuit Pre-Test Configuration and Post-Test Results for S/N: 4

Overcharge Pre/Post Test Result for Cell N2-1052-2

Lithium-Ion Batteries – Cell Performance Testing

- Advanced electrodes successfully scaled-up into large format cells for the first time.
- Aggressive goals not met, but anode reached 91% of expected performance with low flammability electrolyte.
- Cycle life values are ok for lander applications but not EVA.

Legend:
- meets predicted performance
- >90% of predicted performance
- >80% of predicted performance
- < 80% of predicted performance

Measured Cell Peformance at 10 deg C and C/10 charge/discharge rate

Lithium Ion Battery Cells	Cell Components	Capacity (Ah)	Specific Energy (Wh/kg)	Energy Density (Wh/l)	Cycle Life	Charge Voltage (V)
Threshold KPP Goal			210	500	200	
KPP Goal			265	550	200	
LtWt NCA - C -TPP VL52E 2098	Commercial NCA Cathode; **Low Flammability Electrolyte (Gen IV)**; Commercial Graphite Anode	51	188	381	>300	4.2
LtWt NCA - C VL52E 2097	Commercial NCA Cathode; Commerical Electrolyte (Saft); Commercial Graphite Anode	53	198	402	>300	4.2
NMC - C VL52E 2485	**NMC Cathodes**; Commerical Electrolyte (Saft); Commercial Graphite Anode	53	189	386	12	4.7
NCA - 3M Si VL52E 2221	Commercial NCA Cathode; Commerical Electrolyte (Saft); **Silicon Anode (3M)**	48	151	320	20	4.2
NCA - PSI Si - TPP Prismatic LiAX32IX	Commercial NCA Cathode; **Low Flammability Electrolyte (Gen IV)**; **Silicon Anode (PSI)**	35	191	505	50^{+}	4.15

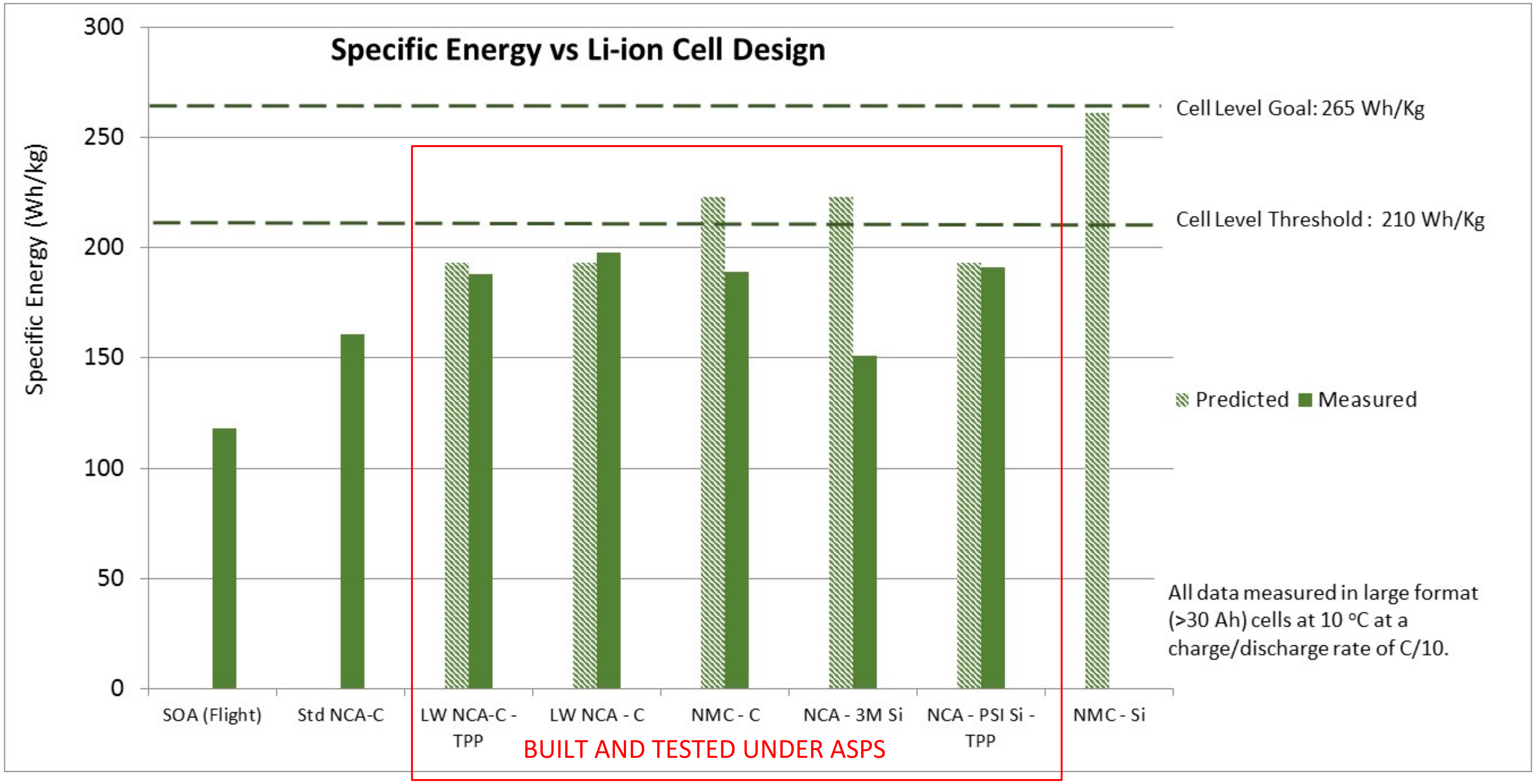
Commercial chemistry with lightweight cell package

