GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

FIFTEENTH QUARTERLY REPORT

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
UNDER CONTRACT NAS 3-9439

TRW EQUIPMENT LABORATORIES
CLEVELAND, OHIO

NAS-CR-72431

FIFTEENTH QUARTERLY REPORT

For

14 December 1967 to 27 March 1968

GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

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Prepared for:

National Aeronautics and Space Administration
Contract No. NAS 3-9439

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14 April 1968

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FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-9439. The purpose of this study is to obtain design creep data on refractory metal alloys for use in advanced space power systems.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager, K. D. Sheffler is the Principal Investigator, and R. R. Ebert contributed to the program. The NASA technical manager is Paul E. Moorhead.

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ABSTRACT

The creep resistance of molybdenum-base TZC and TZM and of tantalum-base T-111 and ASTAR 811C is being evaluated in a vacuum environment of less than 10^{-8} torr. Tests from 5000 to 15,000 hours duration are conducted with parameters selected to provide 0.5 to 1.0% total creep. In addition to conventional constant load tests, selected variables are being evaluated with progressively increasing loads.

Comparisons of TZC and TZM test results on the basis of the Larson-Miller parameters show the influence of composition and thermal-mechanical processing history on 1/2% creep life. At higher temperatures and lower stresses the creep resistance of TZC and TZM are comparable in the stress relieved condition. However, in the low temperature and high stress range, a special heat of TZM processed at higher than normal temperatures and having a higher than normal carbon content shows the best creep resistance.

Several short time tests have been conducted on specimens of commercially pure tantalum tubing. Significantly lower creep strengths are obtained for the tubing than are published in the literature, and this behavior is attributed to the high purity of the material.

Results of twenty long time tests on specimens from five different heats of T-111 alloy show excellent agreement between heats. Analysis of these results indicate that the steady state creep rate $\dot{\varepsilon}$ of recrystallized T-111 can be expressed by an equation of the form:

$$\dot{\varepsilon} = Ae^{B\sigma}e^{-\Delta H/RT}$$

where A and B are constants, σ is stress, ΔH is the apparent activation energy for creep, R is the universal gas constant, and T is absolute temperature.

T-111 is found to creep at progressively increasing rates under the influence of progressively increasing stress. Various methods for correlating data and for predicting the progressive stress life from static creep tests are discussed.

ASTAR 811C, a relatively new precipitation strengthened tantalum base alloy, shows significantly better creep resistance than T-111 after more than 12,000 hours of testing at 2600°F (1427°C) and 2000 psi.

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INTRODUCTION

Molybdenum and tantalum base alloys are currently specified or considered for a variety of applications in space electric power systems. These systems will operate either in the ultrahigh vacuum of outer space or in environments such as metallic vapors or liquids where the partial pressure of reactive gases is extremely low. Since the mechanical behavior of refractory metal alloys is very sensitive to interstitial contamination, it is necessary to test these materials in a non-contaminating environment in order to generate representative design data.

Long time creep strength is a critical property in these applications because of the high operating temperatures encountered. Since creep testing involves long time exposure at elevated temperatures, special precautions must be taken to prevent contamination. Creep tests are therefore being conducted in a vacuum of less than 10^{-8} torr on the molybdenum base alloys TZM and TZC, on commercially pure tantalum, and on the tantalum base alloys T-111 and ASTAR 811C. This test program is a continuation of Contract NAS-3-2545 and all of the previous reports and creep results generated under both contracts are summarized in the first two appendices.

As a result of the interest in the use of T-111 as an isotope encapsulation material, a significant number of the current tests are being conducted with progressively increasing stress. The isotopes involved generate helium as one of the decay products, so that the capsule shell is subjected to continuously increasing pressure at an elevated temperature. As a parallel study, various techniques for correlating progressive stress results and for predicting this type of information from conventional static tests are being evaluated.

In order to gain better insight into the creep behavior of T-111 a mathematical analysis of the test results is in progress. The objective of this analysis is to develop an equation of state relating strain rate to strain, temperature and stress. Although the work is not complete, sufficient results are available to warrant discussion in the current report.

MATERIALS AND PROCEDURES

The experimental program involves creep testing of molybdenum and tantalum base alloys at temperatures ranging from 1600 to 2600°F (871 to 1427°C) and at stresses between 500 and 65,000 psi (3.44×10^6 to 4.48×10^8 N/M^2). A combination of parameters is generally selected which will provide 1/2 to 1% total creep in 5000 to 15,000 hours. Commercially pure tantalum is being tested in the 1100 to 1350°F (593 to 735°C) range at stresses chosen to provide 1% creep in approximately 1000 hours.

Sources of the test materials and details of the available processing data are summarized in a previous report (1), while chemical analyses of each alloy are presented in Table I. Detailed descriptions of both the construction and operation of the test chambers and the service instruments in the laboratory are available in previous reports on this project (Appendix I).

TZM is being evaluated in three forms. Commercial TZM bar was obtained from the Climax Molybdenum Company together with a conventionally processed 11 inch diameter disc forging. AiResearch also supplied a section of a disc forging which was specially processed by Universal Cyclops for improved creep resistance. The latter material had a higher than normal carbon level and was forged at higher than normal forging temperatures to produce an improved structure (2).

TZC is also being evaluated in three different forms. Two rolled plates were obtained from General Electric with widely different drafting practices. One plate was rolled with very small reduction on each pass and a high finishing temperature, while the other was given relatively large reductions and finished at a lower temperature. Climax Molybdenum supplied TZC plate which was broad forged in the 2400°F range from extruded bar stock.

TZM is being studied primarily in the stress relieved condition, while both the stress relieved and recrystallized structures are under investigation in TZC.

T-111 is being tested in the form of rolled sheet, recrystallized 1 hour at 3000°F (1649°C). Six heats have been evaluated, four from Wah Chang and two from Fansteel Metallurgical.

ASTAR 811C is a relatively new dispersion strengthened tantalum base alloy developed by Westinghouse under contract NAS-3-2542. The sample of this material, obtained from Westinghouse through NASA, Lewis, is in sheet form and was recrystallized 1/2 hour at 3600°F (1982°C) prior to testing.

Commercially pure tantalum tubing was obtained from Fansteel Metallurgical through NASA Lewis. It was recrystallized 1 hour at 1832°F (1000°C) prior to delivery and is being tested in this condition.

TABLE 1

Chemical Composition of Alloys Being Evaluated in Creep Program (Weight %)

									ppm			
Material	W	Re	Mo	Ta	Hf	C	Ti	Zr	N_2	O_2	H_2	Finished Form
TZM (Heat 7463)			Bal.			.016	.48	.08	1	2	1(2)	5/8" dia. bar
(Heat 7502)			Bal.			.010	.51	.091	100	20	7	Forged disc
(Heat KDTZM-1175)			Bal.			.035	.61	.120	43	34	9	Forged disc
TZC (Heat M-80)			Bal.			.127(4)	1.02	.17	18	41	10	Rolled plate
(Heat M-91)			Bal.			.113(4)	1.17	.270	34	37	10	Rolled plate
(Heat 4345)			Bal.			.075	1.19	.16	9	19	2	Forged plate
T-111 (Heat 70616)	8.5			Bal.	2.30	.0044			20	55	6	Nominal 0.030"
(Heat 65079)	8.7			Bal.	2.30	.003			50	130	4(2)	Sheet
(Heat 65080)	8.9			Bal.	2.03	.0031			40	105	4(4)	"
(Heat MCN02A 065)	8.6			Bal.	1.95	.004			20	100	3(2)	"
(Heat D-1102)	7.9			Bal.	2.28	.003			34	20	3(2)	"
(Heat D-1670)	7.9			Bal.	2.17-2.44	<.001			20	72	<5(2)	"
ASTAR 811C	8.0	1.0		Bal.	0.7	.250			-	-	-(3)	"
Commercially Pure Ta				Bal.		.0051			2.4	7	3(1)	Tubing

(1) TRW Analysis
(2) Vendor Analysis
(3) Nominal Composition
(4) Average of Several Analyses

The geometries of the sheet and bar specimens are shown in Figures 1 and 2. The orientation of the specimen with respect to the working direction is given below:

Material Form	Specimen Axis Parrellel To
Disc forging	Radius
Plate	Extruding direction
Sheet	Rolling direction (except where indicated)

A special specimen and grip were developed for testing the tantalum tubing. A specimen machined according to this design is shown in Figure 3. The axes of the loading pins are perpendicular to the flats and are centered in the tube to insure equal loading of each gage section. The grips are hollow heavy-walled cylinders which slide over the ends of the tubing to receive the loading pins.

The static creep test procedure involves initial evacuation of the test chamber to a pressure of less than 5×10^{-10} torr at room temperature, followed by heating of the test specimen at such a rate that the pressure never rises above 1×10^{-6} torr. Pretest heat treatments are performed in situ prior to load application after which the specimen is cooled to 600°F (316°C) or lower before reheating to the test temperature. Complete thermal equilibrium of the specimen is provided by a two hour hold at the test temperature prior to load application. Pressure is always below 10^{-8} torr during the tests and generally falls into the 10^{-10} - 10^{-11} range as testing proceeds. Specimen extension is determined over a two inch gage length with an optical extensometer which measures the distance between two scribed reference marks to an accuracy of ± 50 microinches. Specimen temperature is established at the beginning of the test using a thermocouple. An optical pyrometer having a precision of ± 1F° is then calibrated against the thermocouple reading. After calibration the optical pyrometer is used as the prime temperature reference throughout the test.

The continuous loading tests require replacement of the static loading weight pan with an aluminum container which collects lead shot from a feeder driven by a continuous-duty DC motor. The loading rate is regulated by controlling the speed of the feeder drive motor. Figure 4 is a photograph of a shot feeder in operation on creep unit No. 7.

In addition to the long time creep tests in progress on T-111, a series of short time tests have been performed sequentially upon two specimens of this alloy to evaluate the ability of this sequential technique to predict long time results A preliminary test was conducted at 2000°F (1093°C) to establish baseline data, and was followed by a second test consisting of four individual sequences at 2172, 2391, 2000, and 1800°F (1189, 1299, 1093, and 980°C), conducted in that order. The specimen was given the customary pretest anneal at 3000°F for one hour and was provided with a 15 minute anneal at the same temperature between each test sequence. Stress was adjusted for each sequence to provide a nominal 1000 hour 1% creep life. Post test metallographic examination was performed to evaluate possible grain growth resulting from the intersequence anneals.

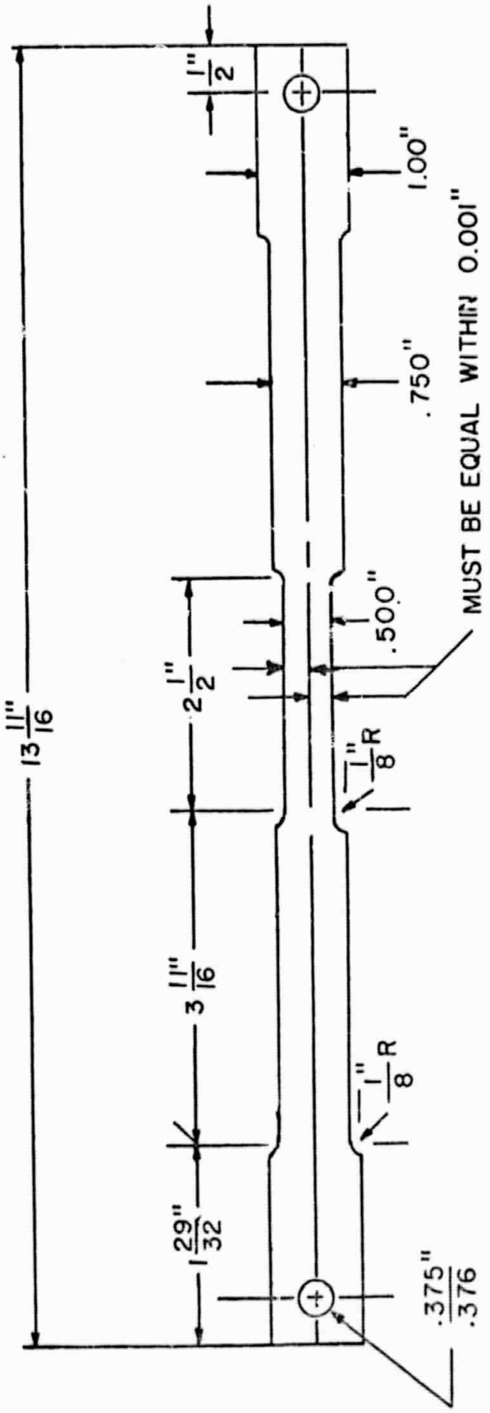
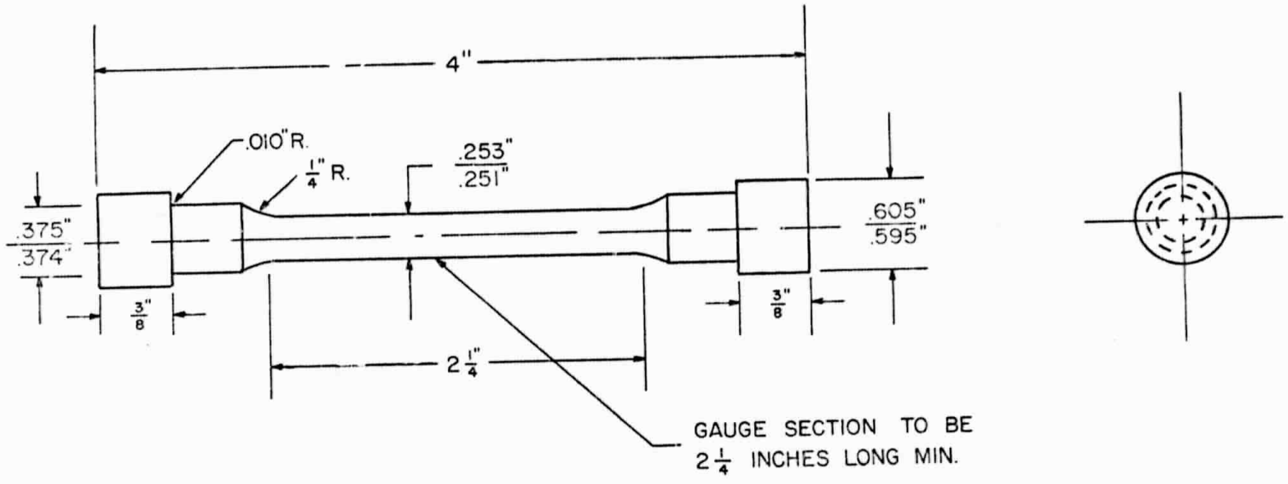


Figure 1. Creep specimen used for sheet stock.



NOTE: ANY TAPER IN GAUGE SECTION MUST BE TOWARDS CENTER

ALL TOLERANCES ± .010" UNLESS OTHERWISE NOTED

Figure 2. Creep specimen used for plate stock.

Figure 3. Creep specimen used for commercially pure tantalum tubing.

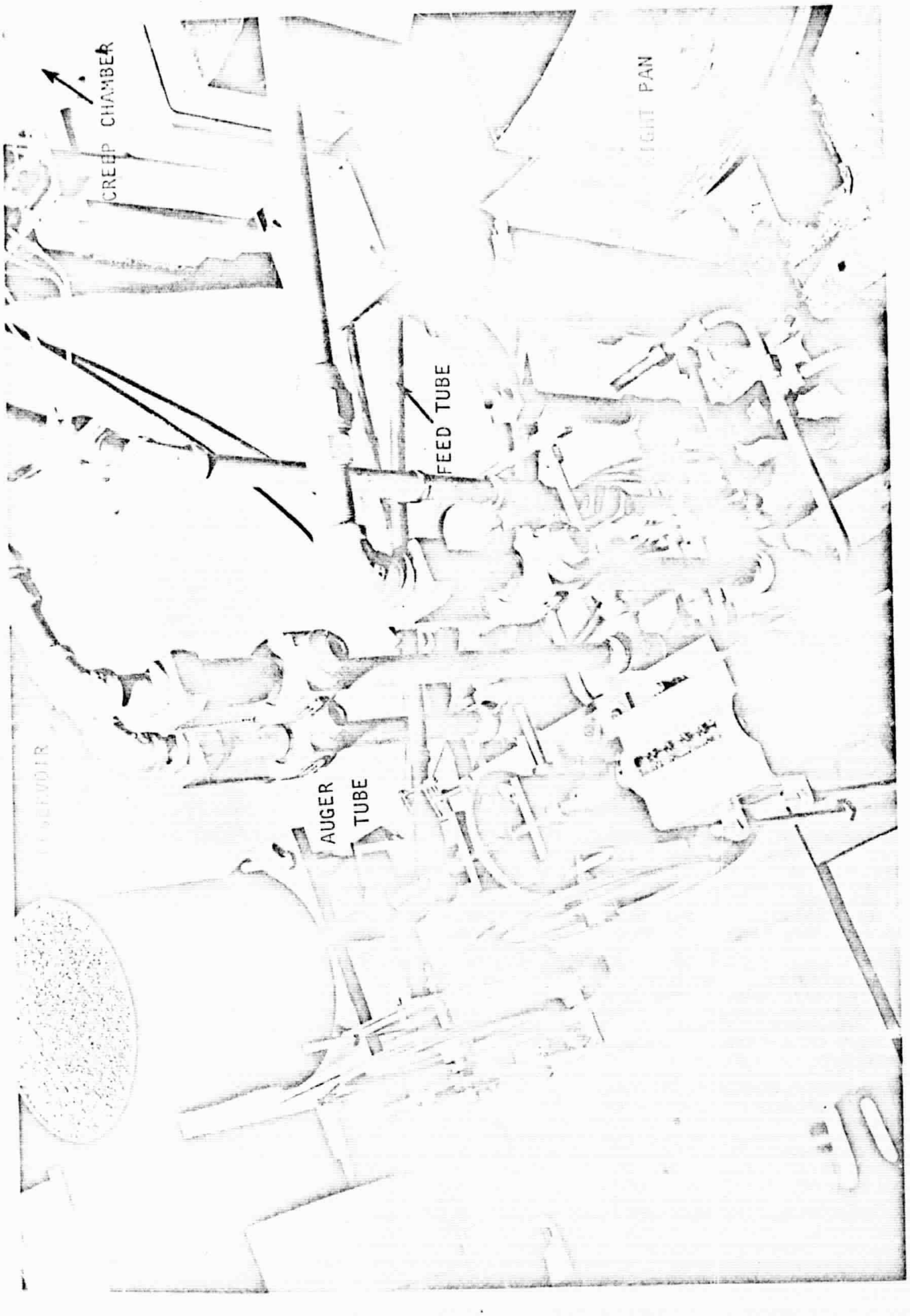


Figure 4. Shot feeder for tests under continuously increasing load.

