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Analysis of Lunar Regolith Thermal Energy Storage

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ANALYSIS OF LUNAR REGOLITH THERMAL ENERGY STORAGE

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ABSTRACT

This study was performed to evaluate the concept of using lunar regolith as a thermal energy storage medium. The concept was examined by mathematically modeling the absorption and transfer of heat by the lunar regolith. Regolith thermal and physical properties were established through various sources as functions of temperature. Two cases were considered: a semi-infinite, constant temperature, cylindrical heat source embedded in a continuum of lunar regolith and a spherically shaped molten zone of lunar regolith set with an initial temperature profile. The cylindrical analysis was performed in order to examine the amount of energy which can be stored in the regolith throughout a number of lunar day/night cycles. A constant temperature cylinder was used to heat the regolith during the day. At night the cylinder acted as a perfect insulator. This cycling was performed until a "steady state" situation was reached in the surrounding regolith. It was determined that a cycling "steady state" occurs after approximately 15 day/night cycles. Results were obtained for cylinders of various diameters. The spherical molten zone analysis was performed to establish the amount of thermal energy, within the regolith, necessary to maintain some molten material throughout a nighttime period. This was done by setting the initial conditions within the regolith to model a molten zone with a surrounding temperature profile and allowing this to cool for one nighttime period. The surrounding temperature profile was modeled after the cycling "steady state" temperature profile established by the cylindrical analysis. It was determined that a molten sphere diameter of 4.76 m is needed to maintain a core temperature near the low end of the melting temperature range throughout one nighttime period.

SYMBOLS

A	area, m^2
C_1	constant
C_2	constant
c	specific heat, J/kg K
c_{eff}	effective specific
k	thermal conductivity
Q_l	latent heat, J/kg K
q	heat flux, W/m^2
r	radial distance, m
r_c	heat transfer cylinder radius, m
r_s	sphere radius, m
T	temperature, K
t	time, sec
ρ	density, kg/m^3

INTRODUCTION

This study was performed to evaluate the concept of using lunar regolith as a thermal storage medium for a solar dynamic power system (Crane and Dustin 1991; Barna and Johnson 1968; Tillotson, 1991). The concept is based on the ability to store enough high temperature thermal energy within the lunar regolith during the daytime to allow for continuous power production throughout the night. Energy would be stored and recovered by circulating a fluid through a heat transfer device in contact with the regolith. During the night the heated fluid would then be used to power a heat engine in order to produce electricity. The thermal energy could also be extracted for other uses such as materials processing and space heating.

Thermal energy can be stored within the regolith either through phase change of the regolith from solid to liquid or as sensible heat. In order for the concept to be feasible, the energy stored during the day must be greater than the thermal losses to the surroundings throughout the complete day/night cycle.

The ability to use latent heat as the energy storage mechanism has advantages over sensible heat storage. With latent heat energy storage a large amount of energy can be stored without a substantial temperature rise in the regolith. The extraction of this heat would take place within the melting temperature range of the regolith (1373 to 1653 K), thereby minimizing the variation in the working fluid temperature of the heat engine. This enables the heat engine to operate more efficiently.

The concept of storing thermal energy within the regolith was examined by mathematically modeling the absorption and transfer of heat by the lunar regolith. Two cases were considered: first, a semi-infinite, constant temperature, cylindrical heat source embedded in a continuum of lunar regolith. The cylinder dissipates heat to the surrounding soil which was initially at equilibrium. Second, a spherically shaped molten zone of lunar regolith that has an initial temperature profile from its center to its surface. This situation assumes sufficient energy has already been deposited to create the molten zone. Heat is dissipated to the surrounding soil, which has a temperature profile extending away from the molten zone that approximates a "steady state" situation.

