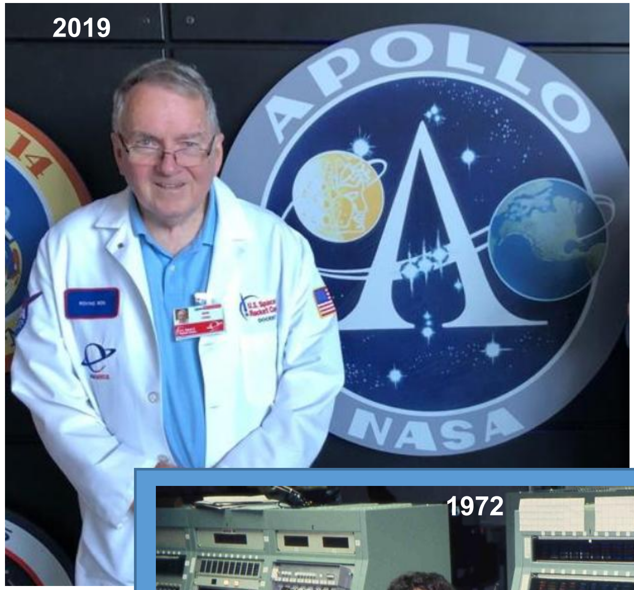
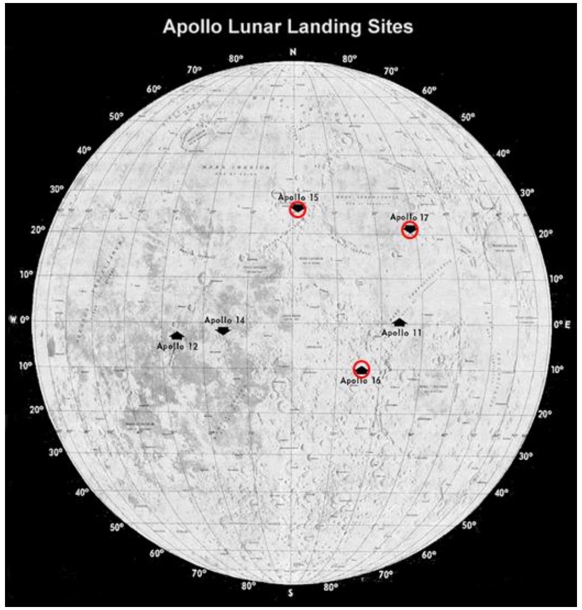
Challenges for Potential Reuse of Apollo Lunar Rovers

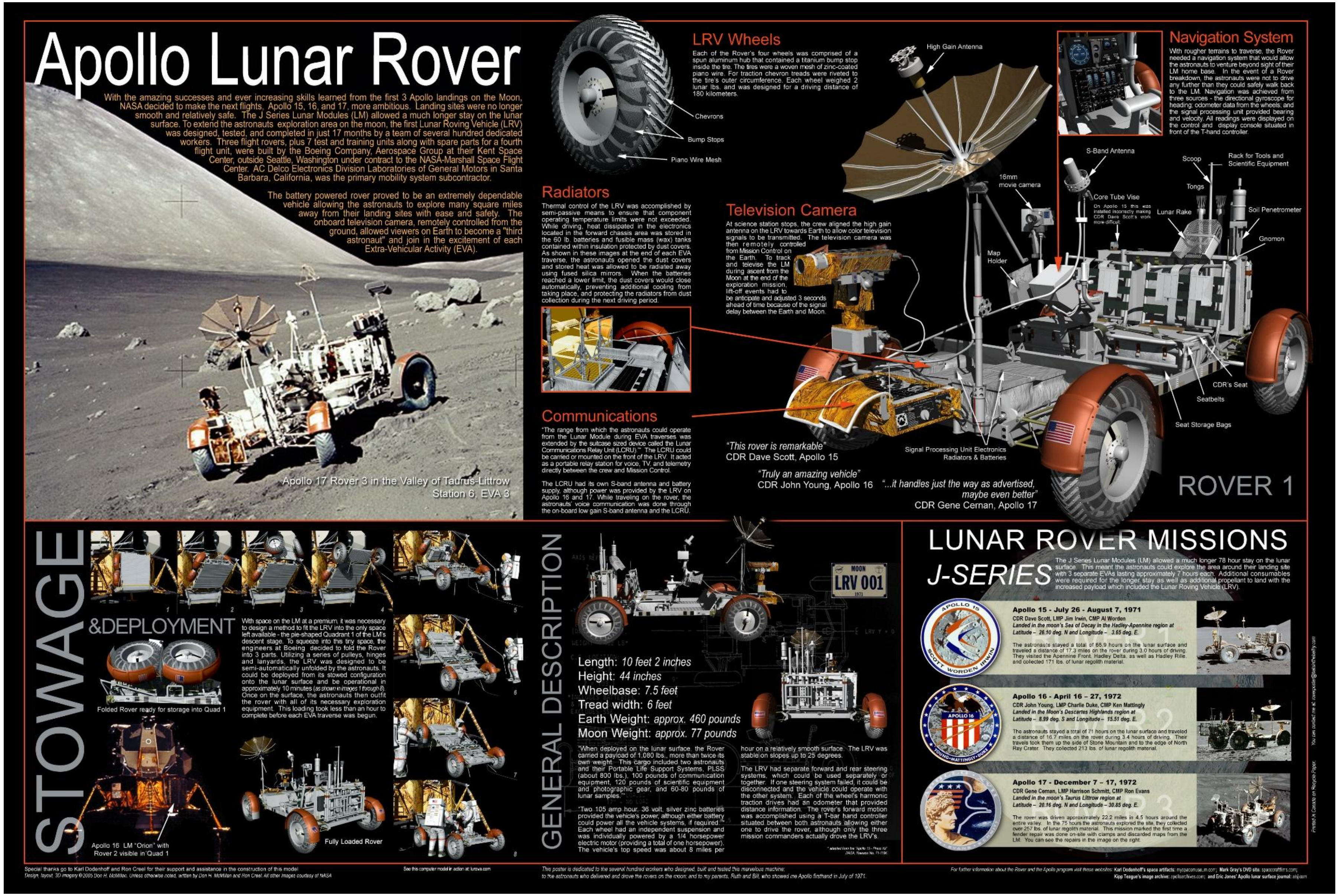


Ron Creel - Retired Space and Thermal Systems Engineer
Member of the Apollo Lunar Roving Vehicle (LRV) Team

roving.ron@gmail.com

Three Apollo Lunar Rovers Are Now Located on the Moon





Non-Polar Latitudes

Apollo 15 = 26.10 deg. N
Apollo 16 = 8.99 deg. S
Apollo 17 = 20.16 deg. N

Poster Created By Don McMillan

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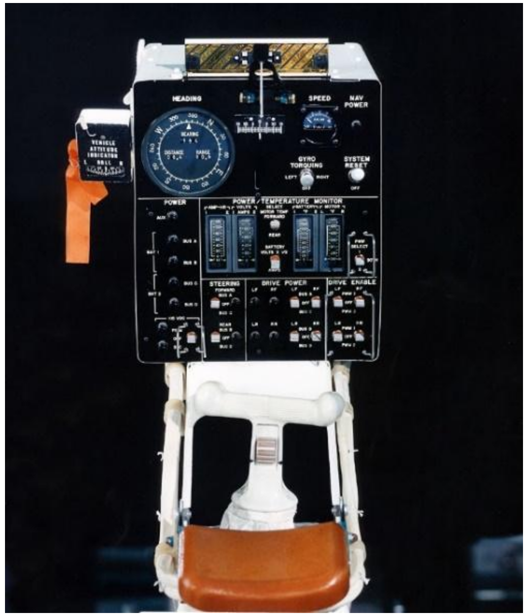
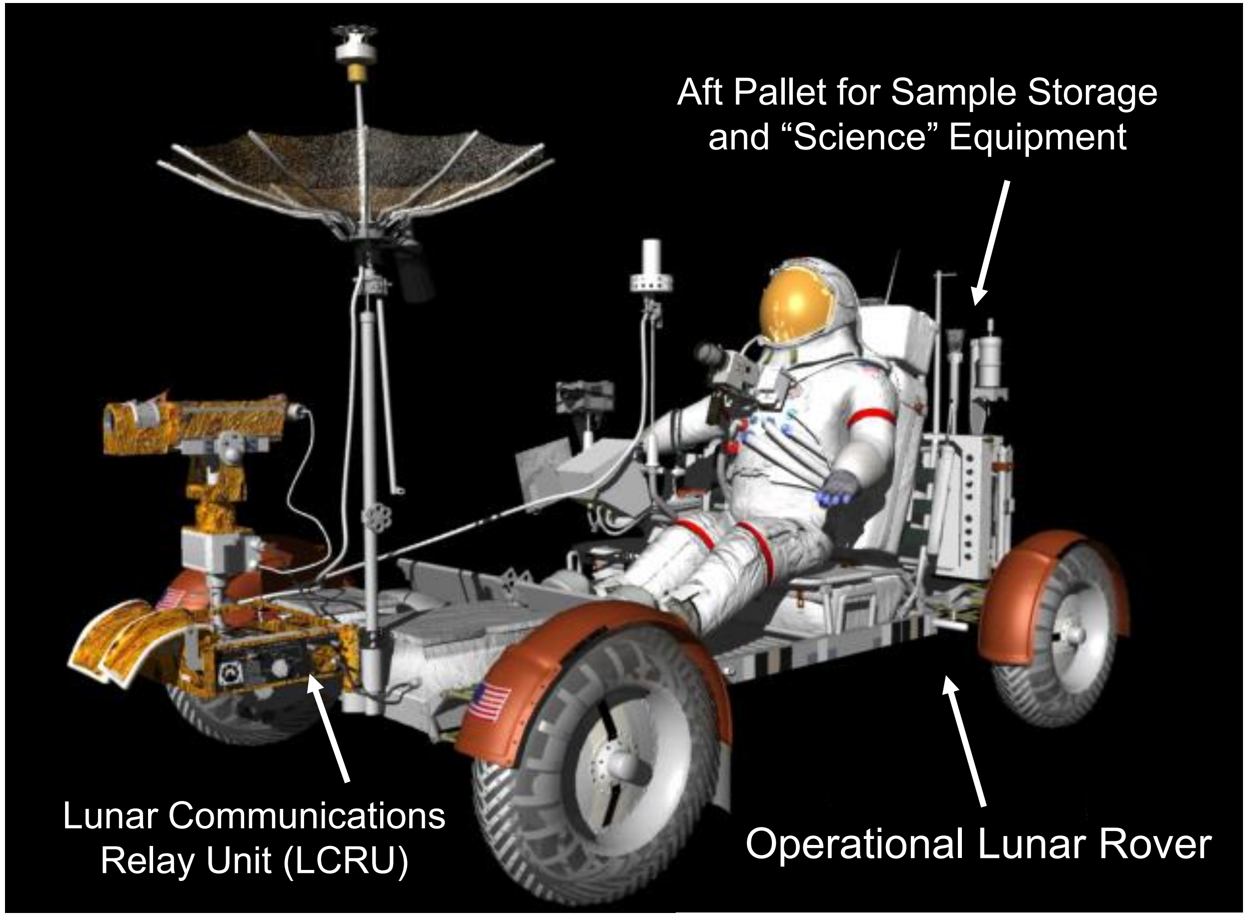
Apollo Rovers Contribute <u>6</u> Component, Power, and Mobility Challenges for Reuse

