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A Thermal Insulation and UV-Resistant System based on Aerogel for Settlements on the Moon and Mars

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Abstract: This paper presents a novel design for a habitable outpost on both the Moon and Mars that leverages the exceptional properties of aerogel - a material composed of 99% air, offering outstanding thermal insulation and UV protection. The outpost is engineered to withstand extreme temperature variations on Mars (-153°C to 20°C) and the Moon (-173°C to 127°C) using a single material. Protection against harmful UV rays is crucial for sustaining human life as prolonged exposure can lead to DNA damage and cancer. To safeguard the aerogel layer from meteoroids, Martian soil is utilized on Mars, and lunar soil on the Moon. The interior features a fiber composite layer, supported by a mechanical structure made from Martian concrete (ice, calcium oxide, and Martian aggregate) or lunar concrete (ice, calcium oxide, and lunar aggregate). The composite can be assembled on Earth with an inflatable system or sent to Mars in multiple missions for on-site assembly. Light transmission with radiation resistance is achieved using translucent silica aerogel filters for glass windows. The paper also includes heat transfer calculations between the internal and external environments of the habitat, as well as strength assessments of the habitat, taking into account the insulation and UV resistance provided by the protective soil layer.
Keywords: Geant4, Thermal insulation, Radiation Protection, Moon/Mars settlement, Aerogel

I. INTRODUCTION

Living conditions on the Moon and Mars are extremely challenging for human survival due to factors such as temperature variations, lack of an Earth-like atmosphere, limited water and oxygen, and high radiation levels. Despite these difficulties, building habitats on these celestial bodies is a crucial step towards achieving the dream of settlement and offers valuable scientific advantages for research purposes.

This paper presents a comprehensive study on the efficient utilization of aerogel in extraterrestrial habitats on Mars and the Moon. Habitats can be broadly classified into three categories: Inflatable, Rigid, and Hybrid habitats. Inflatable habitats are depressurized during transportation and can be sent to the base via rockets before being pressurized. These habitats resemble completely inflatable structures, similar to hot air balloons.

Rigid habitats, on the other hand, involve transporting individual components and sub-structures from Earth for on-site assembly, and they could incorporate regolith in their construction. Hybrid habitats combine features from both inflatable and rigid structures, utilizing a rigid skeletal framework with an inflatable body that is transported via rockets.

The use of regolith can be explored for shielding against micrometeorites and providing partial thermal insulation. Selecting suitable habitat locations is crucial. The optimal location for lunar habitats would be the Moon's south pole. However, identifying an ideal location on Mars is challenging due to the presence of CO2 everywhere.

One feasible approach is to target regions with sub-surface water, primarily found in polar regions. Considering radiation as a significant concern, placing the habitat underground is deemed ideal. Moreover, the study proposes the use of aerogel in combination with regolith from the respective planets to enhance radiation protection and improve thermal insulation. This paper delves into crucial aspects of extraterrestrial habitats, including issues related to shielding against micro-meteorites, thermal insulation, and radiation protection, which are vital for the safety and well-being of future inhabitants.

II. MATERIAL

In this section, we outline the materials chosen for constructing the habitat, encompassing metals for the skeletal structure, composites for the interior, and extraterrestrial soil for producing concrete. The materials selected for the habitat include –

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A. *Aerogel/ Aerogel composite*

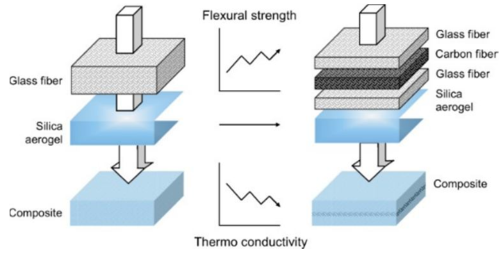

Fig. 1 Utilization of Aerogel Based Composite

For our application, we will utilize an aerogel-based composite as shown in Fig. 1. However, it is essential to understand the fundamental mechanical properties of standard silica aerogel. Various types of aerogel exhibit distinct characteristics, including electrical conductivity and resistance, along with a high internal surface area. This high internal surface area facilitates efficient heat and radiation absorption. Examples of aerogel types include silica aerogel, graphene aerogel, fiber composite aerogel, aerogel alloys, among others.

