Back To The Future

Applying Thermal Control Experiences On Apollo Lunar Rover Project To Rovers For Future Space Exploration

Ronald A. Creel, Space Systems Engineer
Member Of The Apollo Lunar Roving Vehicle Team
Fresh out of college, some 35 years ago, Ron Creel was thrust into a challenging and high speed engineering task – design, test verification, and mission support for the thermal control system of a new kind of spacecraft with wheels, the Apollo Lunar Roving Vehicle (LRV). Success on this project was acknowledged by several NASA performance citations, which culminated in receipt of the Astronaut’s “Silver Snoopy” award for his LRV thermal system modeling and mission support efforts.

Ron is a Senior Space Systems Engineer at Science Applications International Corporation (SAIC), and has been involved in thermal control and computer simulation of several launch vehicles and spacecraft including the International Space Station and Air Force satellites.

Today, Ron will update his LRV thermal experiences, recently presented at the U.S. International Space Development and Return to the Moon Conferences and at the International Planetary Rovers and Robotics Workshop in Russia, with an eye toward applications to future manned and robotic Moon Rovers for the President’s Space Exploration Initiative.
Back To The Future – Moon Rovers

Outline

• Lunar Roving Vehicle (LRV) History And Thermal Design

• LRV Thermal Testing and Computer Model Development

• On The Moon - LRV Thermal Control Performance And Mission Support Experience

• Thermal Control Challenges For Future Moon Rovers
My Start In Space Engineering

• Sputnik Era Model Rocket Launches

• Co-op Student At NASA Marshall Space Flight Center (MSFC)

• Graduated And Assigned To Development Of Apollo Lunar Roving Vehicle (LRV) Thermal Control System
Rover Historical Concepts

Unique Concepts Proposed

Lunar Flying Vehicle Considered

Wheeled Rover Concepts Led To LRV Design
(1969 Start And 1971 First Mission)
LRV Designed To Provide Extended Mobility On The Moon

Lunar Roving Vehicle

The Lunar Roving Vehicle ("Rover") was 10.2 ft. long with a wheelbase of 7.5 ft. It had a turning radius of 10 ft. and a maximum speed of 8.7 mph. The LRV had a lunar weight of 77 lb and an Earth weight of 462 lb. Power was supplied by two 36-volt silver-zinc batteries. Rovers were used in the Apollo "J-Missions" (15, 16 and 17) to greatly extend the lunar surface area explorable by the astronauts.
LRV’s Greatly Increased Science Return From Apollo 15, 16, And 17

LRV No. 1 Delivered “On-Time” For Apollo 15

LRV Performance Comparison On The Moon

<table>
<thead>
<tr>
<th></th>
<th>Pre-LRV</th>
<th>Apollo 15</th>
<th>Apollo 16</th>
<th>Apollo 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA Duration (hrs:min)</td>
<td>19:16</td>
<td>18:33</td>
<td>21:00</td>
<td>22:06</td>
</tr>
<tr>
<td>Driving Time (hrs:min)</td>
<td>–</td>
<td>3:02</td>
<td>3:26</td>
<td>4:29</td>
</tr>
<tr>
<td>Surface Distance Traversed (km)</td>
<td>3.55</td>
<td>27.9</td>
<td>28.9</td>
<td>35.7</td>
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<tr>
<td>Average Speed (km/hr)</td>
<td>0.18</td>
<td>9.20</td>
<td>7.83</td>
<td>7.96</td>
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<tr>
<td>Longest Traverse (km)</td>
<td>–</td>
<td>12.5</td>
<td>11.6</td>
<td>20.3</td>
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<tr>
<td>Maximum Range From LM (km)</td>
<td>–</td>
<td>5.4</td>
<td>4.5</td>
<td>7.6</td>
</tr>
<tr>
<td>Regolith Samples Collected (kg)</td>
<td>97.8</td>
<td>77.8</td>
<td>96.7</td>
<td>116.7</td>
</tr>
</tbody>
</table>