A similar technique is being used to evaluate the creep resistance of the pure tantalum tubing. Seven sequential tests have been performed and an eighth is in progress in the temperature ranges between 1100 and 1350°F (593 and 732°C). A 15 minute anneal at 1832°F (1000°C) was applied between each test sequence.

RESULTS AND DISCUSSION

A tabulation of all of the creep tests performed on this program is provided in Appendix II.

Molybdenum Base Alloys

A Larson Miller comparison of TZC creep test results is presented in Figure 5, while individual creep curves for the two TZC tests in progress during the current reporting period are shown in Figure 6.

The two data points from heat 4345 shown in Figure 5 represent tests conducted at identical stresses and temperatures to evaluate a difference of heat treatment temperature. The results indicate that stress relief at 2400°F (1316°C) produces somewhat better creep resistance than at 2500°F (1371°C) for a one hour treatment.

The results in Figure 5 also indicate that under the limited test conditions evaluated, stress relief at 2500°F (1371°C) and annealing at 3092°F (1700°C) provide comparable creep resistance. The influence of structure upon creep behavior is more pronounced when comparing different heats. Heat M-91 has been shown to fully recrystallize when annealed 1 hour at 3092°F, while M-80 shows only partial recrystallization as a result of this same treatment(1). The data on these two heats indicate the partially recrystallized structure to be significantly stronger in creep. However, Heat M-80 has a somewhat higher carbon content than M-91, and this factor may also be associated with the difference in creep strength.

Figure 7 shows the creep curve for the TZM test currently in progress, while a summary of all the available TZM creep data from Appendix II is presented in Figure 8. The superiority of the specially processed Heat KDTZM-1175 is clearly evident. Comparison of these results with the TZC data shows that at higher stress levels and lower temperatures, this specially processed TZM is also superior to TZC. However, at lower stress levels and higher temperatures the behavior of the two materials is comparable.

Pure Tantalum

Creep curves for the four test sequences performed upon pure tantalum during the current reporting period are shown in Figures 9 and 10 and a summary of all eight sequences is provided in Figure 11. The behavior of this material appears somewhat confusing since the experimental data scatter quite widely on the Larson Miller plot. However, closer examination of the results reveal that each of the first sequences correlate quite well, indicating that the intersequence anneals may not be eliminating the influence of prior creep strain. As a critical test of this hypothesis the first and second sequences on specimen B-42 were performed at identical stresses and temperatures, with the results confirming that the

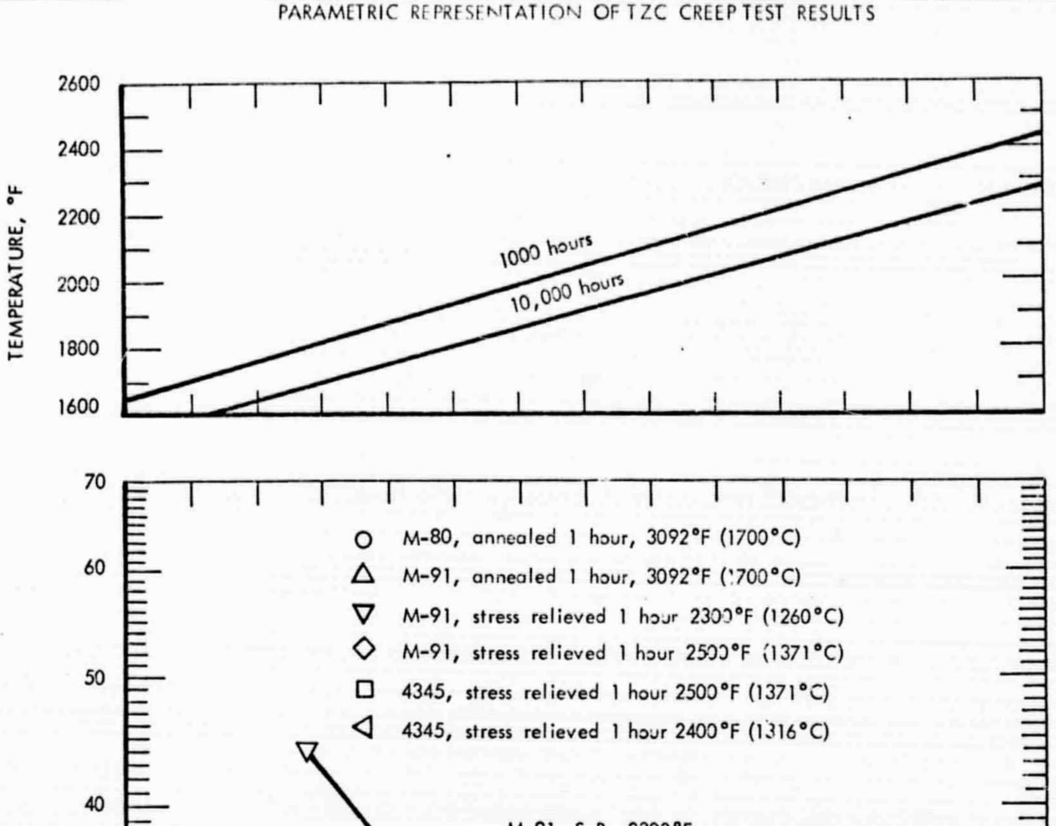


Figure 5. Parametric representation of TZC 0.5% creep test results.

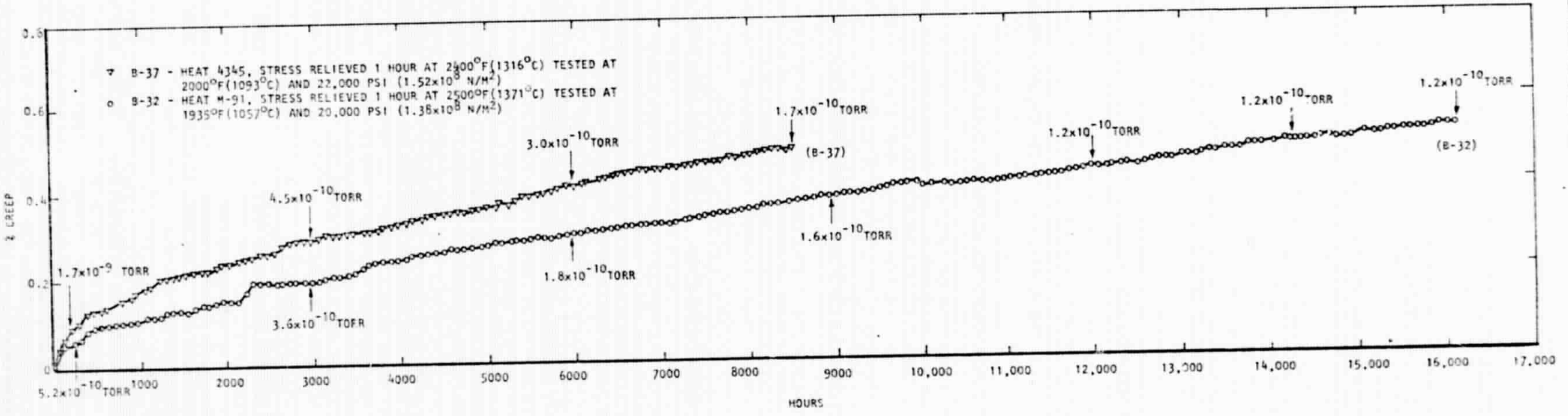


Figure 6. Creep test data, TZC, tested in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate actual pressure at various points during test.

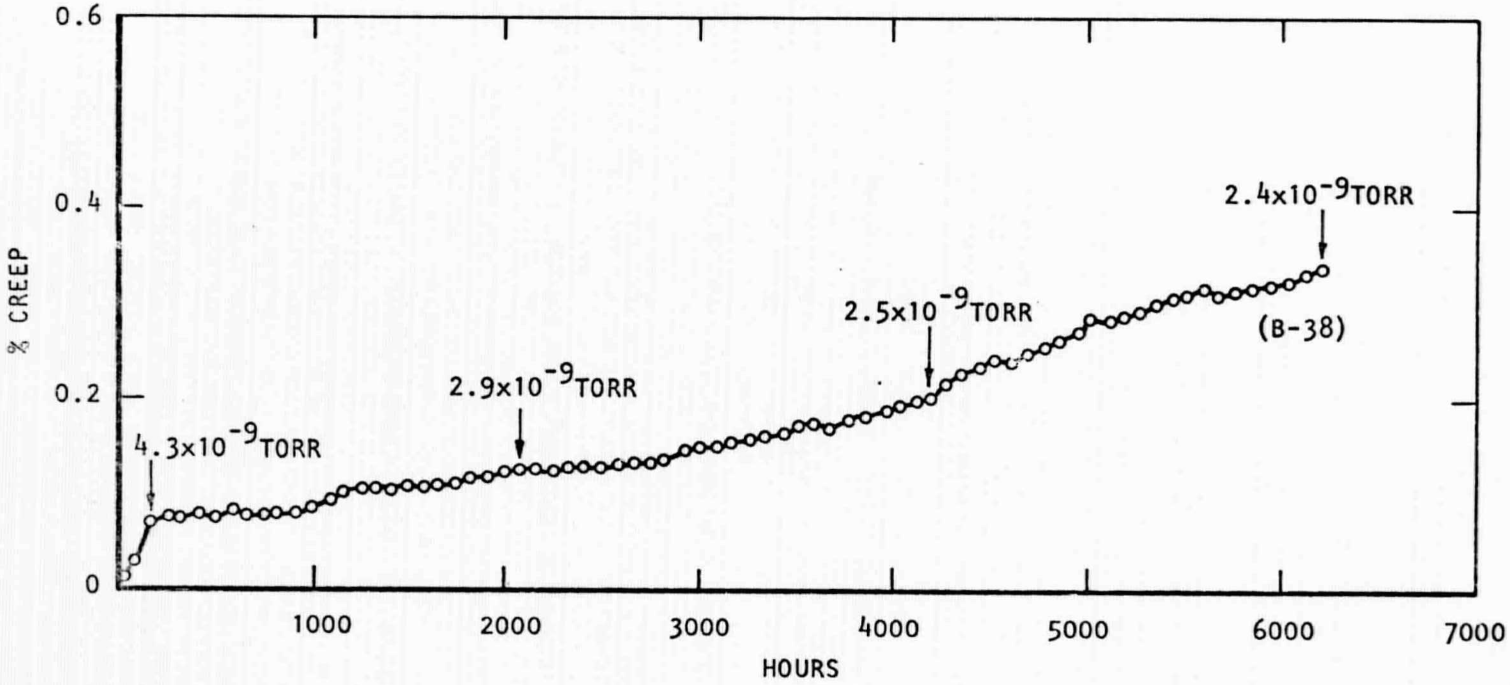


Figure 7. Creep test data, TZM Heat No. KDTZM 1175 stress relieved 1 hour at 2300°F (1260°C), tested at 2000°F (1093°C) and 22,000 psi (1.52×10^8 N/m^2) test No. B-38, tested in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate actual pressure at various points during test.

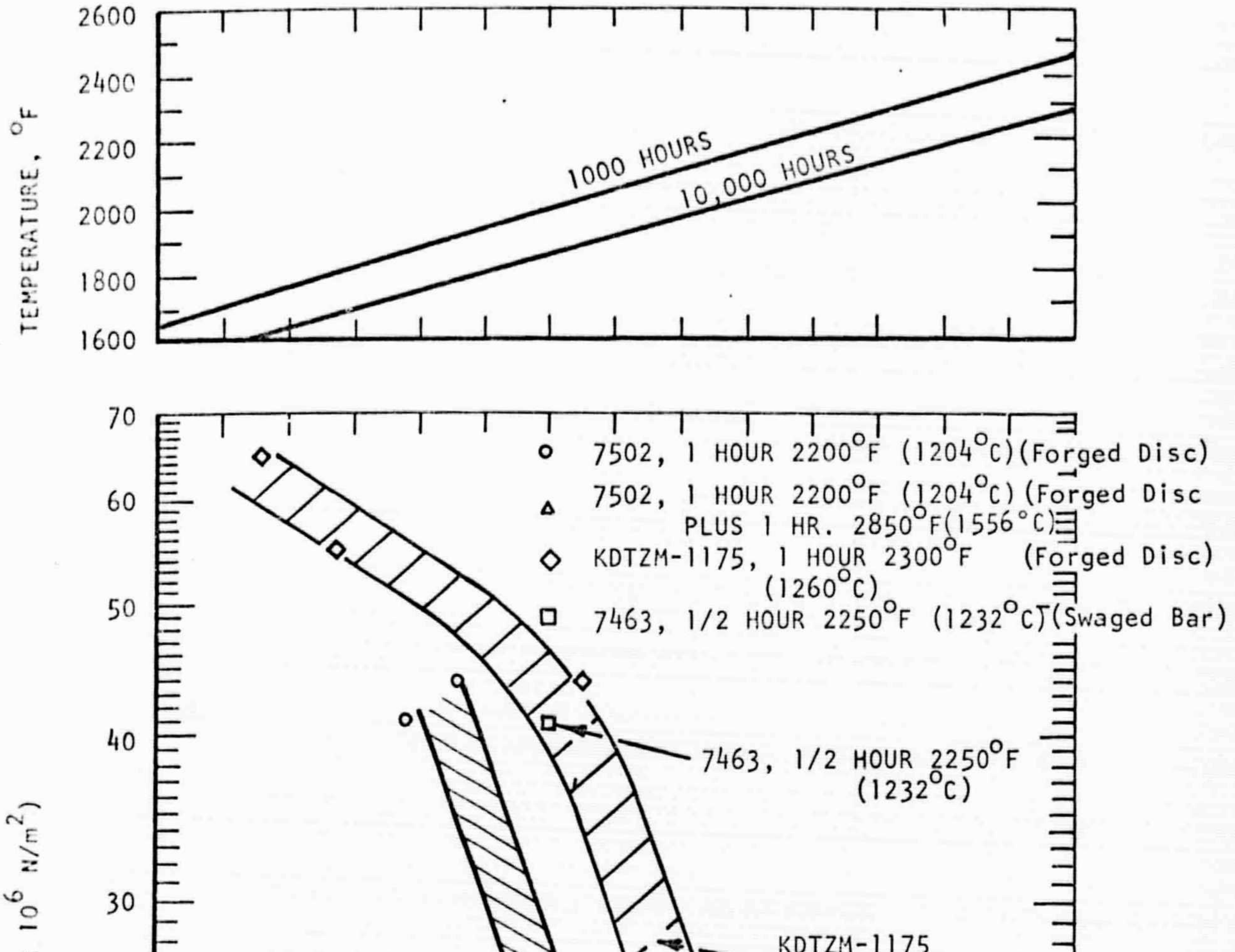


Figure 8. Parametric representation of TZM 0.5% creep test results.

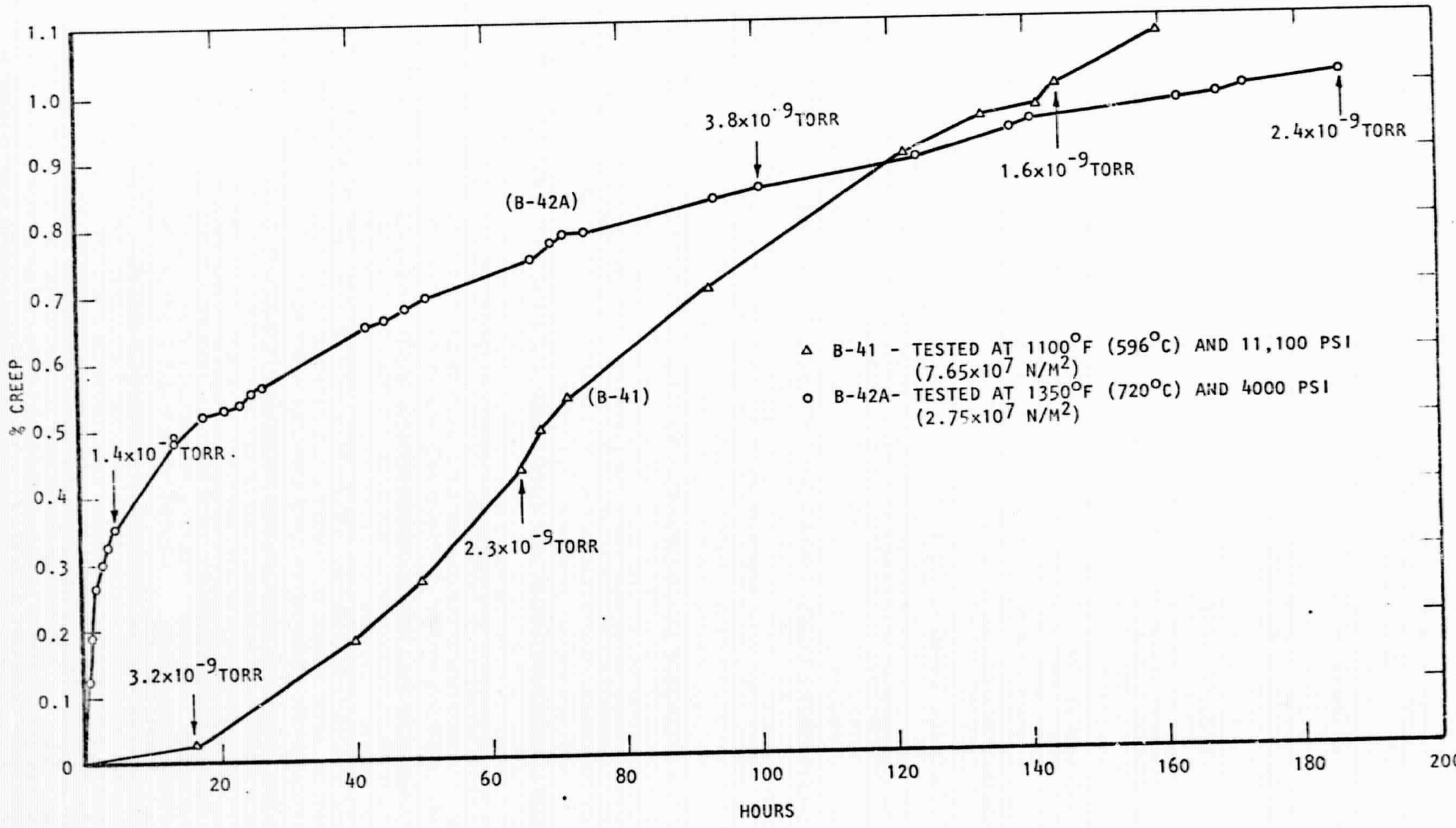


Figure 9. Creep test data, Pure Ta annealed 1 hour at 1832°F (1000°C), tested in sequential test program in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate actual pressure at various points during test.

