COPING WITH DUST FOR EXTRATERRESTRIAL EXPLORATION

Ron Creel

Retired Apollo Lunar Roving Vehicle Team Member

INTRODUCTION

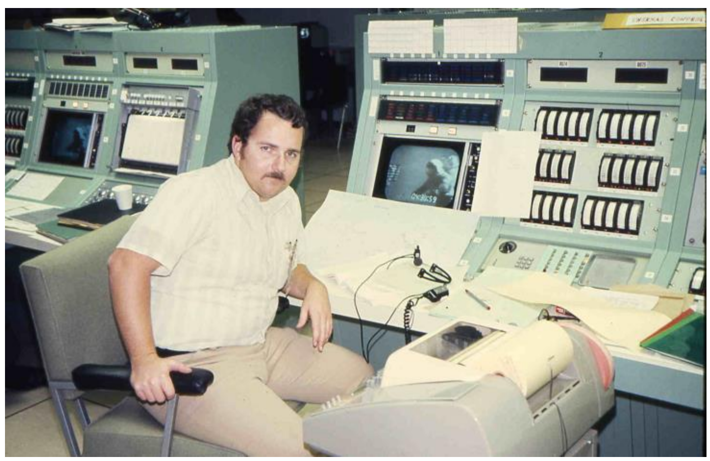
The author worked at NASA on the thermal control system for the Apollo Lunar Roving Vehicle (LRV), America's "Spacecraft on Wheels", shown in Figure 1. This included thermal testing, modeling, and mission support during the Apollo 15, 16, and 17 missions in 1971 and 1972.

Figure 1. Lunar Rover on the Moon.

Figure 2 shows the Apollo 16 LRV racing across the lunar surface and stirring up dust in the "Grand Prix" mobility data collection exercise. The loss of fender extensions on the right rear wheels on both Apollo 16 and Apollo 17 contributed to even more dust being thrown up onto the vehicle and Astronauts.

Figure 2. Rovers Provided Increased Moon Mobility in Apollo 15, 16, and 17 Missions

Figure 3 shows the author at the thermal model control console at the completion of the last LRV dust coping adventure on Apollo 17.



R-1

Figure 3. Ron, Busy at Lunar Rover Thermal Model Control Console

This paper discusses a challenge that has haunted the author for over 46 years – Coping with Lunar Dust. This includes discussions of **Previous Earth-based Dust Removal / Prevention Testing**, **Dust Effects on Lunar Extraterrestrial Missions**, **Dust Effects on Extended Lunar and Mars Extraterrestrial Missions**, **Dust Mitigation Options for Future Lunar Exploration**, and **Experience Based Recommendations for Coping with Dust**.

References start at "R-1", and are listed at the end of the paper.

PREVIOUS EARTH BASED DUST REMOVAL / PREVENTION TESTING

Example solar heating data provided to the “Working on the Moon” section of Eric Jones’ excellent Apollo Lunar Surface Journal is shown in Figure 4. Solar heating follows the trend of the Moon temperature curve, with 14.75 days of solar heating followed by 14.75 days of solar eclipse with no heating. The Rover “J” missions were planned for lunar morning in order to minimize exposure of exploration systems to excessive solar heating and high Moon temperatures.

R-2

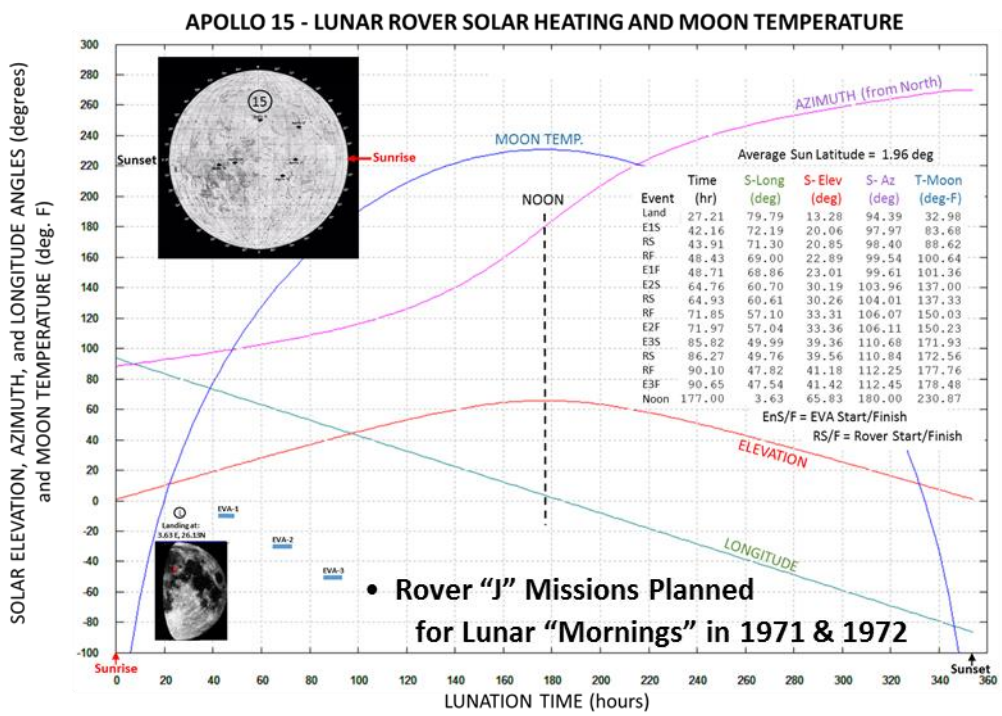
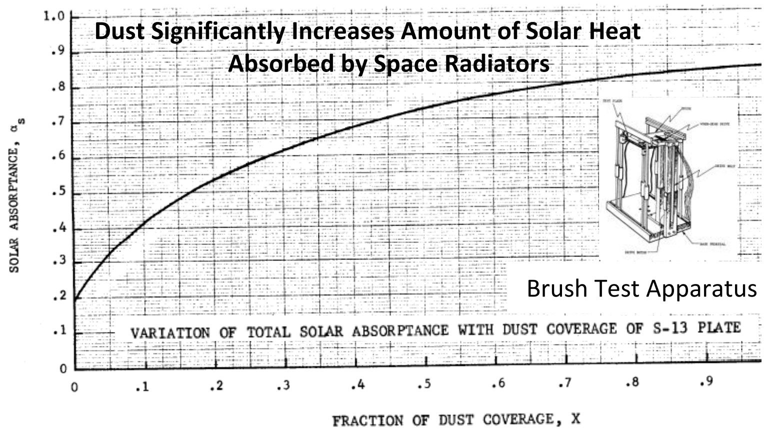
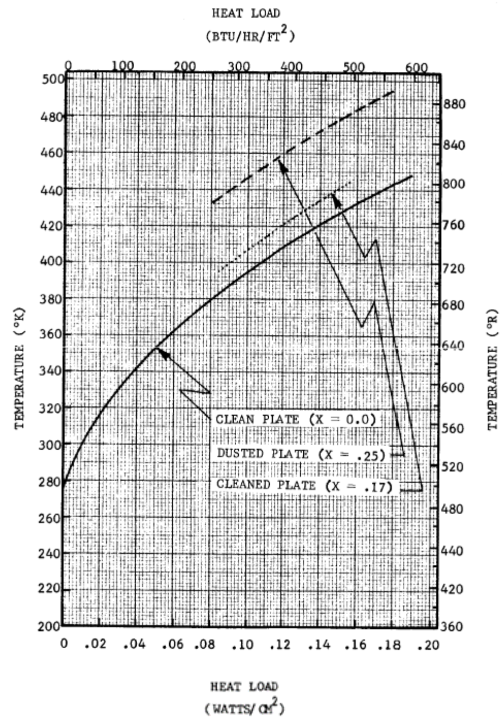


