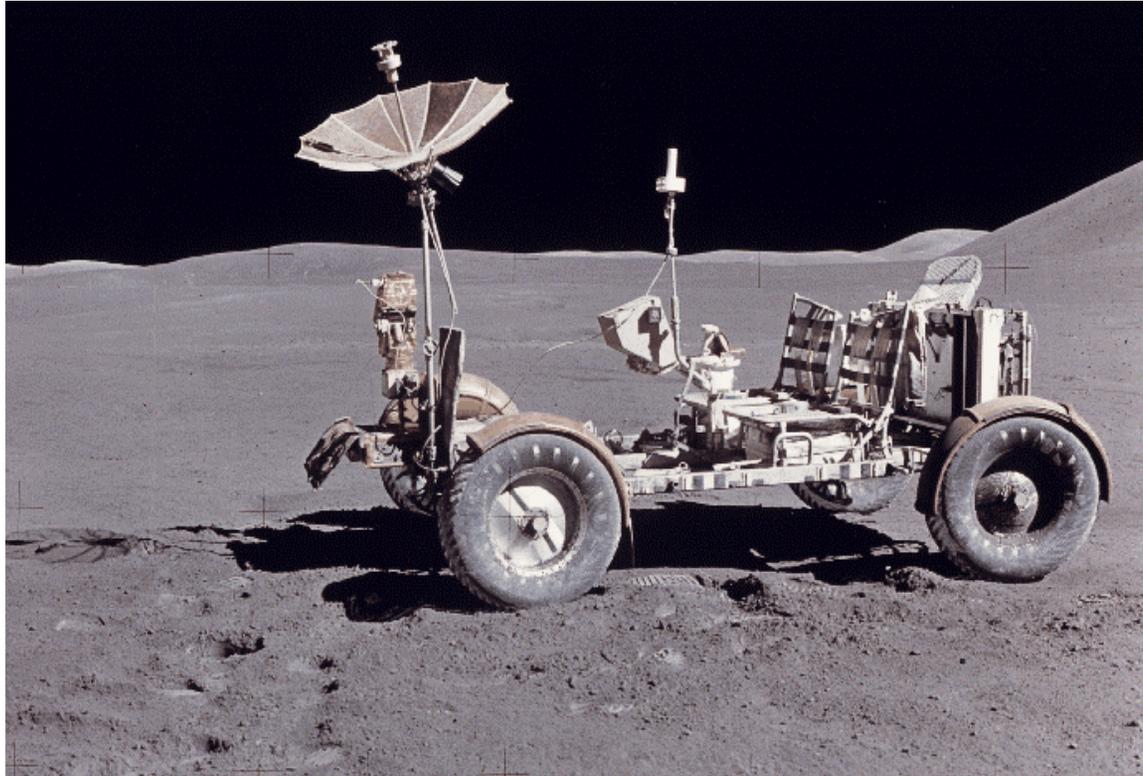


# Apollo Rover Lessons Learned



## Applying Experiences On The Apollo Lunar Rover Project To Rovers For Future Space Exploration

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

# Introduction



Fresh out of college, some 38 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 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 Space Shuttle, International Space Station and Air Force satellites.

Today, Ron will update his LRV thermal experiences, presented at NASA field centers, Universities, International Space Development, Return to the Moon, and Spacecraft Thermal Control 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 “Moon, Mars, and Beyond” Vision for Future Space Exploration.

# Apollo Rover Lessons learned

## 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



Movies Noted in Presentation

# My Start In Space Engineering



- Sputnik Era Model Rocket Launches



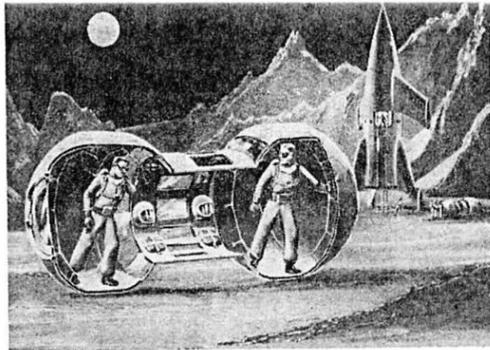
- Co-op Student At NASA Marshall Space Flight Center (MSFC)



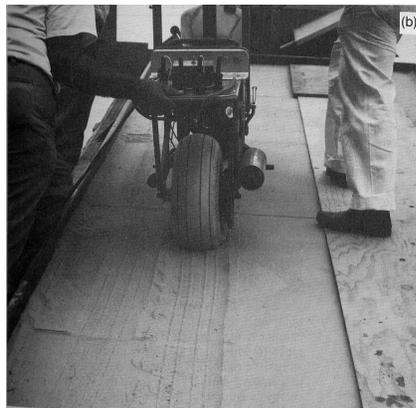
- Graduated And Assigned To Development Of Apollo Lunar Roving Vehicle (LRV) Thermal Control System

# Rover Historical Concepts

## Unique Concepts Proposed



**DO-IT-YOURSELF MOON AUTO**—This unusual collapsible moon sac would provide both protection and transportation for men exploring the moon. Cutaway drawing shows how the pod-shaped vehicle would allow two men to roll along the lunar surface simply by walking a treadmill.



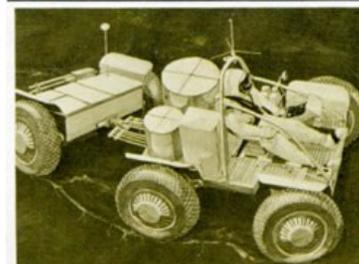
## Lunar Flying Vehicle and Motorcycle Considered



Surveyor Lunar Roving Vehicle



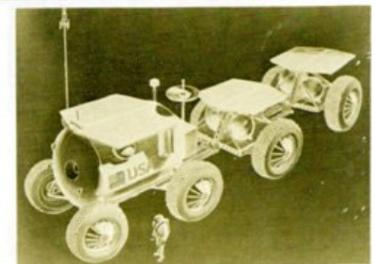
MOLAB



Lunar Mission Development Vehicle

Lunar Scientific Survey Module

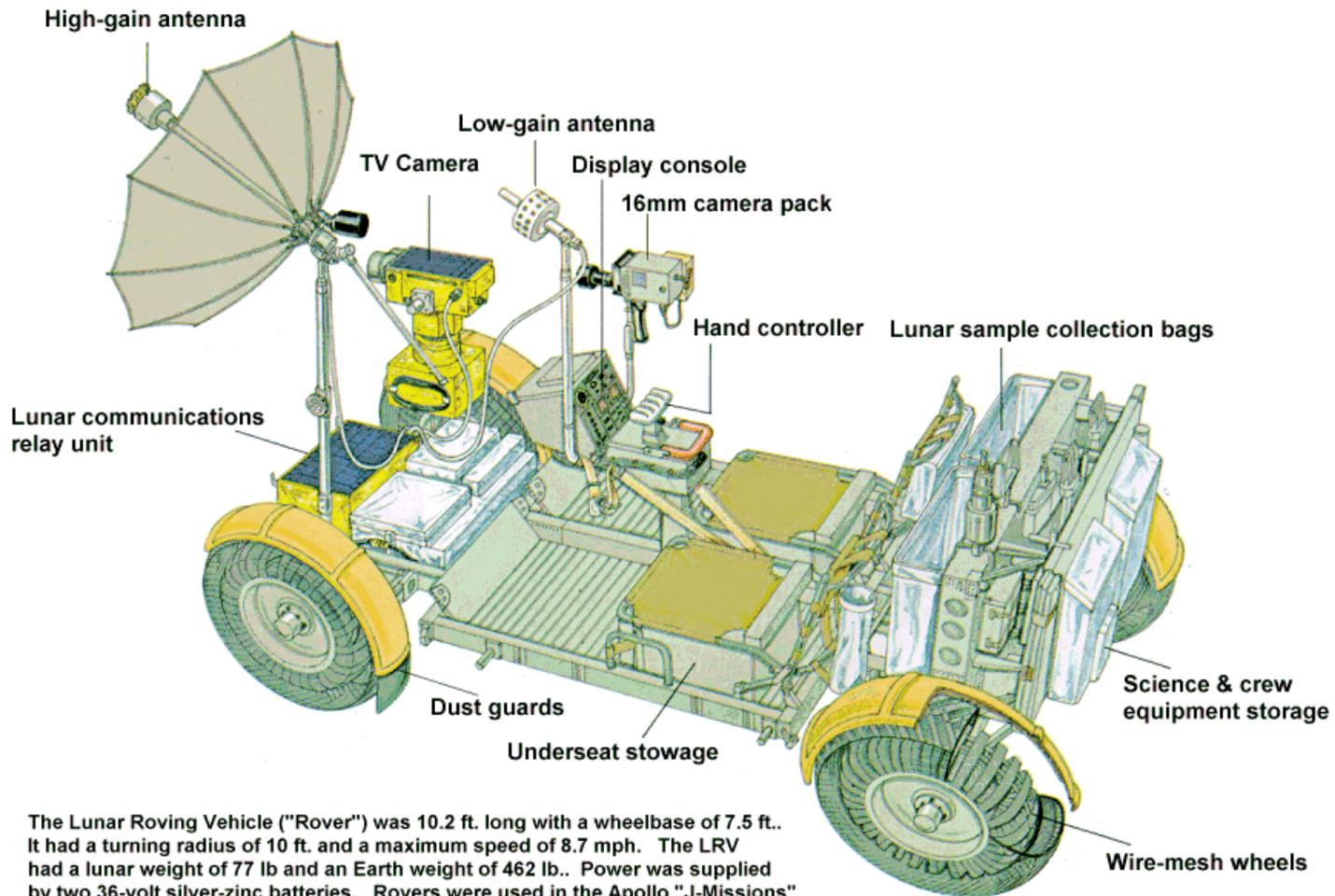
Lunar Vehicle Studies



## Wheeled Rover Concepts Led To LRV Design (1969 Start And 1971 First Mission)

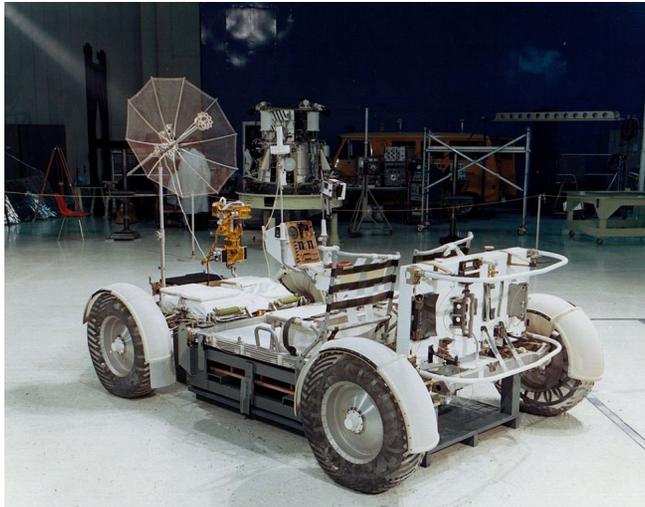
# LRV Designed To Provide Extended Mobility On The Moon

## 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.

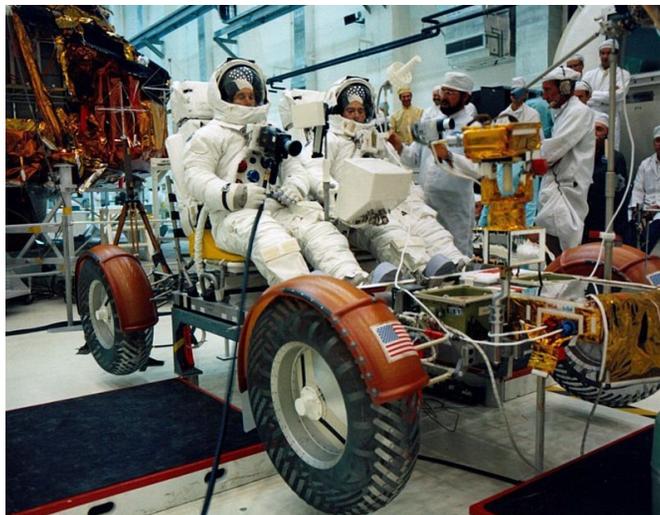
# LRV's Greatly Increased Science Return From Apollo 15, 16, And 17



LRV No. 1 Delivered "On-Time" For Apollo 15

## LRV Performance Comparison On The Moon

	Pre - LRV	Apollo 15	Apollo 16	Apollo 17
EVA Duration (hrs:min)	19:16	18:33	21:00	22:06
Driving Time (hrs:min)	—	3:02	3:26	4:29
Surface Distance Traversed (km)	3.55	27.9	26.9	35.7
Average Speed (km/hr)	0.18	9.20	7.83	7.96
Longest Traverse (km)	—	12.5	11.6	20.3
Maximum Range From LM (km)	—	5.4	4.5	7.6
Regolith Samples Collected (kg)	97.6	77.6	96.7	116.7



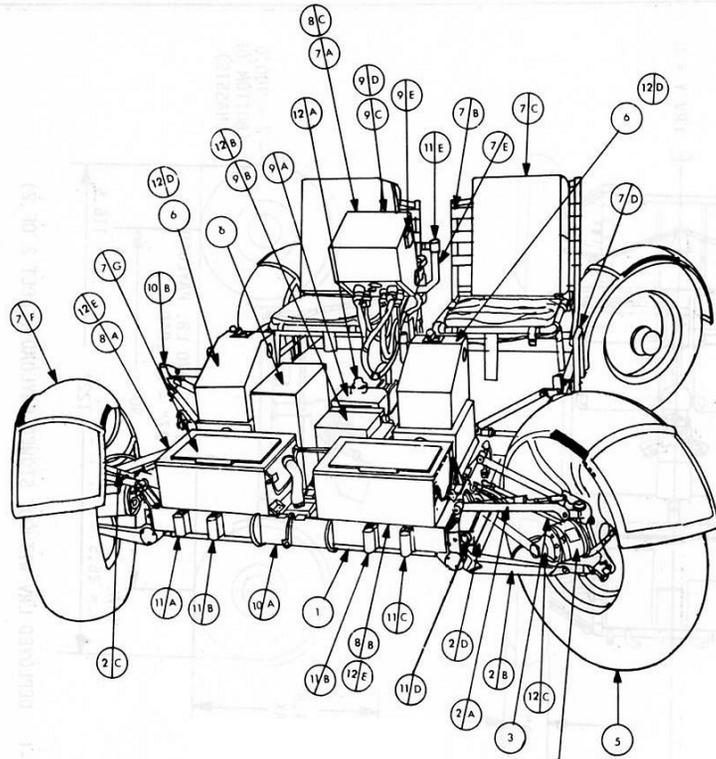
LRV No. 2 Being Checked By Apollo 16 Crew At KSC



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



- |   |  |  |
|---|--|--|
| <p>① CHASSIS</p> <p>② SUSPENSION SYSTEM</p> <p>A. UPPER ARM<br/>B. LOWER ARM<br/>C. DAMPER<br/>D. TORSION BAR</p> <p>③ STEERING SYSTEM (FORWARD AND REAR)</p> <p>④ TRACTION DRIVE</p> <p>⑤ WHEEL</p> <p>⑥ DRIVE CONTROLLERS</p> <p>⑦ CREW STATION</p> <p>A. CONTROL AND DISPLAY CONSOLE<br/>B. SEAT<br/>C. REMOVABLE PAD (FOR UNSUITED CREW USE)<br/>D. OUTBOARD HANDHOLD<br/>E. INBOARD HANDHOLD<br/>F. FENDER<br/>G. SIMULATED DUST COVER</p> | <p>⑧ POWER SYSTEM</p> <p>A. BATTERY #1<br/>B. BATTERY #2<br/>C. INSTRUMENTATION</p> <p>⑨ NAVIGATION</p> <p>A. DIRECTIONAL GYRO UNIT (DGU)<br/>B. SIGNAL PROCESSING UNIT (SPU)<br/>C. INTEGRATED POSITION INDICATOR (IPI)<br/>D. SUN SHADOW DEVICE<br/>E. ATTITUDE INDICATOR</p> <p>⑩ DEPLOYMENT SIMULATION</p> <p>A. FORWARD CHASSIS SADDLE SIMULATOR<br/>B. TRIPOD SIMULATORS (BOTH SIDES)</p> <p>⑪ PAYLOAD INTERFACE</p> <p>A. TV CAMERA RECEPTACLE<br/>B. LCRU RECEPTACLE<br/>C. HIGH GAIN ANTENNA RECEPTACLE<br/>D. AUXILIARY CONNECTOR<br/>E. LOW GAIN ANTENNA RECEPTACLE</p> | <p>⑫ THERMAL CONTROL</p> <p>A. DGU HEAT EXCHANGER<br/>B. SPU HEAT EXCHANGER<br/>C. TRACTION DRIVE BLOWERS<br/>D. ICE BLOWERS<br/>E. BATTERY BLOWER</p> |
|---|--|--|



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

	Component	Minimum Survival	Minimum Operating	Maximum Operating	Maximum Survival
<b>Electronics</b>	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
<b>Mobility</b>	Traction Drive**	-50	-25	400	450
	Suspension Damper	-70	-65	400	450
	Steering Motor	-50	-25	360	400
	Wheel	-250	-200	250	250

Astronauts Read Temperature On Display Panel - \* Batteries \*\* Traction Drive (Start At 200)

# LRV Transported To Moon By Saturn V & Lunar Module

## apollo 15 vehicle characteristics

### VEHICLE DATA

STAGE/ MODULE	DIMENSIONS		WEIGHT AT LAUNCH (LBS)
	DIAMETER FEET	LENGTH FEET	
Launch* Vehicle	33.0	365	6,408,042
S-IC	33.0	138	4,930,000
S-II	33.0	81.5	1,101,000
S-IVB	21.7	59.3	260,000
IU	21.7	3.0	4,500
SLA	21.7 Base 12.8 Top		4,200
LM**			36,200
C & SM	12.8	22	66,900

### ENGINE DATA

STAGE/ MODULE	QTY	MODEL	NOMINAL THRUST LBS		BURNTIME (MINS)
			(EACH)	(TOTAL)	
S-IC	5	F-1	1,522,000	7,787,495	2.7
S-II	5	J-2	232,840	1,164,210	6.5
S-IVB	1	J-2	200,130	200,130	1st 2.43
				193,720	2nd 6.0
LM	1		10,000	10,000	
			3,500	3,500	
SM	1		20,500	20,500	
LES	1		150,000	150,000	

