Boston, Massachusetts, June 24-28 2007
Paper 2035

Materials-of-Construction Radiation Sensitivity for a Fission Surface Power Convertor

Cheryl L. Bowman, Steven M. Geng, Janis M. Niedra, Ali Sayir, Eugene E. Shin,
James K. Sutter, and Lanny G. Thieme
NASA Glenn Research Center
MS49-1 21000 Brookpark Rd, Cleveland, OH 44135
216-433-8462, 216-433-5649 (fax), Cheryl.L.Bowman@nasa.gov

Abstract – *A fission reactor combined with a free-piston Stirling convertor is one of many credible approaches for producing electrical power in space applications. This study assumes dual-opposed free-piston Stirling engines/linear alternators that will operate nominally at 825 K hot-end and 425 K cold-end temperatures. The baseline design options, temperature profiles, and materials of construction discussed here are based on historical designs as well as modern convertors operating at lower power levels. This notional design indicates convertors primarily made of metallic components that experience minimal change in mechanical properties for fast neutron fluences less than* 10^{20} *n/cm*^{2}*. However, these radiation effects can impact the magnetic and electrical properties of metals at much lower fluences than are crucial for mechanical property integrity. Moreover, a variety of polymeric materials are also used in common free-piston Stirling designs for bonding, seals, lubrication, insulation and others. Polymers can be affected adversely by radiation doses as low as* 10^5 *-* 10^{10} *rad. Additionally, the absorbing dose rate, radiation hardness, and the resulting effect (either hardening or softening) varies depending on the nature of the particular polymer. The classes of polymers currently used in convertor fabrication are discussed along possible substitution options. Thus, the materials of construction of prototypic Stirling convertor engines have been considered and the component materials susceptible to damage at the lowest neutron fluences have been identified.*

I. INTRODUCTION

Fission power can provide ample and continuous power for a wide range of space missions. One option under consideration is Fission Surface Power (FSP), which is the operation of a fission surface power system on the surface of the Moon and/or Mars. Other papers have described system level trades on various reactor and power convertor options[1]. This study assumes a design configuration of a fast-spectrum fission reactor combined with a Stirling power convertor (one or more free-piston Stirling engines combined with linear alternators). The purpose of this document is to identify power conversion components and candidate materials-of-construction for these components that may be sensitive to the radiation environment resulting from a fast-spectrum fission reactor. Subsequently, the radiation tolerance of the candidate materials will be established in order to provide future convertor design guidance. Even though many details of a Fission Surface Power Convertor (FSPC) will not be established until later in the design cycle, thus making it impossible to precisely assess the radiation hardness of a to-be-determined design, some reasonable assumptions can still be used to establish a credible component list. For this initial assessment, the convertor system is assumed to have a hot-end temperature of 825 K (552 °C) and a heat rejection, cold-end temperature of 425 K (152 °C). Convertor design options, temperature profiles, and materials of construction discussed here are based on historical designs such as the Component Test Power Convertor developed under the SP-100 Program (for 100 kWe class space power)[2] as well as modern convertors operating at lower power levels. Controllers and sensors *are not* addressed in this assessment.

Modern linear alternator Stirling convertors are free-piston designs that can be further subdivided based on moving or stationary permanent magnet designs[3,4]. Figure 1 illustrates the major components of free-piston designs as well as a notional temperature distribution based on assumed hot-end, cold-end temperatures along with the temperature distributions seen in ~100 W_e class convertors. The components in the linear alternator, for example, likely will be warmer than the heat rejection temperature and the estimate used here is 435 K (162 °C) for all alternator components.