Figure 4. Example Apollo Mission Solar Heating and Moon Temperature

In 1967, Earth based dust testing was sponsored by the NASA Marshall Space Flight Center (MSFC), with the purpose of determining the effect of dust coverage on the solar absorptance for thermal control radiating surfaces. This testing was accomplished using ground basalt in a modest vacuum environment (10^{-5} Torr) with applied solar simulation heating.

The major conclusion of this Earth testing, shown in Figure 5, was that dust could be effectively removed by brushing. Fluid jet removal was more effective, but had considerable weight and safety issues.





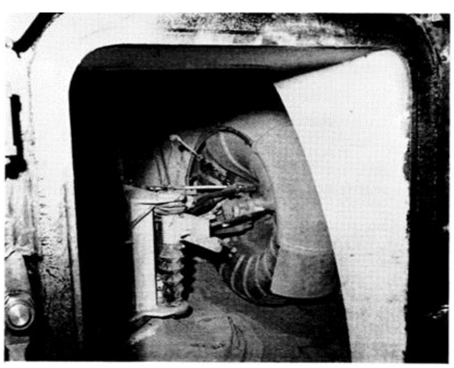
R-3

Apollo Dust Brush

Figure 5. Results of 1967 Earth Based Dust Coverage and Removal Testing

Thermal control weight budget for the Rover was only 10 pounds. As the Lunar Rover design was maturing in 1970, special wheel and fender soil interface testing in a vacuum and reduced gravity environment was conducted using the NASA KC-135 airplane (also called the "Vomit Comet") and the LSS4 lunar soil simulant. The KC-135 test assembly is shown in Figure 6.

R-4



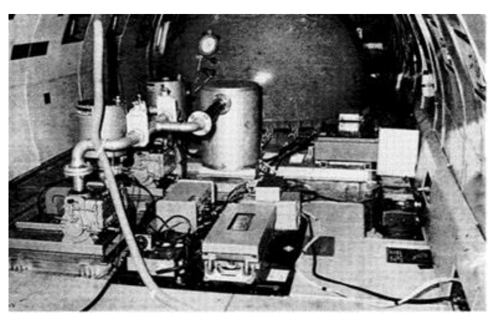


Figure 6. KC-135 Rover Fender Utility Testing Assembly

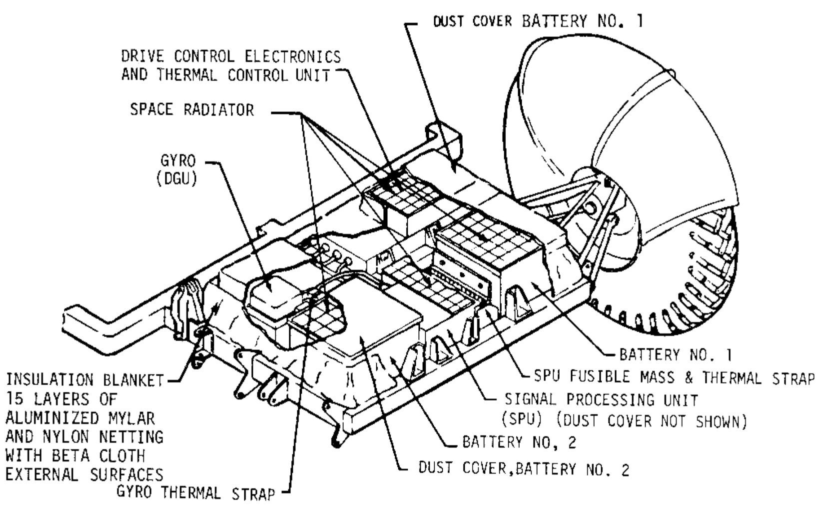
The purpose of this vacuum and reduced gravity testing was to determine the utility of the fenders to contain dust – which was verified. Thankfully, results of this testing also prevented removal of the fenders, which some wanted to do to reduce weight.

