Inflatable SmartReflectors for Multiple Human Space Exploration Applications

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ABSTRACT

This study examines a flexible and multi-purpose system consisting of wide circular inflatable reflectors that can have both their direction and degree of concave / convex nature finely adjusted. One or more reflectors can be used to concentrate solar energy to provide heat and light for photosynthesis, provide energy for sintering regolith or even carve subterranean habitats with minimal mechanical aid. This system can avoid the considerable wear and tear normally associated with that kind of operation. Investigation of the thermodynamics of a subterranean habitat carved out and heated by reflectors. Improvement of mission robustness should any hardware fail with considerable thermal energy stored in the rock surrounding the habitat.

The reflectors can help improve living conditions to create larger, safer, warmer, brighter and greener environments than conventional habitats, with plenty of fresh food and air via photosynthesis. There remain a lot of challenges facing the reflectors such as micrometeorites, abrasive dust, cleaning and placement. The advantages such as improved conditions for the crew, significant mission cost reduction, increased mission robustness and longevity should far outweigh the cost of meeting challenges. This paper describes the concept of operations of the system such as but not limited to, the position and orientation of the reflectors and the duration of operations. Multiple trade-studies will also be presented to compare this approach to more traditional means of heating and building habitats.

INTRODUCTION

This paper investigates a system centered around versatile inflatable reflectors designed for sustainable human habitation on Mars, a prominent focus in contemporary space exploration. These inflatable reflectors, characterized by their precise adjustability in direction and degree of curvature, perform a multitude of pivotal tasks, including solar energy concentration for heating, lighting, and photosynthesis. In addition, the reflectors can enable and augment energy-intensive processes such as regolith sintering and subterranean habitat excavation with minimal mechanical intervention.

Part one describes what mission or objectives this project is trying to accomplish. The Part two deals with the tool or equipment that is being studied to accomplish the previously mentioned objectives. Part three explains how the tool works. This mission concept's versatility extends beyond Mars, making it applicable to the Moon and various solar system locations exposed to sunlight, broadening its scope for future space exploration endeavors' a reference for the use of Mylar as a reflector in space, in 1996 the 77th space shuttle mission launched a reflective antenna that was inflated from a small satellite, see figure 3 and the paper describing the process and results (Robert Freel, Steven Bard, Gordon Veal; 1999.This mission was a success, but as of the date of writing of this paper, no other experiment/project has used an inflatable focusing Mylar reflector to reflect the Sun, which is an abnormality as Mylar was specifically designed to reflect the Sun.

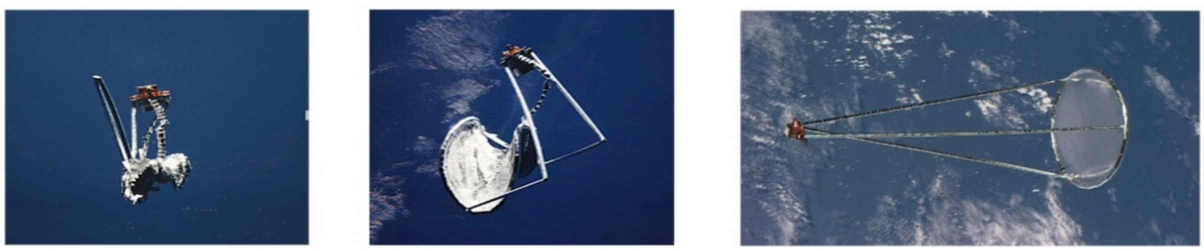

Figure 3. Antenna Inflating after deployment from STS77

PART 1 The Objectives

The primary objective is to design, build, and test an integrated reflector system in space. The additional objectives include:

1. Generate electrical power,
2. Melt basalt rock,
3. Carve a habitat out of a basalt cliff, and
4. Provide light for photosynthesis and crew habitability.

