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

TWENTY-FIRST QUARTERLY REPORT

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

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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. A listing of all reports presented to date on this program is included in Appendix I.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager; K. D. Sheffler is the Principal Investigator with R. R. Ebert contributing to the program. The NASA Technical Manager is Paul E. Moorhead.

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ABSTRACT

Creep test results obtained during the twenty-eight through the thirtieth months of the refractory alloy creep program, Contract NAS 3-9439, are reported for the molybdenum base alloy TZM, pure tantalum, and the tantalum base alloys T-111 and ASTAR 811C. A study of the creep behavior of a cold-formed pure tantalum manifold in the SNAP 8 Hg-NaK boiler has been undertaken during the current report period. The study is divided into three phases, with the first phase involving characterization of the amount of cold work at various locations in the header. The second phase will be to creep test cold worked pure tantalum and the third phase will be a study of the influence of welding on creep behavior of the cold worked structure. Results of the first phase indicate that the header material undergoes a strain of approximately 40%. Creep tests will be conducted on material which has been prestrained in tension by approximately this amount.

SUMMARY

This report contains results generated during the twenty-eight through the thirtieth months of the refractory alloy creep program. The purpose of this program is to generate design creep data for refractory alloys tested in ultrahigh vacuum. In addition to generating this type of data on the alloys TZM, T-111, ASTAR 811C and pure tantalum, the following observations have been made concerning the creep behavior of each of these materials.

TZM

Both composition and processing have been shown to influence the creep strength of the molybdenum base alloy TZM. A specially processed disc having a higher than normal carbon content and forged at higher than normal temperatures was found to be significantly stronger than a conventionally forged TZM disc.

Pure Tantalum

An analysis of total effective strain introduced during cold forming of a pure tantalum manifold for the SNAP 8 Hg-NaK boiler has been performed. The results indicate that the strain is between 35 and 45% in the critical stress areas of the header.

Accelerated creep in the heat affected zone of a bead-on-plate TIG weld in pure tantalum has been shown to be asosciated with grain growth which occurs in this region as a result of the welding operation.

ASTAR 811C

Creep tests of a commercial heat of ASTAR 811C continue to show creep strengths superior to those found in laboratory heats.

T-111 Alloy

A program which was initiated during the last report period to study the creep behavior of T-111 alloy in the 1300 to 1100°F (704 to 593°C) range has been continued during the current report period. This material exhibits almost 3% primary creep at 1100°F (593°C) and 45 ksi (310 MN/M^2) during the first 24 hours of testing.

Radioisotope Capsule Design

An analytical study of the variable-stress, variable-temperature creep behavior of a Type 316 stainless steel has been extended during the current report period to the nickel-base superalloy Inconel 718. The expressions employed are currently being successfully applied in a computer program at the NASA Lewis Research Center to calculate capsule weights and dimensions.

INTRODUCTION

The application of refractory alloys in space power systems has created a need for design creep data on these materials in the 1600 to 2600°F (871 to 1427°C) range. The present program was undertaken to generate the required data. The specific materials currently under test are the molybdenum alloy TZM, pure tantalum and the tantalum base alloys T-111 and ASTAR 811C. Because of the well known sensitivity of refractory alloys to interstitial contamination, the creep tests on these alloys are being conducted in a vacuum environment of less than 1×10^{-8} torr.

The application of radioisotope capsule power sources in space power systems has provided an unusual design problem which is caused by the fact that some of the isotopes under consideration generate gaseous decay products. If the capsule is not vented, the interior is subjected to continuously increasing gas pressure after the shell is sealed. The capsule is also subjected simultaneously to a continuously decreasing temperature because of isotope decay. This problem is being studied both analytically and experimentally in T-111 alloy. The purpose of the analytical study is to develop a method for predicting the variable stress-variable temperature creep behavior of T-111 alloy from isostatic-isothermal data. The purpose of the experimental program is to develop data for testing of the analytical predictions. The first phase of this program, which was a study of variable stress, constant stress with continuously varying temperature is currently in progress, and variable stress, variable temperature tests are planned.

EXPERIMENTAL PROCEDURE

MATERIALS

Processing details and sources of each of the test materials have been summarized previously (2). Chemical analyses of each heat of test material are shown in Table 1.

Only one specimen of TZM alloy is currently on test. This specimen was taken from a specially fabricated, stress-relieved disc of TZM alloy (Heat KDTZM-1175) which had a higher than normal carbon content and which was forged at very high temperatures 3400°F (1871°C) in order to provide an improved carbide dispersion (3).

The pure tantalum is being tested in three forms. The first is 3/4" O.D. x 0.040" wall tubing, while the second and third form are respectively 0.162" and 2.5" plate. The remainder of the tantalum alloys are being evaluated predominately in the form of nominal 0.030" sheet. A few selected tests are also being conducted on T-111 alloy in the form of strip or plate. All of the tantalum materials are being evaluated in the fully recrystallized condition.

TEST PROCEDURES

The experimental program is devoted to the generation of design data by creep testing sheet and bar specimens at temperatures and stresses which will provide one half to one percent total creep in 5000 to 25,000 hours. Two inch gauge length, button-head bar-type specimens and double shoulder, pin loaded, sheet type specimens are used for testing of plate and sheet type materials. The orientation of the specimen with respect to the working direction is given below:

Material Form	Specimen Axis Parallel to
Disc forging	Radius
Plate	Extruding or rolling direction
Sheet	Rolling direction (except where indicated)
Tubing	Tube Axis

The tubing was stressed parallel to the tube axis, with two flats being ground opposite one another to provide two webs in the gauge section.

TABLE 1

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

Material	W	Re	Mo	Ta	Hf	C	Ti	Zr	PPM N_2	PPM O_2	PPM H_2	Finished Form
TZM (Heat KDTZM-1175)			Bal.			.0350	.61	.120	43	34	9	Forged disc
T-111 (Heat 70616)	8.5			Bal.	2.3	.0044			20	55	6	Nominal 0.030"sheet
(Heat 65079)	8.7			Bal.	2.3	.0030			50	130	4	" "
(Heat 65076)	8.6			Bal.	2.0	.0040			20	100	3	" "
(Heat D-1102)	7.9			Bal.	2.3	.0030			34	20	3	" "
(Heat D-1670)	7.9			Bal.	2.4	<.0010			20	72	<5	" "
(Heat D-1183)	8.7			Bal.	2.2	.0036			10	25	6	" "
(Heat 650028)	8.3			Bal.	2.1	.0030			12	30	1.9	" "
(Heat 848001)	7.9			Bal.	2.0	.0010			13	21	1	" "
(Heat 650038)	8.6			Bal.	2.0	.0025			20	100	2.8	Nominal 0.600"plate
(Heat 8048)	7.6			Bal.	1.9	.0037			24	34	1.6	Nominal 0.165"strip
ASTAR 811C												
(Heat NASV-20-WS)	7.3	1.0		Bal.	0.86	.0240			20	14		Nominal 0.030"sheet
(Heat VAM-95)	7.6	1.1		Bal.	0.65	.0300			3	4	0.3	" "
(Heat 650056)	8.2	1.2		Bal.	0.9	.0200			14	30	3.5	" "
Ta-10W(Heat 630002)	9.9			Bal.		.0044			25	100	5	Nominal 0.030"sheet
Pure Tantalum												
(Heat B-1962)				Bal.		.0012			21	20	5	Tubing
(Heat 60249)				Bal.		.0014			20	22	3	"
(Heat 60065)				Bal.		.0015			19	12	5	"
(Heat 60379)				Bal.		.0019			22	15	4	"

Both the construction and operation of the test chambers and the service instruments in the laboratory have been described in detail in previous reports (Appendix I). The 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, and complete thermal equilibrium of the specimen is insured by a two-hour hold at the test temperature prior to load application. The pressure is always below 1×10^{-8} torr during the tests and generally falls into the 10^{-10} range as testing proceeds. Specimen extension is determined over a two inch gauge 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 each test using a W-3%Re - W25%Re thermocouple. Since thermocouples of all types are subject to a time-dependent change in EMF output under isothermal conditions, the absolute temperature during test is maintained by an optical pyrometer. In practice the specimen is brought to the desired test temperature using a calibrated thermocouple attached to the specimen as a temperature standard. The use of this thermocouple is continued during the temperature stabilization period which lasts 50 to 100 hours. At this time, a new reference is established using an optical pyrometer having the ability to detect a temperature difference of ± 1F°, and this reference is used subsequently as the primary temperature standard.

RESULTS AND DISCUSSION

Creep curves for each test which was in progress during the current reporting period are presented in Appendix III, while Appendix II contains a complete summary of all of the creep data generated to date on the refractory alloy creep program.

MOLYBDENUM BASE ALLOY TZM

Only one TZM alloy test was in progress during the current reporting period on a specially processed lot of TZM which had a higher than normal carbon content and was forged in the 3400°F (1871°C) range to produce an improved carbide dispersion. This test at 2000°F (1093°C) and 22 ksi (15.1 x 10^7 N/m^2) reached 1/2% creep at 16,293 hours, which is significantly longer than anticipated for conventional TZM. While a TZM test would normally be discontinued at 1/2% strain, this test is being continued beyond that point to check for possible creep rate instabilities at higher strain levels.

TANTALUM BASE ALLOYS

One percent creep life results for pure tantalum and the tantalum base alloys T-111, Ta-10W and ASTAR 811C are displayed on a Larson-Miller plot in Figure 1 together with data from the literature on ASTAR 811C (4). A discussion of these results for each test material follows.

PURE TANTALUM

The primary application toward which current pure tantalum testing is directed is a SNAP 8 tube-in-tube Hg-NaK heat exchanger assembly described recently by Gertsma and Medwid (5). Most of the effort to data has been concentrated on the pure tantalum tubing which forms the inner element of the boiler. Test results were reported in the last quarterly report for several unwelded specimens and for one tube containing a transverse bead-on-plate TIG weld. These results showed that the creep strength of the welded tube was comparable to the creep strength of unwelded tubing, despite the appearance of significantly accelerated creep in the heat affected zone (Figure 2). Although metallographic analyses were not available at the time, it was postulated that the accelerated creep resulted from grain growth in this region. During the current report period photographic evidence has been obtained to support this hypothesis. The specimen surface shows a heavy orange-peel effect adjacent to the weld bead after testing (Figure 2), and a photomacrograph of the specimen cross-section shows the source of this effect is indeed a large grain size in the heat affected zone. Photomicrographs of the weld bead, the heat affected zone and the base metal (Figure 3) indicate the grain growth which occurred near the weld.

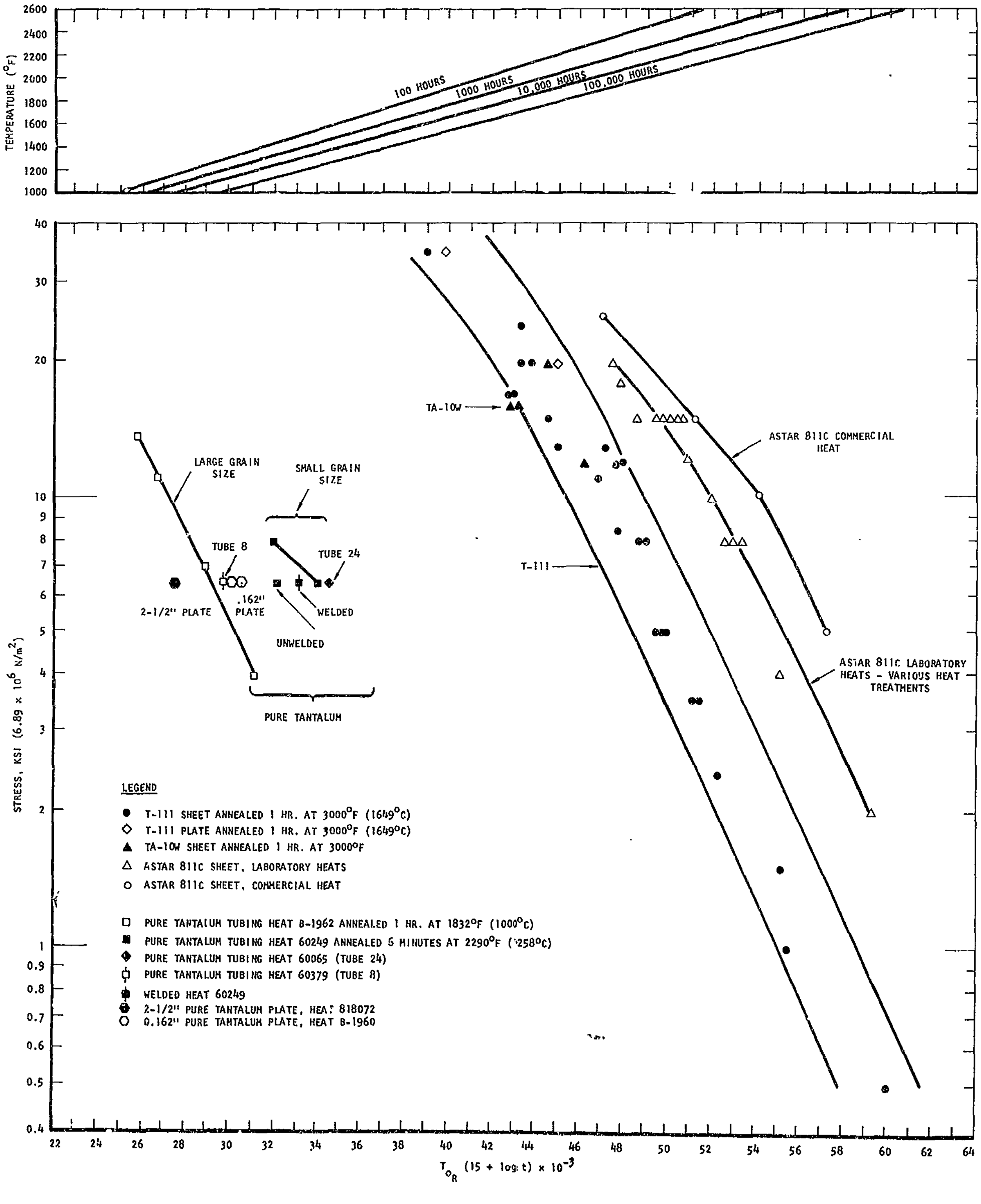

Figure 1. Larson-Miller plot of 1 percent creep life data for tantalum-base alloys creep tested in a vacuum of <1 x 10^{-8} torr.

