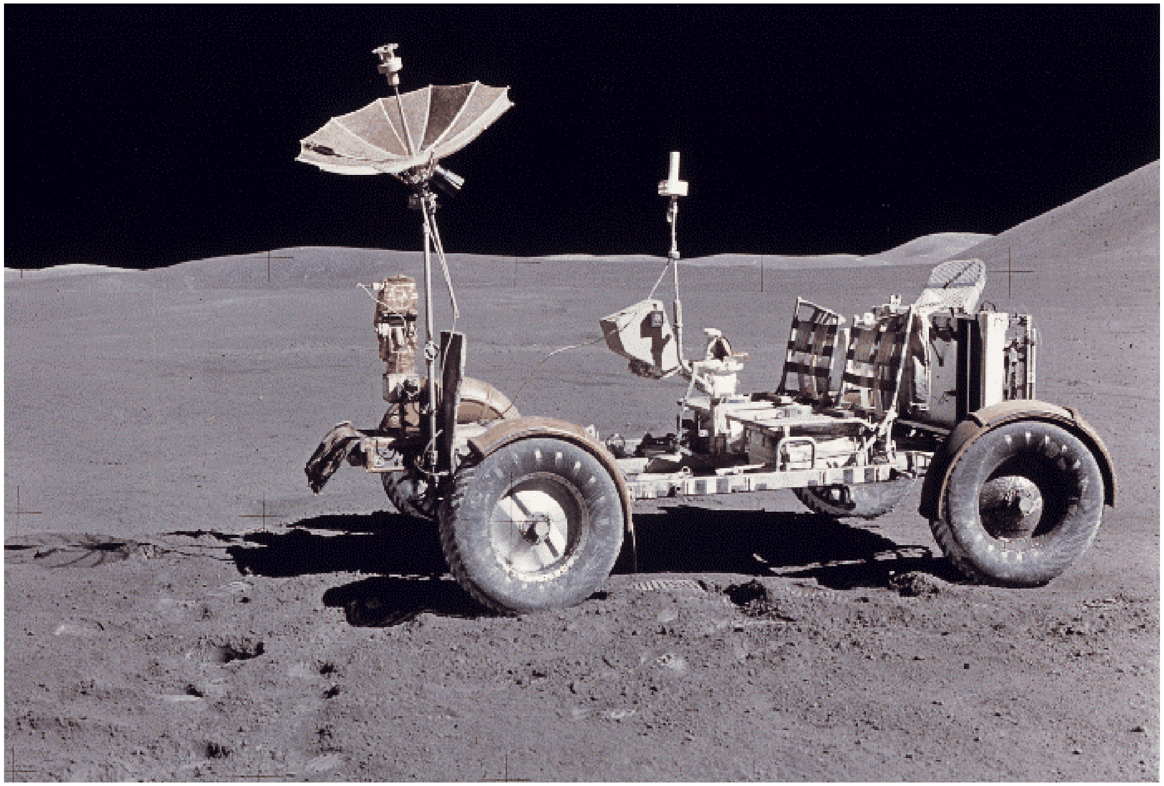
Back To The Future



Thermal Analysis to Meet Moon Mobility and Survival Challenges

Ronald A. Creel, Space And Thermal Systems Engineer, RAI
Member Of The Apollo Lunar Roving Vehicle Team

TFAWS06-1038

roving_ron@comcast.net

Introduction

Fresh out of college, some 37 years ago, Ron Creel was thrust into a challenging and high speed engineering task – design, modeling, 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’s retrospective LRV presentation is available on the NASA Apollo Lunar Surface Journal:

http://www.hq.nasa.gov/office/pao/History/alsj/lrv_thermal_alsj.pdf

Ron is a Space And Thermal Systems Engineer at Ryan Associates, Inc. (RAI), 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 share his LRV thermal modeling experiences, presented in the U.S. and Russia, with an eye toward applications to future manned and robotic Moon Rovers for the President’s “Moon, Mars, and Beyond” Vision for Future Space Exploration.

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Thermal Analysis to Meet Moon Mobility and Survival Challenges

Outline

- Lunar Roving Vehicle (LRV) Thermal Design / Modeling
- Moon Mission Support and Modeling Experiences
- Model Applications For Future Mobility and Survival

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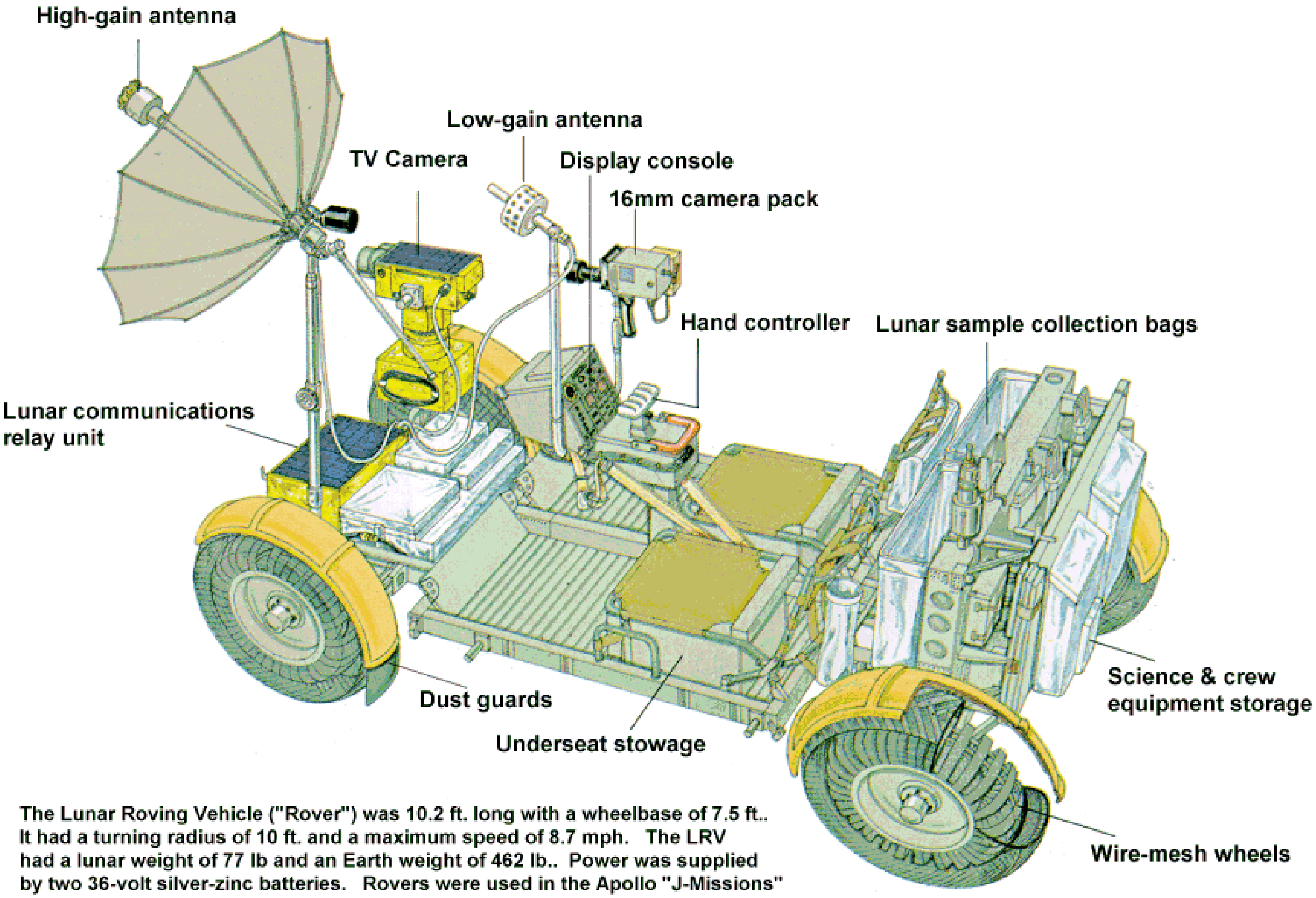
LRV Designed To Provide Extended Mobility On The Moon

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.

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LRV Component Temperature Limits – Deg. F

	Component	Minimum Survival	Minimum Operating	Maximum Operating	Maximum Survival
Electronics	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	450
	Suspension Damper	-70	-65	400	450
	Steering Motor	-50	-25	360	400
	Wheel	-250	-200	250	250

10 Pounds Allotted for Thermal Control System

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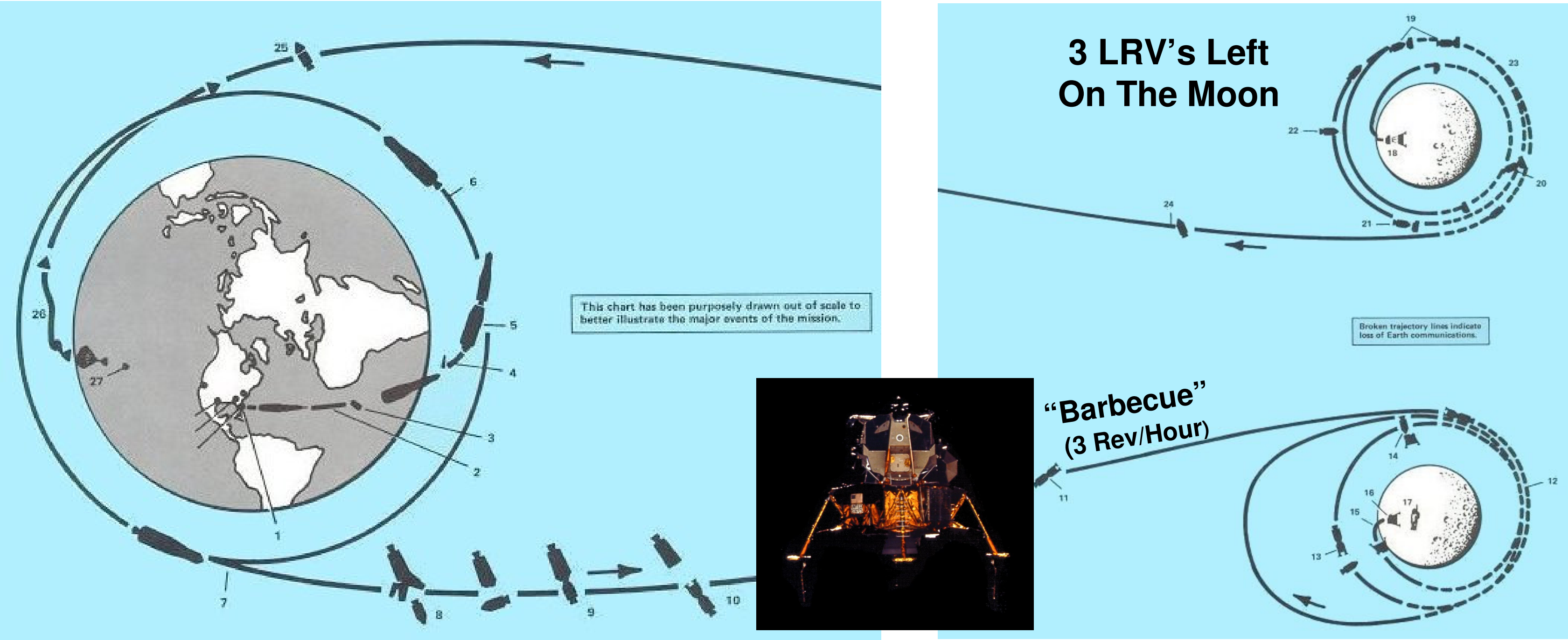
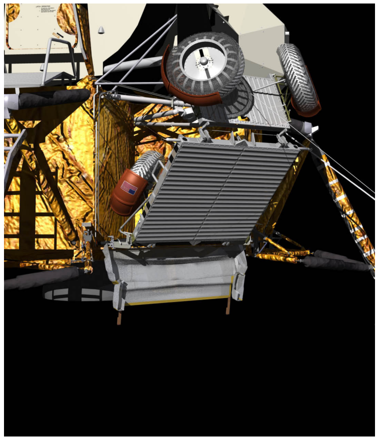
Folded LRV Modeled for Trip to the Moon



3 LRV's Left
On The Moon

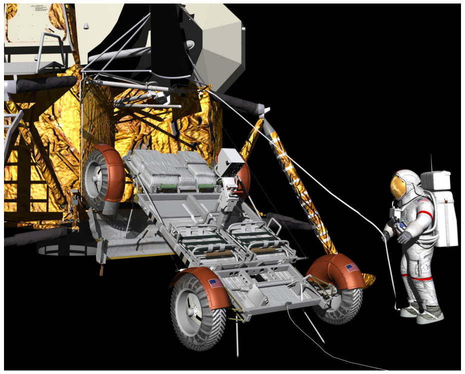
"Barbecue"
(3 Rev/Hour)

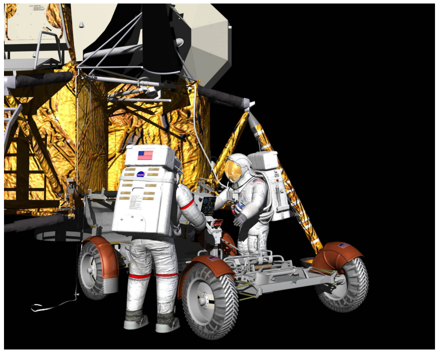
Folded and Unfolding Images From
LUROVA "Edutainment" 3D Simulation
(See Page 27)