As metrics for determining the success of the Reflector project to meet these objectives, there are seven figures of merit (FoMs). These FoMs are:

1. Cost (economics of development in deep space),
2. Power (kW produced)
3. Mass (the lighter weight the better),
4. Value (kW/kg)
5. Reliability (the robustness and fail-operational/fail-safe design of the system),
6. Crew health and safety and

7. Longevity (another measure of reliability and economics) that supports the permanence of the crew habitat and future human settlement.

Beyond the specific focus on establishing sustainable habitats on Mars, it's worth noting that the principles and innovations we're exploring can have broader applications across the solar system. These principles and innovations apply largely to our Figures of Merit that give us a way to measure Value and mission success.

The Robustness FoM, at its core, signifies the mission's commitment to prioritizing the safety and well-being of those who will inhabit the extraterrestrial habitats. This commitment goes beyond traditional safety measures, focusing on an infrastructure that can endure unforeseen contingencies, including hardware in an extremely hostile space environment. Economy is another pivotal FoM, with the mission aiming to significantly reduce the costs associated with missions beyond Earth. This cost-effectiveness is built on the efficient utilization of available resources, ensuring that every element of the mission contributes to its overall viability and sustainability.

Carving habitats out of solid basalt extends the mission's goals to create inviting and comfortable environments within the extraterrestrial habitats. Beyond mere functionality, the habitats are designed to provide warmth, brightness, and greenery—qualities that contrast starkly with the desolate landscapes of space.

The Longevity FoM encompasses the enduring presence of human settlements in space. This objective speaks to the mission's sustainability, viewing it not as a short-term project but as the foundation for ongoing human exploration and habitation in space.

PART 2 The System

This system comprises expansive circular inflatable mylar reflectors that possess the ability to adjust both their orientation and curvature. A reflector weighing just a few Kg can focus many kilowatts of solar energy.

In terms of dimension and output, rearranging the formula πr^2 for the area of a circle, we find the radius of a $10m^2$ reflective circle of Mylar would be $\sqrt{(10 / \pi)}$ which is $\approx \sqrt{3.2} \approx 1.8$m. Due to the inverse square law, solar energy reaching Mars is about half that of Earth at around 500 watts / m^2. So, in the daytime even a 3.6m diameter reflector would reflect approximately 5kW of energy, for a 2.5kW daily average as the sun passes through the sky.

Even very thick heavy duty Mylar weighs just 10g per m^2. So, the reflective Mylar circle inside would weigh only 100g. Reserving a generous 9.9kg for control hardware, our reflector's weight would still only be 10kg.

As the hardware required for this mission is light, it could be delivered to the surface of Mars with existing technology used for example by the Curiosity mission. This would enable this mission to massively reduce transportation costs. After landing, a rover can deploy and inflate the reflectors. A secondary reflector would be required to achieve a much more accurate focal point, depending on whether the reflective Mylar circle may be made to deform parabolically instead of spherically (It is not required to understand these geometric principles to read this paper, though those interested may reference Schiefspiegler telescope designs which use 2 spherical reflectors). In either case the weight and cost above would be similar for either 2 simple spherical reflectors or one modified to deform parabolically. Table 1 compares the mylar reflector with other sources of energy.

Table 1: Power Sources Compared in Value (Watts per kilogram)				
Figures of Merit	**ISS PV Wing**	**Curiosity RTG**	**Kilopower Reactor**	**Mylar Reflector**
Output (kW)	15	0.1	10	2.5
Mass (kg)	1090	35	1800	10
Value (W/kg)	14	3	6	250

The output for the Solar PV (Photovoltaic) system on the ISS has been halved for daily average as well as the Mylar Reflector. The Kilopower and RTG (Radioisotope Thermoelectric Generator) technologies are expensive and unpopular with the public due to their nuclear nature, though offer constant power.

The reflector is over 17 times more effective in terms of power provided per weight, this radically reduces mission cost. One aspect that needs to be addressed in the future is the sporadic nature of the power delivered, indeed this project depends entirely on the presence of a large amount of solar power.

