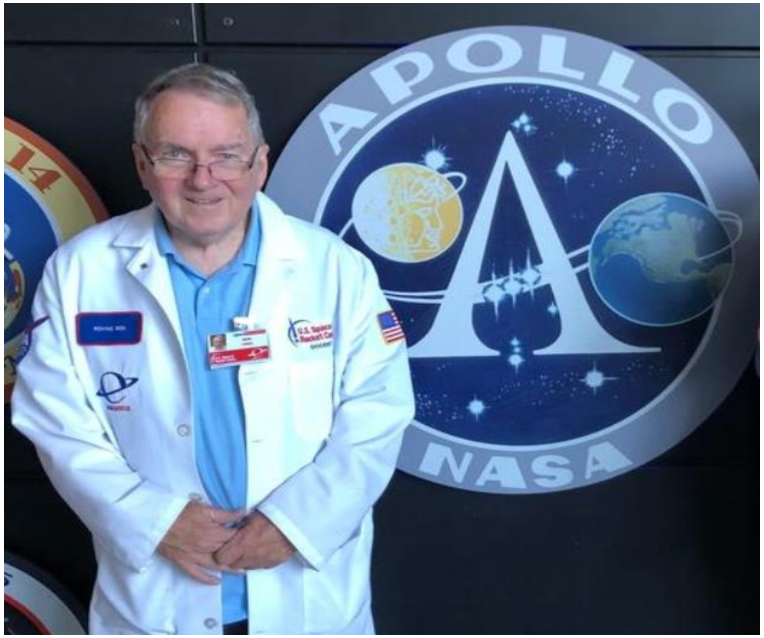
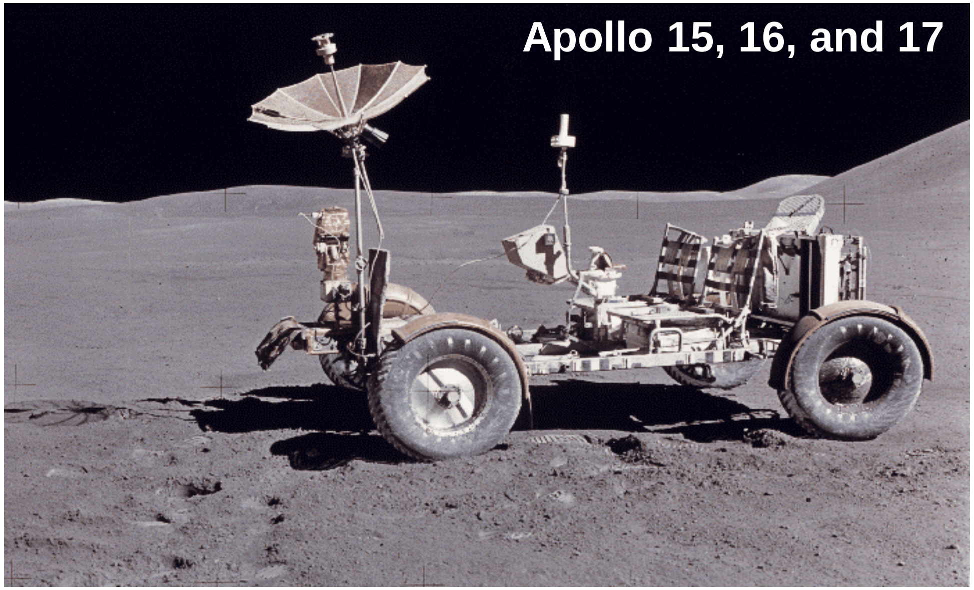
Moon Rover Thermal and Power Analysis for Night and PSR Survival

Ron Creel

Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
College Park, MD

- Retired Space and Thermal Systems Engineer
- Member of the Apollo Lunar Roving Vehicle (LRV) Team





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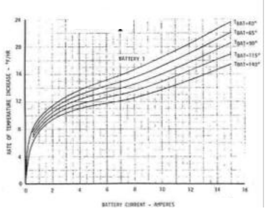
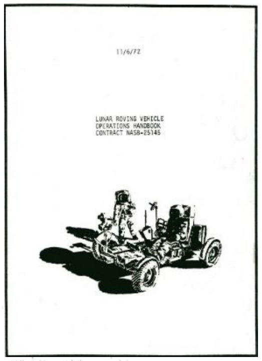
In the Beginning LRV Mission Support Thermal Modeling Was Challenging

- **1969** - Began Full Time Engineering at NASA / MSFC - Assigned to Thermal Control for Apollo LRV
- Initially Supplied Parametric Apollo 15 LRV Battery Heat Up/Cooldown Curves to Mission Control
- Chrysler Shape Factor Analyzer and Lockheed Orbital Heat Rate Package (LOHARP) Used to Calculate Sunlit Surface Radiation and Environment Parameters
  - Could Only Handle a Limited Number of Surfaces in Each Run
- PTD10 Surface Visualization Program Developed by a Colleague at NASA Marshall Space Flight Center

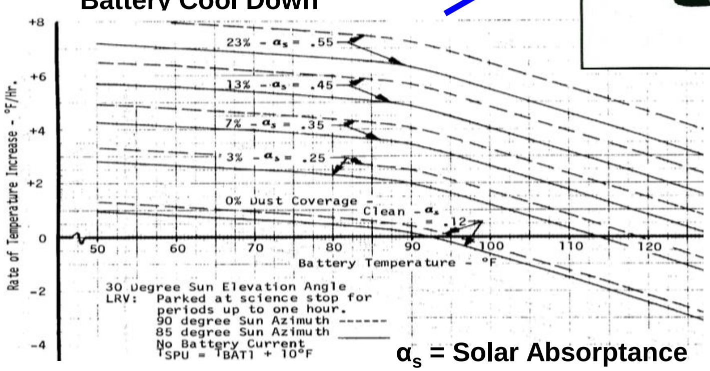
Battery Heat Up



Initial Parametric Thermal Response Curves Supplied for Apollo 15 Operations Handbook

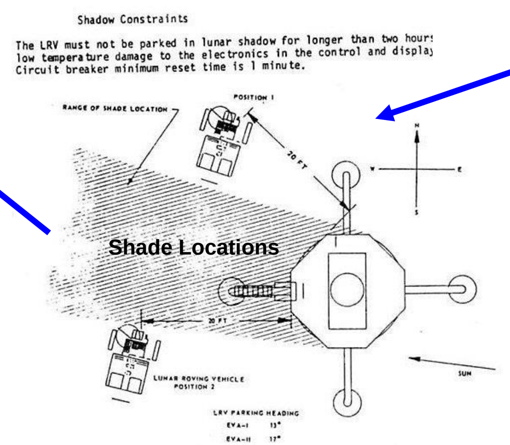


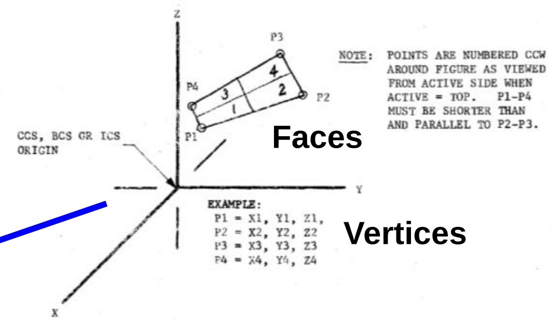
Battery Cool Down



α_s = Solar Absorptance

PTD10 "Wireframe" Verification Plots for Primitive Surface Models





Example Surface Polygon Input for LOHARP Trapezoid Primitives

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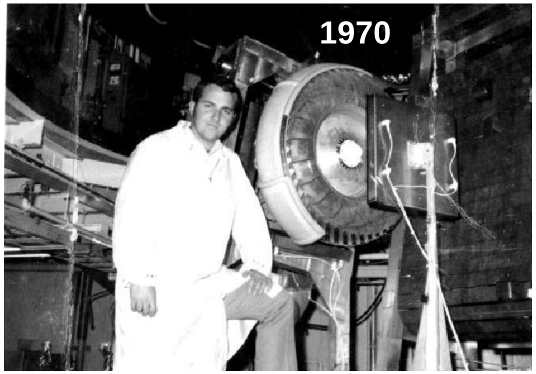
1970 - 1972

