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

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K. D. Sheffler

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Technical Management:
P. E. Moorhead
Materials and Structures Division
National Aeronautics and Space Administration
Lewis Research Center
Space Power Systems

Materials Technology
TRW Equipment
23555 Euclid Avenue
Cleveland, Ohio 44117

FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-13469. This contract involves work similar to that conducted under Contracts NAS-3-9439 and NAS-3-2545. 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.

Prepared by: K. D. Sheffler
K. D. Sheffler
Engineer

Reviewed by: H E Collins
H. E. Collins
Principal Engineer

Approved by: E. A. Steigerwald
E. A. Steigerwald
Manager
Materials Research Department

ABSTRACT

Creep tests were conducted on two tantalum alloys (ASTAR 811C and T-111 alloy), on a molybdenum alloy (TZM), and on CVD tungsten. The T-111 alloy 1% creep life data have been subjected to Manson's station function analysis, and the progress on this analysis is described. In another test program, the behavior of T-111 alloy with continuously varying temperatures and stresses has been studied. The results indicated that the previously described analysis predicts the observed creep behavior with reasonable accuracy. In addition to the T-111 test program, conventional 1% creep life data have been obtained for ASTAR 811C alloy. Previously observed effects of heat treatment on the creep strength of this material have been discussed and a model involving carbide strengthening primarily at the grain boundaries, rather than in a classical dispersion hardening mechanism, has been proposed to explain the observed results.

SUMMARY

Ultrahigh vacuum creep test results have been obtained on four refractory alloys during the current report period. Creep tests were conducted on the tantalum base T-111 alloy (Ta-8%W-2%Hf) to provide additional creep life data for this material and efforts were made to analyze these data together with all of the previously obtained T-111 1% creep life data using Manson's recently developed station function analysis. While the analysis is not complete at the present time, results of the work performed to date are presented to document this new approach to parametric creep life correlation. A limited amount of 2% and 5% creep life data which has been obtained on the T-111 alloy is also presented. A creep test has been performed on a specimen of T-111 alloy having a duplex heat treatment (1 hour at 3000°F (1649°C) followed by 1 hour at 2400°F (1316°C) which was designed to simulate a post weld annealing treatment. No measureable difference could be detected between the results of this test and the conventional T-111 data.

In another phase of the program a creep test has been performed on T-111 alloy with the stress and temperature varying according to exponential equations which approximate the service conditions in an alpha-emitting radioisotope capsule. Results of this test were compared with predictions made using previously described analytical techniques. This comparison showed relatively good agreement between the predicted and the experimental results, particularly regarding the value of the stall strain, which is a maximum creep strain parameter that has been proposed for use in radioisotope capsule design.

Additional creep life data have been obtained on the tantalum base ASTAR 811C alloy (Ta-8%W-0.7%Hf-1%Re-0.025%C) and an interpretation of previously observed influences of heat treatment on the creep strength of this material has been developed. The proposed explanation involves carbide strengthening at grain boundaries, rather than in the classical dispersion hardening role. An experimental technique to provide additional support for this hypothesis has been proposed.

The influence of high temperature liquid metal exposure on the creep strength of ASTAR 811C has been evaluated. Results showed that a significant reduction of 1% creep life at 2400°F (1316°C) and at 15 and 9 ksi (103 and 55.1 mN/m^2) resulted from a 5000 hour exposure to liquid lithium at a temperature of 2400°F (1316°C).

The first of a series of creep tests on CVD tungsten annealed 100 hours at 3272°F (1800°C) was initiated during the current period. Results of this test showed a steady state creep rate of 7.15×10^{-7} hr^{-1} and an extrapolated 1% creep life of 14,000 hours at 2912°F (1600°C) and a 500 psi (3.5 nM/m^2).

In a continuation of a previous study, the influence of both composition and processing on the creep strength of the molybdenum base alloy TZM has been examined. 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.