The first case examines the amount of energy which can be stored in the regolith throughout a number of lunar day/night cycles using a cylindrical heat source as the soil heating mechanism. The heat source was assumed to be a pipe through which a working fluid was passed. This pipe would be used to heat the regolith during the day and extract heat during the night. During the day this is accomplished by conduction from the working fluid, through the pipe walls, to the surrounding regolith. At night the process is reversed. The second case examines the heat loss from a molten sphere of regolith to the surroundings in one night period. This was performed to determine the minimum amount of energy necessary in order to use latent heat as the energy storage mechanism. This part of the analysis was performed in this manner so it would remove any dependence on a particular type of heat transfer device. Both cases approach the problem of heat transfer to and within the regolith in a simplistic manner. In a real life system many additional factors would need to be considered. These cases do however establish bounds and on a preliminary basis asses the feasibility of using lunar regolith for thermal energy storage.

REGOLITH PROPERTIES

In order to model the heat transfer through the regolith, the physical properties and characteristics of the soil must be known. These properties include thermal conductivity, specific heat, latent heat, density and melting temperature range. The accurate modeling of each property is very important since it's these physical properties that dictate how the regolith will behave when heated. The regolith is in granular form up to a temperature of 1373 K, where it will begin to melt. Since the regolith is a mixture of compounds it melts over a range of temperatures. This melting temperature range is 1373 to 1653 K (Langseth et al., 1973). Above 1653 K the regolith is completely molten.

The thermal conductivity is dependent on the temperature of the regolith as well as its physical state (either granular or solid/liquid). For granular regolith the conductivity was approximated by the following expression (Murase and McBirney, 1970):

$$k = C_1 + C_2T^3 \tag{1}$$

where

$$C_1 = 1.281\text{x}10^{-2}, \text{ W/m K}$$

$$C_2 = 4.431\text{x}10^{-10}, \text{ W/m K}^4$$

A plot of this equation is shown in Fig. 1. The values of the constants, C_1 and C_2, were interpolated from the data given in Murase and McBirney (1970). For this interpolation, it was assumed that the ratio between the surface conductivity and the conductivity at a depth of 3 m was constant throughout the temperature range of 253 to 1373 K. The conductivity within the regolith melting region, 1373 to 1653 K, was assumed to be a linear function from the granular value at 1373 K to the completely molten rock value at 1653 K. For completely molten or resolidified regolith, the conductivity was obtained from experimental results on simulated lunar rock given in Langseth et al., (1973). Resolidified regolith was considered lunar rock since it is no longer in the granular form. These conductivity temperature relationships are shown in Fig. 1.

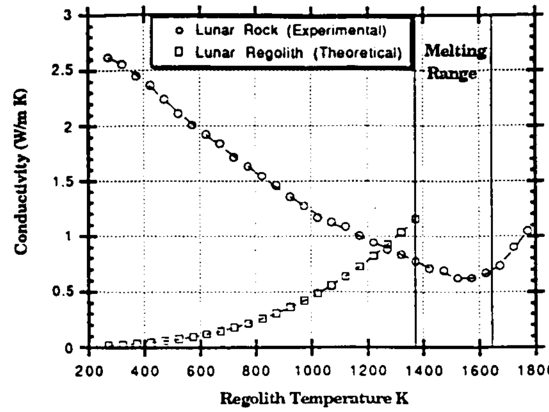

Figure 1. - Conductivity of Granular Lunar Regolith and Lunar Rock.

The temperature dependence of the regolith thermal conductivity was established as follows: as the temperature of the regolith increases, its conductivity increases along the granular regolith curve. Once the initial melting temperature is reached, the conductivity begins to decrease linearly with temperature until the completely molten temperature is reached. This decrease is presumed due to the loss in the effective radiation component of the thermal conductivity as the regolith melts. Conductivity then increases with temperature along the lunar rock conductivity curve. This conductivity temperature curve is shown in Fig. 2. If the regolith had obtained a temperature of 1513 K or higher during the heating process it was considered as lunar rock once it began to solidify. Lunar rock in this context is regarded as fused or molten granular regolith.

