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Steady-State Thermal Analysis of the Multi-layered Shell Structure for the Crewed Lunar Habitat Wall Design

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***Abstract* - The construction of crewed lunar habitats requires thermal protection system to withstand extreme environmental lunar conditions. This study aims to identify the minimum thermal resistance needed for a lunar base envelope and to propose an appropriate multi-layered wall design in shell structure. A steady-state thermal analysis was conducted to determine the minimum thermal resistance required for maintaining an indoor temperature of 298K under varying surface temperatures of Shackleton crater ranging from 40 K to 320 K. The analysis revealed that at least 20.25 m²·K/W of thermal resistance of wall is needed under the most severe conditions (ΔT = 1 °C) to secure indoor thermal environment. Various insulation materials were evaluated, including extruded polystyrene (XPS), vacuum insulation panels (VIP), and multi-layer insulation (MLI). Among them, MLI demonstrated superior thermal performance under vacuum conditions, requiring only 22 layers (approximately 2.02 mm thickness), total 42mm in thick to meet the resistance criterion excluding the effect of regolith covering, in order to consider scenarios such as mobile habitats or various solar exposure conditions. In compliance with NASA guideline JSC-67721, a multi-layered shell configuration as a habitat wall was proposed, integrating MLI with impact-resistant and radiation shielding layers. The results provide a design basis for thermal envelope systems with lunar habitats and are expected to contribute to develop thermally efficient lunar base design concepts**

Keywords - Lunar habitats; Thermal resistance; Thermal protection system; steady-state thermal analysis; a multi-layered shell Introduction

I. INTRODUCTION

A. Background and research purpose

In most advanced countries, space exploration is no longer an optional activity but has become a strategic imperative, and the space industry is expanding from government-led side to a increasingly driven model by the private companies. This competitive movement is being accelerated by several leading nations such as the United States, China and by private U.S. companies, including SpaceX, Rocket Lab, Astrobotic Technology, and Intuitive Machines [1]. In particular, following the Space Policy Directive announced since 2017, the U.S. Artemis program has advanced research aimed at establishing exploration infrastructure on the lunar surface [2,3]. The Artemis I mission successfully performed an uncrewed flight using the Space Launch System (SLS) and the Orion spacecraft. The next step, the Artemis II mission, is scheduled to conduct crewed flights beginning in 2026, followed by the Artemis III mission, which plans human landings from 2028 [4,5].

From an international perspective, more than 40 countries have currently signed the Artemis Accords, promoting transparency and sustainable activities in space exploration [6]. In particular, the republic of Korea officially joined the program by signing the Artemis Accords in 2019 and has recently established the 4th Basic Plan for Space Development, focusing research on participation in international crewed lunar exploration to support the construction of lunar bases [7].

Globally, massive budgets are being allocated to space exploration. As of 2021, the total budget invested in space development was reported to be approximately USD 92.5 billion, demonstrating a steadily growing international interest in space exploration. Notably, about 26% of development funding in private-sector space are directed toward crewed spaceflight which implies that a substantial portion of the budget is used for human exploration missions [8]. Long-term missions require not only habitable space but also infrastructures to support power generation, experiments, resource storage, and transportation. Accordingly, as the space industry expands—particularly in the area of crewed space exploration—research on creating environments that allow humans to remain in space for extended periods has become an urgent necessity. Specifically, for long duration crewed missions on lunar surface, the development of habitat walls capable of withstanding the extreme surface environmental conditions is one of the key factors.

Therefore, in this study, Shackleton Crater, one of the major lunar landing candidate sites for the presence of water and resource exploration, was selected as the analysis site, and the thermal environmental characteristics of the lunar south pole surface were studied. Based on these data, steady-state thermal analysis was conducted to determine the composition of walls to withstand temperature variations and to secure indoor environment. Finally, design criteria for a multi-layered shell structure, capable of enduring both temperature fluctuations and space radiation under the extreme space environment, were derived, aiming to provide a foundation for the future design of crewed lunar habitats.

B. Literature review

In this study, previous research results were surveyed to collect thermal input parameters to derive the composition of habitat walls aimed at securing indoor environments where lunar surface lander might be located. To carry out this research, Section 1. B. reviews (1) data of the thermal environment on the lunar surface, and (2) data of indoor environment analysis in space environments such as spacecraft and lunar habitats.

