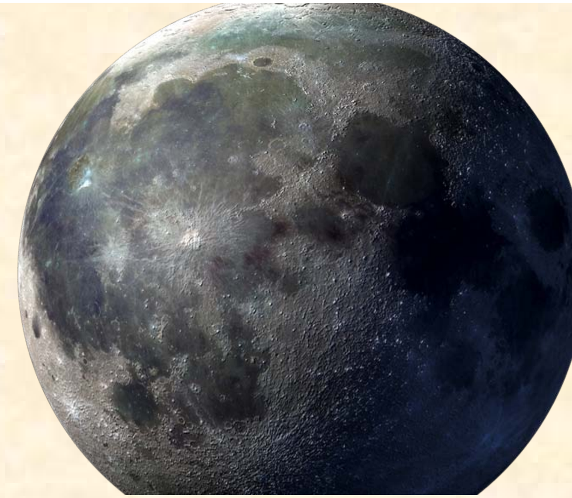


Power Goals for NASA’s Exploration Program

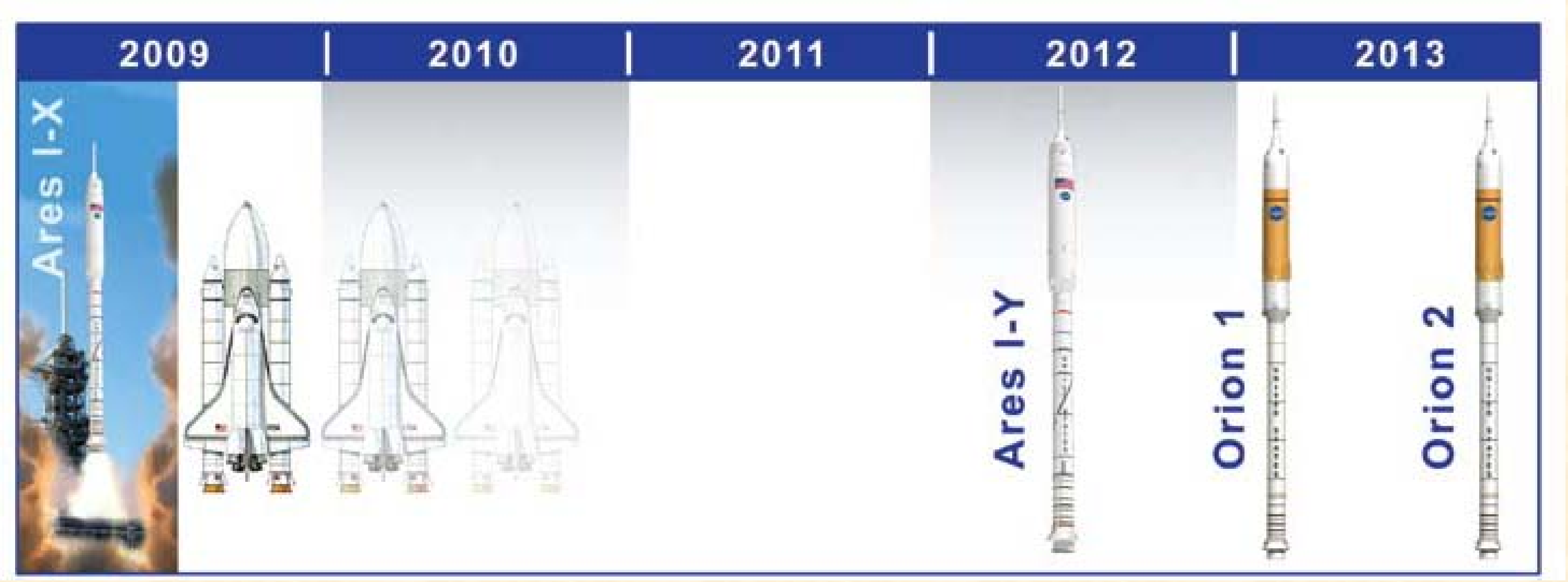
J. Jeevarajan, Ph.D.

NASA-JSC, Houston, TX

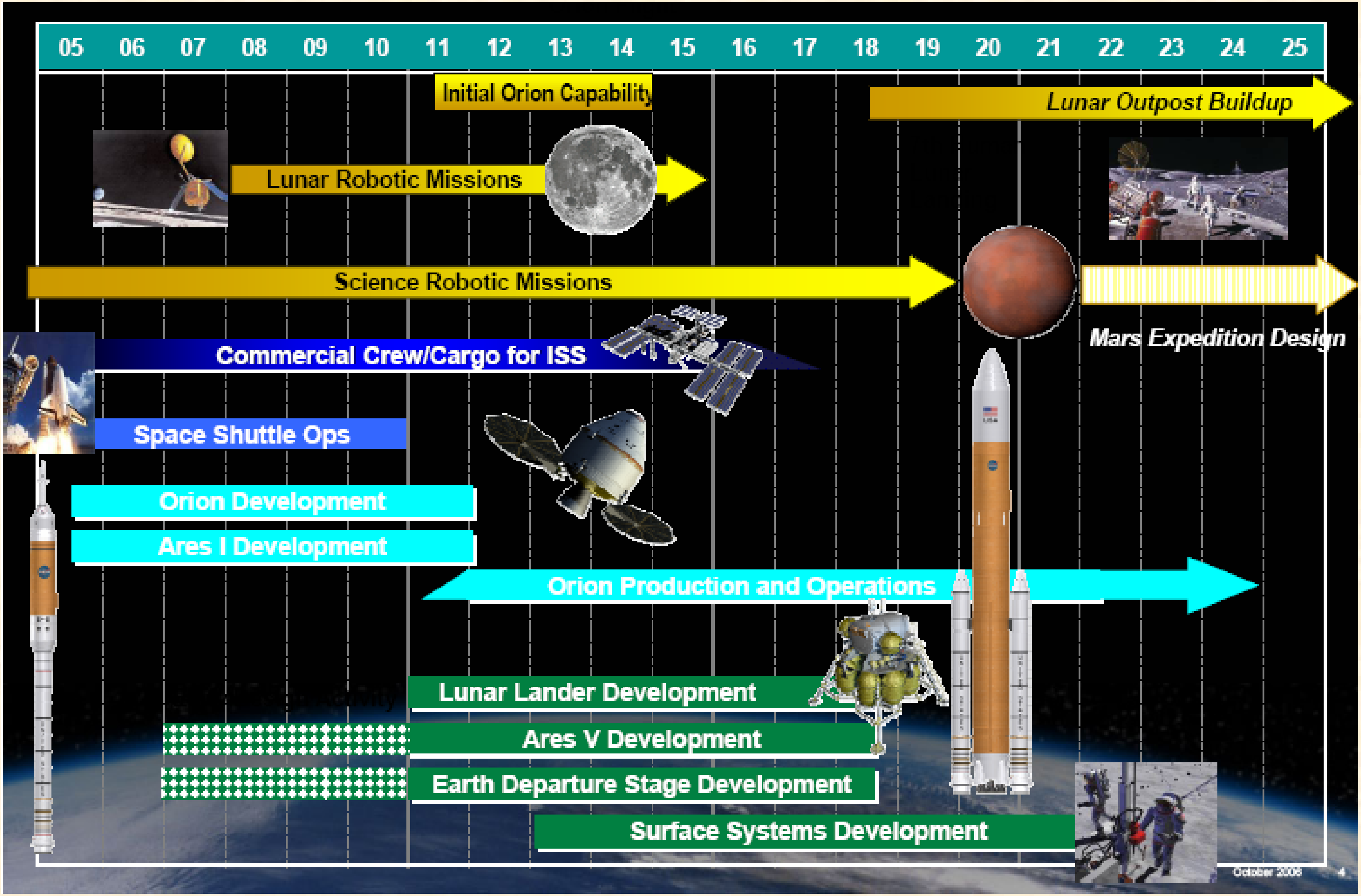
Outline

- Exploration Program
- Power Needs (Customers)
- Safety for Manned Space Missions
- Technology Programs to Achieve Safe Power Goals
- Collaborative work
- Summary and Conclusions

