Power Goals for NASA's Exploration Program

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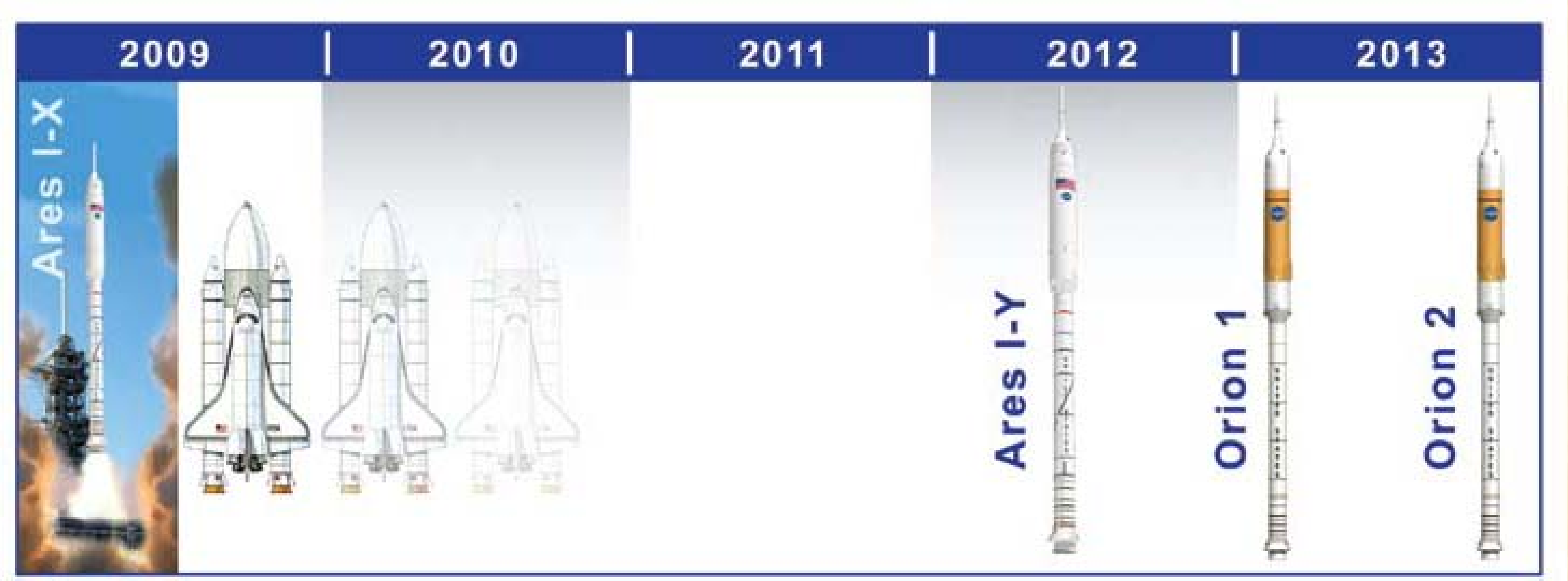
