LOW STRAIN DIAMETER EXPANSION OF INTERNALLY PRESSURIZED ZIRCALOY-4 TUBING AT HIGH TEMPERATURES

(LWBR Development Program)

MARCH 1978

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L. S. White and C. C. Busby

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Tests of closed-end, internally pressurized, Zircaloy-4 tubing specimens were utilized to develop low strain creep characteristics as a function of time at temperatures in the range of 1475°F to 2000°F (802°C to 1093°C) and hoop stresses in the range of 250 to 2500 psi for use in loss-of-coolant accident (LOCA) analyses. The strain rate above the start of the alpha to beta phase transformation region, approximately 1490°F (810°C), was found to be sensitive to the test procedure (stress-temperature history). This is believed to result from variations in the metallurgical structure. A prediction model is presented which provides a conservative upper bound to the low strain test data provided in this report and reported in the literature.

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I. INTRODUCTION

During a postulated loss-of-coolant accident (LOCA) for a pressurized water reactor (PWR), the sudden system depressurization and attendant loss of coolant flow imposes, on the fuel elements, high cladding temperatures which exist simultaneously with a rod internal gas pressure higher than that of the external system pressure. As a result, large diameter expansion and possible bursting are of concern. This report presents the results of testing the response of Zircaloy-4 tubing to the LOCA hoop stress-temperature environment. An analysis model is also presented which may be used in assessing fuel element low strain plastic diameter expansion during a LOCA. This testing is a continuation of the testing reported in Reference (1) and was accomplished as part of the Light Water Breeder Reactor (LWBR) fuel element development effort.

High temperature test data previously reported have generally established only the stresses and strains associated with burst or fracture, for example, References (2) through (5). The tests described in this report, which are a continuation of those reported in Reference (1), were initiated to obtain the stress sensitivity at relatively low strain (less than 5 percent diametral expansion) over the temperature range from 1475°F to 2000°F (802°C to 1093°C).

The low strain information is of interest in reactor design to determine the effect of clad expansion on coolant channel dimensions and potential flow constriction. For the test specimens used in these tests, the alpha to beta phase transformation region ranges from approximately 1490°F (810°C) to approximately 1770°F (965°C). Test procedures were varied to assess the relative effects of this phase transformation on the plastic strain and strain-rate sensitivity.

II. TEST DESCRIPTION

The specimens used in this test were 13 inches long, 0.31 inch OD x 0.26 inch ID cut from 68 percent tube reduced and recrystallized (5-6 hours at 1225°F) Zircaloy-4 tubing. One end was sealed with a welded Zircaloy-4 plug and the other end was connected to the pressurizing system with a Swagelok fitting. The specimens were cut from tubing with measured maximum wall thickness eccentricity (ultrasonic measurements) between 0.0004 inch and 0.0006 inch. The average wall thickness of each specimen was calculated from the density (6.54 gm/cc), the specimen length measured to 0.001 inch, and the average outside diameter based on micrometer measurements (0.0001 inch) for two diametral positions at five positions along the length. This average wall thickness was used in the following thin-wall formula to obtain the required internal pressure for the desired hoop stress:

$$\sigma_{\theta} = \frac{PD}{2t}$$

where

σ_{θ} = hoop stress in psi

P = internal gas pressure in psi

D = mean diameter in inches

t = average wall thickness in inches.

The specimens were heated by placing them in a 1 1/4-inch Vycor chamber located at the axis of a dual elliptical reflector, quartz-lamp furnace as shown in Figure 1. A silicon-controlled a-c power controller with thermocouple feedback provided a closed-loop system to maintain accurately the desired temperature. Investigation showed that the maximum temperature, uniform within ±5°F, was obtained at a distance of 3 1/2 to 5 1/2 inches from the welded end of the sample. The data reported herein are based upon measurements at the 4 1/2-inch location. Temperatures were recorded by three Chromel-Alumel thermocouples, two internal and one external. The beads of the inner thermocouples were exposed through windows cut in a ceramic insulation which projected through the Swagelok

connection of the apparatus and to within 1/4 inch of the welded end plug. However, thermocouple bead contact with the specimen was avoided to preclude reaction with the Zircaloy. The surface thermocouple was in contact with the specimen, but reaction was prevented by enclosing the bead in 0.002-inch tantalum foil. The outside and one of the inner thermocouples were located at the 4 1/2-inch "hot spot." The second inner thermocouple was located 7 inches from the welded end where the temperature was 50-60°F lower.

