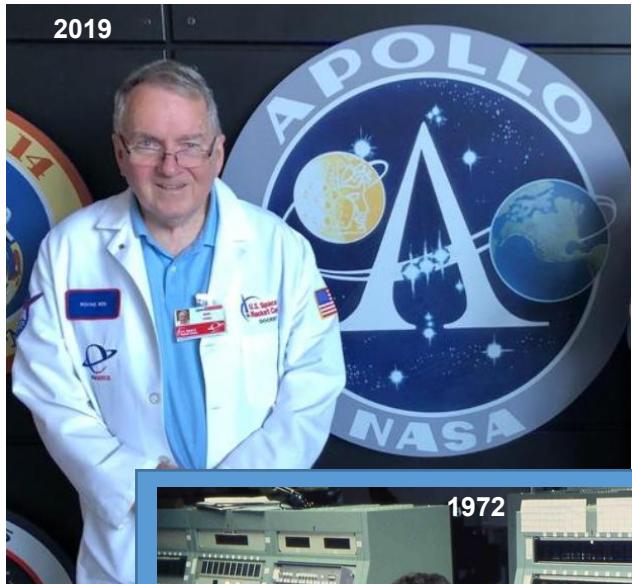
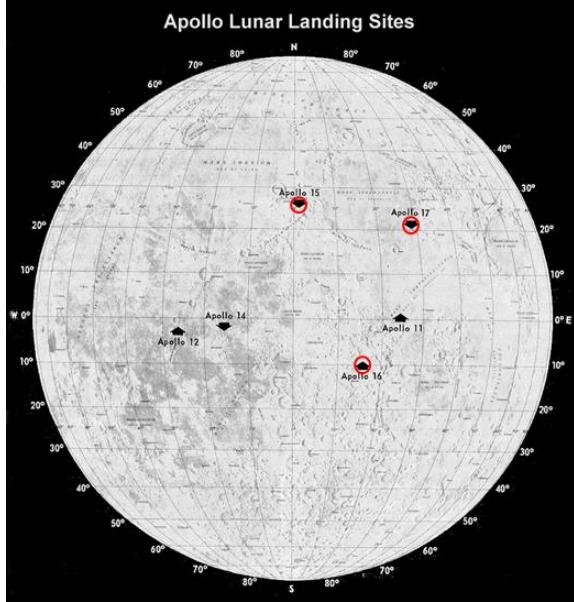


Challenges for Potential Reuse of Apollo Lunar Rovers



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

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

Apollo Lunar Rover

With the amazing successes and ever increasing skills learned from the 1st 3 Apollo landings on the Moon, NASA decided to make the next flights, Apollo 15, 16 and 17, more ambitious. Landing sites were no longer smooth and featureless. The US Apollo Lunar Module (LM) had much longer to stay on the lunar surface. To extend the astronauts exploration area on the moon, the first Lunar Roving Vehicle (LRV) was designed, tested, and completed in just 17 months by a team of several hundred dedicated workers. Three flight rovers, plus 7 test and training units along with spare parts for a fourth flight unit, were built by the Boeing Company, Aerospace Group at their Kent Space Center, outside Seattle, Washington under contract to the NASA-Marshall Space Flight Center. AC Delco Electronics Division Laboratories of General Motors in Santa Barbara, California, was the primary mobility system subcontractor.

The battery powered rover proved to be an extremely dependable vehicle allowing the astronauts to explore many square miles away from their landing sites with ease and safety. The onboard television camera, remotely controlled from the ground, allowed viewers on Earth to become a third astronaut and join in the excitement of each Extra-Vehicular Activity (EVA).



LRV Wheels

Each of the Rover's four wheels was comprised of a seven aluminum hub that contained a titanium bump stop inside the tire. The tires were a woven mesh of zinc-coated piano-wire mesh. The hub and rim were machined to the tire's outer circumference. Each wheel weighed 2 lunar lbs and was designed for a driving distance of 180 kilometers.

Radiators

Thermal control of the LRV was accomplished by semi-passive means to ensure that component operating temperatures did not exceed safe limits. While driving, heat dissipated in the electronics located in the forward chassis area was stored in the rear of the vehicle. The heat was then contained within insulation protected by dust covers. As shown in these images at the end of each EVA, the dust covers were removed and the heat and stored heat was allowed to be radiated away using the two radiators. When the batteries reached a lower level, the dust covers were closed automatically, preventing additional cooling from taking place, and protecting the radiators from dust collection during the next driving period.



Television Camera

At science station stops, the crew aligned the high gain antenna to point back to Earth so television signals could be transmitted. The television camera was then remotely controlled from the Earth. To track and televise the LM during the landing, the astronauts had to be anticipating the landing and the time when the LM would be in the best position to be tracked. The astronauts had to be anticipate and adjust 3 seconds ahead of time because the signal travel time between the Earth and Moon.



Communications

The range from which the astronauts could operate from the Lunar Module during EVA traverses was extended by the suitcase sized device called the Lunar Roving Communications System (LRCS). The LRCS could be carried or mounted on the front of the LRV. It acted as a portable relay station for voice, TV, and telemetry directly between the crew and Mission Control.

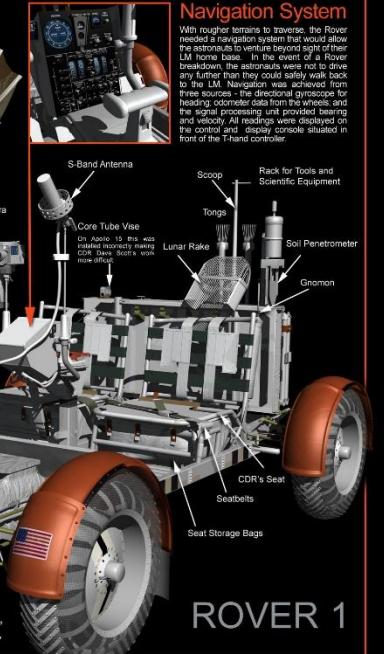
The LRC had its own S-band transmitter and receiver, though it also had a relay function provided by the LRC on Apollo 16 and 17. While traveling on the rover, the astronauts voice communication was done through the on-board low gain S-band antenna and the LCRU.

"This rover is remarkable"
CDR Dave Scott, Apollo 15

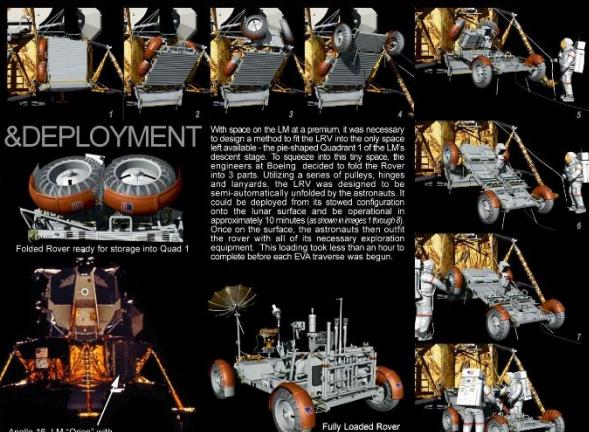
"Truly an amazing vehicle"
CDR John Young, Apollo 16 "...it handles just the way as advertised, maybe even better"
CDR Gene Cernan, Apollo 17

Navigation System

With rougher terrains to traverse, the Rover needed a navigation system that would allow the astronauts to venture beyond sight of their LM. In the event of a problem with the Rover breakdown, the astronauts were not to drive up to the LM, they could still walk back to the LM. Navigation was provided from three sources: the directional gyroscope for orientation, the star sensor for alignment, and the signal processing unit provided bearing and velocity. All readings were displayed on the control and display console situated in front of the Flight controller.

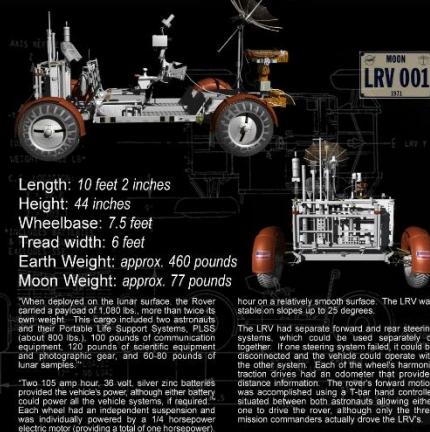


STOWAGE & DEPLOYMENT



Special thanks to Karl Dosthoff and Ron Cress for their support and assistance in the construction of this model.
Design layout, 3D imagery ©2005 Don H. McMillan, unless otherwise noted, written by Don H. McMillan and Ron Cress. All other images courtesy of NASA.

GENERAL DESCRIPTION



This poster is dedicated to the several hundred workers who designed, built and tested this marvelous machine; to the astronauts who delivered and drove the rovers on the moon; and to my parents, Ruth and Bill, who showed me Apollo firsthand in July of 1971.

LUNAR ROVER MISSIONS J-SERIES

The J Series Lunar Modules (LM) allowed a much longer 78 hour stay on the lunar surface. The LRVs were deployed with 3 separate EVAs lasting approximately 7 hours each. Additional consumables were required for the longer stay as well as additional propellant to land with the increased payload which included the Lunar Roving Vehicle (LRV).

Apollo 15 - July 26 - August 7, 1971
CDR Dave Scott, LMP Jim Irwin, CMP Al Worden
Landed in the moon's Sea of Rains in the Hadley-Apennine region at Latitude - 26.10 deg. N and Longitude - 38.5 deg. E



The astronauts stayed a total of 69.6 hours on the lunar surface and traveled a distance of 17.5 miles on the rover during 3.0 hours of driving. Their three EVAs were 7.5 hours long, 1.5 hours of science, and 1.5 hours of Heavily Rode.



and collected 171 lbs. of lunar regolith material.

Apollo 16 - April 16 - 27, 1972
CDR John Young, LMP Charlie Duke, CMP Ron Evans
Landed in the moon's Taurus Littrow region at Latitude - 8.99 deg. S and Longitude - 15.5 deg. E



The astronauts stayed a total of 71 hours on the lunar surface and traveled a distance of 16.7 miles on the rover during 3.4 hours of driving. Their three EVAs were 7.5 hours long, 1.5 hours of science, and 1.5 hours of Heavily Rode.

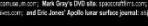


They collected 213 lbs. of lunar-regolith material.

