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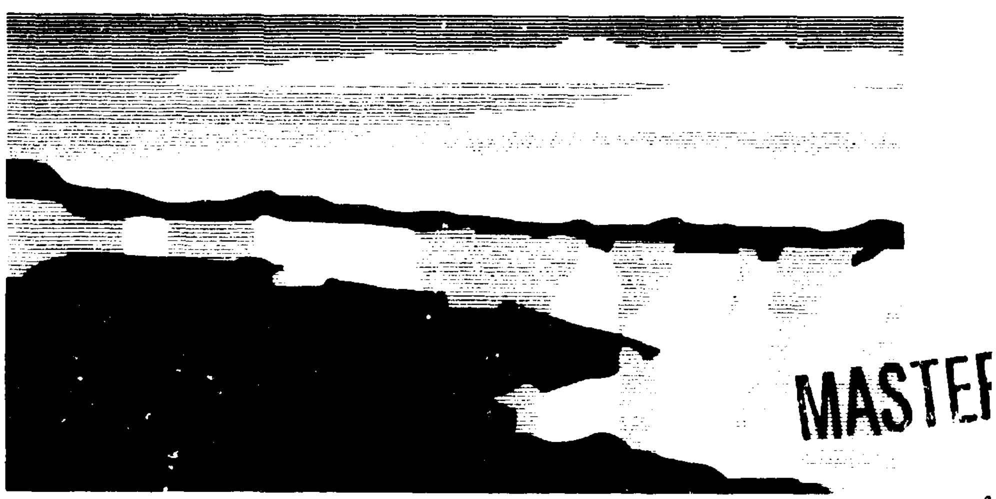

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LUNAR SURFACE FISSION POWER SUPPLIES: RADIATION ISSUES

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Abstract

A lunar space fission power supply shield that uses a combination of lunar regolith and materials brought from earth may be optimal for early lunar outposts and bases. This type of shield can be designed such that the fission power supply does not have to be moved from its landing configuration, minimizing handling and required equipment on the lunar surface. Mechanisms for removing heat from the lunar regolith are built into the shield, and can be tested on earth. Regolith activation is greatly reduced compared with a shield that uses only regolith, and it is possible to keep the thermal conditions of the fission power supply close to those seen in free space. For a well designed shield, the additional mass required to be brought from earth should be less than 1000 kg. Detailed radiation transport calculations confirm the feasibility of such a shield.

Introduction

Nuclear fission is a well-suited energy source for lunar surface operations. Fission power supplies are not adversely affected by the two week lunar night, can be designed to tolerate dust and other adverse conditions created by base operations, and can be scaled to the high power levels that will be required by advanced bases. Fission power supplies have a low mass and small volume compared to other power supply options, and may be the most cost-effective means of providing power to early lunar outposts (manned or unmanned).

Fission power supplies usually require a radiation shield to reduce radiation doses to instruments and crew. The radiation shield can be either brought from earth, or lunar materials can be used. The primary advantage of using lunar material is that the mass that must be brought from earth to the lunar surface can be reduced. Advantages of bringing the radiation shield from earth include the following.

1. The radiation shield can be well characterized before the start of the mission.
2. The handling or processing of lunar regolith is not required.
3. Shield properties and performance are not affected by variations in the available lunar material.
4. The fission power supply does not have to be buried or manipulated on the lunar surface.

The optimal shield may be one in which major components are brought from earth, but lunar regolith is used when advantageous. The fission power supply would be integrated with the empty shield prior to launch, and the reactor and empty shield would land as a single unit. The shield would then be filled with regolith, using equipment already required by the base. No movement of the power supply or lander would be required, and the landing site could be chosen without concern for the power supply. The shield proposed in this paper builds on previous designs[1] and has the following advantages over schemes that rely solely on burying the reactor or placing the reactor in an existing crater.

1. Mechanisms for removing heat from the lunar regolith are built into the shield, and can be tested on earth.
2. The fission power supply does not have to be manipulated on the lunar surface.