The thermal environment on the lunar surface is influenced by direct solar irradiation and terrain due to vacuum by the absence of an atmosphere. In particular, the polar regions on the Moon, known as permanently shadowed regions (PSRs) including Shackleton Crater, are under extremely low temperatures. Solar irradiation reaching the surface varies depending on the terrain and results in differences in surface temperature. In addition, investigation of lunar surface plasma conditions is an important requirement for exterior base wall design. Regarding lunar surface thermal environment, lots of studies have been largely conducted by NASA. Relevant data using the Diviner Lunar Radiometer Experiment (DLR) onboard the Lunar Reconnaissance Orbiter (LRO) were collected remotely and Williams et al. analyzed lunar surface temperatures and the distribution of surface temperatures by region [9]. Temperatures at the equatorial region reached 387–397 K, while temperatures dropped to approximately 95 K just before sunrise, demonstrating significant temperature variations. Similarly, Hayne et al. [10] analyzed the thermal conductivity of the lunar regolith using LRO Diviner data. In infrared data, the thermal conductivity of the regolith was evaluated to be 7.4×10^{-4} W/m· K at the surface. By considering surface thermal inertia, Vasavada et al. [11] conducted detailed analysis of temporal variation characteristics in solar and ground radiation at the lunar south pole through thermal modeling. It showed that some regions had temperatures below 100 K even at the same time while others to exceed 200 K because some part of surfaces were influenced by terrain shading. In particular, Zhong et al. [12] performed precise geographic and solar irradiation simulations for the rim and interior of Shackleton crater separately using the SPICE Toolkit and reported that the crater surface remained below −200°C on average for a whole year. Additionally, Kaczmarzyk et al. [13] calculated solar irradiation on the Moon using MATLAB and proposed equations to estimate solar irradiation on horizontal and inclined surfaces. During a lunar day, a hemispherical area of 10 m in diameter receives a total of 111.75 GJ of solar energy. Malla et al. [14] conducted research for lunar base design near the equator, establishing thermal equilibrium equations and analyzing surface temperature variations using a 132nd-order Runge-Kutta numerical integration method. It revealed that the presence or absence of lunar regolith led to surface temperatures 30 K lower during the day and 30 K higher at night, which demonstrated the effectiveness of regolith as an insulation.

Other studies were also reviewed to analyze environmental conditions for human activity in space. For crewed space exploration, it is essential to provide astronauts with a long-term habitable indoor environment. Steiner et al. [15] created the dome-shaped lunar base model by dividing it into 32 zones and analyzed indoor environments for each zone. While indoor pressure was relatively in uniform, temperature distributions were uneven. This implies that fan systems are necessary for indoor thermal condition maintenance. Einem et al. [16] analyzed indoor heat flux in space environments using CFD simulations and evaluated performance of ventilation system based on indoor temperature settings and internal loads. The results showed that a two-loop ventilation and cooling design was able to remove 8.78 kW of heat. Tripathi et al. [17] developed the 3D thermal model for a hemispherical dome to simulate radiant heat through the shell and convective conditions inside. The outer wall was designed with a thickness of 40 cm, and temperatures ranged from 390 K to 213 K, while varying internal temperatures within ±30 K. In addition, the insulating performance of applying lunar regolith was studied for a concrete dome and resulted that a 20 cm thick regolith layer was enough to reduce internal surface temperature fluctuations to ±2 K [18]. In ESA's moon village project report [19], it was proposed that a multi-material insulation system was suitable for long-term exploration missions in space. Relatedly, Singh et al. [20] experimentally demonstrated the thermal insulation performance of silk-net-based multi-layered insulation (MLI) in cryostats under high vacuum of 10^{-4} torr. It showed that doubling the layers numbers at the optimal density reduced heat load by 50%. Furthermore, Sierra Space has conducted research on inflatable modules and habitats, such as LIFE [21] and multi-layered shell structures for space bases were confirmed to have an efficiently maintaining safety factor of four and expected to have shell lifetime exceeding 60 years.

Lunar thermal environment has also been extensively investigated. many researches have focused on material itself for efficient wall construction. However, research on deriving the required thermal resistance for walls or multi-layered shell wall composition remained limited for maintaining indoor environments for long-term crewed missions. Therefore, thermal analysis under steady-state conditions in space environments were carried out and a prototype wall configuration design was proposed for the required insulation level. Material configuration of the exterior wall of lunar habitat was suggested under the surface environment conditions of Shackleton crater.

II. METHODS

Section 2 described the research methodology applied in this study. Fig.1 presents a flow chart summarizing the research process. In Step 1, data for the target site intended for thermal environment analysis were investigated, and the boundary conditions for the simulation were established. In Steps 2 and 3, steady-state thermal analysis modeling was conducted, and the results were analyzed to derive the required thermal resistance of the envelope under lunar environmental conditions. In Step 4, the derived thermal resistance values were utilized to develop a concept design for the lunar habitat envelope.