Apollo 17 - December 5 - 19, 1972
CDR Gene Cernan, LMP Harrison Schmitt, CMP Ron Evans
Landed in the moon's Taurus Littrow region at Latitude - 20.16 deg. N and Longitude - 38.45 deg. E



The astronauts stayed a total of 72.2 hours on the lunar surface and traveled a distance of 22.2 miles on the rover during 3.0 hours of driving. Their three EVAs were 7.5 hours long, 1.5 hours of science, and 1.5 hours of Heavily Rode.

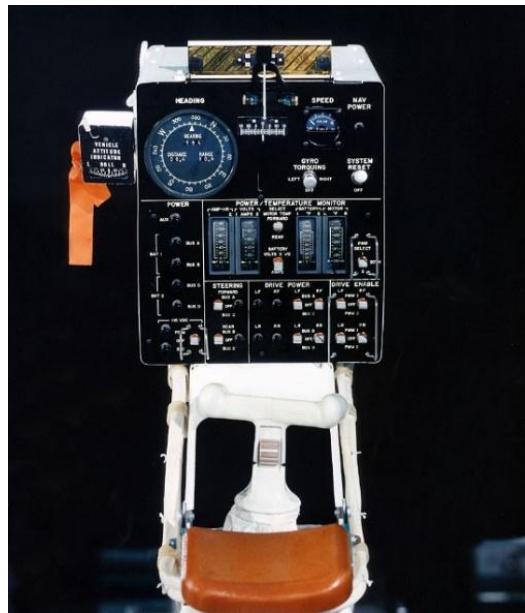


For further information about the Rover and the Apollo program visit these websites: [NASA website](http://www.nasa.gov); [Mark Shay's DMS site](http://www.apollo11.com); [SpaceRef](http://www.apollo11.com); [Eric Jones' Apollo surface journal](http://www.apollo11.com); [Eric Jones' Apollo surface journal](http://www.apollo11.com).

Poster Created By Don McMillan

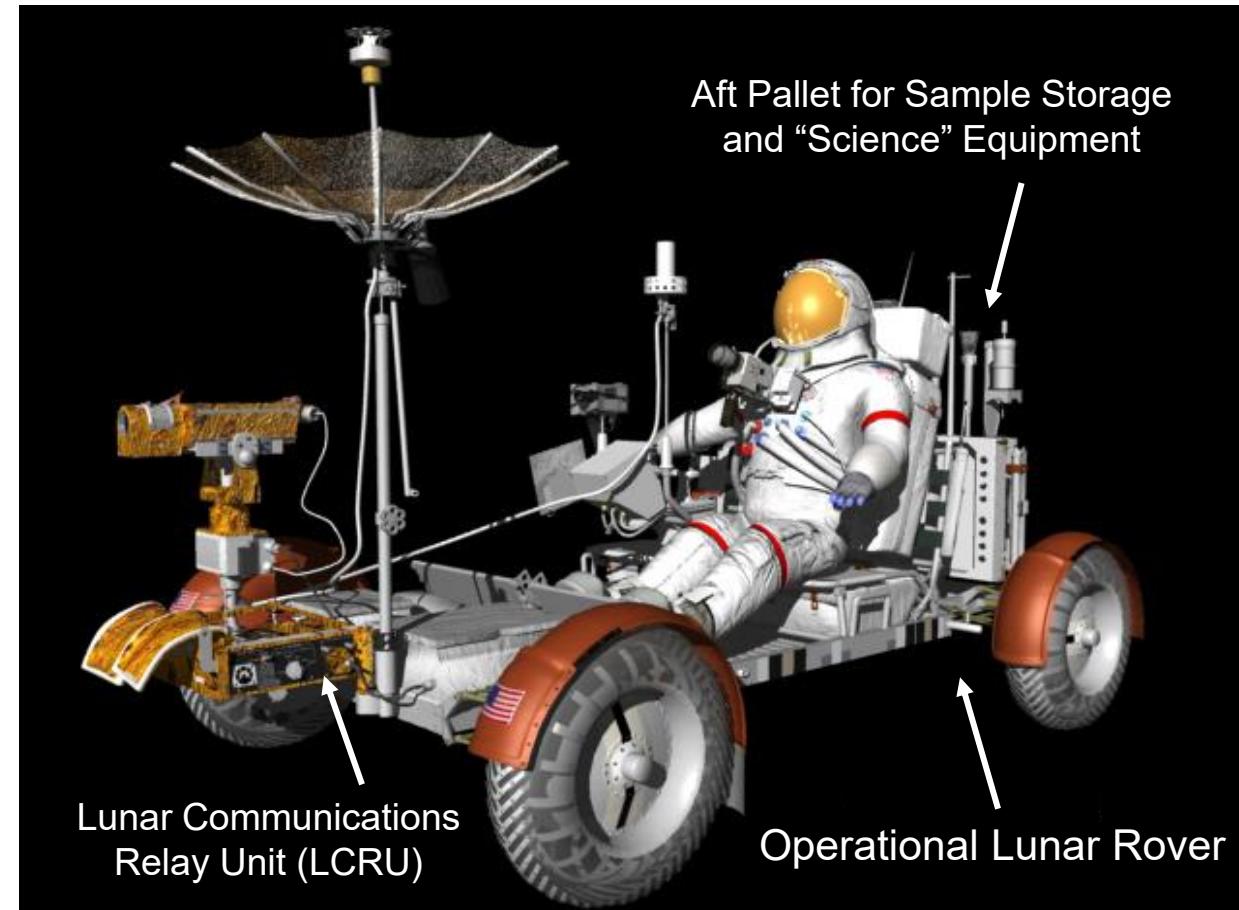
Apollo Rovers Contribute 6 Component, Power, and Mobility Challenges for Reuse

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



Forward Chassis Electronics

Insulate / **Isolate** from Dust

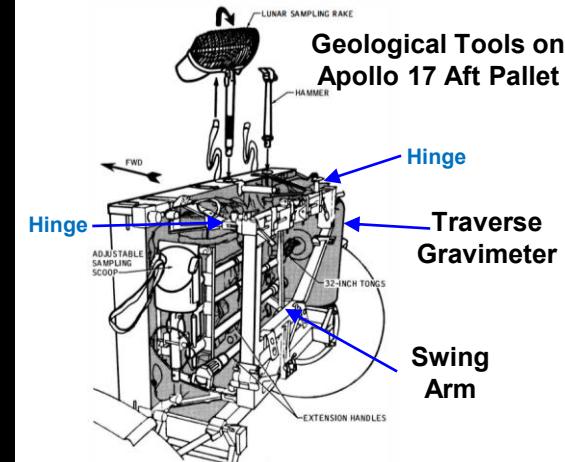
Store Generated Heat in

Batteries and Wax Boxes

Radiator Dust Covers

Opened Back at the LM

Aft Pallet for Sample Storage and "Science" Equipment



Three Different Aft Pallet Configurations

Maintain All Surfaces Within Astronaut Touch Constraints as Replacements are Made

Mobility

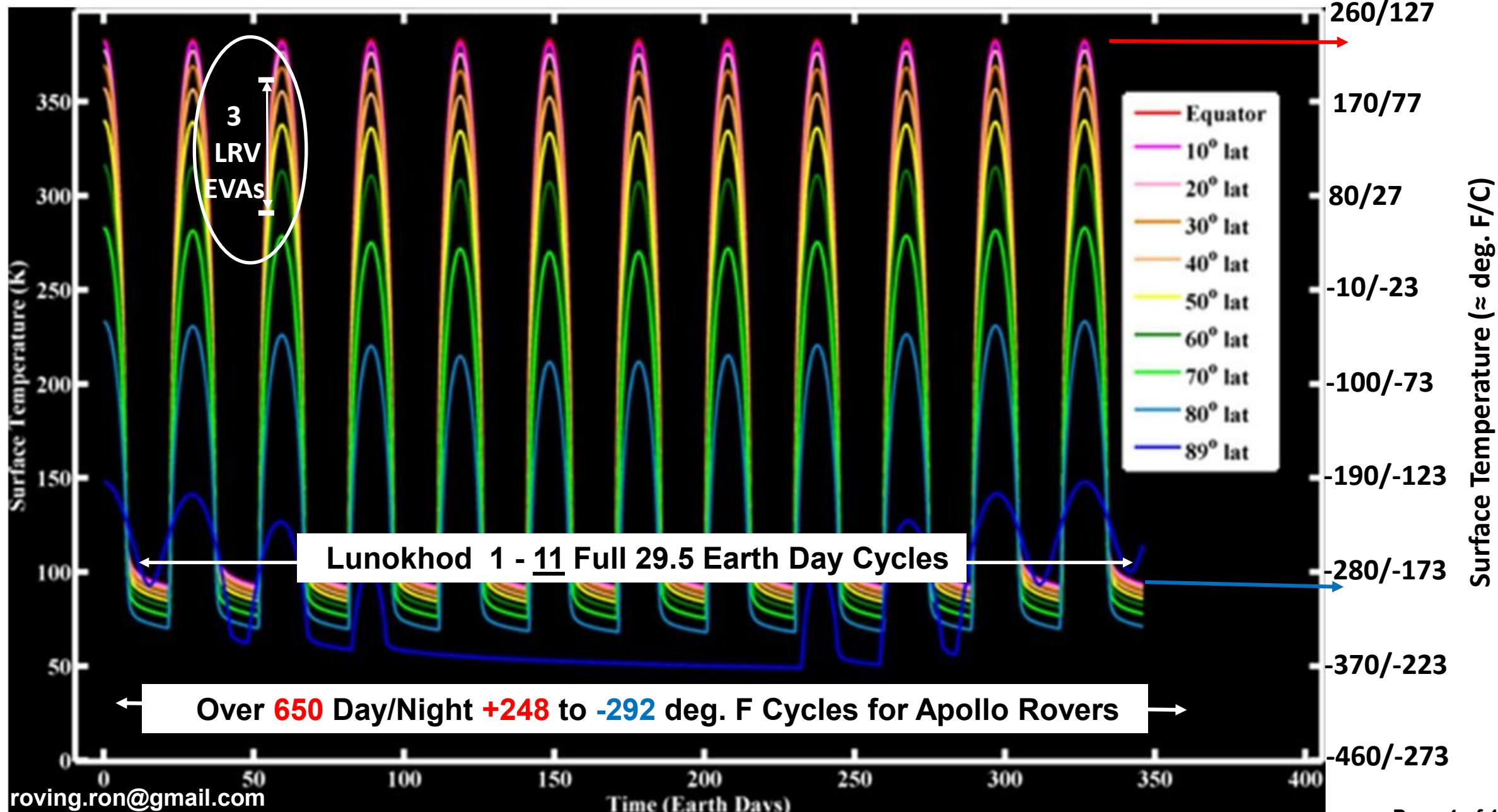
Exterior **Traction Drive**, Fluid Damper, and Steering Components