Also in 1970, additional Earth based dust removal testing in vacuum was sponsored by the Manned Spacecraft Center (later became the Johnson Space Center) using actual lunar dust collected in the Apollo 12 mission. Results were that the nylon bristle brush shown in Figure 5 was effective in removing dust from thermal control surfaces in this additional Earth based testing. It was also noted that proposed second surface mirrors could "apparently be cleaned easily". R-5

It will be shown in this paper that all of this Earth based testing was very misleading, and brushing of dust was very inadequate for previous lunar exploration.

DUST EFFECTS ON LUNAR EXTRATERRESTRIAL MISSIONS

As shown in Figure 7, critical Rover electronics and batteries were grouped together in an insulated forward chassis compartment, with 4 second surface mirror space radiators to remove excess heat when provided dust covers were raised by an Astronaut – nominally at the end of driving traverses on these relatively short 3 days duration lunar exploration missions. Clean second surface space radiators have a solar absorptance value of 0.07.

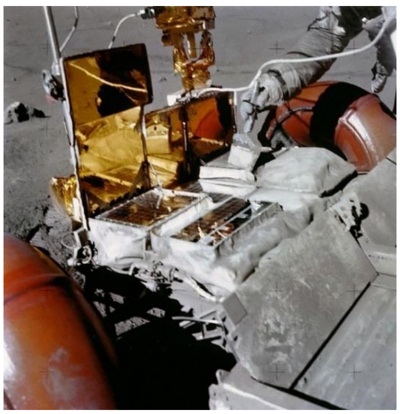


R-6

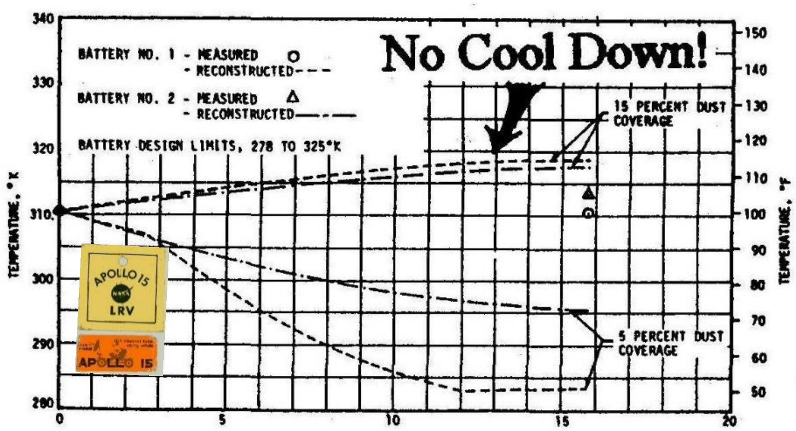
Figure 7. Lunar Rover Forward Chassis Electronics, Batteries, and Radiators

Dust covers protected the Rover radiators from exposure to lunar dust while driving, and were opened to expose the space radiators for cooling. In spite of the dust covers, lunar dust did get deposited onto the LRV space radiators, and the Astronauts spent considerable valuable Moon exploration time trying to cope with dust - with very limited success using the dust brush. R-7

Apollo 15 - Astronauts indicated that there was no dust on the space radiators after the first EVA and no brushing was necessary, which resulted in the only automatic dust cover closure in a Rover mission during the first cooldown period. However, brushing was required for the radiators before the second cooldown period, and the result was that there was no battery cooldown. As shown in Figure 8, radiator solar absorptance approaching 0.45 was experienced. Battery temperatures were then maintained below operating limits during the third EVA.



Astronaut Brushing Space Radiator

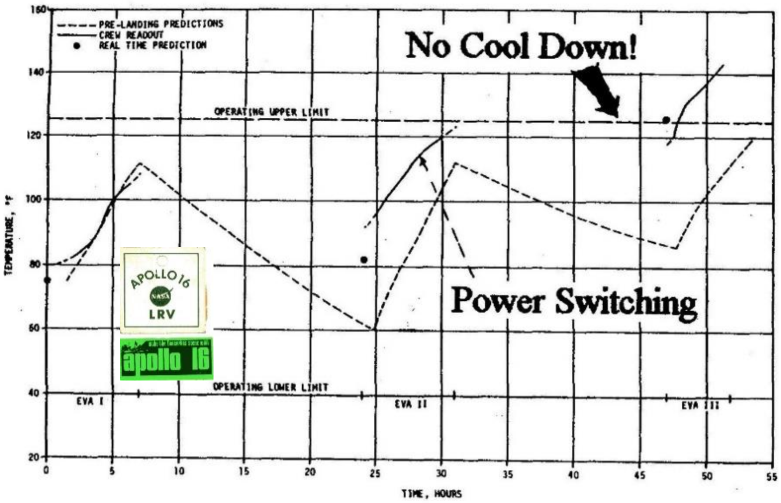


Time from Dust Covers Opening, hours R-8

Figure 8. Apollo 15 LRV Battery Temperatures During Cooldown 2

Apollo 16 – As shown in Figure 9, similar lack of battery cooldown was experienced on the second Rover mission. Loss of the right rear fender extension during EVA 2 caused a “Rooster Tail” which contributed to considerable dust being thrown forward and deposited on the crew and Rover surfaces. The LUROVA™ thermal simulation was used to calculate the best time to switch power to maintain battery temperatures below operating limits.

After Apollo 16, the author was awarded the Astronaut “Silver Snoopy” for development and use of the LUROVA™ thermal simulation for mission support.



