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Long-Term Durability Analysis of a 100,000+ Hr Stirling Power Convertor Heater Head

Paul A. Bartolotta, Randy R. Bowman, David L. Krause, and Gary R. Halford
Glenn Research Center, Cleveland, Ohio

July 2000

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Summary

DOE and NASA have identified Stirling Radioisotope Power Systems (SRPS) as a candidate power system for future deep space exploration missions. As a part of this effort, NASA has initiated a long-term durability project for critical hot section components of the Stirling power convertor to qualify flight hardware. This project will develop a life prediction methodology that utilizes short-term (t < 20,000 hr) test data to verify long-term (t > 100,000 hr) design life. The project consists of generating a materials database for the specific heat of alloy, evaluation of critical hermetic sealed joints, life model characterization, and model verification. This paper will describe the qualification methodology being developed and provide a status for this effort.

Introduction

A Stirling Radioisotope Power System (SRPS) has been chosen as a candidate power system for future NASA deep space exploratory missions. The Europa (one of Jupiter's moons) Orbiter and the Solar Probe are scheduled to launch by January 2006 and February 2007 respectively. DOE is responsible for the successful design and fabrication of the SRPS for these two missions. NASA is aiding DOE by conducting several projects that will reduce the design and fabrication risks of the SRPS.

Projected design life requirements of the SRPS for these missions are over 60,000 hr. Long-term durability of hot section components (i.e., heater heads) of power convertors is a prime area of concern. Since launch dates for both of these missions are within the 2006 and 2007 timeframe, conventional design approaches for long-term durability verification are not appropriate. Instead, a new innovative approach will be required. This new design and verification approach consists of generating a materials test database specific for the Stirling power convertor application, defining the appropriate definition of failure, developing a probabilistic design methodology, and verifying the critical flight hardware using benchmark tests.

Design reviews have identified the heater head of the Stirling power convertor as a critical component. The heater head is a high-temperature pressure vessel that transfers heat to the working medium of the convertor, which is typically helium. Efficient heater head designs result from a compromise between thin walls for increased heat transfer and thick walls for lower stresses thus improved creep resistance/durability. Existing long-term creep data (>50,000 hr) on thin specimens of the proposed heater head material, Inconel 718, for the operating conditions and long-term durability are limited. The proposed approach uses long-term test data generated from the same heat of material from which the flight hardware will be fabricated from and compares it to existing materials databases. Chrome depletion of heater head materials resulting from material temperatures as high as 650 °C while exposed to the vacuum of space is also a concern. With launch dates scheduled for early 2006, innovative life prediction methods and accelerated tests will be required to assure heater head lives of over 100,000 hr. The lifting methodology involves conducting a series of creep tests on thin specimens, characterizing/evaluating various prediction models, and analyzing the heater head structure. Final validation of the flight hardware design will be accomplished by calibrating/verifying the life models using benchmark tests on actual heater heads under prototypical operating conditions.

This paper will discuss the life prediction philosophy and design methodologies being utilized to increase the confidence level of achieving 100,000-hr design life for the convertor's heater head. Current supporting test data, benchmark test description, and structural analyses of the heater head will also be presented.

Stirling Power Convertor

The fundamental operation of a radioisotope Stirling Power convertor is a topic covered in several papers in the open literature[1,2] by NASA and the Stirling Technology Company (STC). This section identifies major components of the convertor and their probable damage modes caused

