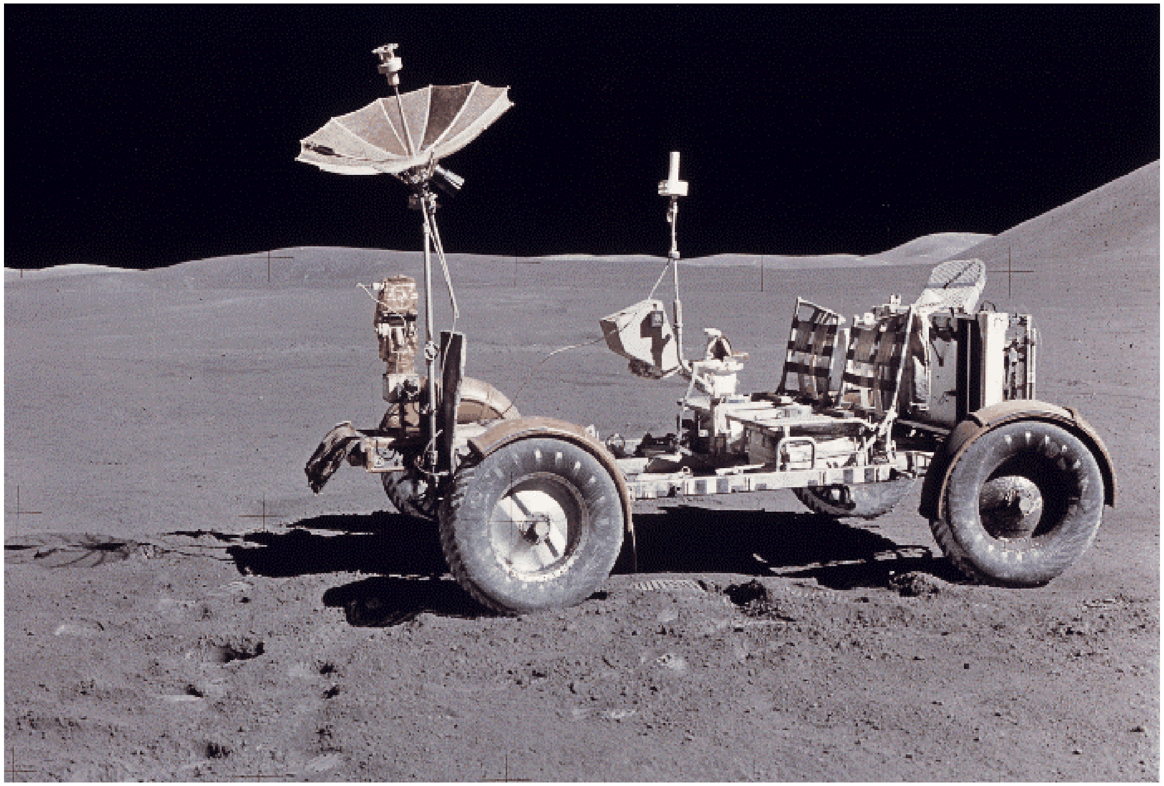
Apollo Rover Lessons Learned



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

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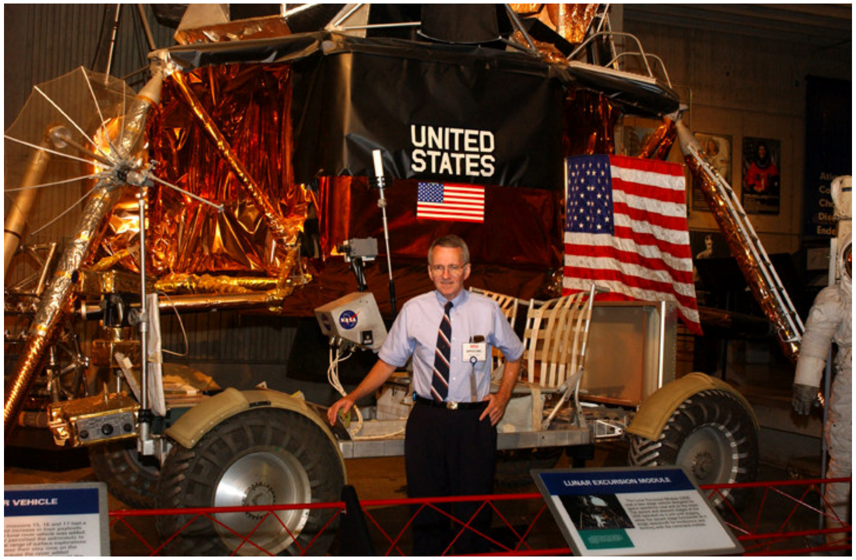
Introduction



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

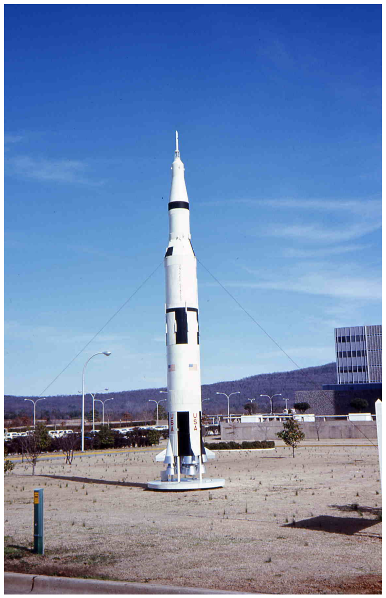
Outline

- 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

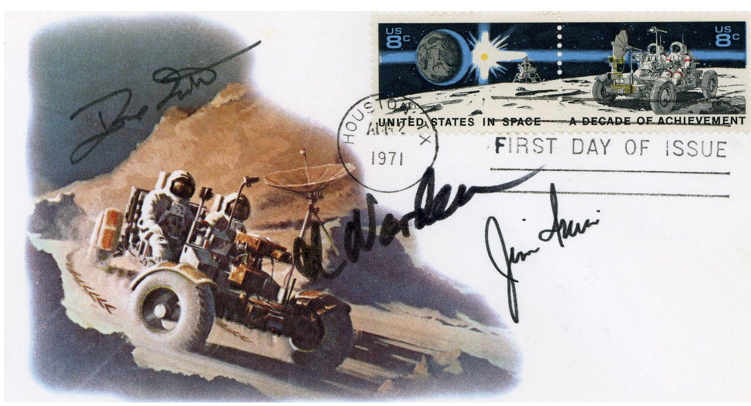
Movies Noted in Presentation

My Start In Space Engineering

- Sputnik Era Model Rocket Launches



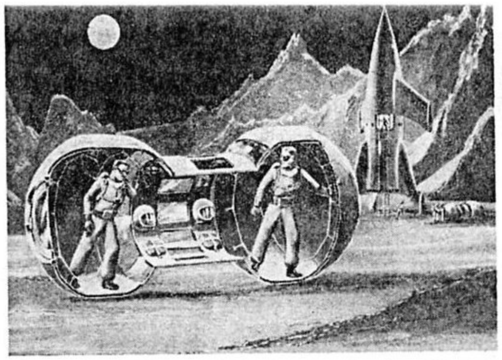
- Co-op Student At NASA Marshall Space Flight Center (MSFC)



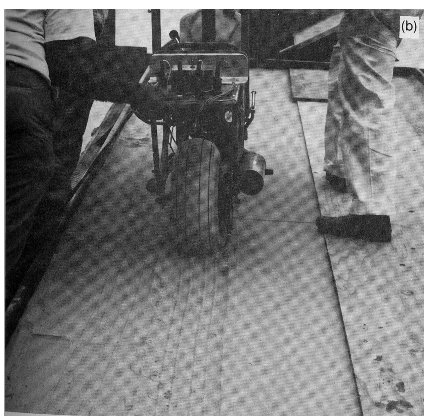
- Graduated And Assigned To Development Of Apollo Lunar Roving Vehicle (LRV) Thermal Control System

Rover Historical Concepts

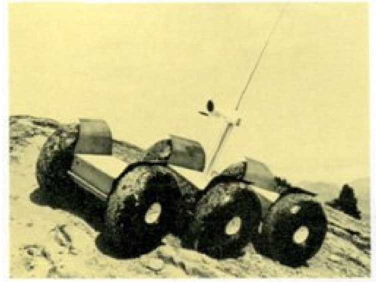
Unique Concepts Proposed



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

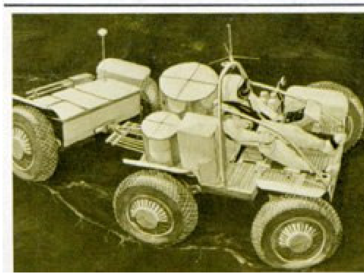


◁ Surveyor Lunar Roving Vehicle

MOLAB ▷

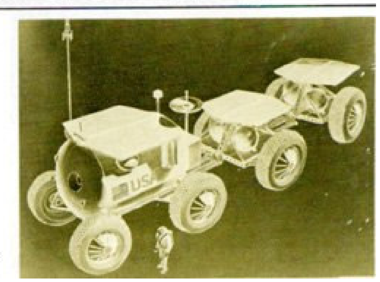
△ Mobility Test Article

△ Lunar Mission Development Vehicle



◁ Lunar Scientific Survey Module

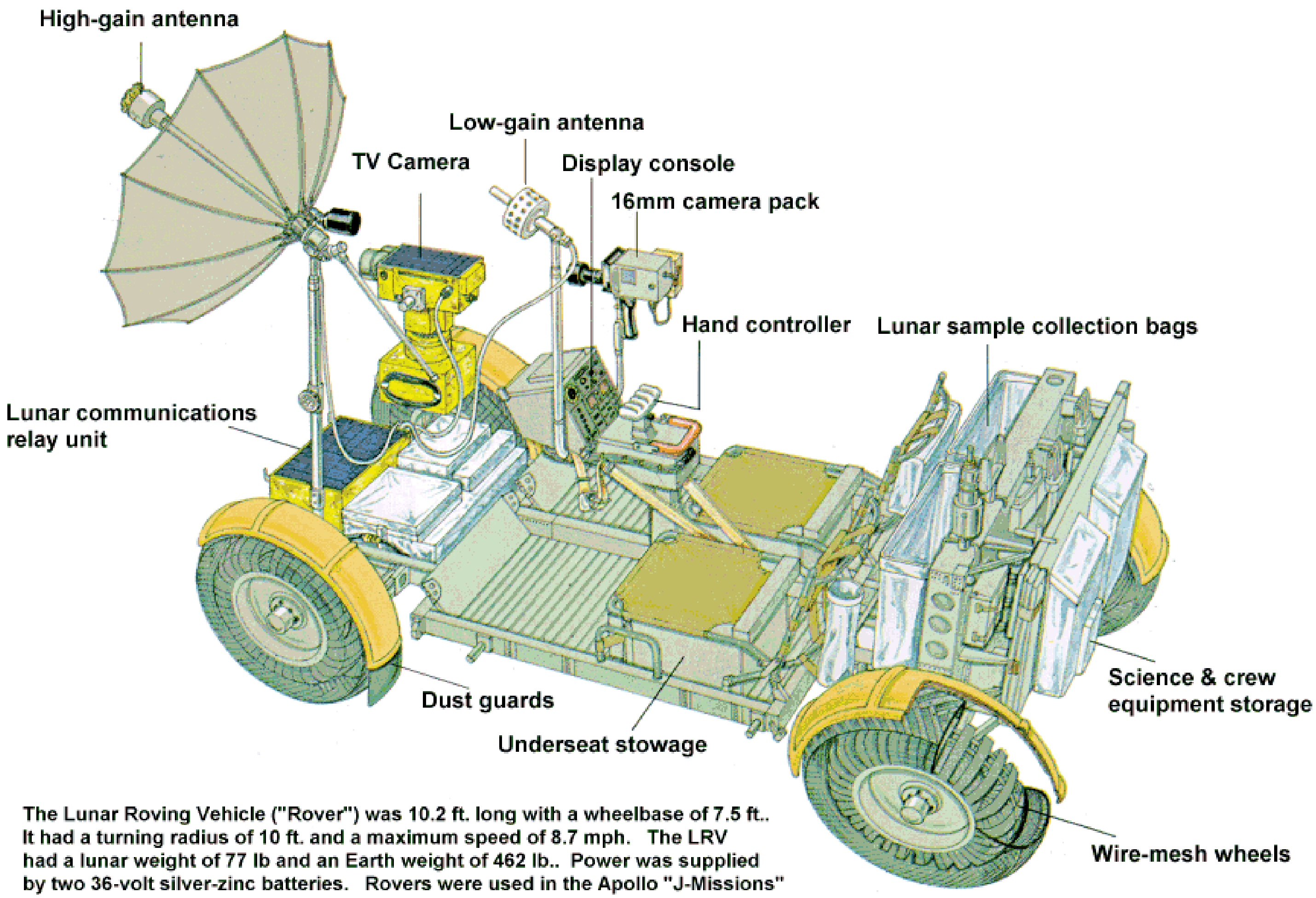
Lunar Vehicle Studies ▷



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

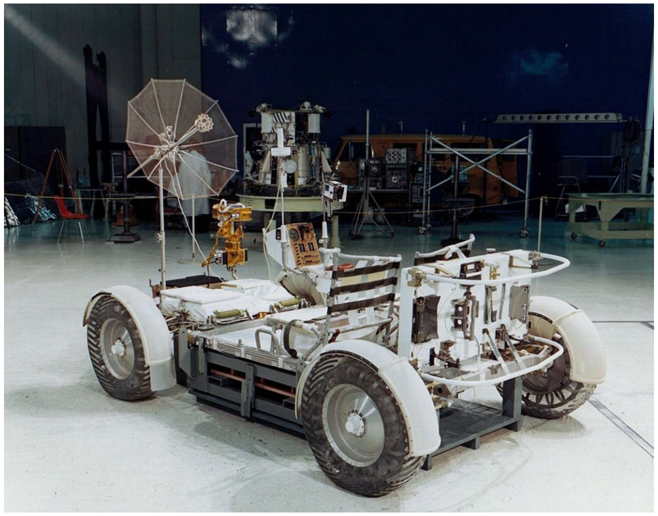
LRV Designed To Provide Extended Mobility On The Moon

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.

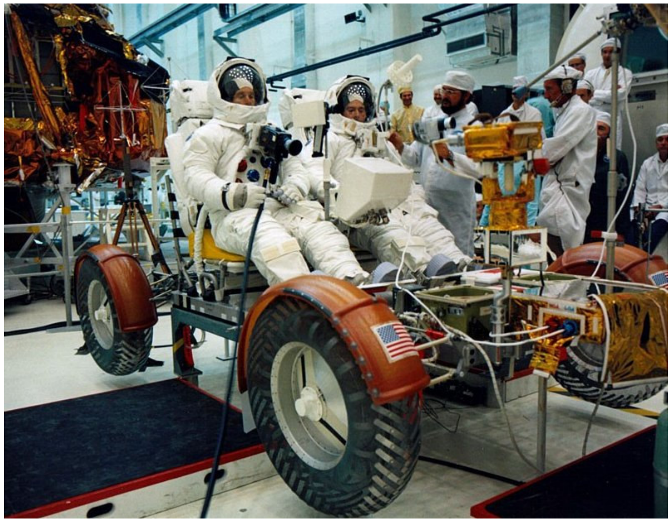
LRV's Greatly Increased Science Return From Apollo 15, 16, And 17



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

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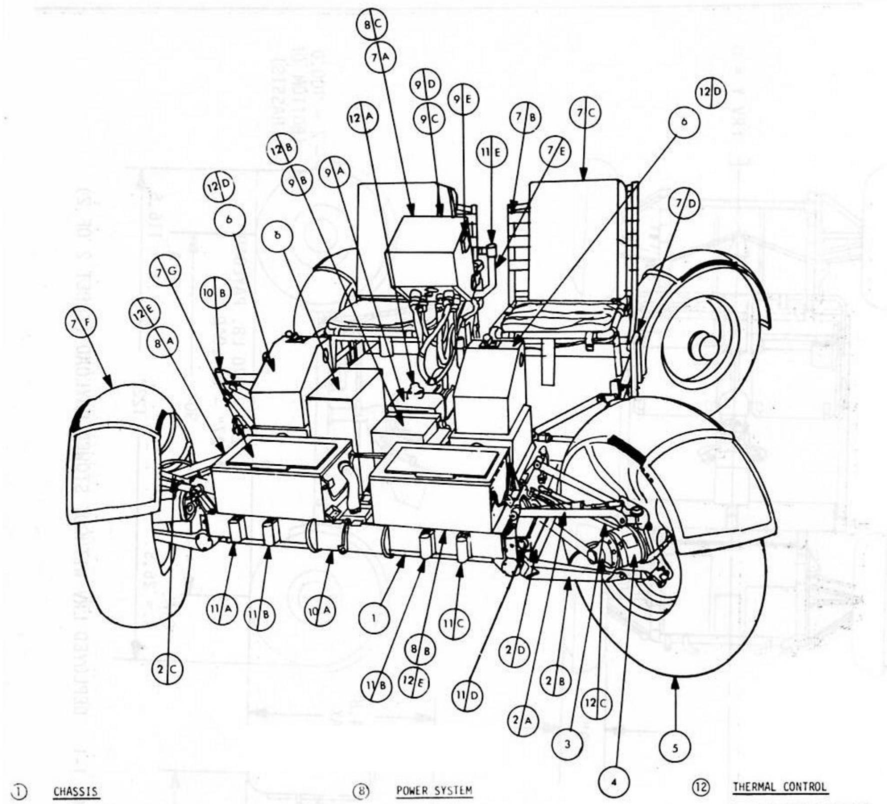
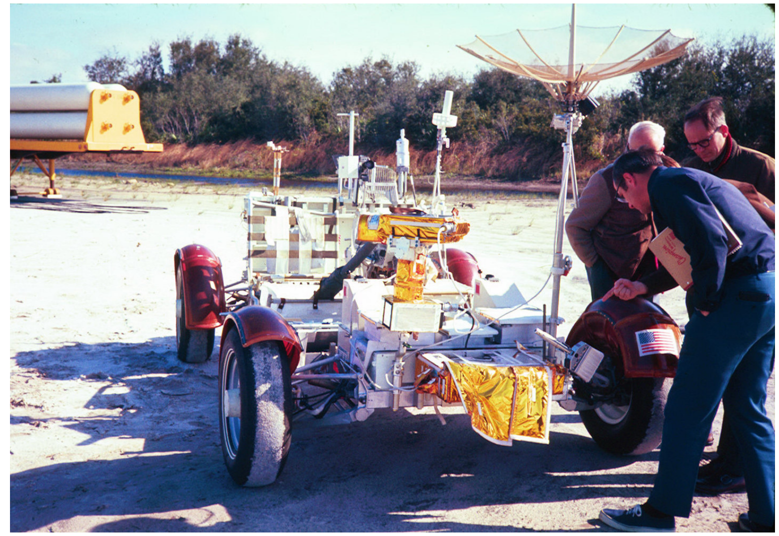
Thermal Control Of LRV “One-G” Trainer