Passive Thermal Control with <u>No</u> Telemetry

No Thermal Testing of This Configuration





LRV's Designed and Modeled for Operation During Sunlit Lunar "Morning"

Moon Temp. = $\sqrt{\sqrt{(Cos(Beta))}} \times \left(\sqrt{\sqrt{443 \times Sin(Sang)/\sigma}} - 460\right)$

Where: Beta = Moon Latitude (Degrees)

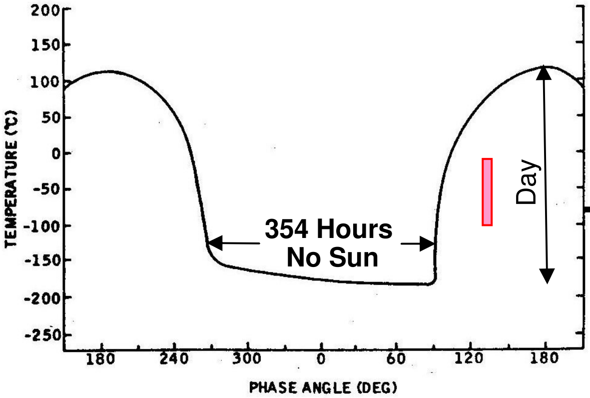
Sang = Solar Elevation Angle (Degrees)

σ = Stefan Boltzman Constant (btu/(hr-ft2-R4)

Lunar Day

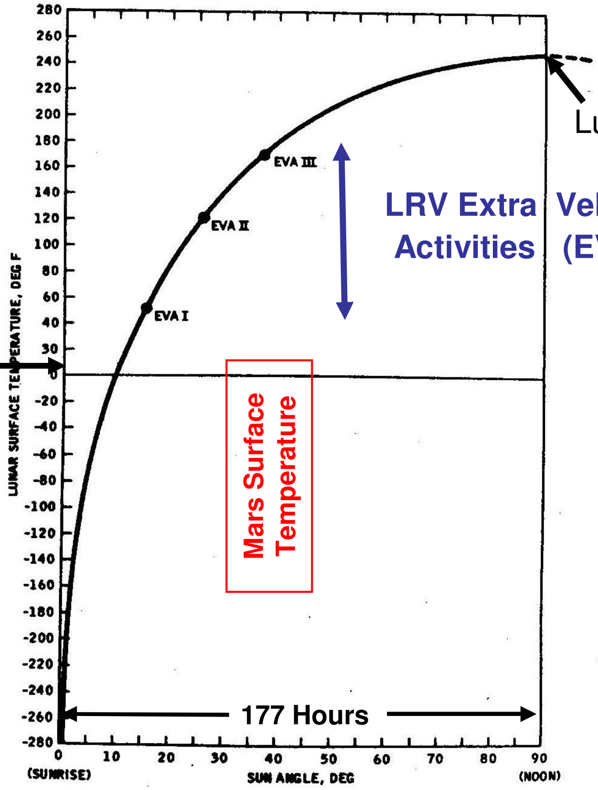
- 354 Hours With Solar, Moon Heating
- Max. Surface Temp. = +250 Deg. F

- Night - 354 Hours No Solar, Cold Moon
- Min. Surface Temperature = -280 Deg. F



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.

Future Extended Operation



Lunar Noon

LRV Extra Vehicular Activities (EVA's)

Mars Surface Temperature

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.

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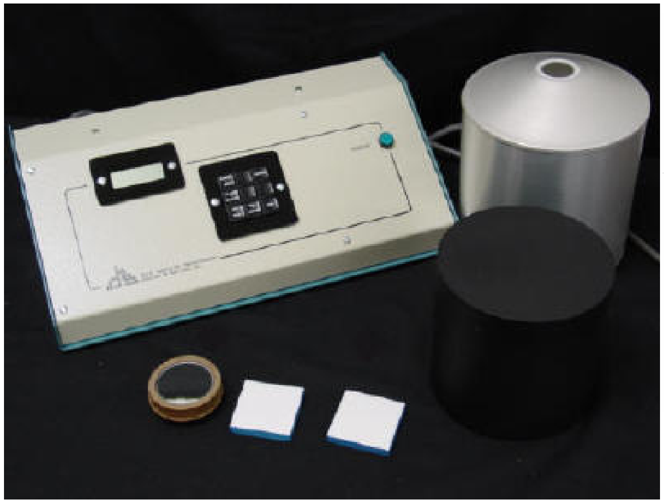
LRV Surface Optical Properties Were Measured For Use In Computer Thermal Models



Solar Absorptance - α

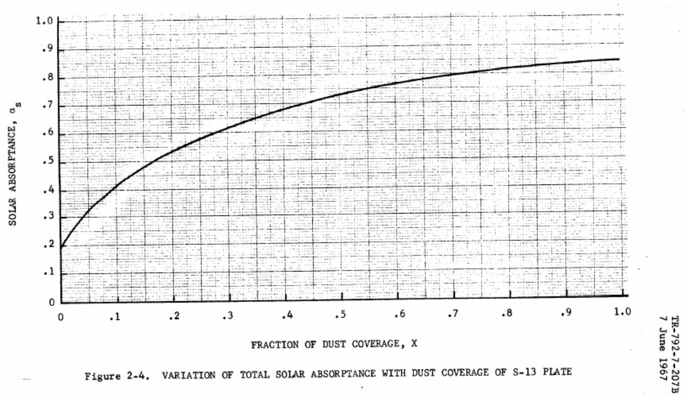


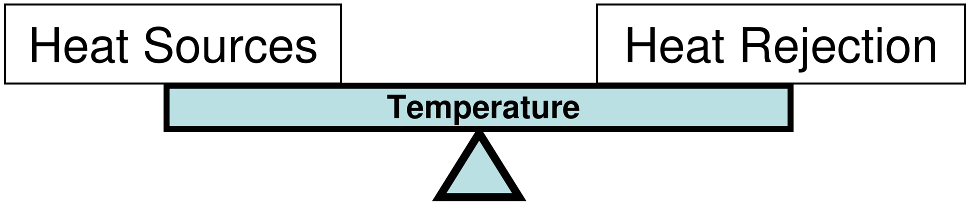
Figure 2-4. VARIATION OF TOTAL SOLAR ABSORPTANCE WITH DUST COVERAGE OF S-13 PLATE

Radiator Dust Degradation and Mitigation (Brushing, etc.) Tested on Earth in 1967

Infrared Emittance - ε

Reflectometers Used to Measure Properties for Clean LRV Surfaces

Dust Assumed to Cover All Exposed Surfaces



Absorbed Solar
(Direct/Reflected)

Absorbed Infrared

Internal Generated

Heat Sources

Heat Rejection

Temperature

Radiated Infrared

Computer Model Thermal Balance

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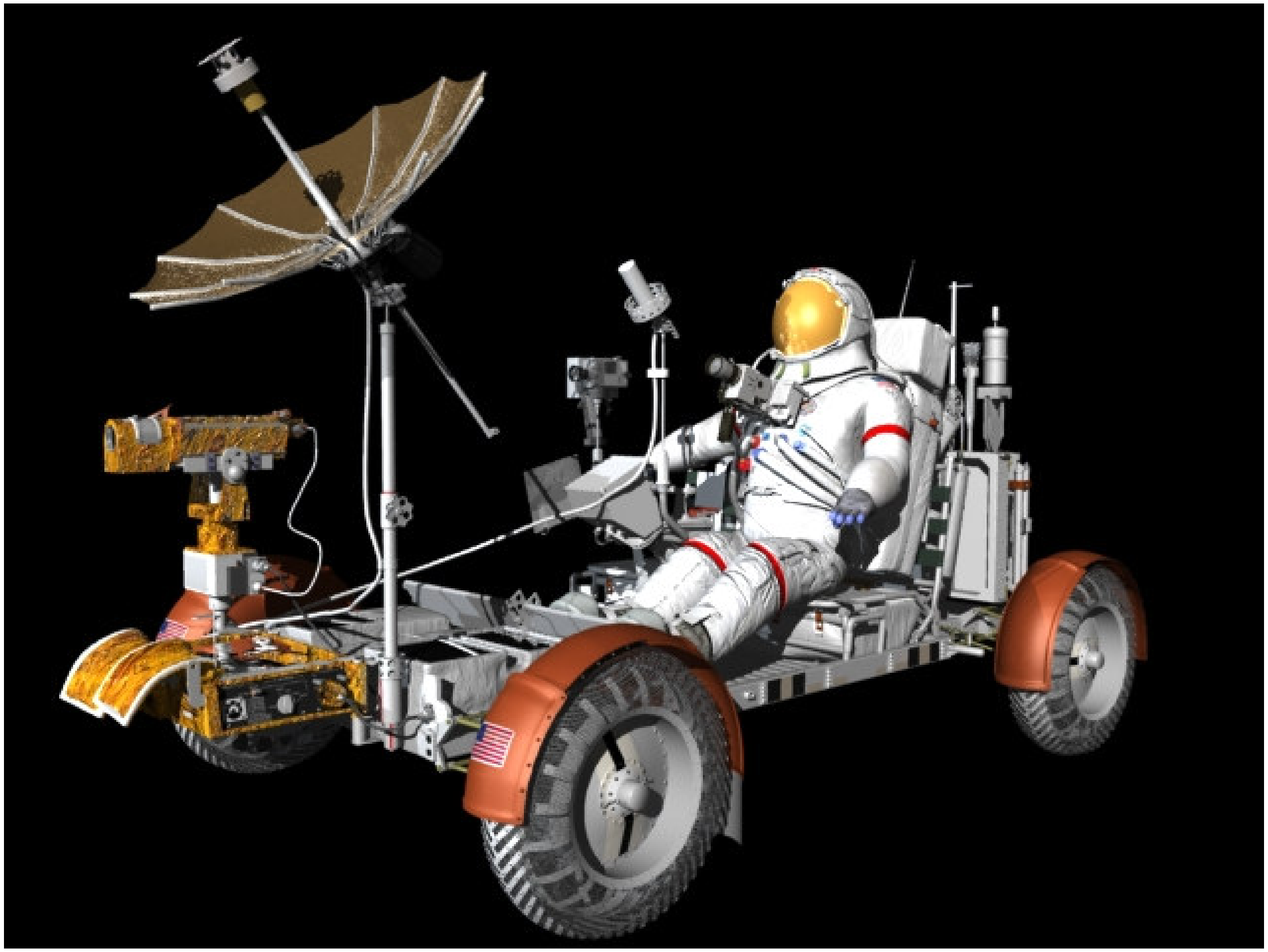
Deployed LRV Subsystems Thermal Models



Maintain All
Surfaces
Within
Astronaut
Touch
Constraints

**Control And
Display
Console**

Insulated
Front Panel,
Exterior Dust
Degraded

Forward Chassis Electronics

Insulate / Isolate from Dust
Store Generated Heat In
Batteries / Wax Boxes

Mobility

Exterior Dust
Degraded
Maximize Internal
Conduction

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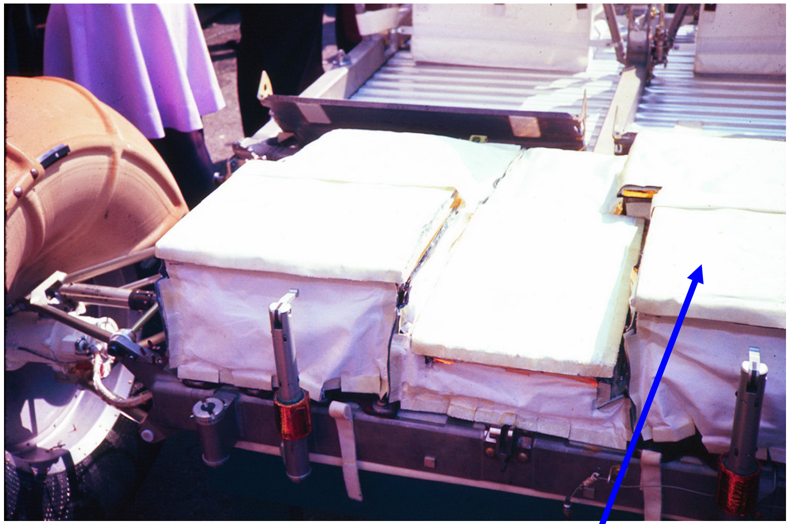
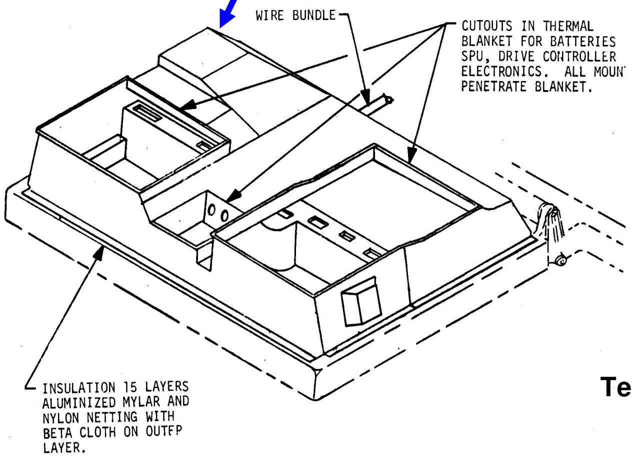
LRV Forward Chassis Electronics Modeled



