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Lunar Prospecting Using Thermal Wadis and Compact Rovers

Part A: Infrastructure for Surviving the Lunar Night

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Abstract

Recent missions have confirmed the existence of water and other volatiles on the Moon, both in permanently-shadowed craters and elsewhere. Non-volatile lunar resources may represent significant additional value as infrastructure or manufacturing feedstock. Characterization of lunar resources in terms of abundance concentrations, distribution, and recoverability is limited to in-situ Apollo samples and the expanding remote-sensing database. This paper introduces an approach to lunar resource prospecting supported by a simple lunar surface infrastructure based on the *Thermal Wadi* concept of thermal energy storage and using compact rovers equipped with appropriate prospecting sensors and demonstration resource extraction capabilities. Thermal Wadis are engineered sources of heat and power based on the storage and retrieval of solar-thermal energy in modified lunar regolith. Because Thermal Wadis keep compact prospecting rovers warm during periods of lunar darkness, the rovers are able to survive months to years on the lunar surface rather than just weeks without being required to carry the burdensome capability to do so. The resulting lower-cost, long-lived rovers represent a potential paradigm breakthrough in extra-terrestrial prospecting productivity and will enable the production of detailed resource maps. Integrating resource processing and other technology demonstrations that are based on the content of the resource maps will inform engineering economic studies that can define the true resource potential of the Moon. Once this resource potential is understood quantitatively, humans might return to the Moon with an economically sound objective including where to go, what to do upon arrival, and what to bring along.

Introduction

The future of human space flight and related robotic missions are topics of energetic debate as this paper is prepared, with much of the debate beyond the scope of a technical paper. Two central issues can be discussed on a technical basis, along with other considerations, namely what should be the consensus basic objectives of the human space flight program in the United States and what should be the technical and programmatic approach to fulfilling these objectives. A great deal has been written on these subjects (Refs. 1 to 3).

There is widespread agreement on the highest level characteristics of space exploration beyond low-Earth orbit: affordable and sustainable human and robotic exploration; expanded human presence; advancement of science, technology and in-space infrastructure; and international and commercial involvement—all linked to the scientific, security and economic interests of the United States. These features may be parsed and arranged into a very broad portfolio of programmatic objectives that together are very difficult to constrain to a finite annual budget and to sustain in the face of naturally shifting national priorities. We suggest that the single organizing principle that motivated the expeditions of Marco Polo, Columbus, Lewis and Clark, and other risk-taking explorers (Euro-American and otherwise) is a suitable basis for the exploration of space, encompassing all of its desirable features. This principle is *the search for exploitable resources that sustain the explorers and economically enable those that either support them or follow them*. If space resource utilization was ever considered no more than a romantic notion, the recent measurements of substantial quantities of water and other valuable materials on the lunar surface should be sufficient to elevate the speculation to serious consideration as more than a means for exploring, but rather the reason for doing so.

Perhaps the central point of contention on how to go about exploration of space is whether or not the establishment of a human space flight destination, and the reasons for its selection, are essential at this time. A destination, on one hand, establishes a basis for highly-focused technology and subsequent flight-hardware development efforts (i.e., “technology pull”). Technology development with multiple candidate destinations may, on the other hand, produce sufficient innovation to inform and enable well-reasoned destination decisions (i.e. “technology push”). The question is whether the objective of technology development, namely innovation with a purpose, is either “efficiently focused” or “overly constrained” by technology pull; and whether such innovation is “empowered” or “unusable” in technology push.

The intention of this paper is to outline a middle ground, namely a campaign of lunar robotic missions, modest in comparison with a human lunar return, with the specific objective of resource prospecting and mapping. We describe some aspects of how this near-term exploration objective can be supported with technology pull development, again modest compared to that of a human lunar return. Such a campaign can involve and inspire student participants who may be associated with it not only as scientists and engineers, but also as entrepreneurs. The results of such a campaign can inspire technology push, potentially privately funded, and further provide a clear basis for human exploration objectives—where to go, what to do upon arrival, and what to bring along.

Space Resource Prospecting

The volume of data returning from the international effort to measure the moon from orbit is enormous, exceeding the volume of all previous planetary probes combined. Two of several compendia of results can be found in References 4 and 5, which also lead to on-line access to the data. These data include high-resolution mapping of terrain, time-varying thermal mapping, and several approaches to remote detection of chemical species using reflected irradiation from the sun and other galactic sources. An inspiring dynamic is occurring in the lunar science community: rapidly-formed collaborations between investigator teams associated with different instruments and different probes are combining their results to answer questions, provide new explanations for observations, and formulate new hypotheses concerning what is on the moon and how it came to be there. In addition to comprising a scientific treasure trove, these data and interpretations are the beginning of a detailed mapping of lunar resources.

