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EXTENSIBILITY OF THE FISSION SURFACE POWER (FSP) SYSTEM FROM THE MOON TO MARS

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Abstract – *Fission reactors have great near-term potential to power human and robotic missions/outposts on the surface of the Moon and Mars (and potentially other planets, moons, and asteroids). The ability to provide a power-rich environment that is independent of solar intensity, nights, dust storms, etc., is of significant (perhaps enabling) importance to the further expansion of humans into our solar system. NASA's Reference Fission Surface Power (FSP) System is a 40 kWe system that has been primarily designed for lunar applications. This paper examines the extensibility of the FSP design and technology for potential missions on Mars. Possible impacts include the effects of changes in heat sink, gravity, day-night cycles, mission transit time, communication delay, and the chemistry of the regolith and atmosphere. One of the biggest impacts might be differences in the potential utilization of in-situ materials for shielding. Another major factor is that different missions will likely require different performance requirements, e.g. power, lifetime and mass. This paper concludes that the environmental differences between potential mission locations will not require significant changes in design and technologies, unless performance requirements for a specific mission are substantially different than those adopted for the FSP. The primary basis for this conclusion is that the FSP has been designed with robust materials and design margins.*

I. INTRODUCTION

Fission Surface Power (FSP) systems are well suited to be the workhorse of near-term human exploration of the Moon, Mars and other solar system destinations. Some potential surface power electrical loads include landers, habitats, in-situ resource utilization plants, mobility and construction equipment, and science experiments. Fission systems can also provide spacecraft power in-transit and for some missions provide power to a Nuclear Electric Propulsion (NEP) system.

The reference NASA FSP concept has been designed to provide 40 kWe for 8 years on the surface of the Moon. The FSP concept has been designed under the mantra of affordability, by utilizing established materials, existing technologies, and a simple approach that minimizes nuclear testing requirements. This paper examines the extensibility of the FSP design and technology to Mars.

Most of the differences between a lunar and Martian application can be placed within the following categories:

- In-Space Transit
- Communications/control
- Gravity
- Heat Sink
- Day/Night Cycle Length
- Materials issues
- Performance Requirements
- Qualitative Shielding Differences
- Quantitative Shielding Differences

II. REFERENCE REACTOR

The reference FSP concept is designed to provide a net power of 40 kWe for 8 years; a description of the overall power system is provided in Mason.[1] An in-depth description of the reference FSP reactor is provided in Poston.[2] The concept uses a stainless-steel based, UO_2-fueled, NaK-cooled fission reactor coupled to free-piston Stirling converters. The heat rejection system uses a pumped-water loop coupled to a water-heat-pipe radiator. The concept was selected based on an assessment that emphasized affordability and low risk. The system is considered a low development risk based on the use of terrestrial-derived and flight-heritage reactor technology, high efficiency power conversion, and conventional materials. Low-risk approaches were favored over other options that offer higher performance and/or lower mass.

Some of the shielding configurations evaluated in this report assume that the reactor operates in-place on the lunar lander. Figure 1 shows the reference FSP placed on a conceptual lander concept that is was evaluated by the NASA Lunar Surface Systems Office. In this concept, the FSP reactor fits within a lander central cavity that would house the lunar ascent stage for a human return mission.

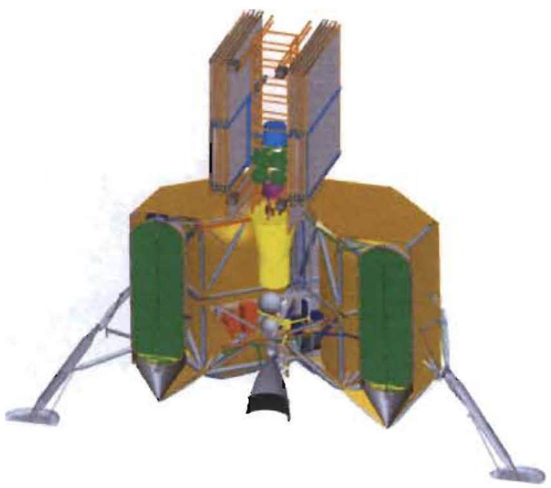

Fig. 1. FSP power system stowed in conceptual lander.

