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Radiation Specifications for Fission Power Conversion Component Materials

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Abstract

NASA has been supporting design studies and technology development that could provide power to an outpost on the moon, Mars, or an asteroid. One power-generation system that is independent of sunlight or power-storage limitations is a fission-based power plant. There is a wealth of terrestrial system heritage that can be transferred to the design and fabrication of a fission power system for space missions, but there are certain design aspects that require qualification. The radiation tolerance of the power conversion system requires scrutiny because the compact nature of a space power plant restricts the dose reduction methodologies compared to those used in terrestrial systems. An integrated research program has been conducted to establish the radiation tolerance of power conversion system-component materials. The radiation limit specifications proposed for a Fission Power System power convertor is 10 Mrad ionizing dose and 5×10^{14} neutron/cm^2 fluence for a convertor operating at 150 °C. Specific component materials and their radiation tolerances are discussed. This assessment is for the power convertor hardware; electronic components are not covered here.

Background

A fission reactor combined with a Stirling engine power convertor is one technology option being explored for generating space-mission power. Fission power offers robust, environment-independent flexibility and adaptability for a broad range of space mission power requirements. A detailed lunar/Mars design concept has been developed previously by a joint NASA and DOE team (Ref. 1), and serves as a foundation for system-level technology development that can be readily adapted to a broad range of missions. The Fission Surface Power System (FSPS) concept developed for the moon and Mars would

provide 40 kW_e (kilowatt electric) power for an eight-year service life. The power conversion system would utilize multiple, dual-opposed, free-piston Stirling engines with linear alternators providing nominally 6 kW_e power output per alternator. The system was designed with convertor engines assuming heater head and heat rejection temperatures of approximately 525 and 125 °C, respectively. This reference design suggested a radiation shield between the reactor system and power conversion system that would limit radiation to 5 Mrad (gamma dose) and 2.5×10^{14} neutron/cm^2 (neutron fluence) at the power convertor components (Ref. 1). One risk reduction task for this program was to examine the power system component materials and establish more rigorous radiation-limit specifications for the power conversion system.

The study of space-mission radiation effects on materials is not new. Guidelines for determining radiation tolerance have been presented previously for space vehicle design (Ref. 2). The recommended three-step approach for assessing spacecraft radiation protection is to first define the environment, then to review the anticipated radiation response on representative component materials, and finally to determine that each design subsystem will perform as required in the predicted environment. The FSPS definition document (Ref. 1) provided the baseline mission and environment definition. Previous reports identified candidate materials-of-construction that may be sensitive to the radiation environment resulting from a fast-spectrum fission reactor (Refs. 3 and 4). The Stirling engine-based power conversion system structure is primarily fabricated from metallic alloys. Metallic alloys experience inconsequential changes in mechanical properties for neutron fluences of less than 10^{17} neutron/cm^2 based on established guidelines and are not structurally affected by ionizing radiation (Refs. 2 and 5). However, there are components within the power conversion system that rely on polymeric and magnetic materials and these materials require radiation hardness scrutiny.

Polymeric Components

Polymeric materials are employed for a number of applications in Stirling power convertors including insulation, bonding, sealing, and surface treatment. In terrestrial Stirling convertors, polymer selection is driven primarily by the upper-temperature limit. Polymer stability can be characterized in a number of ways including mechanical properties, outgassing, and physical properties such as the glass-transition temperature, T_g. The mechanical properties of interest depend on the specific component application. Outgassing refers to the loss of volatile species from the polymers. The T_g refers to the transition from a low-temperature glassy state to a high-temperature rubbery state and is a common gauge of both the chemical stability and the changes in mechanical properties.

Polymeric materials can be used in a variety of bonding applications in a free-piston convertor/alternator system including lamination and permanent magnet attachment, and sensor attachment. Similarly there are potting applications such as coil fixation and feed-through reinforcement. Durability is key to the bonding material functionality in the alternator. The bonding materials must retain thermal and dimensional stability, as well as maintain tensile and/or shear strength. Bonding materials must obtain a highly-cured state at temperatures compatible with the components being bonded. This is a particularly relative concern for adhesively-bonded permanent magnets for which the bonding-material cure temperatures cannot induce demagnetization. In potting applications, dimensional and thermal stability is crucial while the tensile or shear strength is less important. Low resin viscosity also may be required to obtain adequate coverage. Due to the need to keep the assembly temperatures below the demagnetization temperatures, epoxies are the baseline choice for bonding and potting.