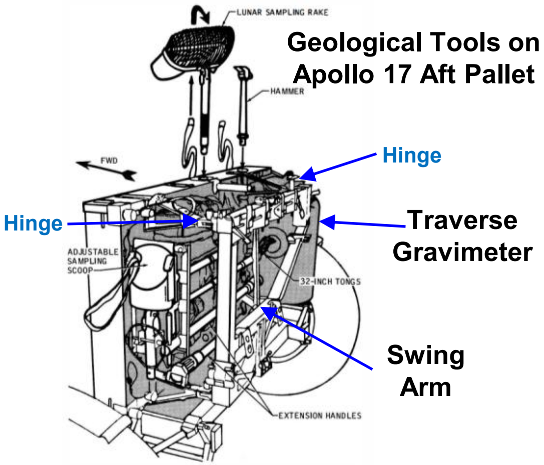
Display and Control Console and Hand Controller for Drive Power, Braking, Steering, and Navigation



Insulated Front Panel for Power and Navigation Initialization/Review
Dust Degraded Exterior Surfaces

Apollo 16 and 17 Switch to Provide Power for LCRU





Three Different Aft Pallet Configurations

Maintain All Surfaces Within Astronaut Touch Constraints as Replacements are Made

<u>Forward Chassis Electronics</u>
Insulate / Isolate from Dust
Store Generated Heat in <u>Batteries</u> and Wax Boxes
Radiator Dust Covers Opened Back at the LM

<u>Mobility</u>
Exterior Traction Drive, Fluid Damper, and Steering Components Have Dust Degraded Surfaces
Internal Conduction Maximized
Vital Fenders and Extensions

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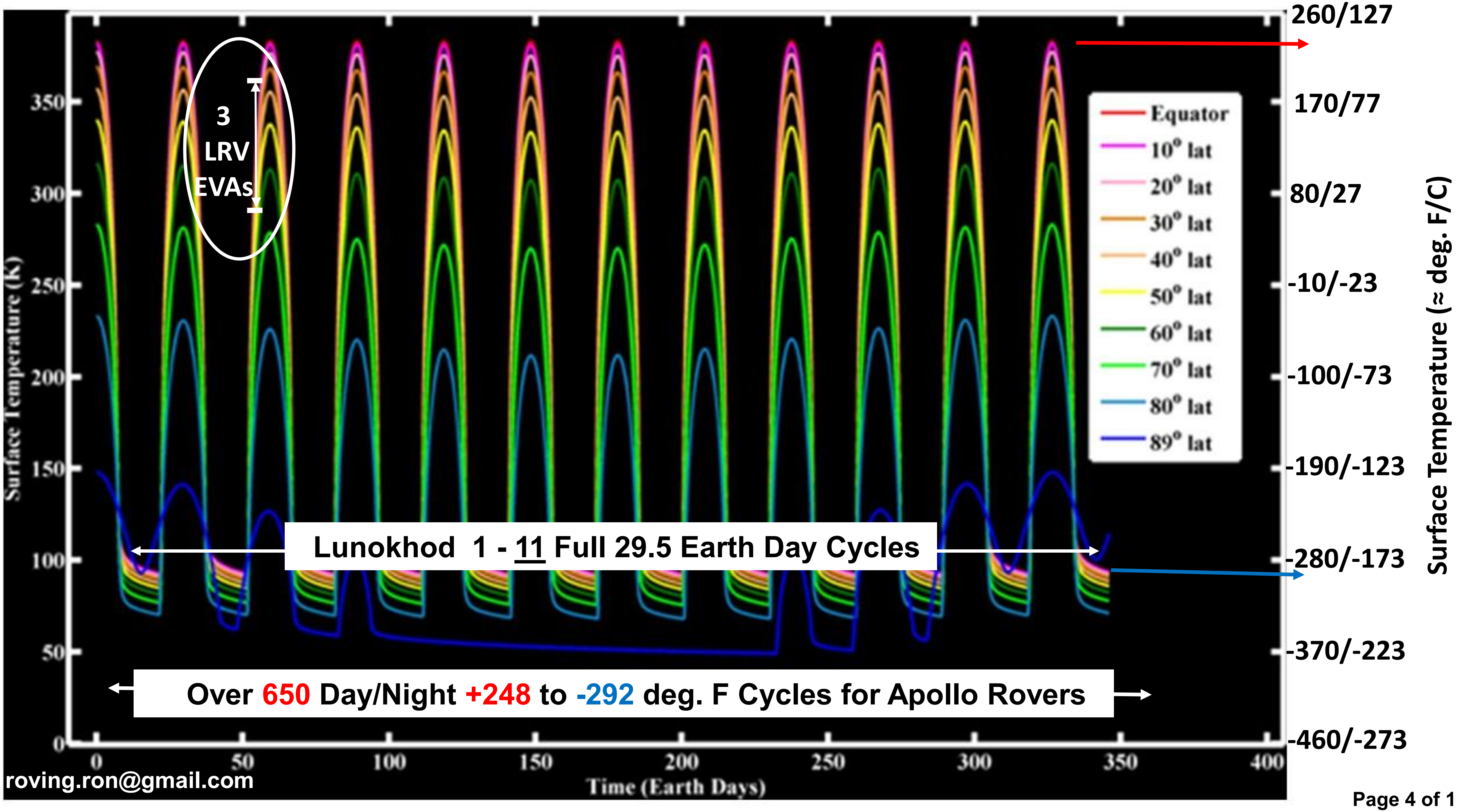
Challenge 1 - 54+ Year Rover Components' Exposure to Temperature Extremes



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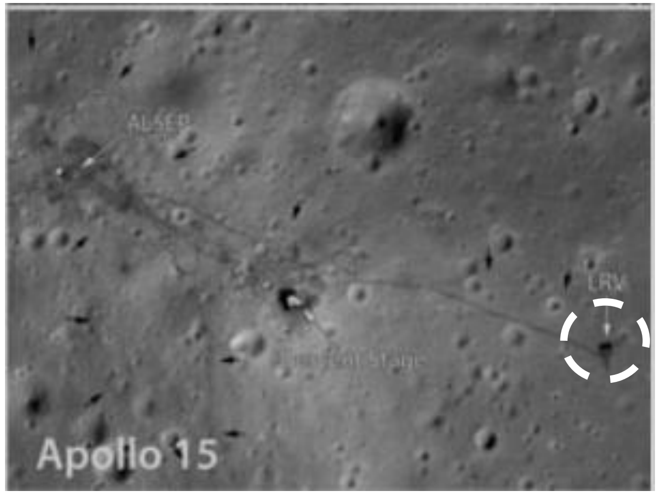
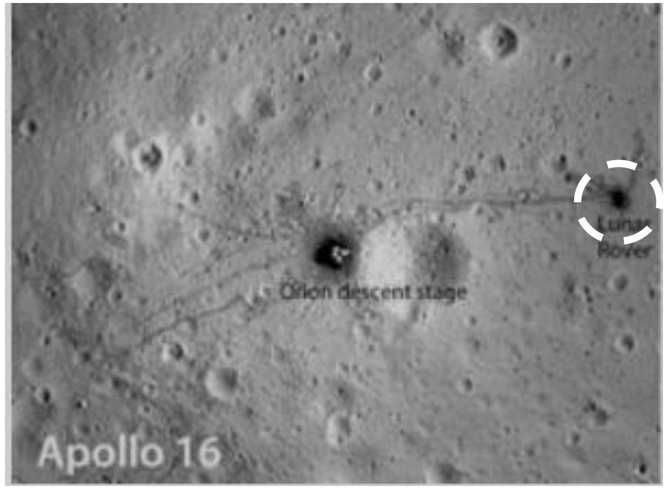
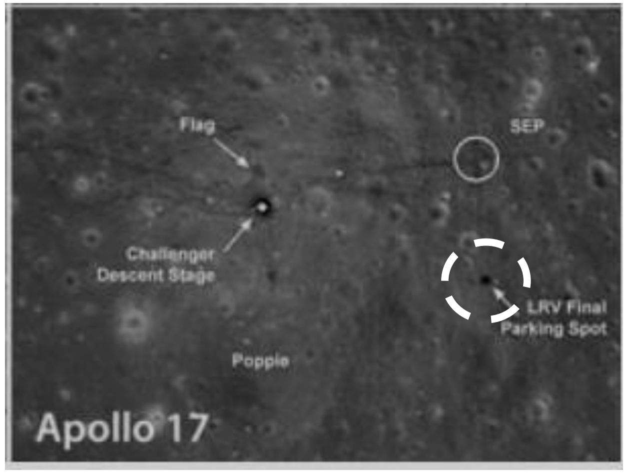
Challenge 2 - Preparation for Unknown Rover Condition and Fenders and Extensions Status

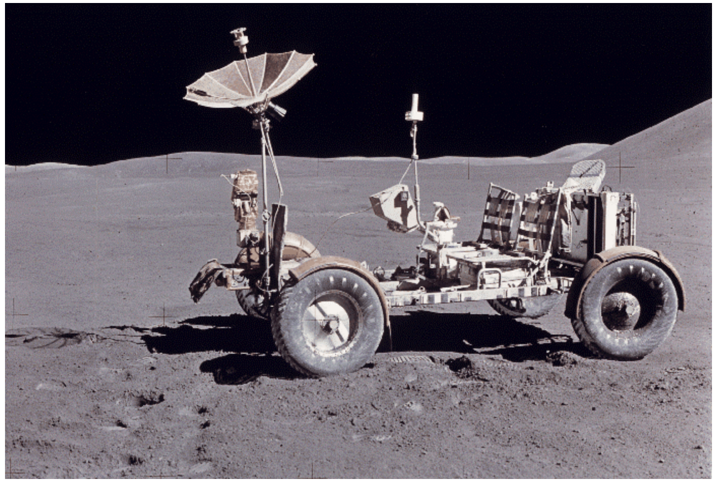
Mysterious “Black” Areas at Present Parked Rover Locations in LRO* Photos!







Required Rover Fenders and Extensions Status Before Multi-year Extreme Temperature Exposure



Left Front Fender Extension
Missing on Apollo 15 Rover

Right Rear Fender
Extensions Lost on
Apollo 16 and 17 Rovers

Temperature Extremes May Have Warped Fenders and/or Removed Fender Extensions

Apollo 17
Right Rear
Fender
Extension
Crew Repair

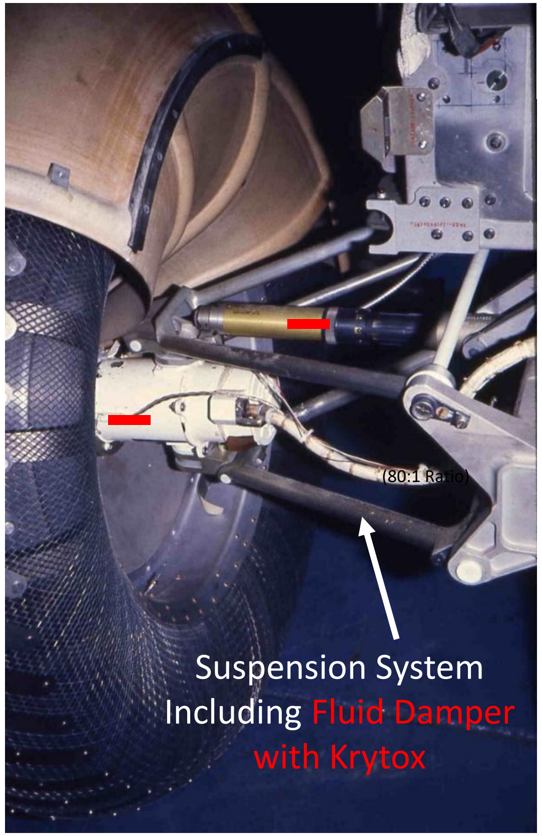
Apollo 17 Fender Repair
and other Extensions
Now in Museums