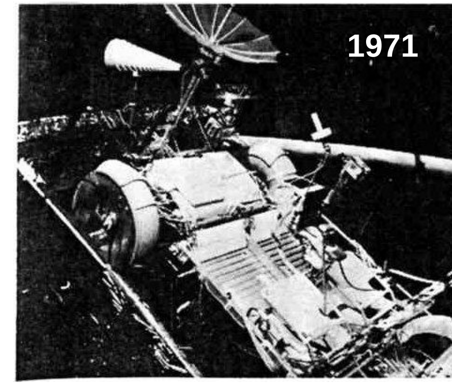


Mobility Subsystem TVAC Testing

- Cumbersome 181 Node "Full" Model Correlated with TVAC* Testing Data for Apollo 15 LRV

- Separate Forward, Center, and Aft Section Models Required Due to LOHARP 140 Surface Node Limit

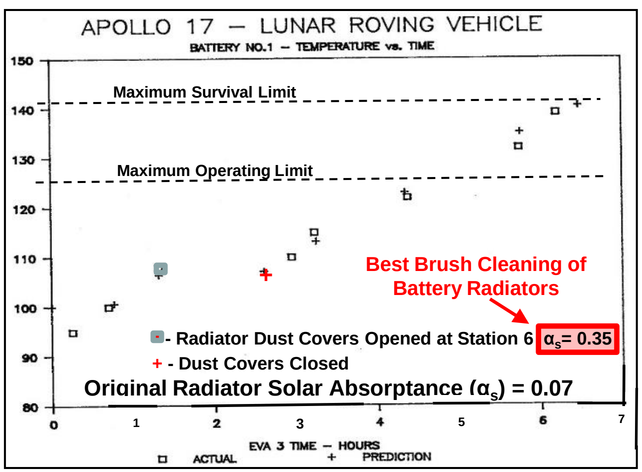
August 1971



Qualification and Flight Units TVAC Testing

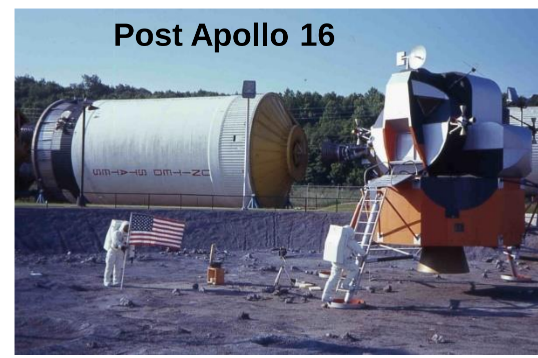
Apr./Dec. 1972

- 19 Node Forward Chassis, Batteries (8712 Watt-Hours), and Electronics Model Developed for Responsive Apollo 16 and 17 Support for Lunar Sunlit Morning Missions



Astronauts Awarded

"Silver Snoopy"



Model View Factor Verification Using Form Factometer and Lunar Module Model at U.S. Space and Rocket Center

Accurate Predictions for Realtime Mission Control

LUROVA = LUnar ROVer Adventures
* TVAC = Thermal VACuum

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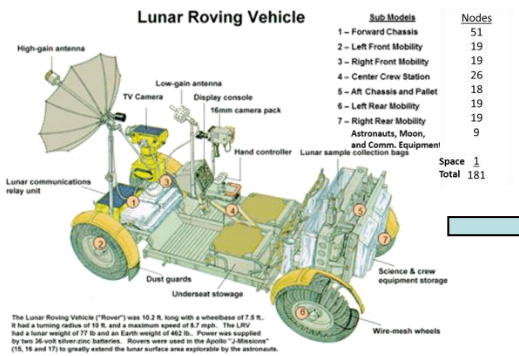
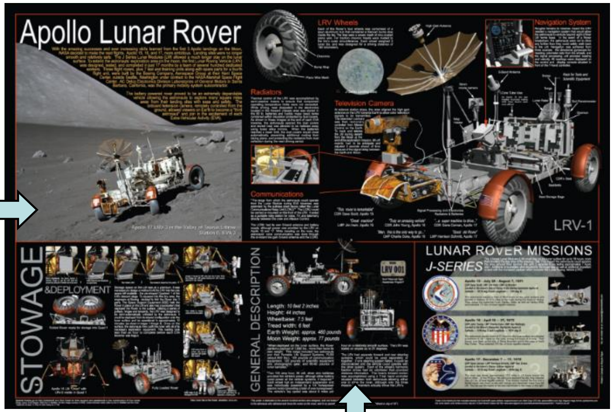
2006

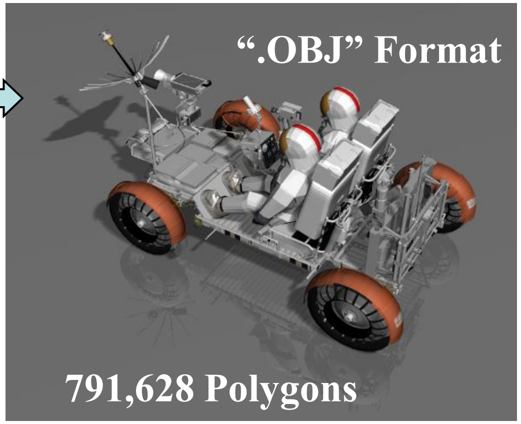
- **Original "Full" Rover Thermal Model Nodes and Linear Conductors List Located**
  - **But No Surface Model for TRASYS Radiation Conductors and Solar Heat Rates**
- **High Quality Candidate "Lightwave" (.LWO) Rendered Polygons Used for Poster**



181 Node TVAC Test Correlated NASA Rover SINDA* Thermal Model Used for Apollo 15 Mission Support



Astronaut Crew Added and Model Converted to .OBJ Format for Polygon Faces and Vertices



  - **Accurate Rover Poster and 3D Model Created by Associate Don McMillan in Ottawa, Canada**

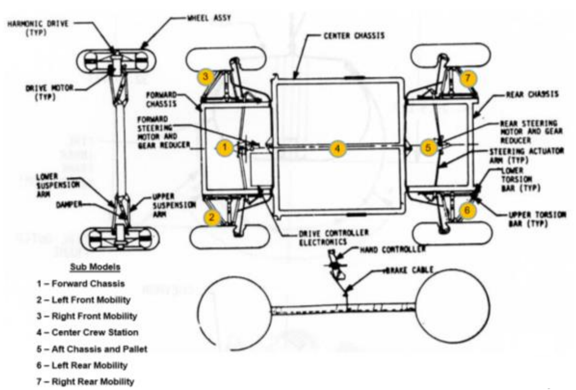
- **Too Many Polygon Surfaces for NASA Thermal Radiation Analysis SYStem (TRASYS) - 4,000 Node (Polygon) Limit, So Sub-Models Were Required**

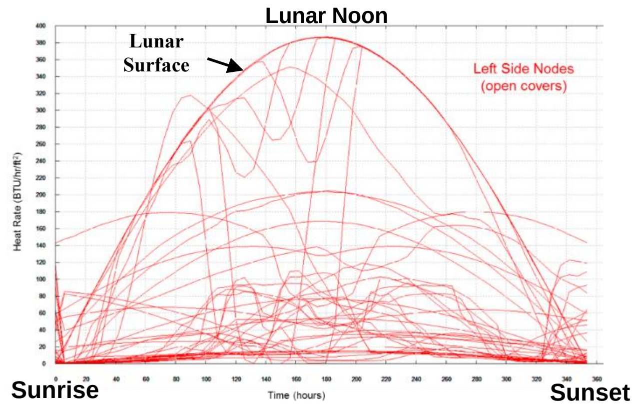
*** SINDA = Systems Improved Numerical Differencing Analyzer**

