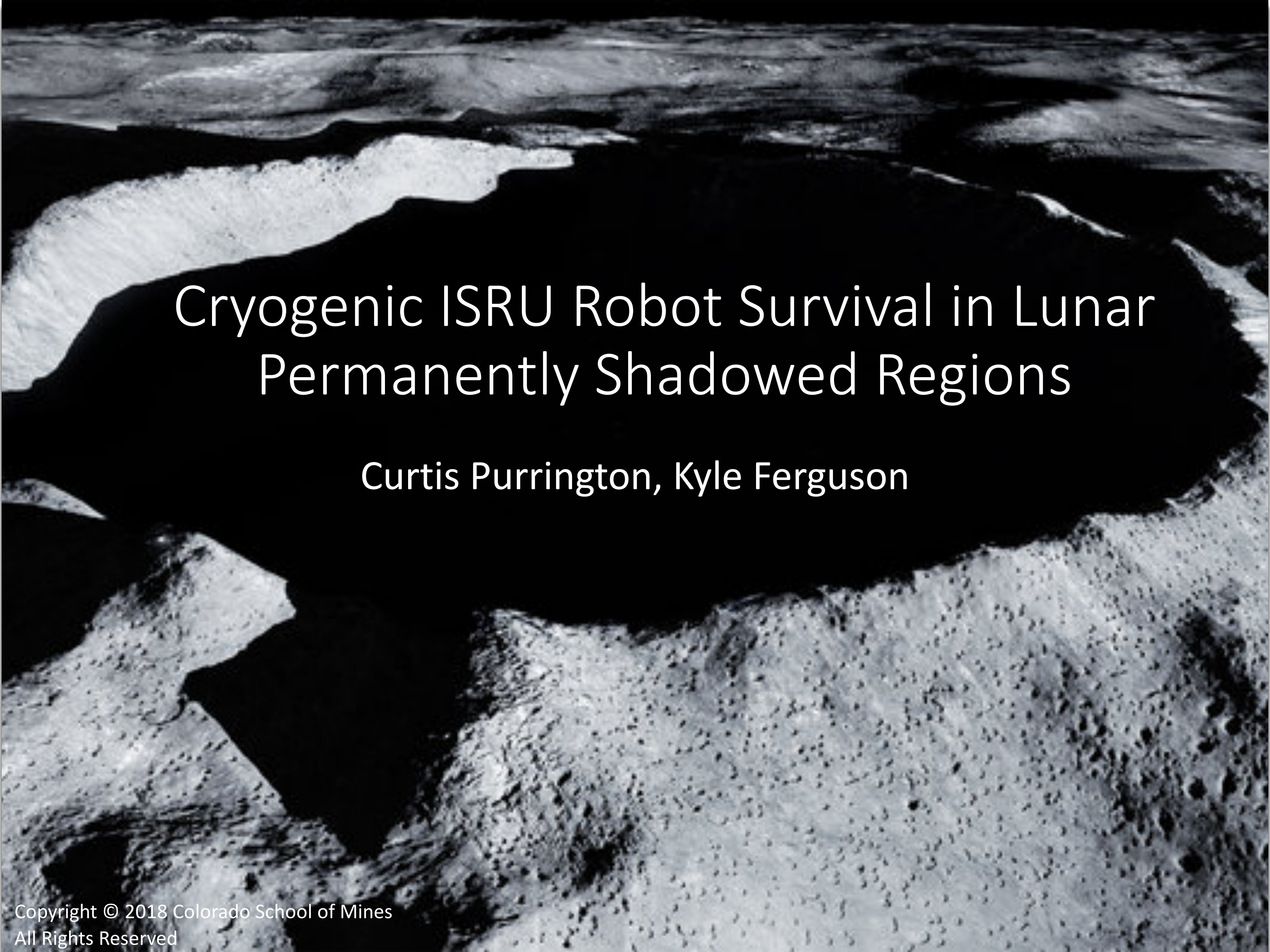
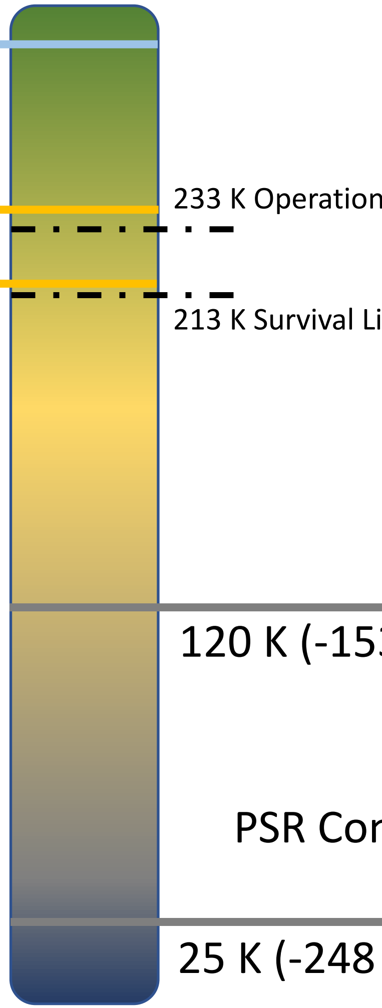


