47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-1339

Analysis of Solar-Heated Thermal Wadis to Support Extended-Duration Lunar Exploration

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The realization of the renewed exploration of the moon presents many technical challenges; among them is the survival of lunar surface assets during periods of darkness when the lunar environment is very cold. Thermal wadis are engineered sources of stored solar energy using modified lunar regolith as a thermal storage mass that can enable the operation of lightweight robotic rovers or other assets in cold, dark environments without incurring potential mass, cost, and risk penalties associated with various onboard sources of thermal energy. Thermal wadi-assisted lunar rovers can conduct a variety of long-duration missions including exploration site surveys; teleoperated, crew-directed, or autonomous scientific expeditions; and logistics support for crewed exploration. This paper describes a thermal analysis of thermal wadi performance based on the known solar illumination of the moon and estimates of producible thermal properties of modified lunar regolith. Analysis was performed for the lunar equatorial region and for a potential Outpost location near the lunar south pole. The results are presented in some detail in the paper and indicate that thermal wadis can provide the desired thermal energy reserve, with significant margin, for the survival of rovers or other equipment during periods of darkness.

Nomenclature

q	Solar heat flux incident on the wadi surface, W/m^2
q_{abs}	Heat flux absorbed by the wadi surface, W/m^2
q_{cond}	Heat flux conducted by the surface into the bulk of the wadi, W/m^2
q_{max}	Maximum solar heat flux, W/m^2
q_{rad}	Radiative heat flux emitted by the surface, W/m^2
q_{rov}	Heat flux supplied by the wadi surface to the rover at night, W/m^2

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t_0	One half of the sinodic time-period, s
t	Time, s
T	Temperature of the wadi surface, K
T_{av}	Time-averaged surface temperature, K
$T_{electronic}$	Reference low temperature limit tolerated by electronic equipment, K
T_{max}	Maximum surface temperature, K
$T_{max,nominal}$	Maximum surface temperature at the equator for basalt with a semi-sinusoidal solar heat flux, K
$T_{max,regolith}$	Maximum surface temperature at the equator for native regolith with a semi-sinusoidal solar heat flux, K
T_{min}	Minimum surface temperature, K
$T_{min,nominal}$	Minimum surface temperature at the equator for basalt with a semi-sinusoidal solar heat flux, K
$T_{min,regolith}$	Minimum surface temperature at the equator for native regolith with a semi-sinusoidal solar heat flux, K
T_{touch}	Touch temperature (reference high temperature limit), K
α_{reg}	Thermal diffusivity of native regolith, m^2/s
ε	Radiative emissivity of the thermal mass surface, dimensionless

I. Introduction

IN this paper, we present the results of an effort to examine one aspect of the technical feasibility of using thermal wadis – engineering sources of heat and power[1,2] – that can protect exploration systems from the extreme cold of the lunar surface. If thermal wadis can be successfully developed, and placed on the Moon as adjunct elements of the lunar surface architecture, they may enable long-term operation of highly productive systems such as robotic rovers that can be teleoperated from the Earth.

Large temperature swings are experienced at most locations on the Moon, in part because of its slow rotation rate (the diurnal cycle of the Moon is about 27 Earth-days long) and in part because native lunar regolith is very resistant to thermal conduction. Heat does not penetrate very deeply – approximately ten centimeters during periods of sunlight – and as a result temperatures typically range from a high of about 400 K to a low of about 100 K, too cold for many scientific and exploration systems that might be useful on the Moon.

More moderate temperature cycles would be obtained with materials that have a higher thermal diffusivity. Accordingly, it has been hypothesized that materials with acceptable properties for thermal energy storage can be produced by using solar energy to sinter and/or melt lunar regolith and allowing it to cool into a solid mass. Along with additional hardware to regulate the absorption and loss of thermal energy, the resulting thermal mass would experience a reduced temperature swing and could serve as a "warming pad" for robotic rovers or other exploration assets during periods of darkness on the lunar surface.

NASA plans to establish a permanent, manned Outpost on the Moon. At the present time, for planning purposes, the Outpost is assumed to be located in very close proximity to the South Pole of the Moon, on the rim of Shackleton Crater. This location has been chosen largely because it experiences nearly constant sunlight[3]. Although the Sun must necessarily always be at or near the horizon from this location, the small tilt of the Moon's axis with respect to the ecliptic results in short periods of darkness primarily when nearby topographic features cast shadows on this location. Presently, the longest period of darkness is estimated to be 52 hours.

Thermal wadis can support the exploration of the Moon in several ways. For example, prior to the establishment of the Outpost, thermal wadis can enable teleoperated rovers to perform ground truthing, calibrating observations from the four orbiting satellites that are or will be gathering data about the lunar surface over the next few years. Equipped with multi- or hyper-spectral imagers, plus various geological tools including ground-penetrating radar, such rovers can perform valuable science and begin to characterize the Moon's resource potential.

In addition, in conjunction with early efforts to establish the Outpost, a thermal wadi with one or more rovers could be placed at or near the planned Outpost location, enabling the acquisition of valuable data about the local topography that will enable Outpost systems to be developed with greater confidence than could otherwise be obtained. Later, after the Outpost is established, thermal wadis can support teleoperated rovers that work in support of astronaut operations to test out planned routes for manned rovers, to travel routes that manned rovers cannot travel, to identify features of interest and which are the most productive locations for astronaut-scientists to visit, and to bring geologic samples to astronauts at the Outpost. In addition, thermal wadis can operate much like the multiple camps that are established in a mountain-climbing expedition, functioning as staging locations, communication relay stations or supply depots for oxygen, fuel, food, and energy for reprovisioning crewed rovers, thereby enabling excursions that are significantly farther from the Outpost than would otherwise be possible.

The basic concept of a thermal wadi is illustrated in Figure and consists of a thermal mass plus one or more energy reflectors for a) reflecting solar energy onto the thermal mass during periods of sunlight and b) reflecting radiant energy back to the thermal mass during periods of darkness. During periods of sunlight, thermal energy is absorbed and stored within the thermal mass. During periods of darkness the stored energy is used to provide temperature control for rovers and other exploration assets.

