SAND95-2974C
CONF-951158--1

A Preliminary Investigation of the Topaz II Reactor as a Lunar Surface Power Supply[1]

Gary F. Polansky[2]
Sandia National Laboratories
Albuquerque, NM

Michael G. Houts
Los Alamos National Laboratory
Los Alamos, NM

Abstract

Reactor power supplies offer many attractive characteristics for lunar surface applications. The Topaz II reactor resulted from an extensive development program in the former Soviet Union. Flight quality reactor units remain from this program and are currently under evaluation in the United States. This paper examines the potential for applying the Topaz II, originally developed to provide spacecraft power, as a lunar surface power supply.

Introduction

Nuclear reactor power supplies are well suited for lunar surface applications. They are not adversely affected by the two-week lunar night and can be designed to tolerate dust from surface operations. These power supplies can be scaled to the high-power levels required by advanced lunar bases and have a lower mass and smaller volume than many competing technologies. Reactor power supplies may represent the most cost effective option for providing power to either unmanned or manned lunar outposts.

The Topaz II reactor was developed in the former Soviet Union to provide spacecraft electrical power. The reactor was extensively ground tested and flight qualified, though never flown, as a part of this development effort. Two flight quality reactor units and massive amounts of other hardware remain from this development program. The Topaz II has been the subject of an extensive testing and evaluation program in the United States for more than three years and most of the existing program hardware has been moved to the United States to support this effort.

This paper provides a description of the Topaz II reactor and a summary of the results of the U.S nonnuclear testing program. The Topaz II is then examined as a potential lunar surface power supply. Issues associated with applying this spacecraft power supply system in lunar surface applications are identified and addressed. The subject of reactor shielding on the lunar surface is then addressed in some detail.

The TOPAZ II Reactor

The Russian Topaz II development program began in 1967. Although the basic design has remained the same, a number of design changes have been made over the years. A total of 26 Topaz II units were manufactured. Most of these units were expended in a test program that included mechanical testing, thermal management testing, electrically heated operation, and six ground nuclear tests. The Topaz II reactor was never tested in space. A total of five units of the final design were manufactured. Two of these units have only been subjected to workman-

---

[1] This work was funded by the Defense Nuclear Agency.

[2] The first author performed this work at Sandia National Laboratories, which is operated by the U.S. Department of Energy under contract DE-AC04-94AL85000.

ship tests and never filled with the sodium-potassium eutectic liquid metal coolant. The Topaz II development effort was curtailed in Russia in 1989.

The Topaz II power system is a 5-6 kWe space nuclear system that is based on thermionic power conversion. The Topaz II reactor system is illustrated in Figure 1. A more detailed description of the reactor system and discussion of its nuclear safety is given in Reference 1. The major subsystems that comprise the power system are (1) the nuclear reactor, which contains the thermionic converters, (2) the radiation shield, (3) the coolant system, (4) the cesium supply system, and (5) the reactor control unit (RCU).

The nuclear reactor contains 37 single cell thermionic fuel elements (TFEs), which are fueled by uranium dioxide (UO_2) fuel pellets that are 96% enriched in U^{235}. Three of the TFEs are used to drive the electromagnetic (EM) pump and the remaining 34 provide power to operate the Topaz II reactor and the satellite payload. The single cell TFE design allows the reactor to be loaded with fuel from the top after the entire power system has been constructed. This design also permits the nuclear fuel to be replaced with electric heaters and allows for nonnuclear system testing of the Topaz II. The TFEs are set within channels in blocks of a ZrH moderator, which are canned in stainless steel. The height and diameter of the reactor core are 37.5 cm and 26.0 cm, respectively.

The reactor core is surrounded by radial and axial beryllium (Be) reflectors. The radial reflector contains three safety drums and nine control drums. Each drum contains a section of a boron carbide neutron poison on its periphery that is used to control the nuclear reaction by drum rotation. During operation, the nuclear fuel heats the TFE emitters to between 1527° and 1627°C (1800 to 1900 K). The waste heat, removed by the coolant system, flows past the outer surface of the collector of the thermionic unit and maintains the collector in the temperature range of 470° to 570°C (743 to 843 K) at the beginning-of-life.

