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Energy requirements of a thermally processed ISRU radiation shield for a lunar habitat

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Abstract

The purpose of this study was to establish, on a first principles basis, the order of magnitude of energy requirements for a thermally processed, lunar regolith radiation shield constructed using an in-situ resource utilisation (ISRU) approach. This was done by developing a reference scenario habitat and using thermodynamic relationships and specific heat capacity expressions to determine the energy required to bring such a regolith volume up to sintering temperatures (c. 1,375 K). Once the energy requirements were developed some power system architectures were outlined conceptually and a nuclear power plant of c. 400 kW was suggested as a means to supply the necessary energy. This is well beyond current space nuclear applications. The study concludes that it is likely that the most efficient near-term solution is chemical processing of regolith, from an energy requirements perspective. The technology is also more mature and likely to be delivered on near term projects as it does not require such scaled-up power system architectures. Alternatively, bringing storm shelters up with the habitat to provide a means of weathering major solar events, and adding additional radiation protection to habitat quarters, possibly through a water blanket or similar mechanism, could provide a non-ISRU solution with current technology. However, in the longer term, the development of MW-scale power system architectures (fission, solar etc.), may permit a very large volume of material to be processed thermally for construction material, making a large, permanent human presence on the Moon more easily realisable.

Keywords: In-situ resource utilisation; Lunar habitats; Fission reactor; Lunar exploration; Regolith

1. Introduction

There are two broad families of ISRU construction materials; chemically and thermally processed. Chemically processed materials are typically regolith mixed with a binder or a polymer and require little on-site energy (unless they are heat-cured) (Hintze et al., 2009), but, due to the high mass of radiation shields, the additional binder mass to be brought up can be a significant upmass cost. In addition, there are concerns around maintaining the liquid phase of the binder in pressure and temperature conditions on the lunar surface (Cesaretti et al., 2014) Fig. 1 and Tables 1 & 2 show the scale of the upmass problem for chemically processed regolith. The values for binder content in Fig. 1 were chosen as illustrative of literature figures in Table 1. As shield volume increases, the additional binder upmass required increases linearly and using Cesaretti's (Cesaretti et al., 2014) data on the D-Shape binder ink density of 1,315 kg/m^3, it soon becomes clear that large-scale

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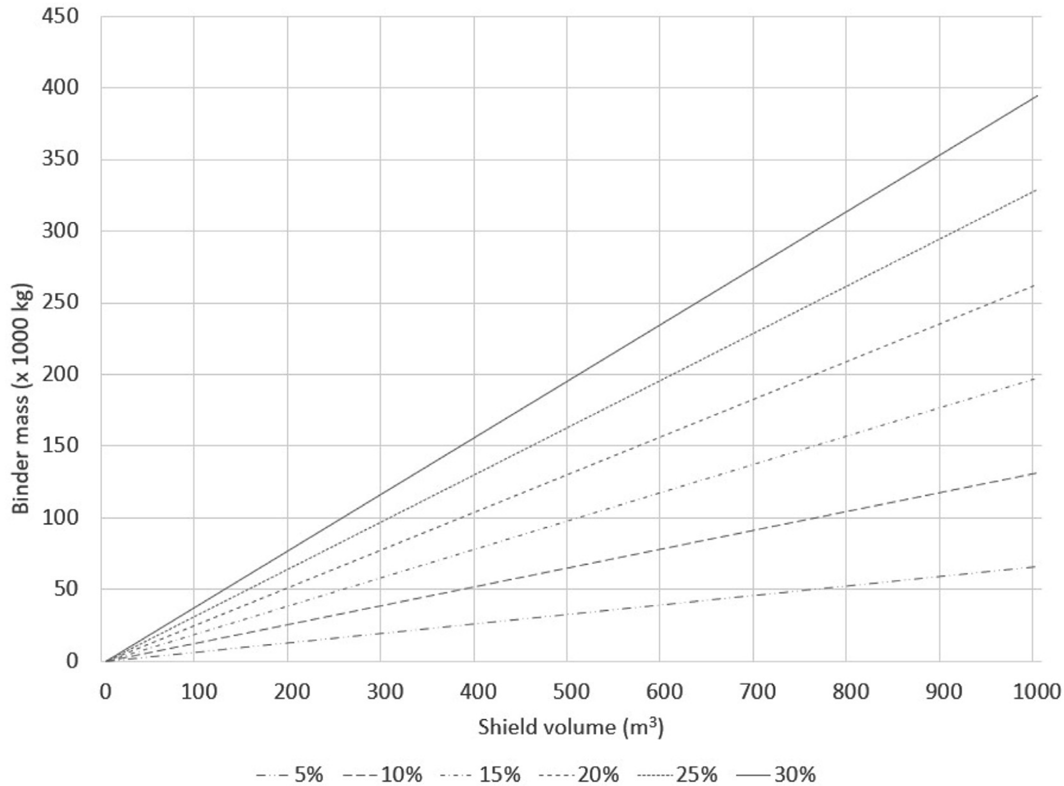