Exploration Program



NASA’S Exploration Roadmap



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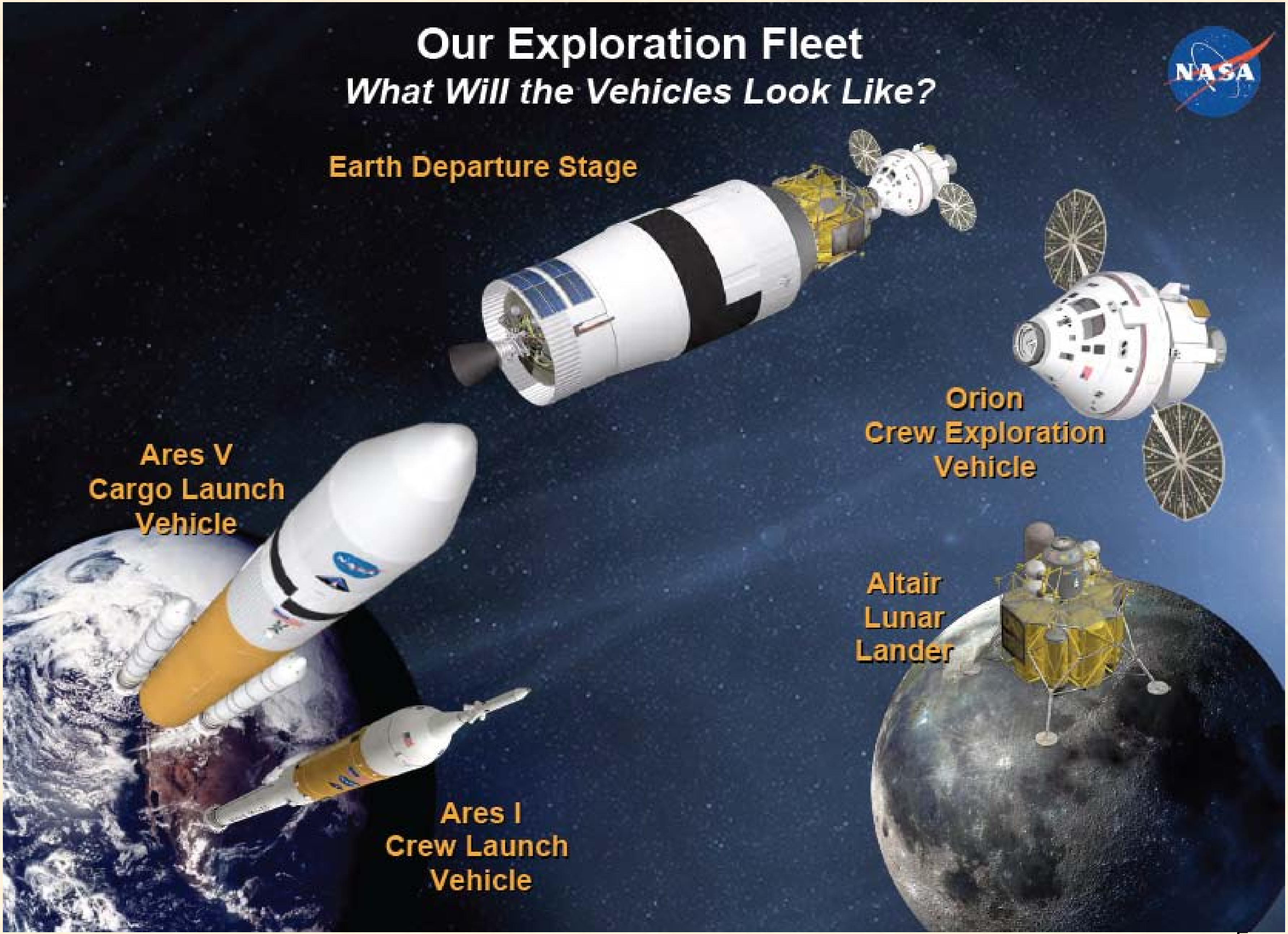
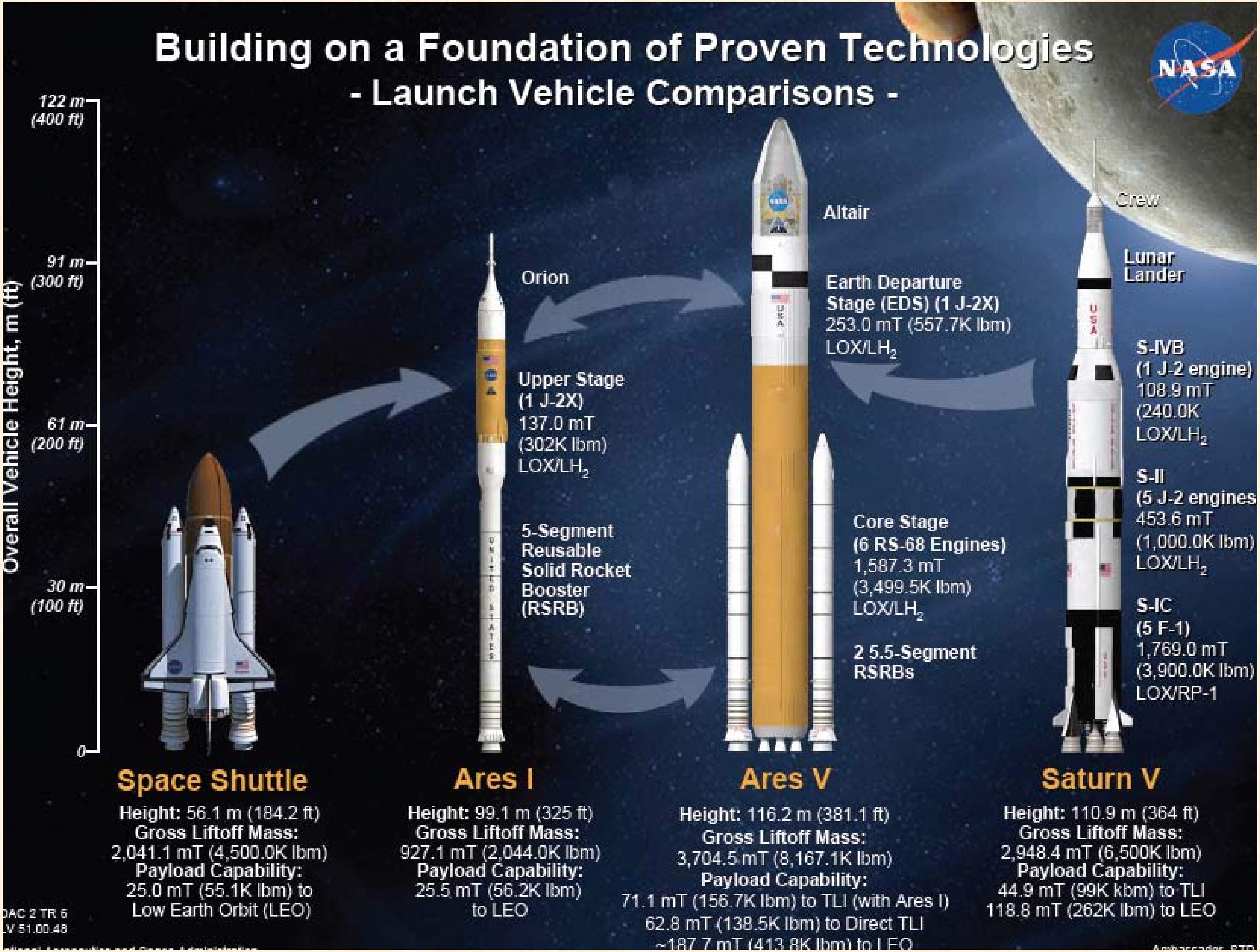

Our Exploration Fleet
What Will the Vehicles Look Like?
NASA
Earth Departure Stage
Orion
Crew Exploration
Vehicle
Ares V
Cargo Launch
Vehicle
Altair
Lunar
Lander
Ares I
Crew Launch
Vehicle