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INTRODUCTION

Current design concepts for space electric power systems specify refractory metals and alloys in a number of high temperature applications where the creep strength of other materials is inadequate. The utilization of the refractory metal alloys depends upon the availability of suitable design creep data. This program has therefore been undertaken to provide the required creep information on selected refractory metal alloys.

The refractory metal components of the space power systems will operate either in a space vacuum or in an environment such as potassium vapor where the concentration of reactive gasses is extremely low. Because of this fact and the well known sensitivity of refractory metal behavior to interstitial contamination, the tests on this program have been conducted in ultrahigh vacuum chambers at pressures of less than 1×10^{-8} torr. Experience during the program has shown that this pressure is low enough to eliminate the possibility of environmental contamination during creep testing.

The majority of tests conducted on this program have been of the conventional constant load, constant temperature type. However, the application of tantalum alloys for structural containment of alpha-emitting radioisotope fuels has led to a need to characterize the creep behavior of these materials with continuously varying stresses and temperatures. In response to this need, both analytical and experimental techniques have been developed to study the creep of T-111 alloy with exponentially varying stress and temperature. The analytical results were described in a previous topical report on this contract[1], and preliminary experimental data will be presented in this report.

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 tantalum alloys are being evaluated predominately in the form of nominal 0.030" sheet, although a few selected tests have been 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. Typical microstructures for these test materials have been presented previously[2]. The standard heat treatment for the T-111 alloy is 1 hour at 3000°F (1649°C), while the ASTAR 811C alloy is being annealed 1/2 hour at 3600°C (1982°C). A small number of ASTAR tests were conducted on specimens from a General Electric Co. corrosion loop program. Details of these tests are given in the discussion section of this report.

The CVD tungsten test specimens were obtained in the form of 4" long by .060" thick sheet-type creep test specimens which were vapor deposited and machined to print by the vendor. Chemical analysis from a typical specimen is shown below:

Chemical Analysis of CVD Tungsten Creep Specimen (ppm)

W	C	O	N	H	F
Bal.	29	12	3	2	-

while a typical microstructure is shown in Figure 1. The specimens were of the duplex type, meaning that the cross section contained approximately 45 mils of a structure typical of the fluoride deposition process, and approximately 15 mils of a structure typical of the chloride deposition process. The annealing treatment for these specimens was 100 hours at 3272°F (1800°C).

TABLE 1

CHEMICAL COMPOSITION OF ALLOYS BEING EVALUATED IN CREEP PROGRAM

Material	Weight % W	Re	Mo	Ta	Hf	C	Ti	Zr	PPM N_2	O_2	H_2	Finished Form
TZM (Heat KDTZM-1175)			Bal.			.0350	.61	.130	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	" "

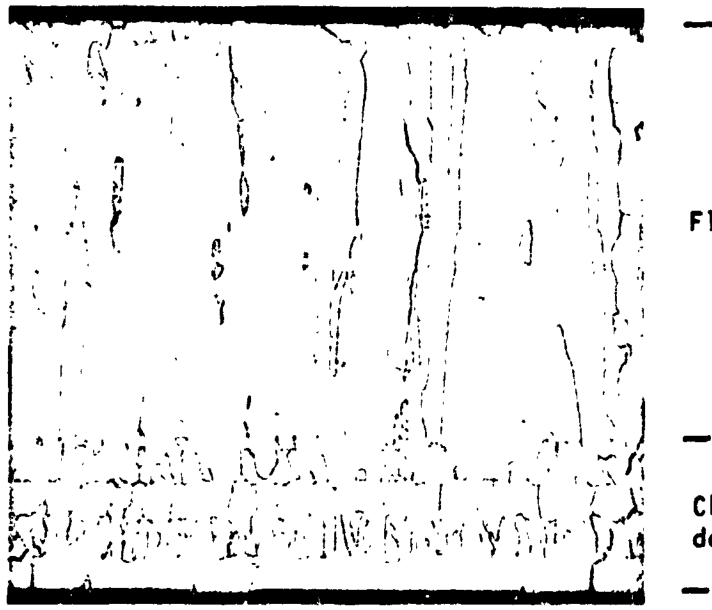

Figure 1. Photomicrograph of CVD tungsten annealed 100 hours at 3272°F (1800°C). 50X

General 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 creep in 2000 to 25,000 hours. Two inch gauge length, button-head bar-type specimens and double shoulder, pin loaded, sheet type specimens were 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)

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} torr 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.

