

Battery and Fuel Cell Development Goals for the Lunar Surface and Lander

Carolyn R. Mercer

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Abstract

NASA is planning a return to the moon and requires advances in energy storage technology for its planned lunar lander and lunar outpost. This presentation describes NASA's overall mission goals and technical goals for batteries and fuel cells to support the mission. Goals are given for secondary batteries for the lander's ascent stage and suits for extravehicular activity on the lunar surface, and for fuel cells for the lander's descent stage and regenerative fuel cells for outpost power. An overall approach to meeting these goals is also presented.



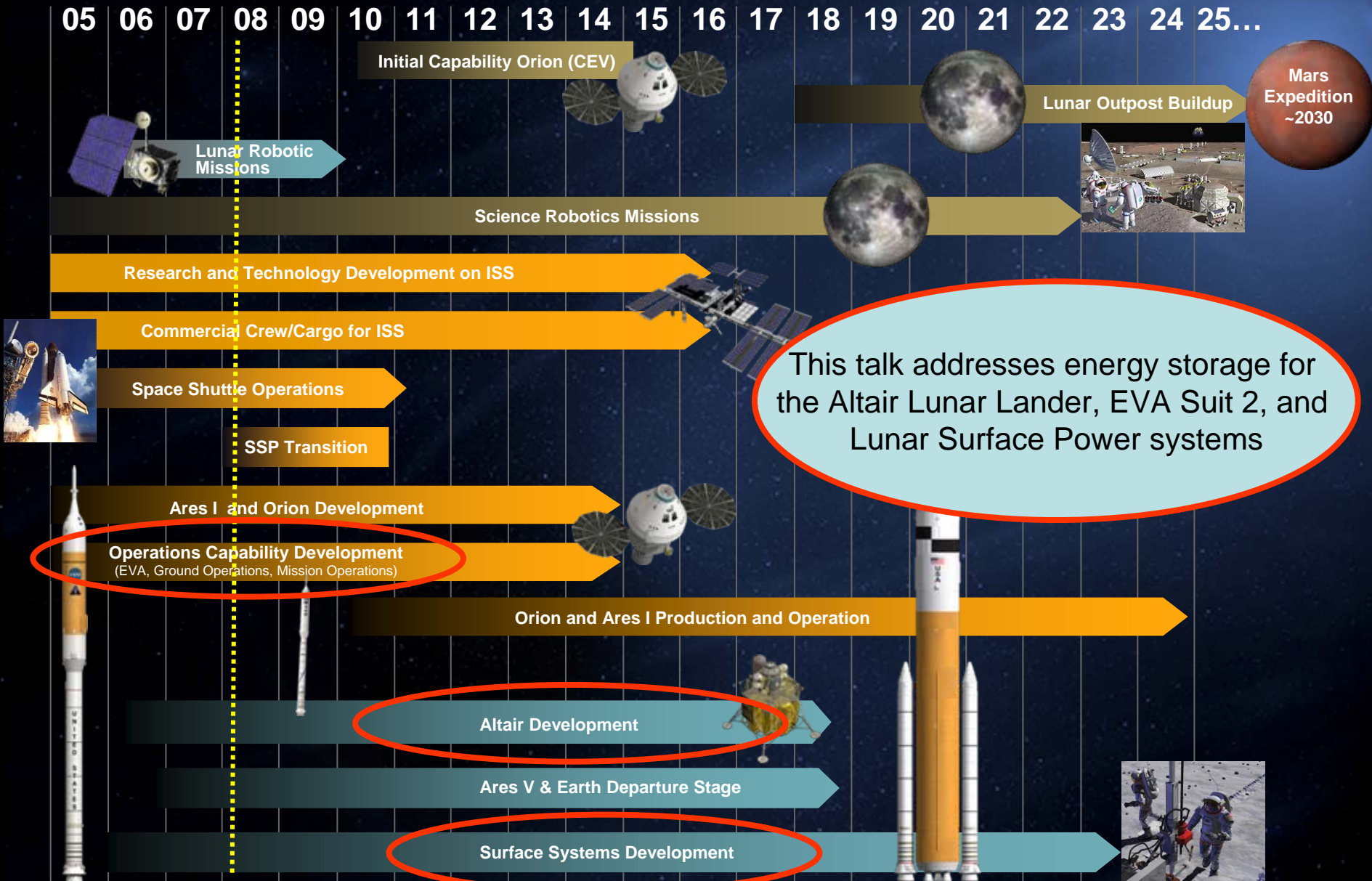
Battery and Fuel Cell Development Goals for the Lunar Surface and Lander