This project uses Rhino and Grasshopper for simulation, two pieces of software that are considered state-of-the-art by computational designers and the AEC (Architecture, Engineering and construction) industry at large. The simulation setup consists of a set of data created for a previous project (Lagarde, Brandić; 2022) and three-dimensional objects that will represent an ideal setup on Mars. This set of data under the .EPW format (EnergyPlus Weather File), represents a collection of multiple weather information coming from Gale crater on Mars. That weather information such as the quantity of radiation reaching the surface, ambient temperature and ambient winds, is imported into Grasshopper.

Those two software then work together to simulate two reflectors at different angles and times in Gale crater, see figure 1 for reference. The receiving surface is slightly angled (33 degrees) to simulate the angle of a theoretical habitat on a flat surface on Mars. Therefore, the light blue area is partially shaded from the sun and only records a small amount of energy, while the colored points represent the concentrated and reflected energy coming from the sun and directed using the Mylar reflectors. The optical properties of the mylar were taken from a previous study (Zoltan Seres, Aaron Galonsky, Kazuo Ieki, Kazuo Ieki 1994). A full shadow was created for reference, the dark gray area casts its shadow onto the large surface and returns a 52.10W/m2 value.

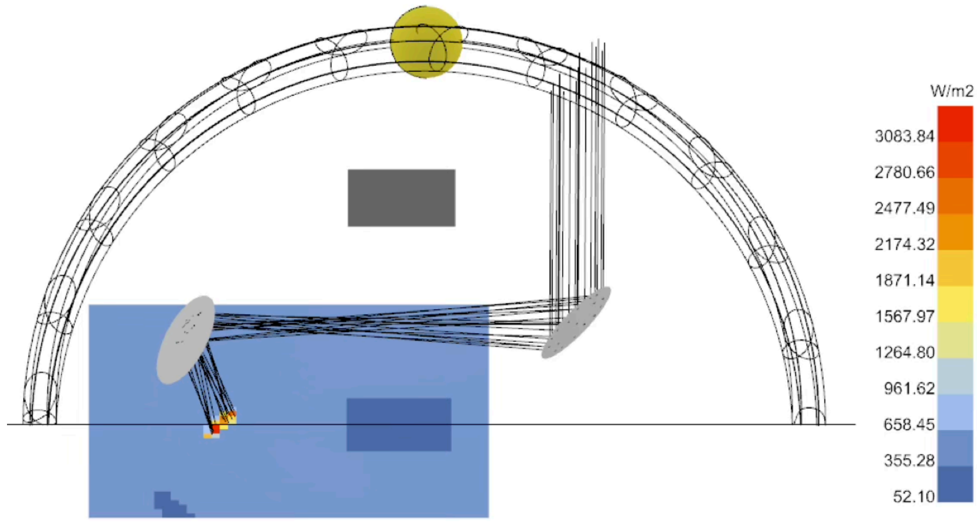

Figure 1. Diagram of the concept of operation (meters and W/m2 showing the arc of the sun in the sky and two reflectors directing the concentrated sunlight to a point of use.

