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A COMPARISON OF MICROWAVE VERSUS DIRECT SOLAR HEATING FOR LUNAR BRICK PRODUCTION

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ABSTRACT

The Michigan Technological University Planetary Materials and Resource Utilization (PMRU) group has been examining the concept of fabricating bricks from lunar regolith. Such bricks are proposed for use in the construction of buildings that will provide protection from radiation and micrometeorite bombardment.

In this paper, two processing techniques considered suitable for producing dense bricks from lunar regolith are examined: direct solar heating and microwave heating. An analysis was performed to compare the two processes in terms of the amount of power and time required to fabricate bricks of various sizes. The regolith was considered to be a mare basalt of composition (in wt.%) 55% pyroxene, 20% plagioclase, 15% olivine, and 10% glass. Overall regolith density was taken to be 60% of the theoretical. Densification was assumed to take place by vitrification; several other mechanisms were considered but rejected since vitrification uses moderate amounts of energy and time while producing dense products. The average ambient temperature was assumed to be 50° C, while 1000° C was used as the temperature sufficient to achieve a viscous silica glass suitable for vitrification. Microwave heating was shown to be significantly faster compared to solar furnace heating for rapid production of realistic-size bricks. However, the relative simplicity of the solar collector(s) used for a solar furnace compared to the equipment necessary for microwave generation may present an economic trade-off. The relative costs and engineering complexity associated with the appropriate furnace design for these processes were not included in this analysis, although the final choice of a processing method will require such considerations.

INTRODUCTION

There has been a renewed interest in space exploration, particularly the establishment of manned lunar/Martian bases, as a result of the proposals outlined by President Bush in his speech on July 20, 1989, commemorating the 20th anniversary of the Apollo 11 mission. The design of such bases can take two general paths. The first would involve bringing up all construction materials or importing pre-fabricated modules. However, the economics of material transportation from earth dictate that a second path be explored, in which local resources such as lunar regolith be used whenever possible, *e.g.*, as construction materials. Toward this end, the PMRU group at Michigan Tech has utilized a multi-disciplinary approach to study the design and fabrication of construction "bricks" made of lunar regolith.

The mechanical behavior of a shelter constructed from "silo stave" bricks with tongue-and-groove joints was examined in a previous study (ref. 1). The technique chosen to fabricate this (or any) brick design will play an important role in lunar/Martian base design and construction in terms of brick production rate, ease of automation, brick production cost, etc. Although a variety of fabrication techniques are possible, the most promising methods to densify regolith into bricks are microwave heating and direct (focused) solar heating. The former is generally considered to be very economical in terms of the energy expended during sintering while the latter does not require a special power generation source.

Microwave radiation for lunar brick production would be generated via an electrical source such as solar cells or a nuclear power plant generator. This radiation must be "tuned" to a desired frequency, which would correspond to a strong absorption peak of the phase to be heated. If that phase is reasonably dispersed throughout an agglomerate, heating takes place uniformly within the green body. A relatively high heating rate and heating efficiency can be achieved since thermal conduction is required only over short distances. In contrast, a solar collector directs a wide range of frequencies (determined by the collector's reflectivity) onto a target. A large portion of the wavelengths fail to achieve maximum energy transfer to any particular phase; thus thermal conduction over larger distances is required. The resulting heating efficiency and rate are expected to be low since the thermal conductivity of the green body is quite low. due to the vacuum of space.

The purpose of the current study was to make a preliminary analysis of the power and time requirements necessary to form lunar bricks using either microwave or direct solar heating. Although there are a number of potential factors that have to be considered, we will limit our consideration to the power and time characteristics of each process in order to determine which technique represents the better choice for a given brick size.