In both moving magnet and stationary magnet designs, the convertors are primarily composed of a variety of metallic alloys that experience minimal change in mechanical properties for fast neutron fluences less than 10^{19} to 10^{20} n/cm^2. The energies absorbed by metals from thermal neutrons and gamma radiation predominately lead to electron excitation and localized heating rather than defect formation. These radiation effects can degrade the magnetic and electrical properties of metals at much lower fluences than are crucial for mechanical property integrity. Electrical conductivity of metallic wiring is not unique to the alternator/convertor and thus those issues are not considered in this paper. However, the reliance on magnetic material properties is critical to the function of the alternator/convertor. In addition to the metallic components, a variety of polymeric materials are often used in Stirling alternator/convertors for bonding, potting, surface treatment, and insulation. In general, polymers can be affected adversely by radiation doses as low as 10^5 - 10^{10} rad.[5] The following sections provide additional information on the identified components and the proposed baseline materials. The ultimate purpose is to provide design options which maximize component life and minimize shielding requirements.

Although the components and discussion focus on a generic Stirling alternator/convertor design, many of the sub-components and functional requirements are applicable to other alternator designs. Thus the results of this research program will be applicable to a broader spectrum of power conversion equipment for fissions systems.

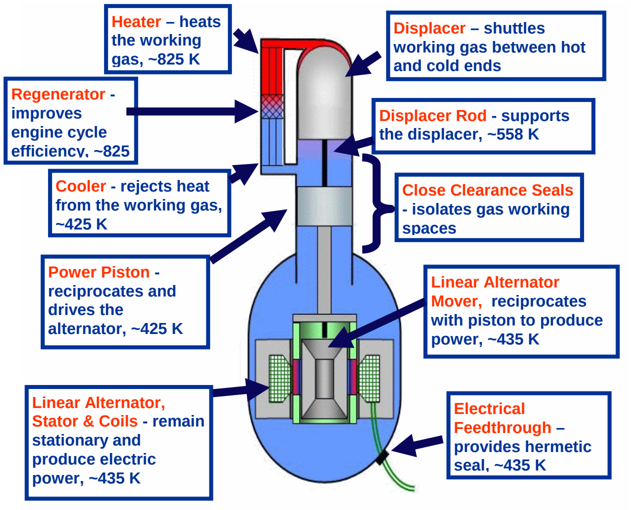

Fig. 1. Major components of a free-piston, linear alternator Stirling convertor with notional component temperatures.

II. MAGNETIC MATERIALS

A magnetic material is one that can be magnetized or carry magnetic flux. A hard magnetic material requires a large magnetic field to induce magnetization and then retains this magnetization in the absence of the applied field unless the Curie (demagnetization) temperature is exceeded. Soft magnetic materials are characterized by high permeability and low coercivity such that the material can be magnetized and demagnetized with minimal hysteresis energy loss. Both types of magnetic materials are employed in traditional linear alternators.

The permanent, or hard, magnetic materials required in the FSPC must have high coercive force strength (coercivity) and high remanent magnetic flux density (remanence); though precise remanence and coercivity requirements will depend on the details of the particular Stirling converter design. Figure 2 plots the manufacturer reported remanence and coercivity of rare earth magnets that could be potentially used in a FSPC design. In general, alternator performance is maximized for high values of both remanence and coercivity (upper right quadrant). At lower temperatures shown by open symbols, NdFeB magnets are preferred for their performance characteristics. Yet the SmCo types have higher intrinsic coercivities with comparable remanence at temperatures of 423K and greater, as indicated by filled symbols. Some studies suggest that SmCo-based magnets also have greater resistance to neutron irradiation,[6,7,8] however, it is important that thermal effects and radiation effects are carefully separated. Magnetic remanence and coercivity are extrinsic properties dependent on processing history, size, shape, application stress, application temperature, and component orientation relative to demagnetization field, therefore manufactures' data based on specific material chemistries can only be used for general guidelines or relative comparisons. Based on the analysis of the magnetic property requirements in Stirling alternators9, it is suggested that magnets with remanence of at least 1 Tesla (T) at 425K and coercivity of at least 7 kilo-Oersteds (kOe) at 425K be considered for the FSPC. As seen in figure 2, there are a number possible magnet materials satisfying those minimum conditions. Establishing the radiation hardness for magnets that fall in different regions of this performance space will provide a range of options to future FSPC designers. Special care will be required when making comparisons and recommendations based on results obtained from different experimental conditions and/or specimen geometries.