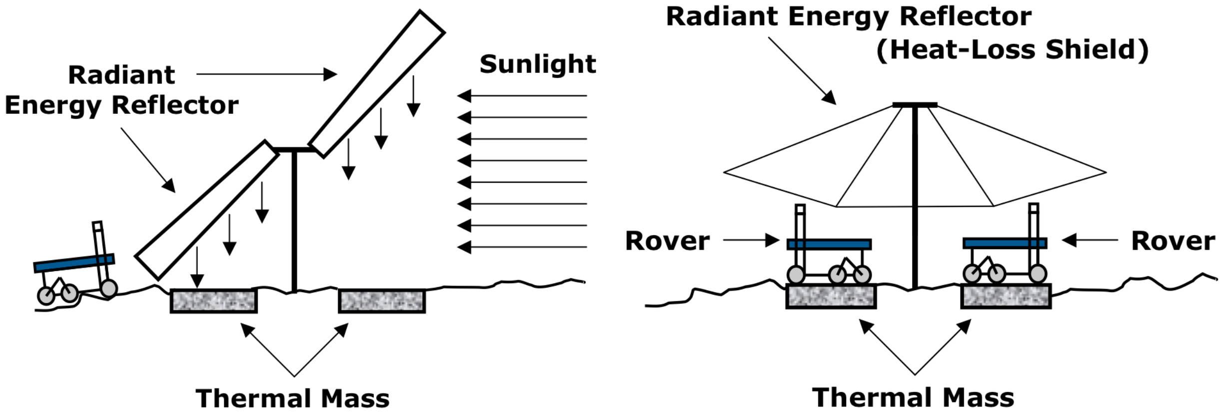

Figure 1. The Lunar Thermal Wadi Concept. On the left, a sun-tracking reflector directs sunlight onto a thermal mass during periods of solar illumination while rovers conduct lunar surface operations. On the right, rovers are thermally coupled to the thermal mass to stay warm during periods of darkness,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

The thermal property values of the thermal mass are critical to the effectiveness of the thermal wadi. In its native state, lunar regolith is a poor material for thermal energy storage. Due to its very low thermal diffusivity, about 6.6×10^{-9} m^2/s per measurements made during the Apollo program,[4] heat does not penetrate the lunar surface very deeply and is lost rapidly due to radiation during periods of darkness. It is this property that accounts, in part, for the large surface temperature swing during the Moon's 27-day diurnal cycle. However, the regolith contains the elemental materials needed for a reasonable thermal energy storage medium, and experiments on Earth have demonstrated that solar and/or microwave energy can enable the necessary conversion processes. Examples of regolith processing methods that can produce thermal masses with improved thermal properties include:

Compacting and sintering. For example, microwave heating of regolith couples the microwave energy with the nanophase metallic iron, which coats individual regolith particles and is present in most impact-produced glass in the soil, yielding a single, sintered/melted mass[5]. This sintering reduces the thermal-contact resistance of the material and increases the bulk-thermal diffusivity of the resulting mass.

Melting processed or unprocessed regolith, then solidifying the melt into a solid block, possibly by concentrated solar energy, microwave energy or electrical resistance heating. This also reduces the thermal-contact resistance within the material and increases the bulk-thermal diffusivity.

Incorporating hardware and/or materials with high-thermal conductivity and/or high-thermal capacity. Examples of hardware include heat pipes, heat-transfer fins, and thermal switches. Examples of materials include graphite, metals, phase-change materials, and/or appropriate heat-transfer fluids.

Reducing regolith, by thermochemical or electrochemical means, to produce a metal-enriched product. For example, various processes that are in development for producing oxygen from regolith are candidates (e.g., hydrogen reduction or carbothermal reduction, vacuum pyrolysis, and electrothermal melting[6].

These methods may be applied individually or in combination to yield thermal-mass materials that, on the lunar surface, would exhibit much smaller temperature swings than are observed for native regolith. Systems and methods for regolith excavation and surface construction, solar concentrators and microwaves for regolith heating, and regolith processing for metal enrichment are preliminarily under development as part of NASA's plans to deploy In-Situ Resource Utilization (ISRU) capabilities at the lunar outpost.

Several technical issues must be resolved in order to show that thermal wadis can be a valuable adjunct element of the lunar surface architecture, including whether thermal mass material can be readily produced at reasonable cost on the lunar surface. To begin, however, we chose to analyze the extent to which a thermal wadi can provide temperature control for a robotic rover based on several simplified configurations of operational hardware and modifications to the native regolith for creating the wadi thermal mass.

In this paper we present the results of a thermal analysis of various wadi concepts to determine the temperature of the thermal mass, especially the surface temperature that is the simplest interface to any hardware the wadi would support during periods of lunar darkness. The analysis was performed for simulated conditions at two locations: 1) near the lunar equator, where the solar illumination of the surface is very periodic and similar over wide areas, and 2) a single selected site near the lunar south pole, where the illumination is very irregular, but considered a promising site for the planned lunar Outpost.

II. Thermal Analysis of Lunar Thermal Wadis

The objective of the thermal analysis is to determine the temperature of the wadi, especially its surface temperature. We determined how the wadi surface temperature varies with time, and how the maximum and minimum surface temperatures depend on the incident solar flux, the depth of the wadi, and its thermal properties, chiefly its thermal diffusivity. Additionally we show the contributions of operational hardware that might accompany the thermal wadi, including a reflector of solar illumination that tracks the movement of the sun with respect to the wadi surface and a reflector that limits the radiative loss from the surface of the thermal mass to space. Throughout our analysis we used the thermal properties, summarized in Table 1, of native regolith and basalt rock.

Table 1: Physical Properties of Wadi Materials

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)

We assumed that the solar flux incident on the surface is spatially uniform and varies with time (e.g. Figure 2 for the equatorial region). The depth of the wadi is likely to be shallow compared to its lateral extent, so that the wadi can be easily constructed. The thermal conductivity of the wadi material is expected to be much larger than that of native regolith. Within the bulk of the wadi, we therefore expect negligible lateral heat loss to the surrounding regolith, and that heat will be transferred primarily in the downward direction. A one-dimensional analysis was therefore sufficient to discern the thermal behavior of the wadi. A one-dimensional analysis has an added benefit of being relatively simple compared to a multi-dimensional analysis, and is sufficient to determine the sensitivity of various design options and system parameters on the maximum and minimum surface temperature of the wadi.

