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Spirited Skies Project: Silica Aerogel Domes for the Habitat of the Future

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Abstract

The hypothesis of this paper is the examination of dome constructions using the space technology nanomaterial silica aerogel as insulating material. Silica aerogels are nanomaterials with excellent thermal insulations properties because 99.98% of their volume can be pure air. Insulation's origin is the Latin insula 'island', an "isolated land" we could say. Planet Earth is a "space island", in other words an oasis enveloped by its atmosphere: a layer of gases named sky surrounds our planet and protects life from genetic damage by ultraviolet solar radiation. By imitating nature -and in order to protect themselves-humans create garments and architectures. The primary function for garments and architecture is to insulate and to protect the human body. Silica aerogels could be considered as the eco friendly "plastic" of the 21st century because they can find application in any field. As aerogels are phenomenal energy savers they could be the paradigmatic materials for designing the insulation for future sustainable space habitats. Aerogels represent one of the most promising materials for thermally insulating buildings of the future, since the material demonstrates high performance, exhibiting thermal conductivities of 10-20 mW/(mK) in insulated, commercial products not used in a vacuum. Aerogels, when manufactured, can exhibit varying degrees of opacity, including both translucency and transparency, thereby enabling a diverse variety of applications for insulation in buildings that might require access to daylight or exploit sunlight for energy. Silica aerogel is the material-epicentre of all of the author's multidisciplinary research. During the interactive presentation we will propose the design of small glass domes entitled Spirited Skies and Heaven in a Glass where silica aerogel was poured into jacketed glass beakers and micro clouds were settled in between the glazing. We suggest that the artificial clouds set on the transparent or translucent shell of these future space domes may relieve astronauts of their nostalgia of Earth, our home planet. With the same intention we also propose for a future space mission to utilise water (or wine) glasses with blue and gold skyscapes in double walled glass utensils.

Keywords: Aerogel; Architecture; Insulation; Future habitats; Interdisciplinary; Space art

Nomenclature: T: Temperature (°C); U: Thermal Transmittance (W/m^{2}K); λ: Thermal Conductivity (W/(mK)); SA: Silica Aerogel

Introduction

Sometimes described as "frozen smoke" [1] or as "puffed-up sand" [2], aerogels constitute the lightest insulator among all solids. A revolutionary, solid-state material invented in 1931 by Steven Kistler of California, then marketed in a granular form by Monsanto three years later [3], aerogel has received acclaim not only for its extremely low density, but also for its outstanding properties of both thermal insulation and acoustic insulation. Silica aerogels (SAs) consist of dried gels with a high porosity, a high specific surface area, and a low density. Their structure consists of cross-linked chains of silicon dioxide (SiO_2) with a large number of air-filled nanopores. The size of these pores can range from 5 nm to 70 nm, and they can account for between 85.0% and 99.8% of the aerogel volume [4] therefore, conduction through the solid remains very low. Although the density of aerogels can reach levels as low as 3 kg/m^3, aerogels used in applications for buildings have densities of around 150 kg/m^3 [4]. They also acquire specific surface areas of up to 500 m^2/gm [5]. Table 1 summarizes the physical properties of such a material.

Aerogels combine high optical transparency with very low thermal conductivity (λ [W/(mK)]). The very low thermal conductivity results from a low structural conductivity (λ), a low gaseous conductivity (λg), and a low Infrared Transmission (TIR) [3,6]. The estimation of the overall thermal conductivity of the material by summing all these factors may prove difficult, since a change in the infrared absorbance, for example, results in a change in the structural conductivity [3,6].

Properties	Values	Properties	Values
Density (kg/m^3)	3-350 (most common~100)	Primary particle diameter (nm)	2-5
Pore diameter (nm)	1-100 (~20 on average)	Surface area (m^2/g)	600-1000
Porosity (%)	85-99.9 (typical ~ 95)	Index of refraction	1.0-1.05
Thermal conductivity (W/m K)	0.01-0.02	Thermal tolerance temperature (°C)	500 (m.p >1200)
Transmittance in0.5-2.5µm,3.7-5.9 µm	0.80-0.95	Coefficient of linear expansion (1/°C)	2.0-4.0 × 10^{-6}
Longitudinal sound speed (m/s)	100-300	Tensile strength (kPa)	16

Table 1: Physical properties of SAs.

