Thermal Wadis in Support of Resource-Based Exploration

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Is Exploring the Moon a Political Decision?

- Successive American presidents have reshaped major aspects of the nation's space program.
- Each administration's vision *seems* to involve the perceived utility of space exploration to broader national goals:
  - Scientific, Technological and Geo-Political Leadership,
  - National Security,
  - Support for Industry, Academia, and Education and the terrestrial economy they feed.

Is Exploring the Moon a Political Decision?

- The most recent presidential policy *may* stem from objectives for human lunar exploration that:
  - Were not sufficiently clear, quantitative, or compelling
  - Did not adequately link human lunar exploration to overarching national needs.

Is Exploring the Moon a Political Decision?

- Alternative destinations such as Near-Earth Objects, Martian moons and Mars *may*
  - Drive longer-term technological development,
  - Inspire STEM education in the same general way as before
  - Maybe give us the ability to mitigate an NEO on a collision course with Earth, and
  - Put off the difficult job of landing and returning from a non-terrestrial gravity well.

Is Exploring the Moon a Political Decision?

- So are there still good reasons to send robots or humans to the moon?
  - Science: Lunar, Terrestrial, Solar System, Physical and Life Science
  - Demonstrate (close by) living away from Earth, including ISRU, radiation shielding, etc.
  - Build very large and very cool robots
  - Build a new launch vehicle system quickly
  - Establish a human backup records cache
- The constituencies behind these causes have not yet prevailed.

Any Other Reason for Lunar Exploration?

- The Lunar Reconnaissance Orbiter and the LCROS probes are indicating widespread sources of H20/OH and possibly other volatile species
  - Within permanently shadowed craters
  - Outside craters in often-dark locations
- Are these resources real? How plentiful?
- Are they harvestable?
- Could they be converted to usable mission consumables?
- Could such consumables be economically useful on the moon or elsewhere?
- Would anyone care?

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Resource-Based Lunar Exploration

Updated Economic Study: Lunar-Produced Oxygen, Water and Propellants for: LEO, GSO, L1, NEO and Mars Exploration.

Initial Robotic Ground Truthing Mission to High-Value, Low-Risk Volatile Resources Site

Enable low-cost robotic missions with simple survival-based lunar infrastructure

Resource Mapping Campaign involving “Low-Cost” robotic assets with potential for broad participation

Public and Private Assessment of the usefulness of further investment in Robotic or Human Lunar Exploration

Public Awareness and Support →

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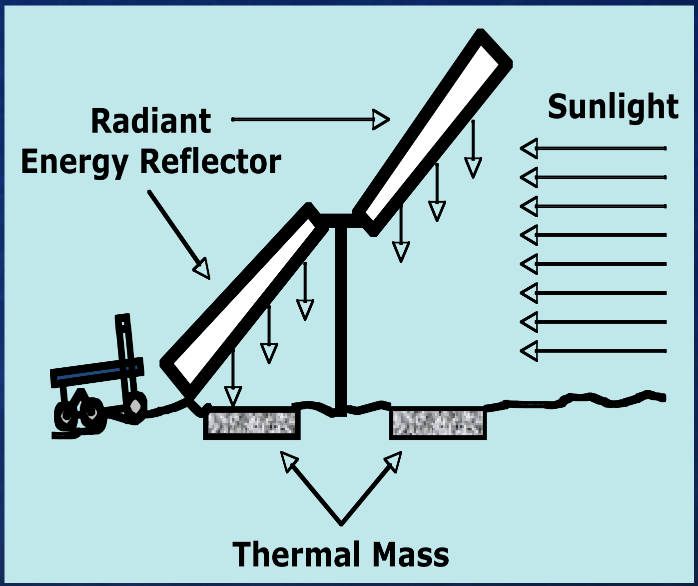
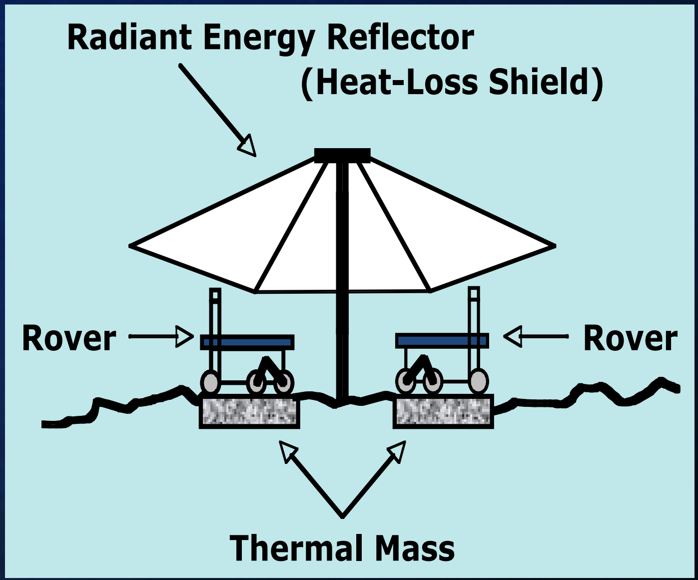
Thermal Wadis Concept