Have **Dust** Degraded Surfaces

Internal Conduction Maximized

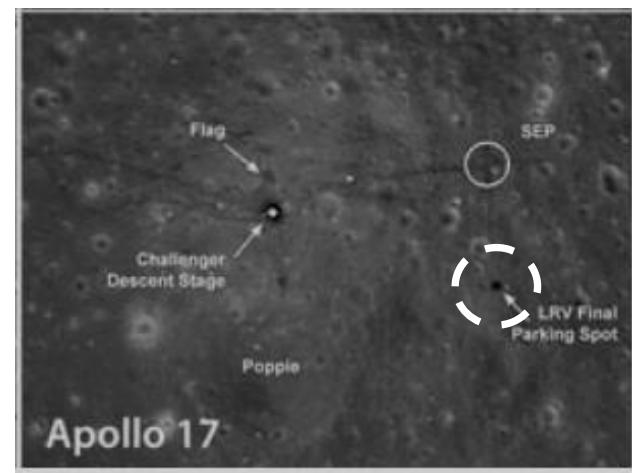
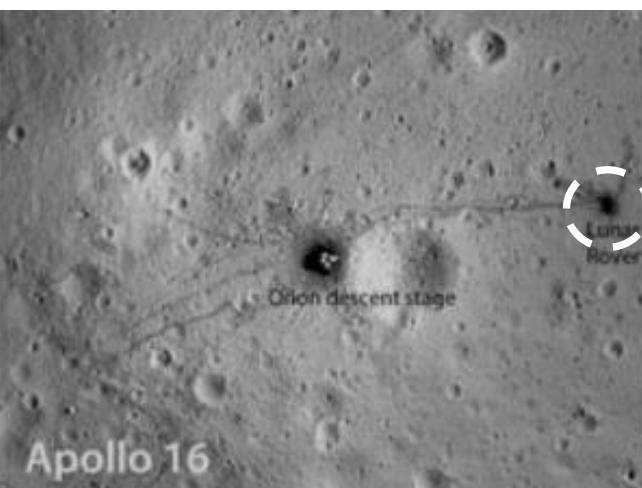
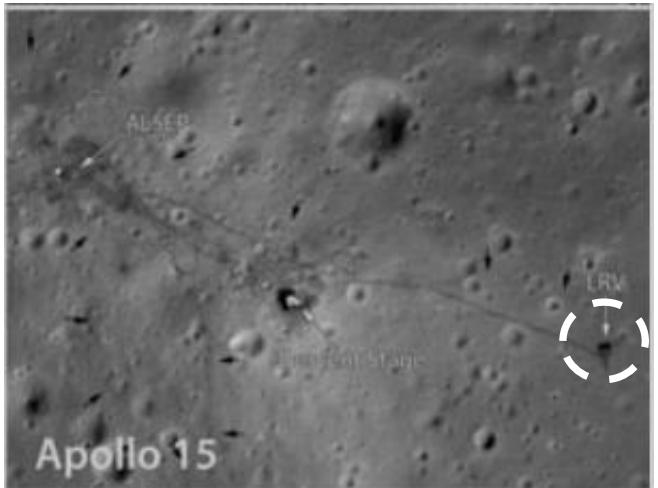
Vital Fenders and Extensions

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

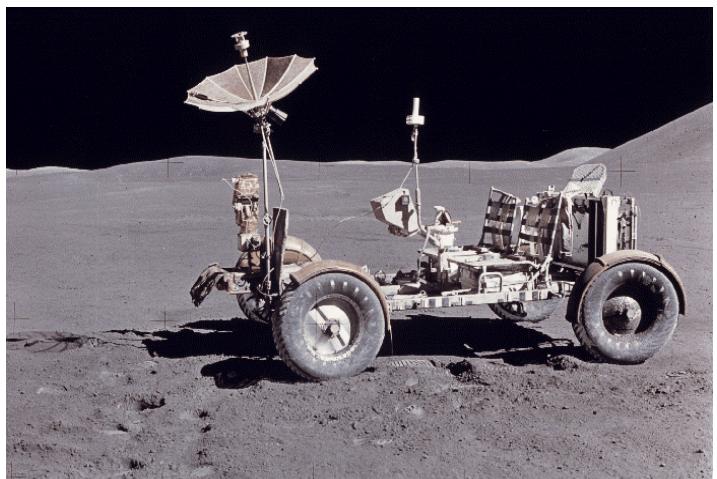


Challenge 2 - Preparation for Unknown Rover Condition and Fenders and Extensions Status

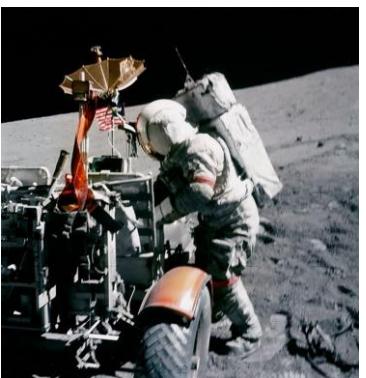
Mysterious “Black” Areas at Present Parked Rover Locations in LRO* Photos!



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



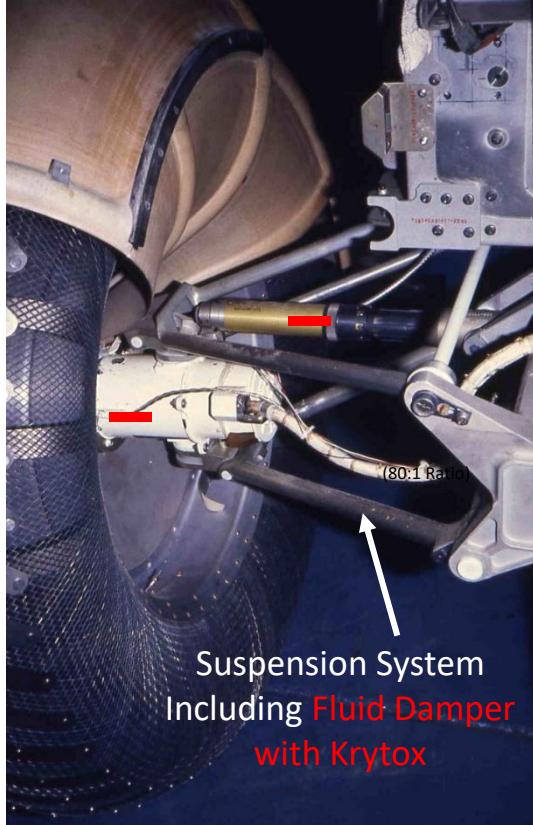
Apollo 17 Fender Repair and other Extensions Now in Museums



All 3 Apollo 17 Fender Extensions and Repair Removed

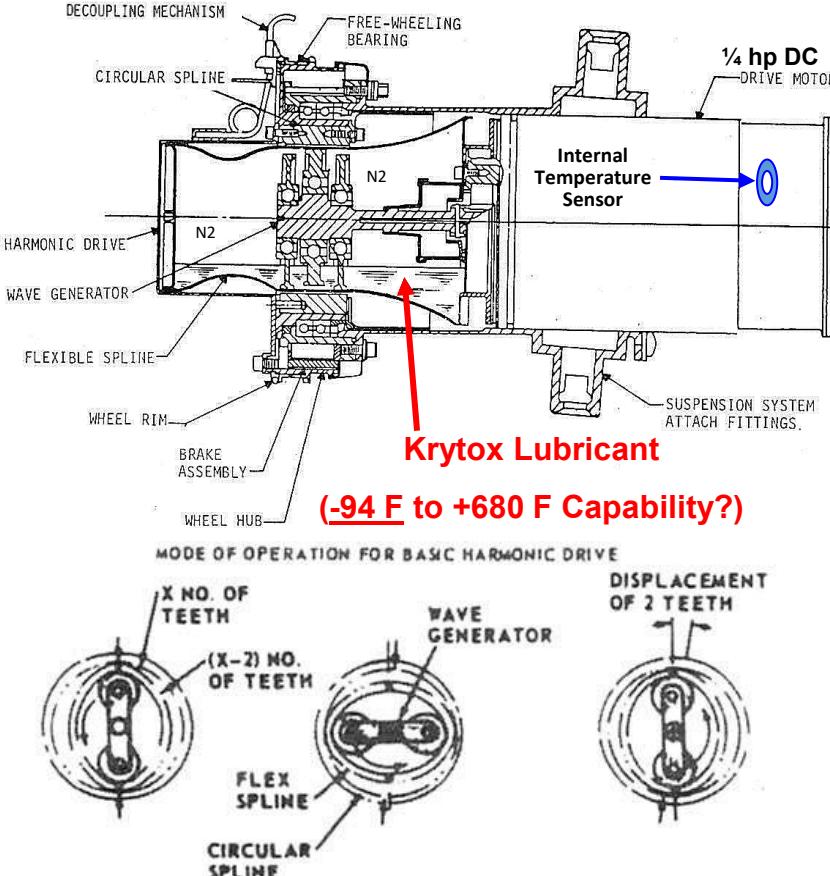


LRV Mobility and Forward Chassis Subsystems Present Reuse Challenges



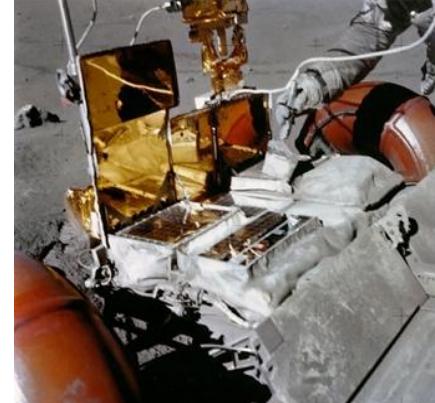
Suspension System
Including Fluid Damper
with Krytox

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 ($\alpha_s = 0.07$) Space Radiators to Reject Heat When Dust Covers Are Opened at the End of EVAs

