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Reliability-Based Life Assessment of Stirling Convertor Heater Head

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Summary

Onboard radioisotope power systems being developed and planned for NASA's deep-space missions require reliable design lifetimes of up to 14 yr. The structurally critical heater head of the high-efficiency Stirling power convertor has undergone extensive computational analysis of operating temperatures, stresses, and creep resistance of the thin-walled Inconel 718 bill of material. A preliminary assessment of the effect of uncertainties in the material behavior was also performed. Creep failure resistance of the thin-walled heater head could show variation due to small deviations in the manufactured thickness and in uncertainties in operating temperature and pressure. Durability prediction and reliability of the heater head are affected by these deviations from nominal design conditions. Therefore, it is important to include the effects of these uncertainties in predicting the probability of survival of the heater head under mission loads. Furthermore, it may be possible for the heater head to experience rare incidences of small temperature excursions of short duration. These rare incidences would affect the creep strain rate and, therefore, the life. This paper addresses the effects of such rare incidences on the reliability. In addition, the sensitivities of variables affecting the reliability are quantified, and guidelines developed to improve the reliability are outlined. Heater head reliability is being quantified with data from NASA Glenn Research Center's accelerated benchmark testing program.

Introduction

Under the auspices of NASA's Project Prometheus (the Nuclear Systems Program), the NASA Glenn Research Center, the Department of Energy, Lockheed Martin of Valley Forge, Pennsylvania, and Stirling Technology Company of Kennewick, Washington, are developing a high-efficiency Stirling Radioisotope Generator (SRG) for possible use on future NASA Space Science missions. The SRG is required to perform efficiently and reliably. Maintenance, of course, is not possible. These missions are typically long lived, lasting up to 14 yr. In order to assure a successful mission, it is important to assess the reliability of the Stirling convertor component parts. The heater head is one of the most critical components of the convertor. It conducts heat from the general-purpose heat source module of the Radioisotope Power System and supplies it to the convertor for the generation of electricity.

Reliable durability along with ample functional performance without maintenance must be demonstrated before long-term structural systems can be accepted for use. In order to achieve the desired performance objective and assure success of the heater head, it is necessary to perform feasible component tests to validate the design. However, because of technical limitations, in addition to time and cost constraints, it is not possible to run full-duration, long-term tests that simulate the actual operational conditions. In addition, it is difficult to capture the effects of uncertainties in the material behavior, fabrication, manufacturing process, operational load conditions, and other areas in a limited number of tests. Therefore, the use of computer simulations, or virtual experiments, validated with the limited test data under different design and operating conditions, is a viable approach to understanding the behavior of components and helping to quantify the long-term behavior and estimate the reliability of these components. Simulations can be performed at lower cost and within a shorter time-period than full-up tests. They also enable engineers to quantify the impact of variations in critical design variables on component performance. Also, computer simulations can be validated with available test data, and the system performance models can be enhanced to consider the interactions between components and the applicable design variables.

The structurally critical cylindrical heater head is made of thin-section wrought Inconel 718 and must operate continuously at temperatures as high as 650 °C. Creep resistance is the prime durability limitation. The design variables governing the performance and life of the heater head will have uncertainties from different sources, such as fabrication (geometry), environmental loads (pressure and temperature), and the long-term creep behavior of the material (Inconel 718).

Approaches taken to ensure the structural reliability, durability, and performance of a Stirling power convertor heater head are described and discussed. Tradeoffs between maximum operating temperature (650 °C) and creep resistance have been examined for Inconel 718 in the condition of proposed use. The internally pressurized cylinder (nominal 2.5 MPa) must not be allowed to distort excessively (or rupture) because of creep. A parametric study of the heater head life for a desired reliability under different operating temperatures is described. In addition, the effect on the heater head life of a thermal excursion of certain duration and magnitude occurring during the mission (possibly because of failure in a control or sensor mechanism) and of taking the time to correct the fault through health-monitoring systems has been evaluated in a pseudoprobabilistic manner. The sensitivity of governing design variables on the life of a heater head is also identified.