Fig. 1. Additional binder upmass per shield volume increase, using %wt values commonly found across the literature.

Table 1
Summary of literature values for %wt binder.

Paper	Binder type	% wt binder	Notes
Omar, 1993 (Omar, 1993)	Sulphur	25–70	Best mechanical properties at 35 %wt
Toutanji et al, 2006 (Toutanji et al., 2006)	Sulphur	35	Added regolith glass fibres for strength
Bodiford et al, 2006 (Bodiford et al., 2006)	Polymer concrete (polyethylene)	10–50	No data on preferred ratio
Bodiford et al, 2006 (Bodiford et al., 2006)	Polymer concrete (liquid polyurethane)	10–30	No data on preferred ratio or water content
Su et al, 2001 (Su and Peng, 2001)	Dry mix/steam injection (concrete)	13–27.5	No data on preferred ratio or water content
Cesaretti, 2014 (Cesaretti et al., 2014)	3D printing	5–35	Binder is in honeycomb structure, total binder mass dependent on ratio of compacted to uncompacted regolith

habitats will require some binderless process (such as a thermal process). The small reference scenario habitat (Montes et al., 2015) we consider in this paper has a shield volume of around 150 m^3, but scenarios with thicker shielding, greater internal volumes or larger numbers of habitats, will quickly reach unacceptable levels of upmass. For example, using the reference scenario and a shielding level recommended by Silberberg et al. (Silberberg et al., 1985) of 700 g/cm^2, shielding volume becomes 1,000 m^3, which equates to between 100 and 600 additional tonnes of upmass for binder alone. Clearly, given the maximum payload mass of a Saturn V was approximately 50 tonnes, this is not a sustainable practice.

This research provides a simple, robust quantitative analysis of energy requirements for thermally processed regolith radiation shields for lunar habitats. As such, we consider only the energy required to raise the material to sintering temperature and not the energy needed during the sintering process. For heating energy, we use a simple 50% heating efficiency factor to estimate the losses involved in heating. In-situ resource utilisation (ISRU) is a critical element of many forward-looking papers for both crewed and robotic exploration of the solar system. ISRU on the Moon is typically the processing of regolith into usable end products via thermal or chemical processing techniques. This study examines the energy and power requirements for thermal techniques, e.g. sintering of regolith into construction materials. The analysis then works backwards to specify the necessary power system architectures required to meet those energy demands. This is achieved by utilising a hypothetical mission scenario, based on work by Montes et al (Montes et al., 2015), developing a robust concept for the lunar radiation shield, which builds on subject literature, and using the geometry, geotechnical data, and thermodynamic relationships to build an estimate for energy consumption. This energy consumption is then compared with the current and future power system architectures. The analysis presented in this paper is of importance as it sets a lower bound for the energy required to thermally process a regolith shield for a medium-sized habitat, in the region of 500–1,000 kWe, that is well beyond current capabilities for space-based nuclear and solar power systems, dependent on the power source.

