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Structural Analyses of Stirling Power Convertor Heater Head for Long-Term Reliability, Durability, and Performance

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Summary

Deep-space missions require onboard electric power systems with reliable design lifetimes of up to 10 yr and beyond. A high-efficiency Stirling radioisotope power system is a likely candidate for future deep-space missions and Mars rover applications. To ensure ample durability, the structurally critical heater head of the Stirling power convertor has undergone extensive computational analyses of operating temperatures (up to 650 °C), stresses, and creep resistance of the thin-walled Inconel 718 bill of material. Durability predictions are presented in terms of the probability of survival. A benchmark structural testing program has commenced to support the analyses. This report presents the current status of durability assessments.

Introduction

Reliable durability along with ample functional performance must be demonstrated before long-term structural systems can be fully accepted for use. Computational analyses and long-term experimental input are essential ingredients for this. The approach taken to ensure the structural reliability, durability, and performance of a Stirling power convertor heater head is described and discussed in this report. The convertor must generate electric power with a high degree of reliability for mission durations up to 10 yr and beyond. The structurally critical cylindrical heater head is made of thin-section wrought Inconel 718 and must operate at temperatures as high as 650 °C. Creep resistance is the dominant durability limitation.

Tradeoffs between maximum operating temperature (650 °C), hoop stress, and creep resistance have been examined for Inconel 718 in the conditions of proposed use. The internally pressurized cylinder (nominal 2.5 MPa) must not be allowed to distort excessively (or rupture) because of creep. The structural durability design criterion for the heater head is expressed as a durability surface with coordinates in temperature T, stress σ, and operational lifetime t_f. Families of nonintersecting durability surfaces reflect various probabilities of successful operation.

In support of the durability analysis activities, the NASA Glenn Research Center is generating creep and rupture data for the material with specified thickness and specific heat that is to be used in the construction of heater heads for flight convertors. A benchmark component testing program is also underway. Because of time constraints, creep testing must be restricted to no more than about a 2-yr duration, far short of the required 10 yr or more. Fortunately, about three decades ago, an extensive long-term creep and creep-rupture data base had been generated (Brinkman, Booker, and Ding, 1991) on Inconel 718 by the Oak Ridge National Laboratories (ORNL) in support of terrestrial electric power generation. Certain aspects of their results are being used extensively in the current evaluations, namely, long-term results and measured statistical variations. The ORNL creep life data cannot be used directly because of quantifiable differences between them and preliminary NASA Glenn data resulting from slight variations in alloy chemistry and grain size. Also of importance is the significant difference in thickness of the creep test specimens used by the two laboratories. The Glenn creep test specimens were only 0.5 mm thick (i.e., about four to five times the diameter of a human hair). This thickness was selected to be reasonably representative of the thickness of the convertor pressure vessel enclosing the regenerator. Preliminary design calculations indicated that the maximum thickness in this area might be as small as 0.38 mm. Based on information of the current study, however, the hot section thickness has to be increased to meet life requirements with high probabilities of success. The new thickness values under consideration range from 0.89 to 1.14 mm. By contrast, the ORNL data (Brinkman, Booker, and Ding, 1991) were generated using test specimens on the order of 20 times thicker (≈10 mm) than those used by Glenn. Creep resistance for wrought alloys generally decreases dramatically with decreasing specimen thickness (below about 20 grain diam.) and with decreasing grain size. Scaling factors accounting for the differences between the ORNL and the Glenn data have been established and will be reexamined as the Glenn data base nears completion.

The heater head benchmark testing program will assess relatively short-term (1 yr) creep growth under realistic operating conditions. The favorable, concave upward shape of the creep curve of Inconel 718 allows realistic extrapolation to longer times from short time behavior.

Finite-Element Analysis

Elastic finite-element structural and thermal analyses of the cylindrical portion of the heater head were performed using the finite-element program MARC (Anon., 1996). Appropriate boundary and symmetry conditions were applied at both ends. No credit was taken for any stiffening or strengthening imparted by either an internal or external heat-conduction structure that might increase durability.

Because of geometric symmetry, only a segment (slice) of the heater head (fig. 1) was modeled and utilized in the analysis. Thin-shell elements were employed. The tapered wall thickness of the segment was incorporated in the shell elements.