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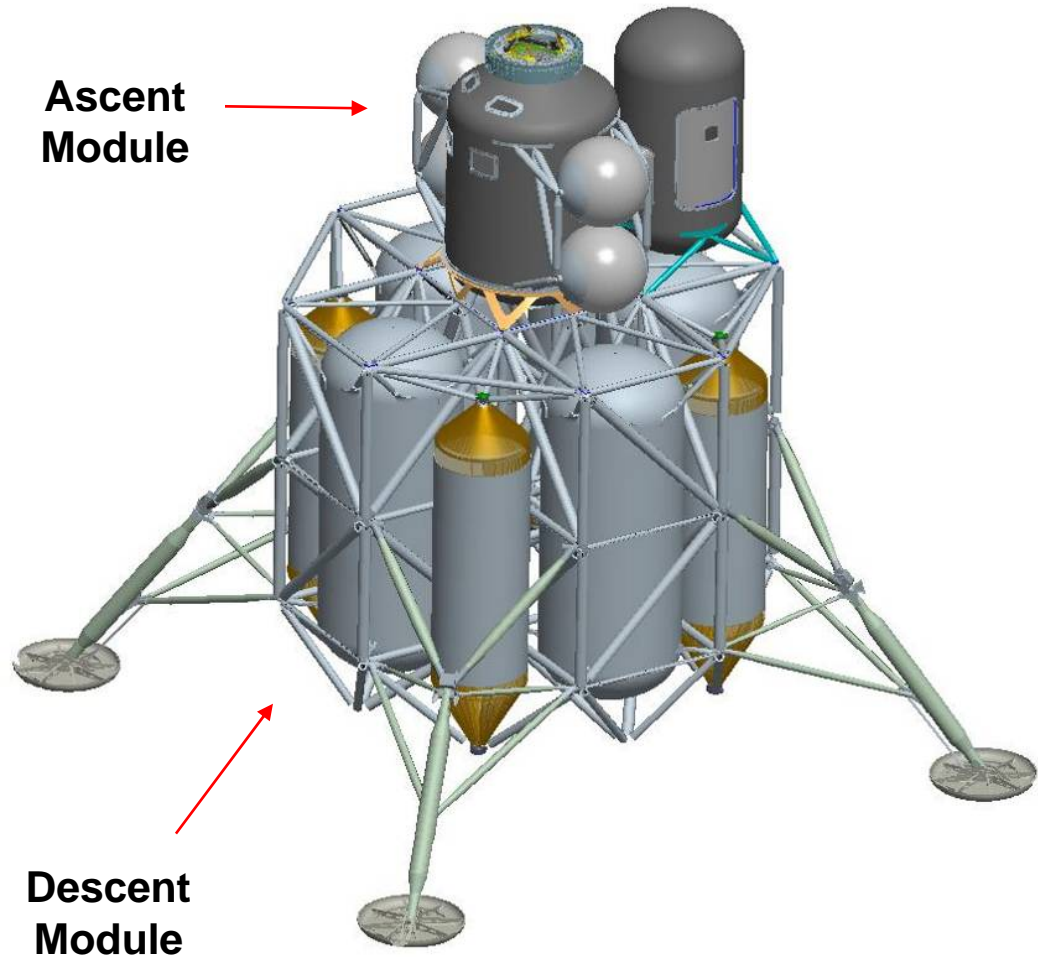


NASA's Exploration Roadmap





Altair Lunar Lander



**Ascent
Module**

**Descent
Module**



Altair Lunar Lander



Preliminary information from “minimally functional” DAC1 design (zero fault tolerant)
Abort and contingency scenarios still to be addressed

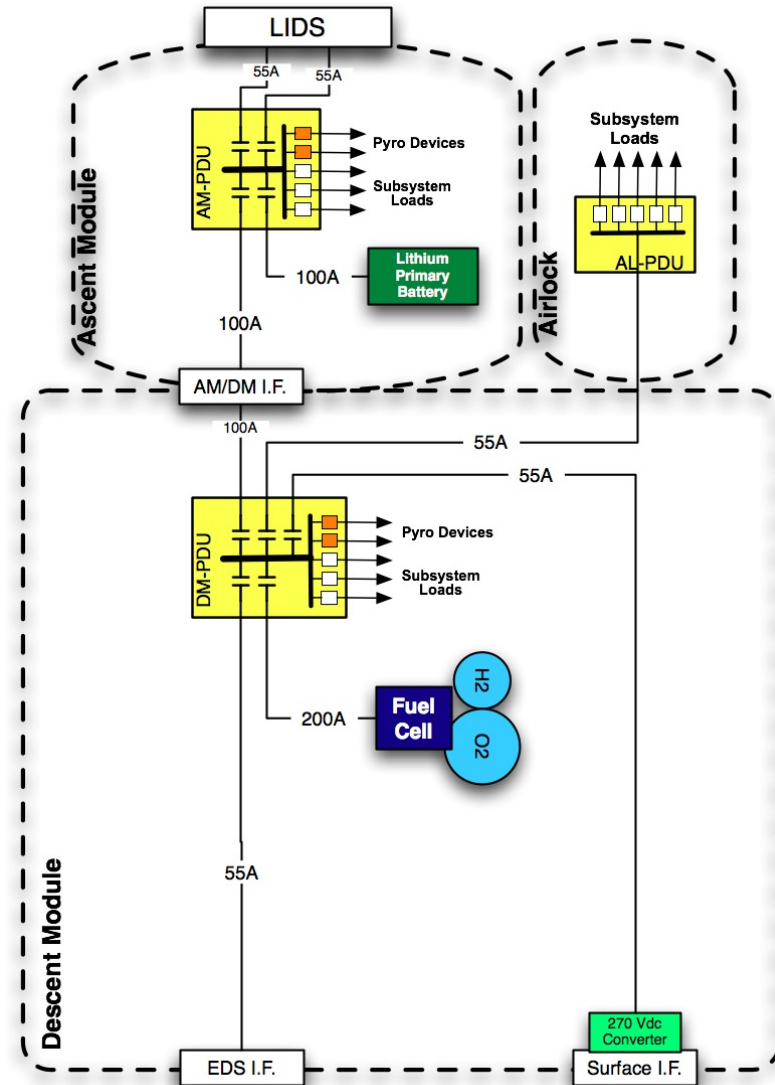
Ascent Module and Airlock

- Single primary battery, LiMnO_2 chemistry, 14.2 kW-hr capacity
- Secondary battery desirable to provide instantaneous power for ascent in case descent stage is ejected during abort; and to provide make-up power during shadow phase of TLI.