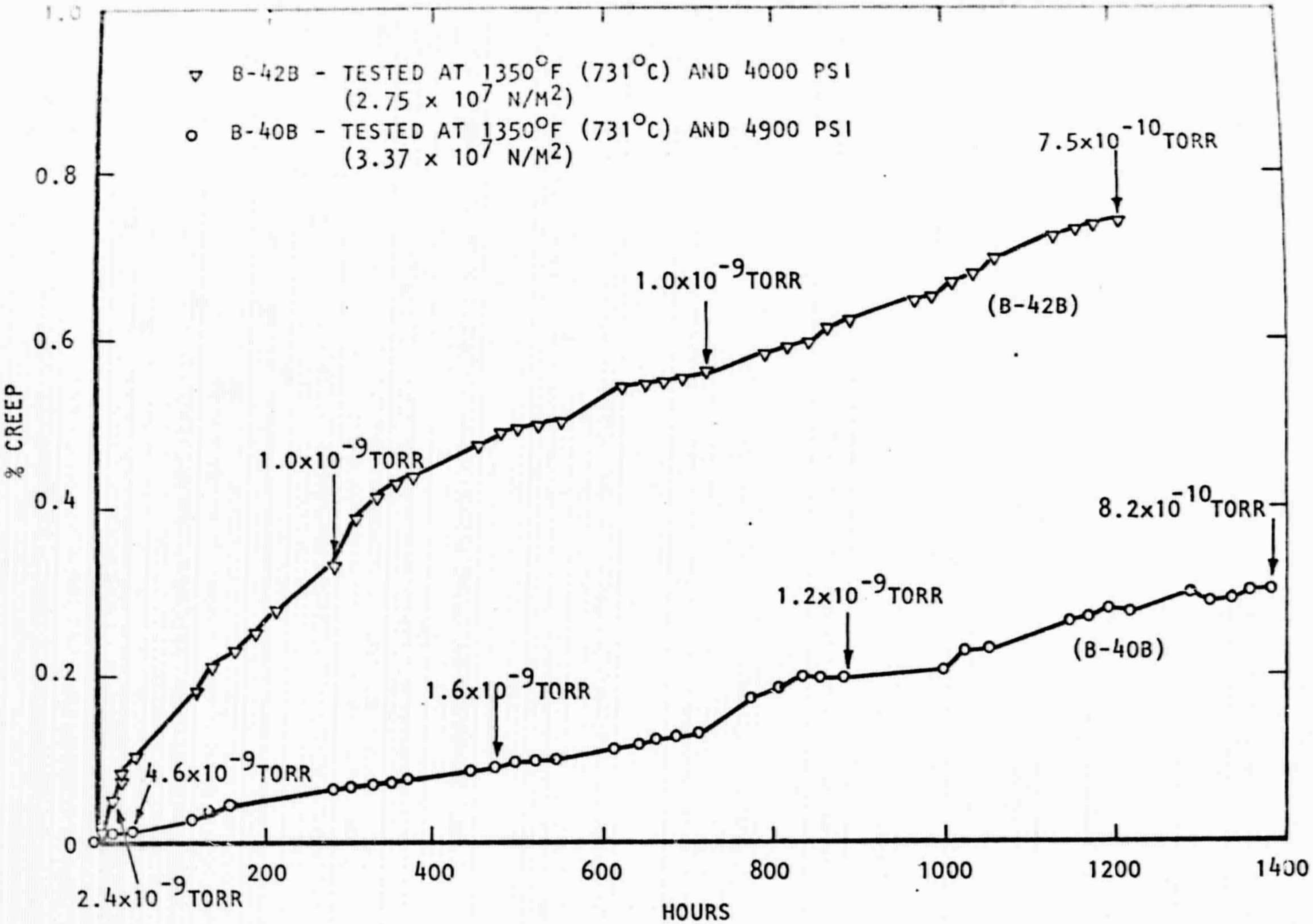


Figure 10. Creep test data, Pure Ta annealed 1 hour at 1832°F (1000°C) tested in sequential test program in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate actual pressure at various points during test.

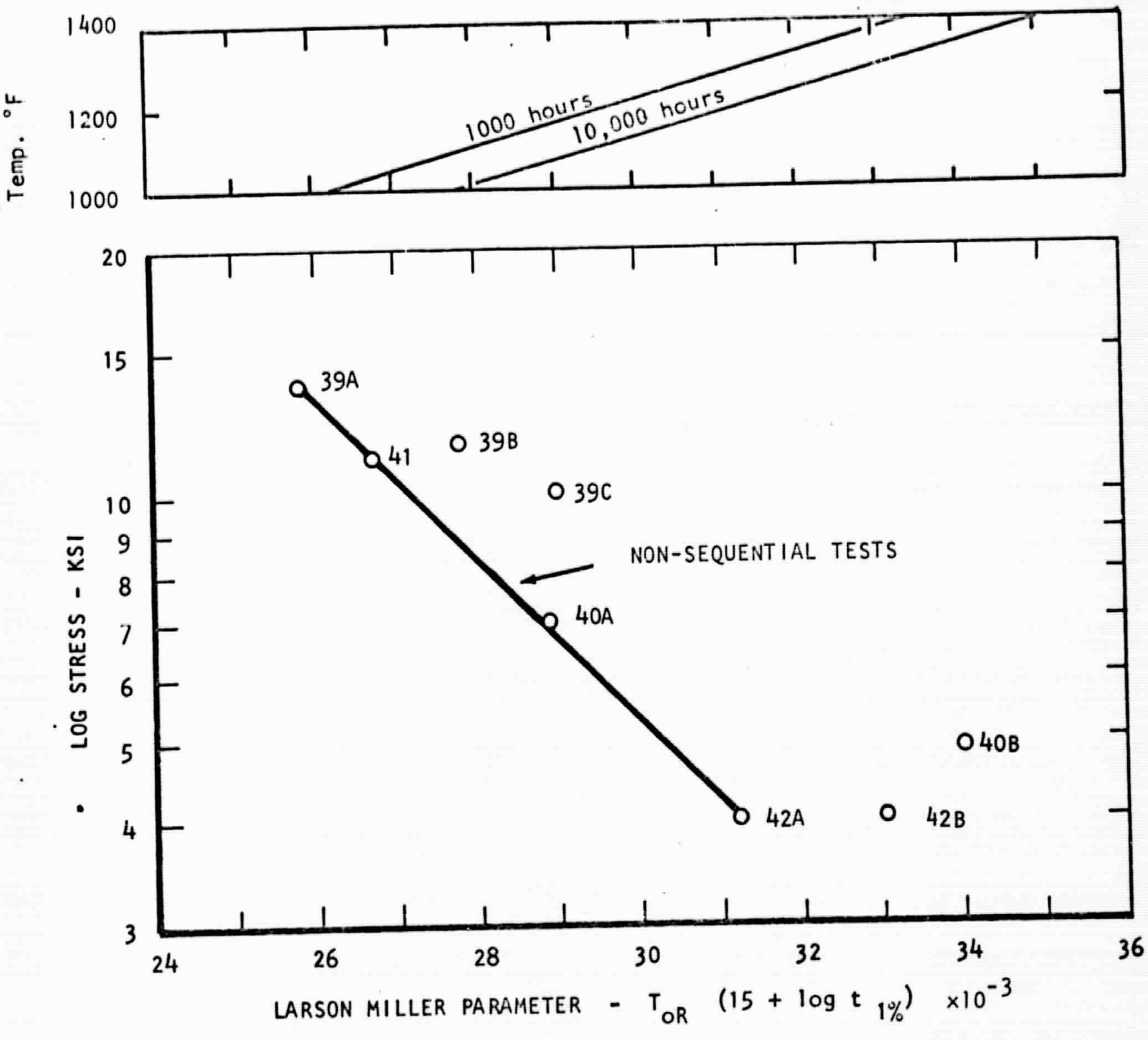


Figure 11. Parametric representation of pure tantalum 1% creep test results.

intersequence anneals do not eliminate history effects. It should be emphasized that the four first sequences were all carried beyond 1% strain and thus constitute valid design data for this material.

Tantalum Base T-111 and ASTAR 811C

Results of static creep tests on T-111 (Figures 12-15) show the behavior of this material to vary widely with temperature and stress. At 2600°F (1427°C) the creep curve is classical in shape, having a first stage during which the creep rate steadily decreases, followed by a second stage where the strain rate is relatively constant. At the opposite extreme, tests at 1800°F (982°C) exhibit strain rates which steadily increase with test time. At temperatures between 1800 and 2600°F (982 and 1427°C) the behavior is intermediate between these two extremes.

All of the static T-111 data available to date are summarized on a Larson Miller plot in Figure 16. Also included on this plot is the single test in progress on ASTAR 811C (Figure 17). The superior creep resistance of ASTAR 811C is readily apparent. The upper data point is taken from the work of Buckman and Goodspeed(3), and represents material annealed 1 hour at 3000°F (1649°C).

Five of the six heats of T-111 tested show comparable creep resistance, while Heat No. 65080 is significantly weaker than the rest. Nothing unusual was noticed in the composition or tensile properties of this heat which might explain such behavior. In the last progress report results of electron probe and microscopy studies showed a sharp difference in the response of this material to high temperature annealing treatments. A one-hour anneal at 3500°F, which ordinarily produces excessive grain growth in T-111, yielded a very fine grained structure in Heat No. 65080. Three distinct precipitate-like features were found in this structure (Figure 18), one of which is distributed preferentially at the grain boundaries and is probably responsible for retarding the grain growth. During the current reporting period this precipitate was studied in the electron microprobe with the results shown in Figures 19 and 20. The X-ray photomicrograp in Figure 19 definitely establishes the precipitate as being Hf rich, while traverses for Ta and W indicated these elements to diminish sharply within the precipitate. Simultaneous traverses for Hf and O_2 shown in Figure 20 indicate the particles to be oxygen rich, while similar scans for C and N_2 yielded no such indications. It is therefore highly probable that these inclusions are hafnium oxide. Although hafnium oxides were also shown in the last report to be present in normal T-111, those in high temperature annealed Heat 65080 are significantly larger than usual.

T-111 Sequential Tests

An experimental evaluation of the sequential test technique for establishing tentative creep data was completed during the current reporting period with the termination of the final test sequence (Figure 21). All of the sequential test results fall within the scatter band for long time tests, Figure 16, indicating the degree of suitability of the technique for T-111. This result must be qualifi

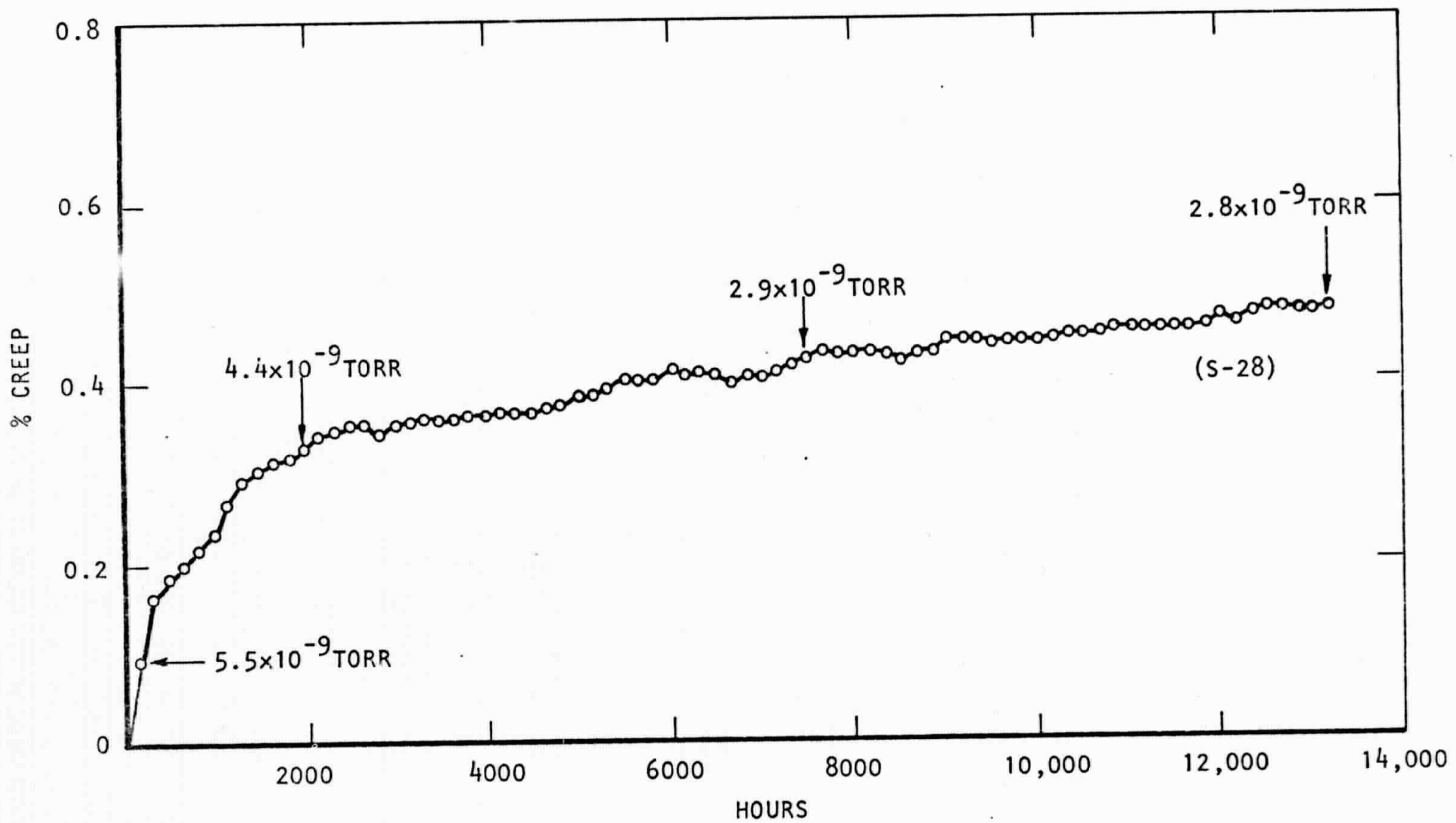


Figure 12. Creep test data, T-111 Heat No. D-1670 annealed 1 hour at 3000°F (1649°C), tested at 2600°F (1427°C) and 500 psi (3.44×10^6 N/m^2), test No. S-28 tested in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate actual pressure at various points during test.

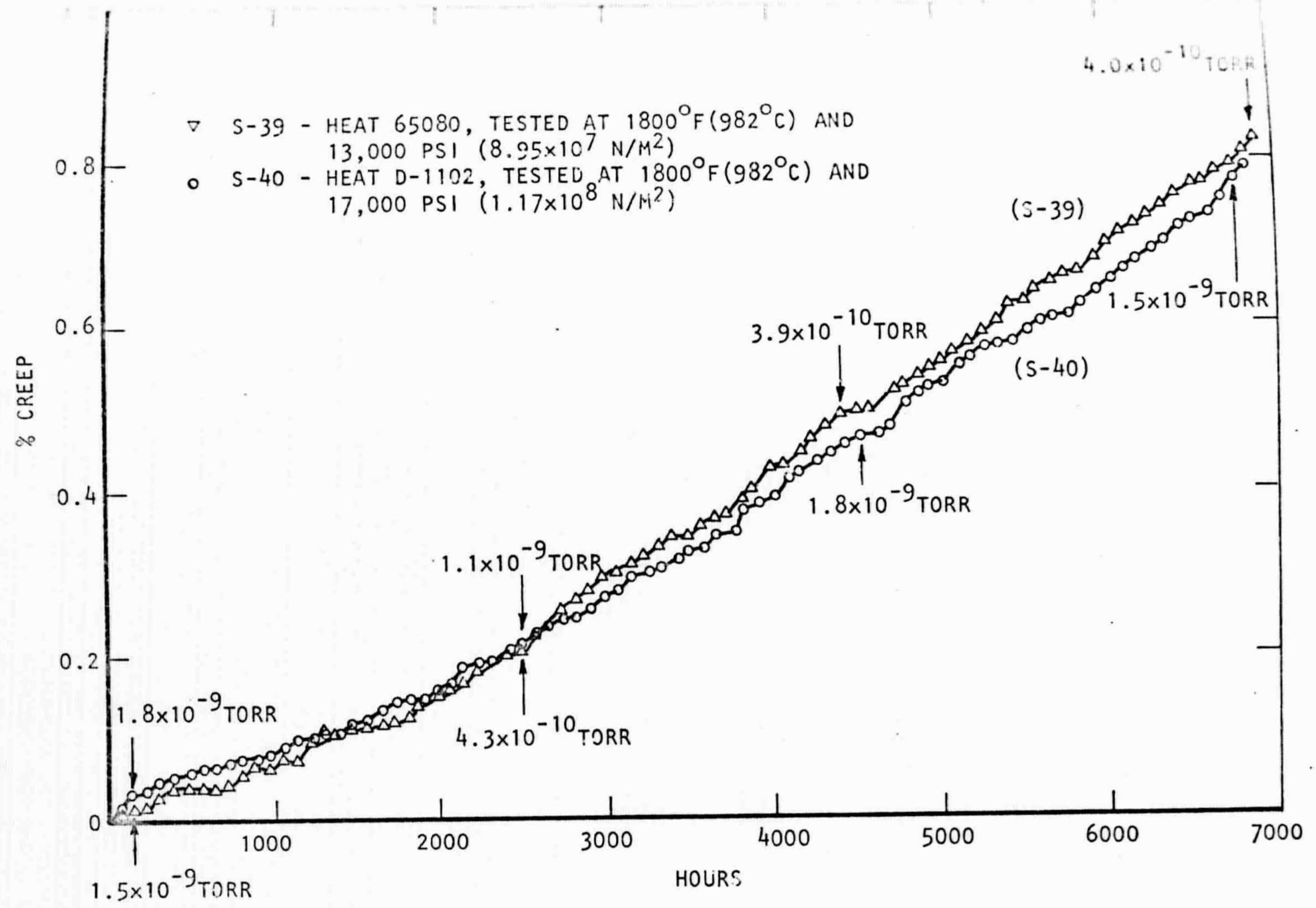


Figure 13. Creep test data, T-111 annealed 1 hour at 3000°F (1649°C), tested in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate actual pressure at various points during test.