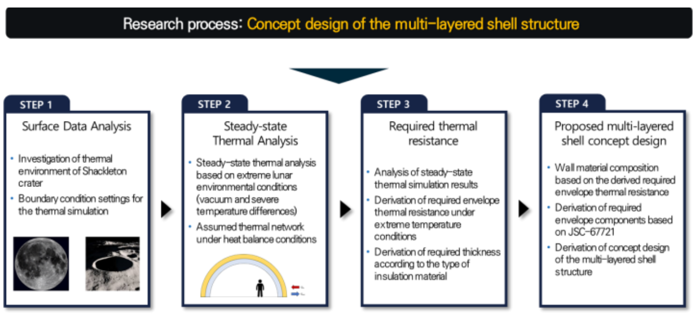

Fig. 1. *Flow chart of research process*

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A. Heat transfer mechanisms in the space environment

Heat transfer through the exterior structure occurs fundamentally through three processes: (1) conduction, (2) convection, and (3) radiation. In this section, the basic governing equations for these processes were described, along with the thermal characteristics that must be considered in the lunar environment.

Steady-state was assumed to perform the fundamental analysis necessary for deriving the required thermal resistance of the exterior walls and determining wall composition. Steady-state implies that the temperature within the exterior structure does not change over time, assuming no heat storage capability of the walls. Accordingly, the analysis was conducted under the condition dT/dt=0 (where *T* is temperature and t is time), meaning that no temporal temperature variations occur. It should be noted that this assumption is made for two purposes: (1) to derive boundary conditions for wall design, and (2) to determine operational conditions and interactions with essential HVAC systems required to maintain habitable indoor environments.

Heat transfer by conduction refers to the process in which heat moves from a region of higher temperature to a region of lower temperature between contacting objects. The heat transfer through a one-dimensional planar wall can be calculated using Fourier′s Law, as expressed in Equation (1) [22, 23].

$$q_{conduction} = \frac{k \cdot A \cdot (T_1 - T_2)}{L} \quad (1)$$

($q_{conduction}$: heat transfer by conduction (W), k: thermal conductivity (W/m·K), A: the area through which heat flows, T_1, T_2: temperatures on both sides of the wall (°C), L: wall thickness (m))

Heat transfer between a solid surface, such as a wall, and the surrounding fluid is referred to as convective heat transfer. In the lunar environment, no atmosphere exists, resulting in a vacuum outside of the habitat. Therefore, exterior convection can be neglected. Heat transfer by convection can be calculated using Newton's law of cooling, as expressed in Equation (2) [22, 23].

$$q_{convection} = \alpha_c \cdot (T_{surface} - T_a) \quad (2)$$

($q_{convection}$: heat transfer by convection (W), α_c: coefficient of convective heat transfer, $T_{surface}$: wall surface temperature (°C), T_a: air temperature (°C))

When the fluid moves naturally due to buoyancy caused by temperature differences, it is referred to as natural convection, whereas movement induced by a fan or blower system is referred to as-forced convection. In Equation (2), α_c represents coefficient of the heat transfer determined by either natural or forced convection, which varies depending on the type of fluid, its velocity, and temperature conditions. Generally, α_c is treated as a constant for practical applications in building interiors. In this study, the analysis was conducted using the indoor standard convective coefficient according to ISO 6946 [24], with α_c = 7.69 W/m²K as the reference value.

In building thermal environments, heat transfer by radiation refers to the process in which thermal energy is transferred in the form of electromagnetic waves without the mediation of a material. A high-temperature object emits energy to a low-temperature object through infrared radiation, and this heat transfer can occur even in a vacuum. Therefore, under the lunar surface thermal environment, radiative heat transfer should be considered and can be expressed using Stefan–Boltzmann's Law, as shown in Equation (3) [22, 25].

$$q_{radiation} = \emptyset \varepsilon_1 \varepsilon_2 C_b \left\{ \left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4 \right\} \quad (3)$$

($q_{radiation}$: heat transfer by radiation between surfaces 1 and 2 (W), Φ: view factor of surface 2 with respect to surface 1, ε_1, ε_2: emissivity of surfaces 1 and 2, C_b: coefficient of blackbody radiation, 5.67 W/m²·K⁴, T_1, T_2: surface temperatures of 1 and 2 (°C))

In general, when thermal environments of building indoor are analyzed, the above complex equation is simplified as expressed in Equation (4). Specifically, for heat transfer by internal surface radiation in typical building interiors, radiative heat transfer coefficient is commonly assumed to be h_r = 5 W/(m²·K) and was applied to this case [26].

