Battery Applications for NASA's Missions - A Historical Perspective

ARPA-E

Robust Affordable Next Generation EV-Storage

January 28-29, 2014

NASA KSC Visitor's Center

Debus Conference Center

Thomas B. Miller

NASA Glenn Research Center

21000 Brookpark Road

Mail Stop 309-1

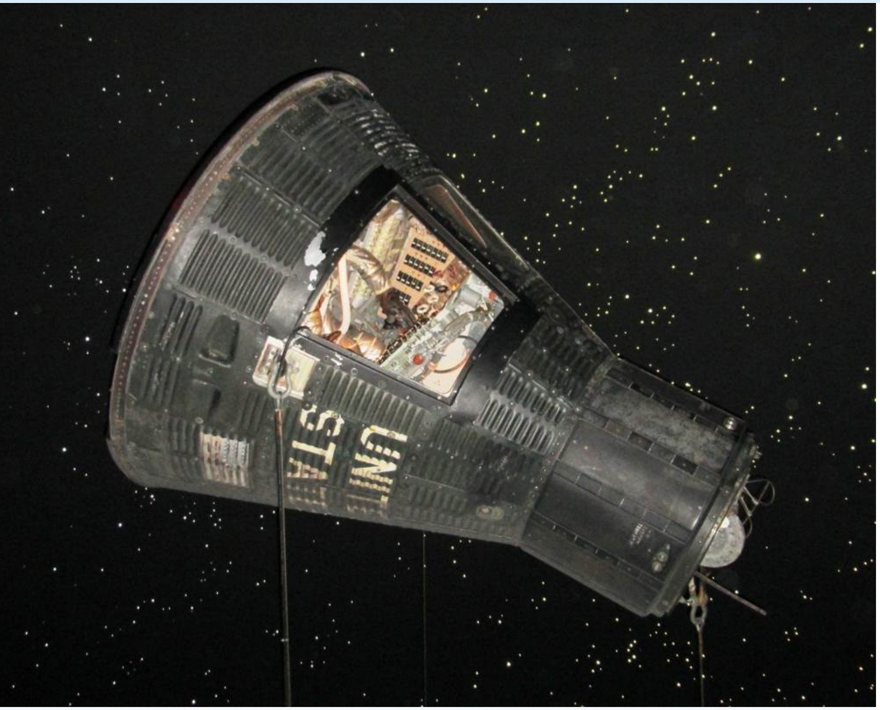
Cleveland, Ohio

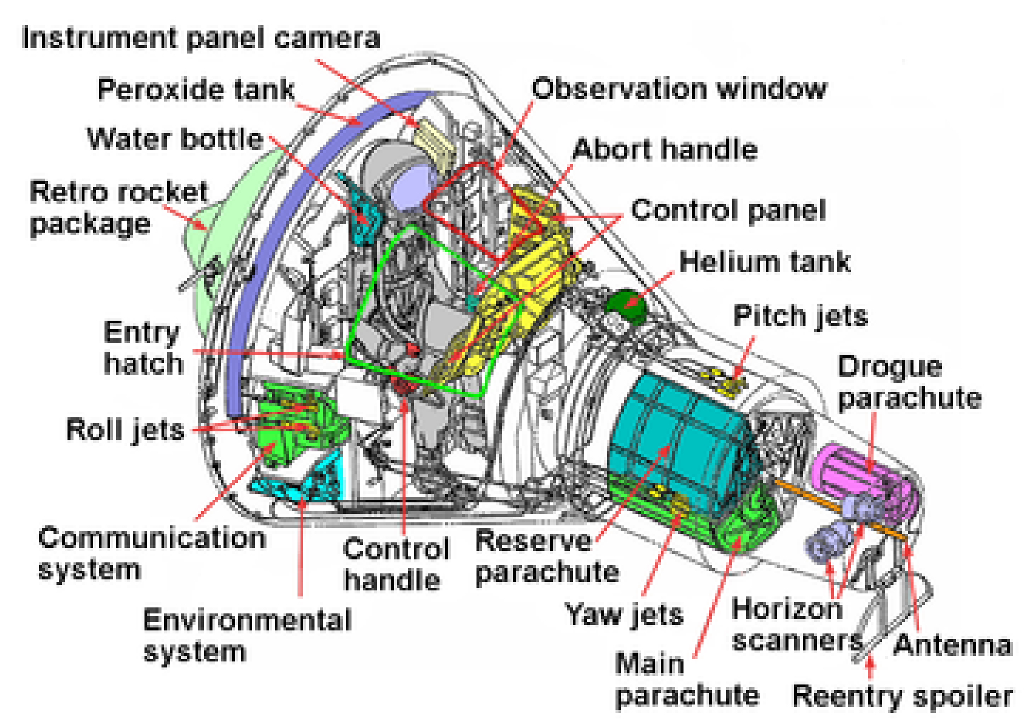
Thomas.B.Miller@nasa.gov

Project Mercury

Duration	1959–1963
Crew size	One
Rockets	Atlas D, Redstone and Little Joe
Contractor	McDonnell Aircraft (spacecraft)
Cost	$1.71 billion (current prices)
Followers	Gemini and Apollo

Mercury Capsule





3 3 kWhr main batteries
2 3 kWhr standby batteries
1 1.5 kWhr squib battery

All batteries were Ag/Zn primary

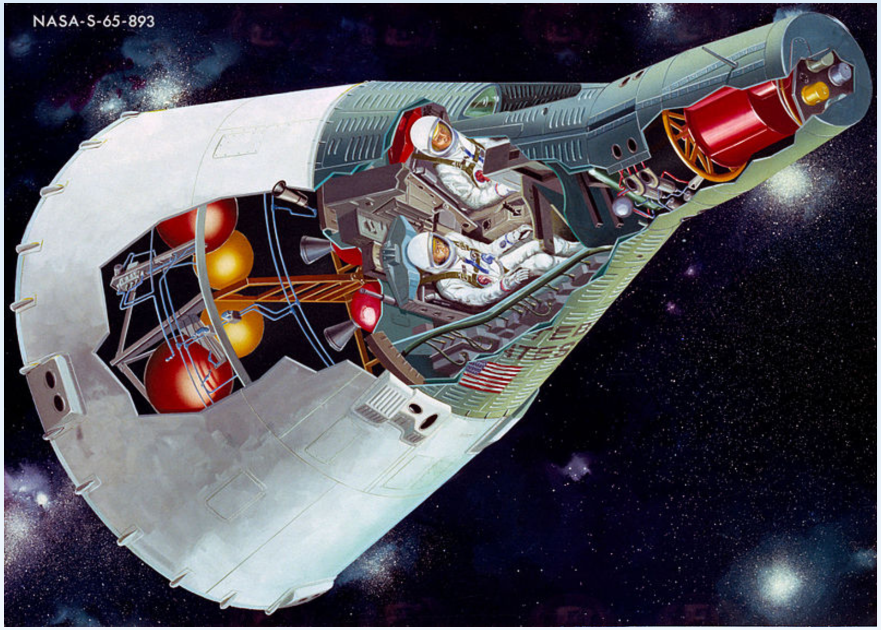
24 VDC main buss
115 VAC 1 Φ 400Hz

13.5 kWhr total energy required

Project Gemini

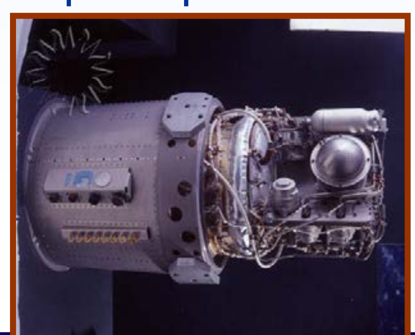
Duration	1962-1966
Goals	Long-duration spaceflight; rendezvous and docking; extra-vehicular activity; targeted re-entry and Earth landing
Achieved	Eight-day flight necessary for Apollo; 14-day endurance flight; first American spacewalk; first rendezvous; first docking; demonstrated ability to work in EVA without tiring
Crew	2
Vehicles	Launch: Titan II GLV Other: Agena, docking target