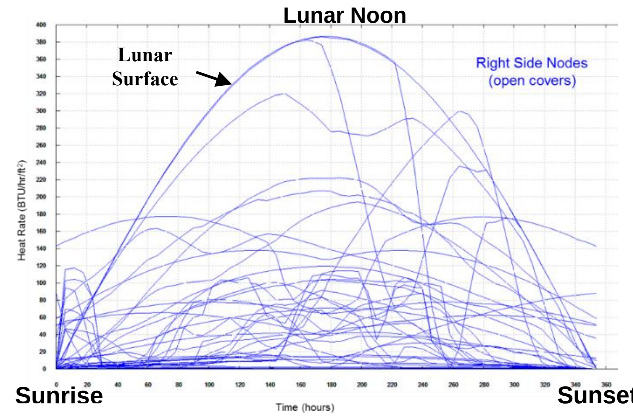
SURFP Subroutine Used for LRV Sub-Model Solar Heat Rates with All Surfaces Assumed Dust Covered (α_s = 0.9)

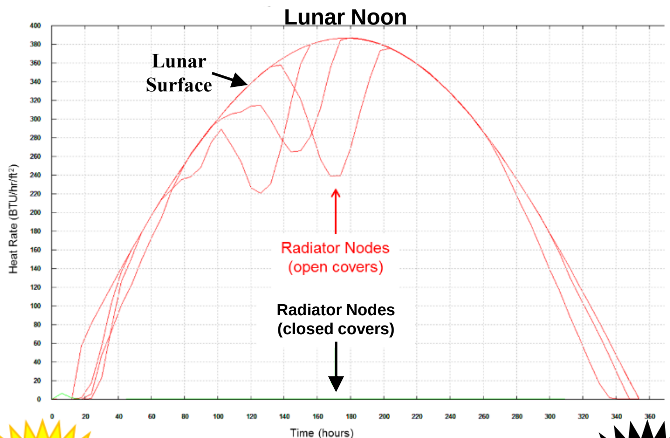
TFAWS 2014 – August 4 -8, 2014

LUROVA Surface Sub Models



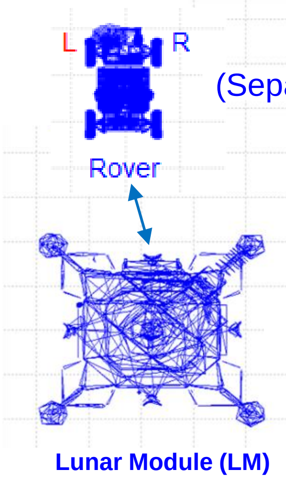






Sunrise

Sunset

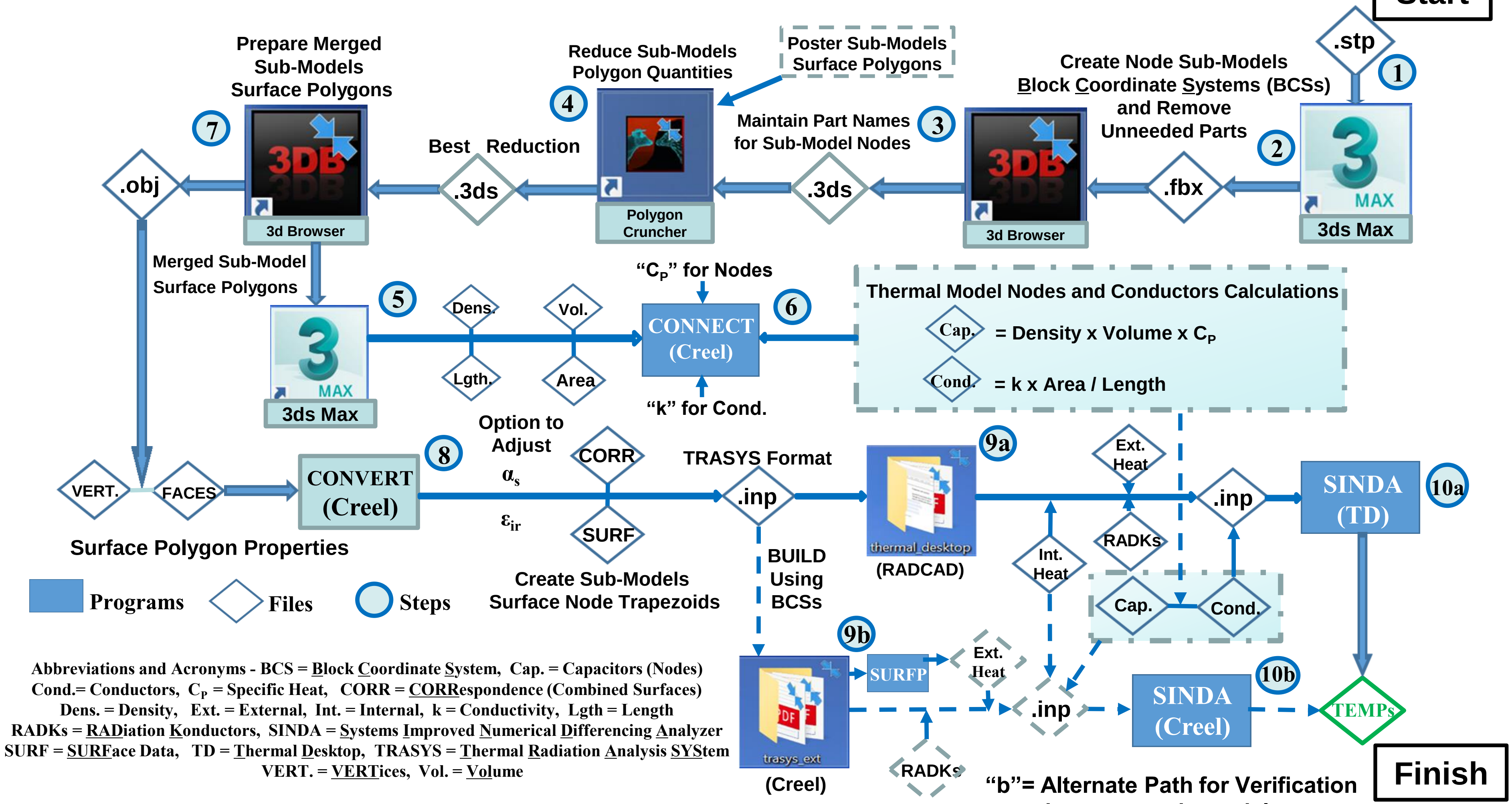


761,628 Polygons (Separated into Sub Models and Crunched)

233,856 Polygons (Crunched to 2000)

Creel Thermal Analysis Modeling (10) Step Process

From CAD “STEP” File to Temperatures



Abbreviations and Acronyms - BCS = Block Coordinate System, Cap. = Capacitors (Nodes)
Cond.= Conductors, C_P = Specific Heat, CORR = CORRespondence (Combined Surfaces)
Dens. = Density, Ext. = External, Int. = Internal, k = Conductivity, Lgth = Length
RADKs = RADiation Konductors, SINDA = Systems Improved Numerical Differencing Analyzer
SURF = SURFace Data, TD = Thermal Desktop, TRASYS = Thermal Radiation Analysis SYStem
VERT. = VERTices, Vol. = Volume

