Proceedings of the Space Nuclear Conference 2005
San Diego, California, June 5-9, 2005
Paper 1072

POWER MONITORING IN SPACE NUCLEAR REACTORS USING SILICON CARBIDE RADIATION DETECTORS

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Abstract – *Space reactor power monitors based on silicon carbide (SiC) semiconductor neutron detectors are proposed. Detection of fast leakage neutrons using SiC detectors in ex-core locations could be used to determine reactor power. Neutron fluxes, gamma-ray dose rates and ambient temperatures have been calculated as a function of distance from the reactor core, and the feasibility of power monitoring with SiC detectors has been evaluated at several ex-core locations. Arrays of SiC diodes can be configured to provide the required count rates to monitor reactor power from startup to full power. Due to their resistance to temperature and the effects of neutron and gamma-ray exposure, SiC detectors can be expected to provide power monitoring information for the full mission of a space reactor.*

I. INTRODUCTION

Space nuclear reactors for power and propulsion in future NASA missions[1] may need from 1 to 5 MW in thermal power. For the reasons of mass, volume and power density optimization, a fast reactor would be a natural choice. Autonomous startup of such a fast reactor is a challenging task involving changes in power level over 8 to 10 orders of magnitude. Initial insertion of reactivity for the startup does not result in a substantial change in core temperature. Therefore, temperature feedback may not be possible during the startup control process. Monitoring the increasing flux of neutrons is a reliable status indicator during the startup process. When used in space, fast reactor startup and control in an unattended manner would require close monitoring of neutrons in conjunction with the core temperature and reflector position indicators. Coolant temperature and the reflector position alone may not be sufficient for operation of a fast reactor. All terrestrial power reactors made so far have such neutron monitoring as an essential component of the control system. Terrestrial reactor requirements for in-core neutron monitors led to the development of high-temperature neutron detectors operating in the range of 200 to 350°C. Since the fast reactor is more sensitive than thermal reactors, there is an even more compelling case for active neutron monitoring as a part of the control system. The core temperature of a metal cooled fast reactor with a few mega watts of thermal power could range from 800 to 1000°C, which is extremely high for any kind of neutron

detector for reliable operation over 15 years of space mission. The leakage flux from a fast reactor is a good indicator of the actual flux inside the core, and neutron monitoring outside the core provides a less hostile radiation and temperature environment for the neutron detectors. However, ex-core neutron detectors will still need to operate at elevated temperatures, because of the radiant heat from the reactor.

II. REQUIREMENTS FOR SPACE REACTOR MONITORING AND CONTROL

For operation of a reactor the required tasks placed upon the core instrumentation are as follows:

- Criticality control while sub-critical and during approach to critical and start-up
- Reactor period control during start-up and power divergence
- Power maneuvers in the temperature feed-back regime for powers above 1 kW
- Load following in the high power range above 500 kW
- Power limiting and period limiting safety channels for the plant protective system
- Flux distribution and performance monitoring to confirm proper operation of neutronic control actuators and coolant flow channels.

In order to achieve these tasks, the core monitoring instrumentation has to operate reliably throughout the wide range of operating conditions. Therefore the system must perform its task in a variety of challenging temperature and radiation environments:

- After running at high power, the core produces a high gamma flux and a significant heat source from delayed fission product decay. These signals can mask neutronic conditions in the core unless instrumentation can discriminate between gamma and neutron radiation, even when the ratio of gammas to neutrons is high. Only the neutron signal provides an accurate indication of the core fission rate and of its dynamics.
- Environmental background, particularly if it is time-dependent, can perturb core monitoring in the sub-critical and start-up ranges. Therefore, instrumentation that can distinguish spectroscopically between fission and cosmic-ray induced events is beneficial.
- The dynamic range of neutron power is very wide, from milliwatts to megawatts, and in order to avoid the possibility of damaging power transients, it is essential to accurately monitor small changes throughout this range.
- The detectors must be resistant to radiation damage, including burn out of the neutron sensitive elements, over the operating life of the spacecraft.

Neutron monitoring could meet these requirements. Temperature monitoring is also valued for high-power operation, and could be the principal control method for slow power maneuvers. Even at high power, though, the plant integrity can only be assured by means of a monitoring system that responds immediately to the core fission rate.