Table 1 shows a range of literature values for %wt binder. This highlights the problems associated with the chemical approach to ISRU as there is a significant upmass cost associated with each cubic meter of shielding as many techniques require significant (10–35 %wt) binder contributions to the material. These binders must be launched or possibly created on site, but both options present new payload mass and mission complexity issues.

1.1. The power/launch mass relationship

Table 2 shows launch mass and power requirement for three technologies (thermal data from Section 4.2, sulphur and D-Shape (Cesaretti et al., 2014) data from Table 1) and three different shield sizes; small, medium, and large (100, 200, 400 tonnes of shielding material respectively). D-Shape provides good launch mass at low power, but it can be seen that it scales linearly, but it is also an immature technology reliant on large volumes of water and susceptible to regolith settling which may provide radiation pathways for incident ions, and therefore is not a preferred technology until these problems are solved. Sulphur concretes are very well documented, and they have very large requirements for upmass (35 %wt of shielding material), or require very intensive in situ manufacture of sulphur from regolith, which is complex and high energy process. Thermal processing technologies require only a 1 MW nuclear reactor of around 25 tonnes and no binder launch mass. The high power of a thermal processing technology permits other uses of the reactor for volatile extraction for oxygen and hydrogen – extremely important for a sustainable, long-term presence on the Moon for fuel and life support. Power for the two chemical technologies has been assumed to be low (c. 10 kW) a as there is no large heating requirements and gravity is low.

It can therefore be seen that there are trade-offs to be made, as regards uplift and the size of habitat (and thus volume of material to process), with thermal processing via a nuclear power plant providing better savings in upmass as the size of the habitat increases. Moreover, a 2005 NASA study concluded that a fission reactor would be the best option (even at polar sites) due to the scaling and extensibility for missions to Mars, although their power system analysis was not conclusive due to a number of limiting factors such as the fidelity of the assumptions made. It should also be noted that in the intervening 15 years, the trade-offs with solar may have changed (NASA, 2005). Even as of 2015, studies have suggested revisiting the SNAP-50 reactor designed in the 1970s to power an ISRU plant. This plant is around 11 tons and 35 kWe. However, the study also suggests that siting at the poles could make solar PV a viable option (Isakowitz et al., 2015).

2. Examining the case for a thermal approach

To develop a useful analytical scenario, a baseline habitat scenario was established. The habitat chosen for analysis is based on the one used by Montes et al. (Montes et al., 2015) and is shown in Fig. 2. One addition was made, however, and that was to include an offset of 1 m to permit inspection and maintenance activities. This changes the length of the interior volume (i.e. the volume beneath the shield) to 14.2 m and the height to 5.6 m.

The thickness of the shield will be dependent on material density as the shield's effectiveness is given by the amount of mass per areal unit (g/cm^2), so higher density materials will have the same amount of mass over shorter thicknesses. The shielding effectiveness required is assessed to be 145 g/cm2, which sits between the 99–2,005 g/cm^2 noted by Montes et al. (Montes et al., 2015) and satisfies the micrometeorite protection thickness implied in Cesaretti et al. (Cesaretti et al., 2014).

Using an estimate of 2.54 g/cm^3 for sintered regolith density (Taylor and Meek, 2005), this yields a thickness

Table 2
Launch mass and power requirements for small, medium and large habitat shields.

Technology	Notes	Power (kW)	Launch mass (tonnes) for shield mass: Small habitat shield (100 tonnes)	Medium habitat shield (200 tonnes)	Large habitat shield (400 tonnes)
Thermal	Nuclear power plant, no binder	1,000	25	25	25
D-Shape	~10 %wt binder	10	10	20	40
Sulphur concrete	~35 %wt binder	10	35	70	140