- Thermal Wadis use modified regolith as a thermal mass to:
  - Store solar energy for nighttime use and/or
  - Function as a radiator for daytime heat rejection





Thermal Performance Simulation

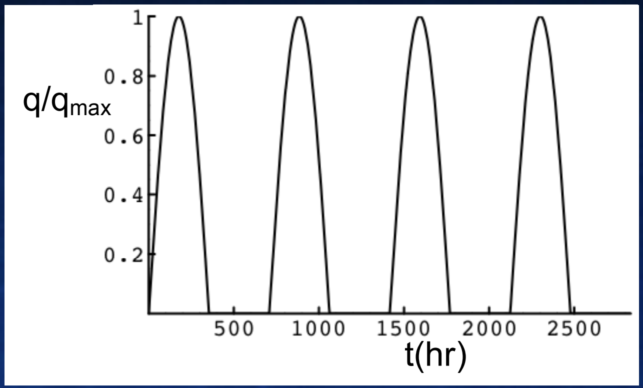
- Thermal properties of native regolith and modified regolith
- Heat conduction with surface radiative boundary conditions, bounded on bottom/sides with native regolith properties.
- Solar illumination models specific to location
- Provisions for steering sunlight and limiting cooling radiative emissions to space
- Provisions for providing heat to lunar surface assets

Properties	Native regolith	Basalt Rock
Thermal diffusivity	6.6×10^{-9} m^2/s	8.7×10^{-7} m^2/s
Density	1800 kg/m^3	3000 kg/m^3
Specific heat	840 J/(kg•K)	800 J/(kg•K)
Thermal conductivity	0.01 W/(m•K)	2.1 W/(m•K)

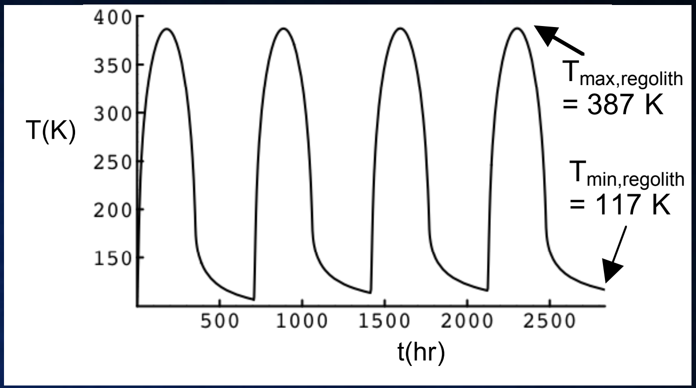
National Aeronautics and Space Administration

Thermal Performance Simulations

Equatorial Surface Temperatures



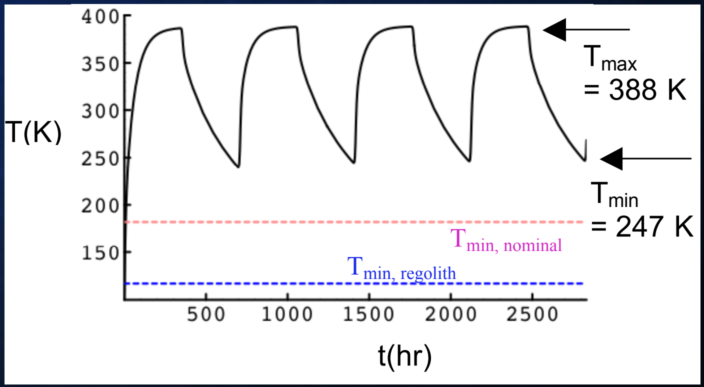
Solar Illumination of the Lunar Surface: Equatorial



Surface Temperature of Native Regolith

Thermal Wadis store solar energy flux in thermal mass then provide nighttime thermal protection

- Modified regolith: α = Basalt Rock
- Sun-tracking reflector ($1300 W/m^2$)
- Night-time heat-loss shield
- Robotic rover heating ($25 W/m^2$)
- Surface Temperature > 247K