Oxidation of the specimens was essentially eliminated by evacuating the Vycor chamber and the specimen to $\leq 5\mu$ pressure prior to heating, maintaining a dynamic vacuum in the Vycor chamber throughout the test, and using inert argon gas to pressurize the specimens. The effect of temperature on the specimen gas pressure was effectively neutralized, and therefore constant hoop stress could be maintained during the test, by the relatively large volume ratio (approximately 20:1) of the system external piping to the specimen.

Two dual-pen strip chart recorders were utilized to monitor specimen pressure and the specimen surface and inside temperatures throughout the test.

III. PREVIOUSLY REPORTED EQUILIBRIUM ISOTHERMAL DATA

The objective of the initial phase of testing described in Reference (1) was to obtain isothermal data unaffected by phase transformations (equilibrium structure) which could be used to formulate a low-strain, high-temperature creep model. The specimens were slowly heated to the test temperature while evacuated. Prior to pressurization, approximately two to seven minutes at the test temperature was allowed for temperature and structure equilibration. Each specimen after being stressed for a preselected time period was depressurized and cooled to room temperature for diameter measurements. The specimen was then retested for additional time periods (same stress and temperature) until a steady-state rate was observed or instability occurred. Individual test times, depending on the stress, temperature, and whether or not transient or steady-state behavior was expected, were as short as 3 seconds and as long as 15 minutes.

These test data are reported in Reference (1). Also presented in Reference (1) is an isothermal prediction model which was formulated to give a conservative upper bound to the test data as shown in Figure 2. These data and model were then used as a base for investigating the effects of nonequilibrium structure on the strain rate.

IV. NEW TEST RESULTS

A. Simulated LOCA Transients

After completing the isothermal testing reported in Reference (1), testing of specimens subjected to representative LOCA high temperature histories was initiated. The intent of this testing was to investigate the adequacy of the isothermal prediction model in predicting strain during a temperature transient. The specimens were pressurized at normal PWR operating clad temperatures and heated as shown in Figure 3. The diametral strain was measured after the specimens were depressurized and cooled to room temperature and compared to the predicted strain, which was obtained by using the Reference (1) isothermal prediction model. This comparison, shown in Figure 3, shows the Reference (1) model conservatively predicted the measured strain only for that transient which stayed entirely within the alpha region, i.e., temperatures less than 1490°F (810°C). The two higher peak temperature transients which entered the alpha + beta and beta regions are underpredicted. Thus, it was concluded that the equilibrium test data could not be used to conservatively predict strain during a LOCA transient that experienced temperatures higher than the alpha transition temperature.

B. Effect of Test Procedures

The disagreement between the predictions based upon the Reference (1) model and the plastic strain obtained from the simulated LOCA temperature transients led to additional testing at faster initial heatup rates and an investigation of the effect of the equilibration hold time at test temperature prior to pressurization. A datatrak programmer was used to control the furnace voltage to enable accurate repeatability of temperature transients. Figures 4 through 6 show the effect of varying the test procedure upon the measured diametral strain. The Reference (1) isothermal test samples were heated slowly to the test temperature (usually taking 15-20 minutes from room temperature to test temperature) and then given an equilibration time of 2 to 7 minutes prior to pressurization. It was found that this equilibration time prior to pressurization has a marked effect on the strain rate at 1600°F to 1800°F (871°C to 982°C) isothermal test temperatures. At 1600°F (871°C) the strain rate is reduced slightly for the zero time delay specimens. At 1800°F (982°C), however, the trend is reversed and decreased equilibration time results in increased strain rates. Equilibration time at 2000°F (1093°C) shows essentially no effect on the strain rate for the two "multi-test" specimens. Figures 5 and 6 also show the difference between a "multi-test" specimen which was subjected to numerous heating, pressurization,

depressurization, and cooling cycles and "single-test" specimens which experienced only one cycle. A small nearly constant strain increment is observed at 1800°F (982°C), but at 2000°F (1093°C), a significant increase in the strain-rate was observed.