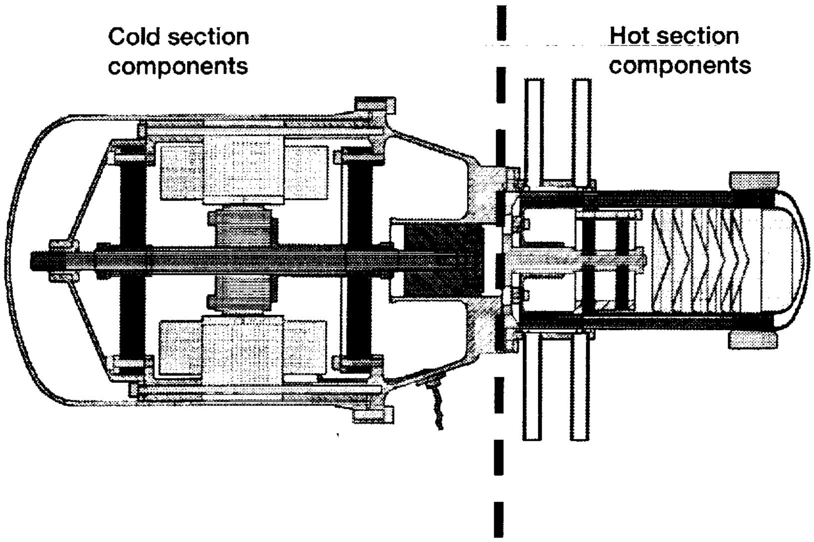

Figure 1.—Schematic of STC's Stirling power convertor showing cold and hot side components.

by long-term exposure to high temperatures and mechanical damage (fatigue, creep, abrasion). The radioisotope Stirling power convertor (Fig. 1) has two basic component sections (hot and cold). In the cold section, mechanical motion is converted into electrical power. Components that are located in this area consist of a linear alternator that produces the electrical power, a power piston that transfers the cycle energy, and the pressure vessel and alternator support structure. Nominal operating temperatures in this section are relatively cool ($T < 120$ °C). Therefore, thermal stability of the materials is not a prime concern. There are only three possible areas for mechanical damage in the cold section of the convertor and they are: (i) tensile rupture of the pressure vessel, (ii) high cycle fatigue (HCF) of the piston flexures, and (iii) abrasion of the power piston-to-sleeve or magnets-to-mover. The first and third damage mode can be eliminated through the use of good conventional design and fabrication methods. The only damage mode that needs to be addressed is the HCF of the piston flexures. However, due to years of test data generation and analysis of this flexure concept and materials by STC,[2] this damage mode is unlikely to occur.

The hot section (Fig. 1) is where heat energy from the radioisotope is converted into kinetic energy (and ultimately into electrical power in the cold section). The hot section of the convertor consists of a displacer that is used to move the working fluid from the convertor hot end to the cold end and vice versa, several heat exchangers to either add (or remove) heat energy from the working gas, and a heater head to contain the working gas and through which the heat energy is transferred from the radioisotope to the working gas. Due to their relatively high operating temperatures (up to 650 °C) and exposure to the vacuum of space, there are several thermal stability issues for the hot section components. Thermal aging of the hermetically sealed heater head joint for the convertor and Chromium loss in the heater head material are the two primary thermal stability issues that have been identified and are being addressed. As for mechanical damage modes, only one has been identified which is creep deformation of the heater head. The remainder of this paper describes risk mitigation on the aforementioned design and validation issues for the Stirling power convertor's heater head.

Heater Head Design/Validation Parameter

One of the most critical components of the Stirling power convertor is the heater head. Basic design considerations for the heater head are diametrically different. The heater head design must compromise between thin walls for optimal heat transfer properties and thick walls for increased structural creep resistance. Furthermore, a balance must be attained with the microstructure of the heater head material. First, the material needs to be creep resistant which requires large grains. For metals the larger grains will provide better creep resistance. However, the grains cannot be too large with respect to the thin walls of the heater head. In order to obtain a material's elastic, plastic, and creep properties, a minimum of 5 to 10 grains across the thin wall must be maintained.

Current heater head design practices are based on the only generally accepted, high-temperature structural design code in the United States' public domain, ASME Code Case N-47.[3] This code was developed for the design assessment of terrestrial-based nuclear power generation plants. The code addresses failure modes due to yielding, ratcheting, over-load, creep, creep-rupture, fatigue, and creep-fatigue interaction. N-47 is truly not a life prediction code, but rather a code for assessing, with a high degree of confidence, that a structure will last longer than some prescribed lifetime. The code is well suited for terrestrial applications that do not have limits on weight or mass. Large factors of safety are imposed on minimums from a large materials database to create design curves that are highly conservative. Furthermore, the code recognizes only a limited number of superalloys (under several limited conditions i.e., heat treatment, thickness) that are currently used in the nuclear pressure vessel and piping industry. None of the Code Case N-47 alloys are candidates for use in the hot section of the Stirling power convertor.