$$q_{radiation} = h_r \cdot A \cdot (T_{surface} - T_a) \quad (4)$$

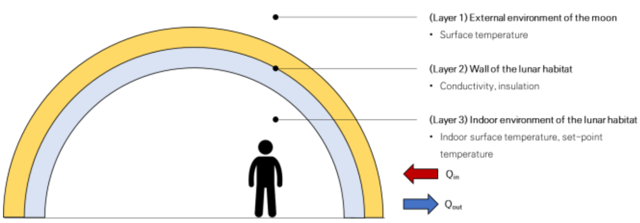
(h_r: coefficient of indoor heat transfer by radiation)

B. Thermal analysis modeling

For the thermal analysis of lunar habitats, multi layers were configured as shown in Fig. 2, and heat transfer calculations were conducted. The calculation expressed the lunar habitat as a multi-layer thermal resistance model. Each layer was constructed with thermal resistance values reflecting the following three heat transfer characteristics: wall layers dominated by conduction, external vacuum layers dominated by radiation, and convection between the interior and the wall surface. This model was analyzed using a thermal network approach to calculate the heat flux incurred by temperature differences.

For the heat transfer calculation process, the area exposed to the environment was assumed as shown in Fig. 3, with solar irradiation applied to the upper roof surface. In this study, the required thermal resistance was derived under steady-state conditions to satisfy indoor and outdoor conditions. Accordingly, the multi-layered wall of the lunar habitat is assumed to be in a steady state, and when thermal equilibrium is reached, the heat flux at the exterior surface of the envelope (q_{so}), the heat flux through the multi-layered wall (q_w), and the heat flux at the interior surface of the envelope (q_{si}) are all equal (i.e., $q_{so} = q_w = q_{si}$ in Fig. 3).

Fig. 2. Thermal layer configuration for heat transfer analysis



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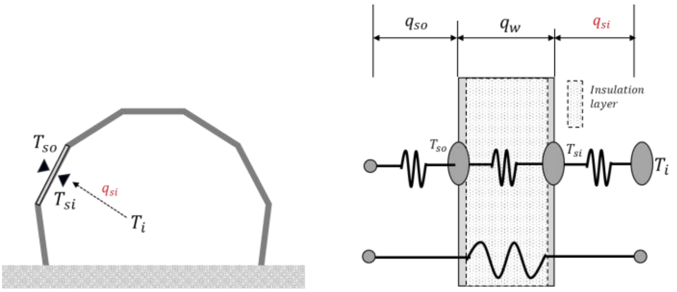

Fig. 3. Procedure for heat transfer calculation (q_{so}: heat flux at the exterior wall (W), q_w: heat flux through the wall (W), q_{si}: heat flux at the interior wall (W), T_{so}: exterior surface temperature (°C), T_{si}: interior surface temperature (°C), T_i: indoor air temperature (°C))

The walls facing underground were assumed adiabatic, and the interior was assumed to be maintained at 25°C, with only the exterior thermal resistance of the upper roof surface calculated. Under steady-state conditions, the heat flux in each section of the thermal network is identical, and the thermal resistance was calculated using Equation (5). On Earth, wall surface temperatures are typically calculated using the sol-air temperature, which accounts for outdoor air temperature and solar irradiation to determine thermal load. However, in space, due to the vacuum environment, the wall surface temperature was assumed to be equal to the lunar surface temperature, and the exterior thermal resistance was calculated accordingly. The lunar surface temperature values used in this study were presented in next section.

$$q_{si} = \alpha_{si} \cdot (T_{si} - T_i) = \frac{(T_{so} - T_{si})}{r_w} \qquad (5)$$

(r_w: thermal resistance of the wall ($m^2 \cdot K/W$), α_{si}: overall coefficient of indoor heat transfer ($W/m^2 \cdot K$))

C. Surface temperatures at lunar landing sites

The lunar environment has extremely harsh conditions for human habitation and survival. The temperature difference along to the day and night shift reaches approximately 300°C, and the surface is directly exposed to solar radiation and intermittent meteorite impacts due to the high vacuum environment [27]. To minimize such hazards, south pole region of the Moon is considered to be a primary candidate for lunar landing sites. The lunar south pole receives sunlight for approximately 90% of the year and is a significant potential spot for solar power generation [28]. Additionally, low temperatures induced by its polar location increase the probability of water presence higher and make it a potential resource for water utilization [29].

When a lunar base is constructed for space exploration, designing wall structures capable of withstanding extreme temperatures is essential. In particular, the lunar surface exists in a high vacuum of approximately 10^{-9} torr, and unlike Mars, there is no atmosphere, so the surface is directly exposed to solar radiation, resulting in extreme temperature variations. In the case of Shackleton crater, located in the south polar region, structures positioned near the crater rim can avoid direct sunlight, thereby mitigating extreme environmental conditions compared to the lunar equator. Consequently, Shackleton crater has been proposed as one of the most promising lunar landing candidates, and literature data on surface and subsurface temperatures in this region according to seasonal variations are summarized in Table 1 [12, 30–33]. Notably, surface temperature data of the crater vary across studies, which is attributed to the fact that temperature ranges were inferred from remote optical measurements rather than direct in-situ data collection.