Our thermal model of the wadi is similar to the Wesselink model of thermal energy transfer in planetary regolith[7,8]. In this model, thermal energy transport beneath the surface is solely by conduction. Radiative heat transfer is allowed only from the surface into space. The absorptivity of the wadi surface was assumed to be constant and equal to 0.9 over the wavelength spectrum of the incident light. The native emissivity of the wadi surface was also assumed to be a constant and equal to 0.9 in the wavelength spectrum of the emitted radiation (infra-red region). In most of the cases that we modeled, we assumed that a radiation shield is used during the night to reduce the radiative loss from the wadi surface. In such cases we assumed that the effect of the radiation shield can be represented by an effective surface emissivity of 0.25. In most of the calculations, we assumed that energy is supplied from the surface of the wadi to a rover to keep it warm during the lunar night. We represent the energy transfer from the wadi to the rover by a constant nighttime surface heat flux. In formulating the mathematical model, the heat flux balance at the surface of the wadi was therefore written as $q_{cond} = q_{abs} - q_{rad} - q_{rov}$, where q_{cond} is the flux of energy supplied to and extracted from the bulk of the wadi by conductive heat transfer.

Within the bulk of the wadi, there is a balance between energy storage (due to sensible heat) and energy transfer by conduction. The bottom boundary of the wadi was assumed to be in contact with a layer of native regolith. At this interface, the temperature and heat flux were assumed to be continuous. In all the calculations that we report, the native regolith layer thickness beneath the wadi was assumed to be 20 cm, which is nearly the same as the characteristic thermal penetration depth $2(\alpha_{reg}\, t_0)^{1/2}$, where t_0 is one-half of the sinodic period on the moon (t_0= 354 hr). The bottom boundary of the layer of native regolith is considered to be adiabatic.

For initial conditions, in all calculations we specified that the temperature at t=0 is 100 K everywhere. The equations and boundary conditions were solved numerically as an initial value problem.

III. Performance of Thermal Wadis in Lunar Near-Equatorial Environments

The equatorial solar flux is shown in Figure 2. The flux is assumed to be sinusoidal during the daytime, and vanishes during the lunar night. The angle between the surface normal and the sun at the peak is further assumed to be the same from lunar month to lunar month. The time-period of the solar flux is the sinodic period, which is 708 hr. The peak heat flux is taken to be q_{max}= 1300 W/m^2. Figure 3 shows how the solar heating of the thermal mass can be enhanced by the use of a reflector that tracks the sun to direct the full solar flux to the surface throughout the lunar day. This constitutes the maximum intensity source of heating without the additional complexity of concentrating or focusing the solar illumination of the surface.

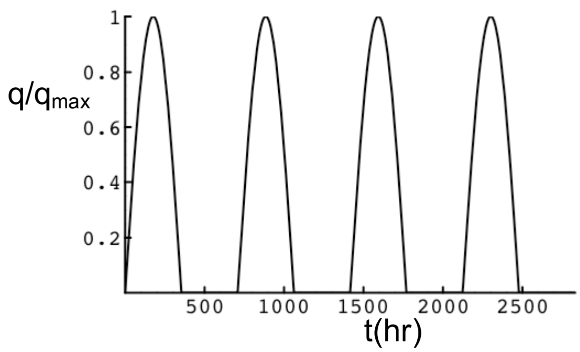

Figure 2. Equatorial solar flux. The solar flux profile is a semi-sinusoid, with q_{max}= 1300 W/m^2.

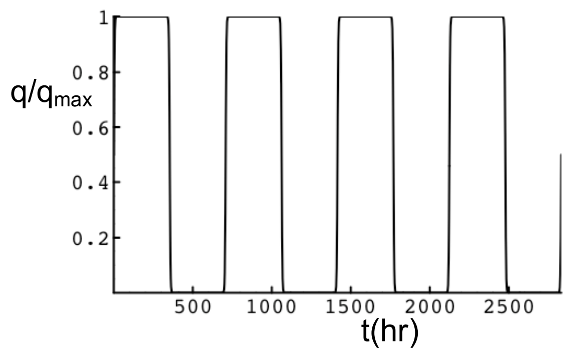

Figure 3. Equatorial solar flux obtained with the use of a sun-tracking reflector. The solar flux profile is a square wave, with q_{max}= 1300 W/m^2.

As a reference for the various thermal wadi configurations to be explored, the variation with time of the surface temperature of unaltered lunar regolith exposed to the solar flux described in Figure 2 was calculated using the thermal model and is shown in Figure 4. The regolith layer depth is taken to be 20 cm, based on the thermal penetration depth argument given above. We assumed that the peak heat flux (q_{max}) is 1300 W/ m^2, and the surface emissivity, ε, is a constant 0.9. At this level of heat flux, the theoretical maximum surface temperature that is attainable is 389 K. This temperature represents a balance between absorption of the peak solar flux and simultaneous radiative emissions, where both the blackbody absorption coefficient and the blackbody emission coefficient are 0.9. The maximum and minimum surface temperatures resulting from the thermal model are 387 K and 117 K, respectively. It is evident from the figure that with the initial uniform thermal mass temperature of 100 K, conditions close to steady-state oscillations are achieved in 4 diurnal cycles. For all the equatorial cases that follow, we show the temperature results at the end of the fourth diurnal cycle.

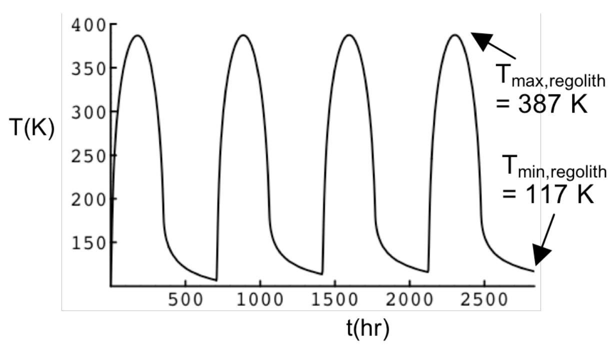

Figure 4. Surface temperature vs. time for native regolith exposed to the equatorial solar flux shown in Figure 2.

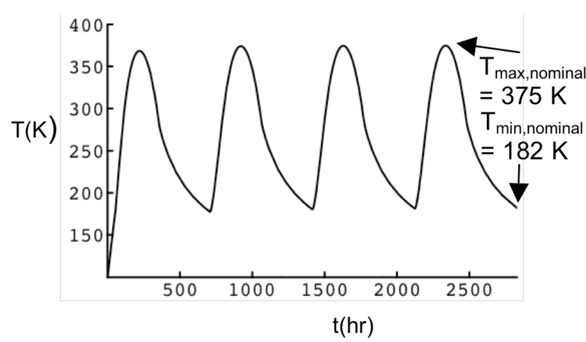

Figure 5. Nominal thermal wadi performance in an equatorial location. Surface temperature vs. time for a 50-cm deep wadi with thermal properties of basalt rock.