PROBLEM BOUNDARY CONDITIONS

Several assumptions are necessary in order to proceed with the calculations. Table 1 describes the average regolith composition used in this study (ref. 2). This raw material was assumed to have an apparent density of 60% of theoretical (ref. 3). The average ambient temperature at the lunar surface during "daylight" was taken as 50° C. The brick morphology was simplified to that of a parallelepiped (see Figure 1). All calculations were made assuming 100% efficiency, *i.e.*, there was no heat loss to mold walls, all incident energy was absorbed by the regolith, and no power losses occurred in the solar collector or microwave generating circuit. These assumptions will be discussed later in more detail.

Table 1. Assumed Regolith Composition

Mineral Class	Mineral Name	Composition	Fraction (wt.%)
Pyroxene	Diopside	$CaMgSi_2O_6$	55
Plagioclase	Anorthite	$CaAl_2Si_2O_8$	20
Olivine	Forsterite	$MgSiO_4$	15
Glass	Silica	SiO_2	10

A variety of potential densification mechanisms exist, including solid-state sintering, liquid-phase sintering, and complete melting and solidification. A variation of liquid phase sintering known as vitrification was chosen for analysis due to the relatively low temperatures and times required for densification. Vitrification relies on the softening and viscous flow of a glassy phase (*e.g.*, SiO_2) to densify the regolith mass. Therefore, a microwave frequency (43 GHz) was chosen to selectively excite the Si-O bond and a processing temperature of 1000° C was chosen in order to soften the glassy SiO_2 phase (ref. 4).

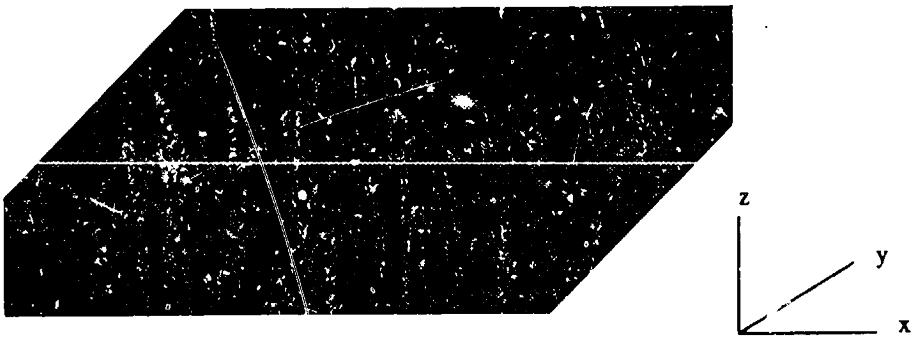


Figure 1. Schematic of the brick morphology.

CALCULATIONS

The two processing methods were compared on the basis of how much power was available to heat regolith bricks of varying size and the time required to attain the appropriate vitrification temperature.

The power available for direct solar heating is a function of the sunlight incident on the lunar surface and the surface area of the collector. The former has a value of 1400 W/m^2, and a representative collector size of 10 m^2 was selected. This results in an available power of 14 kilowatts which is independent of the mass of the regolith brick (see Figure 2).

The power per unit volume [W/m^3] deposited in a dielectric by an electromagnetic field is given by equation (1),

$$P = 5.56\times10^{-11}\, k'\, \tan(\delta)\, f\, E^2 \tag{1}$$

where k' is the relative dielectric constant, tan(δ) is the loss tangent, f is the frequency [Hz], and E [volts/m] is the magnitude of the internal field. Work on a large number of lunar soil samples (ref. 5) has led to empirical relations to describe the relative dielectric constant and loss tangent of these materials as a function of sample density and are shown in expressions (2) and (3). The rule of mixtures, along with the data in Table 1, was used to calculate the theoretical regolith density. The theoretical density was used to calculate k' and tan(δ) rather than integrating power over the range of densities (60-100%) that would result during the sintering of an [illegible] regolith brick; this procedure was used to simplify the calculations, and the results represent an upper bound value for power. The frequency was chosen as 43 GHz since this value corresponds to a characteristic rotational transition in Si-O bonds (ref. 6). Previous work on microwave heating of ceramics has utilized applied voltages of 300-400V; a value of 400V was chosen for this analysis since dielectric breakdown will occur at higher voltages under hard vacuum conditions. Using these values, the microwave power available to heat the bricks as a function of brick volume was calculated and plotted in Figure 2.