In support of the durability analysis activities, Glenn is generating creep and rupture data (ref. 1) on the specific heat and near-thickness of the material to be used in the construction of heater heads for flight convertors. A benchmark-testing program is also underway. Because of time constraints, creep testing must be restricted to no more than about 2 yr, far short of the required 14 yr for service. Fortunately, Oak Ridge National Laboratories (ORNL) generated an extensive long-term creep and creep-rupture database on Inconel 718 about three decades ago (ref. 2) 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 there are quantifiable differences between them and preliminary Glenn results due to differences in (1) alloy chemistry, (2) heat treatments, and (3) grain sizes. Also of importance is the significant difference in the thickness of the creep test specimens used by the two laboratories. The Glenn creep test specimens are only 0.5-mm thick (i.e., less than about 4 times the diameter of a human hair). This thickness was selected to be reasonably representative of the thickness of the highest temperature region of the convertor pressure vessel enclosing the regenerator. Creep resistances for wrought alloys generally increase dramatically with increasing grain size. However, there is a sharp decrease in creep resistance if there are less than about 20 grains across the stressed section (ref. 1). Scaling factors accounting for the differences between the ORNL and Glenn data have been established and will be reexamined as the Glenn database nears completion.

Creep Characterization

An engineering methodology was adopted in an effort to develop a suitable creep durability model for analyses of the heater head and to quantify the heater head's long-term durability. It utilizes the large creep and rupture database generated by ORNL (ref. 2) 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 and associated uncertainties. The following paragraphs provide details of the analyses of the ORNL data and describe the methodology for the heater-head bill of material.

The ORNL data cover the pertinent temperature regime and nearly the entire time regime of the heater head design. However, the Glenn heater head test material is only about 5 percent of the thickness of the ORNL test material. Glenn material creep behavior test results differ appreciably from those of the ORNL material. The mean life observed for Glenn material is much lower since it is much thinner than the ORNL material. However, because of controlled processing and fabrication, the Glenn material shows much less scatter in life compared with the ORNL material. In order to reduce cost and analysis time, Glenn researchers took an engineering approach 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 independent of stress and temperature, equation (1). This model is thoroughly explained by reference 2.

$$\varepsilon^* = \exp[\gamma(t^* - 1)](t^*)^\delta \tag{1}$$

where ε^* 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 γ and δ are constants quantified from test data.

ORNL used nonlinear regression analysis to evaluate the constants in this equation. At Glenn, we further analyzed these data to quantify their statistical distribution and scatter in the magnitude of the constants. It should be noted that scatter in the ORNL results was assessed independently of the product form, heat treatment, test temperature, and rupture time. Hence, it is reasonable to take advantage of the large database generated by ORNL to approximate the shape of the distribution for the relatively small amount of data that it will be possible to generate in the limited-time Glenn program. The magnitude of the scatter, however, will be based on the Glenn results. The ORNL creep rupture law (eq. (2)) was 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 that are, at worst, X times those of ORNL for the same stress and temperature, figure 1.

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

where, 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 $C_4 = -0.01052$), t_r is the rupture life in hours, σ is the stress in megapascals, and T is the temperature in kelvin.

As more Glenn data are generated, this X factor could change. The shift in time-to-rupture reflects the combined effects of thin specimens, chemistry, and grain size (heat treatment). Note that the limited Glenn data are based on creep tests at higher stresses (hence 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, we extrapolated the Glenn results "parallel in log (life)" to those from ORNL. Once the rupture life from equation (2) was calculated, equation (1) could be used to determine the creep strain behavior. Thus, the rupture life was downscaled to give an estimation of the time to the onset of tertiary creep. The scale factor for the time (t_{ss}) to reach
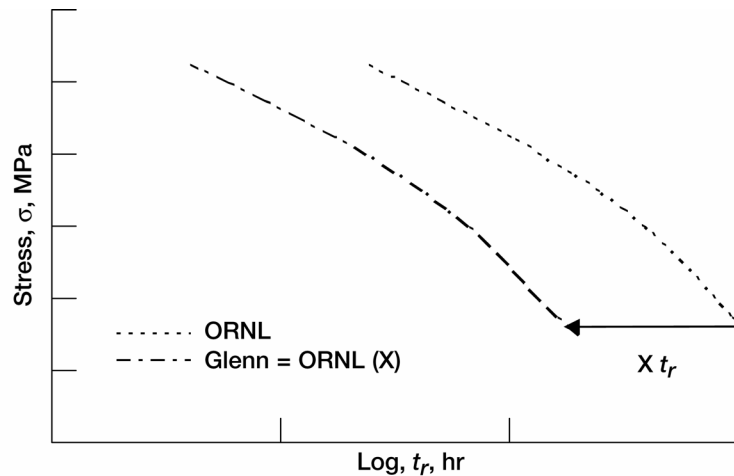
Figure 1.—Comparison between Oakridge National Laboratory (ORNL) and Glenn Research Center creep rupture data.