Neutron detectors for reactor power monitoring and control are usually situated outside the core, observing the leakage neutrons. Additional in-core detectors may be used when it is necessary to monitor the spatial distribution of the power, but these are not necessary for small cores. Terrestrial reactors are surrounded by reflector, moderator and shielding materials and the ex-core detectors are shielded by these to a significant extent, both from nuclear and thermal radiation. In the case of a space reactor, ex-core detectors may be placed in the unshielded leakage field provided the environmental conditions are suitable. The operating temperature of such detectors would be determined by the radiant heat balance. In what follows, a rough estimate for the operating temperature condition for neutron detectors in space reactor is presented.

III. The Temperature Environment for Ex-Core Power Monitors

Without requiring a detailed conceptual design of the reactor, a simple calculation is performed. A conservative assumption made is that the emissivity and absorptivity of the detector surface are equal in all directions (in practice one could make the surface shiny on the reactor side and black on the other side). The emissivity and absorptivity of the detector surfaces are also assumed to be equal to each other. These both depend on wavelength, and hence on the temperatures of the incident radiation and of the emitting surface. So long as the absorptivity is not larger than the emissivity, the calculation will not underestimate the detector temperature. An additional conservative assumption is that the reactor surface is black.

A simple formula results from a heat balance and from the ratio to 4π steradians of the solid angle subtended by the reactor at a small detector. If the only heat transfer is by thermal radiation, the result is

$$\left(\frac{T_d}{T_r}\right)^2 = \left(\frac{R_r}{2R_d}\right)$$, to a good approximation if $R_d \geq 2R_r$

Where:

T_r is the temperature of the reactor surface (equivalent sphere) and
T_d is the temperature of the detector.
R_r is the effective radius of the reactor and

R_d is the radial distance of the detector from the core center.

If one wants $T_d/T_r = 0.25$, then $R_r/R_d = 0.125$. If $T_r = 1300$ K, then $T_d = 325$ K, when $R_r = 30$cm and $R_d = 240$cm.

If the detectors are deployed 2.4 m from the core center, they will only be at 325 K. If one wanted to get the detectors closer without increasing their temperature, then it would be necessary to interpose thermal shields.

At a distance of 120 cm from the reactor, the same detector will be at ~200°C. This defines the operating temperature range from 50°C to 200°C for neutron detectors when placed closer to the reactor. It is assumed here that the detectors are placed as a stand-alone string and not attached to any massive body, which could stay hotter thereby pushing the upper limit of operating temperature.

IV SILICON CARBIDE NEUTRON DETECTORS

A new class of semiconductor neutron detectors[2] based on silicon carbide (SiC) semiconductor provides a good match to the requirements for space reactor neutron power monitoring. SiC semiconductor radiation detectors are being developed for a variety of nuclear applications, including alpha particle,[2-4] beta particle,[5] gamma ray[6,7] and neutron[7-12] detection.

IVA. Neutron Detection With SiC Detectors

SiC detectors based on a Schottky diode design have been produced[2,11] by epitaxial deposition of lightly doped n^- SiC onto a conducting SiC substrate. A Schottky metal contact is applied to the n^- layer, and when a reverse bias is applied to the Schottky contact, the n^- layer is depleted of charge carriers and serves as the active volume of the detector.

SiC p-i-n junctions have also been produced,[2,12] where instead of the Schottky contact, a layer of p^+ SiC doped with aluminum is applied to the n^- layer and covered with a contact metal. As in the Schottky diode case, a reverse bias depletes the n^- layer, which becomes the active volume of the detector.