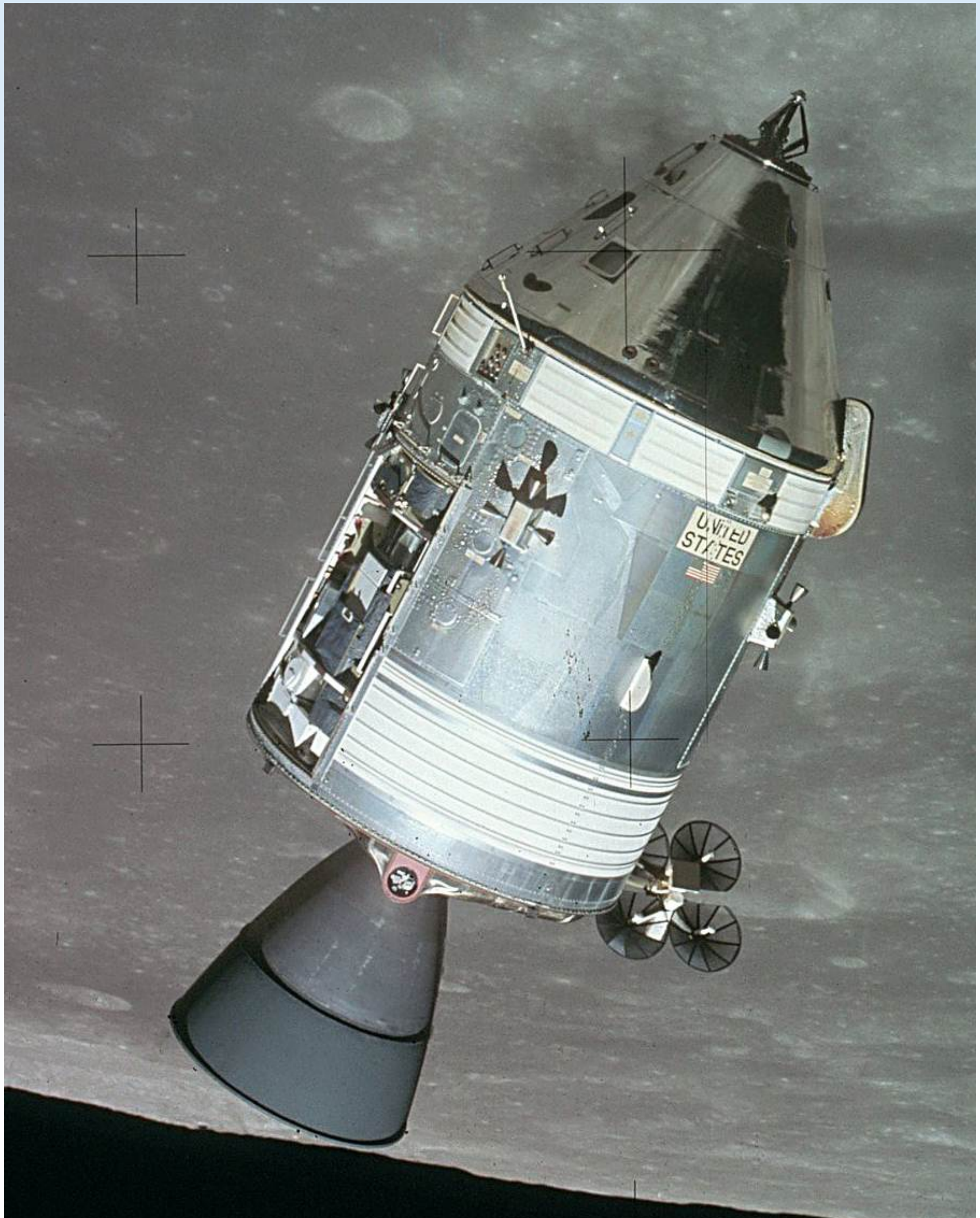
Gemini Capsule



S/C 3,4, and 6 used Ag/Zn 1^0
Could not support missions > 4 days
4 main batteries 45 Ah
3 squib batteries 15 Ah
Total Battery weight was 647 lbs.
28 VDC buss

S/C 5, 7-12 utilized a PEM Fuel Cell
32 cells/stack; 6 stacks total
1 kW peak power 26.5 VDC BOL