LRV No. 2 Being Checked By Apollo 16 Crew At KSC

LRV No. 3 Was The Final Rover On Apollo 17
Thermal Control Of LRV “One-G” Trainer

Earth Operation Allowed Natural And Forced Convection Cooling

1G Trainer Provided Simulation Of All LRV Interfaces

Apollo 16 Astronauts With 1G Trainer At Kennedy Space Center
LRV Thermal Control Design Goal

• Maintain LRV And Space Support Equipment (SSE) Within Prescribed Temperature Limits During:
  – Earth To Moon Transportation - Totally Passive
  – Lunar Surface Operation in 1/6 Gravity And Quiescent Periods Between Traverses

• Minimize Astronaut Involvement, i.e. Primarily Passive

• Mitigate Adverse Effects Of Lunar Dust
# LRV Component Temperature Limits – Deg. F

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

Astronauts Read Temperature On Display Panel - * Batteries   ** Traction Drive (Start At 200)
LRV Transported To Moon By Saturn V And Lunar Module

- LRV Was Folded And Located In Lunar Module (LM) Descent Stage - X

- LRV Weight Goal Of 450 lbs. Drove Design To Passive Thermal Control With No Telemetry Data
LRV Space Support Equipment (SSE) Thermal Control

- Maintained SSE by selection of surface radiation properties and insulation and protection from LM reaction control and descent engine heating environments.

Folded LRV and SSE stowed in LM descent stage quadrant.

Apollo 15 astronauts inspect stowed LRV and SSE.
LRV Transportation Phase Thermal Control

- Goal – Limit Electrical Component Temperature Loss To 30 Deg. F
- Totally Passive – No Temperature Data Available During Transit To Moon
- Radiation To Space And Exposure to Exhaust Plume Impingement And Lunar Radiant And Albedo (Reflected) Heating Environments
- Lunar Module “Barbecues” To Balance Solar Heating And Radiation Loss
# Apollo Mission Profile

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>4. Launch Escape Tower Jettison</td>
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<tr>
<td>5. S-II/S-IVB Separation</td>
<td></td>
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<tr>
<td>6. Earth Parking Orbit</td>
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<tr>
<td>7. Translunar Injection</td>
<td></td>
<td></td>
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<tr>
<td>8. CSM Docking With LM/S-IVB</td>
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<td>9. CSM Separation From S-IVB</td>
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<tr>
<td>10. CSM/LM Sep. From S-IVB</td>
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<tr>
<td>11. Midcourse Correction</td>
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<tr>
<td>12. Lunar orbit Insertion</td>
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<td></td>
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<tr>
<td>13. Crew Transfer To LM</td>
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<td></td>
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<tr>
<td>14. CSM/LM Separation</td>
<td></td>
<td></td>
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<tr>
<td>15. LM Descent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Touchdown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Explore Surface, Exper.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Liftoff</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>19. Rendezvous And Docking</td>
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<tr>
<td>20. Transfer Crew/Equip.</td>
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<td></td>
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<tr>
<td>21. CSM/LM Sep. And LM Jettison</td>
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<td></td>
</tr>
<tr>
<td>22. Transearth Injection Preparation</td>
<td></td>
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<tr>
<td>23. Transearth Injection</td>
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<td></td>
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<tr>
<td>24. Midcourse Correction</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>25. CM/SM Separation</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>27. Splashdown</td>
<td></td>
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</tr>
</tbody>
</table>

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**From The Earth To The Moon**

*This chart has been phonetically drawn out of need to illustrate the major events of the mission.*

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**3 LRV’s Left On The Moon**

*Broken injection line indicates loss of Earth’s gravitational influence.*

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**“Barbecue”**

*(3 Rev/Hour)*
Astronauts Performed Manual Sequenced LRV Unfolding And Deployment On Moon

Retractable Fender Extensions Required For Folding of Wheels

Folded and Unfolding Images From LUROVA “Edutainment” 3D Simulation (See Page 46)
Apollo / LRV Extra-Vehicular Activities (EVA’s) Conducted During Lunar Thermal “Morning”

Moon Temp. = √((Cos(Beta)) × (√(443 × Sin(Sang))/σ - 460))

Where: Beta = Moon Latitude (Degrees)
Sang = Solar Elevation Angle (Degrees)
σ = Stefan Boltzman Constant (btu/(hr-ft²-R⁴))

Temperature of the Moon. The average temperature of the Moon as a function of phase, or time, is shown here. The exact shape of the curve varies somewhat with geographical position on the Moon and is determined by the thermal properties at each position.