The variations in strain-rate and amount of accumulated plastic strain observed for the different experimental procedures is postulated to be due, primarily, to the fact that m , the strain-rate sensitivity,* is highly dependent on the strain-rate range, temperature and/or the particular crystallographic phase or combination of phases present in the material during the test. Depending on the experimental procedure, both the type and the relative amount of crystallographic phases can vary even at the same test temperature. During the initial heating in the "multi-test" procedure, primary or equi-axed alpha transforms to β which, upon rapid cooling, retransforms to the acicular alpha structure, α' . Therefore, the structure of the "multi-test" specimen during heating for subsequent tests would be unlike that present in the initial run of that specimen or in the "single-test" specimen, and this dissimilarity might possibly contribute to differences in transformation rates and/or strain accumulation. In general, strain-rate sensitivity increases with decreasing strain-rate and/or increasing temperature, reaches a maximum in the alpha plus beta phase field, and then decreases again as the structure becomes predominantly beta Zircaloy, Reference (6). The strain-rate sensitivity normally observed for alpha Zircaloy is about 0.2 or less. However, it increases sharply in the alpha plus beta region and can attain a maximum value of unity, Reference (6). The value of m is a relative measure of the amount of plastic strain which can be tolerated prior to the onset of unstable flow and therefore high values of m are consistent with extremely large plastic extensions. A material is considered to exhibit superplastic behavior if the strain-rate sensitivity is about 0.3 or higher. As stated in Reference (7), the maximum superplasticity has been found near the center of the two-phase region, i.e., when the phases are present in nearly equal proportions. Under equilibrium conditions, the percentages of alpha and beta Zircaloy will be the same at about 1650°F (899°C). Therefore, in tests performed at temperatures where the α phase would start to transform to the β phase, i.e., above approximately 1490°F (810°C), the time at temperature prior to load application would have an effect on the resulting strain-rate and amount of plastic strain accumulated. At temperatures below 1650°F (899°C), e.g., 1600°F (871°C), a long

* $m = \delta(\log \sigma) / \delta(\log \dot{\epsilon})$ at constant temperature and plastic strain where σ = true stress and $\dot{\epsilon}$ = true strain-rate.

equilibration period, as opposed to a shorter or zero equilibration time, would result in the most nearly equilibrium composition and the transformation of the maximum amount of α to β consistent with the test temperature. This composition would more closely approach that (50 percent each of α and β) at which maximum superplasticity is observed and therefore more strain would be expected for a long equilibration time specimen than for shorter or no-delay specimens which would contain less of the β and more of the α phases. Conversely, for temperatures above 1650°F (899°C), e.g., 1800°F (982°C), a long equilibration would allow the specimen to transform almost entirely to the β phase, whereas a no-delay specimen would be stressed while transformation is occurring. More strain, therefore, would be developed in the no-delay specimen.

C. Single-Test Specimen Test Data

Based upon the preceding discussion, it was concluded that predictions of the diametral strain during a postulated LOCA would be conservative at temperatures below 1600°F (871°C) when using the Reference (1) clad expansion model. At temperatures above 1600°F (871°C), however, the Reference (1) model would underpredict the strain. Therefore, additional testing was performed to define the stress-strain behavior at the higher temperatures. Measurements were obtained on single-test specimens which were pressurized at room temperature, ramped at 16°F/sec (9°C/sec) to the test temperature, held at the isothermal test temperature for a predetermined time interval, depressurized and cooled to room temperature for measuring. Only one test point per specimen was obtained so each test may be viewed as a controlled LOCA transient up to the point of the evacuation and cooldown. The data obtained in this manner are shown in Table I.

Figure 7 compares the single-test specimen steady-state rates with those reported in Reference (1). The increased strain-rate sensitivity at 1800°F (982°C) is clearly evident. Figure 8 shows that the strain-rate sensitivity versus temperature variation obtained in this phase of testing compares favorably with that reported in Reference (8).

