



Structural Benchmark Testing for Stirling Converter Heater Heads

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Abstract

The National Aeronautics and Space Administration (NASA) has identified high efficiency Stirling technology for potential use on long duration Space Science missions such as Mars rovers, deep space missions, and lunar applications. For the long life times required, a structurally significant design limit for the Stirling converter heater head is creep deformation induced even under relatively low stress levels at high material temperatures. Conventional investigations of creep behavior adequately rely on experimental results from uniaxial creep specimens, and much creep data is available for the proposed Inconel-718 (IN-718) and MarM-247 nickel-based superalloy materials of construction. However, very little experimental creep information is available that directly applies to the atypical thin walls, the specific microstructures, and the low stress levels. In addition, the geometry and loading conditions apply multiaxial stress states on the heater head components, far from the conditions of uniaxial testing. For these reasons, experimental benchmark testing is underway to aid in accurately assessing the durability of Stirling heater heads. The investigation supplements uniaxial creep testing with pneumatic testing of heater head test articles at elevated temperatures and with stress levels ranging from one to seven times design stresses. This paper presents experimental methods, results, post-test microstructural analyses, and conclusions for both accelerated and non-accelerated tests. The Stirling projects use the results to calibrate deterministic and probabilistic analytical creep models of the heater heads to predict their life times.

Introduction

Under NASA's Science/Radioisotope Power Systems program, the Department of Energy (DOE) is developing high-efficiency Stirling power systems with Glenn Research Center (GRC) and the Lockheed Martin Corporation, Valley Forge, Pennsylvania. Lockheed Martin developed the design and began fabrication for the 110-watt Stirling Radioisotope Generator (SRG110) Engineering Unit under contract to DOE and is now transitioning this to the higher specific power Advanced Stirling Radioisotope Generator (ASRG). Infinia Corporation, Kennewick, Washington, developed the Stirling converter for the SRG110. Sunpower, Inc., Athens, Ohio, is developing the Advanced Stirling Converter (ASC), under a NASA Research Announcement (NRA) award. The current ASRG Engineering Unit will use an ASC with an Inconel 718 heater head; a higher-temperature converter with a MarM-247 heater head is also being developed as part of the NRA. GRC is managing the ASC NRA project and is providing supporting technology development for the Stirling converter and overall generator.

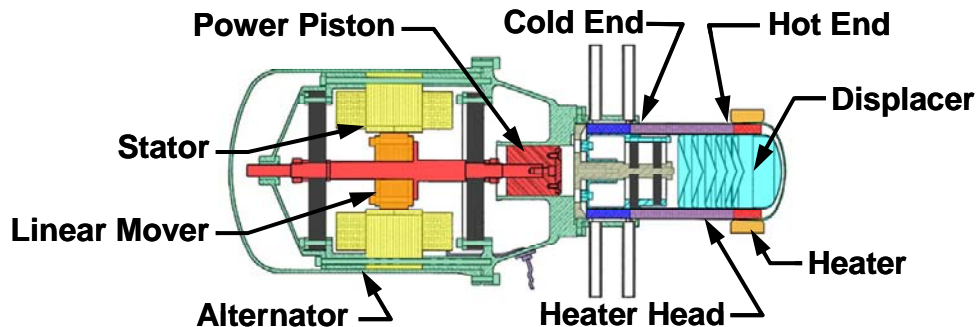


Figure 1.—Laboratory version of SRG110 Stirling converter assembly (adapted from Schreiber and Thieme, 2003).

This Stirling technology is being developed for potential use on long-duration Space Science missions, including deep space and lunar applications (Wong, et al., 2006; Thieme and Schreiber, 2003; 2005). The generators use General Purpose Heat Source (GPHS) modules as energy sources and Stirling free-piston convertors to convert heat to mechanical and then electrical energy. Each convertor contains a nickel-based superalloy heater head (such as that shown in fig. 1), a pressure vessel with maximum temperatures at the hot end interface to the GPHS. This end of the heater head wall is thicker to reduce stresses induced by internal pressure. One system goal under all projects is to provide reliable maintenance-free operations for durations of fourteen years or longer. For such long lives, even the low hot end stresses produce creep deformation, a critical design limit for the heater head. Creep is the accumulation of inelastic strain under sustained loading over time. Because conventional engineering practices and available material property data are inadequate, a detailed life assessment effort is underway at GRC to evaluate accurately the heater head's creep life. The objective of heater head structural benchmark testing is to provide experimental creep data for prototypical stress conditions for the calibration of the life assessment analytical methodologies.