First successful build with advanced cathode. Argonne National Lab has continued interest.

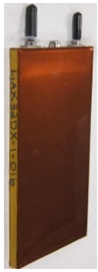
Known manufacturing defects – cells have been re-built and now get ~60 Ah

High-rate (C/2) cycling damaged cells – artificially limited measured cycle life

GCD Advanced Space Power Systems Project: High Energy Li-Ion Batteries Specific Energy



All except PSI Si cells



NCA – PSI Si-TPP Cells

SOA = Li-Ion Cells flown on Mars Exploration Rover

Std NCA – C = Saft Commercial VL52E cells (terrestrial use). NCA cathode, Carbon anode, commercial Saft electrolyte.

LW NCA-C-TPP = Lightweight VL52E packaging with NCA cathode, "Gen IV" TPP electrolyte, and Carbon anode.

LW NCA – C = Lightweight VL52E packaging with NCA cathode, commercial Saft electrolyte, and Carbon anode.

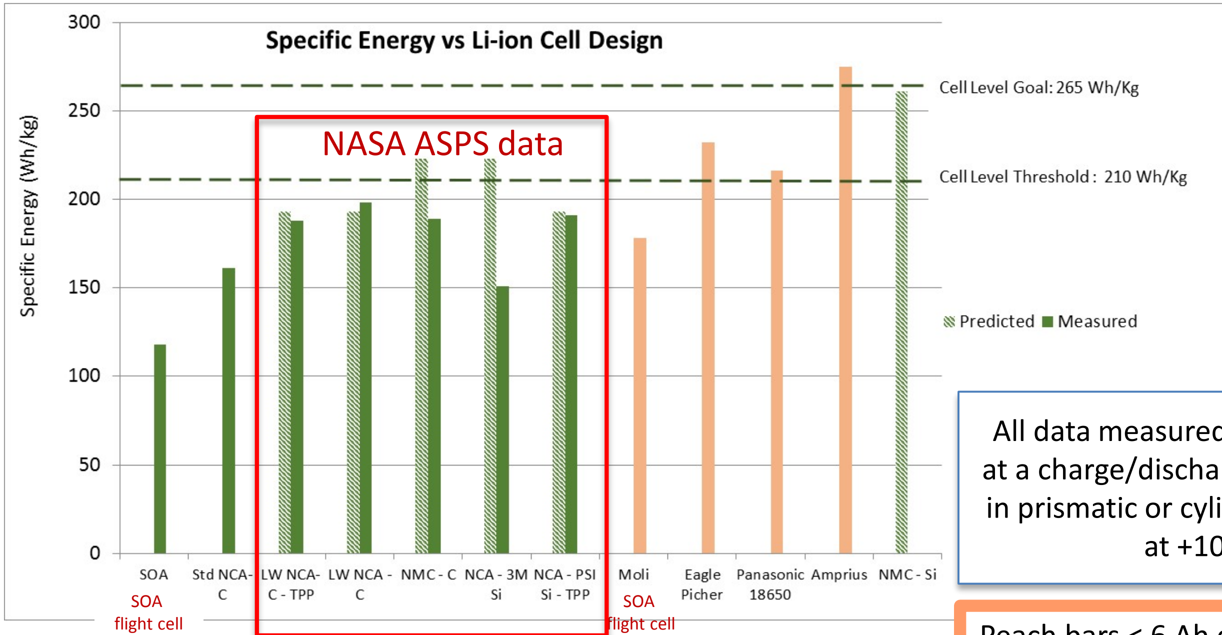
NMC – C = VL52E cells with NMC cathode, commercial Saft electrolyte, and Carbon anode.