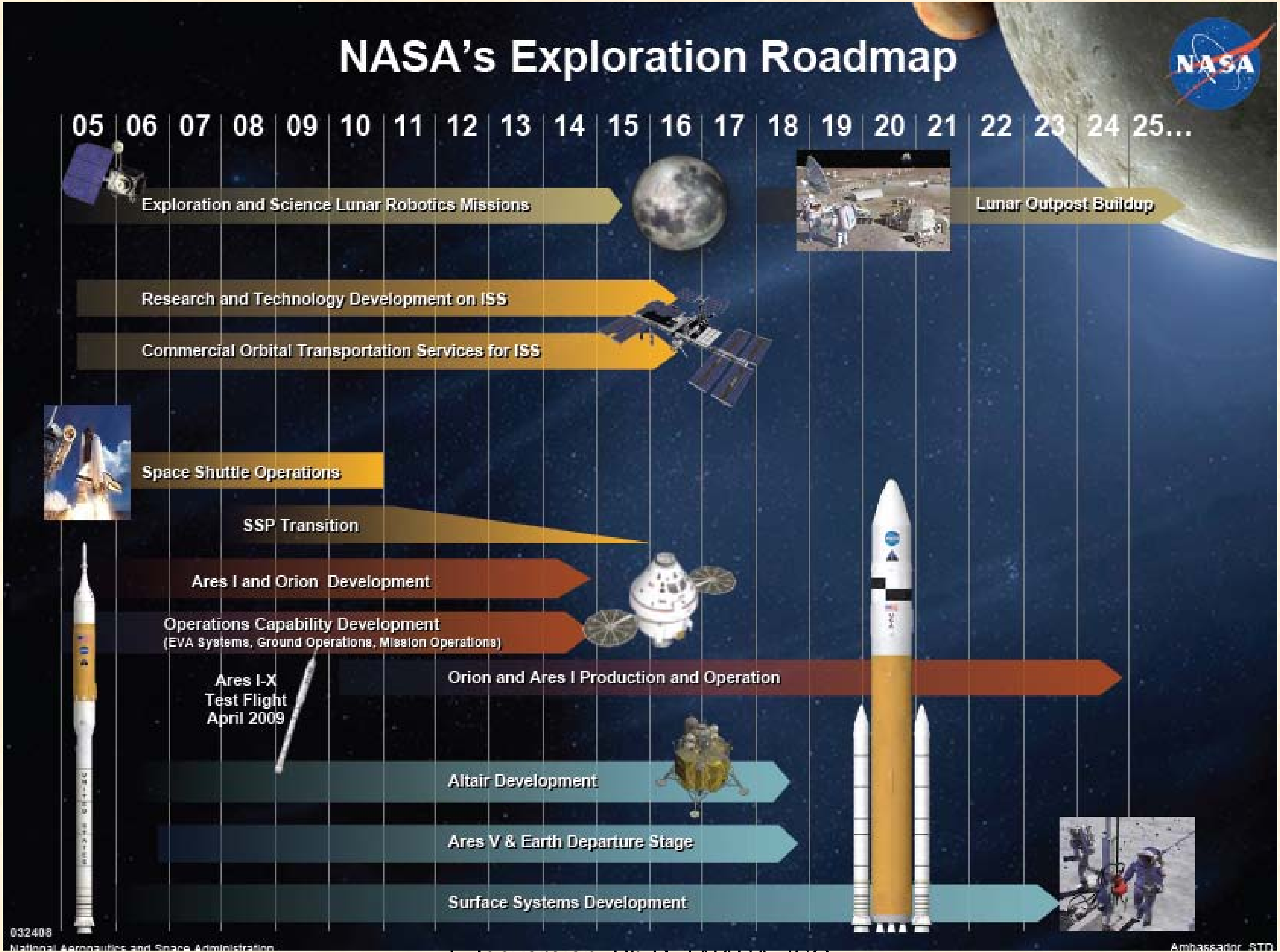
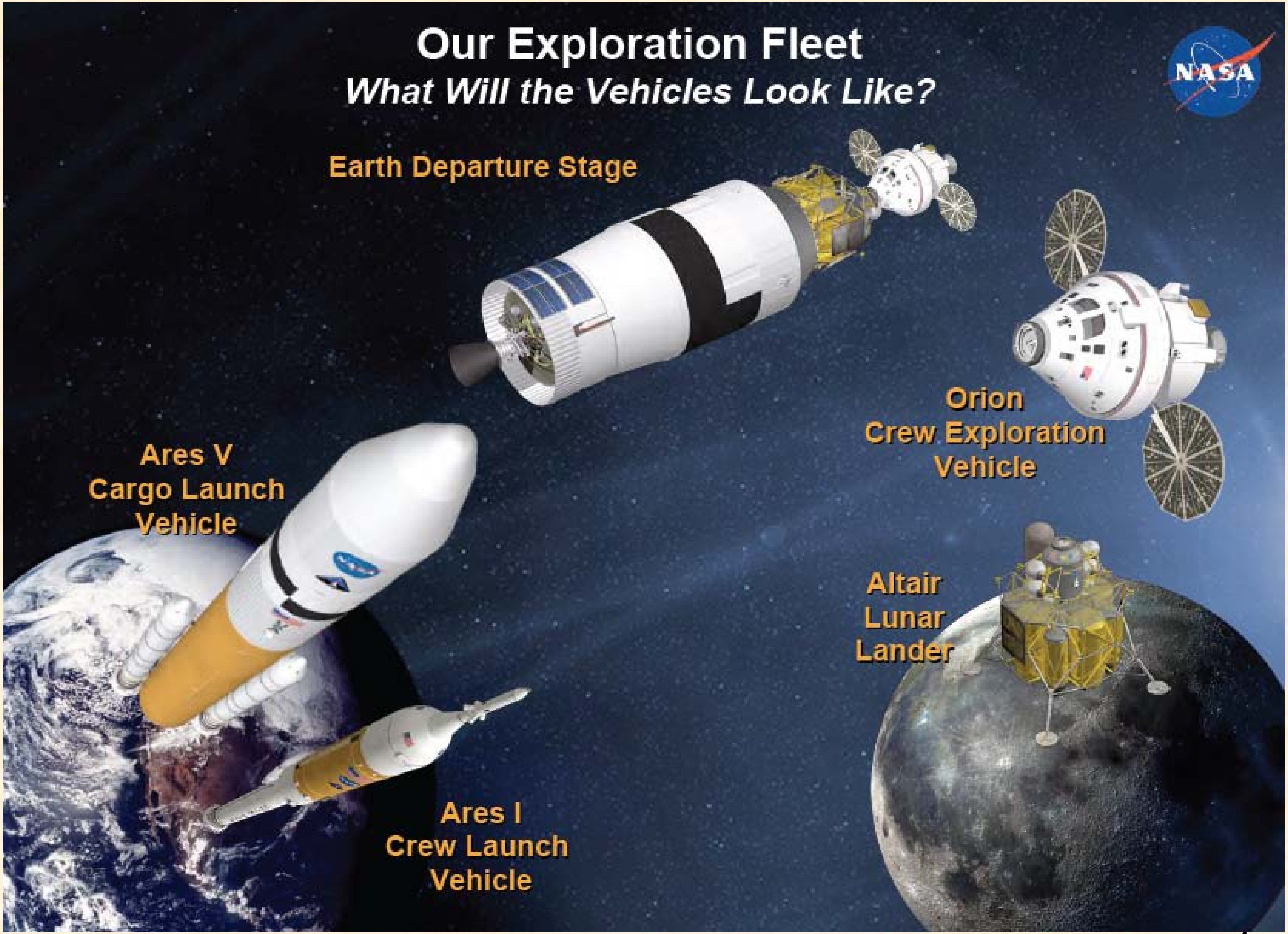
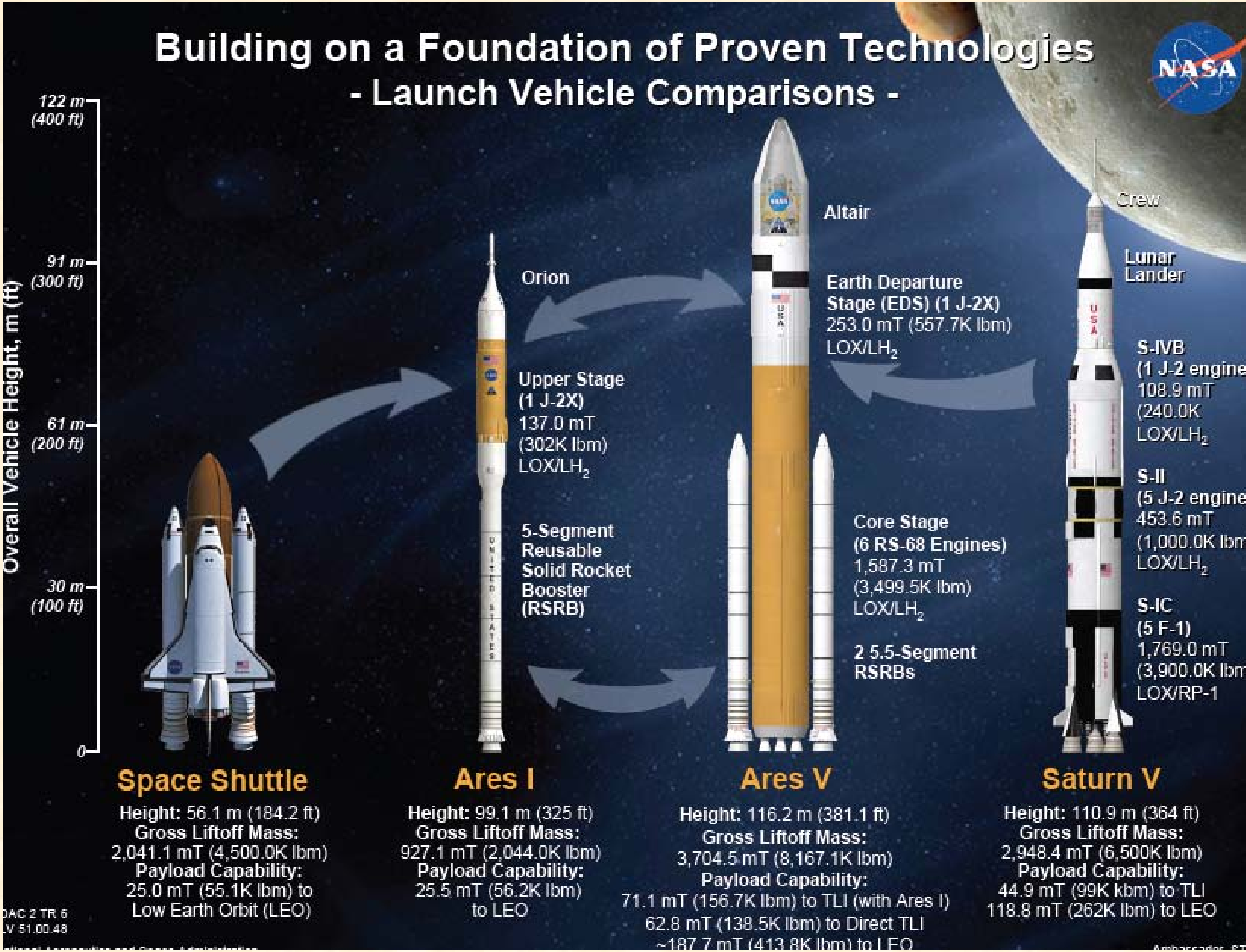
Exploration Program