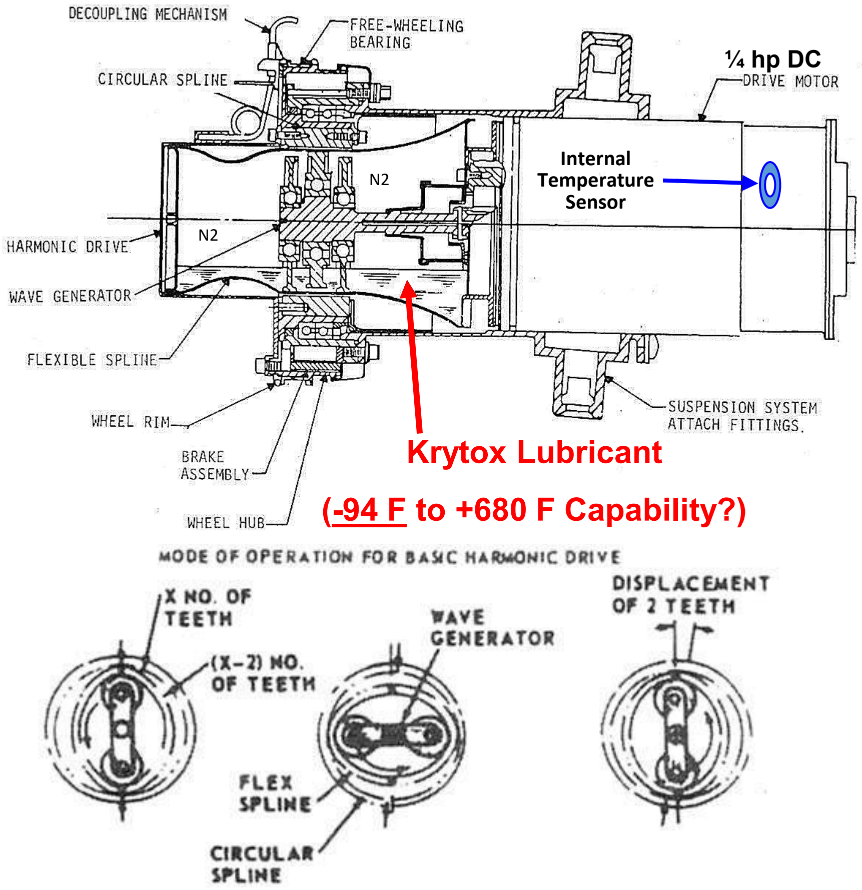
All 3 Apollo 17 Fender
Extensions and Repair
Removed

* LRO = Lunar Reconnaissance Orbiter

LRV Mobility and Forward Chassis Subsystems Present Reuse Challenges

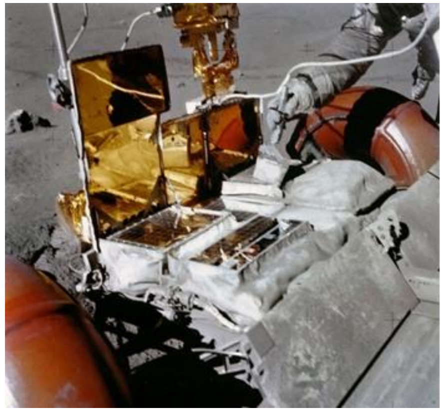
Mobility Subsystem





4 Sealed DC Motor and Harmonic Drive Units Used for Traction Power on the LRVs

Forward Chassis Subsystem



- **Multi-Layer Blanket for Insulation, with Dust Covers for Thermal Radiators**
- **Thermal Straps Conduct Electronics Heat Into 59 Pound Non-Rechargeable Silver-Zinc Batteries**
- **Electronics Heat Also Stored in Wax Boxes (Fusible Mass Tanks) During Extra-Vehicular and Driving Activities (EVAs)**
- **Low Solar Absorptance (α_s= 0.07) Space Radiators to Reject Heat When Dust Covers Are Opened at the End of EVAs**

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Challenge 3 - Maintaining LRV Components Within Temperature Limits - deg. F

Batteries and noted Electronics are protected for Hot exposure, if the integrity of the Forward Chassis insulation blanket can be maintained, but long-term Cold temperature exposure is a challenge → Forward Chassis Electronics

External Mobility components should be all right for Hot temperature exposure, but there is also concern for Cold temperature exposure → Mobility

Group	Component	Minimum Survival	Minimum Operating	Maximum Operating	Maximum Survival
Forward Chassis Electronics	Batteries*	-15	40	125	140
Forward Chassis Electronics	Signal Processing Unit (SPU)	-65	30	130	185
Forward Chassis Electronics	Directional Gyro Unit (DGU)	-80	-65	160	200
Forward Chassis Electronics	Indicating Meters	-22	-22	160	160
Forward Chassis Electronics	Position Indicator	-65	-22	185	185
Forward Chassis Electronics	Drive Controller Electronics (DCE)	-20	0	159	180
Mobility	Traction Drive	-50	-25	400	450
Mobility	Suspension Damper	-70	-65	400	450
Mobility	Steering Motor	-50	-25	360	400
Mobility	Wheel	-250	-200	250	250

*** 163 wt-hr/kg Stored Power per Battery**

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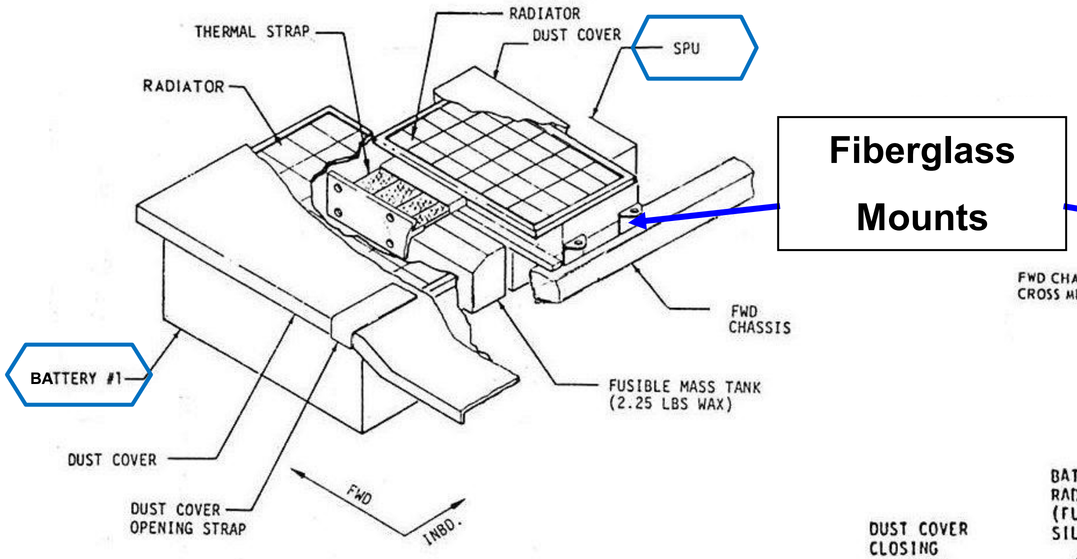
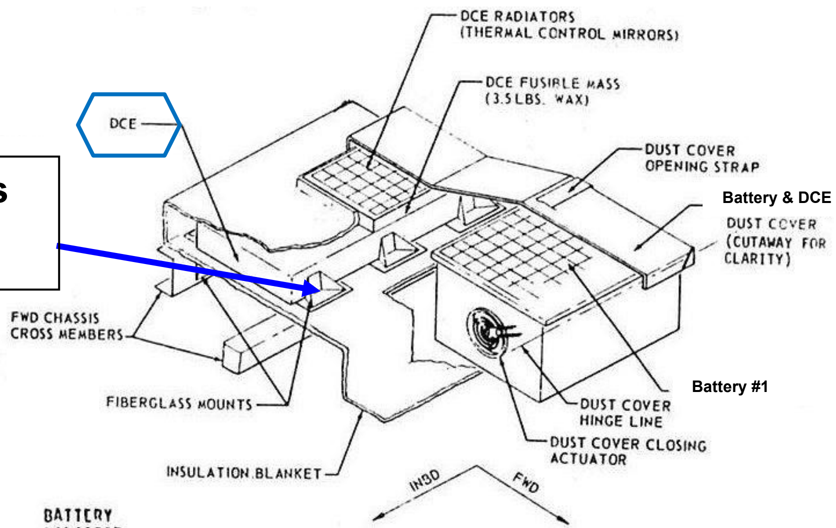
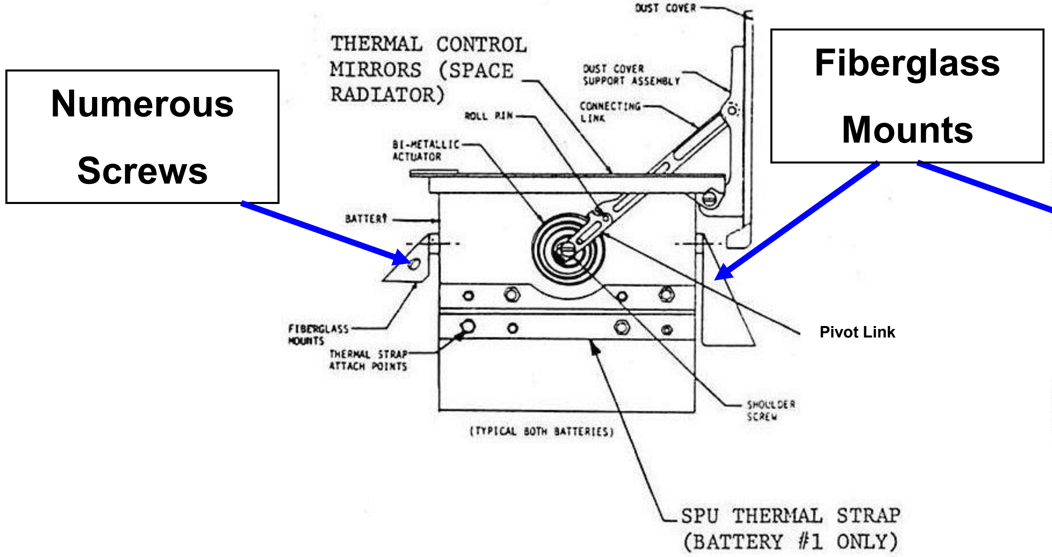
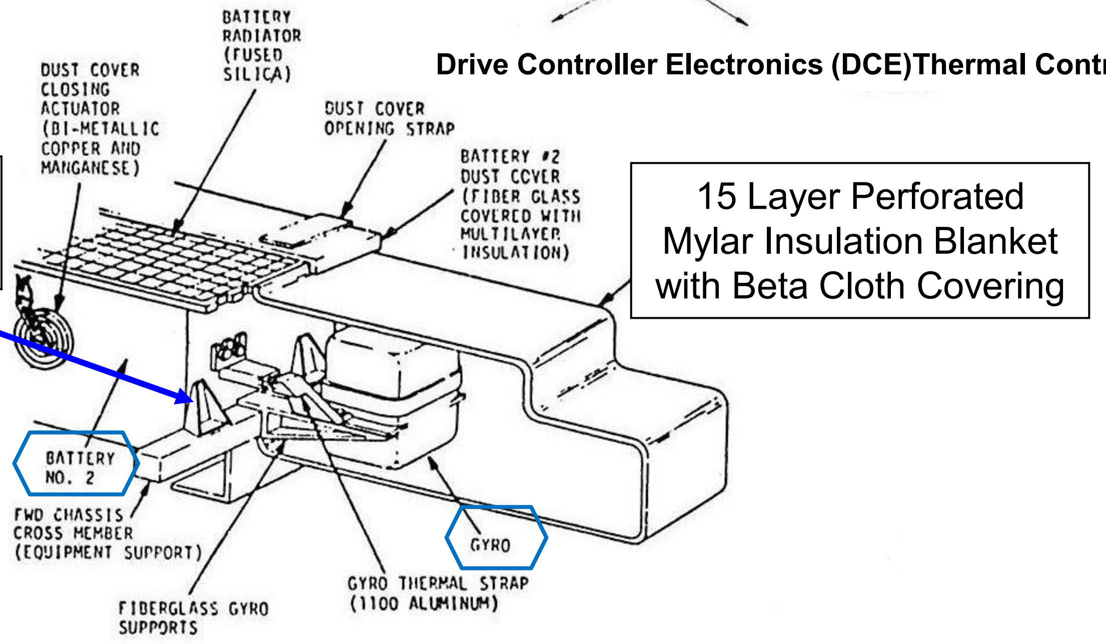
Signal Processing Unit (SPU)Thermal Control