NCA – 3M Si = VL52E cells with NCA cathode, commercial Saft electrolyte, and Silicon anode from 3M. (known manufacturing defect)

NCA – PSI Si-TPP = 30 Ah PSI cell. NCA cathode, "Gen IV" TPP low flammability electrolyte, Silicon anode from PSI.

NMC – Si = VL52E cells with NMC cathode, commercial Saft electrolyte, and advanced Silicon anode from best source.

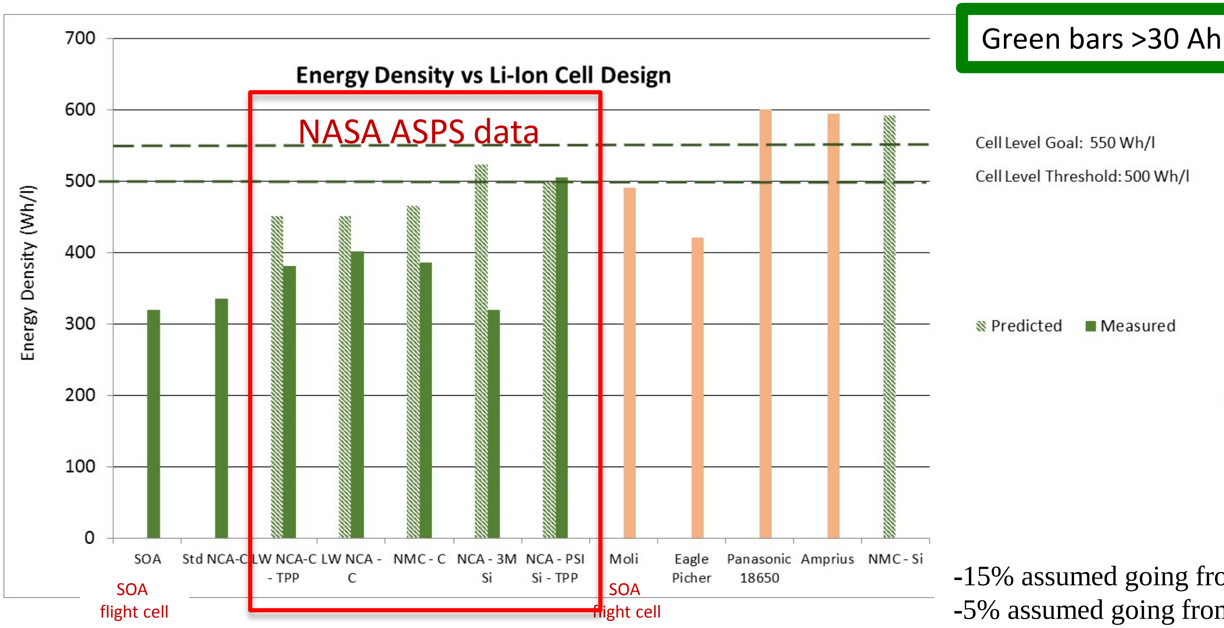
Comparison of Large Format and Small Format Li-Ion Battery Cells



All data measured (or estimated) at a charge/discharge rate of C/10, in prismatic or cylindrical formats, at +10 °C.