Earth Operation Allowed Natural And Forced Convection Cooling



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



1G Trainer Provided Simulation Of All LRV Interfaces

Apollo 16 Astronauts With 1G Trainer At Kennedy Space Center

LRV Thermal Control Design Goal

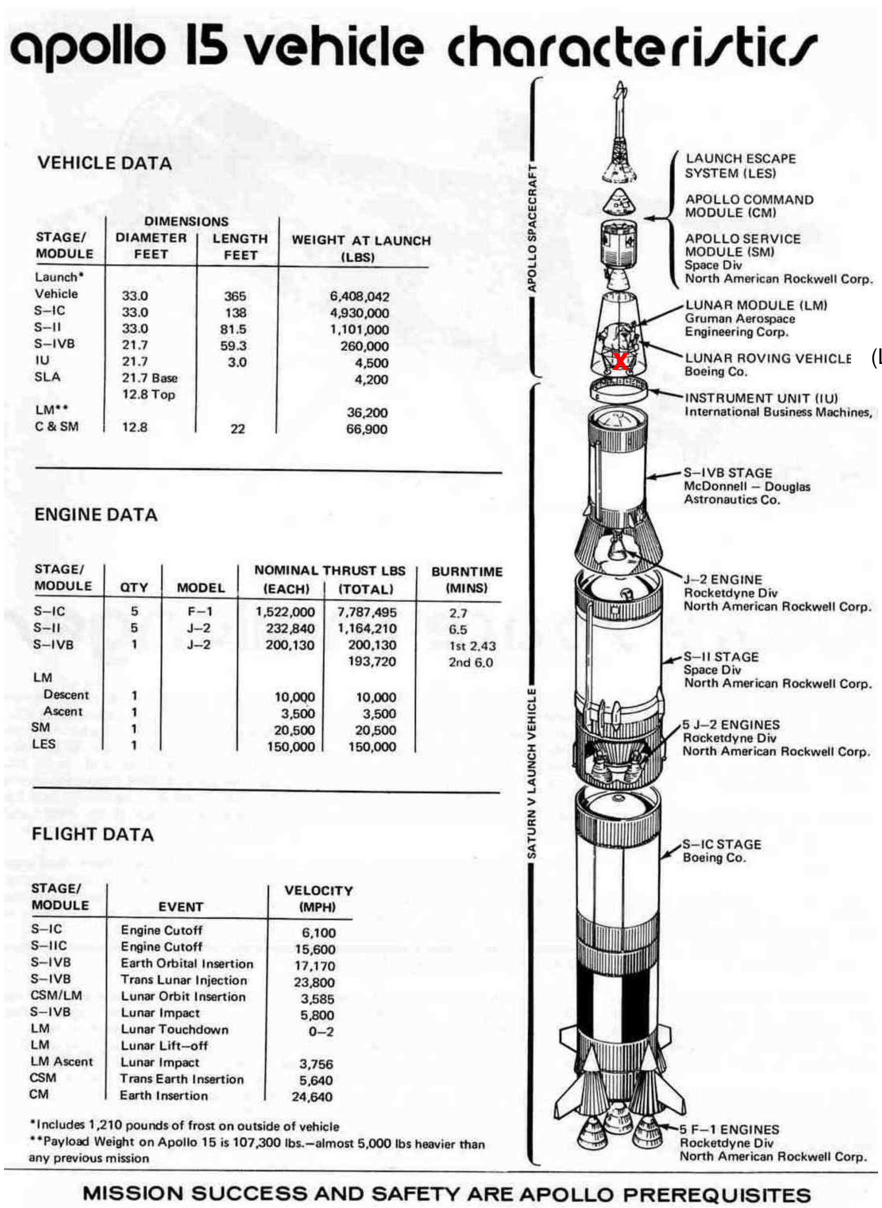
- Maintain LRV And Space Support Equipment (SSE) Within Prescribed Temperature Limits During:
  - Earth To Moon Transportation - Totally Passive
  - Lunar Surface Operation in 1/6 Gravity And Quiescent Periods Between Traverses
    - Minimize Astronaut Involvement, i.e. Primarily Passive
    - Mitigate Adverse Effects Of Lunar Dust

LRV Component Temperature Limits – Deg. F

	Component	Minimum Survival	Minimum Operating	Maximum Operating	Maximum Survival
Electronics	Batteries*	-15	40	125	140
Electronics	Signal Processing Unit (SPU)	-65	30	130	185
Electronics	Directional Gyro Unit (DGU)	-80	-65	160	200
Electronics	Indicating Meters	-22	-22	160	160
Electronics	Position Indicator	-65	-22	185	185
Electronics	Drive Controller Electronics (DCE)	-20	0	159	180
Mobility	Traction Drive**	-50	-25	400	450
Mobility	Suspension Damper	-70	-65	400	450
Mobility	Steering Motor	-50	-25	360	400
Mobility	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 DIAMETER FEET	LENGTH FEET	WEIGHT AT LAUNCH (LBS)
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 (EACH)	(TOTAL)	BURNTIME (MINS)
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	200,130 193,720	1st 2.43 2nd 6.0
LM					
Descent	1		10,000	10,000	
Ascent	1		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–IIC	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

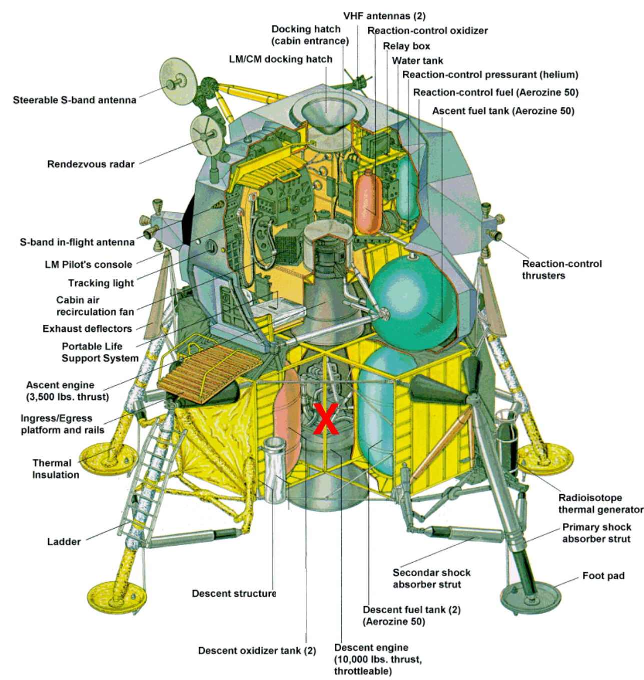
*Includes 1,210 pounds of frost on outside of vehicle
**Payload Weight on Apollo 15 is 107,300 lbs.—almost 5,000 lbs heavier than any previous mission

MISSION SUCCESS AND SAFETY ARE APOLLO PREREQUISITES

(LRV)

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

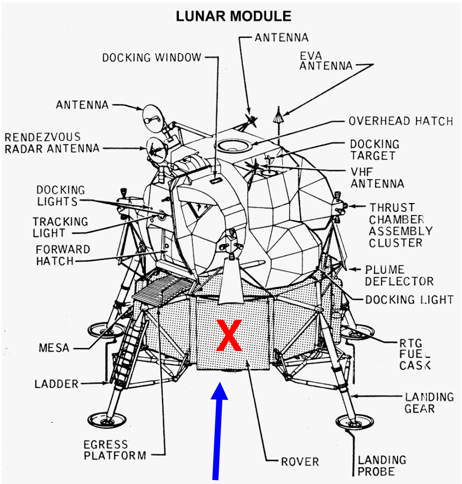
Apollo Lunar Module



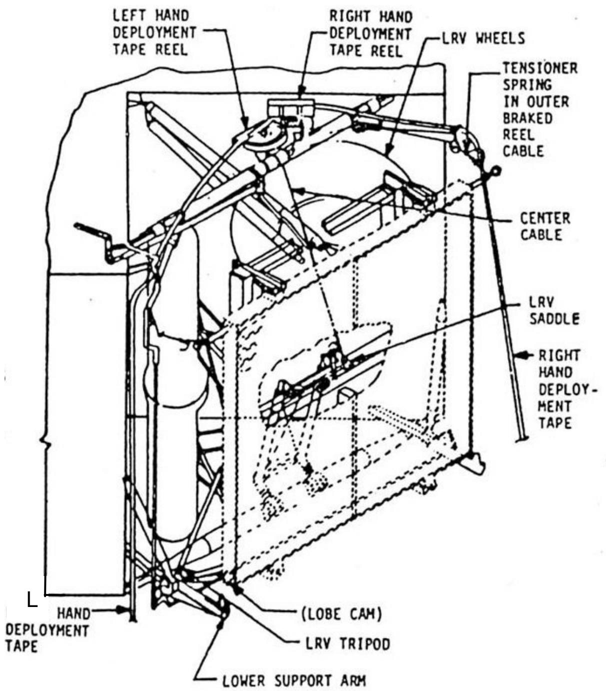
The lunar module was 23 ft. tall and had a launch weight of 33,205 lbs.
(The Apollo 17 J-Series lunar module weighed 36,244 lbs.)

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

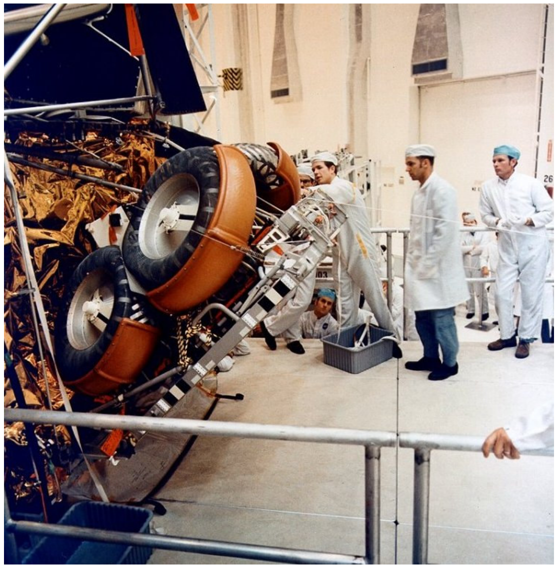
LRV Space Support Equipment (SSE) Thermal Control



Folded LRV And SSE Stowed In LM Descent Stage Quadrant 1



- Maintained SSE During Transit By Selection Of Surface Radiation Properties And Insulation And Protection From LM Reaction Control And Descent Engine Heating Environments

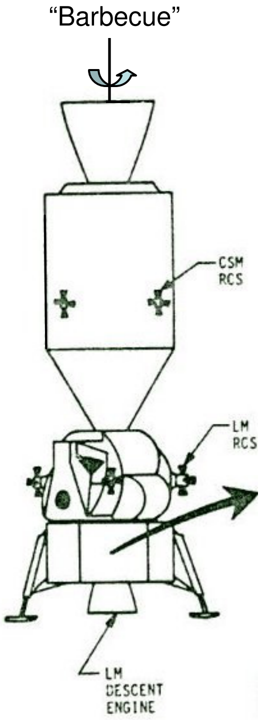


Apollo 15 Astronauts Inspect Stowed LRV And SSE

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

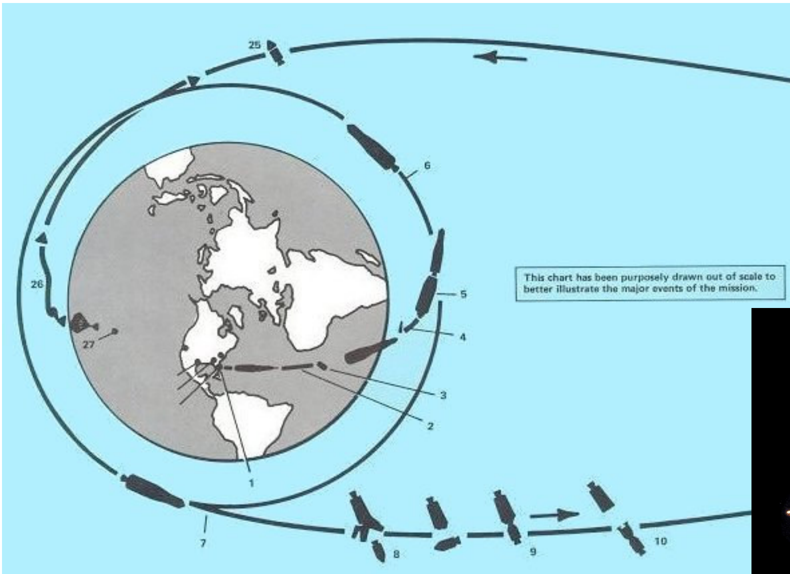
Folded LRV Stowed In Lunar Module With Floor Panels Removed For Battery Installation



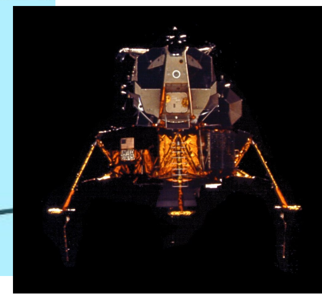
Folded LRV Stowed In Lunar Module With Floor Panels In Place After Battery Installation

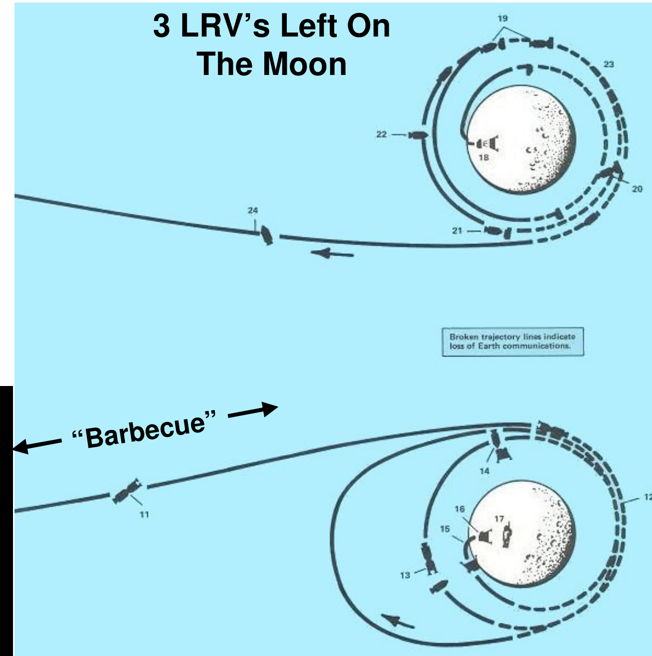
From The Earth To The Moon

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



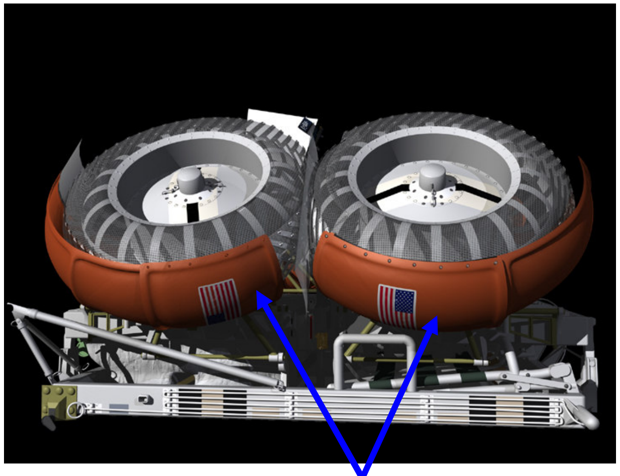
(3 Rev/Hour)



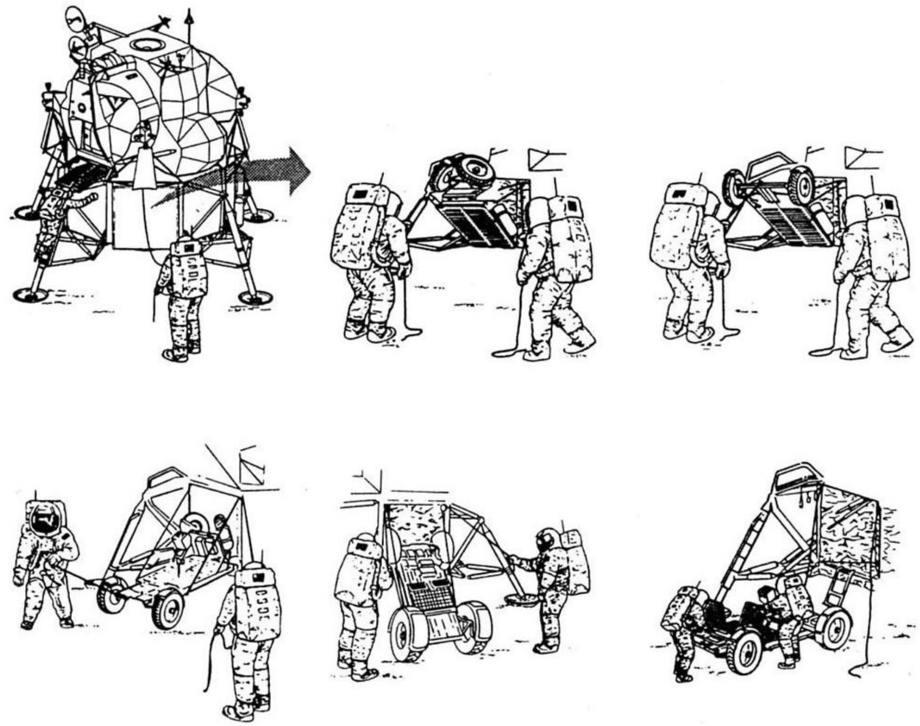


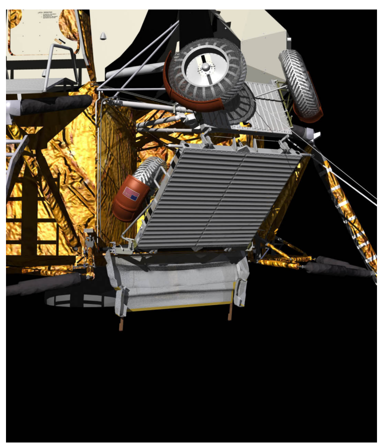
Apollo Mission Profile			1.Liftoff	2. S-1C Powered Flight	3. S-1C/S-II Separation
4. Launch Escape Tower Jettison	5. S-II/S-IVB Separation	6. Earth Parking Orbit	7. Translunar Injection	8. CSM Docking With LM/S-IVB	9. CSM Separation From LM Adapter
10. CSM/LM Sep. From S-IVB	11. Midcourse Correction	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

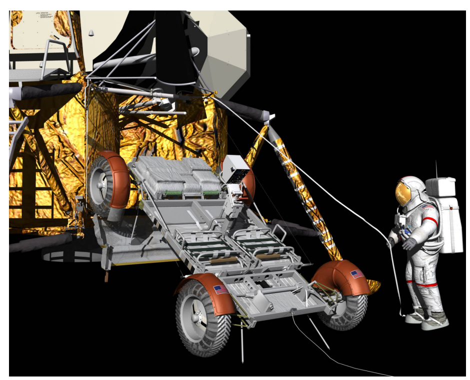
Astronauts Performed Manual Sequenced LRV Unfolding And Deployment On Moon