Descent Module

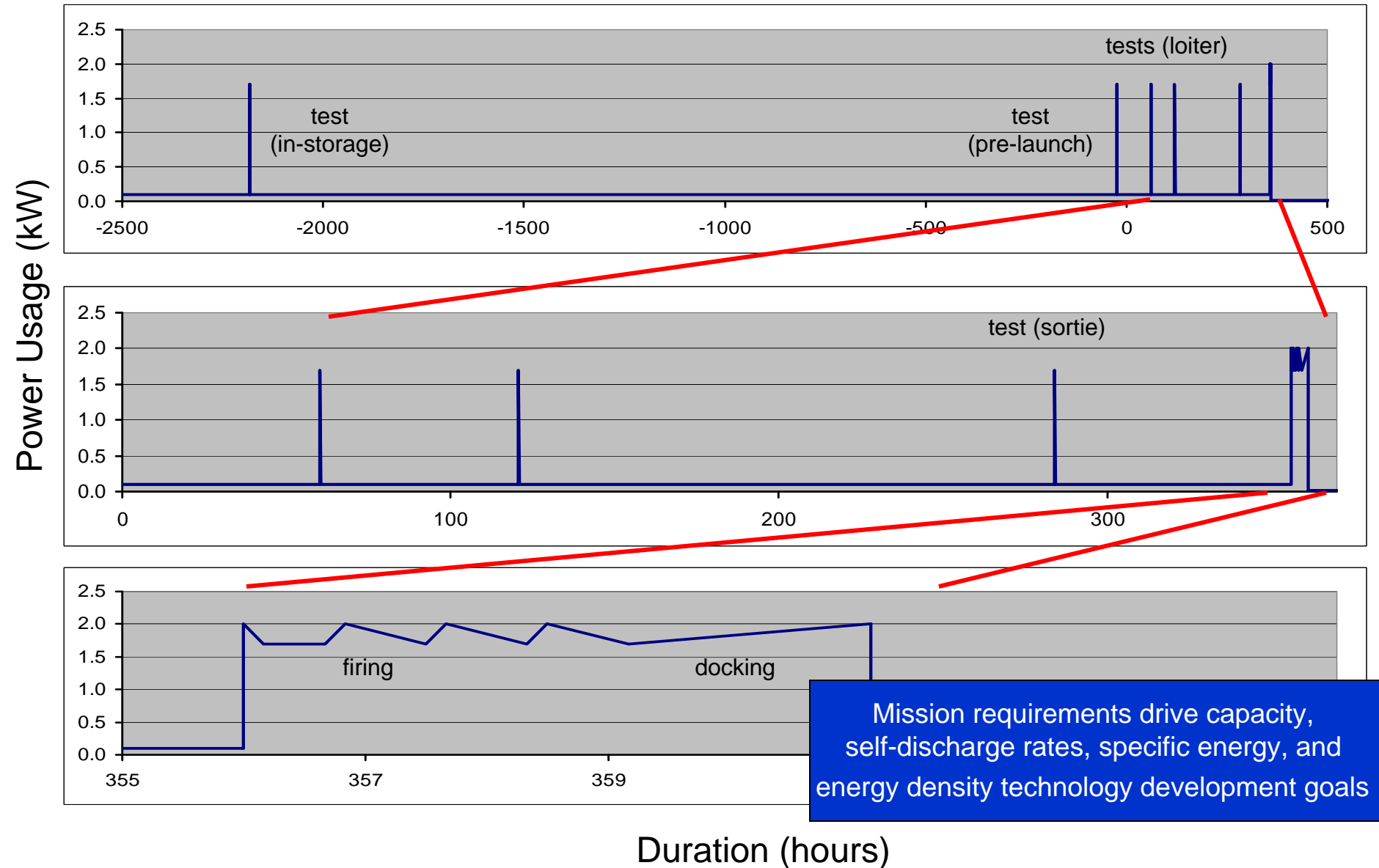
- PEM fuel cell, 5.5 kW peak production
- Provides ascent and descent module power for LLO and surface operations
 - Orion provides 1.5 kW when docked
- Propulsion residuals provide reactants for surface operations

Key mission requirements:
Human-safe, reliable operation;
high energy density; architecture compatibility



Converting Constellation Architecture into Tech Development Goals

Example: Lunar Ascent Stage (nominal mission)



Lunar EVA Suit: "Configuration 2"



Greatly increased electronic capability (HDTV, communications node, displays, etc...) drives need for high energy batteries in small, low-mass package.