Drive Controller Electronics (DCE)Thermal Control





Directional Gyro Unit (DGU) Thermal Control

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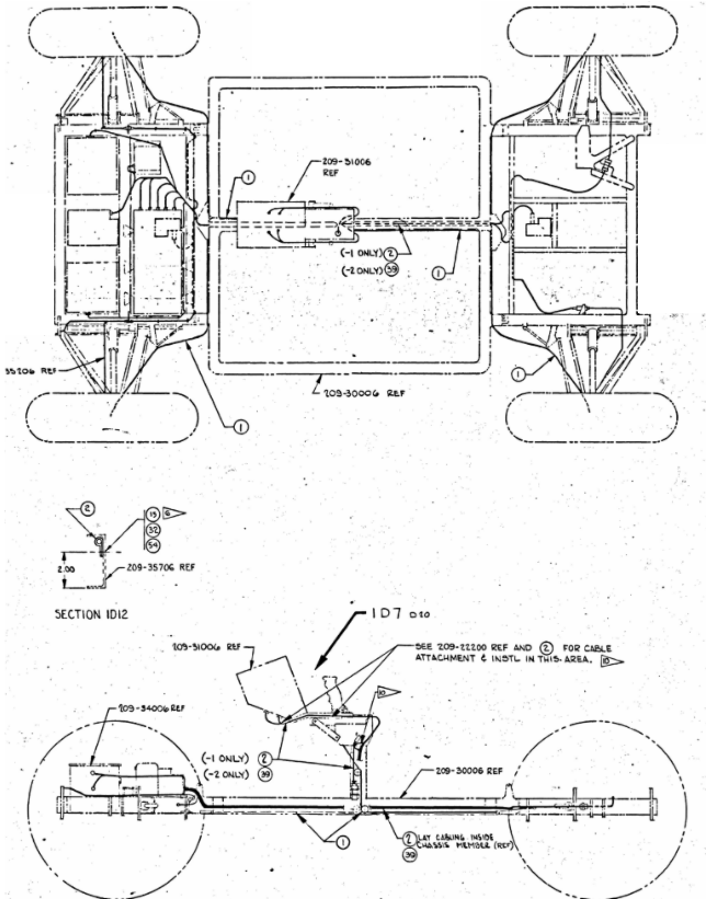
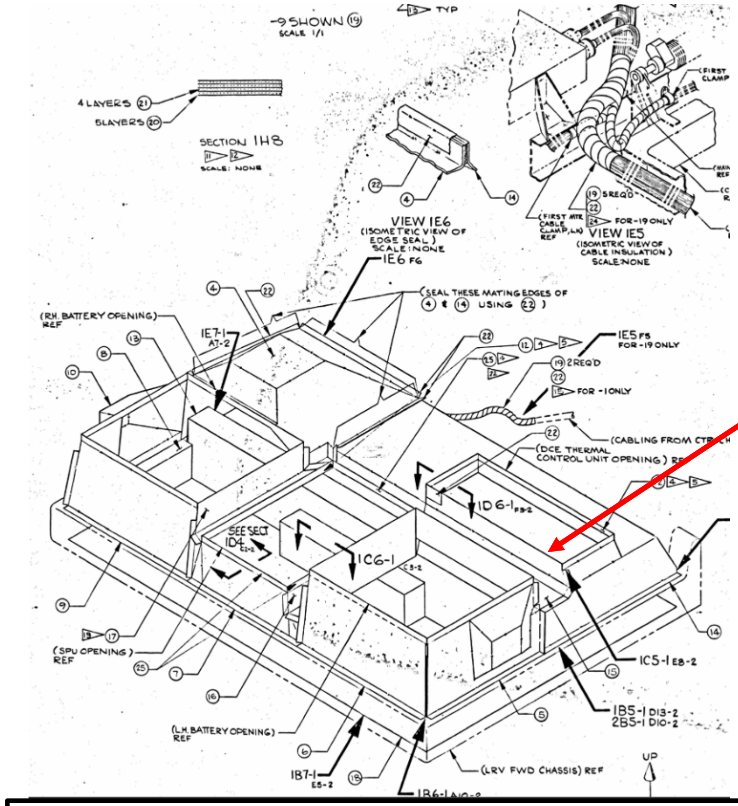
Challenge 5 - Disconnecting Cables and Reconnecting Them Later

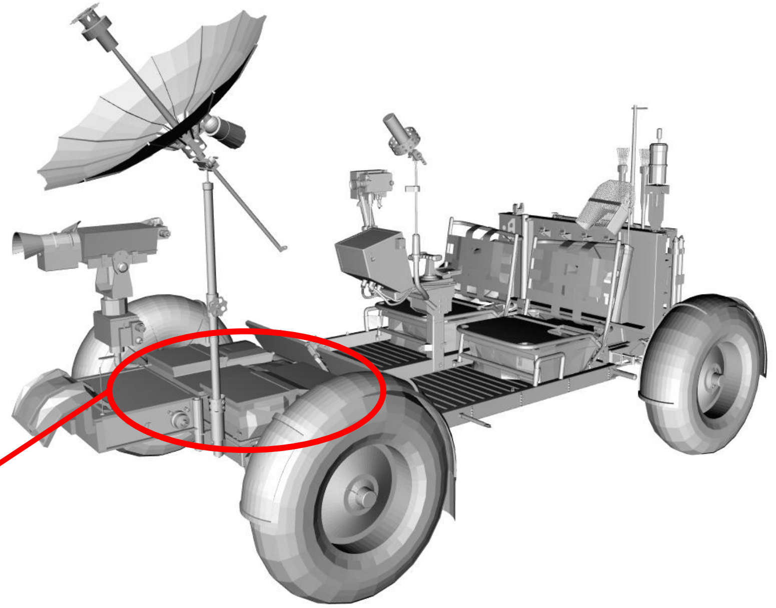
LRV Cable Runs



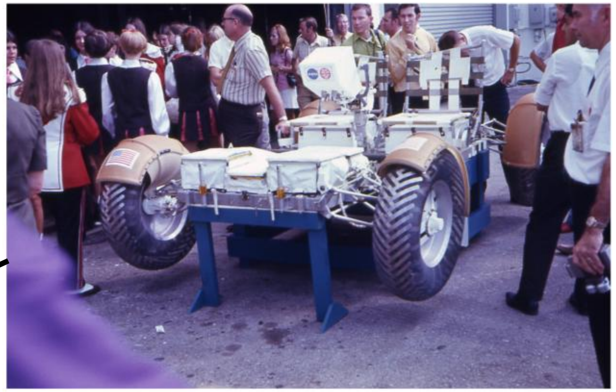
LRV Forward Chassis Cables



181 Node LRV SINDA* Thermal Model



LRV Qualification Unit is now at Smithsonian Air and Space Museum - and 4th Rover is on display at NASA Kennedy Center to help with Reuse testing



Qualification Unit at Marshall Space Flight Center after Apollo 15

* SINDA = Systems Improved Numerical Differencing Analyzer

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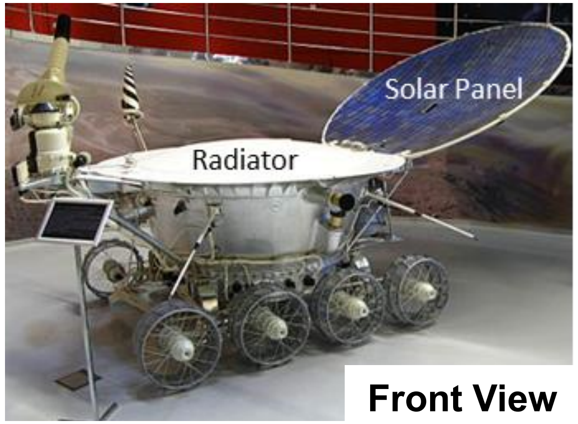
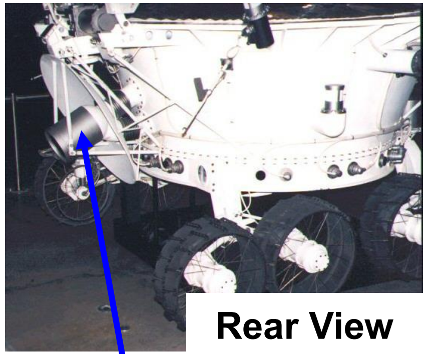
Challenge 6 - Supplying Power for LRV Electronics Nighttime Survival and Operation on the Moon

Russians Successfully Used Nuclear Isotope Heat Sources for Several Lunar Cycles on Their Two Lunokhod (Moonwalker) Robotic Rovers (1970 to 1973)