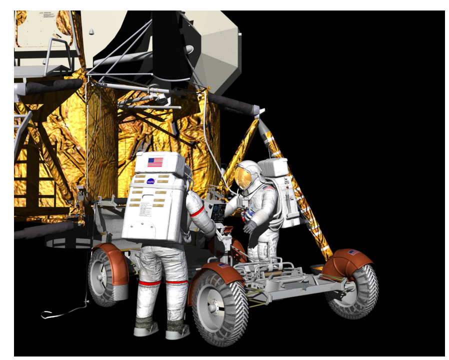


Retractable Fender Extensions Required
For Folding of Wheels









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

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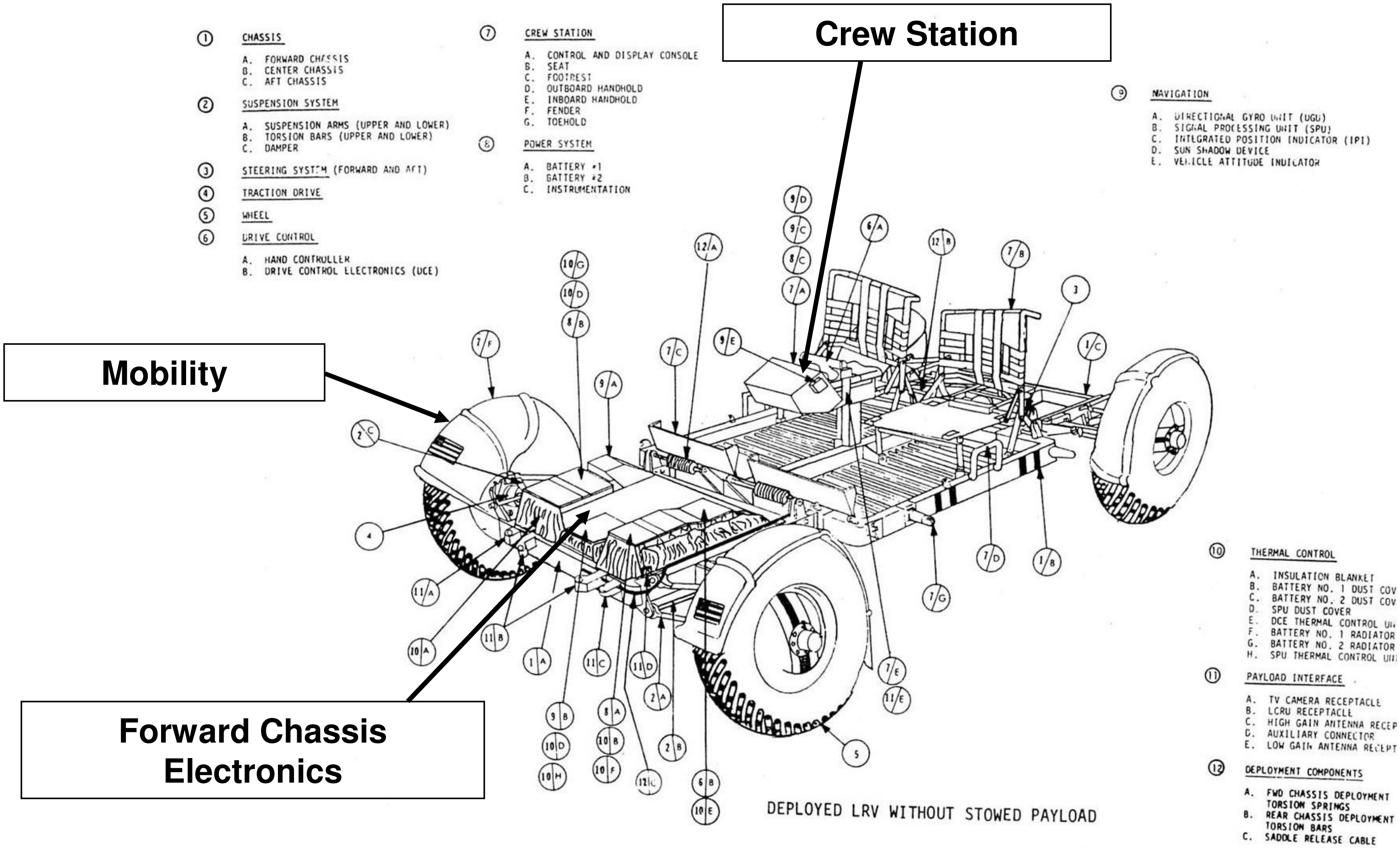
Deployed LRV Subsystems



DEPLOYED LRV WITHOUT STOWED PAYLOAD

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)

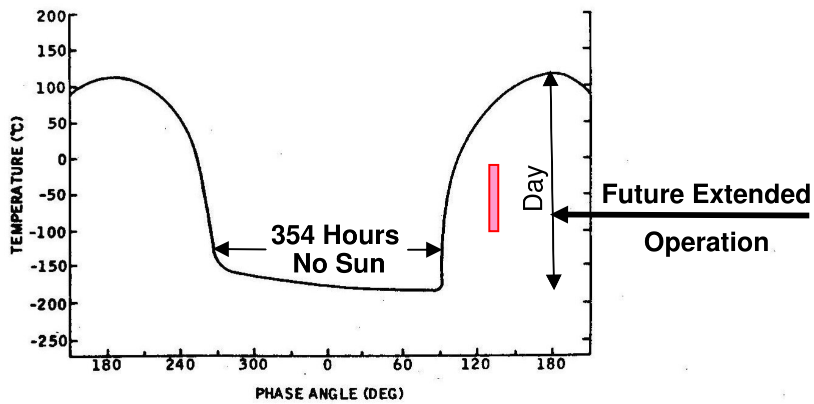
Sang = Solar Elevation Angle (Degrees)

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

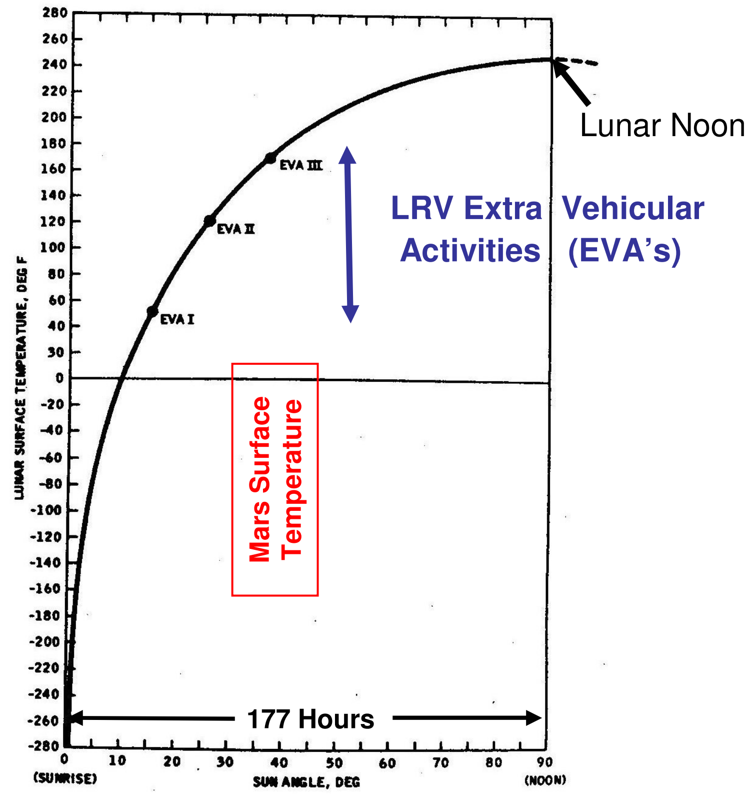
Lunar Day

- 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.



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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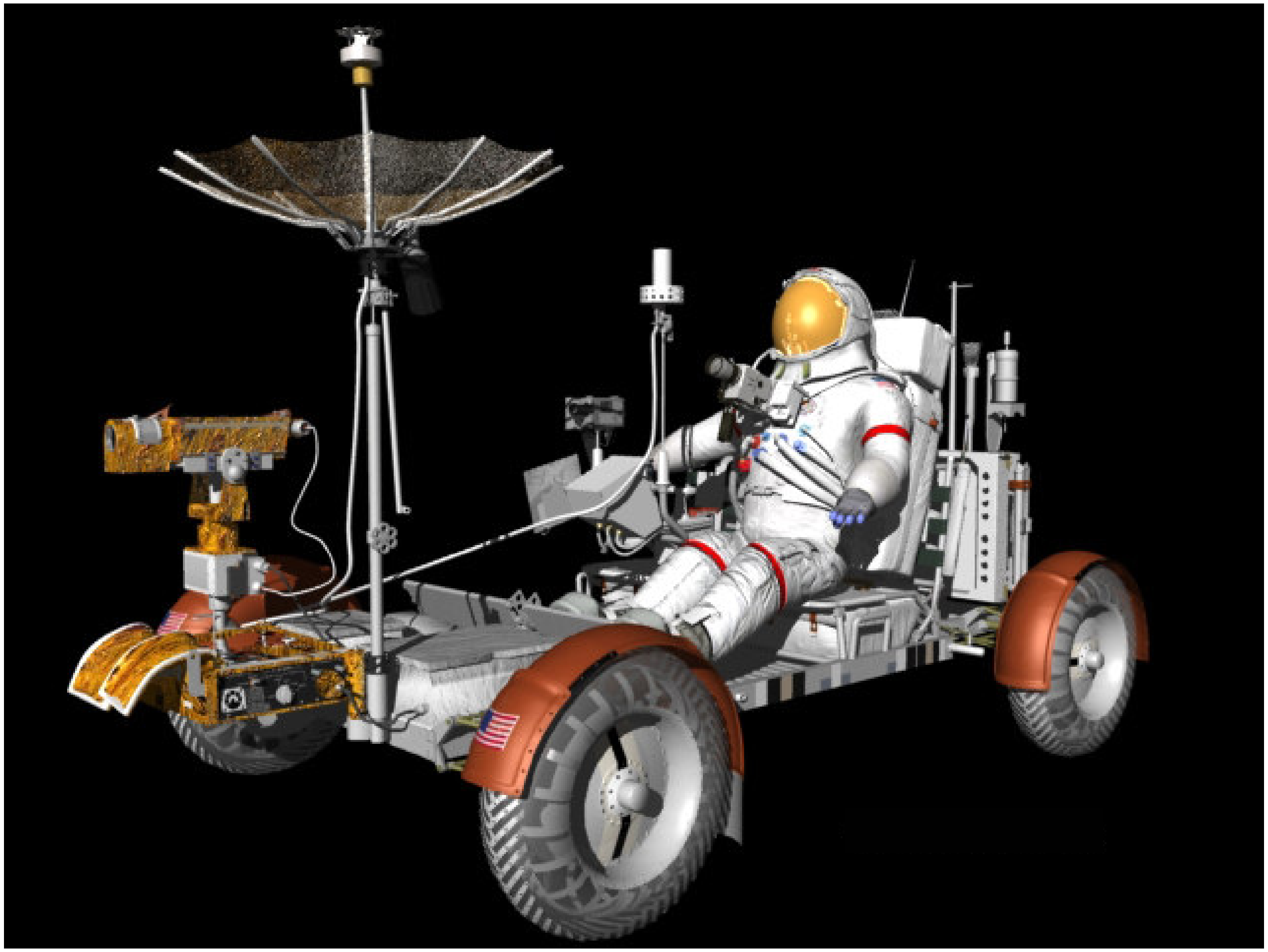
Thermal Provisions for Deployed LRV Subsystems