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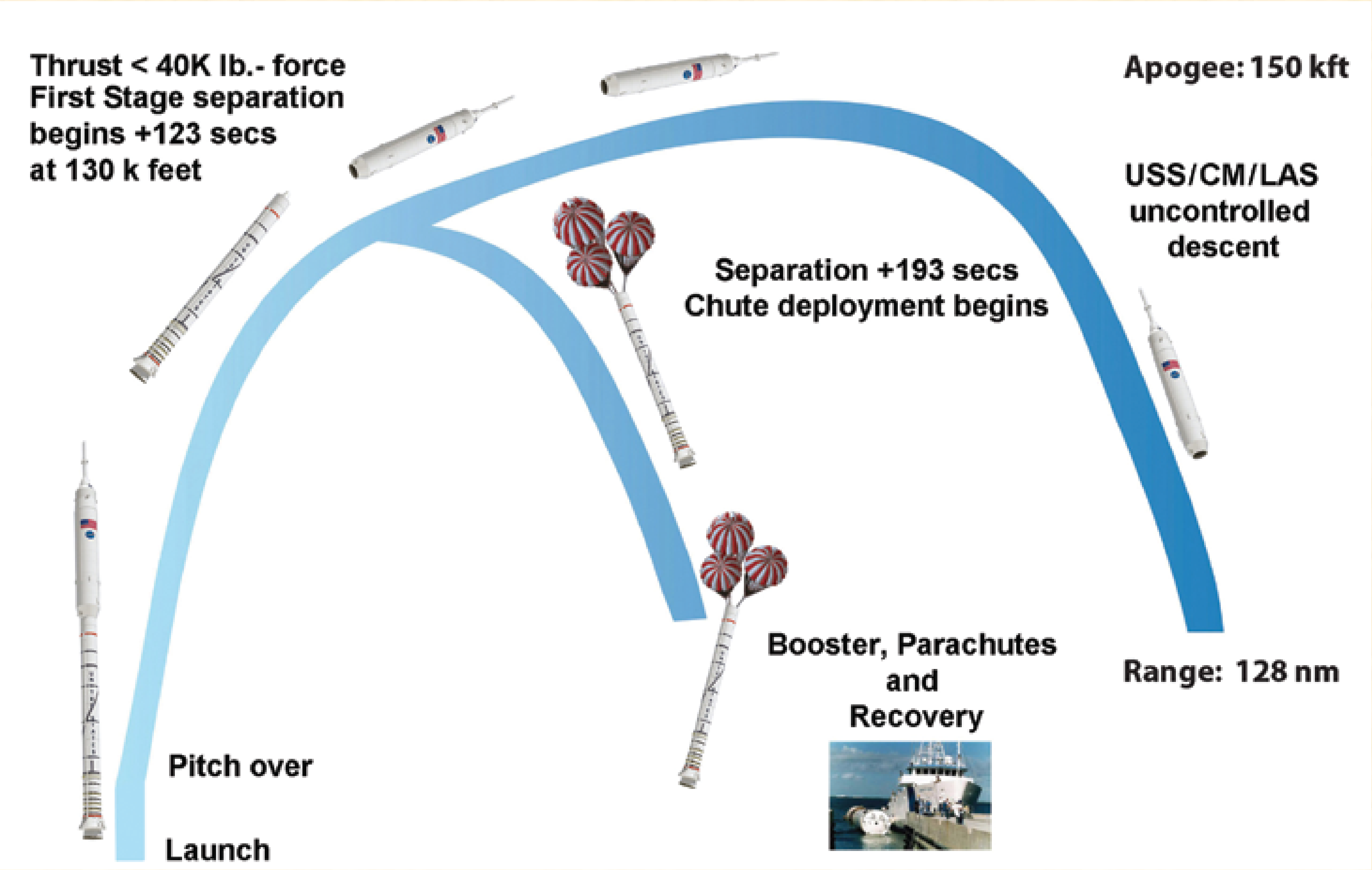
Ares 1-X

Ares 1-X



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Ares I

- Serves as the long term crew launch capability for the U.S.
- 5 Segment Shuttle Solid Rocket Booster
- New liquid oxygen / liquid hydrogen upperstage
  - J2X engine
- Large payload capability

Orion CEV and ISS

- Transport up to 6 crew members on Orion for crew rotation
- 210 day stay time
- Emergency lifeboat for entire ISS crew
- Deliver pressurized cargo for ISS resupply