Aerogel exhibits a low density, boasting an incredibly high porosity ranging from 90% to 99%. Its thermal conductivity is remarkably low, measuring between 0.005 and 0.1 W/m.K. Furthermore, it remains non-reactive with melted metals even at temperatures as high as 950^0C. Additional properties of aerogel can be found in Table 1 below. The thermal conductivity of the composite material, consisting of mineral wool and silica gel, is 0.019 W/m/^{0}K.

Table 1 Properties of Aerogel

Density	0.1g/cm^3
Thermal Conductivity in air	0.016 W/m/°K
Thermal Conductivity in vaccum	0.004 W/m/°K
Young’s Modulus	10^6 - 10^7 Nm^2
Tensile Strength	16 KPa
Thermal Resistance	Upto 500°C

B. *Synthesis of Aerogel*

Aerogel production involves three fundamental steps (Fig. 2): gel preparation, aging of the gel, and gel drying. Silica aerogel is synthesized using the sol-gel process, and the term "aerogel" refers to the dried-out gel filled with air. If alcohol were used as the filling, it would be called "alcogel," and if water were used, it would be termed "aquagel." The sol is derived from a silica-based solution, and gelation is induced by the addition of a catalyst. Aging is a process utilized to reinforce the gel structure before the drying process, minimizing shrinkage. Lastly, gel drying is performed to remove the liquid and create a porous gel, requiring special conditions to prevent its collapse during the drying phase. Generally, aerogel is formed by drying a gel preparation at high temperatures, and the liquid part is removed via a process known as "supercritical drying."

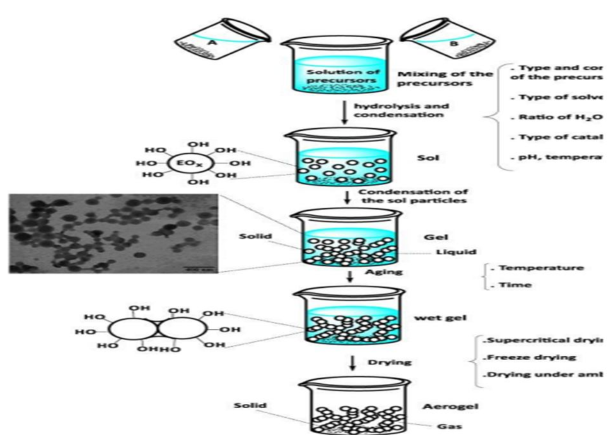

Fig. 2 Steps of production of Aerogel

C. Lunar/Martian Concrete

Aerogel can be effectively incorporated as an aggregate in lunar or Martian concrete, enhancing thermal insulation properties. Lunar regolith serves as an efficient radiation shielding material, and when combined with aerogel, one of the best thermal insulators, it becomes a perfect match. In space missions, mass is a valuable resource, and aerogel's application is advantageous not only due to its exceptional properties but also its cost-effectiveness.

III. THERMAL INSULATION

We will first calculate the thermal resistance of moon and mars before proceeding with heat transfer calculations. We know that, $kaerogel$ = 0.004W/m.K And assuming, L = 0.03m.

A=1 sq.m

Thermal resistivity is given by:-

$Rtaerogel = L/kaerogel.\,A$

$\therefore Rtaerogel$ = 0.03 0.004 × 1

$\therefore Rtaerogel$ = 7.5 K/W

The thermal resistivity value of aerogel remains consistent for both the Moon and Mars, as it represents the material's resistance to heat. To assess its performance, we will compare the thermal resistivity of aerogel with conventional thermal insulators like fiber-reinforced plastics, which have a thermal conductivity ranging from 0.18 to 0.3 W/m.K. It is worth noting that thermal conductivity is inversely proportional to thermal resistivity, meaning that lower thermal conductivity results in better thermal resistivity. Therefore, considering the lower thermal conductivity values of aerogel compared to fiber-reinforced plastics, we can infer that aerogel provides superior thermal resistivity.