Generally, the essence of Code Case N-47 can be applied to the design philosophy of a Space Stirling power convertor and produce designs for launch-weight hardware. However, the basic methodology, minus the excessively large safety factors, could be employed if sufficient long-term data could be generated. Only short-term creep, creep-rupture, and thermal stability data can be generated on the heater head material within the remaining time before design details must be finalized to meet the mission schedule. Consequently, design curves for the 100,000+ hr time frame will have to be estimated using short-term data and extrapolation methods. These curves must be correlated with existing long-term curves of data that does not necessarily have the identical material conditions as the material for the flight hardware. For the subject NASA/DOE project, all test samples will come from the same heat of material as the flight hardware and will be heat-treated using an identical heat-treating schedule as the flight hardware.

Code Case N-47 is based on failure criterion that allows for gross deformations without the concern of how those deformations affect the operation of the structure. In other words, N-47 was developed for pressure vessels and pipes where 2 to 5 percent creep deformation can be allowed, as long as it does not cause a rupture, because the pressure vessel (or pipe) can still function with relatively large deformations. However, the heater head is closely coupled with the performance of the Stirling power convertor and therefore, a specific criteria of failure needs to be defined for the Stirling power convertor heater head. As the heater head is deformed due to long-term creep, the heater head volume for the working gas is increased and the displacer piston appendix gap is increased (increasing the loss in this region); both conditions will decrease the efficiency of the Stirling convertor. A more appropriate measure of failure and/or damage of a heater head should be based on these implications instead of those outlined in N-47.

Design and hardware validation for the NASA/DOE project will use a new failure criterion for the heater head based on the above premise and predictions from Stirling performance codes[4]. Present design criterion uses the time it takes to accumulate 1% creep in the heater head. Permanent creep deformation of the heater head could eventually increase the gap between the displacer piston and its sleeve. Whether and when creep of the heater head will cause increased appendix gap losses will be answered by the outlined NASA/DOE project. An additional design criterion for the heater head would be based on the time it takes the heater head to creep (deform) and significantly increase displacer appendix gap losses. For the NASA deep space missions, the time must be greater than 100,000+ hr for an adequate heater head design. This would be in addition to the conventional N-47 design criteria of time to rupture and time to 1% creep.

To estimate the degradation in the Stirling Convertor performance associated with 1% creep of the heater head, it is proposed to use Stirling performance codes in combination with a finite element analysis (FEA) of the heater head. In this method, FEA and appropriate creep models estimate the displacer appendix gap width for 1% creep of the heater head. This gap is then used for several performance code runs to estimate its contribution to a reduction in system power. Note: power reduction could be caused by a number of items such as isotope decay, magnet degradation, or an increase in the displacer appendix gap. All of these issues could contribute to the overall decrease in power and are being addressed in the NASA/DOE project. The specific distribution of each power loss mechanism and how they interact with each other is still an issue that needs to be determined.

NASA Heater Head Validation

To qualify the design and flight hardware for NASA deep space missions, NASA has developed a validation project for the critical hot section components. This project consists of (i) accelerated testing of IN718 to develop both creep and thermal stability data bases and characterize creep prediction models, (ii) thermal and mechanical finite element analysis (FEA) to verify designs and predict heater head life, and (iii) benchmark tests to characterize/verify the creep prediction model for the FEA and to evaluate the thermal stability of the heater head hermetic seals in the hot section. An outline and status of this project will be given for the remainder of this paper.