tertiary creep for the ORNL material was approximately 70 percent of the rupture life t_r, whereas that for the Glenn material has been observed in the range 40 to 60 percent. Although the percentage of life for the onset of tertiary creep for ORNL and Glenn material are different, we use 70 percent of rupture time to define the deterministic design life t_f. The following sections describe in detail the application of the probabilistic approach on the deterministic model.

Design Criteria and Probabilistics

Reliable design of high-temperature structural components subject to creep is complicated because of the numerous factors discussed earlier that contribute to uncertainties. Conventional deterministic design approaches use sizeable "knock-down" safety factors to ensure adequate durability. This usually results in overly conservative, heavy designs, but in some instances designs can be unconservative if the failure modes are governed by the interaction of several variables. Since space-based power-conversion systems generally cannot tolerate excess weight or rely on maintenance, a rational alternative to deterministic design that ensures high reliability without undue weight penalties is required. Fortunately, a probabilistic approach lends a rational approach to account for uncertainties in material behavior as well as many design variables to quantify the reliability.

Our probabilistic approach for the heater head analysis aims at quantifying the uncertainties in the material behavior, geometry, loads, and other factors by adopting fast probability integration and/or a Monte-Carlo simulation appropriately to perform probabilistic creep and rupture durability analyses. The most-likelihood-event method combined with the least-squares approach was used to quantify the uncertainties in the material behavior (constant C_h in eq. (2)). Since sufficient data for the Glenn heater head material were not available, the uncertainties in the ORNL data were quantified and applied to the Glenn heater head material. The most-likelihood-event method was used to fit the ORNL test data covering stress values from 170 MPa to 1096 MPa and temperatures from 538 °C to 704 °C to a lognormal distribution. Since the rupture life shows a lognormal distribution, obviously the constant C_h in equation (2) showed a normal distribution.

Other uncertainties that are included in the reliability-based life analysis of the heater head are related to geometry, pressure, and temperature. Uncertainty in the geometry was selected such that the bounds on the tolerances relate to the ±3 standard deviations. The uncertainty in the pressure was selected such that the maximum permissible variation of 10 percent corresponded to ±3 standard deviations. In a similar manner, the maximum variation of 10 °C in temperature corresponded to ±3 standard deviations. The magnitude of uncertainties may change when more realistic information becomes available.

Probabilistic life analysis was performed at three operational temperature levels—640, 650, and 660 °C—and four probabilities of survival, PoS, of the heater head—90-, 99-, 99.9-, and 99.99-percent. Results are reported in table I. Uncertainties for operation at 640 and 660 °C were assigned the same coefficient of variation as for operation at 650 °C. It is to be noted here that the analysis involved the following assumptions: (1) SRG environmental factors have a negligible effect on Inconel 718 creep durability, (2) the Inconel 718 creep behavior probability distribution is the same as the ORNL distribution, but scatter is based on the limited Glenn data, (3) the analysis ignores the effect of secondary stresses since they relax over time (slightly nonconservative) and (4) the maximum principal stress (not the equivalent stress) conservatively governs creep durability.