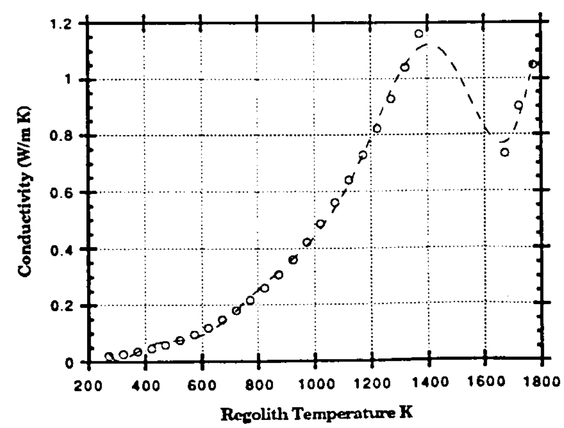

Figure 2. - Conductivity Curve of Initial Heating of Granular Lunar Regolith.

An expression for specific heat was obtained from a curve fit and interpolation of experimental data given in Robie et al., (1970). The expression used was:

$$c = -1848.5 + 1047.41 \log(T) \text{ J/kg K} \tag{2}$$

A plot of this relationship is shown in Fig. 3.

The latent heat of fusion value used was (Crane and Dustin, 1991):

$$Q_l = 1429 \text{ J/kg K}$$

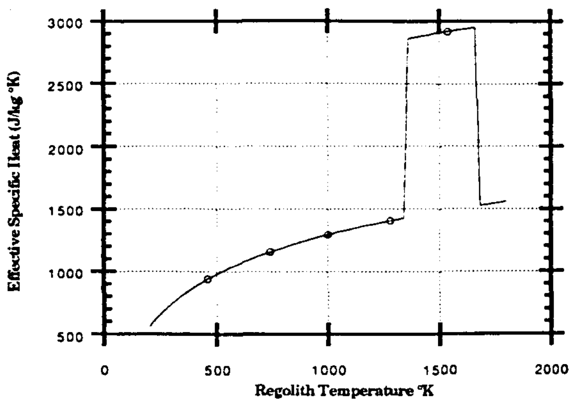

Figure 3. - Specific Heat Curve for Lunar Regolith.

This value was added to the specific heat when the temperature of the regolith reached the initial melting point. The effect of this can be seen in Fig. 3 where the step increase in the specific heat throughout the melting region is due to the addition of this latent heat term. This step increase represents the added ability of the regolith to absorb energy due to its phase change from solid to liquid throughout the melting range. This curve can be considered representative of an effective specific heat given by the following expression:

$$c_{eff} = c \qquad T < 1373 \text{ K}, T > 1653 \text{ K} \tag{3}$$

$$c_{eff} = c + Q_l \qquad 1373 \text{ K} \leq T \geq 1653 \text{ K} \tag{4}$$

Regolith density was assumed to be constant with a value of (Lockheed, 1990):

$$\rho = 1700 \text{ kg/m}^3$$

CYLINDRICAL HEAT SOURCE ANALYSIS

The cylindrical heat source analysis was performed in order to model a heated cylinder surrounded by regolith by using the one-dimensional, unsteady heat diffusion equation in cylindrical coordinates. A diagram of the cylinder is shown in Fig. 4. For simplicity it is assumed the axial variation in temperature is negligible. This equation is given by:

$$\frac{1}{r}\left[\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)\right] = \rho c_{eff}\frac{\partial T}{\partial t} \tag{5}$$

Simplifying yields:

$$\left[\frac{\partial k}{\partial T}\frac{\partial T}{\partial p} + \frac{k}{r}\right]\frac{\partial T}{\partial r} + k\frac{\partial^2 T}{\partial r^2} = \rho c_{eff}\frac{\partial T}{\partial t} \tag{6}$$

As shown previously, thermal conductivity and effective specific heat are functions of temperature. These functions were substituted into the above differential equation thereby incorporating the variation of these quantities with temperature into the analysis.

