LUNAR THERMAL WADIS AND EXPLORATION ROVERS: OUTPOST PRODUCTIVITY AND PARTICIPATORY EXPLORATION

The presentation introduces the concept of a “thermal wadi,” an engineered source of thermal energy that can be created using native material on the moon or elsewhere to store solar energy for use by various lunar surface assets to survive the extremely cold environment of the lunar night. A principal benefit of this approach to energy storage is the low mass requirement for transportation from Earth derived from the use of the lunar soil, or regolith, as the energy storage medium.

The presentation includes a summary of the results of a feasibility study involving the numerical modeling of the performance of a thermal wadi including a manufactured thermal mass, a solar energy reflector, a nighttime thermal energy reflector and a lunar surface rover. The feasibility study shows that sufficient thermal energy can be stored using unconcentrated solar flux to keep a lunar surface rover sufficiently warm throughout a 354 hour lunar night at the lunar equator, and that similar approaches can be used to sustain surface assets during shorter dark periods that occur at the lunar poles. The presentation includes descriptions of a compact lunar rover concept that could be used to manufacture a thermal wadi and could alternatively be used to conduct a variety of high-value tasks on the lunar surface. Such rovers can be produced more easily because the capability for surviving the lunar night is offloaded to the thermal wadi infrastructure. The presentation also includes several concepts for operational scenarios that could be implemented on the moon using the thermal wadi and compact rover concepts in which multiple affordable rovers, operated by multiple terrestrial organizations, can conduct resource prospecting and human exploration site preparation tasks.

Lunar Thermal Wadis and Exploration Rovers

Outpost Productivity and Participatory Exploration

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Thermal Wadis and Compact Rovers

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Outline

- Lunar Thermal Wadi Concept
- Thermal Wadi Feasibility Study: Overview & Results
- Compact Exploration Rovers
- Operational Scenarios on the Lunar Surface
- Looking Ahead

Lunar Thermal Wadi Concept

Taming the Lunar Environment Creates Opportunities

- Lunar surface temperatures vary from highs of about 400 K to lows of under 100 K
- Science and exploration systems will have difficulty surviving the extreme cold of lunar darkness
- Survivable mobile lunar surface assets can provide:
  - Pre-Outpost site assessment and ground truthing
  - Outpost crew exploration support: pre-EVA sample retrieval, EVA planning and execution
  - Expanded opportunity for participatory, planet-wide robotic exploration

Why is the Lunar Surface both so Hot and Cold?

- Thermal properties of lunar regolith make it a better insulator than some of the best engineered materials
- Solar-thermal heating of the lunar surface does not penetrate (conduct) deeper than a few centimeters.
  - Heat remains at the surface (minimal heat storage)
  - Surface temperature rises dramatically during daytime
  - The hot surface radiates to space and cools quickly during darkness
- Enhancing regolith heat conduction enables energy storage
  - Allows heat to conduct more deeply, reducing daytime surface temperatures
  - Reduces losses of subsurface heat to space, increasing dark-period surface temperatures
  - A thermal mass of conducting material can be made from regolith

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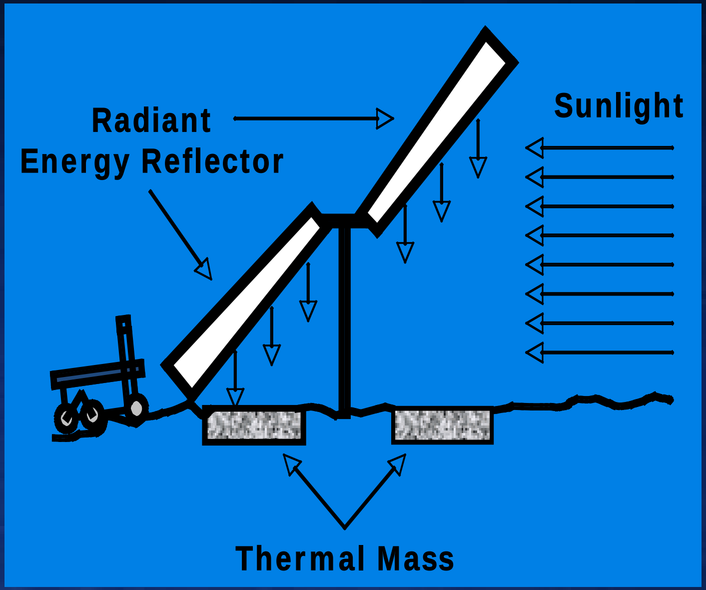
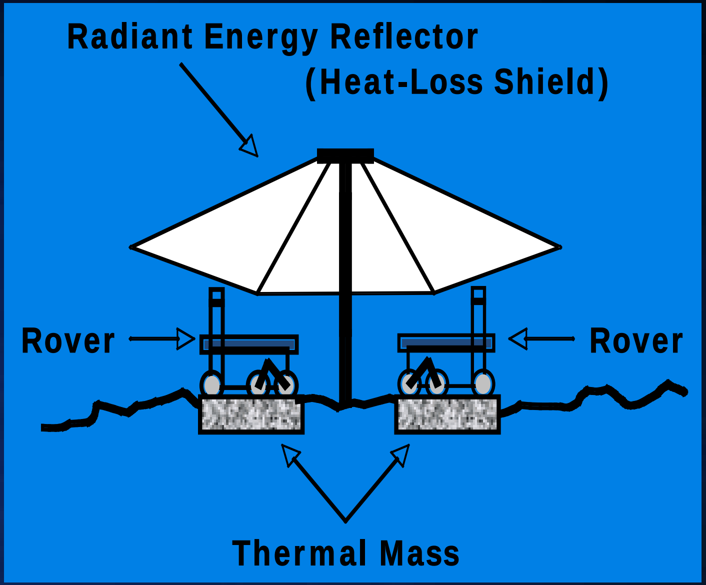
Thermal Wadi System Concept



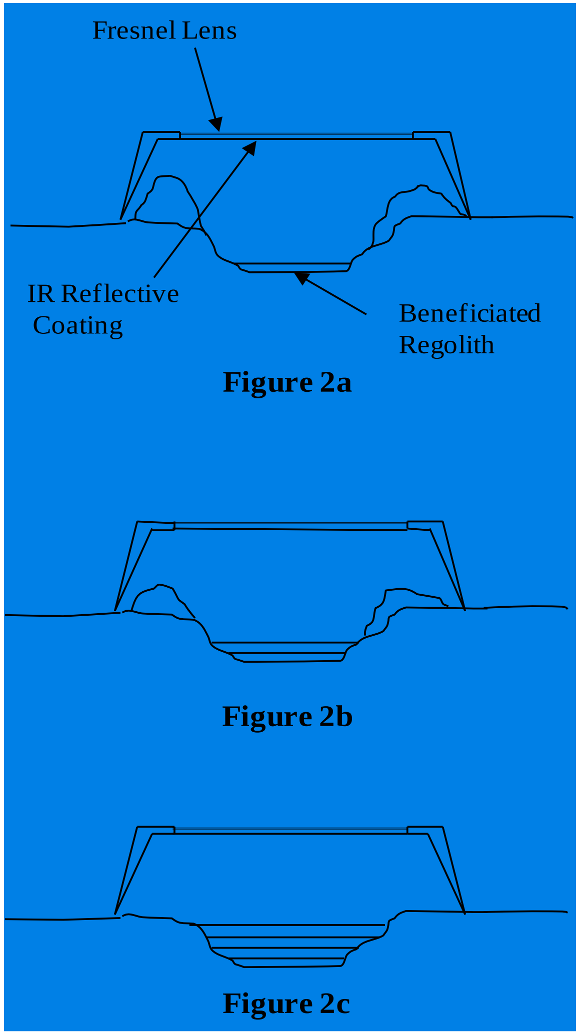


- A Thermal Wadi is an engineered source of heat (and sometimes power)
- Thermal Wadis can be modular infrastructure enabling science and exploration assets to survive periods of extreme cold on the lunar surface