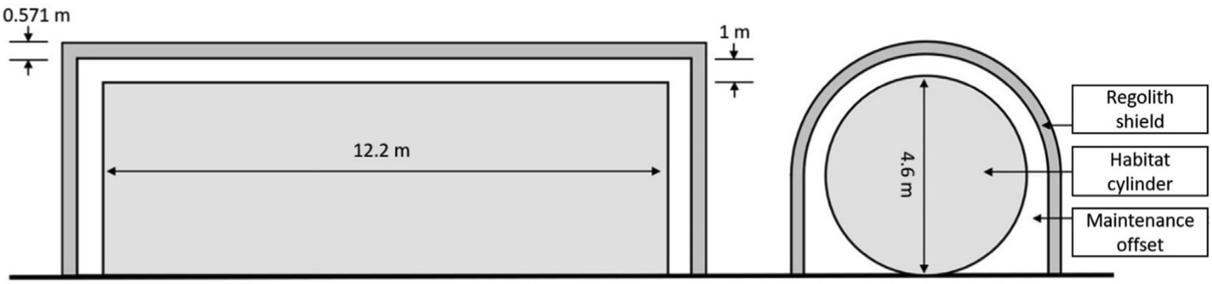

Fig. 2. Habitat design used as a basis for this study [1].

of 57.1 cm. This results in a total volume of shielding material of 173.2 m^3, with a mass of approximately 440.0 tons. This is a significant mass of material to process, and it should be noted that this habitat has a shield of minimum thickness.

3. Energy requirements analysis

A material's specific heat capacity or the amount of heat energy in Joules required to raise the temperature of 1 kg of a material by 1-degree Kelvin, changes with temperature. Colozza (Colozza, 1991) interpolated Robie et al.'s (Robie et al., 1970) work, producing an expression for heat capacity shown in Eq. (1), where C_p is specific heat capacity, and T is the temperature of the material. This expression states the specific heat capacity as a function of temperature, or in other words, more energy is required to raise the temperature of a kilogram of material the hotter it is. The target temperature for this study was chosen as 1,373 K, just below the melting point of regolith (Gualtieri and Bandyopadhyay, 2015; Hintze et al., 2009; Lim et al., 2017; Meurisse et al., 2017; Taylor and Meek, 2005). This has a significant effect on energy requirements, as the value is nearly twice as high at the target temperature than at 100 K, the starting temperature used in this study.

$$C_{p,\mathrm{Colozza}} = -1,848.5 + 1,047.41\log(T) \quad (\mathrm{J/kgK}) \tag{1}$$

Using this expression, it is possible to derive the minimum (i.e., no thermal losses) energy input required to raise this much material from 100 K to a sintering temperature of 1,373 K. Integrating Equation (1) between 100 and 1,373 K, a value for energy requirements was reached of 5.09 $\times 10^{11}$ J. This is equivalent to 141.4 MWh of energy. Assuming a heating efficiency of 50% (Taylor and Meek, 2005), this energy input value becomes 282.8 MWh, which to avoid spurious accuracy, will be rounded to 283 MWh. This equates to an energy requirement of 381 kWh/ton for a thermally sintered regolith component.

Rumpf et al. (Rumpf et al., 2013) used a different expression established using laboratory data from Touloukian et al (Touloukian et al., 1981). The expression is shown in Eq. (2). Using this expression results in an energy requirement of 152.5 MWh, which when applying the 50% heating efficiency becomes 305 MWh, a difference from our result of ~10%.

$$C_{p,\mathrm{Rumpf}} = 1211 - \left(\frac{1.12 \times 10^5}{T}\right) \quad (\mathrm{J/kgK}) \tag{2}$$

Rumpf's expression for Cp plateaus at around 1,100–1,200 J/kgK. For higher temperature sintering processes, this discrepancy will impact the energy requirements significantly, exceeding the 10% difference outlined above. Fagents et al. (Fagents et al., 2010) made use of a static figure for the specific heat capacity of 1,500 J/kgK, which if applied here would result in a significant increase in energy requirements for the low-temperature ranges. Therefore, the choice of expression, or value, of specific heat capacity is important in determining the ultimate energy requirements. Colozza's expression, which results in more substantial energy requirements, was adopted in this study (as opposed to the use of Rumpf's expression) as a conservative assumption.