Front View



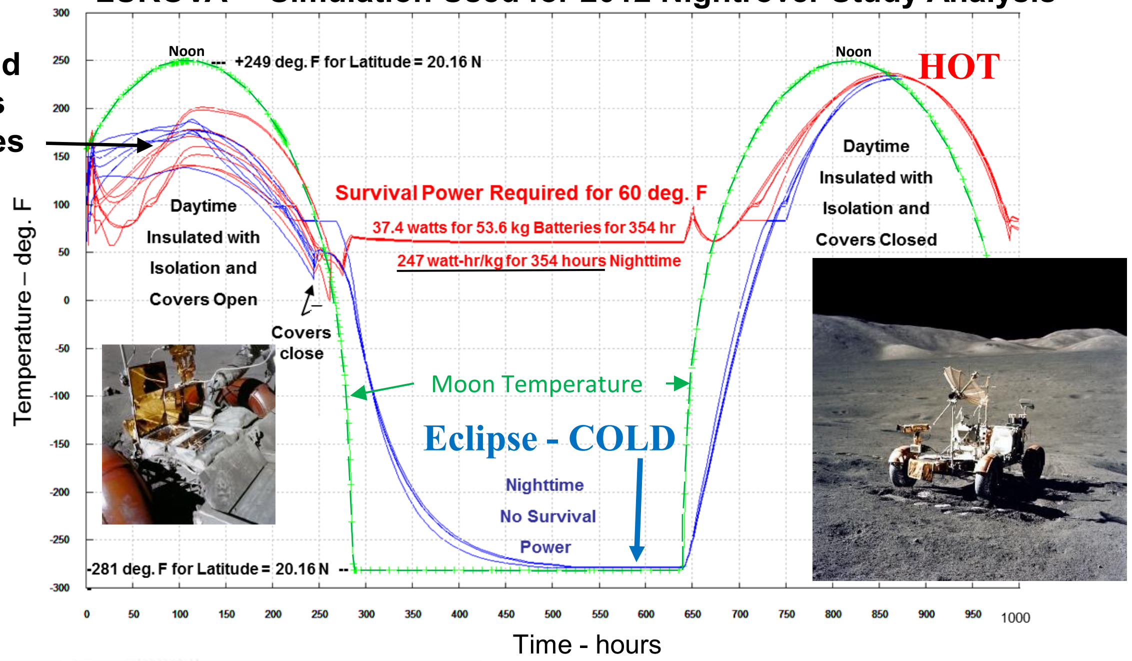
Rear View

LUNOKHOD

Isotope Heater

LUROVA™ Simulation Used for 2012 Nightrover Study Analysis

Batteries and Electronics Temperatures



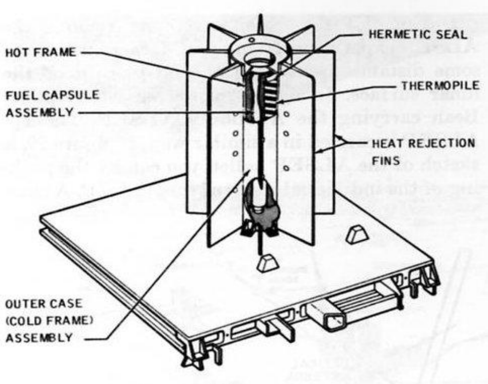
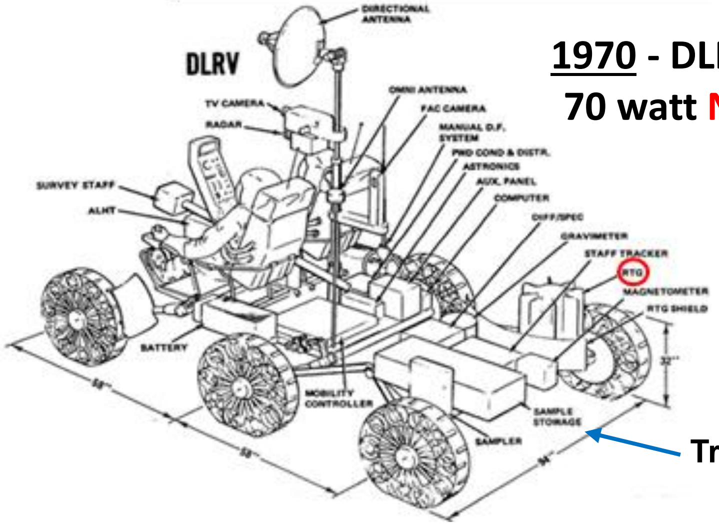


FIGURE 25.—Radioisotope Thermal Generator. This e[...] ment provides all of the power used by the ALSE furnishes continuously about 70 watts.

Five Apollo Lunar Surface Experiment Packages (ALSEPs) Survived for Several Years (1969 - 1977) Using RTGs



1970 - DLRV Dual Mode Rover Concept with a 70 watt Nuclear RTG for Cancelled Apollo 18

RTG = Radioisotope Thermoelectric Generator

Trailer Installed for Robotic Operation

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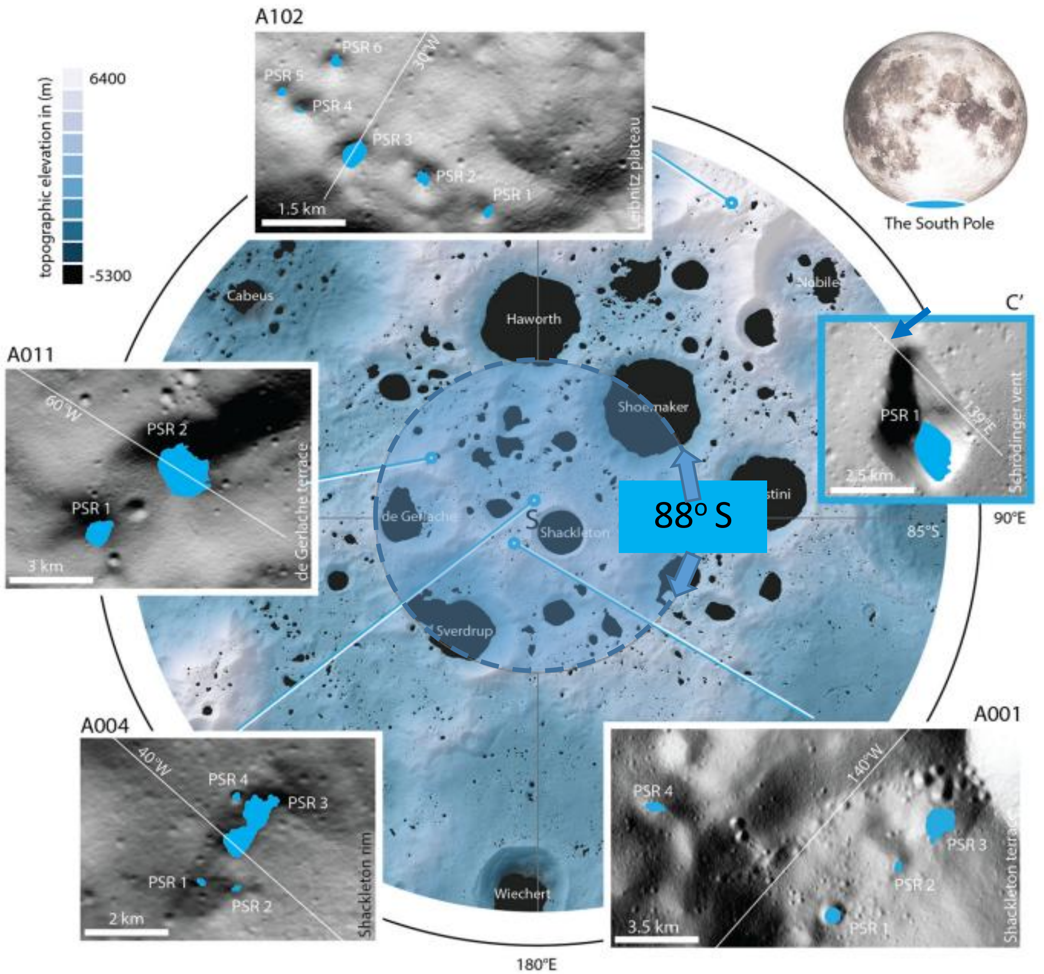
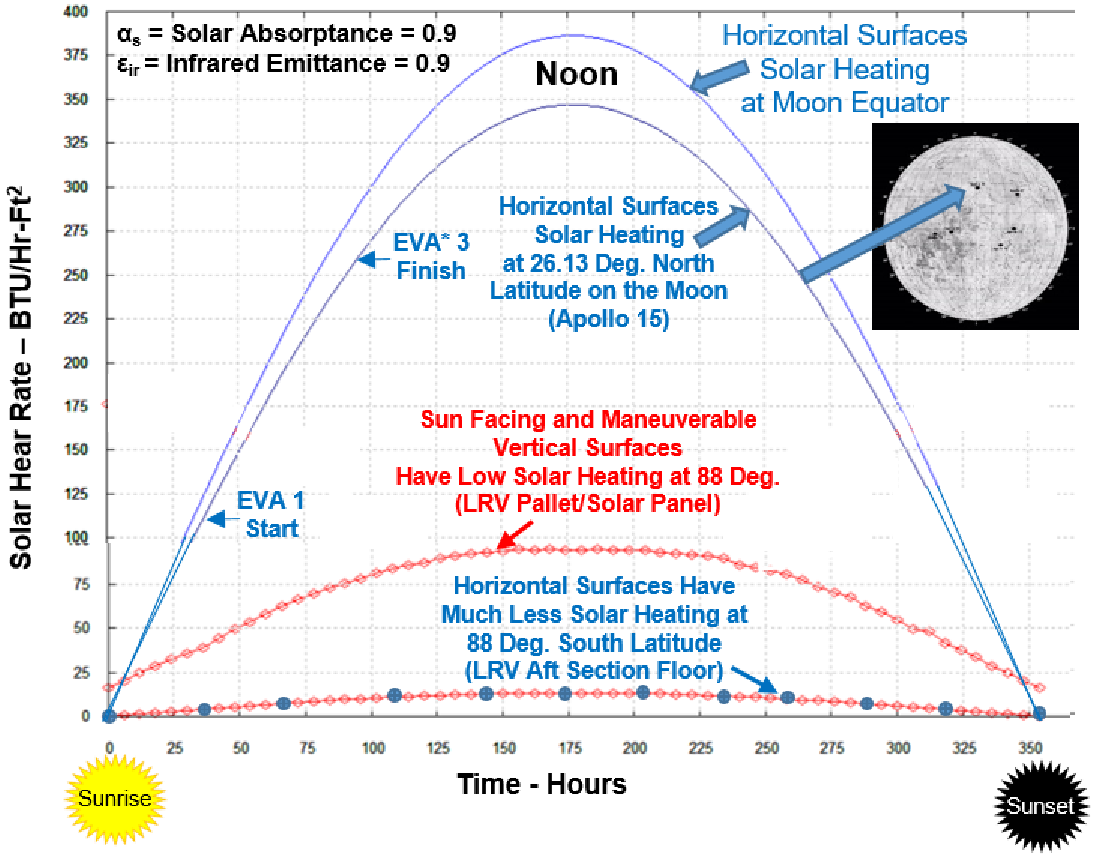
NASA Is Preparing for Candidate Lunar South Pole Permanently Shadowed Regions (PSRs)



2021 Source: "Peering into Lunar Permanently Shadowed Regions with Deep Learning" (https://www.nature.com/ articles/s41467-021-25882-z)

Much Lower Solar Heating in South Pole Region with Difficult and Risky "Chasing the Sunlight" Traverses for Providing Dependable Solar Power



* EVA = Extra-Vehicular Activity

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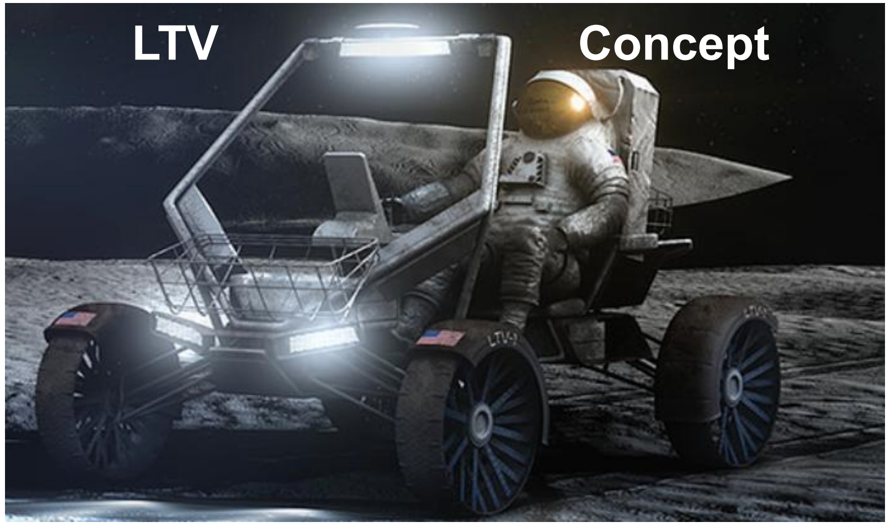
NASA Lunar Terrain Vehicle and JPL Endurance Rover Share Nighttime Exploration Objectives

Alternate Power Recommendation Presented at 2023 JPL Endurance Rover Science Workshop

LUNAR TERRAIN VEHICLE (LTV)