Figure 5 shows the performance of what we describe as a nominal thermal wadi configuration. The nominal equatorial thermal wadi assumes the thermal properties of basalt rock, which is about 100 times that of native regolith, and a wadi depth of 50 cm, which is approximately a fourth of the characteristic thermal penetration depth in basalt. The surface thermal emissivity is set to a constant, ε = 0.90. Compared to those of native regolith, the maximum temperature is reduced slightly, and the minimum temperature increases by 65 K. This configuration is an improvement, but is not sufficiently warm during much of the lunar night to passively provide heat to a rover or other equipment susceptible to cold.

Figure 6 shows how the performance of the nominal thermal wadi configuration is changed with the use of a sun-tracking solar illumination reflector, the solar flux from which is described in Figure 3. From sunrise, it takes approximately 270 hours of absorbing heat for the thermal mass surface to reach the maximum temperature of 388 K, nearly the theoretical maximum. The surface remains at the maximum temperature for 80 additional hours, until sunset. Sufficient additional heat is stored in the thermal mass by the use of the reflector that the minimum temperature is raised by about 10 K. This configuration also does not provide sufficient heat to sustain equipment during the later parts of the lunar night.

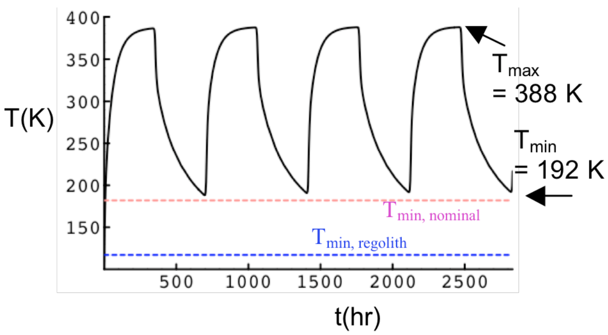

Figure 6. Thermal wadi performance in an equatorial location illuminated by a tracking reflector. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock.

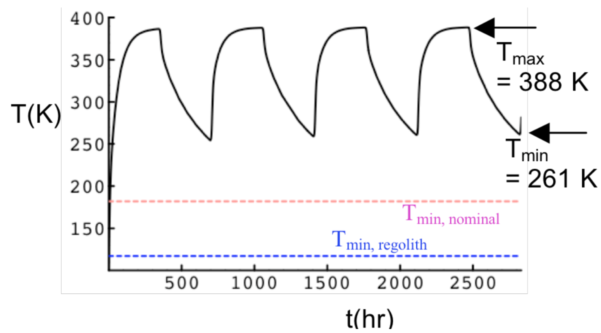

Figure 7. Thermal wadi performance in an equatorial location illuminated by a tracking reflector and protected during darkness by a heat-loss limiting shield. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock.

During the lunar night, heat radiated to space from the surface of the thermal mass of the wadi results in significant heat loss and surface temperature reduction. We introduced the use of a radiation shield concept into the analysis intended to limit these losses. To simulate the heat-loss-limiting shield, the model adopts an effective surface emissivity reduced from 0.9 during the unshielded daytime configuration to 0.25 during the night. Figure 7 shows how the use of the shield substantially increases the minimum surface temperature from 192 K to 261 K. The maximum temperature is not affected by the use of the shield. With the use of the shield, the reflector, and the thermal properties of basalt rock, the thermal mass maintains temperatures high enough to supply heat to a rover or other equipment throughout the equatorial lunar night.

As the principal use of the thermal wadi concept is to provide a supply of sensible heat to a rover during the lunar night, the effect on the thermal wadi performance of supplying heat to a rover is introduced. A typical radiative heat loss from the rover can be estimated by specifying its temperature and the thermal properties and thickness of the insulation material used to protect it. Assuming a rover temperature of 240 K and one-inch to three-inch thick insulation (such as aerogel), we estimated the rover heat loss to be 10-30 W/m^2. Throughout our calculations, we used a rover heat loss of 25 W/m^2. The heat supplied to the rover is estimated as a flux rather than an absolute rate to allow the interpretation of the analysis to remain somewhat independent of the rover size, i.e. the loss is considered proportional to the rover size. These calculations do not address the heat transfer concepts and methods used to couple and transfer the heat to the rover. Figure 8 shows the effect on the surface temperature when the supply of 25 W/m^2 is included in the boundary conditions of the thermal mass model. When rover heating is supplied during the night, the minimum surface temperature is reduced to 247 K from 261 K; the maximum temperature is unaffected.

A key characteristic of the thermal wadi concept is its depth – it affects the mass of material that must be modified to build the wadi and the amount of energy that the wadi can store. Figure 9 shows the results obtained from the thermal model of thermal wadi performance in which the depth of the thermal mass is varied about the nominal depth, from 25-100 cm. The minimum surface temperature is quite sensitive to the depth of the wadi. The shallower the wadi, the colder the surface gets. The maximum temperature is not very sensitive to the wadi depth. Note that a depth of 100 cm is about half the characteristic thermal penetration depth of basalt.

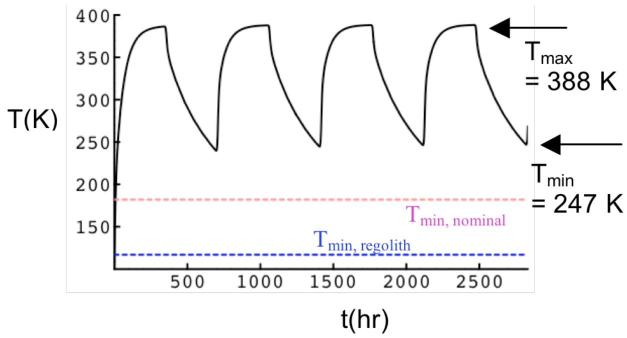

Figure 8. Thermal wadi performance in an equatorial location illuminated by a tracking reflector and protected during darkness by a heat-loss limiting shield while supplying heat to a rover at 25W/m^2. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock.

The thermal diffusivity of the wadi material also has a significant effect on the minimum surface temperature. A thermal diffusivity that is a factor of 10 smaller than that of basalt (which is about a factor of 10 greater than that of native regolith) results in a minimum surface temperature of about 216 K, as compared to the minimum temperature of 247 K for basalt. Figure 10 shows the results of the thermal model in which the thermal diffusivity was reduced to as low as 1/10th that of basalt.