Stirling Converter Heater Head Life Assessment Effort

Stirling converter heater heads under investigation are variable-thickness, thin-walled cylindrical pressure vessels with outer diameters of approximately 30 to 50 mm. The walls are as thin as possible for longitudinal heat transfer resistance and thus low thermal losses, but thick enough to provide low stresses resulting from the internal operating pressure. The thin cylindrical walls' stress fields are nearly biaxial, with circumferential (hoop) stress approximately twice the longitudinal stress. The open, very thin cold ends of the heater heads include integral flanges for sealing to other convertor structures; the wall thickness tapers to the thicker hot ends that terminate with closed, domed heads. The hot ends conduct heat from the external GPHS to internal heat exchangers or receptors. While the overall power system control strategy has not been determined for any particular mission, the most conservative approach for estimating life is to assume that the hot end metal temperature is maintained at the materials' maximum functional temperatures—650 °C for IN-718 (SRG110 and ASRG projects) and 850 °C for MarM-247 (ASC project). Creep resistance in heater head walls at the locations of maximum temperature is of critical importance for long lives of Stirling convertors. The resultant criterion for heater head creep life is the time for creep strains to reach the onset of tertiary creep, when the creep strain rate begins rapid acceleration. Because the walls are thin, the specified IN-718 material is very fine grain to assure un-degraded creep properties due to too few through-thickness grains (Bartolotta et al., 2000; Bowman, 2001). The material specification for MarM-247 heads is currently under development.

GRC uses a thorough four-task approach to quantify creep resistance of heater heads under operating temperatures and stresses (Halford et al., 2002). The first task provides extensive creep testing of thin dog-bone specimens for uniaxial creep property data of heater head materials (Bowman, 2001). This task

provides previously unavailable creep deformation, creep rate, and rupture data for the superalloys at various temperatures and at stress levels from approximately one to ten times the design principal stress.

The second life assessment task includes detailed deterministic structural analyses of heater heads using finite element analyses (FEA). Here, an analyst models heater heads accurately using FEA and calculates linear elastic and thermal stresses and strains conventionally. However, the analyst calculates creep deformations with FEA by using properties derived from testing described in the preceding paragraph as follows. For each test stress and temperature, the analyst determines a steady state creep rate by dividing gross accumulated experimental creep strain at the start of tertiary creep by elapsed time at that point. The FEA program then applies the stress-temperature-creep rate relationship to the calculated equivalent (von Mises) stresses. The nonlinear analyses run in the time domain to determine full-field heater head creep strains at any point in time. This method accurately predicts times to onset of tertiary creep, which is the life criterion. At times before this point, it generally underestimates creep strains slightly; at times over this, it underestimates creep strains by an increasingly large factor.

Because considerable scatter exists in experimental creep rates, the third task (Shah, Halford, and Korovaichuk, 2004) provides probabilistic analyses of test and handbook data and design conditions. For IN-718 heater heads, it also relies on voluminous long-term creep data generated on bulk, large-grain material (Brinkman, Booker, and Ding, 1991) by Oak Ridge National Laboratory (ORNL). In addition, the probabilistic analyses account for other uncertainties such as variability in geometry, pressure, and temperature. This task results in calculation of the probability of survival (PoS) to the onset of tertiary creep for design conditions. A 50 percent PoS is the calculated median heater head life; of course, the required PoS for a flight unit is much higher, perhaps 99.99 percent.

Structural Benchmark Testing Task

The fourth task of the heater head assessment is a comprehensive benchmark testing effort (Halford et al., 2002). Under this element, the experimentalist places heater head test articles under both prototypical and accelerated conditions with real-time monitoring of surface temperatures, diametral strains, and internal pressures. Because the specimens are pressurized, an accurate biaxial stress state exists as in a complete Stirling convertor assembly. Test results provide creep deformation feedback to the analytical models to refine those methods if needed, and provide data for independent experimental assessments of heater head creep lives. In addition, consequences of the superalloys' grain microstructures on thin wall creep response, effects from potentially inhomogeneous heat treatment (if any) on creep deformation and life, and detection of any possible circumferentially directional creep caused by such material processing or other mechanisms are investigated.