Maintain All Surfaces Within Astronaut Touch Constraints



Control And Display Console

Insulated Front Panel, Exterior Dust Degraded

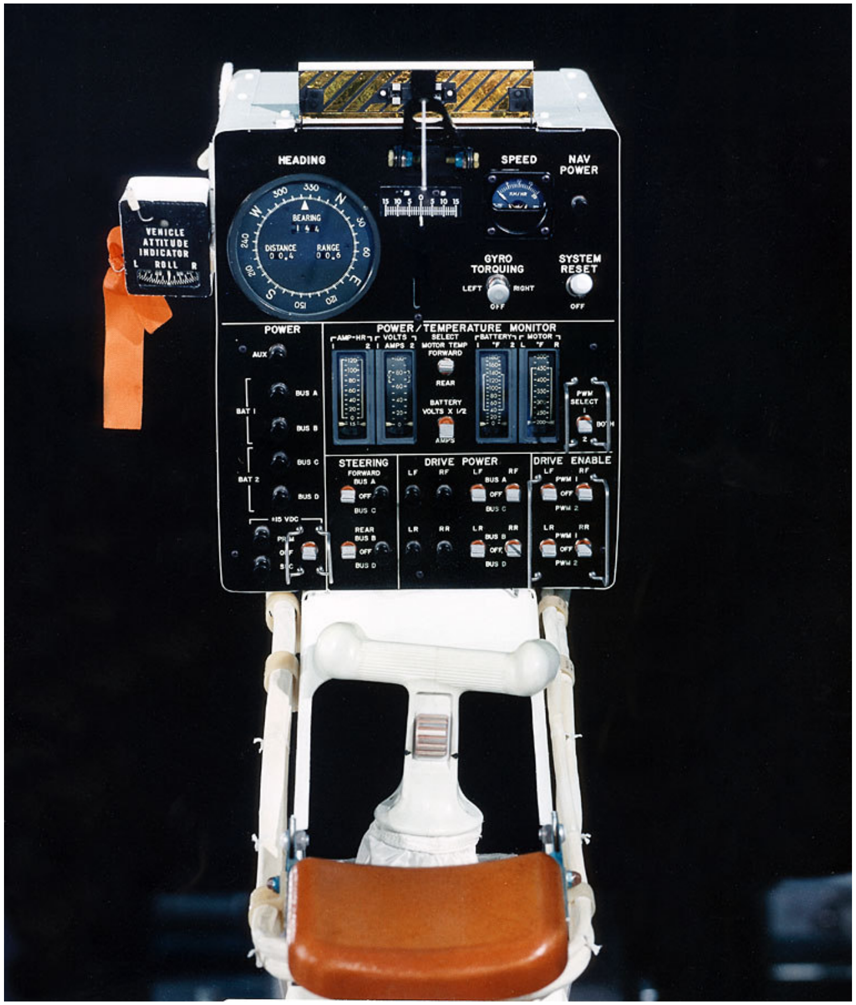
Forward Chassis Electronics

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

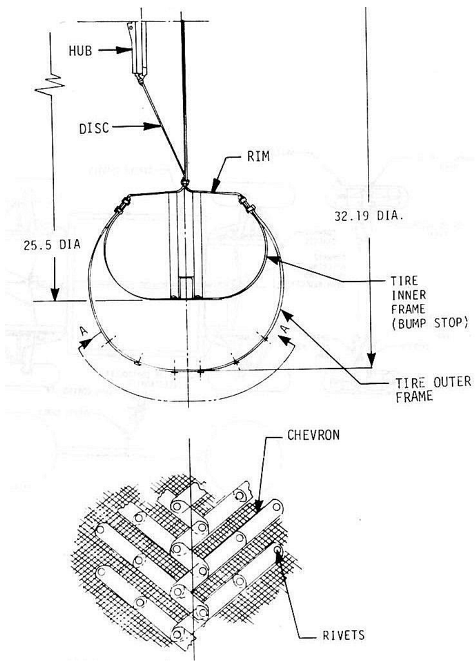


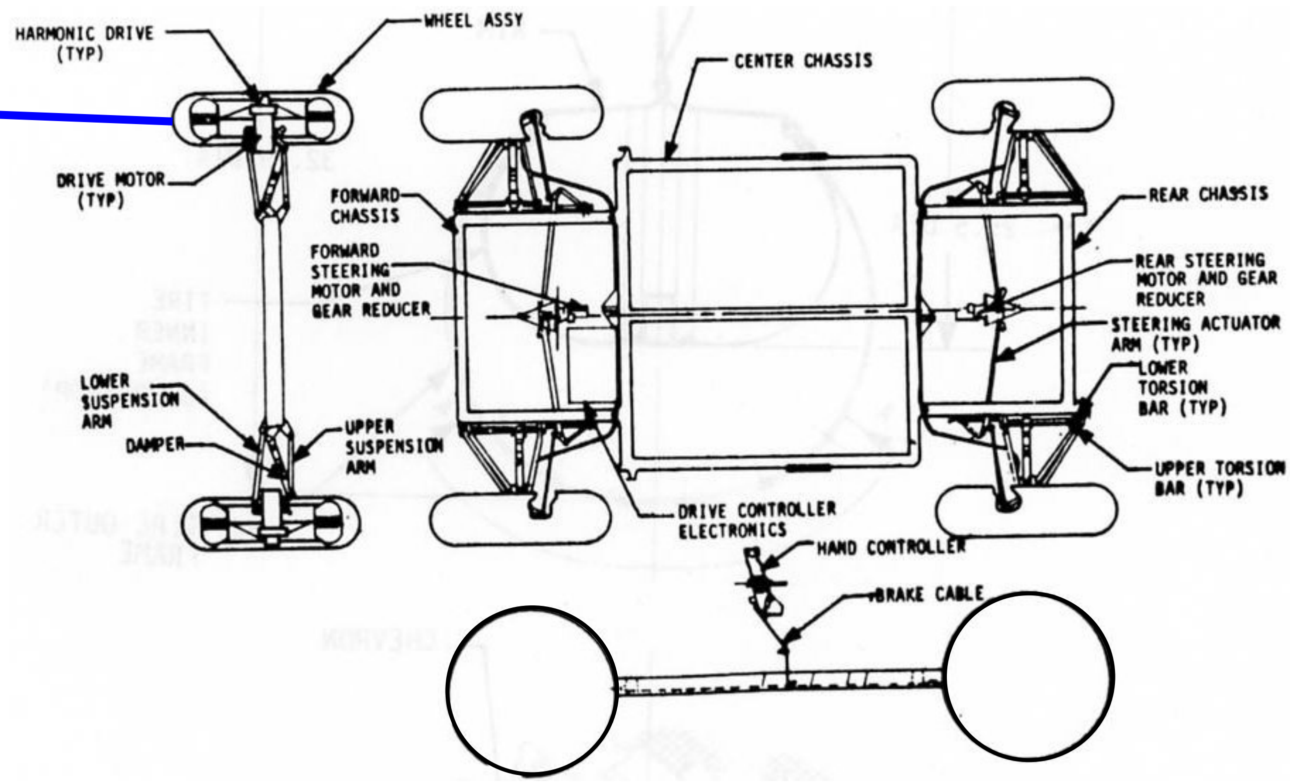
LRV Control And Display Console

- 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

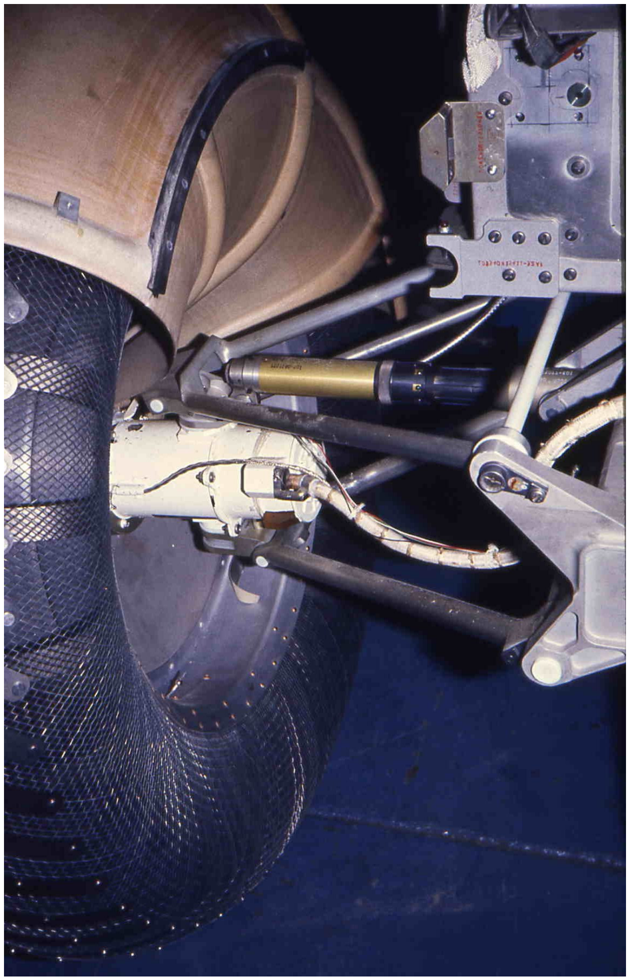




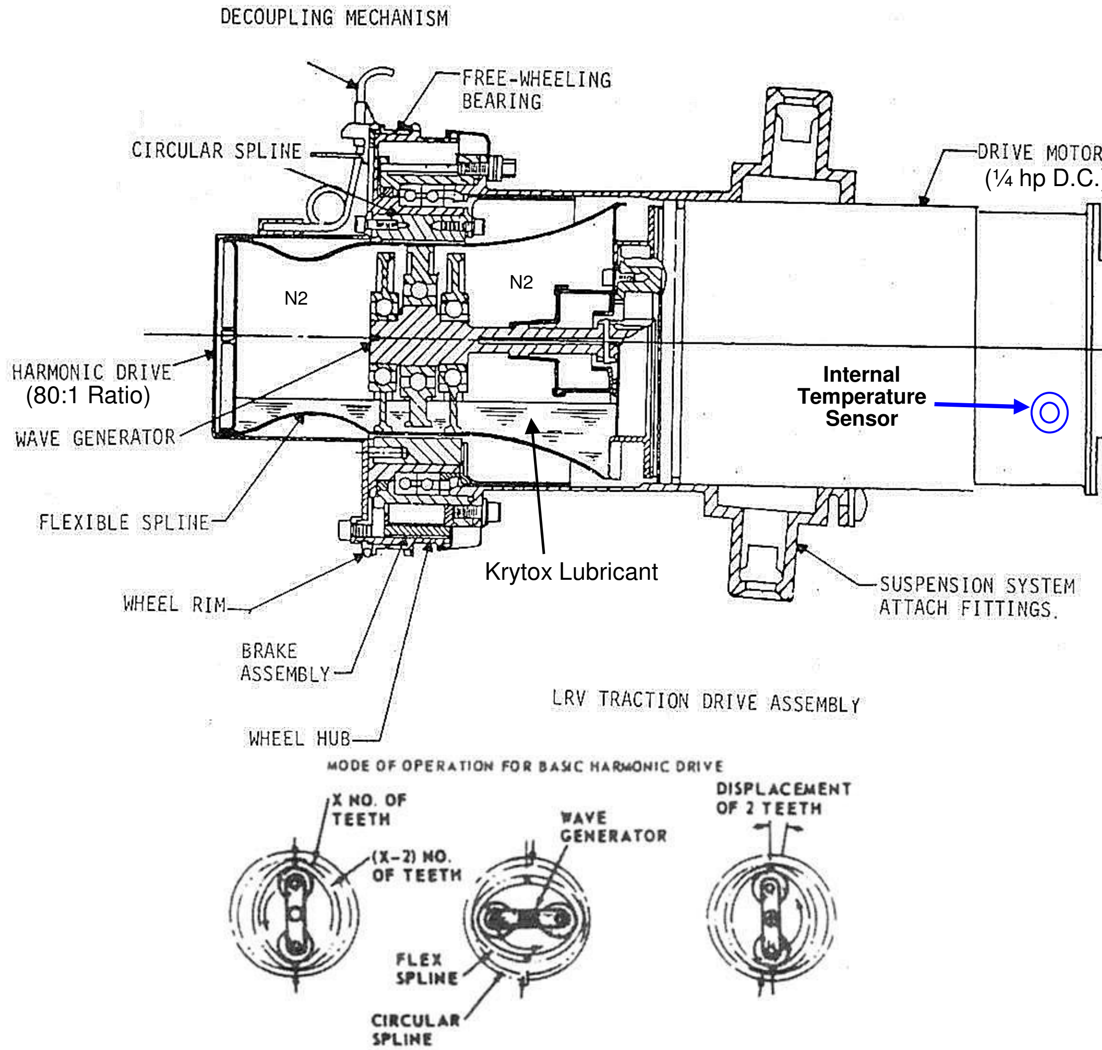
Mobility Subsystem Components

LRV Traction Drive Thermal Control

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

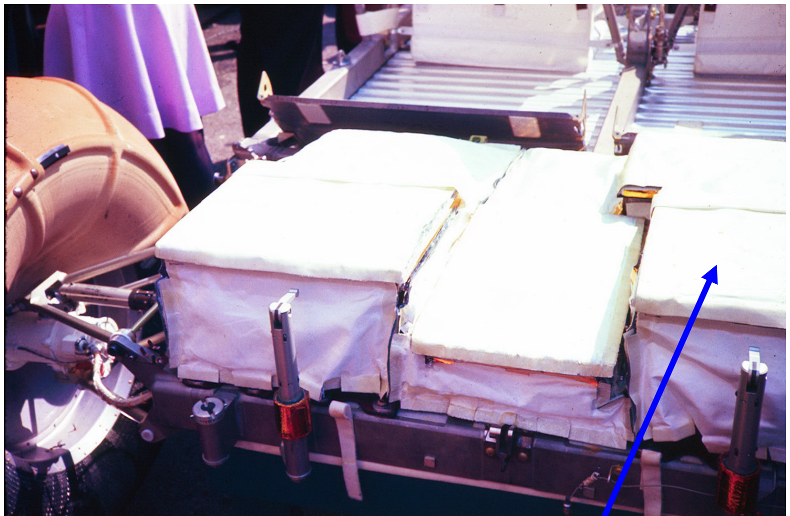


Mobility Subsystem



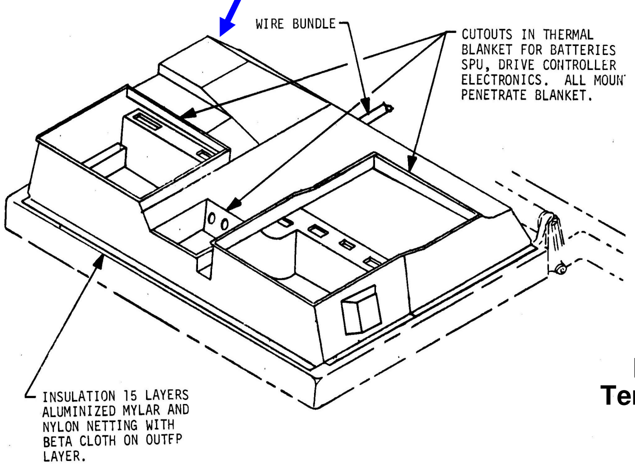
Harmonic Drive Unit Used for Traction Power on the LRV

LRV Batteries Were Heart of Forward Chassis Electronics Thermal Control



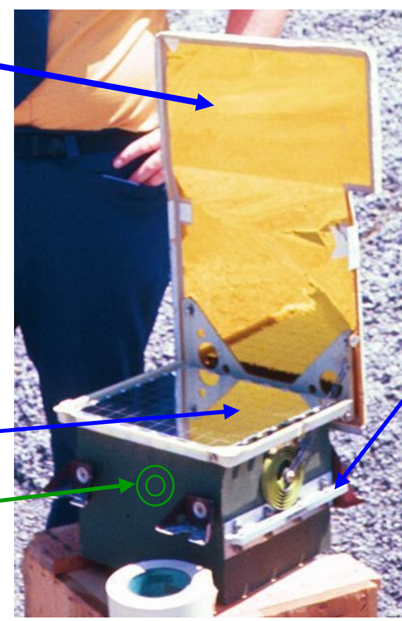
- Multi-Layer Blanket For Insulation, Dust Covers
- Thermal Straps Conduct Heat Into Batteries
- Electronics Heat Also Stored In Wax Boxes (Fusible Mass Tanks) During EVA's
- Low Solar Absorptance (α = 7%) Space Radiators To Reject Heat When Dust Covers Opened for Cooldown Between EVA's

Insulation Blanket And Dust Covers

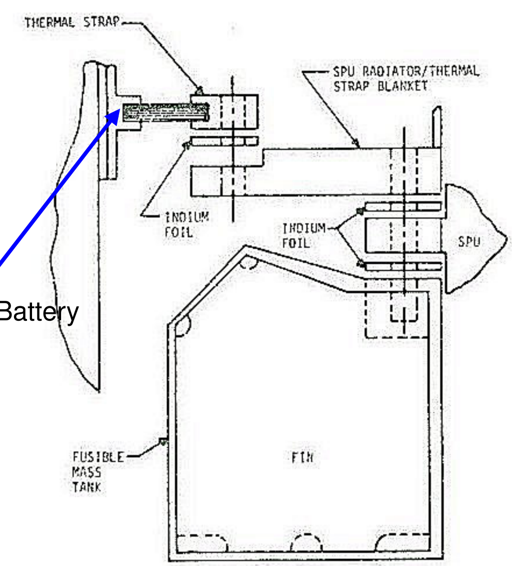


Radiator

Internal Temperature Sensor



Battery



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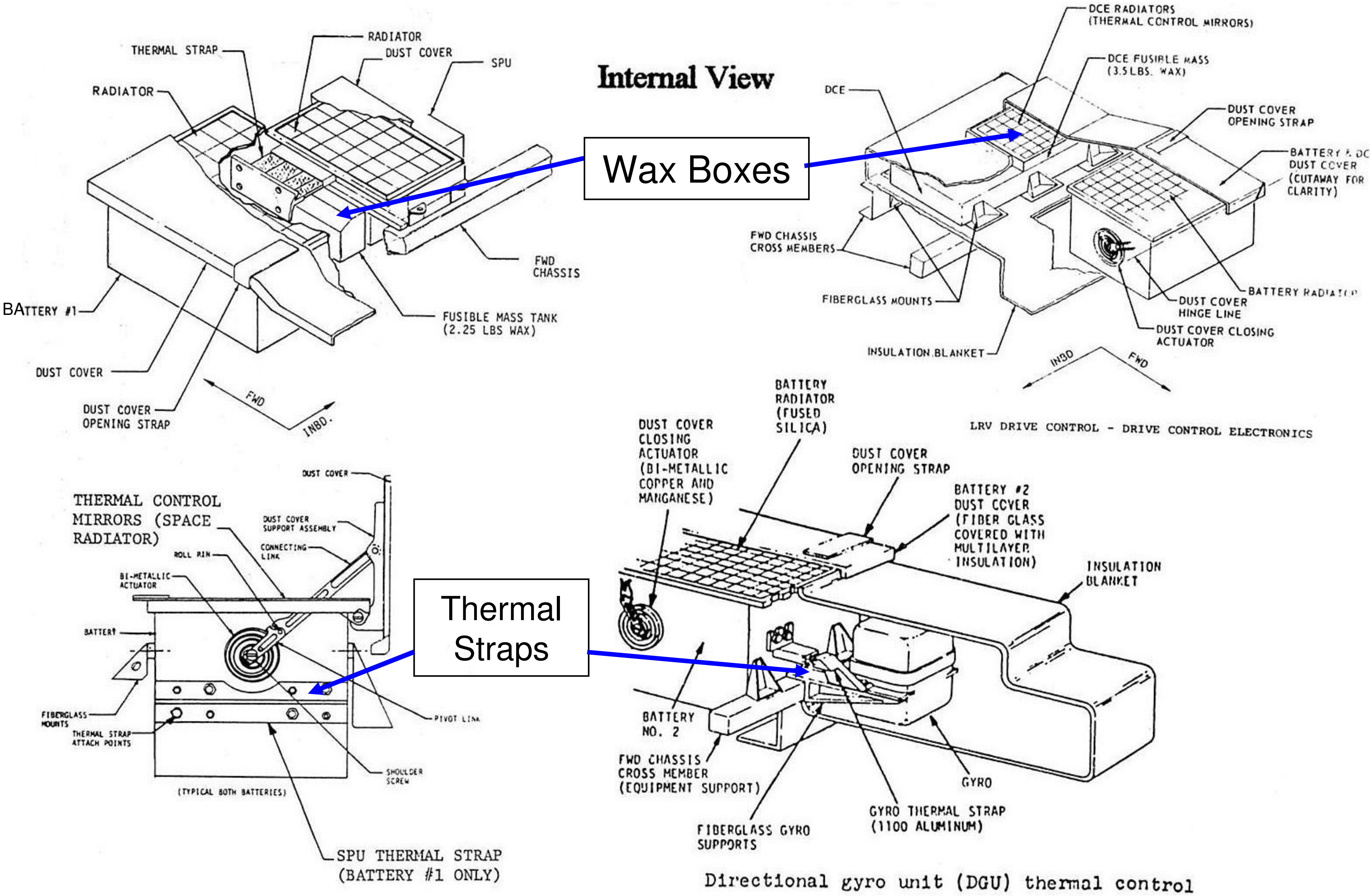
LRV Forward Chassis Electronics Thermal Control



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

Extensive LRV Thermal Testing Was Conducted

- Early Dust Effects And Removal Techniques Simulation (1967)

Oct. 1969
to
Mar. 1971

(17 Months)

- LM Thruster/Engine Environment And Heating Deflectors Verification
- Surface Optical Properties (Absorptance And Emittance) Measurement
- Mobility Power Characterized At Waterways Experiment Station, C 135
- Development Thermal/Vacuum (TVAC) Tests For Subsystems
  - Mobility – Brakes, Steering, Dampers, ¼ Mobility, Fenders
  - Forward Chassis In Lunar "Tub" Environment Simulator
- System Level TVAC Tests With Dynamometers And Solar Simulator
  - Thermal Design Stressed Using "Flight-Like" Qualification Unit
  - Acceptance Level Checkout On Flight Units

Delivery and First Launch in July 1971

- Post Flight Special Adjustments
  - Apollo 15 – Cleaning Agent For Floor Panel Thermal Control Tape
  - Apollo 16 – Battery Radiator Proximity To Lunar Module Effects

    -- Cold Exposure For Stuck Switches In Army Chamber

Lunar Dust Effects And Removal Techniques Were Studied In 1967

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

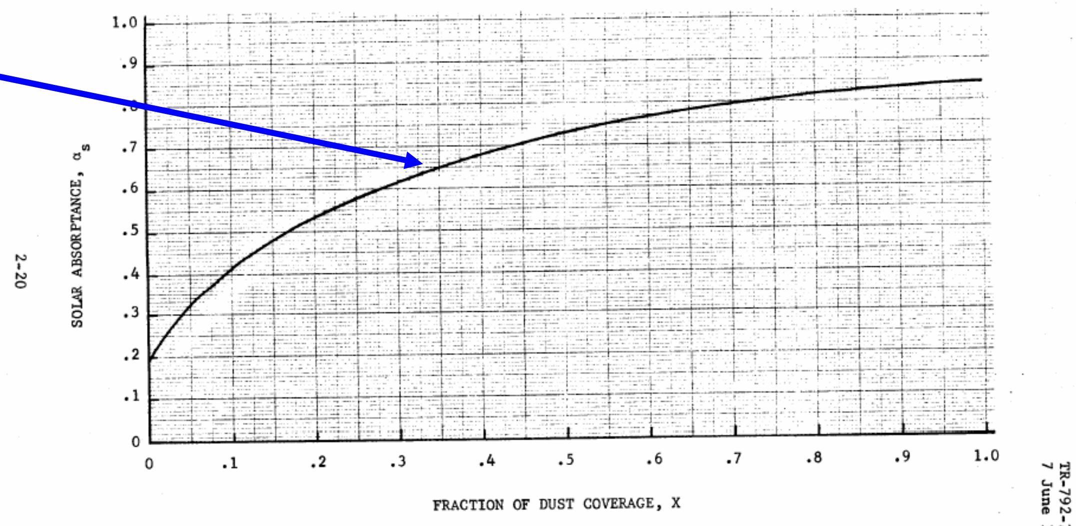


Figure 2-4. VARIATION OF TOTAL SOLAR ABSORPTANCE WITH DUST COVERAGE OF S-13 PLATE

TR-792-7-207B
7 June 1967

Misleading Earth-Based Cleaning Test Results

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

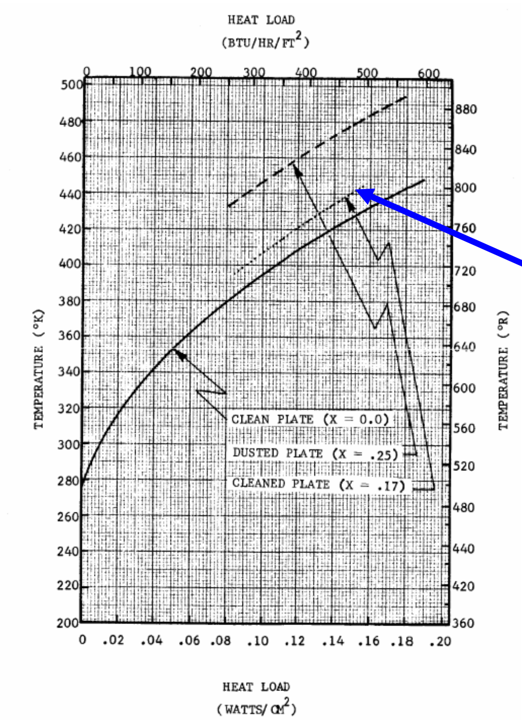
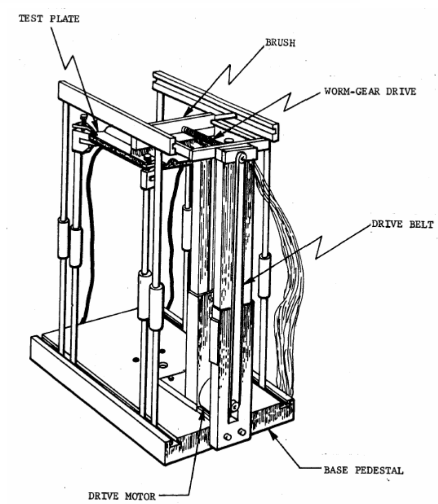
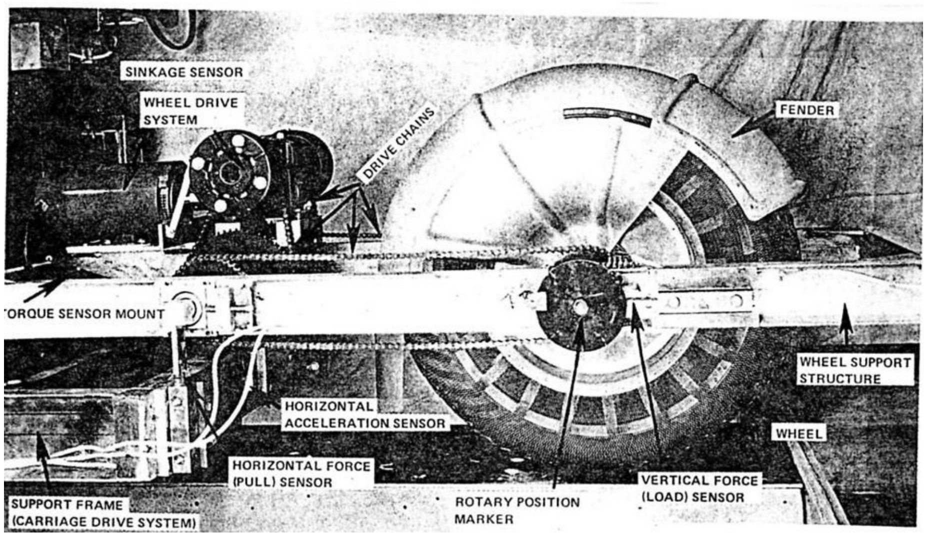