Surface Temperature of 50cm deep Wadi

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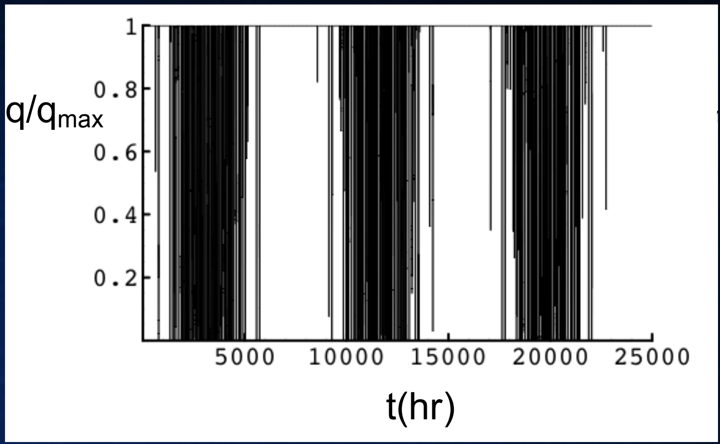
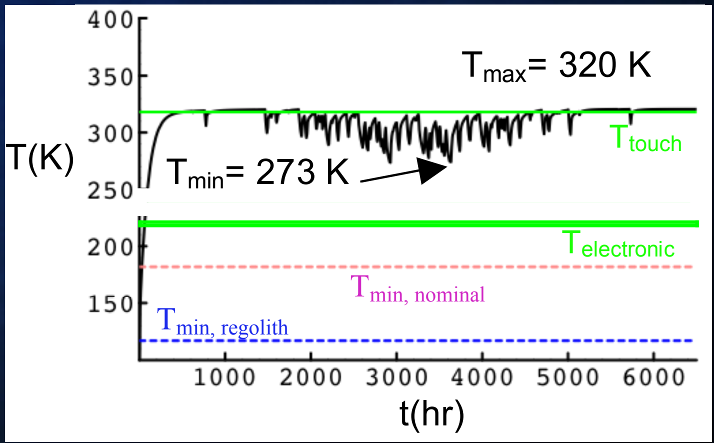
Thermal Wadi Performance
Shackleton Crater Rim – Surface Temperatures

***Solar illumination near the south pole* (from H.J. Fincannon)**
- Annual cycle provides many months without eclipse
- Longest eclipse is 52 hours



Thermal Wadis can be configured to provide a continuous, moderate temperature heat source
- Sun Tracking, Heat-Loss Shield, Rover Heating
- Modest temperatures achieved with managed solar flux input
- Performance margins
- Most forgiving location for wadi demonstration



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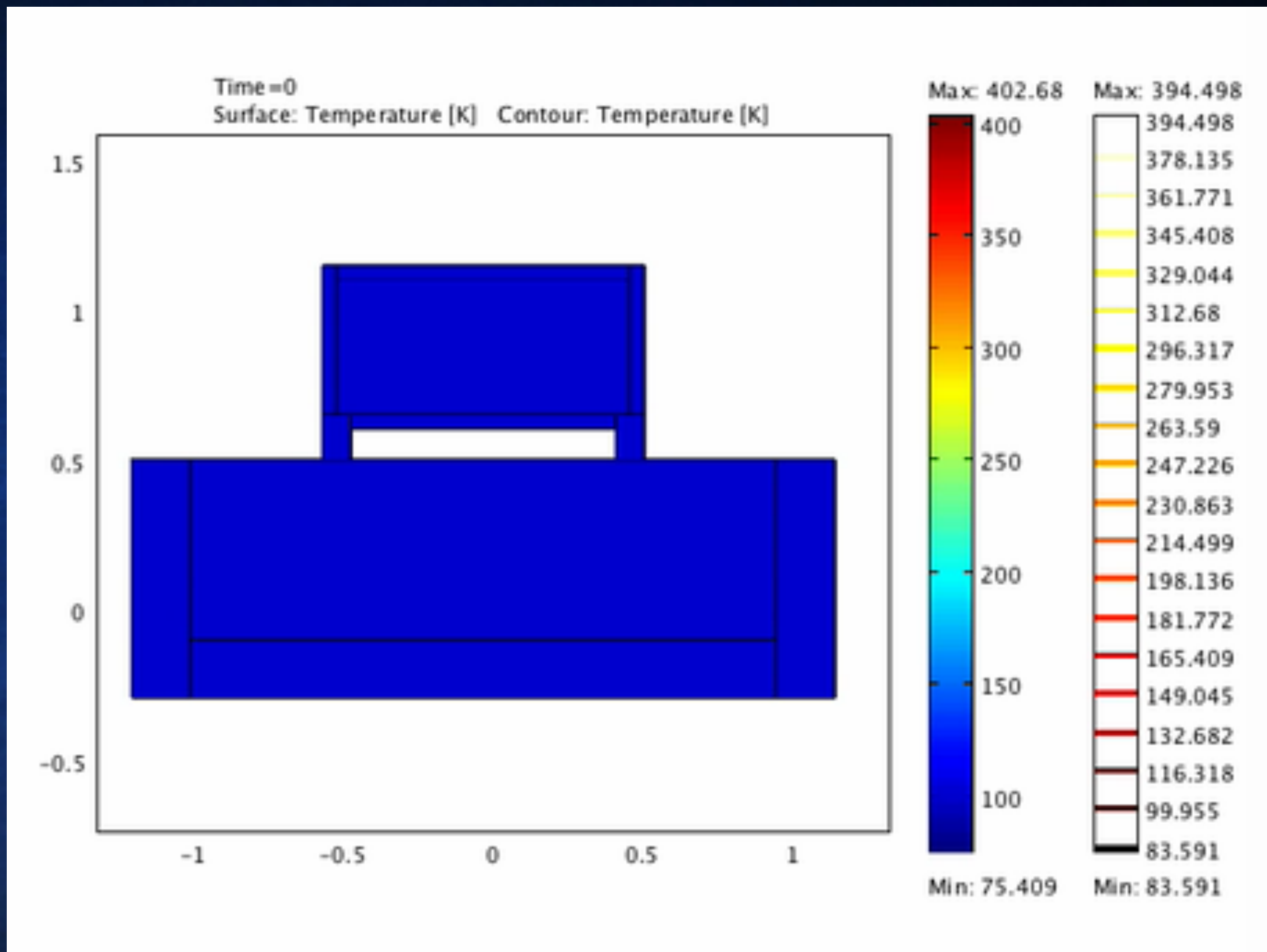
Thermal Wadi Performance