We know that, thermal resistivity is given by:-

$Rtplastics = L\,/kplastics.A$

$\therefore Rtplastics$ = 0.03 0.18 × 1 (Keeping the dimensions same for comparison of resistivity)

$\therefore Rtplastics$ = 0.16K/W

Upon conducting calculations and comparing the thermal resistivity of both materials, we discovered that aerogel exhibits 47 times higher thermal resistivity than the commonly used fiber-reinforced plastics employed for thermal insulation in our daily lives. In space applications, Mylar sheets are utilized, such as in spacesuits, to provide thermal insulation. Therefore, it is essential to assess the performance of both aerogel and Mylar sheets by conducting a comparison while keeping the dimensions constant for accurate evaluation.

We know,

$kmylar$ = 0.14 W/m.K

$Rtmylar = L\ kmylar.A$

$\therefore Rtmylar$ = 0.03 0.14 × 1

$\therefore Rtmylar$ = 0.21 K/W

After comparing the thermal resistivity of Mylar and aerogel, we have determined that aerogel exhibits 36 times greater thermal resistance than Mylar sheets typically used in spacesuits. This implies that aerogel surpasses other materials as a superior insulator, providing enhanced resistance for the same dimensions. Utilizing aerogel in extraterrestrial thermal applications can lead to significant mass and volume savings when transporting materials into space.

Next, we proceed to calculate the heat transfer across lunar and Martian habitats, considering aerogel as a primary layer. For the lunar regolith, the thermal conductivity ranges from 0.9 × 10^-5 to 1.6 × 10^-5 W/cm K for the upper 2 cm, increasing with depth due to rising density and reaching 1.4 × 10^-4 W/cm K at 49 cm[1]. Taking the median value of "k" for lunar regolith as 12.5 W/m.K, and considering an area of 1m^2 with a thickness of 3cm (0.03m), the interior habitat temperature is targeted to be 22^{0}C. Lunar temperature varies from 127^{0}C to -173^{0}C from day to night, respectively. We will calculate the heat transfer during a lunar day.

$Qday = K.\,A.\,\Delta T$ /L

$Qday$ = 0.04 × 1 × (127 − 22) 0.03

$\therefore Qday$ = 140 W

Now, heat transfer during a lunar night is give by;

$Qnight = K.\,A.\,\Delta T/L$

$Qnight = 0.04 \times 1 \times [(22 - (-173)]/0.03$

$\therefore Qnight = 260\ W$

Consequently, the heat transfer for a 1 sq.m area layer of fiber composite aerogel with a thickness of 3cm amounts to 140W during a lunar day and 260W during a lunar night. As for Mars, the highest temperature range recorded is approximately -125^{0}C to 20^{0}C, and the interior habitat must maintain a temperature of 22^{0}C. Heat transfer between the habitat and the higher temperature of the Martian atmosphere can be calculated using the following method.:-

$Qhot = K.A.\Delta T/L$

$Qhot = 0.04 \times 1 \times (22 - 20)/0.03$ -(The dimensions are kept constant for the aerogel composite sheet)

$\therefore Qhot = 2.67\ W$

The heat transfer for the cold martian temperature is given by:-

$Qcold = K.A.\Delta T/L$

$Qcold = 0.04 \times 1 \times [22 - (-125)]/0.03$

$\therefore Qcold = 196\ W$

As a result, the heat transfer for a 1 sq.m area layer of fiber-composite aerogel with a thickness of 3cm amounts to 2.67W for a high surrounding temperature and 196W for a low surrounding temperature on Mars.

IV. RADIATION PROTECTION

Numerous experiments in the form of simulations were conducted using the Geant4 software, producing encouraging and enlightening results. When we subjected Aerogel (SiO_2: 62.5%; H_2O: 37.4%; C: 0.1%) to one lakh cosmic radiation particles, it consistently showed a total energy deposition of 29,589.615 keV (Entries: 7935; Mean: 3.729) from 0.1cm to 45cm. However, slight deviations were observed for 0.002cm and 0.02cm, with energy depositions of 29,626.416 keV (Entries: 7947; Mean: 3.728) and 29,558.358 keV (Entries: 7933; Mean: 3.726) respectively, indicating that Aerogel allowed the entry of approximately 7938 particles out of one lakh particles bombarded. This suggests that Aerogel could be a promising material for radiation protection, although further simulations and studies are required for robust conclusions.

Additionally, we explored other studies conducted by Harvard, which revealed that aerogel effectively blocks all UV rays while permitting visible light transmission, facilitating essential processes like photosynthesis. We have included all the simulation data obtained by exploring various widths of aerogel.