<u>Command</u>

3 entry batteries 40 Ah Ag/Zn

28 VDC buss

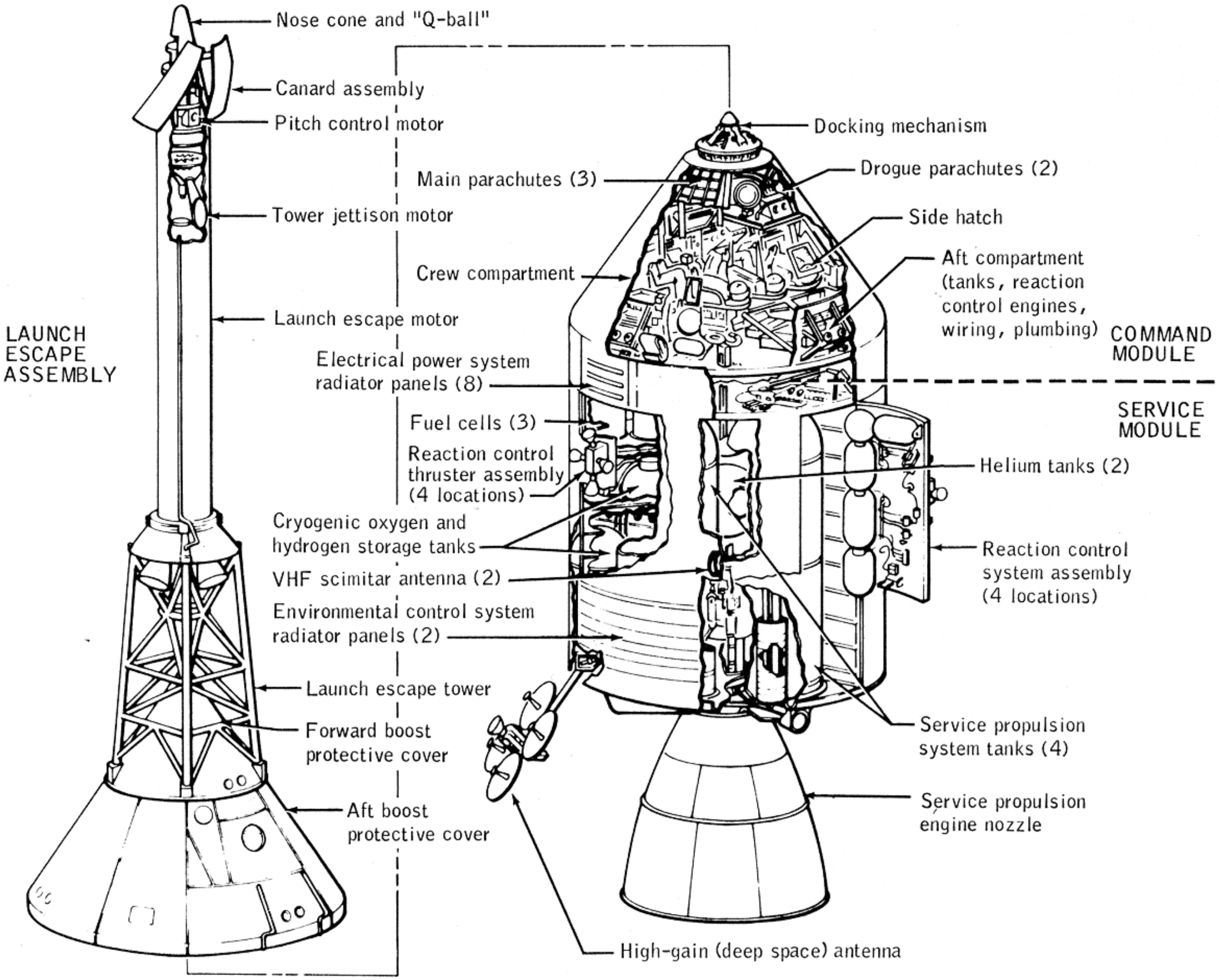
<u>Service Module</u>

3 Fuel Cells 575 W each

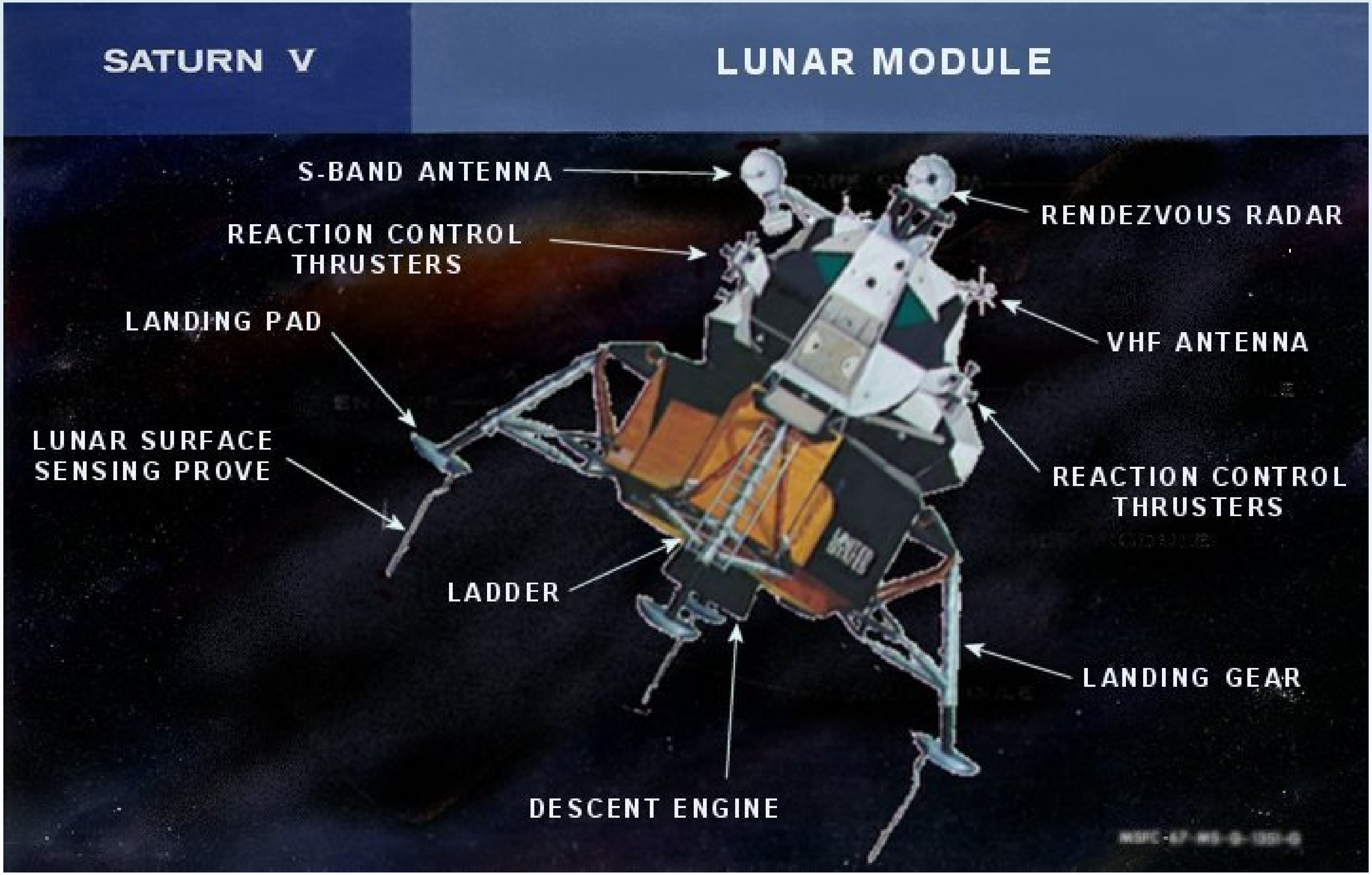
1 400 Ah Ag/Zn

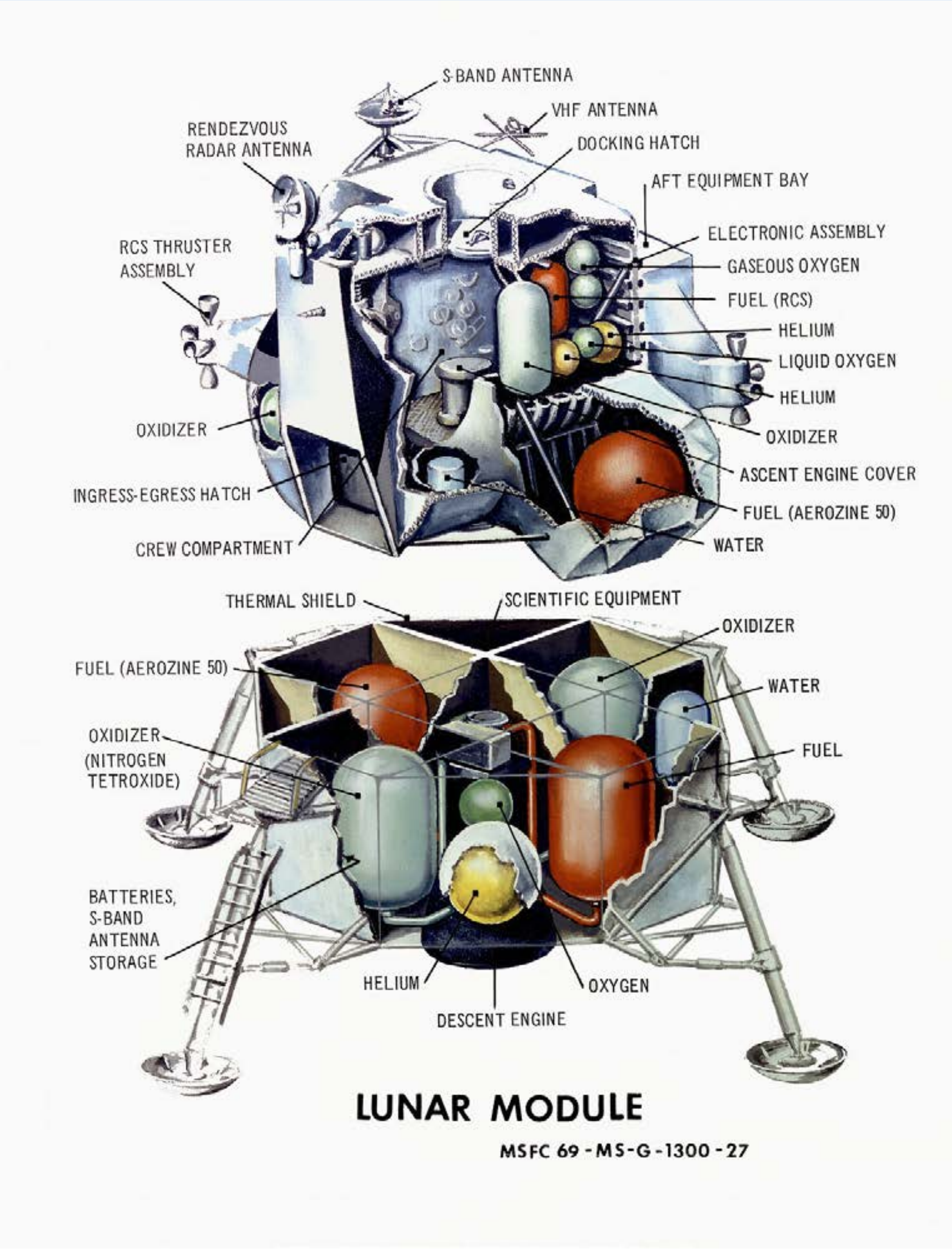
28 VDC buss

115 VAC 3Φ 400 Hz



APOLLO COMMAND AND SERVICE MODULES AND LAUNCH ESCAPE SYSTEM


SATURN V
LUNAR MODULE
S-BAND ANTENNA
RENDEZVOUS RADAR
REACTION CONTROL THRUSTERS
VHF ANTENNA
LANDING PAD
LUNAR SURFACE SENSING PROVE
REACTION CONTROL THRUSTERS
LADDER
LANDING GEAR
DESCENT ENGINE