The specimens used in this testing were taken from recrystallized annealed (RXA) tubing. At normal operating temperature in pressurized water reactors (below 700°F (371°C)), the stress-relief annealed (SRA) tubing has higher initial strength and increased resistance to thermal creep. However, at high temperatures (above 1400°F (760°C)), the SRA material tends to recrystallize in just a few seconds, as evidenced by the metallographic examinations reported in Reference (9). Also, Reference (10) indicates no significant difference in strain rates for RXA

and SRA specimens for isothermal test temperatures in the high temperature alpha range, 1472°F (800°C). For further verification in the $\alpha + \beta$ and β regions, three specimens of 70-percent C.W. (final reduction) and SRA (950°F/4 hours) tube-reduced tubing were tested during the current investigation. Pertinent data for these specimens which were pressurized at room temperature, heated at approximately 7-11°F/sec (4-6°C/sec) and held at the isothermal test temperature for a selected time interval are shown in Table I and Figure 10.

During the initial blowdown phase of the LOCA transient, the predicted cladding temperature sometimes experiences a relatively high temperature "spike." At this time in the LOCA transient, the system pressure is still higher than the fuel rod internal gas pressure and therefore no diametral expansion will occur. This temperature excursion above the alpha-beta transition temperature, however, could alter subsequent phase transformations and material strength, thus affecting the strain rate. Therefore, investigation of possible temperature-spike effects was undertaken.

The specimens of Reference (9) were subjected to peak temperatures of 1770°F (966°C) and 1490°F (810°C) prior to being tested at 1475°F (802°C) and 1400°F (760°C). No discernible differences in strain accumulation are evident in comparing these data to the test data of References (1) and (2) which did not include any pre-test temperature transient. Two spiked samples were tested in the $\alpha + \beta$ and β regions during the current test program. These specimens were heated, unstressed, to peak temperatures of 1850°F (1010°C) and 1720°F (938°C) and later tested at temperatures of 1800°F (982°C) and 1600°F (871°C). The time of the simulated temperature spike above the transformation temperature was approximately 15-20 seconds. Table I shows the test conditions for the two temperature-spike specimens; the resulting plastic diametral strains are plotted in Figure 10. As shown, the two specimens are well predicted by the analysis model.

V. LOW-STRAIN CLAD EXPANSION MODEL

A clad expansion model has been formulated for use in predicting the low-strain clad expansion which may occur during a postulated LOCA transient. The diametral strain is given by:

$$\epsilon(t) = (\bar{\epsilon})_{\max} + \int_0^t \dot{\epsilon}_{ss} dt$$

where

- $\epsilon(t)$ = total plastic hoop strain at time t
- $(\bar{\epsilon})_{\max}$ = maximum intercept strain in the time interval from 0 to t
- $\dot{\epsilon}_{ss}$ = steady-state strain rate.

The intercept strain in the above equation is the strain obtained by extrapolating the steady-state rate back to time zero and includes any instantaneous loading strain and the primary or transient strain. Figure 9 shows intercept strain in the $\alpha + \beta$ and β regions obtained from the current testing and the original Reference (1) isothermal tests. As is typical at these temperatures, a large amount of data scatter is observed. For temperatures of 1600°F (871°C) and below, the expression used in Reference (1), $\bar{\epsilon} = A\sigma^B$, gives an adequate fit to the test data. At the higher temperatures, an expression of the form $\bar{\epsilon} = C \exp(D\sigma)$ is used to give a conservative estimate at the lower stress levels. Therefore, the intercept strain may be calculated by:

$$\bar{\epsilon} = A\sigma^B + C \exp(D\sigma)$$

where

- $\bar{\epsilon}$ = intercept hoop strain
- σ = hoop stress (psi)
- A, B, C, D = property fit constants (function of temperature).

Figure 7 shows that the steady-state strain rates may be expressed by:

$$\dot{\epsilon}_{ss} = K\sigma^n$$

where

- $\dot{\epsilon}_{ss}$ = steady-state hoop strain rate (1/sec)
- σ = hoop stress (psi)
- K, n = property fit constants (function of temperature).

The property fit constants are defined at several reference temperatures. The intercept strain and steady-state strain rate is calculated at two reference temperatures, and the following equation is used to interpolate to the desired temperature:

$$\frac{\log \epsilon(T) - \log \epsilon(T_k)}{\log \epsilon(T_k) - \log \epsilon(T_{k+1})} = \frac{1/T - 1/T_k}{1/T_k - 1/T_{k+1}}$$

where

T = temperature in question ($^{\circ}\text{K}$)

T_k, T_{k+1} = reference temperature ($^{\circ}\text{K}$)

$\log \epsilon(T) = \log$ of $\bar{\epsilon}$ or $\dot{\epsilon}_{ss}$ for temperature T

$\log \epsilon(T_k) = \log$ of $\bar{\epsilon}$ or $\dot{\epsilon}_{ss}$ evaluated at temperature T_k

$\log \epsilon(T_{k+1}) = \log$ of $\bar{\epsilon}$ or $\dot{\epsilon}_{ss}$ evaluated at temperature T_{k+1} .