Although metallic or close-clearance seals dominate Stirling designs, there are instances were polymeric seals can provide additional functionality. Dimensional stability, extrusion resistance, and resistance to embrittlement are required in these sealing applications. Rubbery elastomers, such as silicon, are needed for these seals.

Electrical insulation is required for various wires and electrical connections, especially in the alternator section of a power convertor. Although dielectric strength is the primary requirement of an electrical insulation, the insulation coating must be flexible enough at the beginning of life to

accommodate assembly and launch loads. Over the long-term operation of a FSPS mission, impact and vibration loads are minimal, but severe embrittlement and spallation must be avoided. As with other polymeric materials, chemical stability must be such that there is minimal outgassing induced by elevated temperature, radiation, or a combination thereof. In terrestrial Stirling systems, polytetrafluoroethylene (PTFE/Teflon, Dupont), polythermaleze, and polyimide wire coatings are common choices. Commercially available heat-shrink coatings are typically based on vinylidene fluoride.

Modern Stirling convertors perform without contact at piston and displacer running surfaces during normal operation. Typically, solid lubricant coatings are applied to these running surfaces to minimize friction or stiction at start-up or under severe service conditions. The lubricant coating system must maintain adhesion, lubricity, impact resistance, and scratch resistance to function in the power convertor. The coatings must not generate debris that could interfere with the close clearance seals. There are a number of high temperature, ceramic-based solid lubricant systems, but polymer-based coatings such as Teflon fluoropolymer (DuPont), Emralon fluorocarbon (Acheson Colloids), and Xylan fluoropolymer (Whitford Corporation) are available for the temperatures currently required.

Stirling convertor designs can use composites, such as glass-reinforced epoxies, as structures within the convertor. Dimensional stability, electrical insulation and minimal outgassing would be the primary performance requirements for this type of application.

The definition of the radiation environment and the irradiation response in polymeric component materials is important for the FSPS because polymers can be damaged by radiation levels that are much lower than the levels affecting metallic and ceramic materials. Organic polymers are long, complex chains of covalently bonded atoms. The precise molecular structure including chain length, atom arrangement, and side-bonding (also known as cross-linking) determines the physical properties of the polymer. Ionizing radiation, which includes high energy protons, electrons, heavy particles, gamma-rays, and x-rays, can interact with polymers in several ways. The typical primary event is the ionization of an atom which locally breaks a covalent bond and creates a free radical that can then recombine somewhere else in the molecule (Ref. 6). In fact, the propensity for secondary and tertiary events from each primary radiation interaction is one of the reasons that radiation can be so damaging in all organic materials. The physical manifestation of the polymeric radiation damage is either scission or cross-linking of bonds. The scission or cross-linking can result in either softening or embrittling. The temperature of the polymer during irradiation is important since chemical mobility is a function of temperature. Furthermore, the gaseous environment surrounding the polymer is also key because the free radicals can combine with oxygen and accelerate material wastage.

A perusal of the polymer irradiation literature suggested that the component radiation tolerances should be acceptable for this application. However there were certain concerns. The general radiation tolerance of polytetra-fluoroethylene (PTFE/Teflon) has been demonstrated to be quite low, especially in the presence of oxygen (Ref. 7). Though it has been shown that the specific chemistry of the PTFE can have a significant impact on the radiation resistance (Ref. 8). Also it is important to note that most of the irradiation literature is based on experiments performed in air and at room temperature. Drawing conclusions for the Stirling system radiation tolerance from the literature was problematic since both oxygen and temperature impact the radiation response. Furthermore, numerous studies have shown that additives or changes in formulation of the same basic polymer have a notable affect on the radiation resistance (see for example Refs. 9 and 10). It was deemed appropriate to confirm the radiation tolerance of mission-relevant polymeric materials under the correct environmental conditions of elevated temperature and inert cover gas, as recommended in the third-step of the approach for assessing spacecraft radiation protection (Ref. 2). Moreover, the changes brought about by irradiation were characterized both in terms of general chemical and physical response and in terms of component-specific characterization, such as shear-testing or compression-set, where applicable.

Magnetic Components

Magnetic materials are necessary in the alternator section of the Stirling engine where the relative motion of permanent and soft magnets generates an alternating current. A hard, or permanent, magnetic material is one that requires a large magnetic field to induce magnetization and then retains this magnetization in the absence of the applied field. However, magnetic permanence is a bit of a misnomer because certain combinations of elevated temperature and reverse magnetic field will erase the electron-spin alignment that produces magnetism. The permanent magnetic materials required in the FSPS alternator must have high coercive force strength (coercivity) and high remanent magnetic flux density (remanence) since the alternator performance is maximized for high values of both coercivity and remanence. A soft magnet is a material that will be magnetized in the presence of a magnetic flux and thereby affect the shape and strength of the overall magnetic field. Yet the remanent magnetic field in the soft magnet will be low once the applied field is removed. Soft magnetic materials thus are characterized by high permeability and low coercivity such that the material can be magnetized and demagnetized with minimal energy loss or hysteresis energy (Ref. 11).