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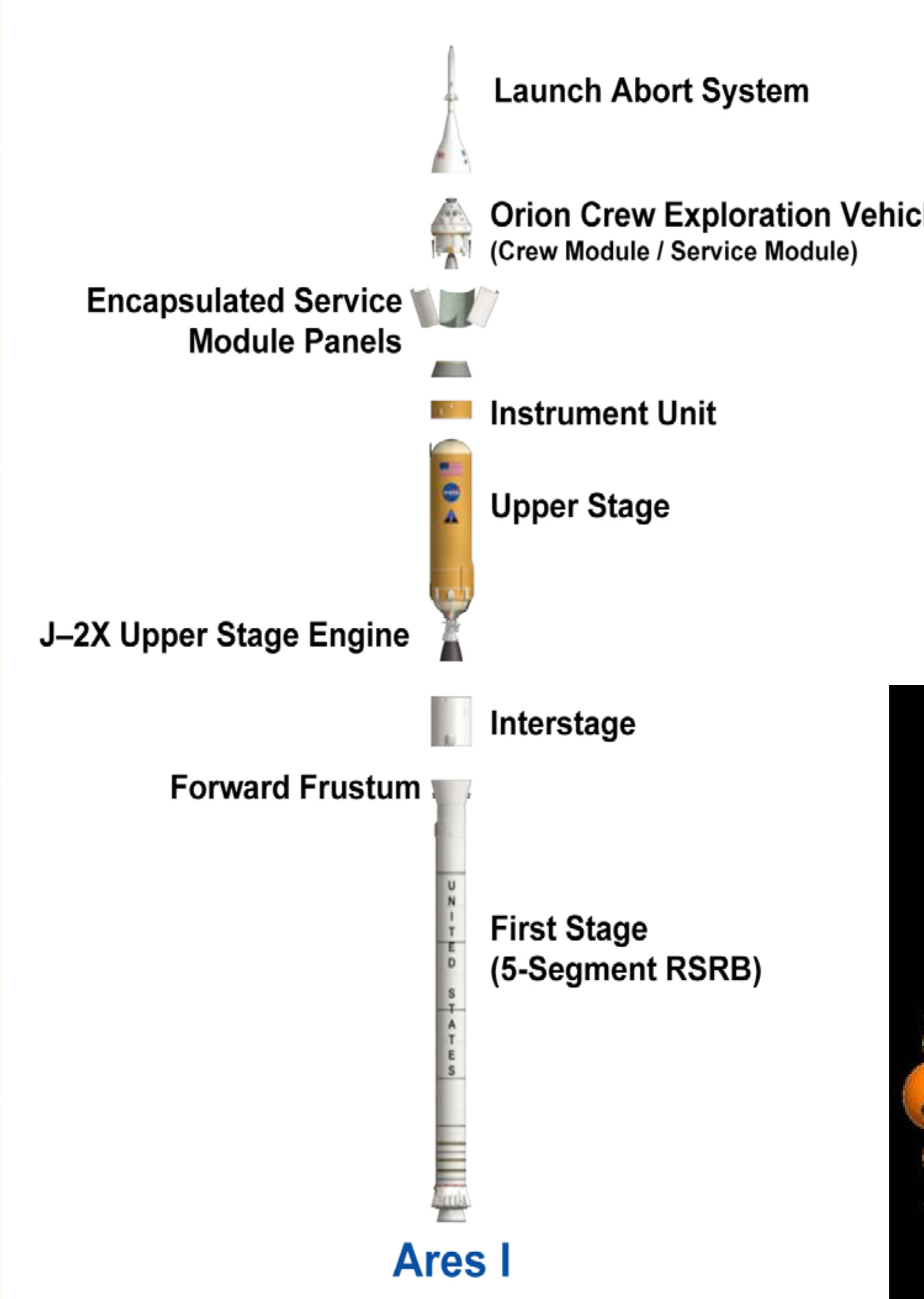
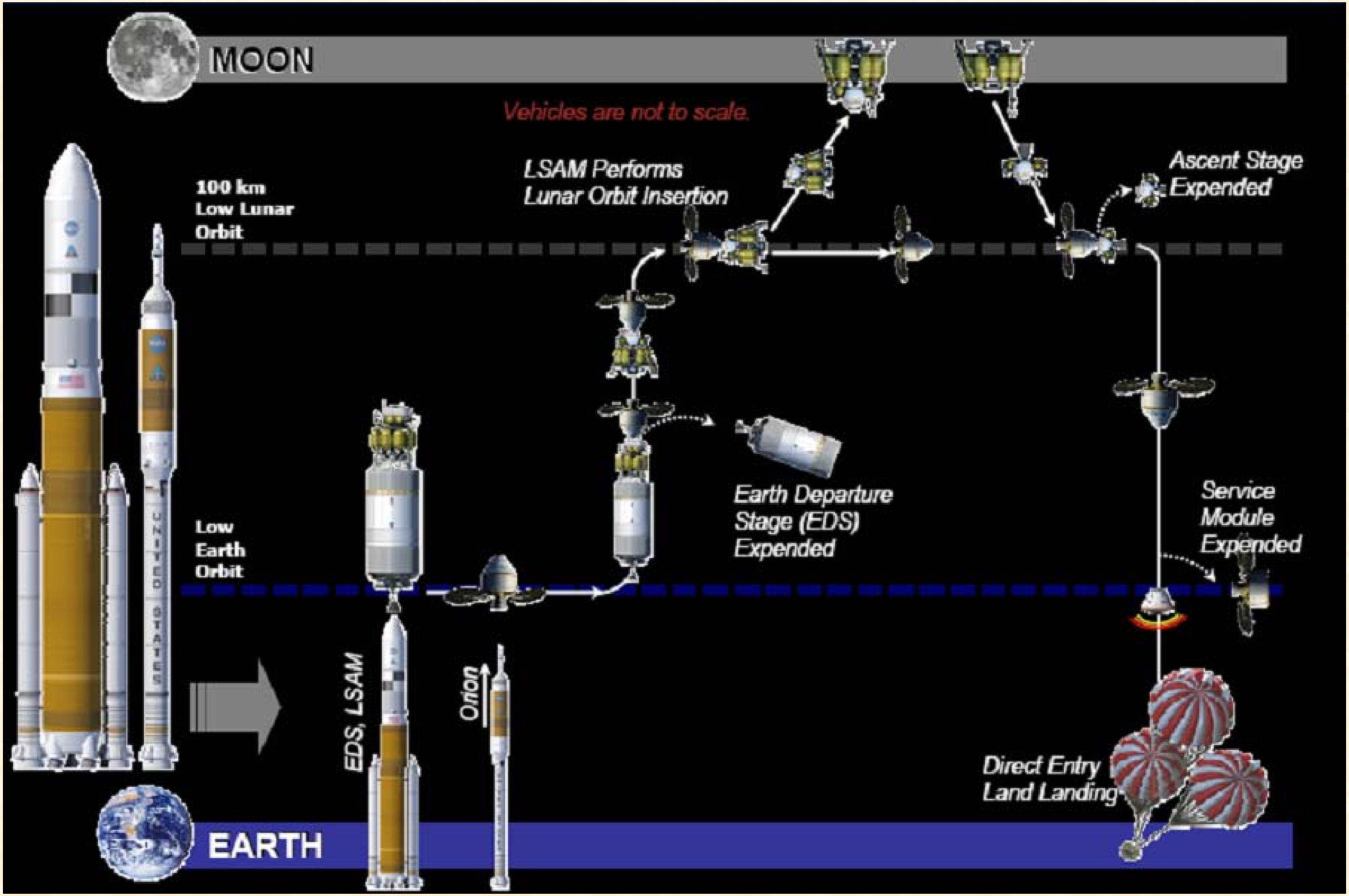

Launch Abort System
Orion Crew Exploration Vehicl
(Crew Module / Service Module)
Encapsulated Service Module Panels
Instrument Unit
Upper Stage
J–2X Upper Stage Engine
Interstage
Forward Frustum
First Stage (5-Segment RSRB)
UNITED STATES
Ares I

Typical Mission Sequence



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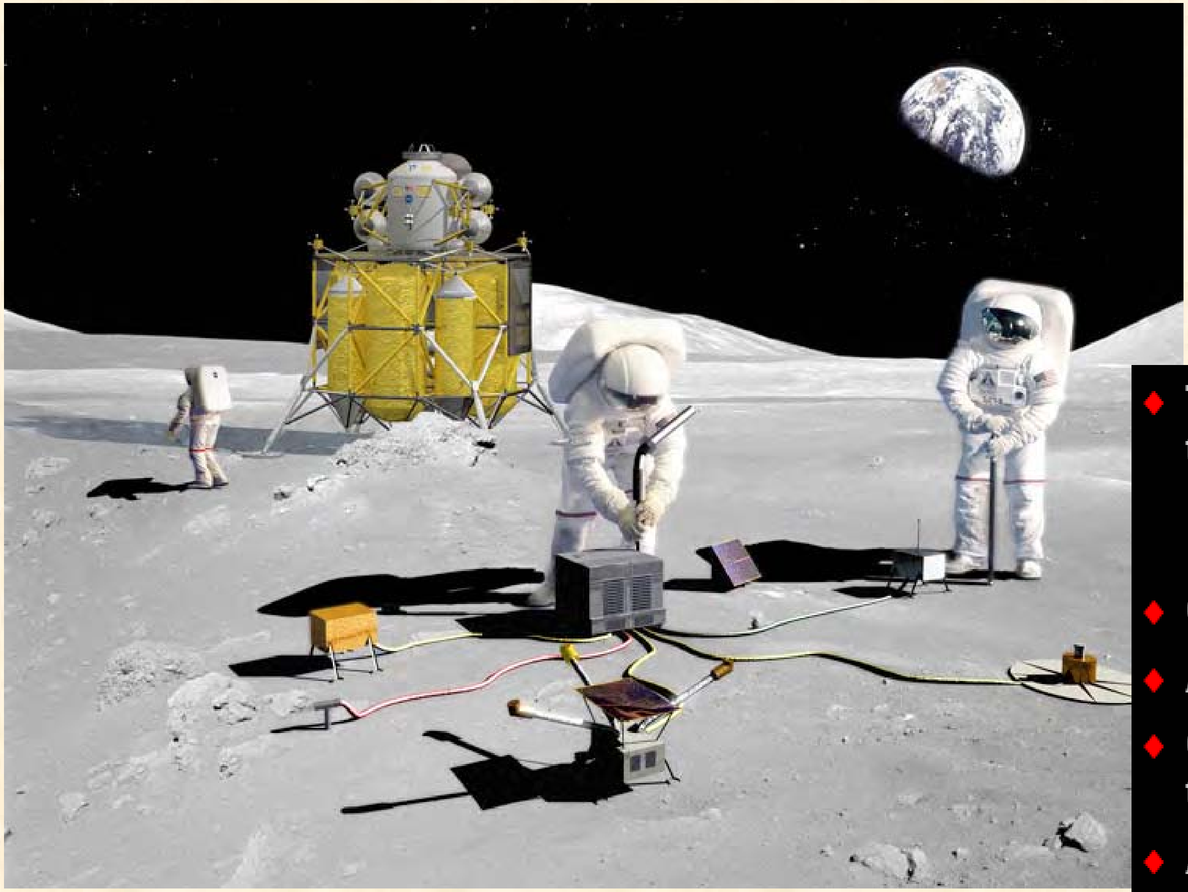
Ares V