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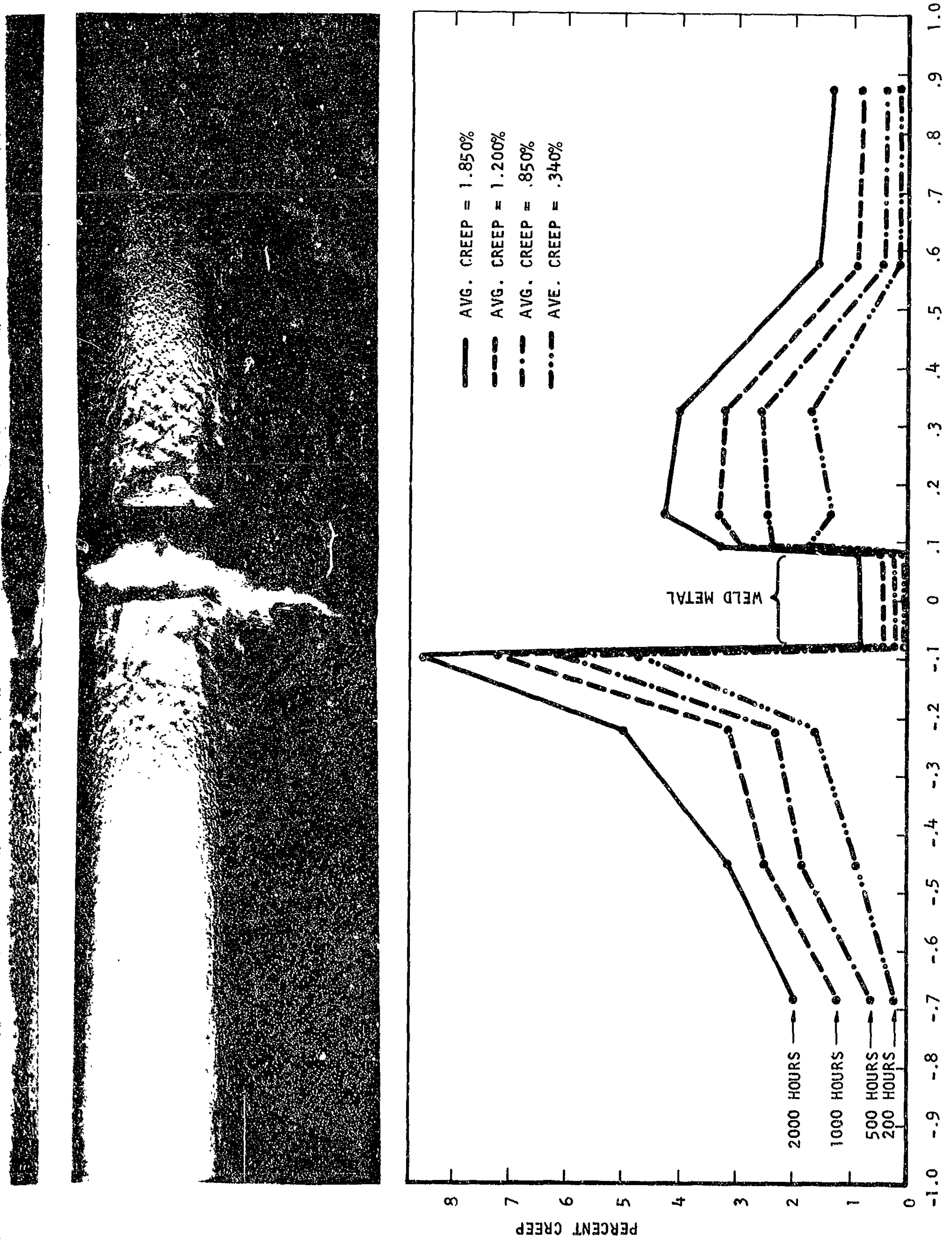
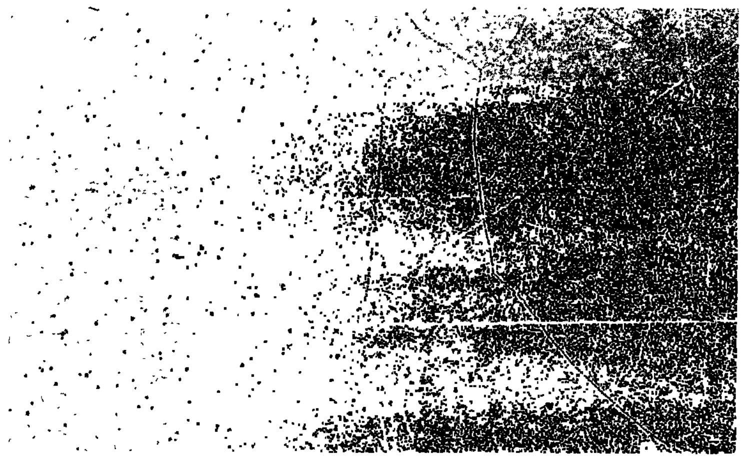
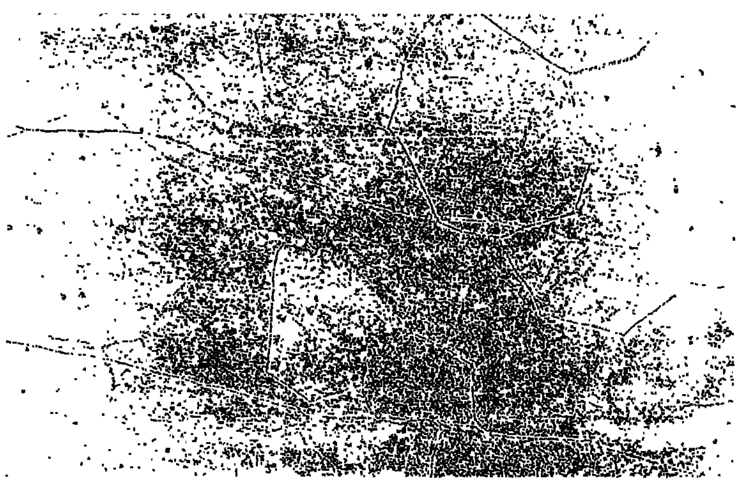


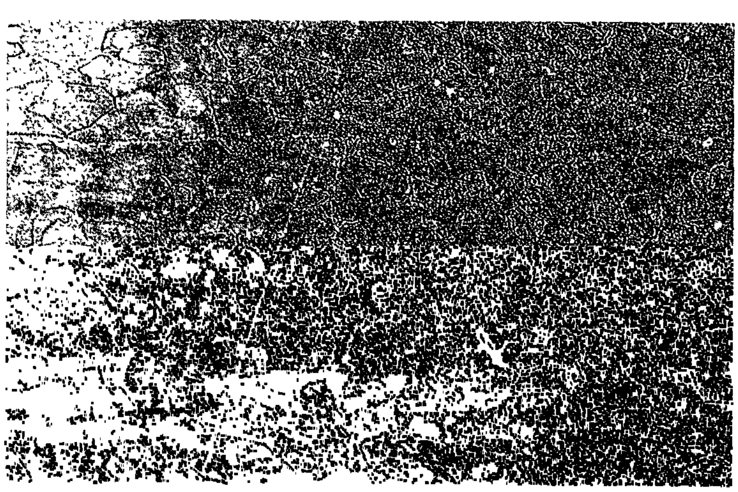
Figure 2. Creep behavior of welded pure tantalum tubing.



(a) Weld Bead



(b) Heat Affected Zone



(c) Base Metal

Figure 3. Microstructures of welded pure tantalum creep specimen. 100X

As indicated above, the creep behavior of the welded tube appeared comparable to unwelded material, despite the significantly accelerated creep in the heat affected zone. Two reasons may account for this effect. First, essentially no creep occurred in the weld bead, which is considerably thicker than the base tube wall. This reduces somewhat the overall specimen extension compared with an unwelded tube. Second, while the creep rate is significantly higher in the heat affected zone, the length of this zone is small enough so that the cumulative extension is not large compared to the total extension over the full 2-inch gauge length. However, in spite of this apparently high weld efficiency, a potential problem exists for longer test times in the form of a slight neck which can be seen developing on the left side of the weld bead in Figure 2. Because of this necking it would appear that the effect of welding on creep could still cause difficulty in a welded assembly. For this reason the entire problem of welding as a potential design limitation is still under review.

The more recent tests on pure tantalum have been directed toward characterization of the creep behavior of the manifolds which distribute and collect fluid flow at each end of the boiler. A photograph of a section of such a manifold is shown in Figure 4. While prototype headers were made by cold drawing, recent consideration has been given to the possible use of a machined part. Since the 2-1/2" thick plate from which the header would be machined has undergone a relatively small amount of work, its grain size is larger than any of the pure tantalum material tested to date, as indicated in Table 2. Based on the trend toward lower creep strength with increasing grain size in pure tantalum, discussed in the last quarterly report, it was anticipated that the creep strength of the plate might be below that of the earlier test material. The data in Table 2 and Figure 1 confirm this prediction, with the large grain size plate having a 1% creep life of only 1.7 hours at 1350°F (732°C) and 6500 psi (4.48×10^7 N/m^2), as compared with an extrapolated 1% creep life of 17,000 hours for the finest grained material tested at these conditions (Tube 24). Additional review should be given to the application of this material in place of the present cold formed header to determine if this reduced creep strength would be adequate.

Presuming that cold drawing continues to be used as a forming method for the tantalum header, it is necessary to develop a technique to measure creep resistance in the critical areas of the manifold. Because direct creep testing of the header itself would be quite difficult, the approach will be to calculate the total cold strain in the important areas of the manifold, and to duplicate this strain as closely as possible using uniaxial tensile deformation.

TABLE 2

Comparison of 1% Creep Life with Grain Size in Pure Tantalum Creep Tested at 1350°F (732°C) and 6500 psi ($4.47 \times 10^7 N/m^2$)

Test No.	Heat No.	Grain Size mm	1% Creep Life Hours
B-52	60065 (Tube No. 24)	.038	15,000*
B-51	60379 (Tube No. 8)	.067	26
P-2	818072 (2-1/2" plate)	.145	1.7

* Extrapolated

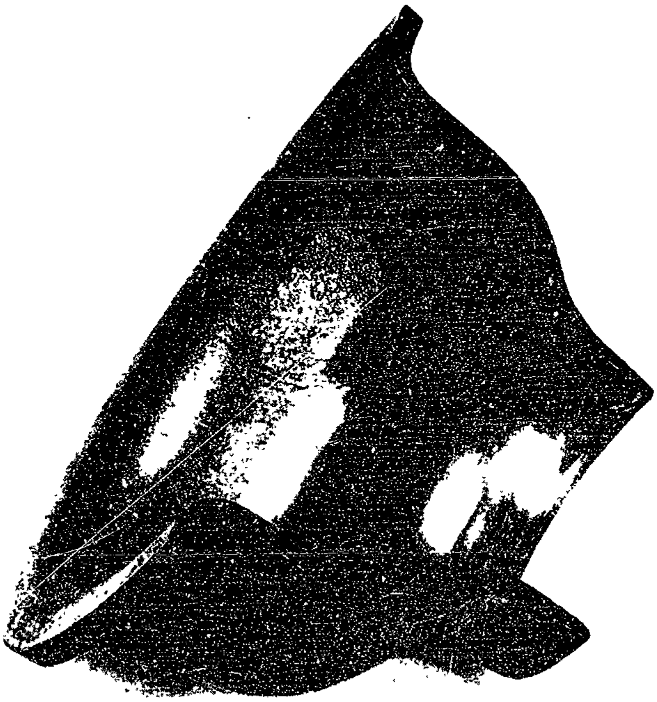


Figure 4. Photograph of pure tantalum manifold.

In any drawing operation, the calculation of strain requires consideration of three strain components, as illustrated in Figure 5. The first of these strain components is compressive (Figure 5a), and is introduced into only those regions of the drawn part which are outside of the die radius in the original blank. This strain is given by the equation

$$\varepsilon_c = \ln r_i/r_o \qquad \text{Equation 1}$$

where r_i is the radius of the die and r_o is the original distance of the segment from the die center.

The second strain component is the thinning which results from stretching of the cup walls during the draw operation (Figure 5b). This strain can be calculated using the formula:

$$\varepsilon_t = \ln t/t_o \qquad \text{Equation 2}$$

where t_o and t are the original and final thicknesses of the plate respectively.

The third strain component results from bending of the plate (Figure 5c). This strain is tensile on the outside and compressive on the inside of the bend, and is non-existent on the neutral axis of the bend. This strain can be approximated by the equation

$$\varepsilon_B = \ln(1 + h^2/a^2) \qquad \text{Equation 3}$$

where h and a are defined in Figure 5c. Forming of the actual part is a two stage process, as illustrated in Figure 6. In order to calculate the effective strain at various points in this piece, a prototype header was sectioned and the thickness was measured at 0.1 inch intervals from the top to the bottom (Table 3). These data are plotted in Figure 7, which shows significant thinning in the wall and small diameter coupling areas and significant thickening in the undrawn flange.

An elemental stress analysis of the manifold at typical operating conditions had indicated that the areas of maximum stress coincide with the regions of maximum thinning shown in Figure 7 (6). The analytical study of forming strain was therefore concentrated in these areas. Calculation of the total strain in the small diameter coupling area is relatively straight forward. It will be assumed that no strain existed in this region of the cup after the end of the first drawn operation and therefore, that all of the strain was introduced by the second punching operation. Since there is relatively little curvature at the thinnest point of the coupling the strain is almost exclusively thinning and can be calculated using equation (2):

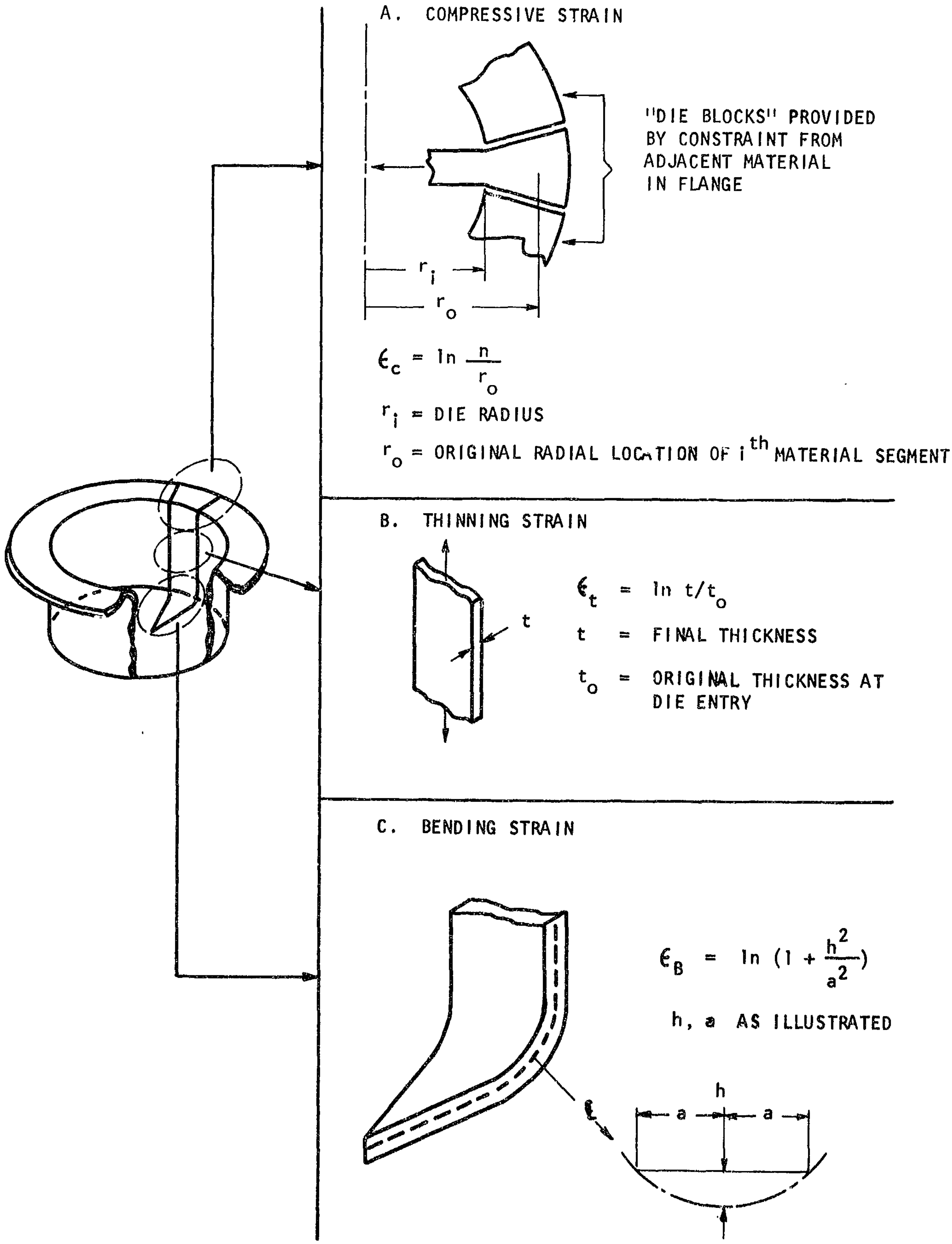


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Figure 5. Schematic illustration of strain components in cold drawn tantalum manifold.

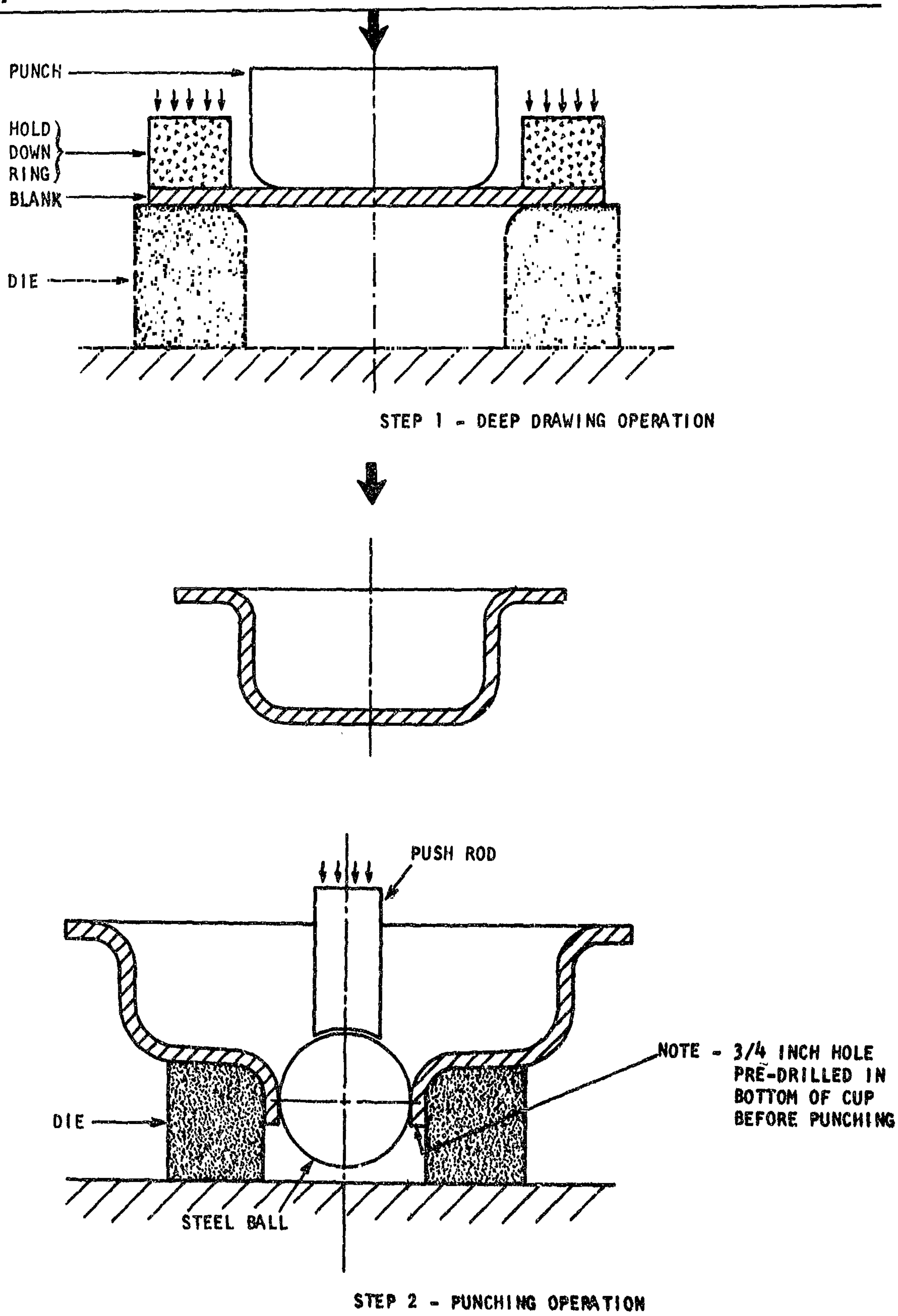

Figure 6. Schematic illustration of pure tantalum manifold forming procedures.