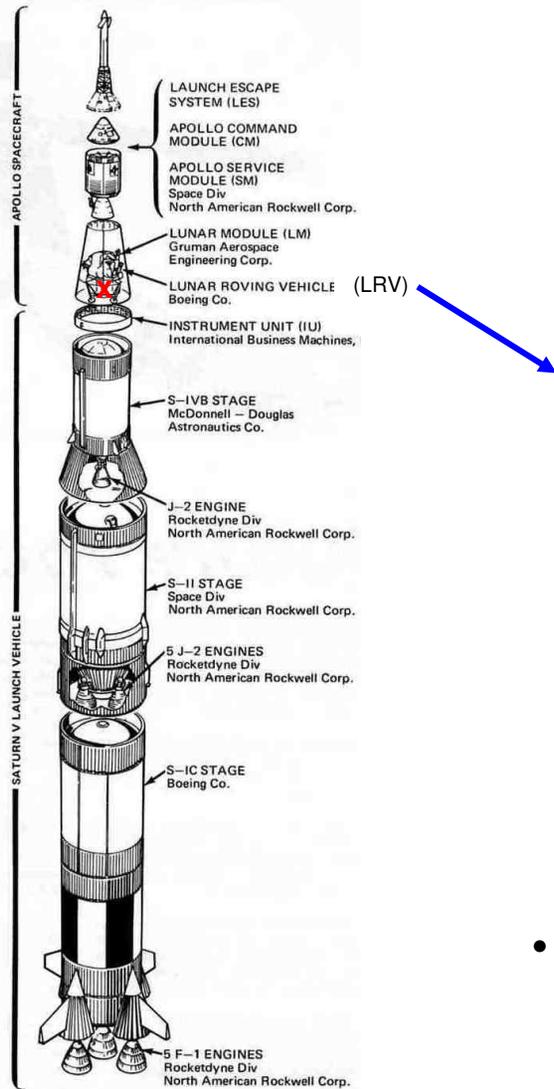
### FLIGHT DATA

STAGE/ MODULE	EVENT	VELOCITY (MPH)
S-IC	Engine Cutoff	6,100
S-IC	Engine Cutoff	15,600
S-IVB	Earth Orbital Insertion	17,170
S-IVB	Trans Lunar Injection	23,800
CSM/LM	Lunar Orbit Insertion	3,585
S-IVB	Lunar Impact	5,800
LM	Lunar Touchdown	0-2
LM	Lunar Lift-off	
LM Ascent	Lunar Impact	3,756
CSM	Trans Earth Insertion	5,640
CM	Earth Insertion	24,640

\*Includes 1,210 pounds of frost on outside of vehicle

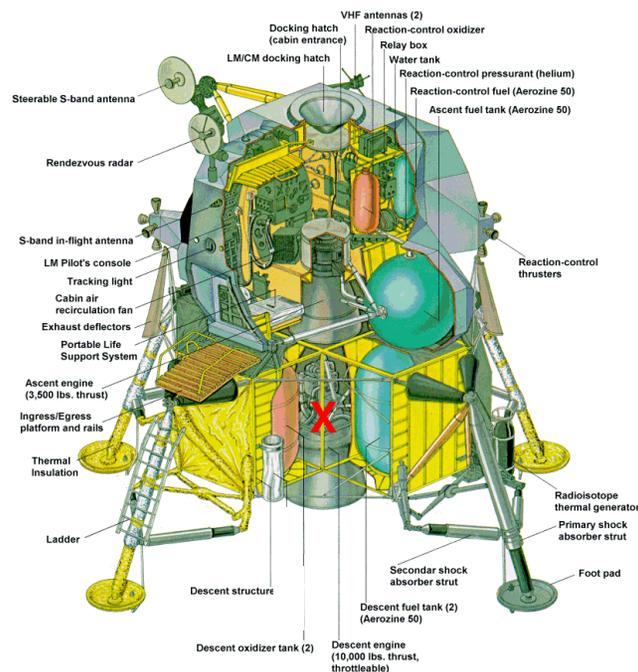
\*\*Payload Weight on Apollo 15 is 107,300 lbs.—almost 5,000 lbs heavier than any previous mission

MISSION SUCCESS AND SAFETY ARE APOLLO PREREQUISITES



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

### Apollo Lunar Module

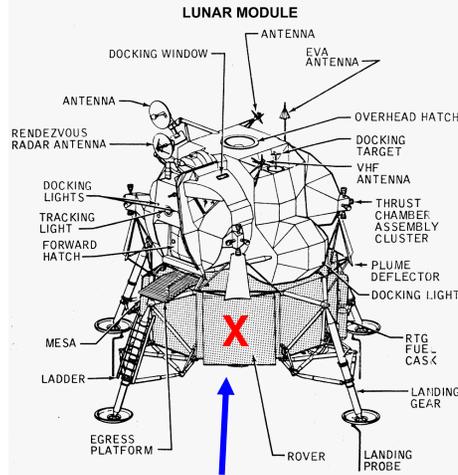


The lunar module was 23 ft. tall and had a launch weight of 33,205 lbs.  
(The Apollo 17 J-Series lunar module weighed 36,244 lbs.)

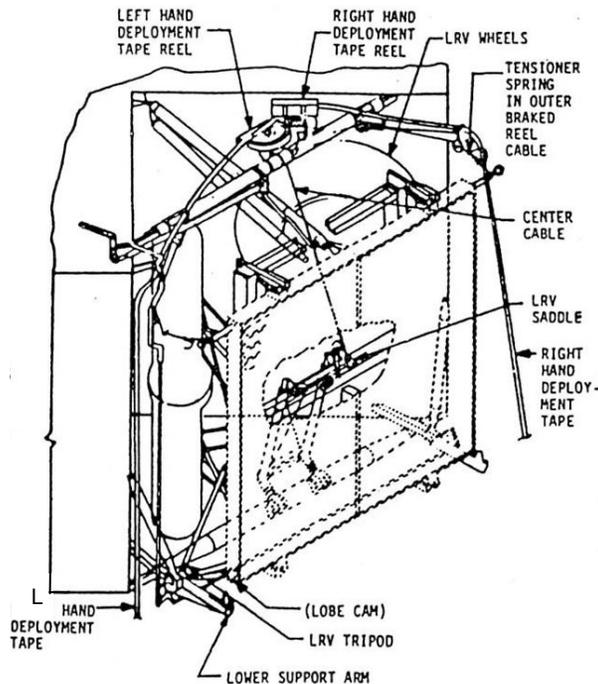
- LRV Weight Goal Of 400 lbs. (10 lbs. For Thermal Control) Drove Design To Passive Thermal Control With No Telemetry Data

# LRV Space Support Equipment (SSE) Thermal Control

- Maintained SSE During Transit 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 1



Apollo 15 Astronauts Inspect Stowed LRV And SSE

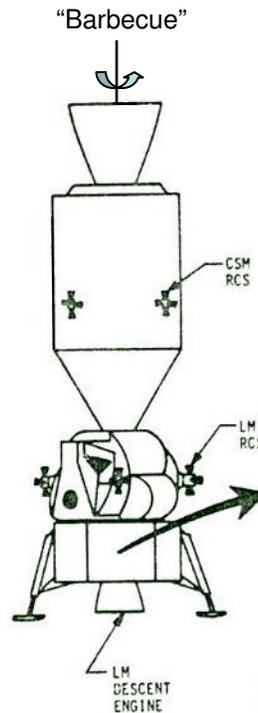


# LRV Transportation Phase Thermal Control

- 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 LM Exhaust Plume Impingement And Lunar Radiant And Albedo (Reflected) Heating Environments
- Lunar Module “Barbecues” To Balance Solar Heating And Radiation Loss



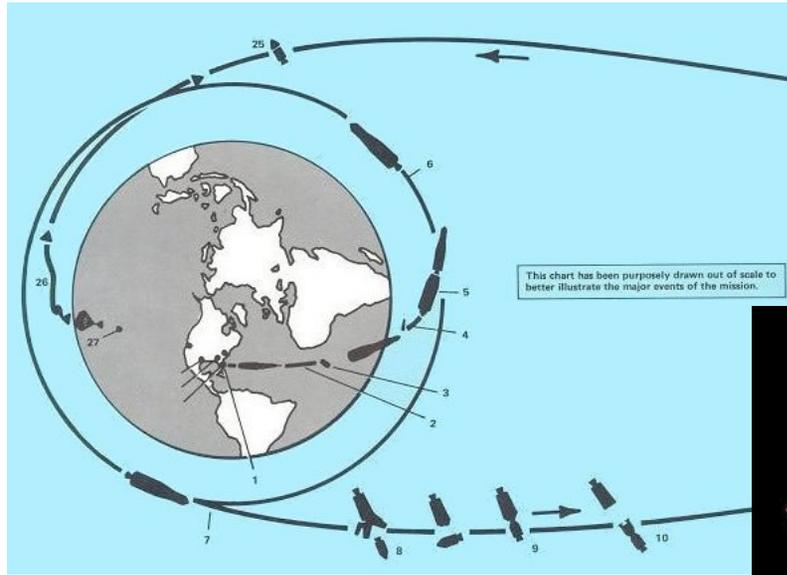
Folded LRV Stowed In Lunar Module With Floor Panels Removed For Battery Installation



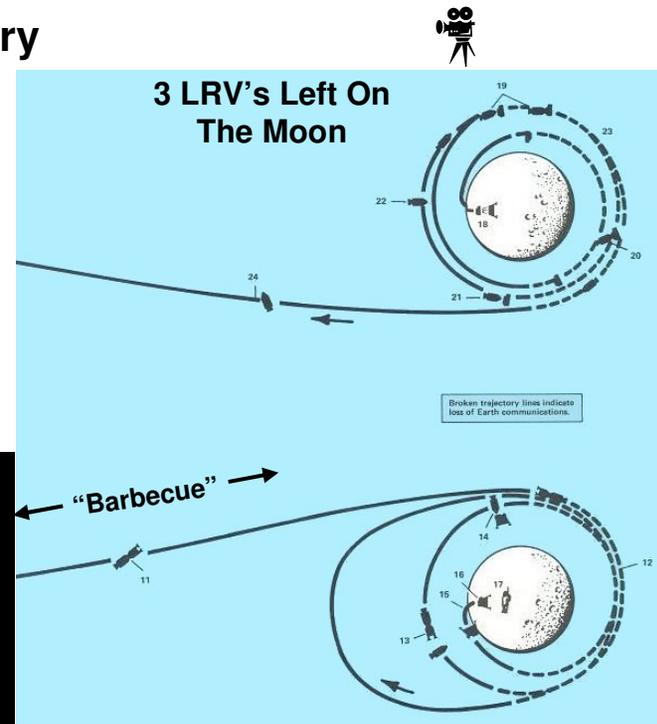
Folded LRV Stowed In Lunar Module With Floor Panels In Place After Battery Installation

# From The Earth To The Moon

Passive LRV Thermal Control with No Telemetry and No Thermal Testing of This Configuration

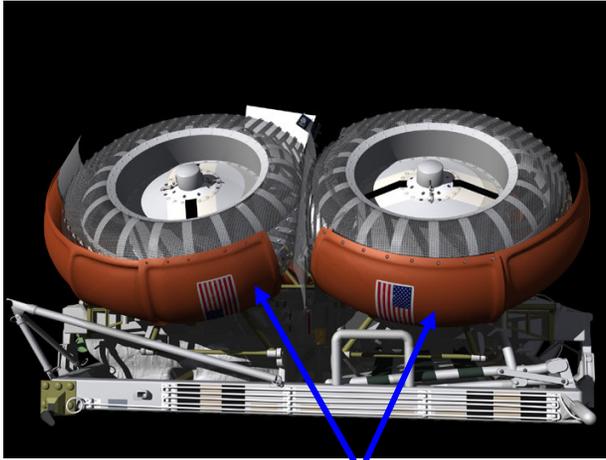


(3 Rev/Hour)

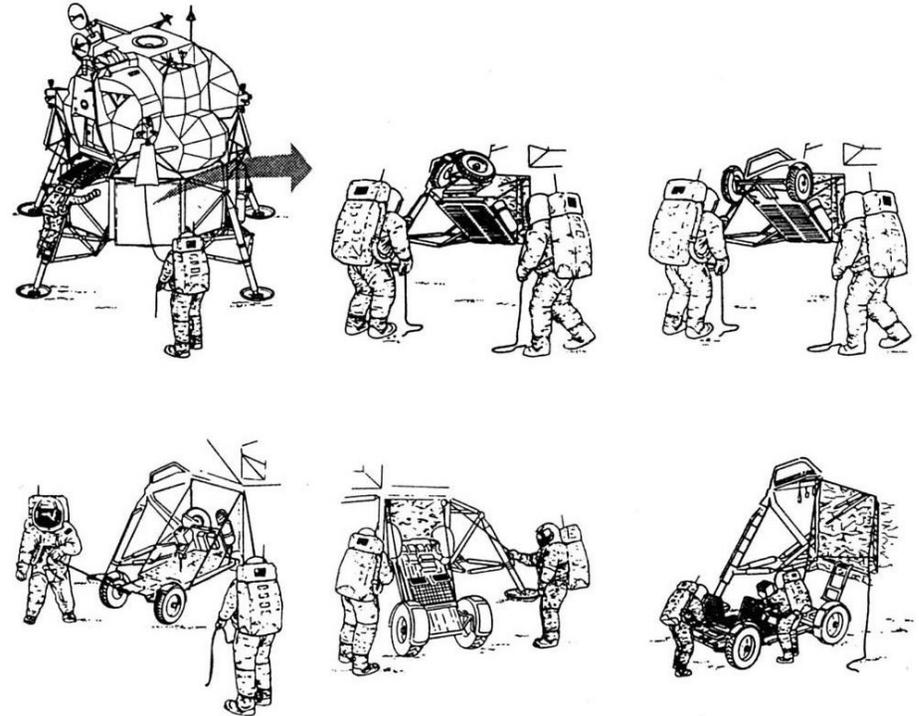


Apollo Mission Profile			1. Liftoff	2. S-1C Powered Flight	3. S-1C/S-II Separation
4. Launch Escape Tower Jettison	5. S-II/S-IVB Separation	6. Earth Parking Orbit	7. Translunar Injection	8. CSM Docking With LM/S-IVB	9. CSM Separation From LM Adapter
10. CSM/LM Sep. From S-IVB	11. Midcourse Correction	12. Lunar orbit Insertion	13. Crew Transfer To LM	14. CSM/LM Separation	15. LM Descent
16. Touchdown	17. Explore Surface, Exper.	18. Liftoff	19. Rendezvous And Docking	20. Transfer Crew/Equip.	21. CSM/LM Sep. And LM Jettison
22. Transearth Injection Preparation	23. Transearth Injection	24. Midcourse Corrention	25. CM/SM Separation	26. Commun. Blackout	27. Splashdown

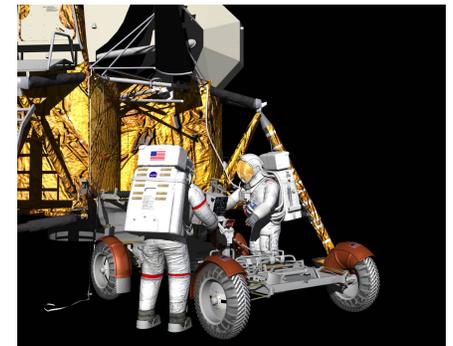
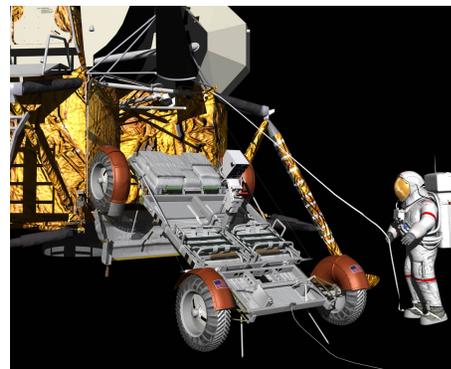
# Astronauts Performed Manual Sequenced LRV Unfolding And Deployment On Moon



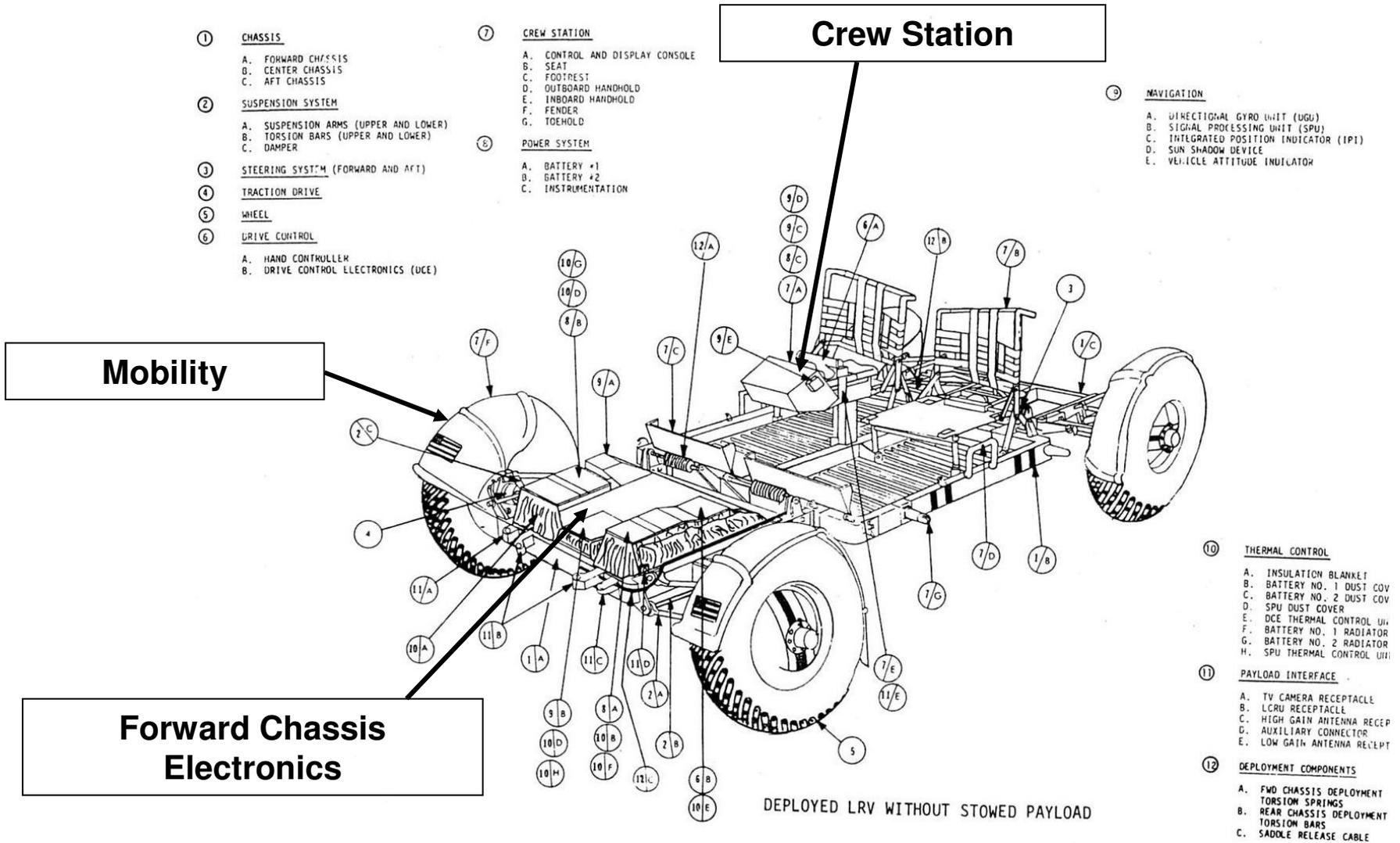
Retractable Fender Extensions Required For Folding of Wheels