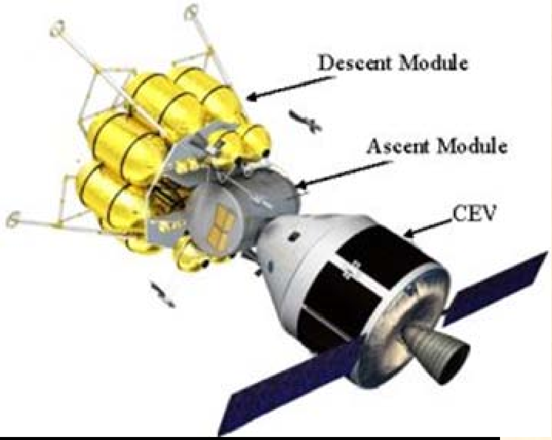
- **5 Segment Shuttle Solid Rocket Boosters**
- **Liquid Oxygen / liquid hydrogen core stage**
  - Heritage from the Shuttle External Tank
  - RS68 Main Engines
- **Payload Capability**
  - 106 metric tons to low Earth orbit
  - 131 Metric tons to low Earth orbit using Earth departure stage
  - 53 metric tons trans-lunar injection capability using Earth departure stage
- **Can be certified for crew if needed**

Ares V

Earth Departure Stage with Altair and CEV

Altair Lunar Lander

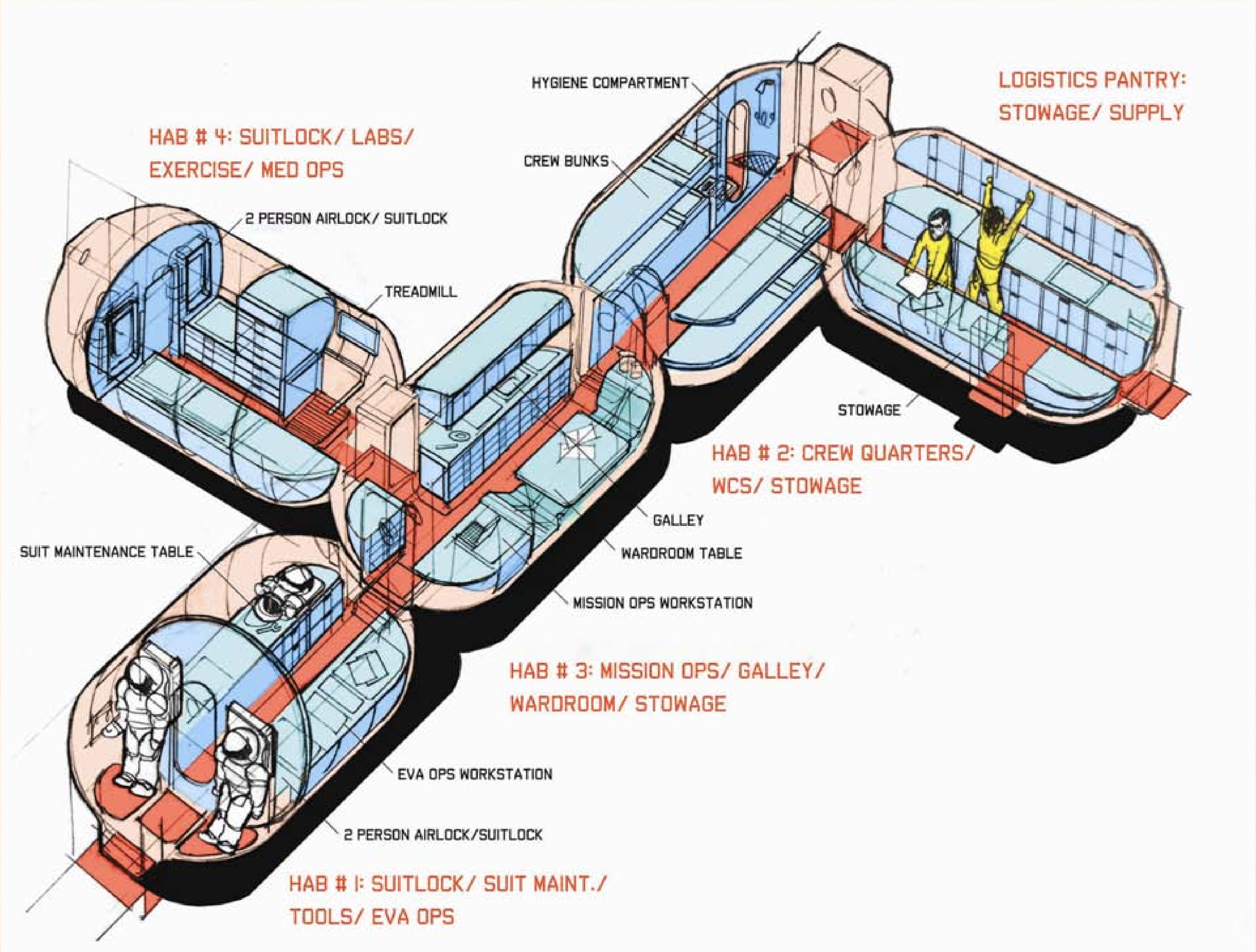




- **Transports 4 crew to and from the surface**
  - Seven days on the surface
  - Lunar outpost crew rotation
- **Global access capability**
- **Anytime return to Earth**
- **Capability to land 20 metric tons of dedicated cargo**
- **Airlock for surface activities**
- **Descent stage:**
  - Liquid oxygen / liquid hydrogen propulsion
- **Ascent stage:**
  - Storable Propellants

Lunar Mobility

Lunar Outpost



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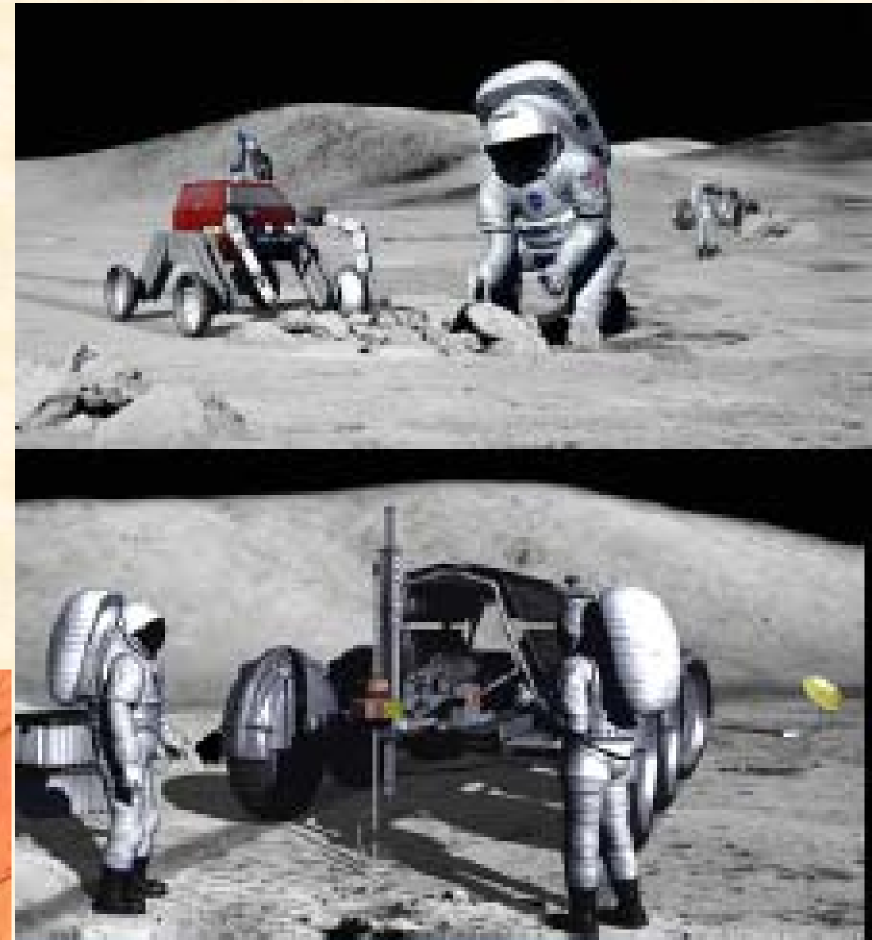
Lunar Missions