Inconel 718 (IN718) Long-Term Material Assessment Status

Due to the relatively volatility (high vapor pressure) of Chromium (Cr), long-term exposure at elevated temperatures in the vacuum of space poses a risk of Cr loss in the IN718 due to volatilization. Volatilization is especially important when the exposed surface area is high and the total volume of material is small, as is the case for the thin walls of the heater head. For these thin walls, even a small depletion layer can represent a large percentage of the total wall thickness. Bourgette demonstrated that, in general, the stability of metals alloyed with volatile elements (Chromium, Manganese, etc.) is only a concern for temperatures exceeding about 815 °C. While the heater head operating temperature is well below the 815 °C critical temperature for species loss, volatilization may still be an issue. This is because even minuscule evaporation rates could eventually result in appreciable Cr loss due to the extremely long times required for deep space missions.

Although vacuum level had little effect on the loss of Cr and Manganese (Mn),[5] the volatilization rate increased with temperature and decreased with accumulating time of exposure. Such behavior is consistent with diffusional processes, which bring the volatile species to the metal surface. Assuming that the loss of Cr is a diffusion-controlled process, then the Cr loss can be accurately predicted by solving Fick's diffusion law for the case of unidimensional diffusion in a semi-infinite medium. In this case, one half of the diffusion couple is the IN718 heater head with an initial Cr concentration of about 20 at % distributed uniformly through the thickness. The other half of the diffusion couple is the vacuum of space.

To verify the validity of Fick's equation to this problem, two 10×22×25 mm IN718 samples were placed in a vacuum furnace at 10^{-7} atm at 985 °C for 500 hr. The samples were weighed before and after exposure. The predicted total weight loss was within 90 percent of the actual measured loss for both samples. Also, the experimentally measured concentration profile of Cr as a function of distance from the surface was found to be very close to the predictions (Fig. 2). With the accuracy of the analytical solution verified, a prediction was then made for the actual operating conditions of 650 °C and 100,000 hr. The predicted weight loss due to Cr evaporation was found to be only 0.0008 g/cm^2 with a surface depletion layer thickness of only about 10 μm. These predictions confirm the general consensus that at 650 °C Cr loss will not be a concern.

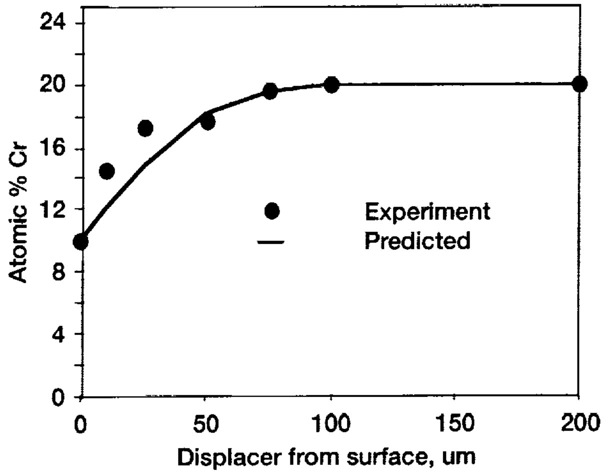

Figure 2.—Experimentally measured (circles) and analytically predicted (line) Cr concentrations as a function of distance from free surface after annealing in vacuum at 985 °C for 500 hours.

Accurately assessing the creep properties of IN718 for the heater head service conditions poses several challenges. The primary difficulty lies in the extremely long times involved – namely 100,000+ hr (~11.4 years). Not surprisingly, very little creep data exists for such long times. This dictates that the creep response will, by necessity, be extrapolated from shorter-time tests. Even when ignoring for the moment the accuracy or appropriateness of a particular predictive creep model, caution must be used if creep data from the open literature is used as the input to the model. Creep response is highly dependent on composition, heat treatment, and grain size of the material. Another complication arises due to the fairly thin wall thickness of the heater head. It is well known that the creep properties of superalloys are dependent on the specimen thickness-to-grain size ratio. Since it is unlikely that thin-section 11-year creep data will be available, it will be necessary to combine short and long-term data from the literature with short term-tests on the actual heater head material and rely on modeling to predict the viability of the material. It is for these reasons, that while the bulk of the creep database will be drawn from the literature, additional creep tests are being performed on samples with the identical thickness, heat treatment, and composition as the flight hardware.