TABLE I. TEMPERATURE DISTRIBUTION OF SHACKLETON CRATER

Region	Season	Temperature
Inside	Summer	40K ~ 95K (-233°C ~ -178°C)
	Winter	40K ~ 50K (-233°C ~ -223°C)
Rim	Summer	70K ~ 200K (-203°C ~ -73°C)
	Winter	60K ~ 70K (-213°C ~ -203°C)
Outside	Maximum	300K ~ 320K (26.9°C ~ 46.9°C)

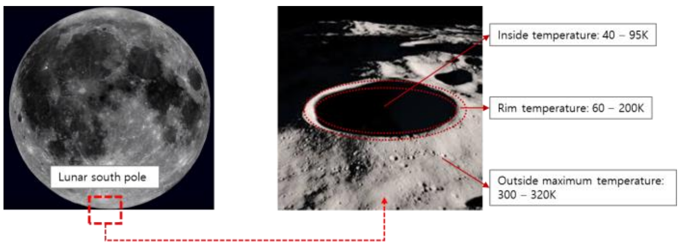

Fig. 4. Investigation of surface temperature of Shackleton crater

Fig.4 shows the temperature ranges of the Shackleton crater, located in the lunar south pole region. The study was conducted based on these temperature values in the thermal analysis. For the steady-state thermal analysis, surveyed values were utilized, with surface minimum and maximum temperatures set at 40 K and 320 K, respectively.

III. RESULTS

A. Required thermal resistance of the envelope under lunar conditions

Section 3. A. aims to determine the required exterior thermal resistance of the lunar habitat based on the methodology defined in Section 2. On steady-state assumption, the surface of the habitat exterior is maintained at a constant temperature and the interior is kept at 25°C. Under these conditions, the minimum required thermal resistance on the exterior was derived for cases where the temperature difference between interior air and interior wall surface ranging from 1 to 5°C.

The lunar surface temperature, as investigated in Section 2. C., was considered within the range of 40 K to 320 K to calculate the required exterior thermal resistance, and the results are shown in Fig. 5. The x-axis in Fig. 5 represents the surface temperature distribution of Shackleton crater, and the exterior thermal resistance was calculated for temperature differences of 1 to 5°C between interior air and interior wall surface. In the most demanding case as of $\Delta T = 1$°C, thermal resistance under the lowest temperature condition was required to have 20.25 $m^2 \cdot K/W$ on the exterior. Meanwhile, it was observed to be 1.7

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m²·K/W under the highest temperature condition. The highest thermal resistance was necessary where no lunar regolith covers. As long as the envelope was covered with regolith, thermal

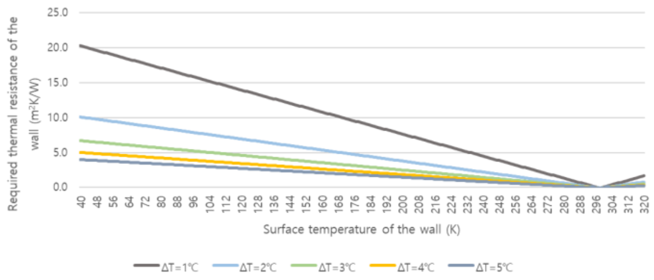

Fig. 5. Required thermal resistance of the wall according to temperature differences between indoor space and wall surface

resistance could be designed to be lower. However, in this study, the boundary condition was derived based solely on the properties of the exterior materials, excluding the effect of regolith covering, in order to consider scenarios such as mobile habitats or various solar exposure conditions.

In Shackleton crater, some areas belong to permanently shadowed regions and receive relatively little solar irradiation compared to other regions, which results in that these parts are one of the coldest surface areas on the Moon. As a result, the required thermal resistance of exterior wall by heat loss is significantly higher than that for heat gain. This is because the maximum temperature in this region is approximately 50°C while the minimum temperature reaches around −230°C. This phenomenon was attributed to the topographical characteristics of Shackleton crater. The crater, located at the lunar south pole, experiences markedly less solar irradiation than other regions because the Moon’s axis is only tilted about 1.5° relative to the Sun. In particular, inside of the crater is a permanently shadowed where sunlight never reaches, resulting in substantially lower surface temperatures compared to other areas. This is consistent with results in other studies show that in equatorial regions, surface temperatures can drop down to approximately 95 K just before sunrise in where sunlight never reaches [9]. In the polar regions, where receive the least solar irradiation, temperatures are even lower than at the equator and lead to require significantly high thermal resistance of exterior wall under heat loss conditions. Therefore, the wall insulation design was initiated based on the most extreme condition as of $\Delta T = 1°C$, applying the lowest temperature in the Shackleton region to define boundary conditions and to determine the configuration that requires the highest level of thermal resistance.