- Regaining and extending operational experience in a hostile planetary environment
- Developing capabilities needed for opening the space frontier
- Preparing for human exploration of Mars
- Science operations and discovery



Lunar Surface Systems (Mobility)
Pressurized Rover

Preliminary Power Requirements:
Safe, reliable operation
 >150 Wh/kg at battery level
 ~ 500 cycles
Operation Temp: 0 to 30 C
Maintenance-free operation

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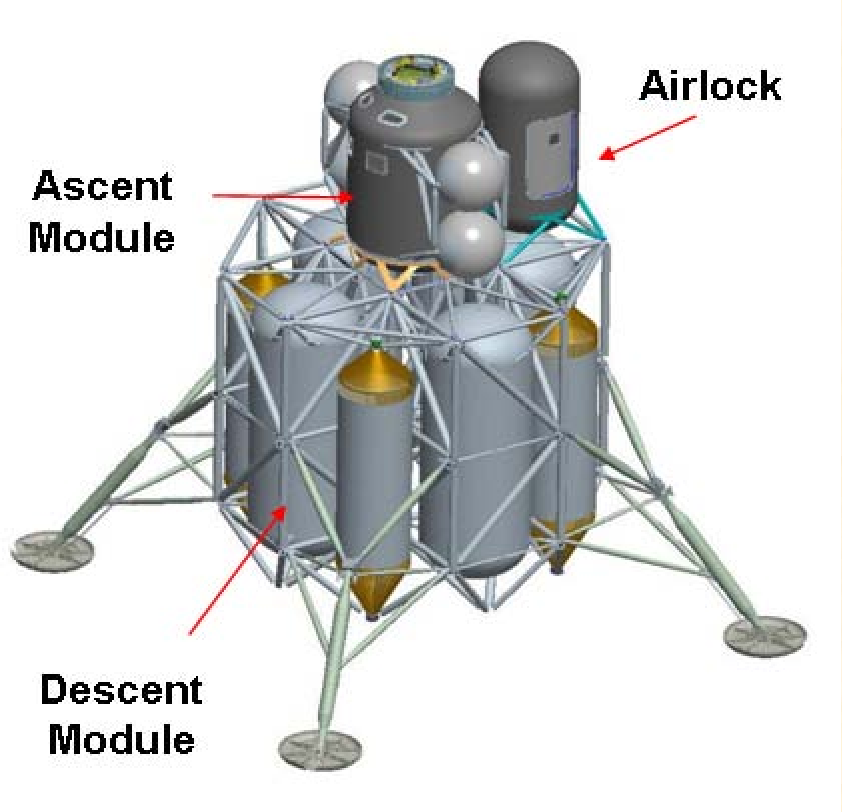
Altair Lunar Lander Ascent Module

Preliminary Power Requirements for Minimum capability (no redundancy):

- **Safe, reliable operation**
- **14 kWh energy, delivered**
- **1.67 kW average and 2 kW peak power**
- **Mass allocation: 67 kg**
- **Volume allocation: 45 liters**
- **7 hours continuous operation**
- **1 cycle**
- **Operation over 0 – 30 degrees C**
- **Operation in 0 – 1/6 G**



Ascent Stage: Batteries
(Current baseline is
Primary Lithium Battery with plan
to change to rechargeable Li-ion)
Required to provide contingency power
for descent stage and translunar
insertion; expect peak power growth;
Rechargeable provides greater ability
to test before flight.

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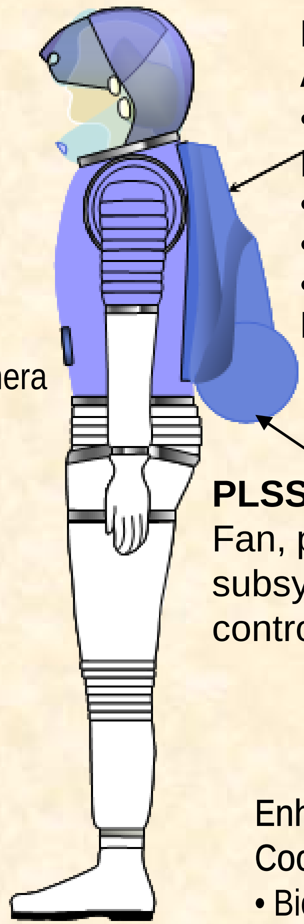
Extravehicular Activity (EVA) Suit
Lunar EVA 2nd Configuration

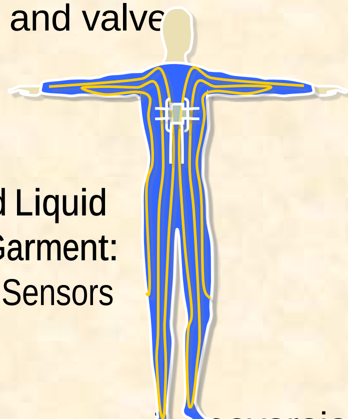
Enhanced Helmet Hardware:
- Lighting
- Heads-Up-Display
- Soft Upper Torso (SUT) Integrated Audio



Power / Communications, Avionics & Informatics (CAI):
- Cmd/Cntrl/Comm Info (C3I) Processing
- Expanded set of suit sensors
- Advanced Caution & Warning
- Displays and Productivity Enhancements

Video:
Suit Camera

PLSS:
Fan, pump, ventilation subsystem processor; Heater, controllers, and valve



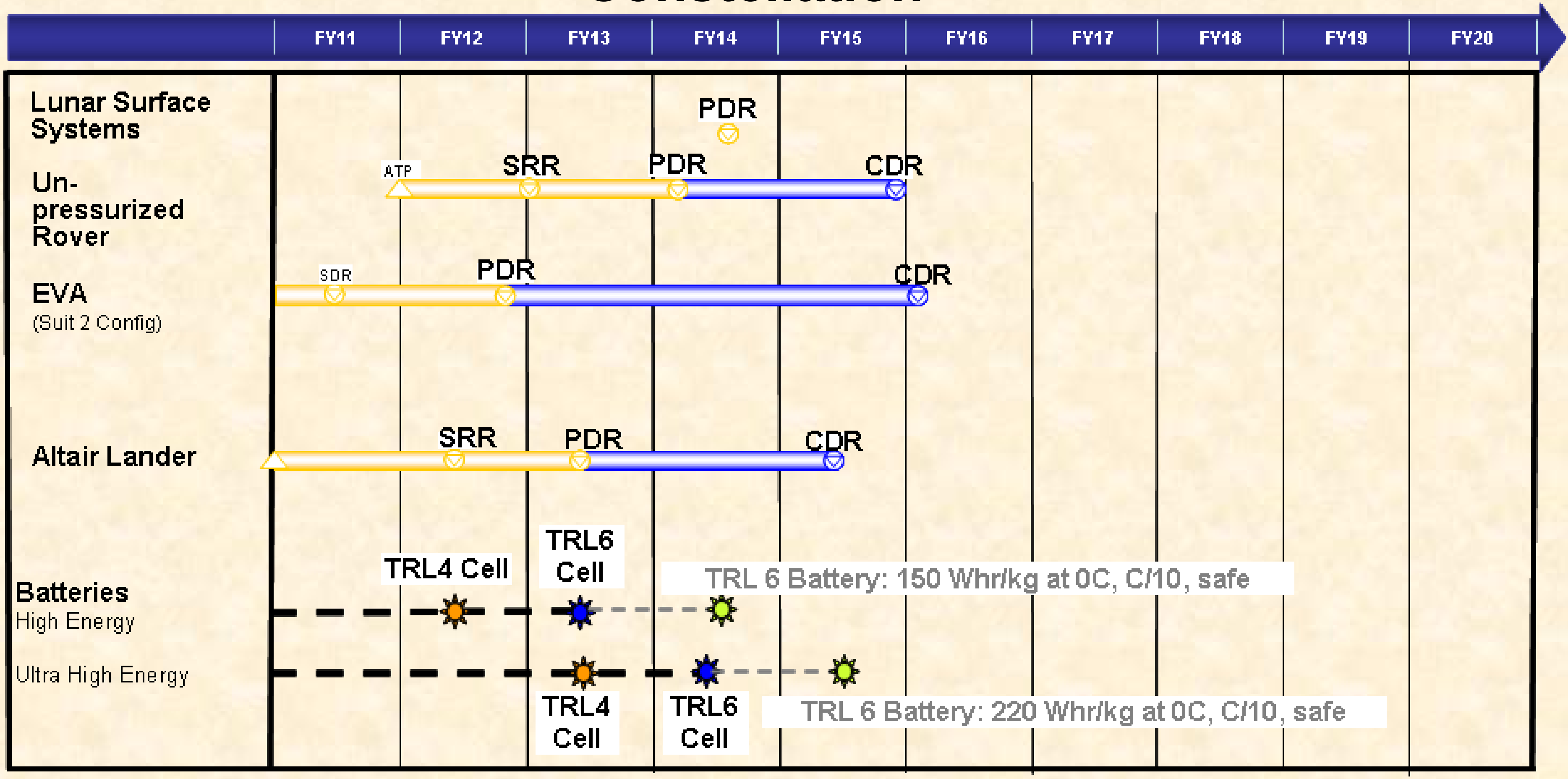
Enhanced Liquid Cooling Garment:
- Bio-Med Sensors