The temperature of the Taurus-Littrow site shown as a function of the Sun angle. Note that EVA 1 at +17° Sun angle should have +50° F, EVA 2 at +27° Sun angle should have +110° F, and EVA 3 at +37° Sun angle should have a temperature of +160° F.
Deployed LRV Subsystems Thermal Control

- **Control And Display Console** – Insulated Front Panel, Exterior Dust Degraded

- **Mobility** – Exterior Dust Degraded - Maximize Internal Conduction

- **Forward Chassis Electronics** – Insulate/Isolate from Dust – Store Generated Heat In Batteries/Wax Boxes

- **Maintain All Surfaces Within Astronaut Touch Constraints**
LRV Control And Display Console Thermal Control

- Special Paints And Surface Treatments
- LRV Parked Outside LM Shade To Prevent Over Cooling Of Instruments
- Low Conductance Standoffs Used And Reduced Glare Black Anodizing For Front Panel
- Astronauts Read Out Battery And Drive Motor Temperatures
- Caution And Warning Flag “Pops Up” To Alert Astronauts Of Overtemp
LRV Mobility Subsystem

Wire Mesh Wheel

Mobility Subsystem Components
LRV Traction Drive Thermal Control

- Special Paints And Internal Conduction Maximized
- External Exposed Surfaces Will Be Dust Degraded

Mobility Subsystem

Harmonic Drive Unit Used for Traction Power on the LRV
LRV Batteries Were Heart of Forward Chassis
Electronics Thermal Control

- Multi-Layer Blanket For Insulation, Dust Covers
- Thermal Straps Conduct Heat Into Batteries
- Electronics Heat Also Stored In Wax Boxes (Fusible Mass Tanks) During EVA’s
- Low Solar Absorptance ($a = 7\%$) Space Radiators To Reject Heat When Dust Covers Opened Between EVA’s
LRV Forward Chassis Electronics Thermal Control

Signal Processing Unit And Directional Gyro Unit Strapped To 60 Lb. Batteries
Extensive LRV Thermal Testing Was Conducted

- Early Dust Effects And Removal Techniques Simulation (1967)
- LM Thruster/Engine Environment And Heating Deflectors Verification
- Surface Optical Properties (Absorptance And Emittance) Measurement
- Mobility Power Characterized At Waterways Experiment Station, C 135
- Development Thermal/Vacuum (TVAC) Tests For Subsystems
  - Mobility – Brakes, Steering, Dampers, ¼ Mobility, Fenders
  - Forward Chassis In Lunar “Tub” Environment Simulator
- System Level TVAC Tests With Dynamometers And Solar Simulator
  - Thermal Design Stressed Using “Flight-Like” Qualification Unit
  - Acceptance Level Checkout On Flight Units
- Delivery and First Launch in July 1971
- Post Flight Special Adjustments
  - Apollo 15 – Cleaning Agent For Floor Panel Thermal Control Tape
  - Apollo 16 – Battery Radiator Proximity To Lunar Module Effects
    -- Cold Exposure For Stuck Switches In Army Chamber
Lunar Dust Effects And Removal Techniques Were Studied In 1967

- Dust Significantly Increases Amount Of Solar Heat Absorbed By Space Radiators

Misleading Earth-Based Test Results

- Brushing Restored Near-Original Solar Absorptance
- Fluid Jet Was Superior, But Had Weight And Safety issues