Peach bars < 6 Ah cells

Green bars >30 Ah cells



-15% assumed going from pouch to prismatic,
-5% assumed going from 20^{0}C to 10^{0}C.

Small format cells show higher performance and cycle life than large format cells.

- Performance is ~15% better in a pouch cell.

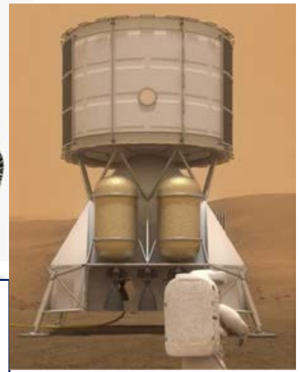
Large format cells retain their mass advantage better when integrated into full batteries

- Fewer interconnects
- Fewer terminals
- Simpler control circuitry

10X more small format (~4 Ah) cells needed than large format (~40 Ah) cells

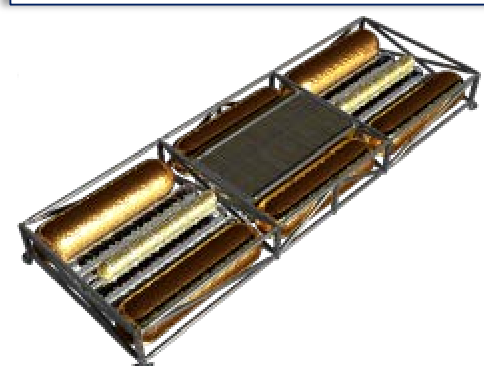
- 1000's vs 100's

Fuel Cell Technology Development
Goals and Key Performance Parameters



Fuel Cells for Surface Mobility Systems and Landers

Regenerative Fuel Cells for Surface Power Systems

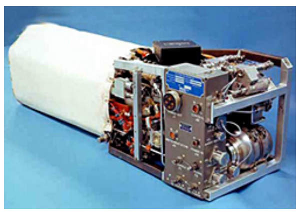


Fuel Cell and Electrolyzer Technology Development Key Performance Parameters

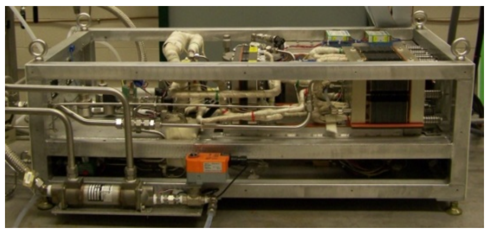
Balance of Plant Mass		9-21 kg
Fuel Cell System	Power Density	88-136 W/kg for Fuel Cell System 107-231 W/kg at Fuel Cell Stack level
	Membrane Electrode Assembly (MEA) Efficiency	73-75% and .90-.92V individual cell Voltage @200 mA/cm^2 for Fuel Cell MEA
	System Efficiency	71-74% at Fuel Cell level (1-2% parasitic losses)
	Operating Life	5000-10000 hrs maintenance-free for MEA 220 hrs for a Fuel Cell System
Regenerative Fuel Cell System	Power Density	25-36 W/kg for Regenerative Fuel Cell System (not including tanks)
	Membrane Electrode Assembly (MEA) Efficiency	84-85% and 1.46-1.44V individual cell Voltage @200 mA/cm^2 for Electrolyzer Cell MEA 62-64% round trip efficiency for Regenerative Fuel Cell MEA
	System Efficiency	43-54% for Regenerative Fuel Cell System (5-10% parasitic losses and high pressure penalty of 10-20%)
	Operating Life	5000-10000 hrs maintenance-free for MEA 5000-10000 hrs for a Regenerative Fuel Cell System

Fuel Cell Technology Progression
… Simpler Balance of Plant to improve reliability