The cumulative probability distribution of the heater head life for a mean operational temperature of 650 °C with all the uncertainties was computed using fast probability integration, and the results are plotted in figure 2. In addition, the sensitivities of life to the design variable uncertainties are plotted in figure 3. Sensitivity was defined as the level of significance, on a scale of 0 to 1 (0 being the least and 1 being the most), of the uncertainties in a given variable to the reliability. The life distribution turned out to be lognormal, and the observed scatter for 1 standard deviation was approximately 90 percent with all the uncertainties considered. The scatter with material uncertainties was only about 70 percent. The life for 99.99-percent PoS was 116 000 hr (13.25 yr). The analysis computes the sensitivity of probabilistic life to the uncertainties in the design variables. Figure 3 shows that the uncertainties in the creep behavior of the material have the most control over the life, followed by those of the pressure, temperature, and thickness. Since it is difficult to control the uncertainties in the material creep behavior, we suggest that the scatter in the pressure, temperature, and thickness be controlled through control mechanisms and quality control in the manufacturing and inspection process to increase the reliability of the desired life.

TABLE I.—LIFE OF HEATER HEAD FOR DIFFERENT TEMPERATURES

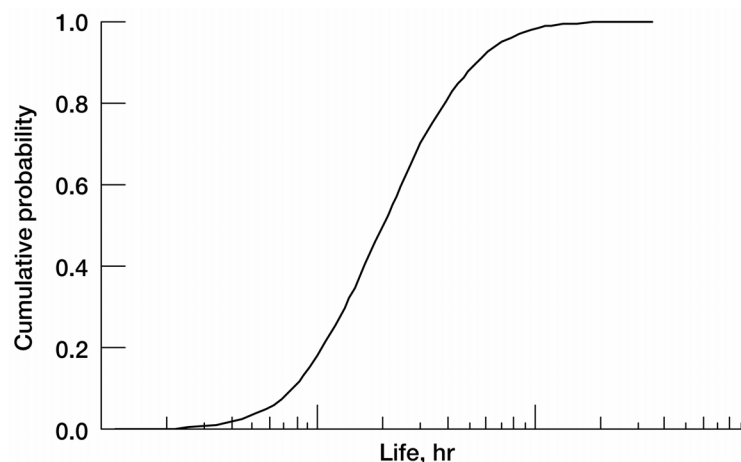| Temperature, °C	Life, hr			
	Probability of survival, percent			
	99.99	99.90	99.00	90.00
640	180 000	291 000	522 000	1 160 000
650	116 000	188 000	337 000	751 000
660	74 800	121 000	219 000	486 000

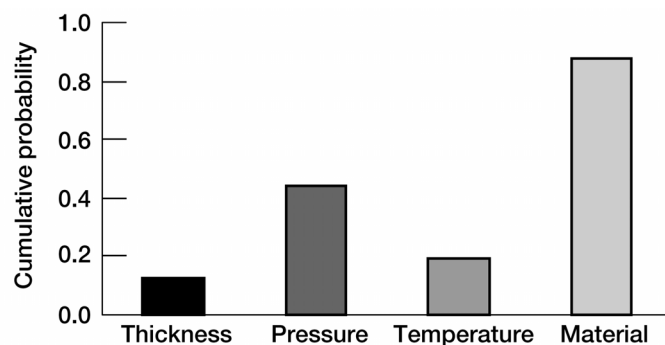Figure 2.—Cumulative probability distribution of heater head life.

Figure 3.—Sensitivity of life to the uncertainties in design variables.

To help readers understand the effect of mean operational temperature, we give the results of the reliability-based life analysis in table II. It is seen that the life for a given temperature decreased exponentially as the reliability increased mainly because the life distribution was lognormal. Note that the estimated life for an operational temperature of 650 °C was at least 13.25 yr with 99.99-percent PoS. Also, as expected, the life for a given reliability decreased as the temperature increased.

The presented durability assessment was checked against a Monte-Carlo simulation to verify that there were no convergence problems associated with highly nonlinear durability response surfaces. Reliability-based durability curves enable the evaluation of life for assured reliability. Also, the sensitivity of design variables could be used for design iterations in order 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.