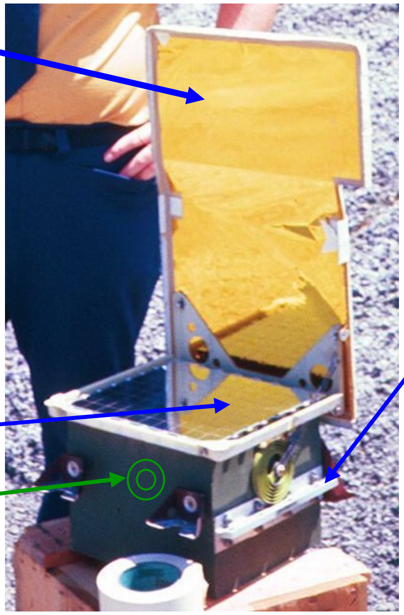
- Multi-Layer Blanket For Insulation, Dust Covers
- Thermal Straps Conduct Heat Into Batteries
- Electronics Heat Also Stored In Wax Boxes (Fusible Mass Tanks) During EVA’s
- Low Solar Absorptance (α = 7%) Space Radiators To Reject Heat When Dust Covers Opened Between EVA’s

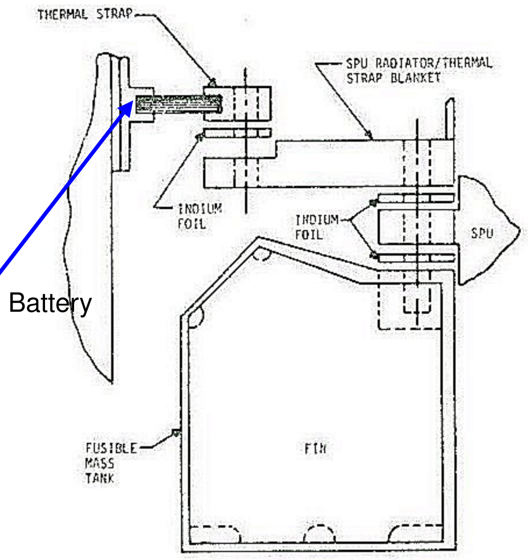
Insulation Blanket And Dust Covers



Radiator

Internal Temperature Sensor





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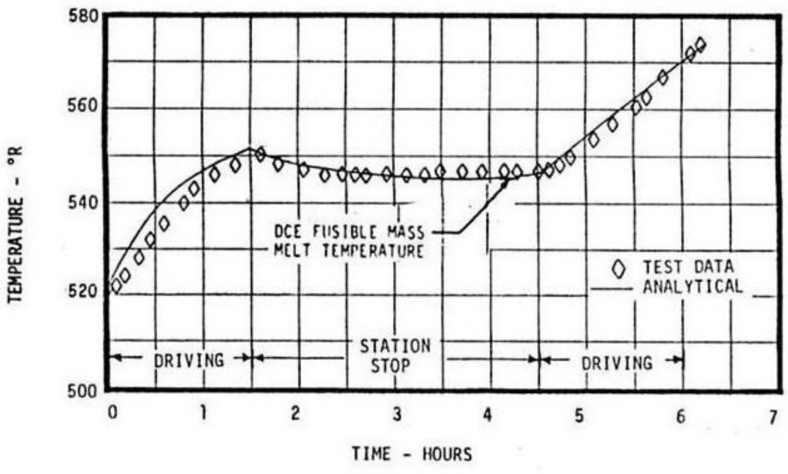
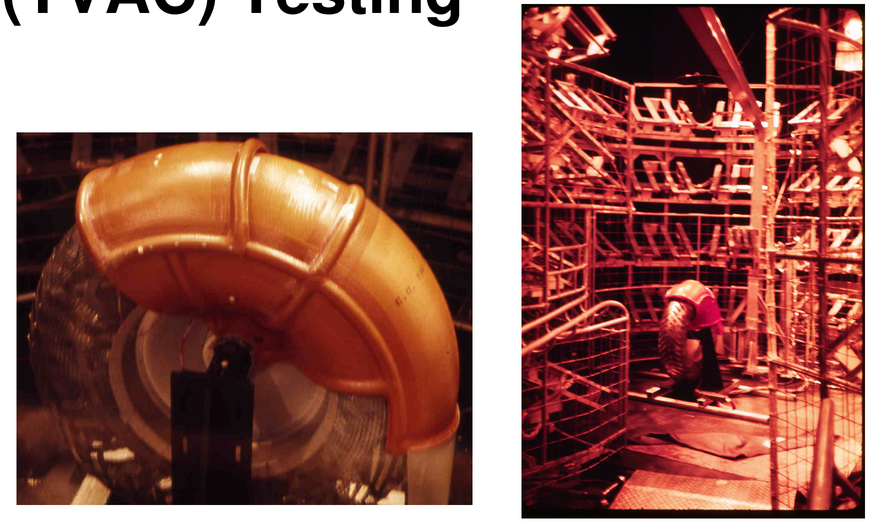
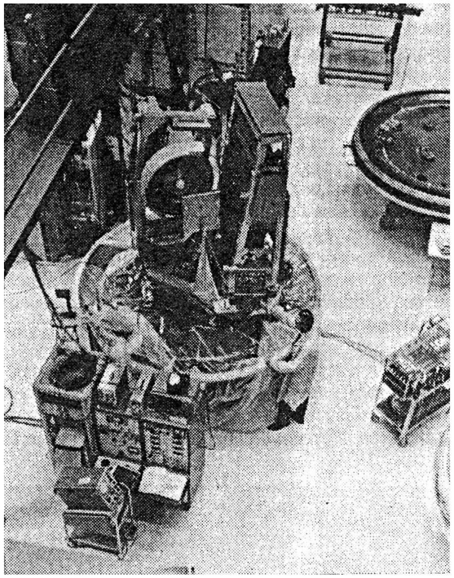
LRV Thermal Models Were Correlated with Extensive Thermal Vacuum (TVAC) Testing



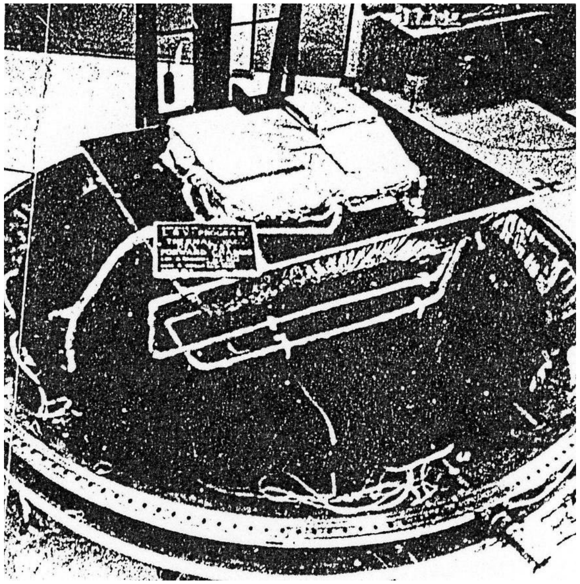
DCE TEST DATA CORRELATION



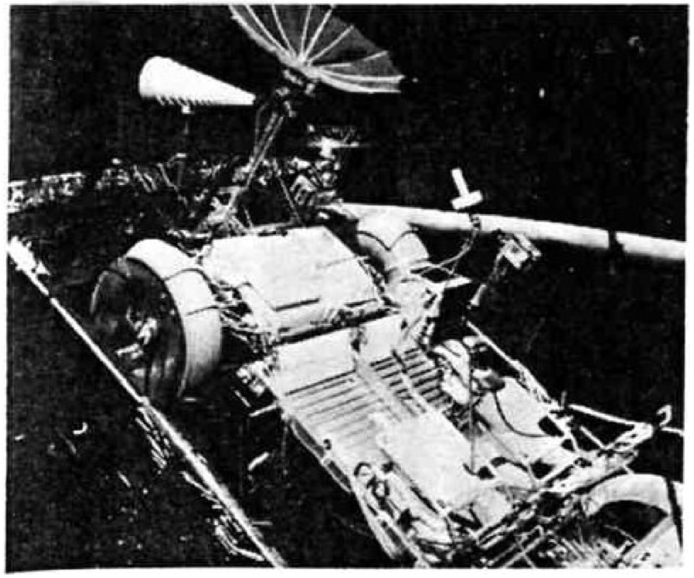
Fender Extension Deployment TVAC



Mobility Subsystem TVAC



Forward Chassis Development "Tub" TVAC



Qualification And Flight Units TVAC

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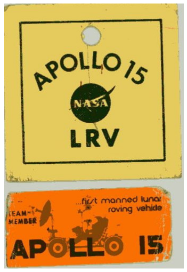
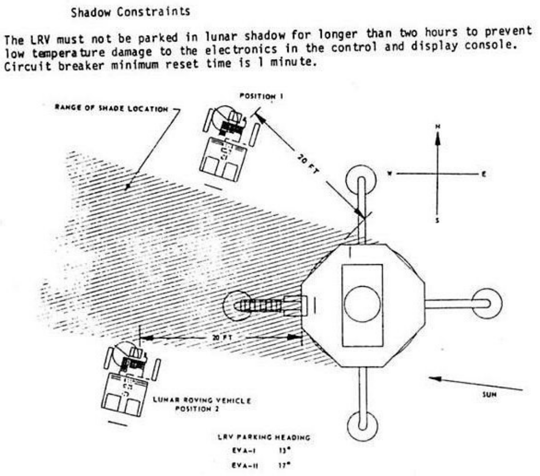
Detailed LUROVA Thermal Computer Model Used First for Apollo 15 Mission Support



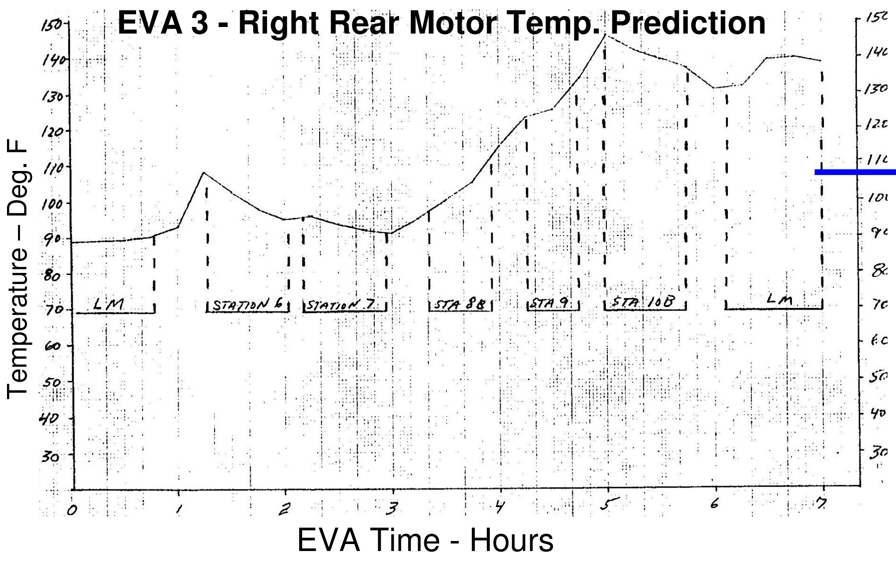
- Electrical Analogy - Capacitors And Conductors
- Chrysler Shape Factor and Lockheed Orbital Heat Rate Package (LOHARP) Used to Calculate Radiation and Environment Parameters – Limited Number of Surfaces
  - -- CINDA Thermal Analyzer Replaced by SINDA in 1971
- Test Correlated Crew Station, Mobility, and Forward Chassis Models Combined Into Detailed “LUROVA” Operational Model - 177 Nodes (Capacitors) and Thousands of Conductors
- Allowed Analysis For Clean Transit, Lunar Surface Dust Degradation, And Sortie Variations
- Cumbersome And Limited To Pre-EVA Predictions Using Univac 1108 Mainframe Computer

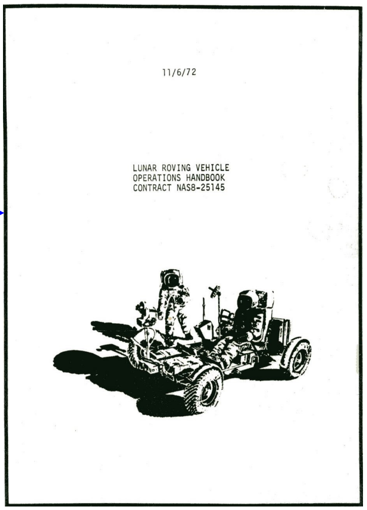


Shadow Constraints

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.