III. MOON/MARS EMVIRONMENTAL DIFFERENCES

There are several differences between the Moon and Mars, e.g. composition, atmosphere, day-length, solar intensity, distance from Earth, background radiation, and gravity. The effect that each of these differences could have on an FSP application is discussed in the following section. Despite the striking visual difference (i.e. Mars' distinction as the Red Planet) the compositions of the Moon and Mars are remarkably similar. Visually, the primary difference is that the iron on Mars is stored in rust colored Hematite (Fe_2O_3) as compared to the black Ferrous Oxide (FeO) on the moon. Table I displays the mass fraction of various constituents in the regolith of Mars and two locations on the Moon: mare and highlands. The mare are the dark areas on the Moon, given the name "mare" (Latin for "seas") by early astronomers who mistook them for seas, while the actual dark shade is caused by of iron oxide. Table I not only shows how close the composition of the Moon and Mars are, but also the Mars composition (albeit based on only a few samples, thus not globally representative) is closer to the mare composition than is the lunar highlands.

For this study, the lunar mare composition is average of measurements on Apollo 11, 12, 14, 15, and 17, the lunar highlands is the average of Apollo 16[3], and Mars is the average of several Pathfinder measurements[4]. Note that Mars regolith compositions measured by Viking I and Viking II were both very similar to Pathfinder. Most measurements are skewed by loss of volatiles or in some cases elements lost by heating (all normalized to 100% with what was measured).

TABLE I

Regolith Mass Fractions

	Lunar Mare	**Lunar Highlands**	**Mars**
SiO_2	45.34	44.65	49.16
Al_2O_3	15.13	27.09	8.38
FeO/Fe_2O_3	13.47	5.06	18.44
CaO	11.19	15.58	6.26
MgO	9.68	5.66	7.82
TiO_2	3.62	0.54	1.23
Na_2O	0.50	0.46	2.35
Cr_2O_3	0.31	0.33	
K_2O	0.27	0.17	0.34
P_2O_5	0.25	0.11	
MnO	0.18	0.30	
SO_3	0.05	0.07	5.47
Cl			0.56

The theoretical density of the regolith at each location is determined in Table II by multiplying each constituent theoretical densities by their mole fraction.

TABLE II

Theoretical Density, Mole Fractions of Regolith

	Theoretical Density (g/cc)	Mole Fraction		
		Lunar Mare	Lunar Highlands	Mars
SiO_2	2.63	0.4738	0.4886	0.5595
Al_2O_3	4.03	0.0932	0.1747	0.0562
FeO/Fe_2O_3	5.75/5.24	0.1177	0.0463	0.0789
CaO	3.35	0.1252	0.1827	0.0763
MgO	3.58	0.1509	0.0923	0.1327
TiO_2	4.23	0.0285	0.0044	0.0105
Na_2O	2.27	0.0051	0.0048	0.0259
Cr_2O_3	5.22	0.0013	0.0014	0.0000
K_2O	2.35	0.0018	0.0012	0.0024
P_2O_5	2.39	0.0006	0.0003	0.0000
MnO	5.37	0.0016	0.0028	0.0000
SO_3	1.92	0.0004	0.0006	0.0468
Average Particle		3.41 g/cc	3.25 g/cc	3.08 g/cc

The actual density will vary greatly depending on porosity. For this study, the following packing factors (percent of theoretical density) are assumed: top surface layer = 40%, refilled regolith 45%, undisturbed regolith below surface = 55%. These percentages are based on the approximate average of measured density values reported in the Lunar Sourcebook[3], although they vary greatly site-to-site.

As a gamma shielding material, the attenuation coefficients of all elements are similar in the ~1 to 5 MeV energy range, which is spectrum that contributes most to dose; thus the material density is the dominant shielding factor. As a neutron shielding material, the atom fractions are important to note, and are shown in Table III.

TABLE III

Regolith Atom Fractions

	Lunar Mare	Lunar Highlands	Mars
O	60.57	60.94	62.65
Si	16.93	16.12	17.96
Al	6.65	11.53	3.61
Ca	4.47	6.03	2.45
Mg	5.40	3.05	4.26
Fe	4.20	1.53	5.07
Na	0.36	0.32	1.66
Ti	1.02	0.15	0.34
Cr	0.09	0.09	
Mn	0.06	0.09	
K	0.13	0.08	0.16
S	0.04	0.05	1.50
P	0.08	0.03	
Cl			0.35

Oxygen, silicon and aluminum are all very transparent to neutrons, thus neutron shielding is mostly affected by the fraction of the minor constituents, in particular iron.