$$k' = 1.919^{\rho} \tag{2}$$

$$\tan(\delta) = 10^{(0.44\rho-2.943)} \tag{3}$$

A calculation of the time required to raise the regolith mass from a temperature of 50° C to 1000° C is possible using the definition of power as the time rate at which work is done, equation (4). E [J] is the heat required to raise the regolith mass from 50° C to 1000° C in time t. The heat is calculated using equation (5) where m is the mass [g] of the regolith brick and C_p is the heat capacity [J/mole K]. C_p values were obtained utilizing known expressions for the heat capacity of the component minerals. The brick mass was calculated for different brick volumes using an apparent regolith density of 60% of theoretical. This value represents a lower bound since some compaction of the regolith may

$$P = \frac{E}{t} \tag{4}$$

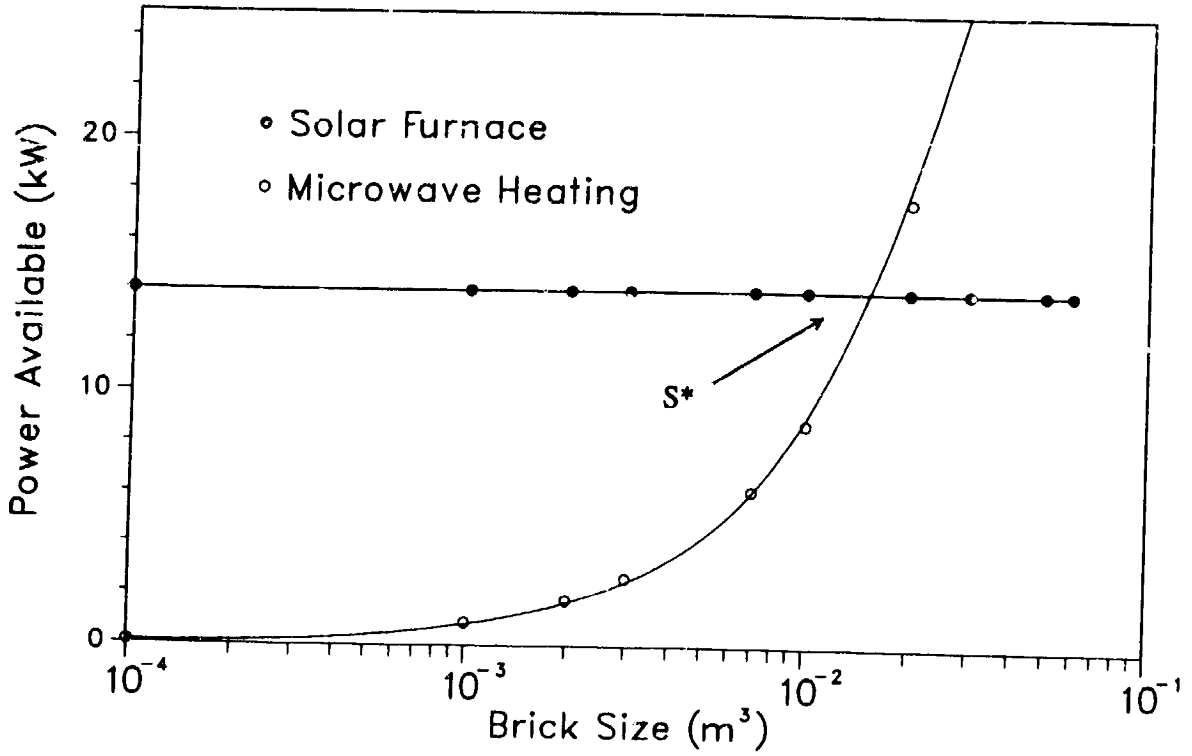


Figure 2. Power available for heating the regolith as a function of brick size. The solar power curve is based on a 10 m^2 collector.