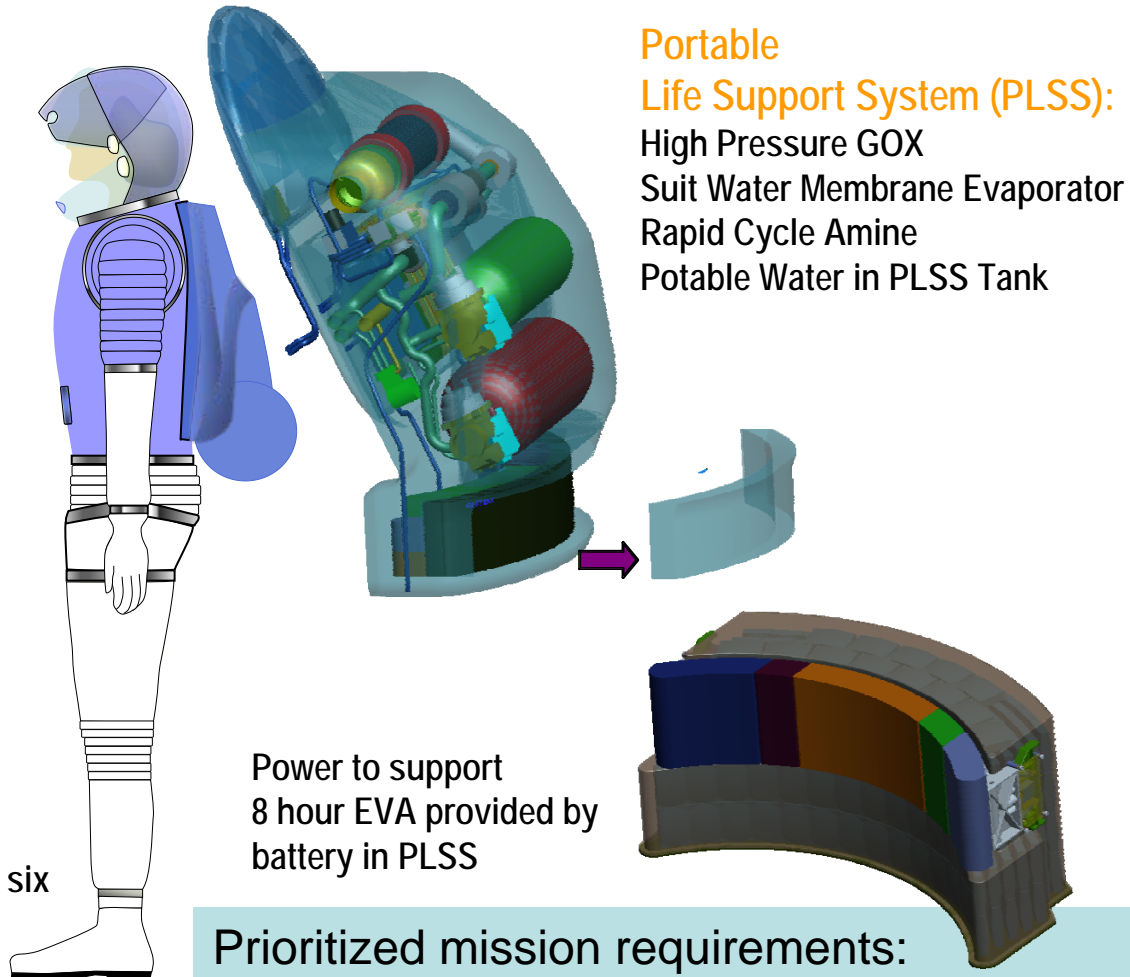
Very high specific energy and energy density with 8-hour, human-safe operation drives technology development.

Power / Communications, Avionics & Informatics (CAI):

- Lithium Ion Batteries
- Cmd/Cntrl/Comm Info (C3I) Processing
- Expanded set of suit sensors
- Advanced Caution & Warning
- Displays and Productivity Enhancements

Preliminary Battery Requirements:

- ~ 900 W-Hr energy, delivered
- ~ 100 W average and 175 W peak power
- Current mass allocation: 5 kg
- Current volume allocation: 1.6 liter
- 100 cycles (operation every other day for six months)



Portable Life Support System (PLSS):

- High Pressure GOX
- Suit Water Membrane Evaporator
- Rapid Cycle Amine
- Potable Water in PLSS Tank

Power to support 8 hour EVA provided by battery in PLSS

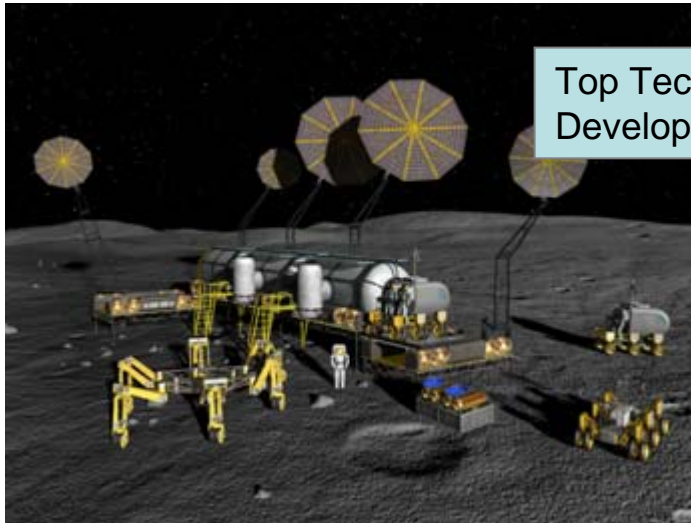
Prioritized mission requirements:
Human-safe operation; 8-hr duration;
high specific energy; high energy-density.