Thermal Animation of Schematic Rover on Equatorial Wadi



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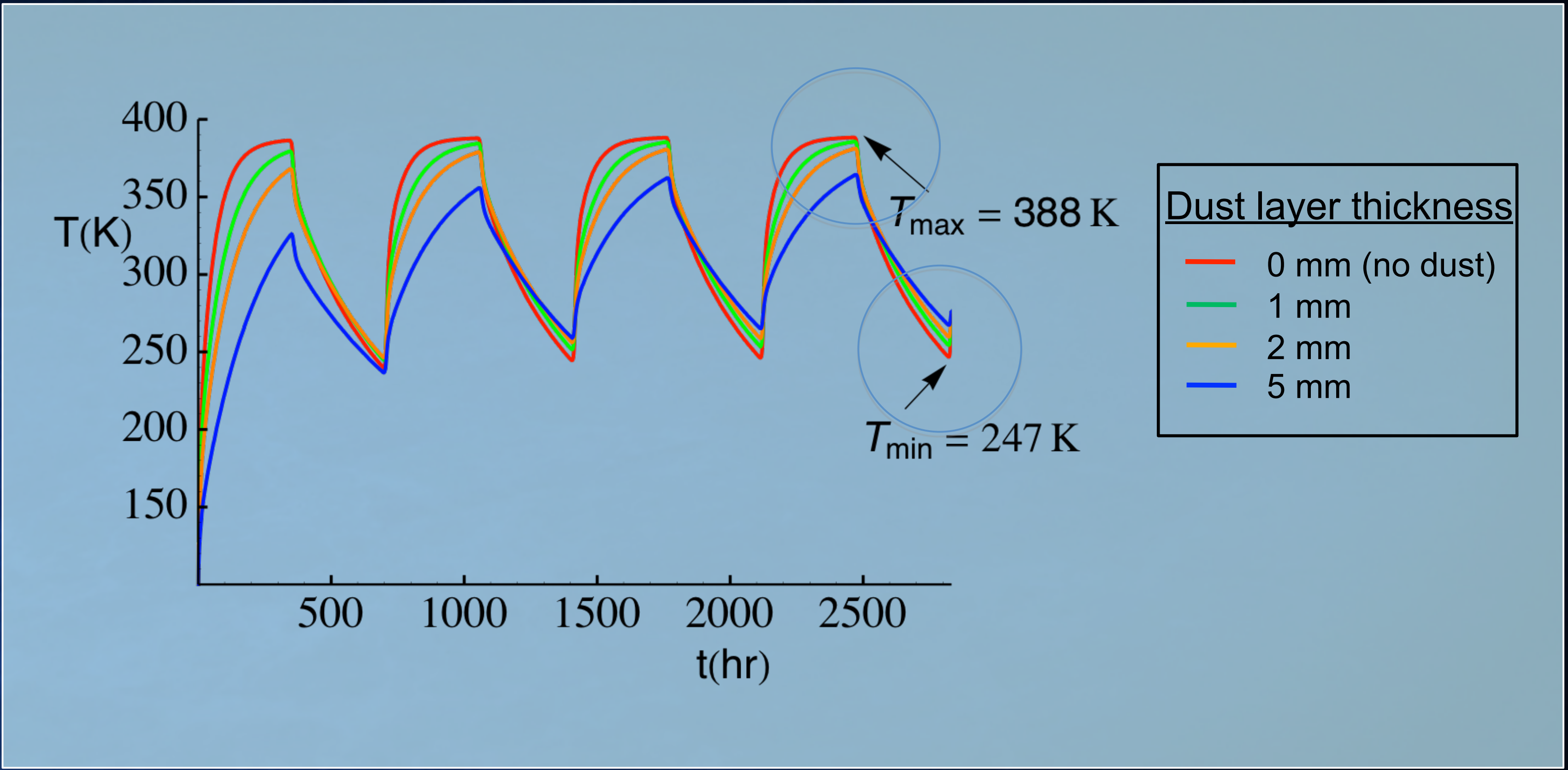
Thermal Wadi Performance

Effect of Lunar Dust Layer on Wadi Surface Temperature



- Dust layer of small thickness mitigates thermal mass surface temperature swing
- Dust may actually be beneficial!