For the SRG110 project, the structural benchmark test effort included four short-term accelerated tests and two long-term non-accelerated tests, all performed with the maximum design temperature of 650 °C at the hot end. The short-term tests used high internal pressures to permit test results within reasonable periods, albeit at higher than operating stresses. The two long-term tests used nominal design pressure to produce prototypical stresses. For the ASC project, full test plans are under development for testing MarM-247 test articles. Initially, two "cascade" tests (described in the following section) will produce accelerated conditions at design pressure by extending the 850 °C maximum temperature area toward the cold end. The thinner wall thickness in that area will result in higher stresses, providing accelerated creep conditions. Other, non-accelerated tests will use a prototypical temperature gradient. For the ASRG project with an IN718 heater head, test plans are also under development and provide prototypical stress and temperature fields only. For all tests with prototypical temperature profiles, the critical strain measurement is at the test article's location corresponding to the hot end of the regenerator. This gage area is critical due to the combined high temperature and stress level.

Structural Benchmark Test: Experimental Details

The main objective of the structural benchmark tests and the experimental dependent variable are measurement of heater head circumferential secondary (steady state) creep strain rates. An additional objective is the quantitative observation of creep strain deformations from primary through secondary creep. For accelerated tests only, the observations continue through the onset of tertiary creep (tests are terminated prior to rupture to avoid damage to the facility). For all cases, test article wall temperature profiles are constant, while stress level varies by internal pressure or by wall thickness in the gage area; thus, stress is the experimental independent variable.

A previous report (Krause and Kantzos, 2006) describes experimental details for structural benchmark testing performed under the SRG110 project; table 1 includes a summary of those test conditions and creep predictions. For the ASC and ASRG projects, test requirements and subsequent experimental details are under development. However, plans and hardware procurement are well underway for the initial ASC accelerated testing, and the remainder of this section focuses on those tests. Note that non-accelerated testing under ASC and ASRG will be very similar to the accelerated tests, with the exception that experimental wall temperature profiles of test articles will simulate the prototypical distribution.

TABLE 1.—SUMMARY OF HEATER HEAD STRUCTURAL BENCHMARK TEST SPECIMENS, CONDITIONS, PREDICTIONS, AND RESULTS

Benchmark test type		Accelerated					Non-accelerated	
Test article		Bitec1	Bitec2	Bitec3	STC209	A2	STC206	STC212
Material		IN-718	IN-718	IN-718	IN-718	MarM-247	IN-718	IN-718
Temperature (°C)		650	650	650	650	850	650	650
Pressure (MPa)		7.1	6.1	6.1	high	low	low	low
Axial preload		no	no	no	no	no	yes	no
Stress factor		very high	high	high	moderate	one to mod.	one	one
Predicted	creep rate (1/sec)	high	mod. high	mod. high	moderate	v.low - high	very low	very low
	time to tertiary (days)	22	67	67	moderate	high to low	high	high
Observed	creep rate (1/sec)	very high	high	v. v. high	low	n.a.	very low	low
	test duration (days)	30	59	25 (rupture)	131	n.a.	235 (online)	330 (online)
	creep rate anisotropy	1.2:1	3:1	2:1	1:1	n.a.	5.5:1	20:1

Cascade Testing

Previous short-term heater head creep tests relied on increased internal pressure to accelerate creep deformation. Safety considerations in the laboratory limited the maximum available acceleration due to hazards associated with potential rupture under high pneumatic pressures. In addition, and most significantly, the method produced only one experimental stress-temperature condition for each lengthy, expensive test. Addressing these issues, GRC developed the “cascade” test procedure for ASC accelerated benchmark testing. Cascade testing, so called for the cascade of experimental creep rates produced by a single test article over a wide range of stresses and at the temperature of interest, subjects a large volume of material amenable to creep strain measurement (fig. 2). The method uses an inductively heated susceptor to create uniform temperature over a major portion of the test article tapered wall. In this way, internal pressure creates a large multiaxial stress range at the desired temperature: near the heat acceptor end, the thick wall results in lower stress; towards the cold rejector end, the thin wall produces higher stresses.