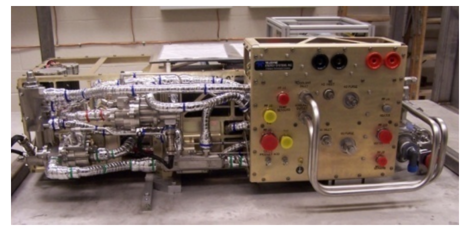
Johnson Space Center / UTC Power	Glenn Research Center / Teledyne Energy Systems, Inc.	Glenn Research Center / Teledyne Energy Systems, Inc.	Glenn Research Center / Infinity
Shuttle "Active BOP" Alkaline	**"Active BOP" PEM**	**"Passive BOP" PEM**	**"Passive BOP" PEM**



Flow-Through

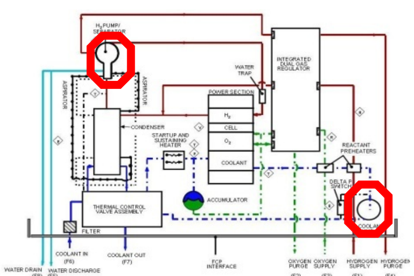


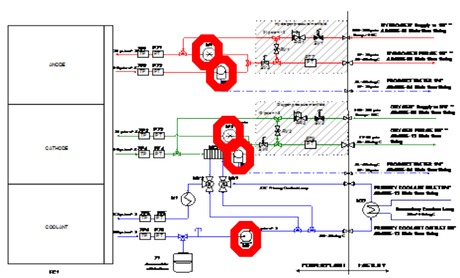
Flow-Through

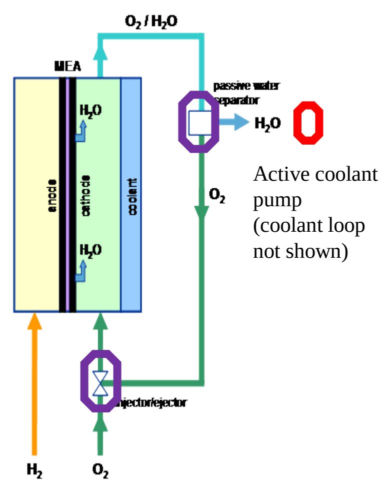


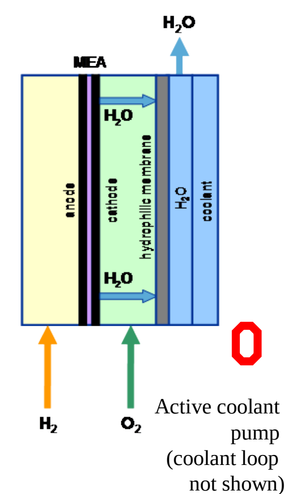
Flow-Through

***Non*-Flow-Through**





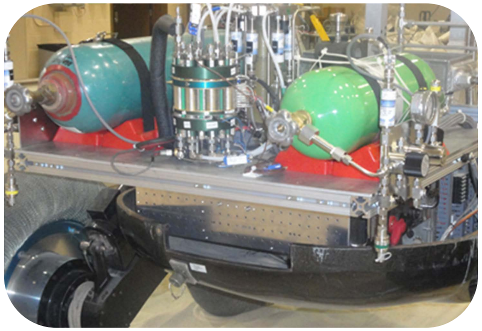




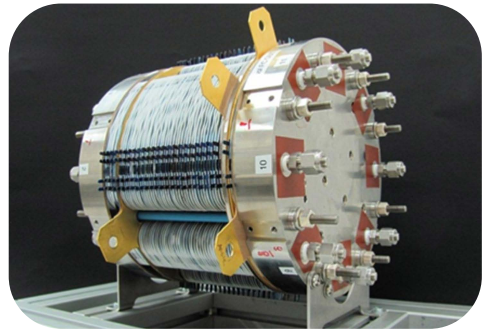
= **Active Mechanical Component (pump, active water separator)**

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

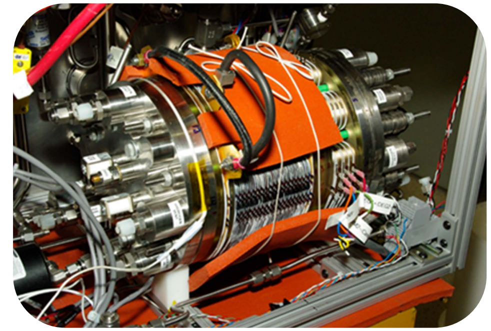
Fuel Cell and Electrolyzer Hardware Builds