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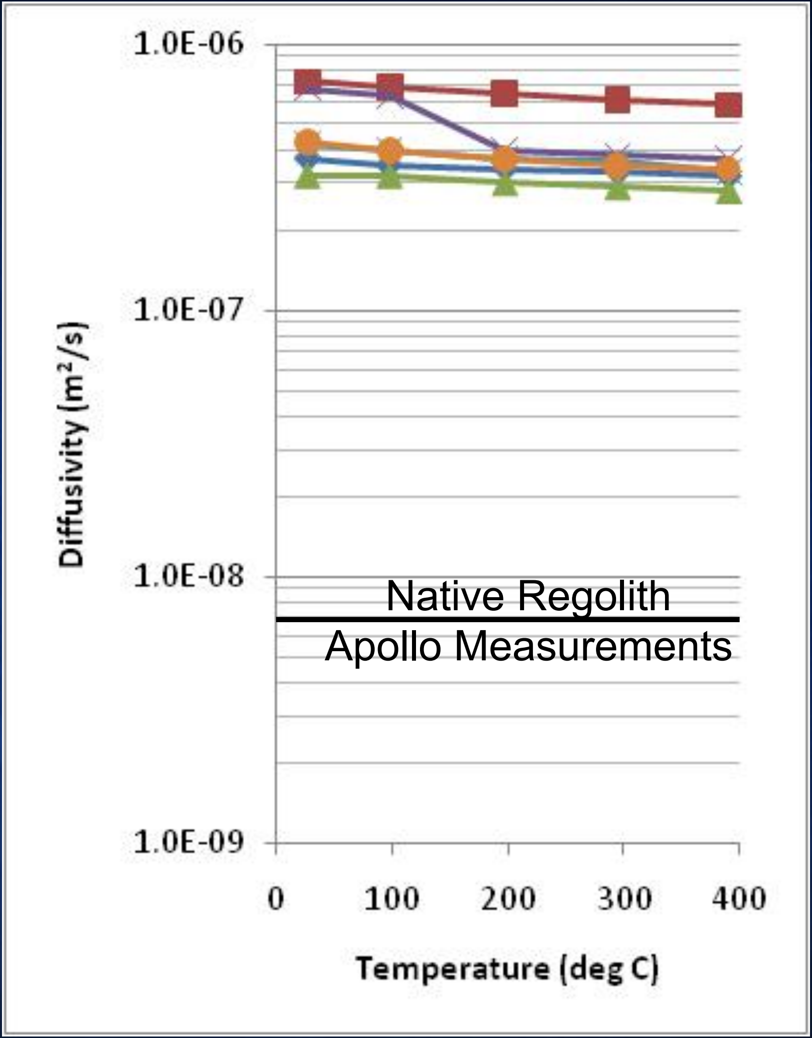
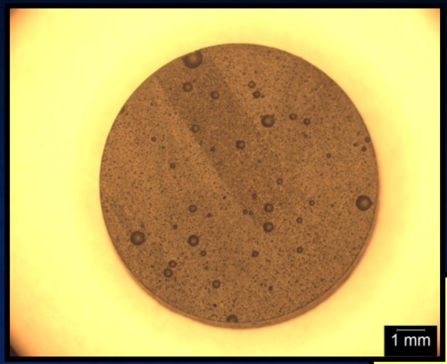
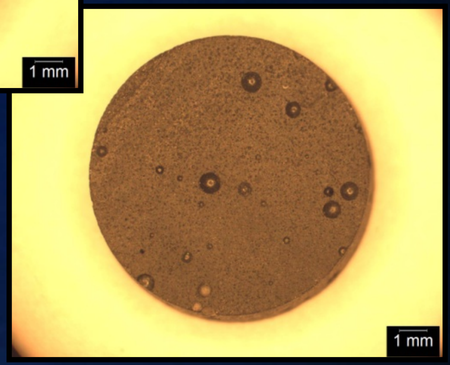
Thermal Property Measurements
Informing Thermal Mass Production Methods







- Measurements of sintered and melted JSC-1AF, produced using various process conditions
- Instrument: Laser-Flash Thermal Diffusivity System