IV. MOON/MARS FSP COMPARISONS

The following subsections discuss some of the discriminators that may exist between an FSP mission on the Mars as compared to the Moon.

IV.A. In-Space Transit

A mission to Mars will require months of in-space transit, as opposed to a few days to the Moon. In addition, the solar insolation will be time dependent (as a function of distance to Earth). Transit times could range from a month for an advanced NEP system, to several months for an NTP system, to almost a year for a chemical propulsion system. Thermal management and system keep-alive (or ability to wake from sleep) could be discriminating factors; however, until a detailed FSP flight design is completed, it is hard to know which systems will be more sensitive to the transit issues of a Mars mission. Issues with batteries, motors, and bearings should be manageable based on previous deep-space missions, and the water heat pipes in the radiator should be robust enough to undergo freeze/thaw sequences without consequence. The water in the secondary loop will likely use the same approach as the lunar FSP – to launch/transport the coolant in a reservoir and fill in-situ. The biggest transit concern for an FSP Mars mission may be the management of the NaK coolant. For the lunar application,, the system thermal inertia and the strong sunlight (when available) should make it relatively simple to keep the NaK liquid—this is the lunar FSP reference approach.

For the Mars FSP, there appear to be 4 options to dealing with coolant freeze/thaw issues: 1) launch with the coolant liquid and staying liquid until system startup (i.e. the lunar FSP approach), 2) launch the coolant frozen, keep it frozen, and thaw during the startup sequence, 3) design the system to maintain integrity throughout uncontrolled freeze-thaw sequences, 4) transport the coolant in a reservoir and then fill the loop in-situ.

Option 1, to launch liquid and stay liquid would be much more difficult than for a lunar mission because of the very long exposure to increasingly cold temperatures; therefore a good deal of power might be needed to prevent freeze, and the system to prevent freeze would have to be very reliable. The options to prevent freeze could be running the pump at low power, the use of Radioisotope Heater Units (RHUs), electric trace heating, or a combination of various techniques.

Option 2, to launch frozen and stay frozen, might be the best approach because it should be easy to provide shading and insulation to keep the coolant frozen. A system will have to be developed to allow the coolant to thaw in a reliable manner upon deployment (including a controlled freeze prior to launch); although this should not be too difficult and considerable previous work has been done in this area. Some additional insulation may be needed to prevent thawing during transit, although it is likely that the "operational" insulation will be adequate. NaK is liquid at room temperature, so it will have to be refrigerated prior to launch (although freezing temp is not extremely cold, ~-10 C). Na could possibly present less of a freeze/thaw issue than NaK, so a change to that technology could be considered (to be weighed with other pros and cons).

Option 3, to accommodate uncontrolled freeze/thaw sequences, would be the best from a mission/performance perspective; however, this would present a significant engineering challenge that would also be difficult to qualify.

Option 4, to transport the coolant in a reservoir and then fill the loop in-situ, is the proposed option for the water coolant in the secondary loop. It should not be too difficult to either keep the coolant warm or keep it frozen and then thaw it in the tank prior to startup. The difficulty with this approach for NaK (or Na) is to ensure filling of all volumes and surface wetting of all heat transfer surfaces.

IV.B. Communications/control

The control system for the FSP is highly automatic, and during nominal operation the system is designed to operate autonomously for extended periods of time (and potentially the entire mission).[5] Ground commands are only anticipated for system tweaks, troubleshooting of low-probability beyond-design-basis events, and possibly facilitating system startup.

One of the obvious differences between a lunar and a Martian mission is the time delay in communications. The Moon is close enough to the Earth that the transit time of light/radio signals is only ~1.3 seconds, while the time delay to Mars is at least several minutes. The control system for the FSP is highly automated, so in this regard a communications time delay to Earth would not be pertinent. However, if an unanticipated problem arose that might be mitigated via ground control (i.e. a control response from Earth), a time delay of a second versus several minutes could make a significant difference. Ground control might be most beneficial during system startup, especially the first time any FSP system is deployed. System startup will be more complex and have more uncertainty than any other aspect of operation, so 1) several small, deliberate action/response steps will be required and 2) some type ground control will be desirable. A time delay of several minutes or more will likely make system startup more difficult and perhaps less likely to succeed.