Folded and Unfolding Images From LUROVA "Edutainment" 3D Simulation (See Page 52)



# Deployed LRV Subsystems



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

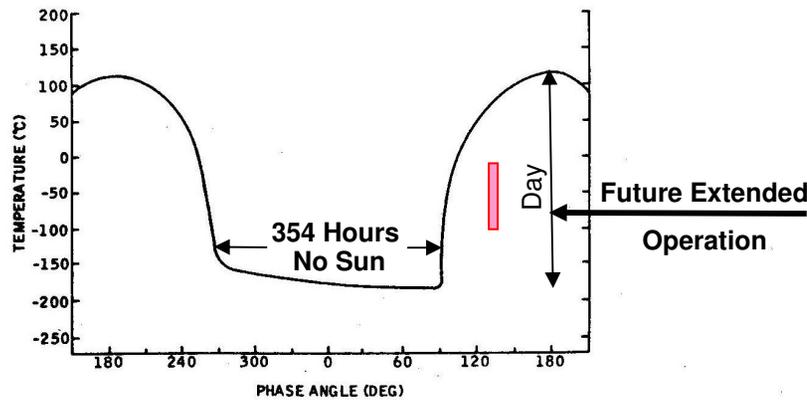
$$\text{Moon Temp.} = \sqrt{\sqrt{\cos(\text{Beta})}} \times \left( \sqrt{\sqrt{443 \times \sin(\text{Sang})} / \sigma} - 460 \right)$$

Where: Beta = Moon Latitude (Degrees)

Sang = Solar Elevation Angle (Degrees)

$\sigma$  = Stefan Boltzman Constant (btu/(hr-ft<sup>2</sup>-R<sup>4</sup>))

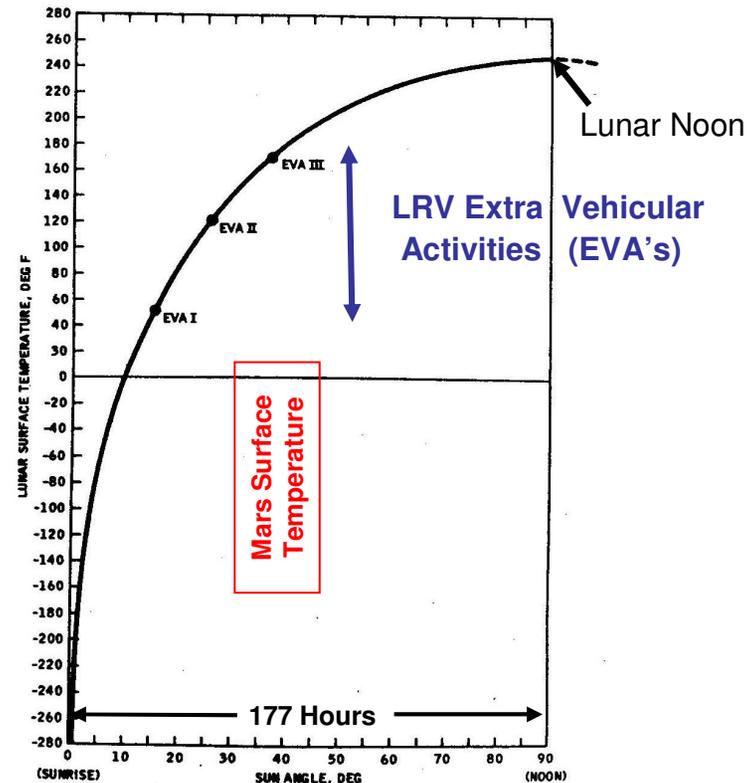
- Night = 354 Hours No Solar, Cold Moon
- Min. Surface Temperature = -280 Deg. F



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.

## Lunar Day

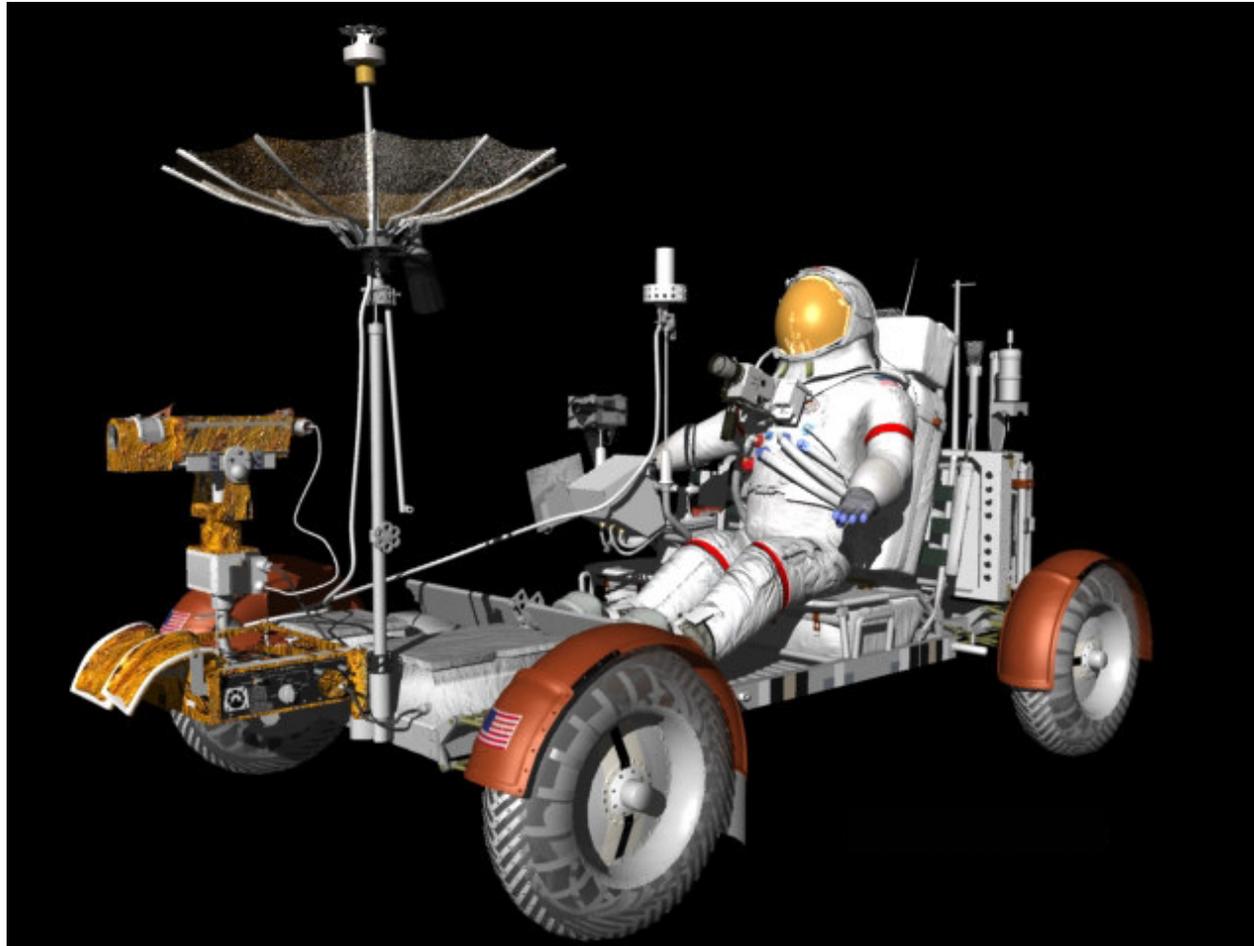
- 354 Hours With Solar, Moon Heating
- Max. Surface Temp. = +250 Deg. F



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.

# Thermal Provisions for Deployed LRV Subsystems

Maintain All  
Surfaces  
Within  
Astronaut  
Touch  
Constraints



**Control And  
Display  
Console**

Insulated  
Front Panel,  
Exterior Dust  
Degraded

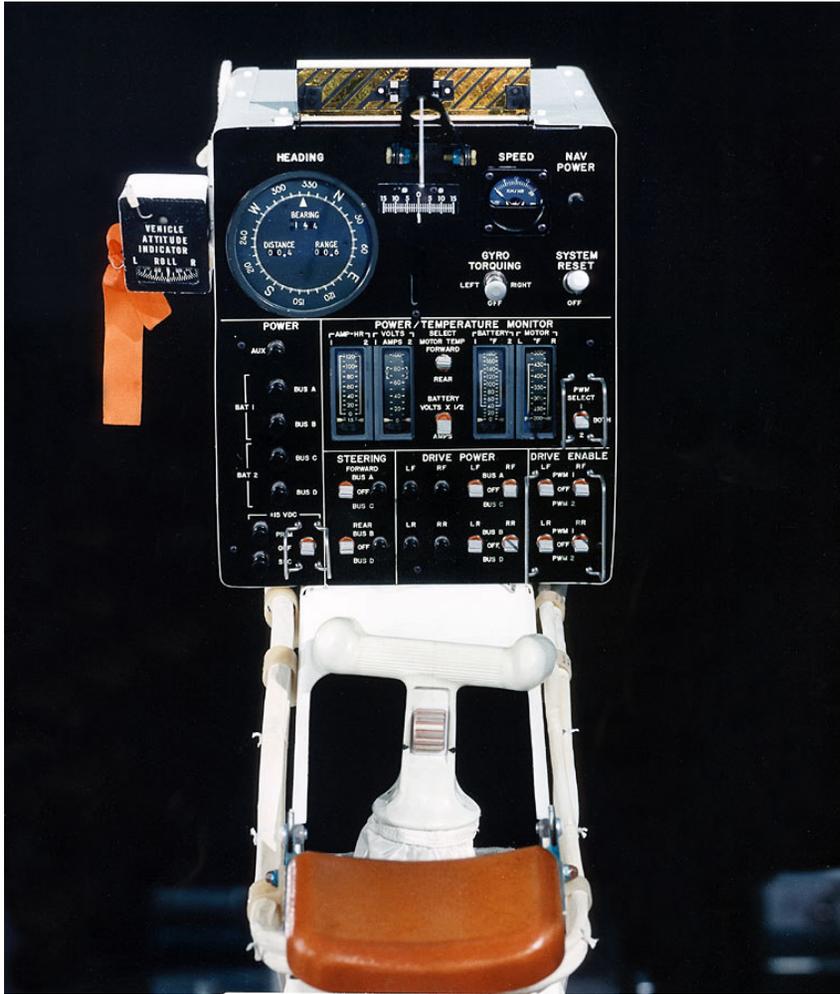
## **Forward Chassis Electronics**

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

## **Mobility**

Exterior Dust  
Degraded  
Maximize Internal  
Conduction

# LRV Control And Display Console Thermal Control



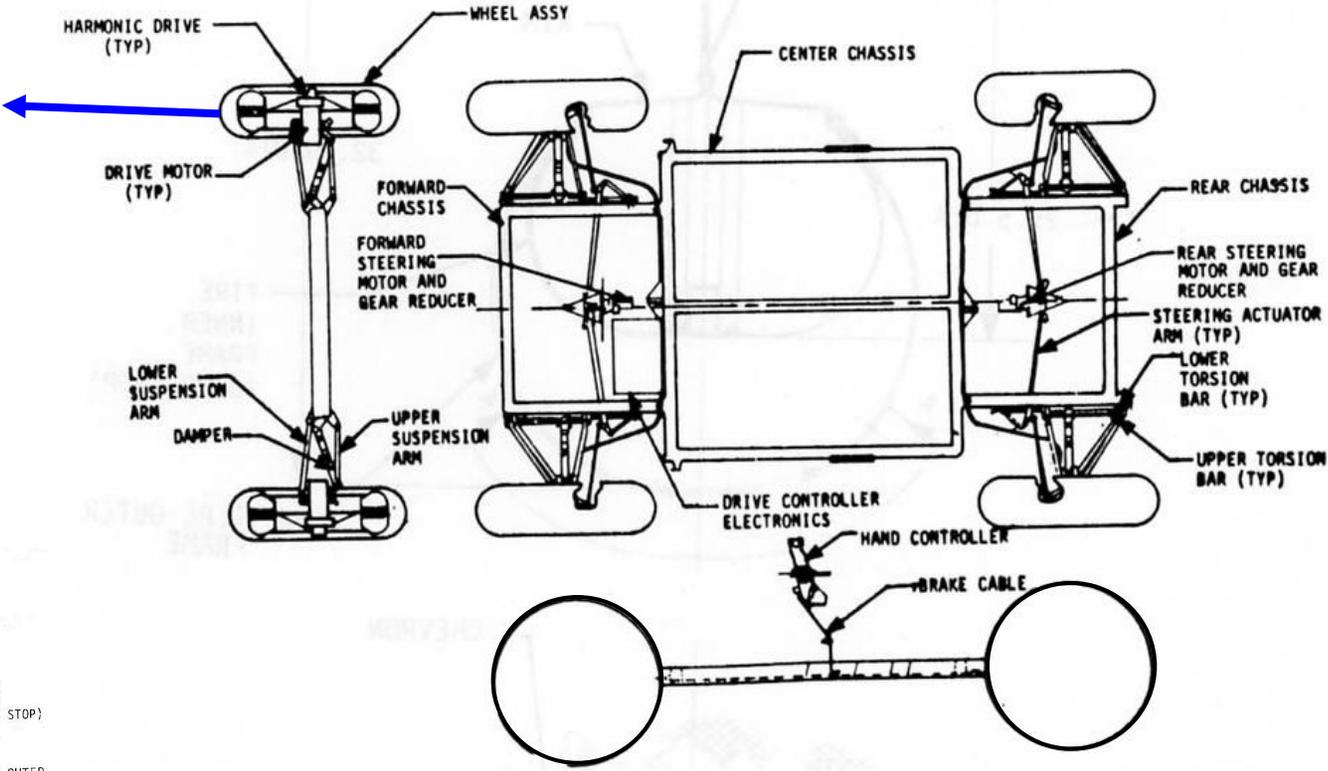
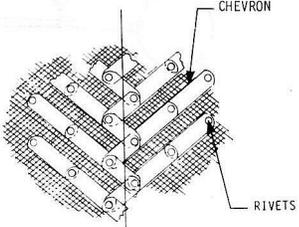
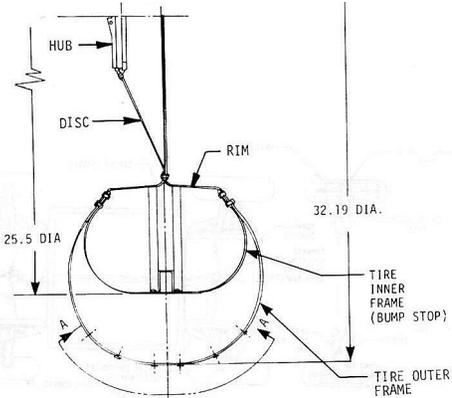
LRV Control And Display Console

- 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

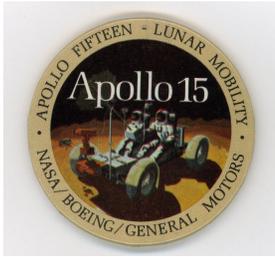
# LRV Mobility Subsystem



Wire Mesh Wheel

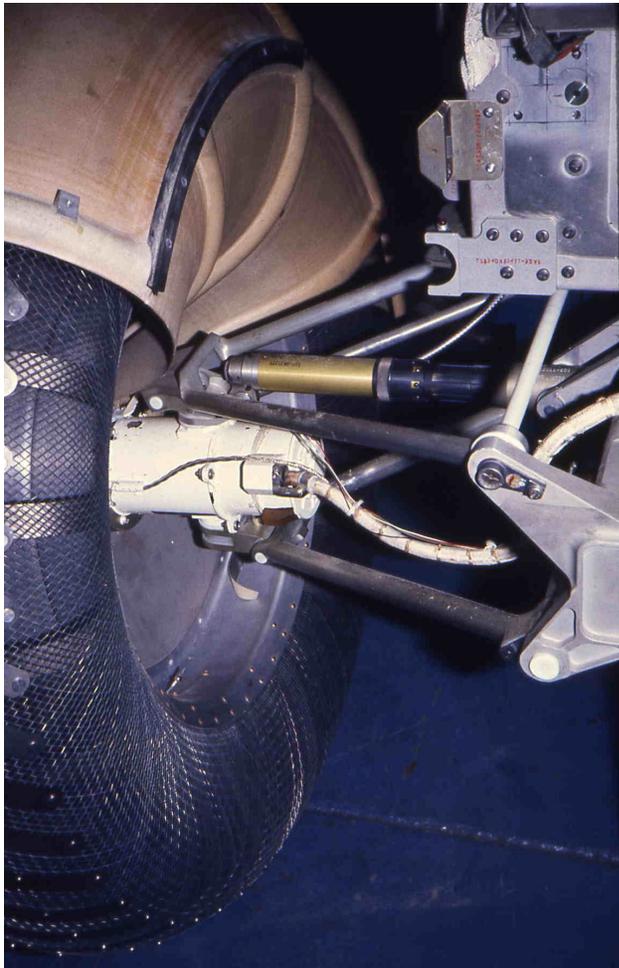


Mobility Subsystem Components

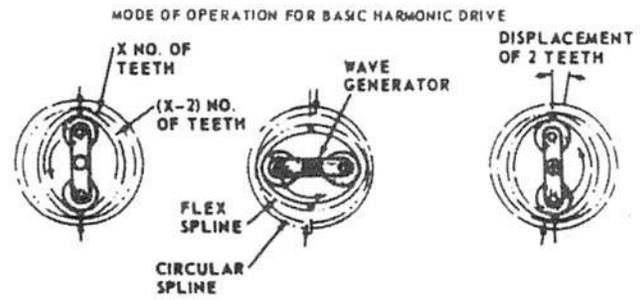
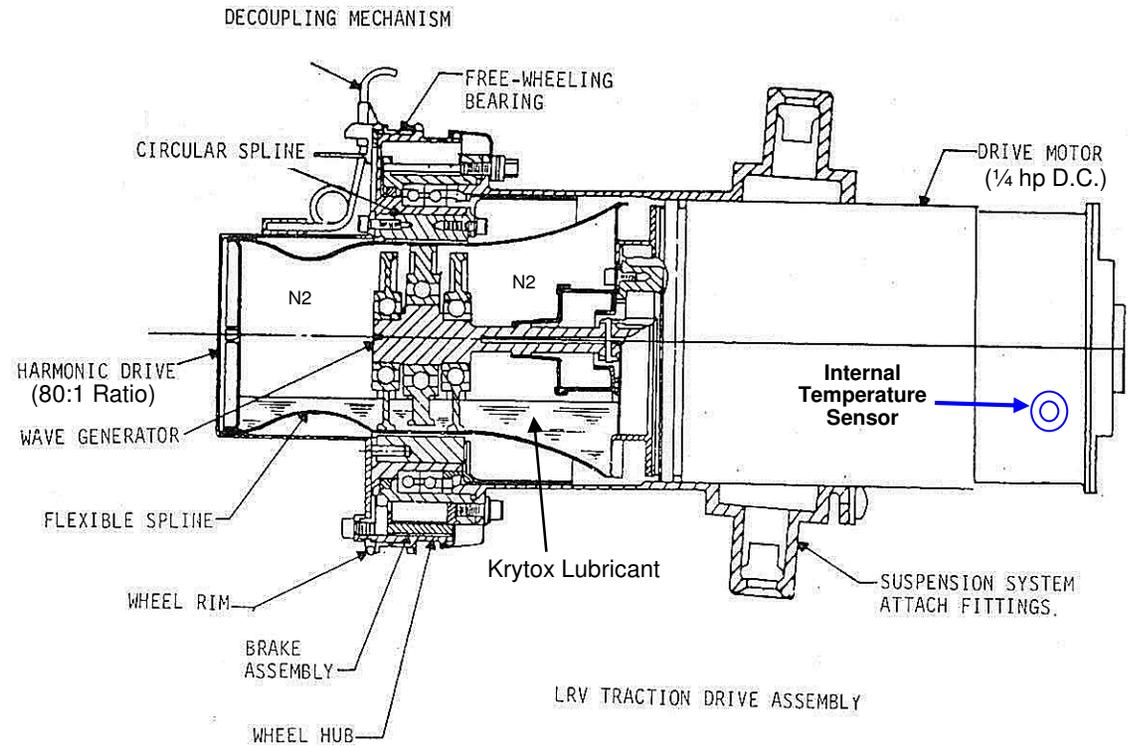