TABLE II.—EFFECT OF THERMAL SPIKES ON
HEATER HEAD DURABILITY LIFE
[99.99-percent reliability.]

Excursion temperature, °C	Occurrence time, yr			
	1		2	
	Excursion duration, days			
	1	180	1	180
650	13.25	13.25	13.25	13.25
660	13.20	13.19	13.18	13.18
670	13.13	13.12	13.10	13.09
680	13.05	13.03	13.00	12.97

Since the Glenn material characterization is based on very limited test data, the reported analysis could be refined as more test data become available from the experiments in progress at Glenn. An appropriately thorough assessment may await the more complete evaluation of the creep and creep-rupture properties of the specific Glenn material, if available. Coupon and heater head benchmark testing is continuing. In addition, procedures and techniques are being evaluated for application, as further information becomes available.

Armed with the information now available, one could now assess, probabilistically, a nonsteady mission loading history. For example, one could assess the impact on usable lifetime of a decaying heater head temperature with time, reflecting a realistic radioisotope decay process. Another nonsteady mission loading referred to as "thermal excursions" is discussed in detail in the next section.

Effect of Possible Thermal Excursions on Heater Head Durability

Stirling radioisotope power systems are required to be investigated for the occurrence of any rare event, and the associated risk must be quantified. Since the Stirling convertor for the SRG converts the heat from the general purpose heat source to electrical energy, under rare conditions the temperature in the heater head could rise because of a faulty sensor or control. Under such conditions, it might take time to correct the system and bring it back to design operation. Such small-duration thermal excursions during the life of the heater head would affect its durability significantly. Heater head durability under such events depends on the time at which an excursion occurs, its magnitude, and its duration. These excursion parameters are random in nature and should be treated in a probabilistic sense. However, probabilistic analysis first requires a deterministic model to capture the mechanics and physics involved. The analysis reported herein is pseudoprobabilistic since the deterministic results are factored by the ratio of life at a given reliability and by the mean life computed from the probabilistic analysis described in the previous section to estimate the PoS describe the formulation developed to perform the excursion analysis. Again, we used the ORNL master-curve approach (eq. (1)) to assess the creep strain. Refer to reference 2 for more details on the master curve. Rupture lives for given stresses and temperatures were calculated from equation (2) and adjusted to represent the Glenn material.

The tertiary creep time, t_{ss} is represented by a simple Power-law expression:

$$t_{ss} = A t_r^\beta \tag{3}$$

with the values of A and β being 0.442 and 1.04, respectively. Note that the equation is nearly linear and that at $t_r = 100\,000$ hr, $t_{ss} = 70\,000$ hr. Also, for the ORNL material, the steady-state creep rate leading up to the onset of tertiary creep $\dot{\varepsilon}_{ss}$ may be represented in the following form:

$$\dot{\varepsilon}_{ss} = B t_r^{-\alpha} \tag{4}$$

where $B = 2.142$ and $\alpha = 1.151$. The concept of a "master curve" was used to develop the following creep-strain relationship:

$$\varepsilon^* = \exp[\gamma(t^* - 1)](t^*)^\delta \tag{1}$$

where $\varepsilon^* (= \varepsilon/\varepsilon_{ss})$ and $t^* (= t/t_{ss})$ are the normalized creep strain and normalized time, respectively; $\gamma = 1.75$; and $\delta = 0.2$.

Using equations (1), (3), and (4) and the chain rule for derivatives, we can express the relationship between the rate of creep strain and the creep strain by the following equation:

$$\dot{\varepsilon} = \gamma \varepsilon_{ss} t_{ss}^{-1} \left(1 + \frac{\delta}{\gamma} \frac{1}{t^*}\right) \exp\left[\gamma\left(t^* - 1\right)\right]\left(t^*\right)^\delta \tag{5}$$