In addition to the Mars time delay being longer, it can also range widely over the course of a mission, whereas the Moon time delay is relatively constant. At opposition Mars is ~56 million km from Earth resulting in a time delay of ~3 minutes, while at conjunction Mars is ~400 million km from Earth resulting in a ~22 minute time delay. Any control approach that might utilize ground commands would have to be able to accommodate this wide range of time delays.

Another possible discriminator between a lunar and Martian FSP mission is the potential for line-of-site communications back to the Earth. An outpost on near-side of moon will always have direct communication (except solar eclipse), while an outpost of far side of moon will depend on transmission through orbiting satellites or linked lunar ground stations. Mars rotates on a 24.7 hour day, so line-of-site communications will be limited to ~12 hour windows (unless polar locations are used). The relevance of having line-of-site communications is hard to put a value on without a detailed architecture design. Line-of-site value is minimal if a robust "global" communications network exists to which the FSP can relay communications through. If line-of-site communications are required nominally or for backup communications, then a near-side lunar application would have a clear advantage.

A Mars FSP application could present a few more communications issues, such as dust storms, high winds, and perhaps orbital situations where the sun is between Earth and Mars. One final control discriminator could be the potential to use of solar panels to provide FSP startup power as opposed to batteries or onsite power. The lunar application has much stronger and more reliable solar insolation and the time window of 14 days provides plenty of margin for FSP startup, as opposed to Mars which provides 12 hour windows of possibly unreliable sunlight.

Overall, it's hard to quantify the significance of communication until a final flight and architecture design is developed, but as with most exploration hardware, the lunar environment provides fewer challenges. An FSP communication and control system to operate on Mars might have to be more robust, unless it has significant prior testing (e.g. a previous lunar test).

IV.C. Gravity

In general, the FSP has been designed to operate irrespective of gravity, e.g. with no dependence on free boiling or natural circulation. The Moon and Mars are both low gravity environments, although their gravitational constants are different enough (Moon = 0.165 g, Mars = 0.376 g) to warrant the mention of possible gravitational dependencies.

It is unlikely the structural concerns will be a discriminator between a lunar and Martian application. Structural issues are likely to be limited by launch, landing, and Earth handling concerns. One relatively small impact could be gas bubble accumulation in coolant loops. It has been assumed that free gas accumulation is likely to work on the Moon, but this has to be verified. Mars would have an advantage by having more than twice the driving force to move bubbles to a desired location. Although during Mars transit, a prolonged zero-micro-g environment might give more time for bubbles to migrate to undesirable locations. System deployment could also be dependent on gravity, especially if astronauts are used in any way during FSP deployment; however, an advantage either way is unclear. Higher gravity on Mars makes things heavier, but more gravity also might make astronauts less clumsy and more comfortable performing operations.

IV.D. Heat Sink

The effective heat sink temperature has a significant effect on system performance, and in terms of heat rejection there are several differences between the Moon and Mars. Solar insolation is very strong on the Moon, and the solar heat flux onto the radiator panels can provide a significant loss in radiator rejection capability on the moon. This negative impact of solar isolation depends largely on how well the radiator panels can be positioned to avoid direct sunlight. A Mars FSP would see significantly less solar insolation on a perfectly clear day, and even less if dust is in the air. The ground temperature may also have a significant effect on performance, depending on the orientation and elevation of the radiator. Lunar ground temperature varies much more than Mars, and gets relatively hot (>300 K) during mid-day – thus reducing the radiation from any panel with a view factor to the surface.

On Mars, the low density, mostly CO_2 atmosphere can provide some differences from a lunar application. With respect to the radiator, the atmosphere will diminish heat rejection by providing a slightly warmer sink temperature for thermal radiation (as opposed to space), but it will also aid heat rejection by proving a conduction/convection path from the panels. Both of these effects are rather small, unless a very strong wind blows over the panels (but even then, the low density of the atmosphere does not promote substantial heat transfer). The atmosphere may be useful in providing a reliable heat sink for some components other than the radiator, by providing a conduction path (poor as it may be) in gaps that might otherwise require radiation. For the same reason, the atmosphere might have a negative affect by causing unwanted, parasitic heat loss from hot-side components, which would reduce system efficiency (standard space insulation will not be as effective).