Methods of Making a Thermal Mass

Thermal mass production methods can be chosen for compatibility with other Lunar Surface System needs:

- Solar: Concentrating solar energy to sinter and/ or melt regolith (surface stabilization, roads, landing pads)
- Chemical: Reducing regolith metal oxides (e.g. ISRU O_2 production)
- Microwave: Sintering to produce thermal bricks
- Joule Heating (electrical resistance): Melting regolith into solid masses



Fresnel Lens used to buildup melted layers of regolith

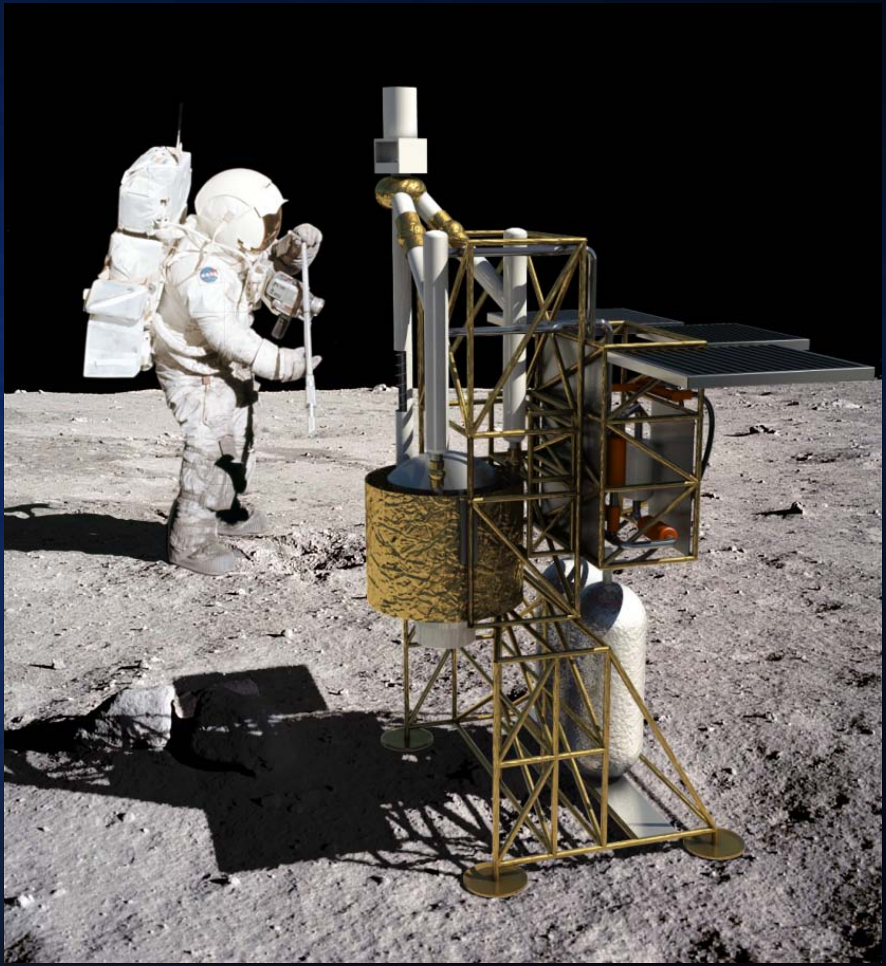
Methods of Making a Thermal Mass

- Fresnel Lens Solar Concentrator

Lunar soil sintering concept using a Fresnel lens to concentrate solar power (Courtesy NASA GSFC)

Methods of Making a Thermal Mass

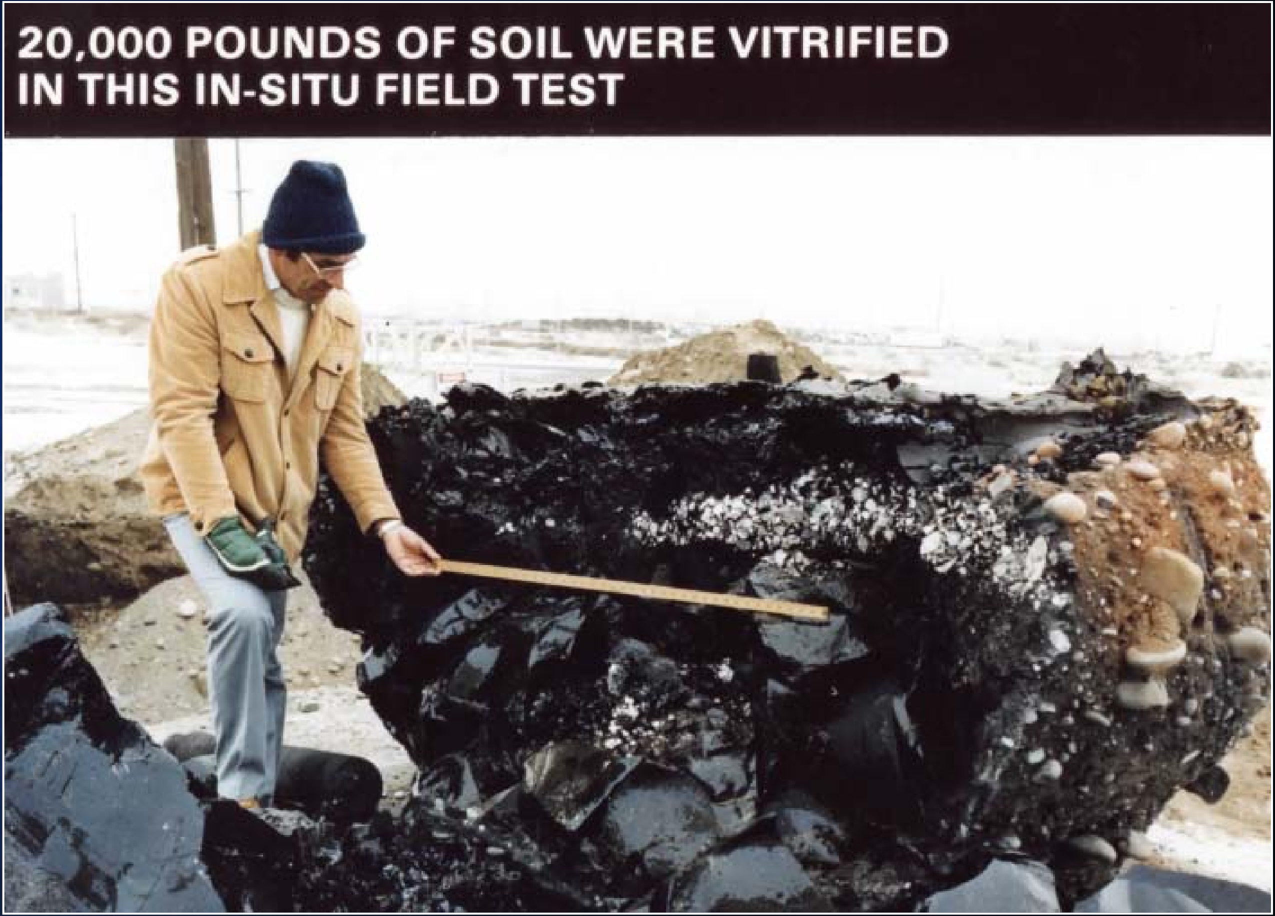
- ISRU: Chemical Reduction of Regolith for Oxygen Production