α_s = Solar Absorptance, ε_{ir} = Infrared Emissivity

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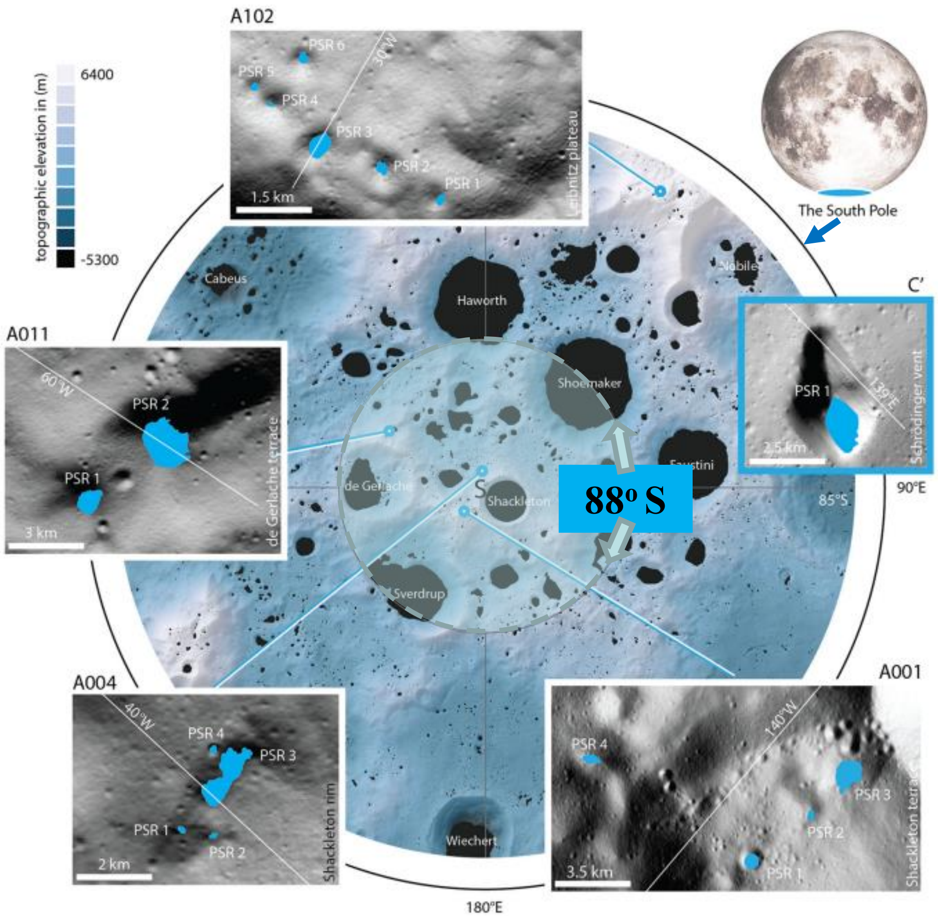
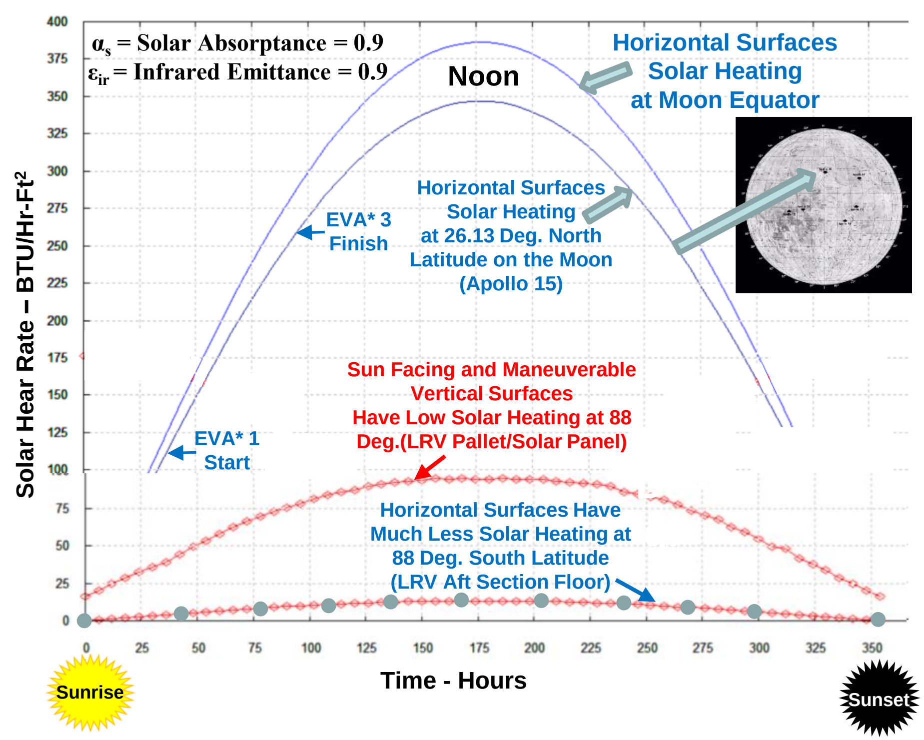
NASA Preparing for Candidate Lunar South Pole PSRs

2023



Much Lower Solar Heating in South Pole Region With Difficult and Risky "Chasing the Sunlight" Traverses for Providing Dependable Solar Power



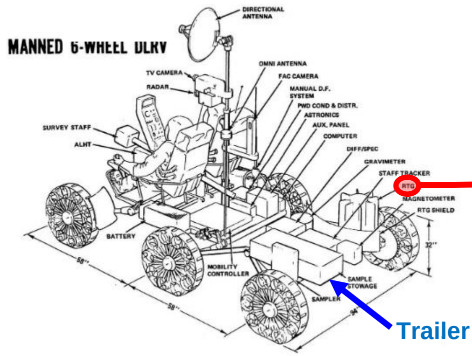
* EVA = Extra-Vehicular Activity

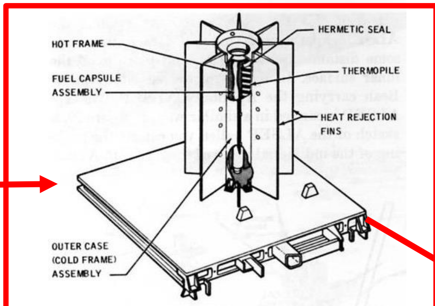
2021 Source: "Peering into Lunar Permanently Shadowed Regions with Deep Learning" (https://www.nature.com/ articles/s41467-021-25882-z)

Nuclear Energy Provided Dependable and Efficient Moon Survival Power/ Heat

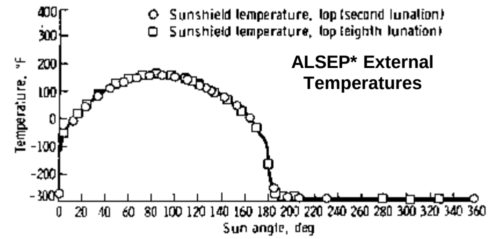
1969 - 1977

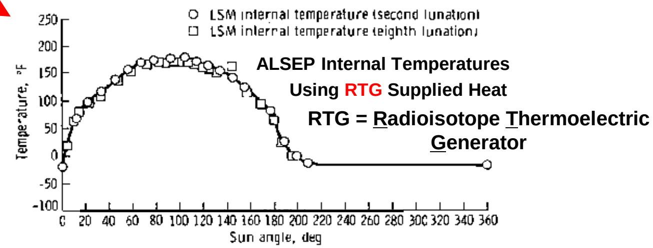
- **Nuclear Sources Studied for Apollo 18 Dual Mode Lunar Rover (DLRV) and Used on 5 ALSEPs***





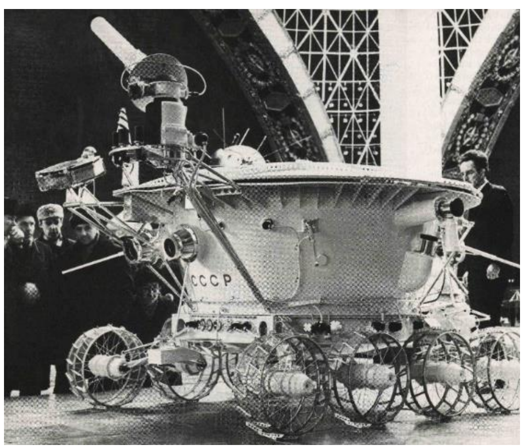
SNAP-27**–Radioisotope Thermal Generator. This equipment provides all of the power used by the ALSEP. It furnishes continuously about 70 watts.