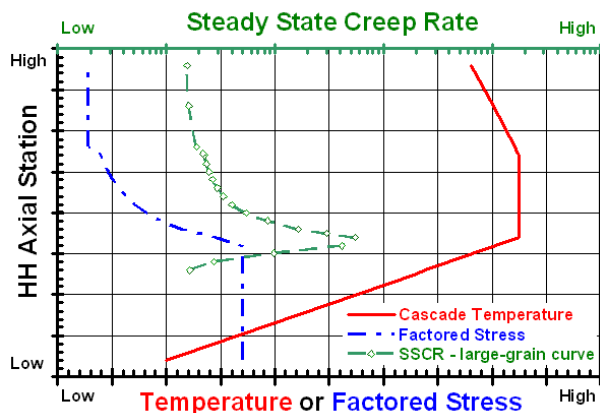


Figure 2.—Conceptual creep rate response for cascade testing of heater head test article.

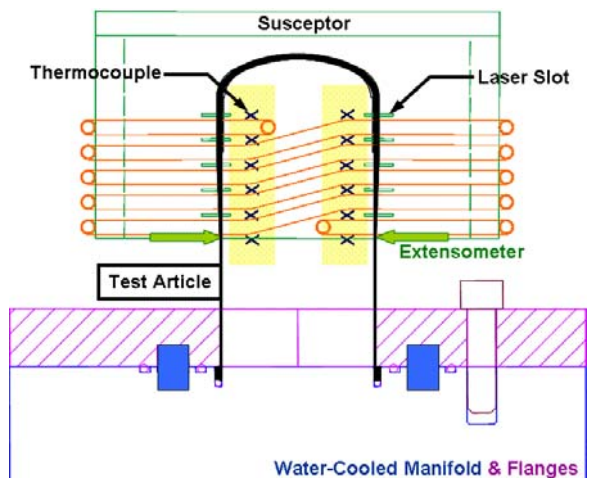


Figure 3.—Cascade test apparatus for applying heat and measuring creep strains on test article.

Cascade Test Article Description

Cascade testing uses pressure vessels of the current ASC heater head design as test articles. Two specimens fabricated as proof-of-machining trials by Pratt & Whitney Rocketdyne are available for testing. The material of construction for both is very large grain MarM-247 nickel-based superalloy. The heater heads are bare shells—that is, they do not contain any internal structures or any brazed-on attachments. They include heat treatment similar to the ASC product specification. Evaluation of test results from the first test article will guide the selection of test parameters prior to the start of testing for the second test article.

Cascade Test Apparatus

GRC will perform this structural benchmark testing on a bench-top test rig (fig. 3) in a laboratory environment. A computer-controlled closed-loop argon gas system produces accurately controlled pneumatic pressures from zero to 20 MPa. A compressed gas cylinder supplies argon through small diameter stainless steel tubing. A flow meter monitors system leakage and vessel rupture. Air-operated solenoid valves provide abort capability, and air-operated regulating valves control test pressure. Relief valves protect the system and test articles from accidental over-pressurization. Custom split flanges capture the test article’s integral rejector end flanges and bolt to a gas manifold/mounting flange. The mounting flange includes machined grooves for high temperature elastomeric o-ring sealing to the test article. The split flanges and mounting flange have machined passageways that provide integral water-cooling through shared, sealed kidney loops. A ceramic plug occupies much of the test article’s interior volume to limit the quantity of compressed gas. Ratings for all system components greatly exceed the test pressure. Personnel barriers and an acrylic enclosure provide personnel safety at this pneumatic test facility.