Lunar Surface Systems



Goal: Continuous human presence on surface
Plan for polar site, but keep capability to go anywhere



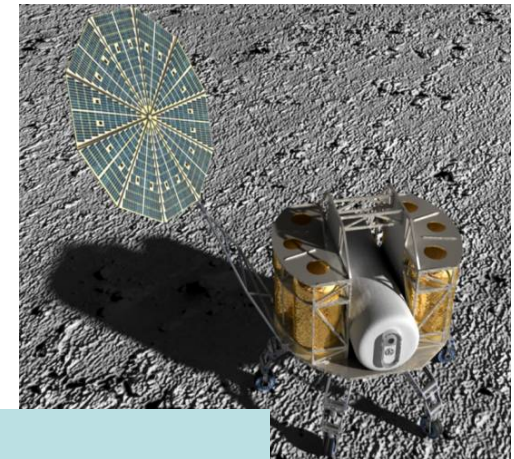
Top Technology Development Driver

- **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
- Autonomous control and operation
- Human-rated
- Low mass and volume
- Little or no maintenance needs

Energy Storage: Regenerative Fuel Cells

- ~250 kWh_{net} energy storage module
 - Equals ~2 kW_{net} minimum fuel cell continuous power at Shackleton Crater
- ~36 cell fuel cell stacks,
~18 cell electrolyzer stacks
 - Based on ~30 Vdc bus voltage
- Cryogenic vs Gaseous reactant Storage



Prioritized mission requirements:

Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy; high system efficiency.

Converting Constellation Architecture into Tech Development Goals

Example: Surface Mobility Systems (nominal missions)

4 classes of rover missions:

- Short duration outpost traverse (Chariot)
- Long duration pressurized crewed sortie (Small Pressurized Habitat + Chariot)
- Long duration habitat transport (ATHLETE)
- Science/ISRU platforms

Power profiles differ for each, but each include some subset of the following functions:

- Pre-sortie vehicle check-out, transport to site(s), return transport, post-sortie checks and shutdown;
- Ingress/egress time for each EVA, boots-on-surface time, crew time in rover;
- Robotic lifting, connecting, emplacement, testing, processing.

Example: Short- and long-term pressurized rover

Length of Sortie (days)	Sorties per year	Energy per sortie per rover (kW-hr)	Energy from Fuel Cell (per sortie, per rover) (kW-hr)	Energy from Battery (per sortie, per rover) (kW-hr)
1	48	22	-	22
3	12	104	-	104
7	10	307	250	57
14	6	557	500	57

Ref: Commonality of Electrolysis Sub-Systems for ISRU, Power, and Life Support for a Lunar Outpost, D.L. Linne et al (2008)

Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.