The most obviously useful resource being evaluated on the moon is water. Water was detected in the ejecta plume from the impact of the LCROSS vehicles in extremely cold and dark craters, but also in far more quiescent and accessible locations outside the permanently shadowed craters. These more accessible sites are likely to be in darkness much of the time and the water is likely to be found at some depth below grade level. Nevertheless these data suggest the presence of retrievable water that could be processed into drinking water, breathable air, radiation shielding material, food-production resource, process reagent, or rocket propellant. Notably, the signatures of the detector data involved in the water determinations also suggest the presence of other volatile species that may contain carbon, nitrogen, and other valuable atomic species. The spatial resolution of the remote sensing measurements limit firm estimates of abundance of these materials or the expected difficulty of extraction and processing them into useable products.

The value of significant quantities of water-based products outside of Earth's gravity-well is substantial; first order estimates of its value may be derived from the anticipated cost of delivering mass to the lunar surface, at least $100,000/kg. What is missing is the means to determine both abundance and accessibility of water on the size scale of the machinery that might collect it; and doing so over a significant fraction of the lunar polar regions. For these determinations, detectors and the capability to manipulate surface material are needed on the lunar surface. These devices can be conveyed around the lunar surface by a "fleet" of small rovers provided that they can be developed, built, delivered, and operated affordably in the context of the resource value they are seeking to establish.

We have suggested (Ref. 6) that establishing a very modest lunar surface infrastructure may allow prospecting rovers to operate without carrying the mass and energy required for unsupported operations, especially the means to readily survive the extreme cold of lunar dark periods and locations. Reducing the payload and complexity of lunar surface rovers to only what is needed to conduct prospecting operations may reduce rover life-cycle costs to levels acceptable to a resource prospecting and mapping campaign. Because the resource potential is uncertain at the outset, it is likely that only space agencies can assume the risk of initiating this campaign with the development of the infrastructure and small affordable rover designs.

The Thermal Wadi Concept

The Lunar Thermal Environment

Among the many challenges faced by the expansion of human and robotic exploration of space is that of surviving and thriving under environmental conditions dramatically different from the Earth, and in particular for our purposes here, the extreme thermal environments experienced while operating on the moon, Mars, and in interplanetary space, including contact with near-Earth objects (NEO) such as asteroids and comets. On the moon, there are large periodic temperature swings in the surface material at most locations, ~120K (~-150 °C) to ~390 K (~+120 °C), over the course of the 708 hour (29.5 day) diurnal cycle, and irregular variations near the lunar poles. The surface material and human or robotic assets also interact with incoming solar flux of over 1300W/m^2, and deep space radiation sinks at nearly 0K. During the middle of the lunar day, the surface material is in radiative equilibrium with the incoming solar illumination, and is therefore also radiating at over 1300W/m^2. Long-term survival of assets depends on successfully insulating from daytime irradiation from the sun and lunar surface while dissipating internally generated heat, then completely reversing course to minimize heat loss during the lunar night.

A recent study considered thermal protection strategies for rovers attempting to survive the lunar thermal environment (Ref. 7). This numerical simulation study assessed the thermal management approaches needed during daylight operations including a photovoltaic array for power generation, thermal insulation against direct and reflected solar gain and heat dissipating radiators, then considered how these could be reconfigured during the lunar night. While employing covers on the radiator and photovoltaic array and ample use of multi-layer insulation (MLI), the study found that very small radiative heat leaks associated with difficult-to-insulate instrument appendages, wheel assemblies, etc., resulted in unacceptably low temperatures late during the lunar night. Mitigation strategies for making up the lost heat using onboard energy storage in the form of mass-efficient batteries was seen to be feasible for large vehicles, but impractical for smaller vehicles for which the needed battery mass approached the total vehicle mass. This study concluded that an external source of heat and externally provided protection from nighttime heat loss could make it possible for a smaller vehicle to survive the lunar night.

Description of the Thermal Wadi Concept

The thermal Wadi concept was conceived as a method for using local materials, modified if necessary, as thermal mass in which solar energy is stored during periods of solar illumination, then retrieved during periods of darkness for use in preventing excessive temperature decreases in human or robotic assets (Ref. 8). Because of the regolith weathering process, most of the lunar landscape is covered with small particles of pulverized rock. Because this granular regolith has a very-low bulk thermal diffusivity, solar heating penetrates very slowly into the surface during the lunar daytime and the surface temperature quickly increases to a near-equilibrium temperature at which the surface radiatively emits thermal energy at approximately the same rate that the sun delivers it. The daytime transient heating does not affect subsurface temperatures more than a few tens of centimeters below grade, and the affected mass accumulates little thermal energy. As the sun angle becomes increasingly oblique late in the lunar day, radiative emissions cool the surface quickly, dissipating the limited heat stored near the surface. By the time the sun sets, the lunar surface is already below the water freezing temperature. During the lunar night, the surface continues to cool, reaching temperatures below 120 K (–153 °C) just before sunrise.