Induction heating at the rig uses a feedback controller for temperature control of the test article. Each high frequency power supply is a 3 kW-rated Ameritherm unit. Custom external induction coils wrap a SiC cylindrical susceptor to heat radiantly the test article’s gage area to test temperature. The susceptor contains small through-thickness ports spaced at 90° for hot laser scanning of the test article outside diameter. Welded-on thermocouples provide test article’s metal temperatures. All wire gage and insulation are rated for long-term use at 850 °C or higher. The thermocouples are spot welded with the minimum energy possible. The heat-affected zone is very small, and the strain measurement method

integrates creep strain over a large circumferential volume of material, minimizing possible influence on creep strain measurement. Sufficient ductility in the MarM-247 material at the test temperature ensures that premature failure due to stress concentration at the welds does not occur.

Extensometry and laser micrometers provide measurement of test article's circumferential strain. The extensometry system uses two diametral extensometers mounted to the test article to measure real-time gage area strains at a critical location determined by stress and temperature. They are placed at 90° to each other in a plane perpendicular to the test article longitudinal axis and near the rejector end of the tapered wall, where the metal temperature remains at 850 °C before decreasing rapidly. The precision of diameter measurement for the extensometers results in a strain resolution of approximately 7 microstrains. A bench-top drift study of the extensometers validated their use for long-term creep strain measurement. To determine circumferential strains in areas of the heater head tapered wall between the extensometer location at the rejector end and the thick wall at the acceptor end, two laser micrometers mounted perpendicularly make diameter measurements at discrete axial locations. Room temperature laser scans record diameters at approximately ten axial stations during test start-up and at planned and unplanned shutdowns, but never more frequently than every four days or less frequently than monthly. Hot scans record diameters approximately once per week at five axial stations through the susceptor ports. The micrometer frame attaches to a vertical positioning stage with an LVDT readout that allows precise and repeatable axial positioning of the measurement location. Laser micrometer resolution is comparable to that of the extensometer's resolution.

A control computer provides set point and conditioning for the pneumatic pressurization system, but its primary purpose is for data acquisition and automated test termination. The computer saves the test article's internal pressure, a leak flow signal, the two extensometer channels, and 28 chosen gage area wall temperatures. Rapid data recording occurs during test startup; long-term data recording occurs at a frequency of once every five minutes. Programmable test limits produce automated safety aborts to the induction heater and pneumatic pressurization system based on pressure level, gas leakage above approximately 0.07 scfm, over- or under-temperature in the gage area, extensometer strain magnitude beyond secondary strain, or power outage. Upon abort, the data system uploads all data to the host PC and archives the file. An uninterruptible power supply provides back up to all systems except the induction heaters. An auxiliary data system records laser micrometer and associated LVDT measurements.

An analysis of experimental precision and sources of error was completed. This study evaluates components of the pressure, temperature, and strain measurement systems, as well as errors in measurement of specimen geometry. The major error source in the pressure system is the pressure transducer, with a calibration accuracy of ± 0.25 percent. For the heating system, 3.5 °C error is possible, due to inherent properties of thermocouples. In the strain measurement system, extensometer drift is a source of error, equal to 7 microstrains. Oxidation on the specimen surface causes erroneous strain measurements from the laser system until the oxide layer growth is accounted. Finally, error in measurement of specimen wall thickness results in 11 percent uncertainty in stress at the thin-wall end of the test article.

Cascade Test Procedures

Prior to the start of cascade testing, a laser scan and extensometer readings record the test article's initial dimensional state at room temperature and at ambient pressure. Following this, the strain measurement devices record room temperature elastic strains as the argon system pressurizes the test article to its test pressure. Upon release of this pressure, the next set of strain readings record thermal expansion strains as the susceptor heats the gage area to 850 °C at ambient pressure. Then the system records the elastic and initial primary creep strains as the argon system pressurizes the test article while at test temperature. Once the test condition is reached, the data acquisition takes extensometer measurements frequently, while the test technician makes laser scans less often due to the required manual effort, to track the creep strain progression. Test termination occurs when the onset of tertiary creep at any axial station is evident in the strain results.

Because cascade testing has not yet started, GRC has identified potential challenges to accurate creep strain measurement with this test procedure. Susceptor-induction heating must provide temperature uniformity in the gage area of the test article. The integrally cooled mounting flanges must attain acceptable o-ring temperatures at the rejector end. The laser micrometer system must provide repeatable, highly accurate diameter measurements. The strain measurements must account for oxidation layer growth. The measurements must consider the influence on creep response of the stress gradient throughout the gage area. Finally, test interruptions for laser measurements must not produce unacceptable high noise in the strain readings. If any of these challenges prove insurmountable, then testing will revert to the “traditional” test methods similar to those performed for the SRG110 project.