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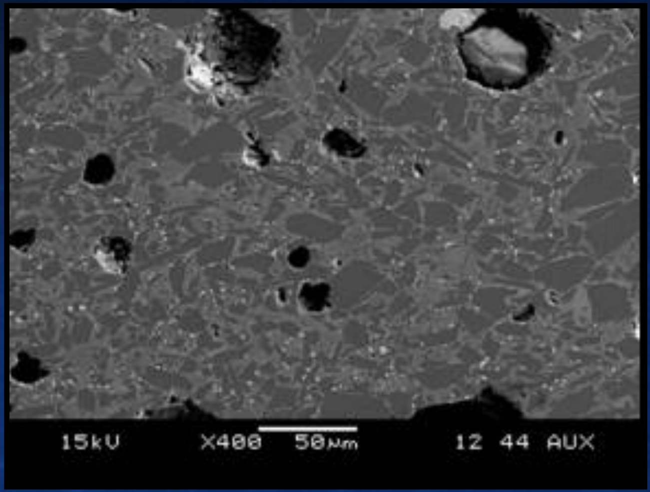
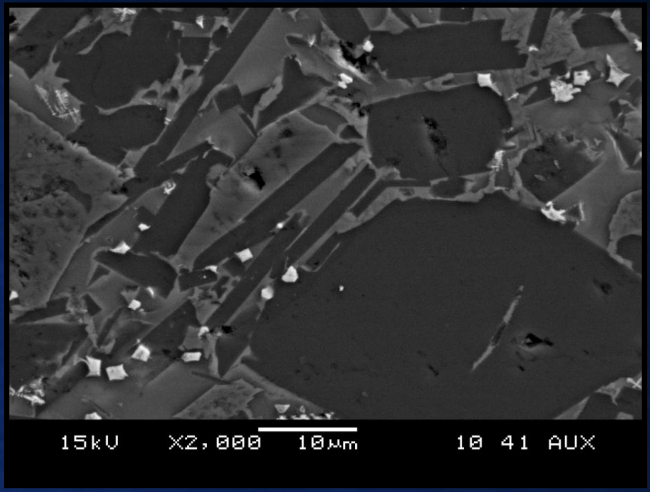
Thermal Property Measurements
1150 C Sample, Processed in Argon Atmosphere

Scanning Electron Microscopy





Crystalline Phases via X-Ray Diffraction:

- Hematite (Fe_2O_3)
- Anorthite ($CaAl_2Si_2O_8$)
- Diopside ($MgCaSi_2O_6$)
- Fosterite ($MgSiO_4$)

Phases	Element, wt%									
	O	Na	Mg	Al	P	Si	K	Ca	Ti	Fe
Dark gray	25.89	2.12	N/A	23.01	N/A	33.55	N/A	14.39	N/A	1.03
Light gray	25.69	3.00	4.39	10.83	0.53	32.13	1.47	9.69	1.84	10.42
White crystals	14.14	0.41	3.45	3.98	N/A	2.21	0.3	0.63	7.34	67.54

Elemental Constituents per Energy Dispersive Spectroscopy

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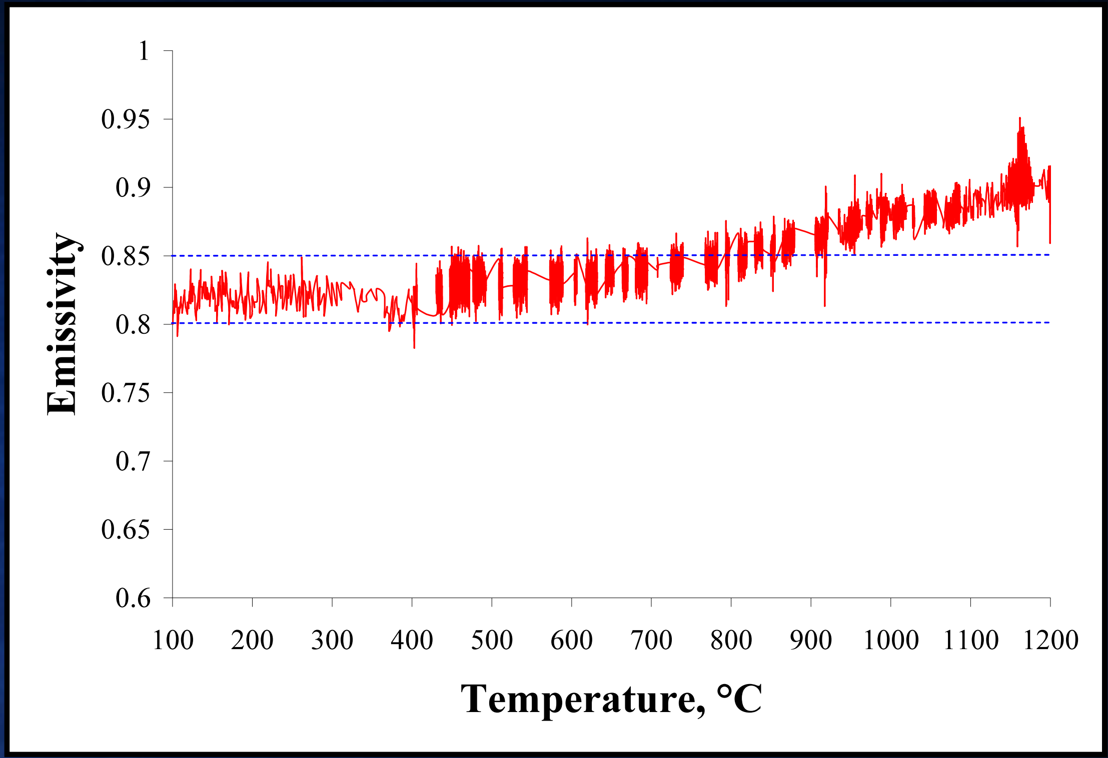
Thermal Property Measurements
Thermal Radiation/Emissivity Changes during Processing