Brush Test Apparatus
LRV Surface Optical Properties Were Measured For Use In Computer Thermal Models

Memorandum

TO: Mr. Creel, SSE-ASTM-PFA
FROM: Chief, Materials Division, SSE-ASTM-M

SUBJECT: Optical properties of Lunar Roving Vehicle thermal control samples

In accordance with your request (Work Order SSE-ASTM-MCS No. 5136-70), the optical properties of the samples have been determined. Results are shown below.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Material Description</th>
<th>α</th>
<th>ε</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Seat Material/beta Cloth/Al Mylar</td>
<td>0.28</td>
<td>0.90</td>
<td>21</td>
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<tr>
<td>2</td>
<td>PLSS Support Straps, Type 15</td>
<td>0.55</td>
<td>0.92</td>
<td></td>
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<tr>
<td>3</td>
<td>PLSS Support Straps/Beta/Al Mylar, Type 4</td>
<td>0.32</td>
<td>0.91</td>
<td>29.5</td>
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<tr>
<td>4</td>
<td>Dry Film Lube MIL-L-81319</td>
<td>0.83</td>
<td>0.76</td>
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<tr>
<td>5</td>
<td>Dry Film Lube MIL-L-23398 Polished</td>
<td>0.79</td>
<td>0.70</td>
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</tbody>
</table>

Heat Sources
- Absorbed Solar (Direct/Reflected)
- Absorbed Infrared
- Internal Generated

Heat Rejection
- Radiated Infrared

Reflectometer Measured Properties
- Solar Absorptance - \(\alpha\)
- Infrared Emittance - \(\varepsilon\)

Computer Model Thermal Balance
Extensive LRV Thermal Vacuum (TVAC) Testing

Wheel to Soil Interaction At Waterways Experiment Station, C 135

Fender Extension Deployment TVAC

Mobility Subsystem TVAC

Forward Chassis Development “Tub” TVAC

Qualification And Flight Units TVAC
“LUROVA” Operational Thermal Computer Model

- Electrical Analogy - Capacitors And Conductors
- Verified By Correlating With Test Temperatures
- Test Correlated Crew Station, Mobility, And Forward Chassis Models Combined Into “LUROVA” Operational Model
- Allowed Analysis For Clean Transit, Lunar Surface Dust Degradation, And Sortie Traverse Variations
- Detailed Model - 177 Nodes (Capacitors) And Thousands Of Conductors
- Cumbersome And Limited To Pre-EVA Use For Predictions
LUROVA Thermal Computer Model Operational Flow

Traverse Team Provided Driving Parameters

Power Profile Provided Internal Heat

- LUROVA Used To Predict Crew Station, Forward Chassis, Mobility Temperatures

Apollo 17 – EVA 3 Right Rear Motor

EVA Time - Hours

Predictions For Mission Operations Handbook

- Traverse Team Provided Driving Parameters
- Power Profile Provided Internal Heat
- LUROVA Used To Predict Crew Station, Forward Chassis, Mobility Temperatures
Apollo 15 – LRV Thermal Control Performance

- LUROVA Thermal Model Used Before EVA’s (Limited Utility)
- Motors Were Off Scale Low (<200 Deg. F) Throughout EVA’s
- Initial Battery Temperatures Higher Than Expected (80 F)
- Left Front Fender Extension Lost During EVA 1
- Good Cooldown Between EVA 1 And EVA 2, Cover 1 Closed
- **No Forward Chassis Cooldown Between EVA 2 And EVA 3**
  - Astronauts Indicated There Was Dust On Radiators
- Maximum Battery Temperature Of 112 Deg. F During EVA 3

Missing Front Fender Extension  
Dust On Radiators
Post Apollo 15 – Astronauts Visited Huntsville, AL

• Crew Thanked NASA And Contractor Workers For Saturn V And LRV Efforts As Part Of Manned Flight Awareness Program