Lunar oxygen production plant concept using hydrogen reduction for 1-2 MT/yr O_2 (courtesy NASA GRC)

Methods of Making a Thermal Mass

- In-situ Vitrification using Joule heating (electrical resistance)



(courtesy Battelle Memorial Institute)

Lunar Thermal Wadi Concept

- Thermal Wadis utilize local materials as thermal mass for solar energy storage
- Methods for making a thermal mass on the moon are well known.
- If we make a thermal wadi, can we store enough energy to enable exploration assets to survive periods of darkness?

Thermal Wadi Feasibility Study Overview and Results

Thermal Wadi Feasibility Study: Thermal Performance of Modified Regolith

- Assume:
  - Thermal properties of native regolith can be modified using feasible technology (melting, sintering, etc.)
  - Lunar vehicles are developed, standardized for interfacing with thermal wadis and utilizing the wadi-provided heat
- How do surface temperatures (the rover interface) vary during solar illumination and darkness?
- Does vehicle heating throughout the dark periods use less than the energy that can be stored from sunlight?
- Does the concept work at equatorial and polar sites?
- What performance margins are predicted that can be used in subsequent engineering trade studies?

Thermo-physical Properties of Lunar Regolith and Basalt Rock

Properties	Native regolith	Basalt Rock
Thermal diffusivity, $\lambda / (\rho \cdot c_p)$	6.6×10^{-9} m^2/s	8.7×10^{-7} m^2/s
Density, ρ	1800 kg/m^3	3000 kg/m^3
Specific heat, c_p	840 J/(kg-K)	800 J/(kg-K)
Thermal conductivity, λ	0.01 W/(m-K)	2.1 W/(m-K)
Radiative Emissivity, ε	0.9	0.9

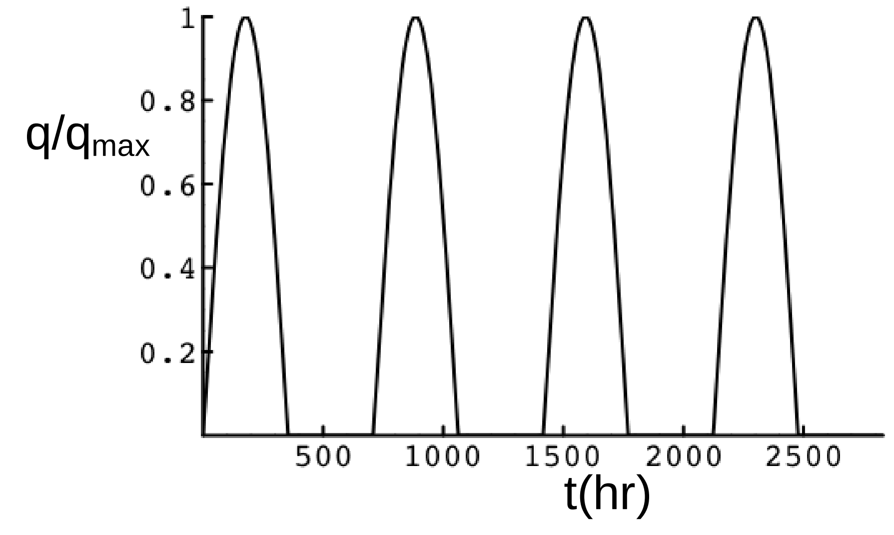
Analytical Thermal Model of Wadi Thermal Mass Behavior

- One-dimensional, transient heat conduction
- Time-varying solar illumination, including model of polar illumination timeline
- Nominal thermal properties of basalt rock
- Exposed surface absorbs sunlight and emits thermal radiation
- Buried surface contacts native regolith
- Study parameters:
  - Depth of thermal mass: 0.2m to 1.0m
  - Thermal diffusivity: native regolith to basalt rock
  - Heat extraction to protect exploration rovers: 25 w/m^2
  - Radiative heat loss limiting “umbrella”

Equatorial Regions: Surface Temperatures

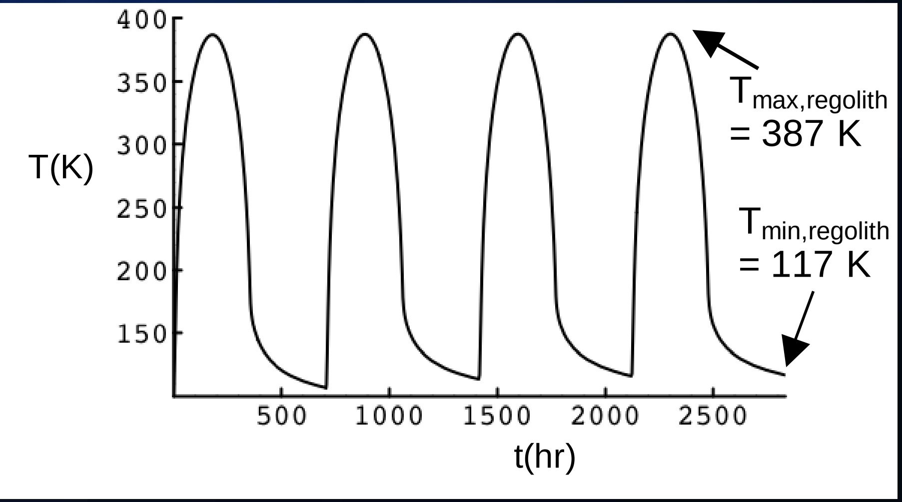
Solar Illumination of the Lunar Surface: Equatorial

- Semi-sinusoidal sunlight
- Peak solar flux, q_{max}= 1300 W/m^2



Surface Temperature of the Native Regolith

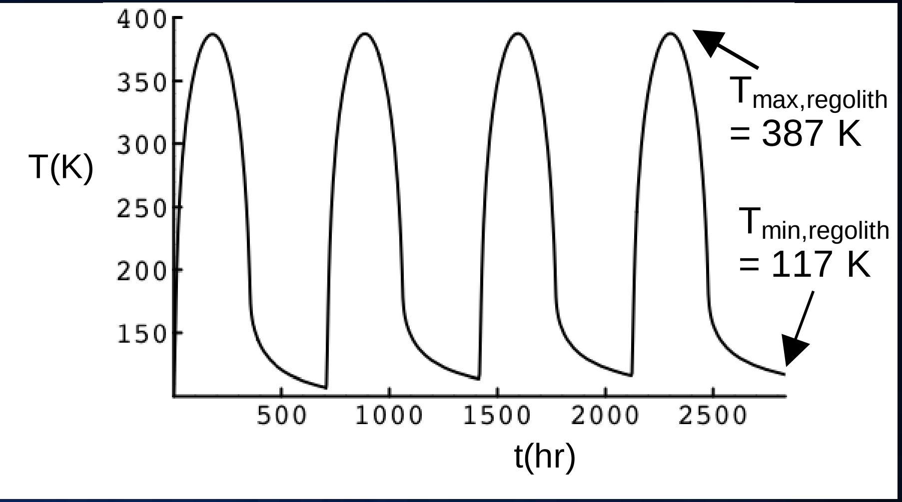
- Model predicts Apollo era surface temperature measurements