A steady mean internal pressure of 2.5 MPa was applied to the heater head. The finite-element analysis provided stress values in excellent agreement with those obtained from considerations of the basic strength of materials equilibrium, which considers the heater head locally as a thin cylindrical shell. Effects on durability resulting from an 82-Hz oscillating internal pressure of ±10 percent of the mean have been considered. However, results of detailed calculations have shown these effects to be of second-order importance and hence are not included in the ensuing analyses.

A linear thermal conductivity analysis of the heater head was performed by employing temperature boundary conditions of 650 °C at the thicker heater end and 80 °C at the cold, thinner end. The temperature distribution over the axial length of the heater head was slightly nonlinear because of the wall thickness tapering. The temperature-dependent values of Young's modulus of elasticity E and the coefficient of thermal expansion CTE for Inconel 718 used in the analyses are listed in table I.

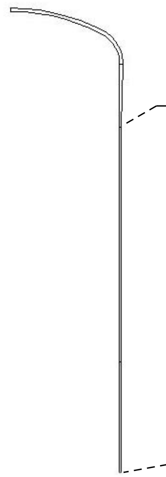

Figure 1.—Stirling heater head structural analysis segment.

TABLE I.—TEMPERATURE-DEPENDENT PROPERTIES OF INCONEL 718

Temperature, °C	Elastic modulus, *E*, MPa	Thermal expansion, *CTE*, 10^{-6}/°C
21	200	12.2
204	190	13.3
427	178	14.0
538	171	14.4
650	163	14.9

For purposes of parametric studies, three values of the pressure vessel wall thickness at the critical hot end of the regenerator were considered: 0.89, 1.02, and 1.14 mm. In all cases, the thickness tapered linearly to a mere 0.28 mm at the cold temperature end. These configurations gave rise to a range of probabilities of survival for a given mission usage.

Creep Characterization

The generation of sufficient long-term (>10^4 h), high-temperature creep data for engineering alloys is a formidable and time-consuming task. It is expensive because of the duration of testing and the range of variables to be covered. Many tests under different temperature and stress conditions generally are required for numerous heats of a material to determine general creep and creep-rupture laws describing the behavior. Also, large numbers of these tests are required because of the significant scatter typically observed in creep and creep-rupture testing.

Because of cost and time constraints, large data bases for long-term creep and creep-rupture behavior are rarely generated. Current industrial practice is to perform accelerated creep tests and extrapolate the results to approximate long-term behavior using what are known as time-temperature parameters, the most common being the classical Larson-Miller parameter (1952). As discussed below, we have not had to resort to such extrapolation methods because of the existence of a large data base for Inconel 718.

In an effort to develop a suitable creep durability model for analyses of the heater head, an engineering methodology has been adopted. It utilizes the large creep data base generated by ORNL (Brinkman, Booker, and Ding, 1991) for various heats, heat treatments, and product forms of Inconel 718. Although there are differences between the material used for the ORNL tests and that to be used in the current heater head, the proposed methodology captures the differences and accounts for their effect on creep behavior. The following paragraphs provide details of the analyses of the ORNL data and a description of the methodology for the material to be used for the heater head.

The ORNL test data encompass 14 heat forms of bar, plate, and forged material over the temperature range 538 to 704 °C. The longest reported rupture life is 87 000 h (10 yr). The data cover the pertinent temperature and time regimes of the heater head design. The Glenn heater head test material is only about 5 percent of the thickness of the ORNL test material. As described in the Introduction, the creep behavior of this material could be appreciably different from that of the ORNL material. Measures have been taken to evaluate correlation constants for the Glenn creep data with respect to those reported by ORNL. The methodology focuses on adopting the ORNL master curve model (eq. (1)). This model is thoroughly explained by Brinkman, Booker, and Ding (1991):

$$e^{*} = \exp\left[\beta\left(t^{*} - 1\right)\right]\left(t^{*}\right)^{\alpha} \tag{1}$$

where e^{*} is the normalized creep strain (with respect to creep strain at the onset of tertiary creep), t^{*} is the normalized time (with respect to time at the onset of tertiary strain), and α and β are constants quantified from test data.