Cryogenic ISRU Robot Survival in Lunar Permanently Shadowed Regions

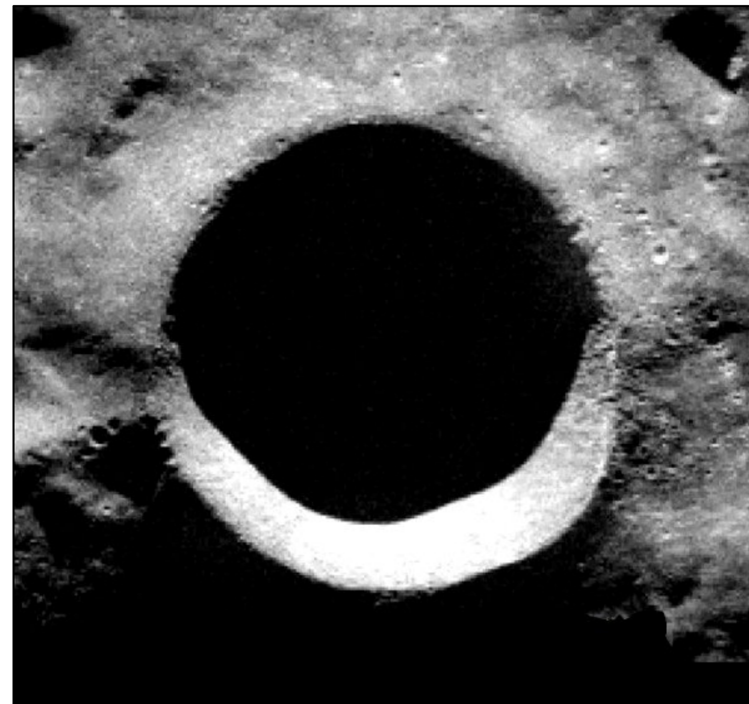
Curtis Purrington, Kyle Ferguson

Replicate Martian Rover Success?



NASA/JPL: MSL Curiosity Rover

Credit: NASA/JPL/Caltech



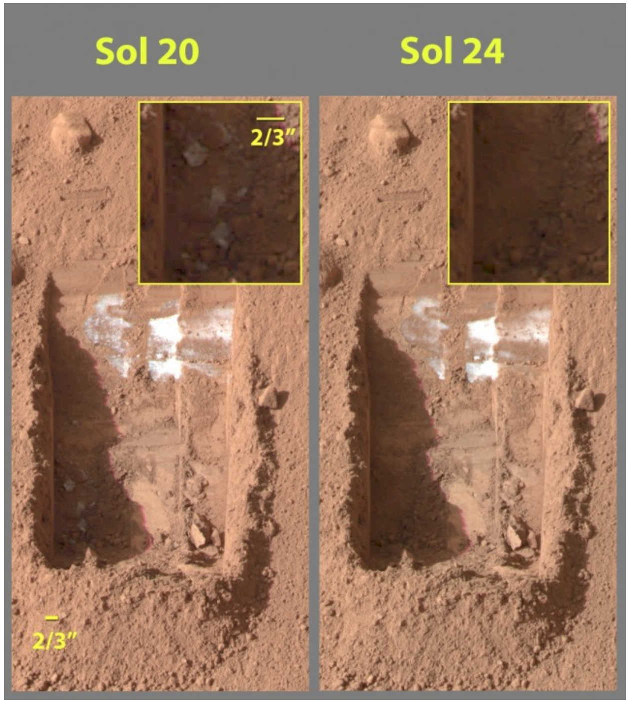
NASA/Zubar: Shackleton Crater

Thermal Model Objectives

How much thermal energy is required to maintain wheel motor operation and survival temperature limits?