Single Spacecraft for Ten Year Crewed and Robotic Moon Exploration



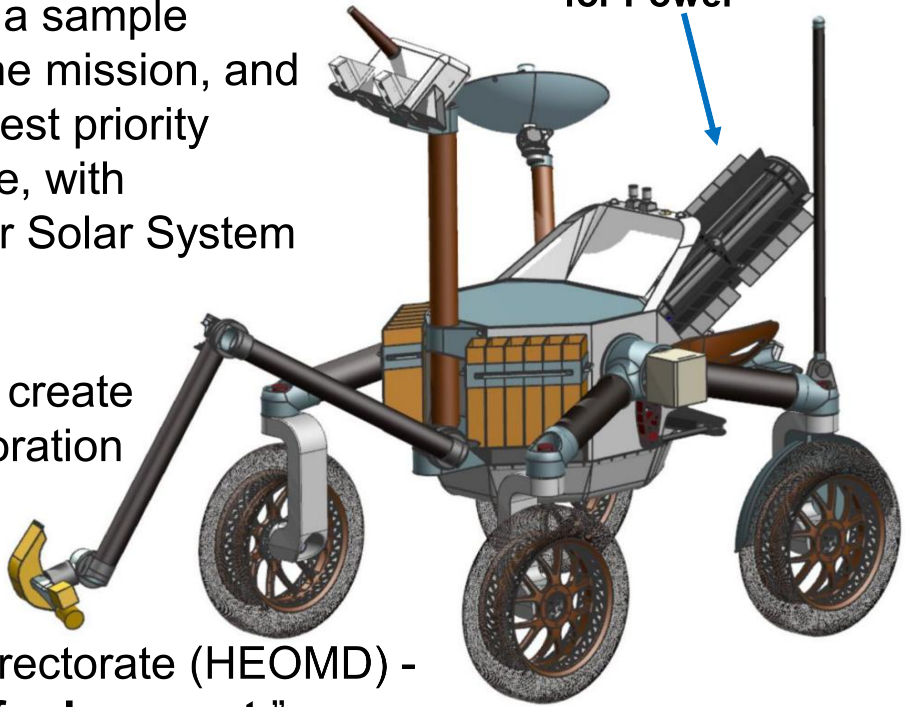
LTV **"Chasing the Sunlight"** Traverses Will Be **Difficult** and **Risky**, and Could be **Dangerous**, Especially for Emergency Need for Dependable and Immediate Energy for Transit Back to the Lunar Home Base

Requires Heavy and Maneuverable Panels for Solar Energy Collection

Endurance-A

"Endurance is effectively a sample collection campaign in one mission, and it would address the highest priority questions in lunar science, with enormous implications for Solar System science.

Endurance-A option would create a new paradigm for collaboration between NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) - **achieving more science for less cost**."



Recommendation - Combine These Rovers to Provide Dependable Exploration Power and Gain Significant Cost Savings

Additional Benefit: Reduces Size/Mass of Batteries and Solar Panels

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Summary

- Apollo Rovers Contribute 6 Component, Power, and Mobility Challenges for Reuse:
  - 1 - 54+ Year Rover Components' Exposure to Temperature Extremes

    ↕ Related?
  - 2 - Preparation for Unknown Rover Condition and Fenders and Extensions Status
  - 3 - Maintaining LRV Components Within Temperature Limits
  - 4 - Detaching and Reattaching Fiberglass Rail Mounts & Connectors for Battery Replacement
  - 5 - Disconnecting Cables and Reconnecting Them Later
  - 6 - Supplying Power for Apollo LRV Electronics Nighttime Survival and Operation on the Moon
- Alternate RTG Power Recommended for Rover Nighttime and Pole Thermal Survival on the Moon

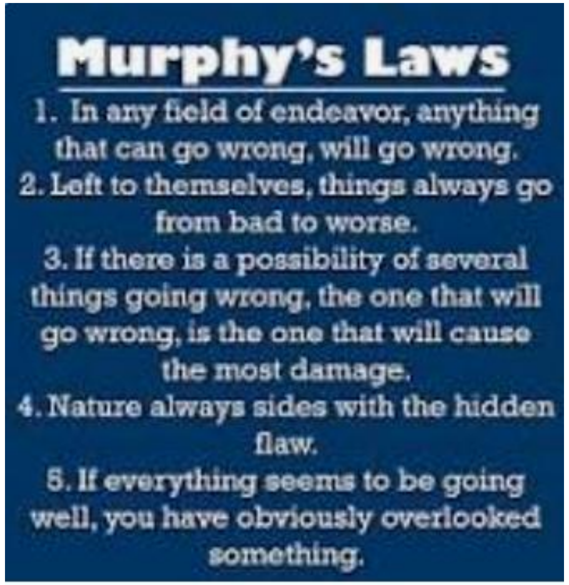
Remember Murphy's Law - "If Something Bad Can Happen, It Will"

So Always Have Backups!

We Certainly Don't Want Another "Houston We Have A Problem"

Call from a Rover Crew on the Moon!

And Please Remember to Always Capitalize "Moon"



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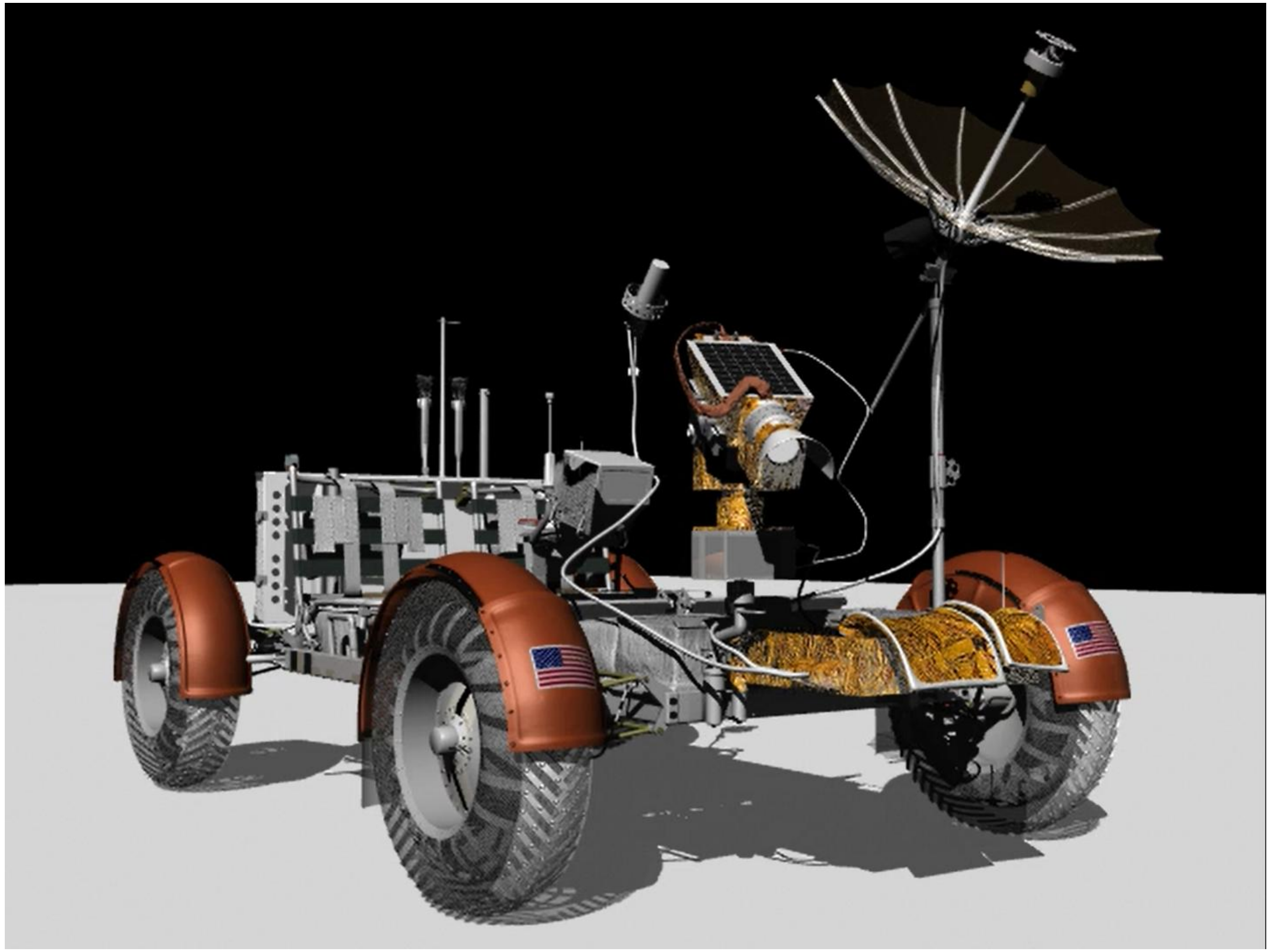
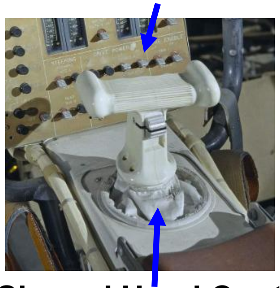
Backup



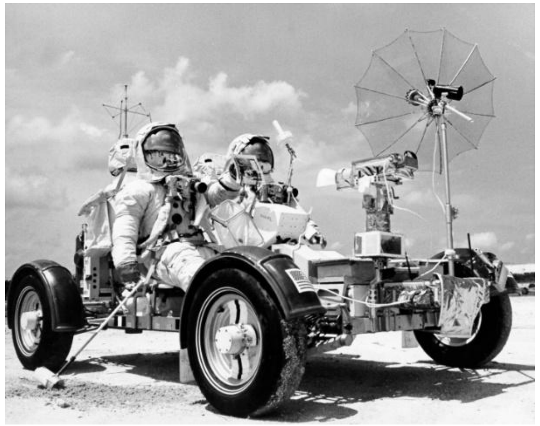
Apollo Astronauts Provided Valuable Assistance for LRV Crew Station Configuration and Component Testing

NASA Astronauts Had a Vested Interest in Development of the LRV - Shown Here are Left to Right Young, Cernan, Haise, Duke, England, Fullerton, Peterson

Protective "Gold" Display Console Front Cover Plate for Earth Handling



"T" Shaped Hand Controller to Fit Astronaut Glove



Practicing Driving Sample Collection

"One-G" Trainer Provided Simulation of <u>All</u> LRV Interfaces

After Apollo 15, the Crew Signed Autographs for NASA Employees

Folded LRV Stowed in Lunar Module with Floor Panels Removed for On-pad Battery Installation

Apollo 15 Crew Checking Out Their Installed LRV

Astronaut "Silver Snoopy" Awarded for Thermal Modelling after Apollo 16 in July, 1972

Astronauts Appreciated Timely and Accurate LRV Thermal Modeling

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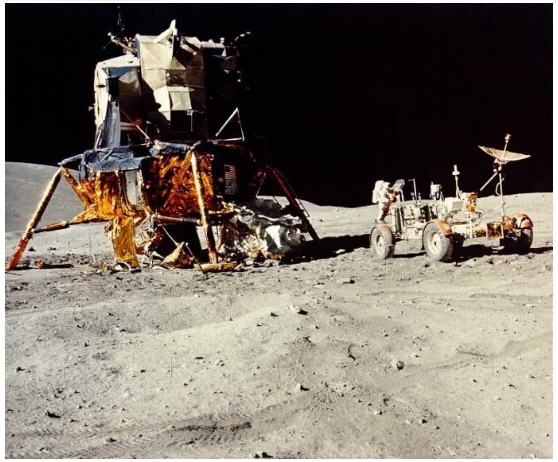
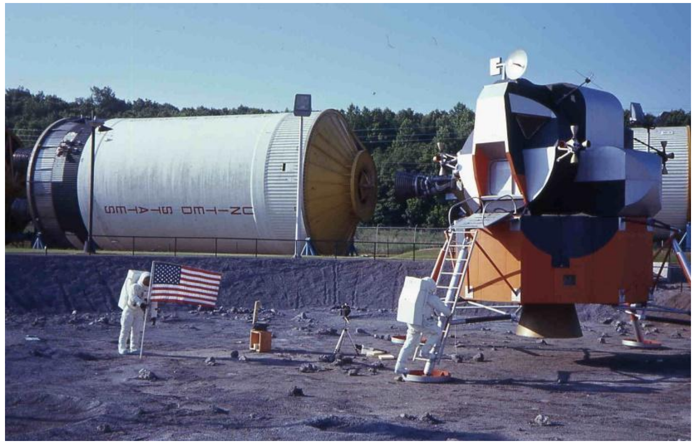
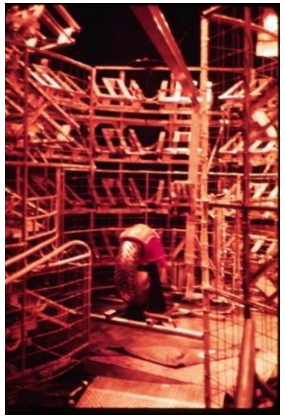
Post Apollo 16 - LM Parking Proximity Constraint Changed, and TVAC Fender Testing