Sonny Morea, LRV Program Manager, Presents LRV Memento To Apollo 15 Crew

Many Autographs Were Graciously Signed And Cherished Souvenir Photographs Were Taken
Post Apollo 15 – Floor Panel Tape Cleaning Agent

• Adhesive Residue On Panel Thermal Tape Contributed To Elevated Battery Temperatures At Deployment

• Toluene Shown As Best Cleaning Agent To Restore Thermal Properties
Forward Chassis Thermal Analyzer Model - FWDCHA

- Flexible, Responsive Mission Support Analysis Needed
- Forward Chassis And Viewed Components Modeled
  - 19 Node Model Derived From LUROVA And Used For Apollo 16 And Apollo 17 Mission Support
  - Included Full Battery Power Switching, Variable Radiator Dust Coverage, And LM Proximity Effects (17)
- Used For Real-Time And Pre-EVA Sortie Predictions

Excellent, Responsive Predictions Provided
Apollo 16 – LRV Thermal Control Performance

- FWDCHA Thermal Model Used For Pre-Sortie And EVA Analysis
- **Switches Stuck At Initial Power-up**, Max. Motor Temp. = 225 Deg. F
- LRV Supplied Power For LCRU And TV
- **LRV Parked Too Close To Lunar Module**
- Right Rear Fender Extension Knocked Off
- Insufficient Cooldowns Between EVA’s
- Battery Power Switching Required
- Max. Battery Temp. = 143 Deg. F On EVA 3

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**Missing Fender Extension**

**Astronaut Brushing Dust From Radiators**

**LRV Supplied LCRU, TV Power**
Post Apollo 16 – LM Parking Proximity Test

LRV Parked Too Close To LM

Battery Proximity Test At Space And Rocket Center

Form Factometer Photographed To Validate Model Radiator “View Factors” To LM

Parking Constraint Changed For Apollo 17
Mr. Ronald A. Creel
1000 Airport Road, SW
Huntsville, AL 35802

Dear Mr. Creel:

This is just a short note to express my appreciation, on behalf of all the astronauts, for the outstanding support you have given to the Apollo Program, and especially your efforts in developing the forward chassis thermal analyzer computer model for the LRV. The use of this model permitted rapid and flexible pre-mission and real-time thermal predictions for the LRV batteries and other critical components. Your work in this field greatly enhanced the probability of success that we realized on the Apollo 15 and 16 missions.

My fellow astronauts and I develop our confidence in the space program through training, experience, and a knowledge that there are men of your ability and dedication supporting this nation’s manned lunar landing program. Through your efforts you have demonstrated that you are a vital link in the success of our program, and I wish to express my thanks for your contributions.

In appreciation, please accept our personal flight crew emblem denoting professional achievement, the “Silver Snoopy.” When you wear this pin, you may do so knowing that it is given only to those individuals whom we regard as among the best in their respective professions.

Best wishes for continued success.

Sincerely,

[Signature]

NASA Astronaut
Pre Apollo 17 – Astronauts Briefed About LRV Temperature Concerns From Apollo 16

- Briefed Apollo 17 And Apollo 16 (Backup) Astronauts In Crew Quarters At KSC
- TV Power Provided, New LM Parking Constraint, Better Dust Prevention Needed
- Delayed Start Of EVA 1 May Have Caused Stuck Switches At First Power-up
  - LRV Qualification Unit Was Exposed To Cold Soak (-30 Deg. F)
    In Army Redstone Missile Labs Environmental Chamber,
    But Switch Malfunction Was Not Duplicated

![LRV Qualification Unit Used In Cold Exposure Test](image-url)
Apollo 17 – Transportation Thermal Control

- Hot Batteries At Launch (Waiver)
- Attitude Data Provided From Houston
- Stowed LRV Model Used To Verify That LRV Had Experienced Hot Flight Attitude Profile
- **Mission Control Alerted To Expect Hot Batteries And Melted Wax**
Apollo 17 – LRV Thermal Control Performance