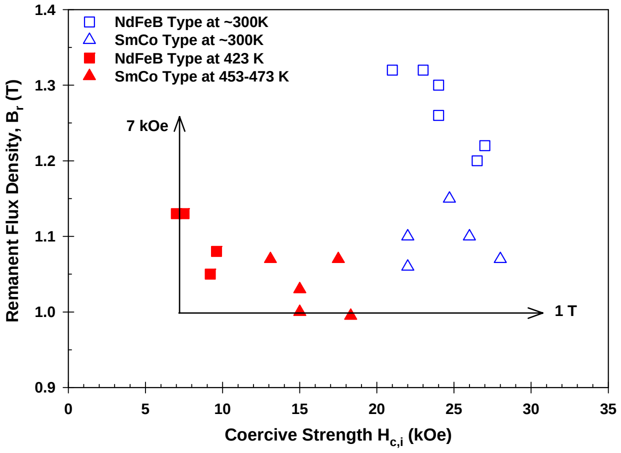

Fig. 2. Compilation of manufacturer's remanent flux density versus coercive strength data.

Soft magnetic materials in the alternator are selected for high permeability and minimal hysteresis loss. In general, magnetic saturation in soft magnets is radiation insensitive for integrated neutron flux up to 2×10^{18} n/cm^2.[10] Also initial permeability & coercivity are only affected when radiation induced defects are large relative to other microstructural features. The recommended baseline soft magnetic material is 48-Fe-48Co-2V (such as Hiperco®50). Preliminary review of irradiation data on similar materials,[10] suggests that the magnetic properties are not adversely impacted at exposures up to 2×10^{18} n/cm^2. However a more complete review of irradiation testing data for 48-Fe-48Co-2V material will be performed.

III. POLYMER-BASED COMPONENTS

Polymeric materials are employed for a number of applications in Stirling Power Convertors including insulation, bonding, sealing, and surface treatment. In terrestrial applications, selection often is driven by the upper temperature limit of the polymer. In the proposed space power application, both component temperature and radiation resistance will be considered. Table 1 outlines application categories and proposed material choices. The functionality refers to the key attributes of the polymeric materials with respect to the particular component class. Most items in the functionality column are self explanatory. The phrase "in situ fabrication" refers to need to apply or cure the polymeric material in system with consideration of other components. The glass transition temperature, T_g, is a common gauge of elevated temperature stability in polymeric materials. Outgassing refers to the loss of volatile species from the polymers; outgassing inside the convertor must be negligible over the life of the component. Therefore, it is essential to obtain a full and stable cure state for each polymeric material.

TABLE I

Summary of polymeric material component applications.

Component/ Application	Functionality	Proposed Materials
Running Surfaces	Tribological, Tg/dimensional stability, adhesion	Perfluoro + Ceramic-based Lubricant
Bonding Materials	Bond strength, outgassing, in situ fabrication, Tg/dimensional stability	Epoxy Adhesives
Potting Materials	outgassing, in situ fabrication, Tg/dimensional stability, stiffness	Potting Epoxies
Sealing Materials	outgassing, Tg/dimensional stability, stiffness	Fluorocarbon elastomers
Insulation	outgassing, Tg/thermo-electric stability, crack resistance	Polyamide insulation
Composite Structures*	Outgassing, dimensional stability	Glass/epoxy

*denotes component not common to all designs.

As can be seen in Table 1, a variety of polymeric materials such as epoxy, cyanoacrylate, polyamide, and fluoro-polymer systems are proposed. Suitability of these materials for the eventual FSPC will require characterizing the functionality (such as cohesive and bond strength for adhesives, dielectric strength for insulators, etc.) with respect to temperature and radiation environment. The following sections will discuss the component/application categories in more detail.