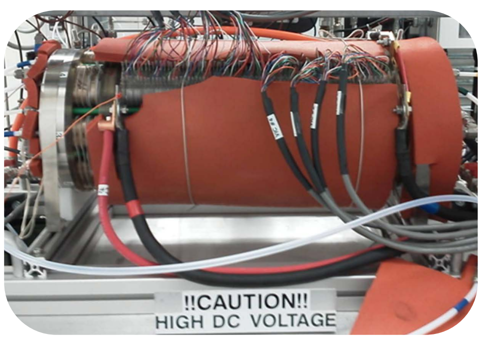
100-W NFT Fuel Cell Stack (16 cells, 50 cm^2, 12 V)



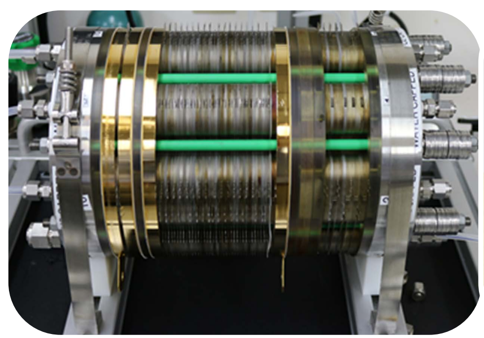
1-kW NFT Fuel Cell Stack (40 cells, 150 cm^2, 30 V)



1-kW Block I NFT Fuel Cell Stack (36 cells, 150 cm^2, 28 V)



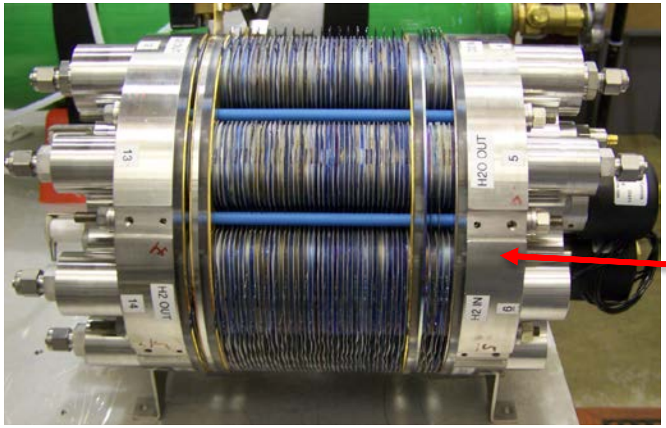
3-kW NFT Fuel Cell Stack (144 cells, 150 cm^2, 120 V)

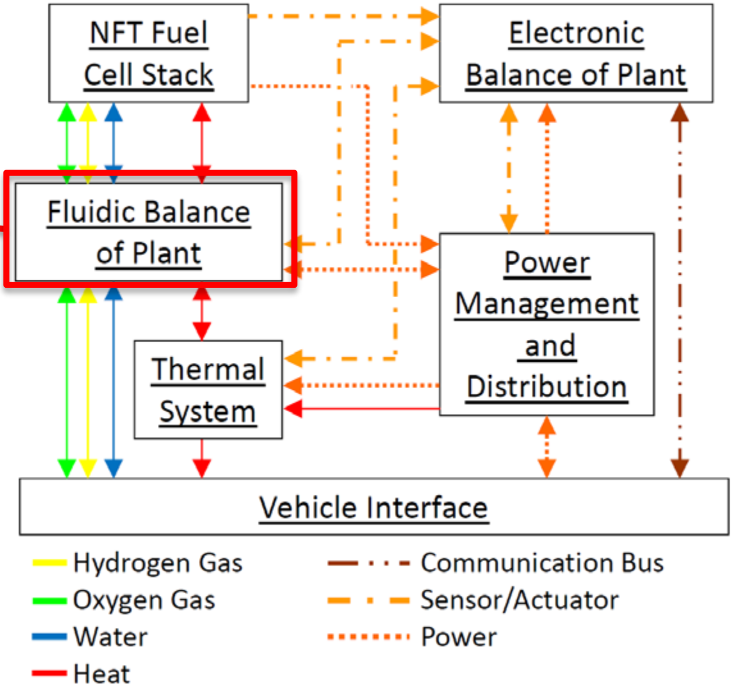


1-kW Block II NFT Fuel Cell Stack (36 cells, 150 cm^2, 28 V)