Table II shows the selected property fit constants. Figures 7 and 9 show that these constants are selected to upper bound the test data and thus provide a reasonably conservative prediction to the low-strain clad expansion.

Figure 10 compares the predicted and measured diametral strain from the current test. This figure shows that this new model conservatively predicts the simulated LOCA transient test specimen strains. Also, the SRA and temperature-spike test data agree well with the rest of the data set, indicating no major effects in high temperature strain accumulation resulting from cold work or pre-test temperature spikes.

Reference (11) presents diametral expansion data obtained by pressurizing the test specimens at room temperature and then ramping the temperature at a rate of $45^{\circ}\text{F}/\text{sec}$ ($25^{\circ}\text{C}/\text{sec}$). Figures 11 through 13 show that the prediction model presented in this report adequately predicts diametral strains up to at least 3 percent over a temperature range of 1475°F to 2000°F (803°C to 1083°C). Figure 14 compares the model predictions to isothermal test data of Reference (12). Good agreement is obtained, with the exception of the 1562°F (850°C) test data in which the measured strains are considerably higher than the model predictions.

VI. ADDITIONAL TESTING AT 1562°F (850°C)

In order to resolve the difference between the predictions and the Reference (12) data at 1562°F (850°C), an additional series of tests was performed. For these tests, a modified test procedure was used so as to reproduce as closely as possible the heating rates at which the data reported in Reference (12) were obtained.

The test specimens used for these tests were 6 inches long and were cut from the same recrystallized Zircaloy-4 tubing utilized for the previous tests. One end was sealed with a solid Zircaloy-4 plug by welding and the other end was welded to a pressurizing stem which was sealed following pressurization of the specimen at room temperature. Following pressurization with argon gas, a

Chromel-Alumel thermocouple was tack-welded to the specimen. Reaction was prevented by enclosing the bead in 0.002-inch tantalum foil. The thermocouple wires were insulated by a 0.1-inch-diameter ceramic rod which was wired to the specimen and also used to support the specimen. The specimen was then placed in a 5/8-inch Vycor tube as shown in Figure 15. The ceramic rod extended into a "necked" portion of the Vycor tube. Epoxy was used to seal the tube with the thermocouple wires extended to a dual-pen strip chart recorder. The Vycor tube was first evacuated and then backfilled with inert argon gas to act as a heat transfer medium. The argon pressure was such that at the 1562°F (850°C) test temperature, the pressure external to the specimen was one atmosphere. The internal gas pressure was inserted at room temperature such that at 1562°F (850°C) the desired hoop stress was achieved, as calculated by using the ideal gas law. The entire assembly was then inserted into a resistance-wound, 2 1/2-inch-diameter tube furnace. The thermocouple was located 2 1/4 inches from the open end in the "hot zone." Investigation showed a uniform temperature distribution over ± 1 inch at this location. All strain measurements were taken in the vicinity of the thermocouple at room temperature.

The heating rate for the test specimens reported in Reference (12) was estimated to have been 72 to 90°F/sec (40 to 50°C/sec). The heating rate used for the single test specimens discussed in Section IV.C of this report was approximately 16°F/sec (9°C/sec) in the α - β transformation region. The limitations of the resistance-wound tube furnace used for the revised test procedure resulted in a relatively slow heatup rate. Figure 16 shows a typical temperature history for this test. In the α - β transformation region, the heating rate is approximately 1.1°F/sec (0.6°C/sec). The specimens used in these tests were pressurized and sealed and thus were stressed during the entire time while they were being heated to the test temperature. The low heating rate resulted in the specimens being stressed during the time when the temperature is below the test temperature, but at a temperature high enough to result in measurable permanent strain. In order to limit this additional strain accumulation, the 5-minute "isothermal" test time was started at 1544°F (840°C) instead of 1562°F (850°C).