Equatorial Regions: Surface Temperatures

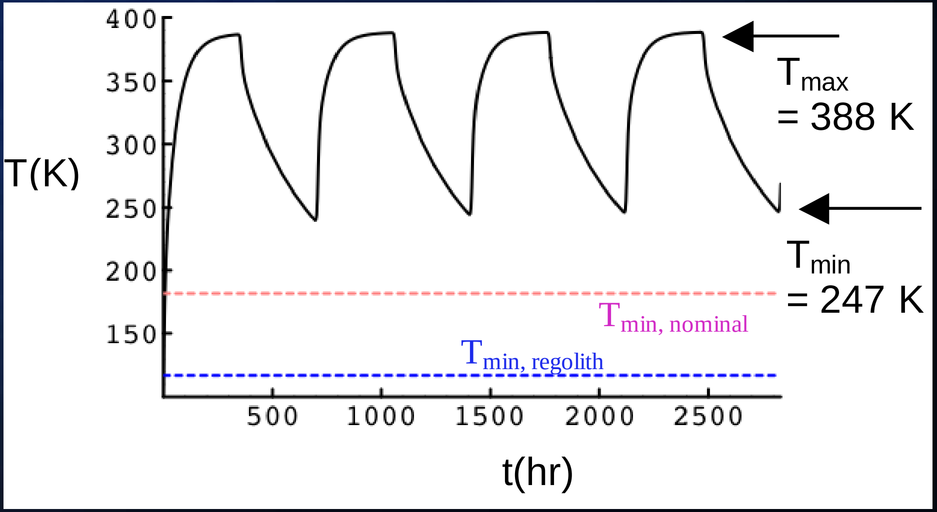
Surface Temperature Of Native Regolith

- Peak surface temperature reflects balance between incoming sunlight and radiative emissions



Surface Temperature of Thermal Wadi

- Modified regolith
- Sun-tracking radiant reflector
- Radiative heat-loss shield
- Robotic rover heating



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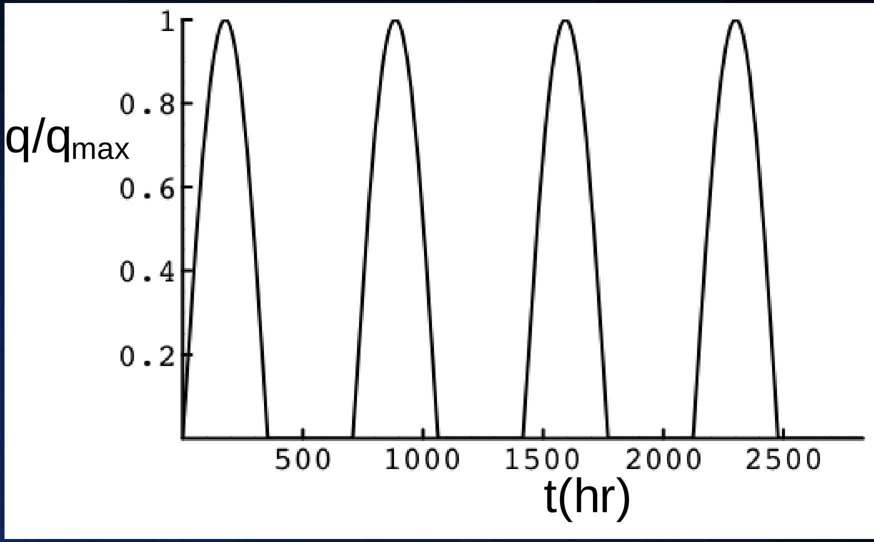
Solar Illumination: Equator versus the Poles

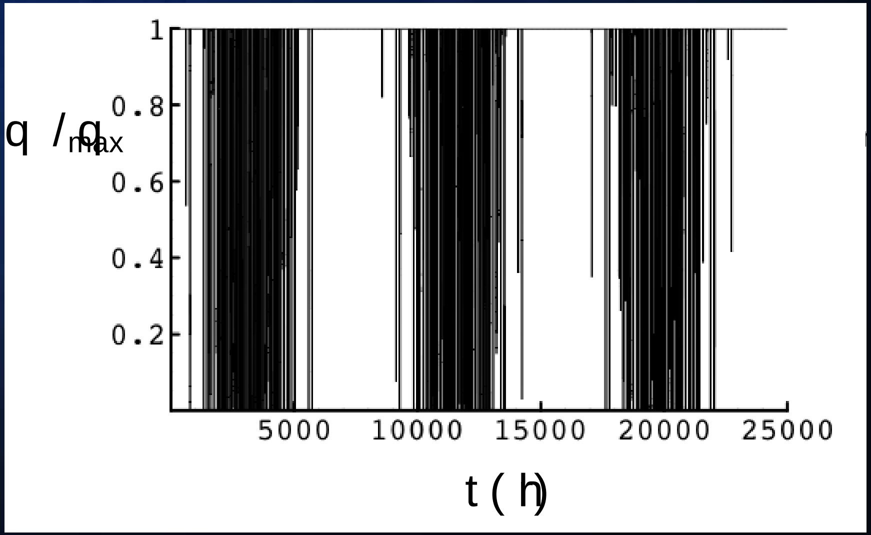
Solar Illumination of the Lunar Surface: Equatorial

- Semi-sinusoidal sunlight
- Solar Flux, q_{max}= 1300 W/m^2



Solar illumination model of the Lunar Surface: Polar Site

- Based on digital elevation model (J. Fincannon / GRC)
- Sun Tracking Reflector, q_{max}= 1300 W/m^2.



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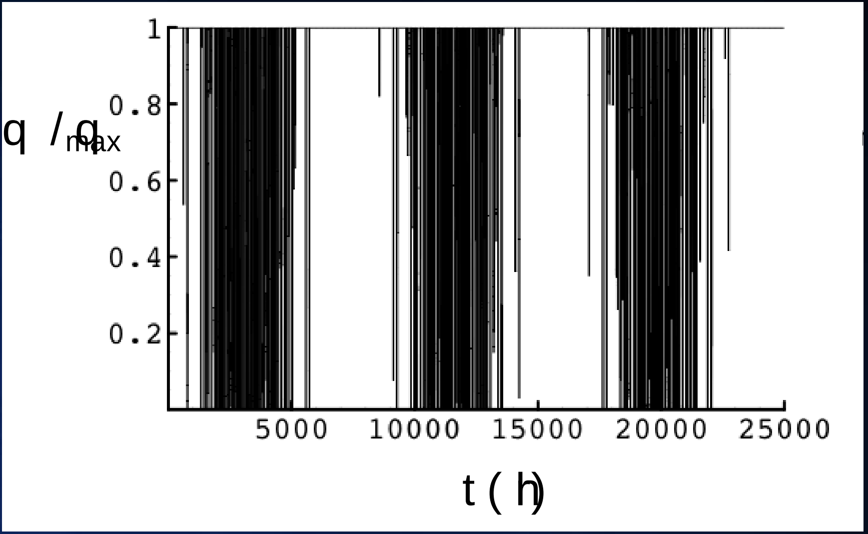
Thermal Wadi Performance near Shackleton Crater Rim