- Data informs thermal mass production energy requirements
- Values calculated using data from a 137 GHz Heterodyne Dual-Receiver Millimeter Wave Radiometer Interferometer

Thermal Wadi Applications

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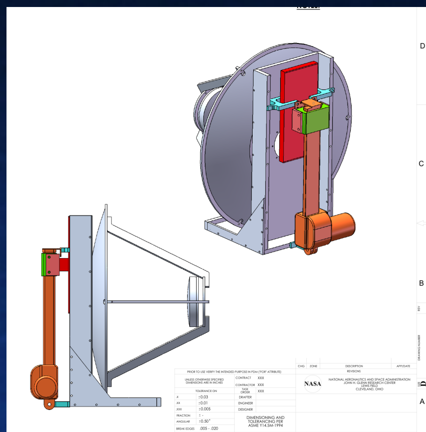
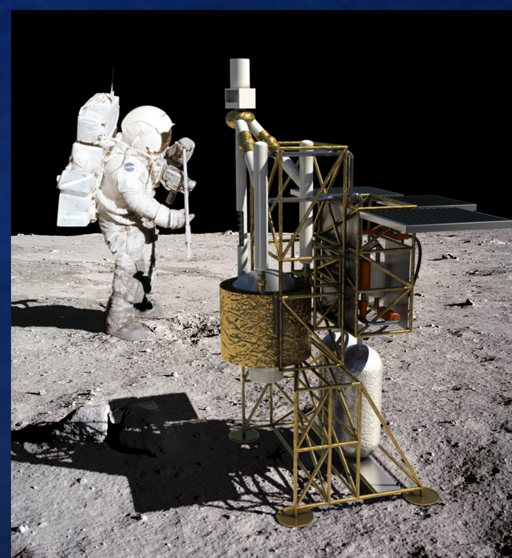
Thermal Mass Manufacturing