LRV Parked Too Close to LM



Battery Proximity Test at U.S. Space and Rocket Center



Re-designed Fender Extension TVAC Deployment Test at MSC

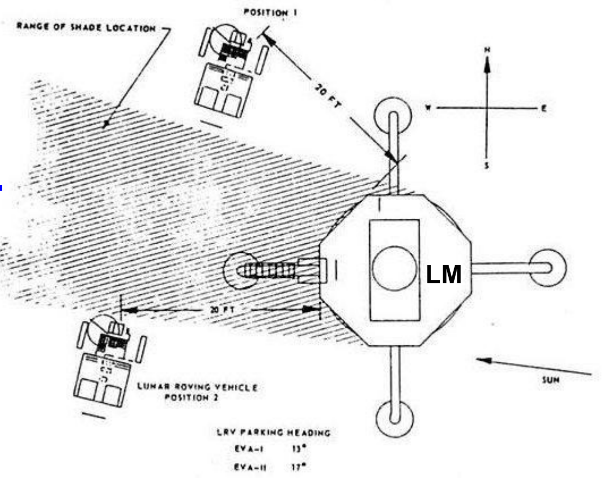
Additional "Switch and Meter Failures" were Not Repeated in Thermal Testing in Redstone Arsenal Army Thermal Test Chamber using the LRV Qualification Unit, so no fix was made for Apollo 17, which had non-critical repeats.

Form Factometer Photographed to Validate Model "View Factors" to LM

FWDCHA Computer Model

Shadow Constraints

The LRV must not be parked in lunar shadow for longer than two hours to prevent low temperature damage to the electronics in the control and display console. Circuit breaker minimum reset time is 1 minute.



Parking Constraint Changed for Apollo 17

Ron With LM and LRV Vibration Test Unit at U.S. Space and Rocket Center

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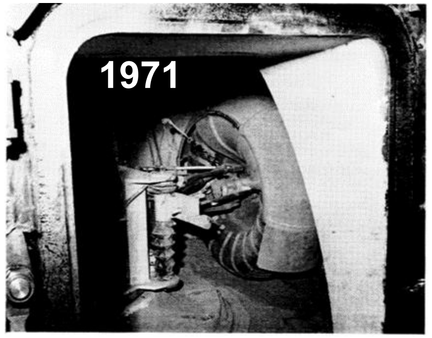
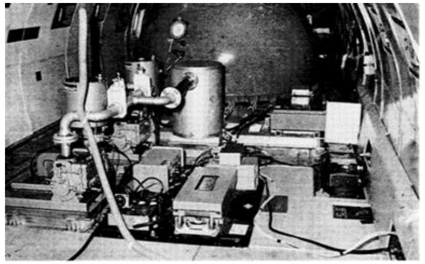
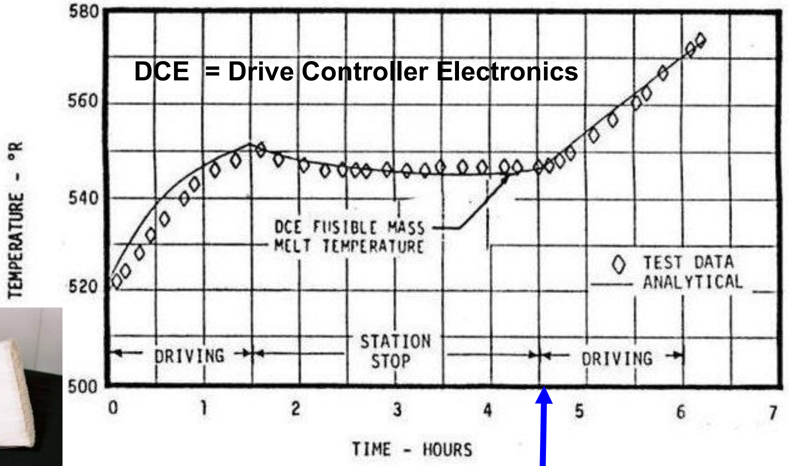
Rover Thermal Models Were Correlated with Extensive Thermal Vacuum (TVAC) Testing Data



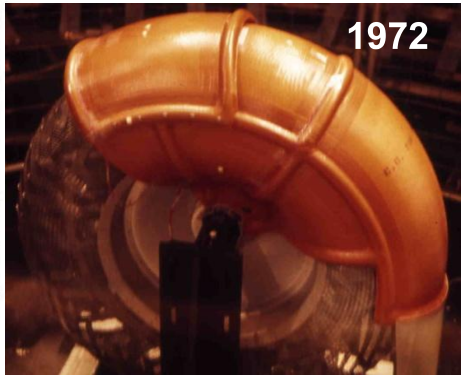


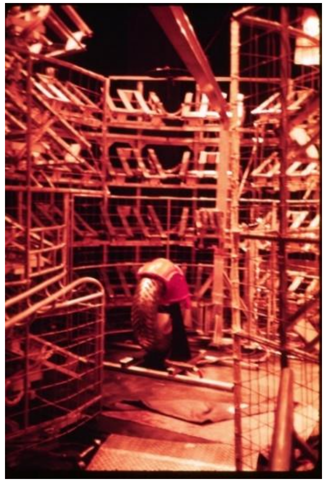
KC-135 Vacuum / Reduced Gravity Tests Verified the Need for Fenders Radiator **Dust Brush** Cleaning Also Tested at MSC* Using Apollo 12 Soil, but Did **NOT** Work on the Moon

Lunar **Dust** Brush

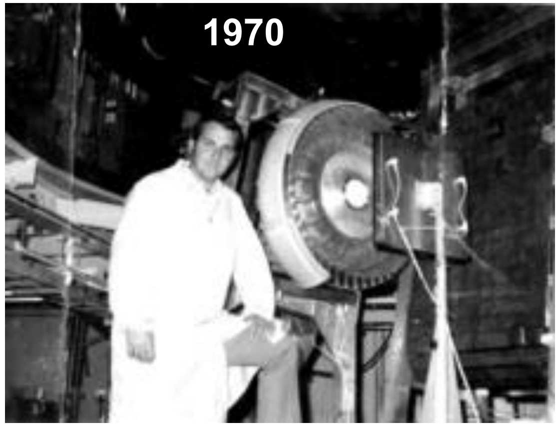


DCE TEST DATA CORRELATION



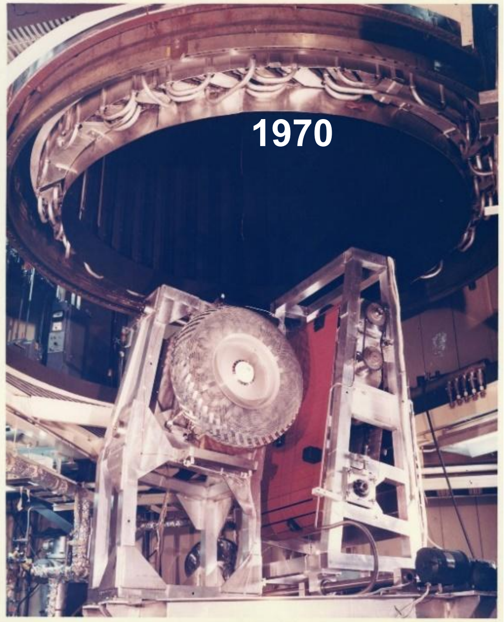


Fender Extension Deployment TVAC

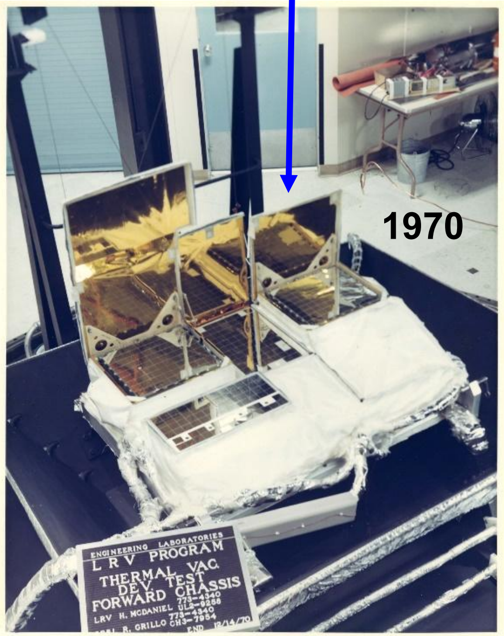


Ron Creel with Rover Mobility "M/4" Thermal Test Unit

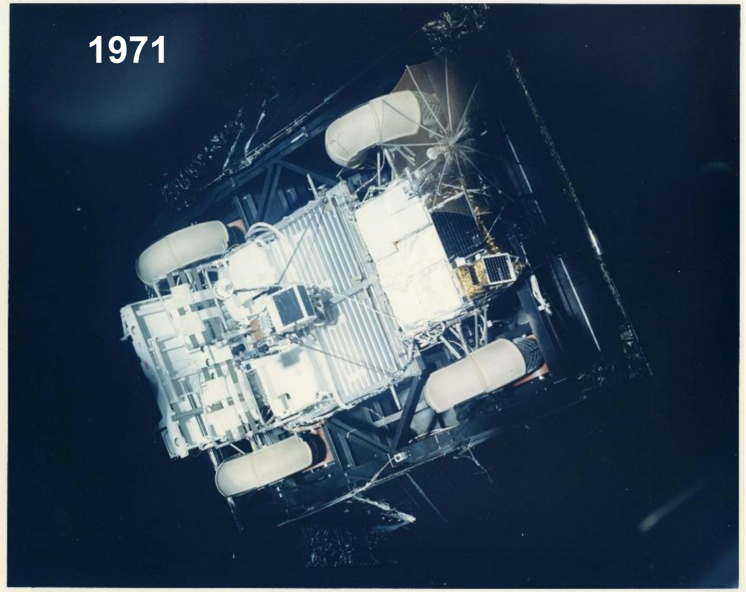
* MSC = Manned Spacecraft Center



Mobility Subsystem TVAC



Forward Chassis Thermal Development "Tub" TVAC



Qualification and Flight Units TVAC

Backup Page 3

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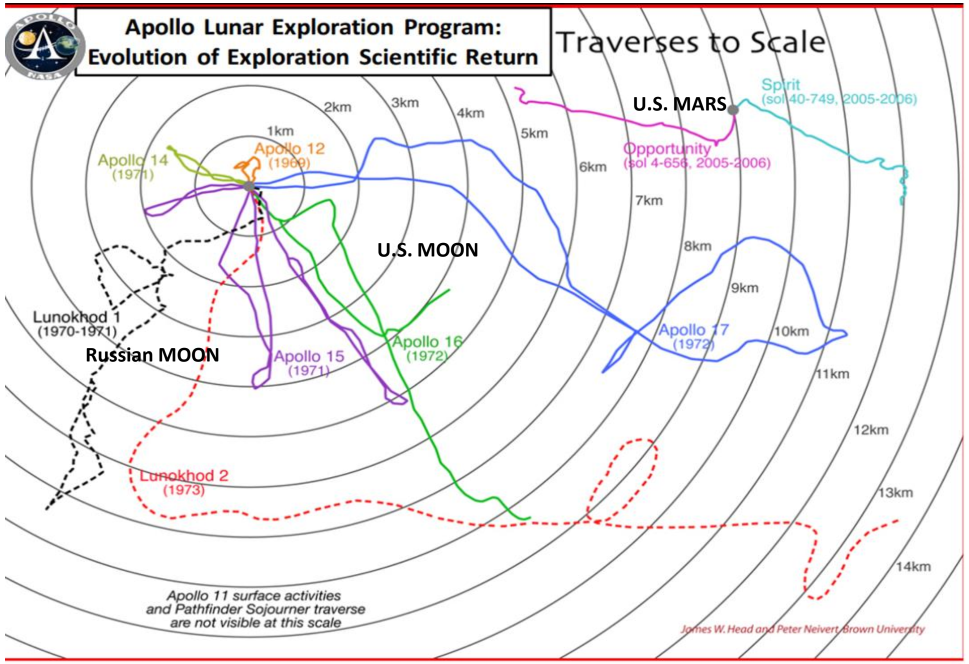
Apollo LRV Performance Comparison and Apollo 17 Wheel Condition after Driving 35.7 km (22.2 mi) on the Moon