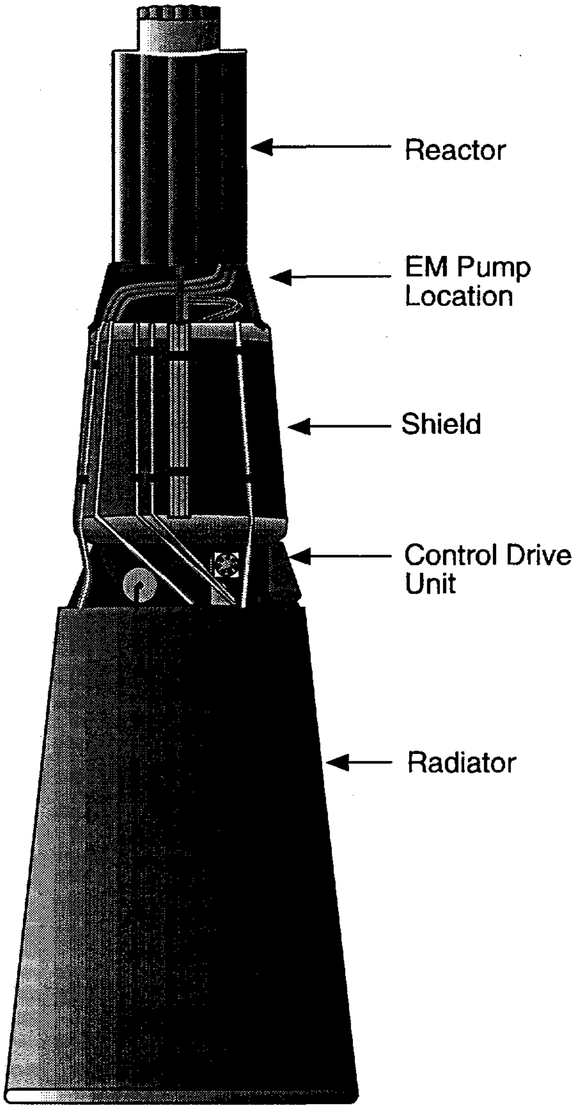

Figure 1. The Topaz II Power System.

The radiation shield is attached to the lower end of the reactor. The shield is composed of a stainless steel shell that contains lithium hydride (LiH). The shell thickness varies along its top and bottom, and serves as both a container for the LiH and the gamma ray shield. The LiH is the neutron shield. The radiation shield is designed to reduce the radiation dose after three years of operation to 10^{11} neutrons/cm^2 and 0.05 Mrad gamma at 18.5 meters from the centerline of the reactor core.

The reactor coolant system includes a sodium-potassium (NaK) coolant, a single EM pump, stainless steel piping, and a heat rejection radiator. The NaK coolant enters the reactor core through a lower plenum. It passes through the core and is heated from 470° to 570°C (743 to 843 K) by the waste heat from the thermionic conversion process. After passing through the core, the NaK exits through an upper plenum and flows through two stainless steel pipes to the radiator inlet plenum. The radiator consists of an inlet and outlet plenum that are connected by 78 coolant tubes. Thin copper fins are attached to the outside of the coolant tubes. After flowing through the radiator, the NaK flows through two coolant pipes that divide into three pipes each. The coolant flows through the six pipes and into the EM pump. The EM pump, which is powered by three of the TFEs, pumps the NaK back to the reactor lower plenum.

The cesium supply system provides cesium (Cs) to the TFE interelectrode gap. Cesium is necessary to suppress the space charge that occurs near the emitters of thermionic converters; suppressing this charge substantially increases the efficiency of the converter. The cesium supply system consists of a cesium reservoir, a throttle valve, a cesium plenum, and stainless steel tubing. During operation, the cesium from the reservoir passes through a wick and throttle valve arrangement and provides cesium vapor to the cesium plenum where it is distributed to all of the TFE interelectrode gaps. Cesium vents to space through a valve at a rate of 0.5 g/day.

Testing and Evaluation of the Topaz II

The Topaz II reactor has been the subject of an extensive nonnuclear testing and evaluation program in the U.S. for almost three years. A large Russian facility for performing electrically heated systems tests of the reactor was moved from St. Petersburg, Russia to Albuquerque, New Mexico and returned to operation [2]. The initial goal of this testing activity was to learn from the Russian space power reactor programs and integrate this experience into U.S. space power reactor efforts.