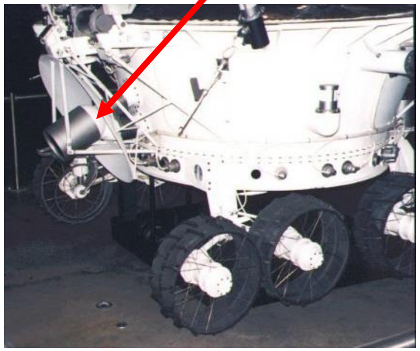




- **Russians Successfully Used Nuclear Isotope Heat Sources for Several Lunar Night Cycles on Their Lunokhod (Moonwalker) Robotic Rovers**

Isotope Heater





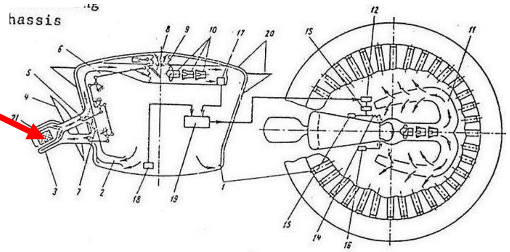


Diagram of lunokhod heat regulating system. 1) air passages of cold channel; 2) air passage of hot channel; 3) heating unit (HU); 4) HU shield; 5) HU "blinds"; 6) control of HU blinds; 7) baffle plate; 8) baffle; 9) connecting sheath; 10) three-step fan; 11) collector; 12) baffle drive; 13) step mechanism;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

*ALSEP = Apollo Lunar Surface Experiments Package

**SNAP = System for Nuclear Auxiliary Power

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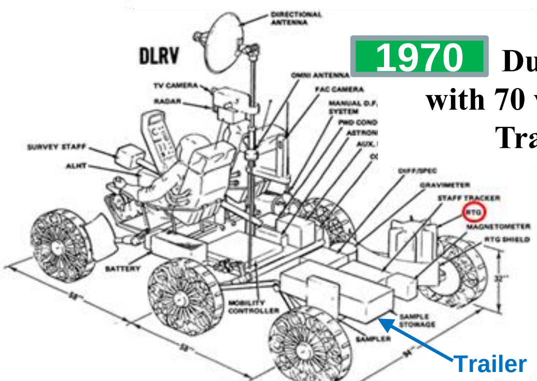
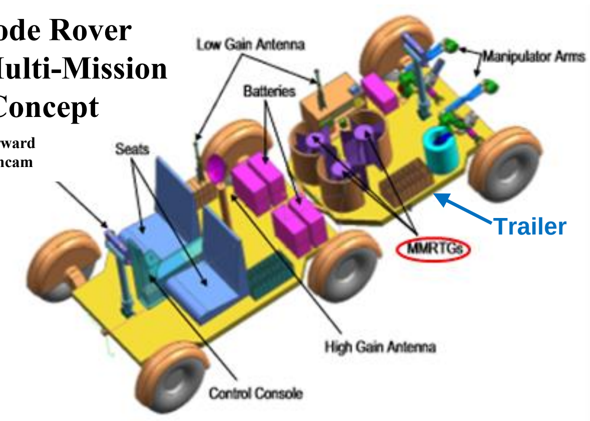
Energy Sources and Storage Studied for Extended Rover Nighttime Survival and Operation

1970 - 2018



1970 Dual Mode Rover Concept with 70 watt Nuclear RTG* on Trailer for Apollo 18

2006 - JPL** Dual Mode Rover (DMLRV) with Nuclear Multi-Mission RTGs* (MMRTGs) Concept

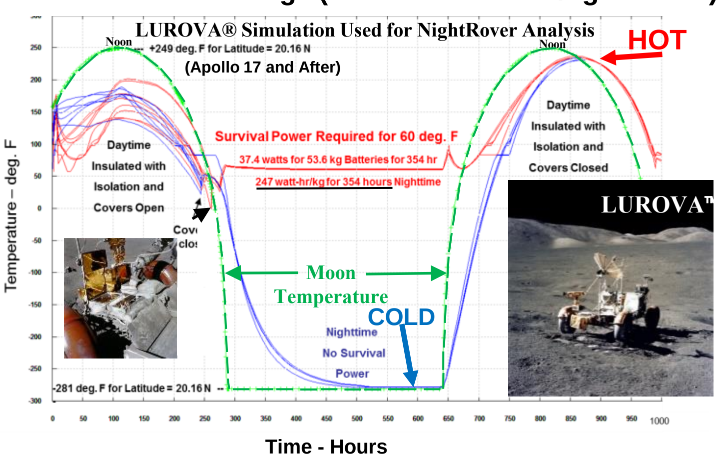


DMLRV Conceptual Design.

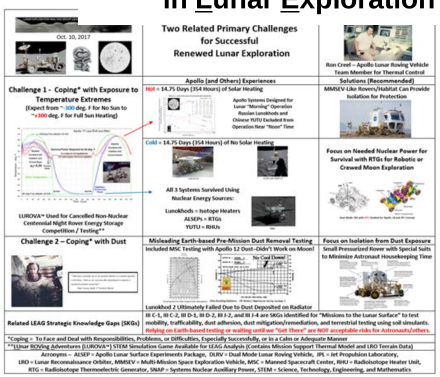
2004 - International Space Development Conference Panel on "Nuclear Energy for the Space Exploration Initiative"

Invited to Present Apollo LRV Thermal Experiences at Lunokhod Facility in St. Petersburg, Russia

2011-2013 - Night Rover Non-Nuclear Energy Storage Centennial Challenge (> 250 Watt-Hours/kg Desired)



2017 - 2018 - Dust and Nighttime Survival and Operation Challenges Presented in Lunar Exploration Analysis Group (LEAG) Poster and Presentation



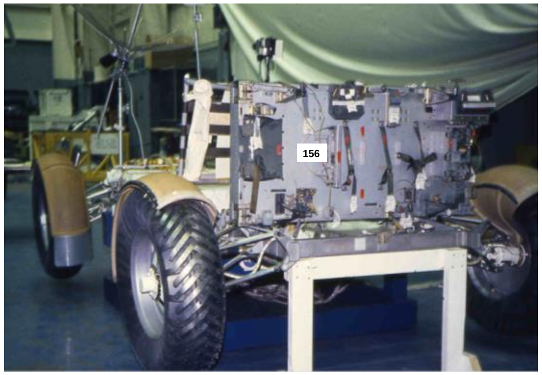
* RTG = Radioisotope Thermoelectric Generator   **JPL = Jet Propulsion Laboratory

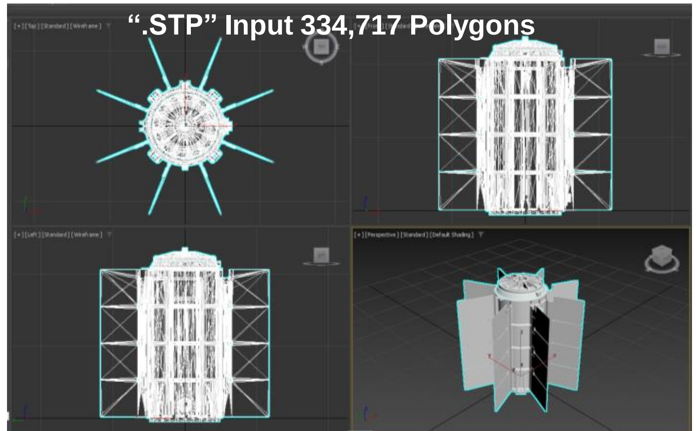
Initial Study of LRV Aft Pallet for JPL MMRTG Radiation Shield

2022

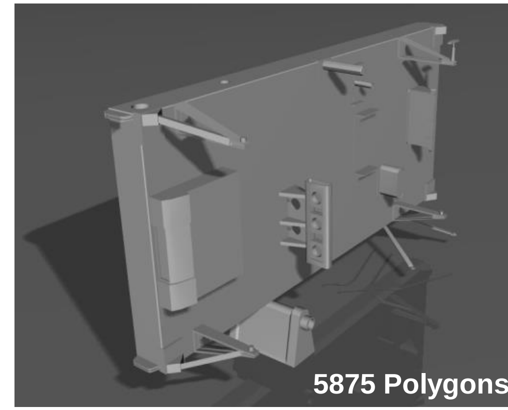
LRV Aft Pallet Reduces Radiation to Crew