be necessary to form the brick shape. It was assumed that no change took place in the density of the green regolith

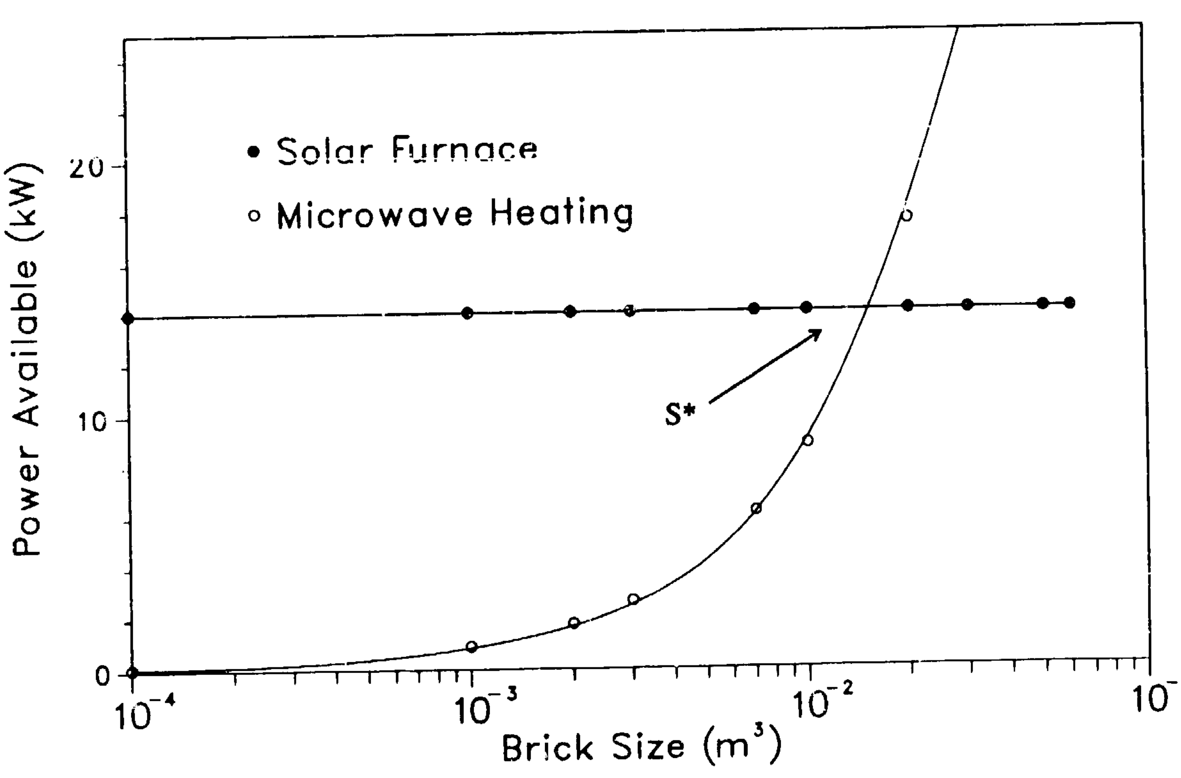
$$E = m \int C_p \, dt \tag{5}$$

brick as the temperature was increased to 1000° C. With this information, the heat required to raise the regolith temperature by 950° C was determined from Equation (5) as a function of brick size; the assumption was also made that no phase changes took place in that temperature range. The time required to attain a temperature of 1000° C could then be calculated for either direct solar heating or microwave heating as a function of the brick mass using Equation 4 (see Figure 3). The actual time required for vitrification to take place at 1000° C was assumed to be equal for both processes.

DISCUSSION

An intersection (S*) occurs in the two curves plotted on Figure 2 since the power available from direct solar heating is a constant while the microwave power increases with increasing brick volume. The plot indicates that more power is available from direct solar heating than microwave heating at smaller brick volumes while the reverse is true at larger brick volumes. The intersection, S*, occurs at a brick volume of 0.016 m^3 . If a brick thickness of 0.1 m is assumed, typical dimensions of the brick at S* would be 0.1 m x 0.4 m x 0.4 m. This yields a brick size comparable to those found in traditional terrestrial buildings. Thus, even though direct solar heating appears to be more efficient at smaller brick volumes, more power is available from microwave heating for realistic brick sizes.