As a part of the Topaz II evaluation, it was decided to assess the viability of employing this reactor in a U.S. space experiment. An initial safety assessment was performed [3] and no "show stoppers" to a U.S. flight were identified. Studies then began to determine if there was a useful flight experiment that could be performed that exploited the unique characteristics of the Topaz II. It was determined that a Topaz II flight experiment could contribute significantly to the knowledge base for nuclear electric propulsion spacecraft environment characterization. A flight program, the Nuclear Electric Propulsion Space Test Program (NEPSTP), was then initiated under the sponsorship of the Ballistic Missile Defense Organization (BMDO). Design work on an electric propulsion spacecraft [4] proceeded through the preliminary design level and the flight qualification of the Topaz II reactor was examined in detail [5]. No barriers to a successful flight were identified. However, refocusing of the activities at the BMDO, combined with budgetary pressures, forced the cancellation of the NEPSTP program at the end of the 1993 fiscal year. The testing and evaluation of the Topaz II continues under the Topaz International Program (TIP).

Despite the termination of the flight program, much has been learned from the Topaz evaluation and testing effort. The Topaz II has been shown to be a very robust and reliable system. A great appreciation has been gained for the capability to perform electrically heated systems tests. During the testing program, several modifications to the Topaz II reactor have been identified that would enhance the capability of the reactor to support a U.S. launch. The most significant modification would replace the Russian automatic control system for the reactor. The existing Russian system was not flight qualified, was massive, and required forced convection cooling. An effort was begun to replicate the functionality of the Russian system using microprocessor technology, that would integrate in a package that is consistent with United States spacecraft design. This effort was terminated soon after the cancellation of the NEPSTP program.

Another significant modification to the Topaz II reactor would serve a safety purpose. Analysis indicates that this reactor may achieve nuclear criticality when immersed in and flooded with water. As this violates United States safety practice, a modification is being considered to store a portion of the nuclear fuel outside the reactor core. A mechanism would then load this portion of the fuel after the spacecraft has achieved a sufficiently high orbit.

The Topaz II testing program continues in Albuquerque. In the near future, at least one of the two flight quality Topaz II units will undergo acceptance testing. As these two reactors are not committed to a flight program, they could become available to support other missions such as lunar exploration.

Issues for Lunar Surface Applications

The use of a reactor power supply, designed to provide spacecraft power, as a lunar surface power supply raises a number of issues. One significant issue for many proposed space power reactors involves thawing the reactor coolant once the lunar surface is reached. Fortunately, the Topaz II uses a NaK eutectic coolant that will thaw naturally during the lunar day.

Many other important issues must be addressed. In order to insure proper heat rejection, the radiator must be given a good view of space. In addition, dust from lunar surface operations could reduce the effective emissivity of the radiator. Fortunately, the testing program has shown that the Topaz II radiator possesses a significant design margin, so minor degradations in radiator performance should not adversely effect system performance. If a specific lunar surface mission were selected, then a combination of calculations and tests could be performed to estimate the degradation in radiator performance for this application. If the degradation in radiator performance is more than can be accommodated by the system design margin, then the system operating power can be reduced. This would have the additional benefit of increasing the reactor operating life for missions not requiring the full six kW electric power output.

The problem of dust on the lunar surface raises other potential problems for a system such as the Topaz II. The reactor mechanical systems must be evaluated to identify systems where dust could pose a problem. The most likely problem area involves the reactor control drum system. It will probably be desirable to employ a lightweight shroud over the reactor unit to minimize potential problems.

Any time a reactor is employed as a power system the issue of shielding must be considered. This issue is especially important for manned systems, but sensitive systems must be protected even in unmanned systems. Many shielding options exist and a separation distance may be combined with a variety of shielding materials to achieve the desired effect. This issue is examined in more detail in the next section.

Another area that must be addressed before the Topaz II can be used as a lunar surface power supply is power transmission. As the thermionic power system produces a relatively low voltage (28V), either large cable masses or significant transmission losses must be accepted for conventional power transmission over significant distances. A potential alternative to this dilemma is presented by microwave power beaming. Systems have been proposed for lunar surface applications [6], that offer transmission efficiencies greater that 80% over large distances. Such systems could minimize the required shielding and also permit power transmission to more than one site.

Shielding for Lunar Surface Applications

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:

- The radiation shield can be well characterized before the start of the mission.
- The handling or processing of lunar regolith is not required.
- Shield properties and performance are not affected by variations in the available lunar material.
- 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 [7] and has the following advantages over schemes that rely solely on burying the reactor or placing the reactor in an existing crater:

- Mechanisms for removing heat from the lunar regolith are built into the shield, and can be tested on earth.
- The fission power supply does not have to be manipulated on the lunar surface.
- 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. 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” [8].