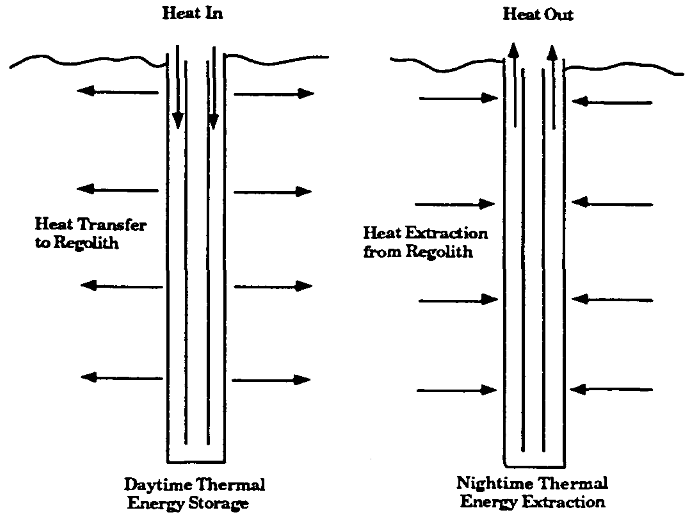

Figure 4. - Daytime and Nighttime Thermal Energy Transfer from Cylindrical Heat Source.

To solve the equation numerically an explicit finite difference method was used. The approximations which were selected for the first and second order derivative terms enabled the equation to be unconditionally stable (Anderson et al., 1984). The derivative term approximations are as follows:

$$\frac{\partial T}{\partial r} = \frac{T^n_{j+1} - T^n_{j-1}}{2\Delta r} \tag{7}$$

$$\frac{\partial^2 T}{\partial r^2} = \frac{T^n_{j+1} - T^n_j - T^{n-1}_j + T^n_{j-1}}{\Delta r^2} \tag{8}$$

$$\frac{\partial T}{\partial t} = \frac{T^{n+1}_j - T^{n-1}_j}{2\Delta t} \tag{9}$$

To numerically solve this model, the continuum was divided into concentric cylindrical shells, or nodes, surrounding the heat source. Boundary conditions were set at the cylinder radius and at 50 cylinder radii. The value of 50 radii was chosen as the infinity boundary condition since at this distance the temperature gradient within the soil should go to zero (Jenson and Linsley, 1990). The boundary conditions for daytime heating were:

$$T(r_c,t) = 1800 \text{ K} \tag{10}$$

$$T(50r_c,t) = 253 \text{ K} \tag{11}$$

and for nighttime cooling:

$$q = kA\left.\frac{\partial T}{\partial p}\right|_{r=r_c} \tag{12}$$

$$T(50r_c,t) = 253 \text{ K} \tag{13}$$

These initial conditions are shown in Fig. 5.

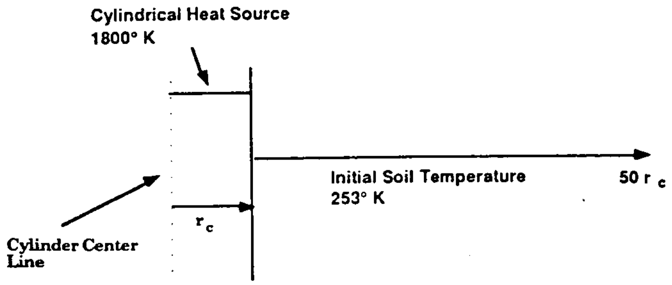

Figure 5. - Initial Configuration of Cylindrical Heat Source.

In setting up the analysis, a number of assumptions concerning the heat source had to be made. The cylinder surface was treated as a constant temperature boundary as opposed to a constant heat flux. Primarily because the buried heat source will be limited by material constraints as well as solar dynamic concentrator temperature limitations and re-radiation effects. The daytime cylinder temperature was assumed to be 1800 K. This temperature is at the upper limit of what the system can be expected to sustain in continuous use. At night the pipe was assumed to be a perfect insulator ($q = 0$). Therefore all heat lost from the system was to the surroundings. It was further assumed that no other heat loss mechanisms were present. The analysis was set up to keep track of the melting history of each node and to use the proper conductivity relationship for that node depending on that history.