B. Multi-layered shell design for thermal performance

In Section 3. B., the insulation configuration of the lunar habitat walls was proposed based on the required thermal resistance of exterior wall as of approximately 20.25 m²·K/W derived in Section 3. A. Thicknesses of each type of insulation material to achieve this thermal resistance are presented in Table 2. On Earth, conduction is the primary mode of heat transfer through walls and insulation materials such as XPS (Extruded Polystyrene) and VIP (Vacuum Insulation Panel) were considered to block the heat transfer by conduction. Meanwhile, in space, heat transfer is dominated by solar irradiation and to resist heat loss, MLI (Multi-Layer Insulation) was applied. Furthermore, considering that space is in a high vacuum of approximately 10^{-9} torr, vacuum insulation materials were considered to mimic this condition as an experimental approach on earth conditions.

TABLE II. REQUIRED THICKNESS DEPENDING ON THE TYPE OF INSULATION MATERIALS

Category	XPS	VIP	MLI
Thermal conductivity (W/m·K)	0.03	0.002	0.0001 (Effective thermal conductivity)
Thickness (mm)	608	41	2.02 (22 layers)

As summarized in table 2, MLI exhibits excellent insulation performance under the required vacuum conditions because it is specialized for solar irradiation blocking, resulting in a relatively low required thickness. In the view of radiation, aluminum has a high reflectivity and low emissivity. So, it might effectively mitigate radiative heat transfer in space than other materials. Therefore, MLI was the appropriate for the thermal insulation layer in terms of weight and effective reflectance as well. In addition, polyester material serving as spacers, the other layer of MLI, which create spaces between layers. For simulation, actual values of MLI were measured and thickness of the aluminum foil was 0.004 mm, and polyester was in 0.09 mm. Considering one aluminum and polyester combination as a single layer, a total of 22 layers were found necessary to meet the minimum. In previous reports, it has shown that the foils of MLI should not be compressed to optimize its thermal performance by minimizing conduction and focusing on radiation blocking because spaces between layers work for the insulation as discussed previously. Optimal performance was reported to achieve when the spacing between foils was 2 mm [34]. Consequently, to obtain the minimum required insulation performance, it was necessary that 42mm thick wall consisting of 22 layers of MLI with 2 mm spacing between foils. For the insulation performance of MLI, the insulating layers must be kept in a vacuum all the time, separating from indoor spaces where air is present in 1 atm pressure. It would be the one of the most challenging issues in designing multi layered shell structured wall for the long-term habitat on lunar surface environment. Specifically, where lunar habitat is covered with regolith, layers can be suppressed by regolith load. Supplementary supports to contain MLI should be considered.

Along with thermal performance, other properties of wall also should be considered to design the habitat wall. The NASA guideline JSC-67721 [35] for inflatable lunar habitat wall configurations defines that habitat walls should include an environmental protection layer, an external impact protection layer (e.g., for micrometeoroids), and a gas barrier bladder. Based on this guideline, a multi-layered shell wall composed of various materials was designed, and the wall configuration is shown in Fig. 6. The wall system is composed of four primary layers: (1) an external protection layer, (2) an insulation layer, (3) a gas barrier bladder layer, and (4) an internal protection layer. The first layer, the protection layer, is designed to shield the habitat from potential physical impacts on the lunar surface and to safeguard insulation layer. Insulation material is unsuitable for independent application because its mechanical

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TABLE III. WALL CONFIGURATION AND THERMAL PERFORMANCE

Category	Material	Material thickness (mm)	Conductivity (W/m·K)	Thermal resistance (m^2·K/W)	Thermal resistance ratio
Protection layer (Outside)	Vectran®	10	1.5	0.00667	0.00032
Insulation layer	MLI	2.068	0.0001	20.68	0.97787
Gas barrier bladder layer	HDPE	10	0.022	0.4546	0.02149
Protection layer (Inside)	Vectran®	10	1.5	0.00667	0.00032
Total thermal resistance = 21.14790 m^2·K/W					
U-value of wall = 0.047 W/m^2·K					

strength and tensile resistance are very low. For inflatable habitat configurations, aramid-based materials with high tensile strength are considered suitable for this protection purpose. The second layer, the insulation layer, serves to minimize radiative heat transfer. Spacer are used to maintain separation between aluminum foils and for the sufficient insulation performance, the system should be configured with minimum thickness to secure thermal performance. Additional critical point is that insulation layer must be maintained in a vacuum all the time by completely isolated from the internal atmosphere pressure and cutting potential thermal bridges, which might deteriorate whole insulation of multi layered shell. To assist the insulation, the third layer, the gas barrier bladder layer, is incorporated. It is responsible for maintaining internal pressure and should be composed of gas-impermeable materials. Technically, the insulation layer must be placed in a vacuum side of this bladder layer. If insulation layer is located within the pressurized interior, the performance of the MLI is drastically reduced because of convective heat transfer between foils. Finally, the internal protection layer is positioned on the habitat's inside to protect the bladder layer against impacts from within the habitat. Similar to the external layer, aramid-based materials are suitable for this purpose.