LRV Qualification Unit Aft Pallet

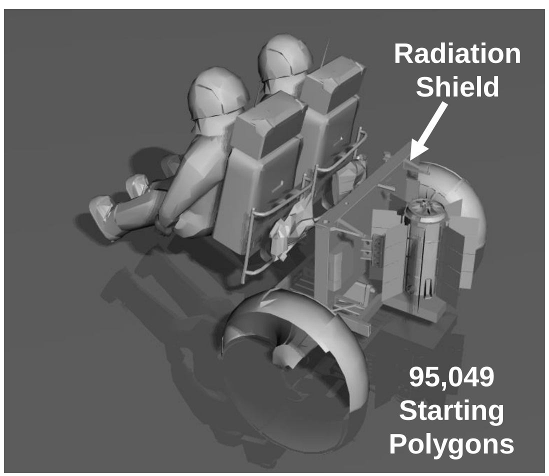


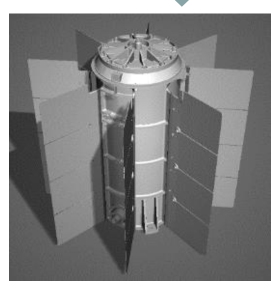


Aft Pallet Thermal Surface Model

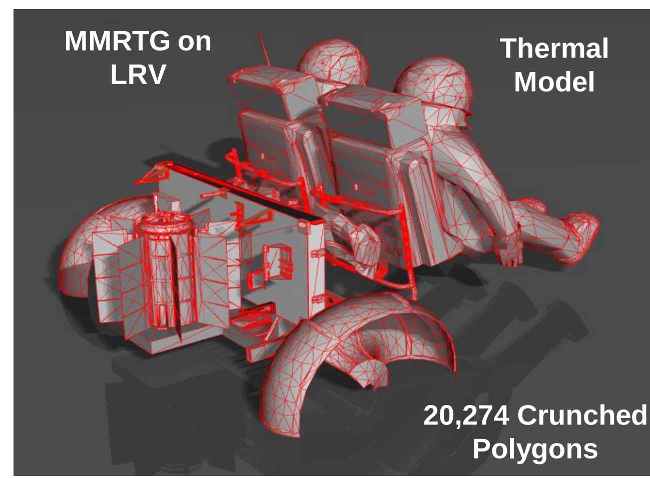


JPL MMRTG*, as Used on Mars Curiosity and Perseverance Rovers (110 Watts Continuous)





10,738 Crunched Polygons



*** MMRTG = Multi Mission Radioisotope Thermoelectric Generator**

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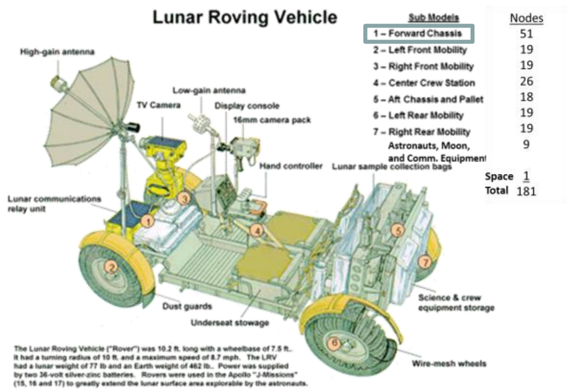
Initial Study Results - LRV Battery Temperatures for Coldest 85 Hour PSR

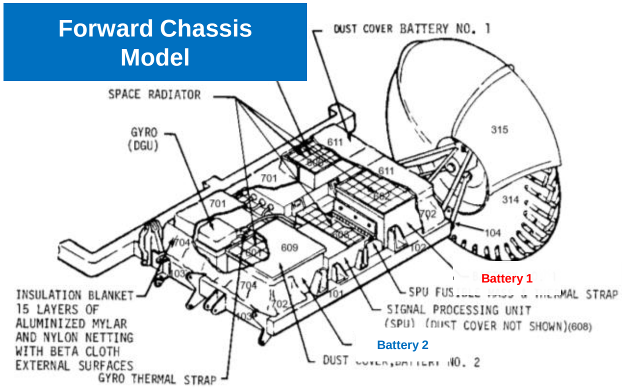
2022

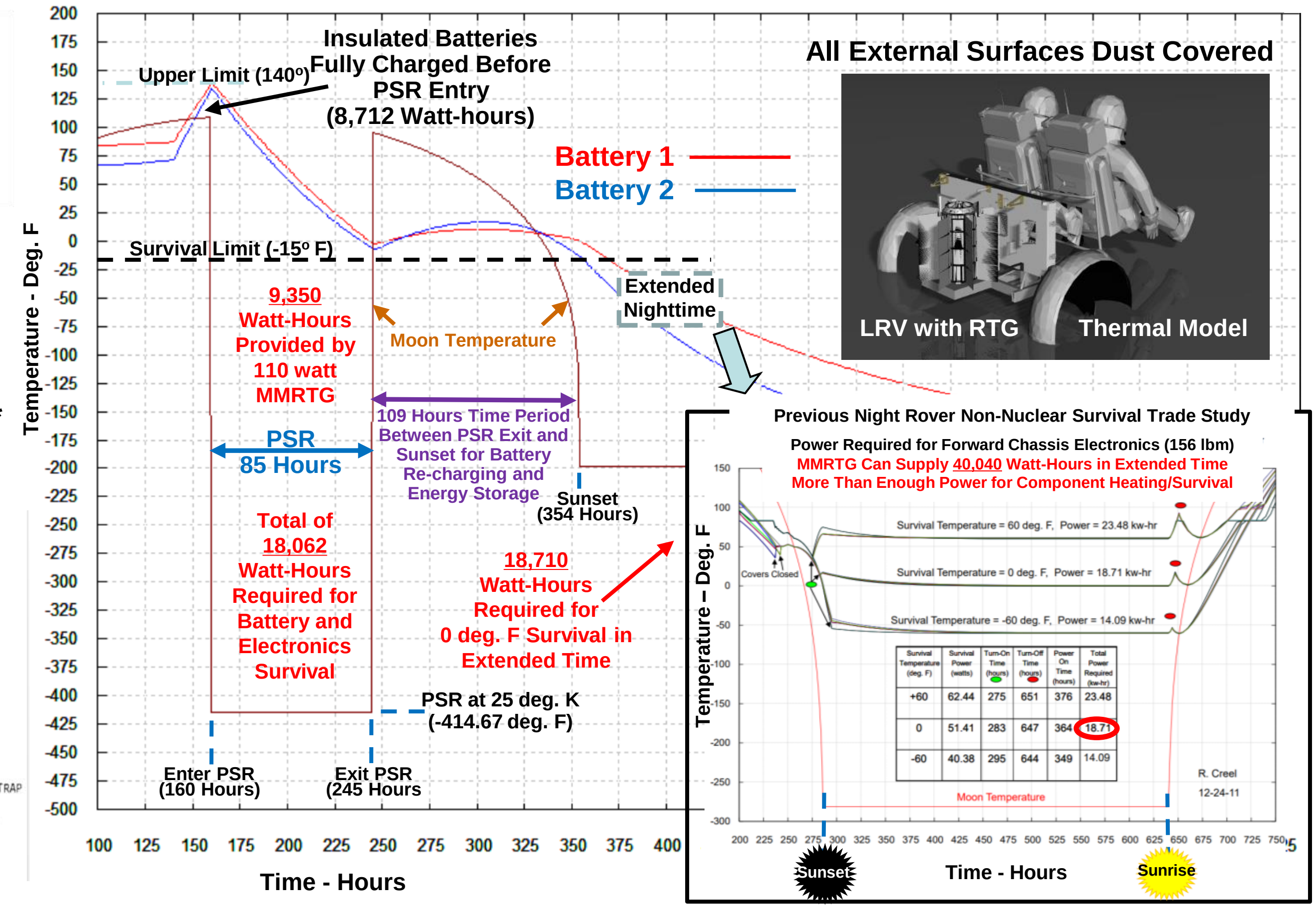
LRV Driven and Parked at 88 deg. South Latitude with 110 Watt MMRTG Added to Battery Power in PSR



181 Node TVAC Test Correlated NASA Rover SINDA* Thermal Model Used for Apollo 15 Mission Support

Forward Chassis Model





Survival Temperature (deg. F)	Survival Power (watts)	Turn-On Time (hours)	Turn-Off Time (hours)	Power On Time (hours)	Total Power Required (kw-hr)
+60	62.44	275	651	376	23.48
0	51.41	283	647	364	18.71
-60	40.38	295	644	349	14.09