Figure 3-30b. TEMPERATURE VARIATION WITH HEAT LOAD (SOLAR SIMULATOR ON) FOR MECHANICAL BRUSH TEST RUN

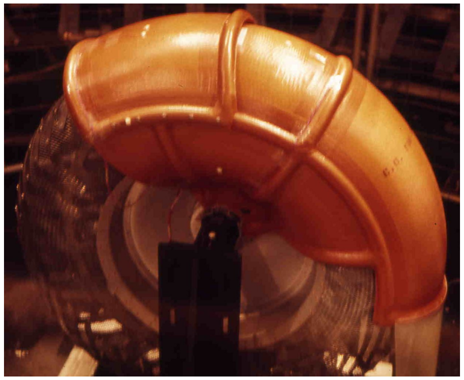


Brush Test Apparatus

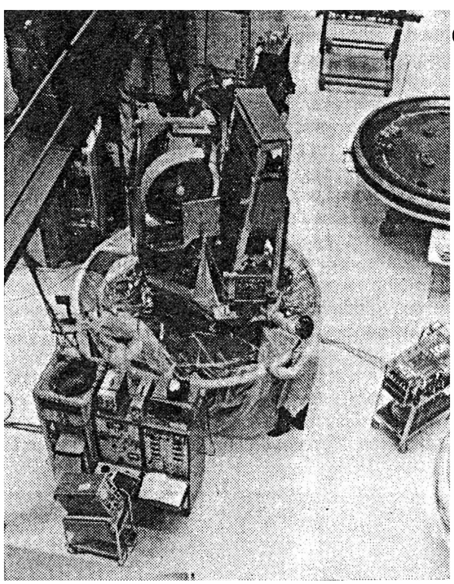
Extensive LRV Thermal Vacuum (TVAC) Testing



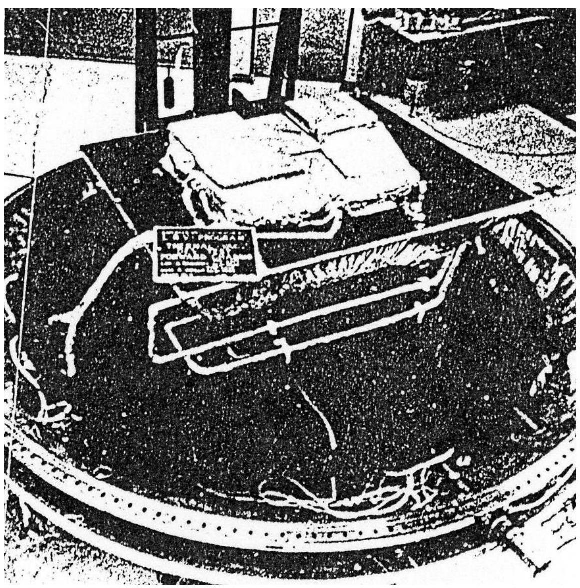
Wheel to Soil Interaction At Waterways Experiment Station, C 135



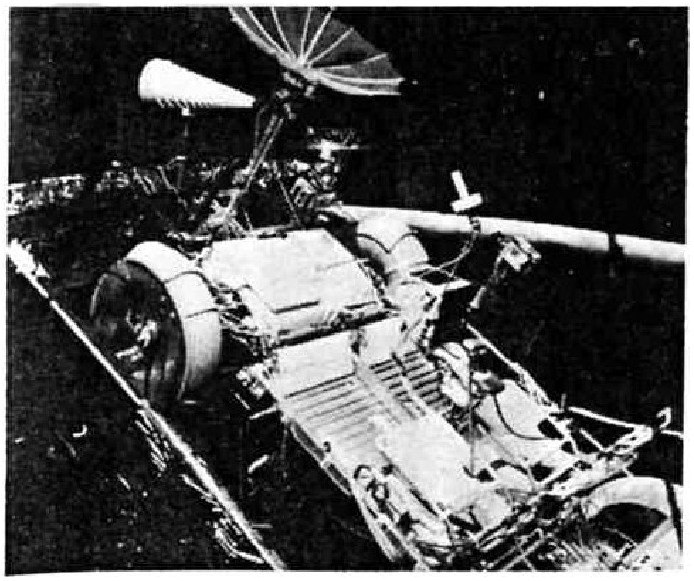
Fender Extension Deployment TVAC at JSC



Mobility Subsystem TVAC

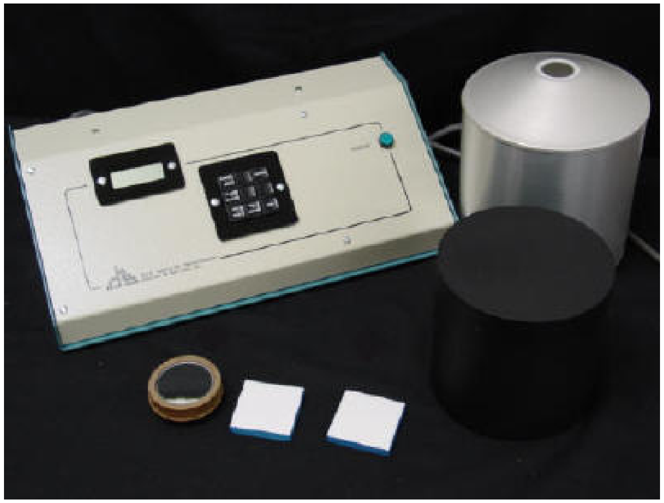


Forward Chassis Development "Tub" TVAC



Qualification And Flight Units TVAC

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



Solar Absorptance - α

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.

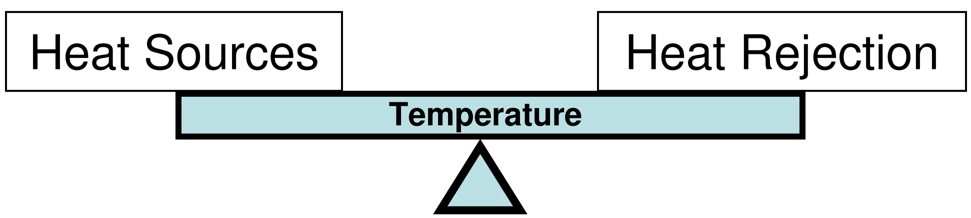
Sample No.	Material Description	α	ε	%T
1	Seat Material/Beta Cloth/Al Mylar	0.28	0.90	
1	Seat Material Only			21
2	PLSS Support Straps, Type 15 Green	0.55	0.92	
3	PLSS Support Straps/Beta/Al Mylar, Type 4 white	0.32	0.91	
3	PLSS Support Straps Type 4 Only			29.5
4	Dry Film Lube MIL-L-81329	0.83	0.76	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

Infrared Emittance - ε

Absorbed Solar
(Direct/Reflected)

Reflectometers Used to Measure Properties for Clean Transit LRV Surfaces

Absorbed Infrared



Radiated Infrared

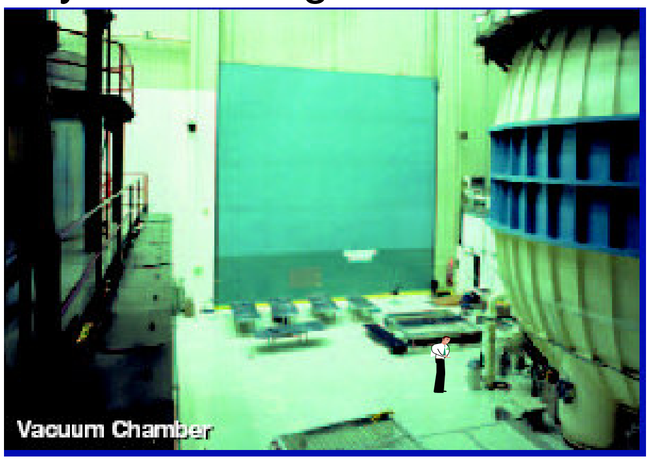
Internal Generated

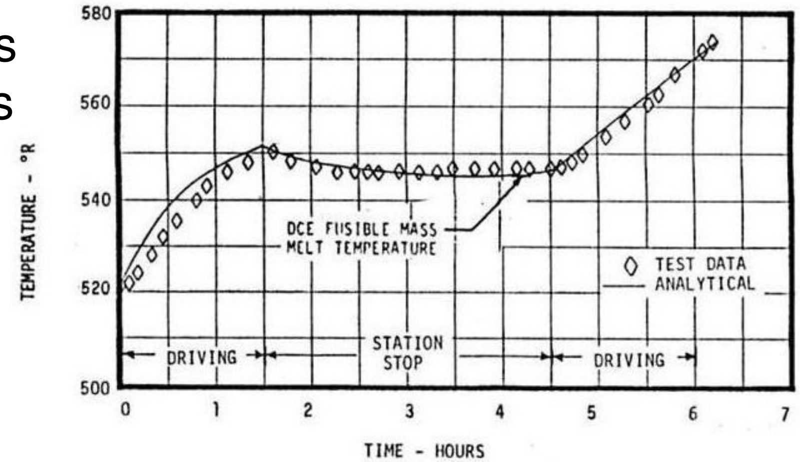
Computer Model Thermal Balance

roving_ron@comcast.net

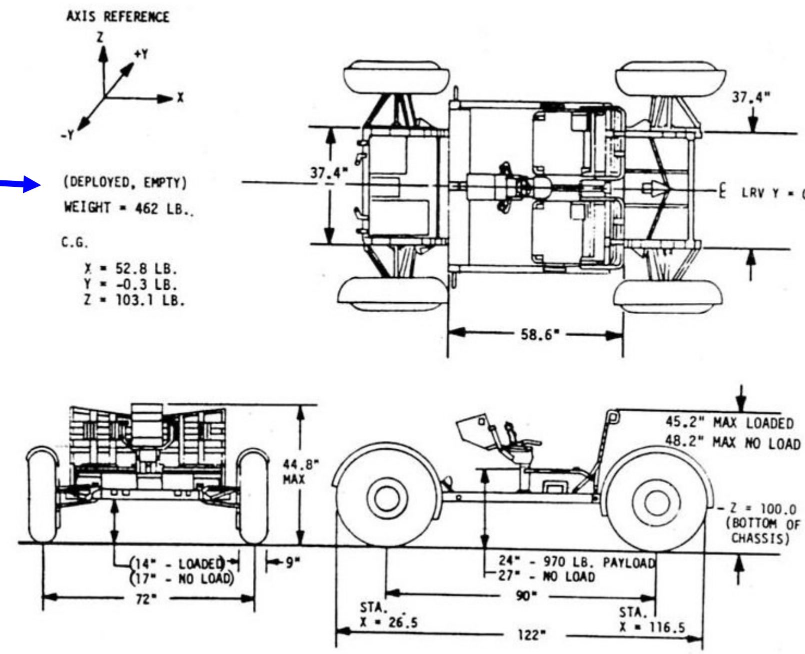
“LUROVA” Operational Thermal Computer Model

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





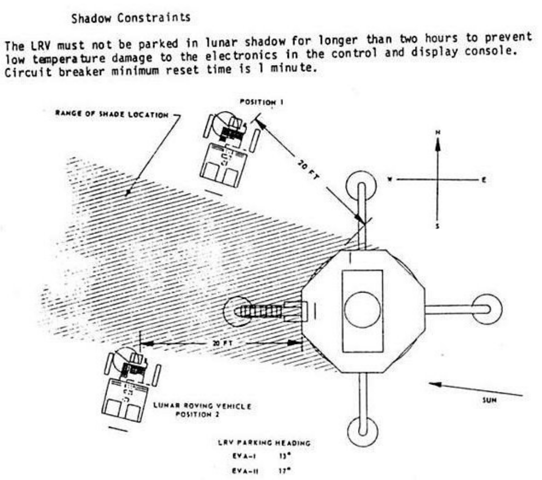
DCE TEST DATA CORRELATION



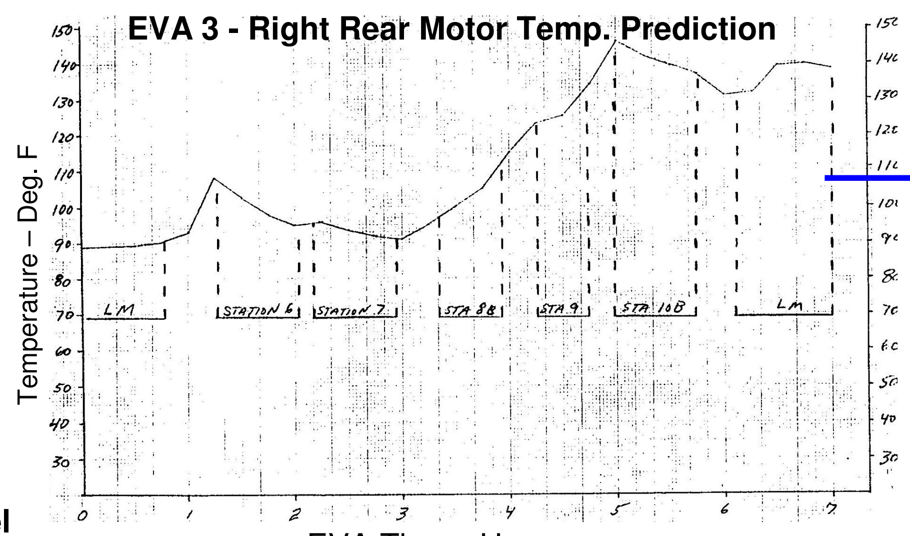
- Test Correlated Crew Station, Mobility, And Forward Chassis Models Combined Into “LUROVA” Operational Model
- Allowed Analysis For Clean Transit, Lunar Surface Dust Degradation, And Sortie Traverse Variations
- Detailed Model -177 Nodes (Capacitors) And Thousands Of Conductors
- Cumbersome And Limited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

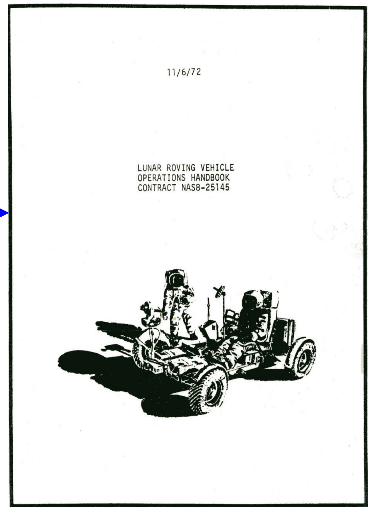
Detailed LUROVA Thermal Computer Model Used First for Apollo 15 Mission Support

- 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



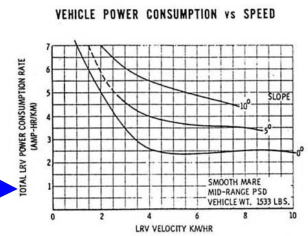


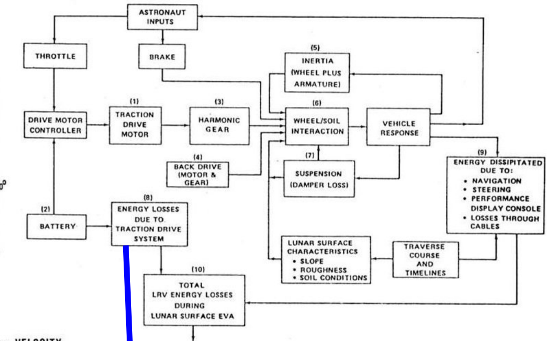
Predictions For Mission Operations Handbook

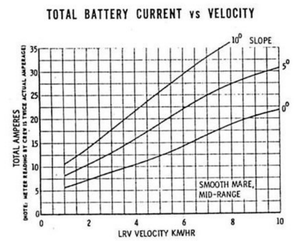
LUROVA Thermal Computer Model Operational Flow

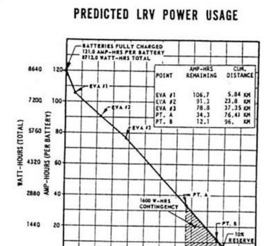
Traverse Team Provided Driving Parameters

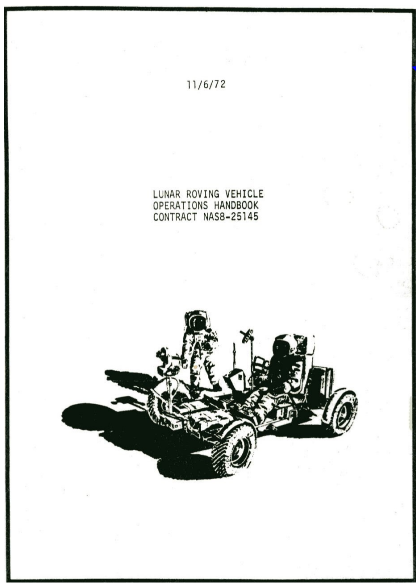
Power Profile Provided Internal Heat



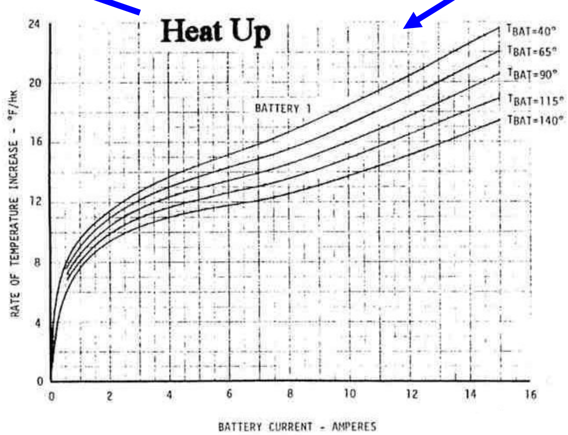


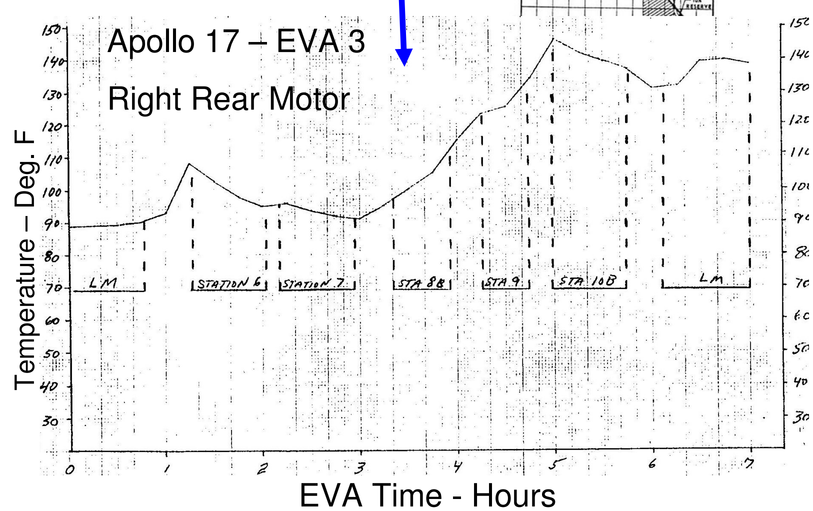






Predictions For Mission Operations Handbook

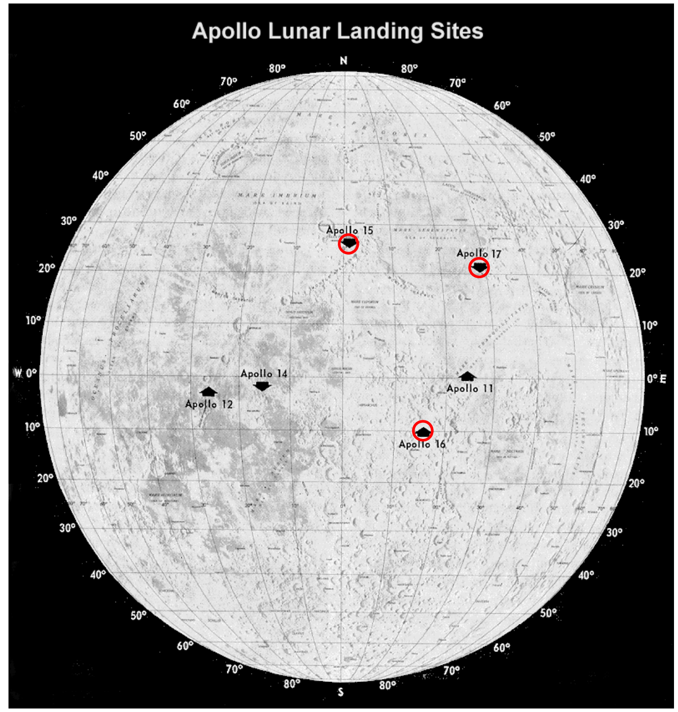


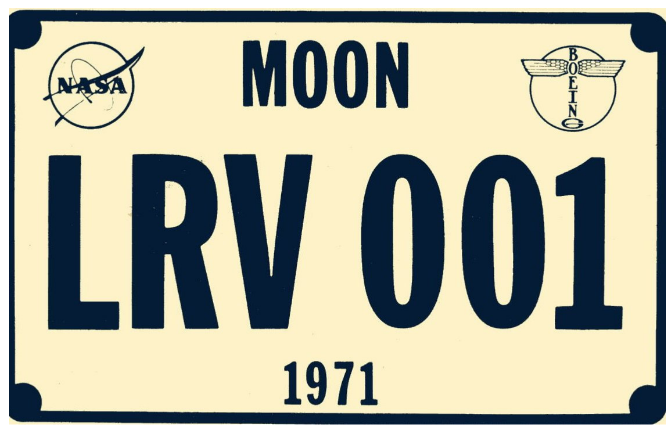


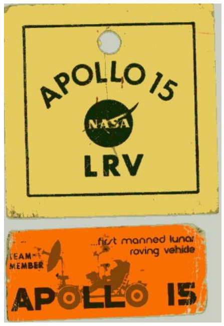
- LUROVA Used To Predict Crew Station, Forward Chassis, Mobility Temperatures