# LRV Traction Drive Thermal Control

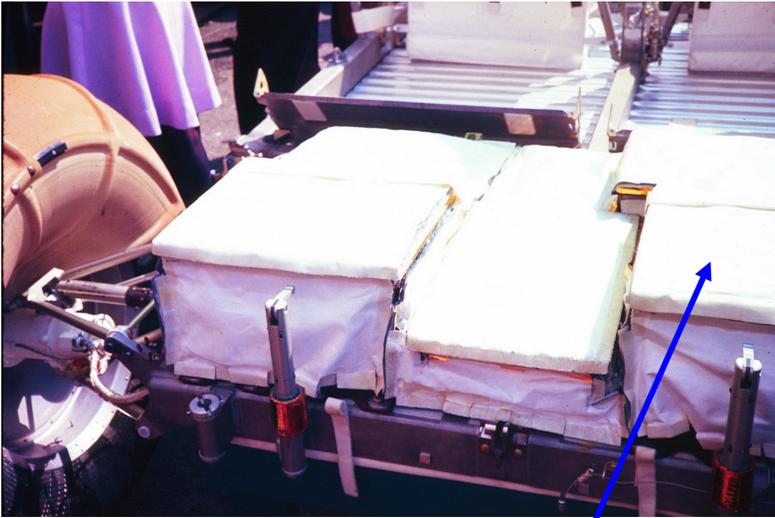
- Special Paints And Internal Conduction Maximized
- External Exposed Surfaces Will Be Dust Degraded



Mobility Subsystem



# LRV Batteries Were Heart of Forward Chassis Electronics Thermal Control

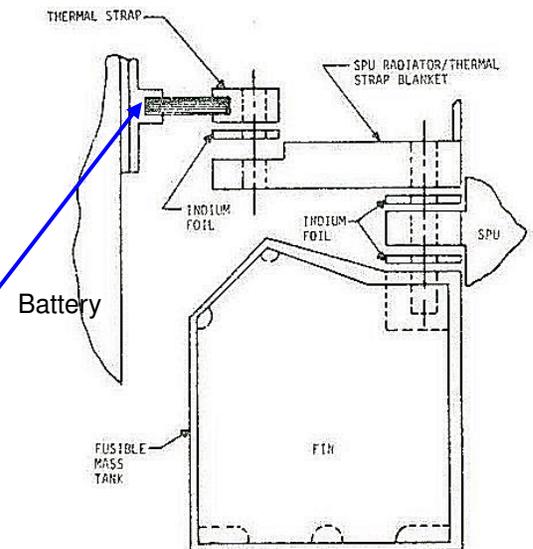
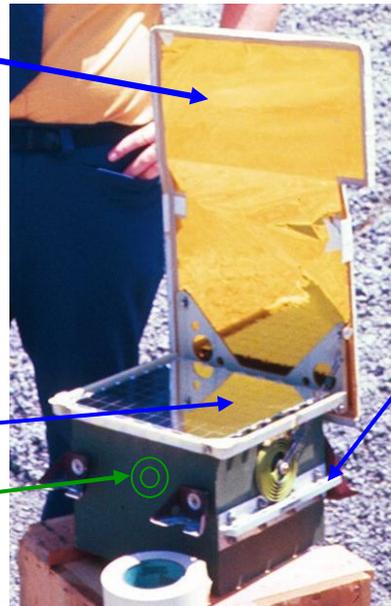
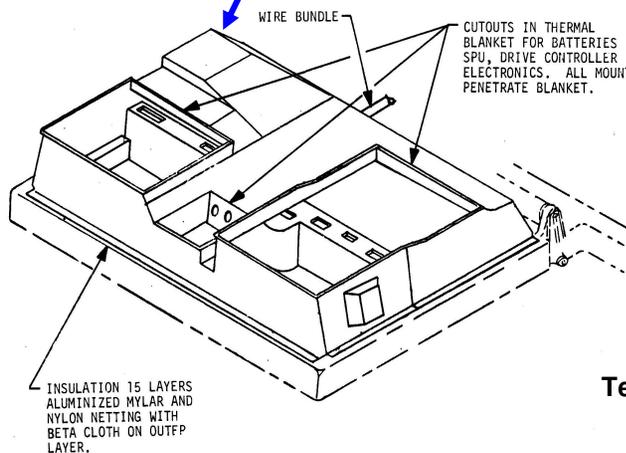


- Multi-Layer Blanket For Insulation, Dust Covers
- Thermal Straps Conduct Heat Into Batteries
- Electronics Heat Also Stored In Wax Boxes (Fusible Mass Tanks) During EVA's
- Low Solar Absorptance ( $\alpha = 7\%$ ) Space Radiators To Reject Heat When Dust

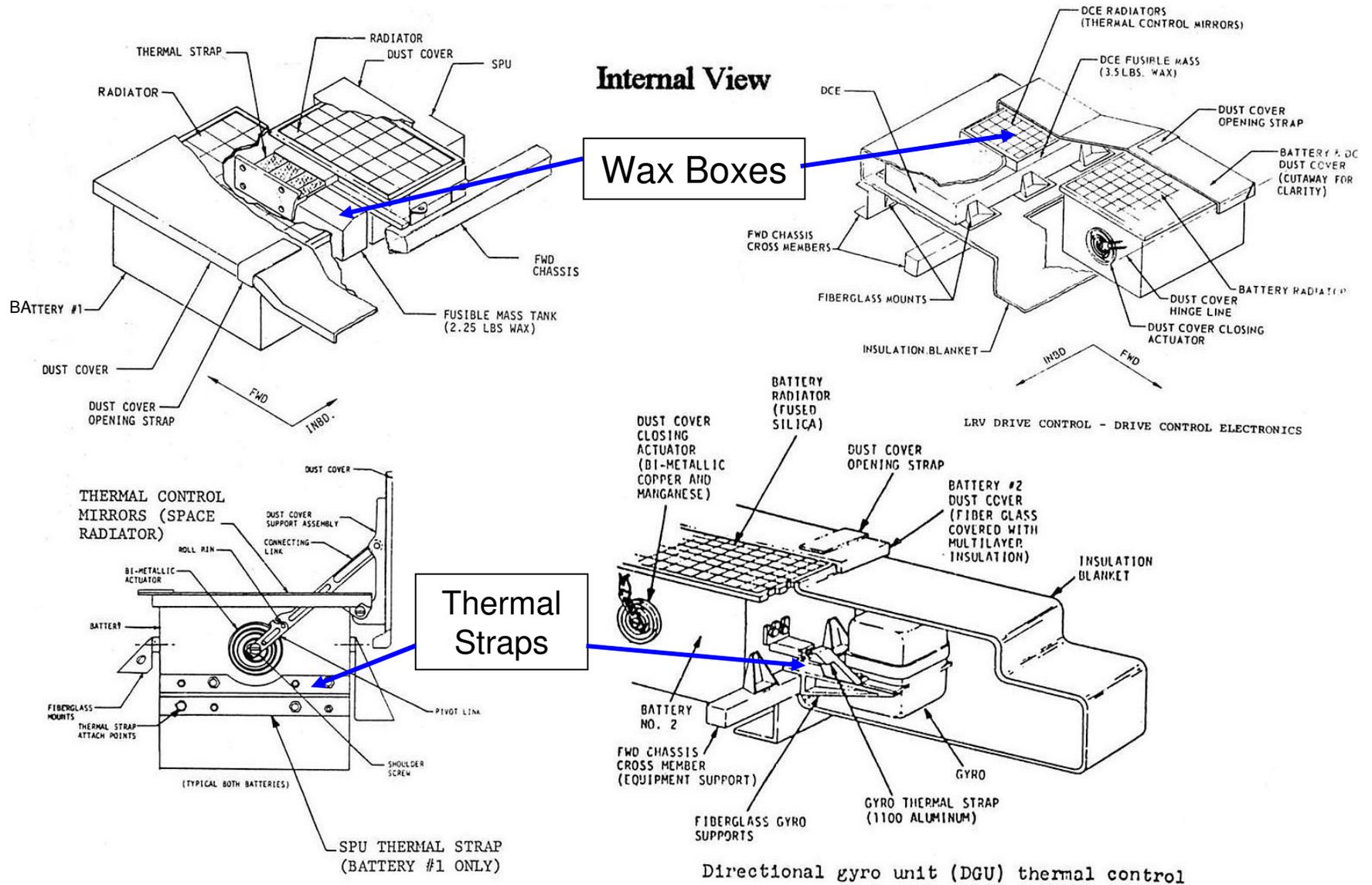
Covers Opened for Cooldown Between EVA's



Insulation Blanket And Dust Covers



# LRV Forward Chassis Electronics Thermal Control



Signal Processing Unit And Directional Gyro Unit Strapped To 60 Lb. Batteries

# Extensive LRV Thermal Testing Was Conducted

- 
- Oct. 1969  
to  
Mar. 1971  
(17 Months)
- 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, 1/4 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

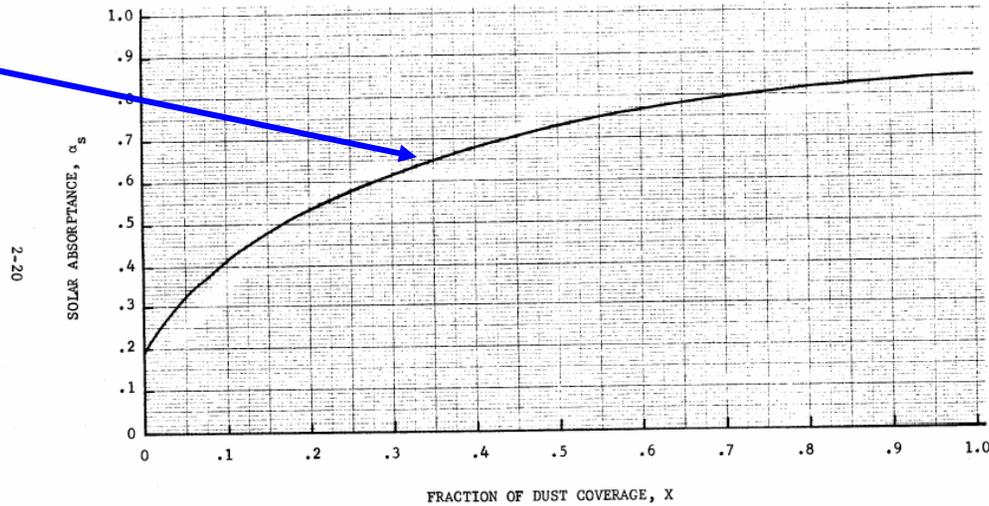


Figure 2-4. VARIATION OF TOTAL SOLAR ABSORPTANCE WITH DUST COVERAGE OF S-13 PLATE

TR-792-7-207B  
7 June 1967

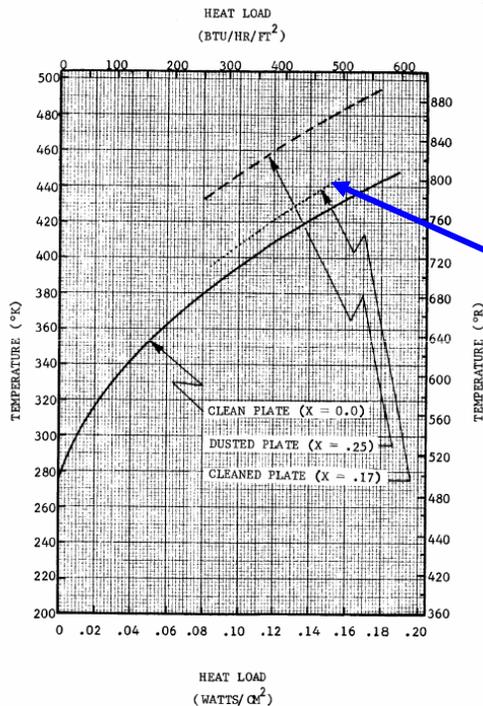
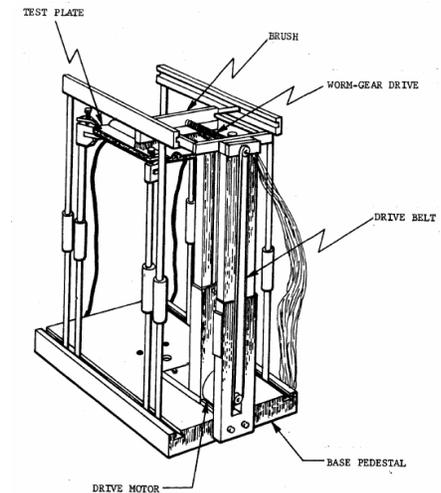


Figure 3-30b. TEMPERATURE VARIATION WITH HEAT LOAD (SOLAR SIMULATOR ON) FOR MECHANICAL BRUSH TEST RUN

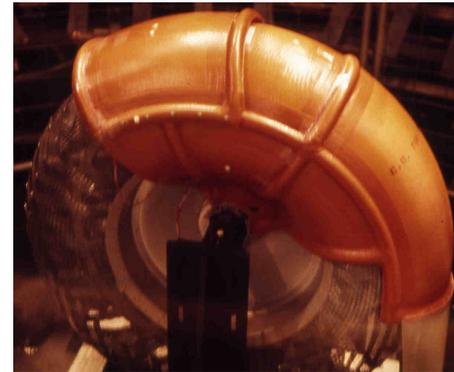
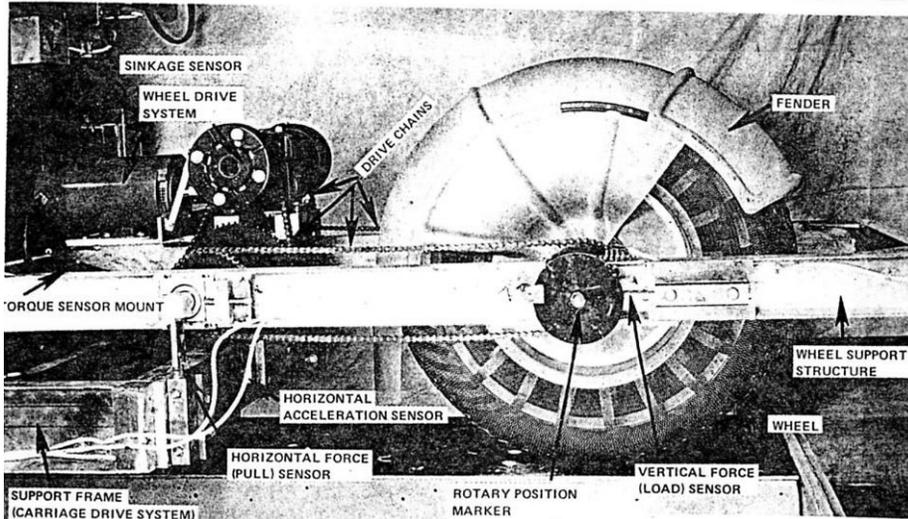
## Misleading Earth-Based Cleaning Test Results

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



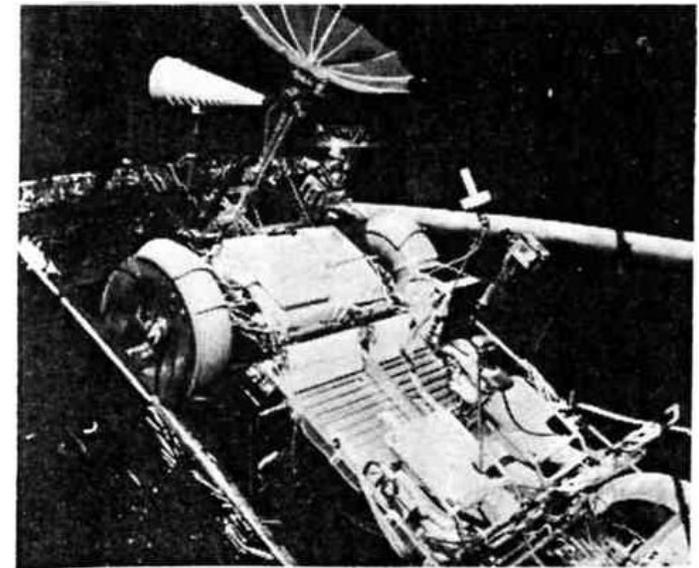
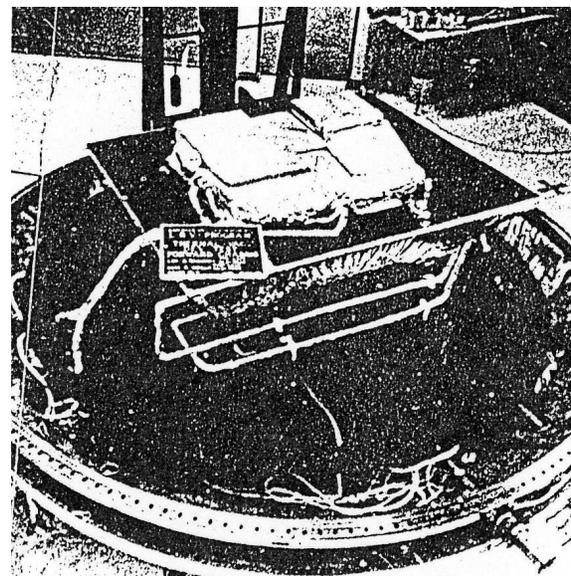
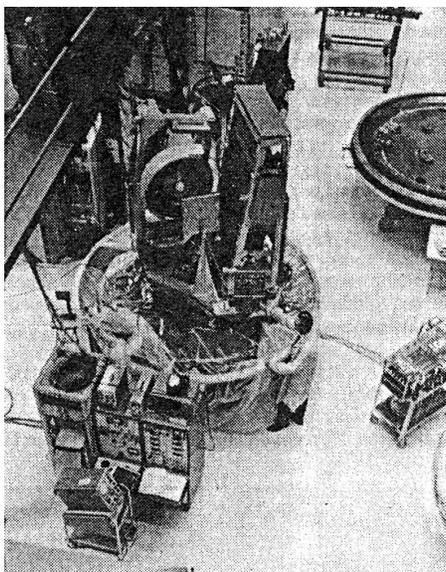
Brush Test Apparatus

