Compiled by Ron Creel – Apollo LRV Team Member

Coping with Dust for Extraterrestrial Exploration

Ron Creel

Apollo Lunar Roving Vehicle Team Member

-1

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

R-1

Ron, Busy at Lunar Rover Thermal Model Control Console

OUTLINE

- **Previous Testing and Apollo Experiences with Lunar Dust**
- **Dust Effects on Extended Extraterrestrial Missions**
- **Post-Apollo Lunar Dust Testing for Strategic Knowledge Gaps**
- **Dust Mitigation Options for Future Lunar Exploration**
- **Experience Based Recommendations for Coping with Dust**

SSERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

Institute for Modeling Plasma, Atmospheres and Cosmic Dust
Boulder, CO, USA

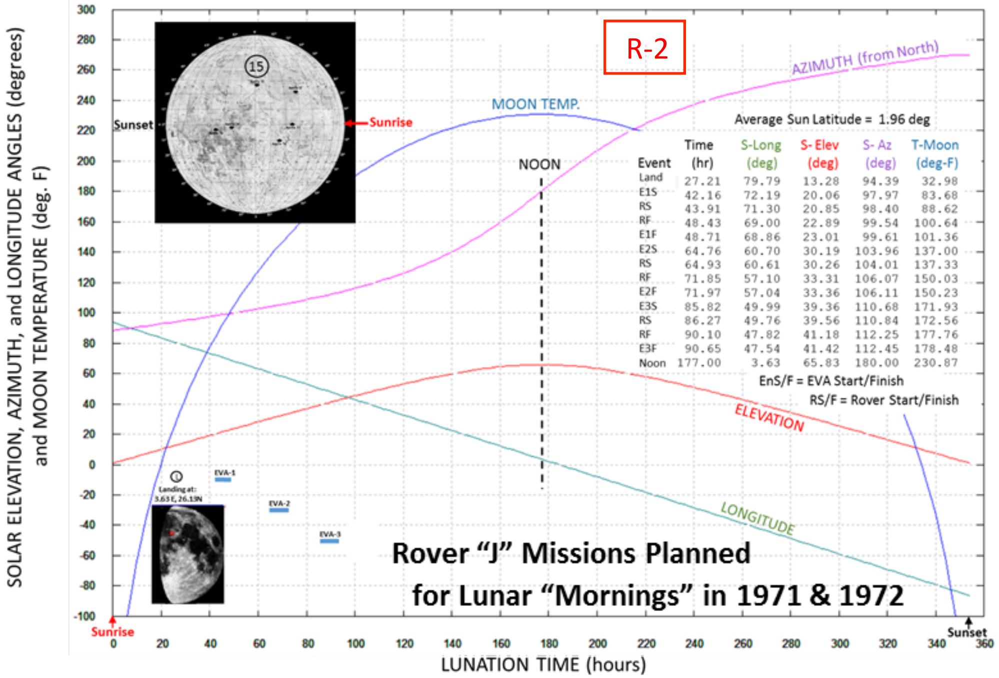
DAP-2017
January 11-13, 2017
Boulder, CO

The Dust, Atmosphere, and Plasma environment of the Moon and Small Bodies

Compiled by Ron Creel – Apollo LRV Team Member

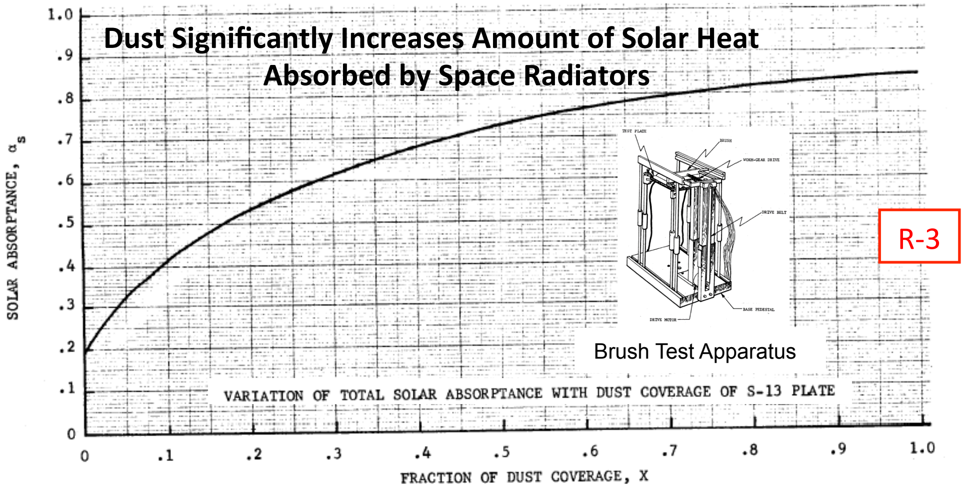
Previous Apollo Rover Dust Removal/Prevention Testing

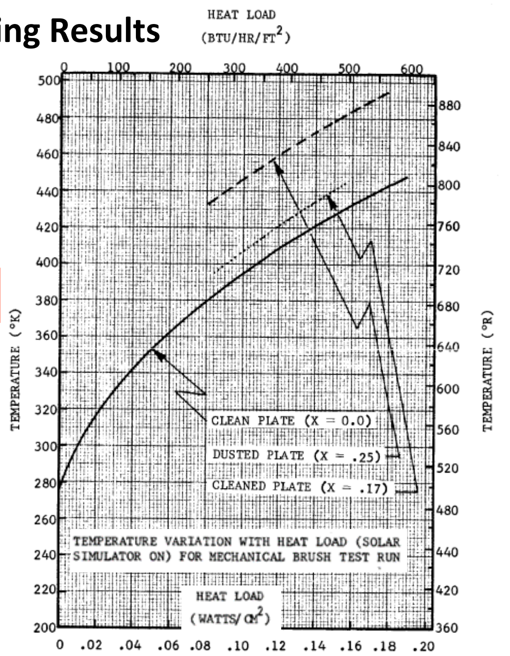
APOLLO 15 - LUNAR ROVER SOLAR HEATING AND MOON TEMPERATURE - LUROVA™ Data for WOTM