Lunar Excursion Module

Ascent Stage

- Batteries: Two 296 Ah Ag/Zn; 125 lb (57 kg) each
- Buss: 28 VDC, 115 V 400 Hz AC

Descent Stage

- Batteries: Four 400 Ah Ag/Zn
- Buss: 28 VDC

Lunar Roving Vehicle (LRV)

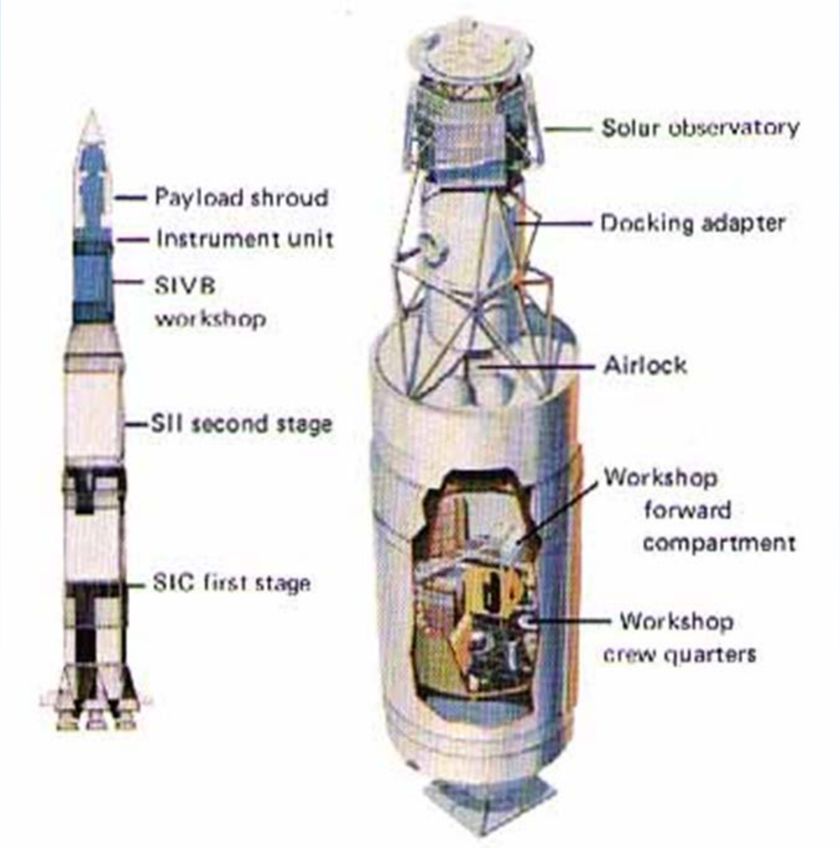
The lightweight electric car greatly increased the range of mobility and productivity on the scientific traverses for astronauts. It weighed 462 pounds (77 pounds on the Moon) and could carry two suited astronauts, their gear and cameras, and several hundred pounds of bagged samples. Two 36-volt silver-zinc primary batteries with a capacity of 121 Ah each for a total of 242 Ah translating into a range of 57 miles (92 km).

Station statistics

Crew	3 (9 overall)
Launch	May 14, 1973 17:30:00 UTC
Launch pad	Kennedy Space Center LC-39A
Reentry	July 11, 1979 16:37:00 UTC near Perth, Australia
Mass	169,950 lb (77,088 kg)[1] w/o CSM
Length	86.3 feet (26.3 m) w/o CSM
Width	55.8 feet (17.0 m) w/ one solar panel
Height	24.3 feet (7.4 m) w/ telescope mount
Diameter	21.67 feet (6.6 m)
Orbital inclination	50°
Orbital period	93.4 min
Orbits per day	15.4
Days in orbit	2,249 days
Days occupied	171 days
Number of orbits	34,981

<u>Apollo Telescope Mount</u>
18 Ni/Cd batteries 20 Ah 28 VDC buss
5800 W CSM Fuel Cell inactive
4700 W CSM Fuel Cell active

<u>Airlock Module</u>
8 Ni/Cd batteries 30 cells 33 Ah



Ready for launch, Skylab was encased in a massive aerodynamic shroud, mounted as the upper portion of the launch vehicle.

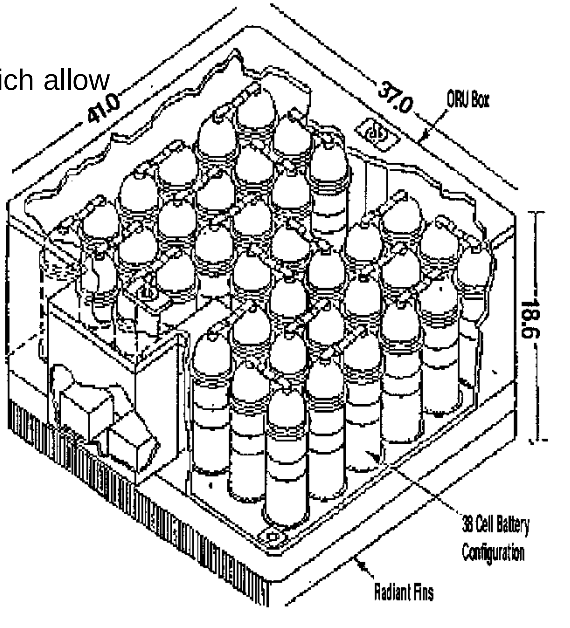
<u>Command Service Module</u>
2 Fuel Cells
3 Entry batteries 40 Ahr Ag/Zn
3 Descent Batteries 500 Ah Ag/Zn
2 Pyro Batteries 40 Ah Ag/Zn

ISS Battery Subassembly ORU

The Battery Subassembly ORU consists of 38 lightweight Nickel Hydrogen cells and associated electrical and mechanical equipment, packaged in an ORU enclosure. The Space Station will use multiples of two series connected Battery Subassembly ORUs which will be capable of storing a total of 8 kWh of electrical energy. These units will be interfaced with a Battery Charge/Discharge Unit (BCDU) which provides charge and discharge control of electric energy. During insolation (daylight), solar electric energy transmitted through the main bus and regulated by the BCDU will replenish the energy stores in preparation for the next eclipse.

The Buyer-Furnished Equipment (BFE) ORU enclosure provides the electrical and thermal interfaces to the Space Station and is designed to allow simple removal and replacement on-orbit. This enclosure is equipped with an integral Radiant Fin Heat Exchanger (RHX) which is used by a number of ORUs and provides a highly reliable, non contact, thermal transfer interface. The ORUs are locked in place by two “ACME” screws which when unscrewed allow the ORUs to be removed by a robotic arm.

The batteries contain monitoring instrumentation (pressure & temperature) which allow assessment of state of change and general health.



Key Data:

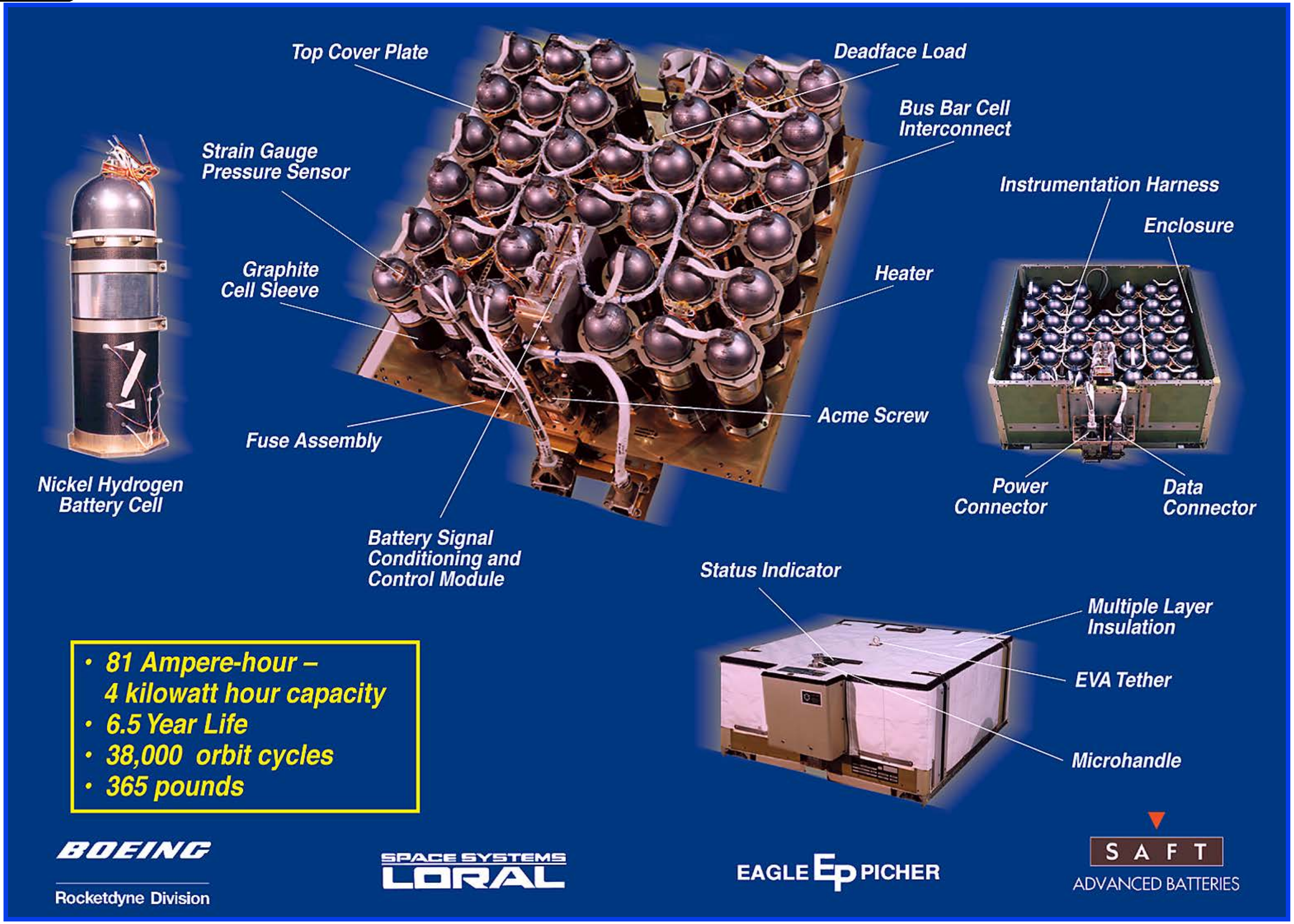
Size:	41 in. x 37 in. x 19 in.
Weight:	356 lb SAFT, 372 lb EPI
Number on Space Station:	48

Performance Data:

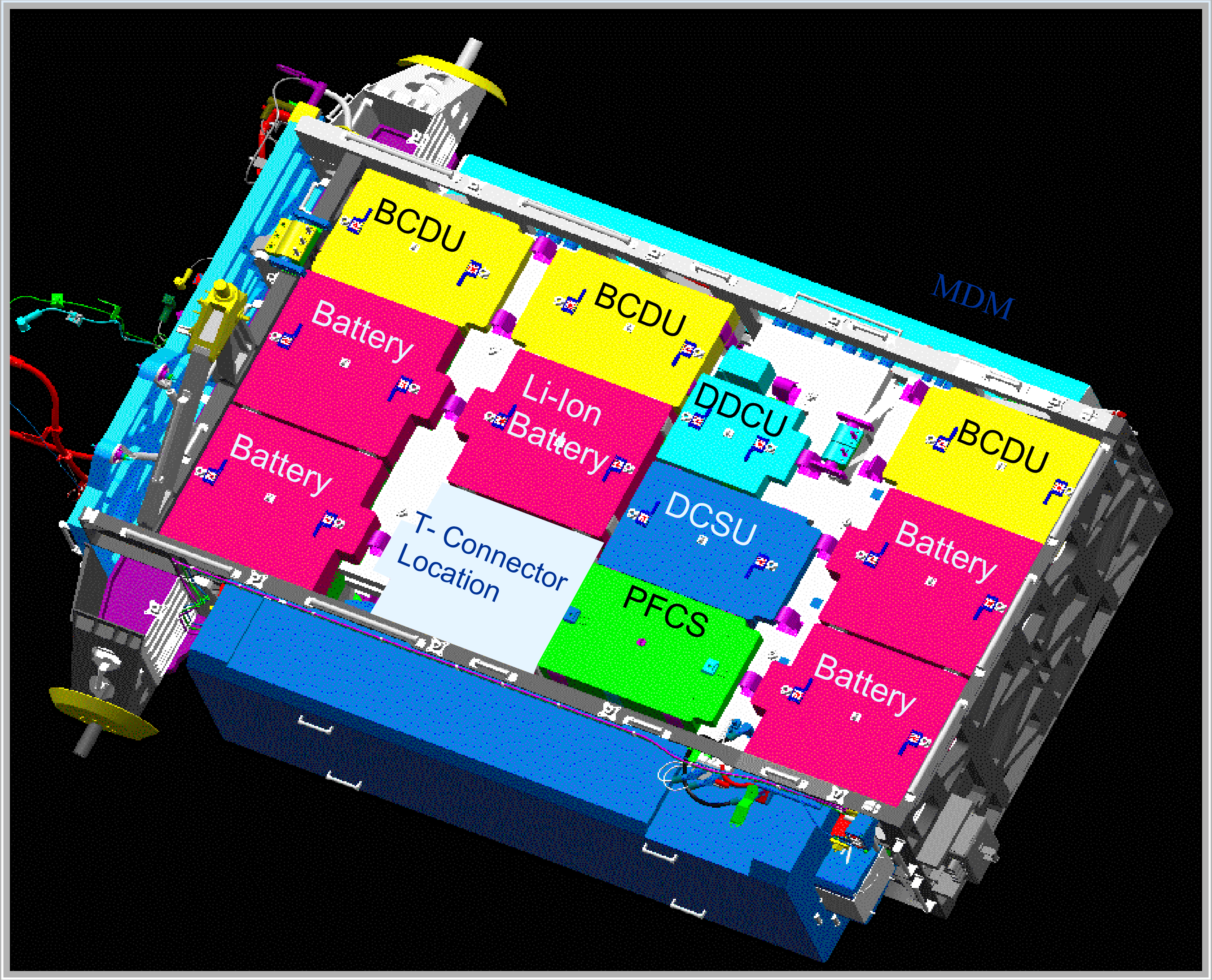
Battery ORU Design Life:	6.5
Battery ORU Charge/Discharge Cycle Life @ 35% Depth of Discharge (DOD):	38,000 cycles
Cell Quantity per ORU/Configuration:	38 series connected
Electrolyte Material:	31% Aqueous (KOH)
Nominal Storage Capacity:	4 kWh
Operating Voltage:	38-61.3 V