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

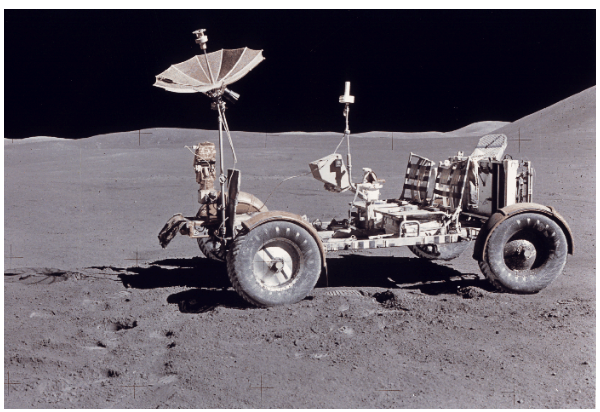
by Nicholas C. Costes, John E. Farmer, and Edwin B. George
George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

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

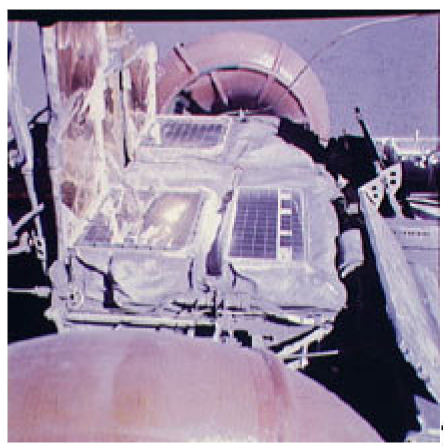
LUNAR ROVING VEHICLE
NAVIGATION SYSTEM
PERFORMANCE REVIEW

by Eurnest C. Smith and William C. Mastin
George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

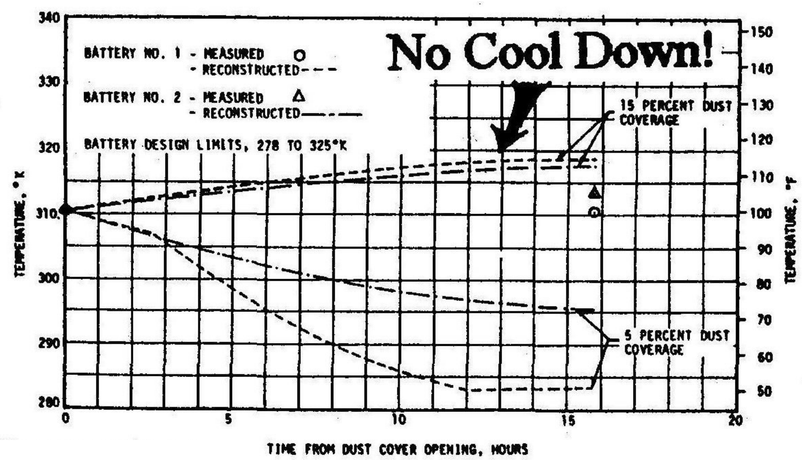
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1973



Missing Front Fender Extension



Dust On Radiators



LRV Battery Temperatures During Cooldown 2

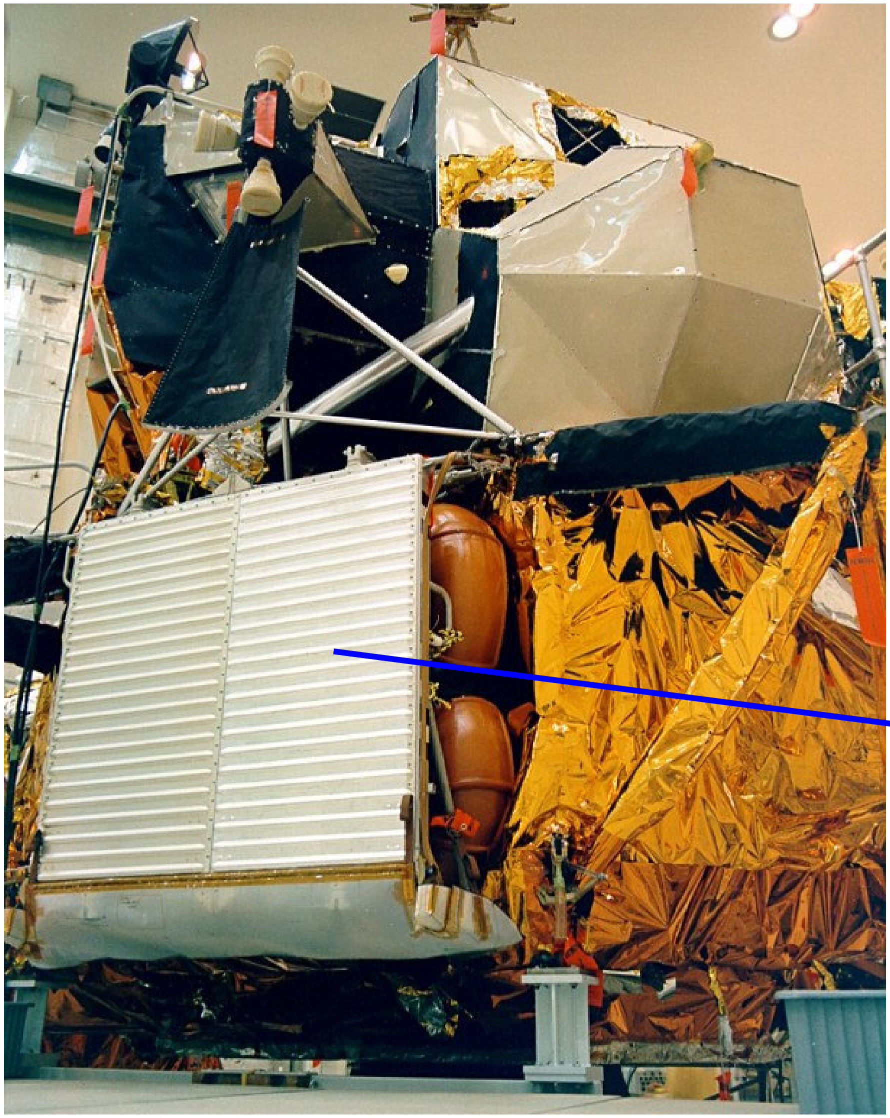
Post Apollo 15 – Astronauts Visited Huntsville, AL

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

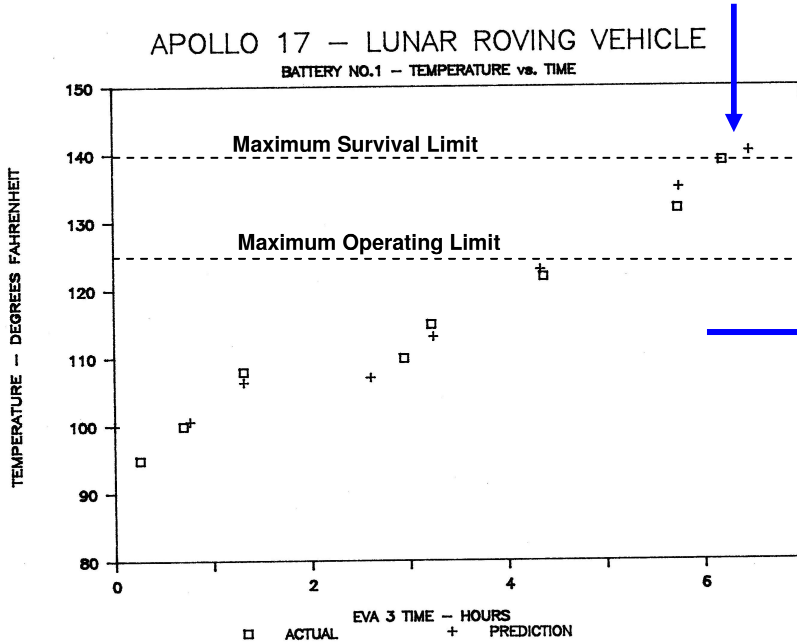
Pre-Launch Tape Cleaning Procedure Adjusted