The stress and temperature independence of the general form of equation (1) over the temperature range up to 650 °C makes it generic in terms of its application. Constants in the equation had been evaluated by ORNL using nonlinear regression analysis. These data were further analyzed to quantify their statistical distribution and scatter in the magnitude of the constants. It should be noted that scatter in the ORNL results is assessed independently of the product form and other variables. Hence, it is reasonable to take advantage of the large data base generated by ORNL to approximate the scatter in the relatively small amount of data that will be generated in the limited-time Glenn program. The ORNL creep-rupture law (eq. (2)) has been applied directly to the existing Glenn results on the heater head material by adjusting only the heat constant C_h, giving rise to rupture lives

$$\log\left(t_r\right) = C_h + C_1 \log\sigma + C_2\left(\log\sigma\right)^2 + C_3\left(\log\sigma\right)^3 + C_4 T \log\sigma \tag{2}$$

where t_r is rupture life in hours, C_h, C_1, C_2, C_3, and C_4 are the constants determined from the ORNL data (for Inconel 718, $C_h = 162.319$, $C_1 = -193.662$, $C_2 = 88.117$, $C_3 = -12.807$, and $C_4 = -0.01052$), σ is stress in megapascals, and T is temperature in kelvin.

These rupture lives are, at worst, one-third of those from ORNL for the same stress and temperature. As more Glenn data are generated, this factor of one-third could change. This difference in rupture lives reflects the combined effects of specimen thickness, chemistry, and grain size governed by the heat treatment. Note that the limited Glenn data are based on creep tests at higher stresses (and shorter times to rupture) than anticipated in the actual design. Therefore, the Glenn results must be extrapolated to the lower stress, longer life regime. Using the rupture life variation pattern at the higher stresses, the Glenn results are extrapolated parallel in life to those from ORNL. Once the rupture life from equation (2) is calculated, equation (1) can be used for determining the creep strain behavior. Thus, the rupture life is downscaled to give an estimation of the time to the onset of the tertiary creep. Based on the ORNL data, the scale factor for the time to reach tertiary creep t_{ter} is approximately 70 percent of the rupture life t_r. The design time to failure is defined as t_f, where $t_f \equiv t_{ter}$. The selection of the tertiary creep strain as the criterion for design lifetime was based on two important considerations: First, it places a deformation limit on the cylindrical section of the heater head that prevents the wall from growing excessively, and second, this measure of strain was fortunately well documented by ORNL. Equation (1) resulted from the recorded data.

Design Criteria and Probabilistics

Considerable scatter is generally observed in both creep rate and creep-rupture life data. The reliable design of high-temperature structural components subject to creep becomes complicated because of these uncertainties. Conventional deterministic design approaches use sizeable knockdown safety factors to ensure adequate durability. This usually results in overly conservative and heavy designs. Since space-based power conversion systems generally cannot tolerate excess weight, a rational alternative to deterministic design is required. Fortunately, uncertainties in material behavior as well as any design variables can be rationally accounted for using a probabilistic approach.

This long-range probabilistic approach for the heater head analysis aims at quantifying the uncertainties in the constants in equations (1) and (2) and adopting a Monte-Carlo simulation to perform probabilistic creep and creep-rupture durability analyses. The methods of most likelihood event (MLE) and least squares will be combined to quantify the uncertainties in the constants. Since sufficient data for the Glenn heater head material are not available, the uncertainties in the ORNL data have been quantified and applied to the Glenn heater head material. ORNL test data covering stress values from 170 to 1096 MPa and temperatures from 538 to 704 °C were fit to a Weibull distribution using the MLE method. Figure 2 shows the cumulative probability distribution of the ORNL test data (in unit normal space) and the analytic Weibull distribution of these data. Note that the rupture life has been represented as a ratio of observed rupture life to the mean rupture life. The quantified mean value of the ratio is 1.57, and the scatter is 91 percent. Since the analytically obtained probability distribution curve matches fairly well with the test data, it is used to compute the life for a desired probability of survival.