Solid Properties of Silica Aerogels

Aerogels have many unusual properties for solid materials [3,6].

Insulating properties

The effective thermal conductivity of aerogels depends strongly on

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their apparent density [7]. Superinsulating samples (e.g., λ<0.020 W/mK) can occur only within a short range of densities, usually between 0.10 g/cm^3 and 0.20 g/cm^3 (Figure 1) [3,8]. Commercially available aerogel insulation for buildings has a thermal conductivity between 13.1 mW/(mK) and 13.6 mW/(mK) at ambient temperature [1], and such insulation suffers little effect up to a temperature of 200°C [6,9].

Hydrophilic nature

Aerogels usually contain lots of unreacted silanol groups (Si-OH) on the surface of their porous structure. On the one hand, the presence of these groups makes aerogels very hydrophilic, so that they might spoil rapidly if either liquid water or water vapour comes into contact with the material. On the other hand, these unreacted silanol groups do make aerogels particularly easy to functionalize, since chemicals introduced into the pores of the gel can react with these silanol groups, resulting in the attachment of other chemical groups to the surface of the gel. A non-polar group, such as trimethylsilyl-Si$(CH_3)_3$, might replace these silanol groups, thereby making the resultant aerogel water-proof [10].

Optical properties

Aerogels also have interesting optical properties. Light reflected by aerogel often appears bluish, while transmitted light appears slightly reddened. A monolithic, translucent aerogel in a packed bed, 10 mm thick, has a solar transmittance (TSOL) of 0.88 [6], and treatment by heat can increase this transparency further. Aerogels also have a high transparency in the infrared spectrum, which increases the thermal conductivity of aerogels, especially at higher temperatures. If such transparency is not desired, the addition of isopropanol (or other opacificers) to the aerogel can reduce the transmission of light in the visible range by up to 50% [6].

Acoustic properties

Absorption of sound corresponds directly to the surface area facing the sound. Since aerogels have a very high porosity with a very high specific surface area, they absorb sound waves and attenuate them very easily. Sound travels at lower speeds through monolithic aerogels than it does through air, with measured reduction in speed to values as low as 40 m/s. Non-monolithic, commercial products claim to have a sound velocity of approximately 100 m/s through the structure [4] compared to 332 m/s in air at 0 °C [5]. Granular aerogels can also act as exceptional reflectors of audible sound, making them useful for acoustic barriers. Combining multiple layers with different, granular sizes can result in average attenuations of 60 dB for a total thickness of only 7 cm [6].

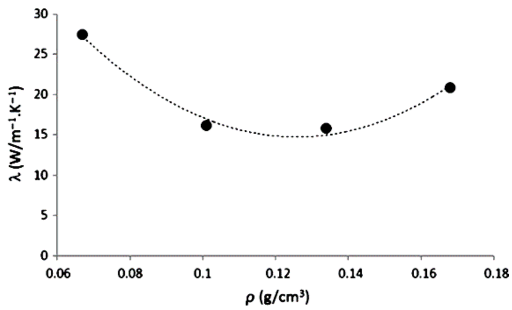

Figure 1: Evolution of the effective thermal conductivity of some monolithic, silica aerogels.

Fire resistance

Aerogels remain generally non-flammable and non-reactive, and commercial products containing aerogels inherit these properties; moreover, aerogel insulation has served as a fire-protecting material, often replacing PET fibres generally used for reinforcement [3,6,11,12].

Types of Silica Products Available to Industry

Monolithic plates

Supercritical drying can produce large, monolithic plates of super-insulating aerogels. Monolithic plates combine very low thermal conductivity with good transparency (Figure 2), so they incite high interest for potential applications that require transparent, thermal insulation (i.e. transparent glazing) [7]. Although supercritical drying allows for the production of crack-free, monolithic plates, the large-scale industrialization of this process for commercialization seems far in the offing [6,12].

Packed granules

Packed beds of granules at atmospheric pressure (or low-vacuum pressure) present effective thermal conductivities slightly better than aerogel plates, largely because of the trapped air between the granules, although the granules themselves have the same values for thermal conductivity as the monoliths [7] (Figure 3).