Table 3 shows the energy requirements per kilogram of thermally processed material (1.37 MJ/kg) against shield effectiveness (in g/cm^2). It shows the scale of the energy requirements as the shield scales up to the 700 g/cm^2 required for acceptable protection from 'gigantic' solar flares, as stated by Silberberg et al. (Silberberg et al.,

Table 3
Energy requirements for reaching sintering temperature for varying shield thicknesses.

Shielding (g/cm^2)	Thickness (m)	Shield volume (m^3)	Shield mass (tonnes)	Energy to 1,373 K	
				J	MWh
50	0.2	46.91	119.2	1.63E+11	45.36
145	0.57	146.2	371.5	5.09E+11	141.4
200	0.79	210.2	533.8	7.32E+11	203.2
400	1.57	485.8	1234	1.69E+12	469.7
700	2.76	1042	2647	3.63E+12	1008

1985). At 700 g/cm^2 of shielding the energy requirements are 1,008 MWh, seven times greater than the requirements for the reference scenario of 145 g/cm^2. Values in this table are before the 50% efficiency penalty assumed for this study has been applied.

4. Power system architectures

Having determined a reasonable estimate for the heating energy requirements of the lunar habitat protection cover, this paper presents an analysis of potential power system architectures to deliver the required energy. Given that the habitation module will need to be in place prior to fabricating the shield, a short build time is necessary to reduce the chance of micrometeoroid damage in the interim period. For simplicity, this has been assumed to be 30 days, although Fig. 3 shows the effect of longer build times on power system architectures. Applying the efficiency penalty of 50%, 141.4 MWh becomes 282.8 MWh. To deliver this energy in 30 Earth days (720 h), requires approximately 390 kW of power generation at a load factor of 100%.

Fig. 3 shows how the power requirements will change based on the build construction time of the radiation shield and the thickness of the shield. The power system requirements are very sensitive to the build time, especially when build time gets shorter. This means that the primary drivers of power system requirements are shield thickness (driven by the desired shield effectiveness) and the maximum build time. The rest of this section will examine what this means in terms of nuclear, concentrated solar sintering, and solar PV architectures.

4.1. Solar power at the equator and the poles

Solar-sintering, effectively the capture and concentration of sunlight for the selective sintering of regolith laminae might be one avenue to avoid the electrical efficiency penalties inherent with other techniques. Current processes usually make use of a Fresnel lens to concentrate solar power and the movement of the feedstock material relative to the focal point to build layers of sintered material. We can consider this as unfeasible due to (i) the small size of hotspot, which significantly impacts the build time for large components and (ii) the poor resolution of the technology. The only feasible way to deliver MW-scale concentrated solar power terrestrially is the use of mirror-tower assemblies. Solar irradiance at an average of 1 AU is 1.361 kW/m^2 (McCluney, 2014), so to capture 390 kW with a mirror of reflectivity of 95% (Stoica et al., 2017), such as aluminium, would require a mirror with a surface area of around 300 m^2. This mirror would require a vibratory mechanism (Stoica et al., 2017) to periodically remove dust and need to be scratch resistant to minimise the ageing of the mirror in an environment where activity and electrostatic charges can agitate the dusty regolith. However, due to the day-night cycle on the Moon, the time available is halved,