Three-dimensional probabilistic durability surfaces (stress, temperature, and design time to failure) for ranges of reliability have been generated. An example durability surface for 50-percent probability of survival (PoS) for extrapolated creep-rupture life for the ORNL data is shown in figure 3. The durability surface is shaded with patterns to show various combinations of temperature and stress that result in the range of life represented by a specific shade. Families of nominally parallel surfaces (parallel relative to the time axis) would represent various levels of PoS.

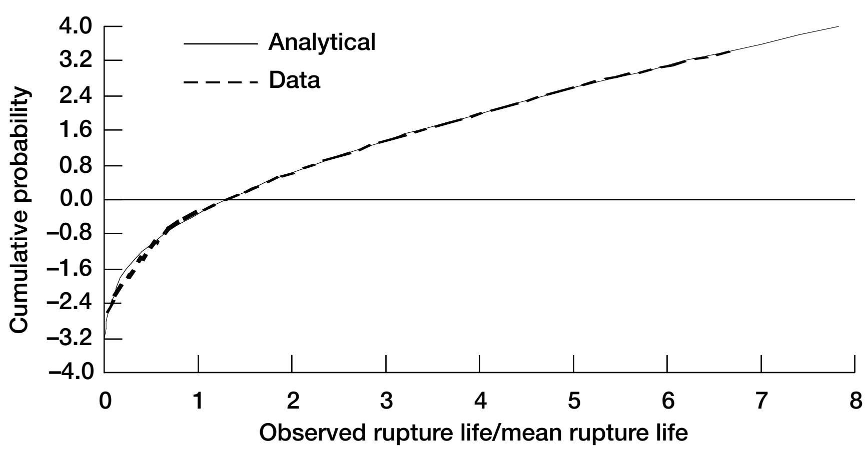

Figure 2.—Probability distribution (in unit normal space) of the rupture life, ORNL data with stresses of 170 to 1096 MPa and temperatures from 538 to 704 °C.

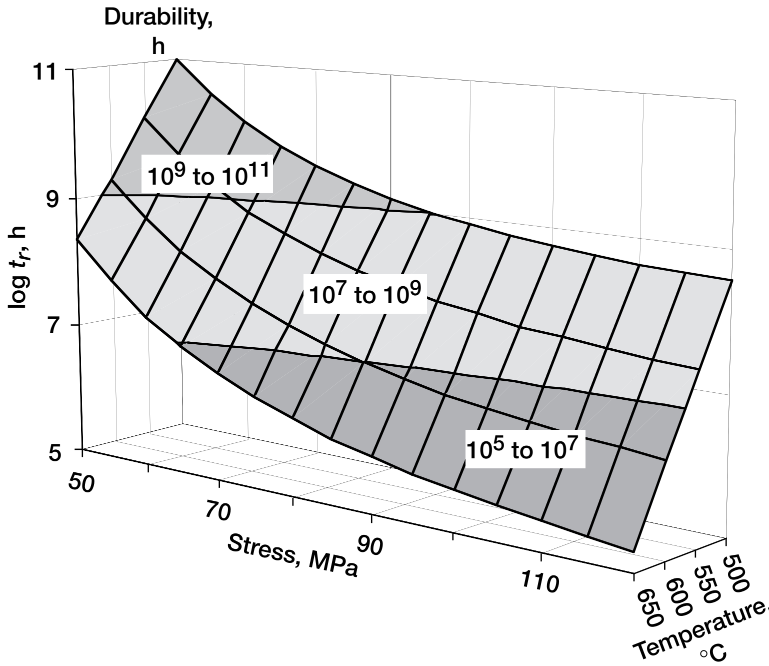

Figure 3.—Failure surface for 50-percent PoS. Extrapolated time to rupture, t_r.

TABLE II.—FACTORS OF SAFETY ON CALCULATED ALLOWABLE LIFETIME RELATIVE TO 100 000 h FOR VARIOUS PROBABILITIES OF SURVIVAL

Probability of survival, percent	Factors of safety		
	Maximum thickness, mm		
	0.89	1.02	1.14
50	13	52	230
90	5	21	93
99	1.2	5	21
99.9	0.2	1	4
99.99	0.05	0.2	1

The factors of safety on design lifetime are indicated in table II for the three maximum wall thickness values (of the pressure vessel enclosing the regenerator) considered. The factor of safety is expressed as the ratio of the calculated lifetime to the desired lifetime of 100 000 h for PoS of 50, 90, 99, 99.9, and 99.99 percent for a constant use temperature of 650 °C and internal pressure of 2.5 MPa.