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

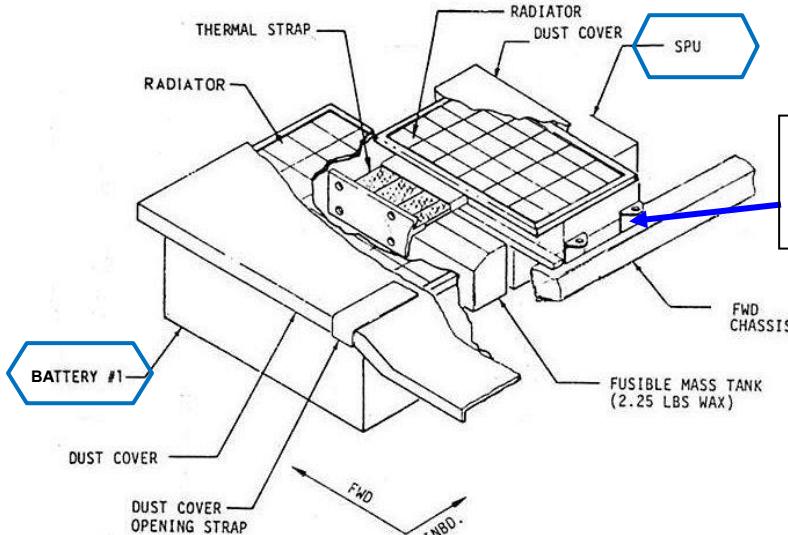
External Mobility components should be all right for Hot temperature exposure, but there is also concern for Cold temperature exposure

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

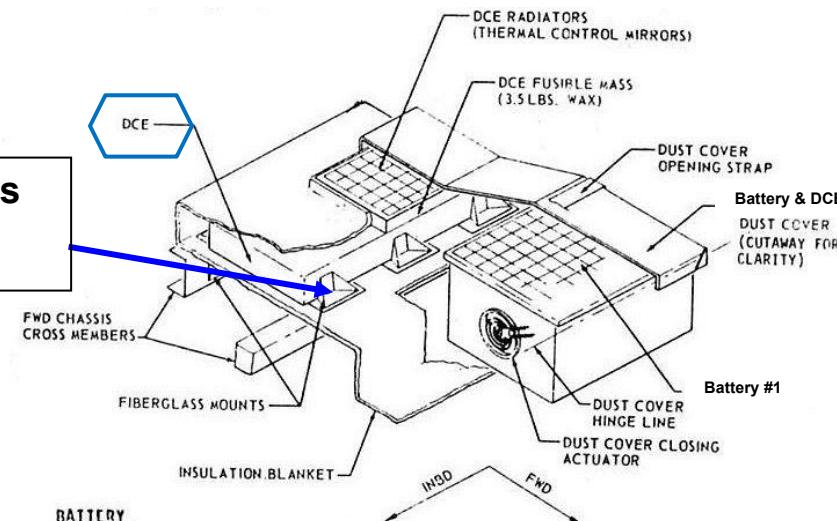
* 163 wt-hr/kg Stored Power per Battery

Challenge 4 – Detaching and Reattaching Fiberglass Rail Mounts & Electronics Component Connectors for Battery Replacement

Signal Processing Unit (SPU) Thermal Control

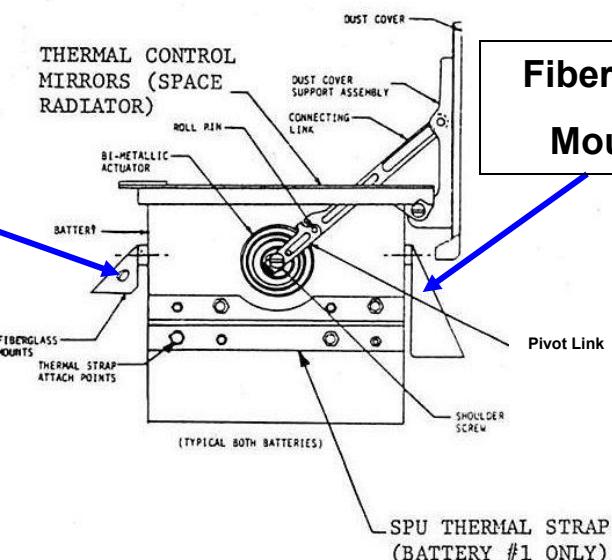


Fiberglass
Mounts

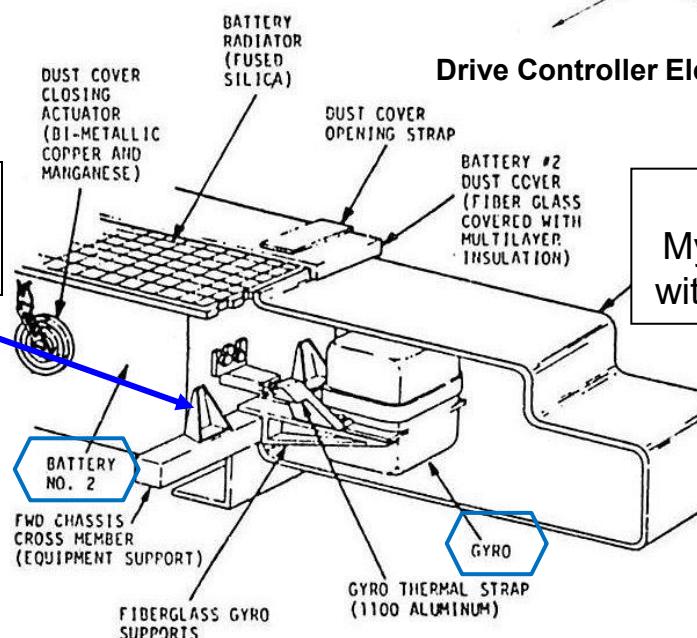


Drive Controller Electronics (DCE) Thermal Control

Numerous
Screws



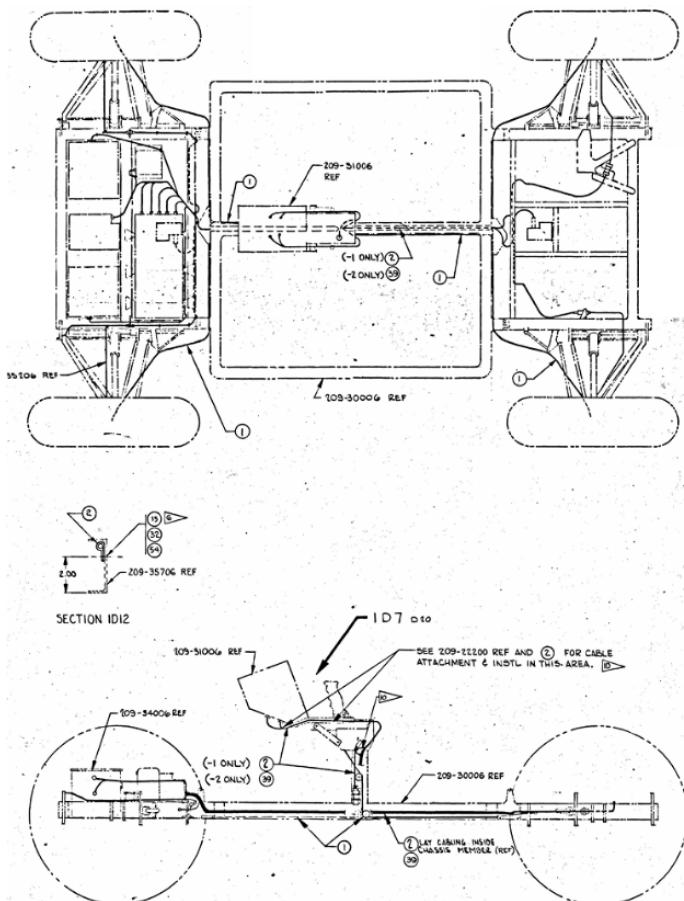
Fiberglass
Mounts



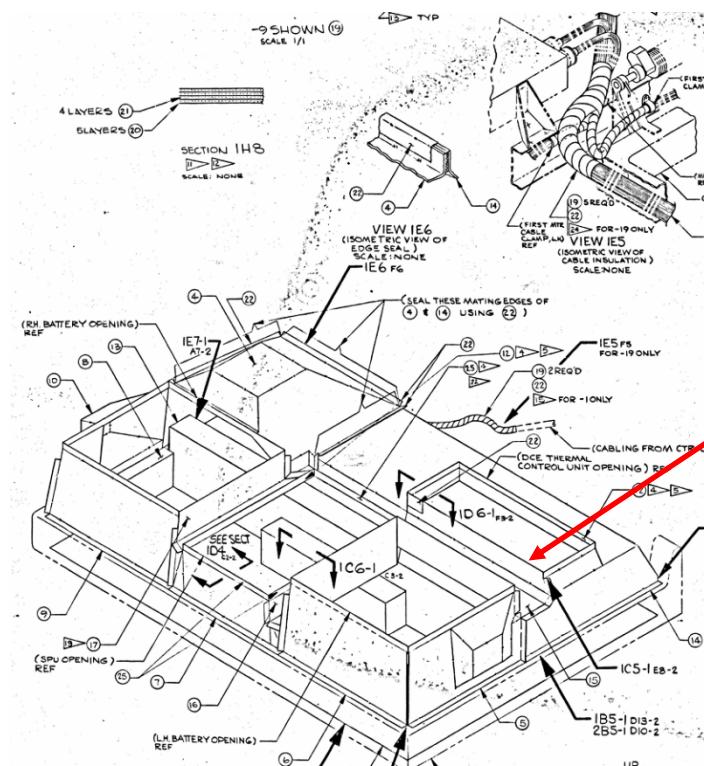
Directional Gyro Unit (DGU) Thermal Control