The analysis produced time-dependent radial temperature profiles (node temperature versus position of each node away from center) of the nodes. For each given cylindrical heat source diameter, the simulation was run over an increasing number of day/night heating and cooling cycles until a cycling "steady state" temperature profile was reached within the regolith surrounding the cylinder. That is, the cylinder was used to heat the soil through a number of cycles until the beginning of night (BoN) and beginning of day (BoD) temperature profiles were the same as the ones from the previous cycle. This "steady state" situation represents the maximum amount of energy which can be placed in the soil given the constraints of the assumed heat pipe temperature, cylinder diameter and the length of the heating and cooling periods.

CYLINDRICAL HEAT SOURCE RESULTS

Temperature profiles were obtained for regolith heating from cylinder diameters of 1, 1.5 and 2 m, simulating time intervals of up to 15 lunar day/night cycles. Beyond 15 cycles, the BoN and BoD temperature profiles no longer changed from cycle to cycle; indicating a "steady state" condition had been reached. The results, shown in Figs. 6 and 7, were obtained with a 1-m diameter cylindrical heat source. These figures depict temperature profiles within the surrounding regolith at various cycles throughout the heating and cooling process. The 1-m diameter cylinder surface temperature for the 15th cycle nighttime period is given in Fig. 8. This figure is an example of the nighttime output temperature profile which can be obtained once the cycling "steady state" situation is reached. The step decrease in the temperature profile slope within the melting region is due to the release of latent heat energy as the regolith solidifies. Since the regolith melts over a range of temperatures, as discussed previously, the ability to extract energy at constant temperature by using the energy released from latent heat is limited. In this situation latent heat only serves to decrease the rate at which the temperature drops as energy is extracted instead of maintaining a constant temperature.

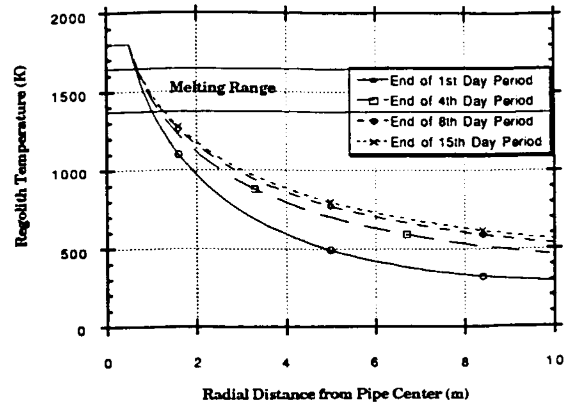

Figure 6. - Temperature Profiles at the End of Each Day Period for Various Numbers of Cycles.

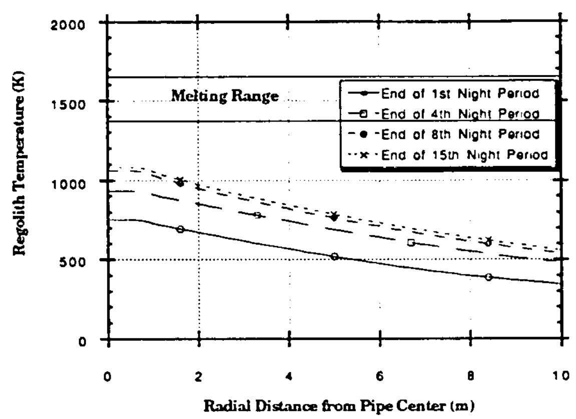

Figure 7. - Temperature Profiles at the End of Each Night Period for Various Numbers of Cycles.