# Extensive LRV Thermal Vacuum (TVAC) Testing



Fender Extension Deployment TVAC at JSC

Wheel to Soil Interaction At Waterways Experiment Station, C 135

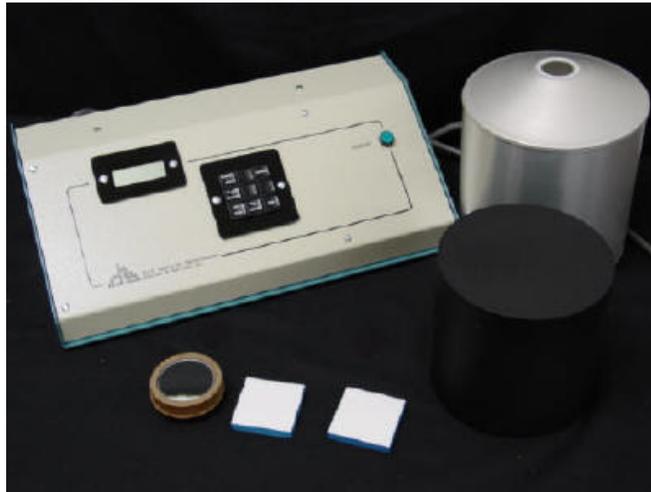


Mobility Subsystem TVAC

Forward Chassis Development "Tub" TVAC

Qualification And Flight Units TVAC

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



Solar Absorptance -  $\alpha$

Absorbed Solar  
(Direct/Reflected)

Absorbed Infrared

Internal Generated

GEORGE C. MARSHALL SPACE FLIGHT CENTER  
HUNTSVILLE, ALABAMA

## Memorandum

TO Mr. Creel, S&E-ASTN-PFA DATE **JUN 1 1970**  
 FROM Chief, Materials Division, S&E-ASTN-M In reply refer to:  
 S&E-ASTN-MCS-70-57  
 SUBJECT Optical properties of Lunar Roving Vehicle thermal control samples

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

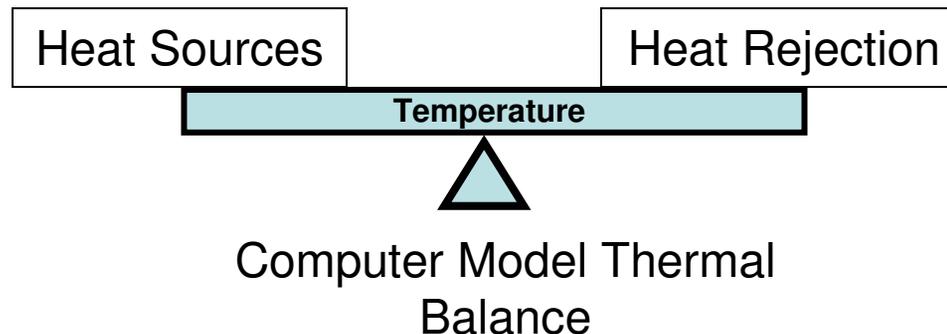
Sample No.	Material Description	$\alpha$	$\epsilon$	%T
1	Seat Material/Beta Cloth/Al Mylar	0.28	0.90	
1	Seat Material Only			21
2	PLSS Support Straps, Type 15 <i>Green</i>	0.55	0.92	
3	PLSS Support Straps/Beta/Al Mylar, Type 4 <i>White</i>	0.32	0.91	
3	PLSS Support Straps Type 4 Only			29.5
4	Dry Film Lube MIL-L-81329	0.83	0.76	
5	Dry Film Lube MIL-L-23398 Polished	0.79	0.70	



Infrared Emittance -  $\epsilon$

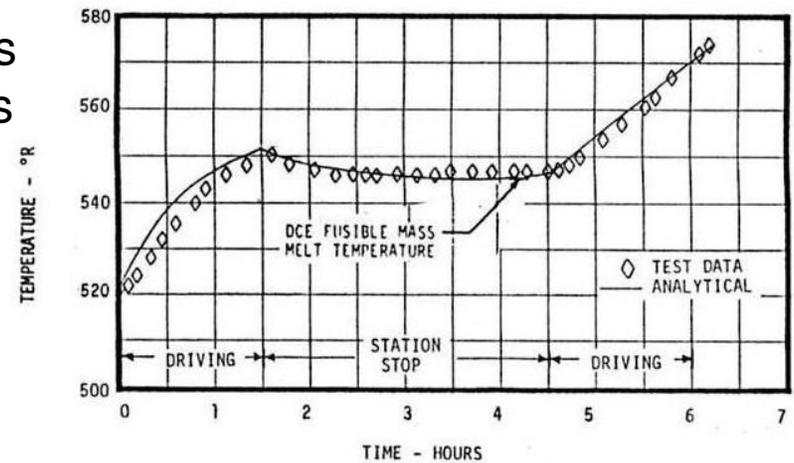
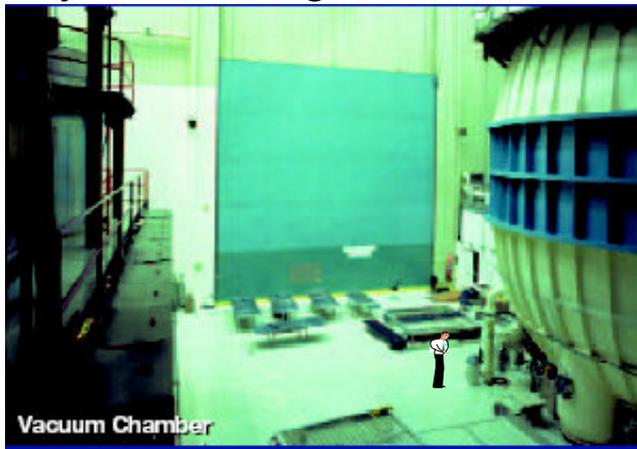
Radiated Infrared

Reflectometers Used to Measure Properties for Clean Transit LRV Surfaces



# “LUROVA” Operational Thermal Computer Model

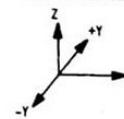
- Electrical Analogy - Capacitors And Conductors
- Verified By Correlating With Test Temperatures



DCE TEST DATA CORRELATION

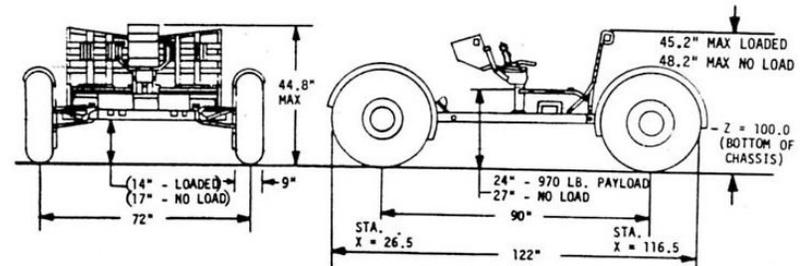
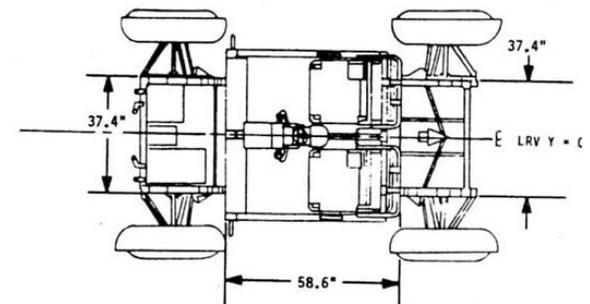
- Test Correlated Crew Station, Mobility, And Forward Chassis Models Combined Into “LUROVA” Operational Model
- Allowed Analysis For Clean Transit, Lunar Surface Dust Degradation, And Sortie Traverse Variations
- Detailed Model -177 Nodes (Capacitors) And Thousands Of Conductors
- Cumbersome And Limited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

AXIS REFERENCE



(DEPLOYED, EMPTY)  
WEIGHT = 462 LB.

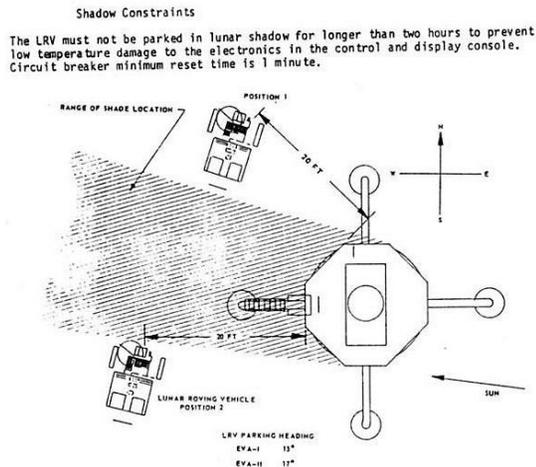
C.G.  
X = 52.8 LB.  
Y = -0.3 LB.  
Z = 103.1 LB.



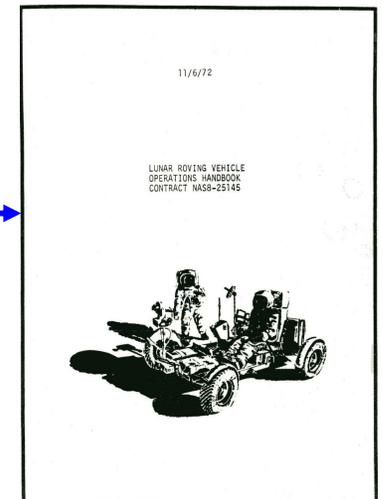
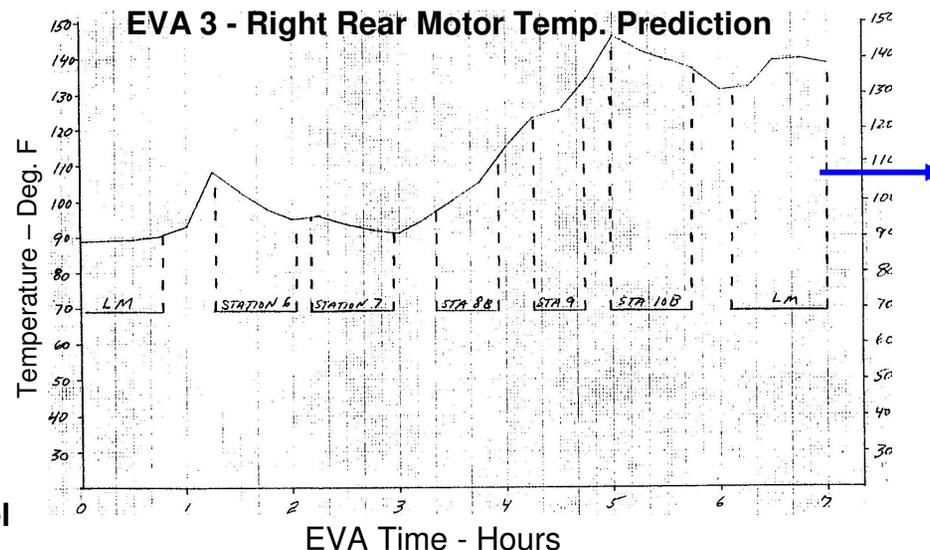
# Detailed LUROVA Thermal Computer Model Used First for Apollo 15 Mission Support



- Test Correlated Crew Station, Mobility, and Forward Chassis Models Combined Into Detailed “LUROVA” Operational Thermal Model
  - Electrical Analogy - 177 Nodes (Capacitors) and Thousands of 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
- Allowed Analysis For Clean Transit, Lunar Surface Dust Degradation, And Sortie Variations
- Cumbersome And Limited To Pre-EVA Predictions Using Univac 1108 Mainframe Computer



“Wireframe” Plot of Surface Model



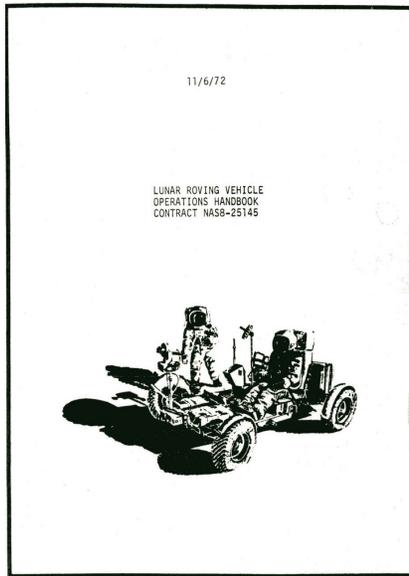
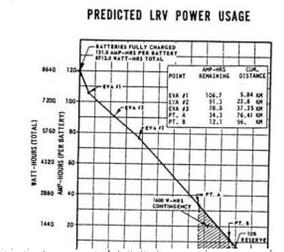
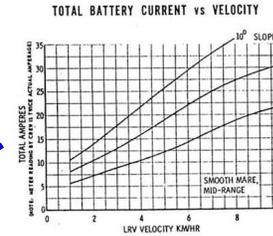
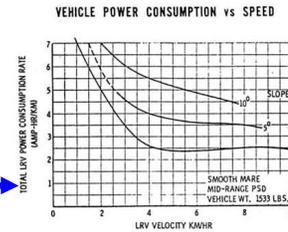
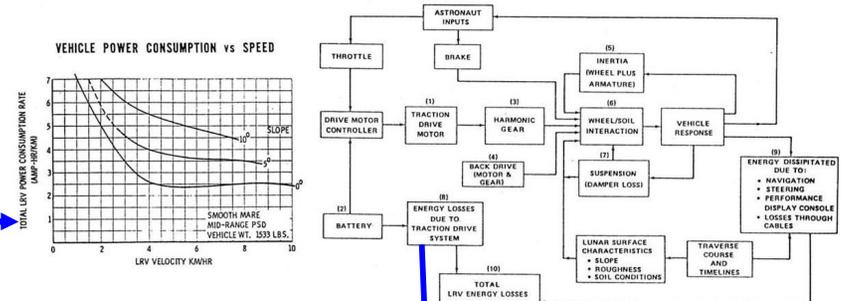
Predictions For Mission  
Operations Handbook

# LUROVA Thermal Computer Model Operational Flow

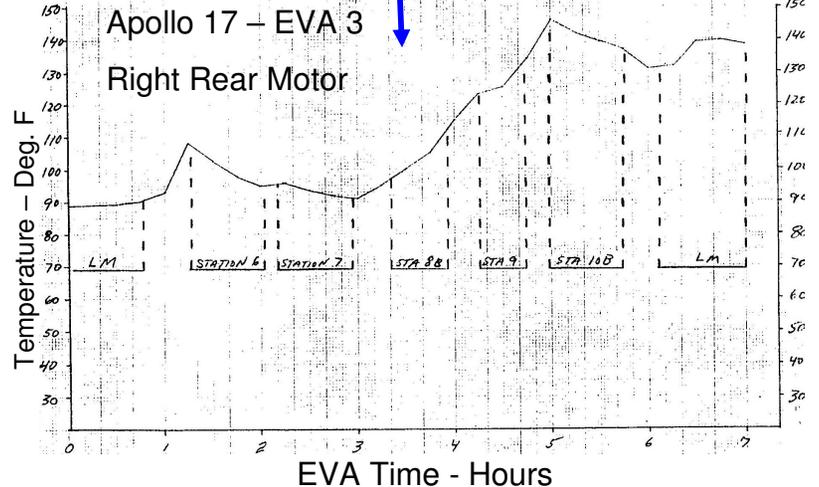
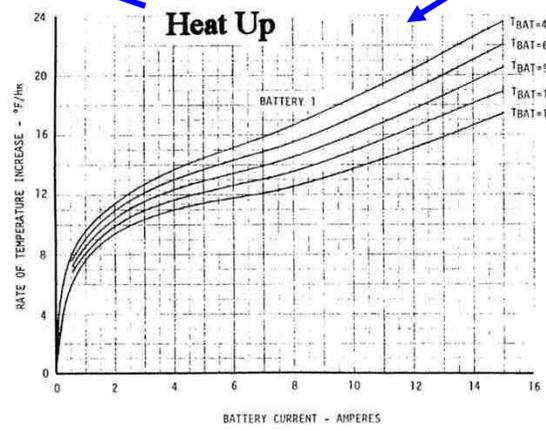
Traverse Team Provided Driving Parameters



Power Profile Provided Internal Heat



Predictions For Mission Operations Handbook

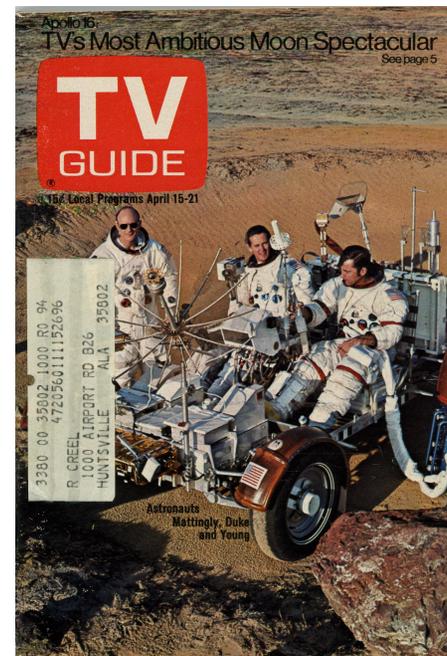
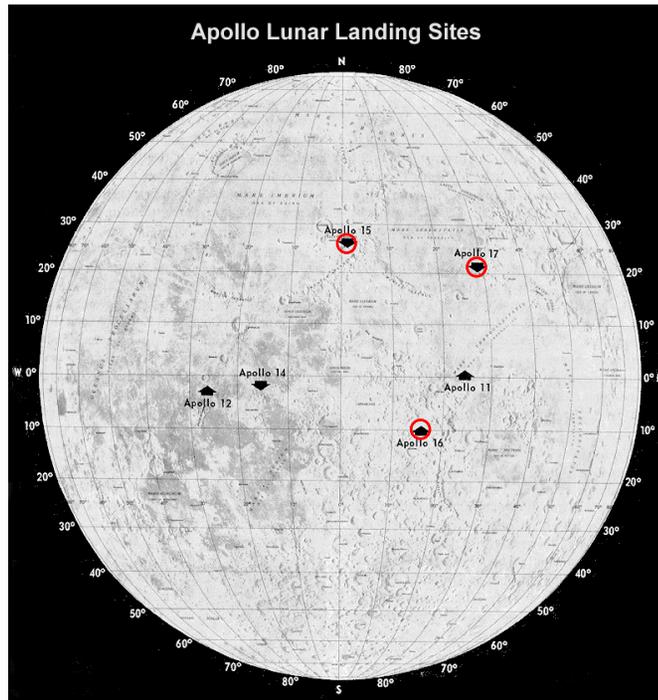