“Wireframe” Plot of Surface Model





11/6/72

LUNAR ROVING VEHICLE
OPERATIONS HANDBOOK
CONTRACT NAS8-25145

Predictions For Mission Operations Handbook

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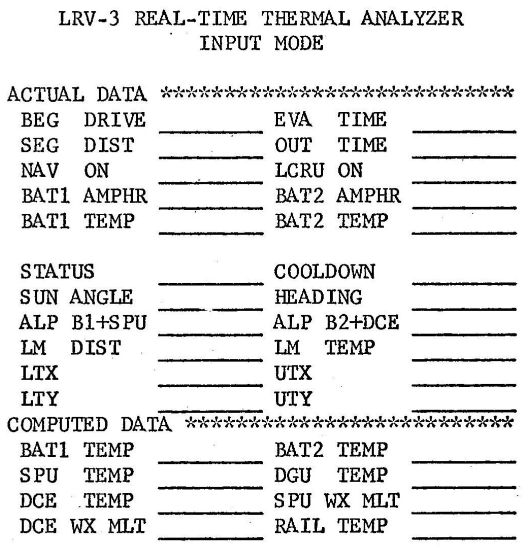
Forward Chassis Thermal Analyzer Model - FWDCHA



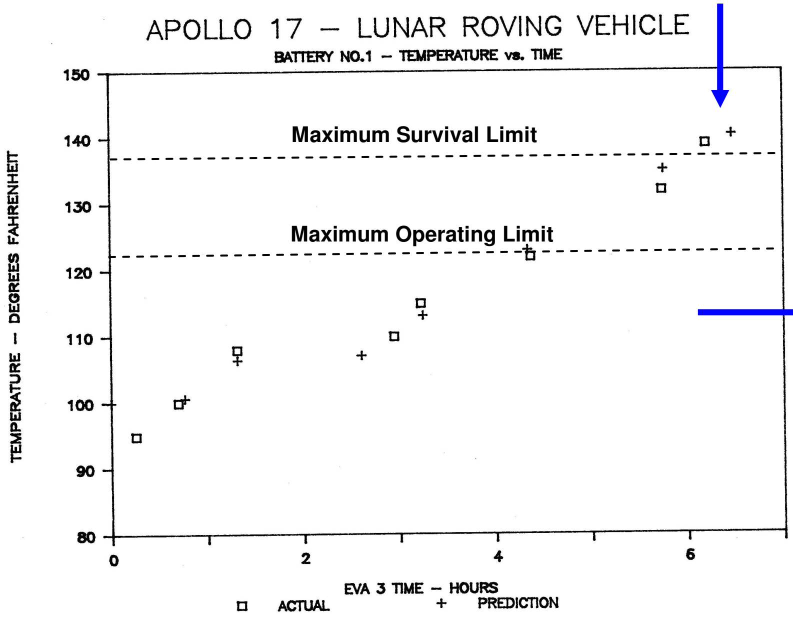
```
          LRV-3 REAL-TIME THERMAL ANALYZER
                    INPUT MODE

ACTUAL DATA ******************************
 BEG  DRIVE ________ EVA  TIME ________
 SEG  DIST  ________ OUT  TIME ________
 NAV  ON    ________ LCRU ON   ________
 BAT1 AMPHR ________ BAT2 AMPHR ________
 BAT1 TEMP  ________ BAT2 TEMP ________

 STATUS     ________ COOLDOWN  ________
 SUN ANGLE  ________ HEADING   ________
 ALP B1+SPU ________ ALP B2+DCE ________
 LM  DIST   ________ LM  TEMP  ________
 LTX        ________ UTX       ________
 LTY        ________ UTY       ________
COMPUTED DATA ****************************
 BAT1 TEMP  ________ BAT2 TEMP ________
 SPU  TEMP  ________ DGU  TEMP ________
 DCE  TEMP  ________ SPU WX MLT ________
 DCE WX MLT ________ RAIL TEMP ________
```

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

LRV Forward Chassis Components Modeled



GEORGE C. MARSHALL SPACE FLIGHT CENTER

SATURN

MPR-SAT-FE-73-1 FEBRUARY 28, 1973

SATURN V LAUNCH VEHICLE
FLIGHT EVALUATION REPORT-AS-512
APOLLO 17 MISSION

PREPARED BY
SATURN FLIGHT EVALUATION WORKING GROUP

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mission Reports

Excellent, Responsive Predictions Provided

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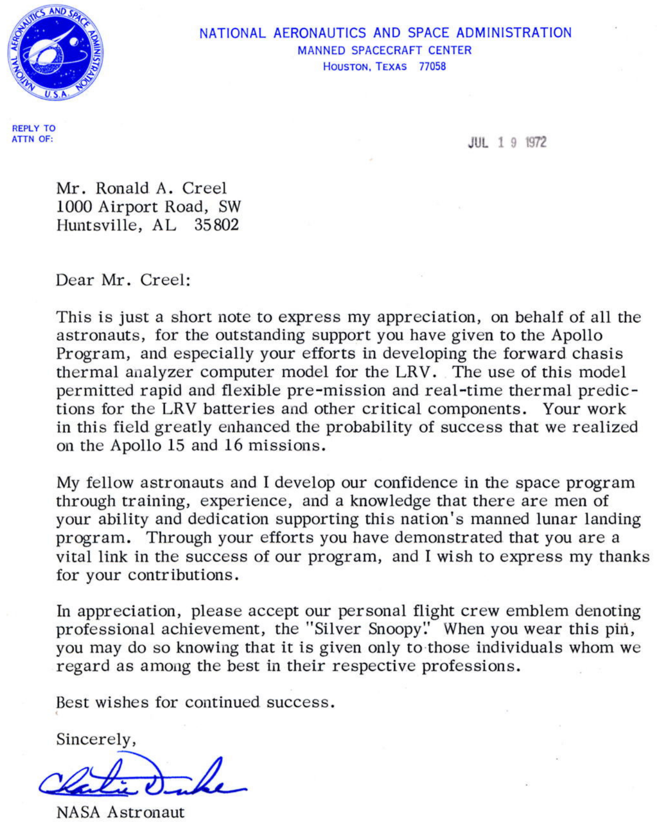
Astronauts Appreciated LRV Thermal Model Work



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS 77058

REPLY TO
ATTN OF:

JUL 19 1972

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 chasis 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.

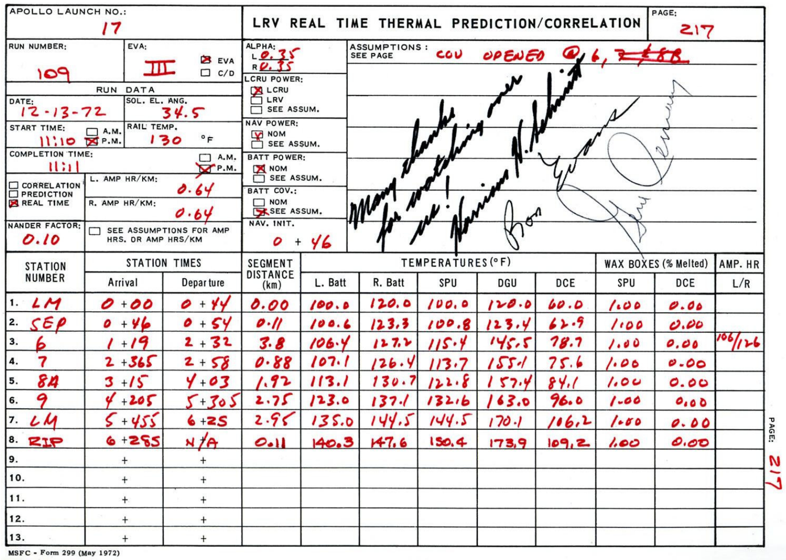
Best wishes for continued success.

Sincerely,

Charlie Duke
NASA Astronaut

Astronaut Rusty Schweickart Presents "Silver Snoopy"

Busy At LRV Thermal Model Control Console



APOLLO LAUNCH NO.: 17

LRV REAL TIME THERMAL PREDICTION/CORRELATION

PAGE: 217

RUN NUMBER: 109

EVA: III ☒ EVA ☐ C/D

ALPHA: L 0.35 R 0.35

ASSUMPTIONS: SEE PAGE COU OPENED @ 6, ~~7 & 8B~~

RUN DATA

DATE: 12-13-72

SOL. EL. ANG. 34.5

START TIME: 11:10 ☐ A.M. ☒ P.M.

RAIL TEMP. 130 °F

COMPLETION TIME: 11:11 ☐ A.M. ☒ P.M.

☐ CORRELATION
☐ PREDICTION
☒ REAL TIME

L. AMP HR/KM: 0.64

R. AMP HR/KM: 0.64

NANDER FACTOR: 0.10

☐ SEE ASSUMPTIONS FOR AMP HRS. OR AMP HRS/KM

LCRU POWER:
☒ LCRU
☐ LRV
☐ SEE ASSUM.

NAV POWER:
☒ NOM
☐ SEE ASSUM.

BATT POWER:
☒ NOM
☐ SEE ASSUM.

BATT COV.:
☐ NOM
☒ SEE ASSUM.

NAV. INIT. 0 + 46

Many thanks for watching over us! Harrison H. Schmitt

Ron Evans

STATION NUMBER	STATION TIMES		SEGMENT DISTANCE (km)	TEMPERATURES (°F)					WAX BOXES (% Melted)		AMP. HR
	Arrival	Departure		L. Batt	R. Batt	SPU	DGU	DCE	SPU	DCE	L/R
1. LM	0 + 00	0 + 44	0.00	100.0	120.0	100.0	120.0	60.0	1.00	0.00	
2. SEP	0 + 46	0 + 54	0.11	100.6	123.3	100.8	123.4	62.9	1.00	0.00	
3. 6	1 + 19	2 + 32	3.8	106.4	127.2	115.4	145.5	78.7	1.00	0.00	106/126
4. 7	2 + 365	2 + 58	0.88	107.1	126.4	113.7	155.1	75.6	1.00	0.00	
5. 8A	3 + 15	4 + 03	1.92	113.1	130.7	122.8	157.4	84.1	1.00	0.00	
6. 9	4 + 205	5 + 305	2.75	123.0	137.1	132.6	163.0	96.0	1.00	0.00	
7. LM	5 + 455	6 + 25	2.95	135.0	144.5	144.5	170.1	106.2	1.00	0.00	
8. RIP	6 + 285	N/A	0.11	140.3	147.6	150.4	173.9	109.2	1.00	0.00	
9.	+	+									
10.	+	+									
11.	+	+									
12.	+	+									
13.	+	+									

PAGE: 217

MSFC - Form 299 (May 1972)

Apollo 17 Astronauts Signed Final Thermal Log Sheet

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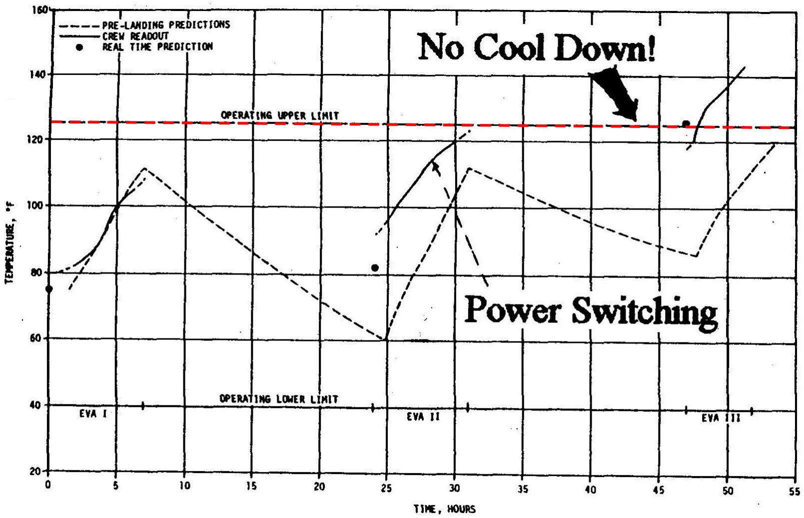
LRV Missions Thermal Control Performance

- FWDCHA Thermal Model Used For Pre-Sortie And EVA Analyses
- Right Rear Fender Extensions Knocked Off on Apollo 16 and 17
  - Increased Dust Exposure for Radiators and Ineffective Cleaning Resulted in Insufficient Cooldowns Between EVA's

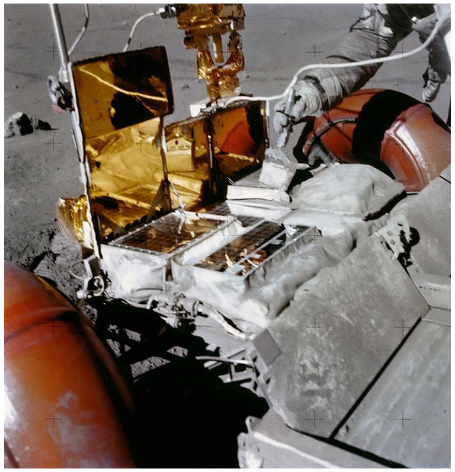
Apollo Dust Brush

- Model Predicted Required Battery Power Switching / Cover Openings
- Batteries and Electronics Ran "Hot", but, Astronauts Were Alerted When to Expect Appearance of "Caution and Warning" Flags

Missing Fender Extension



Apollo 16 Battery No. 2 Temperature



Astronaut Brushing Dust From Radiators

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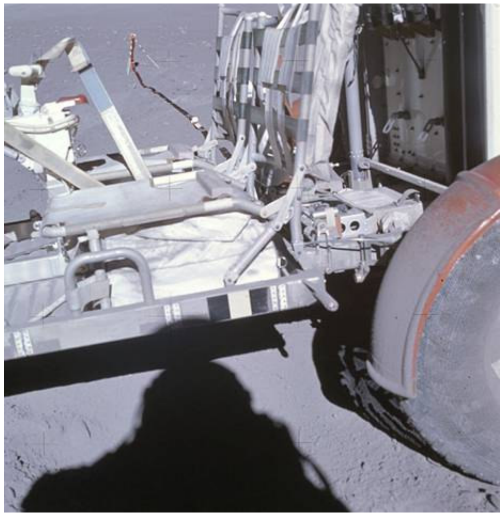
Lunar Mobility Thermal Experience Lesson Learned
Lunar Dust Contamination