NASA's Exploration Roadmap
NASA
05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25…
Exploration and Science Lunar Robotics Missions
Lunar Outpost Buildup
Research and Technology Development on ISS
Commercial Orbital Transportation Services for ISS
Space Shuttle Operations
SSP Transition
Ares I and Orion Development
Operations Capability Development
(EVA Systems, Ground Operations, Mission Operations)
Ares I-X
Test Flight
April 2009
Orion and Ares I Production and Operation
Altair Development
Ares V & Earth Departure Stage
Surface Systems Development
032408
National Aeronautics and Space Administration
Ambassador STD


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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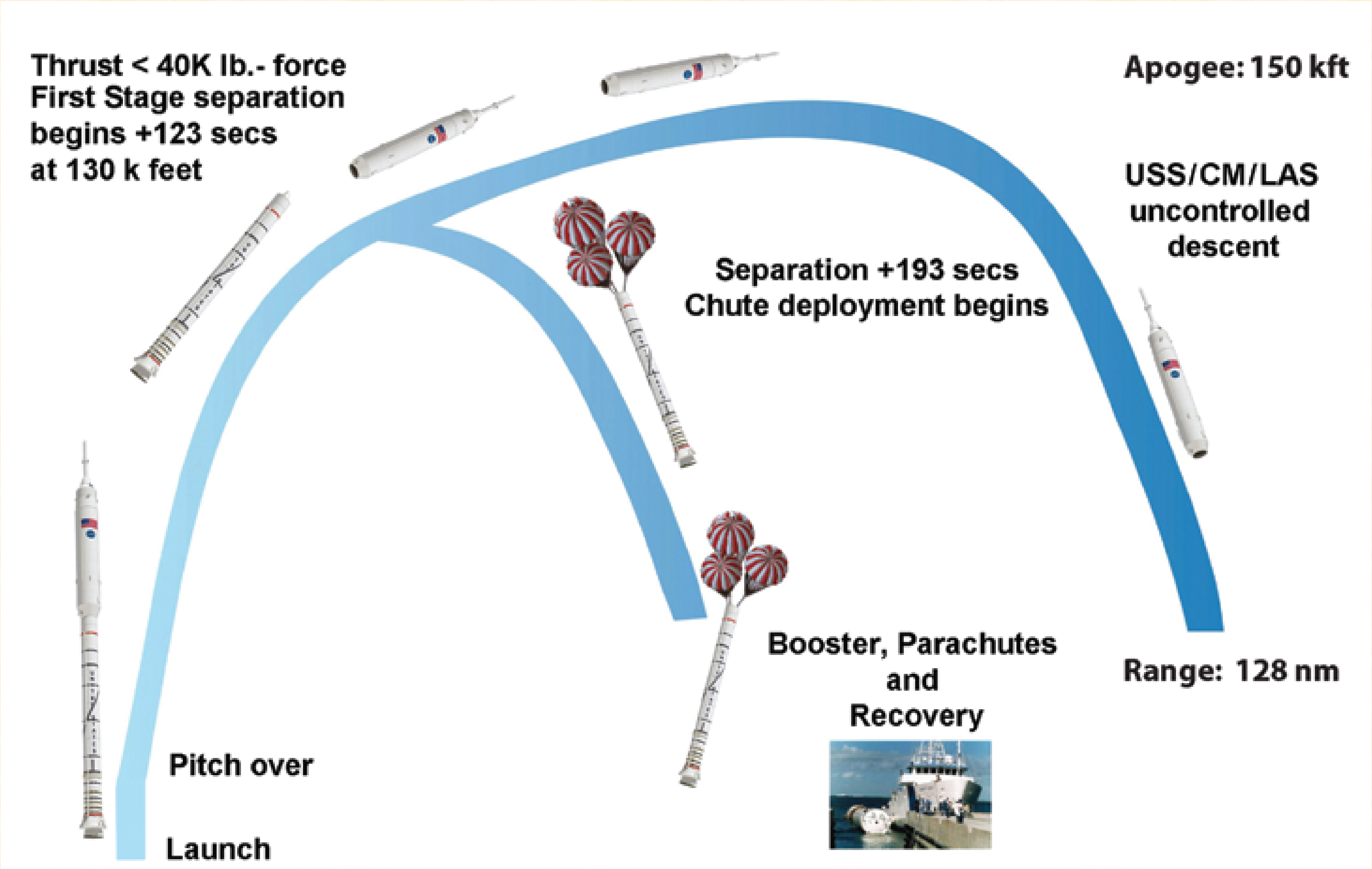
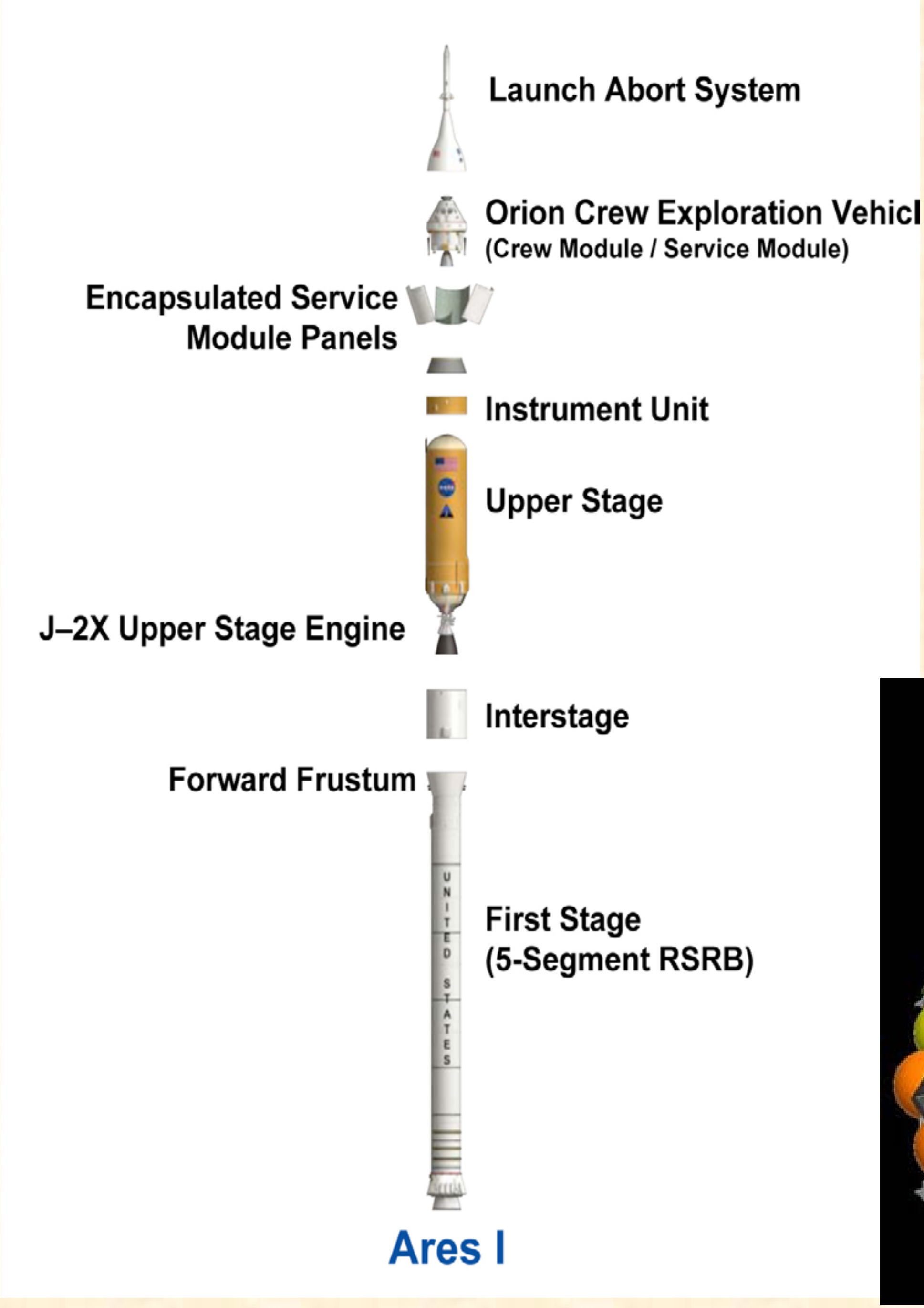
Ares 1-X