Battery No. 2 Temperature

Silver Snoopy Awarded for LUROVA™ Simulation

R-9

Figure 9. Apollo 16 Battery 2 Temperature Profile and Silver Snoopy Award

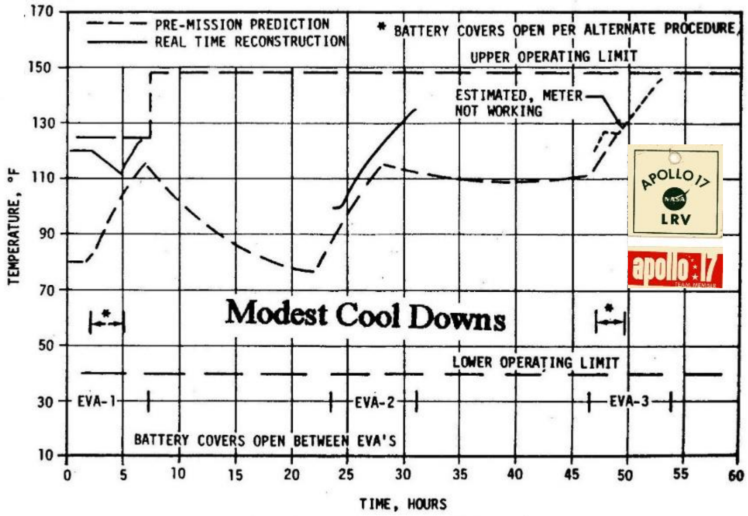
Apollo 17 – A few nights before launch, the author was invited to the crew quarters at KSC for a discussion of how to cope with lunar dust and get better cooldowns. In addition to parking the Rover farther from the Lunar Module (LM) for equipment loading/unloading and cooldowns, it was recommended to spend some time cleaning the outside of the dust covers before raising them.

As shown in Figure 10, modest cooldowns were then accomplished on Apollo 17, even though there was also an accidental removal of the same rear fender extension during the first EVA. Fender repair was accomplished before the second EVA using maps and clamps from the LM. A solar absorptance value of 0.35 for the battery radiators correlated with the cooldown that was achieved. That is five times greater solar absorptance than for the clean radiators.

The LUROVA™ thermal simulation was used to provide Mission Control with the best time to open the dust covers during EVA 3 on Apollo 17 – which kept the batteries within their operating temperature limits as shown in Figure 10. R-11

Other Rover communication equipment required repeated radiator brushing throughout all 3 Rover missions. This included the Lunar Communications Relay Unit (LCRU) and Ground Commanded Television Assembly (GCTA). R-12

Also, the Astronaut crews spent considerable time in unsuccessfully dusting their suits, and had problems with dust jamming mechanisms.



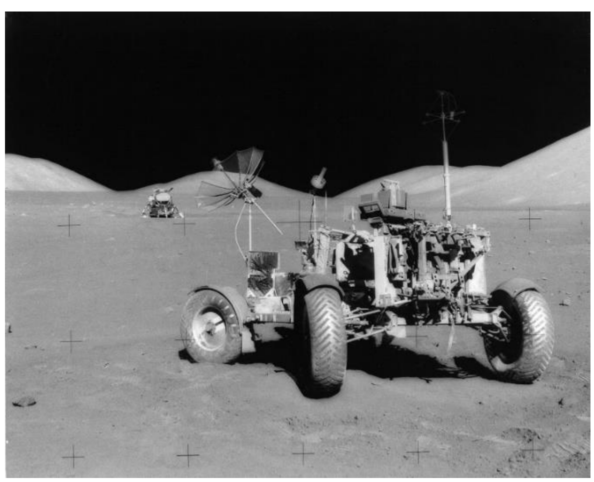
LRV Battery No. 2 (Right) Temperature

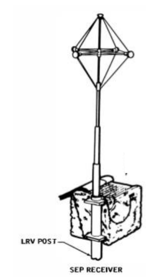
Fender Repair on Apollo 17

R-10

Figure 10. Apollo 17 Battery 2 Temperature Profile and Fender Repair

The MIT Surface Electrical Properties receiver radiator on Apollo 17, shown in Figure 11, had to be brushed frequently, and this experiment equipment ultimately over-heated. The thermal engineers at MIT had been warned before the mission about the adverse effects of lunar dust, and losing the nearby fender extension certainly didn't help the situation.

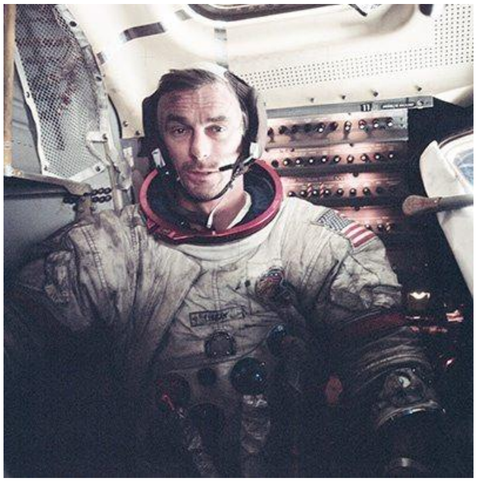




R-13

Figure 11. MIT Surface Electrical Properties Receiver and Rover Fender Extensions Removed

Several Astronauts have expressed major concerns about future lunar exploration with respect to problems with dust – including health concerns – noting the below summary by the Apollo 17 Commander in Figure 12.