It should be pointed out that the intersection point will vary directly with the size of the solar collector(s) used. That is, as the collector area increases, direct solar heating becomes more competitive with microwave heating. However, solar heating of the regolith relies on transfer of heat from the outside of the brick toward the interior. As brick



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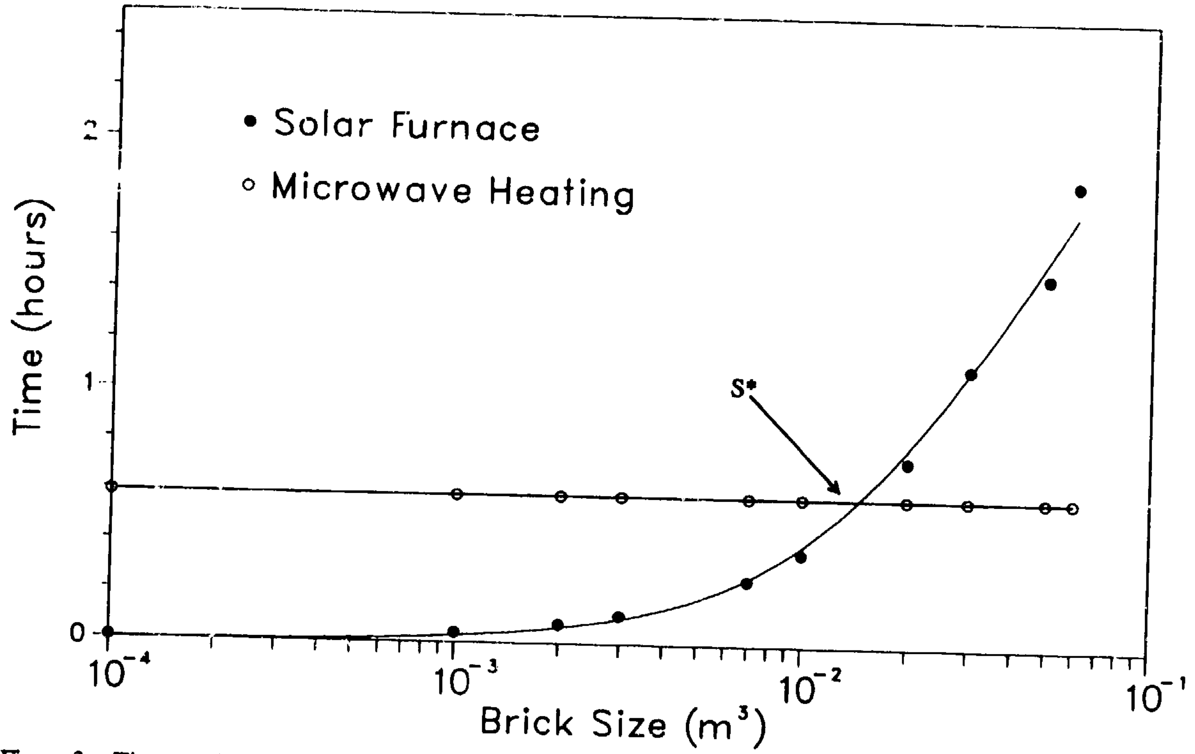

Figure 3. Time required to supply the regolith charge with the calculated amount of energy as a function of brick size. The solar furnace curve is based on a $10 m^2$ collector.

size increases, the very poor thermal conductivity of the regolith (~60 μW/cm K) (ref. 7) may result in very high surface temperatures with little interior heating. This temperature gradient could result in differential shrinkage of the brick, producing internal stresses that could degrade the brick properties. The low thermal conductivity would also increase the processing time for vitrification to take place.