Event	Time (hr)	S-Long (deg)	S- Elev (deg)	S- Az (deg)	T-Moon (deg-F)
Land	27.21	79.79	13.28	94.39	32.98
E1S	42.16	72.19	20.06	97.97	83.68
RS	43.91	71.30	20.85	98.40	88.62
RF	48.43	69.00	22.89	99.54	100.64
E1F	48.71	68.86	23.01	99.61	101.36
E2S	64.76	60.70	30.19	103.96	137.00
RS	64.93	60.61	30.26	104.01	137.33
RF	71.85	57.10	33.31	106.07	150.03
E2F	71.97	57.04	33.36	106.11	150.23
E3S	85.82	49.99	39.36	110.68	171.93
RS	86.27	49.76	39.56	110.84	172.56
RF	90.10	47.82	41.18	112.25	177.76
E3F	90.65	47.54	41.42	112.45	178.48
Noon	177.00	3.63	65.83	180.00	230.87

- **1967 MSFC Earth-Based Dust Removal Testing Results**





- **Brushing Restored Near-Original Solar Absorptance**
- **Fluid Jet Was Superior, but Had Weight and Safety Issues**

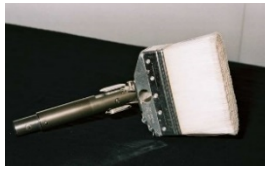
- **1970 MSC Earth-Based Dust Removal Test Results with Apollo 12 Dust**

R-5

1. Brushing dust from the sample surface is an effective method of removing dust.
2. The nylon-bristle brush is far superior to the brass-bristle brush for removing the lunar dust from the sample surface.
3. There is apparently no significant difference between the effect of lunar dust which was stored in a vacuum and that which was stored in nitrogen when both types of dust are applied in a vacuum environment.
4. There is a wide variation in adhesion of lunar dust to various materials.

As a result of these lunar-dust-deposition tests in a vacuum environment, the following additional comments are made:

1. The nylon-bristle brush is quite efficient and should be considered for use in removing lunar dust from thermal control materials.
2. In future ground tests of this type, lunar dust which is stored in a nitrogen environment at atmospheric pressure can be used in vacuum tests without significant loss in efficiency.
3. Of the possible thermal control materials for use in lunar surface operations, quartz second-surface mirrors, which are highly efficient thermally, can apparently be cleaned easily



Apollo Dust Brush

- **1970 MSFC KC-135 Vacuum/Reduced Gravity Tests with LSS4 - Verified Need for Fenders**

Figure 2--Close up of Wheel and Fender.

R-4

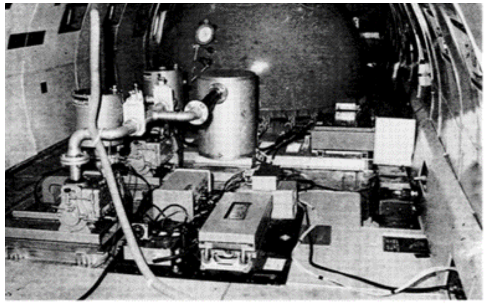


Figure 1--Text Fixture and Instrumentation in C-135A aircraft.

Misleading 1967/1970 Earth Based Testing for Dust Removal by Brushing – Fender Utility Verified in 1970

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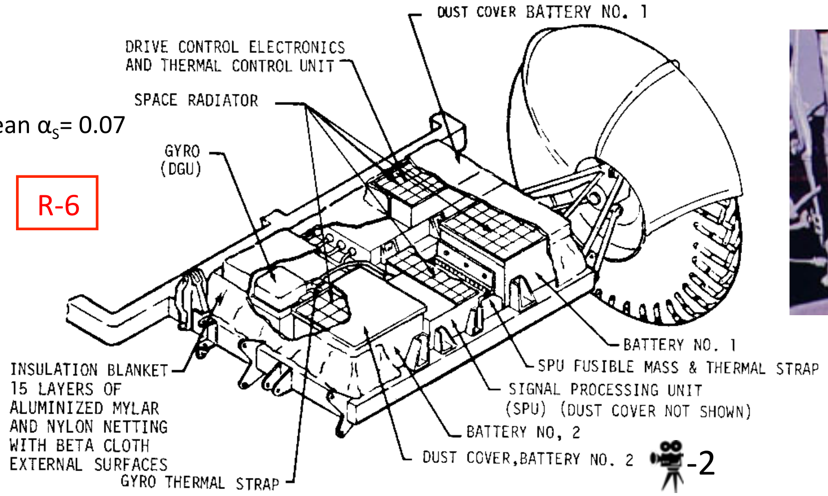
The Dust, Atmosphere, and Plasma environment of the Moon and Small Bodies

Compiled by Ron Creel – Apollo LRV Team Member

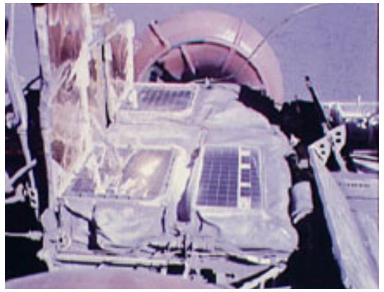
Lunar Rover Exploration Thermal Experiences with Dust