TABLE 3

Thickness of Pure Tantalum Manifold as a Function of Distance from the Small Diameter Opening

Distance from Small Diameter Opening, Inches	Thickness Inches
.1	.1137
.2	.1203
.3	.1285
.4	.1349
.5	.1456
.6	.1519
.7	.1548
.8	.1564
.9	.1550
1.0	.1596
1.1	.1611
1.2	.1582
1.3	.1551
1.4	.1538
1.5	.1529
1.6	.1520
1.7	.1513
1.8	.1485
1.9	.1472
2.0	.1471
2.1	.1449
2.2	.1400
2.3	.1359
2.4	.1376
2.5	.1447
2.6	.1543
2.7	.1626
2.8	.1666
2.9	.1753
3.0	.1789
3.1	.1790

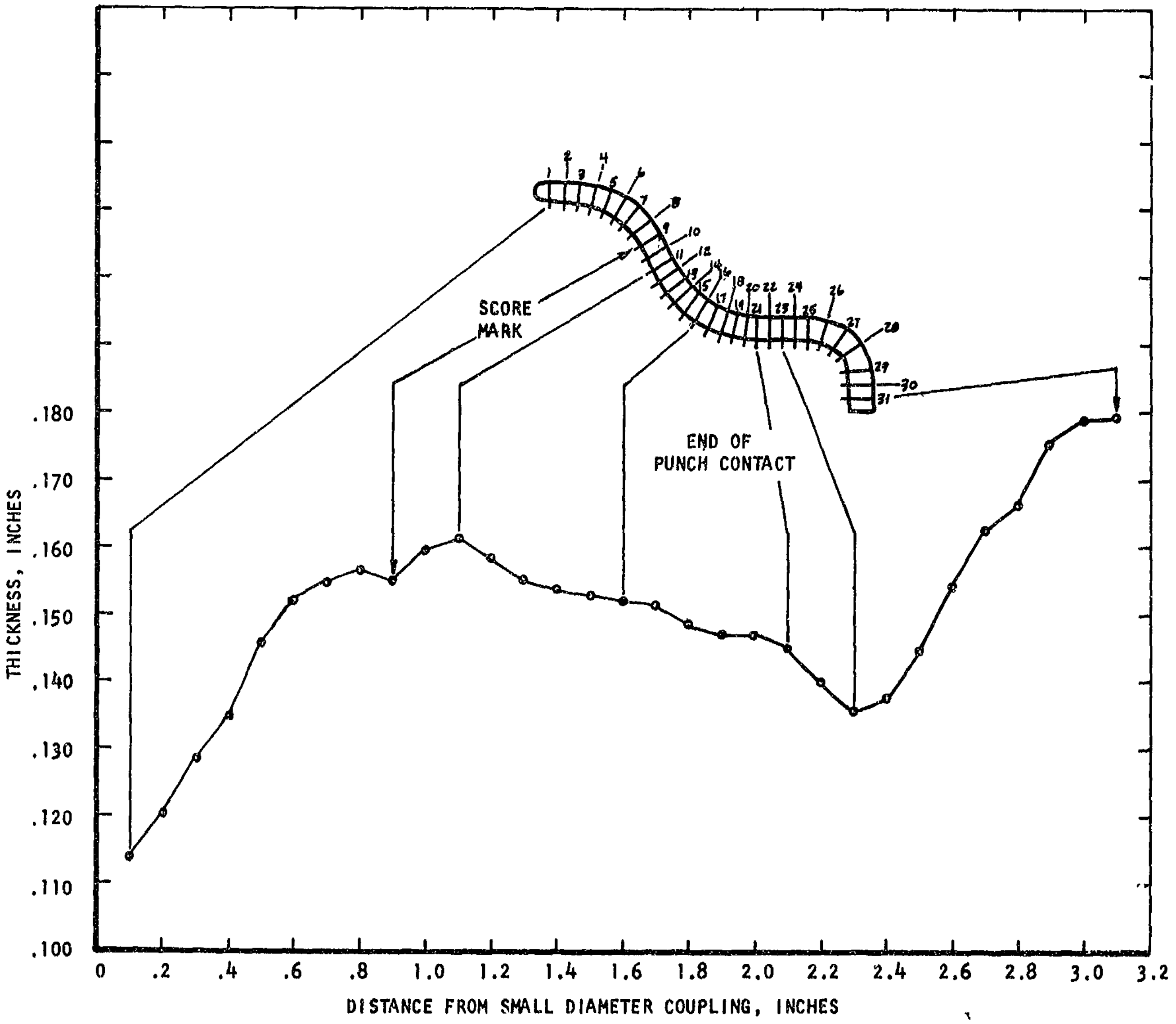

Figure 7. Average of three readings taken at 90° intervals around pure tantalum manifold.

$$\varepsilon_t = \ln t/t_o$$

$$\varepsilon_t = \ln .1137/.161$$

$$\varepsilon_t = -.348$$

Thus, the material in this area of the header has been stretched approximately 35% at the thinnest point.

Calculation of total effective strain in the straight-walled region of the dome is considerably more complicated, because both compression and thinning are involved and the original radial location of the material in this area must be known. This information will be obtained by assuming that all of the thinning which occurred resulted from tensile stretching in the radial direction. In order for this assumption to be reasonable it is necessary to use an original thickness equal to the thickness of the plate just before it entered the die, rather than using the thickness of the as-received plate. The material adjacent to the die at the start of the first draw will of course be equal to the as-received thickness of 0.161 inch. At the end of the draw operation; however, this dimension has increased to approximately 0.179 inch, as indicated in Table 3. In calculating the original thicknesses shown in Table 4, it has been assumed that the thickness at the time of die entry varies linearly with distance between these two locations.

By assuming constant volume of the material during drawing, the original length of each of the 0.1 inch increments can be shown to be equal to the ratio of the final to the initial thickness, assuming all of the stretching occurs in the radial direction. (This calculation also assumes that all of the original thickening resulted from compression in the tangential direction, with no stretching in the radial direction before the material entered the die.) Using this fact, the original radial length of each of the 0.1 inch segments has been tabulated in Table 4, together with the incremental sums of these values, which should be the original radial location of each of the segments. As a check on this development, the calculated original radius of 3.659 inches compares reasonably well with the measured original blank radius of 3-1/2 inches.

From Table 4, the location of the end of the 0.1 inch increment centered on the thinnest portion of the straight wall is 2.914 inches. If one half of the original increment length of 0.0817 inch is subtracted from this value the original location of the center of this increment is found to be 2.873 inches. The die diameter is 2.23 inches (as measured from the O.D. of the formed header) which means that the compressive strain introduced into this piece before passing through the die is

$$\varepsilon_c = \ln 2.23/2.87 = \ln(.777) = -0.252$$

or approximately 25%.

TABLE 4

Calculations of Original Tantalum Plate Dimensions Before Forming of Manifold

Distance From Small Diameter Opening, Inches	Measured Thickness t, Inches	Calculated Thickness at Die Entry t_o, Inches	t/t_o	Original Length of 1/10 Inch Segment Inches	Original Radial Location, Inches
1.1	.1611	*	1.0	.1000	1.81**
1.2	.1582	*	.984	.0984	1.908
1.3	.1551	*	.963	.0963	2.005
1.4	.1538	*	.955	.0955	2.106
1.5	.1529	*	.949	.0949	2.195
1.6	.1520	*	.944	.0944	2.289
1.7	.1513	*	.939	.0939	2.383
1.8	.1485	*	.922	.0912	2.476
1.9	.1472	*	.914	.0914	2.567
2.0	.1471	*	.913	.0913	2.658
2.1	.1449	.1628	.890	.0890	2.747
2.2	.1400	.1646	.852	.0852	2.832
2.3	.1359	.1664	.817	.0817	2.914
2.4	.1376	.1682	.818	.0818	2.996
2.5	.1447	.1700	.852	.0852	3.081
2.6	.1543	.1718	.899	.0899	3.171
2.7	.1626	.1736	.937	.0937	3.265
2.8	.1666	.1754	.950	.0950	3.360
2.9	.1753	.1772	.990	.0990	3.459
3.0	.1789	.1790	1.0	.1000	3.559
3.1	.1790	.1790	1.0	.1000	3.659

* Original location of material was inside die radius; $t_o = 0.161$

** Equals measured diameter of manifold at 1.1 inches from small diameter opening.

Calculation of the thinning strain is again straight forward, as in the case of the small diameter coupling. This strain is

$$\varepsilon_t = \ln .1354/.1664 = \ln(.817) = -0.202$$

or approximately 20%. While it is recognized that the effective strain cannot, in general, be calculated by a simple summation of orthogonal strains, such an approach does provide a qualitative feel for the total deformation present in the dome and will be used in the present case.

Thus, in order to characterize the creep-behavior of the cold drawn tantalum manifold it will be necessary to creep test material having between 35 and 45% cold work. While it is acknowledged that the structure produced by direct tensile strain is not necessarily identical with the structure in those areas of the manifold having an equivalent amount of complex strain, it is felt that the creep behavior of tensile strained material would certainly approximate creep behavior of the dome more closely than does the behavior of the recrystallized tubing.

The approach to the problem will therefore be to creep test pure tantalum plate prestrained in tension at room temperature prior to testing. One such test is currently being prepared and will be initiated during the coming report period. The specimen for this test was cut from the 0.162 inch plate from which the manifolds are made, and was prestrained to the peak load as indicated in Figure 8. The engineering strain at this point was 30.5%. Since the peak load coincides with the onset of necking, this strain represents the maximum uniform elongation that can be achieved in this material. Results from the creep test on this bar should be available for presentation in the next quarterly report.

Another area of concern in fabrication of the Hg-NaK boiler is the influence of welding on the performance of the assembly, particularly in the vicinity of the manifold. This piece is joined to adjacent parts by TIG welding at both the top and the bottom. While the influence of welding on the recrystallized tubing has already been studied, the affect in cold worked material may be significantly different. Therefore, after creep behavior of the cold worked material has been documented, tests will be conducted on cold worked and welded material.

ASTAR 811C

During the current report period design creep test results on a commercial heat of ASTAR 811C (Heat 66-650056) at stress levels of 5, 10 and 25 ksi (34.5, 68.9 and 172 MN/M^2) continued to exhibit strengths superior to the laboratory heats of this material which have been examined previously, see Figure 1. During the coming report period two additional tests will be initiated on this heat at 15 and 20 ksi (104 and 134 MN/M^2) in order to fill in the Larson-Miller curve at the intermediate stress levels.

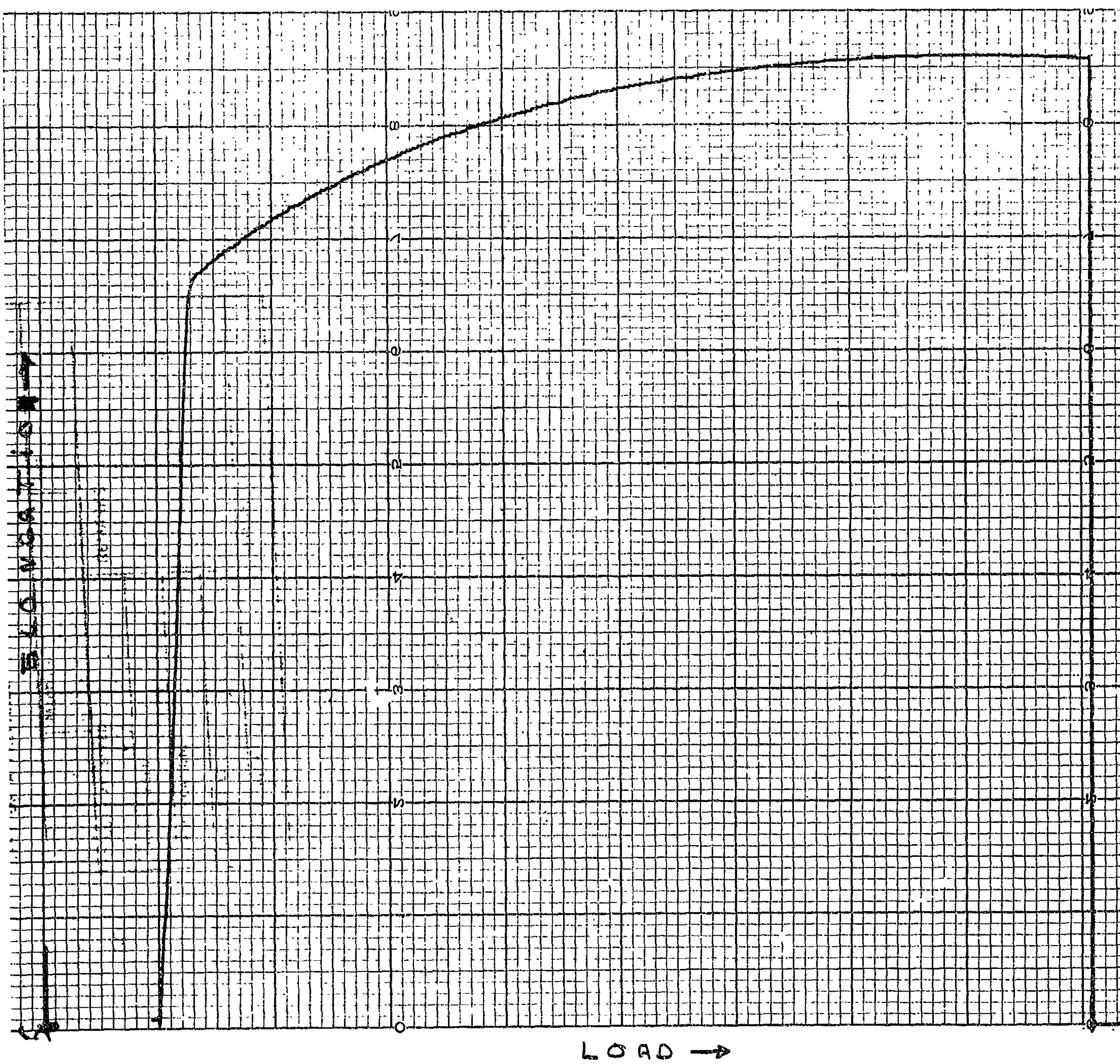

Figure 8. Load-deflection curve from tensile prestraining of pure tantalum creep specimen.

T-111 ALLOY

A recent topical report issued on this contract (7) has discussed the interaction between creep behavior and a strain aging reaction which exists in T-111 alloy between 1100 and 2200°F (593 and 1204°C). While the majority of the design creep tests on T-111 have been conducted near the upper end of this range, results were presented in the last quarterly report for a test at 1300°F (704°C). At the higher temperatures the effect of the strain aging is to essentially stop creep in the early stages of test, even at stresses approaching the yield stress. After relatively long times with essentially no creep, the creep rate undergoes a transition to a higher steady state value. This rate transition occurs because of the loss of oxygen, which is thought to be the interstitial species responsible for the strain age strengthening. While some primary strain (on the order of a 0.1%) is accumulated before the creep arrest at the higher temperatures, the test at 1300°F showed approximately 3/4 percent extension before creep ceased. Since the design limit currently being studied is 1% strain, it was thought that another test should be conducted at an even lower temperature to determine if the primary creep strain increases at the bottom of the strain aging region. A test was therefore initiated at 1100°F (593°C) and 45 ksi (310 MN/M^2), which corresponds to the yield stress at this temperature, and almost 3% primary strain was accumulated on this specimen during the first 24 hours. After primary creep ceased, testing was continued for over 1000 hours during which no further extension occurred. This result indicates a need for further study of T-111 creep in the lower temperature range, particularly when 1% design limitations are contemplated.