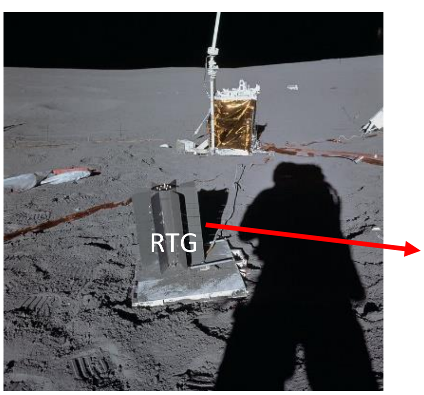
> *"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."*
>
> Gene Cernan, Apollo 17 Technical Debrief

R-14

Figure 12. Astronaut Explorers Have Highlighted Exploration Problems with Lunar Dust

Due to lunar dust interference, it was difficult for the Astronauts to negotiate around the Apollo Lunar Surface Experiment Package (ALSEP) components that were placed on the lunar surface. In fact, the Apollo 16 Heat Flow Experiment cable was hidden by dust and inadvertently kicked out of its socket, and could not be repaired.

Figure 13 is a picture taken by an Apollo 14 Astronaut showing dust kicked up onto the ALSEP nuclear powered Radioisotope Thermoelectric Generator (RTG), which was used to power and maintain components within temperature limits during the long cold lunar night period.



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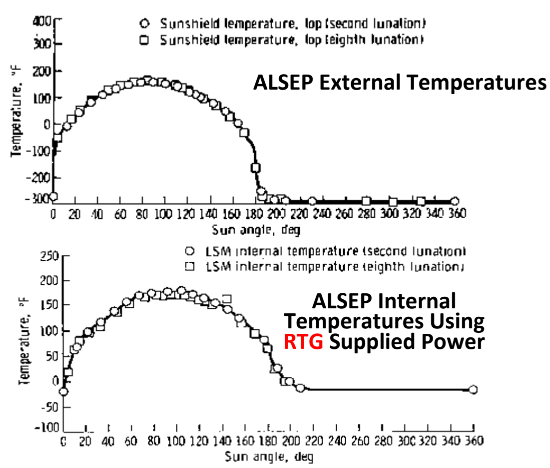


Figure 13. Astronauts Could Not Avoid Getting Dust on Deployed ALSEP Experiments

The author and his senior mentor regretted very much requiring the Astronauts to spend valuable Moon exploration time coping with lunar dust. With more weight budget, a closed thermal control system using an ammonia boiler could have potentially been implemented to avoid adverse dust effects on space radiators.

DUST EFFECTS ON LUNAR EXTENDED EXTRATERRESTRIAL MISSIONS

While helping to develop and test the LRV thermal control system, the author was very interested in how the Russian Lunokhod 1 robotic rover had survived 11 month long lunar temperature cycles in 1970-1971. After the completion of Apollo 15, an unsolicited translation of a full description of the Lunokhod rover appeared on the author's desk. This translated document clearly showed how the Lunokhod used an isotope heater to heat the compartment containing support systems. R-16

In 2004, the author was invited to present his retrospective LRV thermal control experiences at the Lunokhod development and test facility in St. Petersburg, Russia. While there, the author was able to get a full explanation from Lunokhod operator General Dovgan (Figure 14) about why and how the Lunokhod 2 robotic rover only lasted through 4 lunar temperature cycles. The explanation was that an inexperienced ground crew directed Lunokhod 2 down into a crater with the solar panel cover opened. The vehicle began to slide, and when it was driven back up the crater wall, dust was deposited onto the solar panel and later dumped onto the radiator surface – which ultimately resulted in over-heating and failure.

R-17

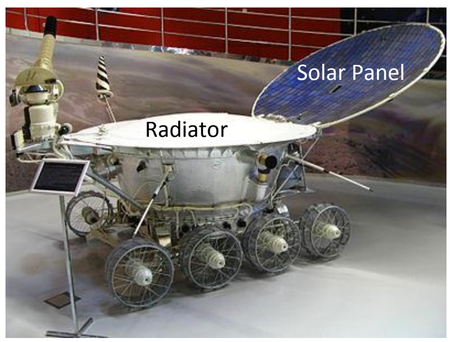
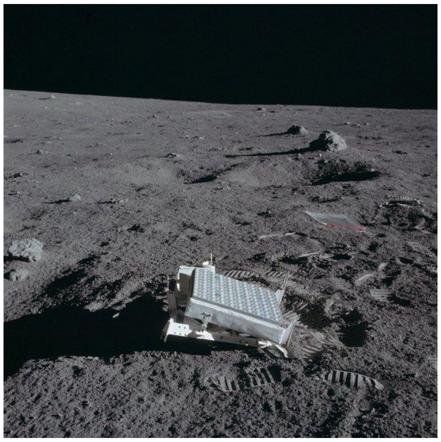


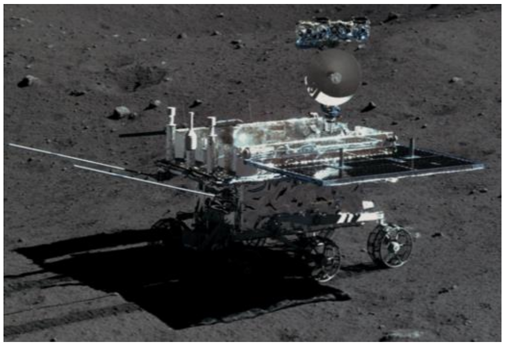
Figure 14. Gen. Dovgan Using Hand Controller to Remotely Guide Robotic Lunokhod

Until several extended exploration ALSEP experiments were turned off in Sept. 1977, they showed increasing temperature behavior, caused by degradation of surface properties, or increasing dust coverage, or both. R-18

There are also indications that laser returns from the three ALSEP Laser Ranging Retro-Reflector (LRRR) systems left on the Moon have continued to be degraded, most likely due to increasing dust coverage (Figure 15).