How long would a motor survive with no heat generation?

Credit: NASA/JPL/Caltech



NASA: Mars Phoenix Lander (Ice Sublimation -80 C (200 K) over 4 Sol)

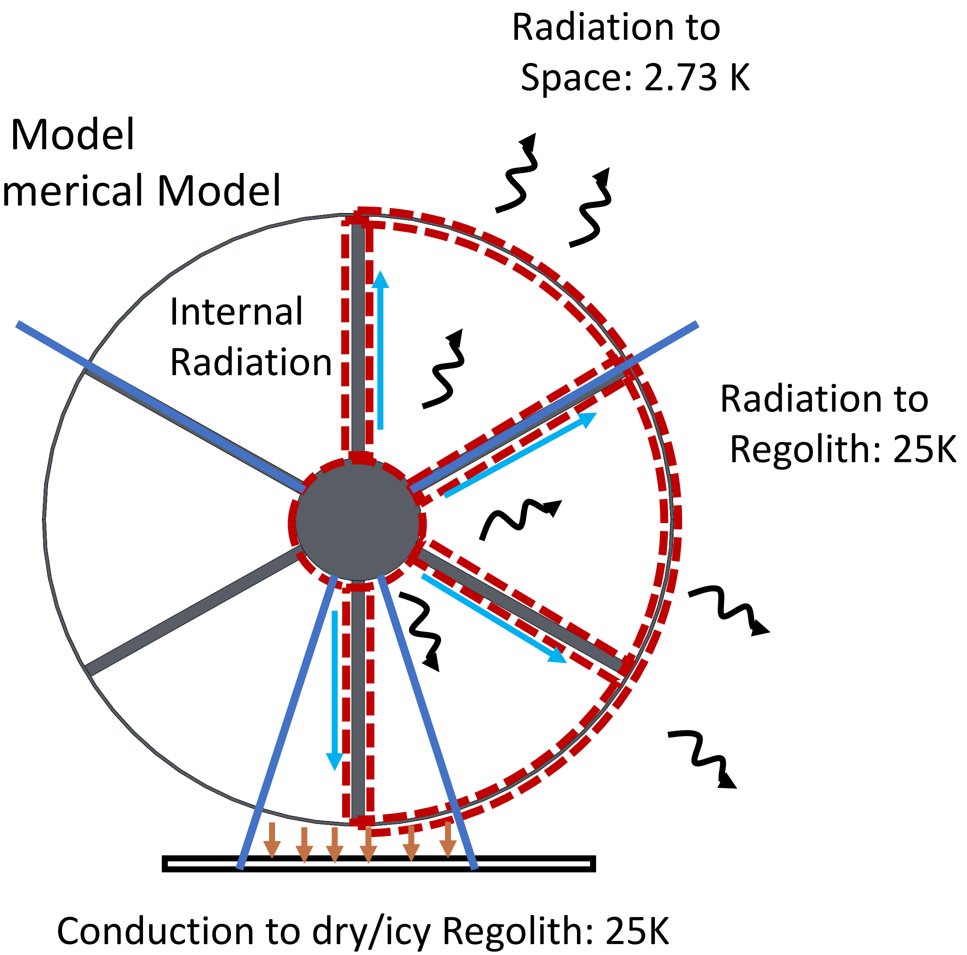
How does heat leaving the motor and wheel assembly affect the immediately adjacent regolith?

What simple strategies can be derived to provide a robust thermal management strategy?