Another aspect of the strain age creep strengthening concerns the form of the creep curve during the rate transition. Since ordinary third stage creep also causes the creep rate to increase with test time, it is necessary to examine closely the shape of the creep curve during and after transition to be certain that the phenemenon being observed is not simple third stage creep. The shape of the creep curve is best characterized for this purpose by plotting the variation of creep rate with creep strain. Figure 9 illustrates this point using data from a test currently in progress at 1600°F (870°C) and 35 ksi (241 MN/M^2). While this type of analysis has been shown previously for tests at higher temperatures, this is the first such report for a test at the peak strain aging temperature. The very distinct minimum at a true strain of about 0.001 is compared in Figure 9 to the type of behavior which would be normally expected to precede third stage creep. In the past the T-111 creep tests have been discontinued at or before this point because of the 1% design limitation selected for this material, with the assumption that true third stage creep would eventually develop. In order to confirm this assumption, it is planned to continue the current test at 1600°F (870°C) until third stage creep occurs.

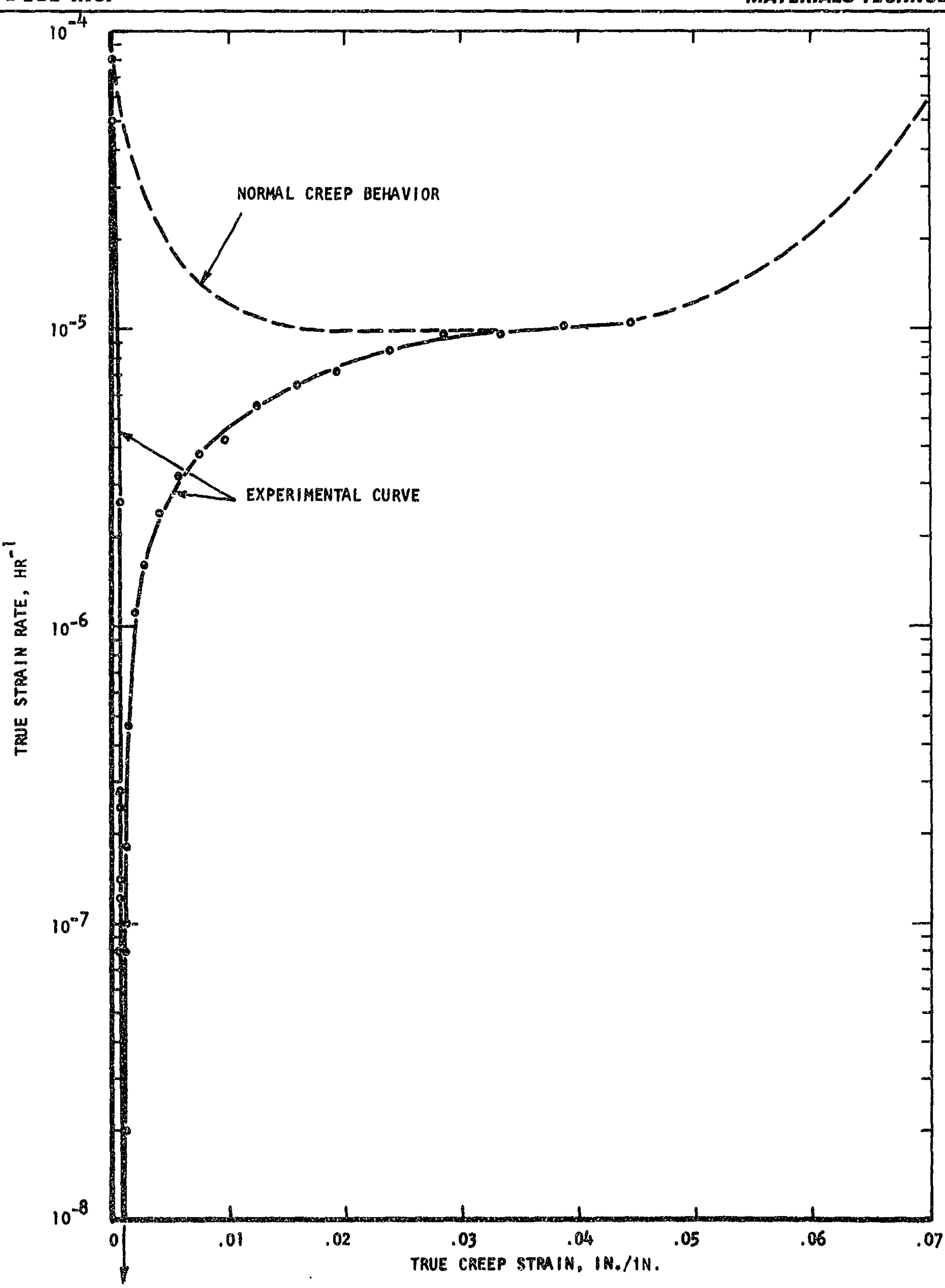

Figure 9. True strain rate as a function of true strain for T-111 alloy annealed 1 hour at 3000°F (1649°C) and creep tested at 1600°F (871°C) and 35 ksi (241 MN/M^2) in a vacuum of <1 x 10^{-8} torr (Test S-60).

5762 B

VARIABLE STRESS, VARIABLE TEMPERATURE CREEP BEHAVIOR

In the last quarterly report an analytical study of the variable stress, variable temperature creep behavior of a type 316 stainless steel was made to evaluate the suitability of this material for radioisotope capsule applications. During the current report period a similar study was conducted on the nickel-base superalloy Inconel 718.

Since the nickel-base superalloys typically exhibit little or no primary creep, the elaborate treatments required to account for the phenomenon in the stainless material are not necessary for the 718 alloy. This fact simplifies the analysis considerably, because minimum creep rate becomes a single valued "state" function and can be integrated directly over the range of temperature and stress, without regard to the direct influence of time or strain on rate.

Minimum creep rates reported in a DMIC Alloy 718 Handbook for solution treated and aged sheet material are tabulated in Table 5, and are plotted in standard form in Figure 10. Since the data are linear on this plot, it is probable that the minimum creep rates can be described analytically using the conventional expression:

$$\dot{\varepsilon} = A\sigma^{n}e^{-\Delta H/RT} \qquad \text{Equation 4}$$

Examination of Figure 10 shows that n is different at 1000 and 1200°F (538 and 649°C), so that it must either be made a function of temperature in Equation 4, or a compromise value must be selected. For purposes of a feasibility study the latter approach will be used, with selection of the compromise value being made as indicated later.

Because the stress ranges of data at the different temperatures do not overlap in every case, it was necessary to extrapolate the stress-creep rate curves to evaluate the ΔH factor in Equation 4. The extrapolated values used for this purpose are tabulated in Table 6 together with the resulting values of activation energy. As with the stress exponent, the activation energy varies with temperature; and again, for purposes of this feasibility study, a compromise value will be chosen. In this case, the arithmetic average of 110,000 calories per mole was selected.

Using this value of activation energy, a parameter of the form

$$\dot{\varepsilon}e^{\Delta H/RT} \qquad \text{Equation 5}$$

was calculated for each of the creep rates tabulated in Table 5, and the common logarithm of these values are plotted as a function of log stress in Figure 11. The effect of using a compromise value of ΔH is readily apparent in this figure, with the data at 1000 and 800°F (538 and 427°C) falling respectively slightly above and slightly below the extrapolated 1200°F (649°C) data.

TABLE 5

Experimental and Temperature-Compensated Creep Rates in Inconel 718 Alloy

Temperature °F	Temperature °C	Stress ksi	Stress MN/m²	Minimum Creep Rate Hour⁻¹	$\dot{\varepsilon}e^{\Delta H/RT}$, Hour⁻¹ ΔH = 110,000 cal/mole
800	427	165	1140	3.50×10^{-7}	8.8×10^{27}
800	427	160	1110	3.00×10^{-7}	7.5×10^{27}
800	427	160	1110	3.00×10^{-7}	7.5×10^{27}
1000	538	160	1110	3.56×10^{-4}	1.6×10^{26}
1000	538	155	1070	2.18×10^{-4}	9.9×10^{25}
1000	538	150	1040	6.18×10^{-5}	2.8×10^{25}
1000	538	150	1040	9.50×10^{-5}	4.3×10^{25}
1000	538	140	967	4.80×10^{-6}	2.1×10^{24}
1000	538	140	967	4.60×10^{-6}	2.0×10^{24}
1200	649	100	689	1.34×10^{-4}	1.5×10^{22}
1200	649	100	689	9.20×10^{-5}	1.1×10^{22}
1200	649	90	620	2.20×10^{-5}	2.6×10^{21}
1200	649	90	620	3.59×10^{-5}	4.2×10^{21}
1200	649	80	551	6.80×10^{-6}	8.0×10^{20}
1200	649	80	551	2.80×10^{-6}	3.3×10^{20}
1200	649	75	516	7.60×10^{-7}	9.0×10^{19}

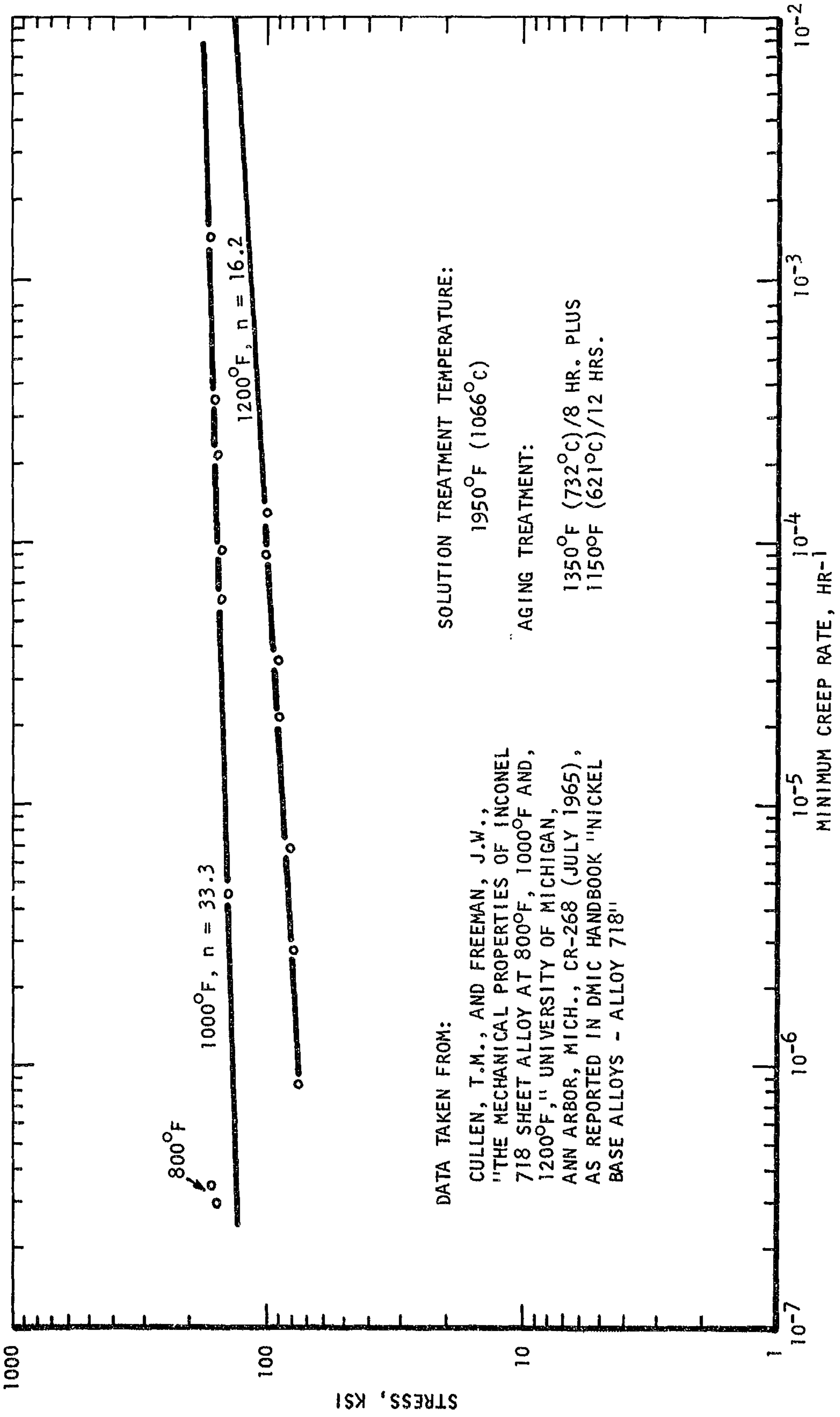

Figure 10. Creep rate data for Inconel 718 sheet.

TABLE 6

Extrapolated Creep Rate Used for Activation Energy Calculations

Stress		Temperature		Creep Rate	Activation Energy
ksi	MN/m²	°F	°C	Hour⁻¹	cal/mole K°
130	899	1000	538	5.0×10^{-7}	134,00
		1200	649	1.0×10^{-2}	
162.5	1120	800	427	3.25×10^{-7}	87,000
		1000	538	1.50×10^{-5}	

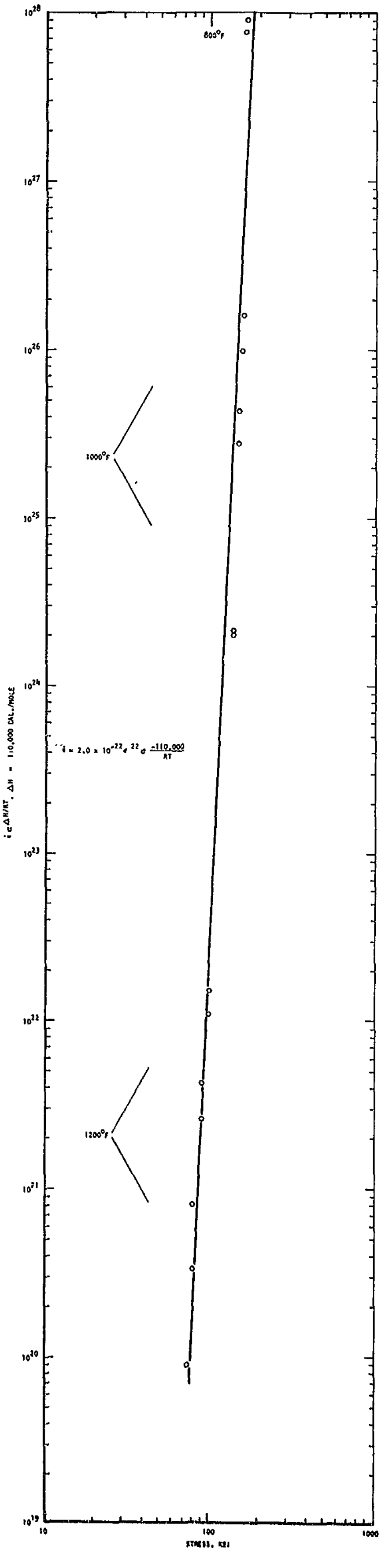

Figure 11. Plot of temperature compensated minimum creep rates in Inconel 718 alloy sheet.

5516 B

The straight line which best fits these data has a slope of 22, which is considered to represent the best choice for an average stress exponent. Using this value and the 110,000 cal/mole activation energy a value of A can be computed for Equation 4 so that the minimum creep rate of the alloy 718 can now be expressed as

$$\dot{\varepsilon} = 2.0 \times 10^{-22} \sigma^{22} e^{-110,000/RT} \qquad \text{Equation 6}$$

with $\dot{\varepsilon}$ in hour^{-1}

σ in ksi

T in °K

R = 1.987 cal/mole °K

Analysis of the variable-stress, variable temperature creep behavior of this alloy may now be accomplished by substitution of Equation 6 for equations 10 and 19 in the 20th quarterly report. This substitution has been made using a computer program developed at the NASA Lewis Research Center and the expression is now being used to compute capsule weights and dimensions.

CONCLUSIONS

Significant conclusions obtained during the current report period are listed as follows:

1. A specially processed heat of TZM alloy (Heat KDTZM-1175) having a higher than normal carbon content and forged at higher than normal temperatures continues to show creep strength superior to conventionally processed TZM alloy.

2. Accelerated creep in the heat affected zone of a bead-on-plate TIG weld in pure tantalum has been shown to result from grain growth which takes place in this region during welding.

3. The creep strength of a commercial heat of ASTAR 811C alloy has been found superior to laboratory heats of this material.

4. Previously developed techniques for the prediction of variable stress, variable temperature creep behavior have been applied to develop an expression for an Inconel 718 alloy proposed for a radioisotope capsule application.

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2. K. D. Sheffler and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Nine Month Summary Report, Contract NAS 3-9439, CR-72391, 14 December 1967.

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APPENDIX I

PREVIOUSLY PUBLISHED REPORTS

ON THE REFRACTORY ALLOY CREEP PROGRAM

J. C. Sawyer and E. B. Evans, "Generation of Valid Long Time Creep Data on Refractory Alloys at Elevated Temperature," First Quarterly Report, Contract NAS 3-2545, October 20, 1963.