Structural Benchmark Test Conditions Summary

Table 1 shows a summary of Stirling heater head structural benchmark test conditions, along with creep predictions based on GRC uniaxial creep testing results applied to test article’s principal stresses, for the three Stirling projects.

Structural Benchmark Test Results

A previous report (Krause and Kantzos, 2006) describes experimental results for short-term accelerated heater head tests under the SRG110 project; those results are included in the following summary figures, but this report provides no further test description. Results are also not provided for the test effort planned under ASC and ASRG projects, as testing has not yet begun. Long-term, non-accelerated benchmark tests are currently running successfully for IN-718 heater head specimens at prototypical stress levels under the SRG110 effort, and results for those follow.

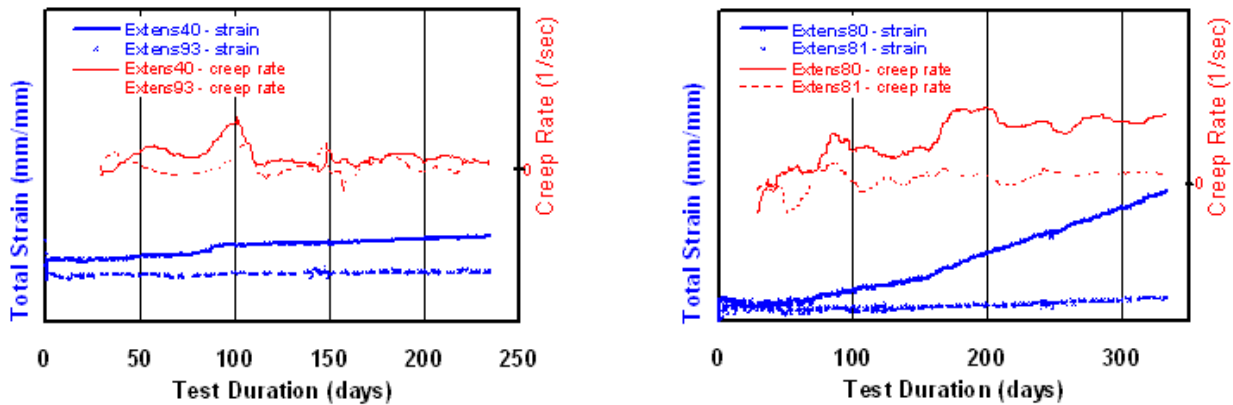
SRG110 Non-Accelerated Heater Head Benchmark Tests

Two test articles of the SRG110 design are currently under test at prototypical stress levels and temperatures. One includes an axial load that simulates contact pressure from the GPHS. Induction heating coils provide the uniform gage area temperature of 650 °C, with long-term variance generally less than 5 °C. The primary measurement is the gage area diameter, taken by two diametral extensometers located 90° apart on the circumference; the measured increase in diameter divided by the original gage diameter provides the calculation of diametral strain. The important calculated quantity of creep strain rate is determined at any point in time by the slope of the strain versus time curve over a selected time interval using linear regression. A 28-day interval is used here as a good compromise between strain rate tractability and repression of experimental noise.

Test article STC206 uses the GPHS axial loading scheme. To date this test has run over 5600 hr (235 days). The observed average creep rate is within 20 percent of the prediction, but the two extensometers record anisotropic creep strain rate behavior at a 5.5:1 ratio. Test article STC212 does not use an axial preload. Currently it has logged over 7900 hr (330 days) under the benchmark test conditions. The observed creep rate from one extensometer is nearly an order of magnitude greater than the prediction, while the other measures a rate somewhat below the prediction. This results in a rate ratio of 20:1. Figure 4 provides current creep strain data from the two tests.

Structural Benchmark Test Results Summary

Table 1 also provides a summary for all available Stirling heater head structural benchmark test results, including data from the short-term accelerated tests previously reported.



(a) Strains and Creep Rates for Test Article STC206.