*** SINDA = Systems Improved Numerical Differencing Analyzer**

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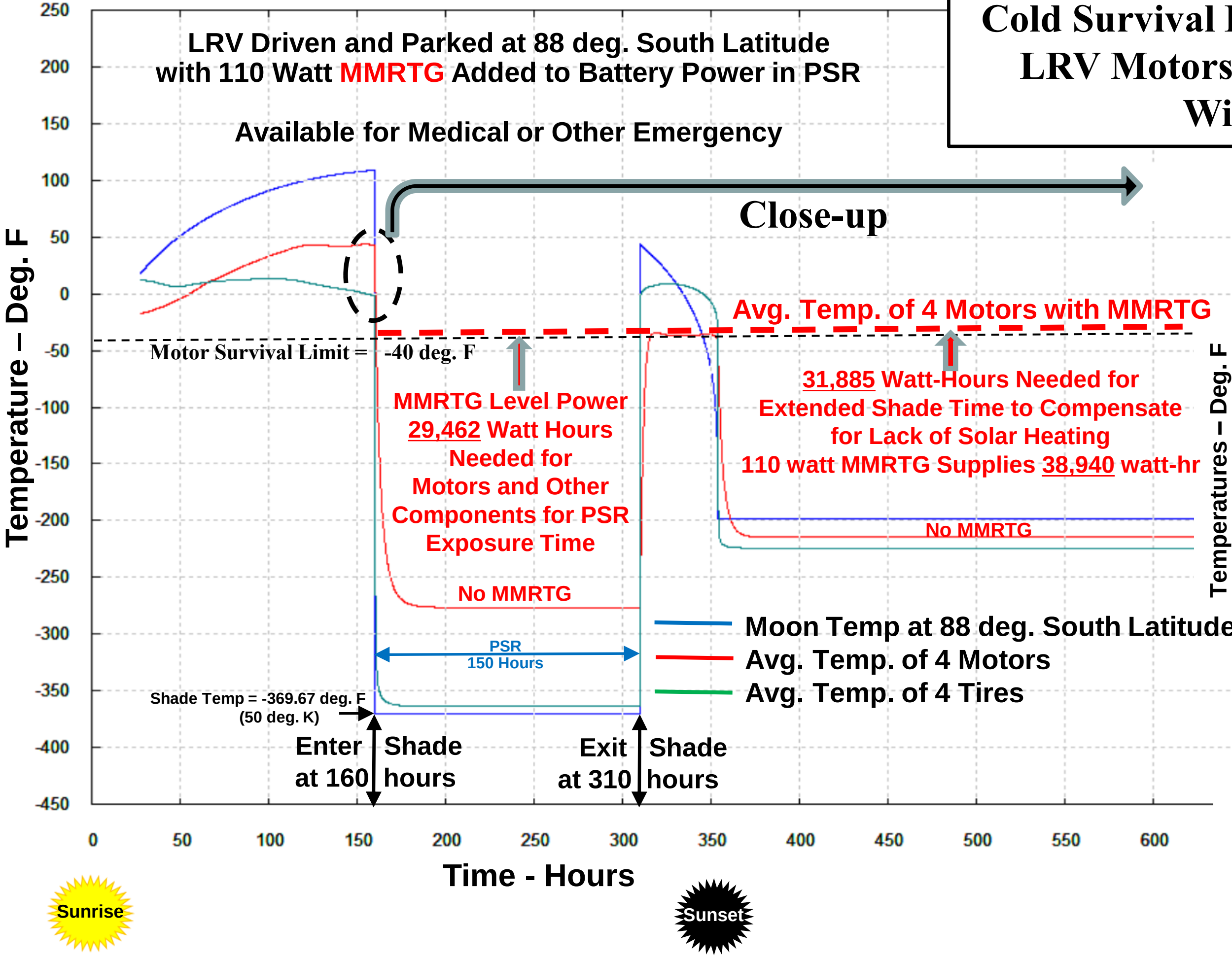
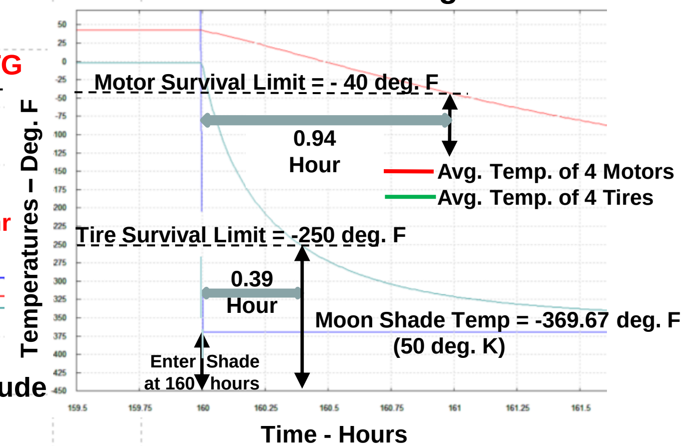
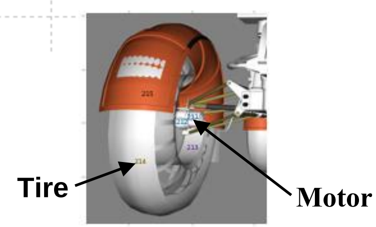
150 Hours LRV Exposure in 50 Deg. K PSR

Cold Survival Limits Reached in <u>0.94</u> Hours for LRV Motors and <u>0.39</u> Hours for LRV Tires Without Heating Power



Close-up of Initial Motor/Tire Cooling in Shade Without Heating Power

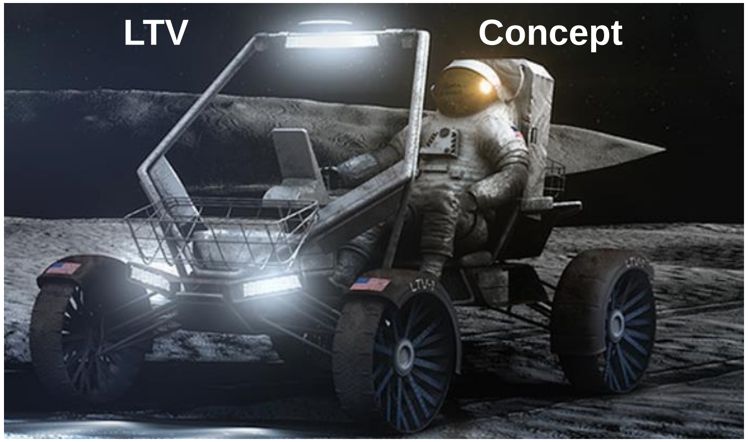




Right Front Mobility Subsystem

2023

NASA LUNAR TERRAIN VEHICLE (LTV)
Single Spacecraft for Ten Year Crewed and Robotic Moon Exploration



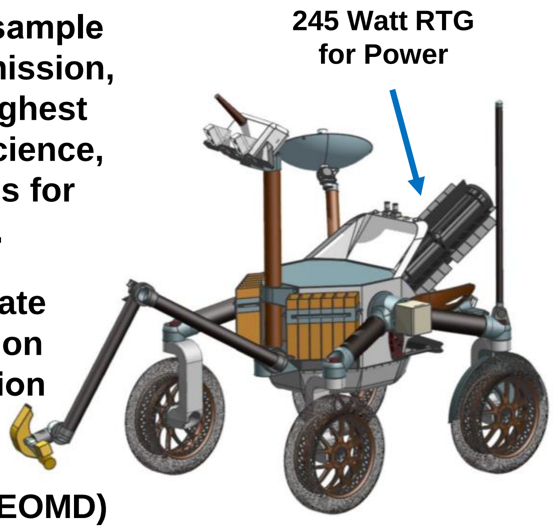
LTV "Chasing the Sunlight" Traverses Will Be Difficult and Risky, and Could be Dangerous, Especially for Emergency Need for Dependable and Immediate Energy for Transit Back to the Lunar Home Base

Requires Heavy and Maneuverable Panels for Solar Energy Collection

JPL - Endurance A Robotic Moon Rover

"Endurance is effectively a sample collection campaign in one mission, and it would address the highest priority questions in lunar science, with enormous implications for Solar System science.

Endurance-A option would create a new paradigm for collaboration between NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) - achieving more science for less cost."