TOPAZ II / Shield Model

A schematic of the TOPAZ II and shield model is shown in Figure 2. 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

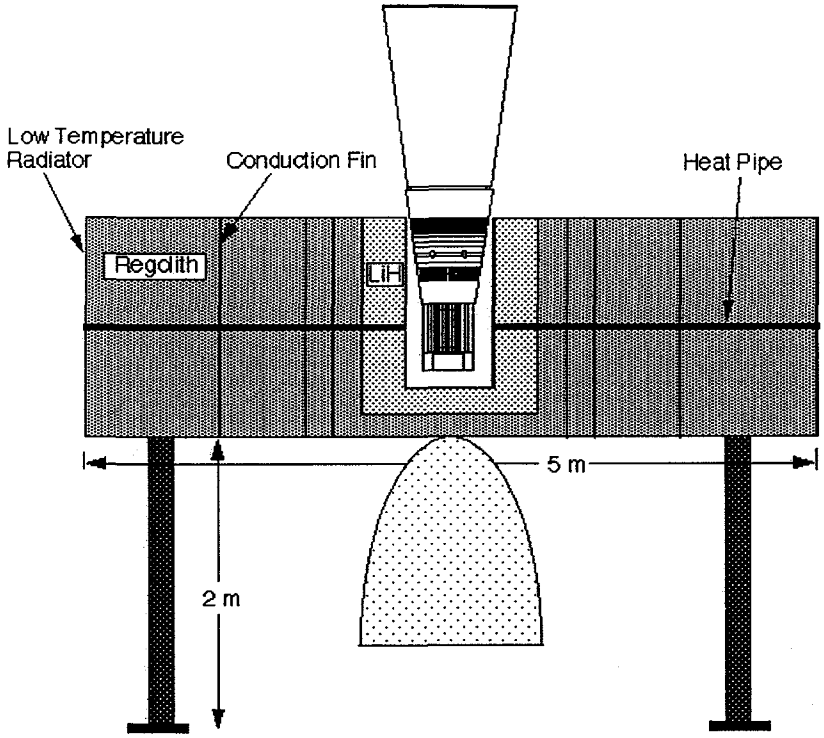

Figure 2. Schematic of the Topaz II and shield model.

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 [9] of that found in the lunar highlands. 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 [10], including the shield, radiator, and other components.

Calculated 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 [7].

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 [11,12].

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 x 10-4 W/cm-K) [9], 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 3. As 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