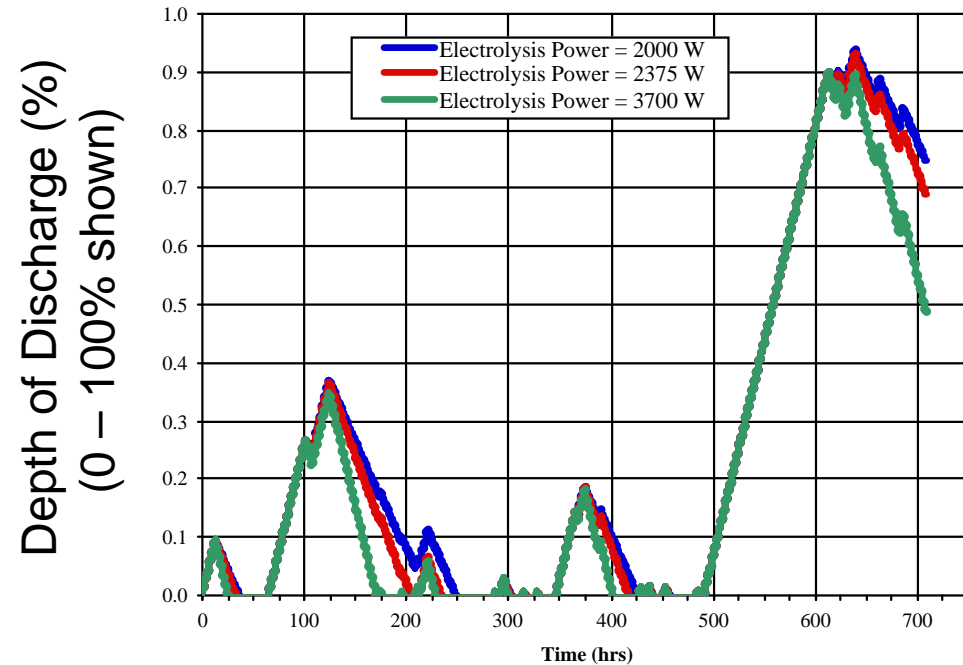


Converting Constellation Architecture into Tech Development Goals

Trade Studies to set Electrolyzer Unit Size

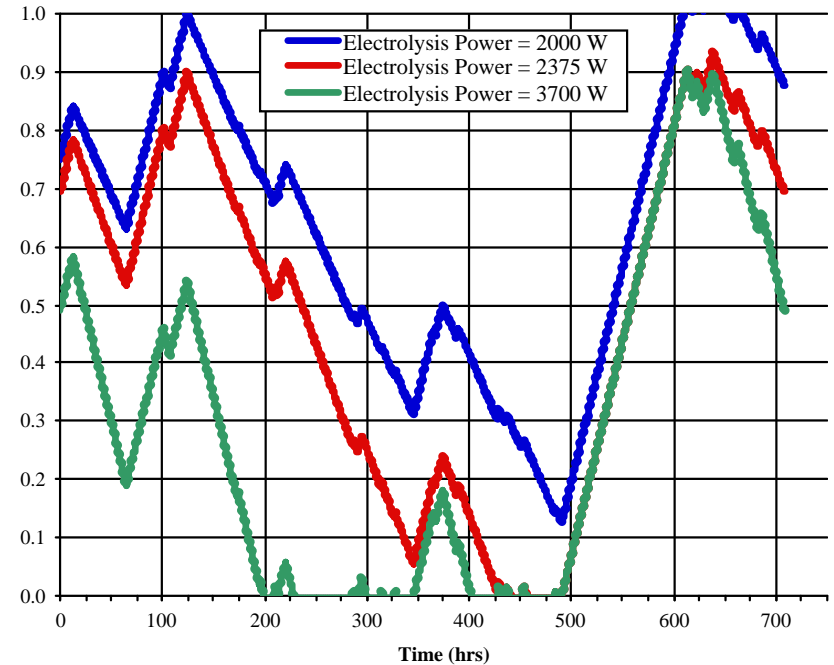


RFC fuel-cell reactant tank Depth-of-Discharge over the course of a month for Electrolysis power = 2kW (blue), 2.375kW (red), and 3.7kW (green)



Time (hours) (0 – 700 hours shown)

Left plot assumes tanks start full.



Right plot assumes tanks are depleted after September.

Key Performance Parameters for Battery Technology Development

Derived Values Based on Customer Requirements



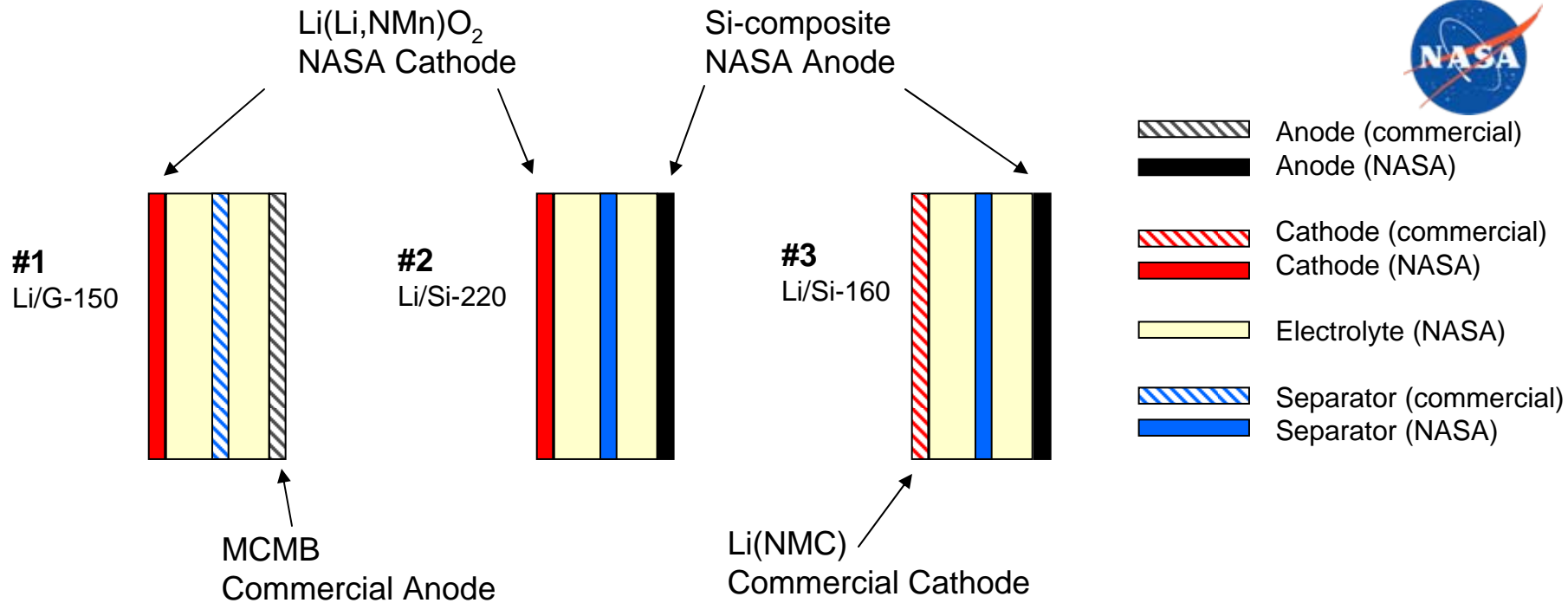
Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	Electrolyte flammability	Controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with non-flammable additives	Non-flammable electrolyte that will minimize thermal runaway	Tolerant to mild abuse, overcharge and over-temperature
Specific energy <u>Lander:</u> 150 – 200 Wh/kg (14KWhr, 67 kg, 45L, 10 cycles) <u>Rover:</u> 150 – 200 Wh/kg <u>EVA:</u> 200 – 300 Wh/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)	105 Wh/kg at C/10 & 30°C 95 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/5 and 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(Li,NiMn)O ₂	140 – 150 mAh/g typical	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		320 mAh/g MCMB 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: TBD 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 for all carbonate- and ester-blend electrolytes in prototype cells	0°C to 30°C	0°C to 30°C