Clean α_s= 0.07

R-6

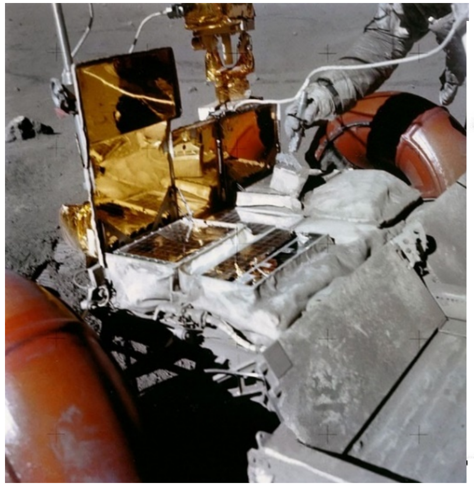


Forward Chassis Electronics, Batteries, and Radiators

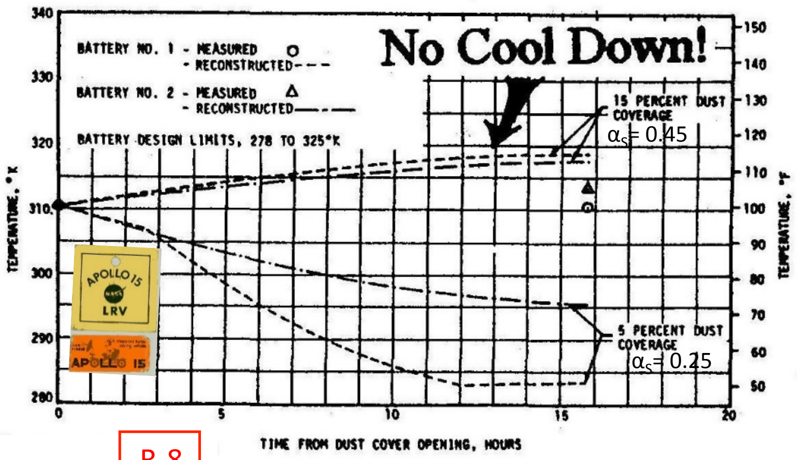


Dust on Radiators

R-7

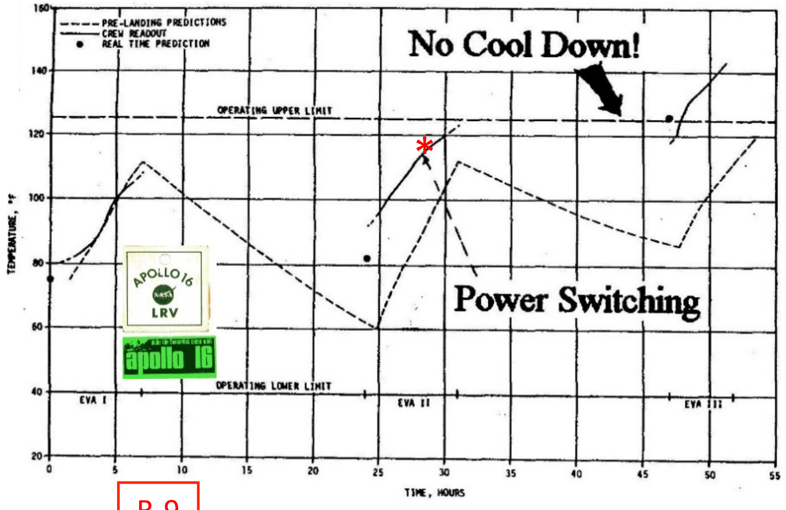


Astronaut Brushing Space Radiator



R-8

LRV Battery Temperatures During Cooldown 2

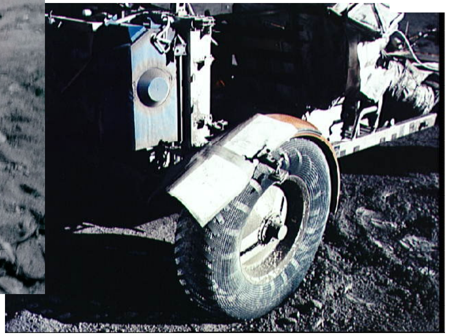


R-9

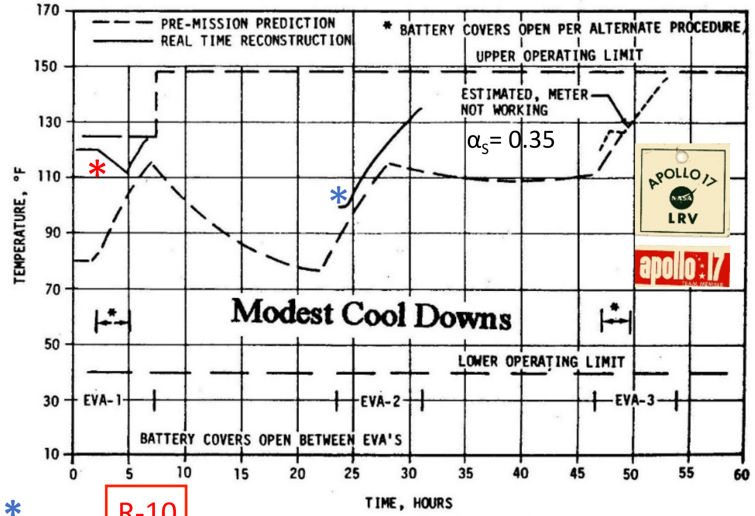
Battery No. 2 Temperature

RR Fender Extensions
Lost on Apollo 16 & 17 *

Silver Snoopy
for LUROVA™
Simulation



Fender Repair on Apollo 17 *



R-10

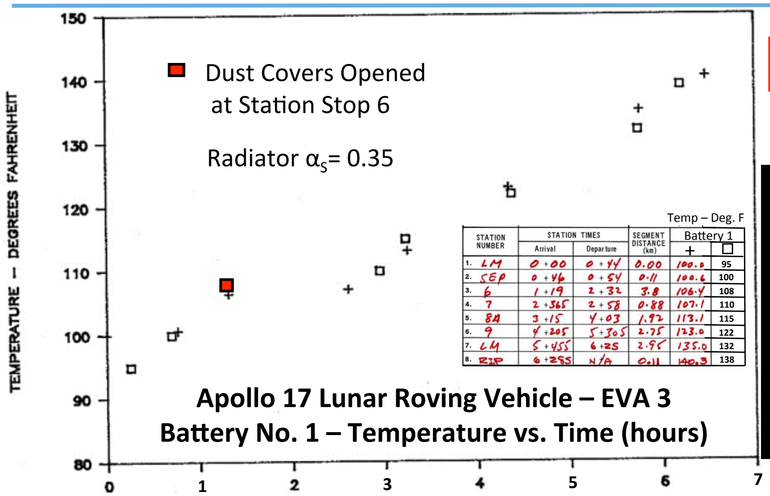
LRV Battery No. 2 (Right) Temperature

Valuable Astronaut Time Spent Coping with Adverse Lunar Dust Effects on Relatively Short Exploration Excursions