Challenge 5 - Disconnecting Cables and Reconnecting Them Later

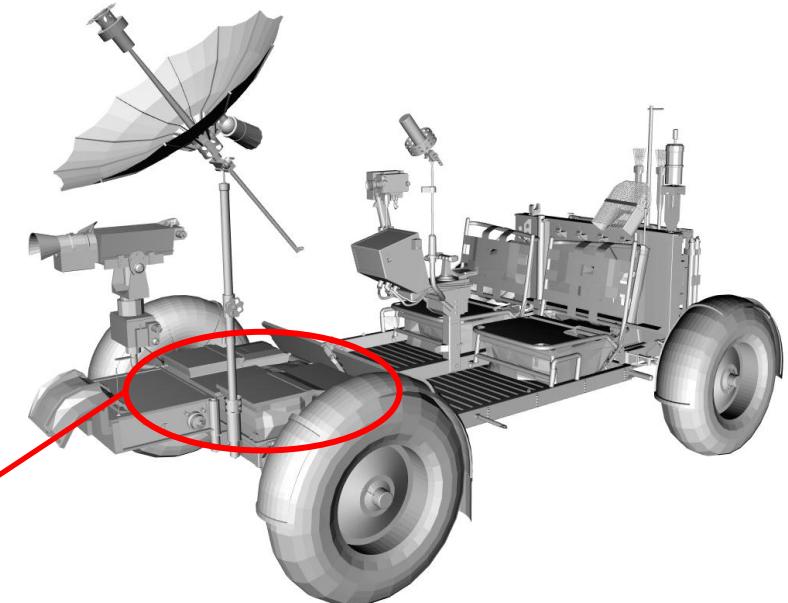
LRV Cable Runs



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

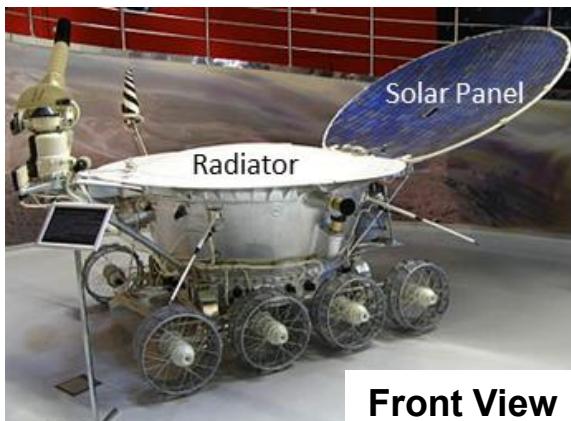
* SINDA = Systems Improved Numerical
Differencing Analyzer



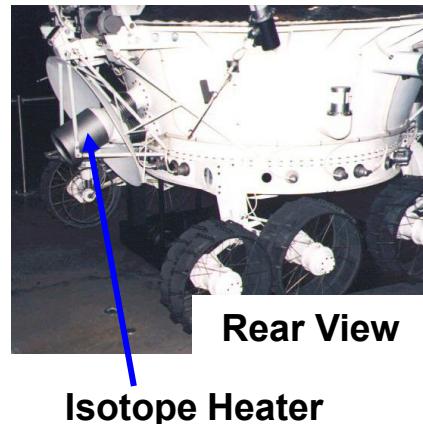
Qualification Unit at Marshall Space
Flight Center after Apollo 15

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)



LUNOKHOD



Rear View

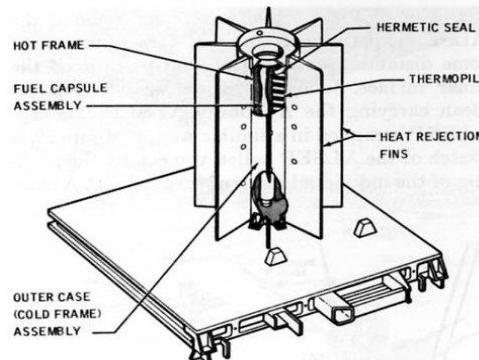
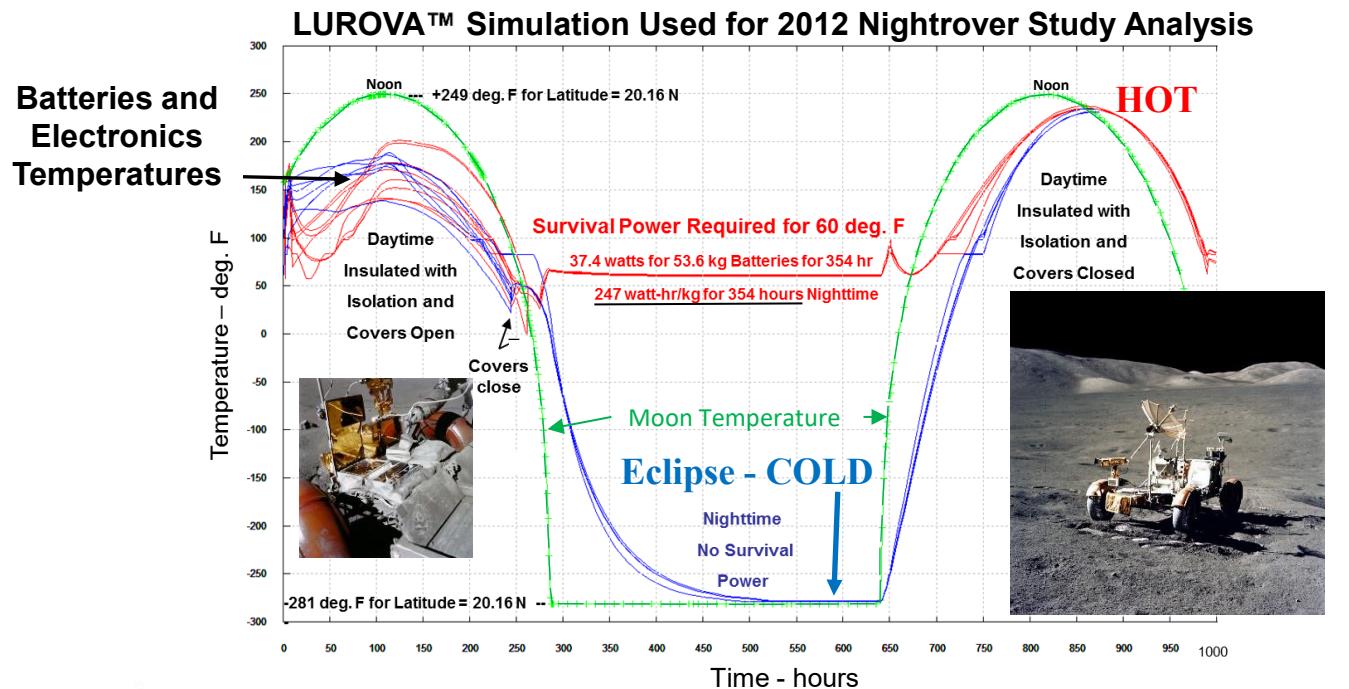
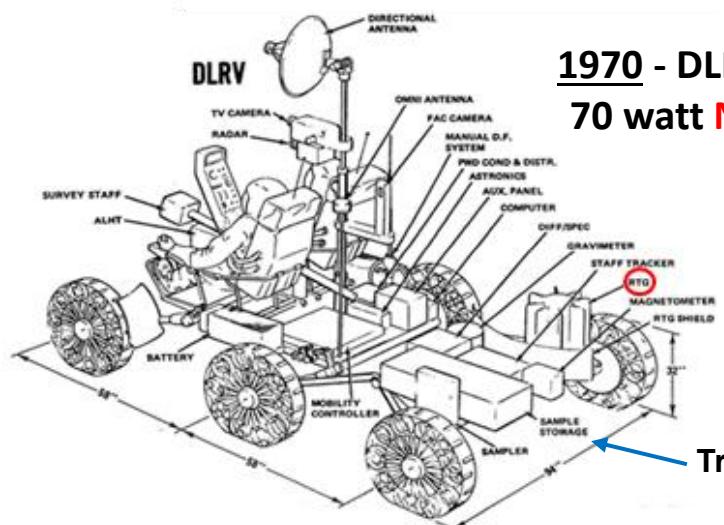


FIGURE 25.—Radioisotope Thermal Generator. This element provides all of the power used by the ALSE and furnishes continuously about 70 watts.

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



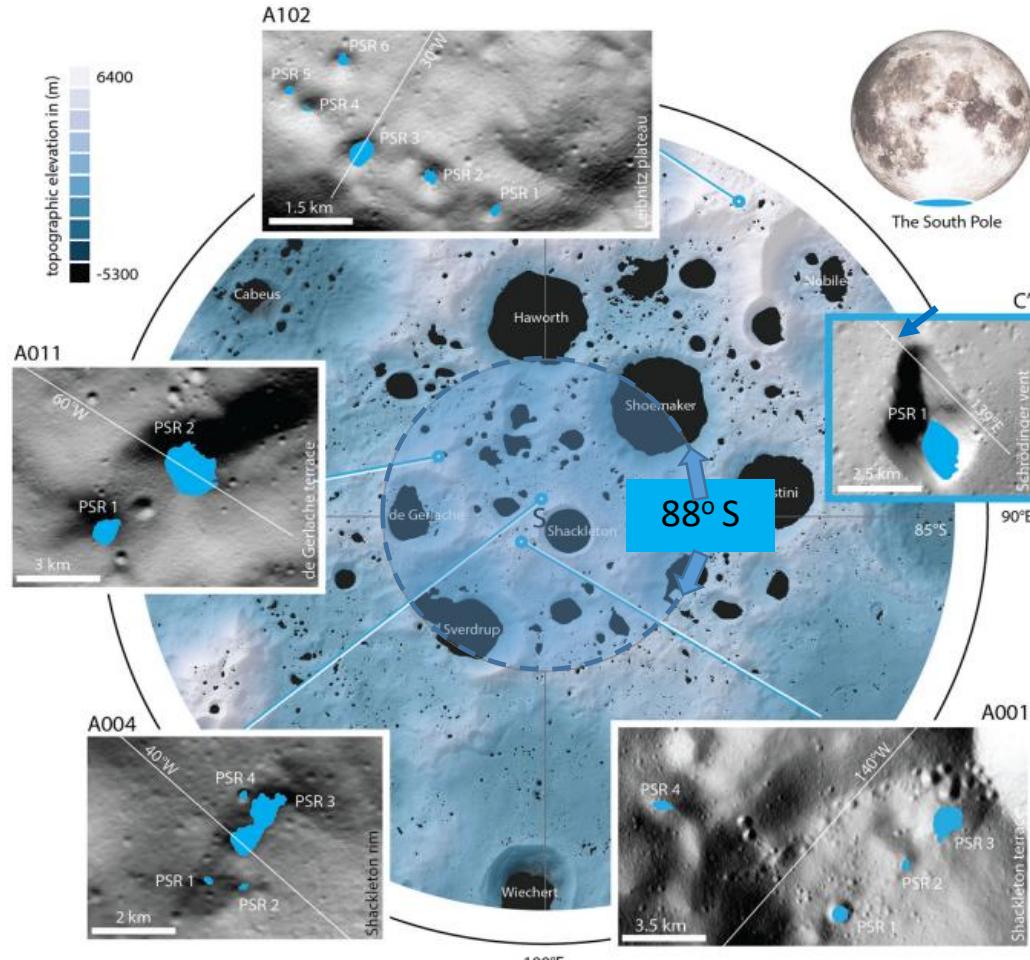
1970 - DLRV Dual Mode Rover Concept with a 70 watt Nuclear RTG for Cancelled Apollo 18