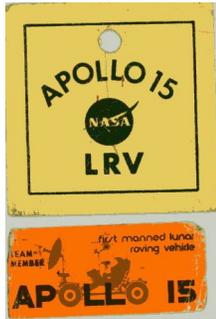
- LUROVA Used To Predict Crew Station, Forward Chassis, Mobility Temperatures

# LRV's On The Moon



PRIME CREW OF NINTH MANNED APOLLO MISSION  
 DAVID R. SCOTT      ALFRED M. WORDEN, JR.      JAMES B. IRWIN





# 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

MOBILITY PERFORMANCE  
OF THE LUNAR ROVING VEHICLE:  
TERRESTRIAL STUDIES - APOLLO 15 RESULTS

by Nicholas C. Costes, John E. Farmer,  
and Edwin B. George

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Ala. 35812

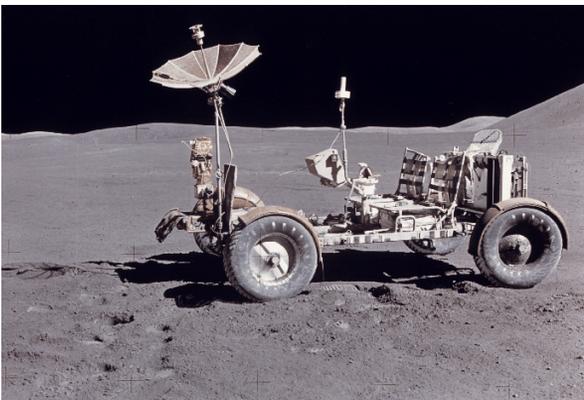
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1972

## LUNAR ROVING VEHICLE NAVIGATION SYSTEM PERFORMANCE REVIEW

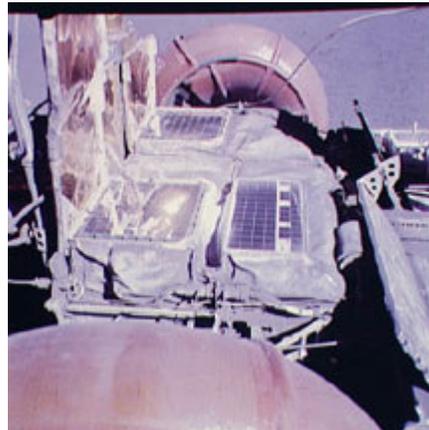
by Ernest C. Smith and William C. Mastin

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Ala. 35812

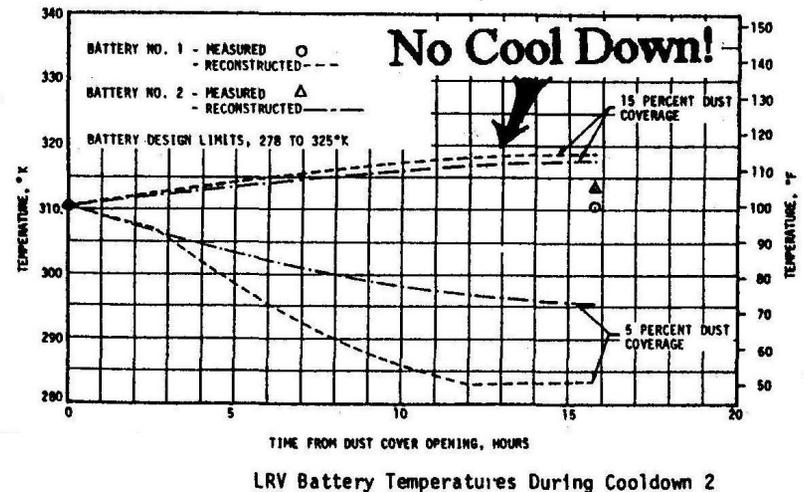
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1973



Missing Front Fender Extension



Dust On Radiators



# Post Apollo 15 – Astronauts Visited Huntsville, AL



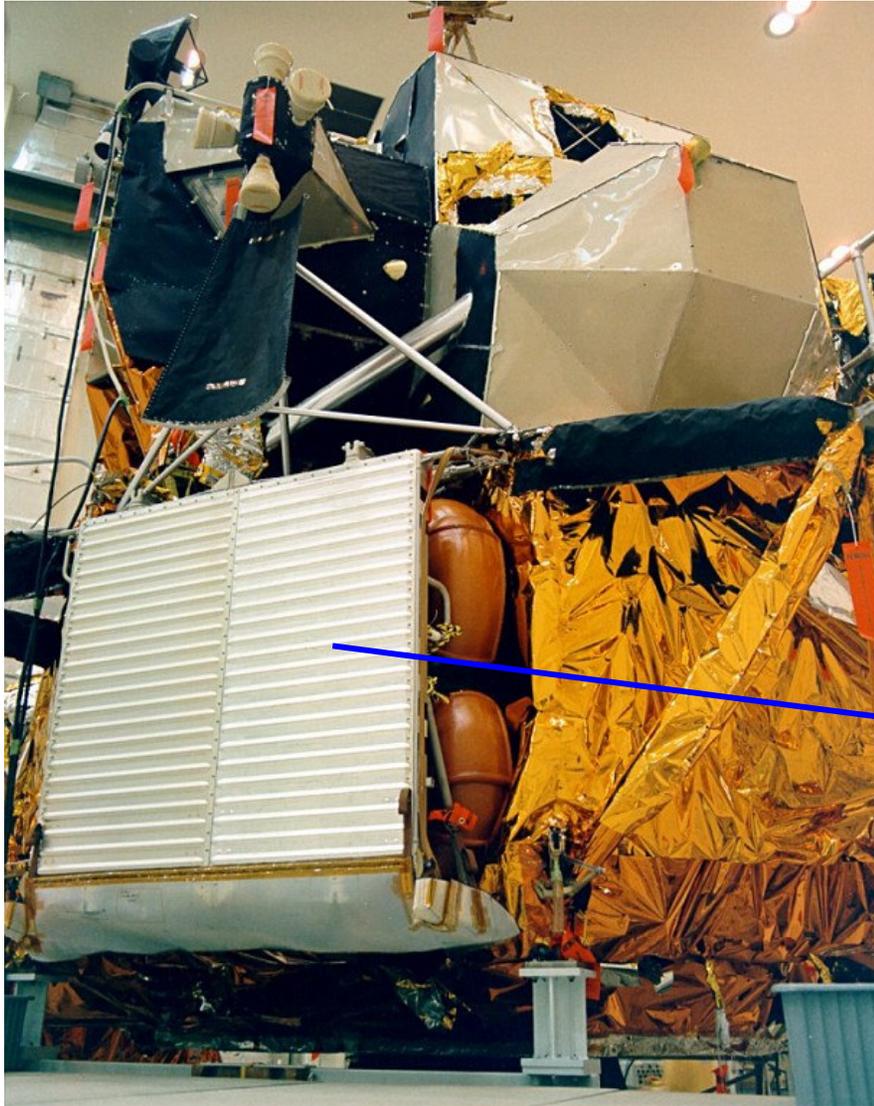
Sonny Morea, LRV Program Manager,  
Presents LRV Memento To Apollo 15 Crew

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



Many Autographs Were Graciously Signed And Cherished Souvenir Photographs Were Taken

# Post Apollo 15 – Floor Panel Tape Cleaning Agent



**Thermal Control Tape On Center Chassis Panels**

- Adhesive Residue On Panel Thermal Tape Contributed To Elevated Battery Temperatures At Deployment
- Toluene Shown As Best Cleaning Agent To Restore Thermal Properties



**Pre-Launch Tape Cleaning Procedure Adjusted**

# 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

LRV-3 REAL-TIME THERMAL ANALYZER  
INPUT MODE

```

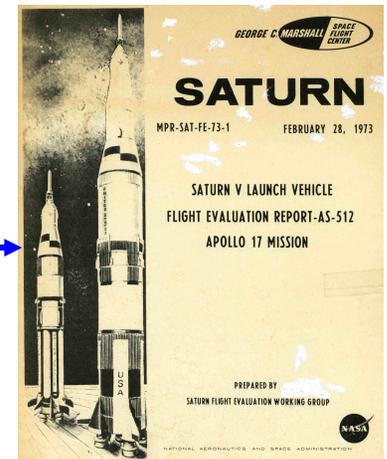
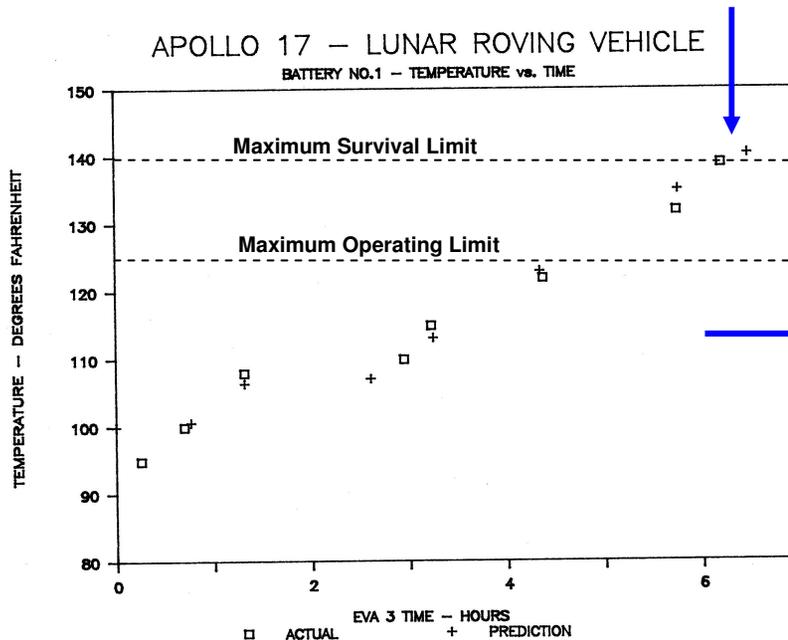
ACTUAL DATA *****
BEG DRIVE _____ EVA TIME _____
SEG DIST _____ OUT TIME _____
NAV ON _____ LCRU ON _____
BAT1 AMPHR _____ BAT2 AMPHR _____
BAT1 TEMP _____ BAT2 TEMP _____

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 _____
    
```



LRV Forward Chassis Components Modeled

roving\_ron@comcast.net



Mission Reports

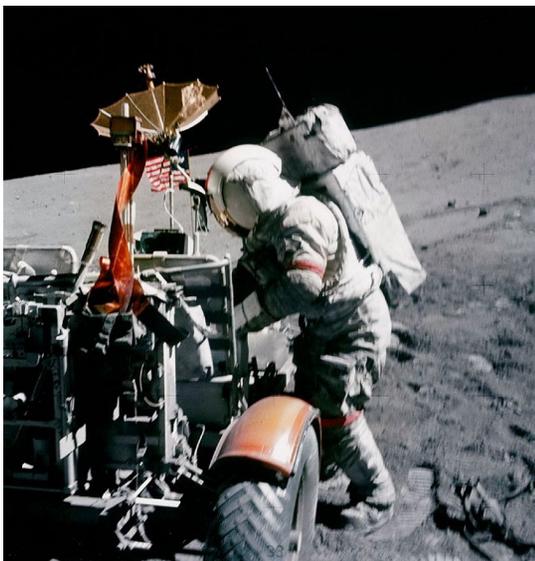
Excellent, Responsive Predictions Provided

# 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 Coolsdowns Between EVA's**
- Battery Power Switching Required
- **Max. Battery Temp. = 143 Deg. F On EVA 3**

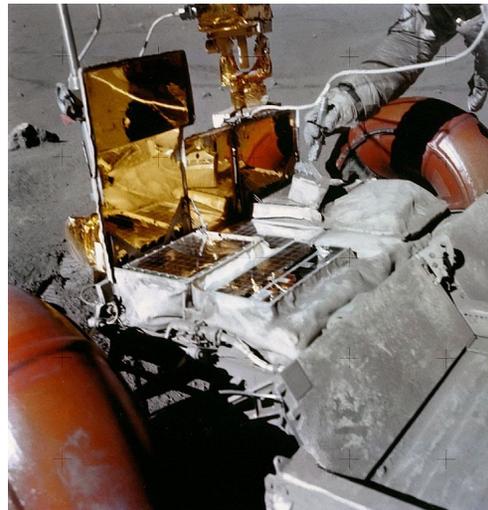


LRV Supplied LCRU, TV Power

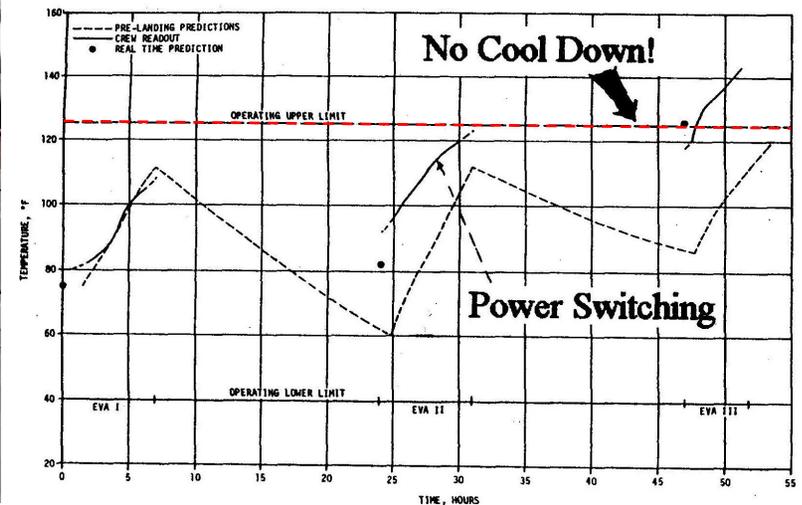


Missing Fender Extension

roving\_ron@comcast.net

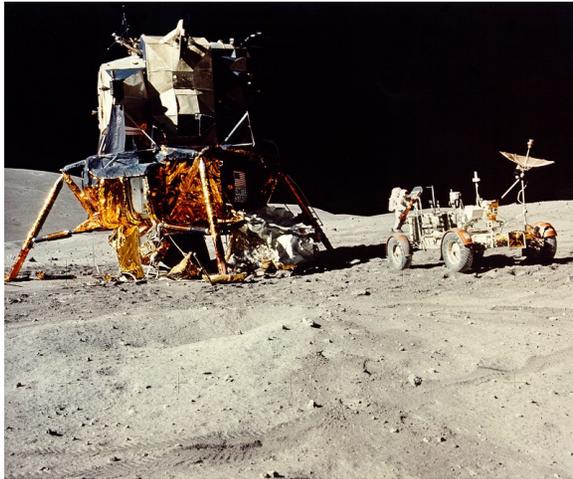


Astronaut Brushing Dust From Radiators



Battery No. 2 Temperature

# Post Apollo 16 – LM Parking Proximity Test



LRV Parked Too Close To LM



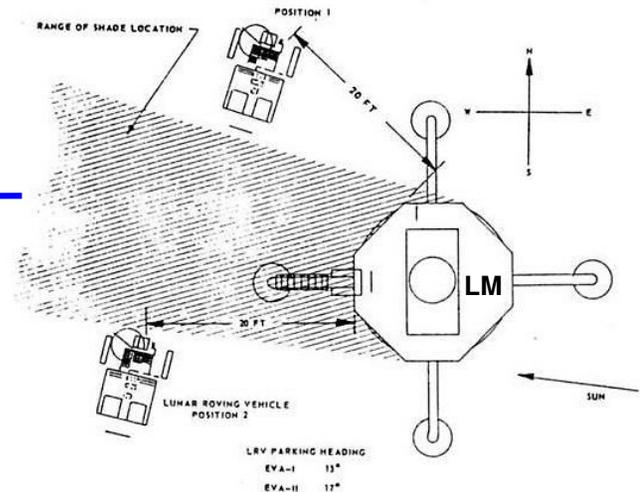
Battery Proximity Test At Space And Rocket Center



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

FWDCHA  
Computer  
Model

Shadow Constraints  
The LRV must not be parked in lunar shadow for longer than two hours to prevent low temperature damage to the electronics in the control and display console. Circuit breaker minimum reset time is 1 minute.



Parking Constraint Changed For Apollo 17

# 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 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.

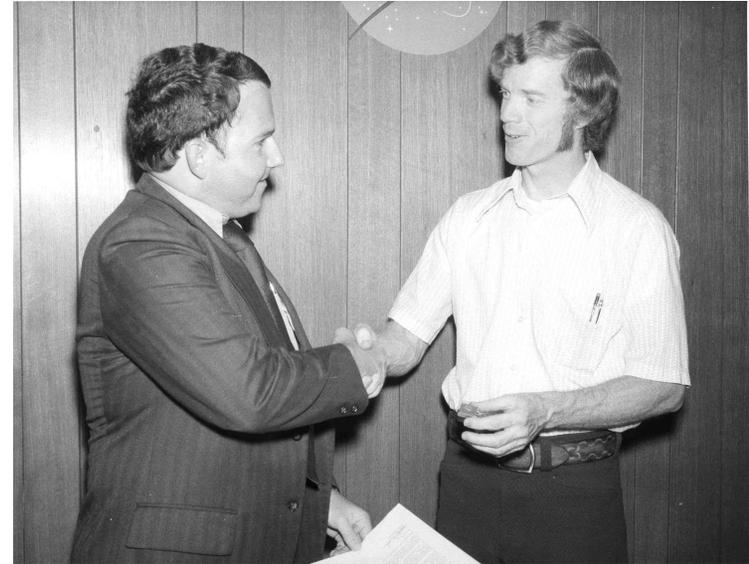
Best wishes for continued success.