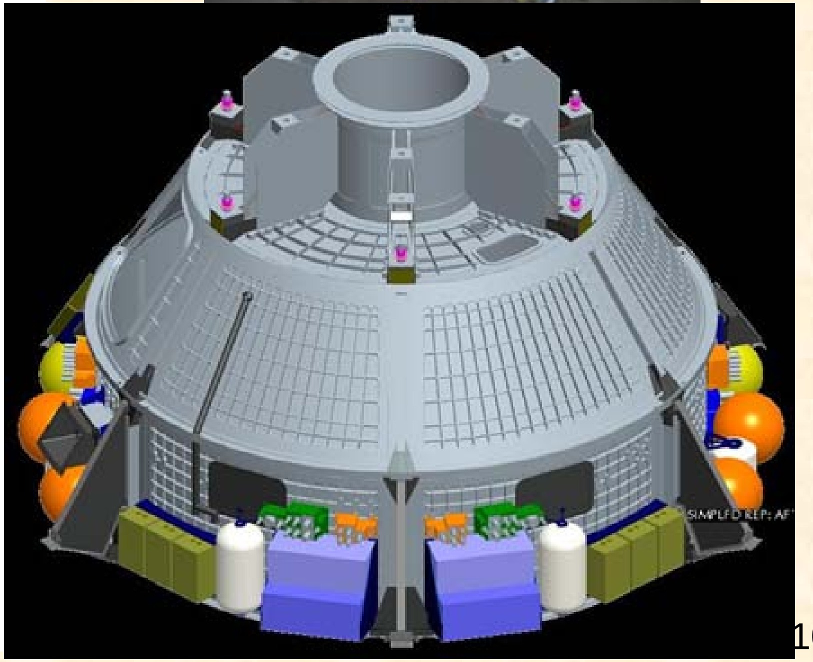
Ares 1-X


Thrust < 40K lb.- force
First Stage separation
begins +123 secs
at 130 k feet
Apogee: 150 kft
USS/CM/LAS
uncontrolled
descent
Separation +193 secs
Chute deployment begins
Booster, Parachutes
and
Recovery
Range: 128 nm
Pitch over
Launch

Ares I

Orion CEV and ISS


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
UNITED STATES
First Stage
(5-Segment RSRB)
Ares I