Assuming that a "design failure time" constitutes the pth fraction of a tertiary creep time $t^* = p$, we obtain

$$\dot{\varepsilon} = a\left(0.2 + c t_r^{\alpha+\beta}\right) t_r^{-\beta} \tag{6}$$

where for $p = 0.7$,

$$a = \gamma\left(1 + \frac{\delta}{\gamma} \frac{1}{t^*}\right) \exp[\gamma(p-1)](p)^\delta = 1.12 \tag{7}$$

$$c = A B = 0.95 \qquad A = 0.442$$

The constant steady-state creep rate is assumed to be a function of only two independent external parameters, stress and temperature, which in turn influence the mechanical behavior of the structure. This allows us to write the creep rate in the following form:

$$\frac{d\varepsilon}{dt} = \phi(\sigma, T) \tag{8}$$

Suppose that at constant stress, the temperature suddenly changes from T to $T_1 = T + \Delta T_0$. The material will respond with a different creep rate in accordance with equation (8):

$$\frac{d\varepsilon_{T_1}}{dt} = \phi(\sigma, T + \Delta T) \approx \phi(\sigma, T) + \frac{\partial \phi}{\partial T} \Delta T$$

By integrating, we obtain

$$t_r = \int_{\varepsilon_0}^{\varepsilon_r} \frac{1 - \phi^{-1} \frac{\partial \phi}{\partial T} \Delta T}{\phi(\sigma, T)} d\varepsilon \tag{9}$$

where ε_r is the maximum creep strain accepted for design and ε_o is the creep strain when the temperature change occurred. This equation may be used to evaluate maximum allowable time for creep in the case when temperature increases and stays constant afterwards, figure 4 (solid lines). In this case, the spike magnitude is constant. If ΔT is not small, additional considerations are needed for model development.

If the stress is dependent on temperature, then

$$\phi(\sigma(T + \Delta T), T + \Delta T) = \phi(\sigma, T) + \left(\frac{\partial \phi}{\partial \sigma} \frac{\partial \sigma}{\partial T} + \frac{\partial \phi}{\partial T} \right) \Delta T \tag{10}$$

Equation (9) can be also rewritten in the form

$$t_r = (t_r)_T - \Delta T_0 \int_{\varepsilon_o^+}^{\varepsilon_r} \phi^{-2}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} d\varepsilon \tag{11}$$
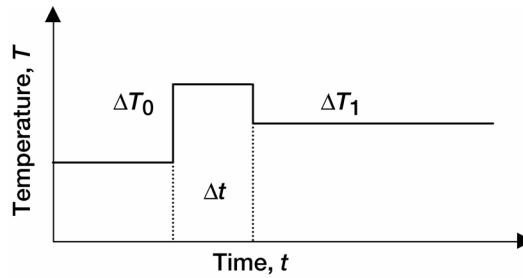

Figure 4.—Thermal excursion.

The same procedure repeated for temperature drops, $\Delta T < 0$, results in the following equation:

$$t_r = (t_r)_T + \Delta T_1 \int_{\varepsilon_1^-}^{\varepsilon_r} \phi^{-2}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} d\varepsilon \tag{12}$$

Combining these equations gives the rupture time for a "thermal step function" when $\Delta T_0 = \Delta T_1 = \Delta T$ is given by

$$t_r = (t_r)_T - \Delta T \int_{\varepsilon_0^+}^{\varepsilon_1^-} \phi^{-2}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} d\varepsilon \tag{13}$$

If the duration of the temperature increment is small, the approximate rupture time is found to be

$$t_r = (t_r)_T - \phi^{-1}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} \Delta T \Delta t \tag{14}$$

In the case of multiple temperature changes T_k, equations (11) and (12) can be generalized as follows:

$$t_r = (t_r)_T + \sum_{k=1}^{M} \Delta T_k^- \int_{\varepsilon_k^-}^{\varepsilon_r} \phi^{-2}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} d\varepsilon \tag{15}$$

$$t_r = (t_r)_T - \sum_{k=1}^{M} \Delta T_k^+ \int_{\varepsilon_k^+}^{\varepsilon_r} \phi^{-2}(\sigma, T) \frac{\partial \phi(\sigma, T)}{\partial T} d\varepsilon \tag{16}$$