An example of the creep data being generated is shown as a Larson-Miller Parameter (LMP) plot in Fig. 3. In Fig. 3, the rupture-time data are compiled from the literature on both thick (>0.25 in.) and thin (~0.025 in.) samples at various stresses and temperatures. Such plots suggests the possibility that creep tests can be performed in a practical time frame (at higher temperatures) under a wide variety of stress-temperature-size conditions and then extrapolate the results to the time-temperature-stress regime of interest. While a LMP plot is a fairly simplistic extrapolation technique, it is useful for quickly estimating long-term behavior. It is readily apparent from this plot that the creep lives for the thin (0.025 in.-thick literature data and 0.02 in.-thick heater head material) samples fall well below that predicted from the LMP graph for thick samples. Note that each three integers of the LMP correspond to a factor of 100 in time for the 650 °C, 100,000-hr design condition. Thus the challenge for accurate creep prediction is to not only accurately predict long-term lives based on short-term data, but also to account for the sample size effect as well.

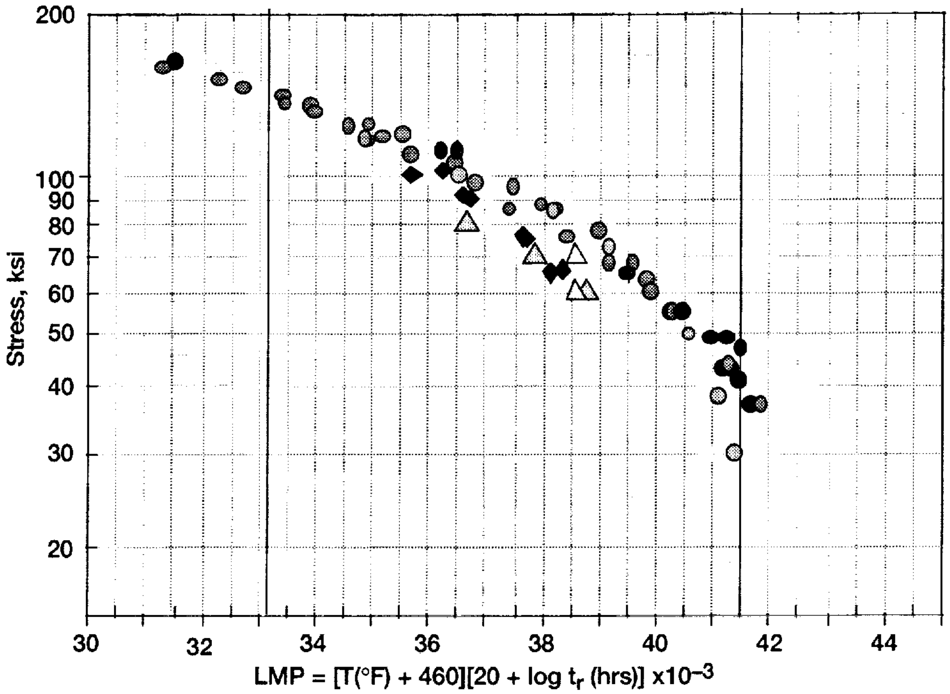

Figure 3.—Larson-Miller plot for IN718. Circles represent literature data generated on thick samples. Diamonds are literature data for thin sheet samples. Triangles are data generated in-house on samples in the heater-head configuration.

<u>Finite Element Analysis of Heater Head</u>

Several FEA will be conducted on the heater head. The first will be a thermal FEA where the temperature profile of the heater head will be based on the physics of the radioisotope Stirling power convertor. This FEA will take into account the heat flow between the radioisotope and the heater head, conduction losses, and convection losses. The outcome of this analysis will be an accurate temperature profile of the heater head and provide the input for the mechanical FEA, the output from which the life of this critical component will ultimately be predicted.