The primary irradiation damage mechanism in all metals is atomic displacement that can occur when a neutron or heavy ion strikes a metal atom with sufficient energy to cause an elastic or non-elastic reaction within the crystal structure. The recoiling atom is referred to as the primary knock-on atom and its energy is distributed to other nearby atoms by a series of secondary collisions in what is called a displacement cascade. This produces empty lattice sites (vacancies) and atoms injected into the interstices between lattice sites (interstitials). Fortunately, most vacancies and interstitials recombine along the original lattice structure. Those that do not recombine are responsible for radiation-induced microstructural and property changes. Materials with metallic bonding are insensitive to ionizing radiation because the electron cloud easily redistributes in response to electron orbit changes. As mentioned previously, mechanical property changes in metallic alloys do not become significant until neutron fluences exceed 10^{17} neutron/cm^2. However, permanent magnets can be affected by irradiation at levels as low as 10^{12} neutron/cm^2 with both temperature and demagnetization field being important correlating factors (Ref 12). Numerous studies have shown that SmCo-based magnets also have greater resistance to neutron irradiation than NdFeB-based magnets possibly due to a combination of thermal and radiation-induced degradation (Refs. 12 to 14). Gordon and Sery reported the onset of degradation in Ni-based soft magnetic material around 10^{17} neutron/cm^2 and the onset of degradation around 10^{18} neutron/cm^2 in a Fe-49Co alloy (Ref. 15). The review of literature irradiation data was deemed sufficient for ensuring that Fe-based soft magnetic materials and SmCo-based permanent magnets would perform as required in FSPS radiation environments.

Radiation Hardness Testing

The linear alternator candidate materials must be capable of tolerating a mixed neutron and gamma-radiation environment to successfully complete the envisioned mission scenarios. The objective was to evaluate the performance of candidate polymeric materials used in the alternator by subjecting material coupons to similar neutron fluences and ionizing doses at the appropriate operating temperature and gas environment. A mixed, neutron and gamma, irradiation environment best simulates the anticipated FSPS mission environment. However, the neutron activation of certain materials greatly increases the safety risk, handling protocols, and hence the cost of those experiments. Therefore, experiments using a combination of test facilities generated a broad range of information in a cost-effective approach. Individual material coupons were exposed to ionizing radiation at a Oak Ridge National Laboratory (ORNL) gamma irradiation facility (GIF). The ORNL coupon-test matrix was augmented with a smaller matrix of samples exposed to a mixed-fluence environment at the Texas A&M University (TAMU)

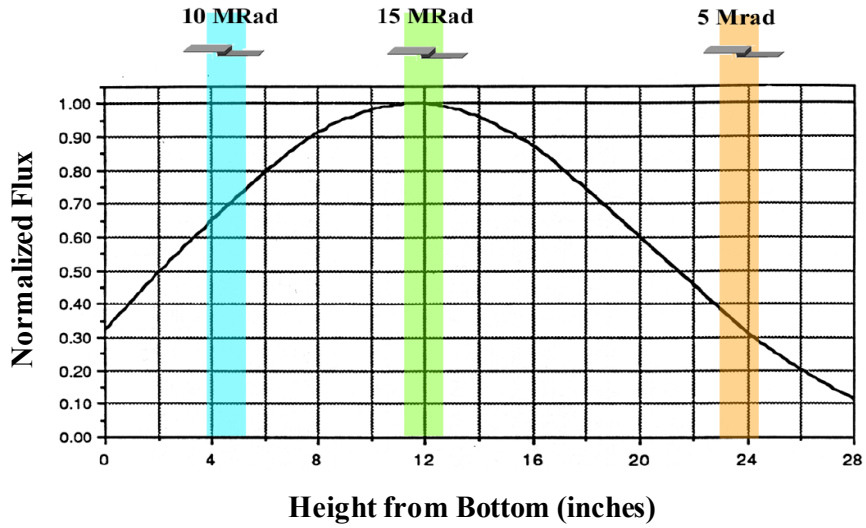

Figure 1.—Gamma flux variation along the axial length of the test canister. Highlighted regions show the target specimen dose examples.

research reactor. Also a prototypic alternator, the Stirling Alternator Radiation Test Article (SARTA), was tested at a Sandia National Laboratories (SNL) GIF. Accelerated dose rates could be used in these experiments since oxidative processes are the major contributor to time-dependent radiation degradation in polymers and an inert-gas environment is relevant for the FSPS power convertor system.