A SiC Schottky diode neutron detector, relying on detection of thermal neutron-induced tritons from a juxtaposed ^{6}LiF foil, has been tested and shown[8,10] to have a highly linear response to thermal neutron fluence rate in the range from 1.76×10^4 cm^{-2} s^{-1} to 3.59×10^{10} cm^{-2} s^{-1}. The detector response to thermal neutron fluence rate had a better than $\pm$0.6% relative precision when compared to a NIST double fission chamber. The entire fluence rate range was covered in the pulse mode of operation, and, because gamma ray and neutron induced pulses are completely separable on the basis of pulse height, no gamma compensation was required. A SiC neutron detector that had been previously irradiated with a fast neutron fluence of 1.3×10^{16} cm^{-2} had thermal neutron sensitivity characteristics that were indistinguishable from those of the previously un-irradiated detector. SiC detectors have also been shown[7] to have an epithermal neutron response that tracks reactor power to an uncertainty of $\pm$2% with a precision of $\pm$0.6%.

The fast-neutron response of SiC detectors is based on the detection of charged particles resulting from fast-neutron reactions with the silicon and carbon atoms that comprise the SiC detector. Fast-neutron response spectra have been measured for ^{252}Cf fission neutrons, ^{241}Am-Be (α,n) neutrons, 14-MeV neutrons from a deuterium-tritium neutron generator, and cosmic-ray secondary neutrons.[11,12] A response spectrum from fast neutrons from the core of a TRIGA reactor measured at a detector temperature of 300°C was also reported.[11] Recent data[13] indicate that the SiC fast-neutron response tracks reactor power to an uncertainty of better than $\pm$0.6% in the pulse-mode of operation, and that a linear response is also obtained in the current mode.

Therefore, SiC detectors can be expected to have the capability to monitor space reactor power based on fast neutron detection.

IVB. Operation of SiC Detectors at Elevated Temperatures

As a consequence of the large band gap of SiC (3.25 eV) compared to conventional semiconductors such as silicon (1.14 eV) or germanium (0.77 eV), SiC is able to operate at elevated temperatures. Whereas germanium semiconductor detectors require cryogenic cooling and silicon detectors are inoperable above 40°C because of the interference of thermally generated charge carriers with the radiation-response signal, SiC charged-particle detectors have been shown to be unaffected by changing temperatures in the 22-89°C range.[2] More recent measurements show that the response of a SiC detector remains constant up to 306°C as shown by the data plotted in Figure 1. A SiC Schottky diode exposed to a ^{240}Pu check source recorded a pulse-height response spectrum that remained constant when measured in eight different temperature ranges between 19°C and 306°C. The normalized peak centroids at each of these temperatures are plotted as a function of absolute temperature in Figure 2. It can be seen from the data of Figure 2 that less than $\pm$2% change in the detector energy response was observed over this temperature range. In practice, other factors such as

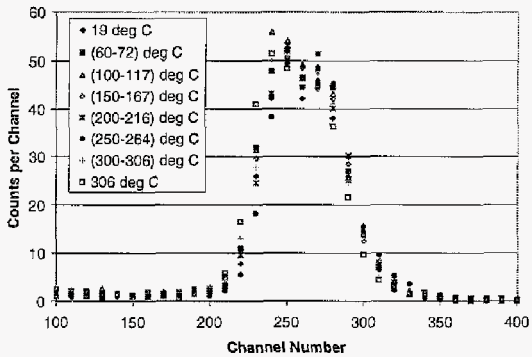

Figure 1. Pulse height spectra for a ^{240}Pu alpha check source as a function of detector operating temperature

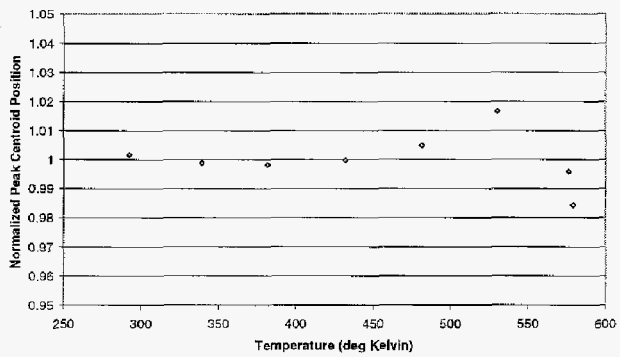

Figure 2. Normalized peak centroid position for a ^{240}Pu check source as a function of temperature.

durability of the Schottky contact at high temperature will limit the detector performance in high-temperature environments. For example, although SiC neutron detectors have been demonstrated[14] to be operational at 700^{0}C, SiC Schottky diodes employing nickel as the Schottky metal will be limited to temperatures less than 300^{0}C as a result of a chemical reaction between nickel and SiC that has been observed to occur over a period of months at 350^{0}C.[15] Other Schottky-contact metals, such as titanium and platinum are expected to be more durable at elevated temperatures, but further test data are needed.