INTERNATIONAL SPACE STATION

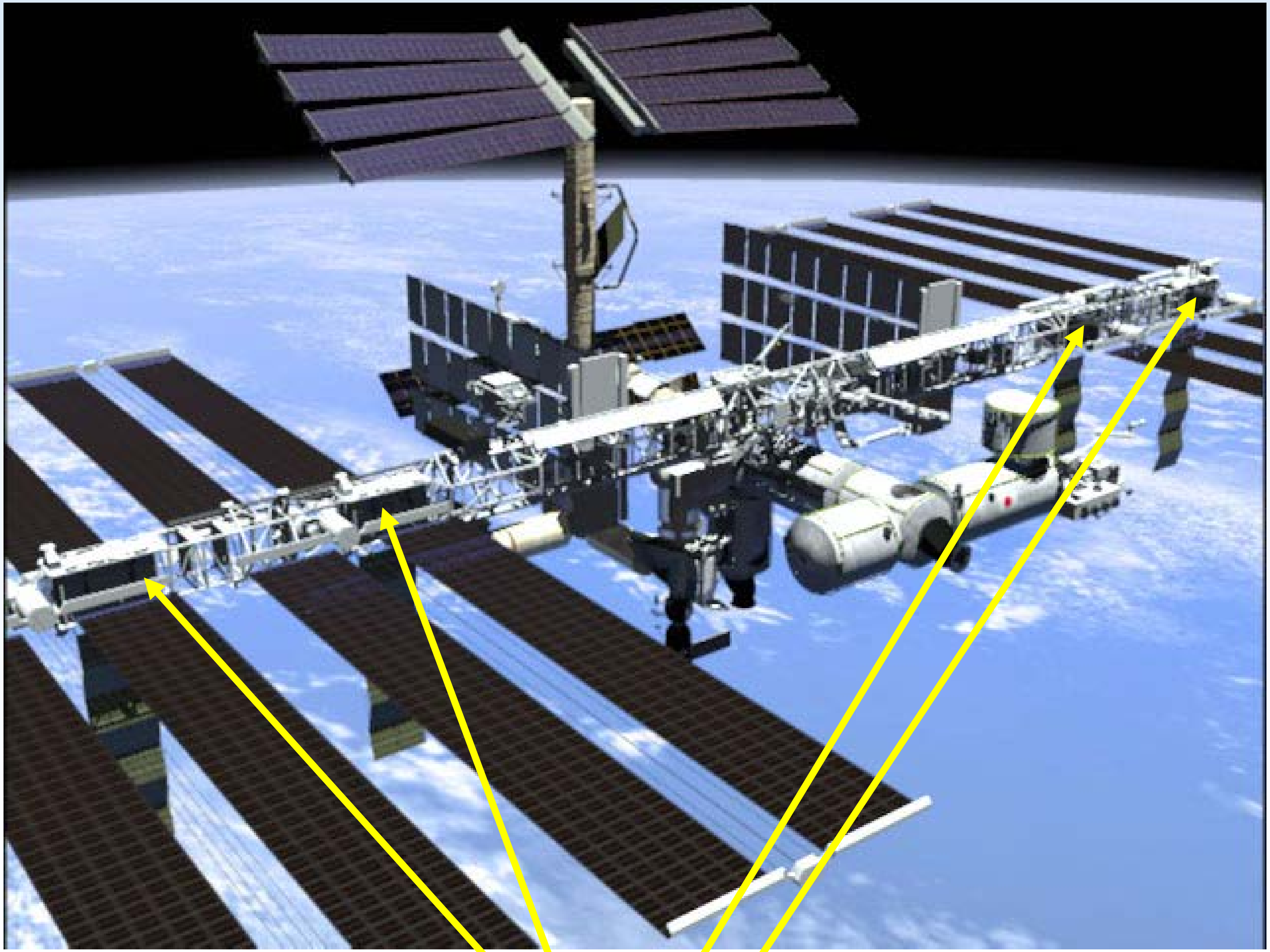
Battery Subassembly ORU



Li-Ion Battery Replacement Concept
ISS Integrated Equipment Assembly (IEA) Detail



ISS Battery Locations



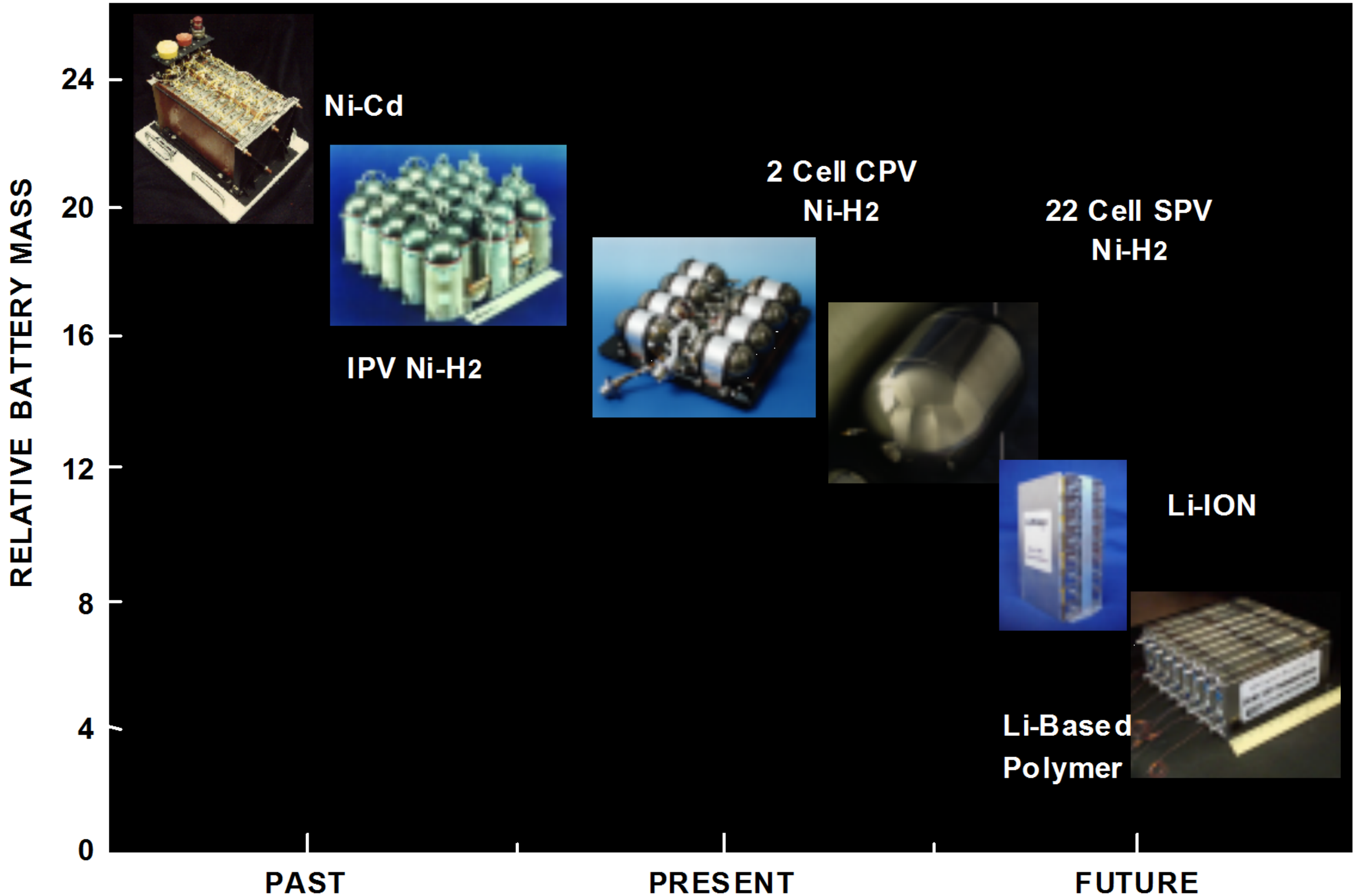
Capabilities of SOA Technologies

System	Application	Battery Capability	Limitations
Silver/Zinc AgO/Zn (Rechargeable)	• EMU • CLV • Mars landers	• 100 Wh/kg } at 25^0C • 190 Wh/l • -10°C to 25°C • <50 deep cycles	• Electrolyte Leakage • Inadequate calendar and cycle life • Poor low temperature performance
Nickel/Cadmium Ni/Cd (Rechargeable)	• Orbital missions • Astronaut tools	• 30 Wh/kg } at 25^0C • 60 Wh/l • -10°C to 25°C • >30,000 cycles @30%DOD	• Heavy and bulky • Poor low temperature performance
Nickel/Hydrogen Ni/H_2 (Rechargeable)	• Planetary orbiters, • LEO/GEO • ISS	• 30 Wh/kg } at 25^0C • 20 Wh/l • -10°C to 25° C • >50,000 cycles @30%DOD	• Heavy and bulky • Poor low temperature performance
Lithium-Ion (liquid) Li-Ion (Rechargeable)	• Orbital Missions • Mars rovers • Astronaut tools	• 90 Wh/kg } at 25^0C • 250 Wh/l • -20°C to 30°C • >500 cycles	• Possible unsafe behavior? • Low power densities • Narrow temperature range • Moderate life