We have also neglected the radiative heat loss that will occur at the brick surface in our calculations for direct solar heating. The heat loss will be proportional to T^4, and as a result, additional energy will be required to compensate for this energy loss. The problem in trying to make the calculation is that emissivity data are required for the minerals and temperature range of interest. Thus, the calculations shown in Figure 2 represent an upper bound case. This would again support the selection of microwave heating although innovative design and engineering of a solar furnace will play an important role in determining the heating characteristics and degree of heat loss associated with brick production.

In contrast to direct solar heating, the temperature gradient in microwave heating is reversed. That is, heating takes place from the interior of a body outwards, which minimizes heat loss to the surroundings. Larger bricks can be more easily fabricated with microwave heating since heating can take place uniformly if the strongly absorbing phase is distributed evenly within the green body, and since thermal conduction is required over much shorter distances. It has also been shown that as densification proceeds, heating via microwave coupling tends to concentrate at pores and other defects, leading to faster and more complete densification (refs. 7 and 8).

The plot of the time required to supply the regolith charge with the energy required to raise its temperature to 1000° C (Figure 3) shows that microwave heating requires less time at the brick volumes that are realistic (*i.e.* greater than 0.016 m^3) and the times themselves are practical for a continuous production process. It should also be noted that the processing time for microwave heating will be considerably shorter than that calculated strictly with the use of equations 1-3. The tuned frequency of 43 GHz was chosen to heat primarily the glassy phase in order to achieve densification via vitrification. However, the other regolith components are also silicates and contain Si-O bonds. As a result, very uniform heating and shorter sintering times should be achieved.

As described earlier, solar heating relies on heat transfer from the brick surface to the interior. As the brick size increases, the surface area to volume ratio decreases, thus leading to sintering times which increase rapidly as brick size increases (see Figure 3). In contrast, microwave heating relies on the excitation of specific bond types which are assumed to be distributed uniformly throughout the regolith. Since the number of these bonds scales directly with the amount of regolith present, the time required to reach a given temperature is independent of brick size. These differences in the heating mechanism of each process lead to the form of the curves shown in Figure 3. It should be noted, however, that the solar furnace curve is a significant underestimate of the time necessary to raise the temperature of the entire brick to 1000° C. The curve in Figure 3 was calculated with the assumption that the entire brick instantaneously attains thermal equilibrium as its temperature is raised to 1000°C. To obtain more realistic results, a one dimensional heat flow model incorporating the thermal conductivity of the regolith was employed. The model (ref.9) assumes conductive heat flow from two faces of a flat plate of thickness z with large or infinite surface dimensions (see figure 1) and non-steady-state conditions. An analytical solution of the one dimensional heat flow equation was obtained using this model. The time required for the center line of the brick to reach 1000°C, as a function of brick thickness, could then be calculated using appropriate values for the parameters (e.g., thermal conductivity = 60 μW/cm K). For comparison purposes, a large constant surface area of one square meter was assumed to insure the assumption of one dimensional heat flow. These calculations, which incorporate a temperature gradient, are plotted in Figure 4 and compared with the solar data from Figure 3, which assumes instantaneous thermal equilibrium. It is apparent that accounting for the regolith thermal conductivity increases the processing time by several orders of magnitude for realistic brick thicknesses. This is primarily due to the nearly perfect vacuum in the void space between regolith particles, which acts as insulation and prevents heat convection between particles. The shaded region of Figure 4 represents a probable processing time "window" for the fabrication of lunar regolith bricks using direct solar heating.