IVC. Radiation Resistance of SiC Detectors

SiC detectors have been shown to have improved resistance to radiation damage compared to other semiconductors. SiC detectors have remained operable after exposures to 1.7 x 10^{17} cm^{-2} fast neutrons (E_n>1 MeV), and 1.1 x 10^{15} cm^{-2} tritons[16] at an ambient irradiation temperature of 45^{0}C. At an irradiation temperature of 230^{0}C, the effects of neutron irradiation are mitigated by a factor of at least 100.[17]

SiC detectors are presently being tested for potential changes in response characteristics following gamma-ray exposure. Measurements to date show that a SiC radiation detector is still operational after a ^{137}Cs gamma-ray exposures of 4.66 x 10^8 rad(Si).[18] A comparison of the ^{238}Pu alpha-particle response spectra for an unirradiated SiC Schottky diode with a 100-μm n$^-$ active layer to an irradiated diode of the same design after a ^{137}Cs gamma-ray dose of 3.78 x 10^8 rad(Si) is shown in Figure 3. It can be seen that

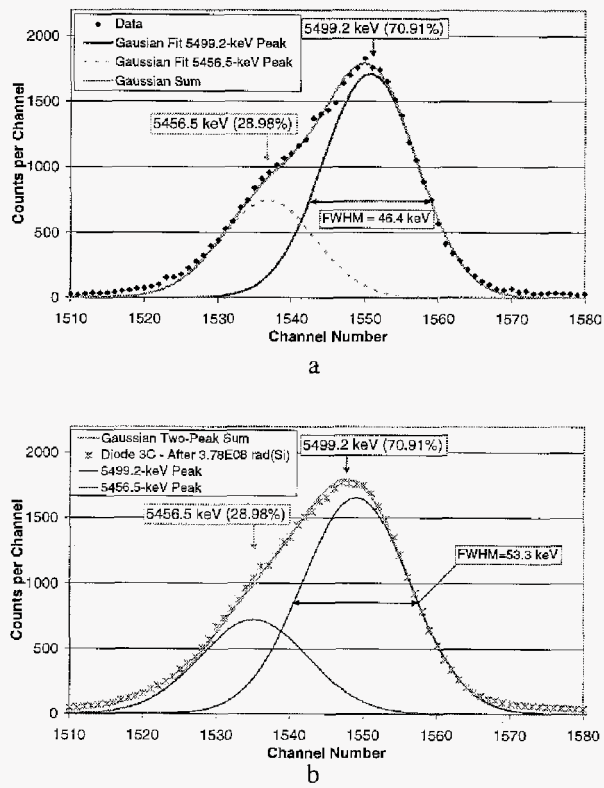

Figure 3. Comparison of the ^{238}Pu alpha-particle responses for an unirradiated SiC detector (a) and a detector irradiated with a 0.378 Gigarad(Si) dose of ^{137}Cs gamma rays (b).

the difference in response between the unirradiated and irradiated detectors is negligible, even after such a high gamma-ray dose. By comparison, silicon radiation detectors show appreciable response degradation after doses of 1 x 10^6 rad(Si)

IVD. Gamma-Ray Discrimination for SiC Neutron Detectors

Gamma-ray induced pulses in a SiC detector have been shown to be completely separable on the basis of pulse height from thermal neutron and epithermal neutron

induced pulses resulting from tritons and alpha particles produced in a juxtaposed ^{6}LiF layer.[2] The fast-neutron response of SiC detectors is caused by the production of charged particles through nuclear reactions in the detector itself, and a broader distribution of pulse heights compared to the thermal and epithermal neutron cases results. A comparison of the pulse-height responses for gamma rays and ^{252}Cf fission neutrons is shown in Figure 4. The measured gamma- and neutron-response data have been adjusted to be characteristic of ^{60}Co gamma and ^{252}Cf fission neutron doses of 2142 rad(Si)/hr and 1.1×10^{9} cm^{-2} s^{-1}, respectively. In the fast-neutron case, the gamma and neutron responses are not completely separable as they are for thermal neutrons. However, the gamma-ray response can be eliminated with a pulse height discriminator resulting in a fraction of the fast-neutron pulses being lost. The efficiency of gamma/neutron separation will depend on the gamma-to-neutron ratio, and will be discussed further in Section VB.

