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# Determination of temperature variation on lunar surface and subsurface for habitat analysis and design

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## ABSTRACT

The ambient environmental factors present on the lunar surface pose some of the most difficult challenges for the success of a long-term human settlement on the Moon. Aside from the dangerous radiation levels and hypervelocity micrometeoroid impacts, the equatorial temperature on the surface of the Moon can range from 102.4 K to 387.1 K. These extremes pose a variety of complications like thermal expansion and contraction, which can, in turn, alter the static, dynamic, and frequency response of a structure. This paper first presents the analytical study of the surface and subsurface thermal/heat flow environments of a potential habitat site located at the Equator of the Moon using a general equation that was developed based on the thermodynamic principle of heat flow to determine the temperature variation/gradient with time as well as depth. This method was then applied, with appropriate modifications, to determine the temperature variation with time and through depth of a 1-m thick regolith shielding layer surrounding a lunar structure. The solution to the general equation was determined through the use of the fourth-order Runge–Kutta technique of numerical integration. The analysis results showed that the outermost layer of regolith fluff has very strong insulating capabilities causing the temperature to drop 132.3 K from the maximum daytime magnitude of 387.1 K within the first 30 cm at which point it then remains constant with increasing depth. At night, the temperature increases from the minimum magnitude of 102.4 K to 254.8 K within the outermost 30 cm. When considering a layer of regolith shielding atop a lunar habitat, the added albedo radiation input from the adjacent lunar surface to the structure increased the maximum daytime surface temperature to 457 K (about 70 K higher than the lunar surface temperature) and displayed a drop of 138 K within the first 30 cm depth of regolith cover. The minimum temperature at night increased 80.3 K over the surface temperature to reach 182.7 K while displaying an increase of 137.2 K through the outermost 30 cm. In general, throughout the lunar cycle, it was observed that at a fixed point in time, as the depth within the regolith increases, the temperature variation throughout the lunar cycle decreases and the temperature ultimately remains constant beyond a certain depth (observed to be approximately 30 cm). The framework of this study, which was completed considering a habitat at the lunar equator, can also be used at different locations of the Moon to study their adequacy for long-term colonization missions.

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## 1. Introduction

The United States of America has identified six goals for pursuit under its national space programs. Among them are the energizing of competitive domestic industries for the advancement of space technologies, the expansion of international cooperation in space, and the improvement of stability within distant environments [1]. The continued pursuit of space technologies is the next step towards exploring the distant corners of the universe, be it by human or robotic initiatives.

The pursuit of these goals necessitates the advancement of lunar surface technologies leading to the eventual construction of a long-term human habitat on the surface of the Moon. The structural analysis and design of a base such as this brings on many challenges including protection from extreme temperature variations, hypervelocity micrometeoroid impacts, and dangerous levels of radiation exposure [2,3]. All of these potential threats are not commonly present to such extremes within the design of terrestrial structures. In addition to these environmental dangers, the habitat location, material selection, architectural layout, and safety mechanisms, among numerous other challenges must be clearly thought out and accounted for. Many of these design items have been investigated and explored previously by several different investigators [3–12].

On the lunar surface, there is an extended diurnal cycle lasting over 29 days resulting in long periods of extreme hot and cold temperatures. According to Vaniman et al. [2], it is estimated that during the daytime, temperatures can rise to 396.1 K (123 °C) at the equator while dropping as low as 40.1 K (−233 °C) within the shadowed polar craters during the night. Structures built in this environment can experience high amounts of expansion, contraction, and fatigue stresses, which must be accounted for within the design. Adequate shielding methods must also be incorporated to lessen the exposure and effects of the harsh lunar environment.

When compared to the Earth, studies suggest that the lunar interior is much less active in a variety of ways [13]. For example: (1) the topography at all scales is much older than the Earth, (2) there exist very few internal seismic sources combined with a relatively low coefficient of attenuation of seismic waves, (3) there exists no general lunar dipole magnetic field, and (4) the internal heat flux as measured from surface experiments is approximately half that of Earth. Early models of lunar temperature show that the central core temperature of the Moon has a temperature of approximately 1000 K [14].

Several lunar habitat concepts have been proposed by different research groups including, the Task Committee on Lunar Base Structures [3], Malla et al. [7–9], Ruess et al. [5], Benaroya et al. [4], Vanderbilt et al. [10], and Kennedy [11,12]. More recently, Malla and Chaudhuri [8,9], Malla and Gionet [15], and Malla and Brown [16,17] have proposed and analyzed two different frame-membrane structural system designs for long-term lunar habitation missions. A key component of these habitat systems is the use of In-Situ Resource Utilization (ISRU) through the use of lunar regolith as an environmental shield. A layer of lunar regolith 1 m thick surrounding the habitat is proposed, thereby protecting both the habitat itself and the crewmembers inside from the harsh environment. It is essential for the design of these structures to know how the temperature will vary through the depth of this regolith cover in order to accurately study the thermal stresses and deflections that can be expected within the frame.

This paper presents the study of the thermal environment at the Equator of the Moon and the temperature variation with time both on the lunar surface and at varying depths beneath the surface, using the thermodynamic principle of heat flow. Using the different input and output radiation sources present at the habitat site, including direct solar input radiation and both non-blackbody and albedo output radiation, a general thermodynamic equation is developed and furthermore solved using the fourth-order Runge–Kutta method of numerical integration. With this temperature profile known through a depth of regolith, it can be applied to the thermal shield surrounding the lunar habitat and its effect on the structural members can be investigated.

## 2. The NASA Apollo missions

During the NASA Apollo missions of the early 1970s, lunar subsurface heat flow experiments were completed in order to determine the temperature profile and the effective thermal conductivity of the lunar material [18]. It is on the basis of this series of experiments that the study presented in this paper is conducted. The Apollo missions used multiple experimental setups and equipment types whose results were replicated using mathematical theories and formulations. The experimentally determined temperature profiles from the Apollo missions are shown in Fig. 1.

At the Rima Hadley site (25.0° N, 3.0° E) used during the Apollo 15 expedition, the mean surface temperature measured was 207 K, which increased rapidly with depth to approximately 252 K at 90 cm [19]. During the lunar night, the temperature fell to 93 K. The topmost 2 cm was very loosely packed and experienced a high degree of temperature change with its depth. For this reason the regolith profile was divided into two gradations to provide a more accurate representation of the lunar surface material [19]. The uppermost had a thermal conductivity of $1.5 \times 10^{-5}$ W/cm K and the compacted layer beneath had a conductivity of $1.4 \times 10^{-4}$ W/cm K.

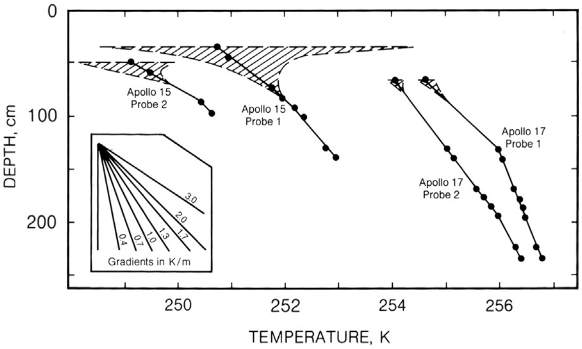

Fig. 1. Experimental lunar temperature profile [26].