The Dust, Atmosphere, and Plasma environment of the Moon and Small Bodies

Compiled by Ron Creel – Apollo LRV Team Member

Additional Apollo Exploration Experiences with Dust



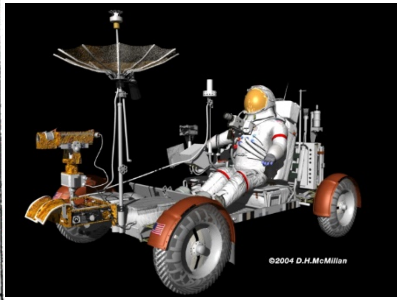
STATION NUMBER	STATION TIMES Arrival	STATION TIMES Departure	SEGMENT DISTANCE (km)	Battery 1 +	Battery 1 □
1. LM	0 +00	0 +44	0.00	100.0	95
2. SEP	0 +46	0 +54	0.11	100.6	100
3. 6	1 +19	2 +32	3.8	106.4	108
4. 7	2 +365	2 +58	0.88	107.1	110
5. 8A	3 +15	4 +03	1.92	113.1	115
6. 9	4 +205	5 +305	2.75	123.0	122
7. LM	5 +455	6 +25	2.95	135.0	132
8. RIP	6 +285	N/A	0.11	140.3	138

Apollo 17 Lunar Roving Vehicle – EVA 3
Battery No. 1 – Temperature vs. Time (hours)

□ ACTUAL + PREDICTION

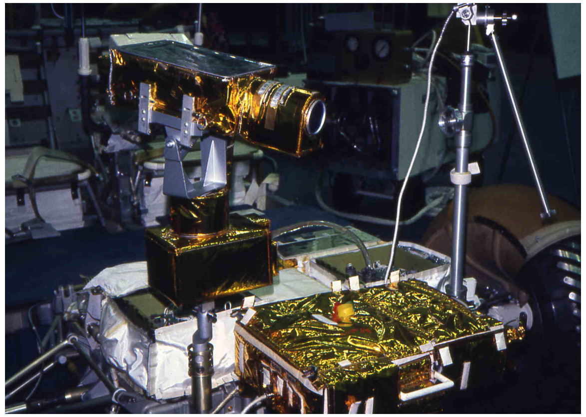
R-11

LUROVA™ Thermal Simulation



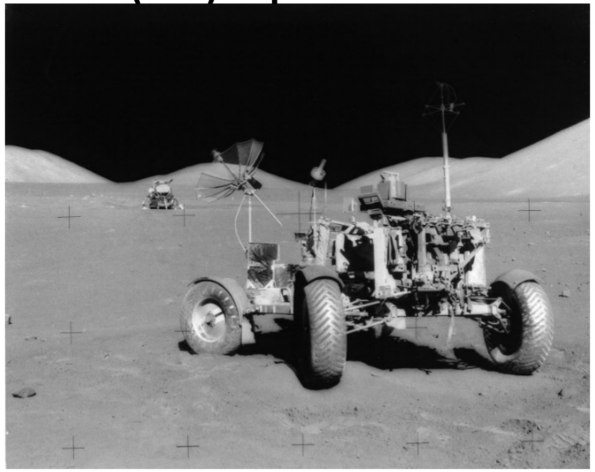
- **Mission Control Appreciated that LUROVA™ Provided Dependable and Accurate Thermal Predictions**

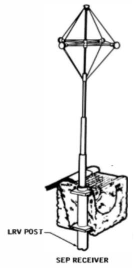
R-12



- **Radiators on Television Camera and Lunar Communications Relay Unit Required Repeated Brushing**

- **MIT Engineers Counseled About Dust for Surface Electrical Properties (SEP) Experiment Radiator**





R-13

-3

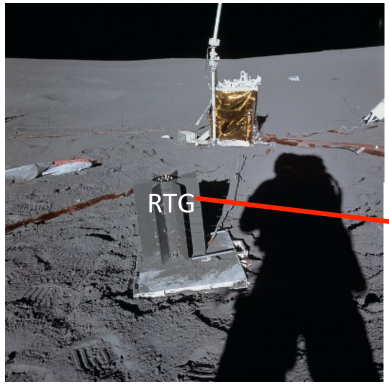
- **Astronaut Explorers Have Highlighted Exploration Problems with Lunar Dust**

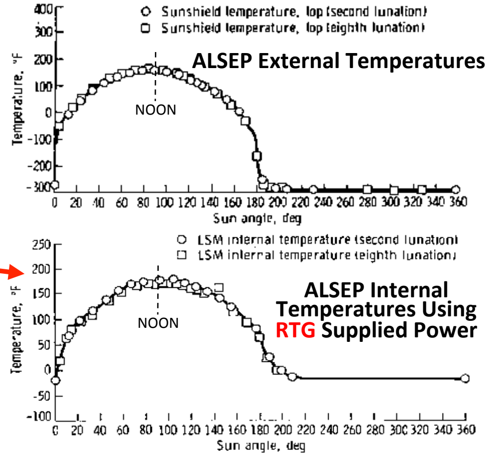
> *"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."*
>
> Gene Cernan, Apollo 17 Technical Debrief