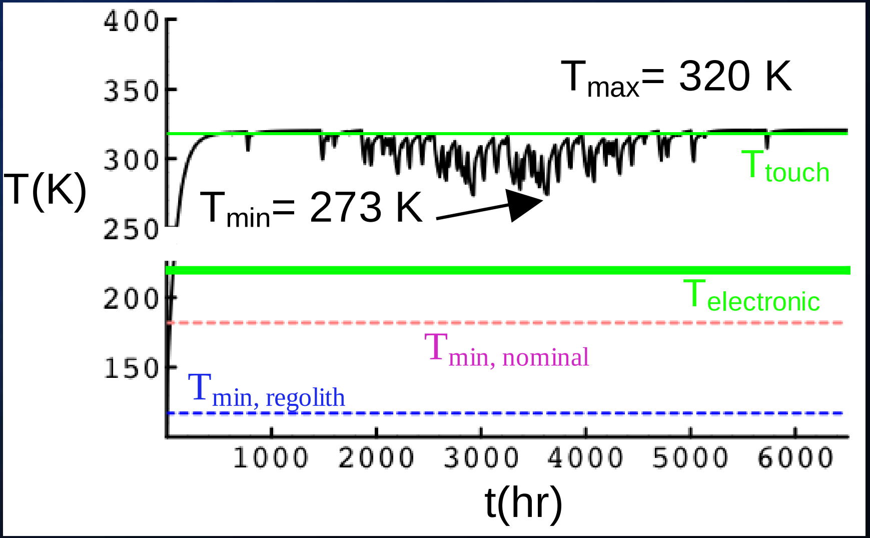
Incident Solar Flux on a Polar Thermal Wadi Site

- Annual cycle provides many months without eclipse
- Longest eclipse is 52 hours



Surface Temperature of Polar Thermal Wadi

- 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 Feasibility Study: Thermal Performance of Modified Regolith

Study Conclusions:

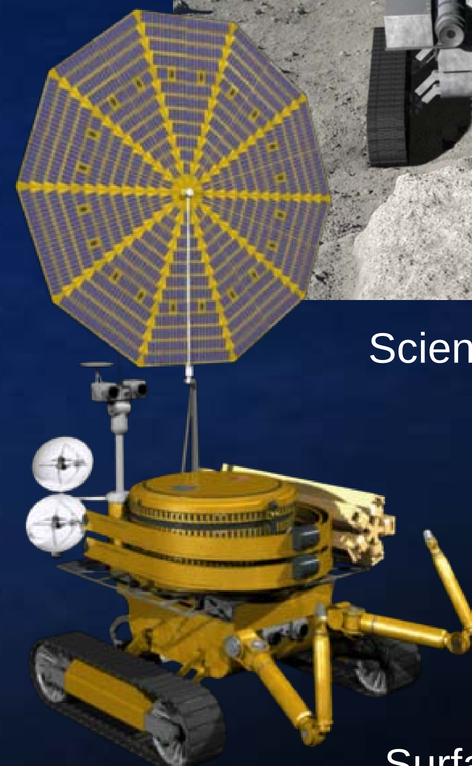
- Thermal mass of modest volume, produced using modified lunar regolith, can be heated with un-concentrated solar irradiation and store thermal energy for sustaining rovers during periods of lunar darkness.
- Constant extraction of heat for rover support is sustainable throughout the two week lunar night away from the poles.
- Support for rovers during dark periods near the lunar poles is sustainable despite very irregular lighting during winter months.
- Performance margins are obtained with combinations of managed solar input, regolith property modification and thermal mass depth to achieve minimum temperatures near the freezing point of water.

Compact Exploration Rovers

Compact Exploration Rovers

- Compact rovers with standardized chassis and tailored outfitting can perform varied exploration tasks:
  - Surveying, prospecting and environmental characterization
  - Site preparations /civil engineering
  - Scientific exploration
- Potential for distributing development and production costs among a pool of vehicle owners

Scientific/Surveying Rover



Surface Operations Rover

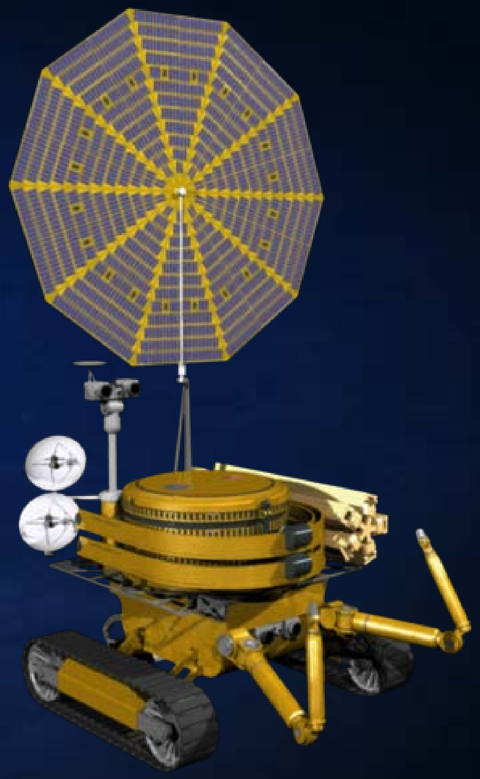
Operational Scenarios on the Lunar Surface

Operational Scenarios on the Lunar Surface

- Robotic Reconnaissance and Preparation of the Outpost Site
- Thermal Wadis and Rovers Supporting Human Exploration from the Outpost
- Thermal Wadis and Robotic Rovers Enabling Participatory Exploration

Robotic Reconnaissance & Preparation of the Outpost Site

- Initial placement of a thermal wadi with multiple rovers (possibly at Site A, on the rim of Shackleton Crater
- Demonstration of a working thermal wadi
- Science/surveying rovers perform ground-truthing and site reconnaissance prior to establishing the human outpost
- Surface operations rovers perform site preparation / civil engineering tasks