The thermal Wadi concept is based on the simple premise that if the thermal diffusivity of material on the lunar surface can be increased to that of consolidated rock, the process described above is altered, primarily by increasing the thermal energy accumulated during the lunar day. Configured properly, energy stored in such a thermal mass can be protected from nighttime radiative cooling and delivered as needed to hardware assets. The ability to manufacture thermal mass from granular regolith eliminates the need to bring the mass from Earth.

Figure 1 shows a simple schematic representation of an operational thermal Wadi concept. The thermal mass is shown as modified regolith, though no modification apparatus is shown. The schematic depicts a reflector that directs sunlight onto the Wadi surface. At most latitudes on the moon, unaided solar heating could suffice to charge the thermal mass during the daytime, but near the lunar poles, directing the highly-oblique solar energy to the thermal mass is essential. During both late daytime and nighttime periods a fully-enclosing reflector is required to control the radiative loss flux from the surface of the thermal mass and from any protected assets using the Wadi. While no engineering development has yet been undertaken, the two reflector functions may be combined into a single device, reconfigured as needed. Distributed thermal Wadis will require these devices at each active Wadi site.

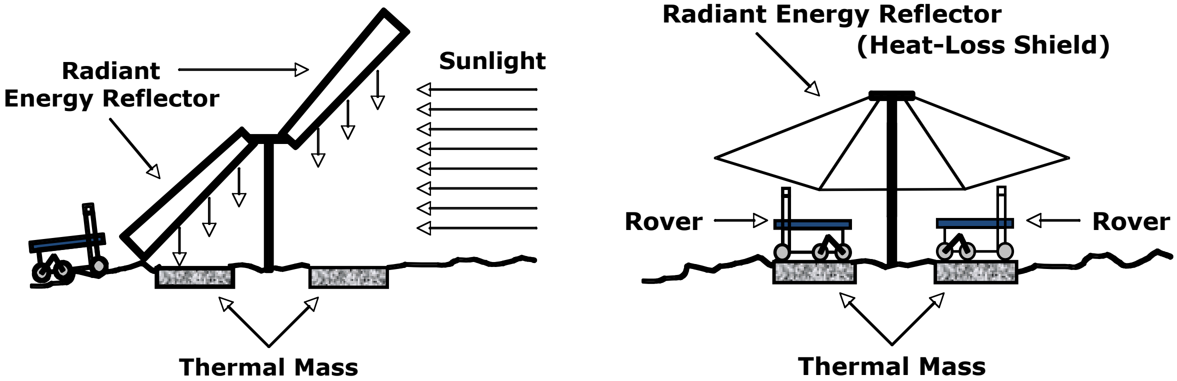

Figure 1.—The Lunar Thermal Wadi Concept. On the left, a sun-tracking reflector directs sunlight onto a thermal mass during periods of solar illumination while rovers conduct lunar surface operations. On the right, rovers are thermally coupled to the thermal mass to stay warm during periods of darkness, and are further protected by a heat-loss shield to limit radiative losses to space.

Technology Development Issues

Thermal Mass Preparation

Several options have been identified for preparing or manufacturing a thermal mass using primarily or entirely the lunar regolith. Each of these methods requires some equipment to manufacture or configure the thermal mass, and some of them consume some mass brought from Earth. None of these approaches have been developed to the point of providing reliable estimates of flight hardware mass, volume, or cost; and such estimates would further depend on the number of thermal masses needed.

Concentrated solar energy could be used to sinter or melt regolith. To arrive at a configuration with the thermal mass surface at grade level, a small pit is dug then refilled with layers of melted and resolidified regolith. This approach requires small scale excavation and a solar concentrator device, but does not consume any payload mass in the manufacturing process of successive Wadi installations. Figure 2 shows a mobile 0.5-m-diam Cassegranian solar concentrator being developed to demonstrate this approach in field trials.

Melting regolith could also be accomplished with resistive heating: initiating an electrical current path along a resistive starter wire between electrodes buried in the regolith, then relying on resistance to current flowing through the molten material to expand the melt to the desired depth and volume. This approach requires a reusable current source, consumable electrodes and starter wire and some modest hardware to implant the wire in the regolith.

The thermite reaction process is a third alternative for consolidating regolith in which an approximately 1:1 mixture of regolith and powdered metal, such as aluminum could be ignited, initiating a self-propagating, high-temperature synthesis (SHS) reaction, delivering a near-net-shape thermal mass (Ref. 9). This approach requires significant amounts of powdered metal that is consumed at each Wadi installation, an ability to mix the metal with excavated regolith, and a small ignition source.