Assumptions and Parameters

Model:
- Simplified Curiosity Rover Wheel
- Motor Information Proprietary
  - Motor Applied Lump Capacitance Model
- Other Components applied Transient Numerical Model

Environmental:
- Background of Space 2.73 K
- Regolith 25 K
- Two Types of Regolith
  - Dry – 0 Water Wt%
  - Icy – 5.6 Water Wt%



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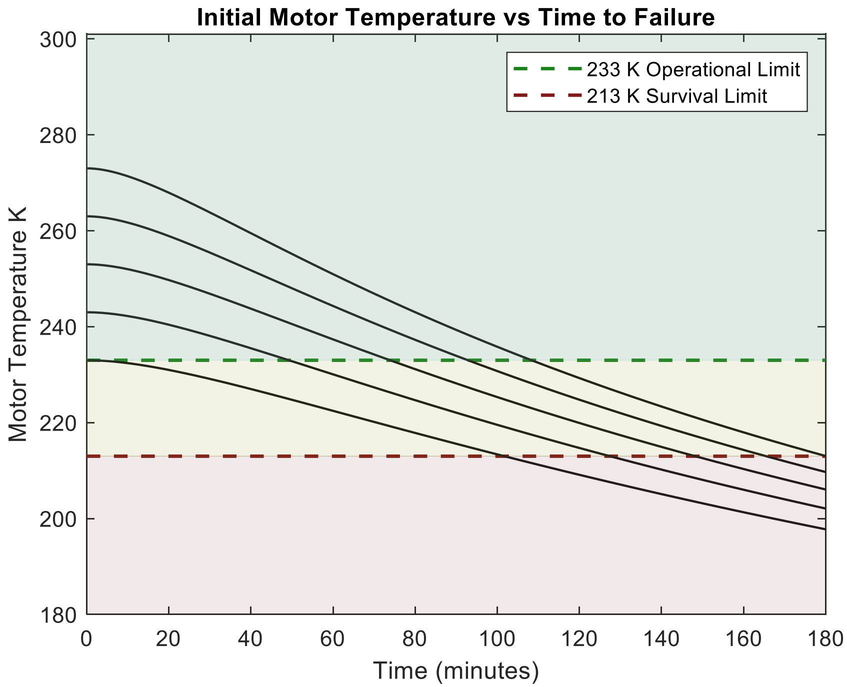
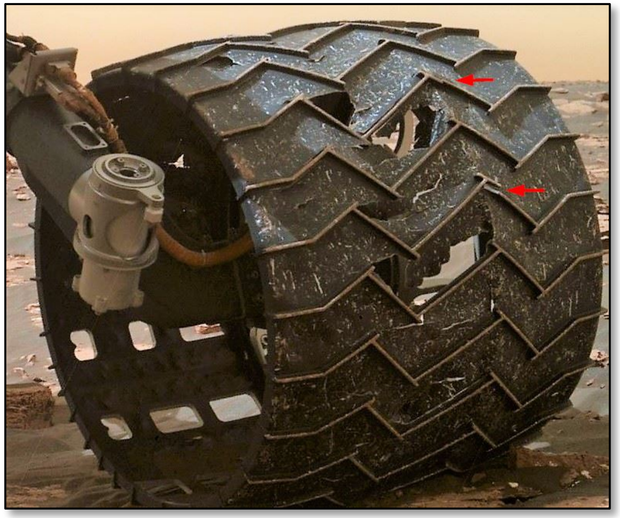
No Heat Generation Scenario