A lifetime ratio >1.0 satisfies the design lifetime requirement. The maximum thickness of 1.14 mm is required for the highest PoS shown, whereas a wall thickness of only 0.89 mm would be ample for a lower PoS of only 99 percent. The difference in weight between the two configurations is only about 25 g and has a negligible impact on the overall weight of the Stirling power convertor system. The greatest thickness also has only a small impact on the operating efficiency of the system.

To compare the lifetime results of table II to more traditional stress-based evaluations of PoS, it is necessary to transform the variables. Graphically, this is straightforward. First, examine the failure surface in figure 3 (shown only for 50 percent PoS) and add the other four failure surfaces for the higher percentages of PoS. Then take the two-dimensional slice of computed lifetime versus stress at a constant temperature of 650 °C. One thus obtains a series of five nonintersecting curves that represent the tradeoff between life and stress at 650 °C. For a constant lifetime of, say, 100 000 h, a horizontal line has five intersection points with the five PoS curves. These intersection points identify the critical stress values for

TABLE III.—FACTORS OF SAFETY ON CALCULATED CRITICAL STRESS FOR VARIOUS PROBABILITIES OF SURVIVAL AT 650 °C

Probability of survival, percent	Factors of safety		
	Maximum thickness, mm		
	0.89	1.02	1.14
50	1.6	1.8	2.0
90	1.2	1.4	1.6
99	1.0	1.2	1.3
99.9	0.9	1.0	1.1
99.99	0.8	0.9	1.0

the five PoS values. If each critical stress is normalized to the stress existing at the thickest section of the pressure vessel enclosing the regenerator (at 650 °C), one obtains the safety factor for the stress needed to achieve the PoS desired. Results are summarized in table III. Note that for 50 percent PoS, the factor of safety for stress ranges from 1.6 to 2.0, depending upon thickness.

The proposed durability assessment methodology described above is straightforward and does not assume a specific underlying probability distribution. It is devoid of the convergence problems associated with highly nonlinear-behaving durability response surfaces and time-dependent reliability algorithms. The curves also identify the magnitudes of stress and temperature for a desired life. Thus, it could be used for design iterations to optimize and improve a given design. The resultant methodology, although currently lacking sufficient intermediate-term creep characteristics of the thin Glenn heater head material, promises a workable approach for evaluating design tradeoffs between temperature, stress, and useful lifetime with assured reliability.

A full probabilistic analysis of the critical factors governing the design life of the heater head is not as yet available. In fact, such an analysis could be misleading in the absence of accurate and pertinent information. An appropriately thorough assessment must await the more complete evaluation of the creep and creep-rupture properties of the specific Glenn material. Another year of coupon and benchmark testing is awaiting completion. In addition, procedures and techniques are being evaluated for application as further information becomes available. Additional reviews are to be held prior to finalizing important details of the heater head design. Clearly, however, relatively small additions of material to increase wall thickness in critical locations or even small percentage decreases in operating temperature can have a profound influence on increasing the reliability of a given mission lifetime. An easily remembered tradeoff is that at a given value of PoS and stress, a 15 °C temperature change causes the creep life to change by a factor of 2. Other tradeoffs between life, temperature, stress, and PoS can be assessed from the family of computed failure surfaces similar to the single surface shown in figure 3.

Armed with the information now available, it is also possible to assess a nonsteady mission loading history. For example, one could assess the impact on usable durability of a decreasing temperature of the heater head with time reflecting a realistic radioisotope decay process. Preliminary calculations by the authors reflect an approximate order-of-magnitude increase in life with an exponential temperature decrease of 100 °C over a 10-yr span.

Benchmark Structural Testing

A series of experimental benchmark tests of the heater head are planned to corroborate the structural analyses and independently determine creep performance of this component under the design loading conditions. This testing is important because predictions of creep strain in general are based on material properties determined from uniaxial creep testing. Both the ORNL historical data and the current NASA creep data are from uniaxial tests. However, the heater head configuration and pressure loading result in a 2:1 biaxial stress state, and the effects of this condition will be captured in the benchmark tests.