Apollo LRRR R-19



Chinese Yutu Rover R-20

Figure 15. Apollo LRRR and Chinese Yutu Rover on the Moon

It has been reported that lunar dust may have contributed to the Chinese Yutu robotic rover's (Figure 15) early mobility failure, after only one lunar temperature cycle.

DUST EFFECTS ON MARS EXTENDED EXTRATERRESTRIAL MISSIONS

All of the JPL robotic rovers have conducted very successful extended extraterrestrial exploration missions on Mars since July 4, 1997. As shown in Figure 16, the Opportunity rover experienced significant dust coverage on its solar panels, but in 2014 wind helped clear the solar panels on one occasion. Dust deposited by winds had significantly reduced power generation capability. The Opportunity rover was fortunately cleaned of heavy dust coverage on its solar panels by strong winds blowing over the rim of the Endeavor crater on Mars. There is no atmosphere or wind available on the Moon to clean solar panels or radiators.

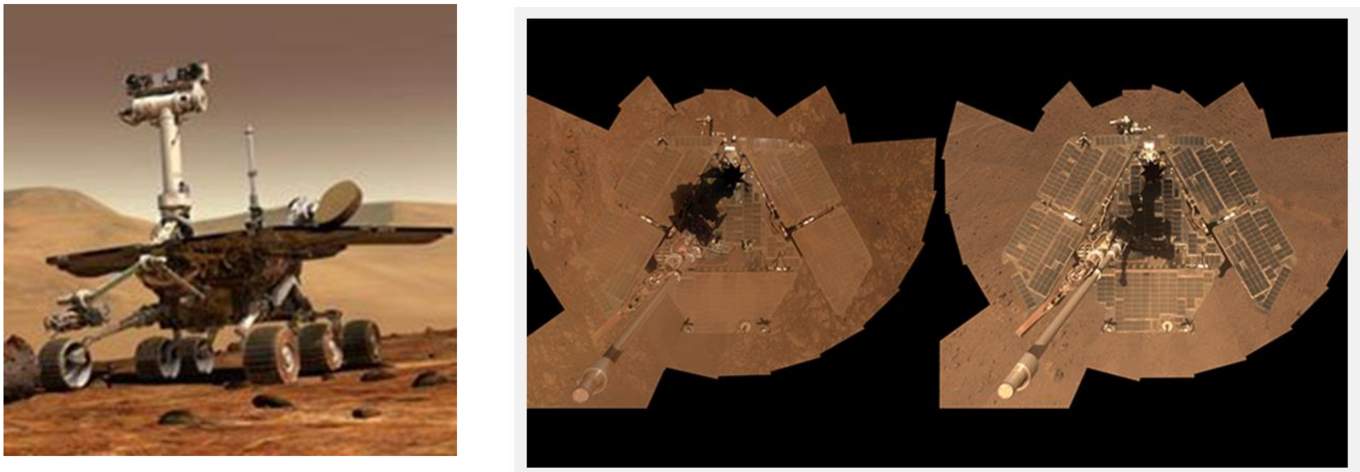
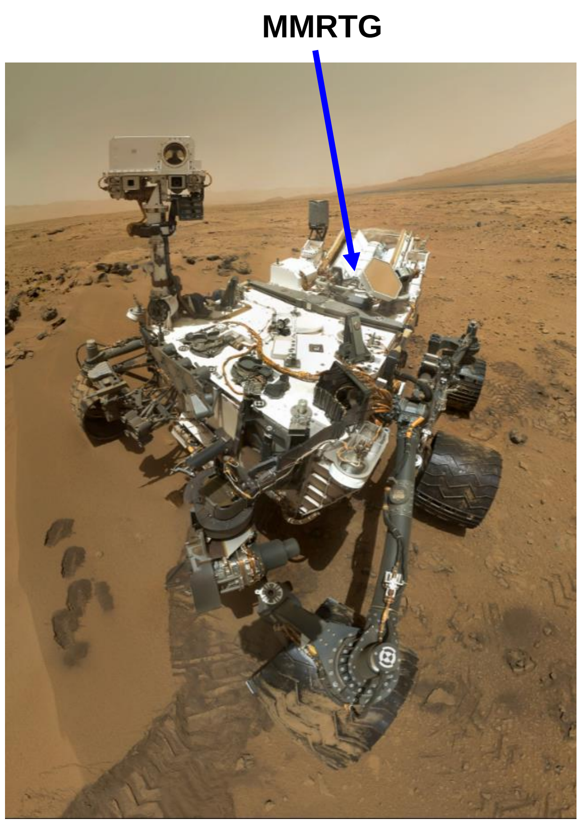


Figure 16. Mars Opportunity Robotic Rover, Dust Coverage (Left), and Wind Cleaning (Right) R-21

JPL now uses nuclear Multi Mission Radioisotope Thermoelectric Generators (MMRTGs) without solar panels to provide power that is not influenced by dust on Mars, as shown in Figure 17.



R-22

Curiosity Self-portrait

Figure 17. Latest JPL Mars Rover Uses Dust Independent Nuclear MMRTG for Power

POST APOLLO LUNAR DUST TESTING FOR STRATEGIC KNOWLEDGE GAPS

Selected dust related Lunar Exploration Analysis Group (LEAG) produced Strategic Knowledge Gaps (SKGs) are listed in Tables 1 and Table 2. Mention of "28 days" missions is puzzling because that length of stay entails the additional solution of the challenge for survival during the long and very cold lunar night. Also, the "Missions to the lunar surface" notation seems to be short sighted, as return missions to the Moon must have firm solutions to dust issues before departure to the Moon, and not be an experiment which could fail and endanger systems and Astronauts.