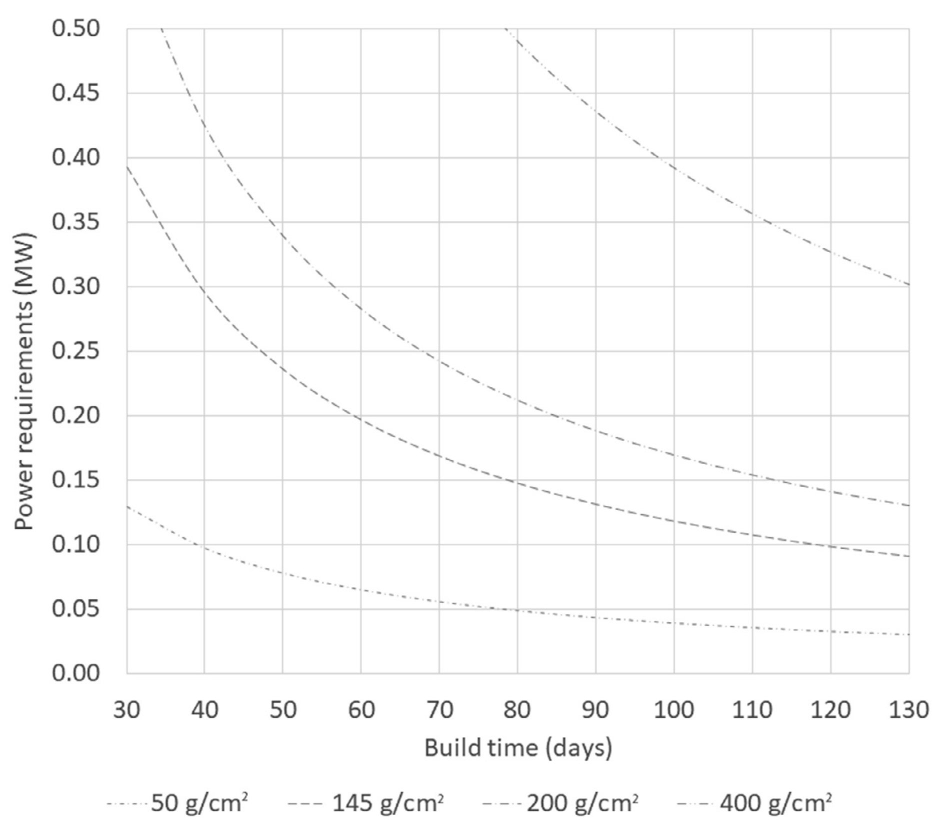

Fig. 3. Power requirements per shield thickness, as build time increases.

doubling the power requirements, i.e. 780 kW (for the same build time), so that the actual area needed is 574 m^2.

The use of concentrated solar sintering, such as proposed by the Regolight ESA project (Urbina et al., 2017), would require a major scaling up of extra-terrestrial solar collection technologies to deliver 780 kW of power. It should also be noted that current regolith 'spot sintering' method produces components with poor dimensional precision and reproduction capacity. This is a major problem for radiation shields as this poor accuracy leads to radiation pathways between shield elements, negating some of the effectiveness of the shield. This would need to be overcome before it could be considered a viable option.

An ambitious polar base concept for providing near-constant MW-scale power was developed by Stoica et al. in 2017 which detailed the use of large reflectors positioned on, or near, crater rims at the south pole reflecting light for process heat (Stoica et al., 2017). These reflectors would be mounted on 100 m tall towers and be 40 m in diameter, well beyond current construction capabilities. For electrical power it implies the use of PV panels instead of reflectors mounted on towers high enough to receive light for 99% of the time. These panels for 2 MW are expected to be roughly 4,000 m^2, which brings substantial engineering challenges, similar to those outlined in the below.

Solar PV, particularly on the Moon's equator, would benefit from the absence of atmosphere that is contended with in terrestrial applications, but would need to be sized to produce 780 kW. Using NASA's Juno spacecraft as an example of state of the art solar panels for space, where 60 m^2 produce 14 kW at 1AU from the Sun and weigh 340 kg (Beauchamp et al., 2015), it is possible to extrapolate a power to size ratio of 0.233 kW/m^2. To generate 780 kW of power with such a ratio, PV panels covering a space of 3,348 m^2 are necessary, or a square field of 58 m along both sides. The mass of such a power system would be approximately 20 tons.

Solar PV requires a complex field of PV panels resistant to the aggressive particle flux on the Moon, and a regolith sintering furnace capable of delivering 780 kW of heating power over 15 days, a significant increase in heating technology as opposed to a nuclear option, needing 390 kW over 30 days.