The benchmark test program includes a first phase of evaluating a prototype heater head (fig. 4) at several combinations of temperature and pressure that result in creep strains representing 1, 3, and 6 months of accelerated creep deformation. These results will be employed in the analyses to more accurately predict creep behavior. The second phase of testing applies the design pressure (2.5 MPa) and temperature gradient (peaking at 650 °C) to the benchmark heater head for 1 yr or longer. A decision is to be made later as to whether a constant temperature or a programmed decreasing temperature history profile is used. Creep deformations will be recorded periodically, and an evaluation of experimental and analytically predicted values will be performed. This study will then result in the final prediction of the creep life under mission conditions for a 10-yr duration.

The experimental equipment includes benchtop hardware mounted with temperature-control and gas pressurization systems. The prototype test hardware is attached to a water-cooled stainless steel mounting flange that has been machined with a metal O-ring groove and threaded holes to match the cold flange. The heating system consists of a 4.5-kVA induction heater with water-cooled copper coils designed to provide the correct temperature gradient throughout the part. The pressurization system includes a regulated high-pressure supply of purified argon gas, a solenoid valve, a direct drive control valve, a proportional pressure relief valve, the connecting tubing, and gas passageways machined into the mounting flange. An alumina volume fill plug is located inside the test cylinder to aid in control of gas pressurization.

A customized digital control system provided by McGaw Technology, Inc., controls pressurization and records experimental data. The control system also provides ramping, mean pressure and alternating pressure cycles, and synchronized thermal cycles, if needed, for any future test requirement. The instrumentation consists of thermocouples to measure metal temperature gradients and monitor argon temperature; a pressure transducer to control gas pressure; and strain gages to acquire initial mechanical pressure strains at room temperature. Creep deformation at the cylinder-head juncture and at the head centerline is continuously monitored with five linear variable differential transformers.

At the present time all test hardware is assembled, and nonintegrated initial testing of the induction heater and the argon system is complete. A geometrically simplified demonstration specimen has been fabricated and is currently being used to verify the performance of the entire test and data acquisition system.

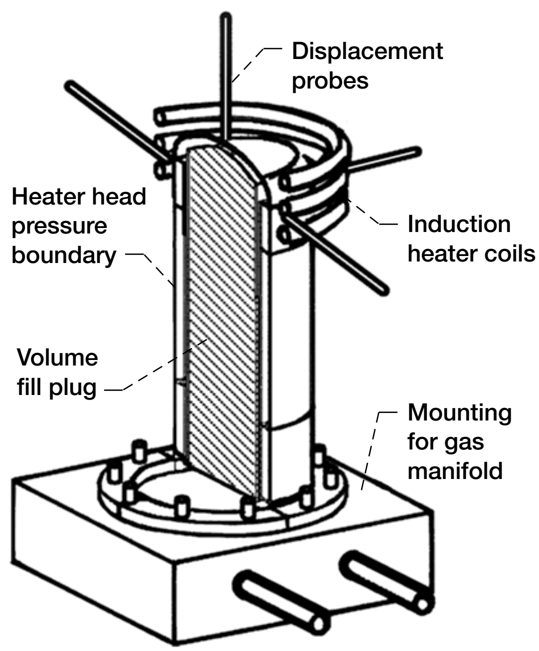

Figure 4.—Benchmark testing hardware.

Concluding Remarks

Preliminary durability analyses emphasizing the probability of survival have been performed to assess the potential capabilities of a Stirling power convertor heater head design for long-term space science missions (deep-space and Mars rover applications). Mission lifetimes of 100 000 h appear achievable with Inconel 718 utilized in thin sections with the maximum thickness of the pressure vessel enclosing the regenerator in the range of 0.89 to 1.14 mm at temperatures as high as 650 °C. Confidence in the calculated probabilities of survival is currently low, as a very small amount of hardware-specific material creep data have been generated in the limited time span available to date. Nevertheless, identified trends in the influence of critical factors such as temperature and stress are now usable as valuable input to finalizing the optimal heater head design for performance and reliable durability.

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