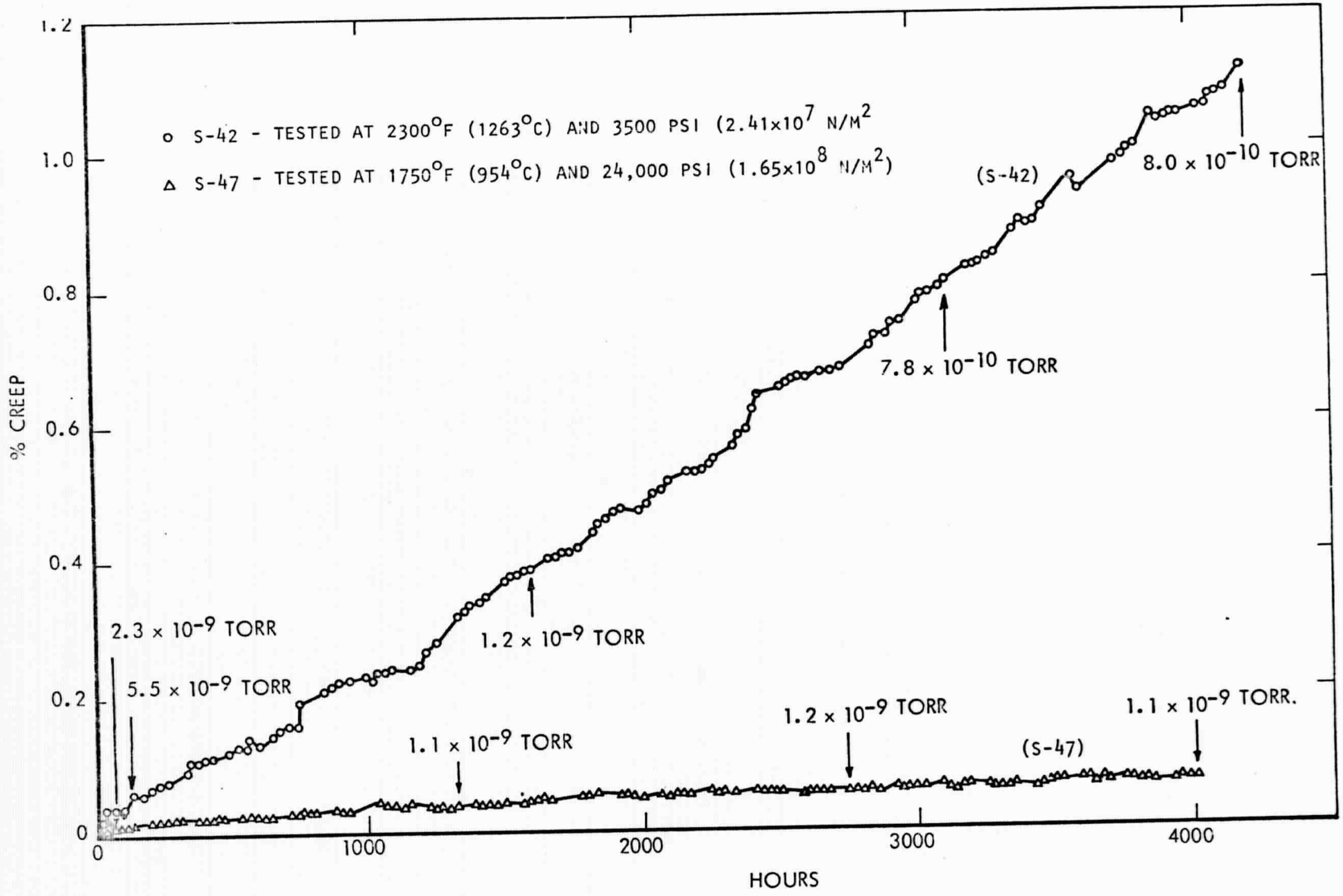


Figure 14. Creep test data, T-111 Heat No. 65079 annealed 1 hour at 3000°F (1649°C), tested in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate actual pressure at various points during test.

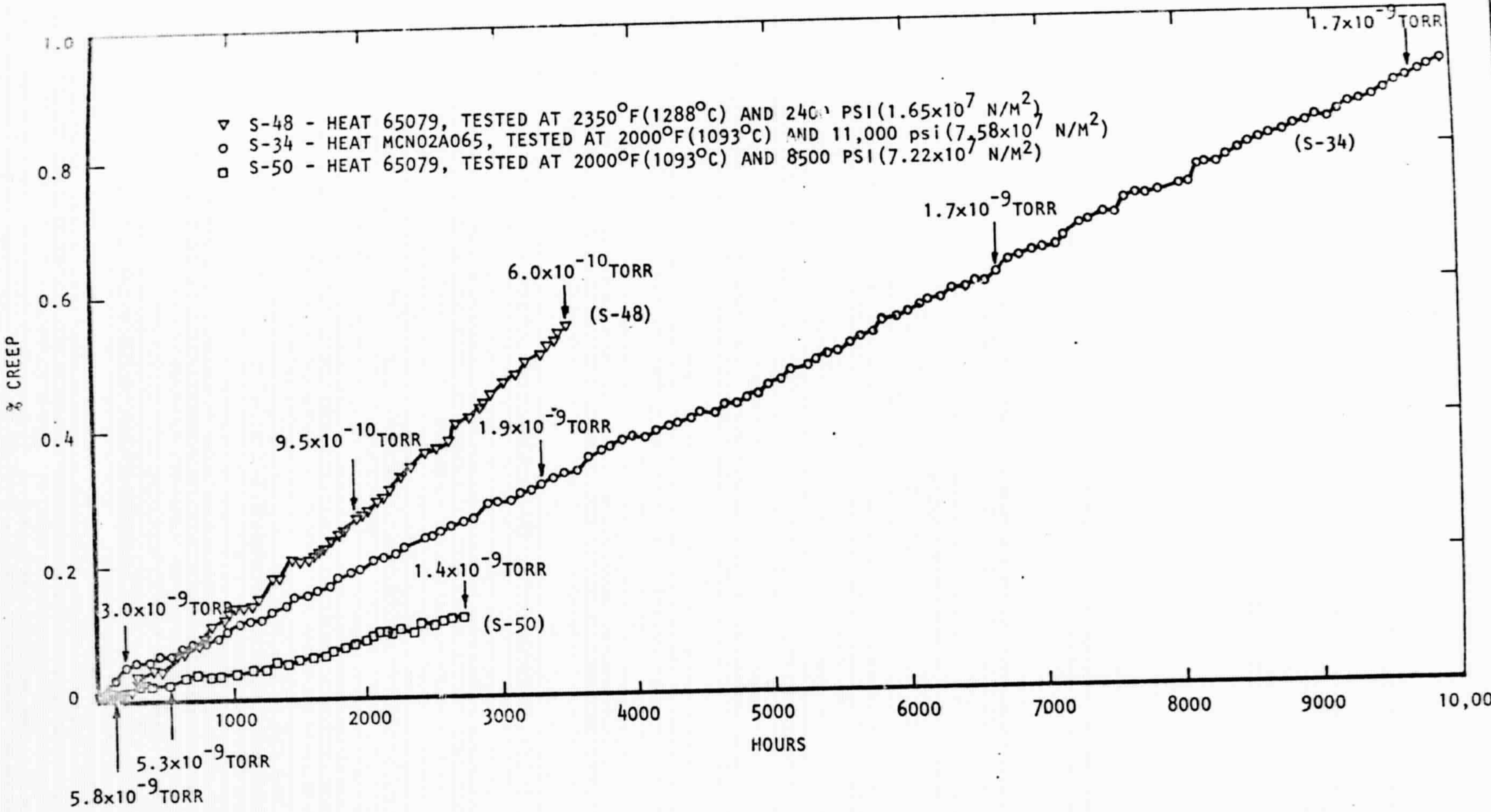


Figure 15. Creep test data, T-111 annealed 1 hour at 3000°F (1649°C), tested in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate actual pressure at various points during test.

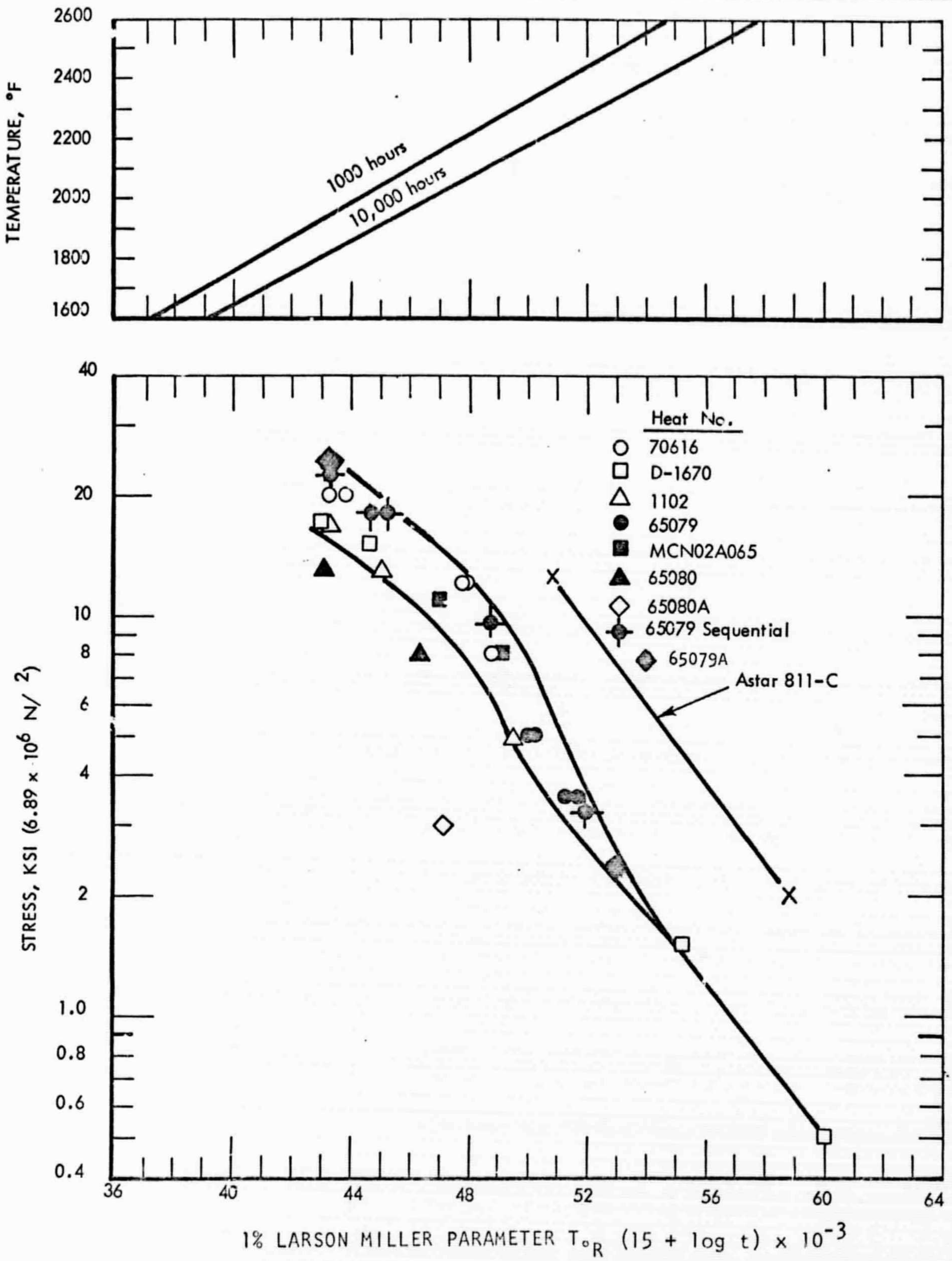


Figure 16. Larson-Miller plot of 1% creep test results on T-111 recrystallized 1 hour at 3000°F (1649°C), plus two data points for ASTAR 811C. High stress ASTAR 811C test recrystallized 1 hour at 3000°F (1649°C), low stress test recrystallized 1/2 hour at 3600°F (2038°C).

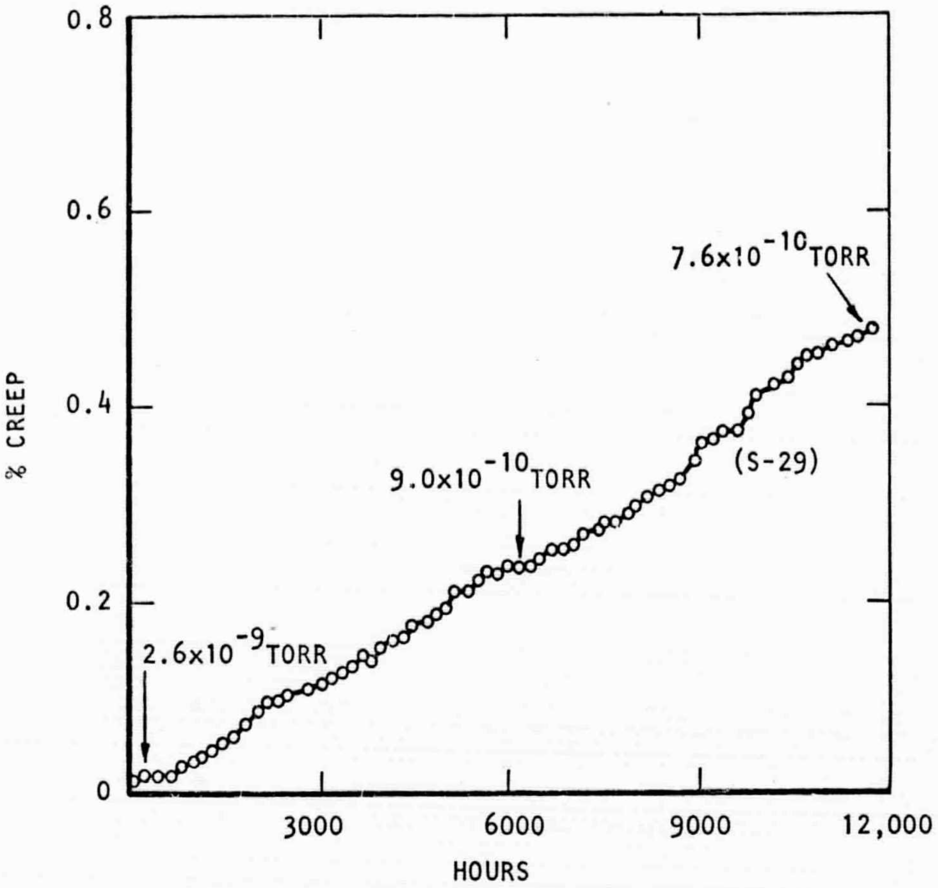
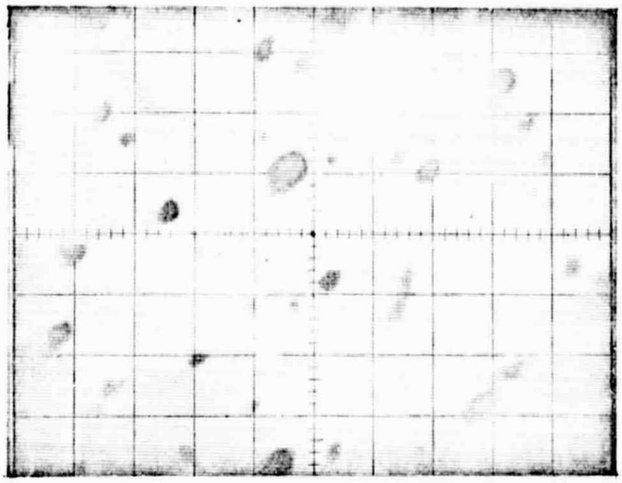


Figure 17. Creep test data, ASTAR 811C Heat No. NASV 20 WS annealed 1/2 hour at 3600°F (2038°C), tested at 2600°F (1427°C) and 2000 psi (1.38 x 10^7 N/m^2), test no. S-29, tested in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate actual pressure at various points during test.

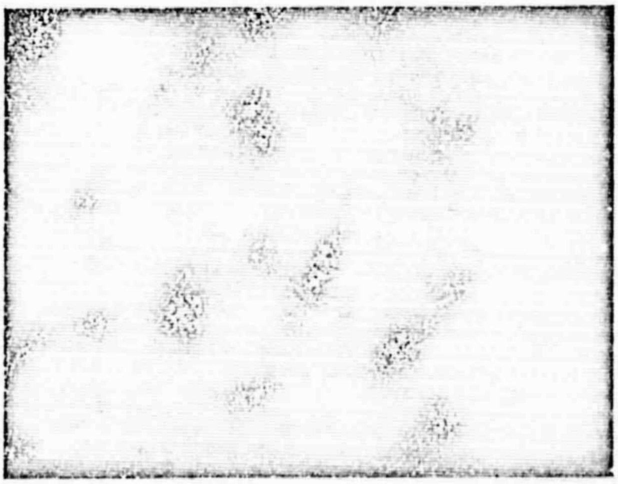
5000X

11,500X

Figure 18. Electron micrographs of T-111 Heat No. 65080 recrystallized 1 hour at 3500°F (1929°C). Light colored precipitate at the grain boundaries in upper photomicrograph, tentatively identified as HfO, is probably responsible for inhibiting grain growth.