Assumes prismatic cell packaging. Goal values assume lightweight battery construction.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3,000 volts/cell, and at 0 degrees C operating conditions

** "High-Energy" = NASA-developed Li(Li,NMn)O₂ cathode with MCMB graphite anode

"Ultra-High Energy" = NASA-developed Li(Li,NMn)O₂ cathode with Silicon composite anode



Cell 1: Li(NMn)/MCMB-150 “High Energy”

Baseline for EVA and Rover

Lithiated-mixed-metal-oxide cathode / Graphite anode

Li(Li,NMn)O₂ / Commercial mesocarbon microbead

150 Wh/kg @ battery-level 0°C C/10, ~2000 cycles at 100% DOD

Cell 2: Li(NMn)/Si-220 “Ultra-High Energy”

Upgrade for EVA and Altair, possibly Rover

Lithiated-mixed-metal-oxide cathode / Silicon composite anode

Li(Li,NMn)O₂ / silicon composite

220 Wh/kg @ battery-level 0°C C/10, ~200 cycles 100% DOD

Cell 3: Li(NMC)/Si-160 (virtually no-cost option)

Lithiated-mixed-metal-oxide cathode / Silicon-composite anode

Commercial Li(Li,NMC) / Silicon composite anode

160 Wh/kg @ battery-level 0°C C/10, ~200 cycles 100% DOD

Proton Exchange Membrane Fuel Cell Design Options

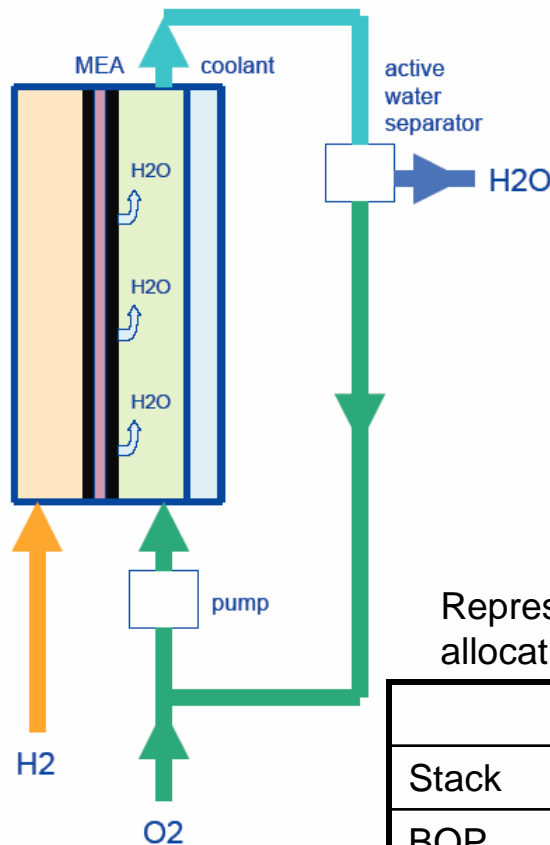


“Flow-Through”

Conventional design.

Used widely in terrestrial applications because venting is required to purge non-O₂ air constituents.

Pump and separator are life-limiting elements of this design.

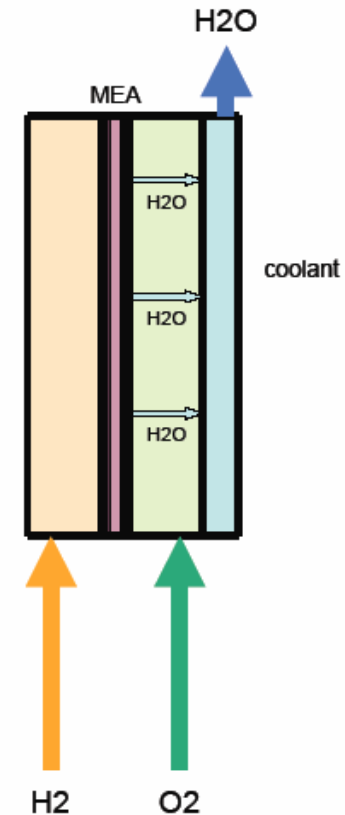


“Non-Flow-Through”

Membrane wicks water through;

Eliminates external pumps and separators.

This design was used on the Gemini capsule.