Sincerely,

*Walter Duke*  
NASA Astronaut



Busy At LRV Thermal Model Control Console



Astronaut Rusty Schweickart Presents "Silver Snoopy"

APOLLO LAUNCH NO.: 17		LRV REAL TIME THERMAL PREDICTION/CORRELATION							PAGE: 217			
RUN NUMBER: 109	EVA: III	<input checked="" type="checkbox"/> EVA	ALPHA: L 0.35	ASSUMPTIONS: SEE PAGE							COV OPENED @ 6, 7, 8	
DATE: 12-13-72	SOL. EL. ANG. 34.5	<input checked="" type="checkbox"/> C/D	LCRU POWER: <input checked="" type="checkbox"/> LCRU									
START TIME: 11:10 P.M.	RAIL TEMP. 130	<input checked="" type="checkbox"/> LRV	<input checked="" type="checkbox"/> SEE ASSUM.									
COMPLETION TIME: 11:21		<input checked="" type="checkbox"/> NAV POWER:	<input checked="" type="checkbox"/> NOM									
		<input checked="" type="checkbox"/> P.M.	<input checked="" type="checkbox"/> SEE ASSUM.									
<input type="checkbox"/> CORRELATION	L. AMP HR/KM: 0.64	<input checked="" type="checkbox"/> BATT POWER:	<input checked="" type="checkbox"/> NOM									
<input type="checkbox"/> PREDICTION	R. AMP HR/KM: 0.64	<input checked="" type="checkbox"/> SEE ASSUM.	<input checked="" type="checkbox"/> SEE ASSUM.									
<input checked="" type="checkbox"/> REAL TIME		<input checked="" type="checkbox"/> NAV. TRIT.	<input checked="" type="checkbox"/> SEE ASSUM.									
WANDER FACTOR: 0.10		<input type="checkbox"/> SEE ASSUMPTIONS FOR AMP HRS. OR AMP HRS/KM	0 + 46									
STATION NUMBER	STATION TIMES		SEGMENT DISTANCE (km)	TEMPERATURES (°F)					WAX BOXES (% Melted)		AMP. HR L/R	
	Arrival	Departure		L. Batt	R. Batt	SPU	DGU	DCE	SPU	DCE		
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	100/126	
4. 7	2+36.5	2+58	0.88	107.1	126.4	113.7	155.4	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+20.5	5+30.5	2.75	123.0	137.1	132.6	163.0	96.0	1.00	0.00		
7. LM	5+45.5	6+25	2.95	135.0	144.5	144.5	170.1	116.2	1.00	0.00		
8. SEP	6+25.5	N/A	0.11	140.3	147.6	150.4	173.9	109.2	1.00	0.00		
9.	+	+										
10.	+	+										
11.	+	+										
12.	+	+										
13.	+	+										

Apollo 17 Astronauts Signed Final Thermal Log Sheet

# 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

# Apollo 17 – Transportation Thermal Control



A Stormy Night

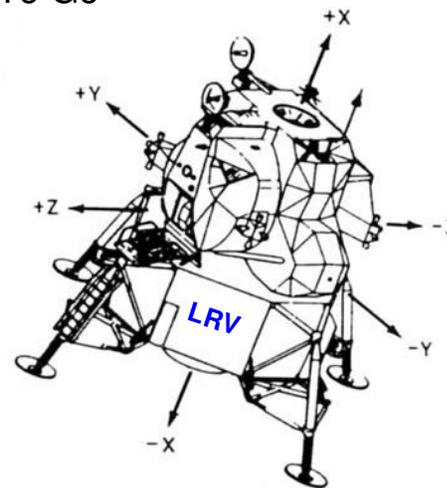


Ready To Go



Spectacular Nighttime Launch

- 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**



Flight Attitude Profile Received Daily From Houston



Stowed LRV Model

# Apollo 17 – LRV Thermal Control Performance

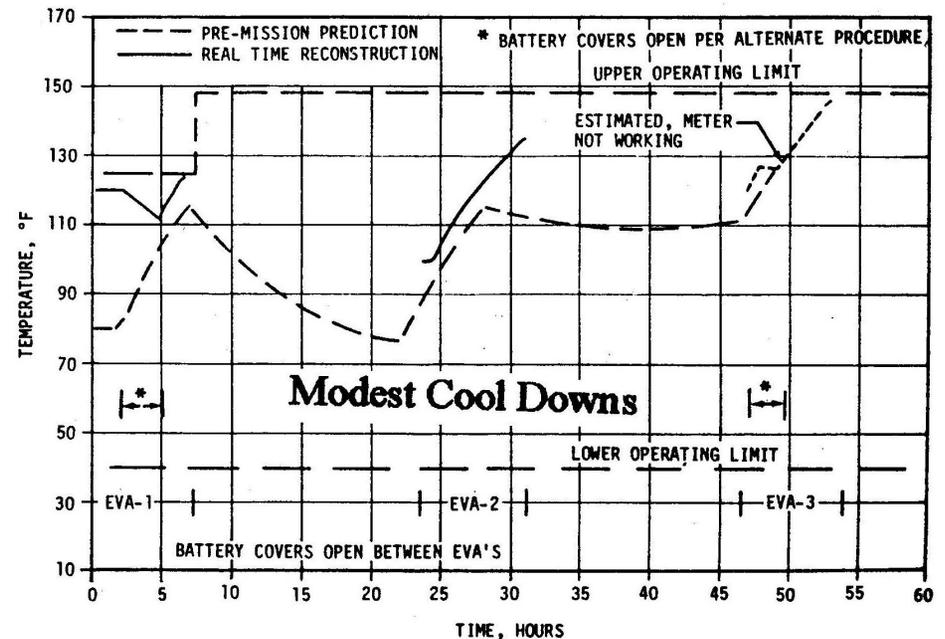
- Improved FWDCHA For Mission
- Max. Motor Temp = 270 Deg. F
- **Hot Batteries At Power-up (95, 110 F)**
- Covers Opened On EVA's 1, 3
- Fender Fixed Before EVA 2
- Modest Battery Cooldowns
- Max. Battery Temp. = 148 Deg. F



Astronauts Provided Fender Extension Fix



Covers Opened During EVA 1 (Also EVA 3)





# 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



LRV Mission Control At Huntsville Operations Support Center (HOSC)

roving\_ron@comcast.net



Extravehicular  
Activity  
Office

## Lunar Dust Degrades Capabilities



- Apollo astronauts cited multiple problems caused by lunar dust
- Dust degradation effects can be sorted into categories
  - Vision obscuration
  - False instrument readings
  - Loss of foot traction
  - Dust coating and contamination
  - Seal failures
  - Clogging of mechanisms
  - Abrasion of materials
  - Thermal control problems
  - Inhalation and irritation risks
- **Lunar dust properties which cause these effects must be understood, simulated, and mitigated if AEVA systems are to operate effectively**



Dust Free



Dust Covered

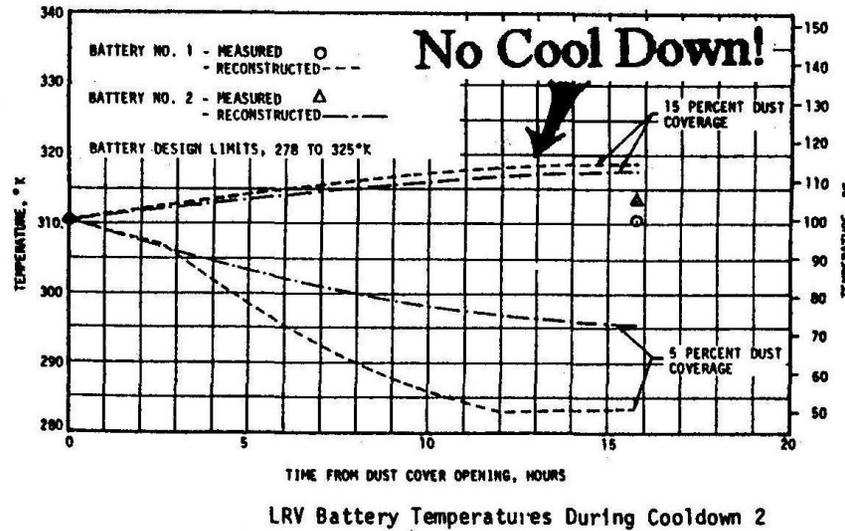
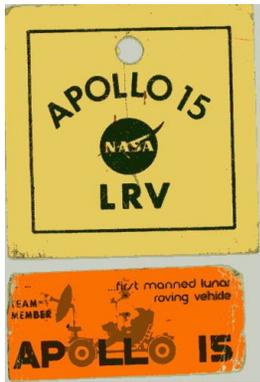


J. G. ...  
1968

Advanced Extravehicular Activity Dust Effects  
Summary Prepared For 2005 Lunar Regolith  
Simulant Material Workshop At MSFC

# Future Moon Rover Challenge 1 – Mitigate Bad Effects Of Dust

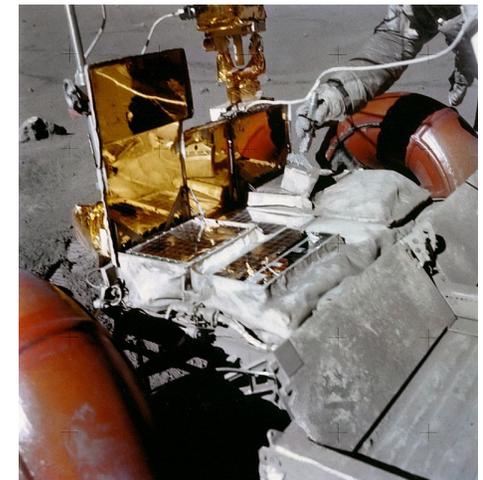
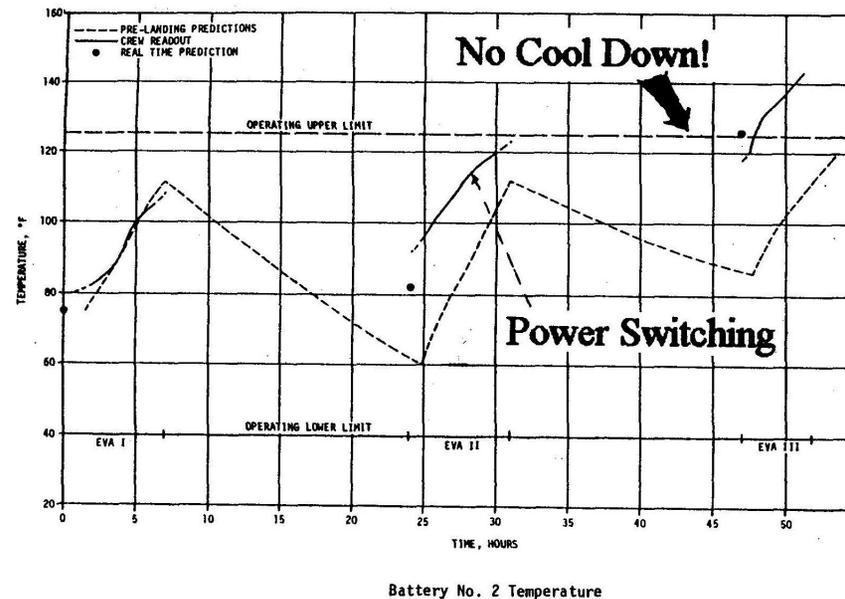
- Dust On Apollo LRV's Severely Reduced Battery Cooledowns – Brushing Radiators Was Ineffective
- Based On Cumulative Dust Effects, Astronauts Stated That They Doubted Longer Missions Possible



Dust On Radiators



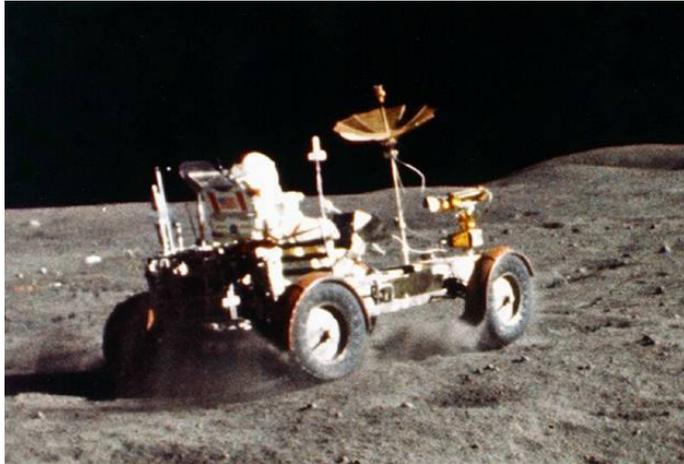
Apollo Dust Brush



Astronaut Brushing Dust From Radiators

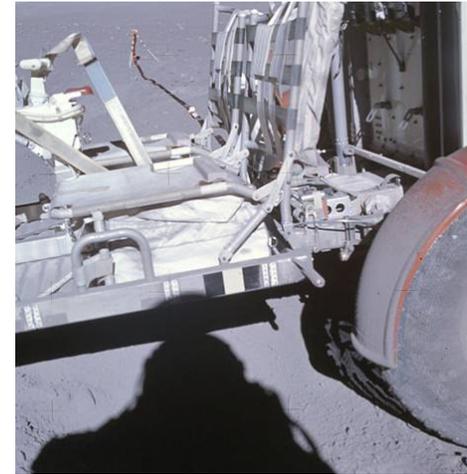
# Lunar Mobility Thermal Experience Lesson Learned

## Lunar Dust Contamination



Rover Checkout Drive

Apollo 16  
Photos



Dust on Rear Fender

- Lunar dust solar absorptance,  $\alpha = 0.93$ 
  - Dust coverage increases radiator heat absorption which increases the rejection temperature
- Stationary or unmanned installations may remain dust free
  - Corner mirrors left by Apollo missions are still reflective
- Mobile 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

# 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



V3 Astronaut Interface Thermal Vacuum Chamber



1A, 1C

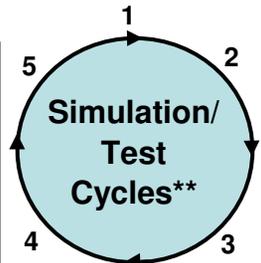
AZ Technology LPSR-300 Portable Optical Property Measurement Equipment

**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**

**Return Chamber to Ambient**



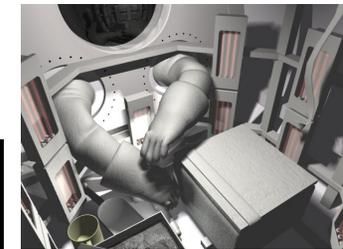
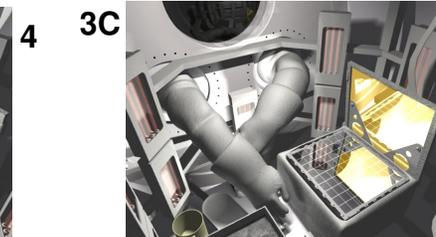
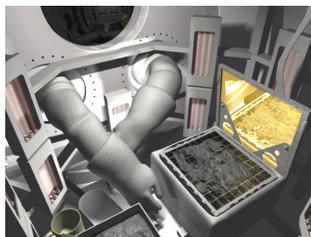
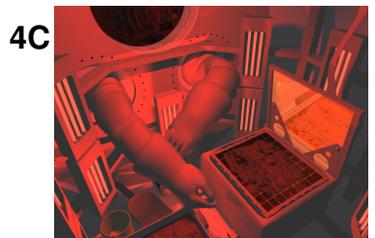
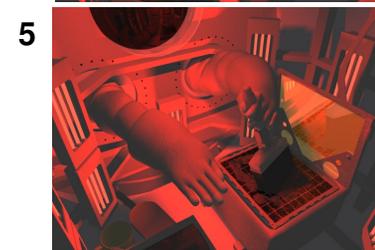
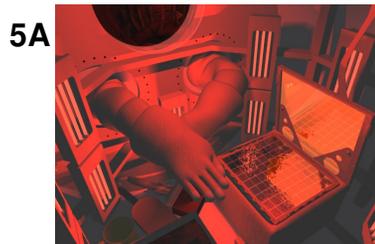
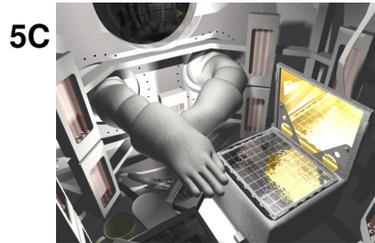
\*\* Several Proposed Mitigation Techniques

**5- Radiator Cleaned\*\***  
A- Heaters On Calibration  
B- Model Correlation  
C- Heaters Off Calibration  
D- Model Correlation

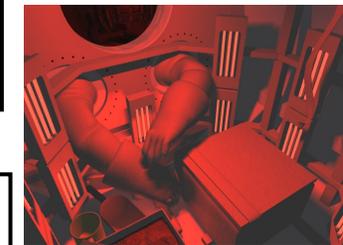
**2- Cover Closed**  
A- Heaters Off Calibration  
B- Model Correlation  
C- Heaters On Calibration  
D- Model Correlation

**4- Radiator Dusted**  
A- Heaters Off Calibration  
B- Model Correlation  
C- Heaters On Calibration  
D- Model Correlation

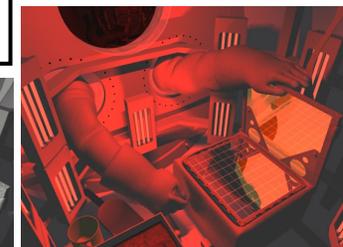
**3- Cover Opened**  
A- Heaters On Calibration  
B- Model Correlation  
C- Heaters Off Calibration  
D- Model Correlation



2A



2C



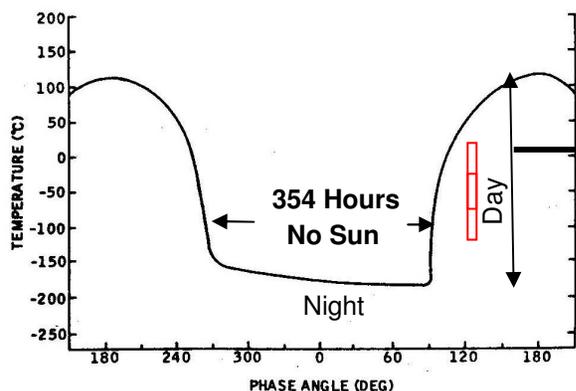
3A

# 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

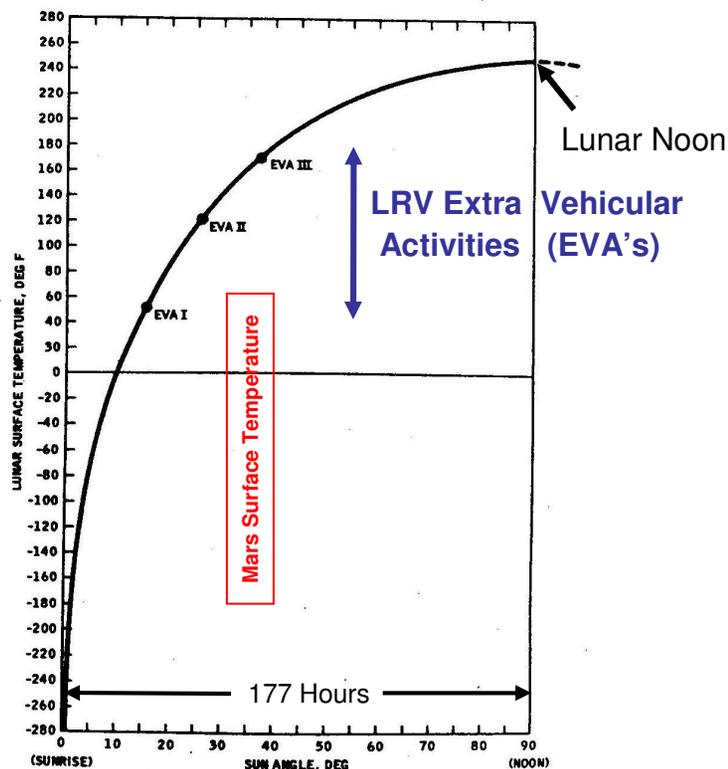


Temperature of the Moon. The average temperature of the Moon as a function of phase, or time, is shown here. The exact shape of the curve varies somewhat with geographical position on the Moon and is determined by the thermal properties at each position.