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3. Regolith activation is reduced.

The thermal conditions of the fission power supply are also maintained close to those seen in free space, which is important if a system designed for use in space is used on the moon instead. A well contoured shield can also reduce radiation scatter in these systems, or a standardized shield could be used to reduce development and flight qualification costs. The proposed standardized shield has a diameter of 5 m, and the total shield mass required to be brought from earth should be on the order of 1000 kg for 360 degree man-rated shielding. The 5-m shield diameter is compatible with most proposed lunar landers, and should provided adequate shielding of direct radiation for most near-term space fission power supply concepts. Radiation from scatter and activation can also be a significant contributor to total dose, and must be evaluated for each system.

The shielding approach presented in this paper is generic. To demonstrate the feasibility of this approach a detailed model of the Russian TOPAZ II space fission power supply was used in conjunction with a less detailed shield model. The US has purchased six TOPAZ IIs from the Russians, and two of these units may be suitable for use on an early lunar outpost. The use of a TOPAZ II thus represents a realistic early scenario.

The TOPAZ II is a moderated single-cell thermionic reactor capable of producing 6 kW of electric power. The TOPAZ II has undergone integrated system tests in both the United States and Russia. Tests have been performed using both nuclear heat (in Russia) and electrical heat (Russia and US). One advantage of the TOPAZ II is that integrated system tests can be performed using electrical heat, reducing the need for full nuclear ground tests. Other advantages of the TOPAZ II include the ability to ship the reactor unfueled and the ability to launch with liquid coolant. System life tests indicate that the TOPAZ II reactors currently available for flight could have an operational lifetime of over three years. A full TOPAZ II system model (including shield and radiator) has been developed for the shielding calculations using the Monte Carlo coupled neutron, photon, and electron transport code "MCNP".[2]

TOPAZ II / Shield Model

A schematic of the TOPAZ II and shield model is shown in Figure 1. The TOPAZ II and empty shield are assumed to remain in their landing configuration, 2.0 m above the lunar surface. The shield is then filled with regolith either prior to manned operation or while the crew is inside a shielded habitat (assuming that TOPAZ II power is required to fill the shield. An as-built TOPAZ II is used, with no major modifications. The TOPAZ II is surrounded radially by 0.3 m of LiH, with 0.2 m of LiH placed below the fission power supply. Heat generated in the LiH is transported by heat pipes to the radial surface of the shield where it is radiated to space. The region beyond the LiH is filled with lunar regolith. The regolith is assumed to have a density of 1.8 g/cm^3, and is representative of that found in the lunar highlands.[3] Heat generated in the regolith is conducted to borated stainless steel fins and removed by the heat pipes. The borated stainless steel also serves to provide structural support and reduce the thermal neutron flux in the regolith. Reducing the thermal neutron flux reduces the production of capture-gammas, which can be important. All major components are included in the detailed TOPAZ II reactor model, including the shield, radiator, and other component.[4]

Results

Radiation Dose Rate

The neutron and photon radiation dose rates at 100 m from the power supply are given in Table 1. For both neutrons and photons, the dose due to scatter off the TOPAZ II shield and radiator is also given, as is the dose due to scatter off the shield, radiator, and lunar surface. As shown in Table 1, a significant fraction of the radiation dose at 100 m is from radiation that scatters around the radiation shield, and only a small fraction of the radiation dose is caused by radiation that travels from the reactor through the shield. This result indicates that future shield design work should focus on reducing scatter, and that the shield thickness is more than adequate for reducing the direct radiation flux. Table 1 also gives the gamma radiation dose caused by NaK activation (activated NaK in the radiator has a direct view of the dose plane at 100 m) and the estimated radiation dose from soil activation and fission product decay. The lithium hydride shield located between the core and the regolith will reduce soil activation to negligible levels.[1]