(b) Strains and Creep Rates for Test Article STC212.

Figure 4.—Experimental results for SRG110 non-accelerated benchmark tests.

Test Results Analysis

The variability in creep strain results for the two non-accelerated tests is indicative of the large scatter commonly found in creep properties of materials, even under highly controlled laboratory environments. In addition, under the very low stress conditions present, the creep strains are very small, and thermal strains due to a few degrees variation in temperature can obscure the creep deformation. The high anisotropy ratios reported may be due in part to the small magnitude of the creep rates.

The experimental creep curves show steady-state secondary creep with no hint to the onset of tertiary creep; that is expected at the low test stress level. Observed anisotropy is unusual for its magnitude and its potential impact to the design life of the Stirling convertor, and its cause remains to be determined at this time. Because the two tests continue to run, a post-test microstructural evaluation is not possible at this time. That study may provide insight into the anisotropic creep response if related to the heat treatment or metallurgy of the test articles. GRC is investigating heat treatment processing records and furnace witness coupons in the meantime. A similar study for the earlier accelerated tests determined significant creep response dependency on the cooling rate used during heat treatment. These tests were done on thin-wall test specimens built especially for these accelerated tests. It theorized that variable and lower than desired cooling rates resulted in out-of-specification formation of precipitates, causing increased scatter, possibly creep rate anisotropy, and higher creep rates compared to those predicted. The one accelerated test article with SRG110 geometry and fabrication heritage (STC209) produced nearly equal creep rates and creep rates lower than predicted.

Conclusions

Glenn Research Center is conducting a robust experimental program to investigate critical life-limiting creep behavior on the heater head component of Stirling convertors. Recent pneumatic testing of six heater head test articles at high temperature included stress ranges from design-level to seven times that value. In general, creep response was proportional to stress. The test results show that average response, especially for SRG110-design test articles, is in agreement with predicted creep strain rates when accounting for the high scatter common in experimental creep results. However, the testing revealed significant variation in creep rate around the circumference of the measured gage area; this condition, if not alleviated, would reduce the calculated median heater head life. A full explanation for the behavior is not available presently. Three non-SRG110-design test articles used for accelerated testing produced less anisotropy but higher than expected creep strain rates; the higher rates are probably due to their less controlled heat treatment procedure.

The probabilistic assessment of secondary creep rates drawn from the ORNL database and GRC uniaxial creep testing provides a measure of the variation of the experimental creep rates from median values (Shah, Halford, and Korovaichuk, 2004). All six benchmark tests fall within the 99.9 percent probability of survival curve (approximately three standard deviations) relating stress and secondary creep rate.

The development of a full life assessment of the Stirling convertor's heater head will continue in the ASC project with further benchmark tests as described herein. Use of the advanced nickel-based superalloy MarM-247 provides an opportunity for improving the convertor efficiency, but the apparent lack of available low stress, long-term creep data for the material will prove a challenge in its durability assessment for long life.

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14. ABSTRACT The National Aeronautics and Space Administration (NASA) has identified high efficiency Stirling technology for potential use on long duration Space Science missions such as Mars rovers, deep space missions, and lunar applications. For the long life times required, a structurally significant design limit for the Stirling convertor heater head is creep deformation induced even under relatively low stress levels at high material temperatures. Conventional investigations of creep behavior adequately rely on experimental results from uniaxial creep specimens, and much creep data is available for the proposed Inconel-718 (IN-718) and MarM-247 nickel-based superalloy materials of construction. However, very little experimental creep information is available that directly applies to the atypical thin walls, the specific microstructures, and the low stress levels. In addition, the geometry and loading conditions apply multiaxial stress states on the heater head components, far from the conditions of uniaxial testing. For these reasons, experimental benchmark testing is underway to aid in accurately assessing the durability of Stirling heater heads. The investigation supplements uniaxial creep testing with pneumatic testing of heater head test articles at elevated temperatures and with stress levels ranging from one to seven times design stresses. This paper presents experimental methods, results, post-test microstructural analyses, and conclusions for both accelerated and non-accelerated tests. The Stirling projects use the results to calibrate deterministic and probabilistic analytical creep models of the heater heads to predict their life times.					
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