J. C. Sawyer and E. B. Evans, "Generation of Valid Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Second Quarterly Report, Contract NAS 3-2545, January 15, 1964.

J. C. Sawyer and E. B. Evans, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Third Quarterly Report, Contract NAS 3-2545, CR-54048, April 20, 1964.

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J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Eleventh Quarterly Report, Contract NAS 3-2545, CR-54973, April 15, 1966.

J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Twelfth Quarterly Report, Contract NAS 3-2545, CR-72044, July 15, 1966.

J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Thirteenth Quarterly Report, Contract NAS 3-2545, October 14, 1966.

J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Fourteenth Quarterly Report, Contract NAS 3-2545, CR-72185, January 17, 1967.

J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Final Report, Contract NAS 3-2545, June 6, 1967.

J. C. Sawyer and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Supplement to Final Report, Numerical Creep Data," June 26, 1963 to March 17, 1967, Contract NAS 3-2545, August 15, 1967.

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.

K. D. Sheffler and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Nine Month Summary Report, Contract NAS 3-9439, CR-72391, December 14, 1967.

K. D. Sheffler and E. A. Steigerwald, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures," Fifteenth Quarterly Report (and Numerical Data Supplement), Contract NAS-3-9439, CR 72431, 14 April 1968.

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APPENDIX II

SUMMARY OF ULTRA-HIGH VACUUM CREEP TEST RESULTS GENERATED ON THE REFRACTORY ALLOY CREEP PROGRAM

TABLE II-1. Summary of Arc-Melted Tungsten 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 MN/M^2	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 (15+logt)x10^{-3}
S-5	KC-1357	24	3200	1760	3.0	20.7	3200	1760	6	32	5.38	57.8
S-7	KC-1357	2	3200	1760	0.4	2.8	3200	1760	***	714	118	***
S-9	KC-1357	2	3200	1760	1.0	6.9	3200	1760	675	3886	2.760	65.4
S-17	KC-1357	2	2800	1538	4.0	28.0	2800	1538	20	908	5.452	53.1
S-18	KC-1357	2	2800	1538	3.0	20.7	2800	1538	125	908	5.535	55.8

***Insufficient creep to extrapolate

TABLE II-2. Summary of Vapor-Deposited Tungsten Ultra-High Vacuum Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Te[illegible]ion of Test Time, Hours	Te[illegible]ion of Test Percent Creep	1% Creep Larson-Miller Parameter T (15+logt)x10⁻³
B-17	--	1	3200	1760	1.0	6.9	3200	1760	1140	2571	1.570	66.0
B-24	--	1	2800	1538	2.0	13.8	2800	1538	1500	6812	3.708	59.2

TABLE II-3. Summary of Tungsten-25% Re 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 MN/M²	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 (15+logt) x10⁻³
S-3	3.5-75002	48	3200	1760	5.0	34.4	3200	1760	12	45	6.03	58.9
S-4	3.5-75002	45	3200	1760	3.0	20.7	3200	1760	25	97	5.22	60.0
S-6	3.5-75002	1	3200	1760	0.5	3.4	3200	1760	***	253	0.090	***
S-8	3.5-75002	1	3200	1760	1.5	10.3	3200	1760	315	1306	5.113	64.0
S-55A	3.5-75002	1	2550	1400	10	68.9	1600	869	--	200	0.005	--
S-55B	3.5-75002		--		10	68.9	1650	900	--	203	0.005	--
S-55C	3.5-75002		--		10	68.9	1700	927	--	196	0.008	--
S-55D	3.5-75002		--		10	68.9	1750	954	--	241	0.018	--
S-55E	3.5-75002		--		10	68.9	1800	980	--	257	0.035	--
S-61A	3.5-75002		--		15	100.4	1600	869	--	235	0.008	--
S-61B	3.5-75002		--		15	100.4	1650	900	--	169	0.022	--
S-61C	3.5-75002		--		15	100.4	1700	927	--	196	0.038	--
S-61D	3.5-75002		--		15	100.4	1750	954	--	200	0.058	--
S-61E	3.5-75002		--		15	100.4	1800	980	--	194	0.078	--

***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 MN/M^2	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 (15+logt) x10^{-3}
S-12	--	2	3200	1760	5.0	34.4	3200	1760	35	170	5.25	60.6
S-15	--	2	3200	1760	3.0	20.7	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 Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	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 (15+logt) x10⁻³
B-2	C5	As-Rolled			12.0	82.7	2000	1093	390	806	1.020	43.3
B-6	C5	As-Rolled			11.0	75.8	2000	1093	450	1192	1.016	43.5
B-7	C5	As-Rolled			8.0	55.1	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 Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M^2	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 (15+logt) x10^{-3}
B-13	KC-1454	1	3092	1700	20.0	138.0	2056	1125	275	568	1.170	43.8
B-14	KC-1454	1	3092	1700	16.3	82.3	2056	1125	340	691	1.026	44.0
B-15	KC-1454	1	3092	1700	7.4	51.0	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 MN/M²	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 (15+logt)x10⁻³
B-1	7502	1	2200	1204	12.6	86.5	2130	1165	605	646	1.105	46.1
B-3	7502	1	2200	1204	10.0	68.9	2000	1095	14,200*	10,048	0.375	47.1
B-29	7502	1	2200	1204	41.0	282.0	2000	1095	100	664	6.215	41.8
B-35	7502	1	2200	1204	44.0	303.0	1800	982	7000	7659	0.535	42.6
B-4	7502	1	2200	1204	10.0	68.9	2000	1095	25,000*	10,012	0.368	47.7
	Plus	1	2850	1566								
B-16	KDTZM-1175	1	2300	1260	23.4	161.0	1855	1013	62,500*	4376	0.035	45.8
B-18	KDTZM-1175	1	2300	1260	55.0	379.0	1600	871	60,000*	2159	0.018	40.7
B-21	KDTZM-1175	1	2300	1260	65.0	448.0	1600	871	15,000*	1630	0.085	39.5
B-25	KDTZM-1175	1	2300	1260	44.0	303.0	1800	982	50,000*	10,152	0.182	44.5
B-38	KDTZM-1175	1	2300	1260	22.0	151.0	2000	1093	16,293	**	**	47.1
B-34	7463	1/2	2250	1232	41.0	282.0	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 Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	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 (15+logt) x10⁻³
B-23A	4305-4	1	2500	1371	20.0	138.0	2000	1093	20,000*	686	0.032	47.5
B-23B	4305-4	-	--	--	28.0	193.0	2000	1093	10,000*	307	0.028	46.7
B-23C	4305-4	-	--	--	40.0	276.0	2000	1093	630*	185	0.188	43.8
B-23D	4305-4	-	--	--	46.0	317.0	1800	982	4000*	403	0.078	42.0
B-23E	4305-4	-	--	--	34.0	234.0	2100	1149	1000*	329	0.170	46.1
B-27	4305-4	1	2500	1371	41.0	282.0	2000	1093	1090	1584	1.040	44.5

*Extrapolated

TABLE II-9. Summary of TZC 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 MN/M²	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 (15+logt) x10⁻³
B-8A	M-80	1	3092	1700	18.0	124.0	2200	1204	1100	2128	1.060	48.3
B-10	M-80	1	3092	1700	17.0	117.0	2200	1204	2500	2749	0.545	48.9
B-9	M-80	1	3092	1700	20.0	138.0	2000	1093	10,408	16,002	0.670	46.8
B-11	M-80	1	3092	1700	25.0	172.0	1856	1013	75,000*	14,406	0.182	46.0
B-12	M-80	1	3092	1700	19.0	131.0	2056	1125	75,000*	14,239	0.280	49.2
B-20	M-91	1	3092	1700	20.0	138.0	2000	1093	3650	12,795	1.008	45.7
B-31	M-91	1	3092	1700	14.0	96.5	2200	1204	329	912	1.092	46.6
B-19	M-91	1	2300	1260	44.0	303.0	1800	982	1075	4604	1.015	41.1
B-28	M-91	1	2300	1260	28.0	193.0	2000	1093	1100	4214	1.138	44.4
B-30	M-91	1	2500	1371	22.0	152.0	2200	1204	70	259	1.280	44.8
B-32	M-91	1	2500	1371	20.0	138.0	1935	1057	14,400	16,130	0.535	45.9
B-33	M-91	1	2500	1371	22.0	152.0	1900	1038	7720	9697	0.585	44.6
B-36	4345	1	2500	1371	22.0	152.0	2000	1093	5940	8563	0.640	46.2
B-37	4345	1	2400	1316	22.0	152.0	2000	1093	8853	9020	0.500	46.3

*Extrapolated

TABLE II-10. Summary of T-222 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 MN/M²	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 (15+logt) x10⁻³
S-13	AL-TA-43	1	3000	1649	12.0	82.7	2200	1204	560	1890	5.720	47.2
S-14	AL-TA-43	1	3000	1649	19.2	132.0	2056	1124	890	1314	1.685	45.1
S-20	AL-TA-43	1	2800	1538	12.0	82.7	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 Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	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 (15+logt)x10⁻³
S-29	NASV-20-WS	.5	3600	1982	2.0	13.8	2600	1427	21,190	21,560	1.028	59.3
S-70	VAM-95	.25	3520	1940	20	130.8	2100	1148	3600*	983.4	0.342	47.5
S-71	VAM-95	.15	3600	1982	20	130.8	2100	1148	3600*	767.5	0.320	47.5
S-70A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	655.8	0.108	50.0
S-71A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	678.9	0.112	50.0
S-70B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1106.4	0.153	51.9
S-71B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1082.2	0.178	51.9
S-73	VAM-95	.33	3600	1982	15	103.0	2400	1316	435	720.5	1.860	50.5
S-74	650056	.33	3600	1982	15	103.0	2400	1316	825	1466	2.185	51.2
S-75	VAM-95	1.0	3000	1649	15	103.0	2400	1316	144	162.3	1.195	49.1
S-76	650056	.5	3600	1982	25	162.0	2175	1191	695	**	**	47.0
S-77	650056	.5	3600	1982	10	69.0	2400	1316	5600*	**	**	53.6
S-78	650056	.5	3600	1982	5	35.0	2550	1399	6600*	**	**	56.6
S-79	VAM-95	5	3450	1800	15	103.0	2400	1316	542	714	1.378	50.8
S-81	VAM-95	24	3270	1700	15	103.0	2400	1316	560	666.5	1.330	50.8

*Extrapolated
**Test in progress
***Insufficient creep to extrapolate

TABLE II-12. 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 MN/M²	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 (15+logt) x10⁻³
S-16	70616	1	2600	1427	8.0	55.1	2200	1204	725	1675	2.570	47.5
S-19	70616	1	3000	1649	8.0	55.1	2200	1204	2000	4870	3.368	48.7
S-21	70616	1	3000	1649	12.0	82.6	2200	1204	1140	3840	6.548	48.0
S-23	70616	1	3000	1649	12.0	82.6	2120	1160	3150	3698	1.225	47.7
S-22	70616	1	3000	1649	20.0	138.0	2000	1093	670	1099	2.010	43.8
S-24	70616	1	3000	1649	20.0	138.0	1860	1016	4730	4946	1.090	43.3
S-25	D-1670	1	3000	1649	15.0	103.0	2000	1093	1340	1584	1.210	44.6
S-26	D-1670	1	3000	1649	17.0	117.0	1800	982	9540	9624	1.030	42.9
S-25A	D-1670	1	3000	1649	1.5	10.3	2600	1427	1100*	482	0.632	55.2
S-28	D-1670	1	3000	1649	0.5	3.4	2600	1427	55,000*	**	**	60.0
S-27	D-1102	1	3000	1649	13.0	89.5	2000	1093	1880	3459	2.082	45.0
S-32	D-1102	1	3000	1649	5.0	34.4	2200	1204	4050	4322	1.042	49.5
S-40	D-1102	1	3000	1049	17.0	117.0	1800	982	8558	8717	1.028	42.8
S-33	65076	1	3000	1649	8.0	55.1	2200	1204	2850	2976	1.048	49.1
S-34	65076	1	3000	1649	11.0	75.8	2000	1093	10,800	10,875	1.010	46.9

*Extrapolated
**Test in progress

TABLE II-12. 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 MN/M²	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 (15+logt) x10⁻³
S-37	6580	1	3000	1649	8.0	55.1	2200	1204	260	274	1.230	46.3
S-39	65080	1	3000	1649	13.0	89.5	1800	982	8202	8728	1.070	42.7
S-45	65080	1	3000	1649	3.0	20.0	2200	1204	554	697	1.165	47.1
S-30	65079	1	3000	1649	3.5	24.1	2400	1316	860	2137	2.372	51.3
S-31	65079	1	3000	1649	5.0	34.4	2200	1204	6160	6594	1.092	50.0
S-35	65079	1	3000	1649	5.0	34.4	2200	1204	5400	5522	1.048	49.9
S-42	65079	1	3000	1649	3.5	24.1	2300	1263	3810	4247	1.122	51.3
S-47	65079	1	3000	1649	24.0	165.0	1750	954	38,000*	**	**	43.3
S-48	65079	1	3000	1649	2.4	165.0	2330	1275	5500	6284	1.200	52.3
S-50	65079	1	3000	1649	8.5	72.2	2000	1093	24,000*	5735	0.272	47.7
S-43	65079	1/4	3000	1649	18.0	124.0	2000	1093	1500*	361	0.108	44.7
S-44A	65079	1	3000	1649	9.5	65.5	2172	1189	3250*	467	0.152	48.7
S-44B	65079	1/4	3000	1649	3.3	22.7	2371	1299	2030*	335	0.168	51.9
S-44C	65079	1/4	3000	1649	18.0	124.0	2000	1093	1670*	1146	0.688	44.8
S-44D	65079	1/4	3000	1649	23.0	158.0	1800	982	14,650*	1391	0.112	43.3
S-59	D-1183	1	3000	1649	13.0	89.5	2000	1093	13,500*	**	**	47.1

*Extrapolated
**Test in progress

TABLE II-12. 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 MN/M²	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 (15+logt) x10⁻³
S-60	D-1183	1	3000	1649	35.0	241.0	1600	870	8550	**	**	39.0
S-68	650028	1	3000	1649	1.0	6.9	2560	1403	2300	**	**	55.5
S-69	650028	1	3000	1649	30.0	207.0	1625	885	***	**	**	***
B-43	650028	1	3000	1649	20.0	138.0	2000	1093	1823	1840.8	1.012	44.8
B-44	650038	1	3000	1649	35.0	241.0	2000	16	1093	55.1	7.582	39.8
P-1	8049	1	3000	1649	19.0	131.0	2000	1093	2070	3649	2.142	45.1
S-80	650028	1	3000	1649	37.0	255.0	1300	704	***	3192.8	0.775	***
S-82A	650028	-	--	--	50.0	34.4	900	482	***	**	**	***
S-83	650028	1	3000	1649	45.0	31.0	1100	593	7	1177.1	2.945	24.8

*Extrapolated
**In progress
***Insufficient to extrapolate

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 Rate PSI/Hr	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	0.22[illegible]
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	2240	2970	5.292
S-54	65079	1	3000	1649	5	2000	1093	3850	6506	6.478
S-56	65079	1	3000	1649	5	1800	982	5500	6375	5.280
S-57	65079	1	3000	1649	1	2200	1204	7748	8833	1.510
S-62	65079	1	3000	1649	2	2000	1093	8300	8599	1.150

*Extrapolated

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 MN/M²	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 (15+logt) x10⁻³
B-39A	B-1962	1	1832	1000	13.6	93.7	1100	596	31	32	1.020	25.8
B-39B	B-1962	1/4	1832	1000	11.6	79.9	1100	596	603*	264	0.542	27.8
B-39C	B-1962	1/4	1832	1000	10.1	69.5	1183	639	463*	282	0.635	29.0
B-40A	B-1962	1	1832	1000	7.0	48.3	1350	732	9	9	1.000	28.9
B-40B	B-1962	1/4	1832	1000	4.9	33.8	1350	732	6600*	1386	0.300	34.0
B-41	B-1962	1	1832	1000	11.1	76.5	1100	596	144	160	1.078	26.7
B-42A	B-1962	1	1832	1000	4.0	27.5	1350	732	170	186	1.015	31.2
B-42B	B-1962	1/4	1832	1000	4.0	27.5	1350	732	2070	1775	0.892	33.1
B-45	60249	0.1	2290	1255	4.0	27.5	1350	732	***	69.6	0.002	***
B-45B	60249	0.1	2290	1255	8.0	55.0	1350	732	520	1800	1.823	32.0
B-46	60249	0.1	2290	1255	6.5	44.8	1350	732	5600*	155.8	0.215	34.0
B-47++	60249	0.1	2290	1255	16 psi/hour		1350	732	544	548.3	1.050	--
B-47A	60249	-	--	--	8.0	55.0	1350	732	714	907	1.190	32.3
B-48A+	60249	0.1	2290	1255	6.5	44.8	1450	788	252	2371	2.885	33.2