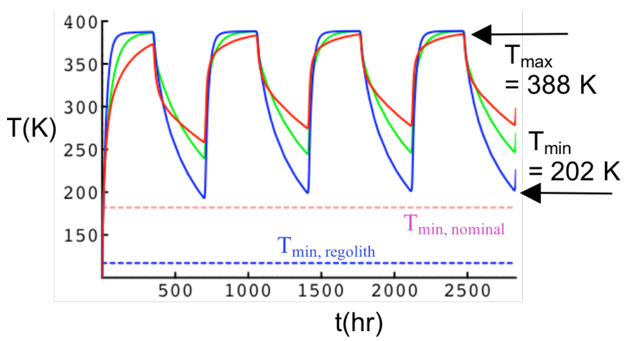

Figure 9. The effect of wadi depth on the performance of an equatorial thermal wadi with solar-reflector, heat-loss shield and rover heating. Surface temperature vs. time for various depths: 25 cm (blue), 50 cm (green) and 100 cm (red); each with the thermal properties of basalt rock.

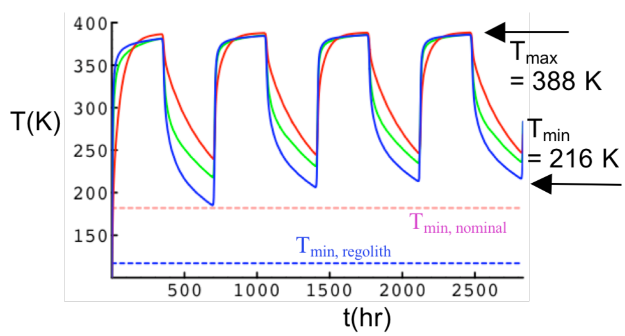

Figure 10. The effect of thermal diffusivity on the performance of an equatorial thermal wadi with solar-reflector, heat-loss shield and rover heating. Surface temperature vs. time for a 50-cm deep wadi with various thermal diffusivity values of the thermal mass: basalt value (red), one-fifth of basalt value (green) and one-tenth of basalt value (blue).

The maximum and minimum surface temperatures for the various equatorial cases that have been described above are summarized in Figure 11. The average temperature, i.e. time-averaged over a diurnal cycle and indicated in the figure, is a measure of the thermal energy stored in the wadi, and provides an additional parameter to consider in the wadi design. The maximum surface temperature, approximately 388 K, at which a balance between insolation and radiative loss to space is established, is reached under nearly any equatorial wadi configuration. While this maximum peak surface temperature is reached using the sun-tracking solar reflector, eliminating the reflector would not significantly reduce the energy stored in the wadi but would reduce the hardware complement needed for wadi operations. It seems, however, that the radiative heat loss shield is needed to maintain adequately high minimum surface temperatures.

The minimum temperatures shown in Figure 11 suggest the engineering trade studies that could be done to refine wadi concepts. The objective of these trade studies would be to minimize the combination of mass and energy costs of the wadi: mass brought to the moon to manufacture and operate the wadi and the energy required on the moon to prepare the thermal mass from the native lunar regolith. Depending on the engineering requirements imposed by the rover vehicles or other surface assets to be thermal protected during the lunar night, the degree to which the

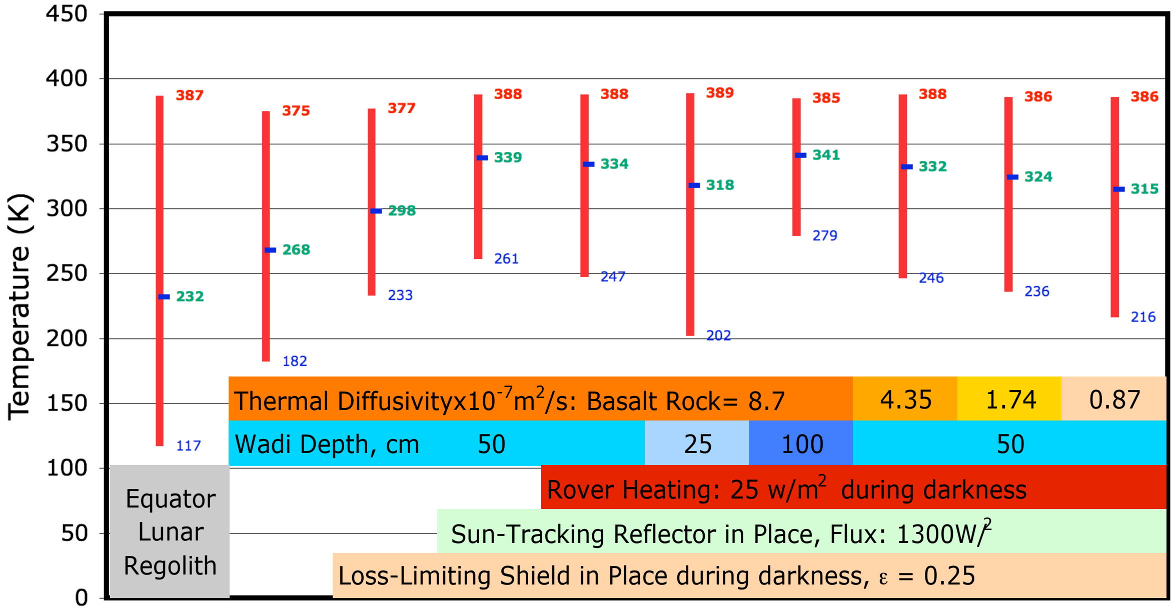

Figure 11. Performance summary of various thermal wadi configurations in equatorial lunar locations. Performance of unaltered regolith is shown as the leftmost case. The colored bars indicate active features of the thermal wadi and show the numerical value of the feature. The effect of adding the radiative-loss-limiting shield, the sun-tracking solar reflector and rover-heating functions are shown. With those features active, the effect of variations in thermal wadi depth and thermal diffusivity of the thermal mass are shown.

thermal diffusivity of native regolith has to be improved versus the amount of regolith processed (ie. the wadi depth) can be traded to achieve the needed temperature range at the minimum wadi construction cost.

IV. Performance of Thermal Wadis in Lunar Near-Polar Environments

Figure 12 shows an image of the lunar south pole. The large mountain at the top is Malapert, the blue arrow points to the south pole, and the yellow arrow to the Site A on the rim of Crater Shackleton. In this paper, we explore the possibility of constructing a thermal wadi at this particular site. The solar illumination data is based on the 2006 GSSR JPL Digital Elevation Model (DEM)[9]. It is pixel 14828, 5711 in the DEM. It is the best-illuminated south pole site based on a lowest continuous eclipse time metric.