In summary, according to the JSC-67721 guideline, vectran® is used as the external impact protection material, MLI is placed within the environmental maintenance layers to preserve insulation performance, and a gas barrier bladder made of polyethylene-based material maintains the vacuum state of the insulation layer. Finally, the interior is finished with vectran® to protect against internal impacts. Thus, the minimum wall configuration required for insulation is as shown in Fig. 6, with MLI responsible for the required thermal resistance. If the outer protection layer with vectran® and gas barrier bladder layer with HDPE are each 10 mm thick, the total thermal resistance is 21.15 m^2·K/W with the MLI layer contributing approximately 98% (Table 3). The final wall thermal transmittance (U-value) was determined to be 0.047 W/m^2·K, which is approximately three times better than the minimum U-value legally required for central regions in the republic of Korea, 0.15 W/m^2·K [36].

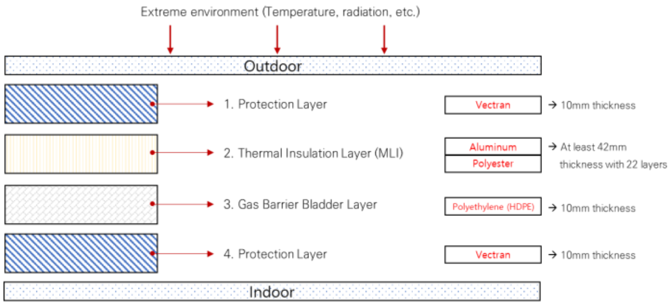

Fig. 6. The composition of multi-layered wall for minimum thermal requirements

On Earth, heat transfer is predominantly governed by conduction. However, in the space environment, heat transfer is dominated by solar irradiation due to the vacuum. In MLI, polyester spacers maintain the separation between layers, forming vacuum gaps that provide high insulation performance. These layers are repeated dozens of times, allowing MLI to achieve high thermal insulation performance despite its relatively thin overall thickness in space. However, because the results of this analysis were obtained under ideal conditions with a steady-state thermal environment assessment, the thermal resistance represents the minimum value that must be ensured where gas conduction between layers were negligible under high vacuum [37]. Therefore, a safety factor should be considered for practical applications. In real world conditions, thermal bridge between materials and the structural components, which might occur by several factors including unexpected solid contact, contact pressure, and vacuum pressure change, results in additional heat gain and loss. For these reasons, it is necessary to ensure a higher thermal resistance under higher temperature than the analysis values as reported in previous research [38]. When applying a degradation factor of maximum 4, the required thermal resistance could be up to 84.59 m^2·K/W (U-value = 0.012 W/m^2·K).

IV. DISCUSSION

Analysis of the thermal environment was conducted under lunar surface conditions by targeting the lunar south pole region, Shackleton crater, as a candidate landing site. It was proposed a multi-layered shell wall configuration from steady-state thermal analysis and NASA guideline for a crewed lunar habitat's exterior wall. According to the results, under the condition of an indoor temperature of 25℃ and a temperature difference ΔT = 1℃ between the interior air and the inner wall surface, the required thermal resistance of the exterior wall was found to be at least 20.25 m^2·K/W and might deteriorated up to 84.59 m^2·K/W. This represents the minimum insulation performance needed to maintain comfortable indoor conditions under extreme conditions where the surface temperature of Shackleton crater drops to approximately −233℃.

In particular, a comparative analysis of different insulation materials showed that, compared to commonly used XPS or Vacuum Insulation Panels (VIP) on Earth, Multi-Layer Insulation (MLI), which is specialized for the space

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environment, can achieve the same thermal resistance with a significantly thinner thickness (2.02 mm, 22 layers). On the lunar surface, due to the vacuum, there is no convective heat transfer, and radiative heat transfer becomes the primary mechanism. This characteristic allows MLI to provide significantly better insulation than XPS (608 mm) or VIP (41 mm), representing a major advantage for minimizing weight and volume in habitat design for space exploration.