While considered an elastic material, aerogels (both monolith and granular) have mechanical limitations that do not allow for real flexibility [13] therefore, engineers have developed new composites, such as blanket-types, in which a silica solution gets cast onto an unwoven, fibrous batting. Although the silylated gel cracks during drying, the fibres maintain their cohesion, thus offering the required flexibility. The physical drawback of such aerogel blankets arises from the fact that they often release dust [8].

Aerogel blankets have applications in the aerospace industry, in military cryogenics, in petroleum processing, and in building construction. The low thermal conductivity of the material ranges from 0.017 W/(mK) to 0.04 W/(mK); however, the porous nature of these blankets requires the definition of an effective thermal conductivity in order to optimize their thermal performance [14].

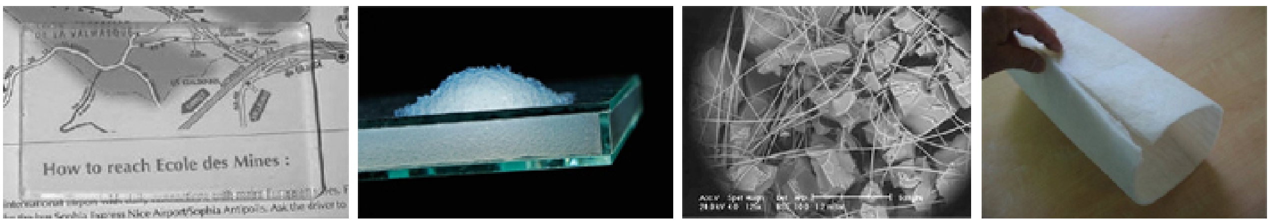

Figure 2: (a) Monolith aerogels [30], with a density of 0.18 g/cm^3 and an effective, thermal conductivity of 0.015 W/(mK) [7], (b) Insulating glass with aerogel in the cavity - Photographer: OKALUX/ Christian Schwab [11], (c) Typical SEM image of an ambient-dried, aerogel-based blanket [7], (d) The blanket seen under the microscope.

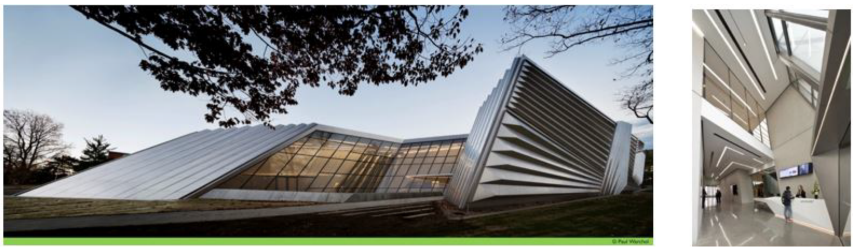

Figure 3: a) Exterior view of the Eli and Edythe Broad Art Museum, b) Interview of the museum.

Aerogel mixtures - Plasters and mortars

Manufacturers have, over the last few years, developed, tested, and patented the thermal, acoustic, and hygrothermal properties of insulation for coating buildings, doing so by adding different percentages of granular, silica aerogels to variable compositions of plaster mixtures for different thicknesses of insulation.

Research demonstrates that such aerogel composites have both the thermal properties and the mechanical properties required to serve as building insulation, with the aim of achieving energy conservation [15,16]. The higher the percentage of aerogel in the mixture, the lower the thermal conductivity achieved. The thermal conductivity of natural plaster represents about 0.50 W/(mK), but by making the mixture consist of 90% granular aerogel, the thermal conductivity of the insulating coating falls to 0.05 W/(mK), and after much development, researchers have reached values as low0.015 W/(mK) [17]. Serina Ng [18] have utilised such aerogels in UHPC formulations so as to create an aerogel-incorporated mortar (AIM). Such mortar (with a volume of 50% aerogel) registers a compressive strength of 20 MPa, while displaying a thermal conductivity of ~0.55 W/(mK). By increasing the quantity of aerogel to a volume of 70%, the thermal conductivity of the concrete decreases by ~20%, but with a sharp decrease in strength to 5.8 MPa.