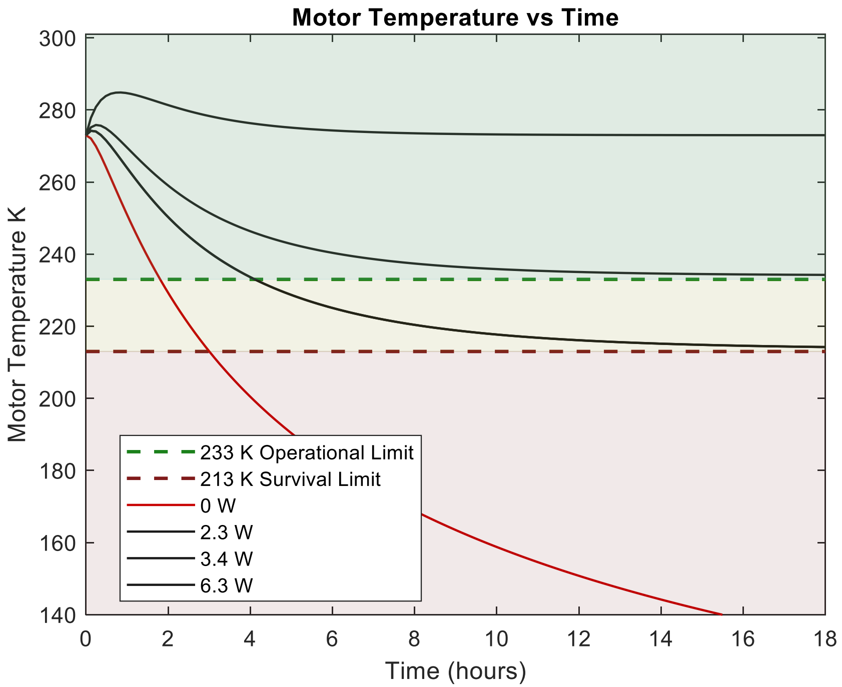


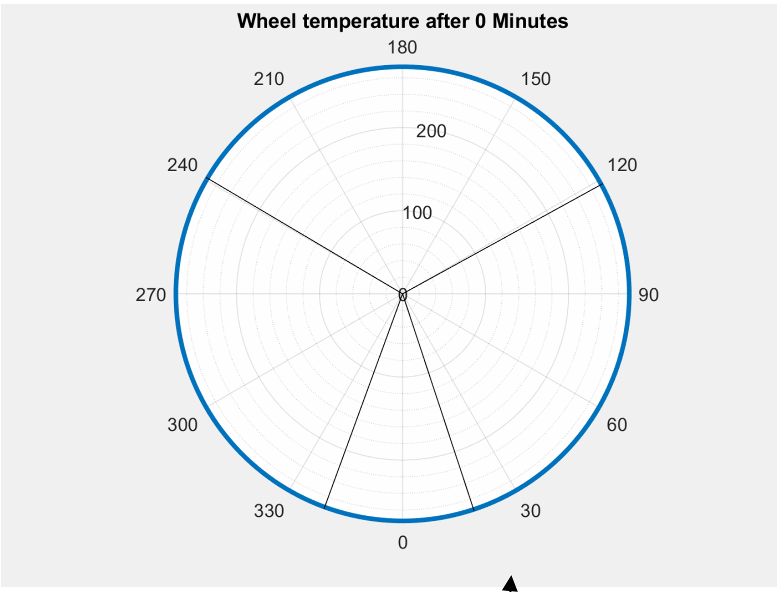
Credit: NASA/JPL/Caltech
Possible cause of a wheel failure

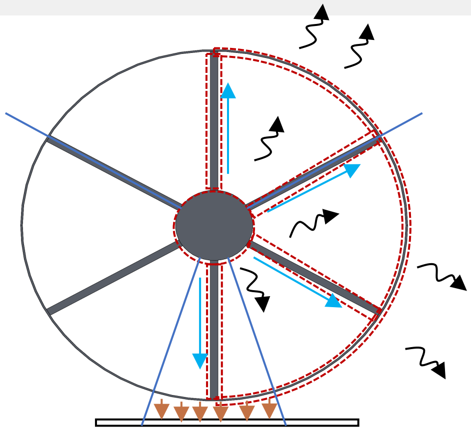
Initial T (K)	Operational Limit (min)	Survival Limit (min)
273	109	181
263	93	166
253	74	149
243	50	128
233	0	102