*Extrapolated
**Test in progress
***Insufficient creep to extrapolate

+welded
++Progressive stress

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 MN/M²	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 (15+logt) x10⁻³
B-48B+	60249	-	--	--	7.5	52.3	1450	788	150	1177.2	3.212	32.8
B-49	60249	0.1	2290	1255	6.5	44.8	1450	788	92	**	**	32.4
B-49A	60249	-	--	--	7.5	52.3	1450	788	180	1363.9	3.282	33.0
B-49B	60249	-	--	--	9.0	62.1	1450	788	24	497.8	5.698	31.3
B-51	60379	0.1	2290	1255	6.5	44.8	1350	732	26	**	**	29.8
B-52	60065	0.1	2290	1255	6.5	44.8	1350	732	17,000*	2062	0.115	34.8
B-53	60381	0.1	2290	1255	6.5	44.8	1350	732	5500*	**	**	33.9
P-2	818072	++	++	++	6.5	44.8	1350	732	1.6	649.7	4.685	27.5
P-3	B-1960	++	++	++	6.5	44.8	1350	732	60	**	**	30.4
P-4	B-1960	++	++	++	6.5	44.8	1350	732	30	**	**	29.8

*Extrapolated
**Test in progress

+Welded
++Not Available

TABLE II-15. Summary of Ta-10W 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 MN/M²	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 (15+logt) x10⁻³
S-58A	630002	1	3000	1649	20	38.0	2100	1148	285	308	1.125	44.7
S-58B	630002	1/4	3000	1649	11.5	79.3	2210	1209	770*	410	0.572	47.7
S-58C	630002	1/4	3000	1649	6.2	42.7	2320	1268	2200*	700	0.330	51.0
S-58D	630002	1/4	3000	1649	3.5	24.1	2430	1332	10,200*	1290	0.202	54.9
S-64	630002	1	3000	1649	16	111.0	2000	1093	250	266	1.060	42.8
S-66	630002	1	3000	1649	16	111.0	2000	1093	135	550	5.150	42.1
S-67	630002	1	3000	1649	12	82.9	2000	1093	5227	6098	1.270	46.0

*Extrapolated
**Test in progress

TABLE II-16. Summary of T-111 Progressive Temperature 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 MN/M²	Starting Test Temperature °F	Starting Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	Rate of Temperature Decrease F°/hr
S-65	65079	1	3000	1649	7	48.2	2400	1316	--	1850	0.105	0.6
S-72	650028	1	3000	1649	7	48.2	2400	1316	370	1322.1	1.282	0.3
S-82	650028	1	3000	1649	31	214.0	1900	1038	235	2013.8	1.180	0.5

APPENDIX III

CREEP CURVES

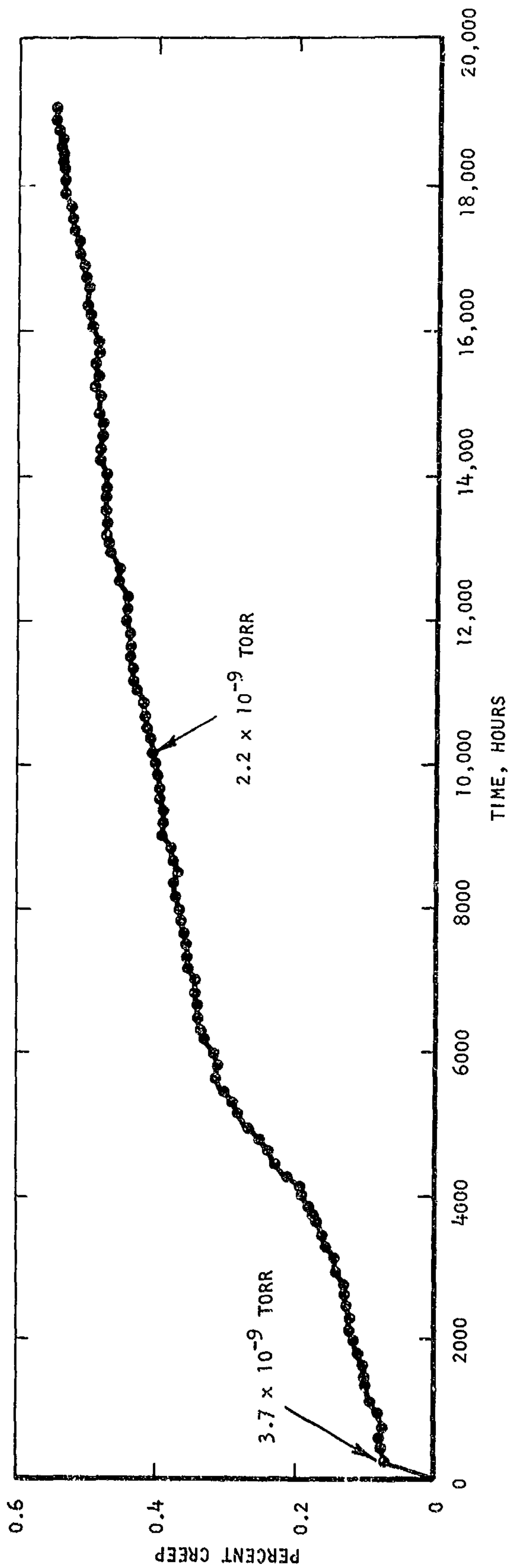

FIGURE III-1. CREEP TEST DATA, TZM, HEAT NO. KDTZM-1175 STRESS RELIEVED 1 HOUR AT 2300°F (1260°C), TESTED AT 2000°F (1093°C) AND 22 KSI (151 MN/m^2), TEST NO. B-38, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5735 B

5730 a

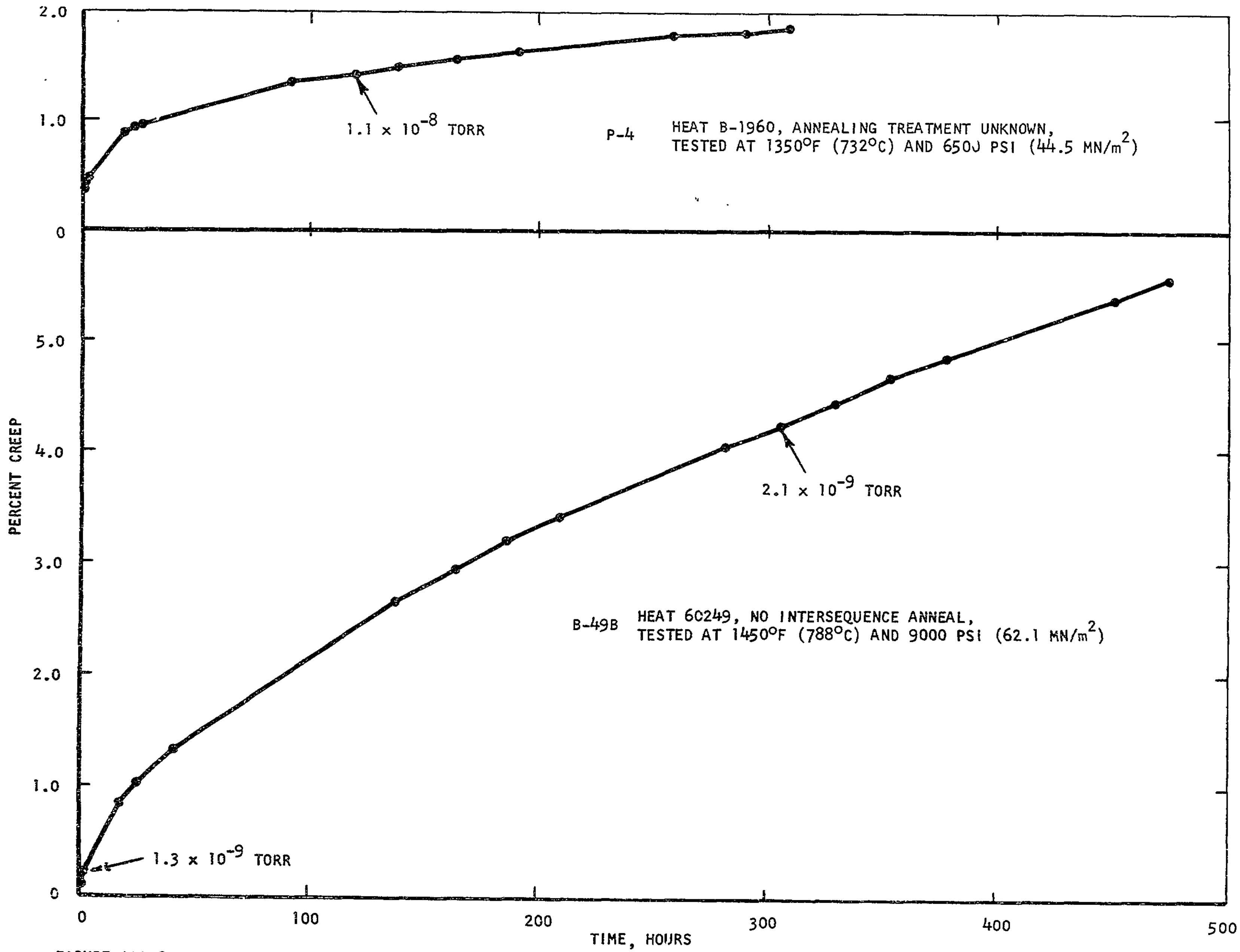

FIGURE III-2. CREEP TEST DATA, PURE Ta, TEST NOS. P-4 AND B-49B, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

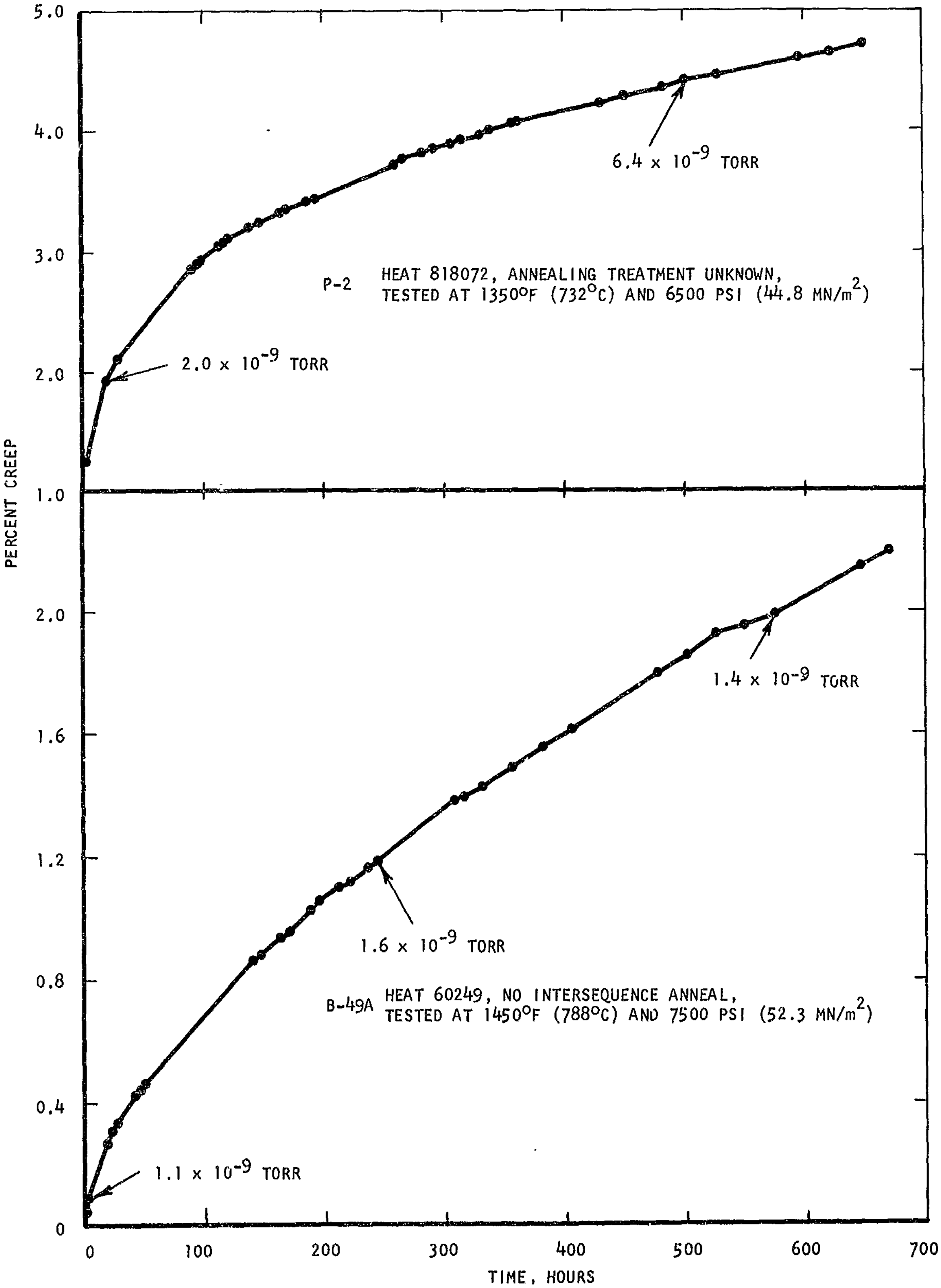

FIGURE III-3. CREEP TEST DATA, PURE Ta, TEST NOS. P-2 AND B-49A, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

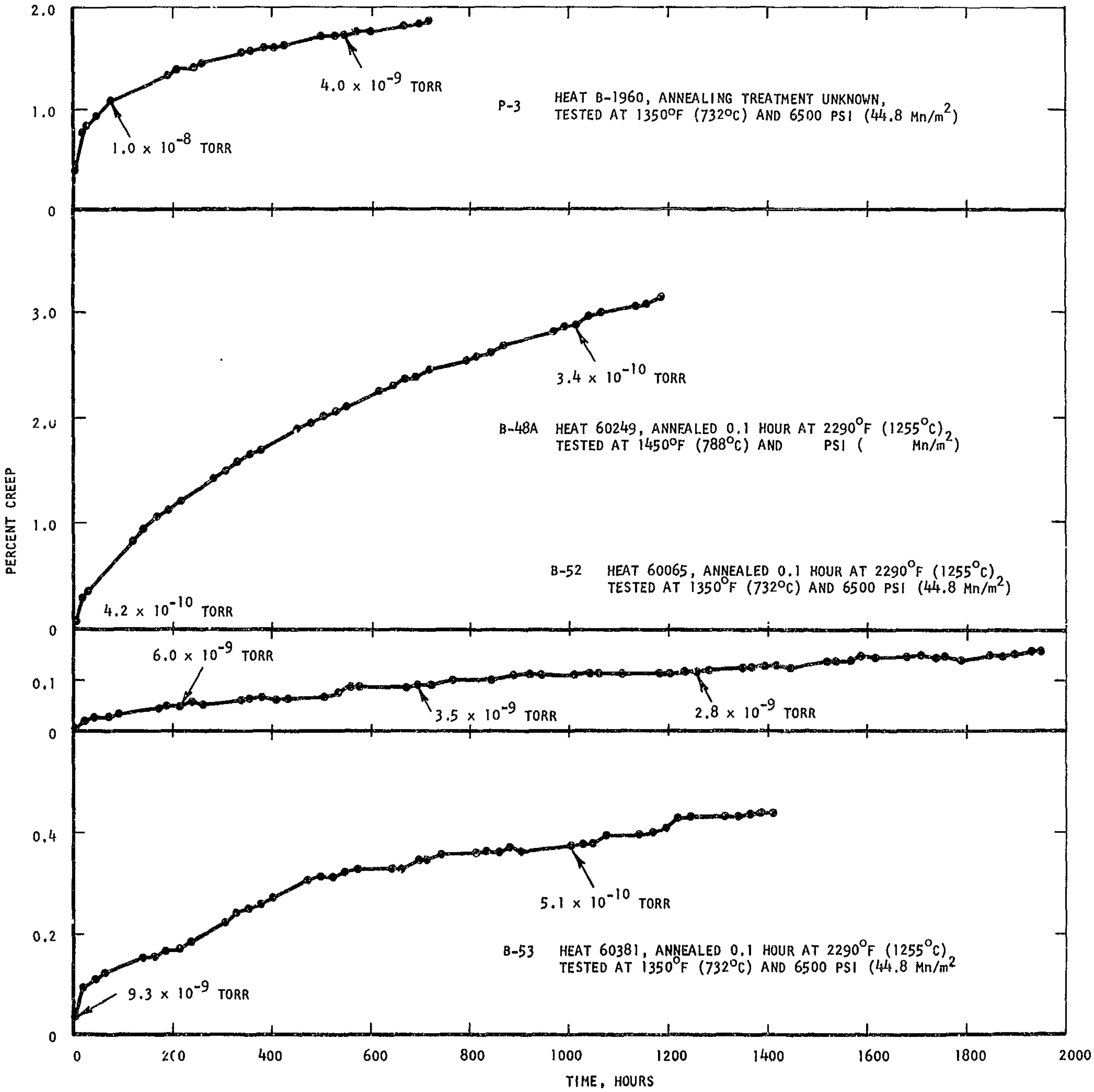

FIGURE III-4. CREEP TEST DATA, PURE Ta, TEST NOS. P-3, B-48A, B-52, and B-53, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