The final entries in Table 1 are the neutron and photon dose rates at 10 m and 100 m when the shield is not filled with regolith. While these dose rates are quite high, they show that the unshielded reactor could be operated for a short period of time in an emergency, especially if the astronauts were more than 100 m from the reactor or if they were in a habitat that had its own shielding (for solar flares and cosmic rays). Also, even fairly sensitive hardware could withstand the unshielded dose rates at 10 m for a few days, thus it should be possible to use the TOPAZ II to power the equipment used to fill the shield with regolith. Even with radiation scattering and NaK activation, the total shielded dose rate (0.010 Rem/hr at 100 m) should be low enough to allow normal base operations, assuming that the shielded habitat is located at least 100 m from the reactor and that unshielded astronauts minimize time spent at 100 m or less from the reactor. Shield design improvements should be able to reduce the restrictions on base operations even further, although it is perhaps more desirable to reconfigure the radiator to reduce astronaut exposure to activated NaK. In the current configuration, over 50% of the total radiation dose to the astronauts would come from the activated NaK. The dose conversion factors used in Table 1 were taken from NCRP-38, ANSI/ANS-6.1.1-1977 and ICRP-21[5,6].

For the first few days after shutdown, activated NaK would be the dominant radiation source. After three days the dose from the NaK (at 100 m) would be less than 0.05 mrem/hr, and would continue to decrease. Gamma radiation from fission product decay also decreases rapidly after shutdown, and radiation from the shielded reactor would be negligible (compared with the natural radiation environment on the moon) within a few days after shutdown.

Heat Generation in the Lunar Soil

Heat generation is another concern with using lunar regolith to provide radiation shielding. The conductivity of lunar soil is extremely low (on the order of 2×10^{-4} W/cm-K)[7], and effective methods for removing heat from the lunar soil must be devised. The heat generation rate as a function of distance from the core centerline is shown in Figure 2. As

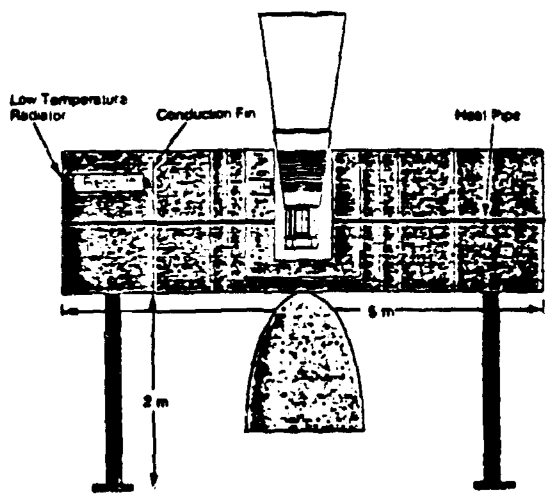

Figure 1. Schematic of TOPAZ II and shield model.

Table 1. Neutron and Photon Dose Rates from Various Sources.

Source	Neutron Rem/hr	Photon Rem/hr
Total Radiation Dose (100 m)	2.7e-3	7.6e-3
Scatter: Shield and Radiator (100 m)	2.4e-3	0.6e-3
Scatter: Shield, Radiator, and Lunar Surface (100 m)	2.6e-3	1.0e-3
NaK Activation (100 m)		5.4e-3
Soil Activation / Fission Product Decay		0.3e-3
Total Radiation Dose (10 m, no regolith)	48	230
Total Radiation Dose (100 m, no regolith)	0.33	2.4

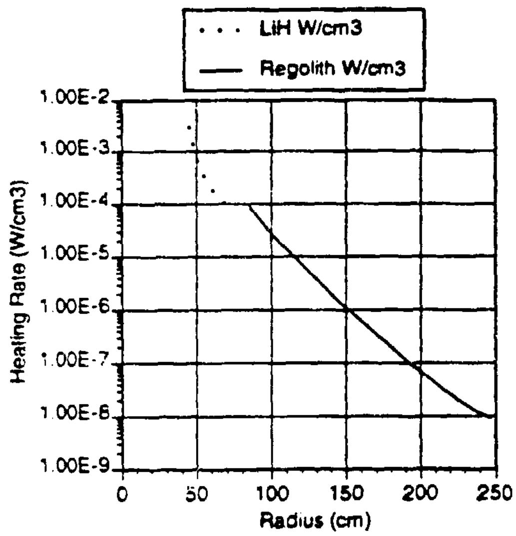

Figure 2. Heat generation rate as a function of radius in the lithium hydride and lunar regolith sections of the shield.