The first coupon irradiation testing was conducted at ORNL's High Flux Isotope Reactor (HFIR) GIF. The HFIR spent-fuel assemblies decay in a water holding facility. Adjacent locations in the pool are available for gamma exposure testing. The advantage of this test facility is that the flux distribution along the length of the test chambers allows for the accumulation of more than one dose in a single experimental run. Figure 1 illustrates the relative gamma flux profile along with approximate sample locations used to achieve three target doses at once. Dose rates in the irradiation canister vary with the age of the fuel assembly, but can be as high as 105 rad/hr. Radiachromic film dosimeters were used to measure the actual gamma dose at the test specimen locations in the sample holders. The inner dimensions of the canister available for irradiation testing are approximately 7.5 cm diameter and 63 cm length. The cap of the irradiation canister was fitted with gas handling and electric power feed-through junctions to incorporate the environmental requirements for the irradiation tests. The canister insert consisted of a multi-zone heater cartridge to which the sample holder assemblies were attached. The canisters were filled with argon to provide an inert cover gas. The sample holder assemblies were made of aluminum to maximize thermal conduction and minimize radiation absorption. Different sample holders were fabricated to accommodate various material specimens.

Table 1 lists the coupon descriptions, the exposure temperatures, and the dose calculated from the dosimetry calibrations and Monte Carlo N-Particle Transport Code (MCNP) calculation with respect to position, exposure time, and maximum dose. All exposures were performed under inert, argon cover gas. Two types of epoxy, Hysol (Loctite) and Duralco (Cotronics), were tested. Two types of elastomer o-rings, silicon and Kalrez (DuPont), were tested. Commerically available coated wires were tested. Viton (DuPont) and Kynar (Arkema Group) heat shrink materials were teste. A Xylan (Whitford Corporation) solid lubricant was tested.

A second set of coupon irradiation tests was conducted at the TAMU TRIGA (General Atomics) Mark I reactor. The samples were exposed in the confinement building, which is a dry, irradiation cell adjacent to the reactor pool. The reactor core is coupled to the irradiation cell through an irradiation cell window. The average thermal and fast neutron fluxes in the vicinity of the irradiation cell window were experimentally characterized through the use of threshold activation foils. The use of several types of

TABLE 1.—TEST MATRIX FOR ORNL IRRADIATED COUPONS AND CALCULATED DOSE

Coupon Type	Temperature, °C	Dose, Mrad
Epoxy and epoxy shear assembly	125, 150 125	3, 12, 14 15, 71
Elastomeric o-rings	125, 150	3, 12, 14
PTFE-insulated wire	125, 150 125	3, 12, 14 15, 71
Polyimide-insulated wire	125	3, 12, 14
Heat shrink tubes over Al rods	125, 150	3, 12, 14
Solid Lubricant Coating	125, 150	3, 12, 14

TABLE 2.—TEST MATRIX FOR TAMU IRRADIATED COUPONS AND CALCULATED DOSE

Coupon type	Temperature, °C	Dose, Mrad	Fluence, n/cm^2
Epoxy shear assembly	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}
Elastomeric o-rings	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}
PTFE-insulated wire	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}
Polyimide-insulated wire	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}
Heat shrink tubes	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}
Solid lubricant coating	125, 150	1.4, 5.4	1×10^{14}, 5×10^{14}

activation foils allowed the neutron spectrum to be estimated at discrete energies. The spectra were then used to benchmark the existing MCNP models in the vicinity of the irradiation cell window. Two types of gamma dosimeters were used to characterize the spatial dose rates as a function of distance from the window. A location 11 cm from the window face was selected as best to achieve the required operational neutron fluence while staying within a mission-relevant dose limit of 10 Mrad. The combined measurements and modeling provided an average total neutron flux estimate of approximately 2.9×10^{11} neutrons/cm^2/sec and a corresponding gamma-ray dose rate estimate of 0.12 to 0.14 Mrad/min at the test location. Aluminum pressure vessels were used to house the specimens during irradiation. The pressure vessels were evacuated then charged with high purity helium and heated to the desire exposure temperature. Additional details on the test configurations are given in References 16 and 17. Table 2 lists the coupon material types exposed in the TAMU testing.