Apollo 16 photos:

← Lunar Rover checkout drive

Dust on rear fender →



- Lunar dust solar absorptance, α = 0.93
  - Dust coverage increases radiator heat absorption which increases the rejection temperature
- <u>Stationary</u> or unmanned installations may remain dust free
  - Corner mirrors left by Apollo missions are still reflective
- <u>Mobile</u> or manned installations have potential to generate more dust movement and require provisions for dust mitigation

Dust Mitigation Essential for Renewed Lunar Missions

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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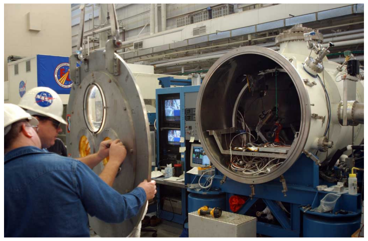
Proposed Realistic Lunar Dust Mitigation Simulation/Testing* Using MSFC Astronaut Interface Vacuum Chamber And Apollo LRV Equipment And Correlation With Actual Mission Support Thermal Computer Model

LRV = Lunar Roving Vehicle

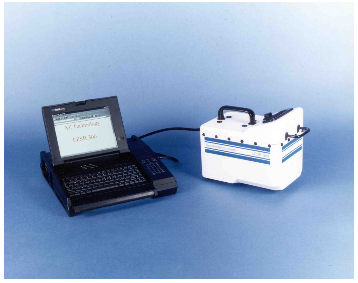
IR = Infrared

1



V3 Astronaut Interface Thermal Vacuum Chamber

1A, 1C



AZ Technology LPSR-300 Portable Optical Property Measurement Equipment

1- Chamber Open

A- Measure Cleaned** Optical Prop.
B- Clean Battery Radiator
C- Measure Opt. Prop.
D- Close Cover
E- Configure For Mitigation Test*

* Testing Using Surplus/Duplicate LRV Equipment And IR Heaters

Pump Down Chamber

2- Cover Closed

A- Heaters Off Calibration
B- Model Corrrelation
C- Heaters On Calibration
D- Model Corrrelation

3- Cover Opened

A- Heaters On Calibration
B- Model Correlation
C- Heaters Off Calibration
D- Model Correlation

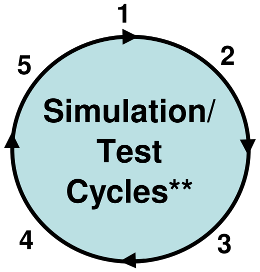
4- Radiator Dusted

A- Heaters Off Calibration
B- Model Correlation
C- Heaters On Calibration
D- Model Correlation

5- Radiator Cleaned**

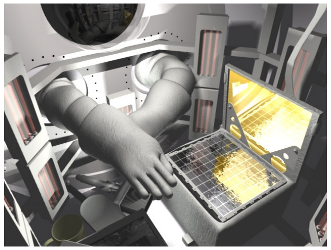
A- Heaters On Calibration
B- Model Correlation
C- Heaters Off Calibration
D- Model Correlation

Return Chamber to Ambient



** Several Proposed Mitigation Techniques

5C



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5

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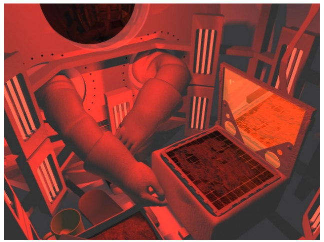

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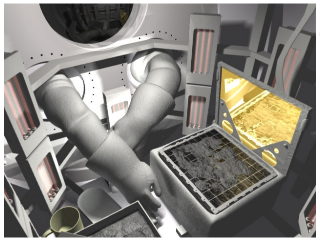

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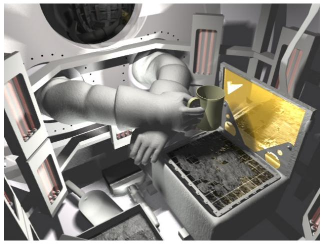

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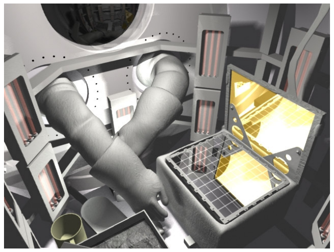

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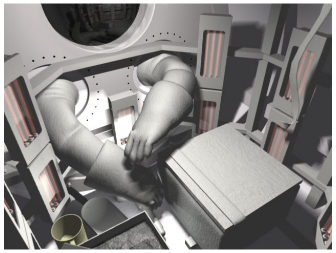

2C

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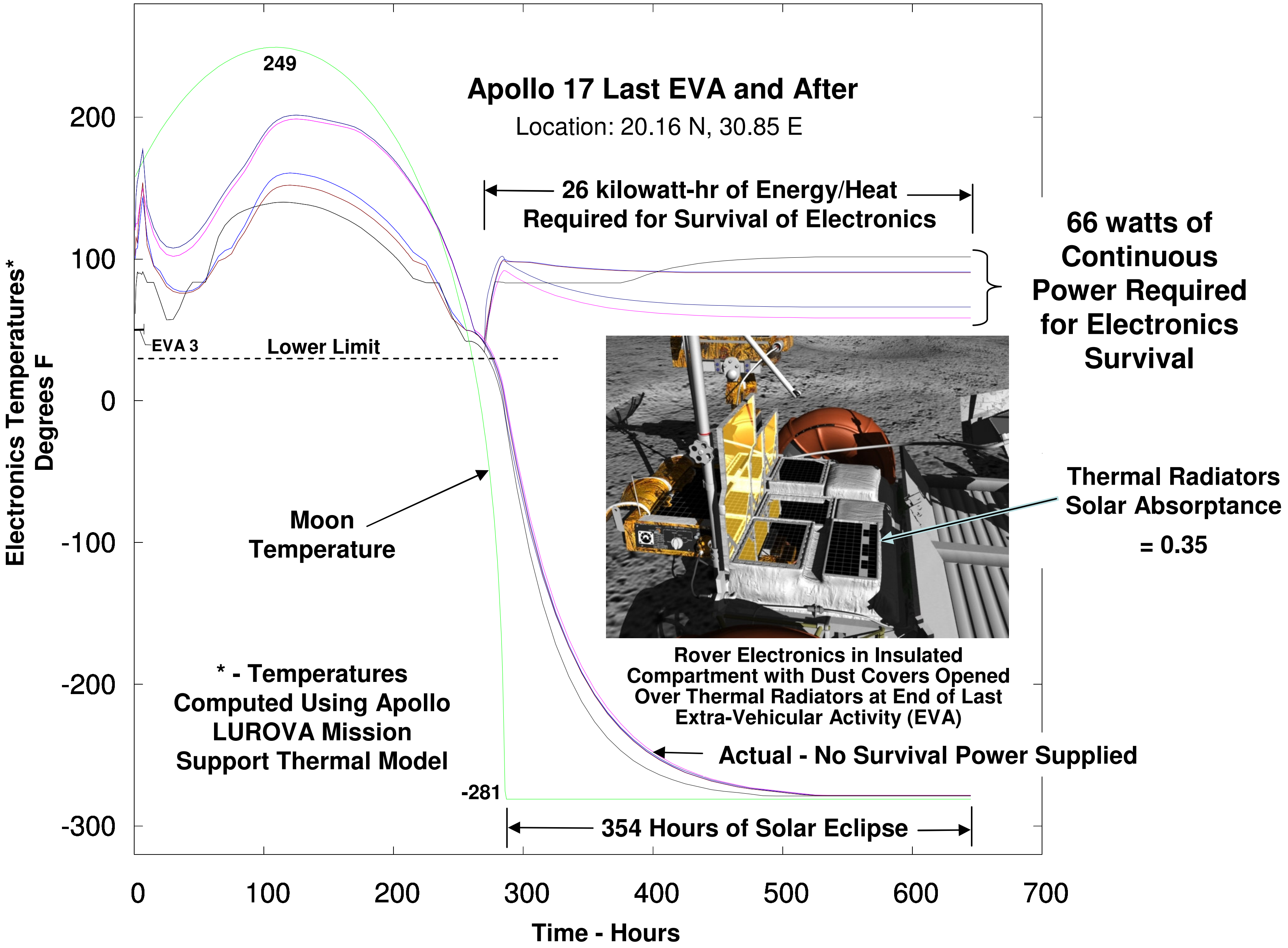
Modeling Power Needed for Extended Thermal Survival on Moon



Apollo 17 Last EVA and After

Location: 20.16 N, 30.85 E

26 kilowatt-hr of Energy/Heat Required for Survival of Electronics

66 watts of Continuous Power Required for Electronics Survival

Thermal Radiators Solar Absorptance = 0.35

Rover Electronics in Insulated Compartment with Dust Covers Opened Over Thermal Radiators at End of Last Extra-Vehicular Activity (EVA)

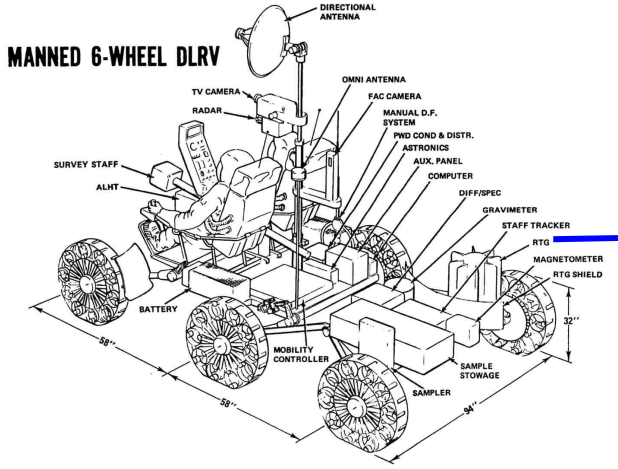
Actual - No Survival Power Supplied

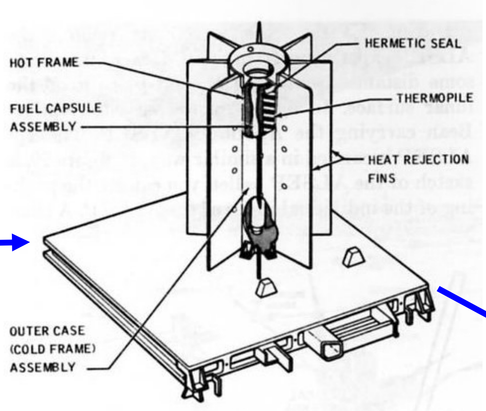
354 Hours of Solar Eclipse

*** - Temperatures Computed Using Apollo LUROVA Mission Support Thermal Model**

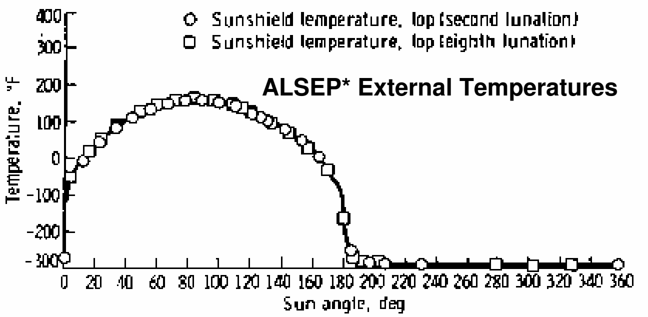
Nuclear Energy Provides Dependable/Efficient Moon Survival Power/Heat

- Nuclear Sources Studied For U.S. Dual Mode Rovers (DLRV's) and Used on Apollo



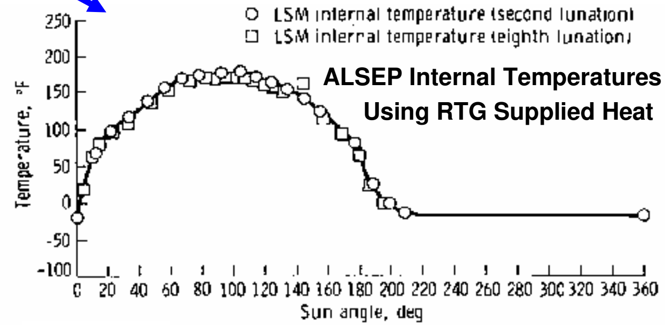


SNAP-27 -Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.
[illegible]