Builders have expressed interest in using such mixtures of plaster and aerogel, and ongoing research continues to evaluate the performance of these materials in buildings. Wakili [19] have taken experimental measurements after retrofitting the facade of an historic building with FIXIT F222 plaster, mixed with enough aerogel [20] to provide a thermal conductivity of 0.028 W/(mK), and the researchers expect to determine the steady-state of hygrothermal properties for this facade after acquiring data for a year. Ibrahim et al., have tested the WIPO Patent WO/083174 belonging to Aspen Aerogels, which manufactures a plaster containing silica xerogel, used as a thermally insulating coating for the external surfaces of buildings. The addition of such plaster to the exterior surface of an un-insulated building (or a building with internally insulated walls) can significantly reduce, if not remove, the risk of moisture. The plaster also significantly reduces the loss of heat through walls by between 80% and 90% [21].

Aerogels in Industry – Current Practices

Aerogels constitute excellent materials for both thermal insulation and acoustic insulation, with applications in the construction of opaque, translucent, or transparent elements in the envelopes of buildings [4]. Aerogel insulation has two different applications: either as an insulation that exploits only the thermal conductivity of the material, or as an insulation that also exploits the optical qualities of the material (doing so through the use of either translucent, granular aerogels or transparent, monolithic aerogels) [6]. In the first case, builders can deploy aerogel blankets or aerogel plasters to a surface (although the elevated price for these available products does limit their use). In the second case, builders can deploy translucent (if not transparent) aerogels, where a building requires access to daylight or exploits sunlight for energy.

Since the envelope of a building plays a critical role in the consumption of energy by the building, the usage of insulating glass in construction has increased, making critical the technical properties of such glass. Even though protection from sunlight and exploitation of sunlight may seem like contradictory functions, a building may have to cater to both needs simultaneously; therefore, translucent, insulating materials provide an alternative to opaque walls with standard, insulating glass. The aerogel makes possible a kind of thermal insulation that can also harness solar radiation [22]. The high prices for such available products does, however, limit their use by industry.

Applications in Architecture

Eli and Edythe Broad Art Museum in Lansing, Michigan, USA

Designed by Zaha Hadid Architects Office, the Eli and Edythe Broad Art Museum has much more to offer visitors than the metallic grandeur of its exterior. Visitors can enter a three-storey foyer flooded with a soft, warm light made possible by the installation of an elegant, glazed skylight (216 m^2) above the Feature Stair-a skylight that consists of OKAGEL glass panels [22]. The architects have paid special attention to the design of this skylight, which diffuses the incident light evenly, while providing both thermal insulation and acoustic insulation. The skylight meets all these requirements, while maintaining a beautiful appearance, through the use of layered panes of glass, filled with aerogel (Figure 3).

ZAE Bayern Centre for Applied Energy Research in Wuerzburg, Germany

Designed by Lang Hugger Rampp GmbH Architekten, the ZAE Bayern Centre for Applied Energy Research has received support from the Free State of Bavaria and the Federal Ministry of Economy and Technology in Germany [23,24] (Figure 4). The building uses

Figure 4: a) Exterior view of the ZAE Bayern Centre for Applied Energy Research, b) Interior view of the complex.

Figure 5: (a) Exterior view of the Halley VI Research Station in winter, (b, c) The exterior of the central pod, with an interior view of the aerogel glazing.

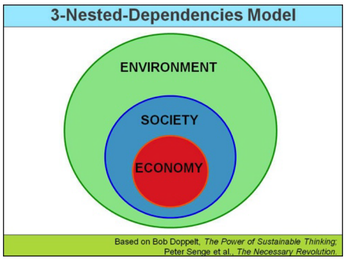

Figure 6: The power of sustainable thinking: How to create a positive future for the climate, the planet, your organization and your life by Bob Doppelt.

innovative, efficient materials in its construction so as to monitor their properties and exhibit their usefulness for the purposes of verifying their application in architectures of the future. The steel structure of the roof, for example, consists of different membranes of material, with a zone of transition between these membranes and the concrete roof. OKALUX has installed into this roof a set of aerogel-filled panels of glass (38 m^2) in order to diffuse the incidental daylight that falls into the interior of the building [25].

Halley VI Research Station at the Brunt Ice Shelf on the Caird Coast of Antarctica

The Halley VI Research Station is an internationally important observatory that monitors the weather on earth and in space, doing so in a polar zone sensitive to climate [26]. Built on the Brunt Ice Shelf, which flows slowly out onto the Weddell Sea, the station stands downstream of a widening crack in the ice, and as a result the station must relocate to a safer site sometime before 2017 (Figure 5).