ABSORBED CURRENT IMAGE



Hf X-RAY IMAGE

Figure 19. Electron probe photomicrographs of T-111 heat No. 65080 annealed 1 hour at 3500°F (1929°C). 1800X.

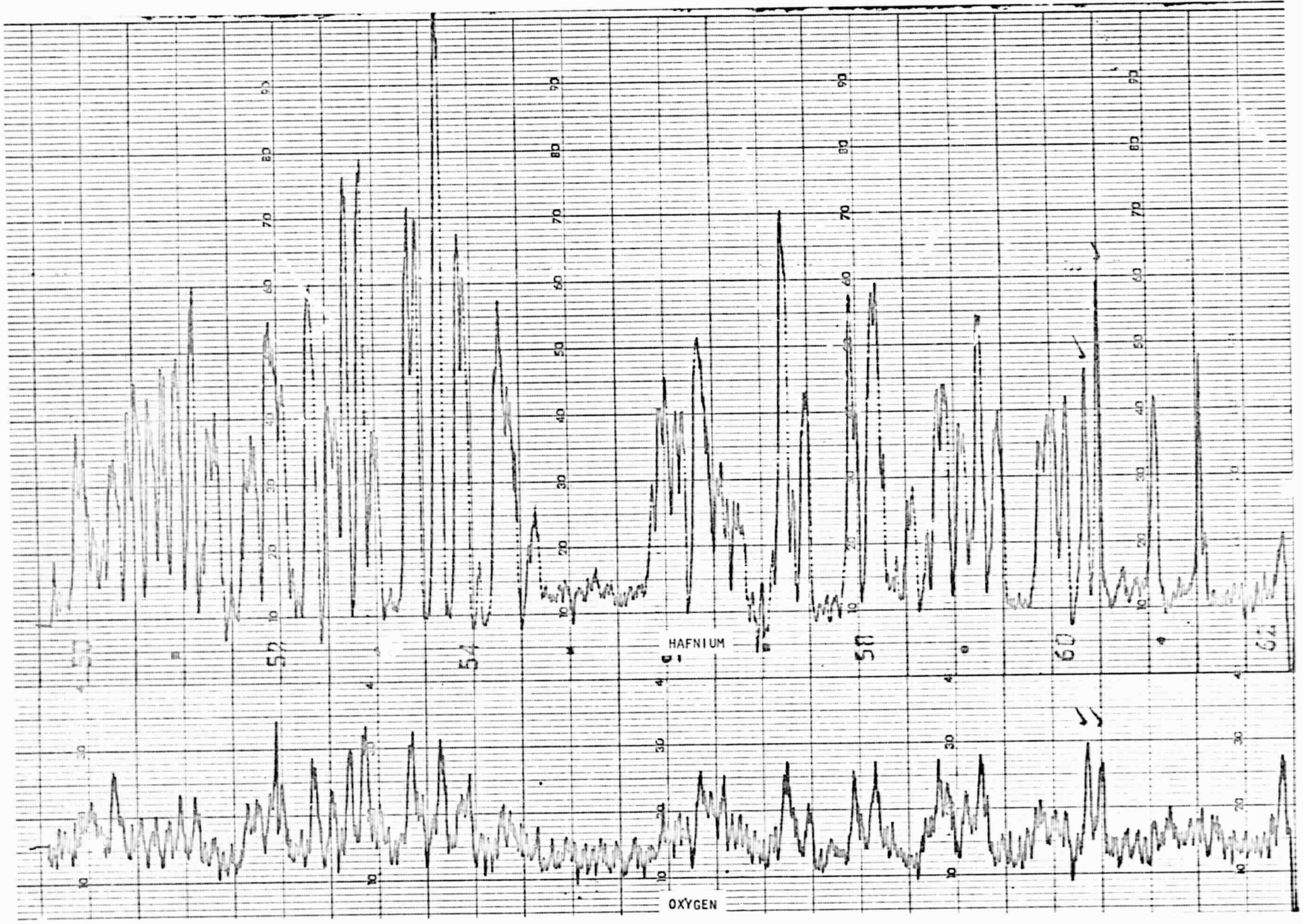


Figure 20. Electron microprobe elemental X-ray distribution scans run simultaneously for oxygen and hafnium in T-111 Heat No. 65080 annealed 1 hour at 3500°F (1929°C).

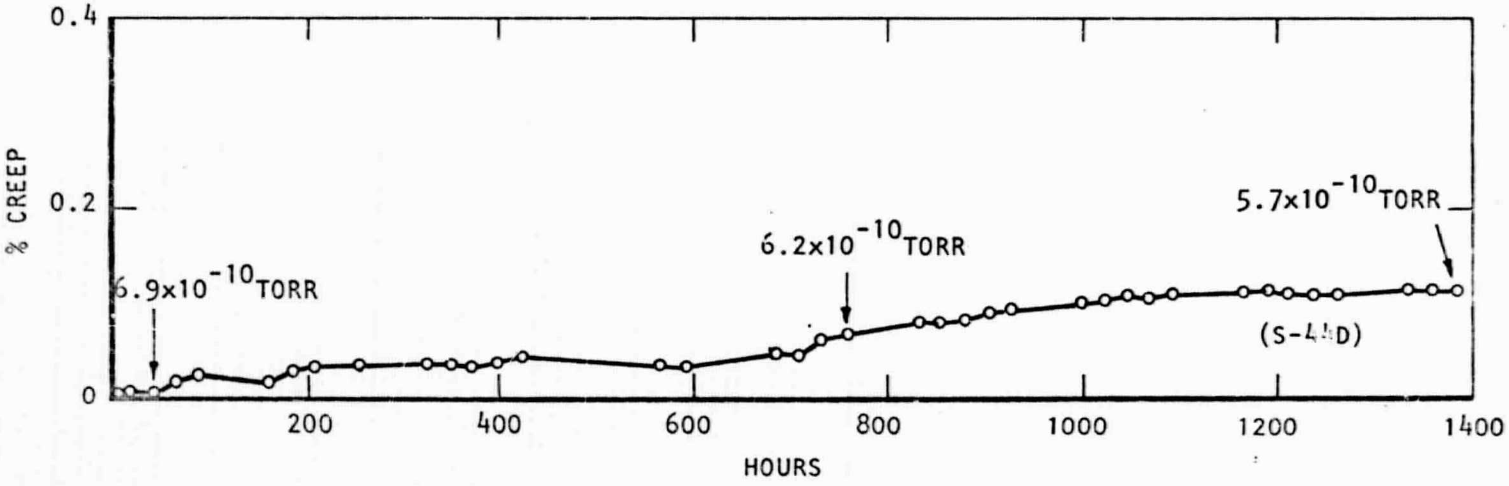


Figure 21. Creep test data, T-111 Heat No. 65079 annealed 1 hour at 3000°F (1649°C), tested at 1800°F (982°C) and 23,000 psi (1.58×10^8 N/m^2), test no. S-44D in sequential test program, tested in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate actual pressure at various points during test.

by the fact that creep curves for the two sequences representing a drop in test temperature were somewhat irregular and it was necessary to run these tests for a period of approximately 500 hours before a reliable extrapolation could be achieved. Thus for best results, sequential tests must be initiated at the lowest temperature in the range of interest and should always progress upward in temperature.

T-111 Progressive Stress Tests

Four progressive stress tests are now completed and four more are currently in progress. In these tests the load is started nominally at zero and continuously increased at a predetermined rate for the duration of the test. Results of the tests involved in the current reporting period are shown in Figures 22 and 23, while data from the entire program are summarized in Table 2. The agreement between observed creep life values and those predicted by a previously described method(1), is quite good in view of the straight line fit of the Larson Miller curve involved in the predictions.

One of the salient results of the theoretical analysis is the prediction of a maximum stress rate above which specimen life is limited by the rate of approach to the yield stress rather than by the rate of creep deformation. Specimen S-49 represents a critical test of this hypothesis, since it is being conducted at a stress rate two orders of magnitude above the calculated maximum. Based on the rate of approach to the yield stress it was predicted that this test would reach 1% strain somewhere between 1200 and 1700 hours and would sustain the bulk of the deformation in the last few hundred hours of test. This has in fact occurred and the creep curve (Figure 22) shows a very abrupt change in creep rate between 1300 and 1400 hours as the stress reaches approximately 3/4 of the yield strength.

Having thus confirmed, at least qualitatively, the methods of analysis and the concept of a maximum stress rate, it is necessary to correlate the experimental progressive stress data in a useful engineering form. The first approach is to define a relationship between the static stress and the dynamic stress rate required to produce equivalent 1% creep lives at a given temperature. According to McCoy(4) those materials which exhibit a power stress dependence of creep life at a given temperature:

$$t_c = (A/\sigma)^n \qquad (1)$$

should also obey a similar relationship under the influence of linear progressive stress at the same temperature:

$$\frac{t_c^{\,n+1}}{n+1} = (A/\dot{\sigma})^n \qquad (2)$$

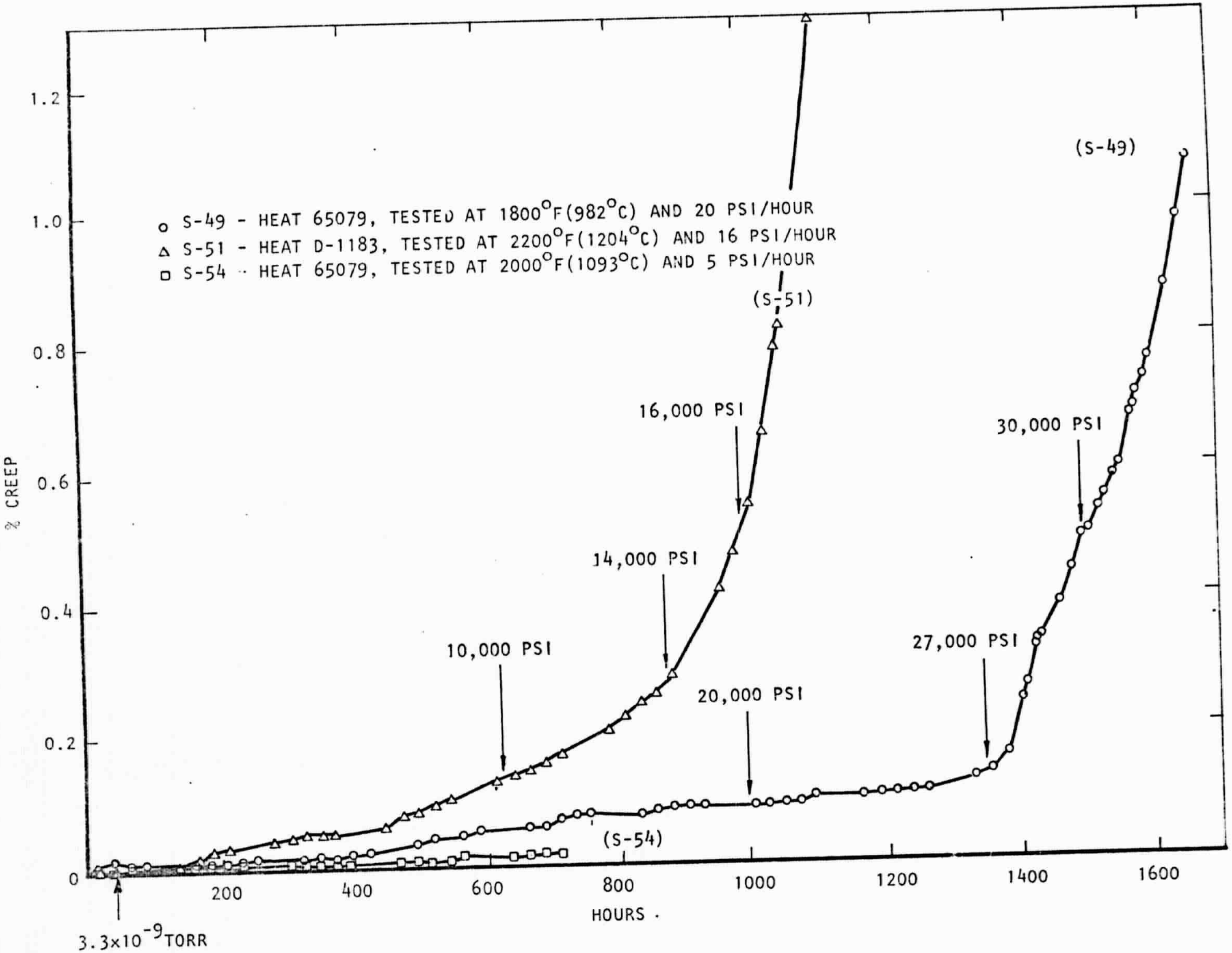


Figure 22. Creep test data, T-111 annealed 1 hour at 3000°F (1649°C), tested in progressive stress program, in a vacuum environment of $<1 \times 10^{-8}$ torr. Arrows on curves indicate stress at various points during test.

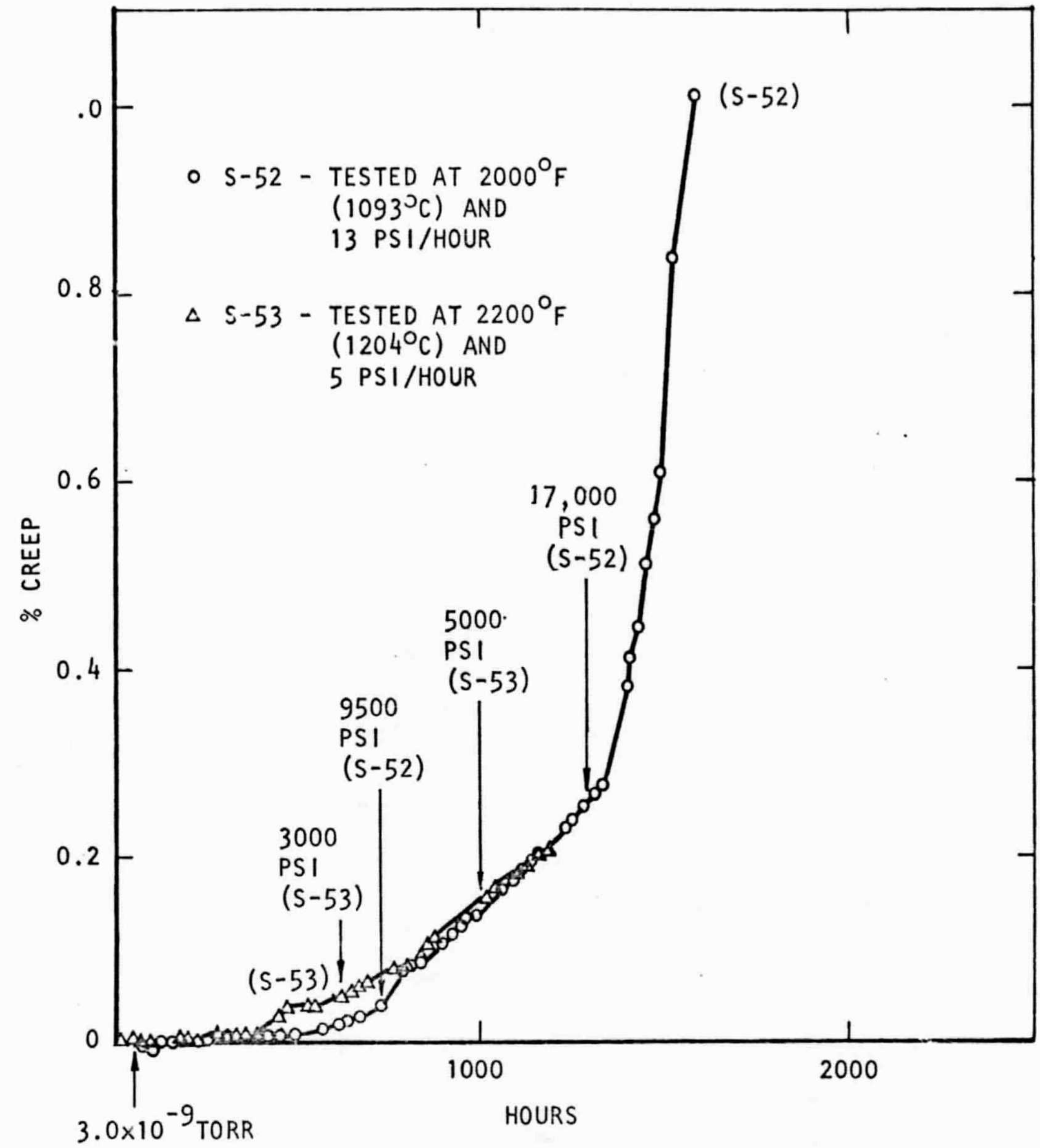


Figure 23. Creep test data, T-111 Heat No. 65079 annealed 1 hour at 3000°F (1649°C), tested in progressive stress program, in a vacuum environment of <1 x 10^{-8} torr. Arrows on curves indicate stress at various points during test.

TABLE 2

Summary of Progressive Stress Tests on T-111 Annealed 1 Hour at 3000°F

				1% Creep Life		Larson Miller Parameter+
Test No.	Heat No.	Temp. °F	Loading Rate psi/hr	Predicted	Observed	$T_{^\circ R}(1+\log t)\times 10^{-3}$
S-36	65080	2200	16	485	600	10.0
S-38	65080	2200	1	4260	3830	12.2
S-46	65079	2200	16	880	1000*	10.6
S-49	65079	1800	20	1200/1700**	1660	9.5
S-51	D-1183	2200	16	880	1080	10.7
S-52	65079	2000	13	2000	1700*	10.4
S-53	65079	2200	5	2200	2000*	11.4
S-54	65079	2000	5	4400	4000*	11.3

* Extrapolated

** Based upon rate of approach to yield strength - see text

\+ See text, page 33, for explanation of very low Larson Miller constant.