Glenn Research Center

EVOLUTION OF FLIGHT BATTERIES

Power and On-Board Propulsion Technology Division



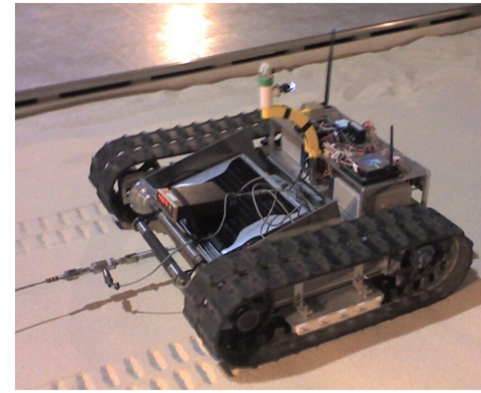
Batteries for Electric Vehicles

Late 1970's Battery and Cell Development for Electric Vehicles

- Spin off of space battery developments
- Space expertise with nickel-cadmium and silver-zinc chemistries applied to nickel-zinc development

Batteries: Leveraged Activities-Rovers

Athlete and Chariot Dozer Rovers



Rover in SLOPE Facility

A technology demonstration is planned to build experience in developing integrated electric power systems for land-based rovers and robotic devices. Lithium-ion cells shall be assembled into a battery and combined with an integrated electric power system. System performance will be evaluated in a land-based, research test vehicle. Experience gained in this project will benefit the development of system integration and modelling, power distribution and management, rover power system control, mechanical design and safety-system development.

Key activities include:

- Develop, build and test an integrated electric power system for a land-based rover demonstrator.
- Investigate lithium-ion battery/cell degradation rates under lunar mission profiles to estimate cycle life and DOD interactions.
- Utilize commercial battery cell balance hardware from Aeroflex to maintain cell-to-cell uniformity.
- Establish control systems and components to assure safety and performance standards are satisfied.

Historical perspectives

PAST

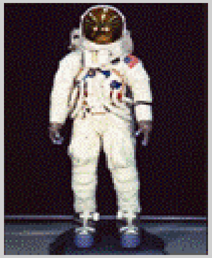
Pressure (emergency only)

Mercury

Umbilical only pressure suit

Gemini

Autonomous Surface pressure suit



Apollo

Simplified Apollo

Skylab

PRESENT

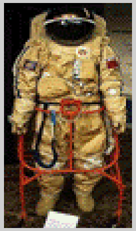
Launch, entry suit

Shuttle ACES

Autonomous 0-G EVA

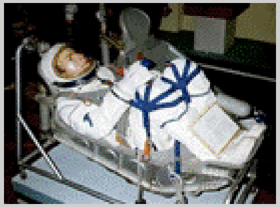
Shuttle/ISS EMU

Orlan (rear entry)



ISS Russian Orlan

Launch, entry suit



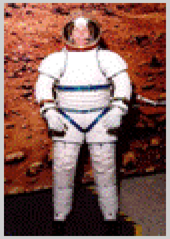
Russian Sokol

FUTURE

Soft, lightweight

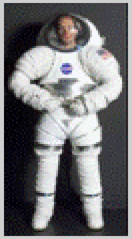
D Suit

Soft w/bearings @ upper body joints



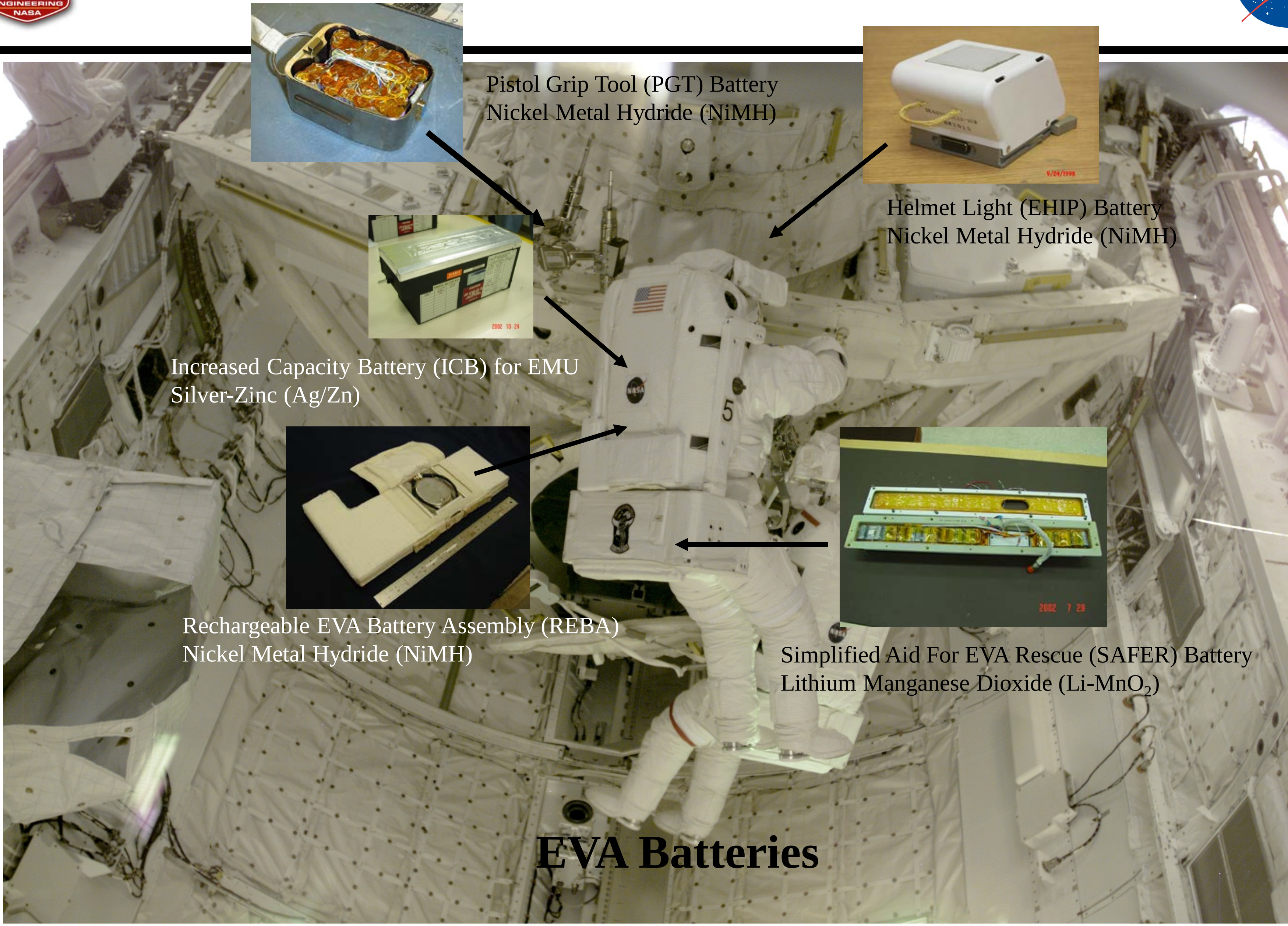
I Suit

Hard/Soft Hybrid w/multi-axis mobility joints



H Suit

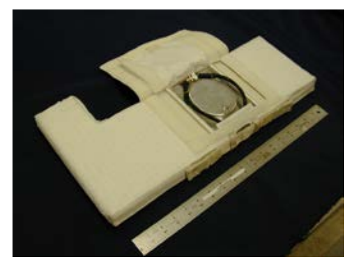
Current EVA Power Systems

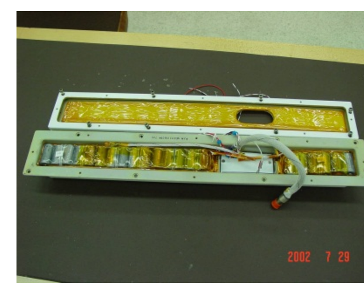


ISS01E5361 2001/02/14 18:52:17

Current EVA Power Systems

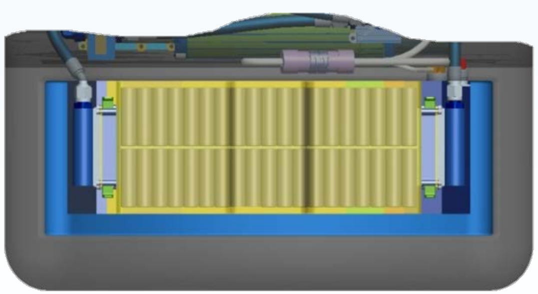
- **Li-ion Battery for EMU-PLSS**
  - ~200 Wh/L, 100 Wh/kg
  - ~1 yr calendar life, ~30 cycles
- **Separate NiMH Batteries for**
  - Pistol Grip Tool (PGT)
  - Helmet Light Assembly (EHIP)
  - Glove Heater and Helmet Camera (REBA)
    - ~120 Wh/L, ~35 Wh/kg
    - >7 yr calendar life, >500 cycles
    - Passivation issues with dormancy
- **Primary Li/MnO_2 Battery for Simplified Aid For EVA Rescue (SAFER)**
  - 200 Wh/L, ~70 Wh/kg
  - Providing >4.5 hrs of runtime when only 13 minutes are needed for self-rescue