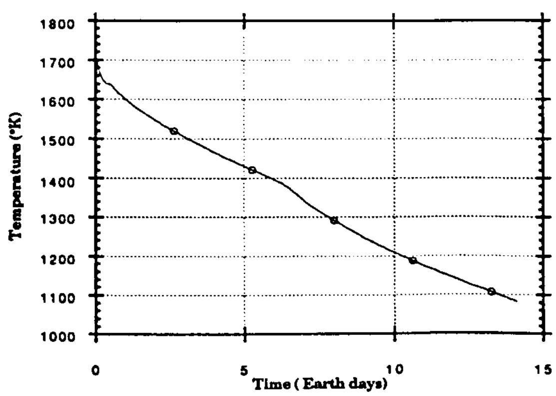

Figure 8. - Temperature of 1 m Diameter Cylinder During 15th Cycle Nighttime Cooling.

For various cylinder diameters the cycling "steady state" end of night (EoN) temperature profiles are shown in Fig. 9. The maximum EoN temperature for a 1-m diameter cylinder is below the low end melting point of the regolith. Consequently, the heat stored within the regolith is in the form of sensible heat since all the latent heat energy has dissipated. A cylinder diameter greater then 1.5 m is required for energy storage in the form of latent heat. For a 2 m diameter cylinder a small molten zone remains at the EoN. However, the majority of the energy resides as sensible heat in the surrounding regolith. Due to the temperature limitations on the cylinder, the regolith temperature profiles do not increase proportionally to cylinder size. As the cylinder size increases, the corresponding temperature rise in the surrounding regolith diminishes. This trend can be seen in Fig. 9.

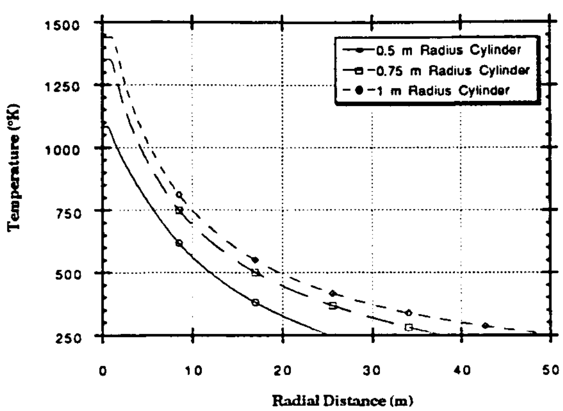

Figure 9. - EoN Cycling Steady State Temperature Profile for Various Cylinder Sizes.

SPHERICAL MOLTEN ZONE ANALYSIS

A spherical molten zone analysis was also performed in order to specifically evaluate the concept of using latent heat as the thermal energy storage mechanism. The analysis was designed to be independent of a particular type of heat transfer device. Therefore the results can be regarded as a general estimate of the amount of energy necessary within the regolith to take advantage of latent heat energy storage. The geometry consisted of a spherical molten zone surrounded by heated soil. A spherical shape was chosen for the molten zone since it has the smallest surface area to volume ratio and is therefore the optimum shape for resisting heat loss. The analysis was conducted by selecting an initial temperature profile within the regolith and allowing the regolith to cool for one night period. The temperature profile within the molten sphere was assumed to be linear with a core temperature of 1800 K decreasing to the low end melting point temperature of 1373 K. The initial temperature profile, established in the surrounding soil, began at the low end melting temperature and decreased according to the BoN temperature profile which was obtained from the "steady state" cylindrical analysis results. This profile was used since it approximated a cycling "steady state" temperature distribution within the surrounding soil. With these initial conditions the regolith was allowed to cool for one night period. A diagram of these initial conditions are shown in Fig. 10.

The size of the molten sphere was adjusted until a small portion of regolith at the core remained at or above 1373 K throughout the night period. The analysis was structured in this manner in order to determine the feasibility of using latent heat as the energy storage mechanism and to estimate both heat loss and required thermal energy within the regolith.

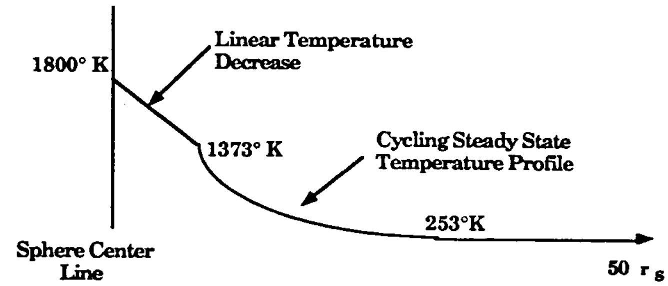

Figure 10. - Spherical Molten Zone Initial Conditions.