Table 1. Selected Lunar Exploration Proposed Strategic Knowledge Gaps (SKGs) R-23

Strategic Knowledge Gap	Narrative (modified from LEAG 2012 GAP SAT report)	Enabling or Enhancing	Status	Exploration Science or Technology	Messurements or Mission needed to retire SKG	Notes 2016 Assessment
III-D-1 Lunar dust remediation	Test conceptual mitigation strategies for hardware interactions with lunar fines, such as hardware encapsulation and microwave sintering of lunar regolith to reduce dust prevalence.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing dust remediation techniques, are required to retire this gap.	Larry Taylor sintering work at Univ. of Tennessee.
III-D-2 Regolith adhesion to human systems and associated mechanical degradation	In situ grain charging and attractive forces, and cohesive forces under appropriate plasma conditions to account for electrical dissipation. Analysis of wear on joints and bearings, especially on space suits.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, testing techniques to counter regolith adhesion, are required to retire this gap.	Gecko' space suit fabric at NASA-JSC. Electro-static 'curtain' experiments at NASA-KSC. DREAM2 SSERVI node. ARES STRATA-1 asteroid regoilth experiment on ISS.
III-J-2 Mobile habitat	The Apollo J-missions clearly showed the benefits of mobility when it comes to human exploration of a planetary surface. Pressurized rovers used as short-duration field camps, or larger mobile habitats for longer duration exploration of a large region of the Moon may provide an exploration architecture that is not necessarily fixed to one point on the lunar surface.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, using mobility systems and mobile habitats, are required to retire this gap.	Desert RATS 2010-2011 efforts; JSC/ER small pressurized rover; JSC/EA habitat; JPL Athlete. Continuing JSC efforts on multi-mission space exploration vehicle (MMSEV).

Additional "Lunar Dust Adhesion Bell-Jar" testing has been conducted by Dr. James Gaier at the NASA Glenn Research Center (GRC), and "Dusty Plasma Lab" testing has been conducted by Dr. Mian Abbas at NASA-MSFC.

Table 2. Selected Lunar Exploration Proposed Strategic Knowledge Gaps (SKGs) - continued

Strategic Knowledge Gap	Narrative (modified from LEAG 2012 GAP SAT report)	Enabling or Enhancing	Status	Exploration Science or Technology	Messurements or Mission needed to retire SKG	Notes 2016 Assessment
III-J-4 Human mobility	Human crews on the Moon need spacesuits to explore and work out on the luar surface. Also, the Apollo J-missions clearly showed the benefits of mobility when it comes to human exploration of a planetary surface. Unpressurized rovers like the Apollo LRV, or one-person Segway-like vehicles could be used for local transportation, while pressurized rovers could provide for longer multi-day traverses.	Enabling for all human missions to the Moon.	**OPEN**	Technology	Missions to the lunar surface, using multiple types of human mobility systems, are required to retire this gap.	Desert RATS 2008-2011 efforts; JSC/ER scout, chariot, and small pressurized rovers. Continuing JSC efforts on multi-mission space exploration vehicle (MMSEV). Continuing JSC efforts on Z-2 suit. Need info on lunar PLSS.
III-C-1 Lunar surface trafficability - modeling	Production of relevant lunar soil simulants. Geo-technical testing (especially trafficability) of prototype or test hardware in high fidelity regolith simulants. Not required for Apollo-zone exploration, but important for unexplored areas like regional pyroclastic deposits, the lunar poles, and melt sheets of large impact craters.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Over 20 different lunar simulants exist, world wide. Terrestrial testing in relevant lunar conditions, using multiple lunar simulants is required to retire this gap.	Over 20 different lunar simulants exist, world wide. University competition at KSC involving regolith manipulation. APL SSERVI node NASA ISRU types at KSC; NASA robotic types at JSC, Ames, JPL; Lunar Catalyst types such as Red Whittaker
III-C-2 Lunar surface trafficability - in situ measurements	Characterization of geotechnical properties and hardware performance during regolith interactions on the lunar surface.	Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.	**OPEN**	Technology	Missions to the lunar surface, at both polar and non-polar locations, measuring geotechnical properties of the lunar regolith and conducting trafficability experiments in polar, pyroclastic, and young impact melt terrains are required to retire this	Requires a NASA (or NASA-funded partner) rover to traverse on the Moon. The Resource Prospector Project rover is the only NASA lunar rover in development and this project is not approved to go the Moon. NASA partners, such a Lunar Catalyst or Lunar Google X Prize may provide some useful information.

The author seriously doubts the utility of "Segway-like vehicles" with fewer than 4 wheels, which would pose significant stability issues for negotiating the highly cratered surface of the Moon. The author also questions whether "Terrestrial testing in relevant lunar conditions" is possible on the Earth. Mining rovers like the "Resource Prospector" will require additional power to survive in lunar temperature extremes. More information about development of the "Resource Prospector" rover is desired.

Survival on the Moon during the almost 15 days without solar heating is a significant challenge. The LUROVA™ thermal simulation was used in a NASA Goddard Space Flight Center "Technology" study, and then to calculate survival energy requirements for the non-nuclear 2012-2013 NASA "Night Rover" Centennial Challenge, as shown in Figure 18. This project was cancelled in 2014 after no potential providers had continued interest in participating in preliminary testing, because they did not see significant marketability of the technology outside of NASA. Also, more than twice the present energy storage capability is required and the duty cycle of 14+ days has little application in the private sector.