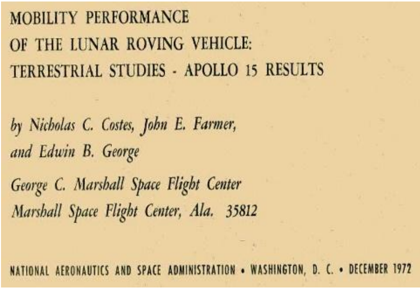
	Pre - LRV	Apollo 15	Apollo 16	Apollo 17
EVA Duration (hrs:min)	19:16	18:33	21:00	22:06
Driving Time (hrs:min)	–	3:02	3:26	4:29
Surface Distance Traversed (km)	3.55	27.9	26.9	35.7
Average Speed (km/hr)	0.18	9.20	7.83	7.96
Longest Traverse (km)	–	12.5	11.6	20.3
Maximum Range From LM (km)	–	5.4	4.5	7.6
Regolith Samples Collected (kg)	97.6	77.6	96.7	116.7

LRV Performance Comparison on the Moon

Range - The LRV will be capable of performing four 30 km traverses in a 78 hour period for a total of 120 km.

Test and Flight Correlated 19 Node LUROVA™ Thermal Model Provided Excellent Thermal Monitoring and Predictions

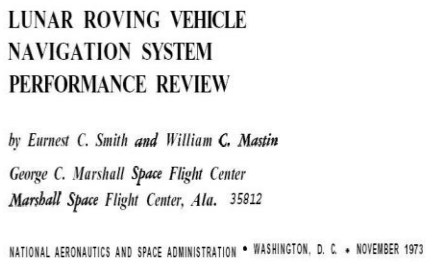
Mobility and Navigation Performance Documents


MOBILITY PERFORMANCE
OF THE LUNAR ROVING VEHICLE:
TERRESTRIAL STUDIES - APOLLO 15 RESULTS

by Nicholas C. Costes, John E. Farmer, and Edwin B. George

George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1972


LUNAR ROVING VEHICLE
NAVIGATION SYSTEM
PERFORMANCE REVIEW

by Eurnest C. Smith and William C. Mastin

George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1973

Apollo Lunar Surface Journal (ALSJ) is Another Good LRV Reference

Final Close- Up View of Apollo 17 Left Rear Wheel with Fender Extension Removed

All LRV components remained within operational temperature limits throughout the surface EVAs on all 3 Missions.
As Predicted, Drive Motor Temperatures were “Off Scale Low” (below 200 deg. F) throughout most of the EVAs.
The Maximum Motor Temperature of 270 deg. F occurred during the longest driving period in EVA 3 on Apollo 17

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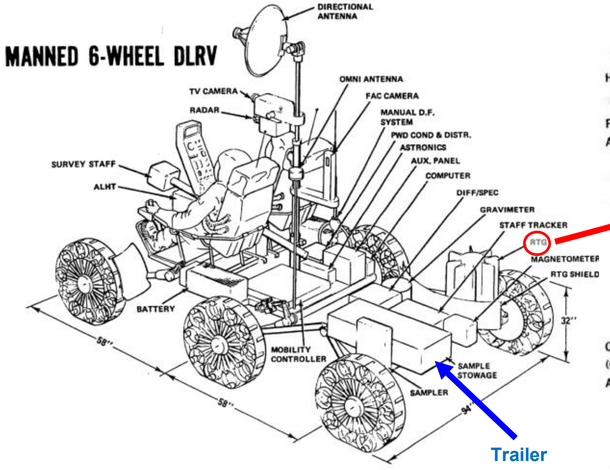
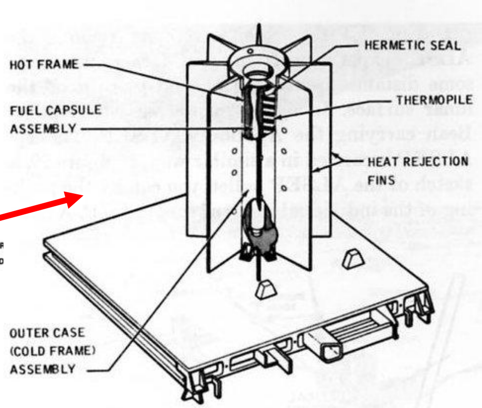
Nuclear Energy Provided Dependable/Efficient Moon Survival Power/Heat

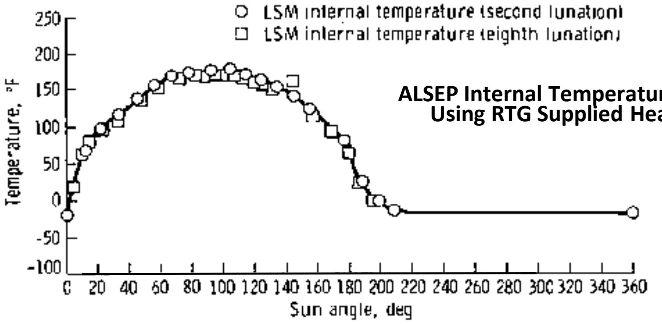
• **Nuclear Sources Used on ALSEPs and Studied for U.S. Apollo 18 Dual Mode Rover (DLRV)**

Lunokhod Wheel Gears



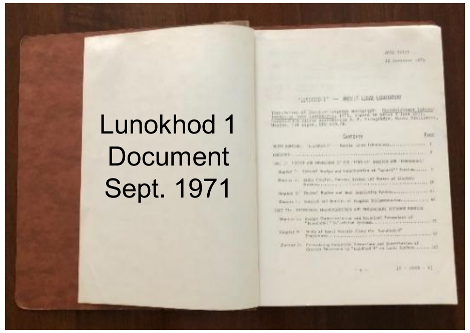


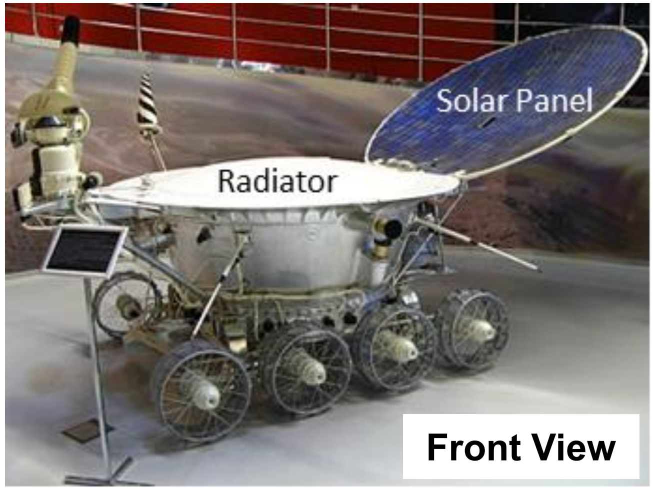
SNAP-27 -Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.



ALSEP Internal Temperatures Using RTG Supplied Heat

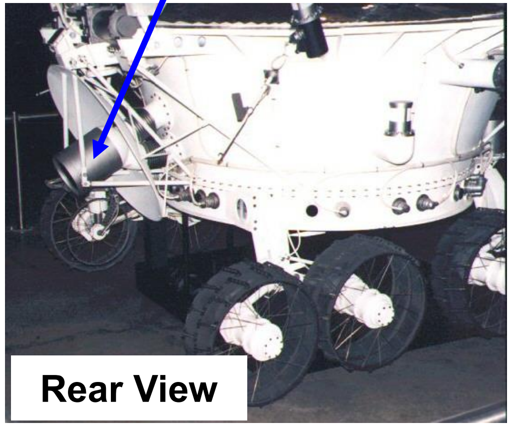
Russians Successfully Used Nuclear Isotope Heat Sources for Several Lunar Cycles on Their Two Lunokhod (Moonwalker) Robotic Rovers (1970 to 1973)





LUNOKHOD

Isotope Heater



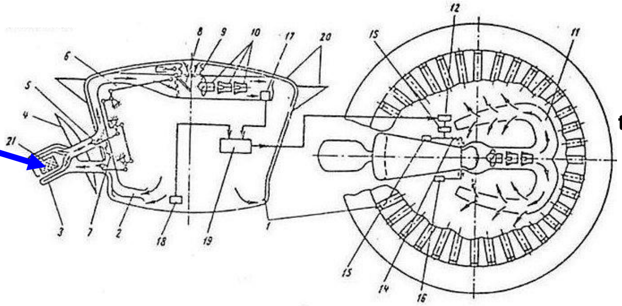
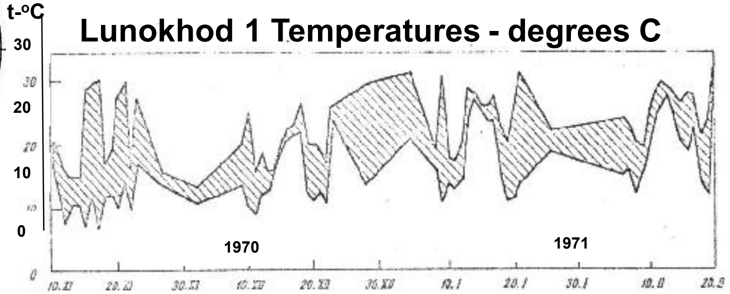


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism; 14) spring traction; 15) cam mechanism; 16) angular movements sensor; 17) SE1 sensing element; 18) SE2 sensing element; 19) radiator-cooler; 20) collector of HU blow-off system; 21) fuel cell.

For monitoring the thermal regime aboard the lunokhod there are telemetric temperature sensors which make it possible to obtain routine information on the temperatures of all lunokhod systems during any communication session.

Lunokhod 1- Mobile Lunar Laboratory

Lunokhod 1 Temperatures - degrees C



Gas temperature in "Lunokhod 1" instrument compartment plotted data. The shading corresponds to the temperature range based on several measurements.

The results of Lunokhod operation on the Moon confirmed the high reliability of the vehicle's chassis. Over a five month period, the undercarriage did not experience a single mechanical failure, thereby demonstrating the probability of establishing a highly reliable chassis for lunar conditions.

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* ALSEP = Apollo Lunar Surface Experiment Package