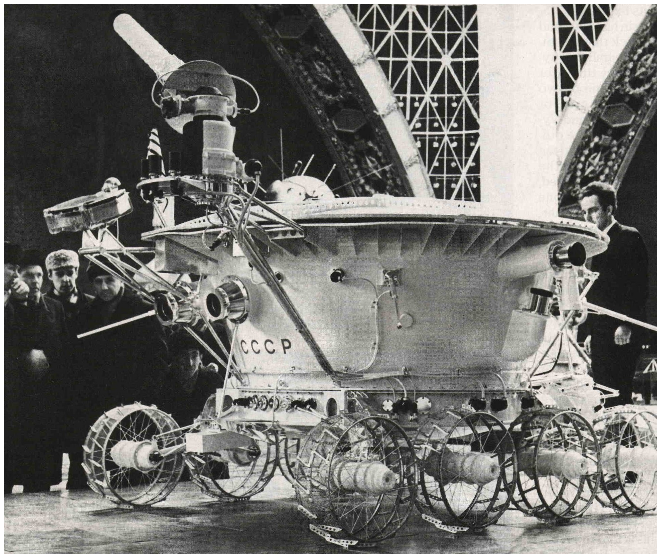
ALSEP* External Temperatures

***ALSEP = Apollo Lunar Surface Experiments Package**

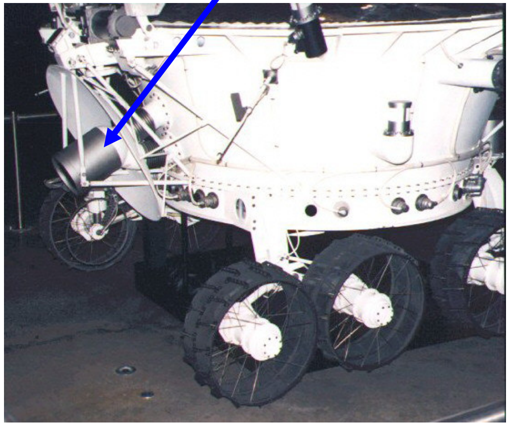


ALSEP Internal Temperatures Using RTG Supplied Heat

- Russians Successfully Used Nuclear Isotope Heat Sources For Several Lunar Cycles On Their Lunokhod (Moonwalker) Robotic Rovers



Isotope Heater



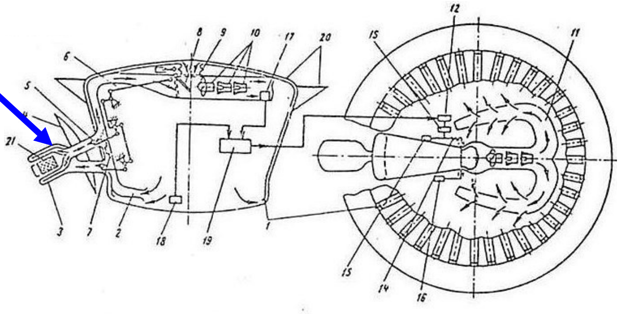


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism;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

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

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Stationary Radioisotope Power Systems (RPS) Heat Rejection Thermal Analysis

- ***Lunar night is too long for solar cells / batteries***
  - ***Application is well suited for RPS***
- ***Lunar surface reduces view to space and exhibits extreme temperature variations***

Key Thermal and Optical Properties for Lunar Heat Rejection Evaluations

- Solar flux on moon, S = 1400 W/m^2
- Lunar dust solar absorptance, $\alpha = 0.93$; emittance, $\varepsilon = 0.9$
- Lunar surface temperature (max) = 127°C

Parameters Investigated for Heat Rejection Study Using TSS and SINDA

- Lunar latitude
- Orientation of radiator surface relative to solar flux
- Lunar surface temperature (day and night dependence)
- Radiator heat dissipation rate (W/m$^{2)}$ and effect on radiator temperature

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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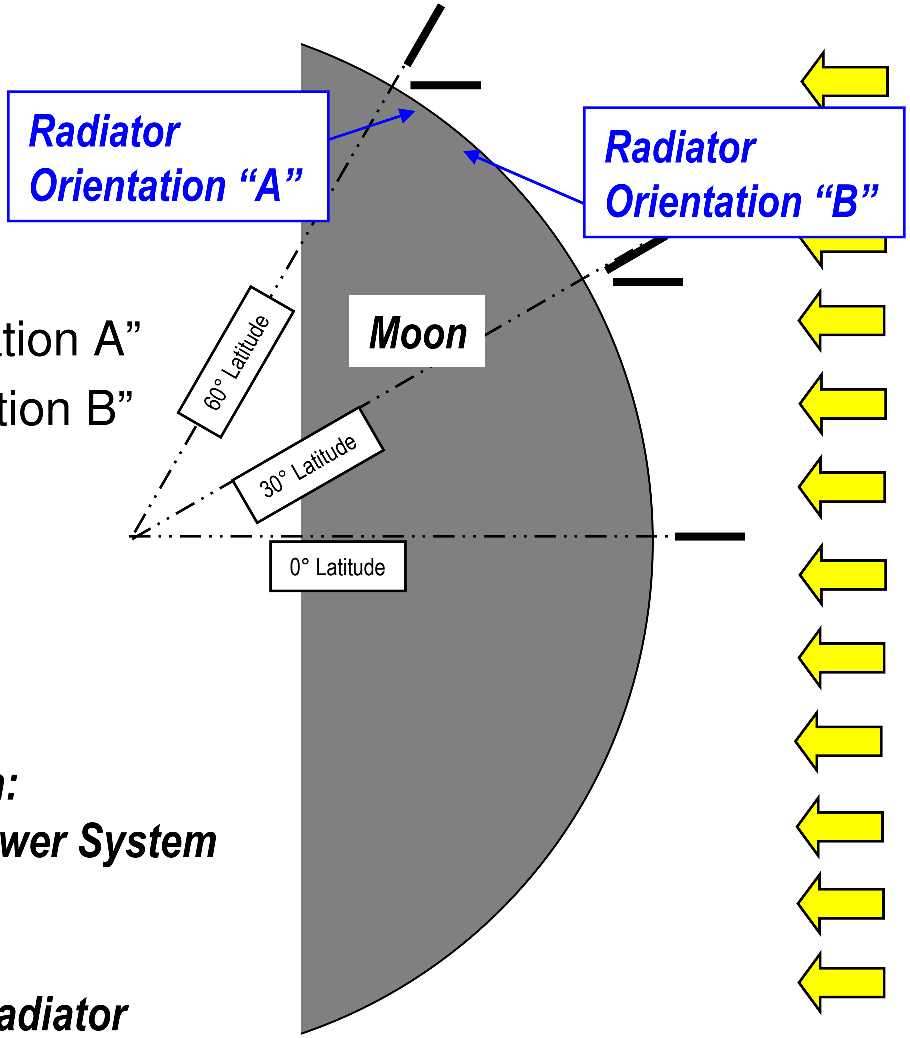
Heat Rejection Configurations For Stationary Lunar Applications

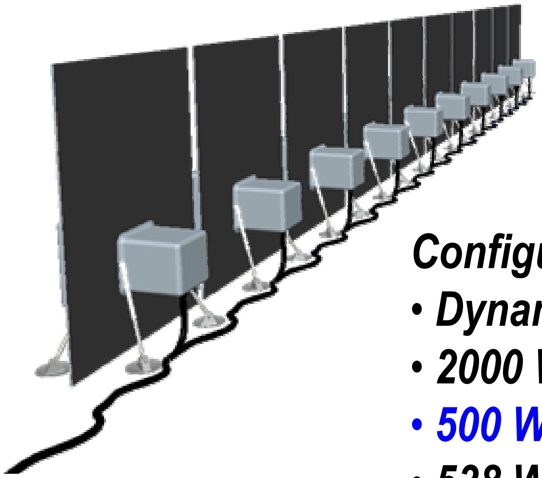
Lunar latitudes analyzed:

- 0°, 30°, and 60°

Radiator orientations analyzed:

- Vertical to lunar surface “Orientation A”
- Edge-on to solar vector “Orientation B”





Configuration:

- ***Dynamic Power System***
- ***2000 W_t***
- ***500 W_e***
- ***538 W_t/m^2 Radiator***

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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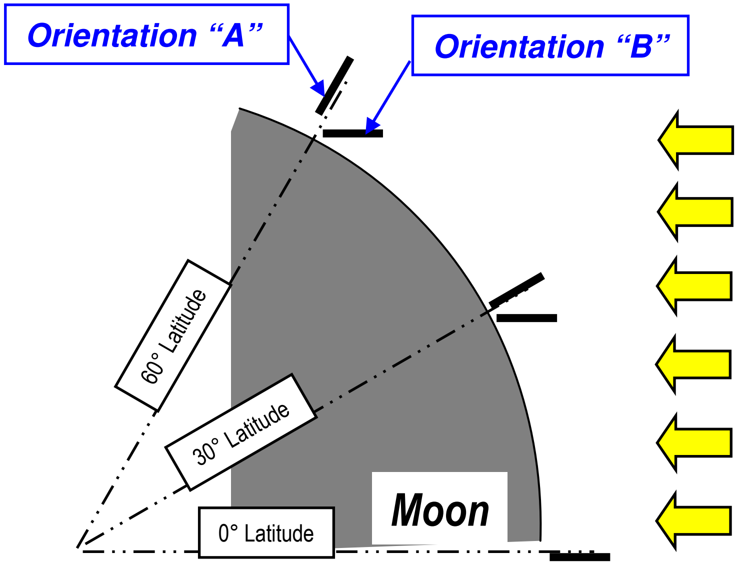
Heat Rejection for Stationary Lunar Application Analysis Results

	Lunar Day						Night
Latitude	0 °		30 °		60 °		All
$T_{\text{Lunar surface}}$ (°C)	127		112		63		-160
Orientation	A	B	A	B	A	B	A & B
$Q_{\text{absorbed Solar}}$, W/m^2	0	0	646	0	1130	0	0
$T_{\text{radiator, } Q=0}$ (°C)	54	54	85	43	87	4	-160
$T_{\text{radiator, } Q/A = 538 W/m^2}$	87	87	111	79	113	52	-3



- ***Rejection temperatures reasonable with 538 W/m^2 radiator sized for 500 W$_e$ system***
- ***Orientation has significant effect on temperatures***
  - ***Lower rejection temperature with orientation B, but more susceptible to dust coverage***

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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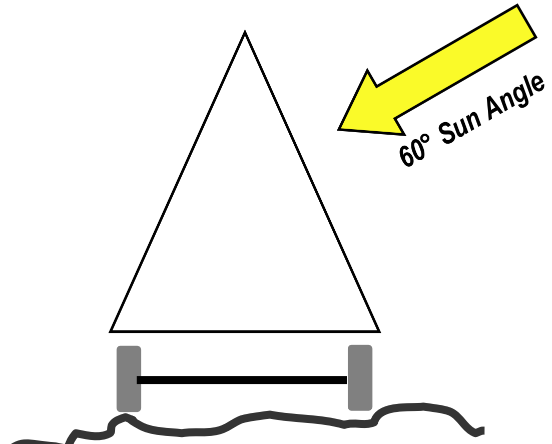
Heat Rejection Configurations for analysis of Mobile Lunar Applications



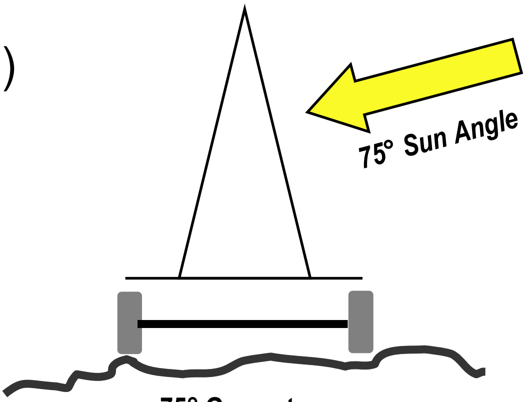
60° Geometry

<u>Two mobile configurations analyzed:</u>

- 60° geometry (smaller view of lunar surface)
- 75° geometry (steeper angle for potential dust mitigation in reduced gravity)

<u>Worst case conditions:</u>

- 0° latitude (127°C surface temp)
- Sun normal to radiator



75° Geometry

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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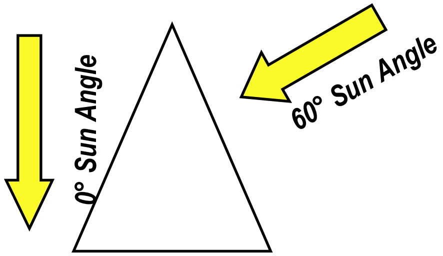
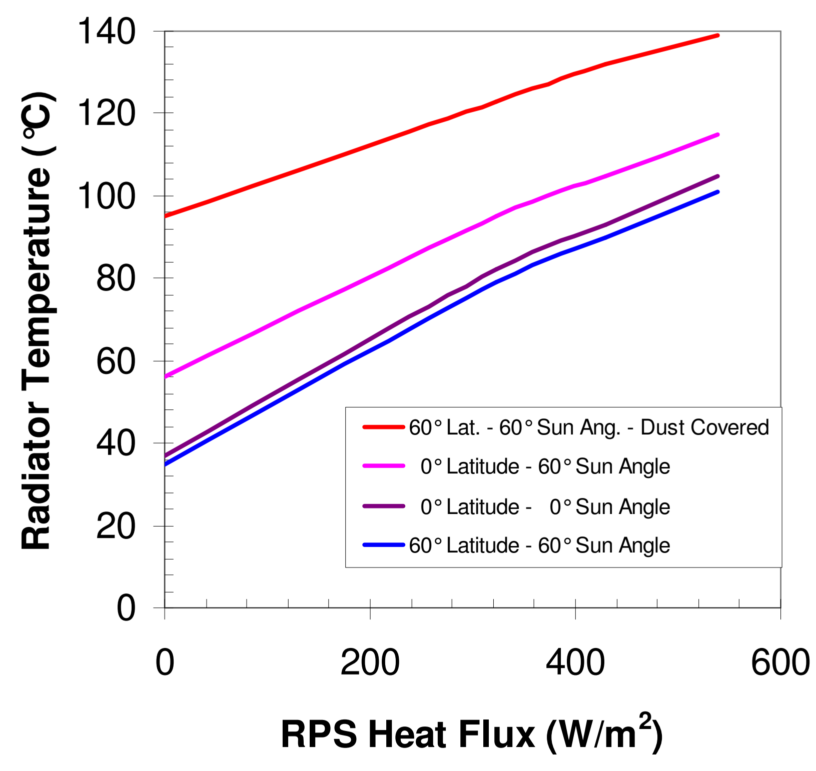
Analysis Results for Mobile Lunar Application with 60° Geometry