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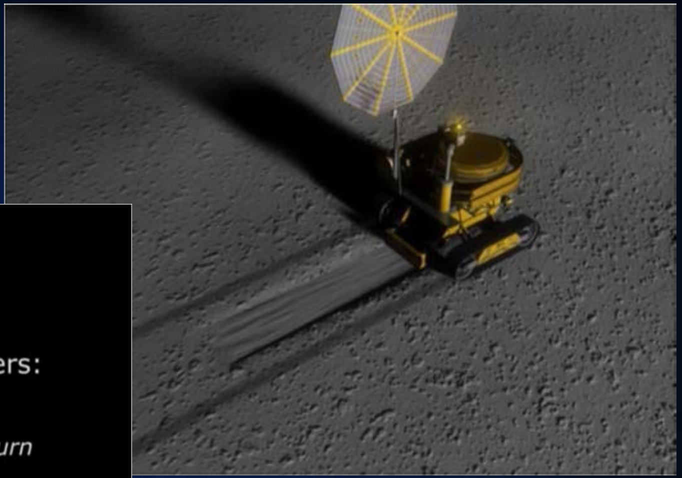
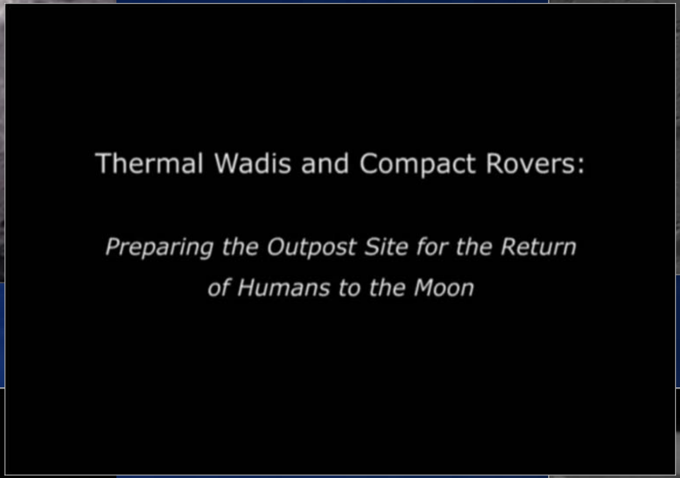
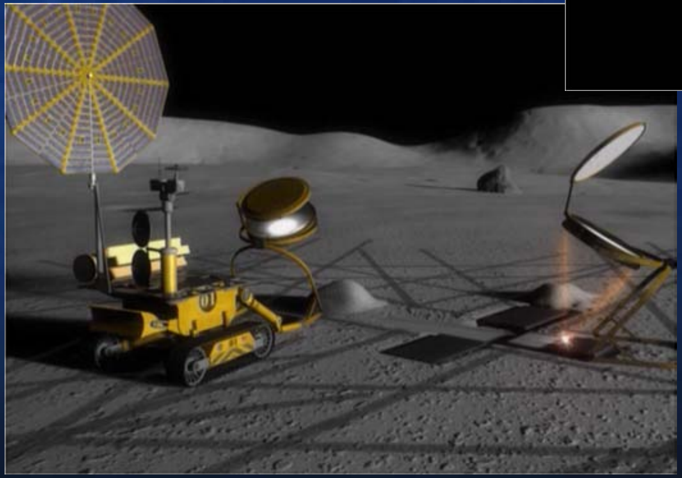
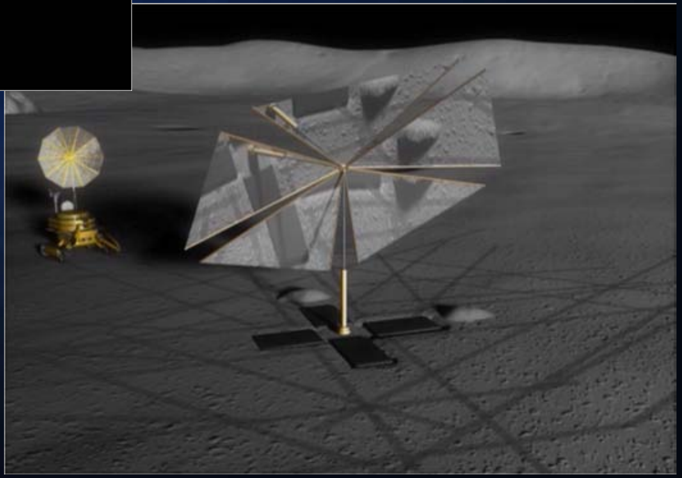
Sneak Preview: Thermal Wadis - The Movie