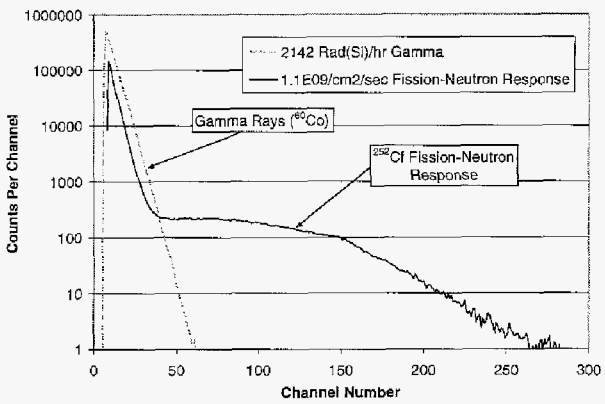

Figure 4. SiC response spectra for ^{60}Co gamma rays and ^{252}Cf fission neutrons.

IVE. Cosmic-Ray Response for SiC Detectors

Only limited data are available on the response of SiC detectors to cosmic rays.[11] A comparison of the SiC response to cosmic-ray secondary neutrons at ground-level to the ^{252}Cf fission neutron response is shown for a 6-mm diameter equivalent x 10-μm Schottky diode in Figure 5.

The cosmic-ray induced neutrons are secondary cosmic rays produced by the interactions of energetic primary cosmic rays (consisting mainly of 1-10 GeV protons) with the nitrogen and oxygen components of the atmosphere. The main features of the cosmic ray neutron spectrum are a direct reaction "knock-on" peak at about 100 MeV and a compound nucleus "evaporation" peak at about 1 MeV.[19] Cosmic-ray neutron response events are visible in the SiC spectrum at very high energies, reflecting the presence of cosmic-ray neutrons of extremely high energy.

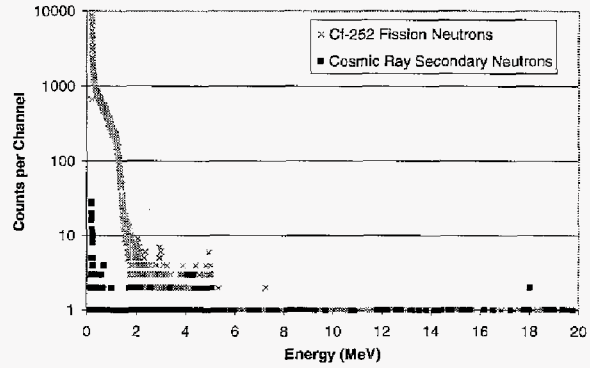

Figure 5. SiC response spectra for cosmic-ray secondary neutrons and ^{252}Cf fission neutrons.

The SiC response cutoff for the low-energy scattering continuum is consistent with the 1-MeV cosmic ray neutron spectrum peak. Both the cosmic-ray and ^{252}Cf responses cover a wide range of pulse heights and no simple discrimination is possible. However, use of upper- and lower-level discriminators to count events only in the ~1-4 MeV response range will tend to discriminate many of the cosmic-ray induced events. In space, the cosmic-ray response spectrum will be much more dominated by high-energy events, including reactions of cosmic-ray primary particles with the SiC detectors. The response to these reactions can also be expected to result in a broad range of pulse heights, and partial discrimination can be achieved by imposing upper- and lower-level pulse height cut offs.