Preliminary Power Requirements:
- Safe, reliable operation
- 1155 Whr energy, delivered
- 145 W average and 233 W peak power
- Mass allocation: 5 kg
- Volume allocation: 1.6 liters
- 8 hour operation per sortie
- 100 cycles (operation every other day for 6 mos.)
- Operation over 0 – 30 degrees C

Current Suit Batteries:

EMU: 20.5 V; min 26.6 Ah (7 hr EVA), 9A peak, 5 yr, <15.5 lbs, 30 cycles
SAFER:42 V; 4.2 Ah (in emergency only)
REBA: 12.5 V, 15 Ah, (7 hr EVA); 5 yr, ~6 lbs
EHIP:6 V, 10.8 Ah; (7 hr EVA); 5 yr, ~1.8 lbs

Exploration Technology Development Program (ETDP) Energy Storage Battery Development Schedule for Constellation



PDR: Preliminary Design Review
CDR: Critical Design Review
SRR: System Requirements Review
TRL: Technology Readiness Level

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 <u>Lander:</u> 150 – 210 Wh/kg 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)	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 $Li(Li,NiMn)O_2$	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)	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: 311 Wh/l Rover: TBD EVA: 240 – 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 3.0 volts/cell, and at 0^0C 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 06/02/2008

ETDP Li-ion Cell Development

- **Component-level goals** are being addressed through a combination of NASA in-house materials development efforts, NASA Research Announcement contracts (NRA), and grants
- Materials developed will be delivered to NASA and screened for their electrochemical and thermal performance, and compatibility with other candidate cell components
- Other activities funded through NASA can be leveraged – NASA Small Business Innovative Research (SBIR) Program and Innovative Partnership Program (IPP)
- Leveraging off other government programs (DOD, DOE) for component-level technology
- Leveraging off other venues through Space Act Agreements (SAA) that involve partnerships with industry partners such as Exxon; non-profit organizations such as Underwriters Laboratory (UL), etc.

Safety Component Development
Led by NASA JSC (Judy Jeevarajan)

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
- Functional components designed to shut down cell in case of overcharge, over- current, or over-temperature
- Standardize safety test methodologies

Current State for Safety of Li-ion Batteries

Although the chemistry is one that can provide very high energy density at this time, it is not the safest

- NASA human-rated safety requirement is two-fault tolerance to catastrophic failures – leakage of electrolyte (toxicity hazard), fire, thermal runaway

Hazards encountered during

- Overcharge/overvoltage
- External shorts
- Repeated overdischarge with subsequent overvoltage
- High thermal environments
- Internal Shorts

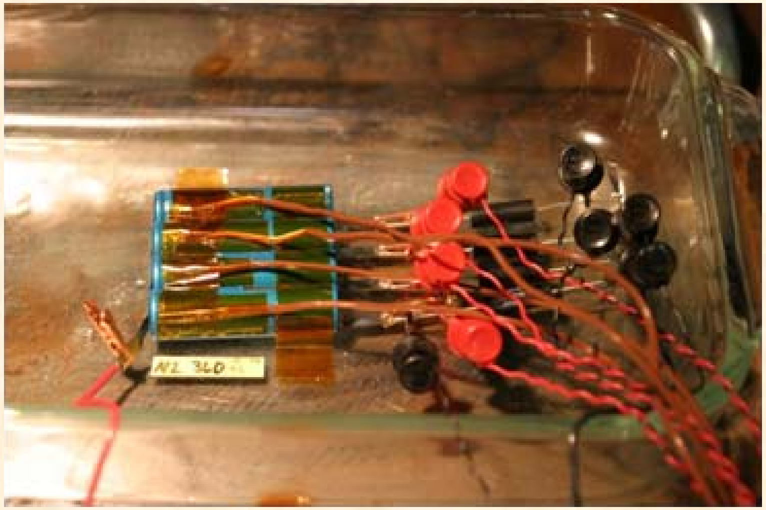
Overcharge of Battery Module

[redacted]

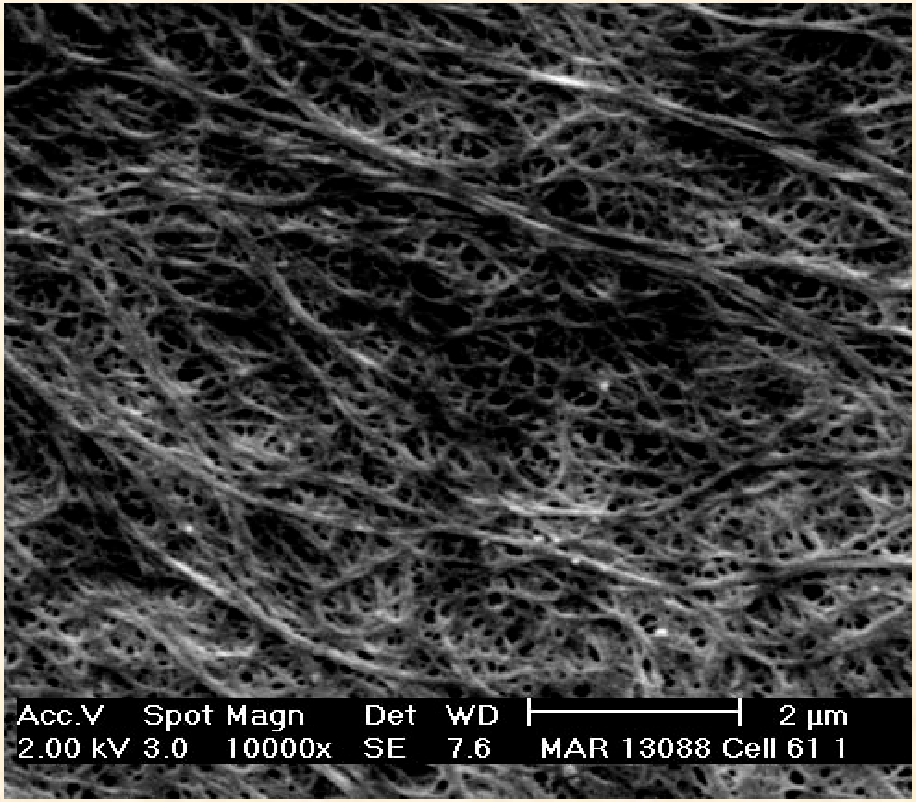
Charge: C/5
To 4.4 V/Cell
Overcharge limit: 5.5 V/Cell
Thermal runaway after 4.8 V/Cell
Highest temp Observed before thermal runaway: 248 ºC