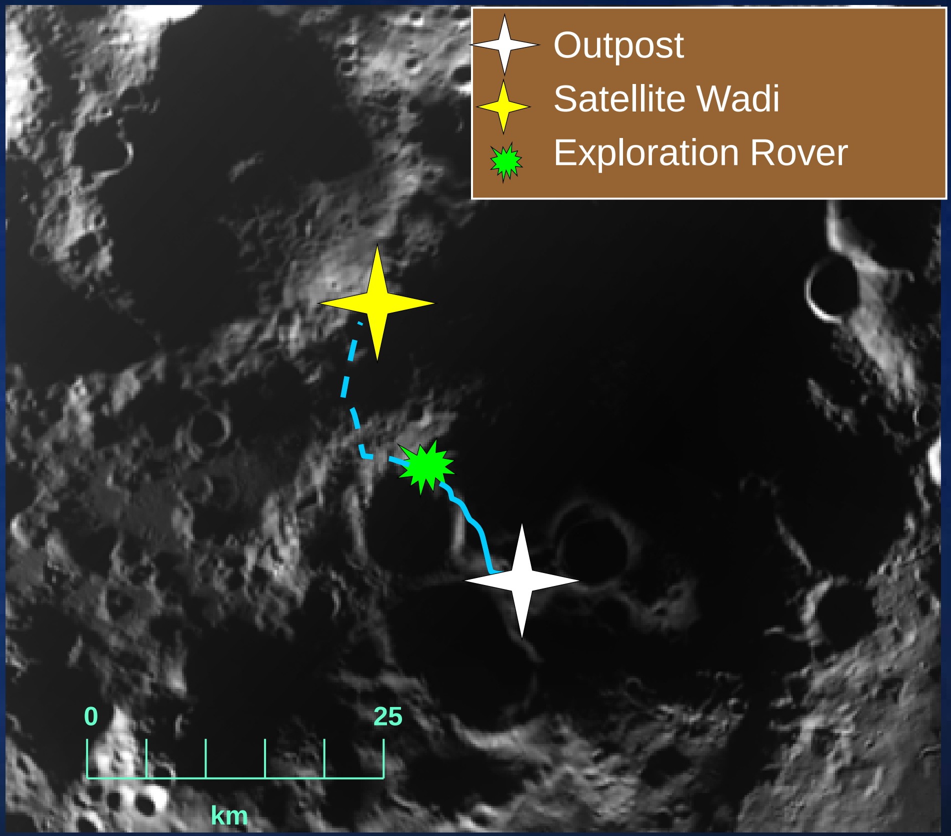


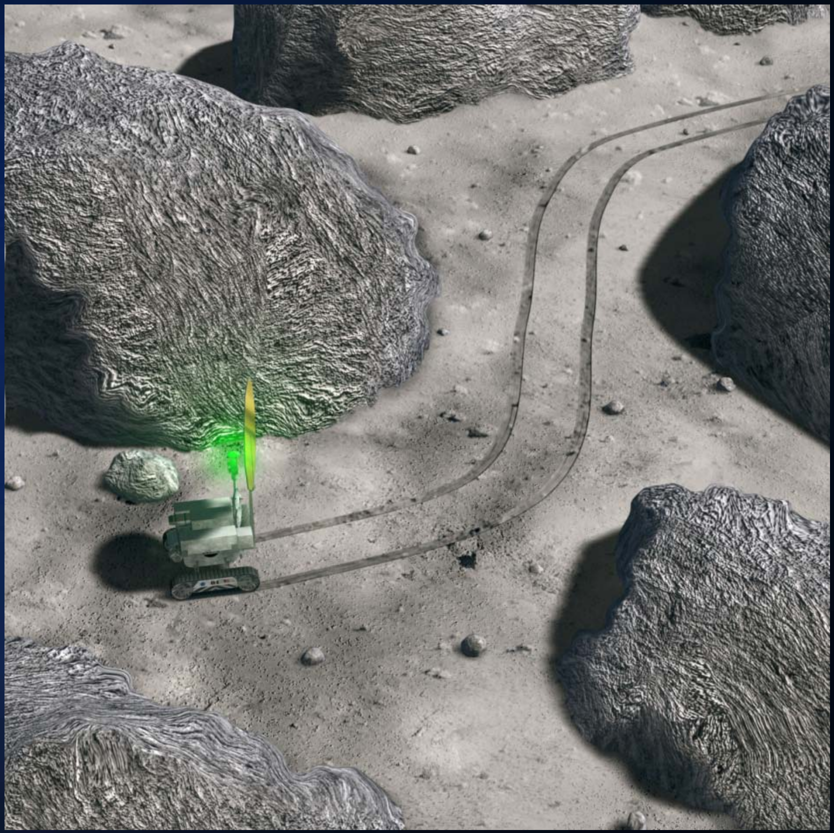




Thermal Wadis and Rovers Supporting Human Exploration from the Outpost

Exploration Route Scouting





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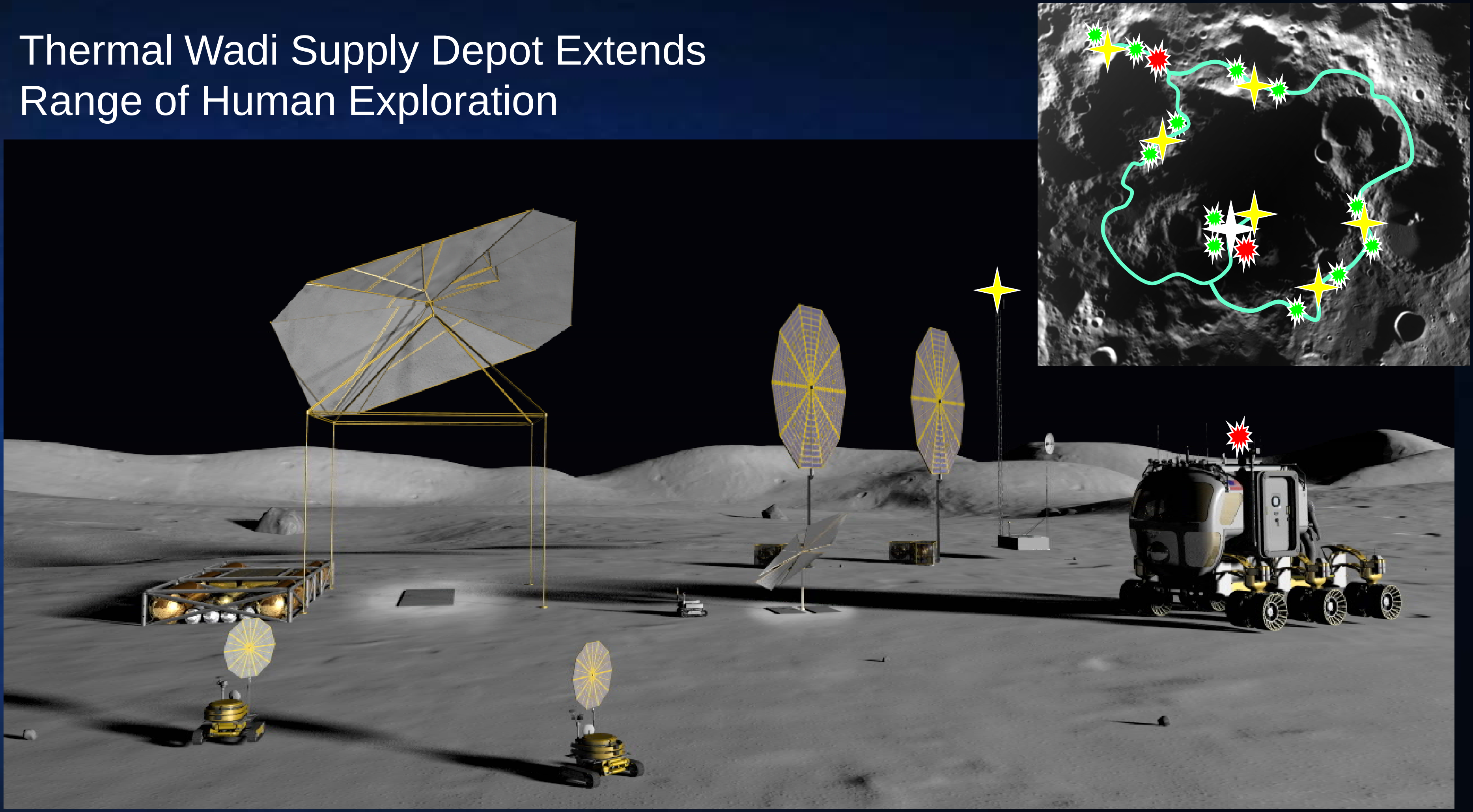
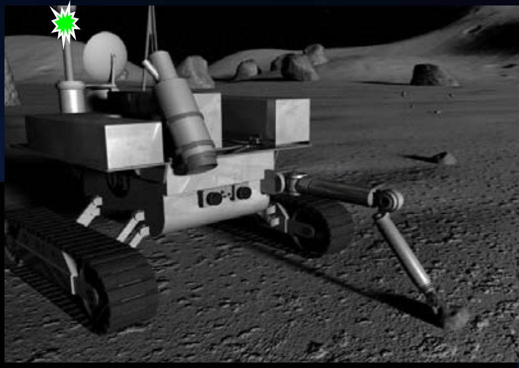
Thermal Wadis and Rovers Supporting Human Exploration from the Outpost

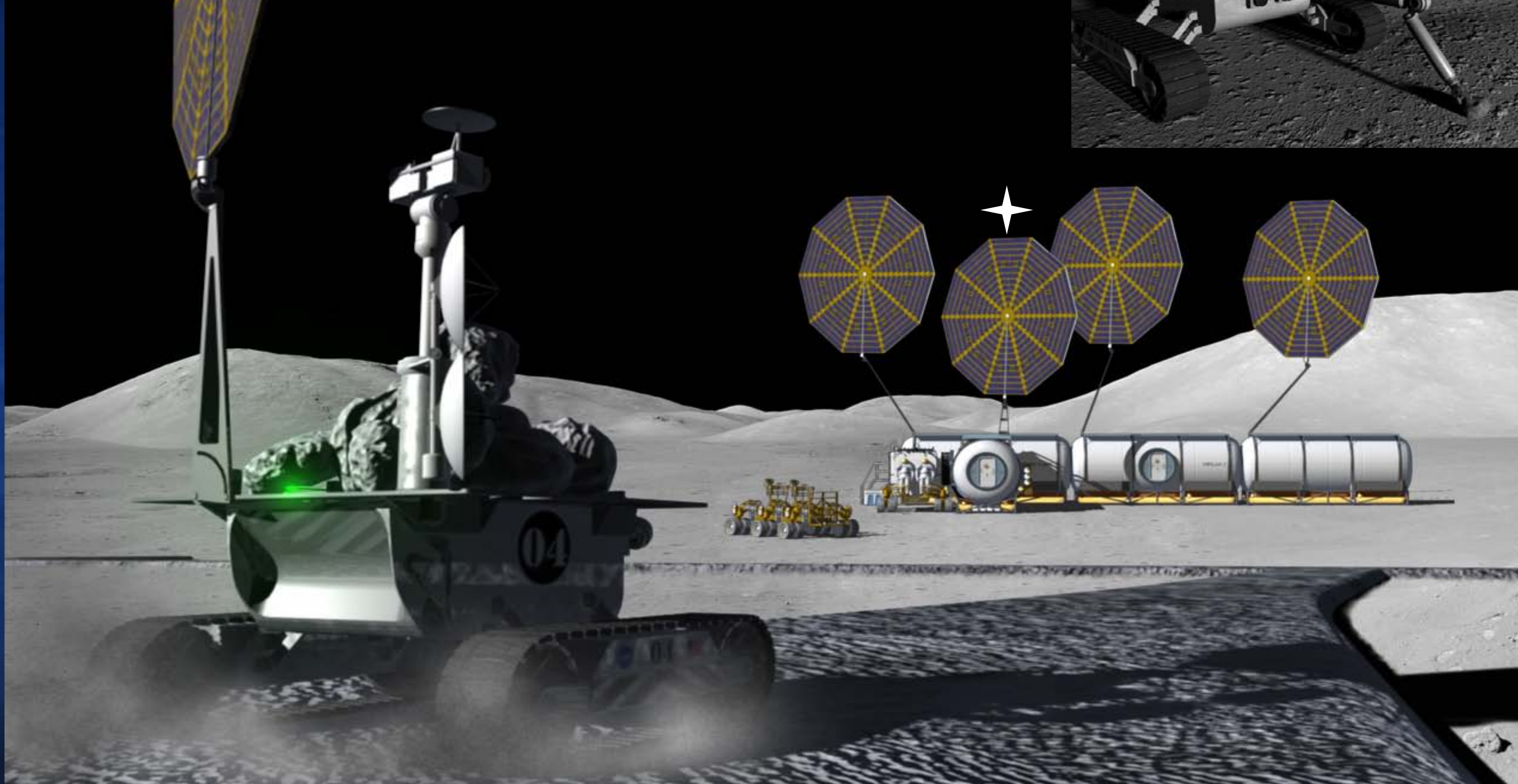
Thermal Wadi Supply Depot Extends Range of Human Exploration