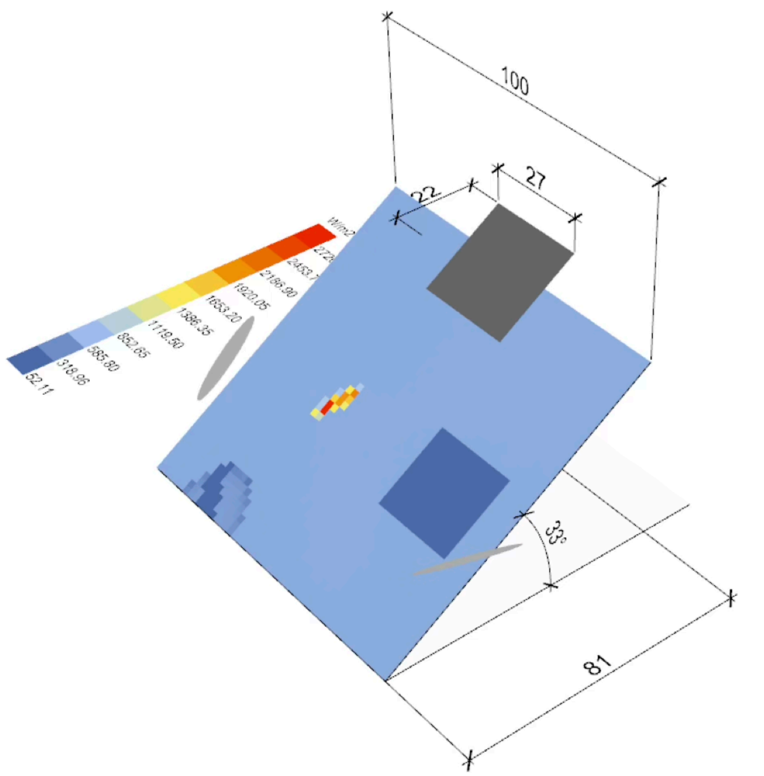

FIGURE 2. Diagram of what?

Depending on the time during a Mars year, the reflectors will adjust their orientation to account for the position of the sun in the sky as seen in Figures 3 and 4 with two different dates but with the same amount of radiation on the blue surface.