Processes for extracting oxygen from lunar regolith produce partially- to completely-reduced minerals with thermally diffusive metal content as a by-product. This material could be used as thermal mass provided that the material is formed into the thermal mass while hot enough to coalesce into a cohesive mass. The simplest reduction method, using hydrogen to reduce the regolith iron content, operates at

Figure 2.—Mobile Cassegranian solar concentrator for testing thermal mass manufacturing techniques. Primary mirror diameter: 0.5 m. (NASA GRC).

temperatures at which the regolith may sinter; if integrated with thermal mass manufacturing the operating temperature could be raised to acceptable levels. Other regolith reduction schemes operate at significantly higher temperatures and would produce readily useable thermal mass material. For each 1000 kg of oxygen produced using the carbothermal process (10 to 14% conversion to oxygen), 4 to 6 m^2 of thermal mass, 0.5 m thick could be made. Hydrogen reduction would produce approximately ten times this amount. Unless the oxygen production capability is deployed on a mobile platform, however, this approach is not amenable to widely distributed thermal Wadis, but it does have the advantage of providing thermal mass material for little or no additional hardware brought from Earth.

A partially buried lunar rock or boulder of sufficient size could be modified using specialized equipment to effectively receive, store, and deliver thermal energy. Smaller lunar rocks or gravel could be gathered to form a sufficient mass, but may not perform as well as a continuous mass because of poor thermal contact between adjacent rocks. Both of these approaches require special equipment, but do not consume any transported mass. They are therefore compatible with multiple Wadi installations provided the materials are found in convenient locations.

A final thermal mass approach is to use unprocessed regolith combined with buried conducting apparatus such as metal spikes or honeycombs to extend the penetration of heat below grade. This option can include phase change materials to further suppress temperature swings. To take advantage of the regolith as meaningful thermal mass, this approach would require small gaps, on the order of 1 to 2 cm, between adjacent sub surface penetrations so that heat conduction occurs laterally on time scales shorter than the lunar day/night time scales. This approach requires Earth supplied conducting apparatus which is consumed in a single Wadi installation, and special installation equipment.

One or more of these options may be selected for more detailed analysis and development depending on missions-scenario choices, especially the number, size and distribution of thermal Wadi installations. The amount of equipment and consumable mass needed from Earth for thermal mass manufacture varies differently for each approach with the mission scale, and there may be value in one approach used early and a different approach used as the missions expand in geographical scope.

Solar Heating and Radiation Loss-Limiting Devices

In order to facilitate numerical simulations of the performance of the thermal Wadi concept, two related functional capabilities were conceived. The first has the objective of guiding and controlling the heating or charging of the thermal mass with solar thermal energy during illuminated periods. The second has the objective of limiting thermal radiative emissions from the thermal mass and from any hardware assets using the Wadi during dark periods. Some potential features of these capabilities evolved from options conceived in the modeling effort, but the engineering development of these concepts remains to be undertaken.

Capturing the maximum available solar thermal energy flux throughout the lunar day, while stopping short of solar concentrator approaches, requires an efficient, sun-tracking solar reflector device. Especially in near-equatorial locations, the daytime heating of the thermal mass could be accomplished with direct solar illumination, foregoing the control functions that the tracking reflector provides and accepting the natural obliquity variations that occur. This option includes variations of total available daily solar flux with latitude with a maximum near the lunar equator and minimum near the poles, and slight seasonal variations. This most-simple alternative may be acceptable for some circumstances, and may be an attractive option for the earliest deployed thermal Wadis.

Two issues suggest that more controlled thermal mass heating may be needed. First, at locations near the lunar poles, where the greatest interest in water prospecting would be focused, the sun is never more than a few degrees above the horizon. The resulting solar flux illuminating the surface is reduced to no more than a few percent of the available flux. Consequently, solar reflectors would be essential to collecting and storing substantial thermal energy.

Second, there may be a practical limit to the allowable surface temperature of the thermal mass. At full solar illumination flux, the surface temperature, either native regolith or Wadi thermal mass, equilibrates at approximately 390 K (117 °C). Vehicles operating near the lunar equator will be designed to contact regolith at these temperatures during daytime operations and should not be disturbed by similar thermal mass surface temperatures. Near the poles, however, the regolith surface temperatures during illuminated periods equilibrate at much lower temperatures. Rover designs for operations there may not be compatible with 390 K thermal mass surfaces that could be achieved with continuous full sun flux levels. Consequently, moderating or modulating the solar illumination of the Wadi thermal mass may be needed in near-polar sites.

Limiting the loss of stored heat is an essential feature of the thermal Wadi concept. Very small leaks of heat through radiation to space are compounded during extended periods of darkness, excessively cooling both the thermal mass and the protected hardware. Consequently, a full coverage thermal radiation shield is required, unlike the simple umbrella shape depicted in Figure 1. In a thermal Wadi configuration that passively collects solar thermal energy (i.e., foregoing the steered reflector, radiative cooling rates may be large enough to require loss-limiting protection well before the sun sets).

Based on the simple notion that both the reflector for heating and the radiation loss shield may accomplish their tasks using lightweight sheets of material with the appropriate reflective and emissive properties, one design approach envisioned is to combine these functions into a single device configured as a flat panel reflector that tracks the sun during the daytime, then drapes into a shelter form during dark periods. The complexity of reconfiguring the reflector may be excessive and avoided by separating the two functions into two simpler devices. A combined system, if development proves feasible, may be operated autonomously or with minimal remote supervision.