Recommendation - Combine These Rovers to Provide Dependable and Safe Exploration Power and Gain Those Significant Cost Savings

Additional Benefit: Reduces Size/Mass of Batteries and Solar Collection Panels

Reducing RTG Radiation to Rover Astronauts

2023

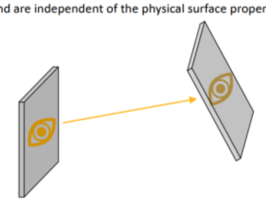
Using Radiation Shield and/or Trailer

What is the View Factor?

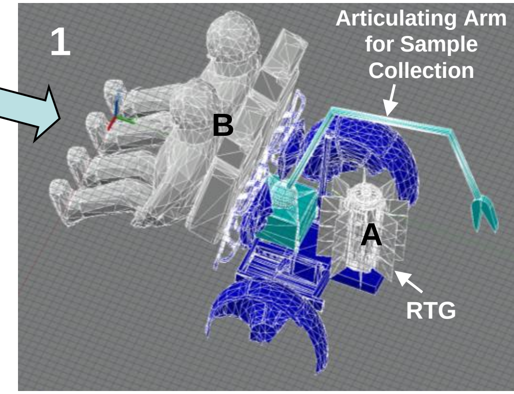
The **View Factor** is the portion of the radiative heat flux which leaves surface A that strikes surface B.

- In simpler terms, the view factor measures how well one surface can see another surface.
- View factors are purely **geometrical parameters** and are independent of the physical surface properties and temperature.

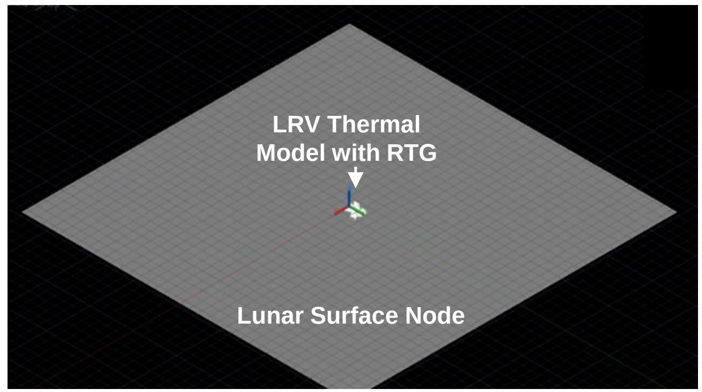
$$Q_{ij} = A_i \varepsilon_i F_{ij} \sigma (T_i^4 - T_j^4)$$

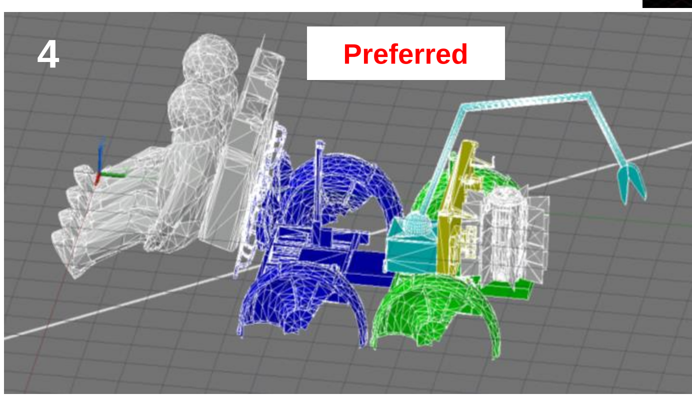


Modeled Starting with Flight Proven Apollo LRV Thermal Model With RTG Placed on LRV Aft Area Without Radiation Shield

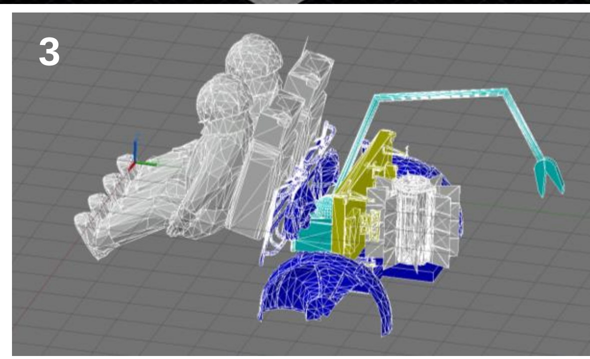


View Factor from RTG to Seated Astronauts is <u>0.00905</u> = 0.91 Percent Without Radiation Shield

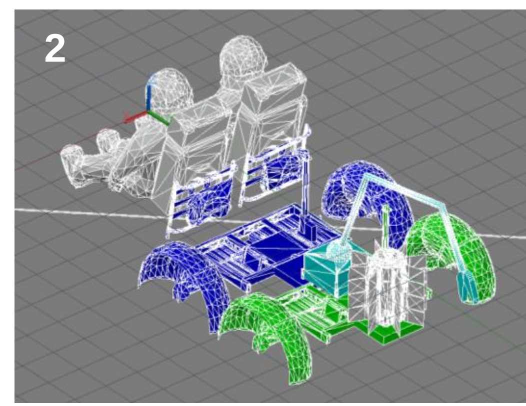




Adding Aft Pallet Radiation Shield to Trailer Reduces the View Factor from the RTG to Seated Astronauts to <u>0.0</u> = 0.0 Percent



Adding a Radiation Shield Using a LRV Aft Pallet Reduces the View Factor from the RTG to Seated Astronauts to <u>0.001023</u> = 0.10 Percent



Moving RTG to Trailer Reduces View Factor from RTG to Seated Astronauts to <u>0.002345</u> = 0.23 Percent

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Summary

- Lunar Rovers Greatly Increased Science Accomplishments on Apollo 15, 16, and 17 Missions
  - Included Very Important Evolution of Accurate Visible Thermal Models for Mission Support

- <u>Accurate</u> Rover Thermal Surface Modeling Has Improved Over the Past 54 Years
  - Mostly <u>Automated</u> Surface Handling Process Developed Using 4 Commercially Available Software Programs : 3ds Max, 3d Browser, Polygon Cruncher, and Thermal Desktop

- Radioisotope Thermoelectric Generator Recommended for New Artemis Lunar Terrain Vehicle
  - Would be a Valuable Addition If Presently Planned "Chasing the Sunlight" is Not Achievable
    - -- Combining the "Endurance" RTG with the LTV Can Reduce Exploration Costs and Provide Important <u>Immediately Available Power</u> for Emergencies
  - Would Reduce Size/Mass of Batteries and Maneuverable Solar Energy Collection Panels

Bottom Line : Let's Get These Rovers Combined for Safe and Reliable South Pole Science Exploration on the Moon

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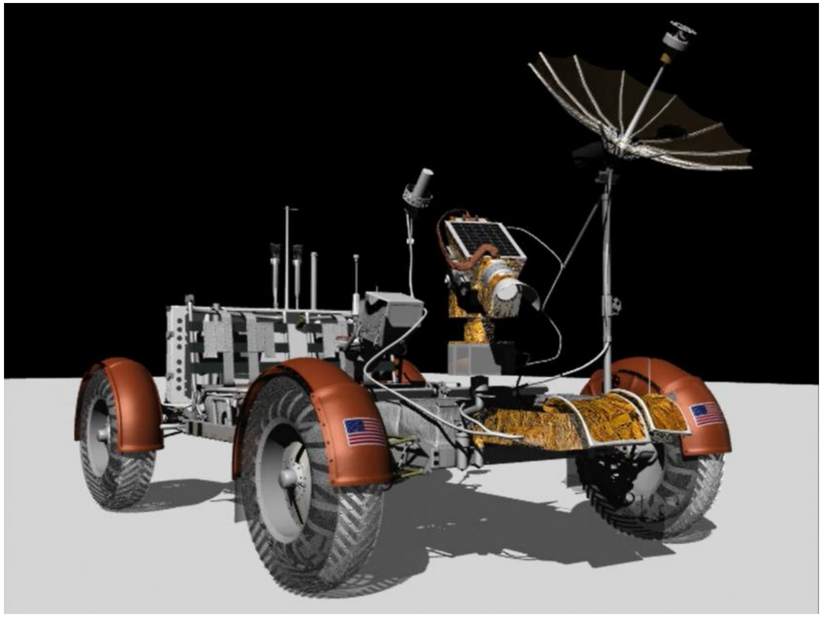
Questions?



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