Extended Operation

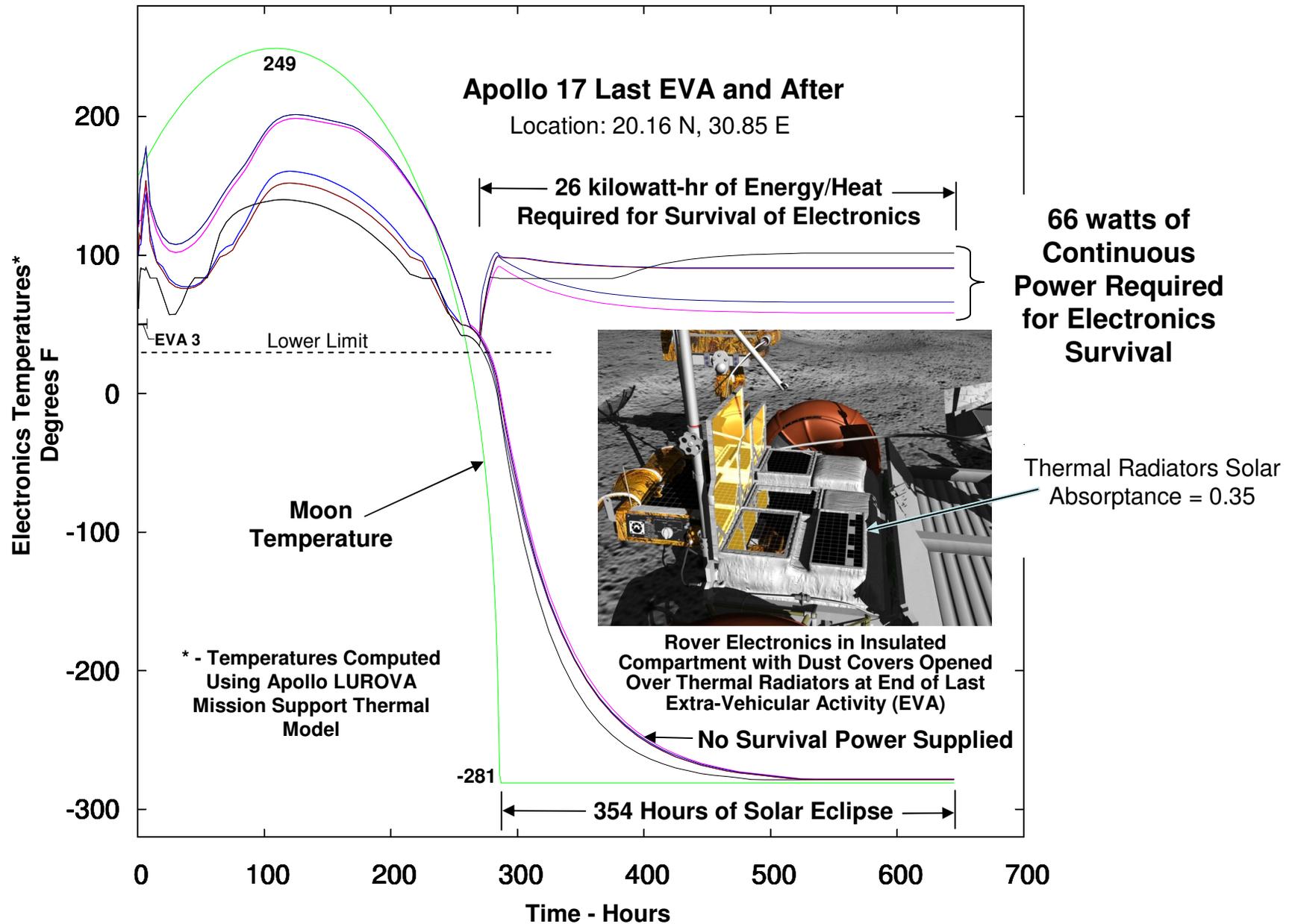
## Lunar Day

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



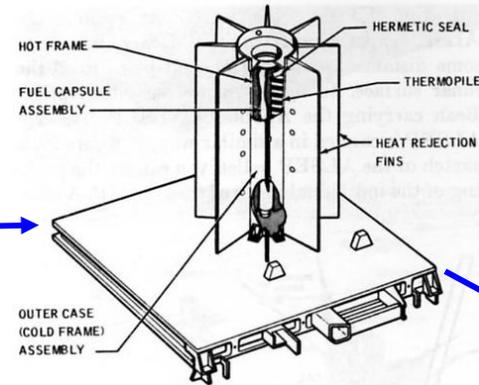
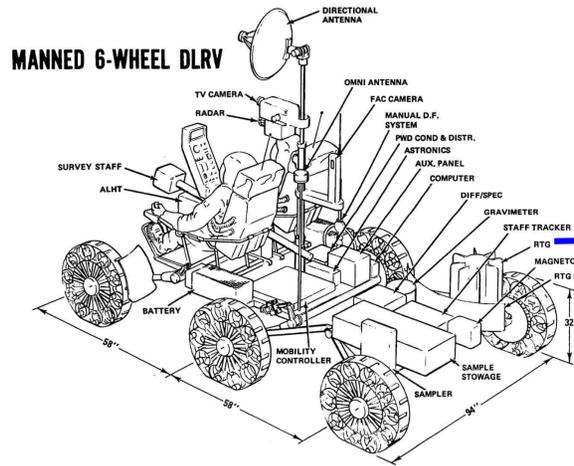
The temperature of the Taurus-Littrow site shown as a function of the Sun angle. Note that EVA 1 at +17° Sun angle should have +50° F, EVA 2 at +27° Sun angle should have +110° F, and EVA 3 at +37° Sun angle should have a temperature of +160° F.

# Apollo LRV- Power Needed for Extended Thermal Survival on Moon

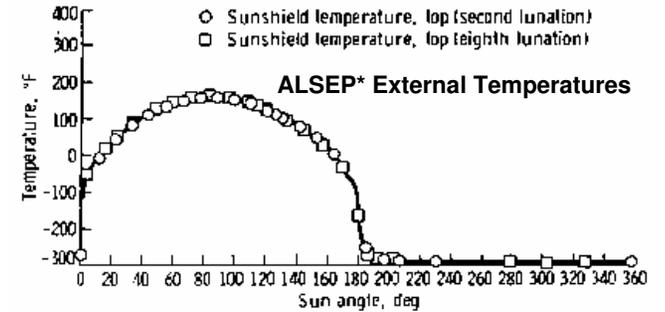


# Nuclear Energy Provides Dependable/Efficient Survival Power/Heat

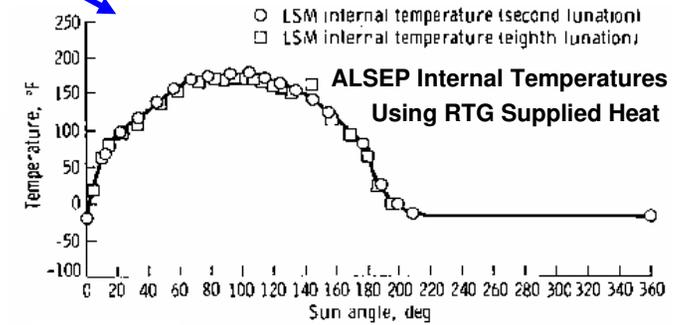
- Nuclear Sources Studied For U.S. Dual Mode Rovers (DLRV's), Used on Apollo



**SNAP-27 Radioisotope Thermal Generator.** This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.  
S-71-25730.



\*ALSEP = Apollo Lunar Surface Experiments Package



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

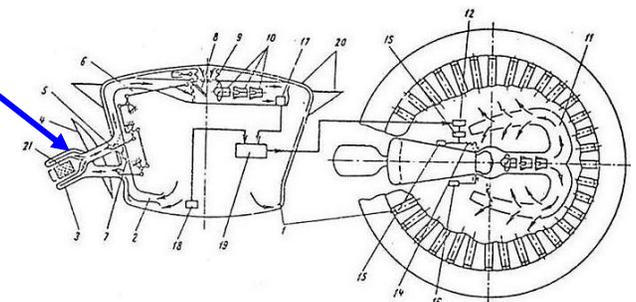
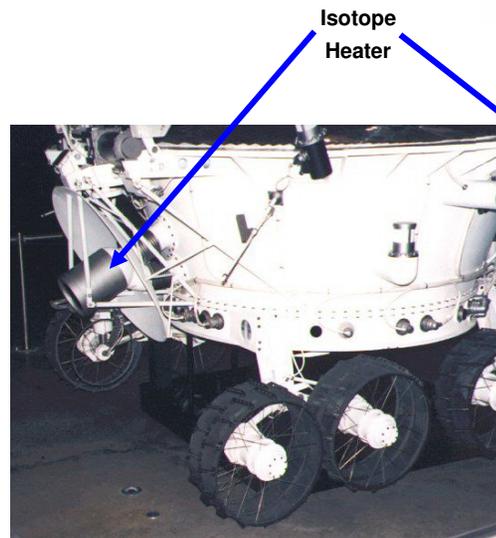
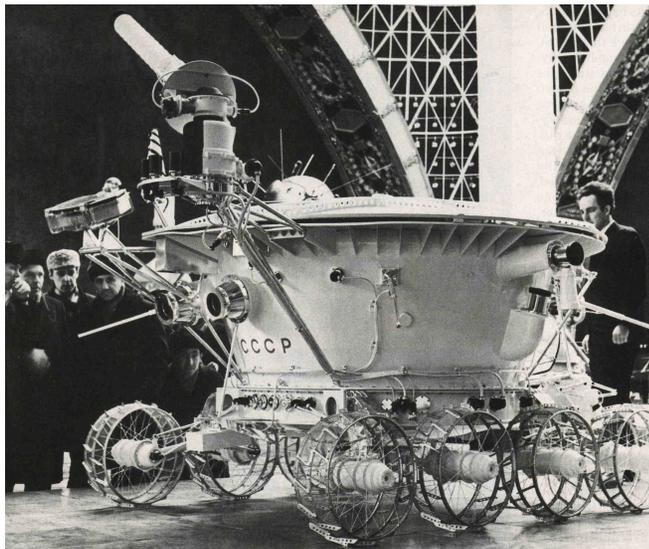


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism;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

# 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**



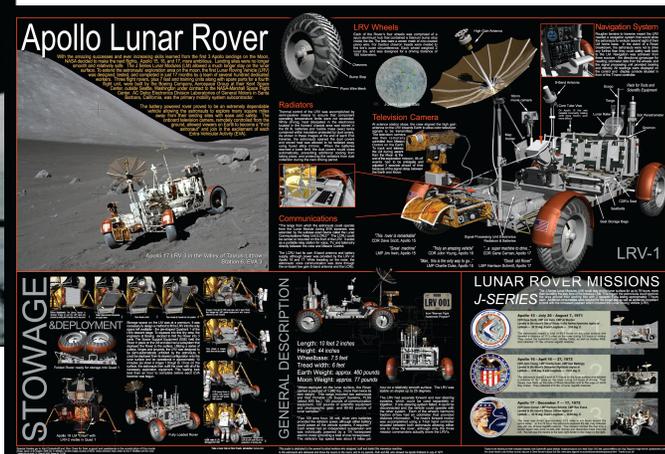
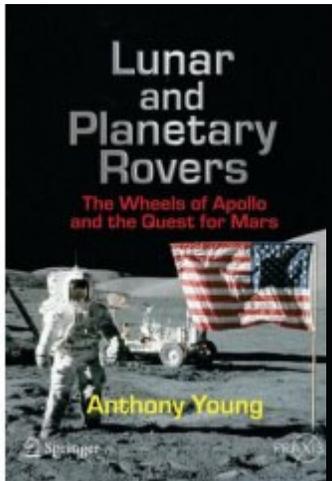
# Ron Creel is Busy Assisting NASA Robotics, Students With Moonbuggy Race, Rover Lectures, Book, Poster, & Developing LUROVA “Edutainment” 3D Simulation



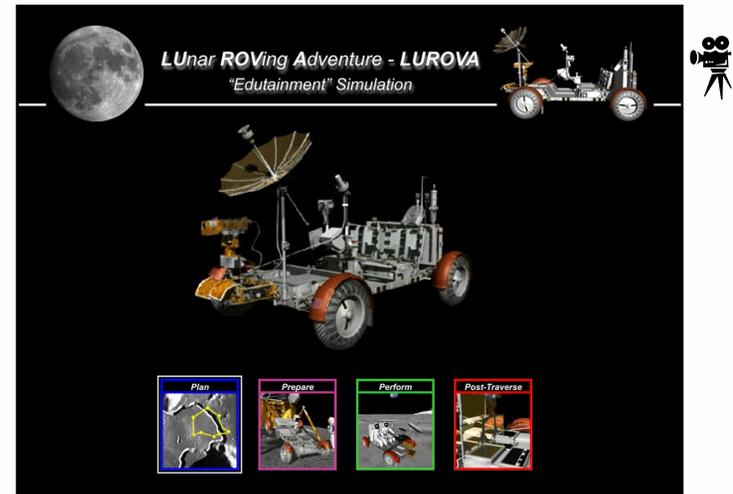
“Most Unique” Vehicle Judge And Added “Dust Challenge” For Great NASA Moonbuggy Race



Lectured and Judged USC “Lunar Design Studio” Project

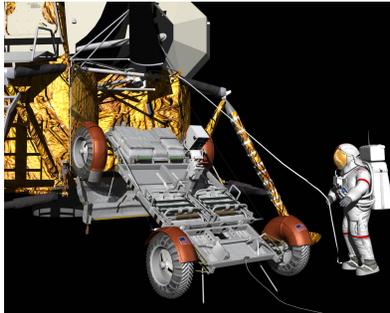


Helped Develop Apollo Lunar Rover Book and Poster



LUROVA Team Is Developing 3D Simulation To Challenge And Involve Students

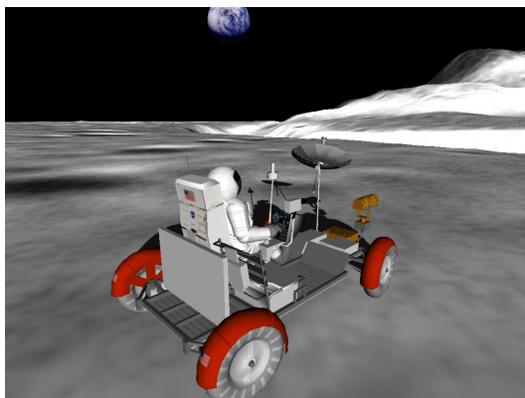
# Lunar ROVing Adventures “LUROVA” Simulation Being Developed For Student Challenge And Involvement



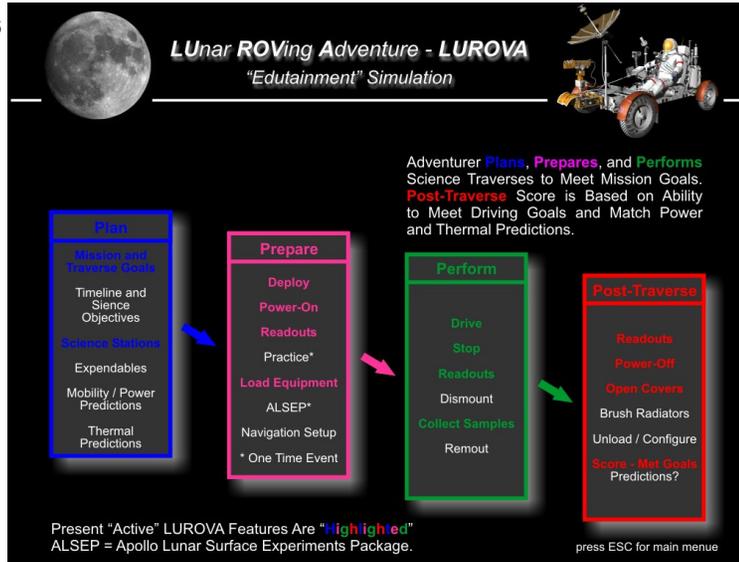
Student Deploys LRV From LM And Loads Equipment



Student Activates LRV Switches and Hand Controller For Driving



Student Drives “LUROVA”



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

- 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
- Includes 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

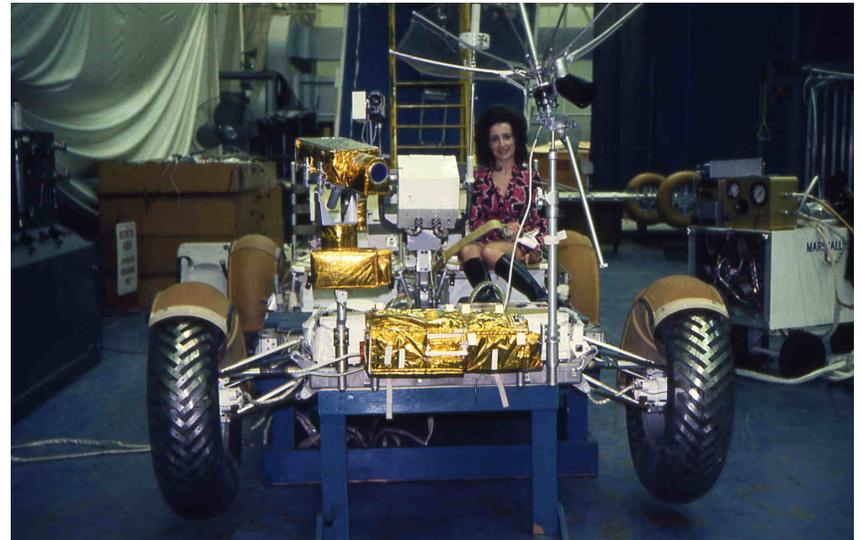
# Dedications

“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