The IN718 creep data being generated in this project will be used to characterize a probabilistic creep model that will be used in the mechanical FEA. The mechanical FEA will be used to validate the design of the heater head for 100,000+ hr lifetimes by predicting the time it takes to increase the displacer gap to some maximum allowable size or 1% creep of the heater head (whichever comes first). An example FEA mesh and an exaggerated deformed output plot are shown in Fig. 4. A series of deformed shape plots can be produced for different time periods throughout the proposed mission life of the power convertor. This will provide information that can be input

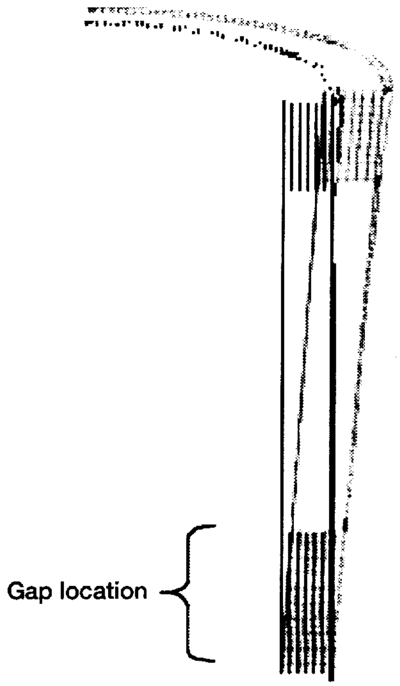

Figure 4.—FEA mesh and deformed output plot of a Stirling power convertor heater head showing the displacer appendix gap critical location.

to the Stirling performance codes to predict power performance at those different time periods.

The FEA predictions and creep models will be calibrated and verified through the use of a series of benchmark tests being developed by NASA. Several of these benchmark tests will be conducted for short durations (2 to 6 months) to calibrate the models. After the FEA prediction models have been calibrated a final long term test (>1 year) will be used to verify the FEA method that will be used, in turn, to qualify the flight hardware.

Benchmark Testing and Life Model Verification

Creep test data being generated in this project are from thin flat specimens of IN718 conducted under uniaxial test conditions. The IN718 heater head thin walls, like most pressure vessels, are under a stress state that is multiaxial. Typically, designers would account for multiaxial stress effects by either taking Von Mises (equivalent) stresses and compare them to uniaxial data or by taking a knockdown factor (based on past experience) in design allowables and design with the degraded properties. Both of these methods would produce a very conservative heater head design that would be unacceptable for the radioisotope Stirling power convertor. In the NASA project, uniaxial test data is being used for the initial model characterization and benchmark tests on heater heads will provide information for the final calibration of the FEA model.

Figure 5 illustrates the test method being developed to calibrate and verify the model. For these tests, purified argon is used as the working gas and is being controlled by a sophisticated computer control system (not shown in Fig. 5). The test system consists of an IN718 heater head (actual flight hardware type), a pressure manifold, a ceramic filler plug, five linear voltage displacement transducers (LVDT), induction heating system, and a computer control system. The induction heating system will provide the appropriate thermal profile to the heater head. Argon will flow from the controller through the manifold into the heater head. The ceramic volume fill plug is used to limit the amount of argon required for pressure cycling. The plug is slightly undersized from the heater head thus significantly reducing the fill volume of the heater head.

The LVDTs will measure the deformation of the heater head as the tests are performed. Four of the LVDT are placed in the hottest elevation around the circumference of the heater head to sense the hoop deformation. The fifth LVDT is placed at the top of the head to measure the axial deformation relative to the base of the heater head. These displacement measurements will be compared to the FEA predictions for each test condition to calibrate and verify the model.