RTG = Radioisotope Thermoelectric Generator

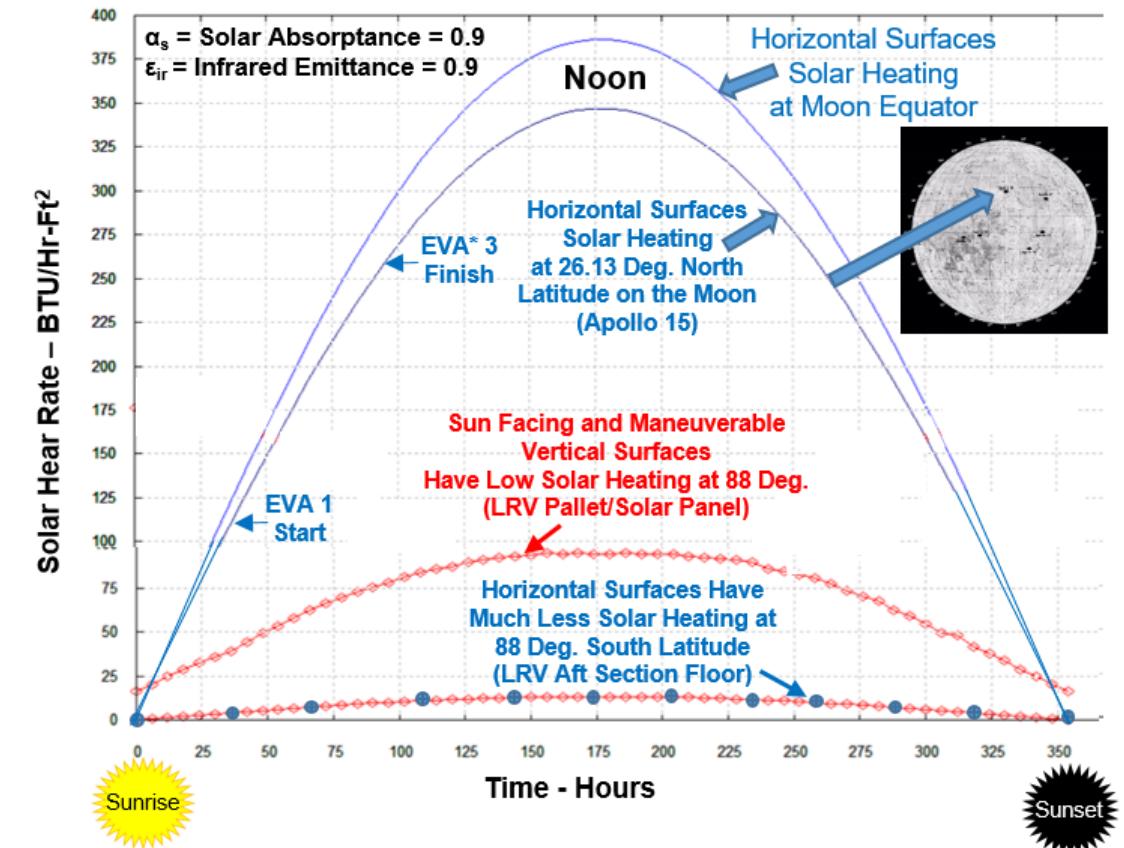
– Trailer Installed for Robotic Operation

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

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



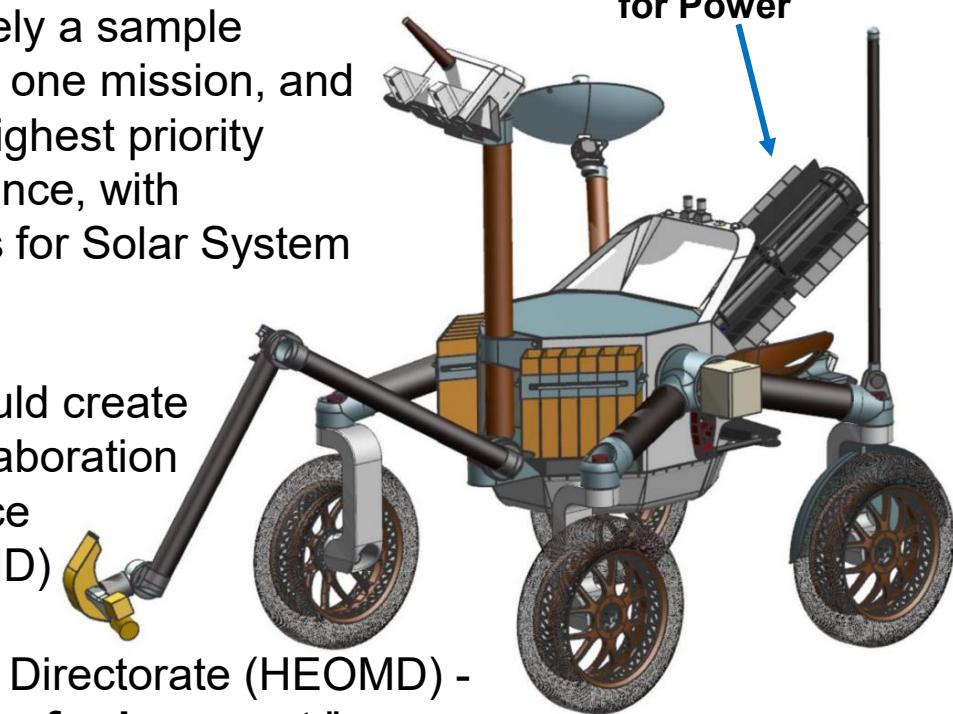
LTV “Chasing the Sunlight” Traverses
Will Be Difficult and Risky, and Could be
Dangerous, Especially for Emergency Need
for Dependable and Immediate Energy for
Transit Back to the Lunar Home Base

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

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"

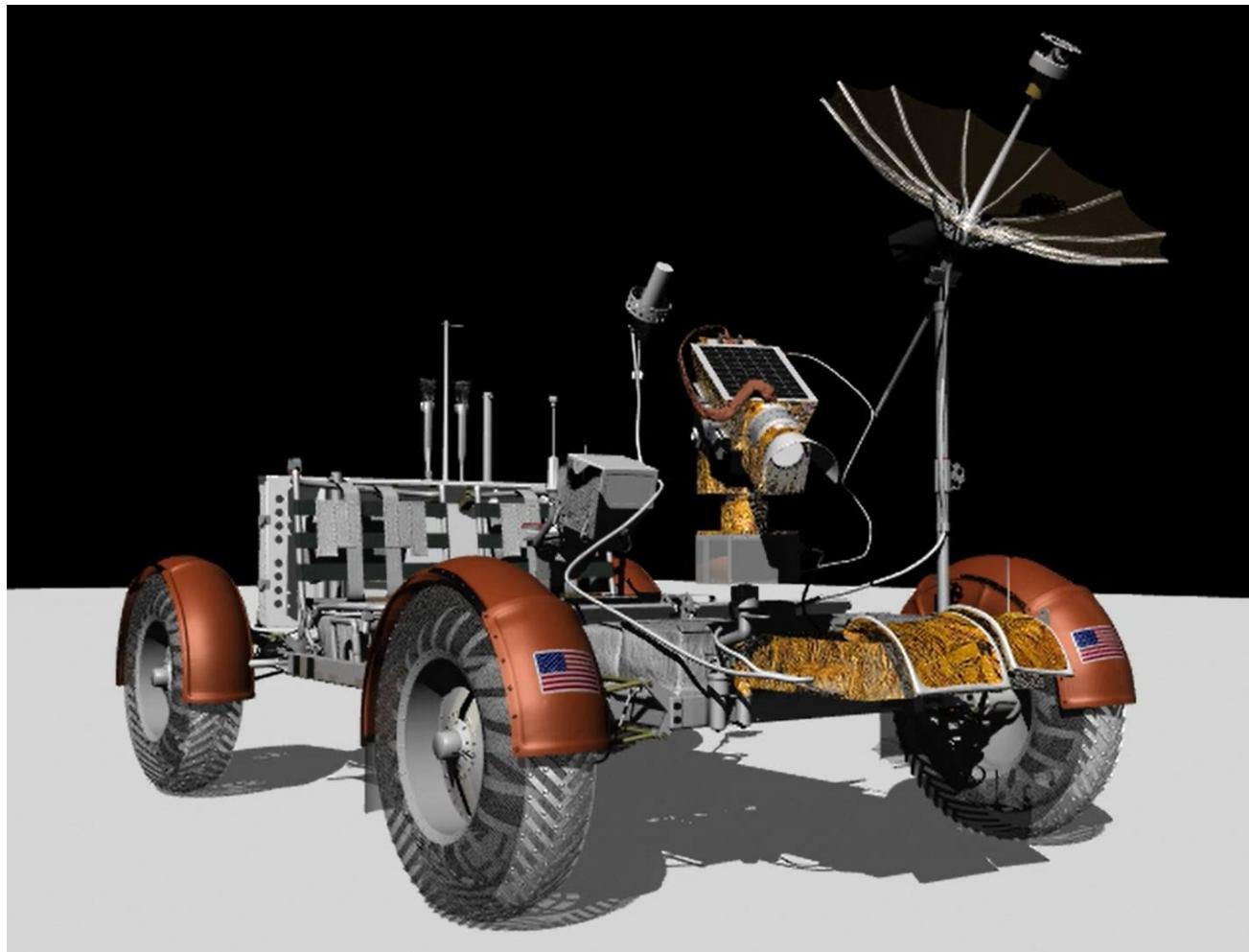
Call from a Rover Crew on the Moon!

And Please Remember to Always Capitalize "Moon"

Murphy's Laws

1. In any field of endeavor, anything that can go wrong, will go wrong.
2. Left to themselves, things always go from bad to worse.
3. If there is a possibility of several things going wrong, the one that will go wrong, is the one that will cause the most damage.
4. Nature always sides with the hidden flaw.
5. If everything seems to be going well, you have obviously overlooked something.