shown in the figure, the peak heat generation rate occurs in the lithium hydride (which has a much higher thermal conductivity than regolith), although there is still significant heat generation in the regolith closest to the reactor. Heat generation in the borated stainless steel is not shown, although it is typically several times higher than that in the adjoining lunar regolith because of its higher density. Heat is removed from the lithium hydride and the lunar regolith by borated stainless steel fins and heat pipes. The heat pipes are sized to also remove heat generated on the inside wall of the shield from thermal radiation heat transfer from the space fission power supply. A low temperature radiator is located on the outer radial surface of the shield. A heat removal capability of 10 kWt (oversized for this application) results in a radiator heat flux of about 600 W/m^2. This low heat flux allows the radiator to operate at a peak temperature of less than 400 K during the lunar day. The radiator could also be designed to remove significantly more heat, especially if higher radiating temperatures (450-500 K) are acceptable.

Observations

Several observations can be made relating to the proposed shield design. First, it is important that the thermal neutron flux be kept low to reduce soil activation and the capture-gamma rays that would be produced. The use of lithium hydride and borated stainless steel fins keeps the thermal neutron flux low, and virtually none of the gamma rays that strike the dose plane are the result of neutron capture in the regolith. Second, NaK activation could be a major concern in large power supplies using a single-loop heat-removal system. The problem could be mitigated by changing the radiator geometry (to eliminate its view of the dose plane) or by using a multiple-loop system where NaK used to cool the core never gets an unshielded view of the dose plane. An advantage of using NaK in lunar space fission power supplies is that the coolant thaws naturally during the lunar day, eliminating the need for a separate coolant thaw system. Third, it may be possible to increase the effective thermal conductivity of the lunar regolith in the regions near the core by filling the void space between the particles with a low vapor pressure liquid. This approach would probably not be mass effective, but is an alternative to adding fins.

Conclusions

A lunar space fission power supply shield that uses a combination of lunar regolith and materials brought from earth may be optimal for early lunar outposts and bases. This type of shield can be designed such that the fission power supply does not have to be moved from its landing configuration, minimizing handling and required equipment on the lunar surface. Mechanisms for removing heat from the lunar regolith are built into the shield, and can be tested on earth. Regolith activation is greatly reduced compared with a shield that uses only regolith, and it is possible to keep the thermal conditions of the fission power supply close to those seen in free space. For a well designed shield, the additional mass required to be brought from earth should be less than 1000 kg. Detailed radiation transport calculations confirm the feasibility of such a shield.

Future Research

The proposed method for shielding a lunar space fission power supply appears feasible, but several issues must be resolved and several optimizations should be performed. Future research should be performed in the following areas.

1. Methods for reducing the dose from radiation scatter by up to an order of magnitude should be devised. Contouring the shield may accomplish this, but could require that a separate shield be designed and qualified for each type of space fission power supply.

2. The final mass of the shield should be minimized. Although the regolith is not brought from earth, decreasing the mass of regolith in the shield decreases the mass of the shield structure and decreases the amount of regolith that must be loaded into the shield. The total mass required to be delivered to the lunar surface should also be minimized.

3. The effect of lunar dust on the space fission power supply should be quantified. Lunar dust could reduce radiator thermal capacity and affect moving parts.

4. A specific method for loading regolith into the shield compartments must be devised. A conveyor-belt-based system (similar to those used on earth) may be an attractive option.

5. Detailed calculations should be performed to ensure that there is adequate heat transfer out of the lunar regolith. Fin spacing should be optimized, and the effects of loading the regolith on regolith density and conductivity should be quantified.

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