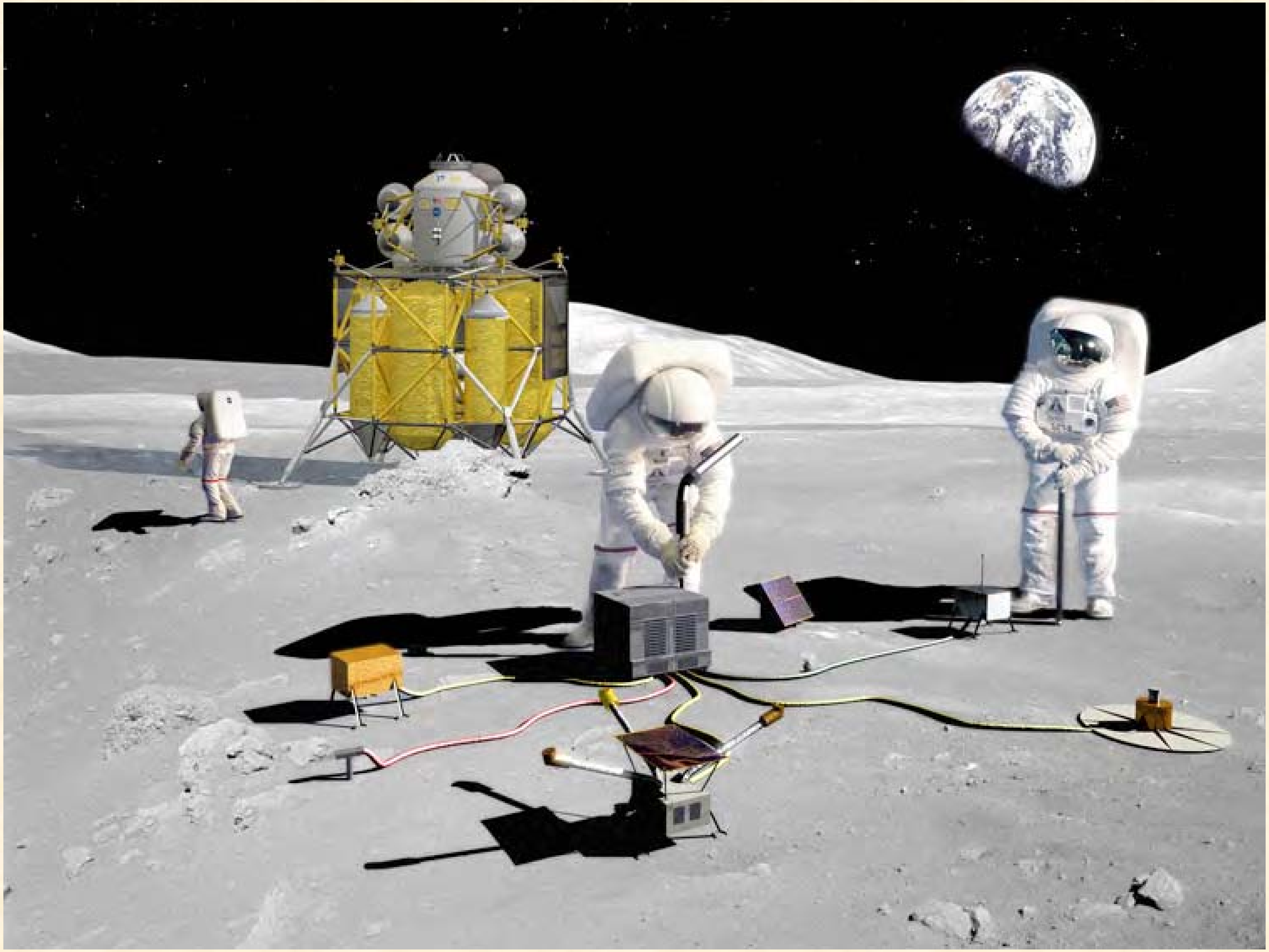


Ares V

Ares V

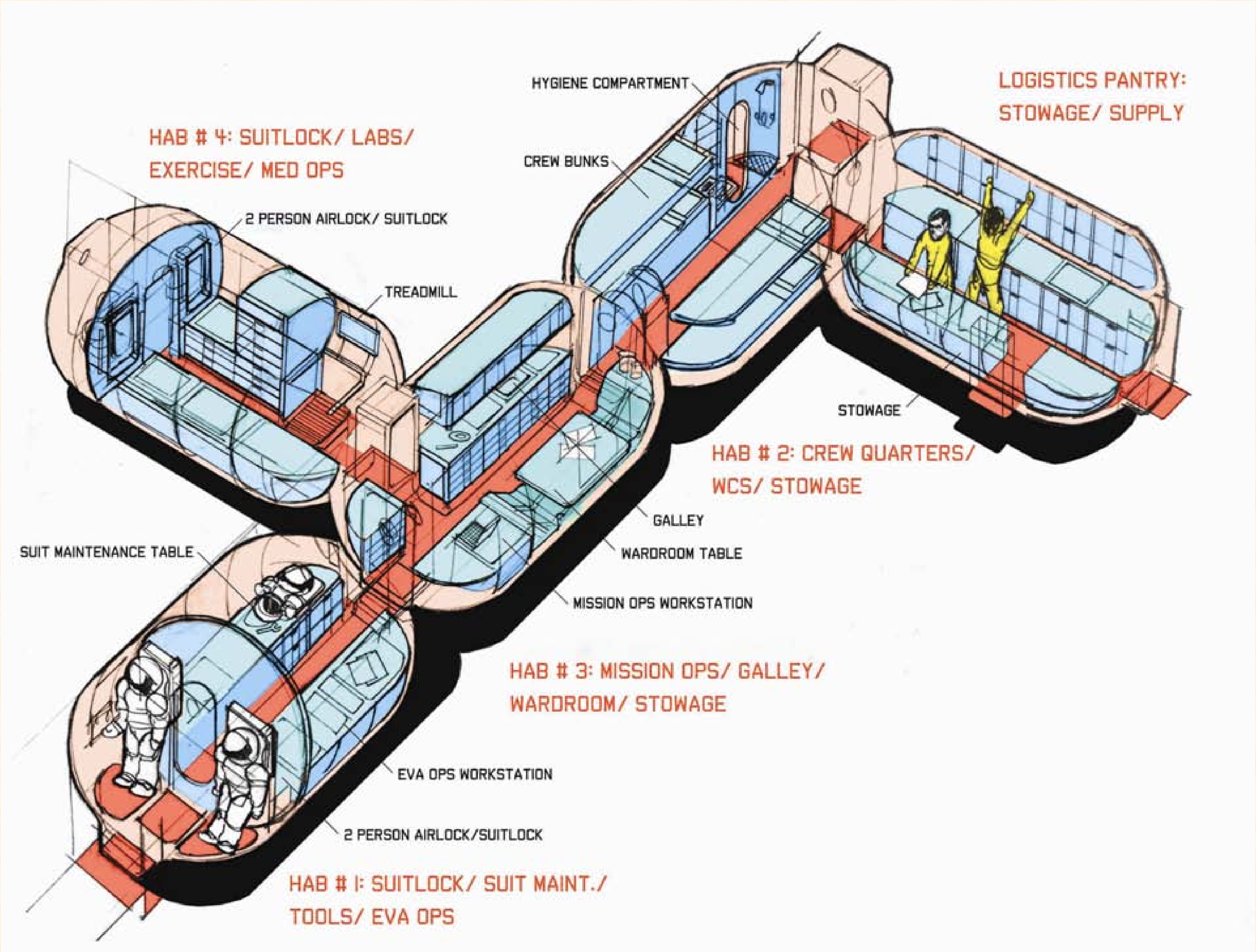

Composite Payload Shroud
Altair Lunar Lander
Earth Departure Stage
LOx/LH_2
1 J-2X Engine
Al-Li Tanks
Composite Structures
Loiter Skirt
Composite Interstage
Core Stage
LOx/LH_2
6 RS-68B Engines
Al-Li Tanks
Composite Structures
2 5.5-Segment RSRBs

Altair Lunar Lander



Lunar Mobility

Lunar Outpost



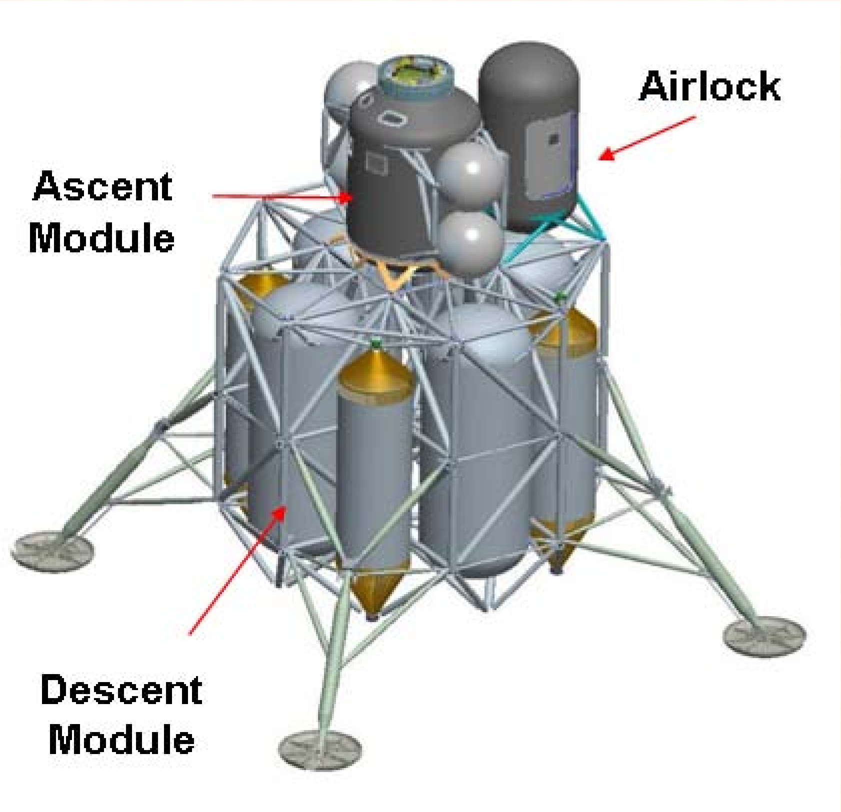
Lunar Surface Systems (Mobility)
Pressurized Rover

Preliminary Power Requirements:
Safe, reliable operation
>150 Wh/kg at battery level
> 100 cycles
Operation Temp: 0 to 30 C
Maintenance-free operation

Altair Lunar Lander Ascent Module

Preliminary Power Requirements for Minimum capability (no redundancy):

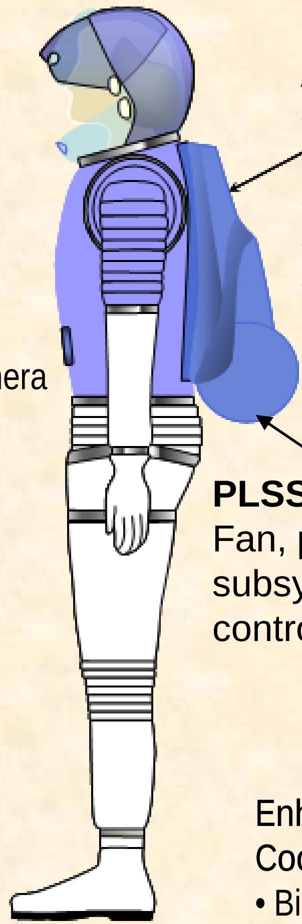
- **Safe, reliable operation**
- **14 kWh energy, delivered**
- **1.67 kW average and 2 kW peak power**
- **Mass allocation: 67 kg**
- **Volume allocation: 45 liters**
- **7 hours continuous operation**
- **1 cycle**
- **Operation over 0 – 30 degrees C**
- **Operation in 0 – 1/6 G**



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.

Extravehicular Activity (EVA) Suit
Lunar EVA 2nd Configuration

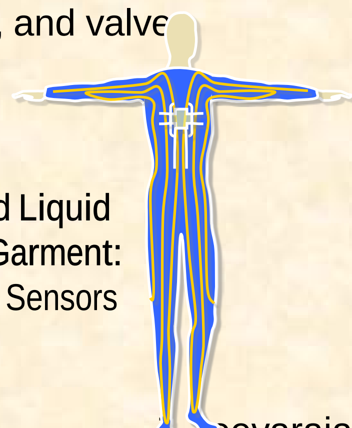
Enhanced Helmet Hardware:
- Lighting
- Heads-Up-Display
- Soft Upper Torso (SUT) Integrated Audio



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:

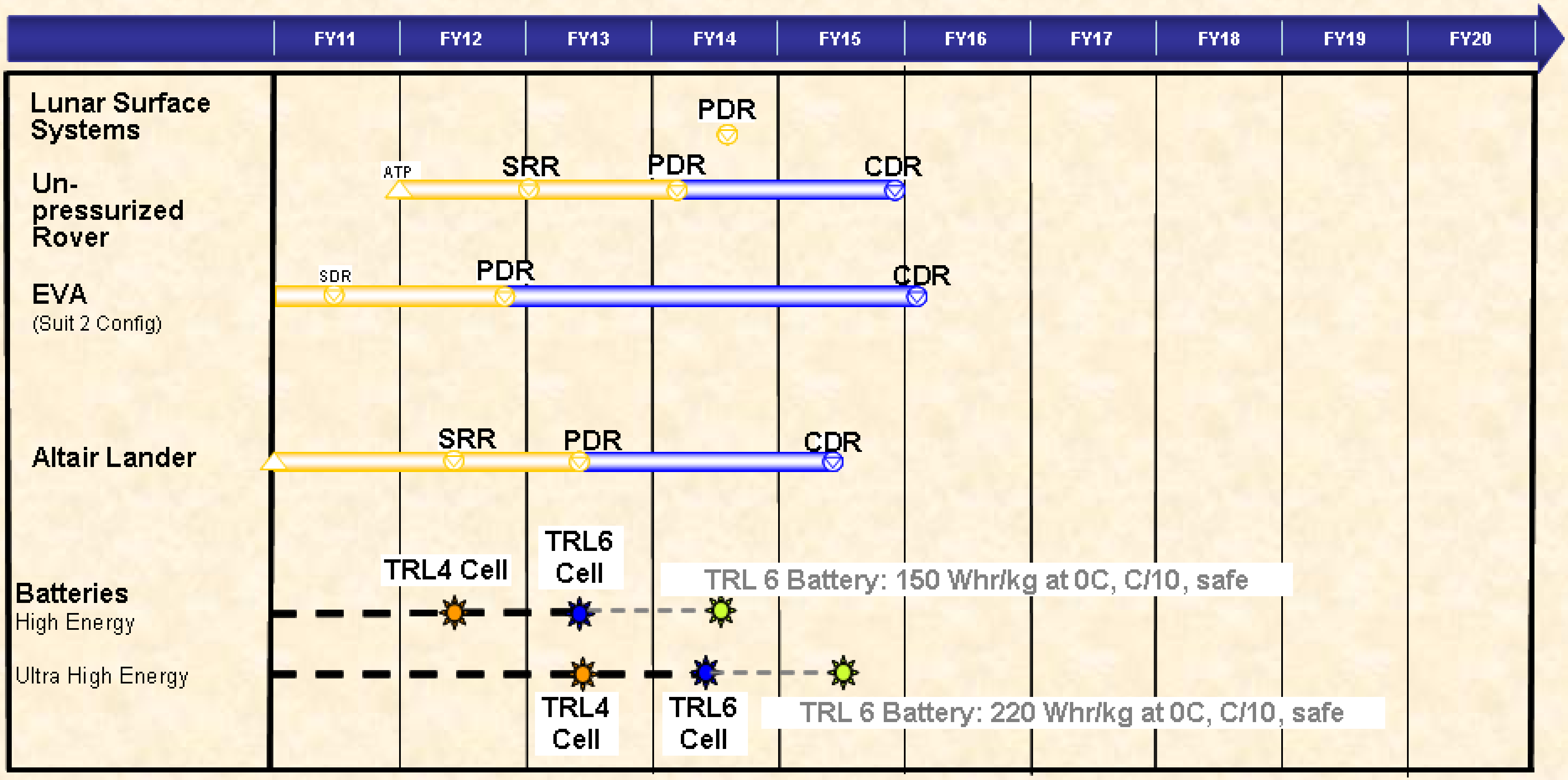
EMU: 20.5 V; min 26.6 Ah (7 hr EVA), 9A peak, 5 yr, <15.5 lbs, 30 cycles

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

Energy Storage Battery Development Schedule for Constellation



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.

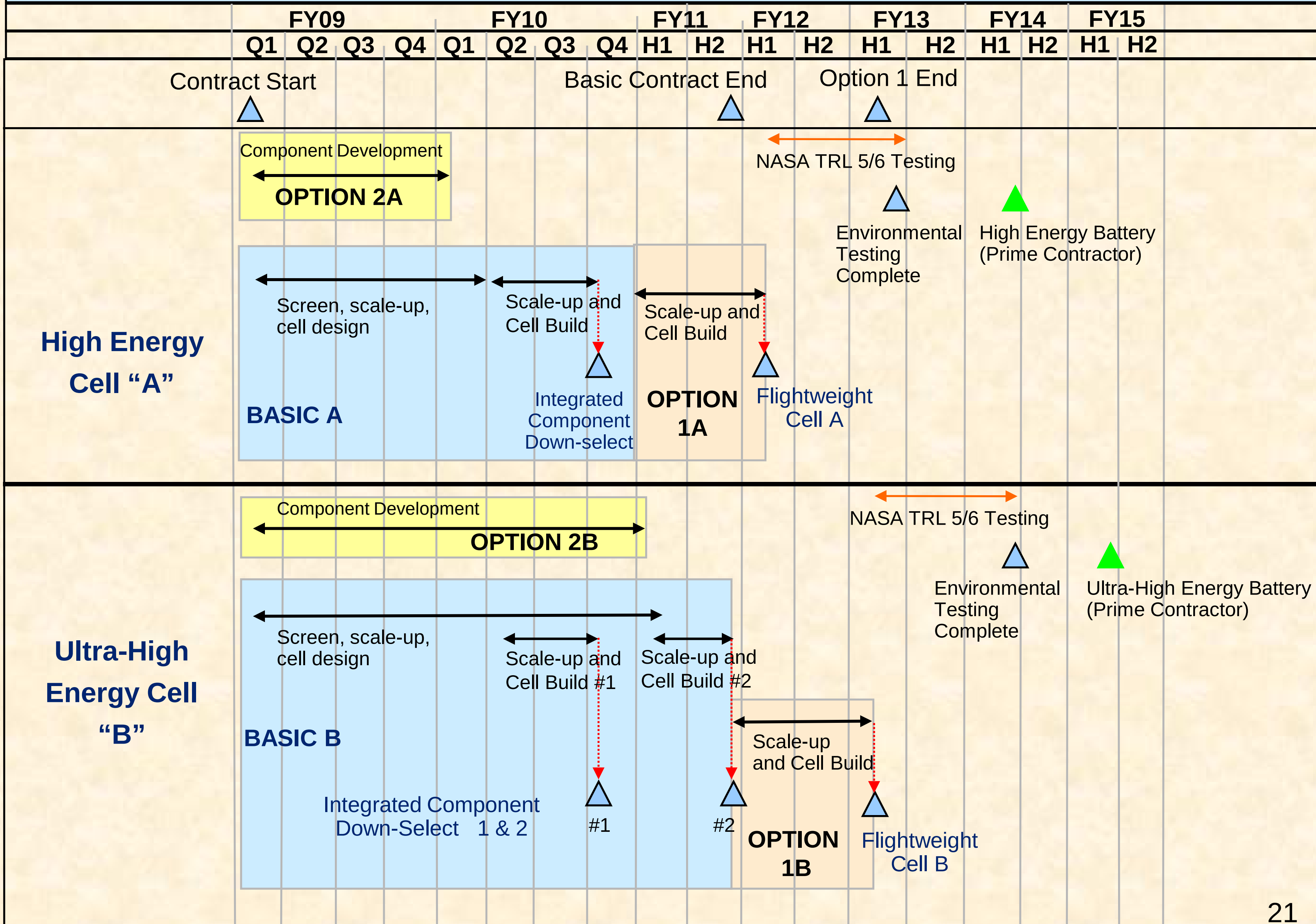
* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 volts/cell, and at 0°C operating conditions

** "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode

"Ultra-High Energy" = Exploration Technology Development Program cathode with Silicon composite anode

Revised 06/02/2008

Advanced Lithium-Based Chemistry Cell Development Master Schedule



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EDTP Program Overview

- Two parallel cell development approaches to meet Constellation customer requirements

- High Energy Cell Development
  - **Safe,** reliable Li-ion cell with improved specific energy and energy density over SOA and good cycle life
  - Combination of newly developed cathode, electrolyte, and separator with a carbonaceous anode with known heritage and performance

- Ultra High Energy Cell Development
  - **Safe,** reliable Li-ion system with greatly improved specific energy and energy density over SOA and low cycle life
  - Very high energy system for applications where mass and volume reduction is enabling and cycle requirements are benign
  - Combination of newly developed anode cathode, electrolyte, and separator
  - Higher developmental risk than High Energy Cell
    - Much higher gains in component level specific capacity over conventional electrode materials required for success
    - Addition of a developmental anode increases risk in areas of electrochemical performance, sufficient maturity by need dates, and scalability and manufacturability.
    - Lithium-alloy anode and higher energy chemistry are inherently less safe – component-level inherent safety features more critical

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 of other government programs (DOD, DOE) for component-level technology