III.A. Running Surfaces

Modern Stirling convertors perform without contact on piston and displacer running surfaces during normal operation. Typically, solid lubricant coatings are applied to these running surfaces to minimize friction or sticking in the event of contact or impact, which can occur at initial starting operation or under severe service conditions. To maintain functionality in the FSPC, the lubricant coating system must maintain adhesion, lubricity, impact resistance, and scratch resistance. The coatings must not generate debris that could interfere with the close clearance seals. Chemical stability must be such that there is minimal outgassing induced by use-temperature, radiation, or a combination thereof. The temperatures envisioned in the FSP convertor mission are comparable to temperature ranges experienced in existing lower-power space designs.

Perfluoro polymers (polymers with fluorine as part of the backbone) are common coatings at 533 K (260 °C) and below. It is recommended that the radiation tolerance along with consideration of appropriate temperature effects is established for the Emralon (Acheson Colloids Comp., Port Huron, MI) and Xylan (Whitford Corp., Frazer, PA) families of fluoropolymers. Information on similar products will be gathered if available. If the combination of use-temperature and radiation-effects makes fluoropolymers unsuitable, alternative options such as inorganic coatings will be considered.

III.B. Bonding Materials

Polymeric materials can be used in a variety of bonding applications in a free-piston convertor/alternator system including lamination and permanent magnet attachment, secondary reinforcement of fasteners, and sensor attachment. Durability is key to bonding material functionality. The bonding materials must retain thermal and dimensional stability, as well as maintain tensile, shear, and fatigue strength and impact resistance. Bonding materials must obtain a highly cured state at temperatures compatible with the components being bonded. This is particularly acute for adhesively bonding permanent magnets where cure temperatures can not induce demagnetization. Post-application chemical stability must be such that there is minimal outgassing induced by use-temperature, radiation, or a combination thereof. It is recommended that the radiation tolerance along with consideration of appropriate temperature effects is established for epoxy-based systems Hysol EA9394, Scotchweld 2216, Masterbond 10HT, Magna-Tac E645 and Tra-Bond 2113; acrylate-based systems Locktite 290, Loctite 401, and Loctite 4014. Due to the alternator temperature in the FSPC, advanced systems such as fluorosilicone, bismaleimide, and cyanate ester adhesives will be included in the review process as well as ceramic-based bonding agents such as Resbond 798H. Mechanical attachments may be an alternative for some applications as well.

III.C. Potting Materials

Polymeric materials can be used in a variety of potting applications in a free-piston convertor/alternator system including coil fixation and secondary feedthrough reinforcement. Potting applications differ from bonding applications based on component functionality. In potting applications, dimensional and thermal stability is crucial while the tensile or shear strength is less important. Low resin viscosity (good flow during application) is also required in most cases. The exposure of temperature-sensitive components to resin curing temperatures as well as resin chemical stability to maintain minimal outgassing are still vital. Because of the volume (thick or deep) involved in potting applications, the removal of trapped air/moisture is important. Also, the cracking resistance (to minimize debris generation) of the candidates should be considered in material selection and process optimization. It is recommended that the radiation tolerance along with consideration of appropriate temperature effects is established for epoxy-based systems Hysol EA9394, Scotchweld 2216, and DOW DER383; crystalline thermoplastic-based systems Parylene HT; and polyether ether ketone-based systems. Due to the anticipated alternator temperature in the FSPC, advanced systems such as fluorosilicone, bismaleimide, and cyanate ester potting materials will be included in the review process as well as ceramic-based potting agents such as Kryoflex.