On both the Moon and Mars, dust build-up could reduce radiator effectiveness, be creating more delta-T from the coolant to the radiating temperature. In both applications it is expected that the panels will be deployed in a vertical configuration to prevent buildup. On Mars it is expected that a significant amount of dust would come in contact with the panels over the lifetime of the FSP. On the Moon dust generally stays very close to the surface (<1 m), so if the radiator is deployed high off the ground there may not be an issue (unless dust is kicked up by nearby activities); although if there is any contact, then moon dust has a reputation of clinging to almost any surface. If Moon dust does build up on the panels the affect might be worse than Mars dust due to general lower emissivity and lower conductivity (because there is no atmosphere between particles). It is unclear whether the dust on Mars or the Moon will prevent more of a heat rejection issue, but it is clear that these issues will be minor compared to the effect of dust on solar panels. Similarly, dust storms might impact heat rejection for a Mars FSP, but is almost a non-issue when compared to the affect a storm could have on solar power.

IV.E. Day/Night Cycle Length

The 28-day long "day" is one of the most difficult aspects of a lunar mission. For almost any technology, keeping a system warm over 14 days of prolonged extreme cold is a major challenge, and in some cases keeping it cool over 14 days of intense sunlight can present a problem. For the FSP, once the system has operated there should be enough decay heat to keep a system that is shutdown warm over a lunar night; however, prior to startup it may be difficult to keep the system warm over a lunar night (the FSP may not have enough thermal inertia to keep the NaK coolant thawed without heating). The optimal scenario would be to deploy the lunar FSP at the beginning of a lunar day and start up the system (to significant power) within the 14-day window. A Mars FSP will not have to endure such a long cold night, but conversely does not have the advantage of a long extended period of sunlight. Most likely a Martian system will require more than 12 hours from landing to full power operation.

System performance is significantly affected during the day/night cycle. The large decrease in heat rejection potential during the lunar day has a modest impact on system power and component temperatures. Thermal cycling may be an issue, and might even have to potential to present fatigue issues in some cases. A Martian application will see more cycles, but the change in temperatures will be much smaller than for a lunar application.

IV.F. Materials issues

The environmental differences between the Moon and Mars are significant, but in general the materials selected for the FSP should adequately handle each environment.

The regolith compositions on the Moon and Mars are similar; they actually vary more site-to-site on their respective globes than they do planet to moon. The Moon may provide more problems because particles tend to be finer, thus providing more opportunity to cling or potentially infiltrate locations within the system.

The background radiation doses are also slightly different. The Galactic Cosmic Ray (GCR) dose on Mars should be higher than the Moon because it is further from the protective e/m field of the Sun, but solar events will be of less magnitude due to the increased distance from the sun. Mars will also get a bit of shielding from the low density atmosphere, but this is probably not significant. Overall, background radiation will not provide any concern to structural materials, but its effect on electronics and potentially other sensitive components may need to be considered.

The atmosphere probably provides the biggest materials discriminator. The Moon has a slight layer of ionized particles above the surface during daylight, but they stay close to ground (~1 m). Mars has CO_2, low levels of volatiles, and blowing dust particles. CO_2 and the volatiles both have the potential to cause corrosion, but SS-316 (the primary structural material) should not have any major issues at the FSP operating temperatures. Perhaps more of a concern could be carburization of the SS-316, which can significantly reduce material ductility.

IV.G. Performance Requirements

For the purposes of this study, system performance is defined as a combination of power, lifetime, reliability, and mass. The assumed requirements for both the Moon and Mars are the same for this comparative study; however there are two aspects that might make a Mars FSP harder to develop.

1) Reliability: A lunar mission is likely to have a reliable low-power, backup solar power system and a rapid return home option for the astronauts. Neither of these is likely to exist for a Mars mission; therefore a Mars FSP will likely have to be proven more reliable than a Moon FSP prior to deployment. Conversely, a human mission to Mars will be expected to have more inherent risk than a lunar mission, so an increase in FSP reliability might not have a significant effect on overall astronaut risk

2) Mass margin and "creep": A mission to Mars is likely to be more sensitive to system mass than a mission to the Moon; i.e. small increases in mass could be acceptable for a lunar mission but a major problem for a Mars mission. History shows that system mass is likely to increase as the design/technology becomes more mature, and space reactor development programs that have been mass limited have been very negatively impacted by having to "cut corners" to reduce mass several times during the program. Therefore, it is possible that a Mars FSP development program would be hampered more by mass concerns than a lunar FSP development program.