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



After Apollo 15, the Crew Signed
Autographs for NASA Employees

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 All LRV Interfaces



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



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

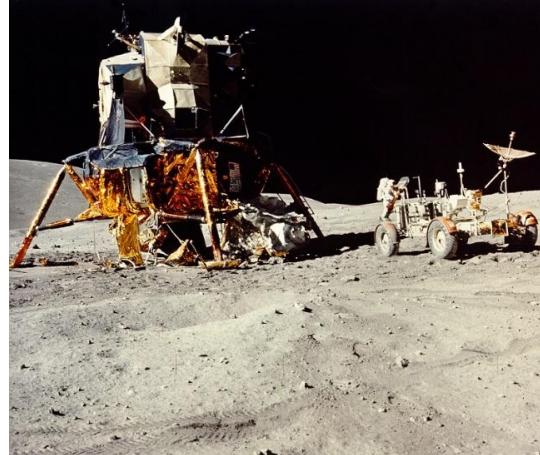


Apollo 15 Crew Checking Out
Their Installed LRV

Astronauts Appreciated
Timely and Accurate LRV
Thermal Modeling



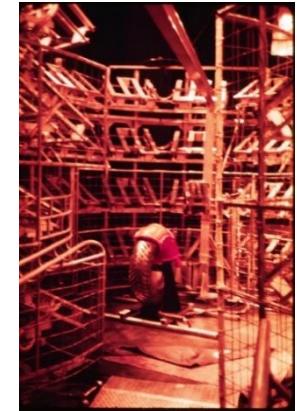
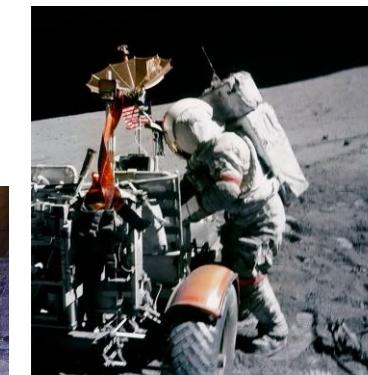
Post Apollo 16 - LM Parking Proximity Constraint Changed, and TVAC Fender Testing



LRV Parked Too Close to LM



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



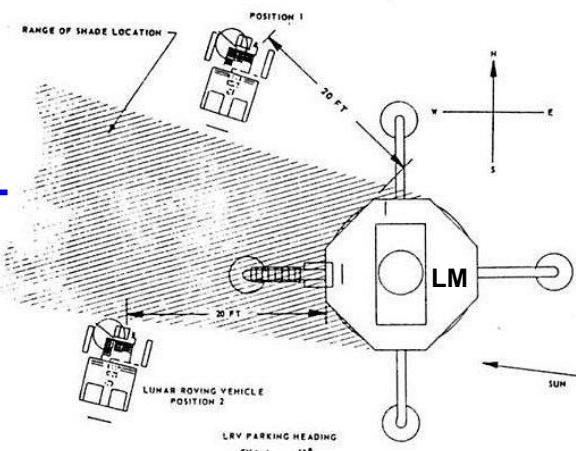
Re-designed Fender Extension
TVAC Deployment Test at MSC



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.

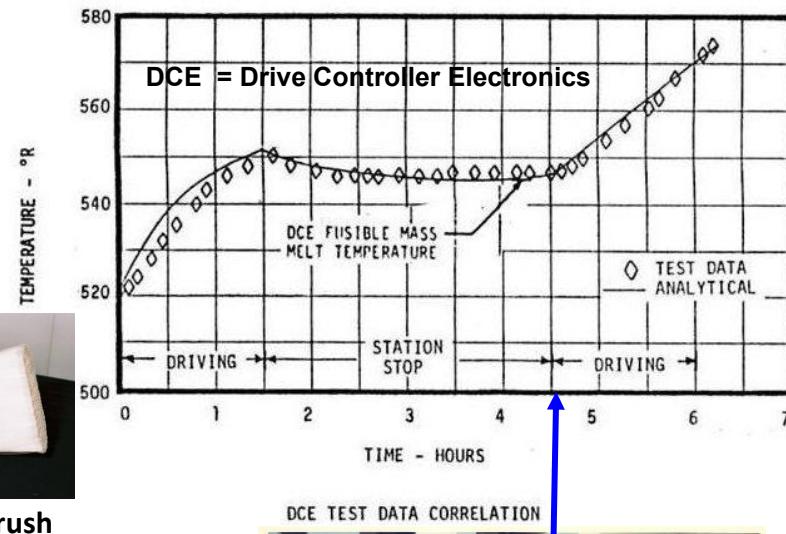
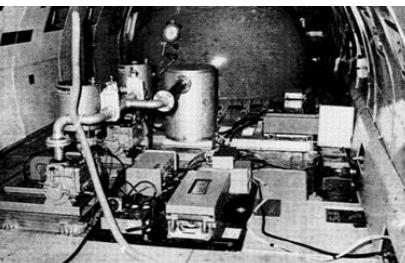
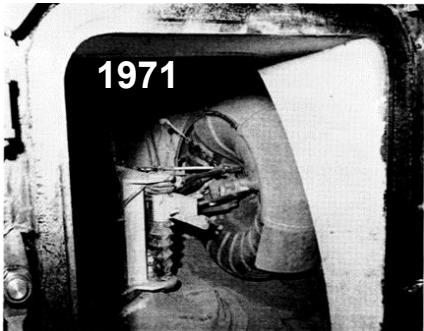


Parking Constraint Changed for Apollo 17

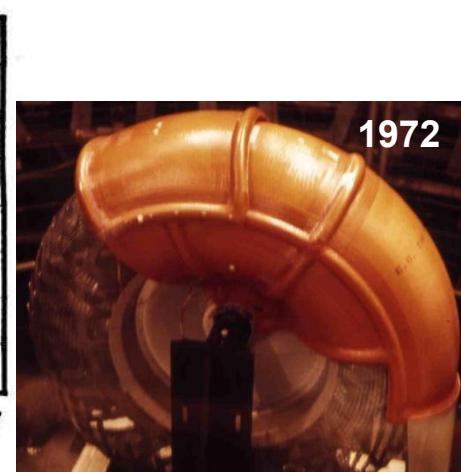


Ron With LM and LRV Vibration Test
Unit at U.S. Space and Rocket Center

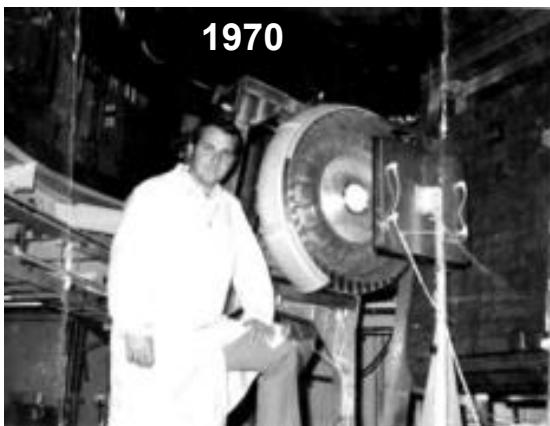
Rover Thermal Models Were Correlated with Extensive Thermal Vacuum (TVAC) Testing Data



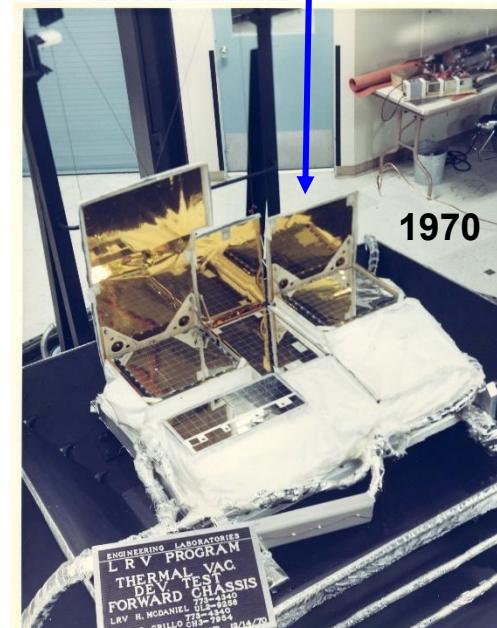
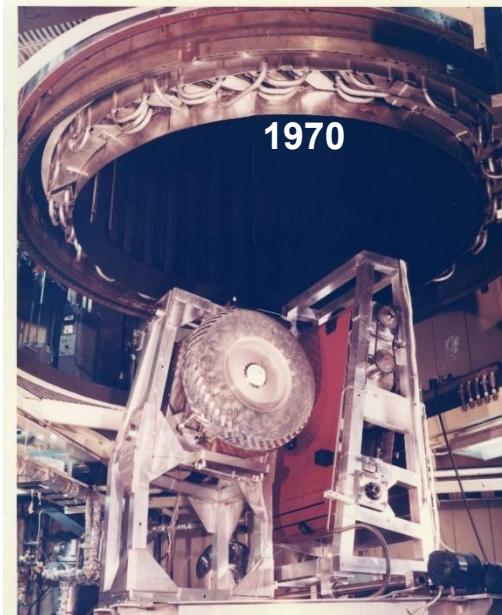
KC-135 Vacuum / Reduced Gravity Tests Verified the Need for Fenders
Radiator Dust Brush Cleaning Also Tested at MSC* Using Apollo 12 Soil,
but Did NOT Work on the Moon