Halley VI consists eight pods, interlinked in series, with each pod built on skis, making the structure towable by heavy vehicles. The station provides scientists with space for both laboratories and Different layering of glass can result in a reduced thermal transmittance (U) of 0.3 W/(m^2K). In a very hostile environment the Halley base provides the staff there with a little more comfort all year long [26].

Rationales for Superinsulation

Ever since the global crises of oil during the 1970s, the scarcity of fossil fuels has highlighted our economic dependency on resources of cheap energy. The governments of the world have found themselves forced to re-evaluate their strategies for managing the usage of energy [27]. Meanwhile, the rising concentrations of carbon dioxide (CO_2) in the terrestrial atmosphere have begun to affect earthly climate, awakening the public to concerns about the burning of fossil fuels. Our use of technology in a 'voracious,' capitalist economy now poses a major threat to the environmental equilibrium of life on the planet.

Predictions by the International Energy Agency (IEA) indicate that our energy-related emissions of carbon dioxide (CO_2) are going to double by 2050 if we take no decisive action [16,28]. The 2012/27/UE Directive sets a framework for the promotion of energy efficiency in Europe, underlining the need to renovate existing buildings, since this sector of the economy has great potential for conserving energy [21] accommodation.

Temperatures at the site can reach -10°C on sunny, summer days, and typical, winter temperatures fall below -20°C, with extreme lows of around -55°C.

The central module accommodates most of the social areas of the station; therefore, the module consists of a room, double in height, with a large easterly window made of OKAGEL, an insulating shield of glass (72 m^2), with its inter-pane cavity filled with translucent Nanogel®, a noncrystalline solid [27], which offers outstanding degrees of both thermal insulation and acoustic insulation, uniquely combining these features with a high degree of both light transmittance and light diffusion.

Principles of sustainable design can provide comfort for the inhabitants of a building, while minimizing the impact of the building on the environment. These principles exhibit two main 'trends': first, "active design," which exploits renewable sources of energy for meeting the needs of users; second, "passive design," which minimizes wasteful usage of energy through efficient structure in a building. Both principles rely heavily upon the insulation of a building envelope to minimise exchanges of heat with the environment [29].

We have come to recognise the urgency of measures needed to maximize conservation of energy. must apprehend the model of "3-Nested-Dependencies" (Figure 6) a model that not only reflects the symbiotic relationship of our society with our economy, but also their collective dependency upon the environment.

Scientists and industries recognize the potential of aerogels to become an alternative to traditional insulation for buildings, since this robust material combines low thermal conductivity with high luminal permeability. If only we could manufacture aerogel for a fraction of the current cost, this material would conquer the market.

Discussion – Looking into the Future

The last two decades have brought significant changes to the priorities of industrial design, when constructing buildings. In response to the increased cost of energy (due shortages, blackouts, embargoes, and warfare), designers now have increased awareness about the environmental impact of their buildings (particularly in the wake of larming concerns over industrial pollution, resource depletion, and environmental degradation). All architects with vision have come to understand that good design results not only in a beautiful building, but also in an efficient environment.

Silica aerogel represents an innovative material that can provide an alternative to traditional insulations due to its high thermal conductivity and its high luminal transmittance, although the price of the material remains high for industrial applications. Research continues to improve the performance of this insulation, lowering the costs required to produce aerogels [30].

Can we envision our buildings of the future made with aerogels?

In March of 2014, the Chinese company WinSun claimed to have printed ten houses in 24 hours, with the use of a 3D printer, deploying a mixture of pulverized, industrial waste made from glass and tailings [31]. WinSun then demonstrated this technology by building a five-storey apartment block, complete with a villa (1,100 m^2) and decorative elements (Figure 7), at Suzhou Industrial Park.

The architectural firm, Foster and Partners, has joined a consortium set up by the European Space Agency to explore the possibilities of 3D printing [32] for the construction of lunar habitations (Figure 8). The study investigates the use of lunar soil, the "regolith," as building matter. To ensure strength while keeping the amount of "bonding matter" to a minimum, the structure of the shell consists of hollow, closed cells (Figure 8).

Figure 7: 3D printed buildings in China during 2014-2015.

Figure 8: Proposal from Foster and Partners for a 3D-printed, lunar habitation, with a detail from the experimental, cellular structure.

Figure 9: Eden Project, Cornwall, UK.