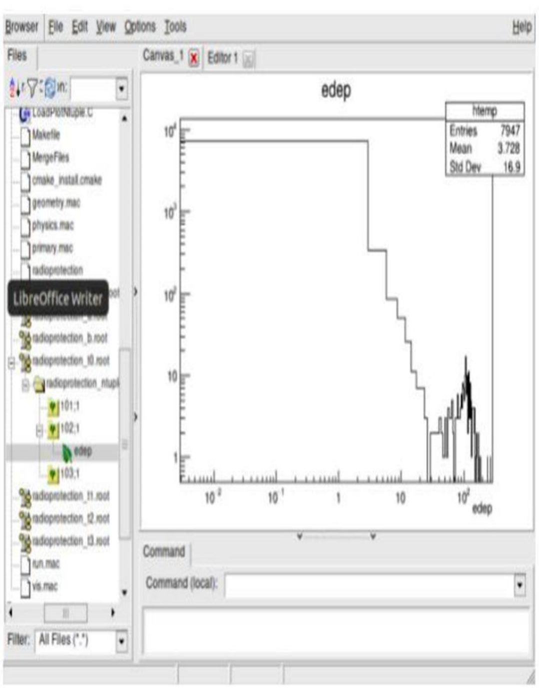

Fig. 3 Geant4 Simulation for 0.002cm Aerogel bombarded with cosmic radiation

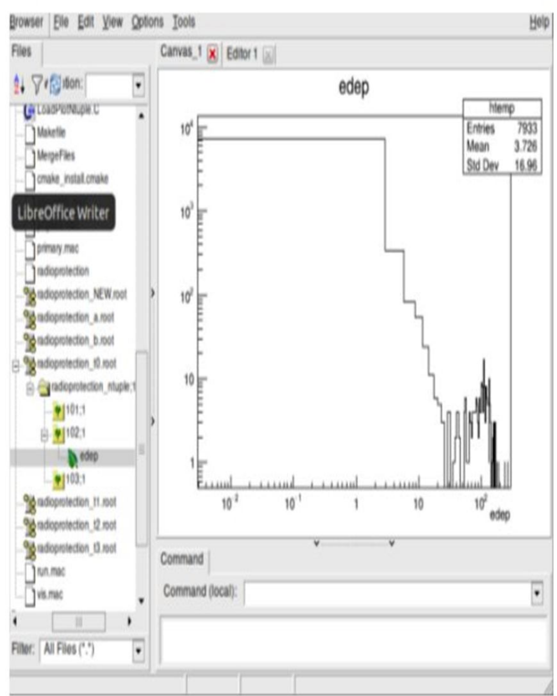

Fig. 4 Geant4 Simulation for 0.02cm Aerogel bombarded with cosmic radiation

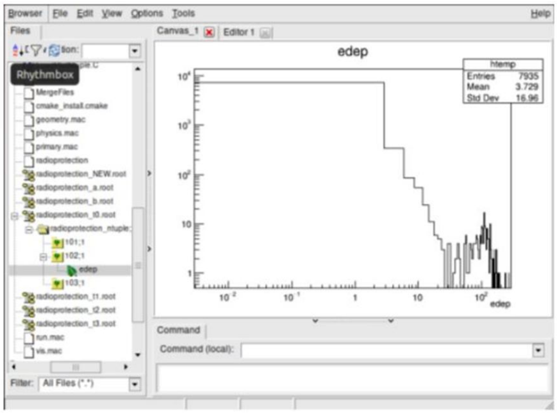

Fig. 5 Geant4 Simulation for 0.1cm Aerogel bombarded with cosmic radiation

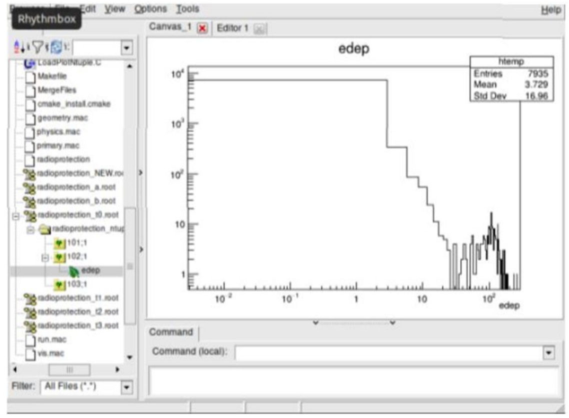

Fig. 6 Geant4 Simulation for 1cm Aerogel bombarded with cosmic radiation

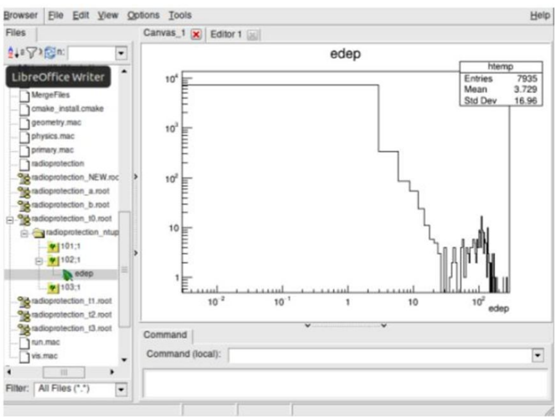

Fig. 7 Geant4 Simulation for 2cm Aerogel bombarded with cosmic radiation

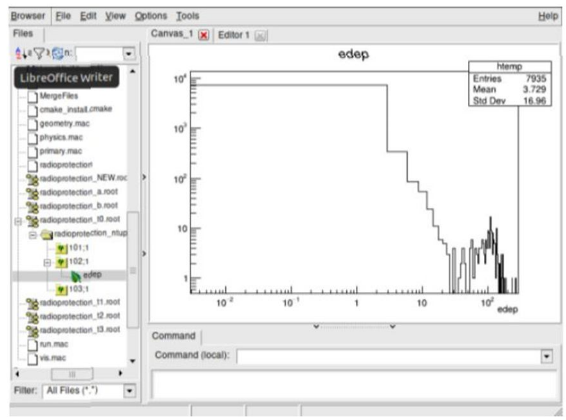

Fig. 8 Geant4 Simulation for 3cm Aerogel bombarded with cosmic radiation

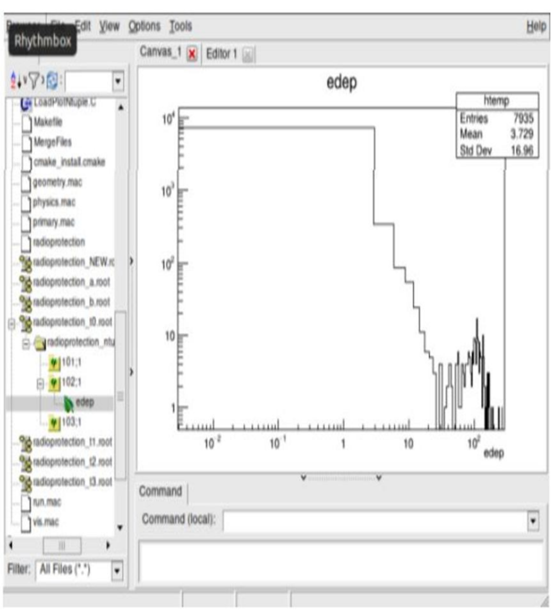

Fig. 9 Geant4 Simulation for 4cm Aerogel bombarded with cosmic radiation

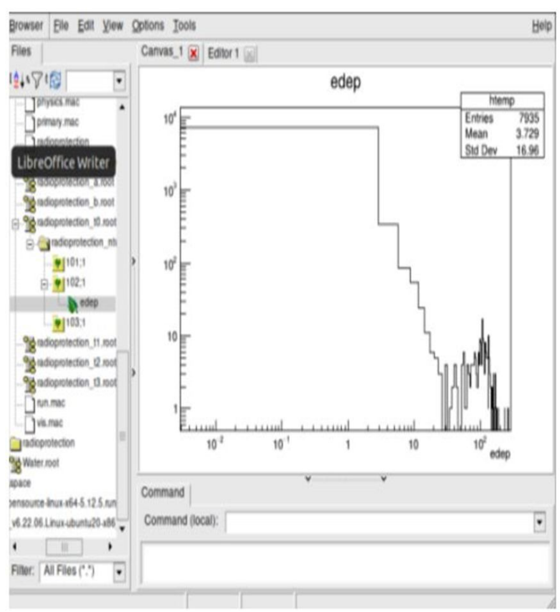

Fig. 10 Geant4 Simulation for 5cm Aerogel bombarded with cosmic radiation

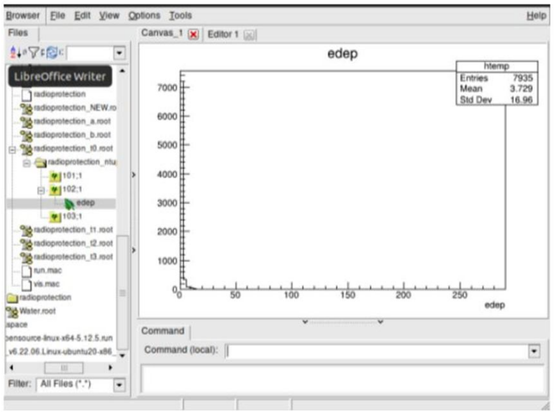

Fig. 11 Geant4 Simulation for 15cm Aerogel bombarded with cosmic radiation

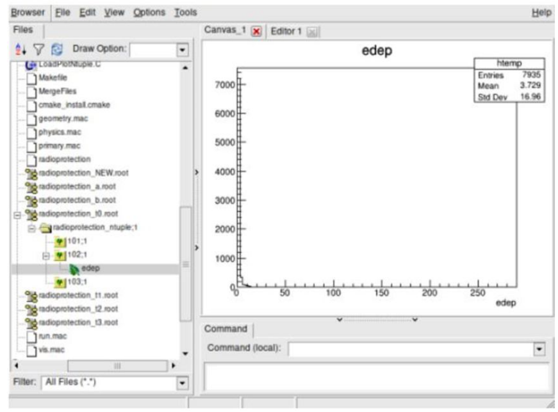

Fig. 12 Geant4 Simulation for 45cm Aerogel bombarded with cosmic radiation.

V. SILICA AEROGEL FOR WINDOWS ON HABITATS