R-14

- **Astronauts Could Not Avoid Getting Lunar Dust on Deployed ALSEP Experiments**

R-15



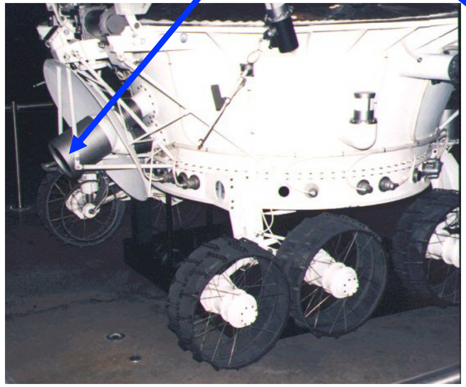


Lunar Dust Degraded Other Rover Radiators and Exploration Equipment - Health Concern for Astronauts

Compiled by Ron Creel – Apollo LRV Team Member

Dust Effects on Lunar Extended Extraterrestrial Missions

R-16



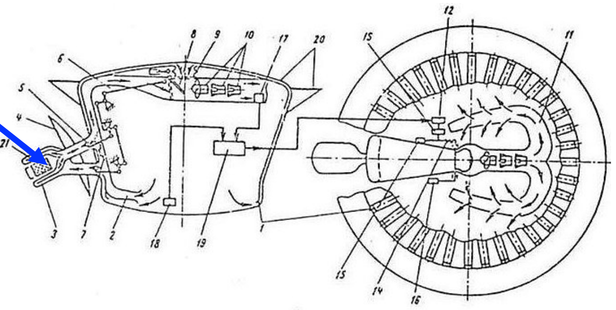
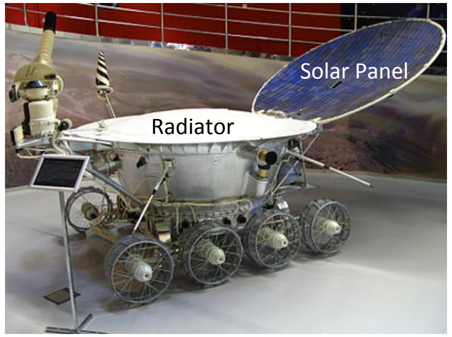


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism;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

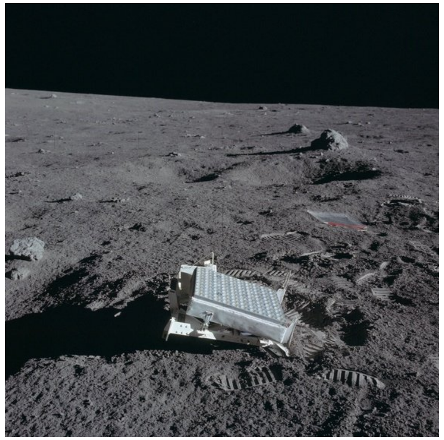
- Translated Lunokhod 1 Description Appeared in Dec. 1971

- Russians Successfully Used Nuclear Isotope Heat Sources for Several Lunar Night Cycles on Their Much Slower Moving Lunokhod (Moonwalker) Robotic Rovers



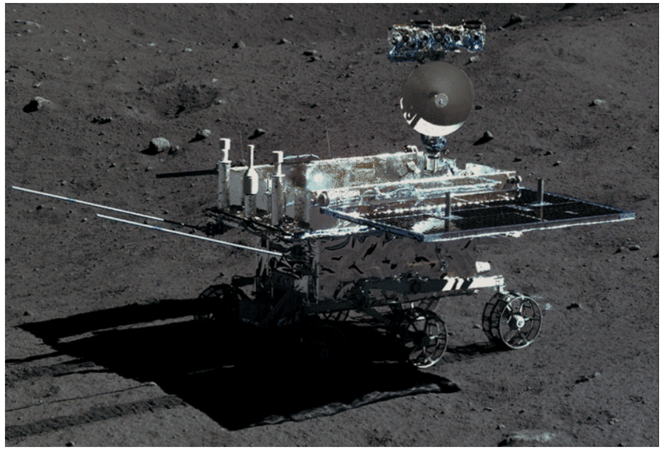
- Gen. Dovgan Shared in 2004 How Accidental Dust on Elevated Radiator Doomed Lunokhod 2 in 1973 R-17

- Dust Accumulation on ALSEP Experiment Equipment May Have Contributed to Temperatures Continuously Increasing Until "Turn-off" in Sept. 1977 R-18
- Indications that Passive Returns from ALSEP Laser Ranging Retro-Reflectors Continue to be Degraded by Accumulated Lunar Dust R-19



Apollo LRRR

- Lunar Dust May Have Contributed to Chinese Yutu "Jade Rabbit" Robotic Rover's Early Mobility Demise in 2014 R-20



Chinese Yutu Rover

American ALSEP Experiments, and Russian & Chinese Robotic Rovers Were Adversely Affected by Lunar Dust