Materials that have spectrally-varying radiative properties, e.g., transparent to most of the solar spectrum but reflective at infra-red wavelengths may be employed in a static shelter configuration, behaving somewhat like modern energy efficient windows on Earth. This approach does not readily accommodate steering the sunlight, and may therefore be appropriate only in equatorial regions, not near the lunar poles.

Retrieval of Stored Thermal Energy

Two general approaches have been envisioned for the harvesting of the thermal energy to maintain the temperature of prospecting rovers during dark period pauses in operations. Among the issues to consider in designing this thermal interface are the alternative objectives to either warm only critical subsystems within a rover, such as specific instruments or electronics, or maintaining the entire vehicle at a moderate temperature.

Establishing a heat conduction path between the Wadi thermal mass and warm locations within the vehicle can be accomplished with simple heat pipe technology, or even more simple solid conduction links. While these options involve additional hardware burden for the vehicle, they can be tailored to deliver heat at specific rates. Additional engineering issues involve establishing repeatable and effective thermal contact between the heat pipe or link and the Wadi thermal mass and the target vehicle component.

The main alternative thermal interface is reliance on radiative exchange between the Wadi thermal mass and one or more surfaces on the vehicle. For daytime operations, the vehicle requires a radiator to dissipate waste heat. To dissipate heat efficiently, the radiator is operated at the highest practical temperature. If the radiator can be designed to alternatively operate at cooler temperatures while inside the Wadi enclosure, it can receive net thermal radiation from the Wadi thermal mass. It is likely that radiative exchange between the vehicle radiator and the Wadi thermal mass would be less effective than the daytime heat dissipation role of the radiator. However, the net vehicle warming requirement may be modest if the enclosure is effective in reducing the overall system losses to space.

Electrical Power Generation

We have focused primarily on the utilization of thermal mass made using lunar regolith as a thermal energy storage medium or heat reservoir. However, especially near the lunar poles, an identical thermal mass can be placed in a shallow trench or artificial crater so as to receive little or no solar illumination, radiating constantly to deep space, and becoming instead a low-temperature heat-sink reservoir. A low-temperature reservoir can be used by a prospecting rover during the daytime as a auxiliary heat sink provided that a simple thermal interface can be devised.

The proximity of high- and low-temperature reservoirs leads quickly to the suggestion of electrical power generation using heat engines or thermo-electric devices. Stirling engines have been under development for many years for space applications using solar and radioisotope heat sources (Ref. 10). Carnot efficiencies of 70% result for a heat engine operating between 389 and 117 K, the nominal temperature extremes on the sunlit lunar surface. Existing Stirling devices deliver conversion efficiencies of ~35% (Ref. 11). In this instance, Stirling engines designed to produce tens of Watts could be placed between adjacent hot and cold reservoirs. Stirling engines have not been developed for operations at these temperatures and there are materials challenges at the low-temperature reservoir.

The Wadi thermal mass can also be used as a temperature bath to house batteries slightly below the lunar surface in order to maintain stable operating temperatures. Batteries located in or adjacent to the thermal mass could be charged during daylight using photovoltaic panels and used to support prospecting rovers during nighttime.

Performance of the Thermal Wadi Concept

Considerable effort has been made to simulate the performance of the thermal Wadi concept to bound discussions about the technical feasibility of using modified regolith as an effective thermal storage medium. The results of these simulations are described in References 12 to 14, and provide a variety of feasible approaches to using thermal Wadis to protect lunar surface assets. Some of the principal results are summarized here to support the objectives of this paper. Additional analysis is described in the references and is the subject of ongoing work.

Using reported thermal properties of lunar regolith, a series of modeling constructs ranging from a useful one-dimensional calculation to a three-dimensional simulation have reproduced the measured lunar surface temperatures and then estimated the spatial and time-varying temperature distributions in a thermal mass on the lunar surface. The dimensions, properties and heating/cooling environment of the thermal mass, located first in an equatorial location then in a near-polar location, were varied to understand the effect of these variables on the ability to retain sensible heat throughout the lunar night, including provisions for extracting heat during the night to sustain a resident lunar surface asset such as a prospecting rover vehicle.