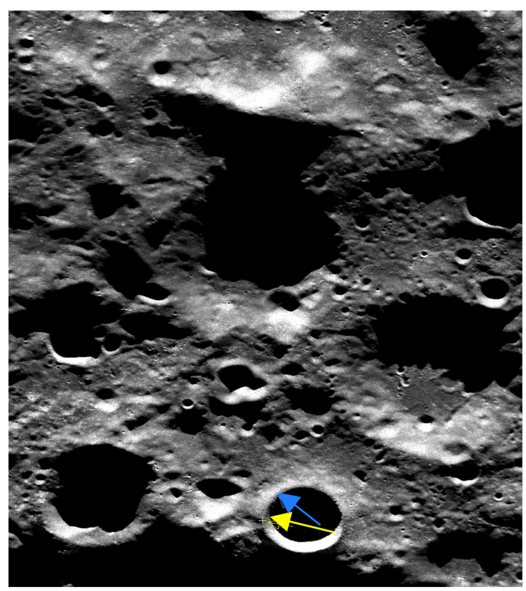

Figure 12. Site "A" (yellow arrow) near the lunar south pole (blue arrow) on the rim of Shackleton Crater.

Figure 13 shows the solar illumination at this site over a compressed time scale. The data starts on 1/1/2008 and is in 1-hour increments. The illumination is considered to be 100% when the sun angle is larger than the local terrain elevation angle. When the sun angle is smaller than the terrain elevation angle, the sun is blocked and the illumination is 0%. Partial sun blockages are also possible. The left panel in this figure shows the illumination for about 2.8 years (25,000 hr) and includes three polar winters (the dark regions of illumination). The right panel shows the illumination in a portion of the first winter (from 2000 to 3000 hr). It is evident that even during winter, substantial solar illumination is available at this site. In this data in Figure 13, the time period with the longest eclipse period

(<100% solar energy) is approximately 71 hours. The longest 0% solar flux (approximately 52 hours) occurs from hour 3256 to 3327. We used the illumination profile shown between t=0 and 6500 hr in Figure 13 in our thermal model to determine the surface temperature of the wadi. We expect the temperature results in this time period to represent the worst-case scenario at this site.

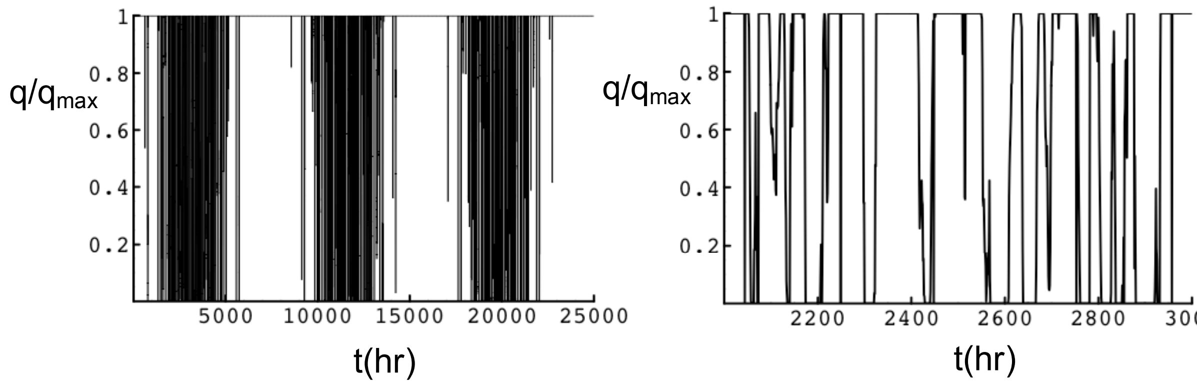

Figure 13. Solar flux at the polar wadi site with the use of a reflector, q_{max}= 1300 W/m^2.

Figure 14 shows the performance of the thermal wadi configuration chosen above to represent a feasible solution for the equatorial sites. While the tracking solar reflector could be considered optional in the equatorial sites, it is essential near the poles where the sun angle is always very oblique to horizontal surfaces. Despite the lengthy exposures to full sun, the maximum surface temperature is about 388 K, about the same as the equatorial case. The minimum surface temperature is about 319 K, and is obtained at two separate times. This is much higher than the equatorial counterparts, because of the extended illumination of the wadi.

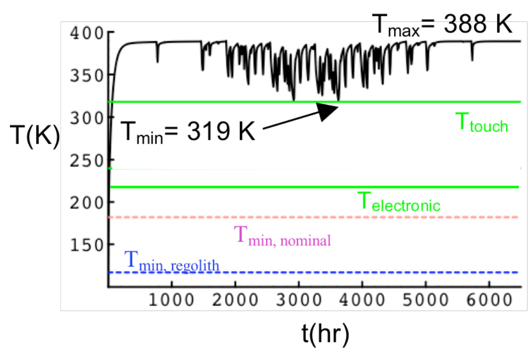

Figure 14. Thermal wadi performance at the lunar polar site using the sun-tracking reflector and the heat-loss limiting shield. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock. Heat is supplied to a rover during the periods of darkness.

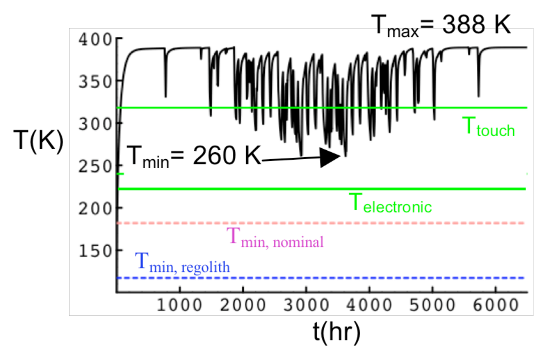

Figure 15. Thermal wadi performance at the lunar polar site using the sun-tracking reflector, but without the heat-loss limiting shield. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock. Heat is supplied to a rover during the periods of darkness.