The transparency of aerogel plays a critical role in scattering light through it. High solar transmittance can lead to elevated indoor temperatures during summertime, even in colder climates, necessitating solar shading and enhanced venting[3]. Due to their exceptional thermal insulation properties and optical transparency in the visible spectrum, aerogels have been proposed for use in double plane windows[2]. However, the decision to incorporate windows in extraterrestrial habitats remains a significant concern. Providing windows not only increases radiation exposure risks for astronauts but also impacts habitat design. For instance, it is challenging to install windows in inflatable habitats. On the other hand, rigid habitats built on the Moon or Mars could accommodate separate arrangements for attaching windows during construction. Among known materials, monolithic silica aerogel stands out for its unique combination of high solar and light transmittance, as well as low thermal conductivity, enabling the possibility of achieving net energy gains during heating seasons[3].

To address psychological needs, it is essential to include windows in the habitat design, as they offer a sense of relief by allowing occupants to observe their surroundings and experience Martian or lunar sunrises and sunsets. These windows should be multi-layered, with silica aerogel being suitable as the middle layer due to its translucency and ability to partially transmit light. Additionally, an outer layer of laminated glass is necessary to prevent dust particles from passing through and to provide robust support to the brittle aerogel layer underneath.

The 99% porosity of aerogel contributes to its excellent thermal insulation and radiation protection properties. Consequently, translucent aerogel windows offer a valuable source of light without compromising on radiation safety and providing efficient insulation.

VI. AEROGEL FOR SETTLEMENT ON OTHER PLANETS

Mars presents a challenging and inhospitable environment, and NASA's findings suggest that terraforming the entire planet may not be feasible. However, Harvard researchers have explored the possibility of transforming specific portions of Mars. They demonstrated that using tiny layers of silica aerogel could potentially warm the surface, block harmful UV rays while permitting visible light, and create a zone where water remains in a liquid state, allowing for photosynthesis and plant growth. While Mars once supported life in a lush, aquatic environment, the current Red Planet is a desiccated landscape, with water mostly confined to polar ice caps or underground saline lakes. The thin atmosphere offers little protection from extreme cold and harmful UV radiation from the Sun.