The final series of experiments involved irradiation of a motoring test article which captured the functionality of a Stirling linear alternator. The Stirling Alternator Radiation Test Article (SARTA) was fabricated by Sunpower, Incorporated. The potentially radiation-sensitive polymeric materials and magnetic materials were represented in their expected component applications. The SARTA utilized typical hard-magnetic material, soft-magnetic-material lamination cartridge, cylinder, and cylinder o-rings. Two, metal-sheathed, type-K thermocouples were bonded within the alternator. The motor was encased in a stainless steel pressure vessel mounted on a transition plate with power, gas, and thermocouple feed-through junctions. Motoring control for the SARTA was provided by a manually-operated, variable-frequency power supply. Temperature control was provided by a combination of external cooling and closed-loop heating. The operating conditions of alternator power, alternator current, alternator voltage, stroke magnitude, pressure, internal temperature, and external temperature were continuously recorded during motoring. Engine noise was monitored through a microphone for audible feedback.

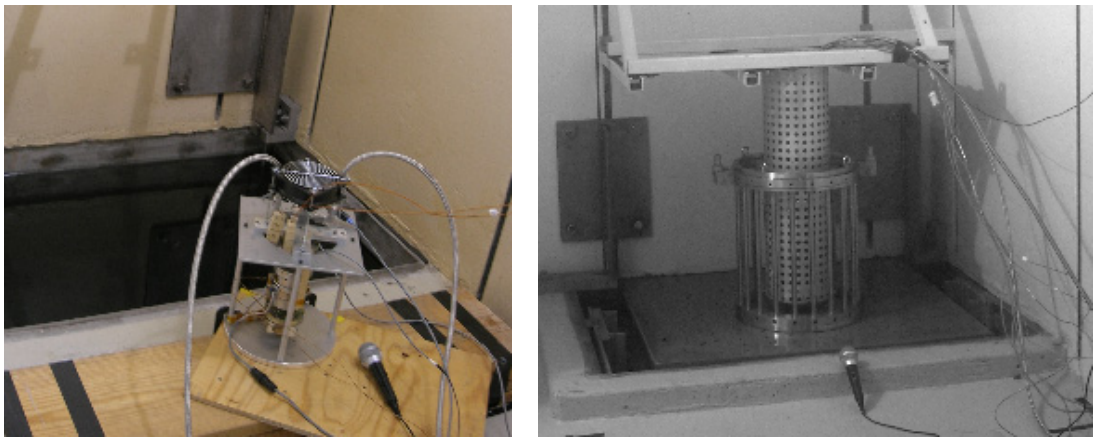

Figure 2.—SARTA mounted in low-dose-rate configuration, source down (left). SARTA mounted in high-dose-rate configuration, source up (right).

TABLE 3.—TEST MATRIX SUMMARY FOR SARTA EXPOSURES INCLUDING CALCULATED DOSE RATE AND CUMULATIVE DOSE

Irradiation runs	Temperature, °C	Dose rate, rad/s	Approximate dose/step, Mrad	Cumulative dose, Mrad
1 to 4	90	80	0.14 to 0.35	0.98
5 to 7	90	80	1 to 1.3	4.0
8 to 9	90	850	0.25	4.5
10 to 13	90	850	2 to 10	22.4
14	125	80	0.3	22.7
15 to 18	125	850	1 to 10	40.1

The SARTA hardware was irradiated at SNL. This facility uses a 155.6 kCi ^{60}Co source (source strength at the time of exposure) that consisted of a 20 pin, 32 cm diameter circular array. Two different locations were used in the test cell to provide two different dose rates. The SARTA test article was placed in the test cell approximately a meter outside the Co^{60} array for the low-dose-rate configuration. The test article was positioned inside the array for the high-dose-rate configuration. Figure 2 shows the test article in each configuration; the high-dose-rate configuration is shown as viewed through a leaded-glass window. CaF_2 thermo-luminescent dosimeters were used to measure the actual dose for six, short-duration test runs. The calculated average dose rate was 78.9 rad/sec for the low-dose-rate configuration and 854 rad/sec for the high-dose-rate configuration.