In the region of the lunar poles maximum allowable temperature limits might be lower than what is possible because of the potential presence of suited astronauts. Among the factors limiting temperatures are rover tires, electronics, astronaut suit materials, etc. To consider the effect on the thermal wadi performance during periods of darkness, we introduced the existing skin touch temperature limit of 318 K (shown as green in performance estimates below) as a desirable maximum temperature. A minimum allowable temperature of 223 K was selected (and also shown as green), corresponding to the low-temperature tolerance of many electronics components. The performance of the nominal equatorial thermal wadi at the polar site has temperature swings limited to approximately 70K, but all the temperatures are above the maximum temperature restriction now imposed.

Figure 15 shows how the minimum temperature can be lowered without ill effect by eliminating the heat-loss limiting shield. With the surface of the wadi allowed to radiate to space during periods of darkness, the minimum temperature falls to approximately 260K and stays above the lower limit imposed for protection of electronics.

Figure 16 shows the effect of reducing the peak heat flux to 600 W/m^2 while keeping the loss-limiting shield during periods of darkness. This is a simple way to show the effect of reducing the total heat flux during illuminated times to less than the maximum, which can be accomplished a number of ways. The result of reducing the total heat available to store in the thermal mass is that the maximum surface temperature is now close to the touch temperature. The reduced heat flux also alters the minimum surface temperature to about 273 K (from 319 K at 1300 W/m^2). We also note that for the equatorial case, if the radiation shield is used approximately 100 hrs before sunset, then the wadi surface temperature at sunset will be lower than the touch temperature of 318 K. This strategy is difficult to simulate in the polar case since the duration of lighted periods and the onset of darkness are irregular.

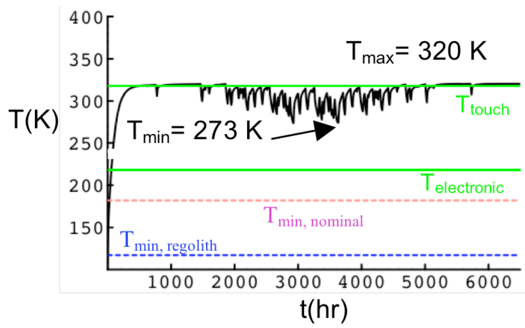

Figure 16. Thermal wadi performance at the lunar polar site using the sun-tracking reflector and the heat-loss limiting shield, but with solar flux decreased to 600 W/m^2. Surface temperature vs. time for a 50-cm deep wadi with the thermal properties of basalt rock. Heat is supplied to a rover during the periods of darkness.

Figure 17 shows the effect of building the wadi to a shallower depth in the lunar polar environment. By reducing the depth the minimum temperature is reduced. Even at a wadi depth of 10 cm, the minimum surface temperature is about 242 K. The wadi surface temperatures are within the reference temperatures. Figure 18 shows the effect of relaxing the improvement of the thermal diffusivity above native regolith to fractional values of the diffusivity of basalt rock. Even when the wadi thermal diffusivity is reduced by a factor of ten from the basalt value, the minimum surface temperature is about 236 K, which is close to the reference minimum temperature.

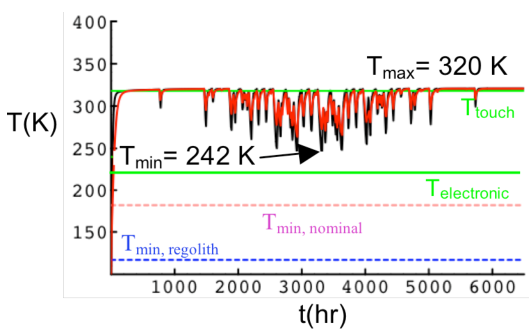

Figure 17. Same as Fig 16 except that the wadi depth is reduced to 25 cm (red) and 10 cm (black).

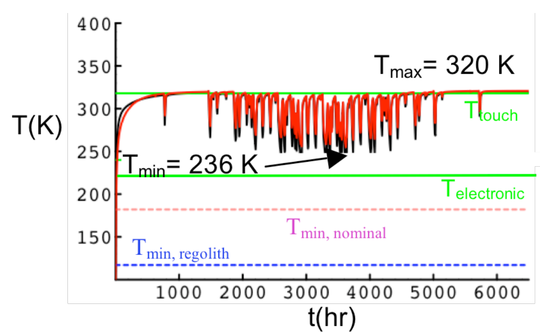

Figure 18. Same as Fig 16, except that wadi thermal diffusivity is reduced to one-fifth of basalt value (red) and one-tenth of basalt value (black).

A summary of the results of thermal model simulations of the various thermal wadi configurations operating at the lunar South Pole is shown in Figure 19. As in the equatorial case, an equilibrium maximum surface temperature is found at a balance between insolation flux and radiative heat losses at the thermal mass surface. When the maximum flux is reduced to 600 W/m^2, the equilibrium temperature is reduced to 320 K. Once the lower equilibrium temperature is established near the touch temperature, the radiative heat loss shield is employed during periods of darkness to maintain a minimum wadi surface temperature compatible with electronics survival. As in the equatorial case, engineering trade studies can be guided by these results to determine the best mix between the thermal diffusivity target of the wadi thermal mass and the quantity of thermal mass processed to create the wadi.