Where the habitat is based at the southern pole, there are areas with access to long periods of solar irradiance, around 80% of the time. This results in a power requirement of 487.5 kW, which is more palatable from a upmass perspective, but still large at around 12.5 tons. The main difficulty associated with this approach is siting, as the low angle of the sun will create very long shadows behind the each panel, leading to their deployment in a long line, perpendicular to the angle of the sun. Assuming an area of 2,092 m^2 and a panel height of 2 m, the length of this line of solar panels would be in excess of 1 km, which adds serious complexity in terms of cabling, access, maintenance and siting.

4.2. Nuclear power

Given that the state of the art in space-qualified reactors is NASA's prototype KRUsTy 1 kWe unit, developing a reactor with nearly 500 times the electrical power is significantly beyond our current capabilities. The primary issues with such a reactor would be the low efficiency of the Stirling engine power conversion mechanism, topping out at around 23% (Mason et al., 2013). Since it is not possible to use a steam turbine, due to corrosion and maintenance issues, alongside the issue of complex, heavy moving parts, current systems use a Stirling cycle, which has a comparatively poor conversion efficiency but is improving. The thermal energy from the reactor is not sufficient as the sole provider of heat, as the heat pipes and Stirling engines maximum operating temperature is around 1,000 K (Mason et al., 2013), several hundred degrees less than is required. Although it should be noted that it could be used to provide pre-warming to the feedstock up to those temperatures, and then rely on electrical power for the final heating stage. However, if KRuSTy's thermal power output is only 4 kWth, then this is still 125 times less than needed.

With regards to mass, NASA's next step in the KRUsTy program is to develop a surface mission concept of approximately 10 kWe, with a power to weight ratio of 5 W/kg (Gibson et al., 2017). Assuming some learning effect, it might be possible to achieve 10 W/kg or more with a larger reactor. Working on this basis, the mass of a 390 kWe reactor would be around 46.5 tonnes. However, Los Alamos National Laboratory (LANL) is working with NASA on their KiloPower project and are envisioning a MegaPower concept for use on Earth. This concept produces 2 MWe and 5 MWth and is designed to fit inside a standard shipping container for transport by road, rail or sea (Tyler, 2018). Assuming road transport, and using the maximum weight of most articulated lorries of 44 tonnes, leads to a specific power of 45.5 W/kg, ten times higher than KiloPower. Using this specific power, a 390 kW reactor would weigh 8.6 tonnes, comparable with the solar PV system. However, it should be noted that the heat rejection system proposed for MegaPower involves an open Brayton cycle, which would not be possible on the Moon as there is no atmosphere or readily available coolant fluid in situ. We also note that there is work being undertaken to design nuclear thermal proulsion reactors,such as DARPA's DRACO project United States Government, Office of the Under Secretary of Defense, 2020, but we do not consider modified versions of those systems here.

Even with a fission reactor as a power source, that the conclusion is that delivering the power system architecture for thermally processing regolith radiation shields is not within current technical capabilities. Before fission power systems can be scaled up to ~MW scale, there are a number of technical barriers to be overcome on the journey to such a power plant. First it will be important to increase the efficiency of the heat-electricity conversion cycle in a predominately radiative cooling regime. Secondly, NASA hasn't launched a fission reactor to space for several decades, and so there is an extensive learning cycle to be undertaken to understand in detail the failure modes, safety and maintenance issues appropriate to the operation of a reactor on the Moon. Thirdly, the sheer size of the technical challenge of going from 1 kWe to 390 kWe which furthermore must, by necessity, push back the delivery of such a project. And finally, the development of some feedstock heating mechanism using the waste heat from the reactor, which will be necessary to drive up the efficiency of the reactor. This last barrier might be solved first, alleviating some of the pressures on power conversion efficiency and reactor size.