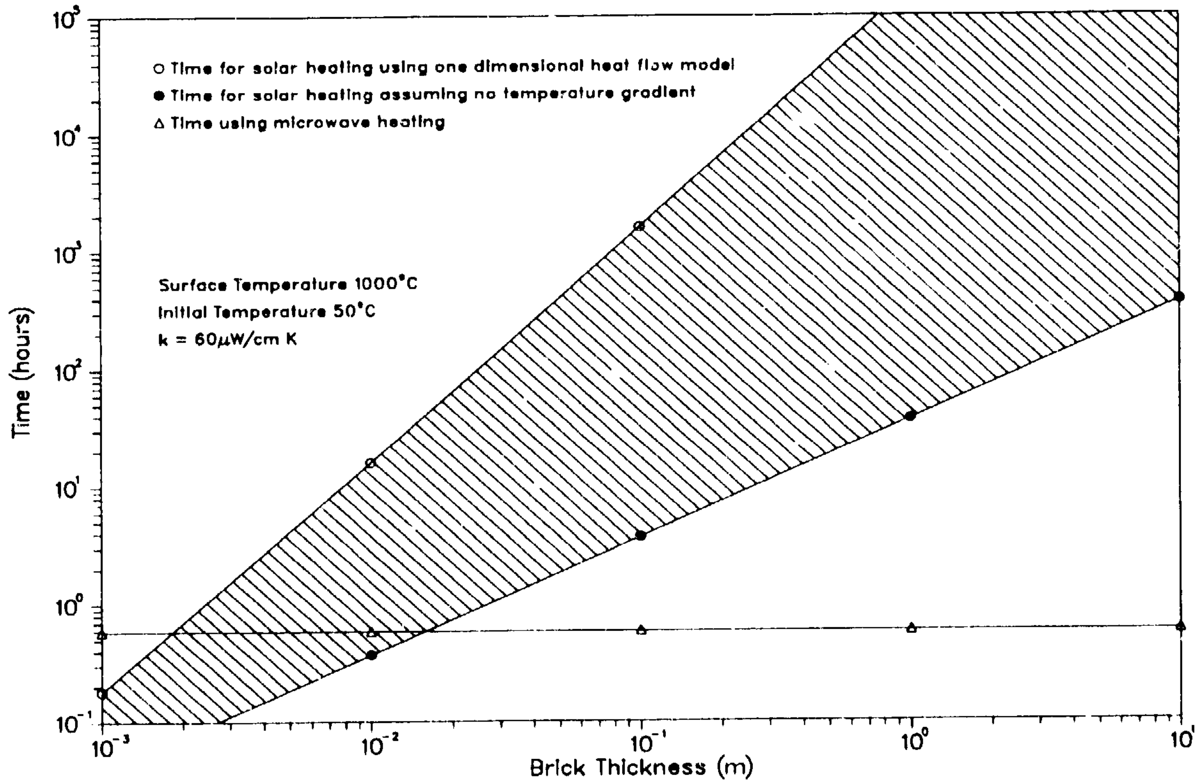

Figure 4. Time required to supply the regolith charge with the calculated amount of energy as a function of brick thickness. The upper most curve takes into account the thermal conductivity of the regolith and the resulting temperature gradients.

This preliminary analysis has ignored economic issues which will have an important impact on the selection process. For example, although solar furnace power increases as collector area increases, the size, mass, and transport of very large collectors must be considered. However, the relative simplicity of a solar collector and furnace is attractive compared to a microwave generation/transmission unit. A solar furnace has the disadvantage of only functioning during the lunar day while a microwave facility would be capable of continuous operation. Electricity for microwave generation would need to come from solar cells or a nuclear generator, although solar cells have been developed recently to operate at 20% efficiency (ref. 10). The conversion of electricity to microwaves is approximately 50% efficient at present, while solar collectors are capable of focusing 90% of incident sunlight. These efficiencies must then be contrasted with the actual sintering efficiency of the two processes. It is apparent that the final choice of technique will have to be based on a combination of technical and economic concerns, as well as environmental factors.

CONCLUSIONS

Microwave and direct solar heating processes have been examined as methods of producing bricks from lunar regolith for potential construction applications. Microwave sintering offers a number of advantages in terms of the power available for densification and the short processing times required for realistic brick volumes based on the assumed regolith composition and selected values for the processing parameters. However, a number of other factors, primarily the economics of power generation, have to be taken into account before an optimal process is developed.

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