V. SPACE REACTOR POWER MONITORING WITH SiC NEUTRON DETECTORS

VA. Detector Locations and Operating Environment

In order to estimate the range of neutron flux and the total neutron fluence and gamma dose to which a detector might be subjected, calculations have been performed for a notional fast reactor operating at a maximum power of 2.5 MW. A load factor of 80% is assumed, over a mission life of 15 years, resulting in energy production of 30 MW-yrs. The calculations are for unshielded positions, and for a reactor with no vessel, no structural materials and no coolant, and so with a maximum possible fast neutron leakage fraction of about 0.4.

At 2 m distance from the center, the neutron flux (1 MeV equivalent in silicon[20]) at full power is 1.8×10^{11} cm^{-2}.s^{-1}, and the fluence after 15 years is 7×10^{19} cm^{-2}. At that distance the detectors are expected to work up to full power, but might not survive more than about four months

without shielding. The radiant heat flux calculation shows that the temperature will be ~350 K at 2 m.

At 25 m distance the flux at full power is 1.1×10^9 $cm^{-2}.s^{-1}$, and the 15 yr fluence is 4.2×10^{17} cm^{-2}. So the detectors will survive about 6 years in an unshielded position, and with minimal shielding can be expected to last the full life of the mission. At this distance the temperature, if the radiant heat from the reactor was the only heat source, would be ~100 K. It would actually be higher because of radiation from the heat sink panels.

Gamma doses in the leakage from a bare fast reactor can be inferred from the above neutron fluences using a gamma dose to neutron fluence ratio of 1 rad(Si) to 2×10^9 cm^{-2}. A higher ratio of gamma dose to neutron fluence can be expected when the effect of structural and reflector and coolant materials are taken into account, but without increasing the total gamma dose.

We assume that the neutron instrumentation that would be required to approach critical would need to produce at least 2 counts per second with the start-up source in the core, and with the multiplication factor, k, equal to 0.95 . Let us also assume that this count rate corresponds to a core power of 0.025 W, eight orders of magnitude below full power. The corresponding fission rate is 8×10^8 s^{-1} with total neutron source strength of 2×10^9 s^{-1}. The subcritical multiplication at k = 0.95 is 20, so the start-up source itself will need to produce 1×10^8 neutrons per second. With the same leakage probability assumed before, the corresponding neutron flux at 2 m is 1.8×10^3 $cm^{-2}.s^{-1}$.

Based on the above, a concept that would work based on proven technology would use small detectors deployed from the outer edge of the heat sink panels in the unshielded reactor leakage field. They could be placed on either side of the panels, for redundancy, and at more than one distance between 2 and 25 m from the core. The closer ones would be valuable for start-up, extending the dynamic range of the system, and the distant ones would survive for the mission life. Having them in unshielded positions makes the signals easily amenable to calculations and scalable for the different distances. Detector sensitivity could also be varied by changing the active volumes. A possible design challenge would be the need to avoid, or account for, the possible effect of variations in control element positions, especially if these are movable reflectors. This problem may be overcome by restricting the control elements to other sectors of the core surface. Additional detectors, employing the same technology, could be used for environmental monitoring in the payload and elsewhere in the vehicle.

VB. SiC Power Monitor Characteristics

Although SiC neutron detectors can be configured with a variety of neutron and gamma-ray sensitivities, two designs, which have already been tested in fast-neutron and gamma-ray fields will be considered here. SiC p-i-n junction detectors with 4.4-mm x 4.2-mm x 90 μm active volume dimensions[12] have been tested and been found to have a ^{252}Cf fission-neutron sensitivity of 1.37×10^{-4} cps/(cm^{-2} s^{-1}). SiC Schottky diodes with 6-mm diameter equivalent x 10-μm active volume dimensions[11] have also been tested and found to have a ^{252}Cf fission-neutron sensitivity of 1.89×10^{-5} cps/(cm^{-2} s^{-1}).

If the SiC p-i-n detectors are positioned at a distance of 2.0 m from the center of the core in an unshielded position near the edge of the heat sink panels and with the ^{252}Cf startup source described in Section VA in place, a single such detector will have a count rate of 0.25 cps (In this discussion and those that follow, differences in detector sensitivity between 1-MeV equivalent reactor leakage neutrons and ^{252}Cf fission neutrons will be assumed to be small). An array of eight such detectors will give the required 2 cps count rate.