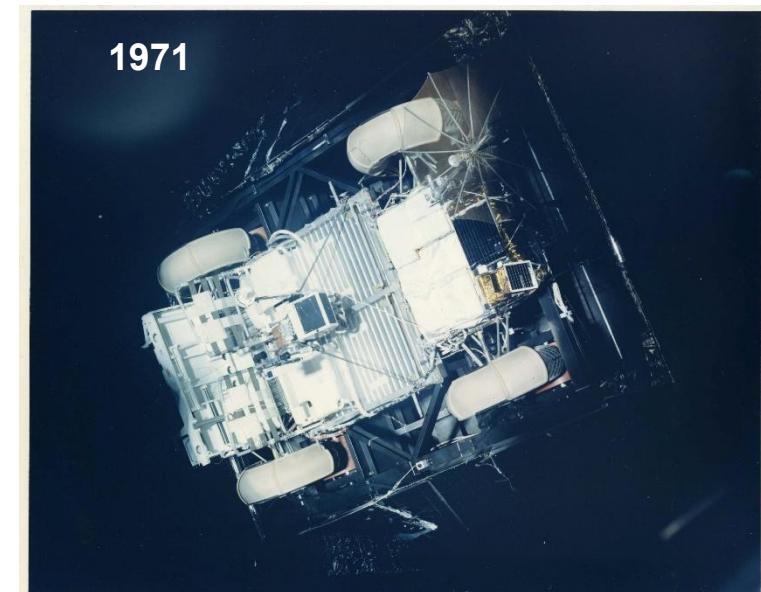
Fender Extension Deployment TVAC



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



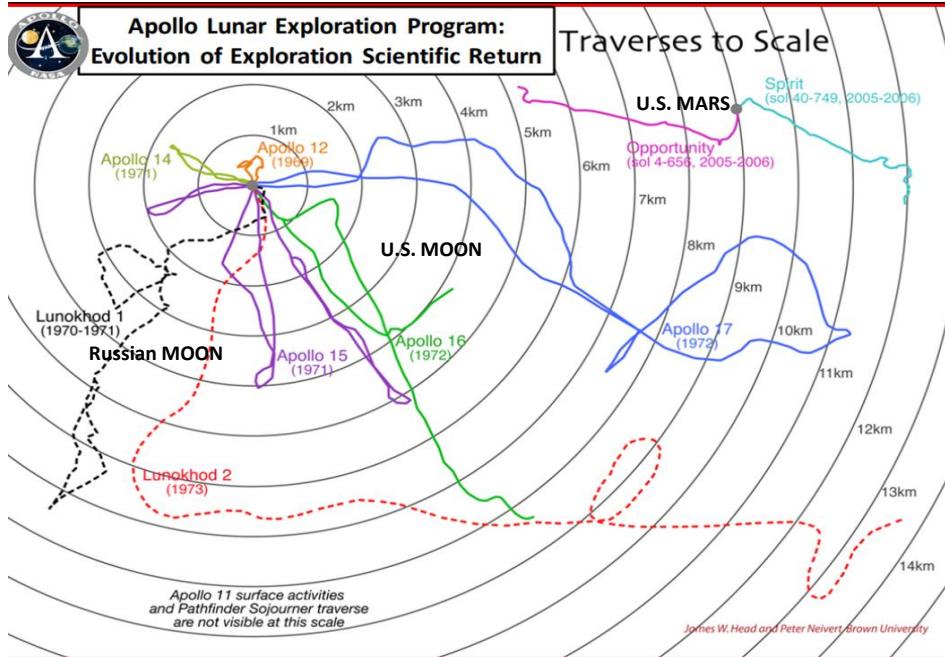
Forward Chassis Thermal Development "Tub" TVAC



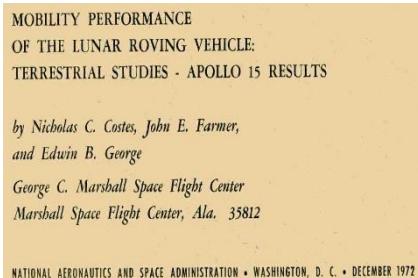
Qualification and Flight Units TVAC

* MSC = Manned Spacecraft Center

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



Mobility and Navigation Performance Documents



LUNAR ROVING VEHICLE NAVIGATION SYSTEM PERFORMANCE REVIEW

by Ernest C. Smith and William C. Martin
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

	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

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



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

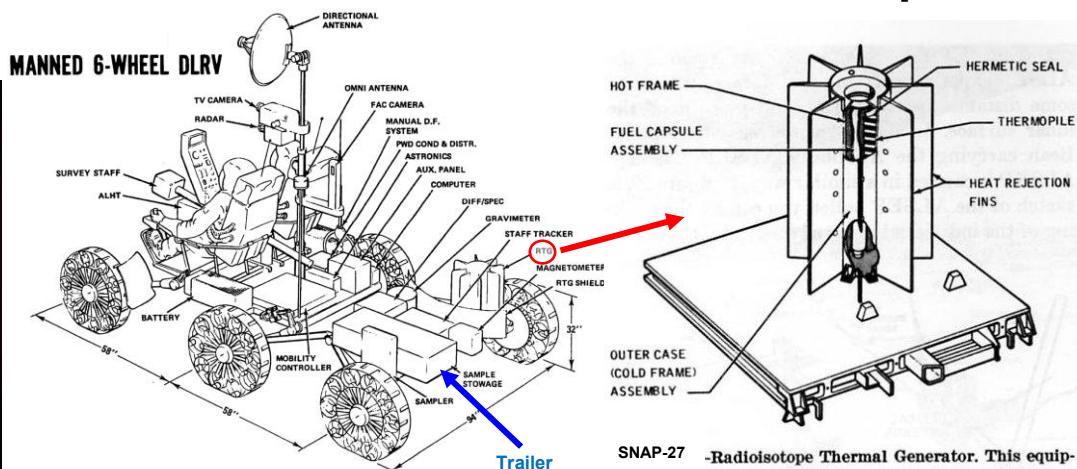
All LRV components remained within operational temperature limits throughout the surface EVAs on all 3 Missions. As Predicted, Drive Motor Temperatures were “Off Scale Low” (below 200 deg. F) throughout most of the EVAs.

The Maximum Motor Temperature of 270 deg. F occurred during the longest driving period in EVA 3 on Apollo 17

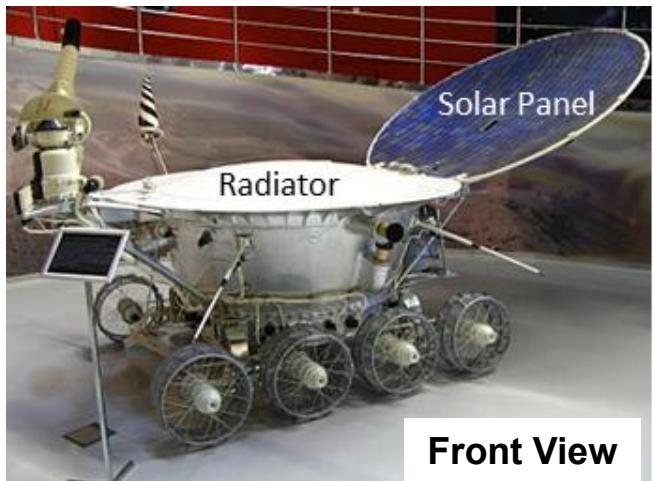
Nuclear Energy Provided Dependable/Efficient Moon Survival Power/Heat

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

Lunokhod Wheel Gears



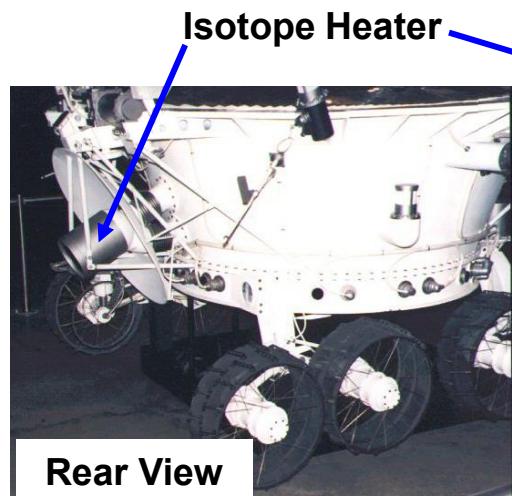
Russians Successfully Used Nuclear Isotope Heat Sources for Several Lunar Cycles on Their Two Lunokhod (Moonwalker) Robotic Rovers (1970 to 1973)



Front View

LUNOKHOD

roving.ron@gmail.com



Rear View

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

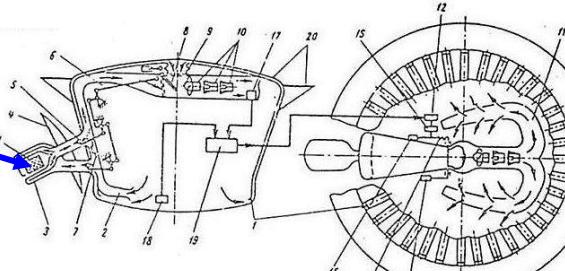
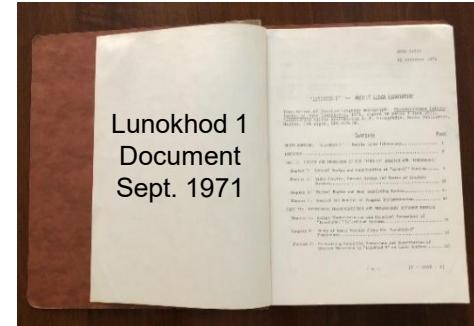
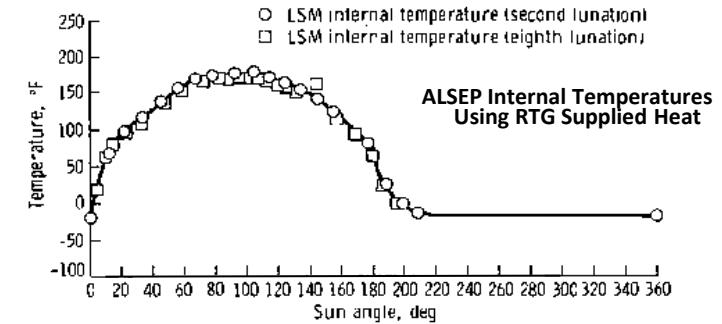
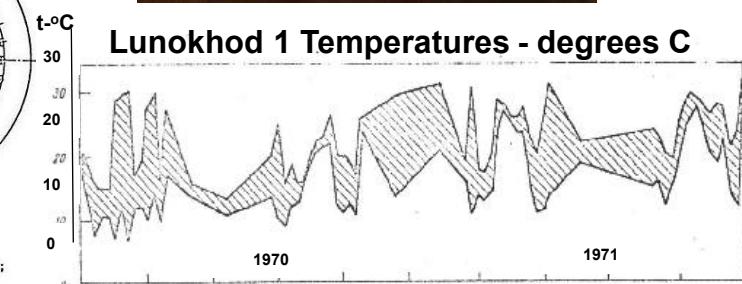


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheet; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism; 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

* ALSEP = Apollo Lunar Surface Experiment Package



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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