Figure 3 shows the surface temperature results of a simulation described in Reference 12 in which a 0.5 m deep thermal mass, located at the lunar equator and with the thermal diffusivity of basalt rock is heated directly by the sun with a semi-sinusoidal solar flux with a peak of $1300 W/m^2$, then cooled radiatively unprotected during the lunar night. While some heat is stored in the thermal mass, the surface temperature cools to an unacceptably low level at the end of the lunar night. Figure 4 shows the improvement in pre-dawn surface temperature for the same equatorial thermal Wadi obtained through the use of a sun-tracking reflector and a nighttime radiative reflector that reduces the effective emissivity coefficient of the thermal mass to 0.25. During the nighttime, the thermal mass simulation also provides $25 W/m^2$ to a resident rover. With this simulated technological improvement, the resulting minimum surface temperature, 247 K (–26 °C) is compatible with conventional electronics. In reference 12 the nighttime reflector is shown to dominate maintaining acceptable minimum surface temperatures over the sun tracking reflector in equatorial locations. Hence, in equatorial regions unassisted heating of a prepared

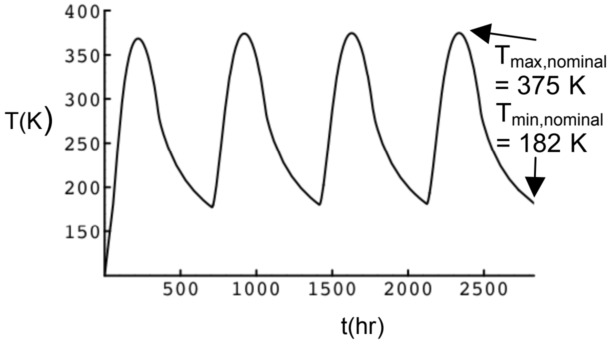

Figure 3.—Surface temperatures of an unassisted Wadi thermal mass, 0.5 m deep, over four diurnal cycles in an equatorial location. The thermal mass has the thermal properties of basalt rock (Ref. 12).

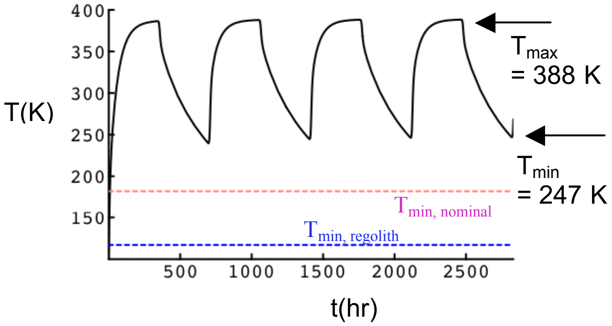

Figure 4.—Surface temperatures of a Wadi thermal mass, 0.5 m deep, over four diurnal cycles in an equatorial location. The Wadi is illuminated by a sun-tracking reflector and protected during darkness by a heat-loss limiting shield while supplying heat to a rover at 25 W/m^2. The thermal mass has the thermal properties of basalt rock (Ref. 12).

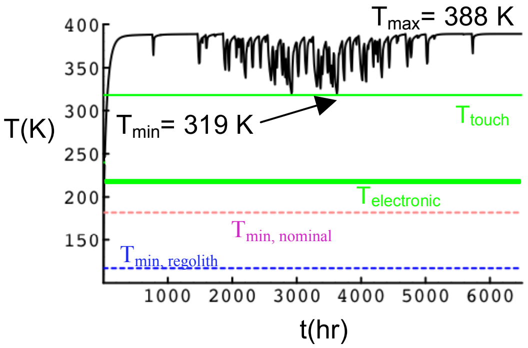

Figure 5.—Surface temperature of a Wadi thermal mass, 0.5 m deep, simulated for nine months in a near-polar location. The Wadi is illuminated by a sun-tracking reflector and protected during darkness by a heat-loss limiting shield while supplying heat to a rover at 25 W/m^2. The thermal mass has the thermal properties of basalt rock (Ref. 12).

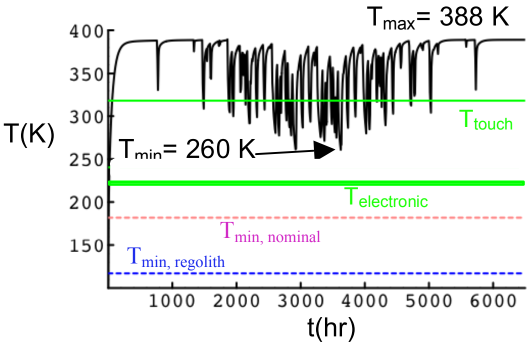

Figure 6.—Surface temperature of a Wadi thermal mass, 0.5 m deep, simulated for nine months in a near-polar location. The Wadi is illuminated by a sun-tracking reflector, but unprotected by a heat-loss limiting shield yet still supplying heat to a rover at 25 W/m^2. The thermal mass has the thermal properties of basalt rock (Ref. 12).

thermal mass and a nighttime shield may suffice to protect prospecting rovers. The maximum surface temperature of around 390 K (117 °C) is not considered a problem near the equator since prospecting rovers would routinely contact surface regolith at this temperature during daytime operations.