In both equations t_c is the time to a specified creep strain, σ is stress, $\dot{\sigma}$ is stress rate, and n is an empirical constant. Solving equation 2 for t_c and setting this expression equal to the right hand side of equation 1 yields the desired analytical expression between stress and stress rate:

$$(n+1)^{\frac{1}{(n+1)}} \left(\frac{A}{\dot{\sigma}}\right)^{\frac{n}{n+1}} = \left(\frac{A}{\sigma}\right)^n \qquad (3)$$

Taking the log of equation 3 and solving for log $\dot{\sigma}$ provides the result

$$\log \dot{\sigma} = (n+1) \log \sigma - n \log A - \frac{1}{n} \log (n+1) \qquad (4)$$

indicating a linear relationship between log $\dot{\sigma}$ and log σ below 3/4 of the yield strength. Although sufficient data are not available at any temperature to confirm this relationship, a plot of the existing data is shown in Figure 24.

Equation 4 suffers from the disadvantage that no account is taken of temperature in the analytical expressions and this variable must therefore be handled on a parametric basis. A slightly different approach which has no fundamental basis, but which may provide a useful engineering correlation of the data, is found in Figure 25 where stress rate is plotted against a Larson Miller parameter calculated in exactly the same fashion as for static results. This form of representation requires that the Larson Miller constant be reduced to a very small value to correlate tests at different temperatures, and thus does not conform to normal engineering practice. Other approaches will be tried during the coming report period, among which will be an attempt to combine the isothermal curves of Figure 24 into a single curve through use of some form of temperature compensated stress parameter. The ability to evaluate these representations should improve as more data become available.

Mathematical Analysis of T-111 Creep Behavior

In pursuit of a better rationalization of the variable stress and temperature creep behavior of T-111 it is desirable to formulate a so-called "equation of state" describing the creep rate as a function of stress, temperature, and instantaneous creep strain. The following paragraphs describe the current progress toward this goal.

The first step in defining a creep equation is to establish the stress and temperature dependence of the steady state creep rate. Although this is difficult because of the unusual shape of the low temperature T-111 creep curves, the required information can be secured by plotting true strain rate as a function of true creep strain. Creep rates are easily obtained by graphical differentiation of the raw creep curves, and typical relationships are illustrated in Figure 26. These particular curves were chosen to emphasize the influence of temperature and stress on the form of the T-111 creep curves. At high temperature the creep rate progressively decreases to a steady state value, whereas at low temperature the creep rate first decreases to a very low value and then rises again. The important point, however, is that both specimens eventually approach a steady state creep rate as strain increases.

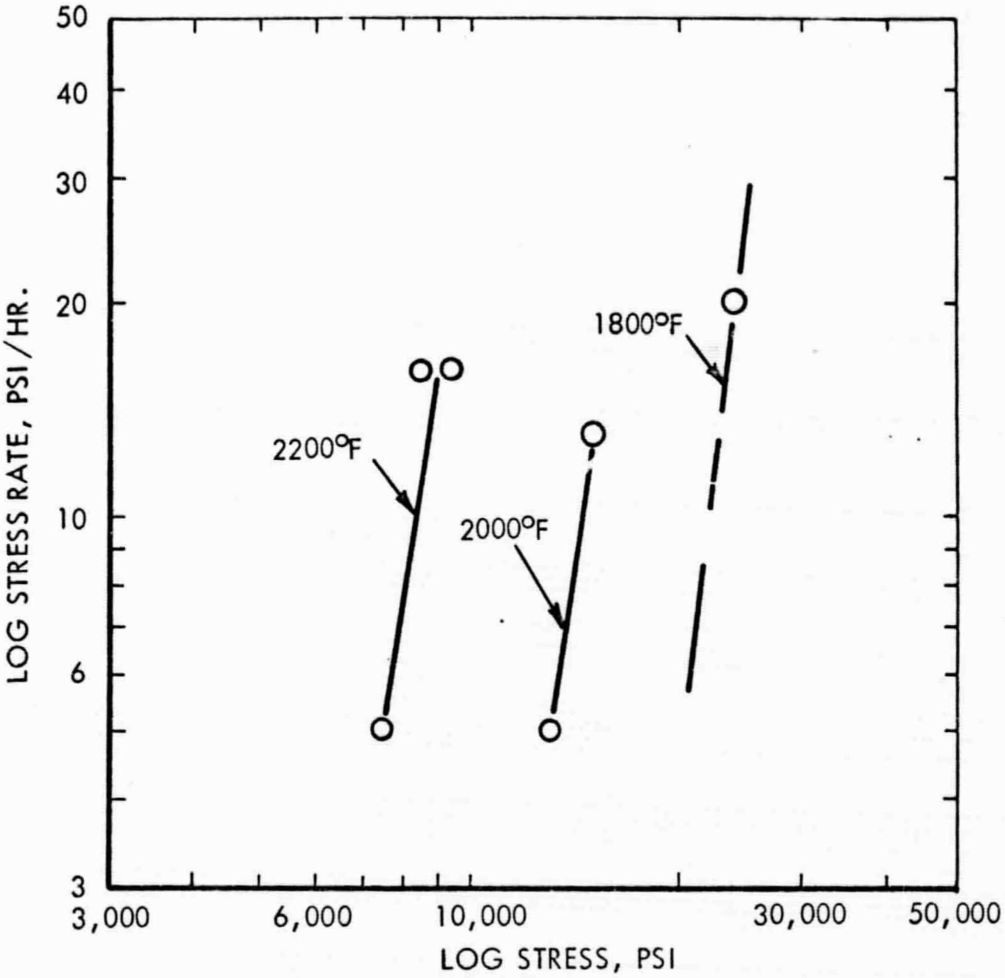


Figure 24. Linear stress rate versus static stress for equivalent 1% creep life in T-111 annealed 1 hour at 3000°F (1649°C).

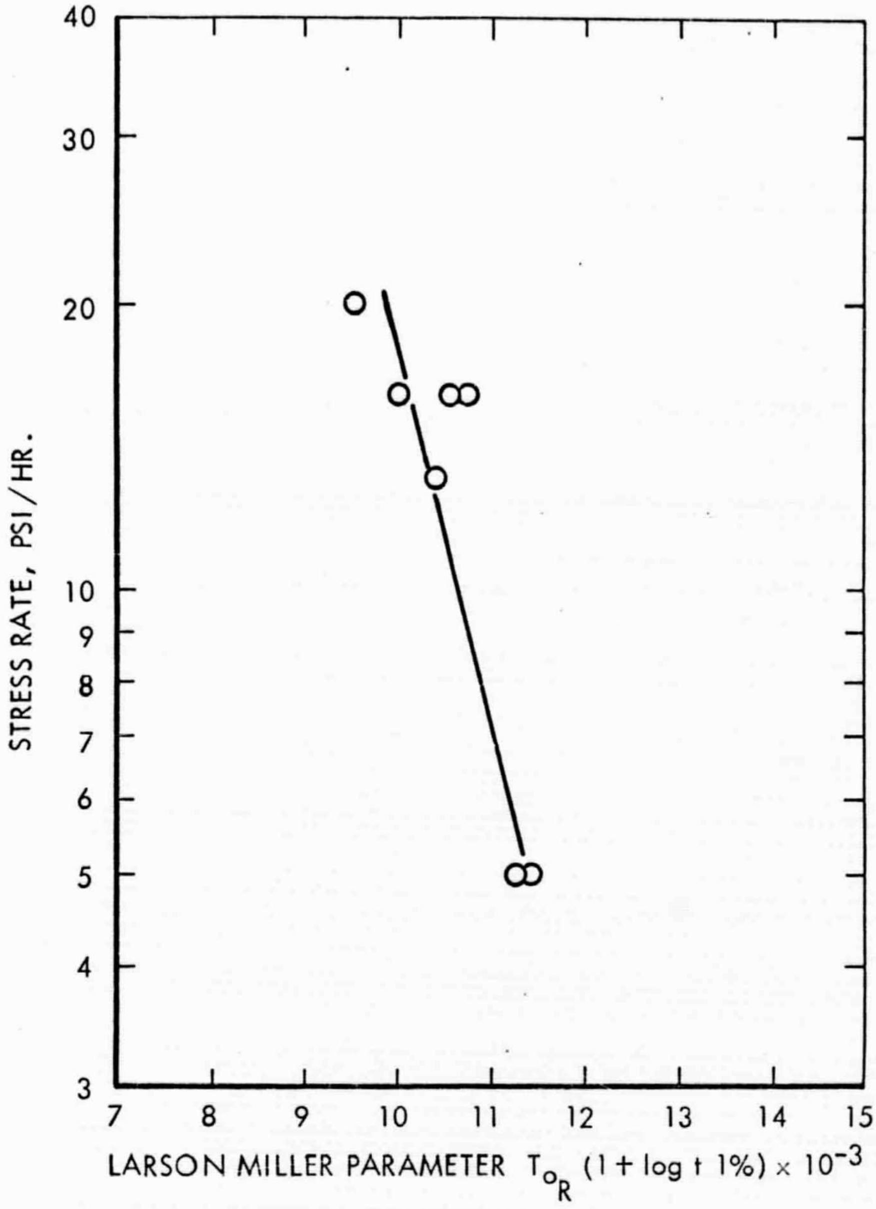


Figure 25. Parametric representation of progressive stress 1% creep results from T-111 annealed 1 hour at 3000°F (1649°C). The unusually low value of the Larson Miller constant is explained on page 33.

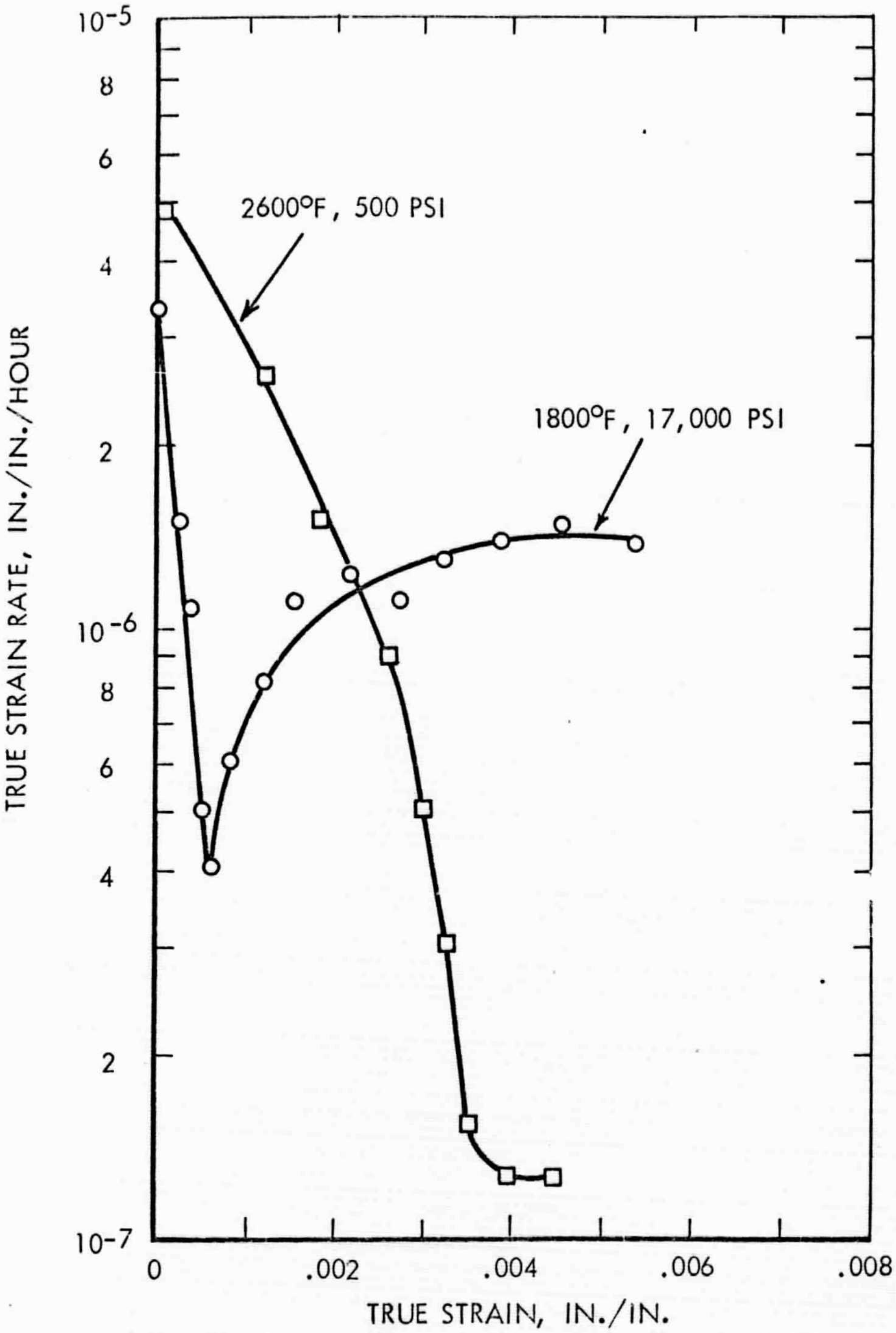


Figure 26. True strain rate as a function of true creep strain in T-111 annealed 1 hour at 3000°F (1649°C) and creep tested at the indicated conditions.

Having obtained steady state creep rates it is necessary to relate these values to temperature and stress in some systematic fashion. The most common engineering representation is a plot of log stress versus log creep rate with temperature as a parameter, but it was found that such a plot does not adequately correlate the data. An alternative treatment is the Arrhenius type of plot where log true strain rate is plotted versus reciprocal absolute temperature with stress as a parameter. The slope of each isostatic curve is directly related to ΔH, the apparent activation energy for creep. Again, it was found that the results were not well represented on this type of plot due partly to lack of sufficient tests at any one stress and partly to statistical variation of the experimental results. However, there was enough correlation to roughly estimate ΔH, which appears to be the order of 10^5 cal/mole throughout most of the stress range involved.

Presuming one creep mechanism to be dominant within the temperature and stress ranges of interest, steady state strain rate generally obeys the relationship

$$\dot{\varepsilon} = Af(\sigma)e^{-\Delta H/RT} \tag{5}$$

Further assuming that A is independent of stress and temperature the form of f (σ) can often be deduced from plots of $\dot{\varepsilon}e^{\Delta H/RT}$ against appropriate stress functions.

With an approximate value of ΔH available it is possible to calculate values of $\dot{\varepsilon}e^{\Delta H/RT}$, which should combine results from different temperatures into a single straight line if plotted against the proper stress function. Various relationships have been proposed in the literature, among which are the common power stress law:

$$\dot{\varepsilon} \propto \sigma^{n} \tag{6}$$

the exponential stress law:

$$\dot{\varepsilon} \propto e^{B\sigma} \tag{7}$$

and the hyperbolic sine relationship:

$$\dot{\varepsilon} \propto \{\sinh(\alpha\sigma)\}^{n} \tag{8}$$

with α, B, and n being empirically fitted constants. Each of these functions is evaluated in Figures 27, 28, and 29. Values of α ranging from 9.1×10^{-5} to 1×10^{-3} were tested in expression 8 with the value of 1.2×10^{-4} providing the best fit.

Several features of these relationships require comment. First, the temperature compensated strain rate parameter has successfully combined all of the data into a single curve on each plot, indicating this to be a valid technique for representation of the T-111 creep data. Second, each of the curves can be repre-

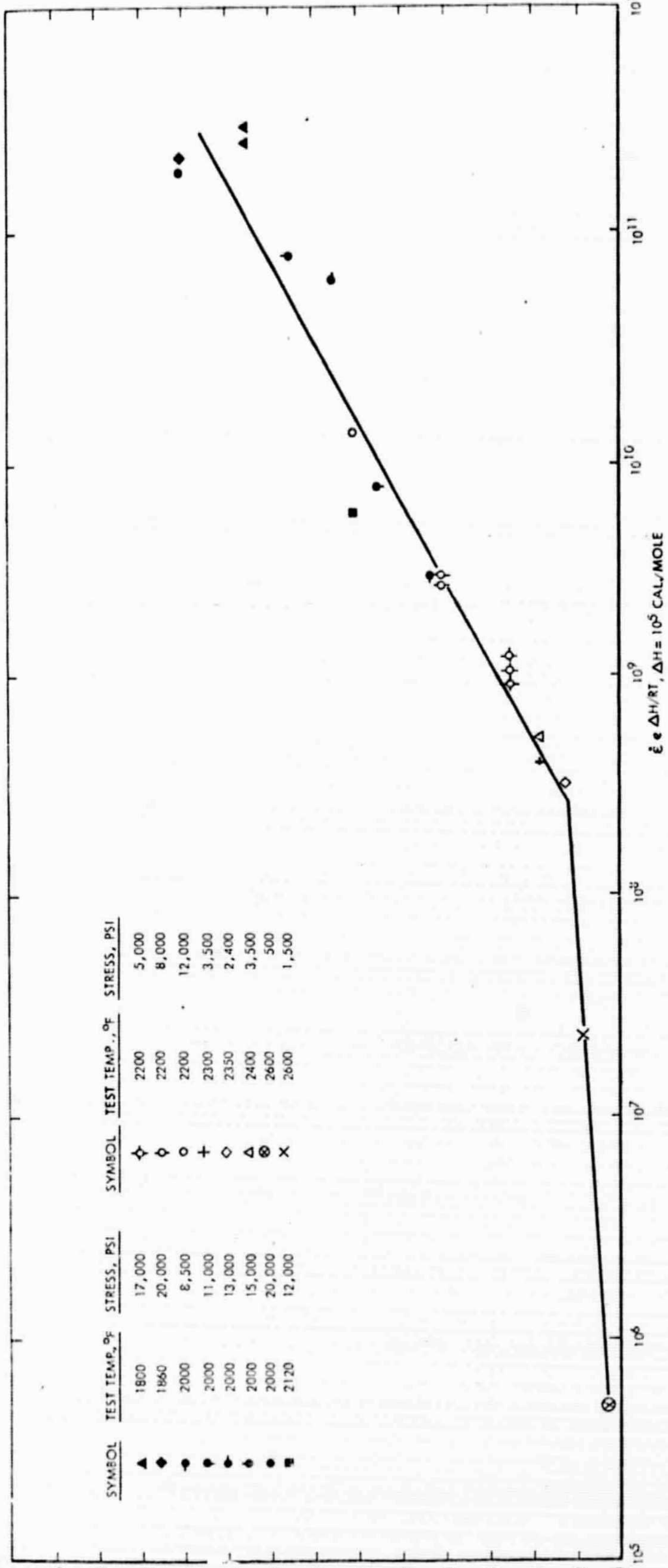


Figure 27. Stress as a function of temperature compensated true strain rate in T-111 annealed 1 hour at 3000°F (1649°C). Straight line segments represent least squares fit of the data.