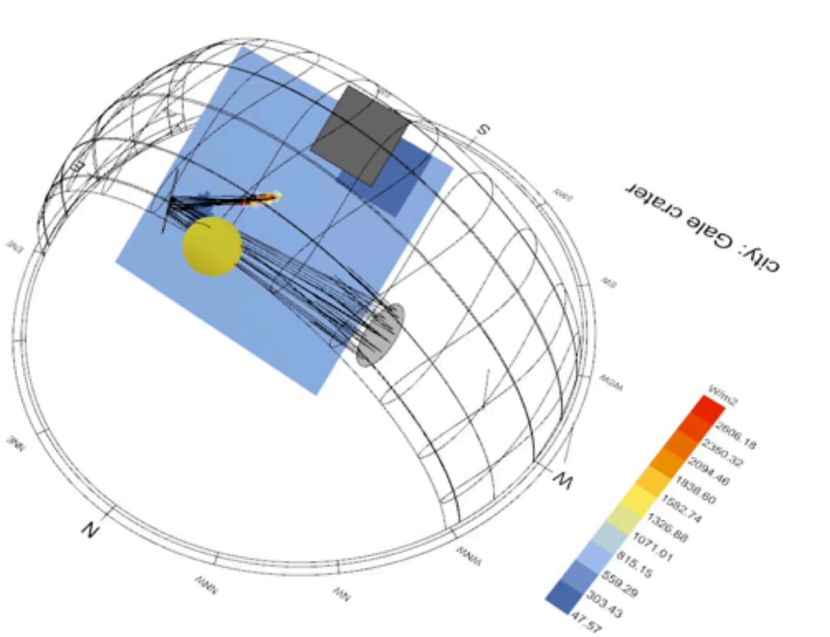

Figure 3. Simulation of month 1, day 12, hour 12 in Gale Crater on Mars

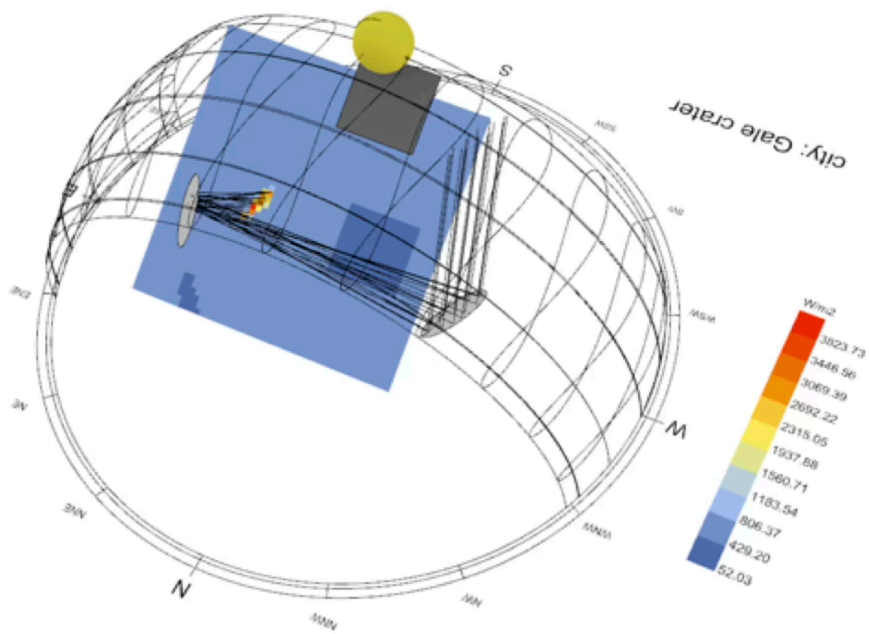

Figure 4. Simulation of Month 6, Day 12, Hour 12 in Gale Crater.

PART 3 The mission

The mission seeks to establish inflatable reflectors as robust tools for an array of functions, including concentrating solar energy, constructing sustainable habitats, and supporting resource production. The mission's resilience in the face of potential hardware issues or environmental adversities hinges on this robustness. To create a large habitat by either carving it out of solid rock with the aid of a rover to remove blocks, or melting together layers of regolith placed by a rover. Afterwards the same reflectors may also heat and light large areas of a habitat through even the smallest and lightest of windows, and later be used to: easily collect subsurface frozen water, provide the energy to produce electricity, oxygen, hydrogen, rocket fuel and to purify water, act as an antenna or maybe even a telescope depth of around 15m of rock is needed in Mars' gravity to match the upward pressure from a habitat containing 1 bar atmospheric pressure underneath, the mechanical effort required to build up that amount of regolith would be considerable. If a habitat could be carved 15m under solid rock, removing that rock would require considerably less mechanical effort. We would select such a butte for its proximity to water.

The Mars environmental conditions require serious consideration. This environment experiences large day/night and seasonal thermal swings, winds and dust storms, and micrometeoroid showers. All these phenomena can do damage to a structure or system on Mars. However, due to Mars' thin atmosphere these reflectors should not deform much even in high winds.

Rock may be carved by focusing solar radiation onto the smallest point possible on the rock, then when it melts dipping an awl into it and drawing it away to produce a solidified strand of rock, which can then be used as the Awl for the next extraction. Equipment should be designed to minimize heat buildup due to the lack of heat dissipation in Mars' thin atmosphere.

After testing, we discovered a far quicker method of carving rock, while still using sun reflected from Mylar, but focusing at a higher concentration. This rapidly heated the outer surface of rock causing it to expand well before the rock beneath, making the outer layers fracture and split off. This method was referred to as exfoliation.

Frank B. Salisbury concluded from experiments that "... only about 15 m^2 plant growth area would be required to provide adequate nutrition to a single crew member if that crew member were willing to eat nothing but wheat! With addition of other crops plus a safety factor, 50 m^2 should be sufficient" (Salisbury, Gitelson, Lisovsky, Martin-Torres; 2015).

Using this metric to calculate the required dimensions of our habitat and the energy required to carve it. We can assume a worst-case scenario of the rock having to be heated to melting point before disintegrating, and take the average equatorial temperature on Mars as -44ºC see reference for basalt thermal properties (Parnell, Halbert; 2022).