The preceding described formulation requires the strain rate information for the Glenn material. The test data for the Glenn material were analyzed to develop a relationship between the strain rate from the ORNL master curve and that observed in the Glenn material tests. The heater head durability methodology for thermal excursions assumes that the strain rate remains constant during the secondary creep zone and that the material recovers the original strain rate during the postexcursion time. The formulation given earlier and the strain rate determined for the Glenn material were used to calculate the effect of thermal excursions to 660, 670, and 680 °C from an operational temperature of 650 °C. Thermal excursions of 1 day and of 6 months occurring after 1 and 2 yr of normal operation were analyzed. The results (table II) indicate that the percentage of life lost was small. However, the loss of life could accumulate if the number of occurrences increased and if the occurrence was in the latter part of the mission. Such an effect may need to be investigated if the reasons for thermal excursions warrant this.

Summary of Results

The durability of a Stirling power convertor heater head was assessed in relation to its requirements for long-term space science missions. A large database on Inconel 718 generated by ORNL and data from a small number of tests performed at Glenn on 0.50-mm-thick thin samples of the Inconel 718 to be used in the heater head were used to quantify uncertainties in the material behavior. Also, uncertainties in the

geometry, pressure, and temperature were included in the analysis. The assessment shows that the heater head has a lifetime of 13.25 yr with 99.99-percent PoS. Sensitivities of uncertainties in the material behavior, thickness, pressure, and temperature were also quantified. As expected, the heater head reliability is most sensitive to uncertainties in the long-term creep behavior of Inconel 718. Also, the effect of possible thermal excursions on the heater head durability was investigated. The evaluation shows that thermal excursions up to 680 °C for durations of up to 180 days within the first 2 yr of mission life have, at most, a small effect on life. Evaluation of the effect of thermal excursions occurring in the latter part of a mission as well as the effect of more than one excursion need to be performed in a true probabilistic sense.

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Appendix—Symbols

A	constant
a	constant
B	constant
C_h, C_1, C_2, C_3, C_4	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 $C_4 = -0.01052$)
c	$A * B$
M	number of thermal spikes
p	fraction of time to tertiary creep
T	temperature
T_k^-	temperature drop
T_1	$T + \Delta T_0$
ΔT_0	change in temperature
t	time
t^*	normalized time (with respect to time at the onset of tertiary strain)
t_f	deterministic design life
t_r	rupture time
t_{ss}	scale factor for the time to reach tertiary creep
$\alpha, \beta, \gamma, \delta$	constants quantified from test data
ε	creep strain
ε_k	creep at temperature T_k
ε_r	maximum creep strain accepted for design
ε_0	creep strain when the temperature change occurred
$\dot{\varepsilon}$	rate of creep strain
$\dot{\varepsilon}_{ss}$	steady-state creep rate leading up to the onset of tertiary creep
ε^*	normalized creep strain (with respect to creep stain at the onset of tertiary creep)
σ	stress
ϕ	creep law

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13. ABSTRACT (Maximum 200 words)

Onboard radioisotope power systems being developed and planned for NASA's deep-space missions require reliable design lifetimes of up to 14 yr. The structurally critical heater head of the high-efficiency Stirling power convertor has undergone extensive computational analysis of operating temperatures, stresses, and creep resistance of the thin-walled Inconel 718 bill of material. A preliminary assessment of the effect of uncertainties in the material behavior was also performed. Creep failure resistance of the thin-walled heater head could show variation due to small deviations in the manufactured thickness and in uncertainties in operating temperature and pressure. Durability prediction and reliability of the heater head are affected by these deviations from nominal design conditions. Therefore, it is important to include the effects of these uncertainties in predicting the probability of survival of the heater head under mission loads. Furthermore, it may be possible for the heater head to experience rare incidences of small temperature excursions of short duration. These rare incidences would affect the creep strain rate and, therefore, the life. This paper addresses the effects of such rare incidences on the reliability. In addition, the sensitivities of variables affecting the reliability are quantified, and guidelines developed to improve the reliability are outlined. Heater head reliability is being quantified with data from NASA Glenn Research Center's accelerated benchmark testing program.

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