5. Discussion

Before discussing the implications of the findings from the energy requirements and power system architecture analyses, it is necessary to address the nature of the assumptions made in the research. The assumptions made were deliberately optimistic as this study was undertaken from a first principles approach to find out the order of magnitude of the thermal processing energy needs. In addition, the assumptions were simplistic, as there is no detailed concept upon which to base any more sophisticated assumptions. A perfect example of both an optimistic and simplistic assumption made in this paper was the way that the heating process was considered to be continuous, that is to say, the whole mass of the structure was processed in one pass. This will not be the case, as the shield will need to be discretised into elements and hence so must the process be discretized, introducing new forms of losses and mechanical work to be done which is not addressed by this analysis. Additionally, it is unreasonable to expect a MW-scale heating system to operate at a load factor of 100%, as overheating and wear will cause maintenance issues, which introduces another route for losses which must be accounted for in the power output. Finally, the use of static values for solar PV power output is simplistic as the power output will degrade in the aggressive radiation environment on the Moon's surface.

With regards to assumptions about the geotechnical aspects of the regolith, this area is not particularly well understood – there are limited actual samples from the Moon itself, and much of the data comes from analysis of the way regolith simulants, or Earth-analogues behave (Taylor and Meek, 2005), which means that assumptions in this area may not be wholly accurate. Nevertheless, assumptions about density and melting temperature are unlikely to ever be truly accurate as there will always be some mineralogical discrepancies between samples, but the figures used in this paper are widely used elsewhere in the literature.

This analysis is highly dependent on the value for specific heat capacity, a property that is reasonably variable from a physical perspective, as mineralogical differences will exist across the lunar surface. Most values are based on empirical observation and interpretation of laboratory testing on simulants and natural regolith. Since the energy requirements are so heavily dependent on this value, given the high temperatures and masses involved, it would appear to be a point in need of further research.

As regards the results of the analysis, the technological and economic case for sintered lunar regolith as a construction material is poor. In order to develop the radiation shield for a habitat that will use, at most, 50 kW of power, there must be infrastructure in place to deliver more than 9 times that power, which only begins to make sense once multiple, collocated habitats are seriously proposed. Otherwise, the majority of the ~500 kW power output that has so expensively been placed on the Moon would never be utilised.

All of the power systems architectures require significant volumes in the rocket fairing, additional mass, complexity and power delivery infrastructure, which would need to be designed, tested and flight-qualified before mission launch, adding an extra layer of complexity. Given that complexity and mass are good proxies for cost with regards to spaceflight, this is an area that should be minimised where possible. In addition, this study does not consider the mass, cost, or complexity of installing a 0.5–1 MW scale heating unit, or the advanced construction robotics to assemble the habitat whatever the energy source.

These barriers are unlikely to be overcome before the first medium-sized permanent or semi-permanent outposts are deployed on the Moon's surface, and so logically, it follows that thermally processed regolith shields are unlikely to be in use in the near future.

From the above, it seems likely that the most efficient near-term solution is chemical processing of regolith, from an energy requirements perspective, but this habitat would need to be small to reduce binder upmass. The technology is also more mature and likely to be delivered on near term projects as it does not require such scaled-up power system architectures. Alternatively, bringing storm shelters up with the habitat to provide a means of weathering major solar events, and adding additional radiation protection to habitat quarters, possibly through a water blanket or similar mechanism, could provide a non-ISRU solution with current technology. However, in the longer term, the development of MW-scale reactors or other power system architectures may permit a very large volume of material to be processed thermally for both construction material and volatile extraction, making a large, permanent human presence on the Moon more easily realisable.

6. Conclusions

The analysis presented here describes a physically determined lower bound for the amount of energy necessary to thermally process a regolith radiation and meteorite shield. This lower bound is far in excess of current capabilities ranging from around half a megawatt to a megawatt dependent on the power source available. However, it is not only the power source that precludes the use of such techniques, it is also the heating, cooling and construction infrastructure which are some years away from viability. In addition, even if the technology currently available to provide power and heating was in that range, economically, the concept is unsound. Any medium sized habitat would at most draw around one tenth of that power, leaving the power generation and heating assets stranded, unless plans are explicitly made to expand the habitat with other modules. The view of this paper is that nuclear power is the best option for providing thermal processing heat, probably through some pre-heating mechanism making use of the plant's thermal power output, but this still does not make optimal, long-term, use of the asset once it is in place.

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