100-W SF Electrolysis Stack (4 cells, 50 cm^2)

Fuel Cell Technology Development: Balance Of Plant





1-kW NFT Fuel Cell Stack with attached Fluidic BOP

Fuel Cell Power System Architecture

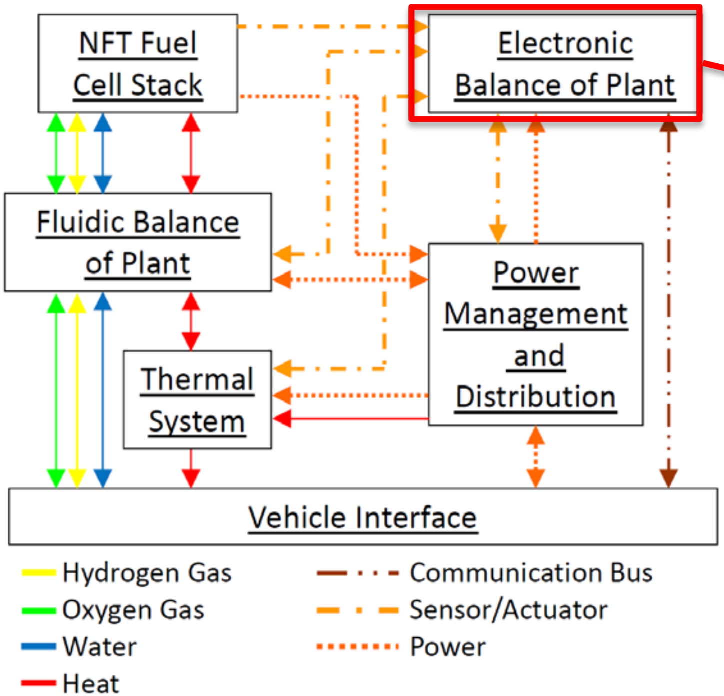
Goal: efficient packaging into an interface plate to mount directly to the fuel cell stack endplate.

Manifolds, instrumentation, and actuators manage and control:

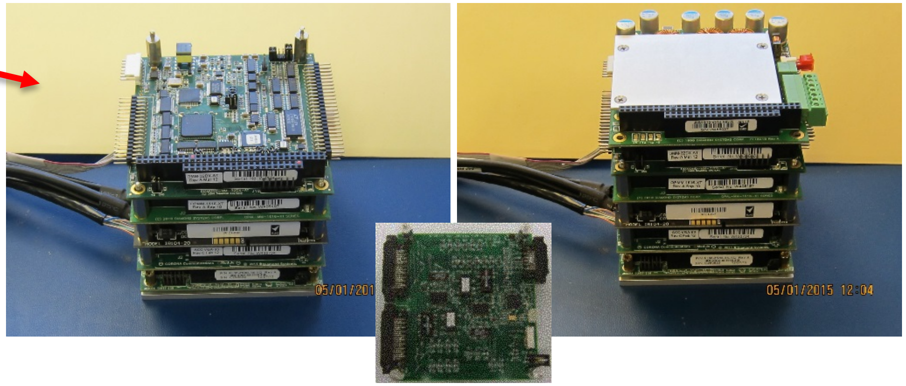
- flow of reactant gases through the stack interfaces
- and product water out of the stack.

The fluidic BOP worked reliably and robustly in the scarab demonstrations.