Five specimens, with hoop stresses (at the test temperature) ranging from 250 to 1250 psi, were tested using this revised test procedure. Table III presents the results of these additional tests. Figure 17 compares these additional test data with the Reference (12) test data and the prediction model

using the Table II property fit constants. Figure 17 shows that the measured strains are less than those reported in Reference (12), but are substantially higher than the prediction.

The underprediction of the model is most likely due to the use of the multi-test-specimen data obtained at 1600°F (871°C) property constants shown in Table II. The inability of the prediction model based on use of the multi-test-specimen data to predict the single-test-specimen data may be due to the partial transformation to the β phase which occurred on heating during the initial run. This β phase would retransform to acicular α phase upon cooling to room temperature. The presence of the acicular α phase could possibly affect the strain-rate sensitivity when the specimen is reheated to the test temperature for subsequent testing.

The reason for the disagreement between the single-test-specimen data at 1600°F (871°C) presented in this report and that presented in Reference (12) can not be definitely determined at this time. The most probable explanation is that the strain rate in this temperature region is a complex function of present and prior phase transformation as well as the classical variables such as temperature, stress, and strain state. Figure 17 shows that all of the low strain test data in this temperature region may be conservatively predicted by using the 1700°F (927°C) property constants of Table II. Therefore, the property constants shown in Table IV can be used for conservatively predicting low strain behavior ($\leq 3\%$) at temperatures between 1475°F (802°C) and 2000°F (1093°C).

VII. SUMMARY

This report presents high temperature, low strain test data for pressurized Zircaloy-4 tubing relevant to a postulated LOCA. The measured hoop strains were found to be very sensitive to the test procedure at temperatures above the α - β transformation temperature for Zircaloy. This sensitivity is attributed to time-dependent material, micro-structural transformation and the resulting impact on superplasticity. This sensitivity should be accounted for in developing tests and models for use in predicting the response of the cladding to a rapid LOCA transient. Also presented in this report is a low strain prediction model which has been shown to give conservative predictions to simulated LOCA transients and other data sets obtained by different test procedures. This model is valid for predicting diametral strains up to at least 3 percent over a temperature range of 1475°F to 2000°F (802°C to 1093°C).

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TABLE I. LIST OF SINGLE-TEST HIGH TEMPERATURE TEST DATA

<u>Specimen</u>	<u>T</u> <u>(°F)</u>	<u>σ_θ</u> <u>(psi)</u>	<u>Δt</u> <u>(sec)</u>	<u>ϵ_θ</u> <u>(%)</u>	<u>Specimen</u>	<u>T</u> <u>(°F)</u>	<u>σ_θ</u> <u>(psi)</u>	<u>Δt</u> <u>(sec)</u>	<u>ϵ_θ</u> <u>(%)</u>
44-5	1600	750	0	0.11	44-6	1900	350	40	0.77
18-8	↓	1500	0	0.17	44-8	↓	↓	100	1.52
195-3*	↓	↓	100	1.60	77-4	↓	500	0	1.15
43-6**	↓	↓	180	2.79	18-2	↓	↓	25	2.05
65-7	1700	500	90	1.52	18-3	↓	↓	50	2.74
65-3	↓	↓	150	2.07	65-6	↓	750	0	1.06
65-8	↓	1500	10	0.60	65-4	↓	↓	10	2.25
65-2	↓	↓	40	2.02	65-5	↓	↓	20	10.3
195-1*	↓	↓	30	2.23					
44-1	1800	350	50	1.40	77-7	2000	350	0	0.62
44-4	↓	↓	100	1.90	18-6	↓	↓	10	0.71
44-3	↓	500	0	0.30	18-5	↓	↓	25	1.24
18-4	↓	↓	0	0.37	77-2	↓	500	0	1.23
44-3	↓	↓	0	0.17	77-8	↓	↓	15	3.58
77-3	↓	↓	50	1.94	18-7	↓	↓	30	6.56
44-2	↓	↓	100	2.97					
77-6	↓	750	0	0.21					
77-5	↓	1000	0	0.64					
77-1	↓	↓	15	1.40					
44-7	↓	↓	30	3.17					
195-2*	↓	540	40	1.77					
65-1**	↓	500	50	1.99					

NOTES: 1 - Specimen pressurized at room temperature and heated at 16°F/sec to test temperature.

2 - Δt indicates time held at the isothermal test temperature.