The operating performance of the alternator was measured continuously during irradiation. Between each irradiation test the inductance, resistance, and resistance-to-ground were measured for the alternator coil and the fast linear displacement transducer coil. Table 3 summarizes the operating temperature and dose accumulated for the SARTA irradiation testing runs (Ref. 18). Itterative step changes were made to increase the test condition severity based on the component temperature, the dose rate, and the accumulated dose per step. Although the variation in operating parameters between the baseline testing at NASA Glenn Research Center (GRC) and the testing at SNL were greater than anticipated, the operating conditions measured during all 18 irradiation experimental runs appeared to be quite stable. Differences in the support systems at GRC and SNL resulted in larger pressure leak rates during the testing at SNL, presumably due in part to leakage around thermocouple fittings and at the pressure regulator. In fact, the biggest influence in electrical performance found during the irradiation runs appeared to result from the fluctuation in system pressure.

Post-Irradiation Evaluation Techniques

A range of techniques were used to evaluate possible physical and chemical changes due to the combined thermal and radiation exposures. Specimen weights were measured before and after irradiation using standard, calibrated scales to assess possible weight loss or gain due to mechanisms such as oxidative processes. Specimen dimensions were measured before and after irradiation using standard, calibrated calipers to assess possible shrinking or swelling. A standard drying process was used prior to weight or dimension measurement. Visual changes were assessed using manual inspection as well as optical microscopy up to 1000× magnification. Scanning electron microscopy was used for higher magnification visualization of select samples as well as qualitative surface chemistry using energy dispersive spectroscopy. The bonding strength of the candidate epoxies was assessed using sub-scale, lap-shear tensile specimens. Lap-shear tests were performed at 120 °C in air with a standard, screw-driven, universal load frame. The o-ring samples were evaluated through a combination of leak testing, compression set, and residual tensile strength. Various micro and nano-scale tests were employed to determine potential radiation-induced mechanical property changes in the polymers used as insulation sleeves, insulation coating, shrink tubing, and rub-surface coating. The nano-scale coating tests were performed by Nanovea, Irvine, California. A Thermo Electron Nicolet 380 FTIR was used to obtain surface chemical spectra for material samples. This technique provides a good indication of the changes in surface chemistry, as indicated by the presence of different peaks, peak shifting, or large changes in peak intensity. A TA Instruments Q-1000 Differential Scanning Calorimeter (DSC) was used to produce heat-flow-difference curves from specimens weighing 5 to 10 mg. This technique identifies exothermic or endothermic reactions, phase transitions such as melting, glassy-rubbery transitions, and the degree of curing. A TA Instruments Q-500 Thermo Gravimetric Analysis (TGA) system was used to measure outgassing through weight change as a function of temperature and the thermal degradation temperature (T_d). For all physical and chemical measurements, control specimens were tested which had experienced thermal aging comparable to the time-at-temperature experienced in the elevated-temperature irradiation testing.

Post-Irradiation Evaluation Results

Epoxy coupons experienced no systematic or statistically significant changes in weight, dimensions, appearance, or physical/chemical properties as a function of irradiation under the conditions studied. The epoxy-bonded lap-shear test results exhibited a high degree of variability, which made trends in strength or strain-to-failure difficult to isolate. There did appear to be a slight decrease in both strength and strain-to-failure as the result of thermal aging and, possibly, an additional decrement due to irradiation at elevated temperature. However, it must be emphasized that the changes between average values were less than the scatter as defined by standard deviation.

Elastomeric o-ring samples experienced no systematic or statistically significant changes in weight, appearance, or physical/chemical properties as a function of the irradiation under the conditions studied. There was a slight compression-set for the o-rings irradiated under load (ORNL gamma testing) and slight swelling for o-rings irradiated not under load (TAMU mixed-fluence testing). In post-irradiation inspection of the SARTA hardware, there was considerable compression-set observed for a silicon o-ring, but no loss of sealing was apparent. In the ORNL gamma-irradiated coupons there was no loss in sealing as a result of irradiation but there were slight changes in residual tensile strength. In post-irradiation tensile testing of the o-rings, gamma radiation appeared to decrease the strain-to-failure and increase the tensile strength for silicon o-rings. However, gamma radiation exposure decreased both the strain-to-failure and the tensile strength for Kalrez o-rings. Tensile testing was not performed after mixed fluence exposures.

Compression-set of the elastomers was a particular area of concern based on the previous irradiation literature. The compression-set property, C_B, was defined by $C_B = (t_o - t_f)/(t_o - t_{shim})$, where: t_o = original specimen thickness, t_f = final specimen thickness, and t_{shim} = shim thickness (i.e., $t_{shim} = 0.75\ t_o$). The

residual compression set was measured at 30 min after unloading and also measured at other times up to 48 hr after unloading to monitor recovery. Figure 3 shows the compression-set results for the two types of elastomeric o-rings tested. Here open symbols represent post-gamma-only irradiation and filled symbols represent post-mixed-fluence irradiation. Cross symbols represent as-received or after thermal aging. Scatter bands are shown for the as-received material data set. The silicon material experienced less compression-set than the Kalrez. For the silicon, there might be some increase in compression-set for exposures at the highest temperature, but more data would be required to confirm that the trend is real and not an artifact of scatter within the data. The irradiated Kalrez samples experienced relatively the same compression-set as the controls specimens.