In-Situ Vitrification/
Joule heating



Reduction of Regolith/
O_2 Production

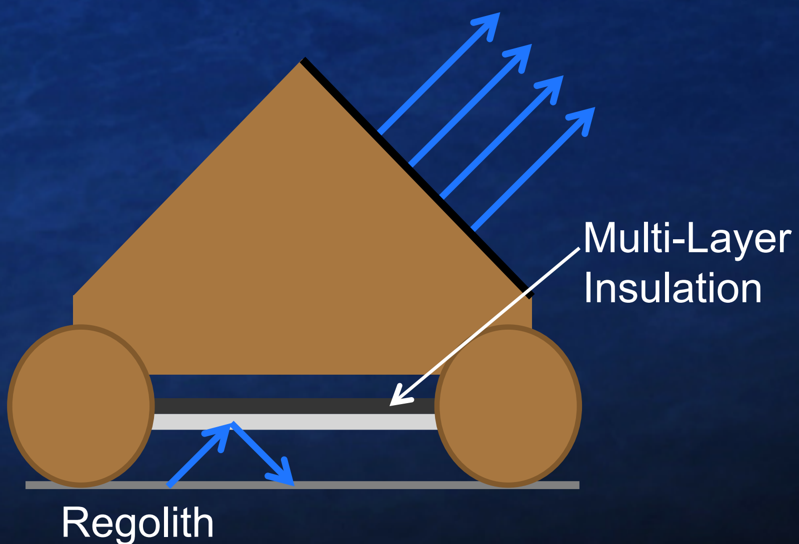
Lightweight
Solar
Concentrators

Bi-Modal Rover

Courtesy of Heather Jones, Carnegie-Mellon University

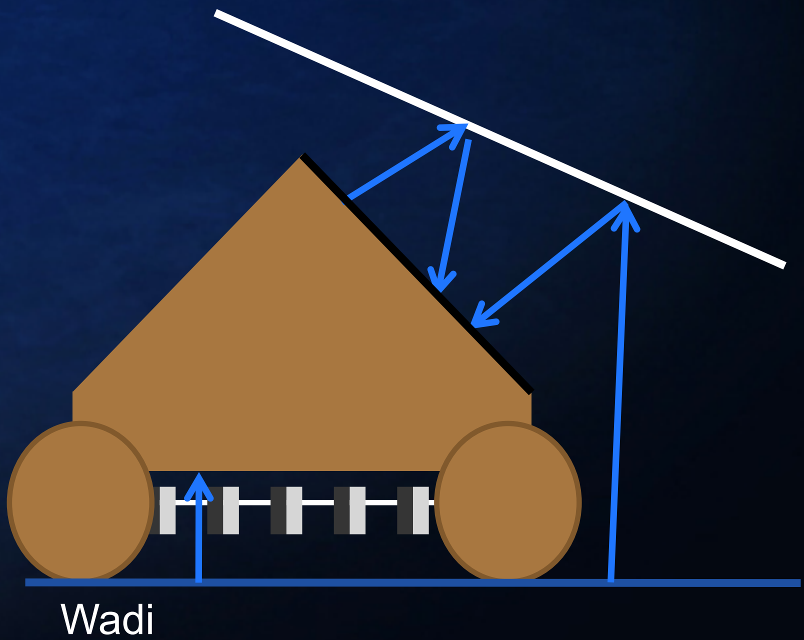
Lunar Day

- Radiator rejects heat to space
- Rover insulated from high temperature regolith



Lunar Night

- Rover absorbs heat from Wadi
- Reflector retains heat from robot and Wadi



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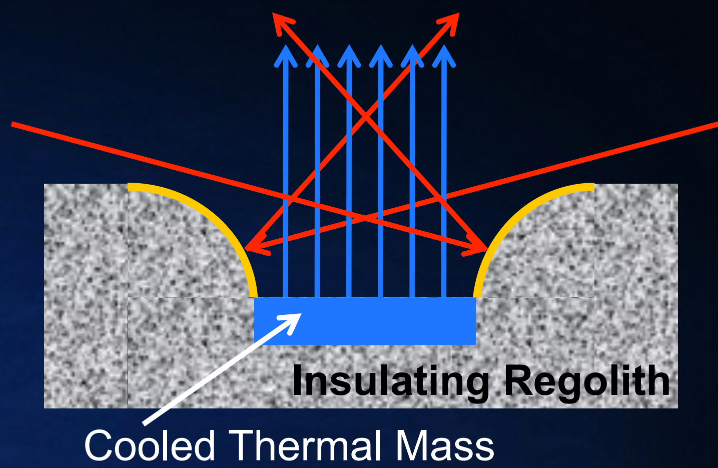
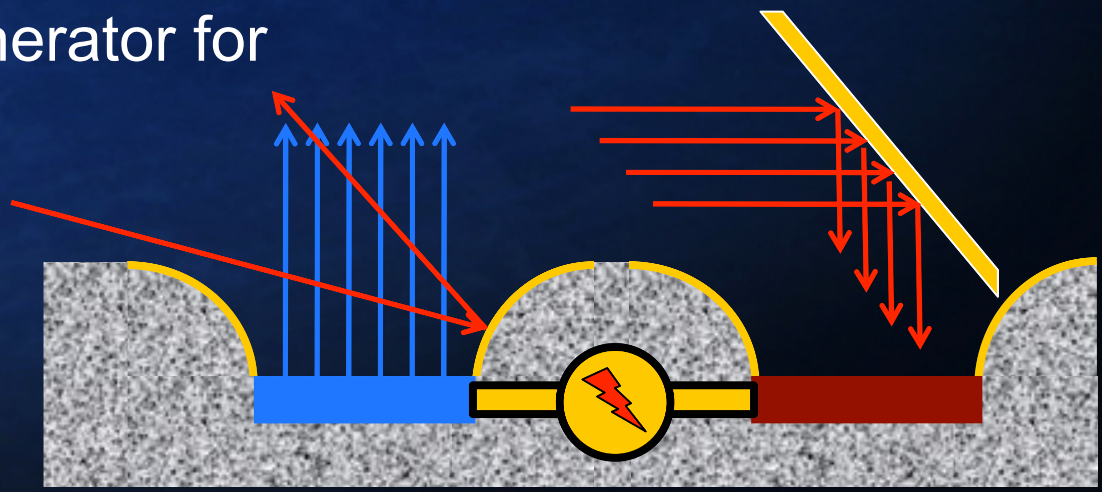
Additional Applications of Thermal Wadis

- A thermal mass can be configured in an artificial "PSR" to serve as a daytime heat sink.



- Thermal mass pairs can be configured as high-temp/ low-temp reservoirs, joined with a Sterling generator for electrical power.



Current Work

- Developing joint small-rover/thermal wadi thermal modeling to extend feasibility study
- Detailed model of solar reflector/radiation shield
- Prepare hardware demonstration of solar concentrator based thermal mass manufacturing
- Prepare joule-heating concept for thermal mass manufacturing
- Extending thermal property measurements to include additional regolith simulants

Resource Characterization:
Paving the Way for Humans to Return to the Moon

- Robotic prospectors, based from thermal wadis, identify resource concentrations & sites
- Promising sites are selected for near-term lunar resource extraction demonstrations
  - Oxygen from regolith
  - Water and other Volatiles
- ISRU technology demonstrators, operated at thermal wadis, further reduce cost and performance risks
- Architectural and engineering studies evaluate the economic potential of lunar resources
- Humans return to the Moon with clear value driven goals: Site location, work objectives, necessary infrastructure, tools and instruments.