Apparatus and Procedures for Exponentially Varying Stress and Temperature Tests

A previous analysis[1] has shown that the stress σ and absolute temperature T in a radioisotope capsule will vary according to the equations:

$$T = T_A + (T_0 - T_A)e^{-\lambda t} \tag{1}$$

and

$$\begin{aligned} \sigma &= F(T)(1-e^{\lambda t}) \\ &= F\{T_A + [T_0 - T_A]e^{-\lambda t})(1-e^{-\lambda t})\} \end{aligned} \tag{2}$$

where

T_A = ambient temperature (absolute)

T_0 = initial capsule temperature (absolute)

λ = isotope decay constant = ln (2)/half life

F = proportionality constant

The stress and temperature profiles provided by these equations are illustrated in Figure 2. The objective of the experimental program was to conduct creep tests on T-111 alloy with the stress and temperature changing continuously according to the Equations 1 and 2 to evaluate the accuracy of the analytical predictions based on constant load, constant temperature tests. To facilitate this objective a computer program was written to calculate the desired values of σ and T at periodic intervals throughout each test (Appendix IV). A typical output from this program is shown in Appendix V. These data correspond to the experimental test S-109 which was conducted during the current report period. Values used for the starting temperature, half life, stress level, etc. are shown at the beginning of the table. An ambient temperature of 75°F was used in the calculations and the stress factor F was calculated by the program so that the stress versus temperature profile would be tangent to the yield strength versus temperature profile for the T-111 alloys, as indicated by the stress level of unity. A detailed discussion of the meaning of each of these parameters can be found in Reference 1. The width and thickness of the specific test specimen to be used for each test is provided to the program so that the loads and load changes may be calculated from the stress data. The W-3%Re/W-25%Re thermocouple outputs are generated internally by a sixth order polynomial which was fit to calibration data supplied by Englehart. The calibration factor shown in the heading is the deviation of the individual thermocouple to be used for the test from the general W-Re calibration curve. (This individual calibration is performed by the vendor on each thermocouple purchased for the creep program.) The desired millivolts column shown in the output includes this correction factor as well as the reference junction correction factor so that the indicated value corresponds exactly to the correct