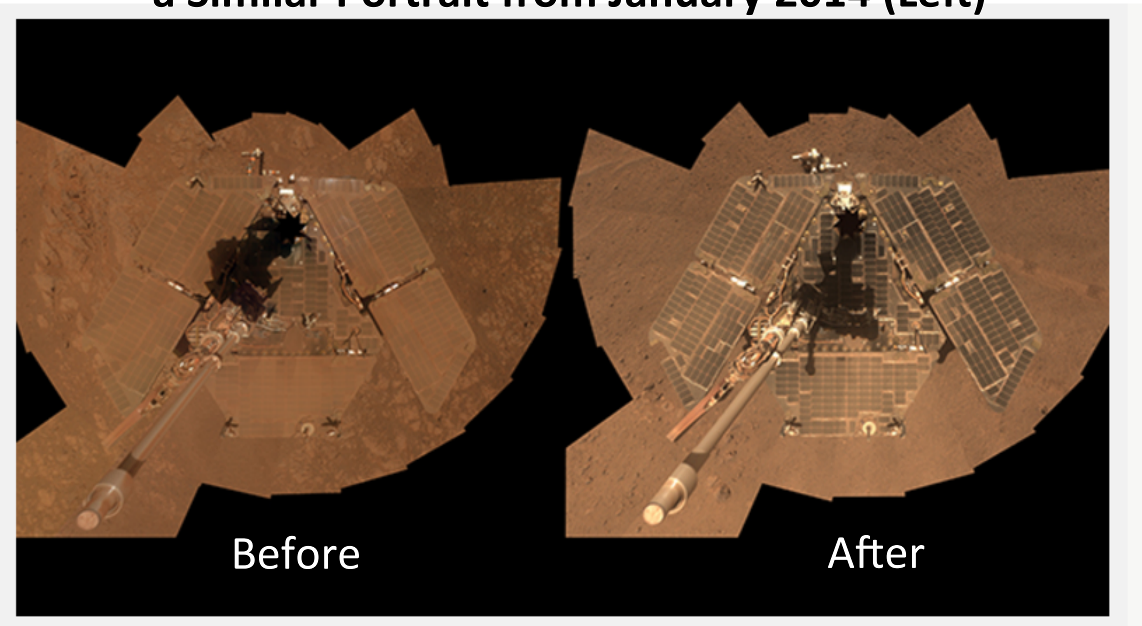
Dust Effects on Mars Extended Extraterrestrial Missions

Opportunity Rover

R-21

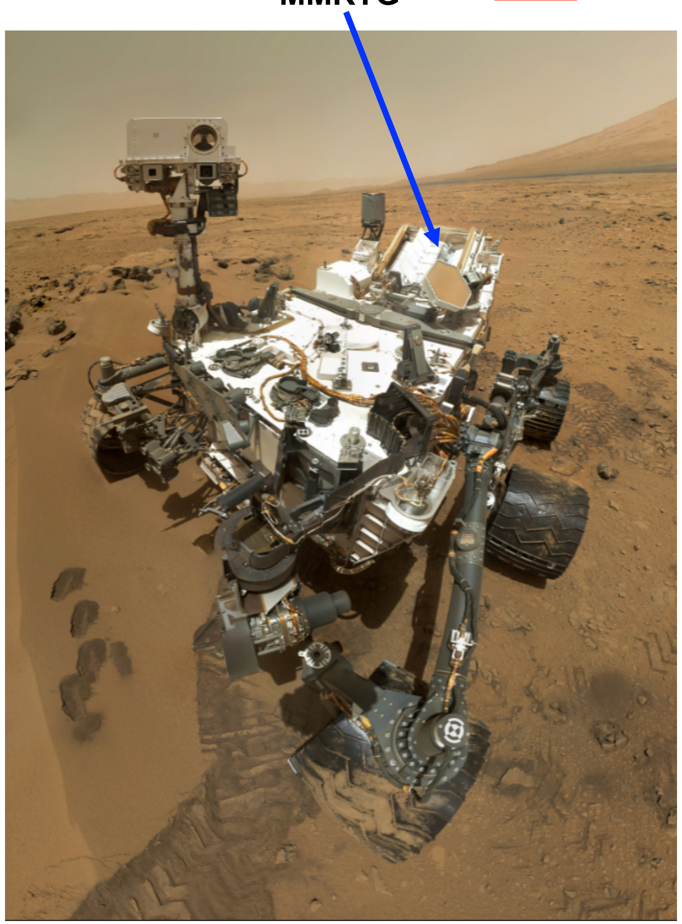
- Dust Deposited on Opportunity Solar Panels Significantly Reduced Power Generation Capability

- Overhead Self-portrait of Mars Exploration Rover "Opportunity" Taken in Late March 2014 (Right) Shows that Much of the Dust on Solar Arrays was Removed, Since a Similar Portrait from January 2014 (Left)



R-22

MMRTG



Curiosity Self-portrait

- Mars Robotic Opportunity Rover Was Cleaned of Heavy Dust Coating on Solar Panels Thanks to Strong Winds Blowing Over the Rim of Endeavor Crater
- Newest "Curiosity" Mars Science Laboratory Rover Avoids Adverse Dust Effects by Replacing Solar Panels with a Multi-Mission Radioisotope Thermoelectric Generator

Variable Wind on Mars was Helpful in Removing Dust from Rover Surfaces – Curiosity Rover Now Uses MMRTG for Power

Post-Apollo Lunar Dust Testing for SKGs – 1 of 2

- **Dust Related <u>Strategic Knowledge Gaps</u> Identified by 2016 Lunar Exploration Analysis Group Special Action Team**
  - **Theme III is to "Understand How to Work and Live on the Lunar Surface"**

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 (≤ <u>28 days</u>) lunar missions. Enabling for long-term, sustained human operations on the Moon.	OPEN	Technology	<u>Missions to the lunar surface</u>, 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 (≤ <u>28 days</u>) lunar missions. Enabling for long-term, sustained human operations on the Moon.	OPEN	Technology	<u>Missions to the lunar surface</u>, 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 (≤ <u>28 days</u>) lunar missions. Enabling for long-term, sustained human operations on the Moon.	OPEN	Technology	<u>Missions to the lunar surface</u>, 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 by Dr. James Gaier at GRC, and "Dusty Plasma Lab" Testing by Dr. Mian Abbas at MSFC

Testing Gaps Identified for Dust Adhesion & Remediation and Mobile Human Habitats – Present Pursuits Listed