<u>Speed Limit</u>
Mars: 0.1 mph
Lunar: ?? mph

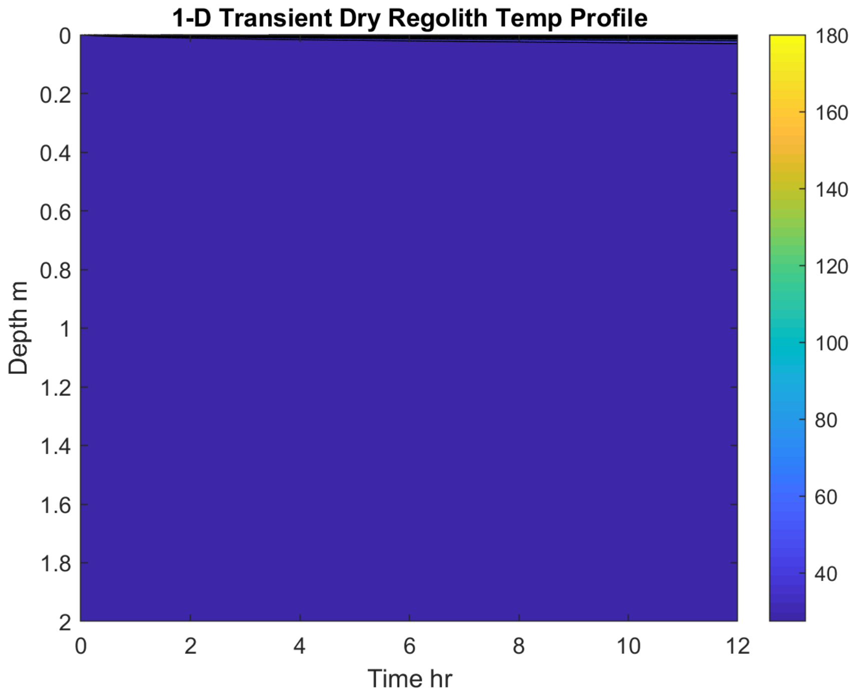
Watts per Steady State Condition

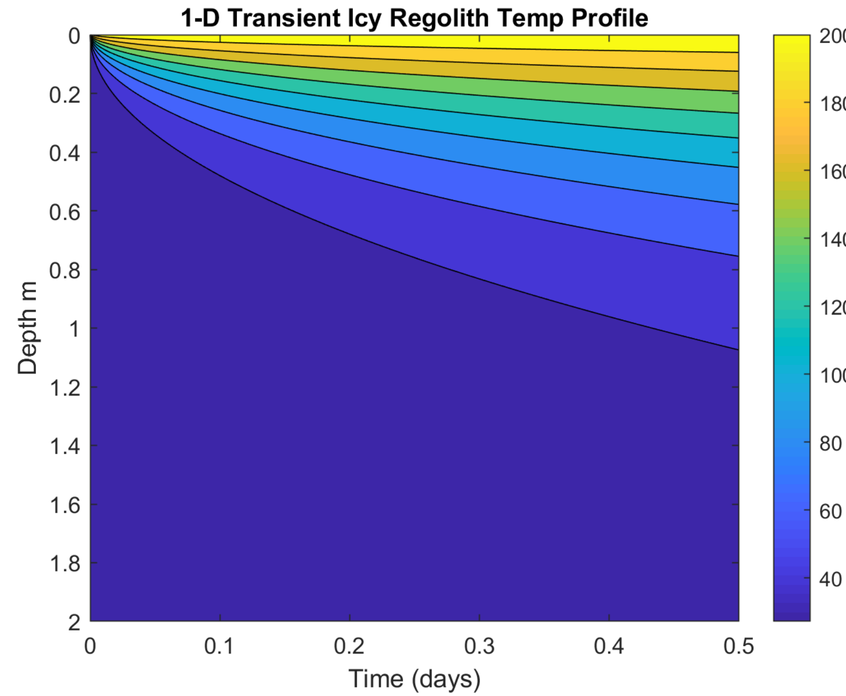






Regolith Temperature Profile

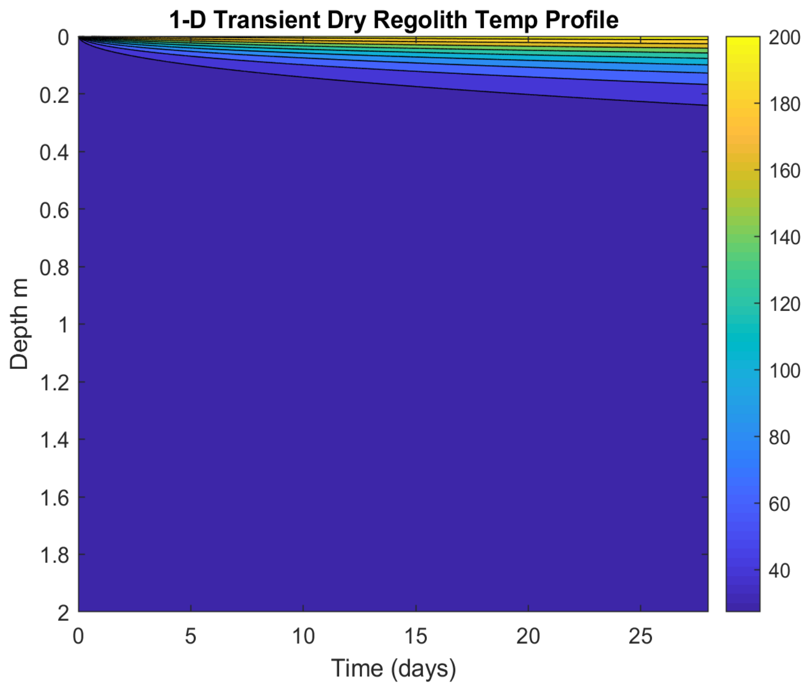




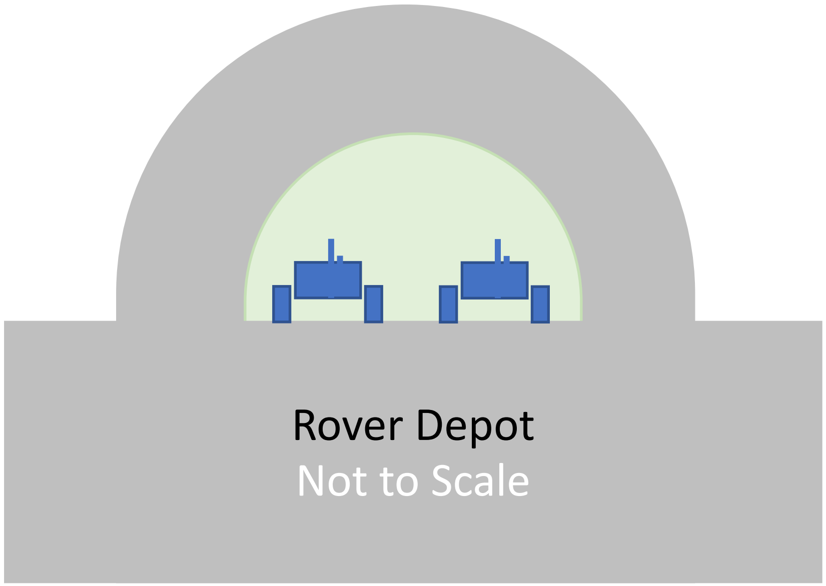
Dry 0.0 wt%
Thermal Conductivity: 0.0017 W/m-K

Water (Ice) 5.6 wt%
Thermal Conductivity: 3.04 W/m-K

Tips and Tricks



Dry Regolith Shielding



Shameless Poster Plug

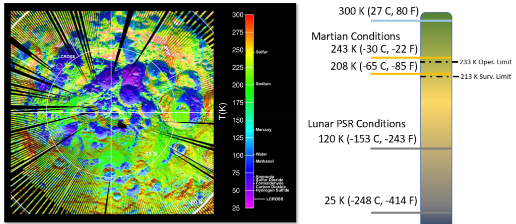
Strategies for Cryogenic Rover Operations in lunar Permanently Shadowed Regions

Curtis Purrington, Kyle Ferguson

Center for Space Resources

How Long can a rover survive in a Lunar PSR?

Lunar Permanently Shadowed Region (PSR's) contain valuable resources vital to space exploration. However, with temperatures ranging from 25 K to 120 K [3], rover operators and engineers need additional thermal models to build a proper thermal management strategy to survive in a thermally unique environment.



Temperature of Moon's South Pole. Credit. UCLA/NASA/Goddard/JPL

Model Objective

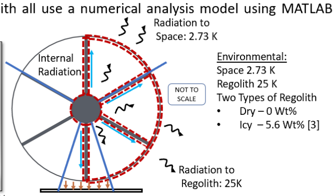
Rovers operating in the cold Martian atmosphere have had remarkable success. Lunar PSR's are magnitudes cooler with near constant cryogenic temperatures. Can the same success be achieved in a lunar PSR?

1. During a catastrophic wheel failure how long would a motor thermally survive?
2. How much thermal energy is required to maintain wheel motor operation and survival temperature limits?
3. How does heat leaving the motor and wheel assembly affect the immediately adjacent regolith?
4. What simple strategies can be derived to provide a robust thermal management strategy?