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**

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

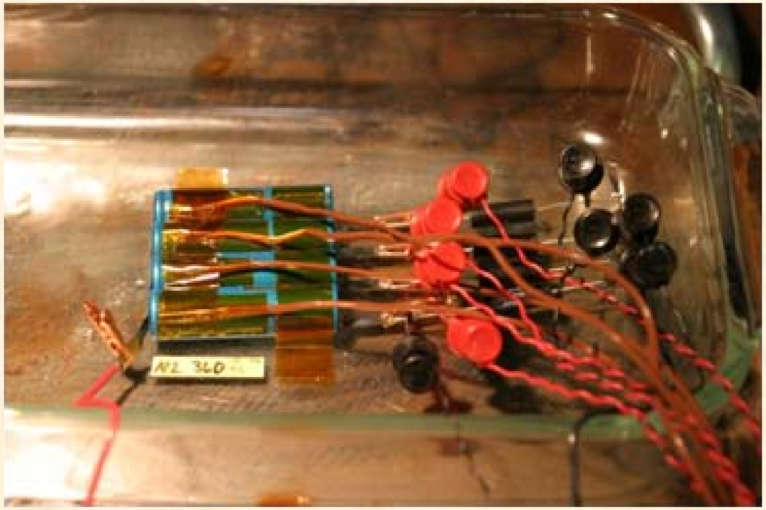
Overcharge of Battery Module

[redacted]

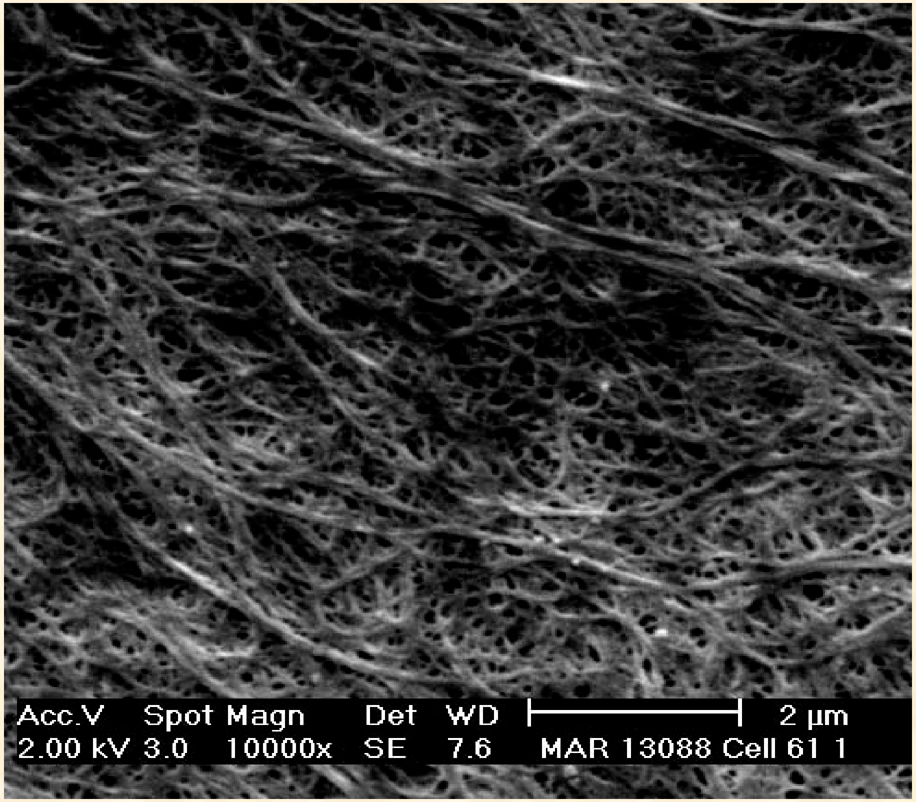
Charge: C/5
To 4.4 V/Cell
Overcharge limit: 5.5 V/Cell
Thermal runaway after 4.8 V/Cell
Highest temp Observed before thermal runaway: 248 ºC