IV.H. Qualitative Shielding Differences

The radiation shield is generally the highest mass component of an FSP system. There are many potential options for using in-situ resources as shielding materials, which can provide substantial mass savings. The shielding potential of both lunar and Martian regolith (e.g. cross sections and attenuation coefficients) are very similar. As shown in Section III, both the density and composition of lunar and Martian regolith are similar, except for site specific locations on each globe. The most important difference in composition with respect to shielding is the amount of iron, which creates high energy gammas upon neutron capture.

On the Moon or Mars, there is the potential to use regolith in several ways: berming, sandbagging, digging/burying, or any combination of these. In-situ resources could also be used to fill permanent structures or cans as a fixed part of the reactor structure (e.g. sand could be scooped or vacuumed), and in the most optimistic scenarios in-situ water could fill shield tanks or and perhaps in-situ concrete could be made. Mars also offers the option of condensing the atmosphere, but this would have inherent reliability risk. Overall, it should be easier to utilize the shielding potential of regolith on the Moon as opposed to Mars. The lunar regolith layer is deeper and more uniform across surface. In addition, the lunar regolith is also generally looser and finer than on Mars, and in most locations there should be fewer large rocks. Each of these characteristics should be an advantage for any operations to dig, move and deploy regolith. The lower gravity on the Moon also might make digging and moving easier.

Another tool at the disposal of the mission architect is distance and topography. The radiation dose drops by approximately the square of the distance as one moves away from the reactor. The optimal distance is generally based on balancing the shield mass against the power system voltage, cable weight, and on-site logistics. In this study it is assumed that "permanent" human presence would be preferable within ~100 m of the reactor. Topography (ridges, valleys, craters) has significant shielding potential, but this relies heavily on an excellent surveying, landing, and/or transportation capability. Topographic shielding might better suited for Mars, as there may be more potential to identify large boulders or ridges to place the system behind. There could also be enough appropriately sized rocks around for astronauts to make simple berms without tools/equipment.

The Mars atmosphere is largely negligible with respect to reactor radiation shielding because of the low density (~0.01 atm). In general, for architectures with long separation the atmosphere helps a little, but for shielding locations close to the system or for architectures that use a berm the atmosphere can make things worse.

IV.I Quantitative Shielding Differences

An in-depth study of radiation shielding for a lunar FSP is described in Poston et. al.[6] This previous work provided a basis to calculate some quantitative differences between using lunar and Martian regolith in various configurations. The requirements, assumptions, materials, and definitions that are used for this comparison are too numerous to list in this report, so a copy of the previous shielding report (Poston et al.[6]) is needed for a true understanding of this comparison

In the previous study, four different architectures were evaluated: 1) buried, 2) on-surface bermed, 3) on-lander, as-landed, 4) on-lander, regolith-filled. For this study, doses were calculated for the buried and bermed architectures using the 3 regolith compositions provided in Table III. The densities used are: top surface layer = 40% of TD, refilled regolith = 45% of TD, undisturbed regolith below the surface = 55% of TD, where the TDs are provided in Table II.

The previous study used a human dose requirement of 3 mrem/hr for an unshielded astronaut at the edge of the outpost—the reference for that study includes a lengthy discussion of how this dose rate and the FSP component dose limits were selected. The actual dose limits are not the focus of this study, rather the difference between the doses for the various deployment locations. It should also be noted that the lunar regolith used in the previous study was of slightly different composition than those used in this study, and the Stirling engines are modeled in more detail in this study; but these differences are not relevant to the comparison in this study. The dose calculations in this study are performed with MCNPX[7], using the same methodology as described in the reference for the previous study. The relative error in Tables IV and V are: ~3% for the human dose, ~2% for the Stirling gamma, ~8% for the Stirling fast neutron fluence.

TABLE IV

Shielding Comparison for Buried Configuration

Buried System Doses	Lunar mare	Lunar highland	Mars
Human dose rate (mrem/hr)	2.48	3.37	3.58
Stirling gamma dose (MRad)	0.86	1.12	1.18
Stirling fast neutron fluence (nvt)	8.9e13	1.1e14	1.2e14

The results in Table IV show there are modest differences between the dose calculations for the 3 regolith types. Some of these differences are due to composition, but density is the dominant factor. Separate results were calculated with each material at identical density and in those cases Mars provided the best shielding, followed closely by mare, with the highlands 10% higher. The reason why Mars provides the worst shielding on Table IV is because its density is 5% lower than the highlands and 10% lower than the mare. As a rule of thumb for the buried configuration, a 5% increase in density results in a 25% increase in shielding or vice-versa.