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

Key Performance Parameters for Fuel Cell Technology Development

Derived Values Based on Customer Requirements

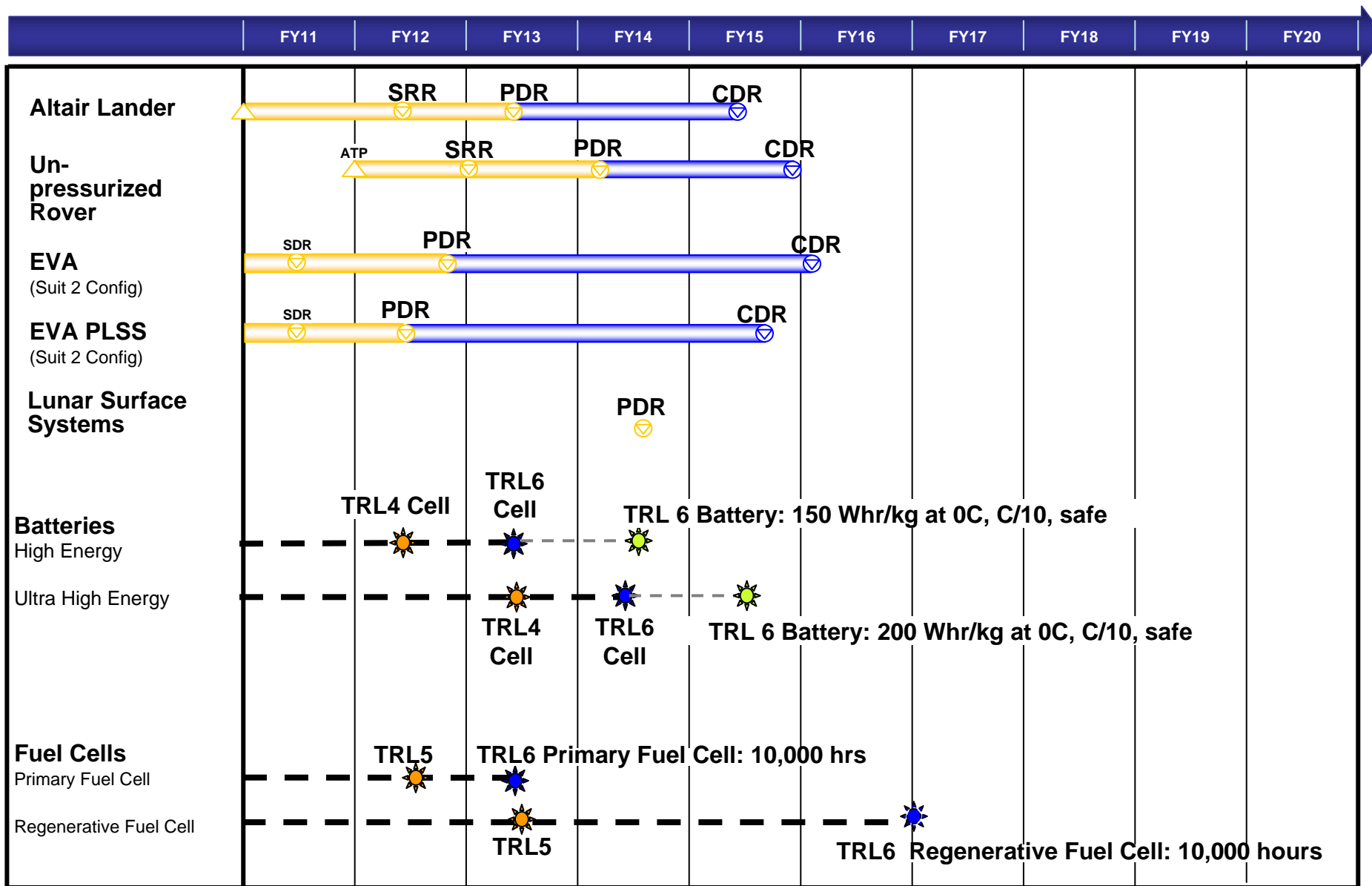


Customer Need	Performance Parameter	SOA (alkaline)	Current Value	Threshold Value	Goal
Lander: 3 kW for 220 hours continuous, 5 kW peak.	System power density @ nominal power (3 kW)				
	Flow-Through Fuel Cell	49 W/kg	33 W/kg	65 W/kg	81 W/kg
	Non-Flow-Through Fuel Cell	n/a	n/a	88 W/kg	136 W/kg
Lunar Surface Systems: TBD kW for 15 days continuous	RFC (without tanks)	n/a	11 W/kg	25 W/kg	36 W/kg
	Stack power density @ nominal power (3 kW)				
	Flow-Through Fuel Cell	97 W/kg	132 W/kg	97 W/kg	188 W/kg
Rover: TBD	Non-Flow-Through Fuel Cell	n/a	n/a	107 W/kg	231 W/kg
	Balance-of-plant mass (3 kW system)				
	Flow-Through Fuel Cell	30 kg	n/a	30 kg	21 kg
**Stack efficiency values assume 200 mA/cm ² operation.	Non-Flow-Through Fuel Cell	n/a	n/a	21 kg	9 kg
	Stack efficiency**				
	Flow-Through Fuel Cell	73%	70%	71%	73%
	Non-Flow-Through Fuel Cell	n/a	67%	71%	73%
	System efficiency				
	RFC	n/a	n/a	46%	56%
Maintenance-free lifetime Lander: 220 hours (primary) Surface: 10,000 hours (RFC)	Fuel cell system maintenance-free operating life				
	Flow-Through Fuel Cell	2500 hrs	1000 hrs	5,000 hrs	10,000 hrs
	Non-Flow-Through Fuel Cell	n/a	n/a	5,000 hrs	10,000 hrs
	RFC	n/a	n/a	5,000 hrs	10,000 hrs

Constellation Program Summary Schedule Lunar Capability Content



PMR '07 Baseline – 10/19/07



Summary: Technology Development Goals for the Lunar Surface and Lander



LAT-1 and LAT-2 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 hours 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 assumed; 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:
200 – 300 W-hr/kg; ~400 Wh/liter
Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lunar 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.



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