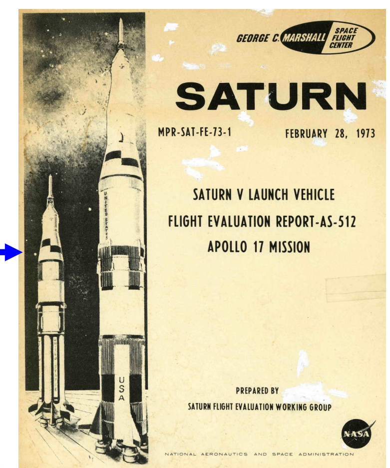
Forward Chassis Thermal Analyzer Model - FWDCHA

```
        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 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 Forward Chassis Components Modeled





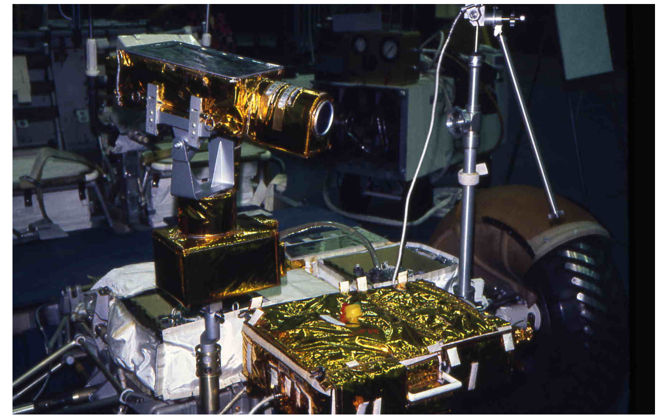
Mission Reports

Excellent, Responsive Predictions Provided

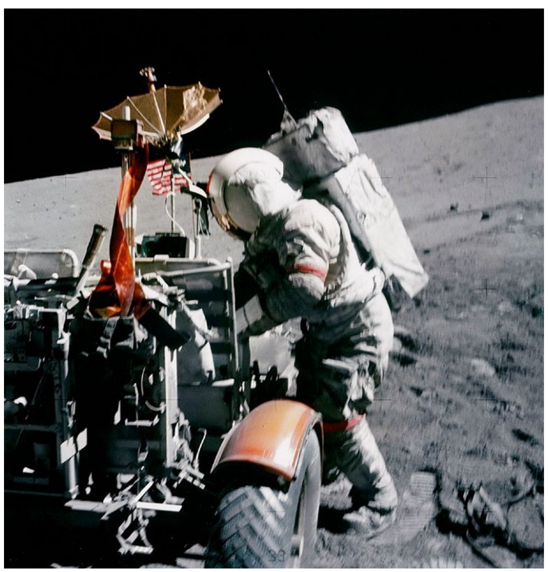
roving_ron@comcast.net

Apollo 16 – LRV Thermal Control Performance

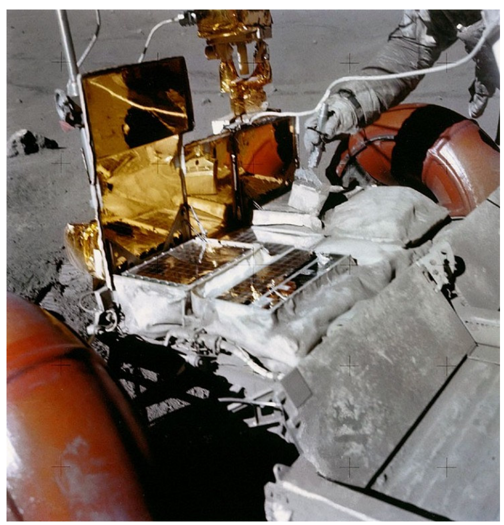
- FWDCHA Thermal Model Used For Pre-Sortie And EVA Analysis
- **Switches Stuck At Initial Power-up**, Max. Motor Temp. = 225 Deg. F
- LRV Supplied Power For LCRU And TV
- **LRV Parked Too Close To Lunar Module**
- Right Rear Fender Extension Knocked Off
- **Insufficient Cooldowns Between EVA's**
- Battery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



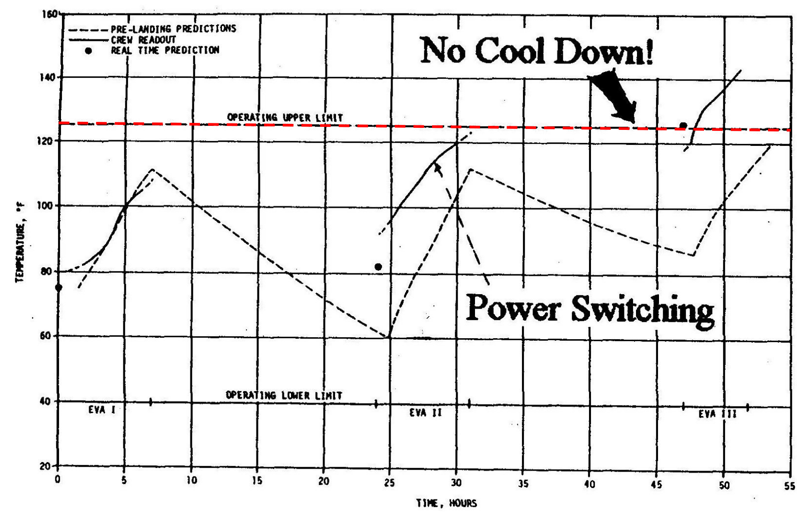
LRV Supplied LCRU, TV Power



Missing Fender Extension



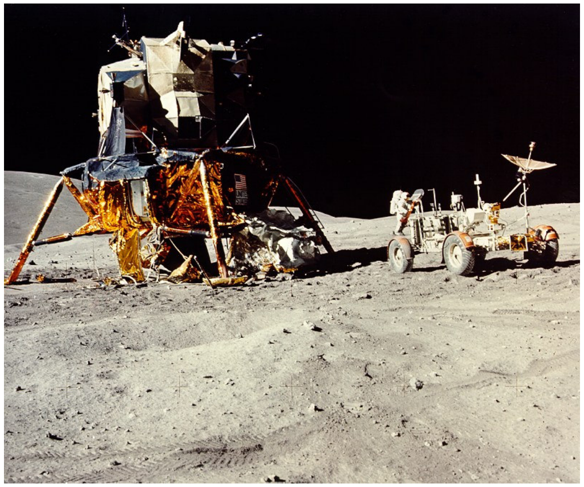
Astronaut Brushing Dust
From Radiators



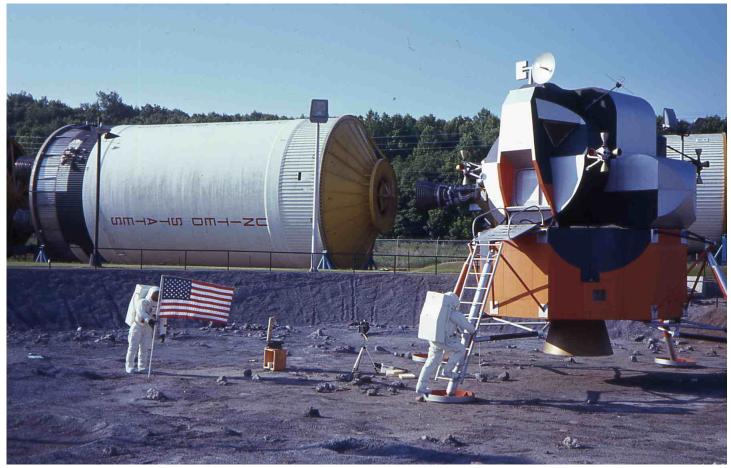
Battery No. 2 Temperature

roving_ron@comcast.net

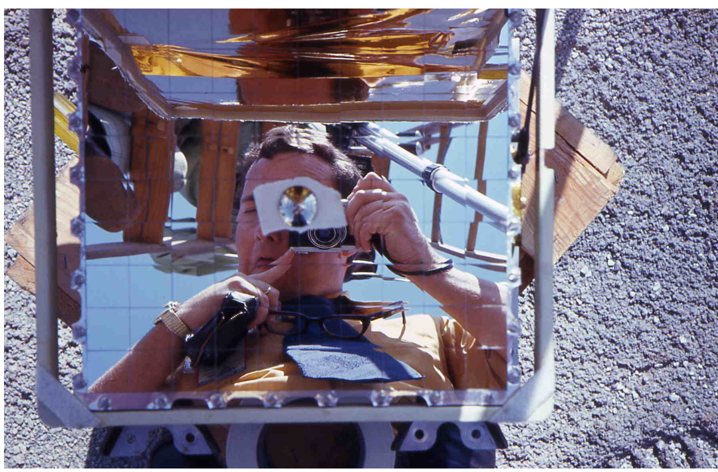
Post Apollo 16 – LM Parking Proximity Test



LRV Parked Too Close To LM

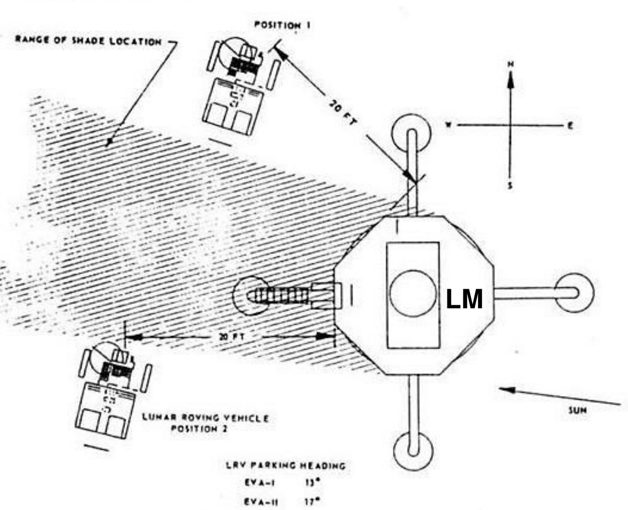


Battery Proximity Test At Space And Rocket Center



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 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.

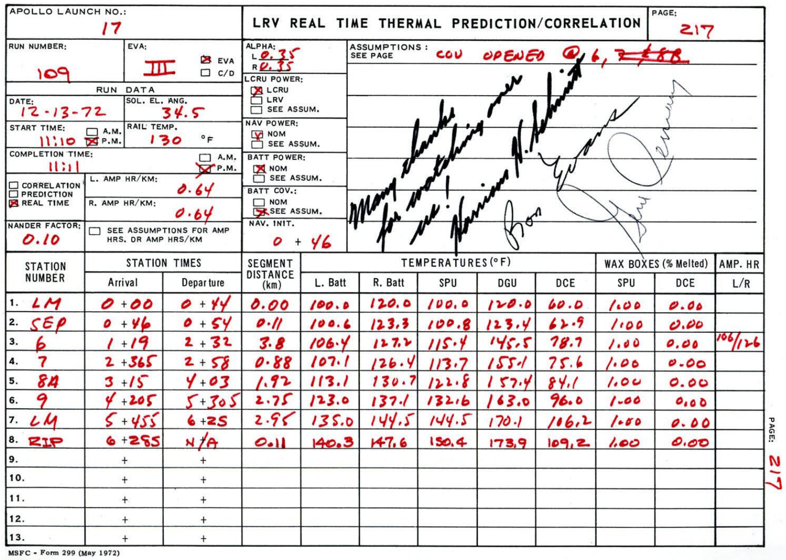
Sincerely,

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

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

ALPHA: L 0.35 R 0.35

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

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

Many thanks for watching over us!
Harrison H. Schmitt
Ron Evans
Gene Cernan

STATION NUMBER	STATION TIMES Arrival	Departure	SEGMENT DISTANCE (km)	TEMPERATURES (°F) L. Batt	R. Batt	SPU	DGU	DCE	WAX BOXES (% Melted) SPU	DCE	AMP. HR 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)

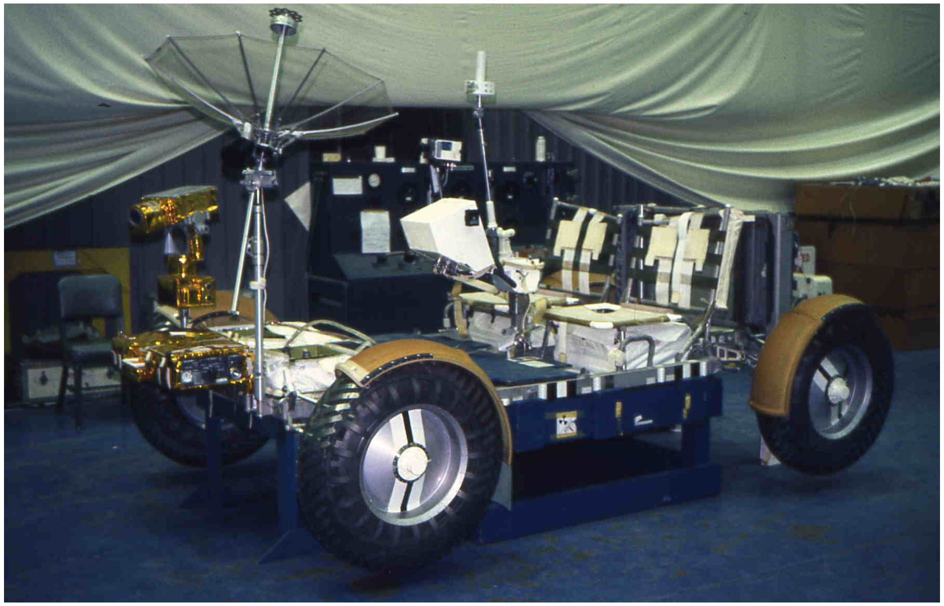
Apollo 17 Astronauts Signed Final Thermal Log Sheet

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

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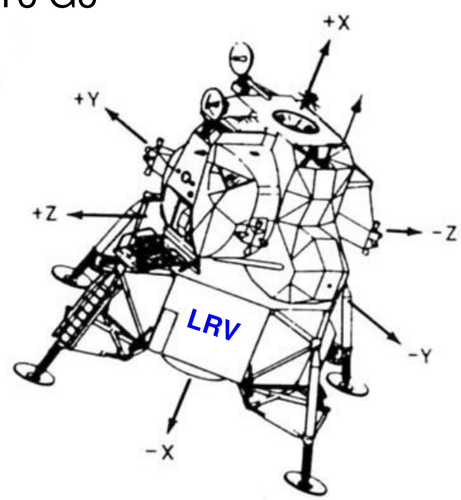
Apollo 17 – Transportation Thermal Control

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

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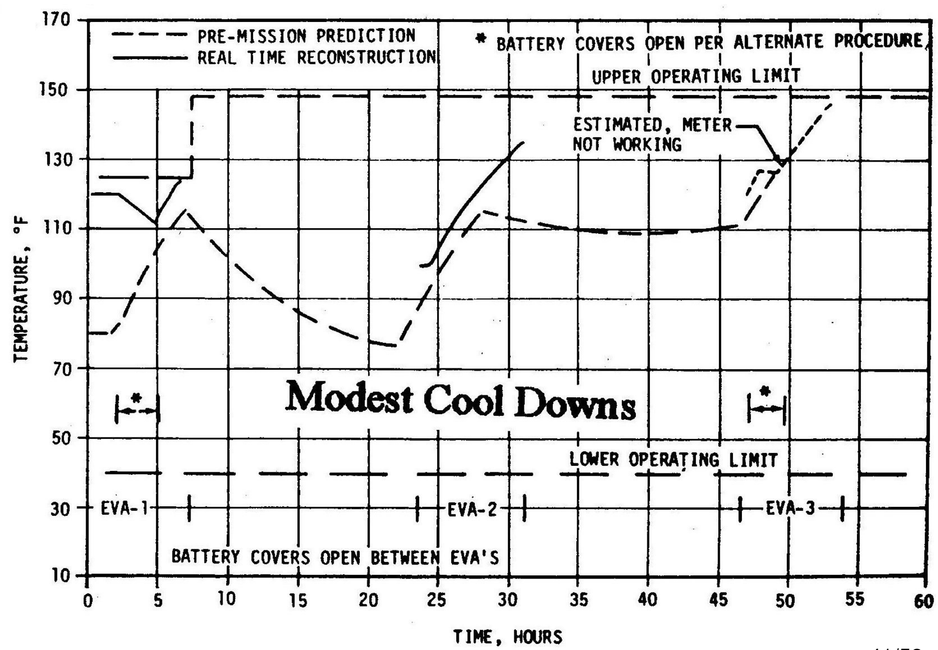
Apollo 17 – LRV Thermal Control Performance

- 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)



LRV Battery No. 2 (Right) Temperature

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Post Apollo 17 – Astronauts Met With LRV Team

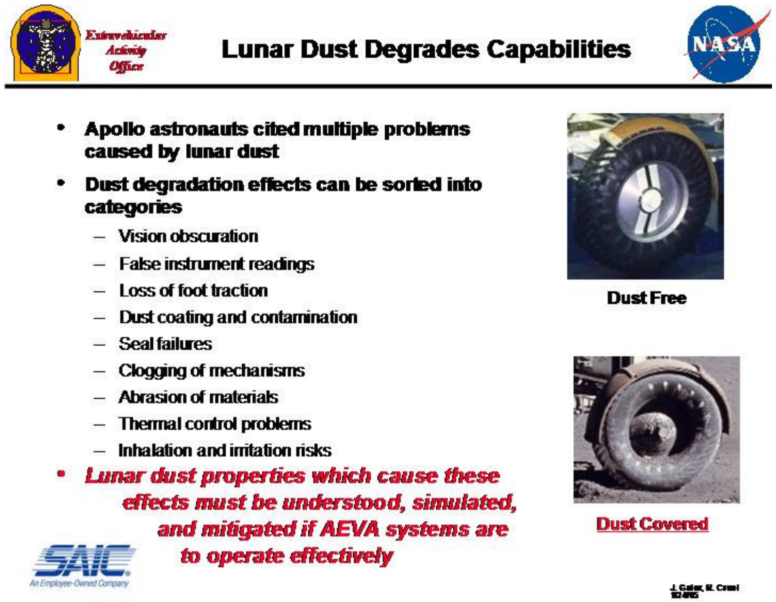
Astronauts Were Presented With Fender Extension From LRV Qualification Unit

Autographed By MSFC Support Team

Summary of LRV Thermal Control Experiences

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

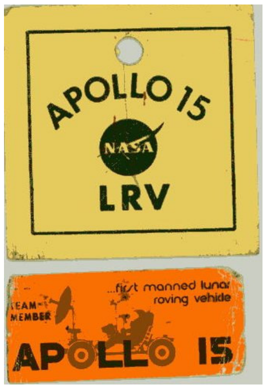
LRV Mission Control At Huntsville Operations Support Center (HOSC)

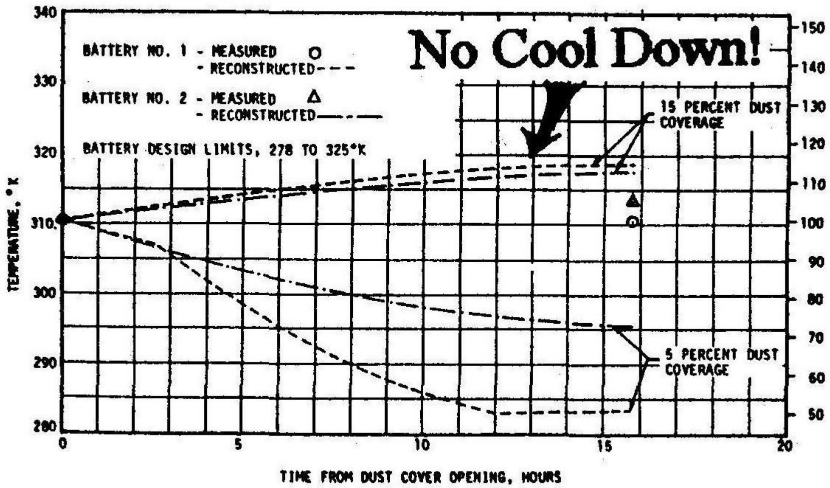


Advanced Extravehicular Activity Dust Effects Summary Prepared For 2005 Lunar Regolith Simulant Material Workshop At MSFC

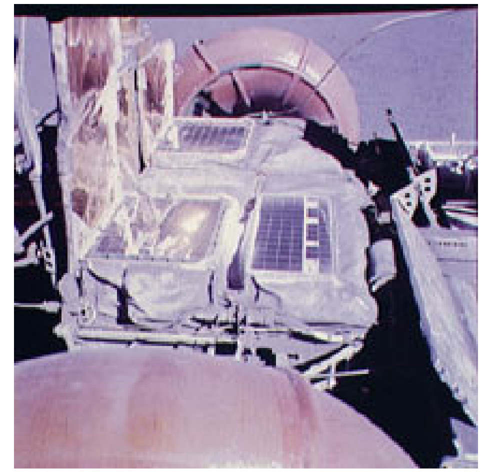
Future Moon Rover Challenge 1 – Mitigate Bad Effects Of Dust

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



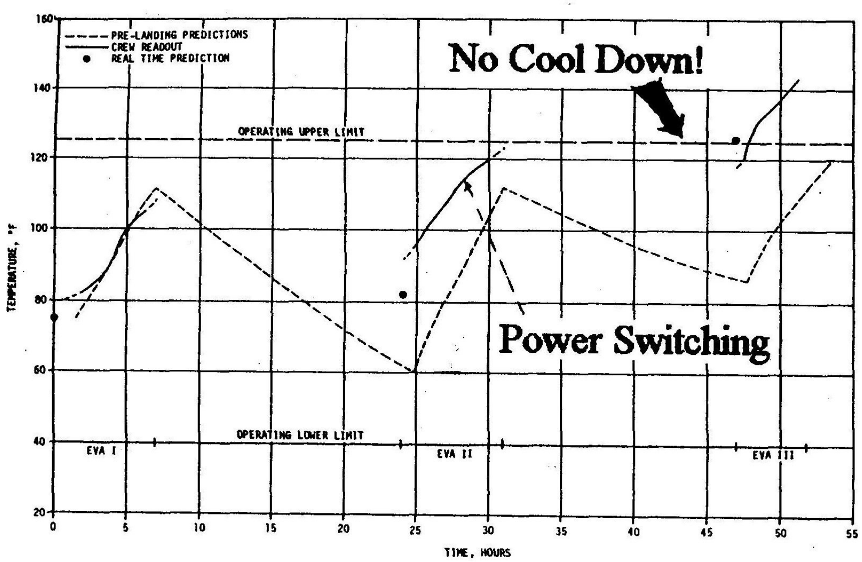


LRV Battery Temperatures During Cooldown 2

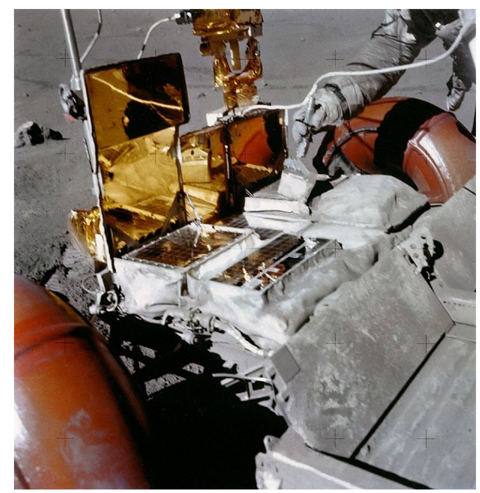


Dust On Radiators

Apollo Dust Brush



Battery No. 2 Temperature



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

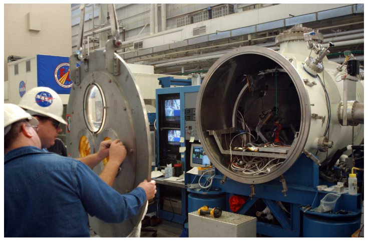
Source – Lockheed Martin – STAIF 2006 and IECEC 2006

