UPDATE ON RADIATION TESTING FOR SPACE FISSION POWER SYSTEMS

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Radiation effects on materials and electronics is a major topic that needs to be addressed for a nuclear reactor flight demonstration of the Kilopower reactor. The Kilopower project team has taken steps towards developing a standardized radiation environment qualification program for components and materials. Candidate nuclear reactor facilities for both low fluence electronics and high fluence materials irradiations have been identified and approached. Collaborations are being pursued with both NASA and external experts to ensure that the results of the qualification testing are appropriate and relevant to nuclear fission power flight systems.

I. INTRODUCTION

Interest has been growing in a potential flight demonstration mission of the Kilopower nuclear fission power system following the success of the Kilopower Reactor Using Stirling Technology test (KRUSTY)[1,2]. The mission focus will be a lunar surface demonstration as part of NASA's renewed interest in operations on the Moon. The push towards a flight mission will require qualification for all components and subsystems. Of particular interest is the impact of the additional neutron/gamma radiation produced by the fission power source on materials and electronics. Radiation tolerance testing is standard for high reliability components used in aerospace applications, but such testing focuses on the natural space radiation environment which is significantly different from the radiation produced by a nuclear reactor. A parallel radiation test program is being developed using research nuclear reactors to replicate the specific radiation environment expected from the Kilopower reactor[3]. This test program will be used to perform both component level qualification and subsystem accelerated life testing. Candidate facilities have been identified for both low flux electronics testing and higher flux materials testing. Collaborations are being pursued with internal NASA experts on radiation effects testing and external groups with shared interest in nuclear radiation electronics qualifications.

II. KILOPOWER RADIATION ENVIRONMENT

The Kilopower reactor is a nuclear fission power source for space applications capable of producing 1 kW of electrical power in its current iteration. It is designed to be as simple and as small as possible. The nuclear core consists of a cylinder of highly enriched uranium metal alloyed with molybdenum for high temperature properties. A single boron carbide neutron poison control rod is withdrawn from the middle of the core to initiate the fission chain reaction and set the temperature of the core. A beryllium oxide neutron reflector surrounds the core. Kilopower operates as fast nuclear reactor, meaning the neutrons remain at high energies to avoid the use of a bulky neutron moderator such as water or graphite. Operating at 1 kW electrical power using a Stirling engine dynamic power conversion cycle with an overall efficiency of approximately 25% would require 4 kW thermal power from the reactor. The reactor thermal power is directly proportional to the amount of radiation produced from the core. At 4 kW thermal, the reactor will emit about 10^{12} neutron/cm^2/s immediately outside the core envelope. In addition to the neutron radiation, there will be around 1 MRad(Si)/hr of high energy gamma ray irradiation. For a one year mission concept, the materials around the core will receive a fluence on the order of 10^{19} neutrons/cm^2 and 10 GRad(Si) gamma irradiation. Shielding will be required to protect the materials and electronics associated with the power conversion and mission payload systems. Figure 1 shows the expected shielding mass needed for electronics compared to three levels of neutron and gamma total dose tolerance at varying separation distance from the reactor. Identifying more tolerant electronics can reduce shield mass by approximately 40-50%.

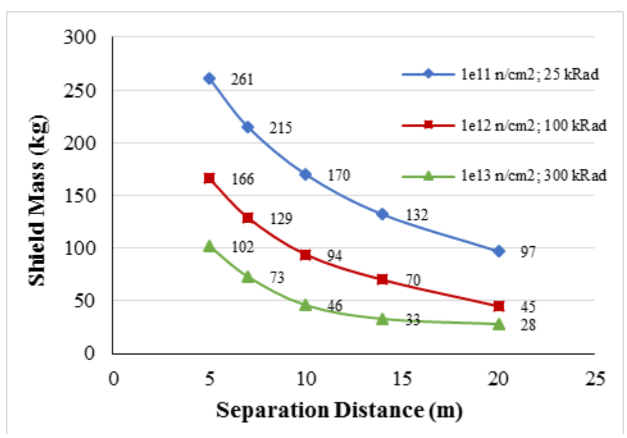

Fig. 1. Shield mass comparison of electronics tolerance and separation distance for 4 kW thermal Kilopower reactor core.

Typical radiation fluence values associated with state-of-the-art electronics tolerance are believed to be 10^{11} neutrons/cm^2 and 25 - 100 kRad(Si) gamma. While the gamma value is based on extensive literature produced by standard space radiation tolerance testing, the neutron value has not been as thoroughly researched. Closing this knowledge gap is one of the main purposes of the nuclear reactor facility program being developed for the Kilopower program.

III. RADIATION FACILITIES

The major cause of radiation damage is the deposition of incident particle energy in the lattice of the target material. However, this translates into different failure mechanisms depending on the function of the material. For metals used in structural and interface applications, radiation induced displacement defects in the material lattice lead to degradation of physical properties. Plastics are affected strongly by ionization caused primarily by gamma radiation, which weakens bonds in the structure to cause embrittlement[4]. While the same damage mechanisms are present in electronic materials, the active function of such materials means that failure mechanisms occur at irradiation fluences several orders of magnitude less than those tolerated by structural metals. Furthermore, the intricacies of electrical device design mean that specific failure mechanisms are technology dependent[5]. Due to the wide range of failure modes depending on material function and application, it is necessary to use a variety of radiation facilities to investigate the radiation tolerance of each part of the Kilopower reactor design.