At full power, a single SiC p-i-n diode will give a count rate of 2.5×10^7 cps. Although this count rate exceeds the limits of conventional pulse-processing electronics, preliminary results[13] indicate that specially designed electronics can handle such a count rate. If a 6-mm diameter equivalent x 10-μm Schottky diode is used at this location, a count rate of 3.4×10^6 cps would result. A 1-mm diameter x 10-μm diode will produce a count rate less than 10^5 cps.

At a distance of 2 m, the detector temperature would be approximately 356 K or 83^0C. Over the 15-year lifetime of the reactor, the detector would receive a fast-neutron fluence of 6.8×10^{19} cm^{-2} and a gamma dose of 3.4×10^{10} rad(Si). The fast neutron dose is expected to be a much greater limiting factor on the detector lifetime. Although the SiC detectors will withstand a fast-neutron fluence of 1.7×10^{17} cm^{-2} at 45^0C, the ambient 83^0C detector temperature would extend the lifetime by about a factor of 10, corresponding to about 140 days. If the detector were to be heated to 230^0C, the anticipated lifetime would be more than 3.7 years. A full 15-year lifetime can be assured for the detectors by either maintaining the detectors at 300^0C or using a combination of shielding and elevated temperature. For example, shielding the neutron flux by a factor of four and operating at 230^0C will allow the detectors to survive the full mission lifetime. In this case, the detector array must be increased to 32 detectors to maintain the necessary 2 cps count rate.

Alternatively, the detectors positioned at 2m could be used for startup only, and detectors positioned in a lower neutron flux could be used for power maneuvers from 20-100% power. At 25 m a single 4.2-mm x 4.2-mm x 90 μm SiC p-i-n junction detectors would give 1.51×10^5 cps at 25 m at full power and a 6-mm diameter equivalent x 10-μm Schottky diode would give a count rate of 2.08×10^4 cps.

At 25 m, the SiC detectors would receive a 15-year fast-neutron fluence of 4.2 x 10^{17} cm^{-2} and a gamma dose of 2.1 x 10^8 rad(Si). SiC detectors currently being tested have been shown to be virtually unaffected by twice the anticipated 25-m gamma dose (see Figure 3), but the fast-neutron dose will limit detector lifetime. The temperature at 25 m would be only 101 K (-172^{0}C), and without heating or shielding, the detectors would not last more than 6 years. Heating to about 100^{0}C or shielding the fast neutrons by a factor of 2.5 would ensure that the detectors will survive the full 15 years at the 25-m location.

Deployment logistics may preclude locating the detectors at 25 m, but locations closer to the reactor could be utilized with appropriate combinations of detector sensitivity, detector operating temperature, and neutron shielding. Arrays of either the p-i-n or Schottky detectors could be assembled to give the required count rates for reactor operation at 20-100% power.

The spectral response of a 6-mm diameter equivalent x 10-μm Schottky detector with the calculated gamma dose rate to neutron flux ratio is shown in Figure 4, Although these data correspond to the neutron flux and gamma dose rates anticipated at 25 m, the gamma-to-neutron ratio is independent of distance from the core, so the relative detector responses to gamma rays and neutrons are typical of all unshielded locations. The sensitivity was calculated for a discriminator setting that will reject all but 1% of the gamma-ray response. Raising the discriminator to reject all but 0.1% of the gamma-ray response would result in only an 8% reduction of the fast-neutron sensitivity.

VI. CONCLUSIONS

Power monitoring of space nuclear reactors could be accomplished by monitoring the fast leakage neutrons at a distance from the reactor core. Fast-neutron detectors based on SiC semiconductor provide an effective and versatile means for ex-core power monitoring. SiC detectors can operate in changing and elevated temperatures and are resistant to the effects of neutron and gamma-ray exposure. Indeed, operating the detectors at elevated temperatures mitigates the effects of radiation exposure.

Based on calculations of the anticipated neutron fluxes, gamma dose rates, and temperatures at various locations outside of the reactor core, power monitor configurations based on arrays of SiC diodes have been evaluated. It can be anticipated that these detectors would provide power monitoring information over the entire operating power range of the reactor and for the full 15-year mission lifetime.

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