The PTFE-coated wires were the component most affected by irradiation. Although there were no systematic or statistically significant changes in weight or dimensions, visible cracks were seen after 15 Mrad at 125 and 150 °C in gamma-only ORNL testing. Cracks were also found in the PFTE-insulated wires during SARTA disassembly and inspection (Ref. 19). This cracking can be seen most readily when the wires are cut. Examples are shown in Figure 4. DSC results appeared to indicate an increase in heat-of-melting which would suggest an increase in crystallinity after 3 Mrad exposure, but the data variation was too large to be conclusive. Limited nano-indentation data suggests an increase in hardness due to thermal history alone, followed by an additional increase in hardness due to irradiation. The limited data generated between 3 and 15 Mrad makes it difficult to assign a safe radiation limit based on these results. PTFE insulation is not recommend for FSPS applications above 5 Mrad without additional experimental verification.

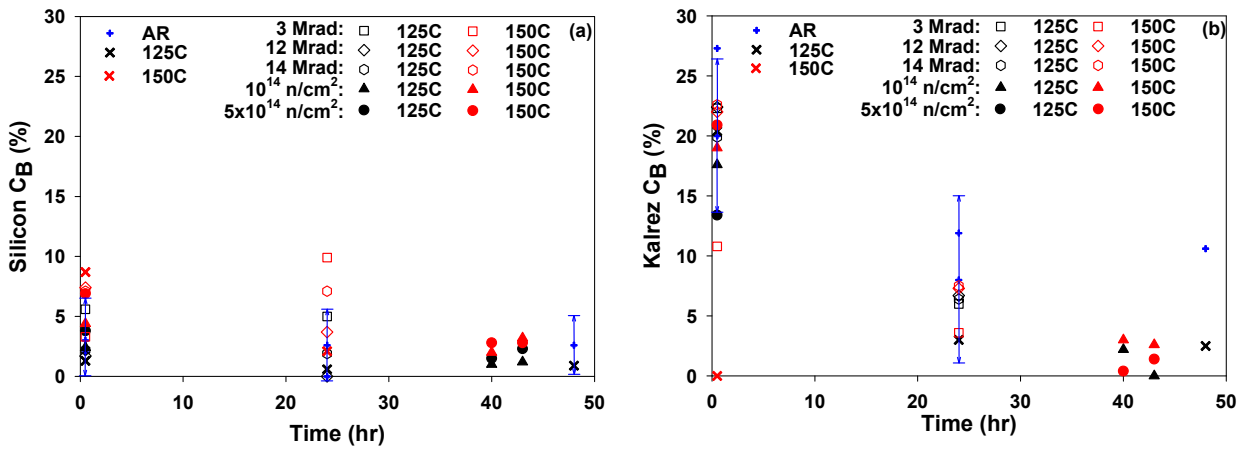

Figure 3.—Percent compression-set versus relaxation time for (a) silicon and (b) Kalrez o-rings.

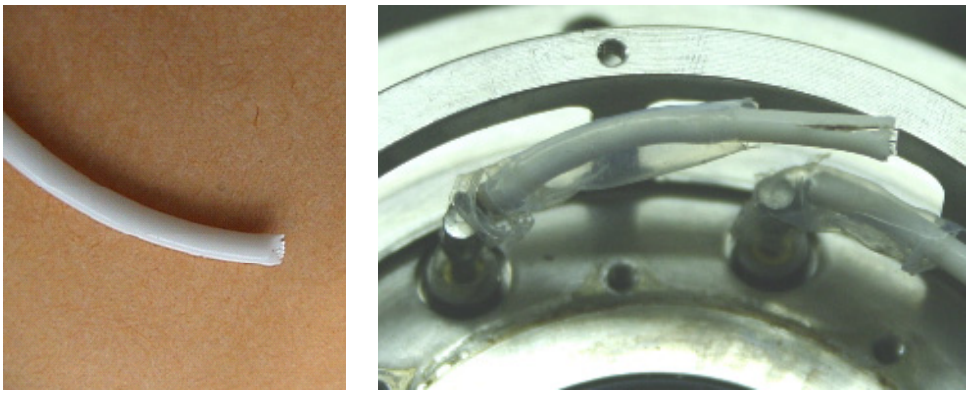

Figure 4.—Cracks developed in PFTE wire insulation are readily observed when irradiated wires were cut after (a) 15 Mrad gamma exposure at 125 ºC and (b) the cumulative SARTA exposure.