MINIMUM PLANT HABITAT VOLUME PER CAPITA:

$\approx 5m^2 \times 25m$
$= 125m^3$

Mars basalt rock thermal behavior:
thermal capacity $C = 0.6$
mass $M = 2{,}900\ kg / m^3$

To heat $1m^3$ by 1ºC

Joules thermal energy equation
$\Delta E = C \cdot M \cdot \Delta T$
$\Delta E = 0.6 \times 2.9 \times 10^6\ j$
$\approx 1.74 \times 10^6\ j$ (Watt-secs)
$= 1.74 \times 10^6 / 60 \times 60 \times 24$ (Watt-days)
$= 1.74 \times 10^6 / 86{,}400$
≈ 20 W days (1000 W days = 24kWh)

To heat $1m^3$ by 1240ºC
$= 1240 \times 20$ W days
$= 25$ kW day

Equations 1: Size and energy calculations for a plant habitat

A $10m^2$ reflector rated at 2.5kW could carve out a cubic meter in 10 days, so the time to carve our entire $125m^3$ minimum plant habitat volume is 250 days assuming a generous 10% of the rock must be exfoliated with only the other 90% being carried away. Of course, this volume will need a window to let the focused sun in. A couple of thick oval sheets of glass as used in our space capsules could seal it. Each would be recessed into holes cut from inside the habitat, the oval shape also allows them to be fitted from outside the habitat by placing them sideways through the smaller holes. Two panes of glass for each window opening would provide redundancy.

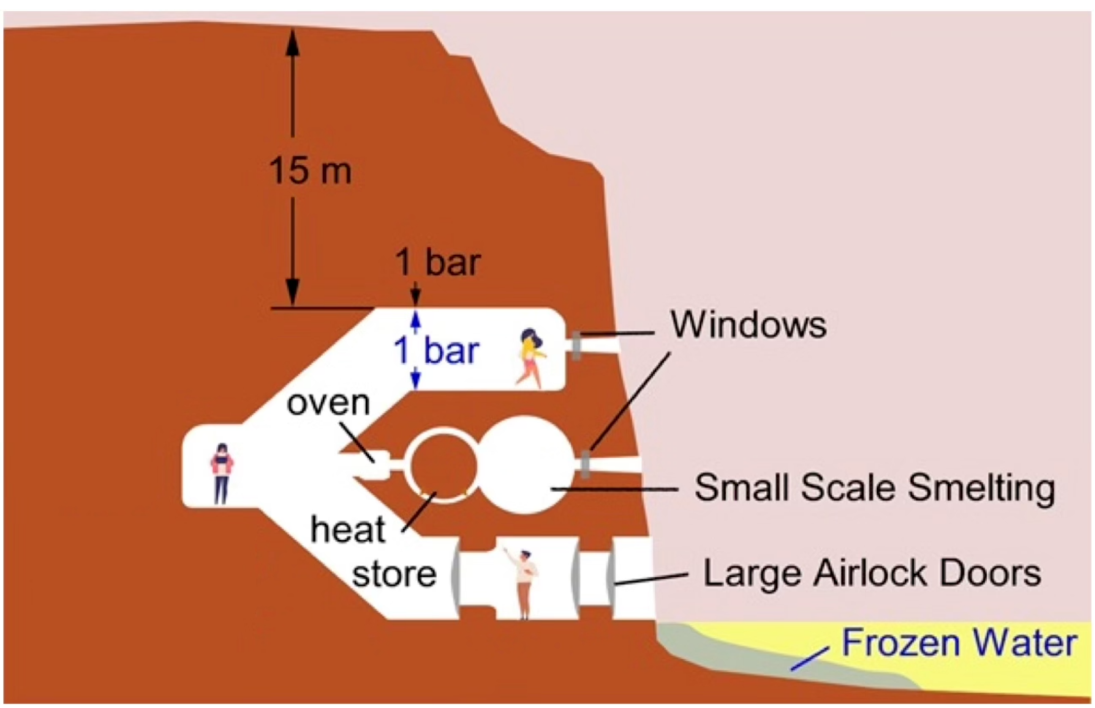

Figure 4: Simple habitat carved in the side of a butte.