Figures 5 and 6 show the surface temperatures of Wadi thermal masses now located on the rim of Shackleton crater near the lunar south pole (Ref. 12). This location receives sunlight during most of the year, with over 6 months of continuous illumination and the longest dark period of 52 hours (Ref. 15). Figure 5 indicates the surface temperature of a Wadi thermal mass that is heated with a sun tracking reflector and protected during the night with a radiation shield while providing 25W/m^2 to a rover. The surface temperature stays above 319 K (46 °C) throughout the lunar year, including throughout all dark periods. In Figure 6, removing the nighttime shield is shown to reduce the surface temperatures during dark periods, with significant time in temperatures around 300 K and the coldest temperature slightly below the water freezing point.

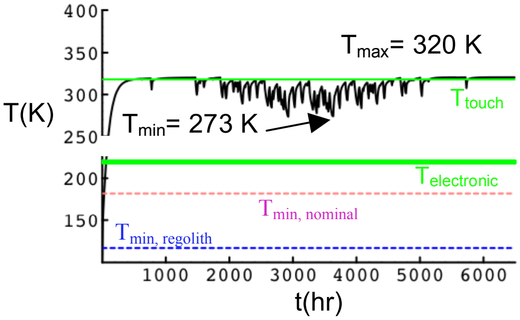

Figure 7.—Surface temperature of a Wadi thermal mass, 0.5 m deep, simulated for nine months in a near-polar location. The Wadi is illuminated by a sun-tracking reflector adjusted to provide an average solar flux of 600 W/m^2 and protected during darkness by a heat-loss limiting shield while supplying heat to a rover at 25 W/m^2. The thermal mass has the thermal properties of basalt rock (Ref. 12).

Since rovers operating near the lunar poles contact surface materials that are only obliquely heated by the sun and are therefore much colder, the rovers may not be compatible with the peak thermal mass temperatures obtained with full sun tracking illumination. Figure 7 shows the surface temperature of a Wadi thermal mass near Shackleton crater with the same features as that in Figure 5 (i.e., the sun-tracking reflector), the nighttime heat-loss shield, and nighttime rover heating. In this case, however, the solar heating is attenuated, either by diverting or diffusing the steered solar illumination, so that the average illumination is 600W/m^2 instead of the full sun 1300W/m^2. The maximum simulated surface temperature is reduced to 320 K (47 °C) and the minimum dark period temperature is 273 K (0 °C). By controlling the solar illumination the maximum surface temperature of the thermal mass can be adjusted as needed to accommodate prospecting rover material limitations. The narrow temperature range of the Wadi thermal mass surface may be deceptively important from a practical perspective. The rover thermal analysis described in Reference 7 was focused on equatorial locations where daytime heat protection and dissipation are critical operational rover features. In polar locations the rover will not be subjected to hot surface regolith and the incident sunlight is always near the horizon. Rovers near the poles may therefore conceivably accept thermal support from a Wadi thermal mass even during illuminated operational periods. Further analysis of rover thermal management in polar locations is needed to clarify this issue.

Additional published simulations (Refs. 12 to 14) of thermal Wadi performance include investigating the effect of thermal diffusivity property values lower than that of basalt rock, the effect of the thermal mass thickness or depth, the effect of lunar regolith dust covering the surface in thin layers, the effect of augmenting the thermal mass with either conducting-metal spikes or volumes of phase change materials. Each of these alternative features, including dust, provides additional flexibility in configuring a thermal Wadi to suit the local operational requirements of the proposed rover prospectors.

In the midst of conducting these simulations, an opportunity arose to perform some laboratory measurements of the thermal properties of processed lunar regolith simulants. Small samples were melted and re-solidified into tablets from which thermal diffusivity and surface emissivity measurements were obtained. These results, which have not yet been published, show that the assumption of basalt rock thermal diffusivity in the thermal simulations was appropriate, with measured values between 3×10^{-7} m^2/s to 7×10^{-7} m^2/s, compared to the value for basalt rock: 8.7×10^{-7} m^2/s, and native regolith: 6.6×10^{-9} m^2/s. Estimated radiative emissivity of 0.9 used in the simulation was also shown to be reasonable with measured values between 0.8 and 0.95. The measurements combined with the performance simulations using widely varying thermal diffusivity suggest that significant engineering margin exists with respect to the degree of processing needed to prepare acceptable thermal mass material from lunar regolith.

Discussion

The concept of the thermal Wadi and implementation approaches adaptable to various locations and thermal environments on the lunar surface have been simulated numerically with validated material properties. The simulations support concluding that the thermal Wadi is a feasible basis, with ample margin, for a simple lunar infrastructure that could be implemented in multiple locations on the lunar surface providing shelter to mobile lunar assets. Additional features such as the use of the Wadi for producing electrical power and providing a low-temperature daytime heat sink extend the utility of the concept.