Polyimide-coated wires had very thin coatings which were difficult to interrogate by visible inspection. Limited nano-indentation data on the polyimide-coated wires suggested an increase in polyimide hardness due to thermal history alone, followed by a slight decrease in hardness after 3 Mrad, a larger decrease after 12 Mrad and then an additional increase after 14 Mrad. More analysis is underway to attempt to understand this apparent change in mechanism. Load-to-initiate delamination appeared to increase as a function irradiation for the polyimide-coated wires. The SARTA performed within expected variation through motoring up to 40 Mrad. However, a short-circuit was detected in post-radiation inspection after the unit was removed from the test cell. Post-irradiation disassembly suggested that the short-circuit occurred in the SARTA alternator windings, which are conductive wires coated with polyimide insulation. The alternator wire could not be unwound for detailed inspection because the wire was encased in potting material. It was determined that removing the potting material might damage the coating and it would be impossible to discriminate between disassembly damage and irradiation damage. Therefore the source of short-circuit could not be identified. It should be noted that the SARTA was a one-offering, proto-type designed specifically for this test and the steady-state operational life of the unit in absence of irradiation is likewise unknown. Even though literature data suggests that polyimide materials in general have high radiation resistance, the current work suggests that alternator windings with thin polyimide coatings should not be used for FSPS applications above 10 Mrad without additional experimental verification.

The heat-shrink materials irradiated in the ORNL gamma-exposure testing had been pre-shrunk on aluminum rods under controlled furnace conditions. These heat-shrink samples experienced no systematic or statistically significant changes in weight, appearance, or physical/chemical properties as a function of irradiation after ORNL gamma exposures. The heat-shrink samples irradiated in the TAMU mixed fluence testing were not thermally aged before irradiation. The thermal changes experienced during irradiation at elevated temperature overwhelmed any additional changes due to irradiation. Heat shrinking in SARTA assembly was performed using a heat gun. This standard assembly practice introduces variation in the amount of heat applied to the heat shrink material. Therefore, it was problematic to make physical-state comparisons between the SARTA, post-irradiated heat shrink materials and various controls.

The solid lubricant-coated samples experienced no systematic or statistically significant changes in weight, appearance, or physical/chemical properties as a function of irradiation under the conditions studied.

Conclusion

Acceptable levels of radiation tolerance have been established for a candidate set of FSPS power convertor materials through a combination of coupon testing and experiments with an alternator-like test article. Experiments were performed in inert gas and at elevated temperatures up to 150 °C. Extensive data was collected up to 15 Mrad of ionizing radiation from different sources and limited data was generated at higher doses. Most of the samples were functionally unaffected by the irradiation conditions. Ionizing radiation up to 10 Mrad and neutron exposures up to 5×10^{14} neutron/cm^2 produced insignificant degradation for all of the materials tested except the PTFE-based wire insulation. Therefore, it is recommended that future space fission power concept design iterations can proceed with higher neutron and gamma fluence limits for the power conversion units than those previously proposed (Ref. 1). Power conversion system designers must be cognizant of the fact that the radiation response of polymers can be greatly affected by specific additives (Ref. 9) and deviations from the specific materials tested must be made judiciously.

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13. SUPPLEMENTARY NOTES
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14. ABSTRACT
NASA has been supporting design studies and technology development that could provide power to an outpost on the moon, Mars, or an asteroid. One power-generation system that is independent of sunlight or power-storage limitations is a fission-based power plant. There is a wealth of terrestrial system heritage that can be transferred to the design and fabrication of a fission power system for space missions, but there are certain design aspects that require qualification. The radiation tolerance of the power conversion system requires scrutiny because the compact nature of a space power plant restricts the dose reduction methodologies compared to those used in terrestrial systems. An integrated research program has been conducted to establish the radiation tolerance of power conversion system-component materials. The radiation limit specifications proposed for a Fission Power System power convertor is 10 Mrad ionizing dose and 5×10^{14} neutron/cm^2 fluence for a convertor operating at 150 °C. Specific component materials and their radiation tolerances are discussed. This assessment is for the power convertor hardware; electronic components are not covered here.

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