Inside the habitat, protruding down from the ceiling behind the window, there should be a wedge shape cut out of the rock, covered in reflective Mylar and shaped to evenly disperse light across the plants. The window could be used to look out of as well of course, to do this 2 distinct recesses cut to the window would be best, one for the wedge above to distribute light, and the other to look out of see figure 4 for an example of an habitat.

For our 150m² of plants per habitant there would only be 40m² max equivalent of Earth sunlight, so all sunlight inside the habitat should be directed towards the plants. It is equatorial sun though and the plants would get more sun in the mornings and evenings than on Earth, plus there's rarely a grey day on Mars. Further testing should show this arrangement to be optimal, otherwise larger or more numerous reflectors to address this wouldn't be expensive.

Previous projects that aim to accomplish the same objectives are usually using Fresnel lenses for focusing sun and melting rocks/dust. Because of Chromatic aberration (the lens bending different wavelengths of solar energy by differing amounts, preventing all the energy from being focused at the same point) Fresnel lenses tend to melt instead of exfoliate rock. Our reflectors do not suffer from chromatic aberration though so we can focus sunlight more intensely for carving rock by exfoliation, or defocus it to melt the rock. Quadrupling our minimal 125m³ plant habitat and adding the extra personal features gave us a new habitat volume of 500m³ per each crew member, so a four-person habitat would now be 2,000m³. Adding a 250m³ shared water section above and a 250m³ shared utility section below for a clean medical area and future larger airlock for a rover, would add another 500m³ bringing the full habitat total to 2,500m³.

This area is 20 times larger than our minimum plant habitat size of 125m³ so it would require 20 reflectors. Assuming these habitat sections are spaced roughly in a sphere which is 75% solid rock for structural integrity, the sphere would be 10,000m³.

TIME TO HEAT

By rearranging the formula for the volume of a sphere ($4\pi r^3/3$) we find the radius of our habitat

$= \sqrt[3]{(3 \times 10{,}000 / 4\pi)}$
≈ 13.4m

The energy to heat our habitat sphere of rock by 60ºC with a natural heat gradient emanating 10m outwards would be ≈ the energy to heat an entire solid sphere of rock with a 5m greater radius (or 18.4m total) by 60ºC. From $4\pi r^3/3$, this larger sphere would have a volume:

$= (4 \times \pi \times 18.4^3 / 3) - 2{,}500$
$\approx 23{,}446$m³.

So, the energy to heat our habitat by 60ºC, changing the -40ºC average to 20ºC inside, is

≈ 23,446m³ x 60ºC x 20 W days
≈ 28,135 kW days

So, for our 20 reflectors at 2.5kW each, totaling 50kW, the time taken to heat our habitat by 40ºC

= 28,135 kW days / 50 kW
= 563 days

Equations 2: Size and energy calculations for crew habitat

Larger reflectors could also be used, so instead of 20 reflectors of 3.8m diameter each rated 2.5kW the mission could have 5 large 10kW reflectors at 7.6m diameter. The final mission will most likely have a variety of sizes, but to simplify calculations we are using 2.5kW 3.8m reflectors.

CONCLUSION

In conclusion, this mission proposal underscores the scientific potential and practical viability of utilizing inflatable reflectors in space exploration missions. The reflectors help make a long-duration human Mars mission feasible. Specifically, the reflector system can assist by generating power, melting and removing basalt, illuminating plants to enable photosynthesis, and enhancing habitability for the crew. By demonstrating the reflectors adaptability and multifaceted utility, we can achieve mission robustness, economic efficiency, enhanced habitability, and enduring sustainability. The concept embodies an innovative approach that has the capacity to significantly reduce mission costs, improve living conditions, and establish a prolonged human presence on sun-exposed celestial bodies.

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