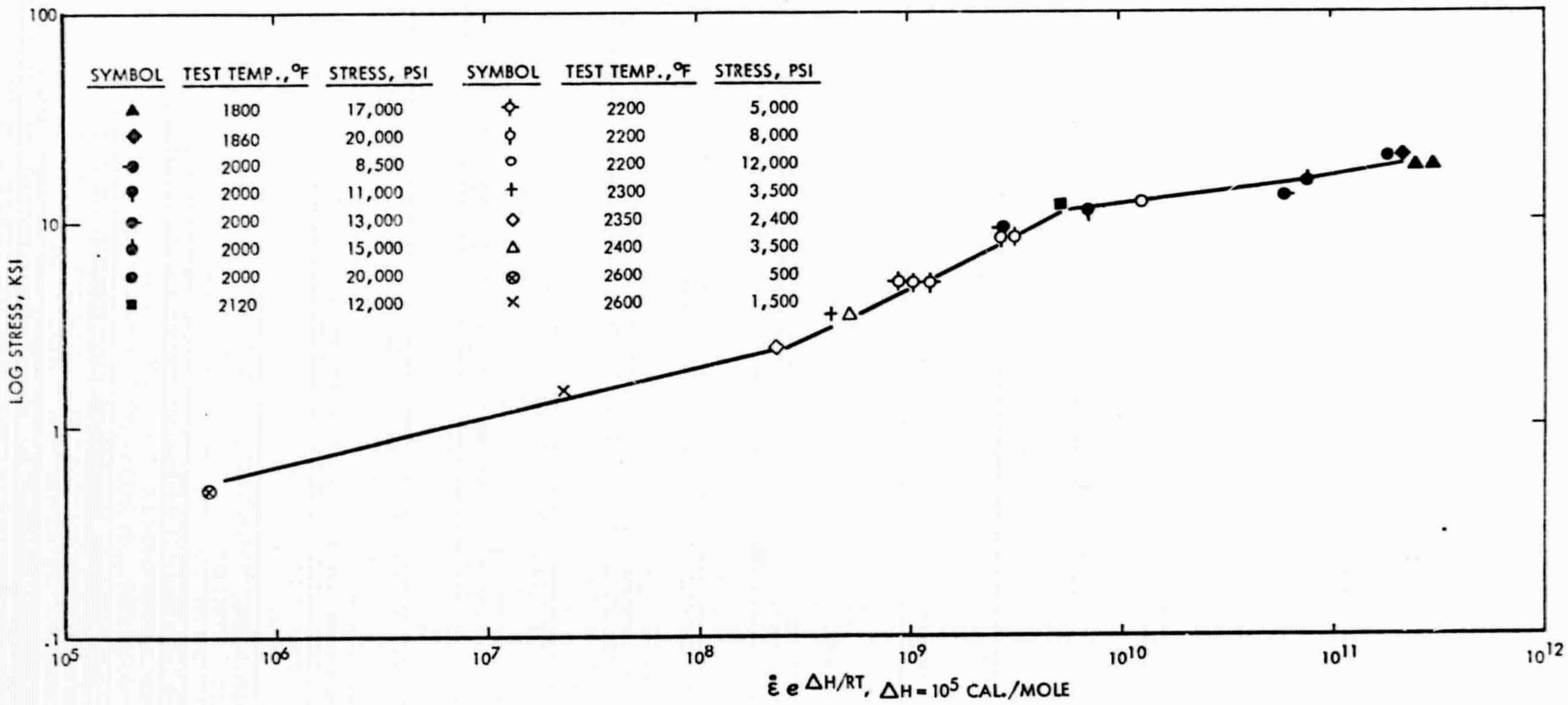


Figure 28. Log stress as a function of temperature compensated true strain rate in T-111 annealed 1 hour at 3000°F (1649°C).

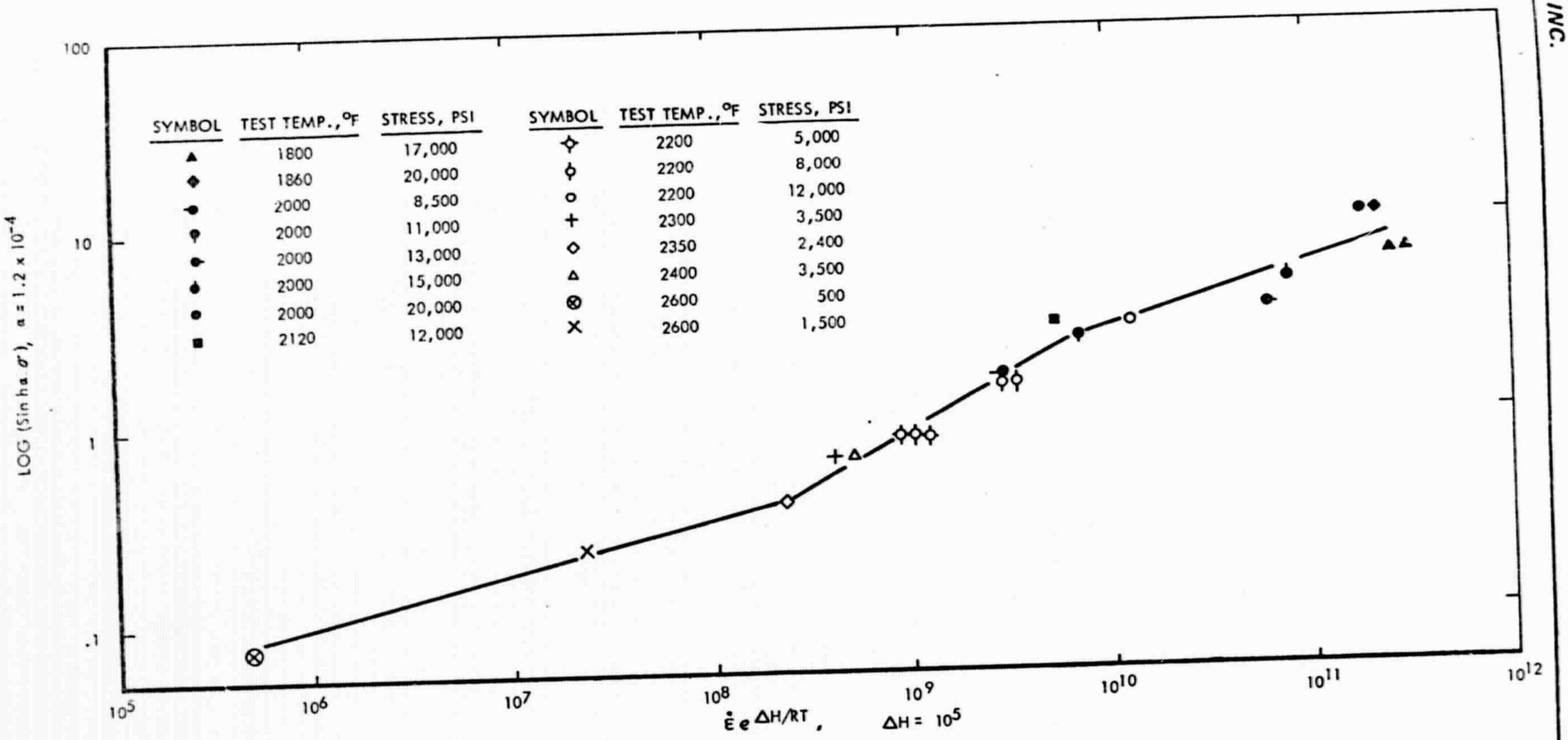


Figure 29. Log {Sinh (ασ)} as a function of temperature compensated true strain rate in T-111 annealed 1 hour at 3000°F (1649°C).

sented by two or three straight line segments, indicating that each of the respective stress functions will correctly describe the stress dependence of the steady state creep rate within limited ranges. Third, the exponential function provides two straight line segments whereas the other two functions appear to provide three segments, although the hyperbolic sine curve has only a slight change of slope between the upper and middle ranges. Therefore, since it is simpler to work with two ranges of stress dependence than with three, the exponential stress function has been chosen for the subsequent portion of the analysis.

Within each of the two linear ranges in Figure 27 the behavior of T-111 can be described by the straight line equation of the form

$$\sigma = M(\log \dot{\varepsilon} e^{\Delta H/RT}) + K \tag{9}$$

which is an alternative form of the statement

$$\dot{\varepsilon} = Ae^{B\sigma}e^{-\Delta H/RT} \tag{10}$$

where the constants A and B are related to the slope M and intercept K by the equations:

$$B = 2.303/M \quad \text{and} \quad A = e^{-2.303K/M} \tag{10B}$$

A linear regression analysis was used to evaluate the best fit of the data in Figure 27. This analysis provides the correlation coefficient, in addition to the values of M and K. Thus it is possible to statistically evaluate the degree of fit of the data as a function of the value of ΔH used in the temperature compensated strain rate parameter. This is desirable since the value of 10^5 originally used for ΔH was an approximation, and a more exact value is needed.

Results of the statistical analysis are tabulated in Table 3 for the two stress ranges delineated in Figure 27. The best values of ΔH are respectively 90,000 and 157,000 cal./mole in the high and low stress regions. This latter value is open to considerable question since only three tests are involved, a small error in any one of which would cause a large variation in the best fit value of ΔH. The creep data are replotted in Figure 30 using these values. An alternative representation of the same data is provided by the Arrhenius type plot shown in Figure 31, where a stress compensated strain rate parameter of the form $\dot{\varepsilon}e^{B\sigma}$ has been plotted using values of B calculated from the slopes of the straight line segments in Figure 30. The low stress data have been omitted from this plot because of the uncertainty involved in the statistical fit. Figures 30 and 31 are alternative representations of equation (10), and the best values of B and ΔH could have been obtained with equal facility by optimizing B on the Arrhenius plot.

To summarize results, it has been found that the true steady state strain rate of T-111 annealed 1 hour at 3000°F (1649°C) can be related to temperature and stress with an equation of the form

$$\dot{\varepsilon} = Ae^{B\sigma}e^{-\Delta H/RT}$$

TABLE 3

Influence of Activation Energy on the Correlation Coefficient Between σ and $\dot{\varepsilon}e^{\Delta H/RT}$

Low Stress Range		High Stress Range	
ΔH	Correlation Coefficient	ΔH	Correlation Coefficient
100,000	.987869	80,000	.9715985768
112,000	.993082	86,000	.9730575347
120,000	.995591	88,000	.9732448366
129,000	.997579	89,000	.9733476812
138,000	.998915	90,000	.9733912336
150,000	.9998581839	91,000	.9733608488
155,000	.9999856330	92,000	.9733602498
156,000	.9999947998	94,000	.9732328204
157,000	.9999993599	96,000	.9729846922
157,500	.9999999596	98,000	.9727107822
158,000	.9999992840	100,000	.9725489012
159,000	.9999946381	110,000	.9697780468
160,000	.9999846856	120,000	.9664536800
165,000	.9998655609		
170,000	.999657		
180,000	.998980		
200,000	.996752		
220,000	.993791		

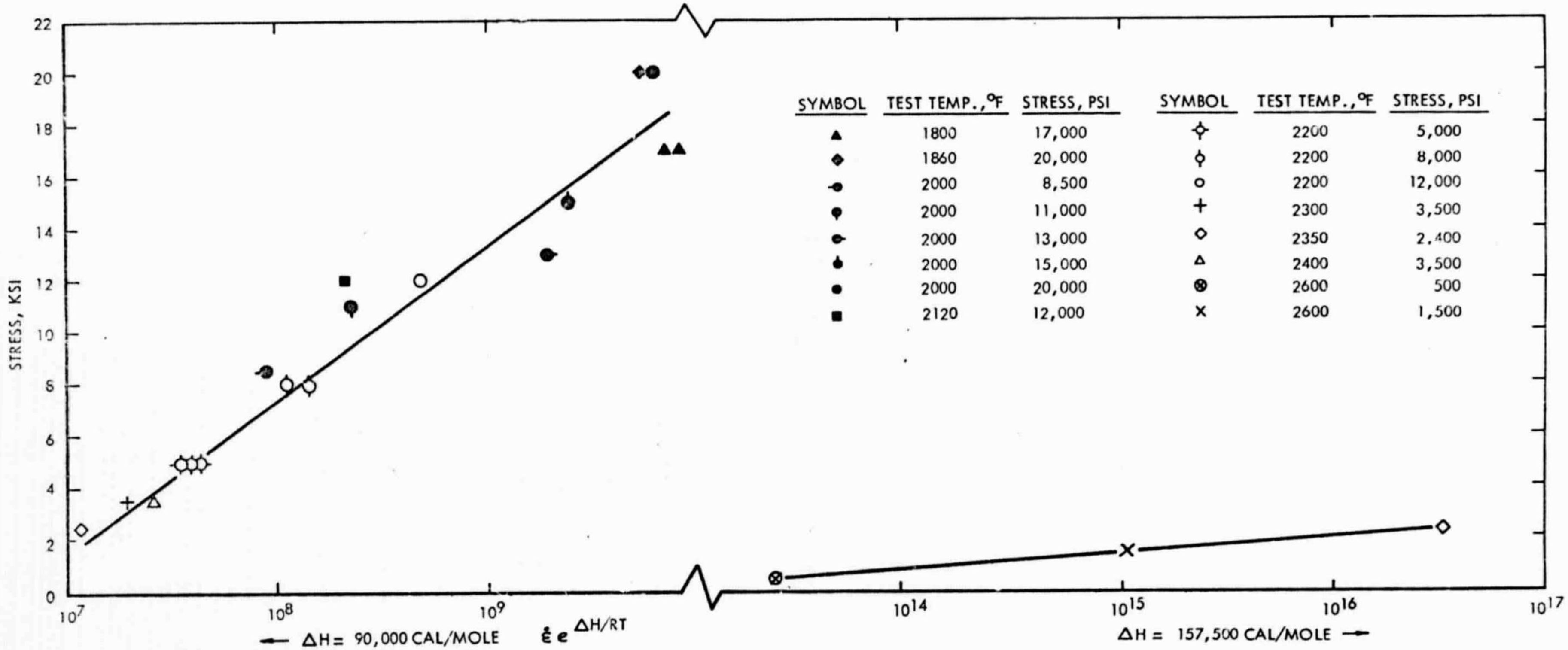


Figure 30. Stress as a function of temperature compensated true strain rate in T-111 annealed 1 hour at 3000°F (1649°C), plotted using the optimum values of ΔH.

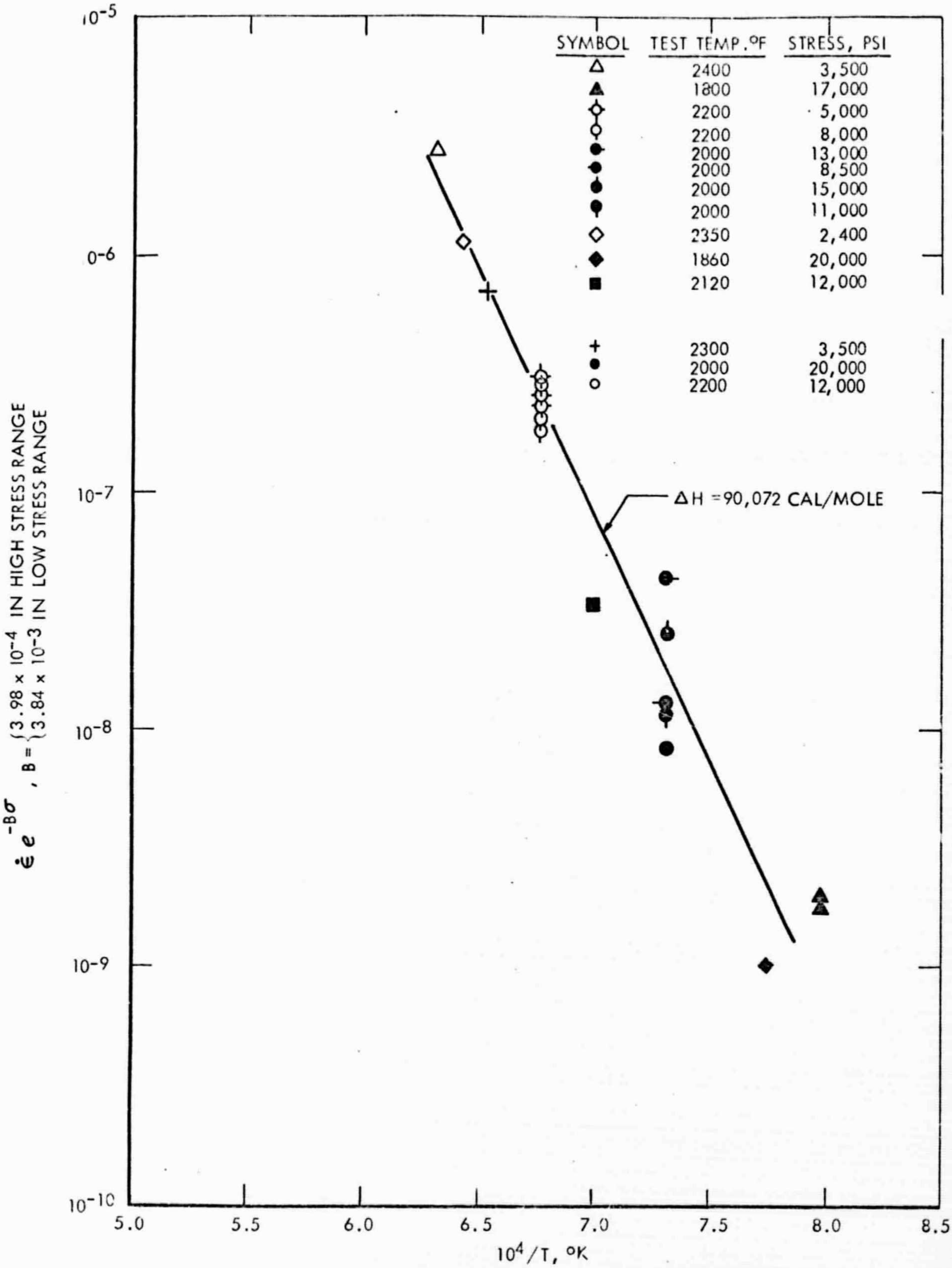


Figure 31. Arrhenius plot of stress compensated true strain rate in T-111 annealed 1 hour at 3000°F (1649°C), plotted using value of B obtained from Figure 30.