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

Table 1: Neutron and Photon Dose Rates from Various Sources

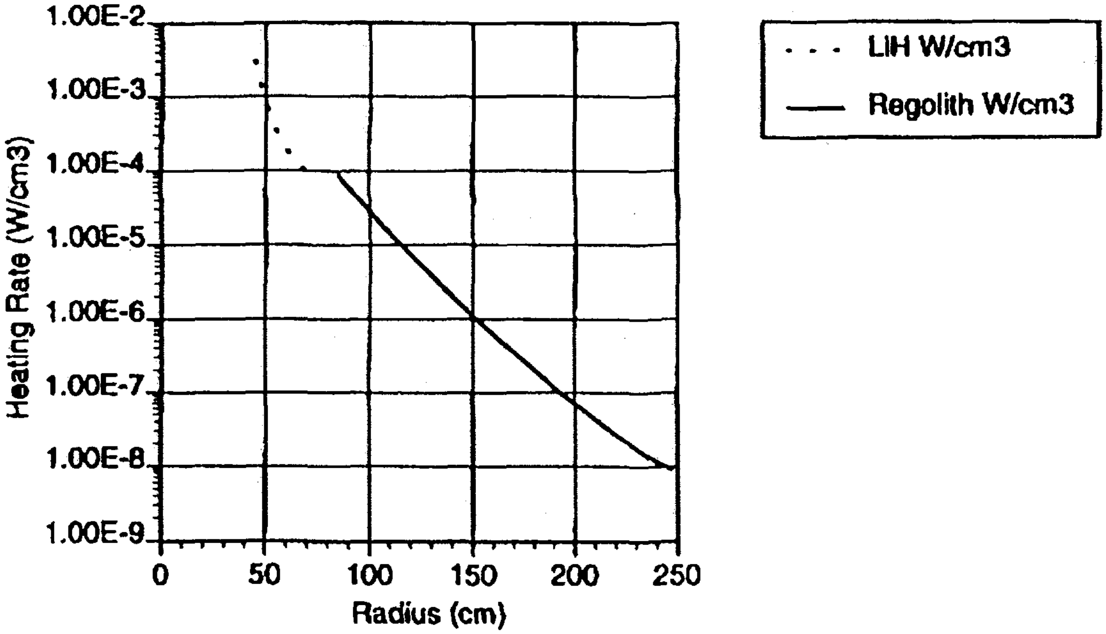

Figure 3. Heat generation rate as a function of radius in the lithium hydride and lunar regolith section if the shield.

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/m2. 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 on Shielding

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. Fourth, radiation levels near the reactor decrease rapidly after operation is ceased. Within a few days after shutdown, the radiation levels at the edge of the shield are not significantly higher than those which occur naturally on the lunar surface.

Conclusions

The Topaz II possesses the potential to serve as a lunar surface power supply to support near-term missions. Several important issues must still be resolved, but this resolution will depend on the characteristics of the proposed mission.

References

1 Voss, S. S., "Topaz II System Description," *Engineering, Construction, and Operations in Space IV - Proceedings of Space 94*, American Society of Civil Engineers, Vol. 1, pp. 717-728, February 26 - March 3, 1994.

2 Morris, D. B., "The Thermionic Systems Evaluation Test (TSET): Descriptions, Limitations, and the Involvement of the Space Nuclear Power Community," *Proceedings, 10th Symposium on Space Nuclear Power and Propulsion*, CONF-930103, M. S. El-Genk and M. D. Hoover, eds., American Institute of Physics, AIP Conference Proc. No. 271, 3: 1251-1256, January 10-14, 1993.

3 Marshall, A. C., V. Standley, S. S. Voss, and E. Haskin, "Topaz II Preliminary Safety Assessment," *Proceedings, 10th Symposium on Space Nuclear Power and Propulsion*, Albuquerque, NM, January 10-14, 1993.

4 Cameron, G., and G. Herbert, "Systems Engineering of a Nuclear Electric Propulsion Testbed Spacecraft," *29th Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, AIAA-93-1789, June 28-30, 1993.

5 Polansky, G. F., G. L. Schmidt, E. L. Reynolds, E. D. Schaefer, B. Ogloblin and A. Bocharov, "A Plan to Flight Qualify a Russian Space Nuclear Reactor for Launch by the United States," *29th Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, AIAA-93-1788, June 28-30, 1993.

6 Bharj, S., S. Perlow, R. Paglione, L. Napoli, R. Camisa,H.C. Johnson, M. Lurie, D. Patterson, and J. Aceti, "A Microwave Powered Rover for Space Exploration in the 21st Century," 1st Annual Wireless Power Transmission Conference, San Antonio, TX, February 23-25, 1993.

7 Lee, S., M. Houts, and J. Buksa, "Nuclear *Power Supply for Early Lunar Bases," Proceedings, Eleventh Symposium on Space Nuclear Power and Propulsion,* DOE CONF-940101, American Institute of Physics, AIP Conf. No. 301, 2:689, January 9-13, 1994.

8 Briesmeister, J.F., "MCNP- A General Monte Carlo Code for Neutron and Photon Transport," LA-7396-M, Los Alamos National Laboratory, Los Alamos, New Mexico.

9 Heiken, G., D Vaniman, and B. French (1991), *Lunar Sourcebook: A User's Guide to the Moon*, Cambridge University Press, pg 38.

10 Houts, M.G., E.W. Hones, J. Birn, G. Scrivner, W. Fan, and P. Agnew, "Nuclear Electric Propulsion Space Environmental Studies," *Proceedings, Eleventh Symposium on Space Nuclear Power and Propulsion,* DOE CONF-940101, American Institute of Physics, AIP Conf. No. 301, 3:1203, January 9-13, 1994.

11 NCRP Scientific Committee 4 on Heavy Particles, H.H. Rossi, Chairman, "Protection Against Neutron Radiation," NCRP-38, National Council on Radiation Protection and Measurements, January 1971.

12 ICRP Committee 3 Task Group, P. Grande and M.C. O'Riordan, Chairmen, "Data for Protection Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15," ICRP-21, International Commission on Radiological Protection, Pergamon Press, April 1971.

DISCLAIMER