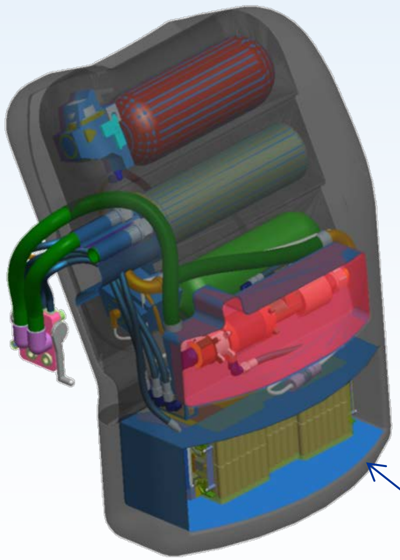


EVA Surface Suit

- Power to support 8-hour EVA provided by battery in Portable Life Support System
- Preliminary battery design goals:
  - Human-safe operation
  - 144 W (average) and 233 W (peak) power
    Assumes 1% connector loss and 30% margin for growth in power requirements
  - No more than 5 kg mass and 3 liter volume
  - 100 cycles (use every other day for 6 months)
  - 8-hour discharge
  - Operation from $10^{o}C$ to $+30^{o}C$
- Secondary batteries are considered critical for EVA Suit 2.



Assembly-Aft



Battery Assembly in PLSS

Portable Life Support System (PLSS)

Architecture Elements and Energy Storage Needs

ESAS Architectural elements		Missions/ Applications	Energy System Sizing	Battery Performance Drivers
Crew Exploration Vehicle (CEV)		Command Module (CM) Service Module (SM)	• 5-10 KWh • 4.5 kW Ave • 3X 28 V bus	• Human-rated (Safety) • High energy density • Long life, high power • High temp. resilience
		Crew Launch Vehicle (CLV)		
Lunar Surface Ascent Module (LSAM)		Ascent Stage	• 13.5 kWh • 3 x 28 V bus	• Human-rated (Safety) • High energy density • Long life, high power • High temp. resilience
		Descent stage	• 4.5 kW Ave • 1 x 28 V bus	
Surface Missions	Sorties	EVA	• 0.1 – 1 kW	• Human-rated (Safety) • High energy density • Long life, high power • Low and high temp perf.
		Un-pressurized Rovers/landers	• 1 kW	• Low and high temp perf • High energy density • Long life, high power • Safety
	Outpost missions	Un-pressurized Rovers/landers	• 1 kW	
		Pressurized Rovers/landers	• 1-5 kW	• Human-rated (Safety) • High energy density • Long life, high power • Low and high temp perf.
		Fuel cell/battery hybrid power Station	• 10-100 kW	• Human-rated (Safety) • High energy density • Long life, high power

Exploration Technology Development Program
Energy Storage Project

Exploration Technology Development Program

Multiple focused projects to develop enabling technologies addressing high priority needs for lunar exploration. Matures technologies to the level of demonstration in a relevant environment – TRL 6

Energy Storage Project –

Developing electrochemical systems to address Constellation energy storage needs

Altair - Lunar Lander

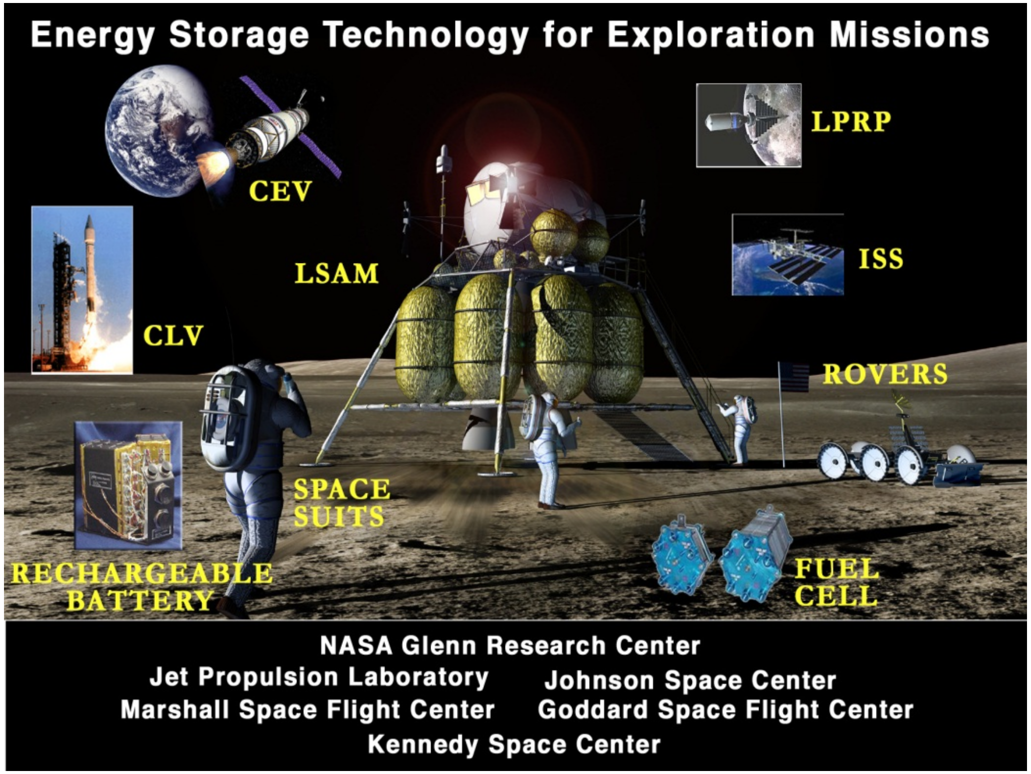
- **Primary fuel cells**
- **Secondary batteries**

EVA

- **Secondary batteries**

Lunar Surface Systems

- **Regenerative fuel cell systems for surface systems**
- **Secondary batteries for mobility systems**



Constellation Energy Storage Requirements

Extravehicular Activities

Power for Portable Life Support Systems and Communications/Avionics/Informatics:

Human-safe operation

8-hr duration

High specific energy >200 Wh/kg

High energy density >300 Wh/l

Altair - Lunar Lander

Descent Stage:

Functional primary fuel cell with 5.5 kW peak power.

Human-safe reliable operation; high energy-density; architecture compatibility

Ascent Stage:

Rechargeable battery capability

Nominally 14 kWhr in 67 kg, 45 liter package

Human-safe, reliable operation; high energy-density.

Ares I/V

Thrust Vector Control: Replace hydrazine with batteries

Earth Departure Stage: Replace solar cells/batteries with fuel cells

Energy Storage Project
Lithium Based Battery Development

- Improve the performance of Lithium-based cells for integration into battery modules to meet the energy storage requirements for Constellation Customers
- Performance parameters
  - Safety human-rated systems
  - Specific energy
  - Energy density

- Two level approach to meet customer requirements
- Safe, reliable Li-ion systems improved specific energy and energy density
- Very high energy systems – Li/S or high voltage Li-ion systems

  Under consideration for applications where mass reduction is enabling and cycle requirements benign

Thank you. Questions?

Thomas B. Miller
NASA Glenn Research Center
21000 Brookpark Road
Mail Stop 309-1
Cleveland, Ohio
Thomas.B.Miller@nasa.gov