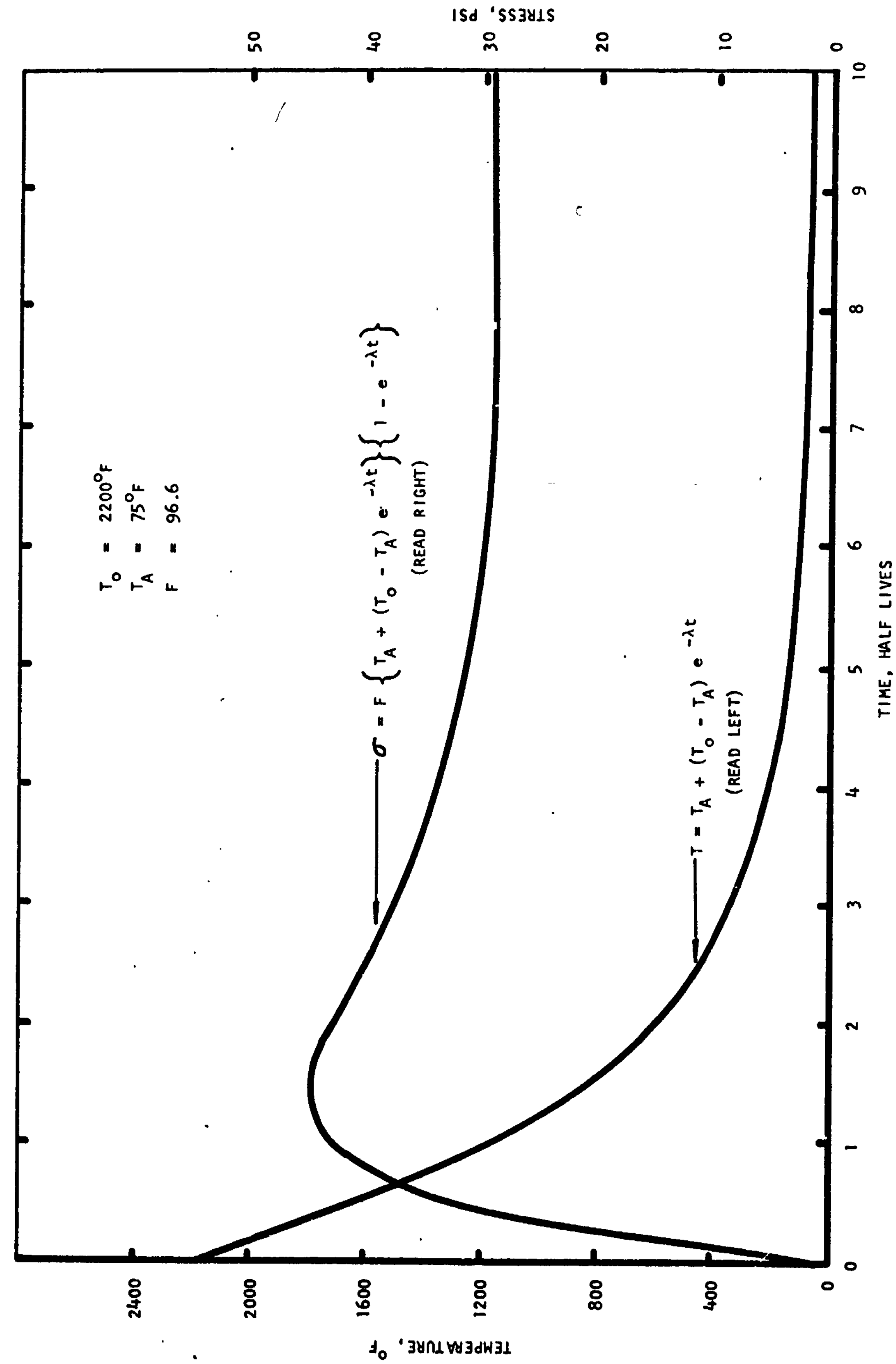

Figure 2. Variation of temperature and stress with time.

temperature for the specific thermocouple being used for the test. The actual millivolts and patch hole columns are used as set up data on the experimental apparatus, as are the delta load columns.

The equipment used for continuous varying of the load consists of a lead shot feeder and a collector assembly attached to the load train in place of the static load pan. This equipment was described in an earlier report, Reference 4. As used previously, the shot feeder was driven at a uniform speed by a fractional horsepoqer DC motor which provided a load that increased linearly with respect to time. For the present tests it was necessary to modify the motor speed control so that a continuously varying loading rate could be achieved. This was done by adding a system of resistors, stepping switches, and patch boards to the system which allowed complete flexibility in the programming of the loading rate with time. Typical results obtained with this system are illustrated in Figure 3a where the experimentally applied loads for the first 400 hours of test S-109 are compared to the desired loads from Appendix V. These data demonstrate the extremely close accuracy of loading which this equipment provides.

Temperature variation was accomplished using a somewhat different approach. A synchronous drive motor was attached to the temperature controller (see Figure 4) and this motor was driven intermittently to achieve the desired rate of temperature variation. A system of cams, stepping switches, and patch boards (Figure 5) was used to program the rate of temperature variation and thereby provide the desired temperature-time profile. Typical results are shown in Figure 3b where the measured temperatures from the first 400 hours of test S-109 are compared with the desired values from Appendix V. Again, there is extremely close agreement between the desired and the observed values.