Compiled by Ron Creel – Apollo LRV Team Member

Post-Apollo Lunar Dust Testing for SKGs – 2 of 2

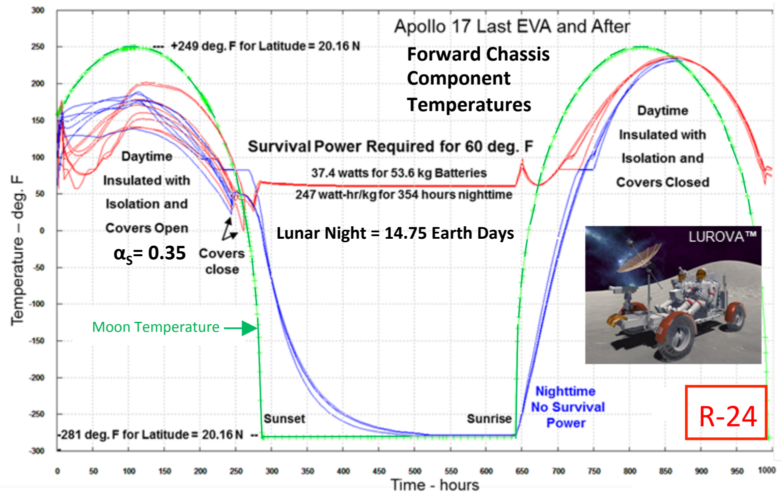
R-23

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-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.

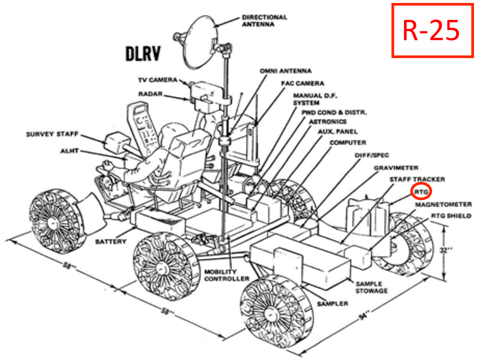
Lunar Mobility and Surface Trafficability Testing Gaps Identified – Resource Prospector Rover Being Studied

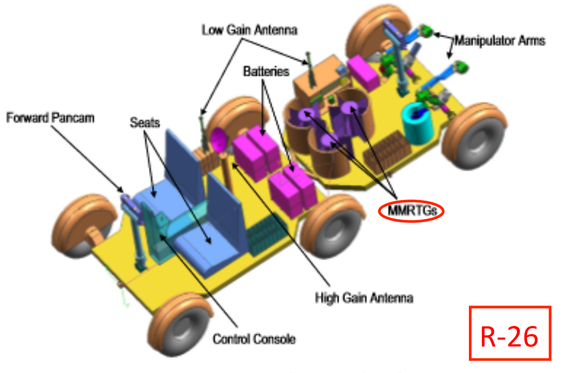
Compiled by Ron Creel – Apollo LRV Team Member

Dust Mitigation Options for Future Lunar Exploration



- Mining Rovers Like "Resource Prospector" Will Require Additional Power to Survive in Lunar Temperature Extremes

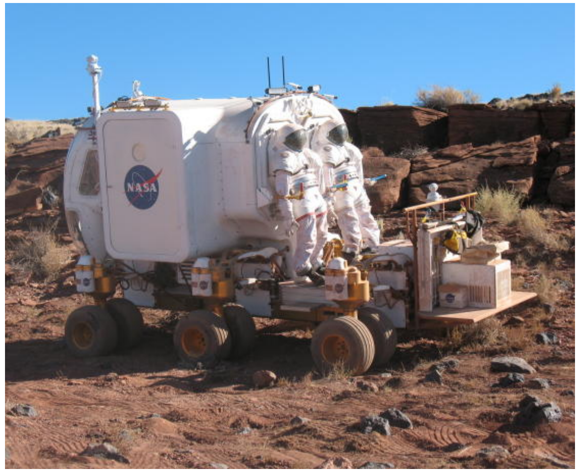




DMLRV Conceptual Design.

- Dual Mode LRV with RTG Studied for Apollo 18 and JPL Concept with MMRTG Power
  - Closed Thermal Systems Avoid Dust Exposure Issues for Space Radiators

- Cancelled Non-Nuclear Energy Collection and Storage Project for "Night Rover" Centennial Challenge

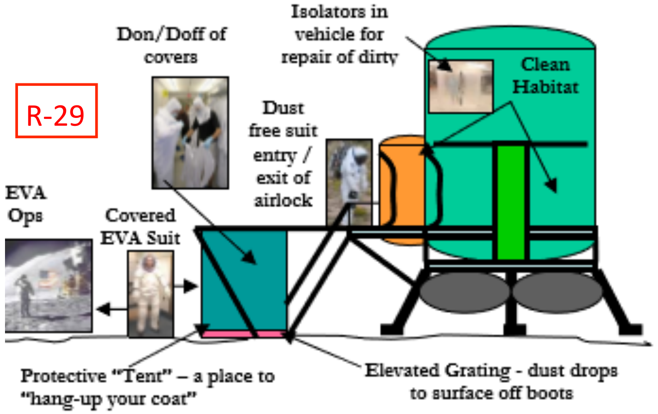


JSC "Chariot" Provides Dust Isolation

Z-2 Suit

- Rovers Like Chariot with Astronaut Z-2 Suits or I-Suit Covers Can Provide Dust Avoidance for Astronaut Explorers
- Dust Retardants Also Being Studied

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

Nuclear Power and Dust Avoidance are Keys to Success in Future Lunar Exploration – Potential Pursuits

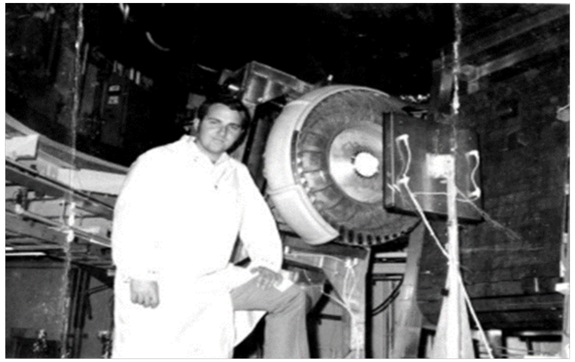
Experience Based Recommendations for Coping with Dust