TABLE V

Shielding Comparison for Bermed Configuration

Buried System Doses	Lunar mare	Lunar highland	Mars
Human dose rate (mrem/hr)	2.91	2.83	3.88
Stirling gamma dose (MRad)	1.32	1.27	1.28
Stirling fast neutron fluence (nvt)	2.8e14	2.7e14	3.1e14

The results in Table V show essentially no difference between any parameters except that the human dose rate on Mars is significantly (~25%) higher. The reason that most dose results are similar is that the berm is made thick-enough that it "over-shields" the radiation that enters it; therefore the density and composition do not make a difference (the berm will absorb all of the radiation regardless, unless a very low density is used). The vast majority of radiation that reaches the astronauts is scattered off of the FSP system and radiator. On Mars, reflection off of the atmosphere (sky shine) introduces a new path for radiation to scatter to the astronauts, thus the noticed increase in dose rate on Table V.

One of the previous architectures that was not examined in this study was the on-lander, regolith-refill option. It is expected that the regolith-refill option would show the same trend as shown in Table IV, although the magnitude of the differences would be reduced. The other architecture not studied was the on-lander, as-landed option. This option was not studied because it should be insensitive to the regolith composition (which is one of the advantages of the as-landed configuration).

Another radiation issue that is of considerable use to potential mission architects is how "approachable" the area next to the reactor is following shutdown (note: shutdown in this case might refer to a very low power (<1%) warm standby). There might be useful operations that could be performed close to the reactor if the dose was acceptable. The previous study found that during initial reactor startup operations, the reactor site can be visited minutes after shutdown if needed, and after extended operations (including full 8-year operation) the reactor site can be visited (with negligible risk) within days of shutdown, and could be visited within minutes depending on the urgency of the visit. The lunar and Martian regolith compositions are similar enough that regolith activation differences between sites should generally be <10%. Also, a good deal of the activation dose is from the fuel, NaK and Ni within the FSP itself, which would be independent of the regolith composition. Therefore, the previous study findings should generally be applicable regardless of FSP deployment location.

V. CONCLUSIONS

Several differences are discussed that discriminate between FSP applications on the Moon versus Mars. While some of the differences are significant, none of them should provide any major development challenges. In fact, the most significant comparison between FSP systems for use on the Moon and Mars is one of similarity; i.e. that they both use the same technologies and materials. In this light, all of the differences pointed out are rather minor, and the difference between developing a Mars FSP or a Moon FSP is not substantial. In either case, once the first FSP system is developed, regardless of location, it should be relatively easy to extrapolate it to may other uses.

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REFERENCES

1. L. S. MASON, "Affordable Fission Surface Power System (AFSPS) Reference Power System Concept" *Proceedings of Space Technology and Applications International Forum (STAIF-2008)*, AIP Conf. Proc. #969, Melville, NY (2008).
2. D. I. POSTON, R. J. KAPERNICK, D. D. DIXON, J. WERNER, A. L. QUALLS, and R. RADEL, "Reference Reactor Module Design for NASA's Lunar Fission Surface Power System", *Proceedings of Nuclear and Emerging Technologies for Space (NETS-2009)*, American Nuclear Society, La Grange Park, IL, (2009).
3. G. H. HEIKEN, D. T. VANIMAN, and B. M. FRENCH, Lunar Sourcebook, a User's Guide to the Moon, Cambridge University Press, New York, NY (1991).
4. C. C. ALLEN et. al., "Martian Regolith Simulant JSC Mars-1", 29th Annual Lunar and Planetary Science Conference, Houston, TX (1998).
5. A. L. QUALLS, "Fission Surface Power System Power Control Strategies", in these *Proceedings of Nuclear and Emerging Technologies for Space (NETS-2011)*, American Nuclear Society, La Grange Park, IL, (2011).
6. D. I. POSTON, L. S. MASON, M G. HOUTS, "Radiation Shielding Architecture Studies for NASA's Lunar Fission Surface Power System", *Proceedings of Nuclear and Emerging Technologies for Space (NETS-2009)*, American Nuclear Society, La Grange Park, IL, (2009).
7. L. S. WATERS, et. al., MCNPX, Version 2.5.d, LA-UR-03-5916, Los Alamos National Laboratory, Los Alamos, NM (2003).