VII. CONCLUSIONS

Based on our analysis of simulations and research data, we firmly establish that aerogel serves as an excellent thermal insulator and holds great potential for thermal insulation in moon and Mars settlements. Its remarkable feature as one of the lightest thermal insulating materials makes it highly suitable for extraterrestrial applications. Moreover, we observed its effectiveness as a cosmic radiation shield, but it proves to be an exceptional UV radiation shield, making it particularly advantageous for Martian settlements. The ability to block harmful UV radiation while allowing visible light transmission adds to its value for future human habitats on Mars.

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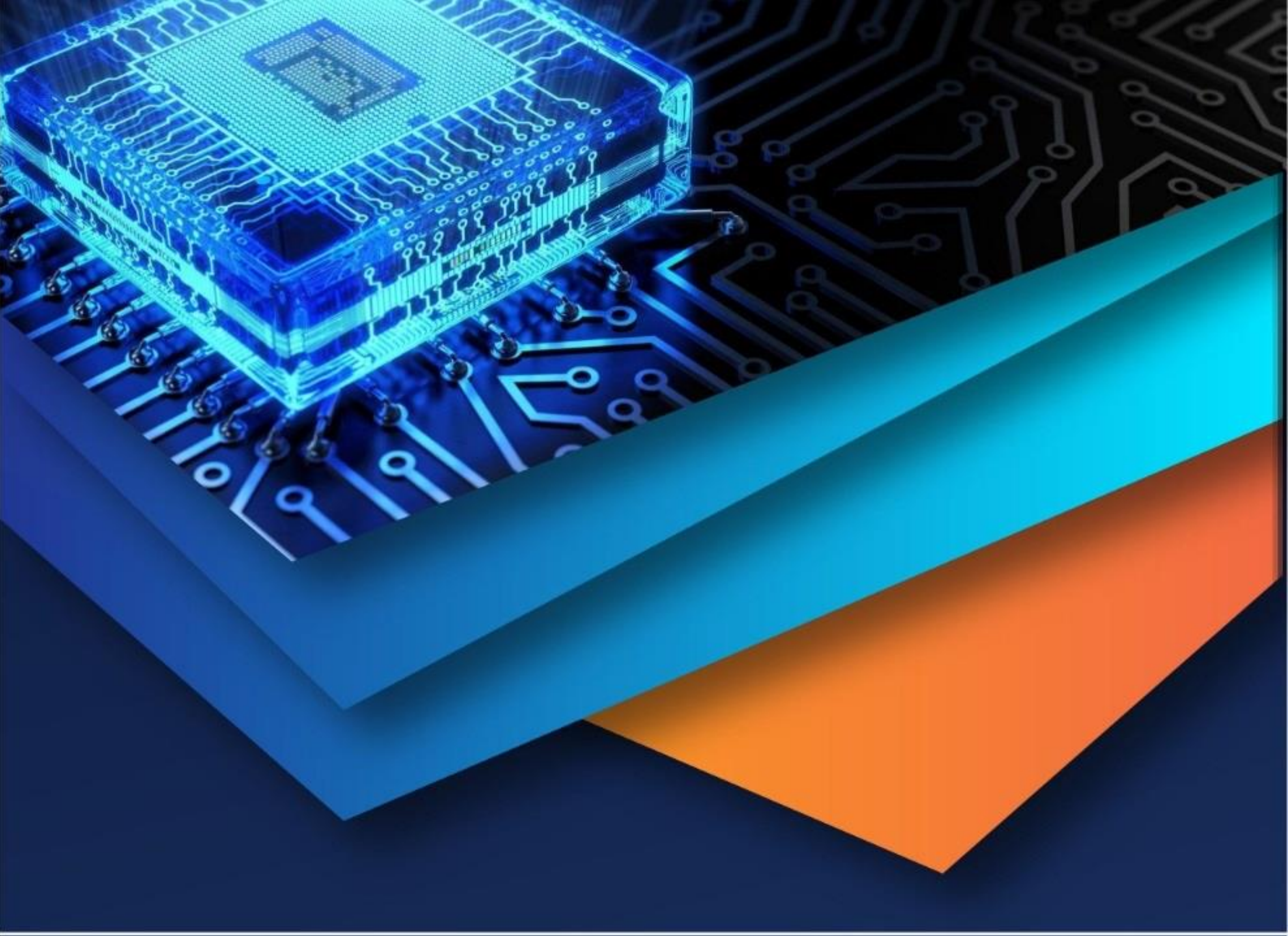

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