Fuel Cell Technology Development: Balance Of Plant



Fuel Cell Power System Architecture

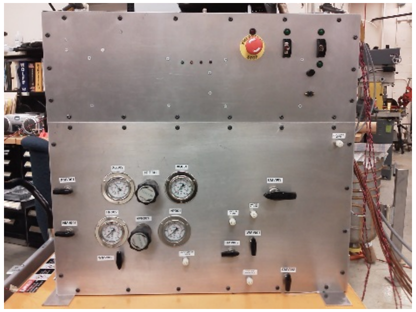


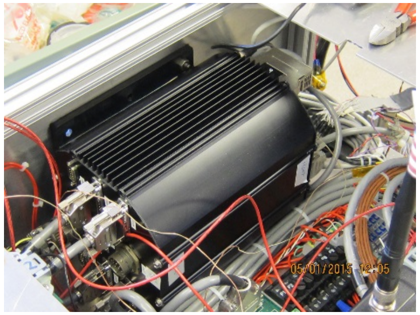
Electronic BOP

PC/104 format electronics module includes:

- On-board processor,
- Data acquisition/control,
- Communications,
- Power management, and
- Quad-channel cell voltage monitoring
    - measures ±10 mV out of up to 50 Vdc,
    - common-mode voltage of up to 600 Vdc

This unit has been built into an enclosure, and integrated with the fuel cell, fluidic balance of plant, and batteries for a self-contained test unit.





(Left) Fuel Cell System (includes everything but tanks)
(Right) Top view showing packaged electronics

Regenerative Fuel Cell Hardware Builds

<u>100-W RFC</u>

NFT Fuel Cell Stack
on Test Stand

Static Feed
Electrolysis Stack in
Test Stand

- **Bench-top conceptual demonstration**
- **Fuel cell efficiency of 66.3%; electrolysis efficiency of 71.0%**
- **Overall round-trip efficiency of 47.1%, with no allowance for parasitic power losses**

Fuel Cell Technology Infusion

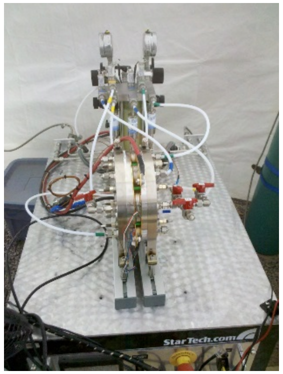
Lessons learned in

- scale up,
- sealing,
- operability, and
- manufacturing techniques

have enabled successful follow on work with broad applicability.

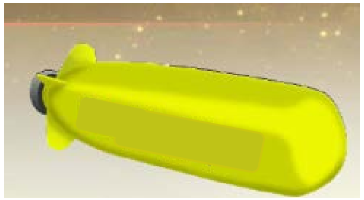
Demonstrations

Collaborations

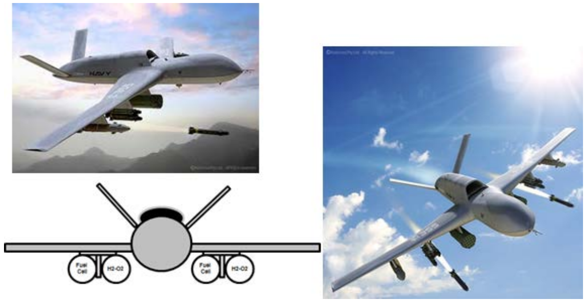


2010 Desert RATS Demonstration

2012 AMPS Scarab Rover Range Extender Demonstration



Navy LDUUV Program



Missile Defense Agency (MDA) High Energy Laser SBIR Program

Summary and Lessons Learned

- Advanced high voltage NMC cathode, Silicon anode, and flame retardant electrolyte materials were developed and scaled-up to fabricate large format battery cells (>30 Ah)

- Non-flow-through fuel cell technology was scaled-up to a 3 kW stack, and regenerative operation was demonstrated with smaller scale hardware (nominally 100 W).

- Our aggressive goals have not yet been met – but progress has been made:
  - Demonstrated the scalability of advanced lithium ion battery components, and met portions of predicted performance
  - Worked through numerous design iterations on the non-flow-through fuel cells such that they have competed well for short-duration applications

- These project elements have ended – principal lessons learned include:
  - A short project life with modest funding is very challenging to produce a useful product from truly new electro-chemical systems

    For comparison, NASA's previous lithium-ion development took about $30M and six years (1995 – 2001) to fabricate, test and qualify cells for infusion into flight missions, using electrode materials that were known to be scalable
  - Building large-scale systems early was beneficial to discover interaction and scaling issues for the battery components, but building larger sized fuel cells before learning the lessons from smaller sizes cost time and money in the long run