Thermal Wadis and Rovers Supporting Human Exploration from the Outpost

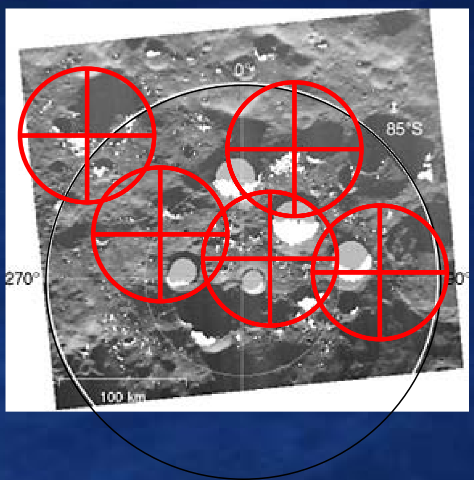
Exploration Rovers Bring Samples to Outpost Scientists

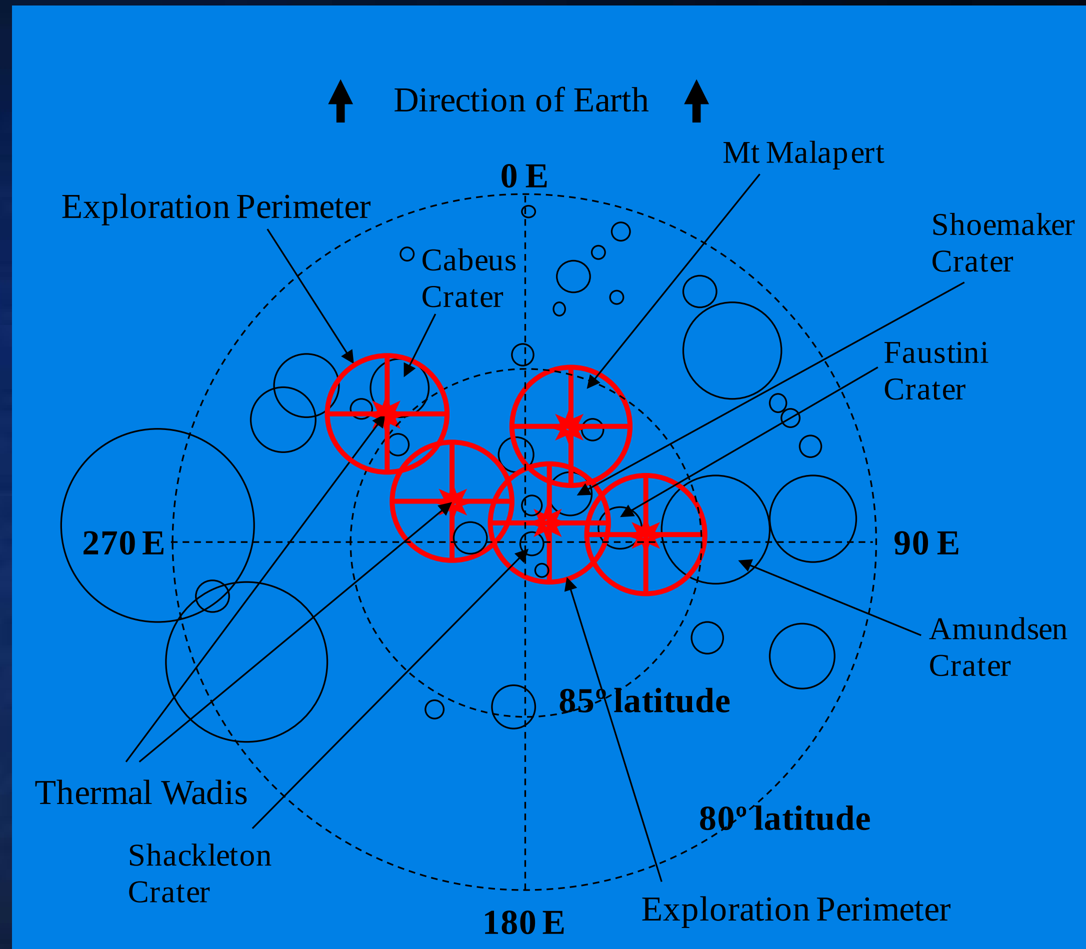




Thermal Wadis and Rovers Supporting Human Exploration from the Outpost

Thermal Wadi Networks





Thermal Wadis and Robotic Rovers Enabling Participatory Exploration

Thermal wadis and standardized light-weight exploration rovers enable a *New Paradigm for Participatory Exploration*

Thermal Wadis and Exploration Rovers: Architectural Value

- Support the Establishment of the Human Outpost
  - Reduce risk with robotic reconnaissance
  - Prepare Outpost site prior to human return
- Enhanced Crew Productivity
  - Establish acceptable routes for crewed rovers
  - Identify sites of interest and retrieve samples
  - Extend human exploration range with staging depots
- Participatory Exploration
  - Widely accessible participation in lunar operations using standardized light-weight rovers

Looking Ahead

Possible Next Steps

- Develop lunar mission scenarios utilizing thermal wadis and robotic rovers
- Extend the thermal wadi model to simulate more detailed Outpost mission scenarios
- Experimentally validate thermal model
  - Manufacture thermal mass from simulated regolith
  - Measure thermal properties
- Investigate potential for analog site field demonstrations

Thermal Wadi / Exploration Rover Animation

Acknowledgements

- Thermal Analysis of Thermal Wadis
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Questions?