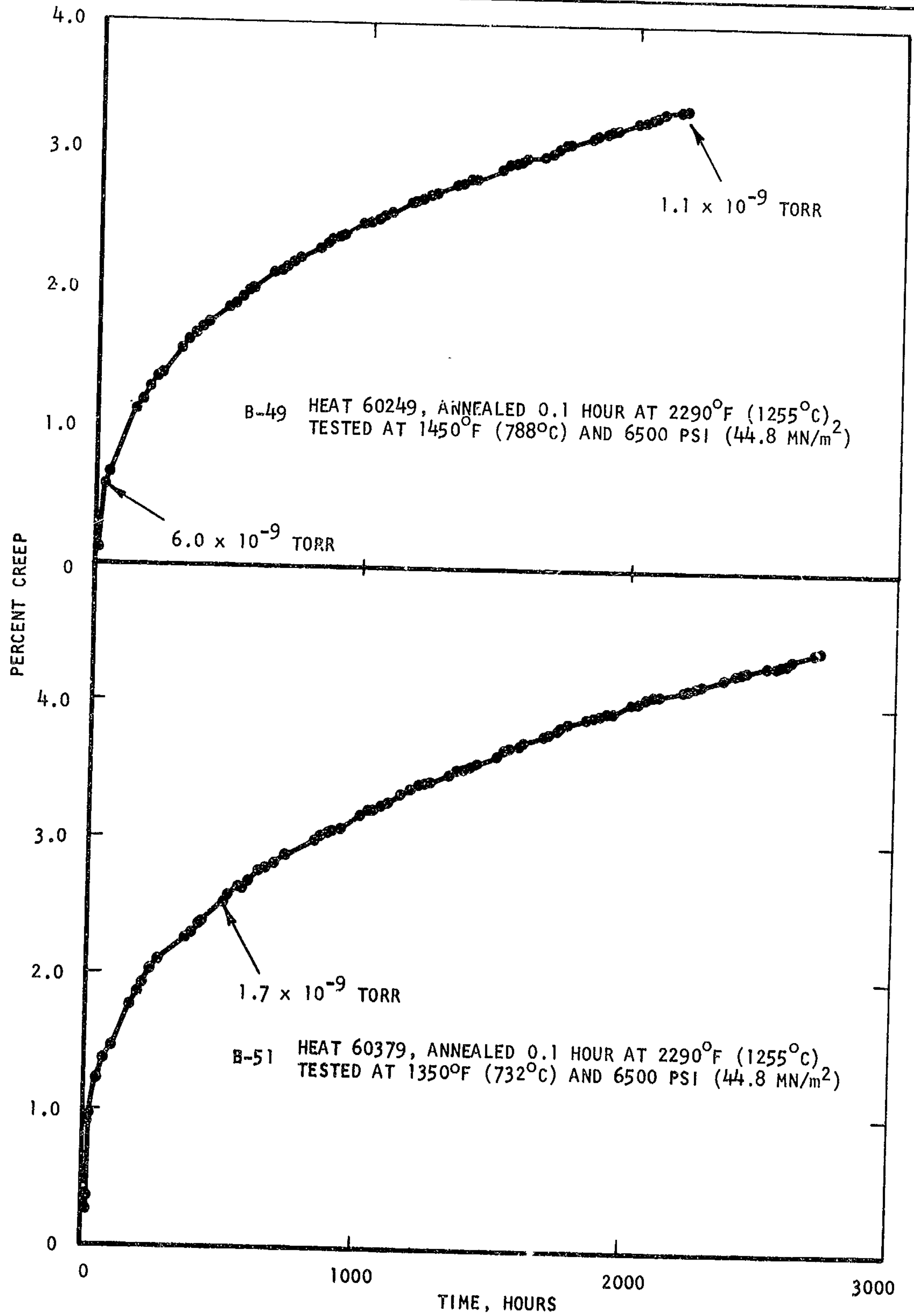

FIGURE III-5. CREEP TEST DATA, PURE Ta, TEST NOS. B-49 AND B-51, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

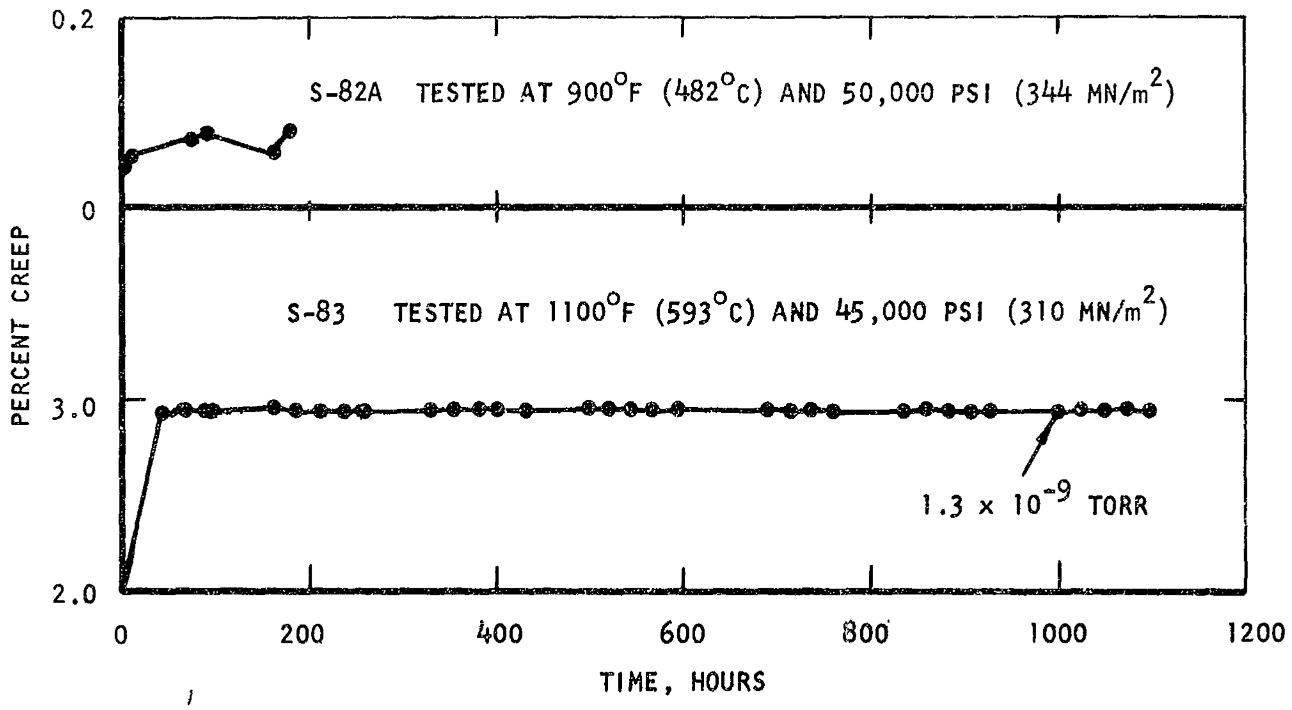

FIGURE III-6. CREEP TEST DATA, T-111, HEAT NO. 650028, ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S-82A AND S-83, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

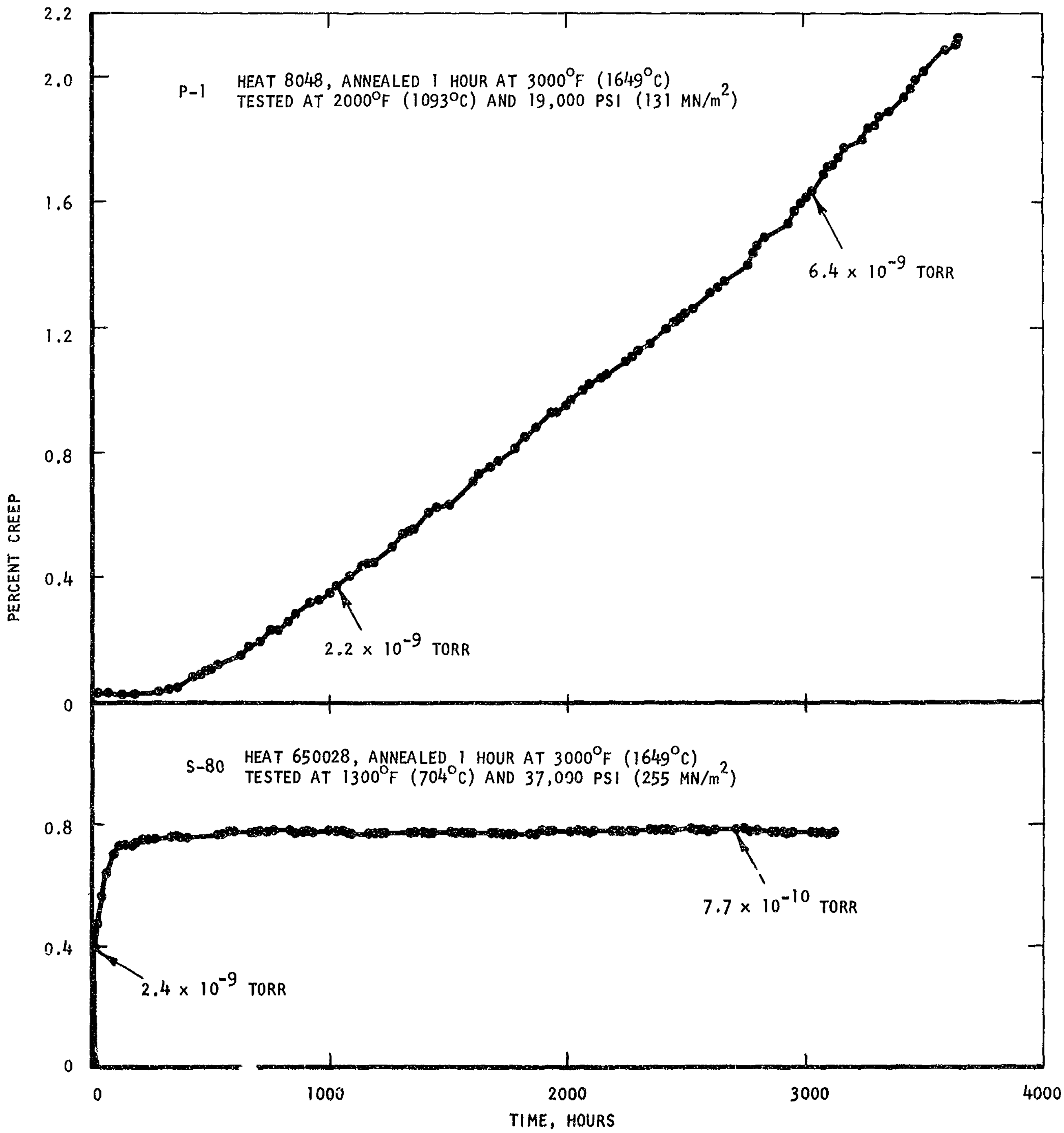

FIGURE III-7. CREEP TEST DATA, T-111, TEST NOS. P-1 AND S-80, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5729 8

5724 B

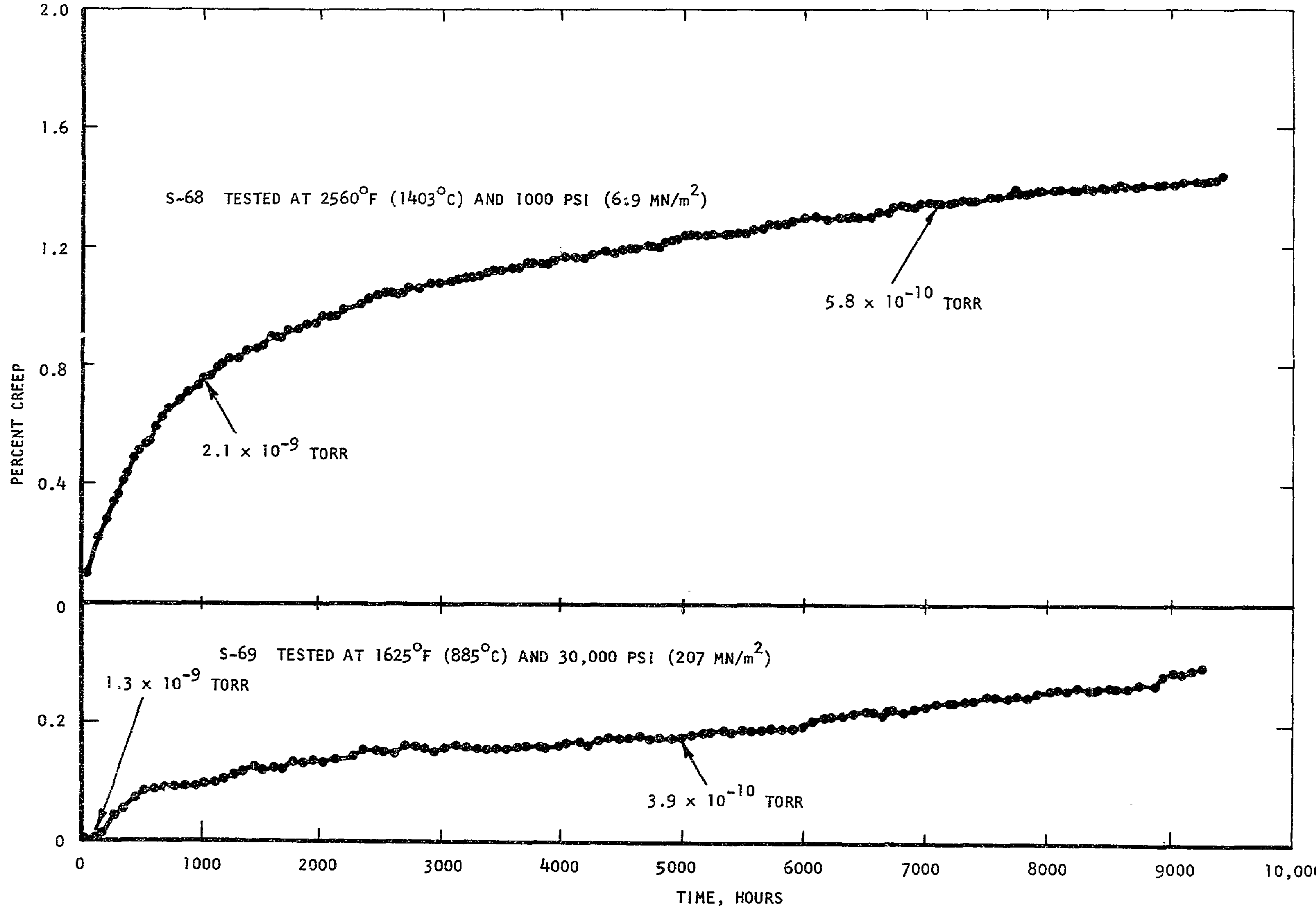

FIGURE III-8. CREEP TEST DATA, T-111, HEAT NO. 650028, ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