III.D. Sealing Materials

Although metallic or close-clearance seals dominate Stirling designs, there are instances were polymeric O-rings can provide additional functionality. Dimensional stability, extrusion resistance and resistance to embrittlement are required in these sealing applications as well as sufficient chemical stability to prevent out-gassing. It is recommended that the radiation tolerance along with consideration of appropriate temperature effects is established for fluorocarbon elastomers such as Viton, Simriz, Chemraz and Aflas.

III.E. Insulation

Electrical insulation is required for various wires. Flexibility of the wire coating is important during initial installation and sufficient dielectric strength is required throughout the component lifetime. It is well known that sufficiently large radiation doses can induce polymer chain scission which in turn embrittles these materials. As with other materials, chemical stability must be such that there is minimal outgassing induced by use-temperature, radiation, or a combination thereof. It is recommended that the radiation tolerance along with consideration of appropriate temperature effects is established for commercially available wires coated with polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyvinylidene fluoride (PVDF), tetrafluoroethylene, and polyamide-based systems. Polyamide-based sheet insulating materials such as Nomex Paper will also be reviewed.

III.F. Composite Structures

Past Stirling convertor designs have occasionally used composites, such as glass reinforced epoxies, within the linear alternator. Dimensional stability, electrical insulation and minimal outgassing would be the primary performance requirements for this type of application. Additional scrutiny of the radiation tolerance of composite structures is not recommended at this time since radiation tolerance of epoxies will be scrutinized in consideration of other components.

IV. CONCLUSIONS

This document proposes possible materials-of-construction for a future space power system. These are materials that can be adversely affected by high levels of radiation and thus could dictate the dose limits of the alternator/convertor system. Past studies suggest the reactor induced radiation for a Fission Surface Power Convertor may be on the order of 2 Mrad and 10^{14} n/cm^2. However, further design refinements are likely to change these estimates. Sound data on the radiation tolerance of the convertor/alternator components can be used to define the shielding mass required in Fission Surface Power System. The component classes in question are summarized and relative locations are shown in Figure 3. These are the component materials that could be use-limited based on radiation effects or dictate the shielding levels required between a fission reactor and Stirling power convertor. Currently in progress is a review of available irradiation test data for these and closely related materials. Based on the results of this review, prioritized recommendations will be proposed on the need for additional irradiation and post irradiation testing.

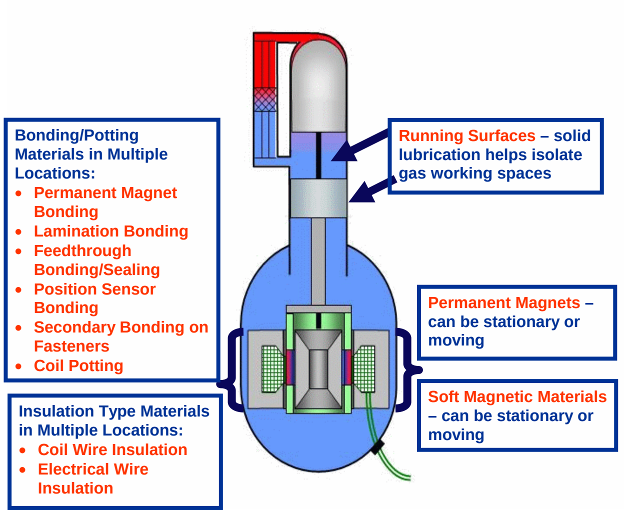

Fig. 3. Component material types that may be irradiation sensitive in a space power convertor.

ACKNOWLEDGMENTS

The authors wish to acknowledge valuable discussions with Paul Willis, NASA JPL and Keith Leonard, ORNL. This research was supported through the Prometheus Power and Propulsion Program under NASA's Exploration Systems Mission Directorate. Any opinions expressed are those of the authors and do not necessarily reflect the views of NASA or the Prometheus Program.

NOMENCLATURE

FSPC—fission surface power convertor
Oe—Oersteds
n—neutron
rad—radiation absorbed dose
T—Tesla
T_g—glass transition temperature
W_e—electric watt

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