- Baseline - dust mitigation

  α = 0.45 (cleaned)
- Dust covered, α = 0.93
- Emittance = 0.90





- ***Temperatures are 25 to 30 °C higher without dust mitigation***
- ***Radiator capable of 538 W/m^2, but approaching rejection temperature limit of studied 500 W_e Stirling system***

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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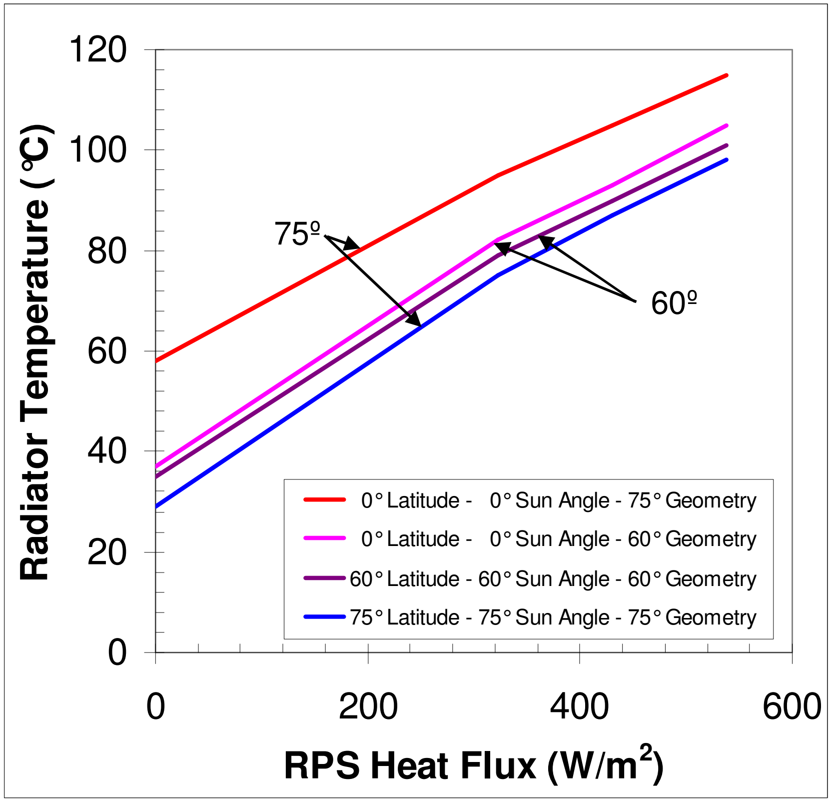
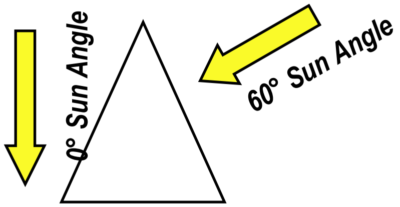
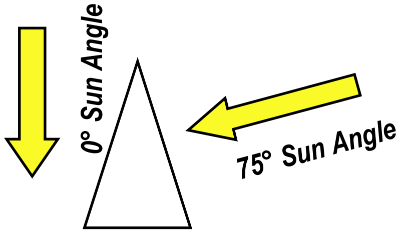
Analysis Results for Mobile Lunar Application
60 °versus 75 ° Geometry







- ***On equator, 75 ° geometry runs 10 °C to 20 °C hotter than 60 ° geometry due to lunar surface interaction (smaller view to space, higher absorbed heat)***
- ***Temperature difference between 60 ° and 75 ° geometry small at higher latitudes***

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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Moon RPS Thermal Analysis Summary

Stationary Applications

- Orientation makes significant difference in radiator temperatures
- System studied (538 W/m^2) has acceptable rejection temperature at all latitudes

Mobile Applications

- Relationship between geometry and dust mitigation is complex
  - Radiator with 75° geometry ran 10-20°C hotter than radiator with 60° geometry
  - Steeper radiator (75° geometry) should mitigate dust more readily than shallower radiator
  - Dust covered radiators ran 25 to 30°C hotter than radiators with partial coverage
- Radiator with 538 W/m^2 heat rejection approaches the maximum temperature for many Radioisotope Power Systems

- ***Lunar radiator design is a complex trade balancing temperature constraints, weight, orientation, and dust mitigation***

Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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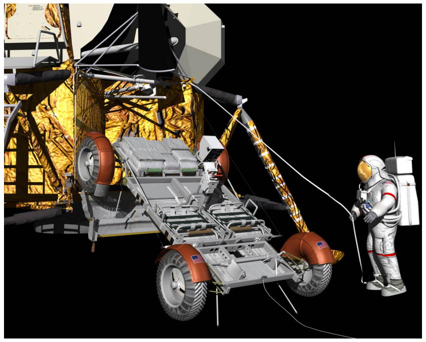
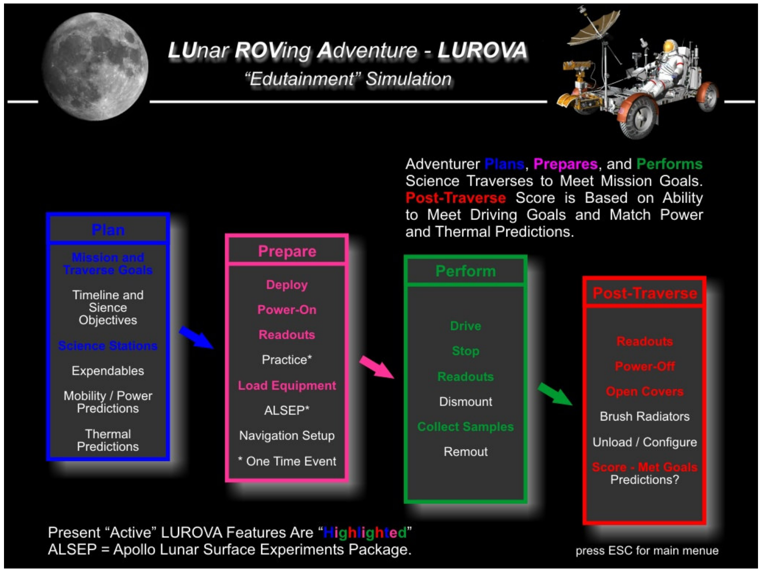
LUnar ROVing Adventures "LUROVA" Simulation Being Developed For Student Challenge And Involvement



Student Deploys LRV From LM And Loads Equipment



LUnar ROVing Adventure - LUROVA

"Edutainment" Simulation

Adventurer Plans, Prepares, and Performs Science Traverses to Meet Mission Goals. Post-Traverse Score is Based on Ability to Meet Driving Goals and Match Power and Thermal Predictions.

Plan
- Mission and Traverse Goals
- Timeline and Sience Objectives
- Science Stations
- Expendables
- Mobility / Power Predictions
- Thermal Predictions

Prepare
- Deploy
- Power-On
- Readouts
- Practice*
- Load Equipment
- ALSEP*
- Navigation Setup
- * One Time Event

Perform
- Drive
- Stop
- Readouts
- Dismount
- Collect Samples
- Remount

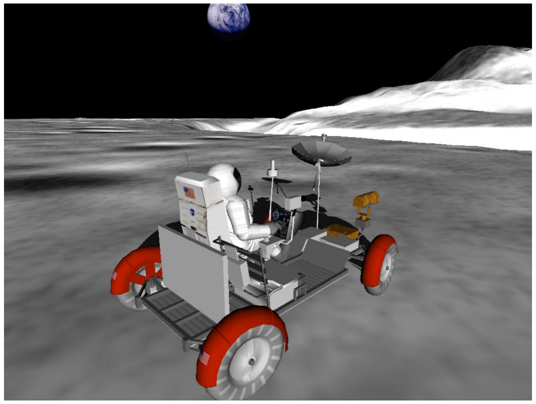
Post-Traverse
- Readouts
- Power-Off
- Open Covers
- Brush Radiators
- Unload / Configure
- Score - Met Goals Predictions?

Present "Active" LUROVA Features Are "Highlighted"
ALSEP = Apollo Lunar Surface Experiments Package.

press ESC for main menue

LRV Forward Chassis Components Thermal Mission Model Supplies Thermal and Power Predictions

Student Activates LRV Switches and Hand Controller For Driving



Student Drives "LUROVA"

- 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
- <u>Includes Actual Thermal Model From Apollo LRV Missions</u>
- Displays To Mimic Operation Of LRV Hand Controller, Navigation And Power Systems On Control And Display Console, And Moon Terrain While Driving And Parked

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Notes for TFAWS06-1038 – “Thermal Analysis to Meet Moon Mobility and Survival Challenges”

Page 1 - Ron Creel, a member of the NASA Apollo Lunar Roving Vehicle (LRV) team, shares thermal modeling and analysis experiences in developing and providing mission support for the LRV Thermal Control System, and relates these experiences to challenges for future renewed Moon mobility and survival. Applications of thermal analysis for meaningful lunar dust mitigation testing and heat rejection concepts for needed Radioisotope Power Systems on the lunar surface are also presented.

Shown in the picture is the first LRV parked at its final resting place after the three highly successful Apollo 15 driving traverses. The thermal radiator dust covers have been opened to provide some cooling of electronics as the crew waits for liftoff from the Moon, which will be watched by millions of Earth bound remote adventurers using the TV camera mounted on the LRV.

Page 2 - This presentation contains several charts excerpted from Ron’s full LRV thermal control experiences presentation located at the highlighted web site. Ron has presented at several NASA centers, universities, and shared at the Great Moonbuggy Race as shown below:

Lunar “DesignStudio” at USC

Ron with Utah State Moonbuggy

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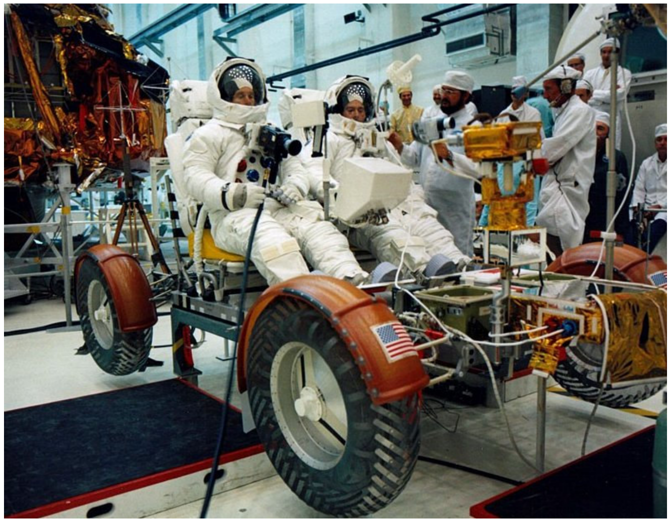
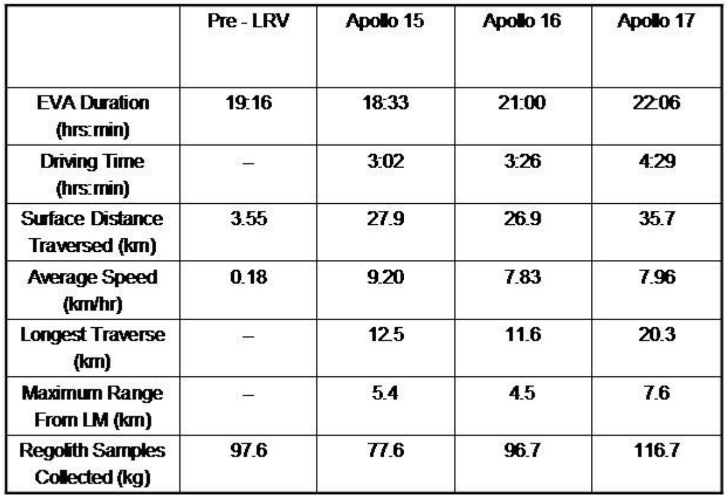
Page 3 - These three main outlined subjects will be shared in this presentation. The Apollo 16 crew is shown checking out their Rover at KSC in this picture:





	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

Page 4 - Primary features of the “Spacecraft on Wheels” are pointed out on this chart. Pervious Moon mobility studies and a total weight goal of 400 pounds had led to the open-air “Jeep-like” design. The LRV’s carried two seated astronauts along with communications and science equipment – over 2.5 times their own weight, which is the reverse of Earth mobility vehicles. The LRV’s had dual front and rear “Ackerman” style steering which allowed the vehicles to be turned inside of a vehicle length of about 10 ft. There was also independent suspension for each of the four unique wire mesh wheels with fluid damper shock absorbers and electric motors with harmonic drive mechanisms. Mobility accomplishments are summarized in the above table:

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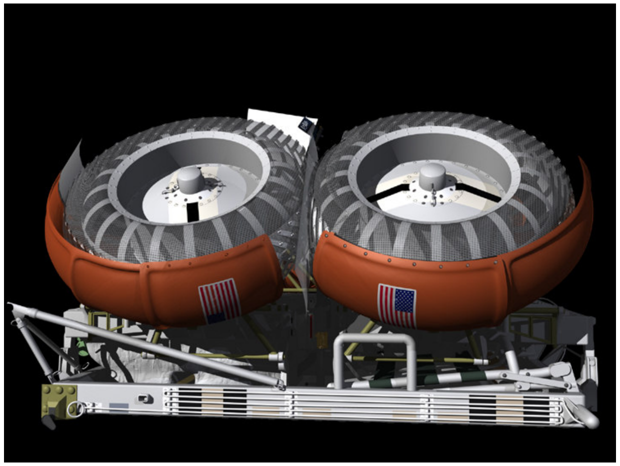
<u>Page 5</u> - The temperature limits are shown for the LRV components which had to be thermally controlled within the survival limits during transit to the Moon and within the operating limits during operation and driving on the Moon.