- 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)

NASA JPL ATHLETE Rover

- Dual Mode (Crewed, Followed by Robotic Operation) Rovers Increase Utility for Exploration
- Full Coverage Fenders are Required for Wheels (Especially for Higher Speed Rovers)
- Can Rely on Experience and Advice of Apollo Exploration Veterans R-30
- LUROVA™ (Lunar Roving Adventures) Simulation Can be Used for Analyses and Interactive Exploration Experience

(roving.ron@gmail.com)



Ron Creel with Apollo Rover Mobility M/4 Test Unit

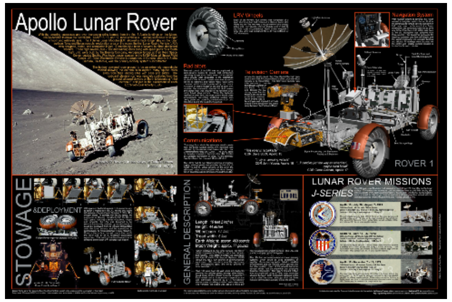
Post Apollo 17 – Astronauts Met with LRV Team

Astronauts Were Presented with Fender Extension from LRV Qualification Unit Autographed by MSFC Support Team

Summary – Be Careful About Relying on Earth Based Testing, and Focus on Dust Avoidance & Nuclear Power for Survival

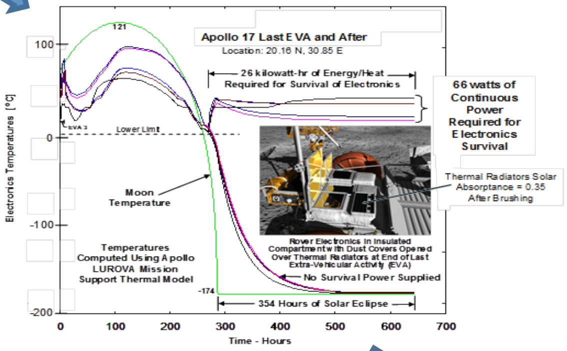
LUROVA™ (LUnar ROVing Adventures) Simulation Game Being Developed for Student STEM Challenge and Interactive Exploration Experience

R-11



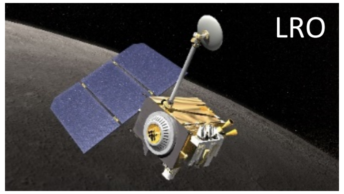
Render Engine Used To Create Detailed Surface Model of NASA Lunar Rover (Poster Created in 2005)

Thermal Model



Apollo Lunar Rover Mission Support Thermal Model Used for NASA GSFC and GRC Exploration Reports, ARC "Virtual Worlds" Workshop, "Night Rover" Centennial Challenge, and TFAWS Conferences (2006 and 2014)

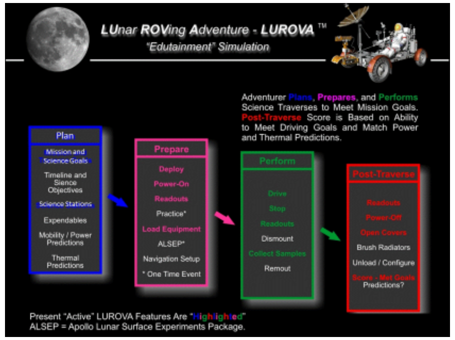
ARC = Ames Research Center
GRC = Glenn Research Center
GSFC = Goddard Space Flight Center



Rover Surface and Thermal Models Combined with NASA Lunar Reconnaissance Orbiter (LRO) Terrain Data for Exploration Realism (2014-2016)

LRO Terrain Data

STEM Simulation Game Being Programmed for Realistic Exploration Experience (2014-2016)



LUROVA™ STEM Simulation Game Demonstration Video Showing Development Progress:

https://drive.google.com/file/d/0BxRJjyvPeTKkZExaak44b29kVkU/view

STEM = Science, Technology, Engineering, and Mathematics
TFAWS = Thermal and Fluids Analysis Workshop

Good Progress Being Made in Developing LUROVA™ for STEM

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SERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

Institute for Modeling Plasma, Atmospheres and Cosmic Dust
Boulder, CO, USA

The Dust, Atmosphere, and Plasma environment of the Moon and Small Bodies

Compiled by Ron Creel – Apollo LRV Team Member

Acronyms and References

Acronyms

ALSEP	Apollo Lunar Surface Experiments Package
APL	Applied Physics Laboratory
ARES	Astromaterials Research and Exploration Science
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
DREAM2	Dynamic Response of the Environments at Asteroids, the Moon, and moons of Mars
DGU	Directional Gyro Unit
EA	Enterprise Architecture
ER	Software, Robotics, and Simulation Division at JSC
EVA	Extra Vehicular Activity
GRC	Glenn Research Center
ISRU	In-Situ Resource Utilization
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEAG	Lunar Exploration Analysis Group
LRRR	Laser Ranging Retro Reflector
LRV	Lunar Roving Vehicle
LSS4	Lunar Soil Simulant 4
LUROVA	LUnar ROVing Adventures (Simulation Game)
MIT	Massachusetts Institute of Technology
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MMSEV	Multi-Mission Space Exploration Vehicle
MSC	Manned Spacecraft Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PLSS	Portable Life Support System
RATS	Research And Technology Studies
RR	Right Rear
SAT	Special Action Team
SEP	Surface Electrical Properties
SKG	Strategic Knowledge Gap
SPU	Signal Processing Unit
SSERVI	Solar System Exploration Research Virtual Institute
WOTM	Working On The Moon (Apollo Lunar Surface Journal)

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