3 - Specimens evacuated at the end of Δt and cooled to room temperature for measurement.

*SRA test specimens

**Temperature "spike" test specimens

TABLE II. INITIAL PREDICTION MODEL PROPERTY FIT CONSTANTS

Temperature (°F)	Intercept Strain Constants				Steady-State Strain Rate Constants	
	A	B	C	D	K	n
1475	2.753×10^{-14}	3.2660	0	10^{-6}	8.701×10^{-22}	4.9162
1600	1.561×10^{-17}	1.4943	0	10^{-6}	7.187×10^{-10}	1.6193
1700	0	1	4.653×10^{-3}	7.29×10^{-1}	8.551×10^{-9}	1.4933
1800	0	1	6.644×10^{-3}	7.701×10^{-4}	5.824×10^{-10}	2.0306
1900	0	1	6.948×10^{-3}	1.008×10^{-3}	3.757×10^{-12}	2.9567
2000	0	1	6.036×10^{-3}	1.997×10^{-3}	2.170×10^{-18}	5.5258

NOTE: Values at 1475°F and 1600°F are based upon the equilibrium structure isothermal test data of Reference (1). Higher temperature values are based upon the single-test-specimen data presented in this report.

TABLE III. RESULTS OF ADDITIONAL TESTS AT 850°C

<u>Specimen</u>	<u>Hoop Stress (psi)</u>	<u>Hoop Strain (%)</u>
44-9	250	0.87
93-9	500	1.48
20-9	750	2.09
62-9	1000	3.47
43-9	1250	4.37

TABLE IV. FINAL PREDICTION MODEL PROPERTY FIT CONSTANTS

Temperature (°F)	Intercept Strain Constants				Steady-State Strain Rate Constants	
	A	B	C	D	K	n
1475	2.753×10^{-14}	3.2660	0	10^{-6}	8.701×10^{-22}	4.9162
1500	0	1	4.653×10^{-3}	7.29×10^{-4}	8.551×10^{-9}	1.4933
1700	0	1	4.653×10^{-3}	7.29×10^{-4}	8.551×10^{-9}	1.4933
1800	0	1	6.644×10^{-3}	7.701×10^{-4}	6.824×10^{-10}	2.0306
1900	0	1	6.948×10^{-3}	1.008×10^{-3}	3.757×10^{-12}	2.9567
2000	0	1	6.036×10^{-3}	1.997×10^{-3}	2.170×10^{-18}	5.5258

NOTE: Values at 1475°F are based upon the equilibrium structure isothermal test data of Reference (1).
 Values at 1700°F and higher are based upon the single-test-specimen data presented in this report.
 Values at 1500°F are taken to be the same as those at 1700°F in order to conservatively predict the Reference (8) test data at 1562°F (850°C).

Figure 1. Schematic of Test Apparatus

Figure 2. Comparison of Isothermal Predictions
to Measured Data

Figure 3.. LOCA Temperature Transient Simulations

Figure 4. Effect of Test Procedure Upon Strain Accumulation
(1600°F - 750 psi Hoop Stress)

1800°F $\sigma_\theta = 500$ PSI

Figure 5. Effect of Test Procedure Upon Strain Accumulation
(1800°F - 500 psi Hoop Stress)

Figure 6. Effect of Test Procedure Upon Strain Accumulation
(2000°F - 500 psi Hoop Stress)

Figure 7. Comparison of Steady-State Strain Rate

Figure 8. Strain Rate Sensitivity Variation with Temperature

Figure 9. Comparison of Intercept Hoop Strain in the $\alpha + \beta$ and β Regions

Figure 10. Comparison of Predicted and Measured Strain

Figure 11. Comparison of Predictions to the Reference (11) Data

Figure 12. Comparison of Predictions to the Reference (11) Data

300 SEC., ISOTHERMAL, CONSTANT-STRESS DATA OF REFERENCE (12)

○ TEST DATA OBTAINED IN VACUUM
 △ TEST DATA OBTAINED IN STEAM
 — PREDICTION

Figure 14. Comparison of Predicted and Measured Diametral Strain

Figure 15. Schematic of Test Apparatus

Figure 16. Typical Test Temperature History

300 SECOND ISOTHERMAL TESTS AT 850 °C (1562 °F)

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Figure 17. Comparison of Test Data and Prediction Models