III.A. The Ohio State University Research Reactor

The Ohio State University Research Reactor (OSURR) is a 500 kW thermal pool type research reactor that operates on-demand within the standard 8 hour work day. There are a number of vertical and horizontal irradiation ports available for component irradiation with access for instrumentation, allowing in-situ measurements to occur. The fast flux level in these ports is around 1×10^{11} n/cm^2/s, which is high enough to investigate the radiation induced failure mechanisms in electronic components without prohibitively long irradiation times[6]. In fact, the reactor will most likely be run at <1% power to allow for longer irradiation times on electronic components before failure. Characterization work for one candidate port, the OSURR Beam Port 1, has been performed in order to design the irradiation procedure for the Kilopower qualification program. Metal foils were irradiated and the resulting activated isotopes were analyzed to determine the neutron spectrum and profile. A gamma probe measurement was also taken to quantify the electromagnetic radiation component, results are shown in Figure 2. The first component tests will take place by the end of 2018, starting with simple linear devices such as power MOSFETs and leading up to full subsystem functional tests.

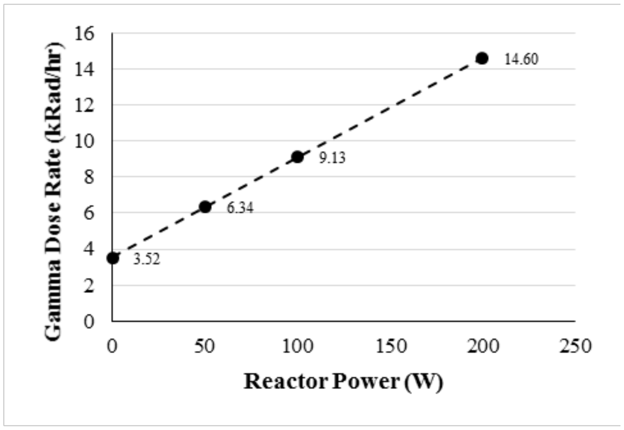

Fig. 2. Gamma dose rate probe calibration of Beam Port 1 at the OSURR.

III.B. University of Missouri Research Reactor

The University of Missouri Research Reactor (MURR) has several key capabilities that differentiate it from the OSURR. First, it operates at 10 MW continuously 24/7 during each irradiation cycle, allowing for longer irradiation times and higher fluences. Second, the irradiation facilities receive higher flux than those in the OSURR, with some MURR facilities receiving up to 6×10^{14} n/cm^2/s[7]. This makes MURR less suited for electronics radiation, but allows for the high fluences required for materials qualification. Finally, the MURR facility also includes hot cells where post-irradiation work can be done on highly activated samples. This capability allows for material properties testing to occur on site immediately following irradiation. The Kilopower group has had initial discussions with the MURR staff regarding Haynes 230 nickel alloy irradiation testing. There is also interest in studying lithium hydride as a neutron shielding material up to the fluences expected from the Kilopower reactor.

III.C. Standard Radiation Test Facilities

In addition to the nuclear reactor facilities, Kilopower components will need to pass qualifications using standard space radiation test facilities. These include facilities such as the Lawrence Berkeley National Laboratory 88-inch Cyclotron, a heavy ion facility, and the Goddard Space Flight Center (GSFC) Radiation Effects Facility, a gamma irradiator source. The Kilopower program plans to collaborate closely with space radiation effects experts, both within NASA and from industry, in order to draw on the abundance of test experience using these facilities.

IV. COLLABORATIONS

There is a large supporting body of work in the field of radiation effects testing, both for structural and electronics materials. The key to successful qualification testing for Kilopower materials will be to collaborate with the experts in these fields to determine what knowledge gap exists for the specific radiation environment of a nuclear reactor system, and what testing protocols can be adapted to close that gap.

IV.A. NASA Radiation Effects and Analysis Group

A key collaborator in this effort will be radiation effects testing experts from within NASA. The Radiation Effects and Analysis Group, under the Electrical, Electronic, and Electromechanical Parts discipline as part of the Office of Mission Safety and Assurance, is set up as NASA centralized repository of electronics radiation testing and knowledge. Kilopower has engaged this group, which operates out of GSFC, to provide best practice electrical test circuitry and procedures for the upcoming irradiation tests at the OSURR. They will also provide access to a pool of high reliability electronics parts that Kilopower can use for testing. The goal is to integrate nuclear reactor testing into the standard space radiation testing schedule to provide a mechanism for parts to be qualified for the combined space and nuclear radiation environment.

IV.B. Industry Partners

Several industry partners will be involved in the system integration of the Kilopower flight system. At the same time that the systems are being designed and integrated, Kilopower will engage with these partners to qualify materials and components in the nuclear radiation environment. The Stirling power conversion control electronics are of primary concern for this effort. Radiation tolerance will be a major design criteria for the solicitation of power conversion technologies for the Kilopower flight demonstration.

IV.C. Nuclear Thermal Propulsion

A third area for collaboration lies with the other major application of nuclear fission in space, nuclear thermal propulsion (NTP). Although the function and design are radically different between a 1 kW electric power reactor and a multi-MW nuclear thermal rocket, there are several areas that are common to both systems. Key among these common areas are the control electronics. Both applications have to account for the additional neutron/gamma radiation environment coming from the nuclear fission reaction. The NTP program also has an interest in using the reactor qualification program developed by Kilopower to test instrumentation and sensors that would be specific to the NTP reactor core.

V. CONCLUSIONS

Qualification of structural and electronic materials in a nuclear reactor environment is one of the major maturation steps needed for a flight demonstration of the Kilopower system. Over the past year, the Kilopower project team has begun laying the ground work for a standardized electronics radiation testing protocol, and preliminary characterization is underway at the OSURR. Component testing will begin by the end of 2018 and continue through the Kilopower flight mission development process. Initial discussions have also taken place regarding high fluence materials testing at MURR. Key collaborators and partners have been identified and engaged to ensure that best practices are followed and to provide a steady stream of components for testing and qualification.

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