Above 2400 psi the values of the parameters in this equation are

$$A = 4.68 \times 10^{6}$$

$$B = 3.98 \times 10^{-4} \text{ psi}^{-1}$$

$$\Delta H = 90{,}000 \text{ cal/mole}$$

while below this stress they become

$$A = 3.31 \times 10^{12}$$

$$B = 3.84 \times 10^{-3} \text{ psi}^{-1}$$

$$\Delta H = 157{,}500 \text{ cal/mole}$$

for σ and T in units of psi and °K respectively.

The value of 90,000 cal/mole seems quite reasonable when compared with the figure of 110,000 cal/mole reported for high temperature self diffusion in pure tantalum and for tests conducted in the homologous temperature range of 0.38 to 0.49. On the other hand, the apparent activation energy for creep of 157,500 cal/mole in the low stress region seems unreasonably high and may reflect a lack of sufficient experimental data in this stress range. Results are available from 18 high stress tests, whereas the low stress analysis is based on only 3 data points, a small error in any one of which would cause a large variation is the best fit value of ΔH. Although ΔH is probably higher at the very low stresses a large degree of confidence cannot be placed on the specific value.

During the coming reporting period attempts will be made to correlate the constant A, sometimes called the "structure constant," with strain in the transient range of creep. This approach has met with limited success in the characterization of Al alloys (5) but suffers from the drawback that ΔH and B are not necessarily strain independent. Further difficulty may also occur because of the drastic change of shape of the log $\dot{\varepsilon}$ versus ε curves with temperature.

SUMMARY

1. Larson Miller correlation of TZC and TZM data show that at high temperatures and low stresses the creep resistance of these two materials is comparable in the stress relieved condition, but that in the low temperature and high stress range a special heat of TZM processed at higher than normal temperatures and having a higher than normal carbon content has better creep resistance than TZC.

2. Design data for pure tantalum in the temperature range of 1100 to 1350°F (593 to 735°C) are presented in the form of a Larson Miller plot for 1% creep.

3. Results of a sequential test program on T-111 have shown this technique to be useful for establishing a tentative Larson Miller relationship on an unknown material, provided each test sequence represents an increase over the previous test temperature.

4. A 1% creep Larson Miller design curve is presented for T-111 annealed 1 hour at 3000°F. The curve is based upon twenty separate tests covering the temperature range from 1800 to 2600°F (980 to 1427°C).

5. T-111 has been shown to creep according to the equation

   $$\dot{\varepsilon} = Ae^{B\sigma}e^{-\Delta H/RT}$$

   at temperatures from 1800 to 2600°F (980 to 1427°C) and stresses between 500 and 20,000 psi.

6. ASTAR 811C, a relatively new precipitation strengthened tantalum base alloy, appears on the basis of a single test to possess significantly better creep resistance than T-111 at 2600°F (1427°C).

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APPENDIX I

PREVIOUSLY PUBLISHED REPORTS ON THE REFRACTORY ALLOY CREEP PROGRAM

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J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Eighth Quarterly Report, Contract NAS 3-2545, CR-54457, July 7, 1965.

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J. C. Sawyer and K. D. Sheffler, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Mid-Contract Report, Contract NAS 3-9439, CR-72319, August 1967.

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APPENDIX II

Summary of Ultra-High Vacuum Creep Test Results Generated on the Refractory Alloy Creep Program

TABLE II-I

Summary of Arc-Melted W Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS N/m^2 $x10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1% CREEP LARSON-MILLER PARAMETER $T_{°R}(15 + \log t) x10^{-3}$
S-5	KC-1357	24	3200	1760	3.0	2.07	3200	1760	6	32	5.38	57.8
S-7	KC-1357	2	3200	1760	0.4	0.28	3200	1760	***	714	118	***
S-9	KC-1357	2	3200	1760	1.0	0.69	3200	1760	675	3886	2.760	65.4
S-17	KC-1357	2	2800	1538	4.0	2.80	2800	1538	20	218	5.452	53.1
S-18	KC-1357	2	2800	1538	3.0	2.07	2800	1538	125	908	5.535	55.8

*** Insufficient creep to extrapolate

TABLE II-2

Summary of Vapor-Deposited W Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1% CREEP LIFE HOURS	TERMINATION OF TEST		1% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	TEMPERATURE °C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t) \times 10^{-3}$
B-17	-	1	3200	1760	1.0	0.69	3200	1760	1140	2671	1.570	66.0
B-24	-	1	2800	1538	2.0	1.38	2800	1538	1500	6812	3.708	59.2

TABLE II-3

Summary of W-25%Re Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1% CREEP LIFE. HOURS	TERMINATION OF TEST		1% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	TEMPERATURE °C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t)\times 10^{-3}$
S-3	3.5-75002	48	3200	1760	5.0	3.44	3200	1760	12	45	6.03	58.9
S-4	3.5-75002	45	3200	1760	3.0	2.07	3200	1760	25	97	5.22	60.0
S-6	3.5-75002	1	3200	1760	0.5	0.34	3200	1760	***	253	0.090	***
S-8	3.5-75002	1	3200	1760	1.5	1.03	3200	1760	315	1306	5.113	64.0

*** Insufficient creep to extrapolate

TABLE II-4

Summary of Sylvania A Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS N/M^2 $\times 10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1% CREEP LARSON-MILLER PARAMETER $T_{^\circ R}(15 + \log t)\times 10^{-3}$
S-12	-	2	3200	1760	5.0	3.44	3200	1760	35	170	5.25	60.6
S-15	-	2	3200	1760	3.0	2.07	3200	1760	250	907	5.862	63.7

TABLE II-5

Summary of AS-30 Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1/2% CREEP LIFE HOURS	TERMINATION OF TEST		1/2%CREEP LARSON-MILLER PARAMETER $T_{^\circ R}(15 + \log t)\times 10^{-3}$
		TIME HOURS	TEMPERATURE °F	°C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	
B-2	C5	As-Rolled			12.0	8.27	2000	1093	390	806	1.020%	43.3
B-6	C5	As-Rolled			11.0	7.58	2000	1093	450	1192	1.016%	43.5
B-7	C5	As-Rolled			8.0	5.51	2200	1204	115	230	1.025%	45.4

TABLE II-6

Summary of Cb-132M Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1/2% CREEP LIFE HOURS	TERMINATION OF TEST		1/2% CREEP LARSON-MILLER PARAMETER $T_{°R}(15 + \log t) \times 10^{-3}$
		TIME HOURS	TEMPERATURE °F	°C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	
B-13	KC-1454	1	3092	1700	20.0	13.80	2056	1125	275	568	1.170	43.8
B-14	KC-1454	1	3092	1700	16.3	8.23	2056	1125	340	691	1.026	44.0
B-15	KC-1454	1	3092	1700	7.4	5.10	2256	1236	250	596	1.100	47.2

TABLE II-7

Summary of TZM Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS N/M^2 $\times 10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1/2% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1/2% CREEP LARSON-MILLER PARAMETER $T_{°R}(15 + \log t)\times 10^{-3}$
B-1	7502	1	2200	1204	12.6	8.65	2130	1165	605	646	1.105	46.1
B-3	7502	1	2200	1204	10.0	6.89	2000	1095	14,200*	10,048	0.375	47.1
B-29	7502	1	2200	1204	41.0	28.20	2000	1095	100	664	6.215	41.8
B-35	7502	1	2200	1204	44.0	30.30	1800	982	7000	7659	0.535	42.6
B-4	7502	1	2200	1204	10.0	6.89	2000	1095	25,000*	10,012	0.368	47.7
	Plus	1	2850	1566								
B-16	KDTZM-1175	1	2300	1260	23.4	16.10	1855	1013	62,500*	4376	0.035	45.8
B-18	KDTZM-1175	1	2300	1260	55.0	37.90	1600	871	60,000*	2159	0.018	40.7
B-21	KDTZM-1175	1	2300	1260	65.0	44.80	1600	871	9600*	1630	0.085	39.1
B-25	KDTZM-1175	1	2300	1260	44.0	30.30	1800	982	50,000*	10,152	0.182	44.5
B-38	KDTZM-1175	1	2300	1260	22.0	15.10	2000	1093	8500*	**	**	46.5
B-34	7463	1/2	2250	1232	41.0	28.20	2000	1093	790	1440	1.658	44.0

* Extrapolated data

** Test in progress

TABLE II-8

Summary of Cb Modified TZM Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1/2% CREEP LIFE HOURS	TERMINATION OF TEST		1/2% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	°C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t)\times 10^{-3}$
B-23A	4305-4	1	2500	1371	20.0	13.80	2000	1093	20,000*	686	0.032	47.5
B-23B	4305-4	-	-	-	28.0	19.30	2000	1093	10,000*	307	0.028	46.7
B-23C	4305-4	-	-	-	40.0	27.60	2000	1093	630*	185	0.188	43.8
B-23D	4305-4	-	-	-	46.0	31.70	1800	982	4000*	403	0.078	42.0
B-23E	4305-4	-	-	-	34.0	23.40	2100	1149	1000*	329	0.170	46.1
B-27	4305-4	1	2500	1371	41.0	28.20	2000	1093	1090	1584	1.040	44.5

* Extrapolated

TABLE 11-9

Summary of TZC Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1/2% CREEP LIFE HOURS	TERMINATION OF TEST		1/2% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	°C	KSI	$N/M^2 \times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t)\times 10^{-3}$
B-8A	M-80	1	3092	1700	18.0	12.40	2200	1204	1100	2128	1.060	48.3
B-10	M-80	1	3092	1700	17.0	11.70	2200	1204	2500	2749	0.545	48.9
B-9	M-80	1	3092	1700	20.0	13.80	2000	1093	10,408	16,002	0.670	46.8
B-11	M-80	1	3092	1700	25.0	17.20	1856	1013	75,000*	14,406	0.182	46.0
B-12	M-80	1	3092	1700	19.0	13.10	2056	1125	75,000*	14,239	0.280	49.2
B-20	M-91	1	3092	1700	20,0	13,80	2000	1093	3650	12,795	1.008	45.7
B-31	M-91	1	3092	1700	14.0	9.65	2200	1204	329	912	1.092	46.6
B-19	M-91	1	2300	1260	44.0	30.30	1800	982	1075	4604	1.015	41.1
B-28	M-91	1	2300	1260	28.0	19.30	2000	1093	1100	4214	1.138	44.4
B-30	M-91	1	2500	1371	22.0	15.20	2200	1204	70	259	1.280	44.8
B-32	M-91	1	2500	1371	20.0	13.80	1935	1057	14,400	16,130	0.535	45.9
B-33	M-91	1	2500	1371	22.0	15.20	1900	1038	7720	9697	0.585	44.6
B-36	4345	1	2500	1371	22.0	15.20	2000	1093	5940	8563	0.640	46.2
B-37	4345	1	2400	1316	22.0	15.20	2000	1093	8000*	**	**	46.3

* Extrapolated

** Test in progress

TABLE II-10

Summary of T-222 Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1% CREEP LIFE HOURS	TERMINATION OF TEST		1% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	TEMPERATURE °C	KSI	N/M^2 $\times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t)\times 10^{-3}$
S-13	AL-TA-43	1	3000	1649	12.0	8.27	2200	1204	560	1890	5.720	47.2
S-14	AL-TA-43	1	3000	1649	19.2	13.20	2056	1124	890	1314	1.685	45.1
S-20	AL-TA-43	1	2800	1538	12.0	18.27	2200	1204	405	1389	5.060	46.9

TABLE II-11

Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT			STRESS		TEST TEMPERATURE		1% CREEP LIFE HOURS	TERMINATION OF TEST		1% CREEP LARSON-MILLER PARAMETER
		TIME HOURS	TEMPERATURE °F	°C	KSI	$N/M^2 \times 10^{-7}$	°F	°C		TIME, HOURS	PERCENT CREEP	$T_{°R}(15 + \log t) \times 10^{-3}$
S-29	NASV-20-WS	1/2	3600	1982	2.0	1.38	2600	1427	24,000*	**	**	59.3

* Extrapolated
** Test in progress

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS $N/M^2 \times 10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1% CREEP LARSON-MILLER PARAMETER $T_{°R}(15 + \log t) \times 10^{-3}$
S-16	70616	1	2600	1427	8.0	5.51	2200	1204	725	1675	2.570	47.5
S-19	70616	1	3000	1649	8.0	5.51	2200	1204	2000	4870	3.368	48.7
S-21	70616	1	3000	1649	12.0	8.26	2200	1204	1140	3840	6.548	48.0
S-23	70616	1	3000	1649	12.0	8.26	2120	1160	3150	3698	1.225	47.7
S-22	70616	1	3000	1649	20.0	13.80	2000	1093	670	1099	2.010	43.8
S-24	70616	1	3000	1649	20.0	13.80	1860	1016	4730	4946	1.090	43.3
S-25	D-1670	1	3000	1649	15.0	10.30	2000	1093	1340	1584	1.210	44.6
S-26	D-1670	1	3000	1649	17.0	11.70	1800	982	9540	9624	1.030	42.9
S-25A	D-1670	1	3000	1649	1.5	1.03	2600	1427	1100*	482	0.632	55.2
S-28	D-1670	1	3000	1649	0.5	0.34	2600	1427	55,000*	**	**	60.0
S-27	D-1102	1	3000	1649	13.0	8.95	2000	1093	1880	3459	2.082	45.0
S-32	D-1102	1	3000	1649	5.0	3.44	2200	1204	4050	4322	1.042	49.5
S-40	D-1102	1	2000	1649	17.0	11.70	1800	982	9015*	**	1.028	42.8
S-33	65076	1	3000	1649	8.0	5.51	2200	1204	2850	2976	1.048	49.1
S-34	65076	1	3000	1649	11.0	7.58	2000	1093	10,750*	**	**	46.9

* Extrapolated
** Test in progress

TABLE II-12 (Continued)

Summary of T-111 Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS N/M^2 $x10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1% CREEP LARSON-MILLER PARAMETER $T_{°R}(15 + \log t)x10^{-3}$
S-37	65080	1	3000	1649	8.0	5.51	2200	1204	260	274	1.230	46.3
S-39	65080	1	3000	1649	13.0	8.95	1800	982	8345*	**	**	42.7
S-45	65080A	1	3000	1649	3.0	2.07	2200	1204	554	697	1.070	47.1
S-30	65079	1	3000	1649	3.5	2.41	2400	1316	860	2137	1.165	51.3
S-31	65079	1	3000	1649	5.0	3.44	2200	1204	6160	6594	2.372	50.0
S-35	65079	1	3000	1649	5.0	3.44	2200	1204	5400	5522	1.092	49.9
S-42	65079	1	3000	1649	3.5	2.41	2300	1263	3810	4247	1.048	51.3
S-47	65079	1	3000	1649	24.0	16.50	1750	954	38,000*	**	**	43.3
S-48	65079	1	3000	1649	2.4	1.65	2330	1275	7270*	**	**	53.0
S-50	65079	1	3000	1649	8.5	7.22	2000	1093	24,000*	**	**	47.7
S-43	65079	1/4	3000	1649	18.0	12.40	2000	1093	1500 *	361	0.108	44.7
S-44A	65079	1	3000	1649	9.5	6.55	2172	1189	3250*	467	0.152	48.7
S-44B	65079	1/4	3000	1649	3.3	2.27	2371	1299	2030*	335	0.168	51.9
S-44C	65079	1/4	3000	1649	18.0	12.40	2000	1093	1670*	1146	0.688	44.8
S-44D	65079	1/4	3000	1649	23.0	15.80	1800	982	14,650*	1391	0.112	43.3

* Extrapolated
** Test in progress

TABLE II-13

Summary of T-111 Progressive Stress Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS N/M^2 x10^{-7}	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP
S-36	65080	1	3000	1649	16		2200	1204	600	624	1.120
S-38	65080	1	3000	1649	1		2200	1204	3830	4686	1.562
S-46	65079	1	3000	1649	16		2200	1204	1000*	761	0.225
S-49	65079	1	3000	1649	20		1800	982	1660	1964	5.125
S-51	D-1183	1	3000	1649	16		2200	1204	1080	1274	5.823
S-52	65079	1	3000	1649	13		2000	1093	1700*	1657	1.150
S-53	65079	1	3000	1649	5		2200	1204	2000*	**	**
S-54	65079	1	3000	1649	5		2200	1204	4000*	**	**

* Extrapolated
** Test in progress

TABLE II-14

Summary of Pure Ta Ultra-High Vacuum Creep Test Results

TEST NO.	HEAT NO.	HEAT TREATMENT TIME HOURS	HEAT TREATMENT TEMPERATURE °F	HEAT TREATMENT TEMPERATURE °C	STRESS KSI	STRESS $N/M^2 \times 10^{-7}$	TEST TEMPERATURE °F	TEST TEMPERATURE °C	1% CREEP LIFE HOURS	TERMINATION OF TEST TIME, HOURS	TERMINATION OF TEST PERCENT CREEP	1% CREEP LARSON-MILLER PARAMETER $T_{\circ R}(15 + \log t)\times 10^{-3}$
B-39A	-	1	1832	1000	13.6	9.37	1100	596	31	32	1.020	25.8
B-39B	-	1/4	1832	1000	11.6	7.99	1100	596	603*	264	0.542	27.8
B-39C	-	1/4	1832	1000	10.1	6.95	1183	639	463*	282	0.635	29.0
B-40A	-	1	1832	1000	7.0	4.83	1350	720	9	9	1.000	28.9
B-40B	-	1/4	1832	1000	4.9	3.38	1350	720	6600*	1386	0.300	34.0
B-41	-	1	1832	1000	11.1	7.65	1100	596	144	160	1.078	26.7
B-42A	-	1	1832	1000	4.0	2.75	1350	720	170	186	1.015	31.2
B-42B	-	1/4	1832	1000	4.0	2.75	1350	720	1900*	**	**	33.1

* Extrapolated
** Test in progress