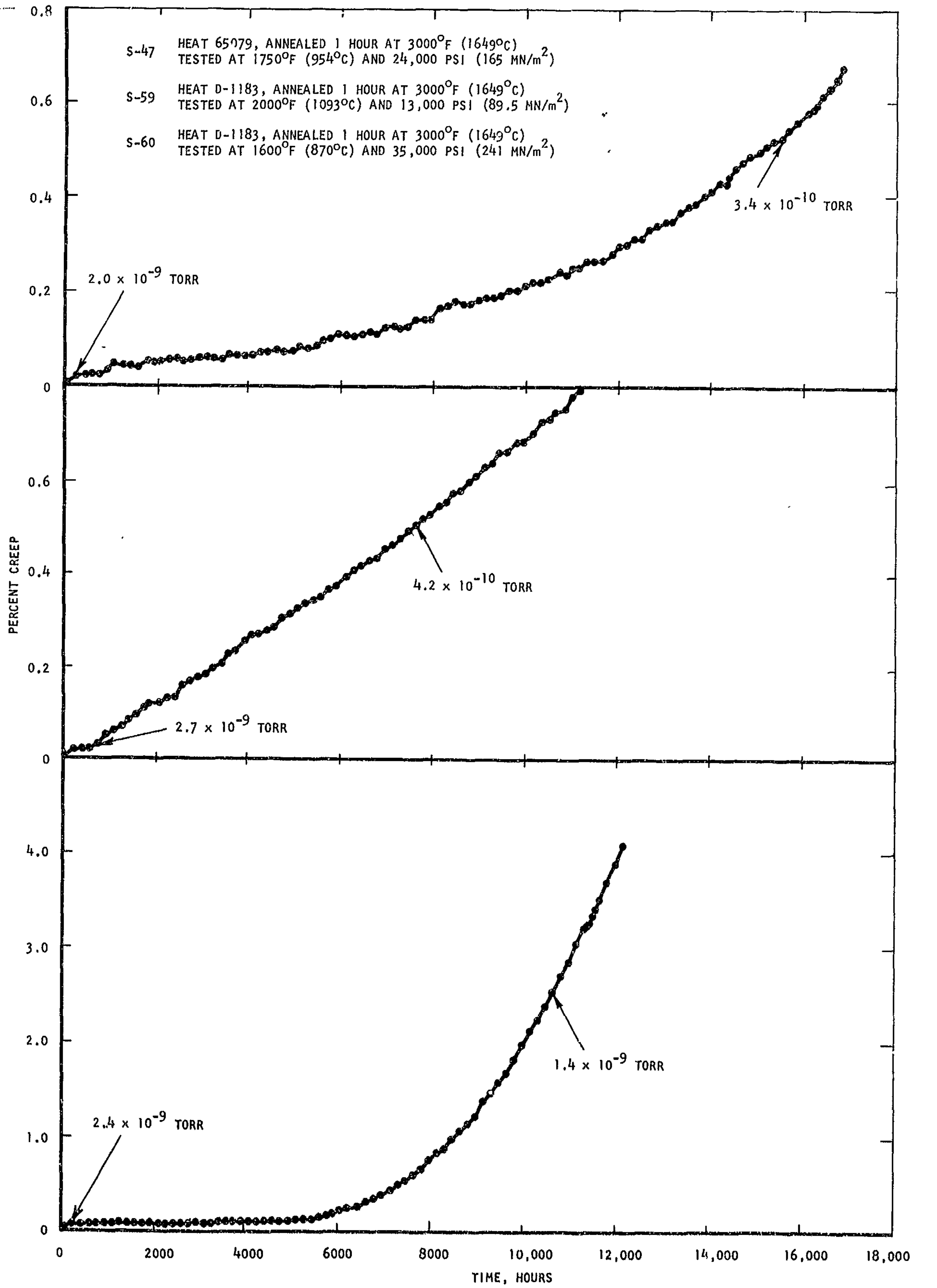

FIGURE III-9. CREEP TEST DATA, T-111, TEST NOS. S-47, S-59, AND S-60, TESTED IN A VACUUM ENVIRONMENT $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5733

7732 8

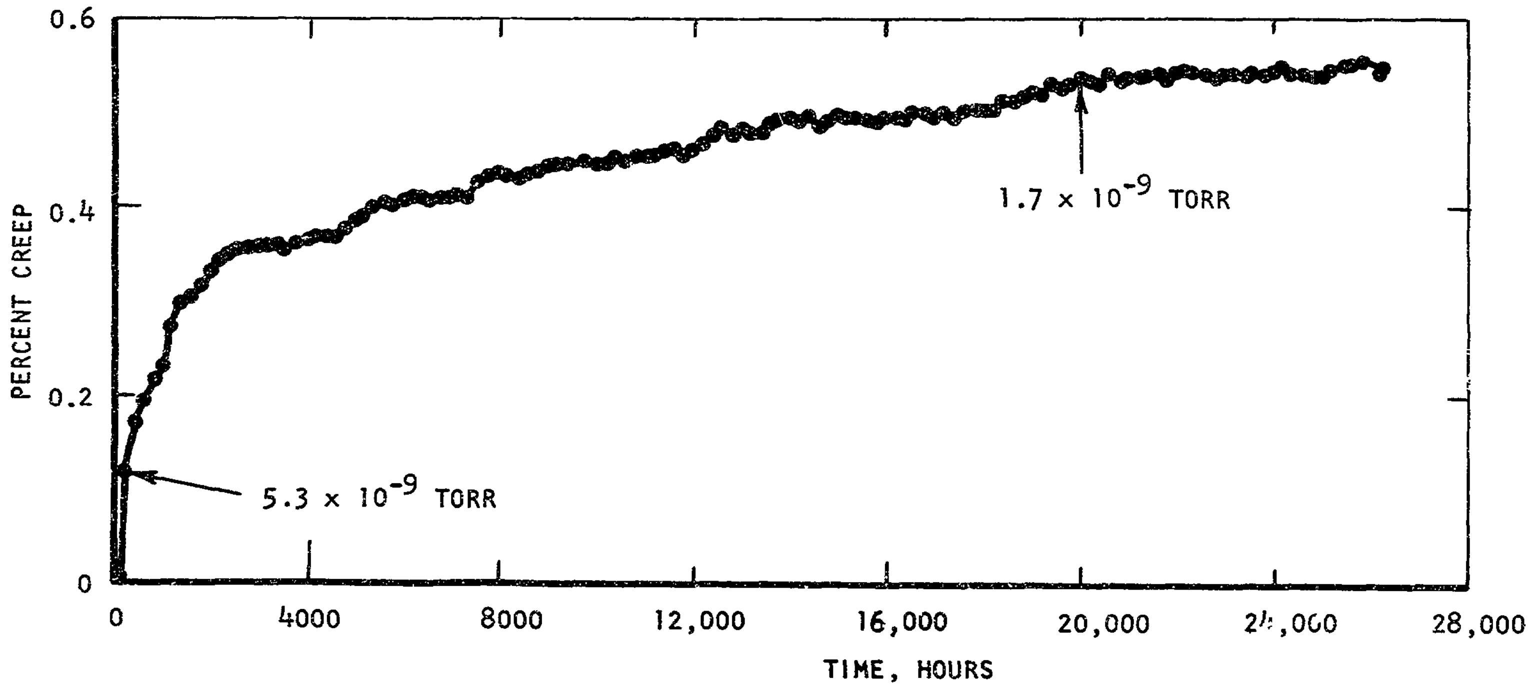

FIGURE III-10 CREEP TEST DATA, T-111, HEAT NO. D-1670, ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2600°F (1427°C) AND 0.5 KSI (3.4 MN/m²), TEST NO. S-28, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10⁻⁸ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

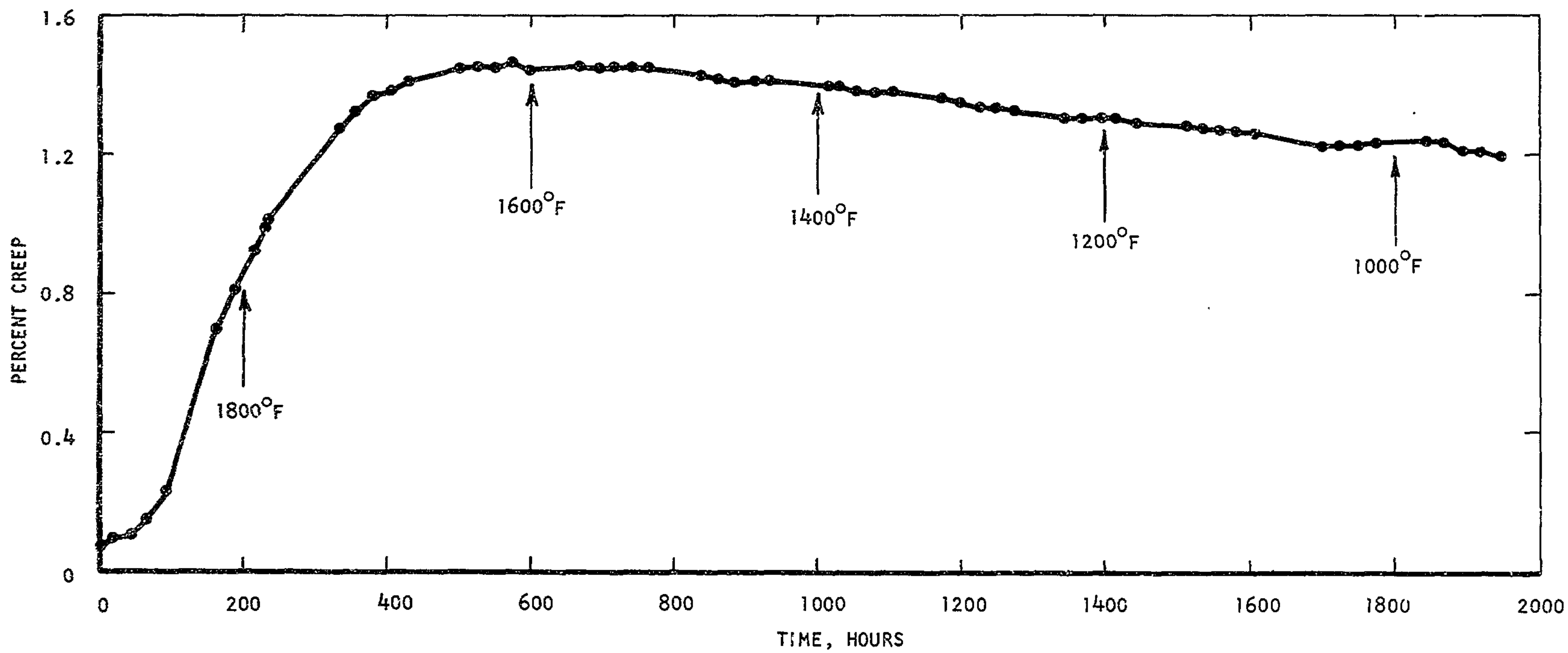

FIGURE III-11. CREEP TEST DATA, T-111, HEAT NO. 650028 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED STARTING AT 1900°F (1038°C) WITH TEMPERATURE CONTINUOUSLY DECREASING AT A RATE OF 0.5 F°/HR., AND AT 31 KSI (214 MN/m^2), TEST NO. S-82, IN THE VARIABLE TEMPERATURE PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE TEMPERATURE AT VARIOUS INTERVALS DURING THE TEST.

5723 8

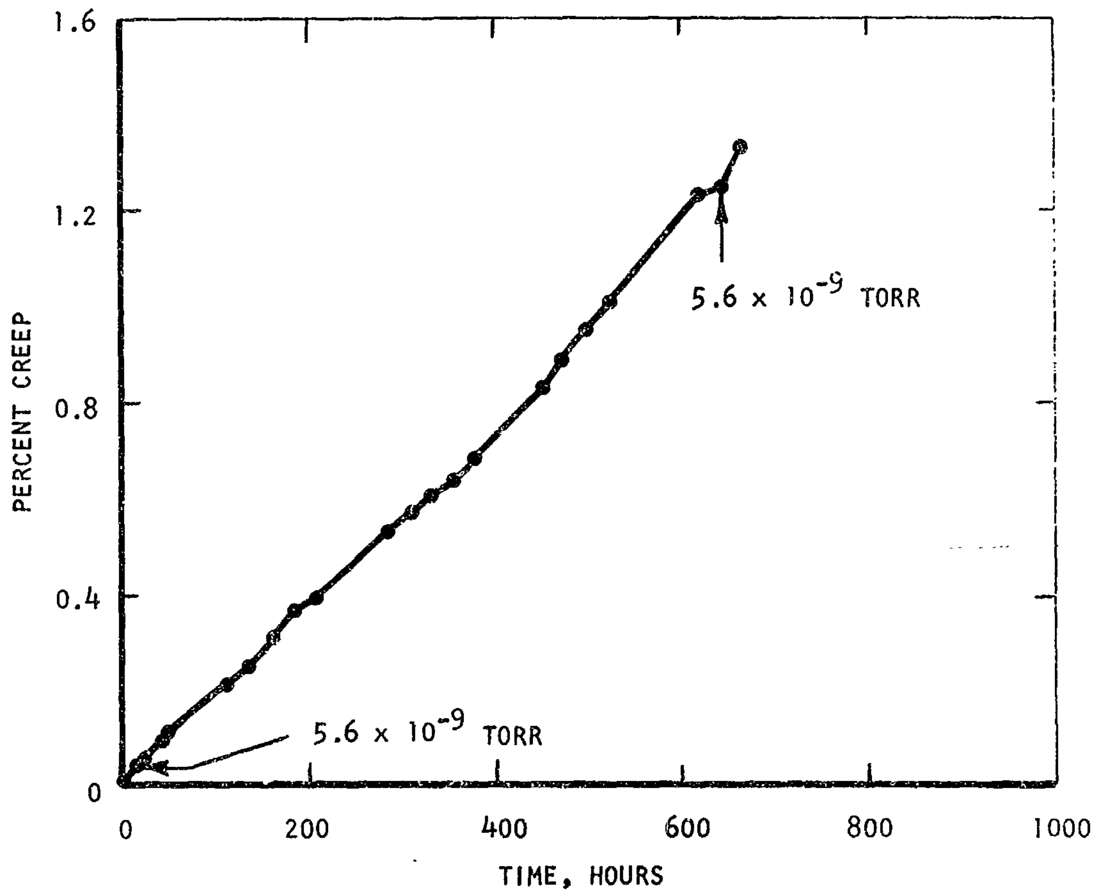

FIGURE III-12. CREEP TEST DATA, ASTAR 811C, HEAT NO. VAM-95 ANNEALED 24 HOURS AT 3270°F (1700°C), TESTED AT 2400°F (1316°C) AND 15 KSI (103 MN/m^2), TEST NO. S-81, TESTED IN A VACUUM ENVIRONMENT OF $< 1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

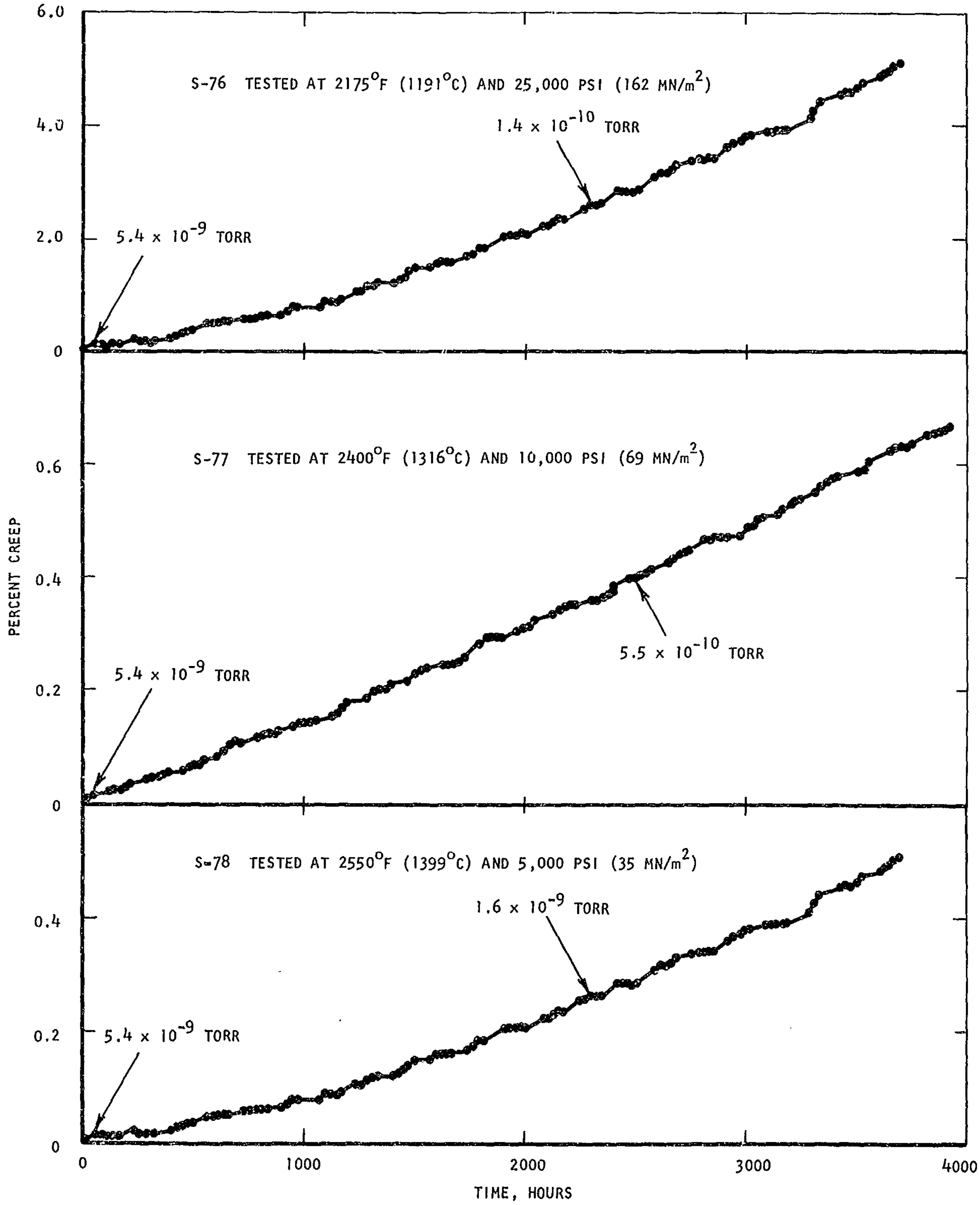

FIGURE III-13 CREEP TEST DATA, ASTAR 811C, HEAT NO. 66-650056, ANNEALED 0.5 HOUR AT 3600°F (1982°C), TEST NOS. S-76, S-77, AND S-78, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

5734 B