However, while MLI excels at radiation blocking in space, each layer is composed of aluminum foil and polyester spacers, and multiple layers together form a single MLI layer. This structure has low mechanical strength and is vulnerable to damage during long-term operation. Additionally, the insulation performance is optimized only if the layers are maintained under vacuum. Therefore, for practical application in habitat structures, it is necessary to include an external frame to stably support the MLI layers, or to design the insulation layer in a way that ensures the vacuum layer using spacers or vacuum-insulated panel-like layers. Consideration of buffer layers to protect against external impacts such as meteoroid strikes is also required. To address this, this study referred to the NASA JSC-67721 guideline and proposed a multi-layered shell composite exterior design, consisting of vectran® layer for external impact protection, an MLI layer for insulation, and a polymer layer (e.g., high-density polyethylene) for pressure retention and radiation shielding. This prototype wall structure integrates insulation, structural stability, impact absorption, and radiation shielding, making it a viable wall configuration for achieving the required insulation performance in an actual lunar habitat.

Meanwhile, the thermal analysis of the wall in this study was conducted under steady-state conditions. For this reason, the thermal storage effects due to wall heat capacity were not considered. On the lunar surface, one day is approximately 29.5 Earth days, with extreme temperature variations between daytime and nighttime recurring over this period. Therefore, the thermal inertia and heat storage capacity of the habitat walls become crucial factors. In addition, since the solar irradiation conditions vary over time, it is necessary to take weather conditions into account when performing detailed thermal analysis in space. Accordingly, factors in Fig. 7 such as the solar irradiation incident on the building envelope surface, the irradiation emitted from the envelope surface into space, and radiative heat exchange with surrounding terrain or structures must be considered.

Since steady-state analysis does not reflect these dynamic characteristics, future studies will perform transient thermal analysis using dynamic simulations to provide a more realistic evaluation of heat transfer, while also integrating assessments of HVAC energy requirements and the feasibility of maintaining indoor comfort.

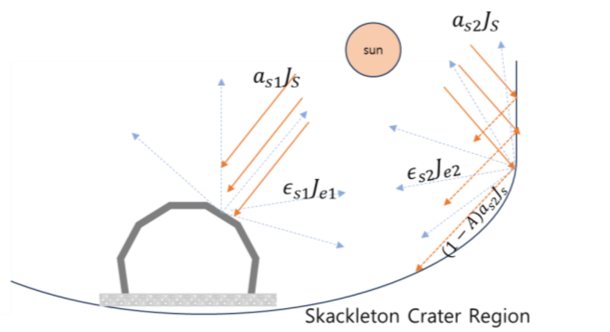

Fig. 7. Solar irradiation conditions for dynamic analysis (J: heat flux by solar irradiation, A: albedo, α: absorption rate, ε: emissivity)

V. CONCLUSIONS

It was aimed to determine the required thermal insulation performance for a crewed lunar habitat envelope and to propose a multi-layered shell configuration that capable of meeting the minimum requirements. The quantitative thermal analysis indicated that the minimum thermal resistance of exterior should be 20.25 m²K/W to maintain stable indoor temperatures and to ensure indoor comfort under extreme low-temperature conditions.

In particular, among three insulation materials, Multi-Layer Insulation (MLI) demonstrated the best performance for radiative heat blocking in space and lunar surface environment that achieving the required thermal resistance in a minimal thickness and density. The analysis also indicated that at least of 22 layers was required for the performance. Based on these thermal analysis results, a multi-layered shell exterior design for other functions of wall, referencing NASA's structural design guidelines, was proposed to provide a practically applicable wall configuration.

Overall, the key contributions of this study are as follow:

- It was quantitatively determined the required thermal resistance to maintain indoor temperatures based on the Shackleton crater was derived by a numerical benchmark for the insulation performance required in crewed lunar habitats.
- Basic design data for a habitable crewed lunar base wall was obtained under the extreme thermal conditions of the lunar south pole for a practical applicability.
- A multi-layered shell configuration was designed by applying NASA JSC-67721 guidelines and by ensuring structural stability of the MLI layer and by considering impact resistance and radiation shielding as well. Thereby, a comprehensive prototype wall design was offered.

As described, thermal analysis data of multi-layered shell can be utilized as foundational data to design passive standards of lunar habitat wall exteriors and offers an academically significant contribution by providing quantitatively and practically evaluable criteria of the minimum passive wall performance. However, as assumed on steady-state thermal

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analysis, temperature variations over time, heat transfer and thermal capacity were not reflected for the actual conditions. Therefore, future studies are required to plan to apply transient model based dynamic simulations to reduce a more realistic design approach. As thermal performance of the multi-layered shell is necessary for maintaining habitable indoor conditions, further detailed analysis would consider the integration with indoor HVAC systems, operation of exploration equipment, and astronaut physical activities according to mission schedules within the habitat.

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