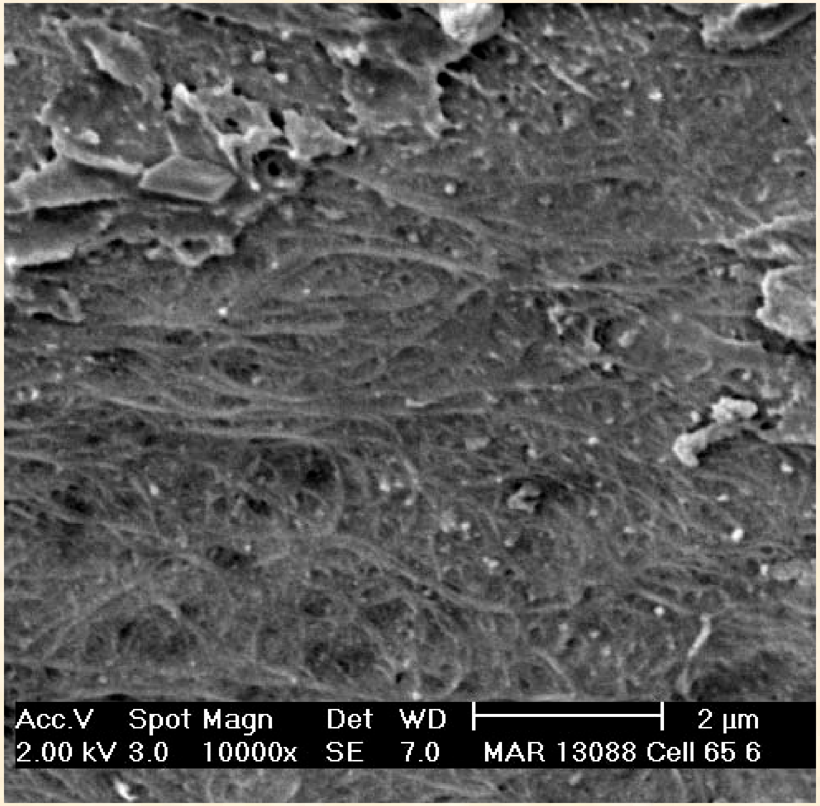
41S 5P

Overcharge of Li-ion Cell Module



Current Separators in Commercial-off-the-Shelf Li-ion Cells

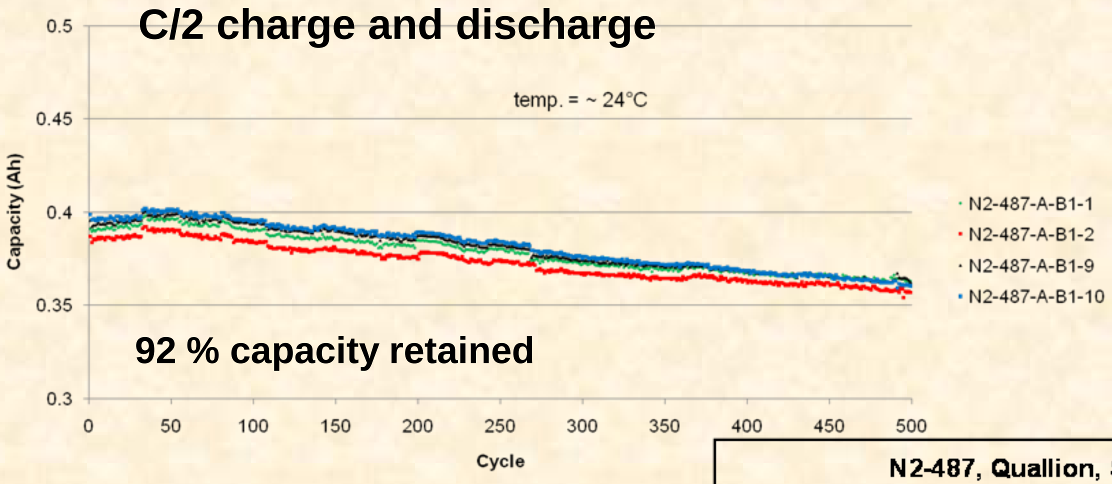


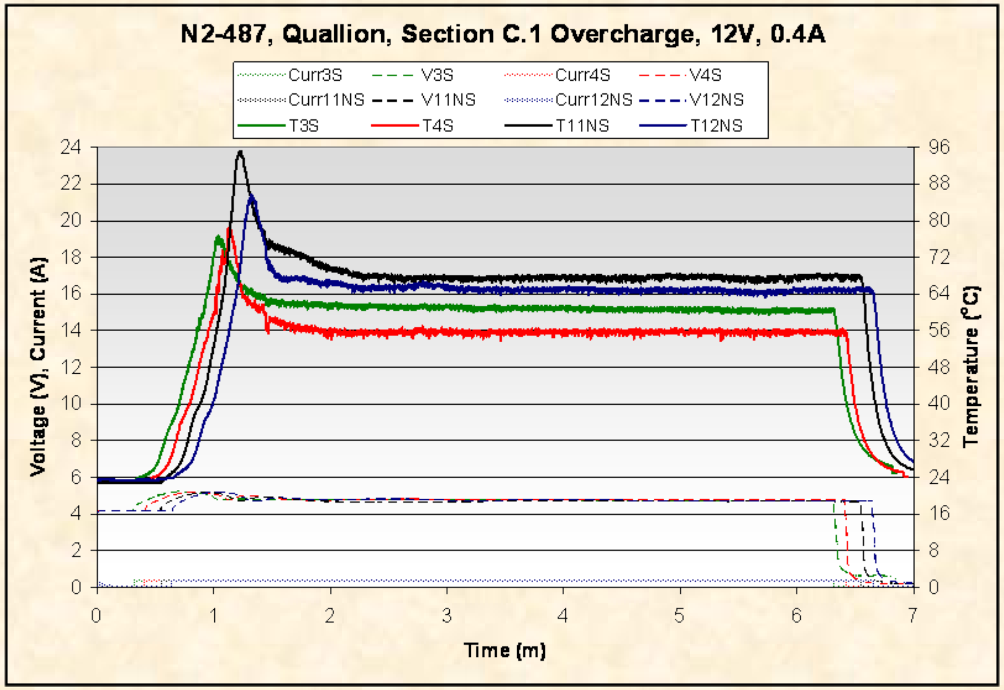


Unactivated Separator **Activated Separator**

Shut-down temperature is very close to temperature at which initiation of thermal runaway occurs.

SafeLyte® Additive (IPP)





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Composite Thermal Switch (SBIR)

Now: 2009 ETDP NRA (NASA Research Announcement)

Giner Inc.

Development and demonstration of a composite thermal switch for lithium-ion and lithium primary batteries to increase the safety of these batteries by an increase in resistance at high temperatures.

Coating for Improved Cathode Safety (2009 ETDP NRA)

Physical Sciences Inc.

Development and demonstration of a nanomaterial coating over the traditional cathode particles to improve performance and safety.

Screening for Internal Shorts

- NASA –JSC uses vibration method for screening against cell internal shorts.
- Other methods used that can provide screening for internal shorts are X-rays and CT scans.
- NASA-JSC also uses a crush test method for determining the tolerance of a cell chemistry /design to internal shorts.
- Foresee collaboration with UL in the near future to standardize the method for determining tolerance of li-ion cells to internal shorts.

Summary

- Exciting Future Programs ahead for NASA
- Power is needed for all Exploration vehicles and for the missions.
- For long term missions as in Lunar and Mars programs, safe, high energy/ultra high energy batteries are required.
- Safety is top priority for human-rated missions
  - Two-fault tolerance to catastrophic failures is required for human-rated safety
- To meet power safety goals - inherent cell safety may be required; it can lessen complexity of external protective electronics and prevents dependency on hardware that may also have limitations.
- Inherent cell safety will eliminate the need to carry out screening of all cells (X-rays, vibration, etc.)

Acknowledgment

Exploration Program photos and information – courtesy of NASA Publications and Presentations; NASA Ambassador packages