MATLAB Numerical Analysis 'ODE 45'

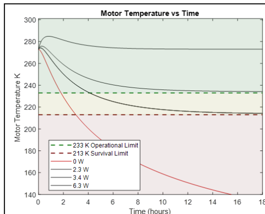
MSL Curiosity is a successful established rover and its external sensors face the greatest risk of thermal failure being located away from the rover's Radioisotope Thermoelectric Generator (RTG). A MSL rover wheel was chosen as good case study of a component that will face a higher level of thermal stress in a lunar PSR. The Lump Capacitance model was applied to the entire volume of the motor, while the spokes, wheel and regolith all use a numerical analysis model using MATLAB 'ODE45'.

SolidWork Model of MSL Curiosity Wheel Assembly
Credit: www.GradCad.com



Conduction to dry/icy Regolith: 25K

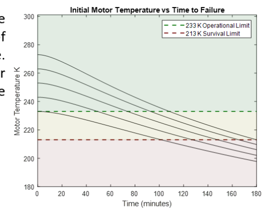
Rover Motor Survival Results



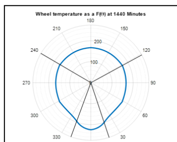
The steady state motor temperature is a function of input thermal energy. The energy source is irrelevant, the motor, localized heaters or a thermal circulation system are all possible heat sources. Even though 3.4 Watts may keep the motor above the operational limit, it reduces the time to total failure. A higher steady state temperature is prudent.

During a catastrophic heat source failure, time to failure is a function of the steady or operational temperature. With five remaining wheels the rover has the time below to limp out of the PSR or to a place of thermal safety.

Initial T (K)	Operational Limit (min)	Survival Limit (min)
273	109	181
263	93	166
253	74	149
243	50	128
233	0	102



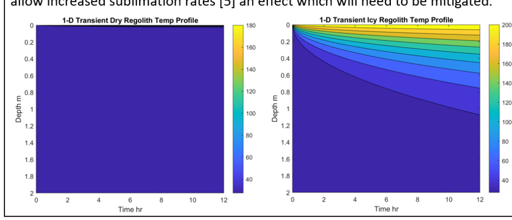
Rover Wheel Affect on Lunar Regolith



Steady State Wheel Temperature Profile (maintaining motor temp 273 K)

Applying the highest steady state temperature (273 K) the temperature profile of the wheel is modeled. As seen in the figure to the left, the portion of the wheel in contact with the regolith maintains a higher temperature. This is due to the low conductivity of dry (k = 0.001 W/m-K) [1],[4] or derived icy regolith thermal conductivity (k = 3.04 W/m-K) [4],[5] compared to the high radiation heat transfers into deep space and the surrounding PSR crater walls.

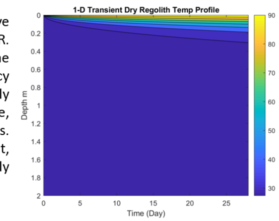
As can be seen below, the dry regolith has low thermal conductivity at k = 0.001 W/m-K. While, icy regolith with a higher thermal conductivity range k = 3.04 W/m-K, which allows the energy to penetrate deeper. The temperatures in the regolith allow increased sublimation rates [5] an effect which will need to be mitigated.

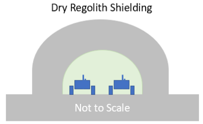


Thermal Operational Strategies

Home Base

It's possible not all rovers will have the energy resources to leave a PSR. By placing a thermal sanctuary in the PSR a rover will have an emergency egress and a location to thermally reset. Fortunately an in-situ resource, dry regolith has insulation properties. As shown in the figure to the right, after 28 days of 220 K heat has only transferred 20 cm's into dry regolith.

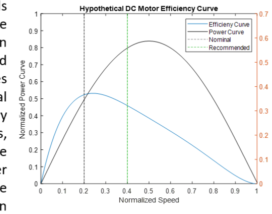




A rover depot constructed on an initial mission and then covered in a meter of dry regolith. Would provide a location to reduce thermal loss and may be doubled as a location for rover maintenance and a storage depot for temperature sensitive spare parts.

Increase Speed Limit

Martian rovers operate at speeds around 0.1 mph. NASA and JPL have adopted this operational design primarily for energy conservation and obstacle avoidance. While both issues will be present in a lunar PSR, thermal management will also be a primary priority. By operating at faster speeds, 1-5 mph, more waste heat can be generated for the motors. Faster operating speeds also reduce the time to the rover depot in case of an equipment failure.



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