The components are divided into two groups – mobility, which had a greater range of limits, and the electronics, which has a much narrower temperature range. These limits were used for analyses using thermal models, and for Earth based testing.

<u>Page 6</u> - The standard Apollo mission flight profile to the moon is shown. The LRV's were folded (as shown below) and stored in a bay of the descent stage of the Lunar Module (LM). This necessitated special provisions for removal and replacement of the center chassis floor panels to allow loading of the batteries into the stacked launch and spacecraft vehicles. All thermal modeling of this phase was accomplished by thermal engineers at Boeing, the LRV Prime contractor.

It was planned to "barbecue" the LM and LRV's at a rate of about three revolutions per hour during most of the flight to the Moon. This would help balance the solar heating on systems and the amount of heat radiated away. It was expected that the batteries and electronics would be reduced in temperature by about 30 degrees F during this period. This configuration was not tested on the Earth, so accurate thermal modeling was especially important



New Folded LUROVA model from
the 3D "Edutainment" simulation

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Page 7 - Once the LRV's were deployed onto the lunar surface, they would encounter a temperature range from about 40 to 180 degrees Fahrenheit (F). All of the lunar exploration equipment including the astronauts was designed to operate in the more benign sunlit "lunar morning" surface temperature environment. The shown Moon temperature equation was used in thermal models – adjusted for the expected latitude and solar elevation angle for each of the planned missions. Future longer duration missions will have to endure both the much hotter lunar noon and the more than 14 days with no solar heating and very cold lunar surface temperature.

The LRV's, as well as many other Moon exploration systems were designed and modeled to survive and operate in sunlit conditions. The shade of large boulders or even the LM shadow would have allowed for better cooling of components, but there was no assurance that a delayed crew might not exit the LM before over-cooling could have occurred. Also, lighter weight uninsulated components needed solar energy to stay within their temperature limits.

Note the two different temperature scales used on the plots. During the missions and for post mission reports, all four temperature scales (C, F, K, and R) were used at times in models and for mission support and reporting, which was sometimes confusing.

Page 8 - For LRV thermal models, it was very important to characterize surface optical thermal properties – solar absorptance and infrared emittance were regularly measured both for candidate and then installed materials using reflectometers like those shown. This allowed use of these measured properties in the Boeing thermal model for the "clean" LRV's in the folded configuration for the trip to the Moon.

Earth based tests using lunar soil simulant were conducted in 1967 in order to characterize the effects of lunar dust on radiating surfaces and to evaluate proposed cleaning methods. Brushing was shown to have almost as good an effect in removing dust as using a propelled gas or liquid cleaner – and the brush was light in weight and already available. However, this Earth based simulation of dust behavior on the very foreign extra-terrestrial Moon was misleading, at best.

It was assumed for thermal modeling purposes that all exposed surfaces, as in the mobility and crew station subsystems, would be covered with lunar dust and both the absorptance and emittance would have values of 1.0.

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Page 9 - The three deployed LRV subsystems which were thermally modeled are shown – mobility, crew station/console, and the forward chassis electronics. Thermal models of the mobility subsystem (wheels, motors, harmonic drives, suspension, steering motors, and dampers) was accomplished by the author and thermal engineers at the General Motors AC Delco Electronics Division, the prime mobility subcontractor. Thermal modeling of the crew station/console and forward chassis electronics was done by thermal engineers at Boeing, and are further described later.

It was also a requirement that all surfaces which might come into contact with the astronauts be maintained within the astronaut "time-touch" temperature constraints.

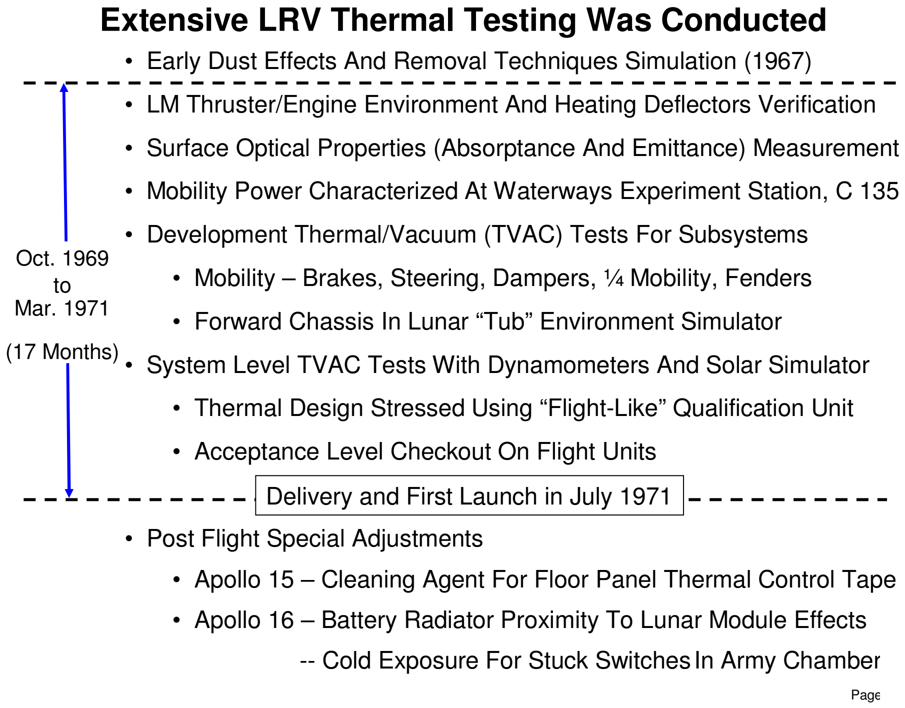
Thermal radiation surface models of seated astronauts were provided by the Crew Systems Division at NASA/JSC, and the LRV crew station thermal model was shared with thermal engineers at JSC.

Page 10 - The two 60 pound batteries were the heart of the insulated forward chassis electronics thermal control compartment. Thermal straps were designed and modeled to conduct heat from navigation components to the batteries, which served as thermal sinks. Fusible mass "wax tanks" were provided to store extra heat generated during operation –as heat pipes were not a mature technology at the time of LRV development in 1970, and there was only 10 pounds allotted for the entire thermal control system.

Insulated dust covers were modeled and provided to protect the radiators from exposure to lunar dust. Space radiators were provided to allow planned cooling of electronics when the astronauts opened the protective dust covers at the completion of each driving period in order to initiate cooldown of the forward chassis electronics. Bi-metallic actuators were provided to automatically close the dust covers when the batteries had cooled to 40-50 degrees F.

All of these unique thermal provisions were modeled in both clean test and dust degraded operational configurations

Page 11 - Extensive thermal vacuum testing and correlation of thermal models during the 17 month LRV development period was vital. As shown, good correlation of thermal model performance was obtained, as well as qualification of LRV performance in simulated operation and environments. It should be noted here that all of the test verification listed below (except for the 1967 dust/cleaning characterization was necessarily accomplished for "clean" configurations.



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

Oct. 1969
to
Mar. 1971

(17 Months)

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

Page 12 - Separate thermal models of the LRV crew station/console, mobility subsystems, and the forward chassis compartment were combined at NASA by the Teledyne Brown Engineering support engineers into the "LUROVA" operational thermal model. The size (177 nodes) of this model made its use cumbersome and time consuming at that time using available computer systems. This thermal model was accurate, but not responsive or useful for real time mission support.

Predicted temperature results for the driving traverses of each mission were provided for inclusion in the LRV Operations Handbook. Heat-up and cooldown curves for the Handbook for various operating conditions were also created using the LUROVA operational thermal model

Note the "wire frame" graphical representation of this thermal model positioned near the LM thermal model, and the hand plots of temperature results.

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Page 13 - Based on the difficulty experienced in using the detailed LUROVA thermal model during the Apollo 15 mission, the need for a simpler and more responsive thermal model for mission support was identified. Since the mobility components exhibited no thermal issues (maximum motor temperature of 270 deg. F during all missions, versus 400 deg. F upper limit), only the forward chassis electronics, radiators, dust covers, and "viewed" systems were included in this reduced 19 node model.

The simplified FWDCHA thermal model was developed and operated on several mini-computers, including the Digital PDP-8, IBM 7044, and General Electric 3200. The computed temperature display is shown below (on the left side monitor) being viewed by the LRV mission support team in the Huntsville Operations Support Center (HOSC).

This thermal model produced excellent correlation with actual thermal performance on the Moon, and was then used to produce plots for inclusion in the post mission Flight Evaluation Working Group reports.

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Page 14 - The author was honored to receive the Astronaut “Silver Snoopy” award for his LRV thermal model and mission support work. He proudly wears this pin whenever he can.

Note the teletype terminal data input console for the 19 node mission support thermal model, and the handwritten thermal model case log sheet.

Page 15 - The simplified and more responsive mission support thermal model was used during the Apollo 16 and 17 missions.

Accidental removal of right rear fender extensions on both missions resulted in increased dust exposure for the dust covers and even deposited dust directly onto the radiators. Brushing was not effective in removing lunar dust from the radiators, which resulted in hotter electronics temperatures and having to implement alternate procedures for battery load switching and opening of dust covers during driving traverses – which was also included in the mission support thermal model.

The astronauts and mission controllers were appreciative that the thermal model predicted temperatures accurately enough to advise them about alternate procedures and alert them to anticipate the appearance of the high temperature “Caution and Warning” flag.

Page 16 - Several lunar exploration systems, including the LRV’s, operated hotter than planned due to dust coverage and the inability to adequately clean them on the Moon.

The astronauts have stated that based on degradation due to dust ingestion and coverage and intrusion into mechanisms, they doubt that more extensive missions could have been accomplished.

Dust mitigation (prevention and/or removal) will be essential for future extended lunar exploration missions.

Page 17 - The author has proposed to NASA to design and perform “correlated” dust mitigation testing as depicted in this sequence, using surplus LRV components, a thermal vacuum facility like the astronaut interface test chamber at NASA/MSFC, and the actual LRV mission support thermal model.

Page 18 - The author has re-programmed the LRV mission support thermal model and simulated what would have happened to the forward chassis electronics after the conclusion of the last Apollo 17 mission – when the LRV would have been exposed to the severe higher temperature and long lunar night periods without solar energy.

Using this model, it was calculated that a continuous power source of 66 watts would have been required in order to maintain the LRV electronics in the forward chassis compartment within survival temperature limits during the long lunar night.

This prediction was supplied to associates at Lockheed Martin for presentation at the 2006 STAIF and IECEC conferences.

The pictured 3 dimensional forward chassis model was provided by Don McMillan in Canada as part of the LUROVA simulation which is being developed and shown and described on Page 27.

Page 19 - Dependable power for Moon operation and survival was supplied by nuclear energy sources on both the U.S. Apollo Lunar Surface Experiments Packages left on the Moon, and the highly successful Russian Lunokhod robotic rovers. Nuclear energy sources were also being considered for use on the fourth rover, which was curtailed when the Apollo 18 mission was cancelled.

The author was able to share Rover thermal control experiences with Russian engineers at the Lunokhod development and test facility in St. Petersburg, Russia, in October 2004.

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Pages 20 – 26 - Dr. Jaime Reyes and associates at Lockheed Martin Space Power share the author's vision of the need for nuclear energy for renewed extended Moon exploration and survival. Dr. Reyes participated with the author on a panel at the National Space Society 2004 International Space Development Conference. Since then, they have collaborated on studies of applications of nuclear energy for Moon power and survival in 2005 and presentations for the 2006 Space Technology and Applications International Forum (STAIF) and International Energy Conversion Engineering Conference (IECEC).

The objectives, model descriptions, and analysis results of the Lockheed Martin heat rejection study for configuration, sizing, and orientation for radiators for nuclear powered Radioisotope Power Systems for lunar mobility and survival applications are presented.

Other Lockheed Martin contributors to this thermal analysis were Dennis Hill, E. Wayne Tobery, David R. Pantano, and Frank Dottore.

Page 27 - As recommended by the President's Space Policy Commission, the LUROVA "Edutainment" 3D simulation is being developed by the author and associates to challenge and involve students and space enthusiasts in the renewed Moon exploration "Vision".

This interactive simulation will allow the adventurer to Plan his/her lunar roving mission, Prepare his/her vehicle for exploration, Perform the driving and science experiments, and receive a Post excursion score for his/her simulated LUROVA mission.

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