41S 5P

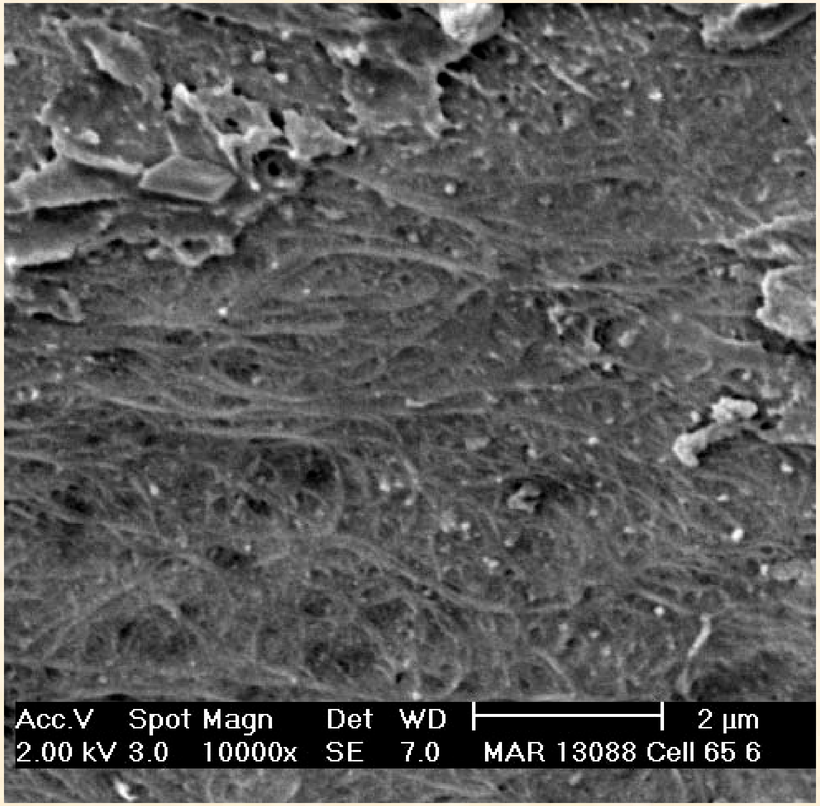
Overcharge of Li-ion Cell Module



Current Separators in COTS Cells



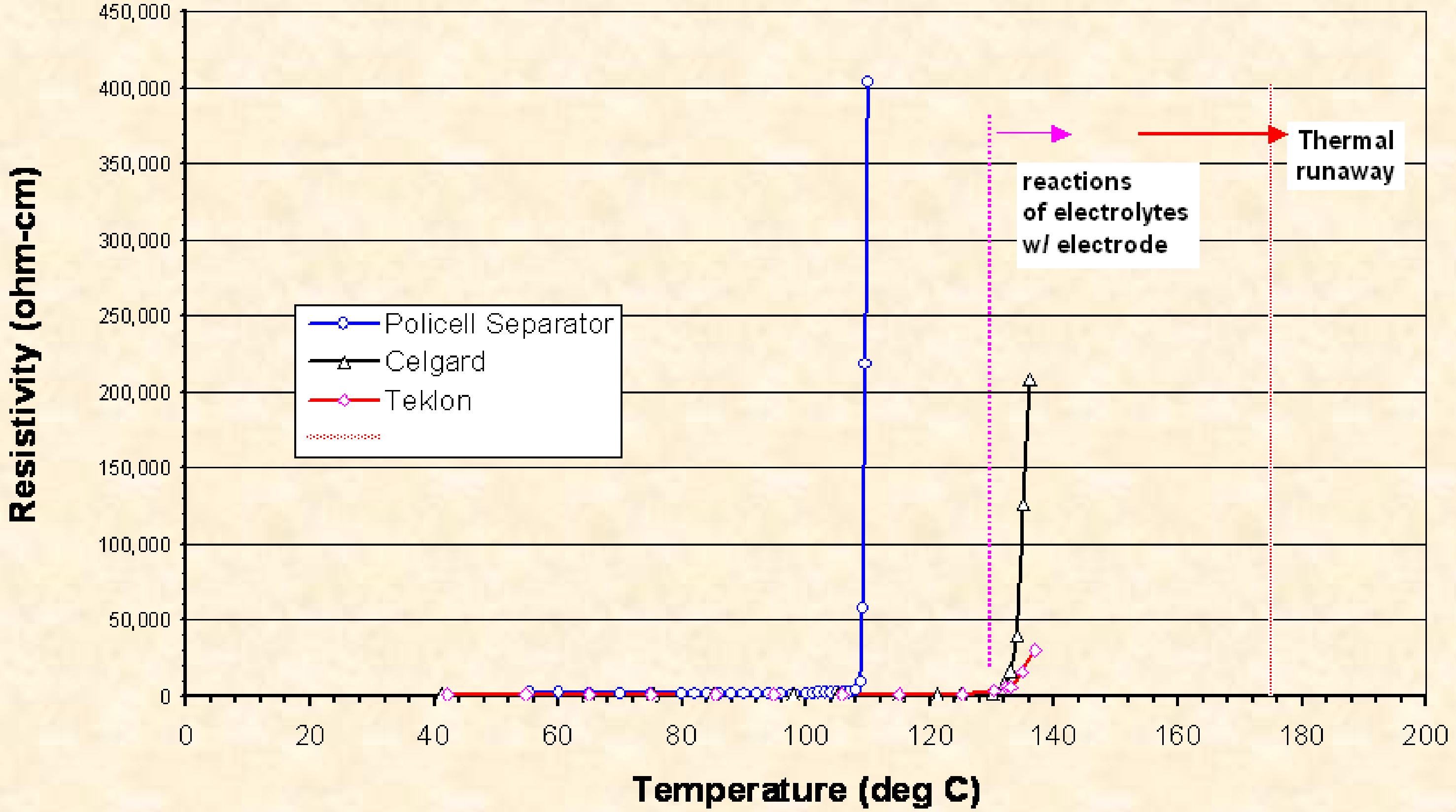
Unactivated Separator

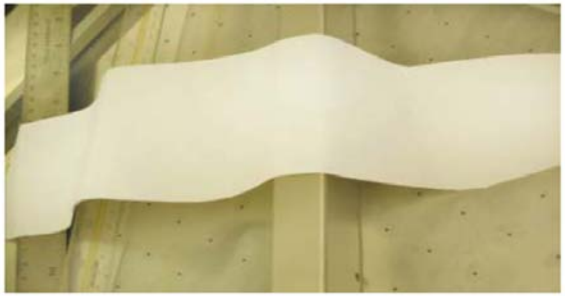


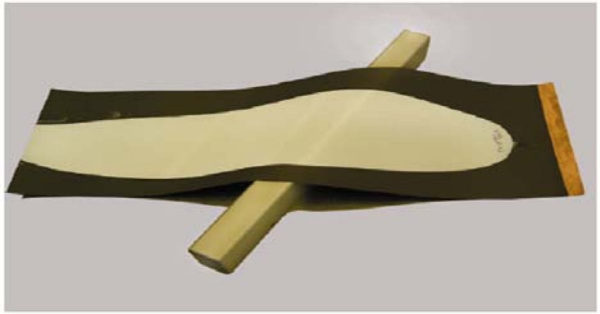
Activated Separator

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

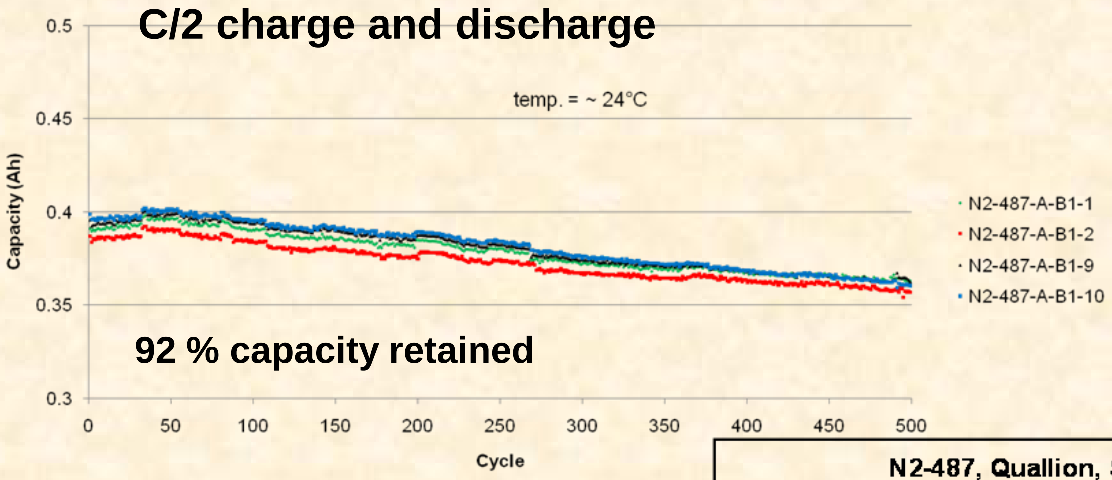
Variable Temperature Shut-down Separators (SBIR)

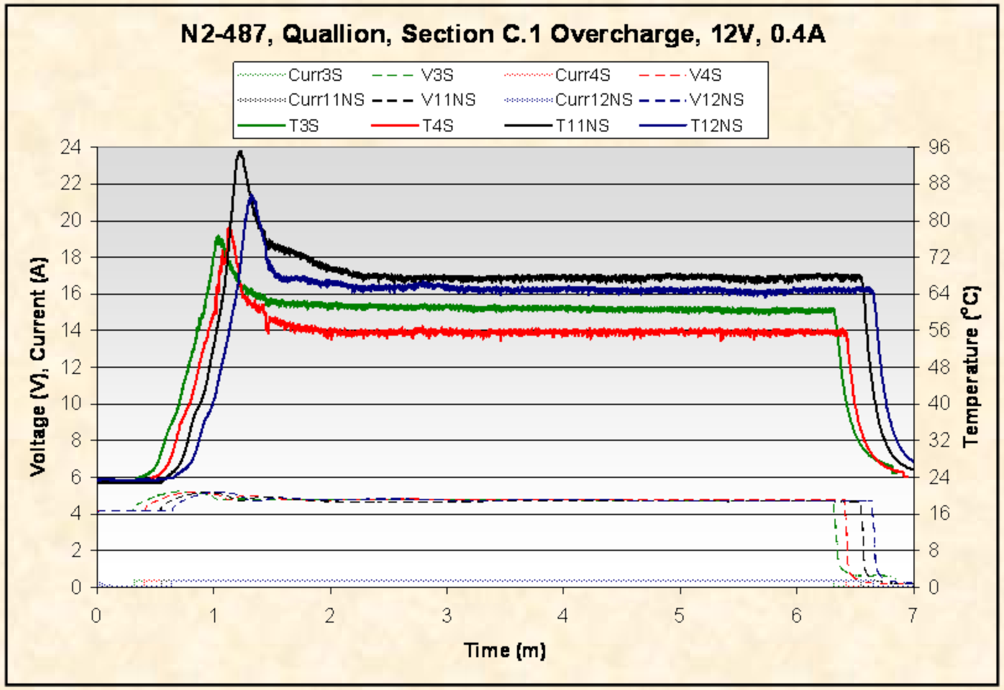






SafeLyte® Additive (IPP)





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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.

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.

Summary

- Safety is top priority for human-rated missions
- Two-fault tolerance to catastrophic failures is required for human-rated safety
- Inherent cell safety can lessen complexity of external protective electronics and prevents dependency on hardware that may also have limitations.
- Inherent cell safety can also remove the need to carry out screening of all cells (X-rays, vibration, etc.)
- For long term missions as in Lunar and Mars programs, safe, high energy/ultra high energy batteries are required.