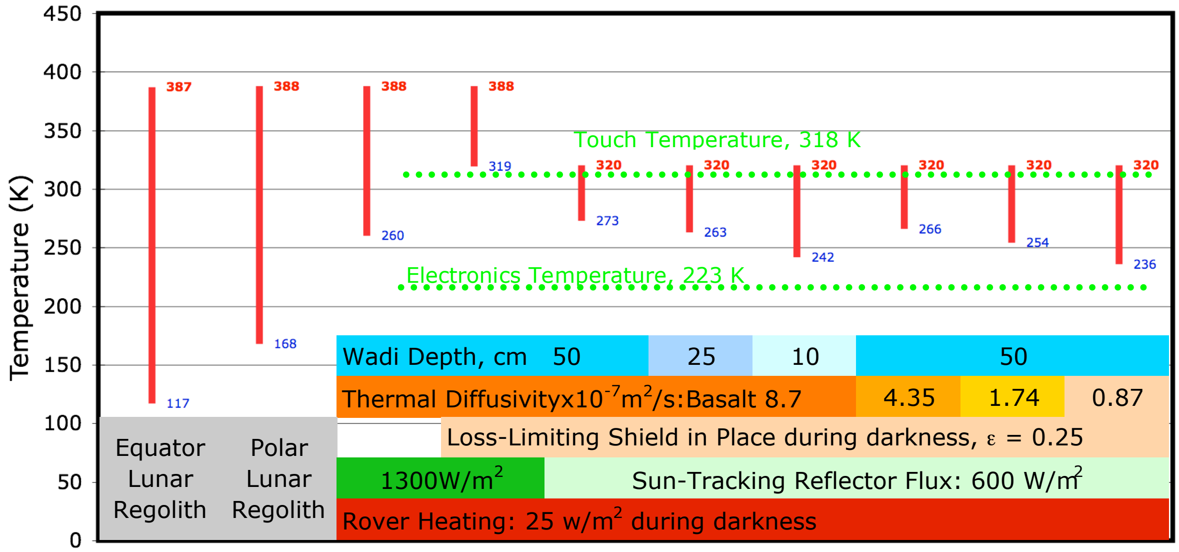

Figure 19. Performance (Tmax, Tmin) Summary of Various Thermal Wadi Configurations in Lunar Polar Locations. The performance of unaltered regolith at both the equator and our selected polar site (both with a peak heat flux of 1300 W/m^2) is shown as the leftmost two cases. The colored bars indicate active features of the thermal wadi and show the numerical value of those features. Rover heating is active in all thermal wadi configurations shown. The effects of adding the radiative-loss-limiting shield and reducing the reflected solar flux are shown. With the shield and reduced flux active, the effect of variations in thermal wadi depth and thermal diffusivity of the thermal mass are shown.

V. Discussion

The objective of this study was to determine the answer to the question: Can engineered thermal wadis function as safe havens for exploration assets, protecting them from the extreme cold of lunar darkness? The present analysis provides an affirmative answer to this question. That is, the analysis shows that thermal wadis of the present concept, if constructed on the lunar surface using modified regolith as the thermal mass, can protect exploration assets from the extremely cold conditions that are otherwise encountered on the lunar surface.

Other than in a permanently shadowed crater at either of the lunar poles, the two cases considered represent reasonable bounds of best case (Shackleton Crater rim, with a maximum period of darkness of about 52 hours) and worst case (equatorial locations with maximum periods of darkness of about two Earth-weeks). In either case, if the thermal mass is a reasonable depth, if energy is stored in the thermal mass in sufficient quantities through the use of reflecting surface, if heat loss by radiation is controlled through the use of a radiant energy reflector, and if suitable thermophysical properties are achieved when producing the thermal mass, the analysis shows that thermal mass temperatures are maintained with *substantial margins* within limits that might be set by the engineering requirements of lunar surface assets such as rovers. For equatorial regions, the margin is about 30 K above the 223 K limit and on the rim of Shackleton Crater the margin is about 50 K.

The presence of margin is viewed as a positive finding. It allows engineering *tradeoffs* to be made with respect to the design of the thermal wadi and the design of the system that must be placed on the Moon in order to produce thermal mass materials and assemble the thermal wadi. These tradeoffs are useful in that they will allow engineers and designers to optimize the mass of what must be launched from Earth while also taking into account other requirements related to reliability and performance.

Margin can also translate to longer-life performance in space systems. Just as the martian rovers, Spirit and Opportunity, have benefited from the provision of power generation systems that have margin, allowing them to exceed their design lifetimes of 90 days by factors over 20, margin for a thermal wadi can enable continued protection of exploration assets even after subsystems begin to degrade or fail.

We can also contemplate improvements to the design of the thermal wadi that provide yet greater margin in the range of achievable temperatures. For example, solar concentrators can be provided that charge the thermal mass with more energy that we have considered in our analyses and the radiant energy reflector can be designed so that an even greater proportion of the sky is covered, yielding lower effective emissivities and further reducing heat loss. Likewise, if a small amount of encapsulated phase change material (e.g., paraffin wax) is brought from Earth, and incorporated in the thermal mass, greater energy storage capacity will be enabled coincident with reduced radiant heat losses and reduced temperature ranges. While these features have not been considered in our thermal analysis, it is nevertheless clear that they would provide improvements to the functionality of the thermal wadi.

As previously discussed, the analysis of the thermal wadi on the rim of Shackleton Crater yielded a margin of about 50 K above the 223 K temperature constraint chosen for exploration hardware. This being the case where margins are greatest, the implication is the *rim of Shackleton may be the most forgiving location for an initial demonstration of the thermal wadi concept.*

A demonstration mission to the rim of Shackleton Crater might therefore serve multiple purposes. Along with testing and demonstrating the system that can manufacture thermal mass materials and assemble the thermal wadi, the inclusion of one or more teleoperated rovers could allow surface-level scouting of the area in advance of committing and deploying exploration assets. Since this site has the greatest margin, it may also provide the greatest likelihood that the rovers would be protected from cold even if the thermal wadi does not perform as expected.

Substantial work still needs to be accomplished before a mission of this type should be committed. This work includes development of the system that makes thermal mass materials as well as the overall system that assembles the thermal wadi. Designs must provide assurances that these systems will fit within critical constraints such as launch mass.

VI. Conclusion

This study shows that thermal wadis, if constructed on the lunar surface, can enable exploration assets to survive the extreme cold of the Moon and operate for months (or years) as opposed to weeks on the lunar surface. For both equatorial regions and the rim of Shackleton Crater, the analysis shows that thermal wadis can provide substantial margin in the range of achievable temperatures, respectively 30 K and 50 K, of protection for teleoperated rovers and other hardware.

A significant advantage of the concept is the use of modified lunar regolith as the thermal mass material. This will substantially reduce the mass that must be brought from Earth. However, this advantage presents another challenge: Can a system that constructs a thermal wadi, including the manufacturing of thermal mass materials from regolith, be designed to meet critical system constraints such as launch mass? While we believe that an affirmative answer to this question is likely, additional work is needed to satisfactorily resolve this question.

Finally we note that, if a thermal wadi manufacturing system can be made to fit within critical system constraints such as launch mass, the rim of Shackleton Crater appears to be an ideal demonstration site for a thermal wadi with one or more teleoperated rovers. The site has the advantage of providing the greatest margin – therefore providing the greatest likelihood of mission success – and is also a location where teleoperated rovers could perform the extremely valuable exploration function of returning data that informs the design of the planned Outpost.

Acknowledgments

The authors would like to gratefully acknowledge the valuable contributions made by H.J. Fincannon of NASA Glenn Research Center by providing data to us from the lunar illumination model he developed based on the digital elevation model discussed above. We hope that by using this standardized model that the utility of our results can be compared to other features of the lunar Outpost. We also gratefully acknowledge the support for this work by the Directorate Integration Office of the NASA Headquarters Exploration Systems Mission Directorate.

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