R-24

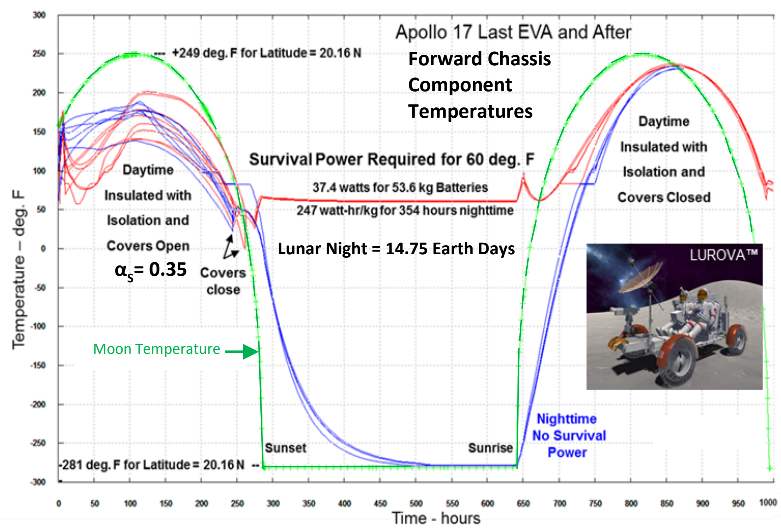


Figure 18. LUROVA™ Thermal Model Used For NASA Centennial Energy Storage Challenge

An RTG nuclear power source for a "Dual Mode" rover was studied for the fourth LRV for Apollo 18 (Figure 19), until this mission was cancelled in 1970. The author contributed to a dual mode Rover study at JPL in 2006, also shown in Figure 19.

R-25

R-26

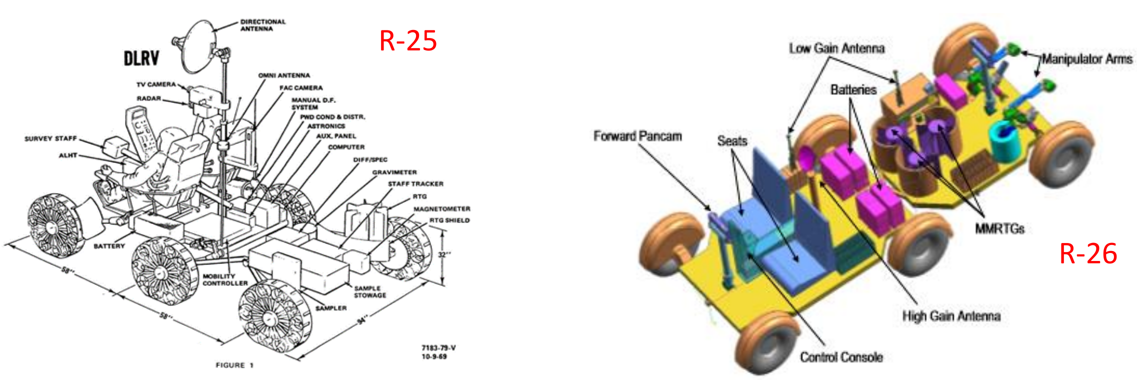


Figure 19. Dual Mode LRV with RTG Studied for Apollo 18, JPL Concept with MMRTG Power

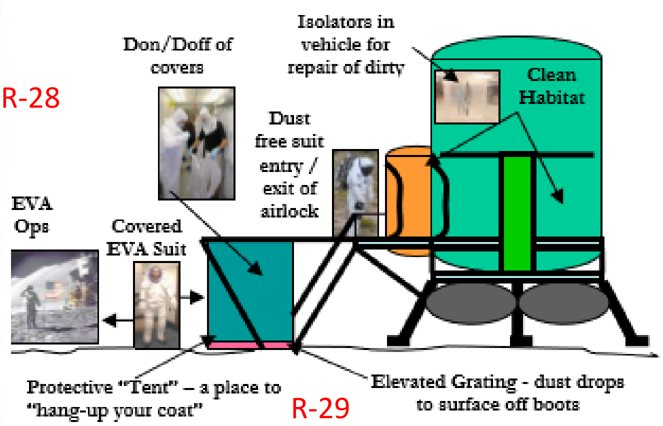
Dust mitigation options for dust exposure avoidance include potential use of the "Chariot" rover (Figure 20) with isolation suits and/or suit covers. This kind of protected Rover and suit covers can provide dust avoidance for Astronaut explorers.

JSC "Chariot" Provides Dust Isolation R-27

Figure 20. JSC Chariot Rover Provides Isolation from Direct Dust Exposure

This kind of Chariot Rover and suit can also hook up with a clean habitat, as shown in Figure 21.

R-28



I-Suit with a modified DuPont Tyvek® cover garment in first order interface test

Operational scenario for reusable space suit covers on the lunar surface

Figure 21. Special Suits and Habitat Can Provide Additional Dust Exposure Avoidance

EXPERIENCE BASED RECOMMENDATIONS FOR COPING WITH DUST

The author's experience based recommendations for coping with lunar dust are presented here. This includes relying on Apollo exploration veterans for advice, and potential use of the LUROVA™ test and mission correlated thermal simulation.

- **Be Very Careful with Interpretation/Extrapolation of Earth Based Dust Testing Results**

  - Lesson Learned that Pre-Apollo Testing for Dust Removal by Brushing was misleading

- **Remove/Minimize Astronauts Having to Spend Valuable Time on Lunar Dust Removal**
- **Design Exploration Systems that Isolate Astronauts and Equipment from Dust Exposure**
- **Focus on Nuclear Systems to Provide Power (Especially for the Long Lunar Nights)**
- **Dual Mode (Crewed, Followed by Robotic Operation) Rovers Increases Utility for Moon Exploration**
- **Full Coverage Fenders are Required for Wheels (Especially for Higher Speed Rovers)**
- **Can Rely on Experience and Advice of Apollo Exploration Veterans**
- **LUROVA™ (LUnar ROVing Adventures) Simulation Can be Used for Analyses and Interactive Exploration Experience** R-30

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