The spherical analysis was very similar to that for the cylinder. The governing heat transfer equation was changed to spherical coordinates given by;

$$\frac{1}{r}\left[\frac{\partial}{\partial r}\left(kr^2\,\frac{\partial T}{\partial r}\right)\right] = \rho c_{eff}\,\frac{\partial T}{\partial t} \qquad (14)$$

simplifying yields;

$$\left[\frac{\partial k}{\partial T}\frac{\partial T}{\partial r} + \frac{2k}{r}\right]\frac{\partial T}{\partial r} + k\,\frac{\partial^2 T}{\partial r^2} = \rho c_{eff}\,\frac{\partial T}{\partial t} \qquad (15)$$

The numerical approximations for the derivative terms as well the as expressions for conductivity, effective specific heat and density were the same as those used in the cylindrical heat source analysis. Due to symmetry, the heat flux at the sphere center is zero. The boundary conditions used were:

$$q(0,t) = 0.0 \qquad (16)$$

$$T(50r_s,t) = 253\text{ K} \qquad (17)$$

Once the required sphere size was determined, the corresponding temperature profile within the sphere and surrounding soil was used to calculate the amount of thermal energy remaining within the soil. By comparing this with the energy initially in the soil, obtained from the initial temperature profile, an estimate can be obtained of the losses to the surroundings. In addition the total thermal energy initially stored within the regolith, in order to maintain a molten region throughout the night period, can be determined.

SPHERICAL MOLTEN ZONE RESULTS

It was determined that a 4.76-m diameter molten sphere is necessary in order to maintain a core temperature near the lower limit of the melting range after one night period. This result is shown in Fig. 11. From the initial and final temperature profiles for this size sphere, heat losses and required energy were calculated. These are listed in Table I.

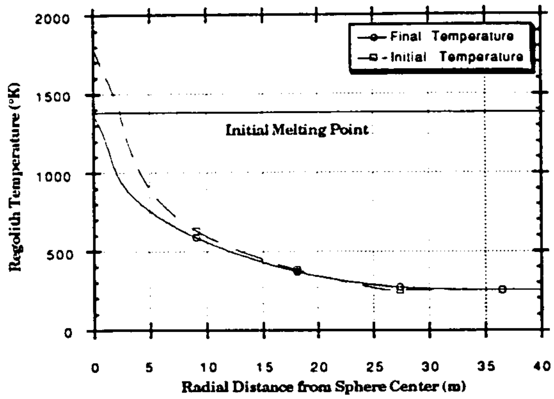

Figure 11.- Initial and Final Temperature Profiles for a 4.76 m Diameter Spherical Molten Zone.

TABLE I. - THERMAL ENERGY STORED IN REGOLITH BEFORE AND AFTER NIGHTTIME COOLING

	BoN energy in regolith, J	EoN energy in regolith, J
Molten region	$1.95x10^{11}$	$1.09x10^{11}$
Surrounding soil	$1.83x10^{13}$	$1.71x10^{13}$
Total system	$1.85x10^{13}$	$1.72x10^{13}$
Percent of latent energy lost from the molten zone, percent . . . 100		
Percent of total energy lost from the molten zone, percent . . . 44		
Percent of energy lost from the total system, percent . . . 7		

CONCLUDING REMARKS

The results have shown that a cycling "steady state" exists for a cylindrical heat transfer device within the regolith. By examining the temperature profiles for the cylinder once this steady state situation is reached, it can be seen that a cylinder size greater then 1.5 m in diameter is necessary to maintain some molten material throughout the night period. Below this size, no matter how many day/night cycles the system experiences, no molten material will remain after the night period. By using a more efficient heat transfer device, that is one which can transfer a larger quantity of energy into the regolith, the necessary size may be reduced. However, it can also be concluded that the heat transfer device will need to be distributed throughout the desired molten region. This can lead to a complicated deployment scheme as well as the need for substantial infrastructure. Regardless of the heat transfer device configuration, it cannot be readily assumed that the desired regolith temperatures can be achieved by running the system for a number of day/night cycles. Each device after a given number of cycles will reach a cycling "steady state" which may or may not produce the desired regolith temperature.