A mission-focused technology development effort is needed to advance a simple lunar infrastructure based on the thermal Wadi concept as an affordable precursor to human exploration. Mission options include consideration for the variation in the thermal and solar irradiation environment with geographical latitude and the timing of extending a thermal Wadi network over the lunar surface to complete a thorough resource mapping campaign. Performance metrics including total mass from Earth, reliability, electrical power consumption, and the potential for prospecting rover cost reduction can be evaluated on a mission campaign basis or on a “per Wadi” basis. These metrics can be applied to individual or system-level technology options encompassing methods for thermal mass production, managing the solar heat source and dark period heat losses, Wadi-rover thermal interfaces, power generation and thermal heat sinking, and additional components and subsystems that are identified during the development efforts.

A focused effort to refine estimates of lunar resource potential utilizing ongoing remote sensing results and evolving lunar science is essential, comprising the basis for quantifying the potential benefit of investments in the technology development and operations we have outlined for surface-based prospecting. Resource potential includes water harvesting and oxygen production but also other materials that might be extracted and utilized locally or away from the moon. In addition to providing cost/benefit evaluations, remote sensing and scientific evaluation informs the detailed mission strategy for surface site selection and operational capability.

Ultimately, evaluating the resource potential of the moon requires mobile surface prospecting instruments to identify resource materials of interest and demonstrated methods for resource extraction and varying degrees of in-situ resource processing. While in this paper we have outlined elements of a simple infrastructure that could reduce the complexity and cost of surface prospecting and resource mapping, development of these capabilities, affordable in the context of the perceived resource value potential, is needed. In that large fractions of the moon may warrant surface evaluation, many copies of a versatile design may be needed. Development with versatility, affordability and “mass production” as a goal is not currently the standard approach for robotic exploration vehicles and will require innovation in the planning of the work, not unlike the achievement of Henry Ford a century ago.

As this paper is prepared great attention is being given to mission requirements and technology developments needed to undertake a human exploration to a Near-Earth Object (NEO), and the reasons for directing human space exploration to such a goal. Naturally and appropriately, indomitable proponents of various technologies and mission capabilities developed with the moon in mind are laboring to adapt the principles if not the products of their work to a very different destination, however strained the adaptation may be. Because comparatively little is known of NEO properties, however, rigorous translation of lunar surface capability to a NEO may be impractical at this time. While we do not suggest that a thermal Wadi type infrastructure as we have described it is relevant to a NEO, it is very reasonable that the underlying objective is just as valid: *to search for exploitable resources that sustain the explorers and economically enable those that either support them or follow them*.

Two threads of logic follow from this proposition. If one practical rationale for travelling to a NEO is the avoidance of overcoming a gravity well to return to Earth, then resources obtained there are as easy to utilize, even on Earth, as bringing the crew home. If another practical rationale for travelling to a NEO is to demonstrate implementation of planetary protection techniques, i.e. mitigating the risk of a collision with Earth, then resources obtained there may be the simplest source of high energy-density material useful as propellant for gradual orbit modification or explosives for the destruction of the NEO.

In either case, work undertaken to robotically evaluate the resource potential of the moon prior to undertaking the same for NEO evaluation provides valuable operational experience close to Earth for later work farther away. Lunar resource characterization may prove to be sufficiently fruitful, however, to alter the evaluation of human lunar exploration and the associated gravity well challenges. Such an outcome may provide experiential and technological support for the human NEO exploration but would certainly provide very clear objectives for humans on the moon: where to go, what to do when they get there, and what they bring along.

Conclusion

A modest lunar surface infrastructure based on the feasible Thermal Wadi concept for energy storage and nighttime environment survival constitutes an affordable approach for an extended campaign of robotic resource prospecting on the moon, and may lead to focused objectives for the return of humans to the moon. By overcoming one of the most challenging of environmental obstacles for sustainable lunar operations, the Thermal Wadi concept eliminates forever the development of hardware for the moon that cannot survive the night.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Recent missions have confirmed the existence of water and other volatiles on the Moon, both in permanently-shadowed craters and elsewhere. Non-volatile lunar resources may represent significant additional value as infrastructure or manufacturing feedstock. Characterization of lunar resources in terms of abundance concentrations, distribution, and recoverability is limited to in-situ Apollo samples and the expanding remote-sensing database. This paper introduces an approach to lunar resource prospecting supported by a simple lunar surface infrastructure based on the Thermal Wadi concept of thermal energy storage and using compact rovers equipped with appropriate prospecting sensors and demonstration resource extraction capabilities. Thermal Wadis are engineered sources of heat and power based on the storage and retrieval of solar-thermal energy in modified lunar regolith. Because Thermal Wadis keep compact prospecting rovers warm during periods of lunar darkness, the rovers are able to survive months to years on the lunar surface rather than just weeks without being required to carry the burdensome capability to do so. The resulting lower-cost, long-lived rovers represent a potential paradigm breakthrough in extra-terrestrial prospecting productivity and will enable the production of detailed resource maps. Integrating resource processing and other technology demonstrations that are based on the content of the resource maps will inform engineering economic studies that can define the true resource potential of the Moon. Once this resource potential is understood quantitatively, humans might return to the Moon with an economically sound objective including where to go, what to do upon arrival, and what to bring along.

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