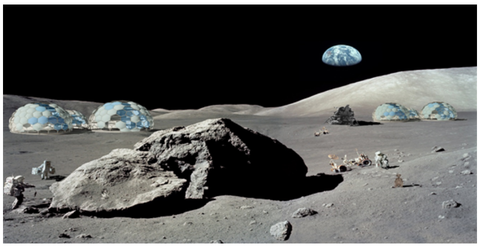

Figure 10: Lunar glass domes "Spirited skies".

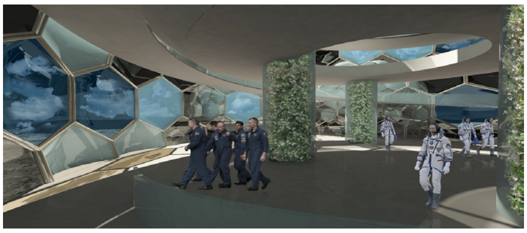

Figure 11: Lunar glass dome's interior.

One could expect designers to add aerogels to the "aggregates" for these mixtures used in 3D printers, doing so in the same way that designers now add aerogels to cements and mortars. One could imagine surfaces made from this kind of transparent concrete, except that instead of optical fibres used in such mixtures today, one could use aerogels for thermal insulation and luminal transmittance.

Highly efficient, insulating systems are going to become increasingly important in the future [33]. Such developments are only going to accelerate in response not only to industrial regulations intended to reduce energy consumption, but also to environmental consciousness intended to reduce resource degradation [34]. Facades filled with translucent aerogels might improve the performance of a building, combining excellent thermal insulation with efficient protection from sunlight. Facades with glazed surfaces in solid walls may well transform themselves into large panels of "translucent skins."

We envision geodesic domes, first developed by Buckminster Fuller in the early 50s and since adopted in innumerable applications such as the Eden Project (Figure 9), as the habitations of the future on Earth, which access daylight through permeable, insulating glazing made of aerogel panels. Such a configuration could have not only a positive influence on the energy consumption of the building, but also on the comfort of its users, since diffused sunlight can improve the wellbeing of people indoors [35,36].

Likewise we envision the architectural form of the geodesic dome as the habitat of human future settlements on the Moon, where this structure could withstand hostile environmental conditions. Apart from serving its functional purpose, the translucent protective shell embodies fragments of the Earh's Sky, clouds as seen in the work of Michaloudis, aiming in the creation of a Earth-like environment for the astronauts. It would be a place nurturing human activities and life as shown in (Figures 10 and 11).

Conclusion

On 1 August 1971, the astronaut David Scott conducted a ceremony at Halley Rille on the surface of the Moon, commemorating the

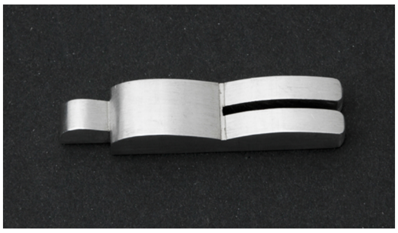

Figure 12: Paul Van Hoeydonck, *Fallen Astronaut*, 8.5 × 3 × 3 cm, aluminium in 1971.

Figure 13: Ioannis Michaloudis, *Bottled Nymph*, silica aerogel, glass, aluminium, photo and copyright Michalous in 2008.

deaths of astronauts during the era of spaceflight by leaving behind an aluminium statuette about the size of a large clothespin (8.5 cm)-a "eidolon" entitled Fallen Astronaut by Paul Van Hoeydonck (Figure 12). By smuggling this artwork to the Moon, the crew of Apollo 15 set a precedent for the artist Lowry Burgess, who later imagined sending to the Moon, a small "museum" entitled Moon Ark—a capsule intended to serve as an archive of miniature artworks, including, among others, etched photos of the aerogel "eidolon" entitled Bottled Nymph by Ioannis Michaloudis (Figure 13).

In the future, a stranded astronaut on the Moon could exploit the architectural principles, described in this paper, to construct a shelter for himself by building ageodesic dome out of the regolith, its skeleton reinforced by the same kind of material found in the artwork by Van Hoeydonck, and then insulated by the same kind of material found in the artwork by Michaloudis. At such a point, the Fallen Astronaut and the image of the Bottled Nymph would themselves reside at home together, protected at last from the ravages of the lunar waste.

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