- Improved FWDCHA For Mission
- Max. Motor Temp = 270 Deg. F
- Hot Batteries At Power-up (95, 110 F)
- Covers Opened On EVA’s 1, 3
- Fender Fixed Before EVA 2
- Modest Battery Cooldowns
- Max. Battery Temp. = 148 Deg. F

Covers Opened During EVA 1 (Also EVA 3)

Astronauts Provided Fender Extension Fix

Modest Cool Downs

LRV Battery No. 2 (Right) Temperature
Post Apollo 17 – Astronauts Met With LRV Team

Astronauts Were Presented With Fender Extension From LRV Qualification Unit
Autographed By MSFC Support Team
Summary of LRV Thermal Control Experiences

• Adequate Thermal Control Of LRV’s Was Accomplished On Apollo 15, 16, And 17
• We Provided Accurate, Responsive Temperature Predictions To Mission Control
  • Test Correlated Thermal Models Were Vital For Mission Support
• We Had Very Limited Success Coping With Adverse Lunar Dust Effects
  • Losing Fender Extensions Increased Dust Exposure For Forward Chassis
  • Earth Testing Results For Dust Removal By Brushing Were Misleading
• Regret Spending Valuable Astronaut Time Trying To Clean Radiators
Future Moon Rover Challenge 1 – Mitigate Bad Effects Of Dust

- Dust On Apollo LRV’s Severely Reduced Battery Cooldowns – Brushing Radiators Was Ineffective
- Based On Cumulative Dust Effects, Astronauts Stated That They Doubted Longer Missions Were Possible
Future Moon Rover Challenge 2 – Design For Extended Cold/Hot Missions

- Extended Operation In Much Colder And Warmer Environments Than Apollo LRV’s Or Mars Rovers

**Lunar Night**

- 354 Hours Without Solar, Cold Moon
- Surface Temperature = -280 Deg. F

**Lunar Day**

- 354 Hours With Solar, Moon Heating
- Max. Surface Temp. = +250 Deg. F

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The temperature of the Moon. The average temperature of the Moon as a function of phase, or time, is shown here. The exact shape of the curve varies somewhat with geographical position on the Moon and is determined by the thermal properties at each position.

The temperature of the Taurus-Littrow site shown as a function of the Sun angle. Note that EVA 1 at +17° Sun angle should have +50° F, EVA 2 at +27° Sun angle should have 110° F, and EVA 3 at +37° Sun angle should have a temperature of +100° F.
Nuclear Energy Needed To Meet Moon Thermal Challenges

• Nuclear Power Sources Were Used On Apollo, Studied For Dual Mode Rovers

• Russians Successfully Used Nuclear Isotope Heat Sources For Several Lunar Cycles On Their Lunokhod (Moonwalker) Robotic Rovers
Presentation and Interface with Lunokhod Engineers at Oct. 2004 Russian “International Planetary Rovers & Robotics Workshop”

Presentation Was Well Received At Lunokhod Design And Test Facility In St. Petersburg, Russia

Included Good Discussions About Lunokhod Experience With Dust And Temperature Extremes

“Sputnik” Medal Was Accepted From Lunokhod Driver Gen. Dovgan On Behalf Of Apollo LRV Workers

Russian Hero and Cosmonaut Georgi Grechko Presented Commemorative Vostok Pin To International Attendees
**LUnar ROVing Adventure “LUROVA” Simulation Being Developed For Student Use**

- Interactive 3D “Edutainment” Simulation Responds Well To Space Policy Commission Recommendation (page 46)
- Student Plans Exploration Traverses And Views Computed Position, Speed, Power And Temperature Results
- Based On Actual Thermal Model From Apollo LRV Missions
- Displays To Mimic Operation Of LRV Hand Controller, Navigation And Power Systems On Control And Display Console, And Moon Terrain While Driving And Parked
Dedications

“If I Have Seen Further, It Is By Standing On The Shoulders Of Giants”

Sir Isaac Newton - 1675

Hugh Campbell, My Thermal Mentor, At Work

My Wife And Surrogate Astronaut, Dottie