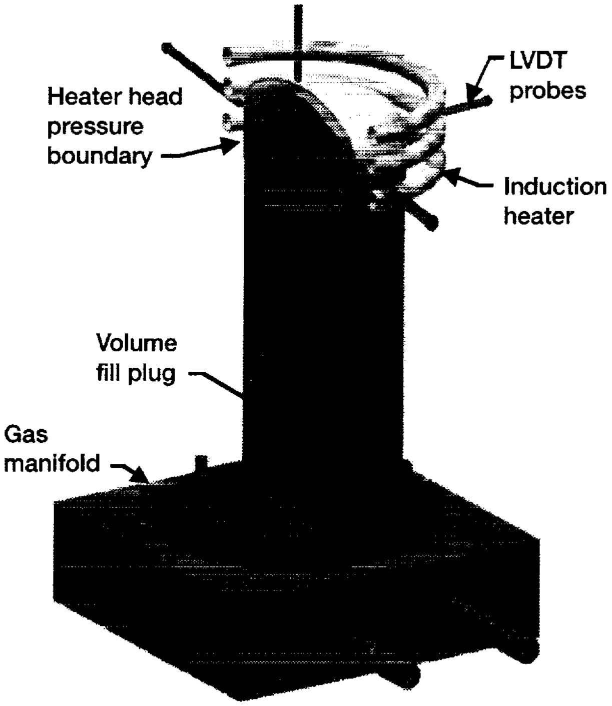

Figure 5.—Schematic of heater head benchmark test setup that will be used to calibrate and verify life prediction design method for 100,000+ hour mission life hardware.

Initially, test conditions of argon pressure and heater head temperatures will be chosen to produce a fixed amount of creep deformation corresponding to exposure lives of 2, 4, and 6 months. The test conditions are chosen to accelerate creep damage (higher pressures and temperatures) without inducing creep damage mechanisms that are different from those that the heat head will encounter during actual 100,000+ hr operations at a 650 °C maximum. Tests results from these short-term tests will be correlated with prediction results and the models will then be recalibrated.

The final long-term test will verify the prediction model by having the test conditions chosen by the model. Periodically throughout this test, the deformation will be monitored and compared to the predicted deformations. The life method will be valid if the measured strains (deformations) fall within a 10 percent error band. The final prediction of the verified life method will be for the actual 100,000+ hr design life of the flight hardware.

Concerns for the hermetic seal of the Stirling power convertor has prompted NASA to develop an innovative test method to verify the joint in the hot section. A Stirling power convertor pressure shell is fabricated using the stainless steel outer body in the cold section and the IN718 in the hot section of the convertor. The pressure shell is then charged with helium (He), which is the working gas for the deep space Stirling convertor. The pressure of the He is twice that of the normal operating pressure in flight applications. Likewise, the temperature of the hermetic joint location will be higher than normal at 500 °C (normal operating temperature at this location is ~100 °C).

The assembly will be installed into a leak detection chamber and He content will be monitored for a minimum of two years. The basic premise behind this test is that by heating the joint location up to 500 °C, the thermal aging of the joint will be accelerated. Likewise, doubling the working pressure of the He gas, the main driver for diffusion of the He gas is significantly increased. The failure definition for this test is if helium is detected at a certain parts per million (ppm) level. If failure in this accelerated test does not occur within the two-year period, the hermetic seal design and joining process will be verified. By passing this thermal aging test, there will be a high level of confidence in the design and fabrication processes of the hermetic seal.

Summary

Radioisotope Stirling Power Convertors are candidate power systems for deep space probes. Critical components have been identified and a design and validation philosophy has been defined. A new design and validation methodology has been created for the heater head that is based on system performance instead of structural damage such as creep rupture. FEA plays an important role in the process and will be used to calibrate life models and predict ultimate component life. A heater head material has been chosen and a preliminary materials database is being generated. Chromium loss due to the high operating temperatures and the vacuum of space has been shown to be insignificant for the heater head material. However, creep behaviors of thin specimens when compared to existing data have shown to be an area of concern. This does not represent an insurmountable issue but just an issue that needs to be resolved by using good engineering judgment and design methods.

A series of planned benchmark tests are in the process of being developed. These tests will aid in the calibration of life prediction methods and the eventual verification of those methods. A benchmark test for evaluating the hermetic joint has been defined and is presently being developed. This test will thermally age the joint and monitor for He gas leakage within a two-year period. The proposed plan will provide a significantly high level of confidence that the hot section components of a Radioisotope Stirling power convertor will survive its 100,000+ hr mission life for deep space probes.

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