The spherical molten zone results show that a minimum size (surface area to volume ratio) is necessary to maintain any latent heat through the lunar night. To build up a molten zone of this size a substantial amount of energy, in the form of low grade heat, must be deposited first. But the high grade heat within this molten zone, like the peak of a pyramid, is most rapidly dissipated by the natural losses.

One point that should be made is that both the cylinder and molten sphere analysis were for minimally sized systems, that is no energy was extracted to do work. So for a system, operating under the same conditions and assumptions, in which thermal energy is extracted throughout the night the resulting EoN temperature profiles would be lower and more energy would need to be supplied during the day period then what was shown in this analysis.

Since this was a numerical analysis, various assumptions had to be made which, if changed, could alter the results and conclusions. Also, for simplicity reasons, various factors were not considered in the analysis; these factors could also have an effect on the results. A summary of some issues which should be considered if a more detailed analysis is to be performed are as follows:

(1) Examination of convection heat transfer within the molten regolith to determine if this will allow larger amounts of heat to be transferred to the regolith.

(2) Two-dimensional analysis which would take into account radiative heat losses from the surface of the heated region to the sky.

(3) Consideration of the effect the formation of voids would have if they formed during the regolith melting and resolidification process.

(4) Issue of replenishing regolith material due to the increase in density when it transitions from the granular to molten and or solid state.

(5) Re-examination of regolith properties to asses their validity. Possibly conduct an experiment to directly determine these properties for circumstances similar to those under the proposed system.

(6) Examination of the effects of out-gassing and chemical reactions which may occur when the regolith is heated, this may increase conductivity.

By examining the results it is evident that the ability to store a sufficient amount of energy in the form of latent heat is questionable. However, a substantial amount of energy is stored as sensible heat.

There is a substantial advantage in being able to store energy in a substance which is already present on the lunar surface. Even if the use of sensible heat to operate a heat engine proves to be undesirable this method of storing energy may still be applicable for other uses such as space heating or material processing. Regardless of the application, any use of this type of storage can substantially increase our ability to explore and inhabit our closest neighbor, the moon.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study was performed to evaluate the concept of using lunar regolith as a thermal energy storage medium. The concept was examined by mathematically modeling the absorption and transfer of heat by the lunar regolith. Regolith thermal and physical properties were established through various sources as functions of temperature. Two cases were considered; A semi-infinite, constant temperature, cylindrical heat source embedded in a continuum of lunar regolith and a spherically shaped molten zone of lunar regolith set with an initial temperature profile. The cylindrical analysis was performed in order to examine the amount of energy which can be stored in the regolith throughout a number of lunar day/night cycles. A constant temperature cylinder was used to heat the regolith during the day. At night the cylinder acted as a perfect insulator. This cycling was performed until a "steady state" situation was reached in the surrounding regolith. It was determined that a cycling "steady state" occurs after approximately 15 day/night cycles. Results were obtained for cylinders of various diameters. The spherical molten zone analysis was performed to establish the amount of thermal energy, within the regolith, necessary to maintain some molten material throughout a nighttime period. This was done by setting the initial conditions within the regolith to model a molten zone with a surrounding temperature profile and allowing this to cool for one nighttime period. The surrounding temperature profile was modeled after the cycling "steady state" temperature profile established by the cylindrical analysis. It was determined that a molten sphere diameter of 4.76 m is needed to maintain a core temperature near the low end of the melting temperature range throughout one nighttime period.

14. SUBJECT TERMS

Solar dynamic power system; Regolith; Heat storage; Thermal energy; Numerical analysis

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