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

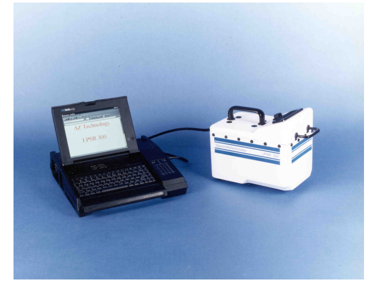
IR = Infrared

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

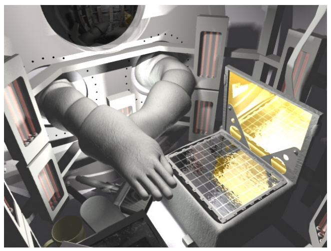
Return Chamber to Ambient

1 2 3 4 5

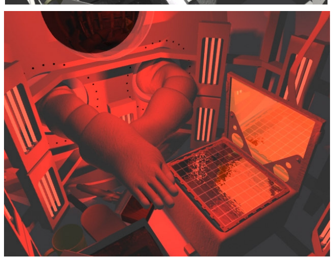
Simulation/ Test Cycles**

** Several Proposed Mitigation Techniques

5C



5A



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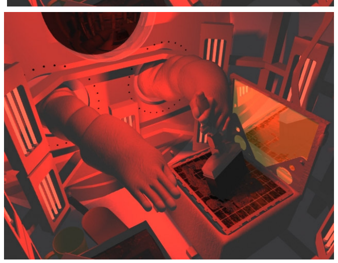
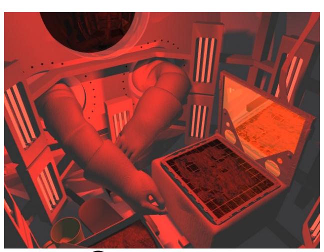
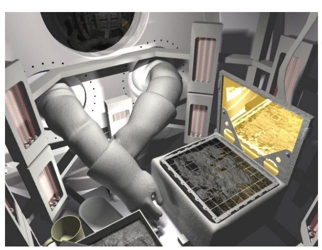


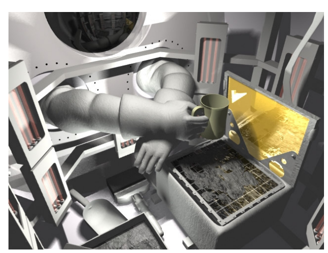
4C



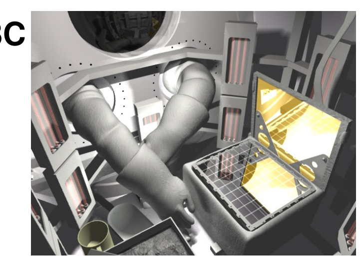
4A



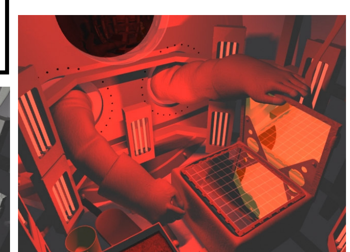
4



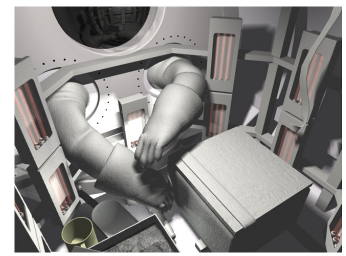
3C



3A



2A



2C

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Future Moon Rover Challenge 2 – Design For Extended Cold/Hot Missions

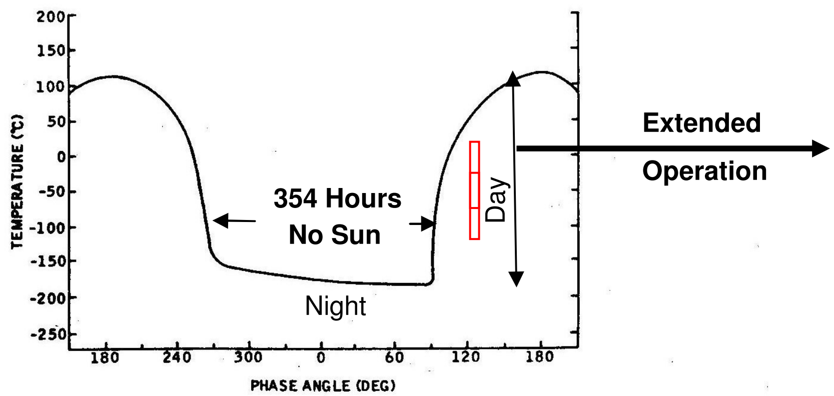
- Extended Operation In Much Colder And Warmer Environments Than Apollo LRV's Or Mars Rovers

Lunar Night

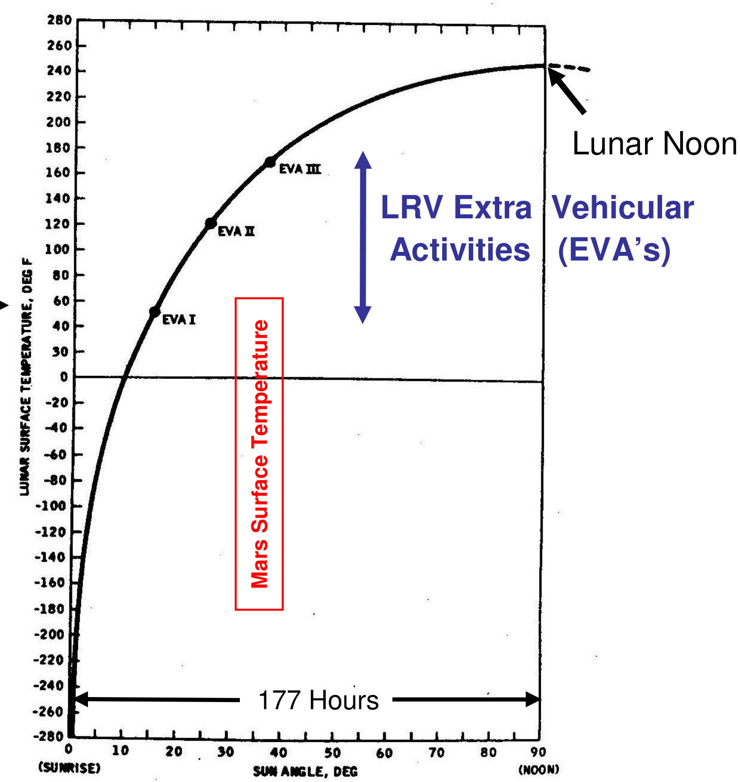
- 354 Hours Without Solar, Cold Moon
- Surface Temperature = -280 Deg. F

Lunar Day

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

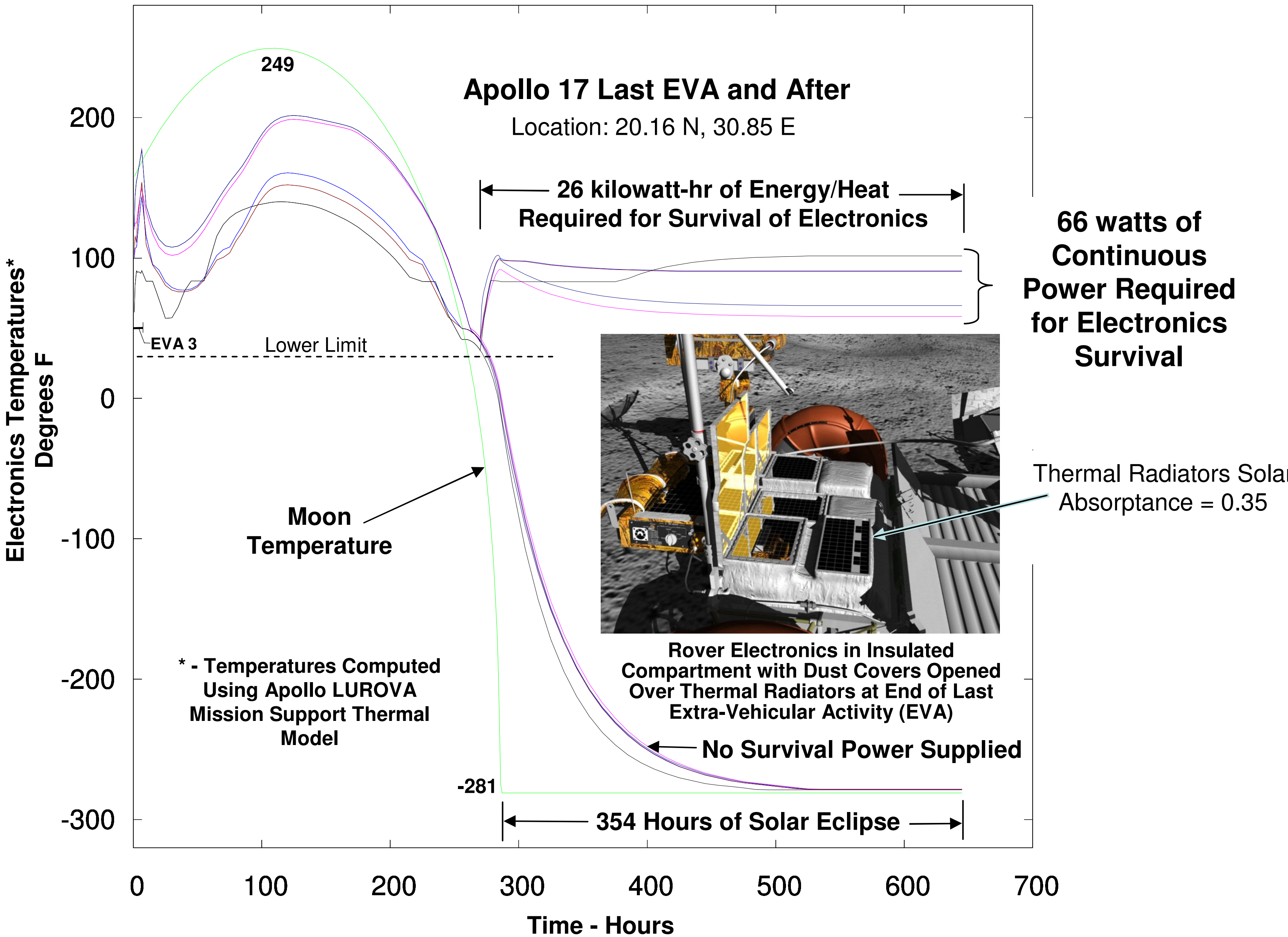


Temperature of the Moon. The average temperature of the Moon as a function of phase, or time, is shown here. The exact shape of the curve varies somewhat with geographical position on the Moon and is determined by the thermal properties at each position.



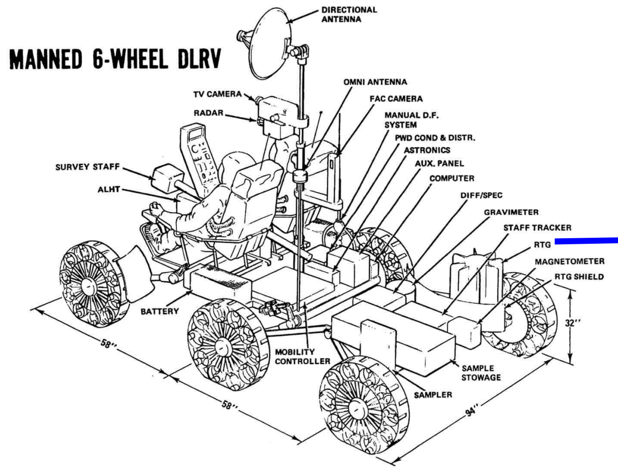
The temperature of the Taurus-Littrow site shown as a function of the Sun angle. Note that EVA 1 at +17° Sun angle should have +50° F, EVA 2 at +27° Sun angle should have +110° F, and EVA 3 at +37° Sun angle should have a temperature of +160° F.

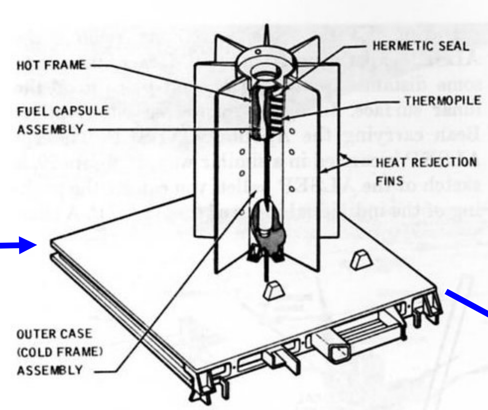
Apollo LRV– Power Needed for Extended Thermal Survival on Moon



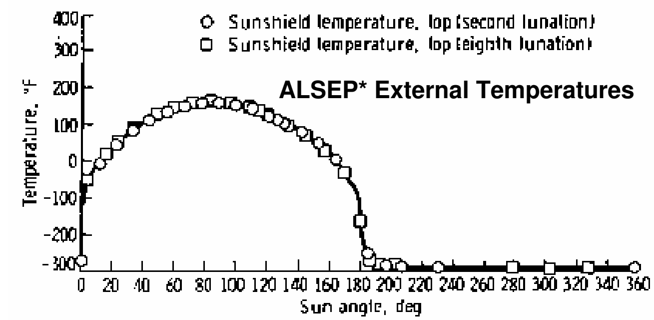
Nuclear Energy Provides Dependable/Efficient Survival Power/Heat

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

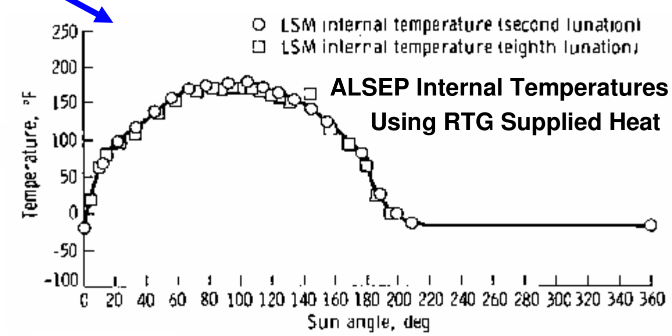




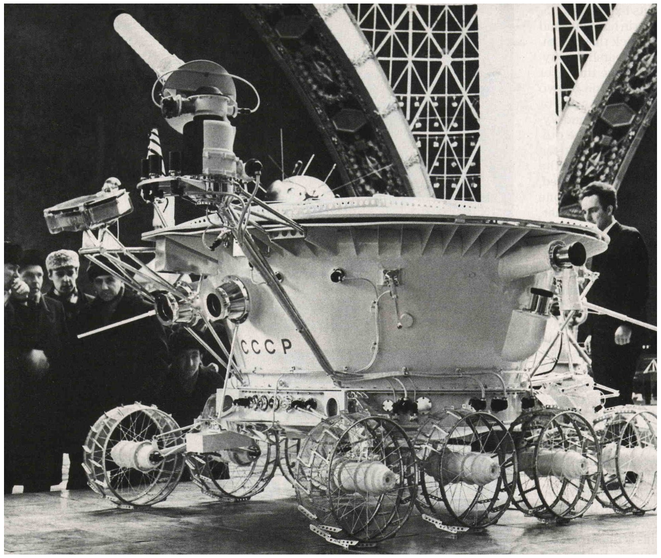
SNAP-27 -Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.



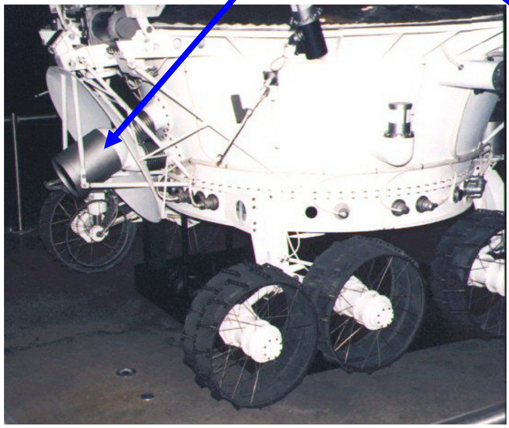
*ALSEP = Apollo Lunar Surface Experiments Package



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



Isotope Heater



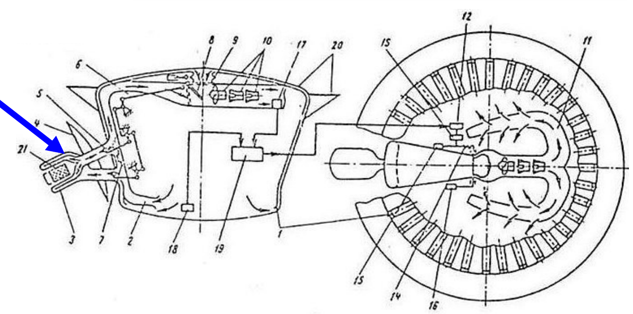


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism;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

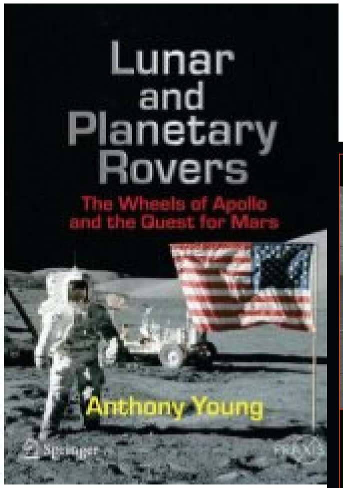
"Sputnik" Medal Was Accepted From Lunokhod Driver Gen. Dovgan On Behalf Of Apollo LRV Workers

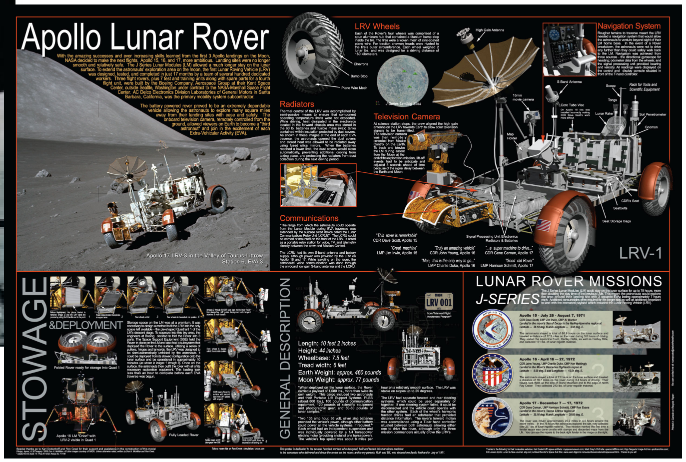
Russian Hero and Cosmonaut Georgi Grechko Presented Commemorative Vostok Pin To International Attendees

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

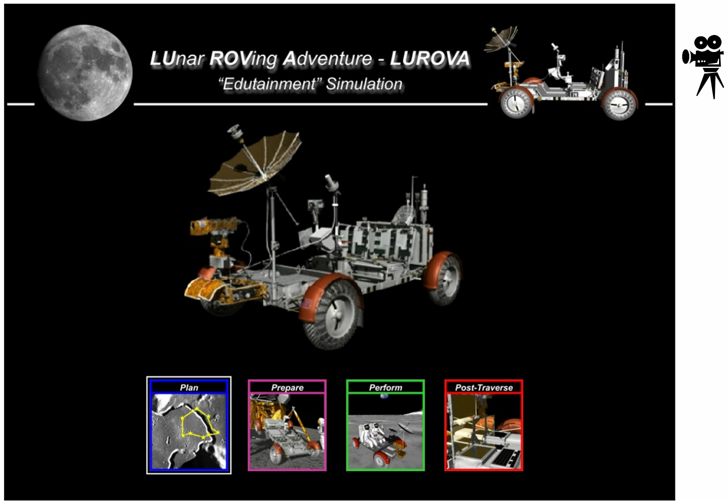
"Most Unique" Vehicle Judge And Added "Dust Challenge" For Great NASA Moonbuggy Race

Lectured and Judged USC "Lunar Design Studio" Project



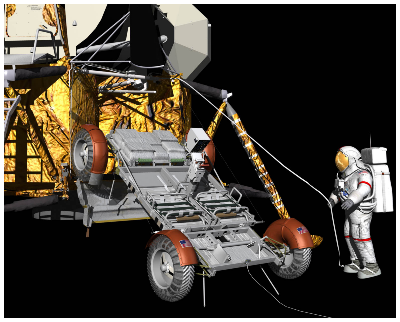


Helped Develop Apollo Lunar Rover Book and Poster



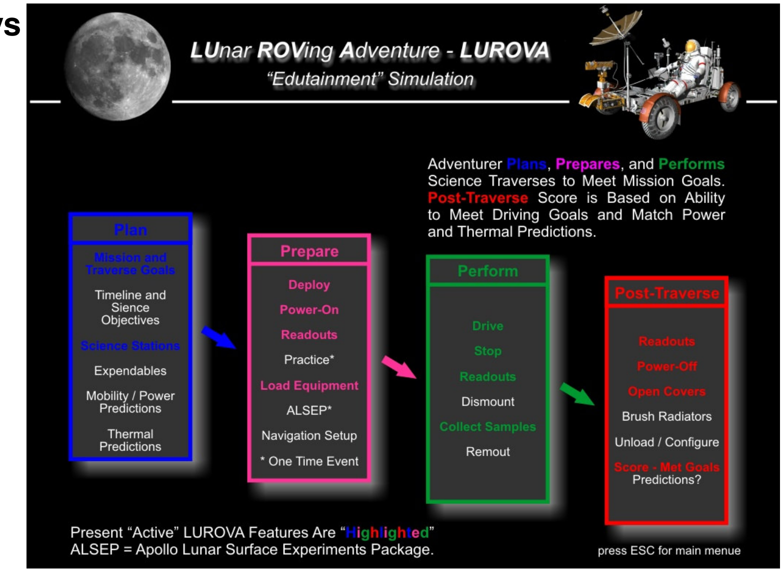
LUROVA Team Is Developing 3D Simulation To Challenge And Involve Students

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

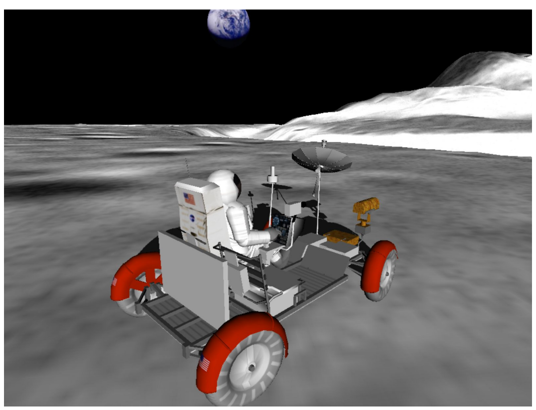


Student Deploys LRV From LM And Loads Equipment

Student Activates LRV Switches and Hand Controller For Driving



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



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
- 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

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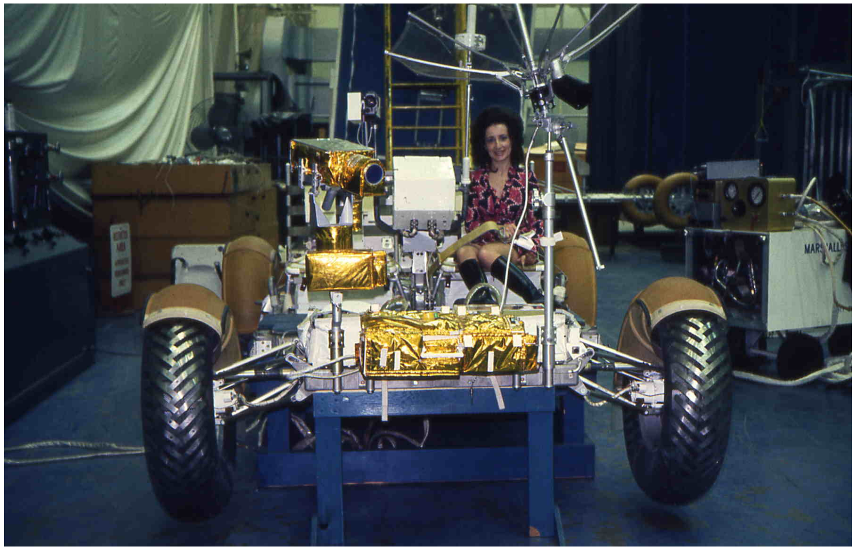
Dedications

“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