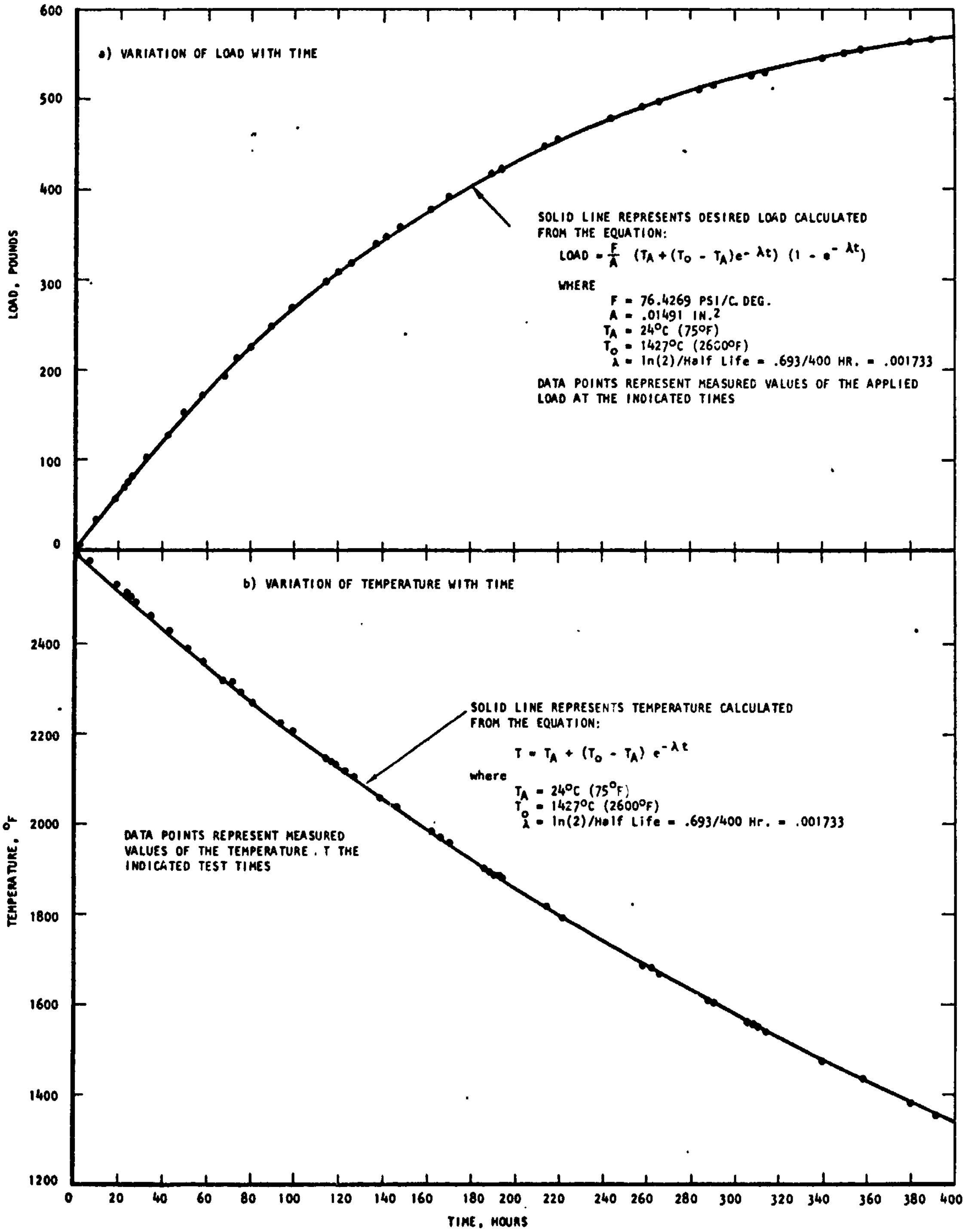

FIGURE 3 COMPARISON OF DESIRED AND EXPERIMENTAL LOAD AND TEMPERATURE VARIATION FOR CREEP TEST S-109

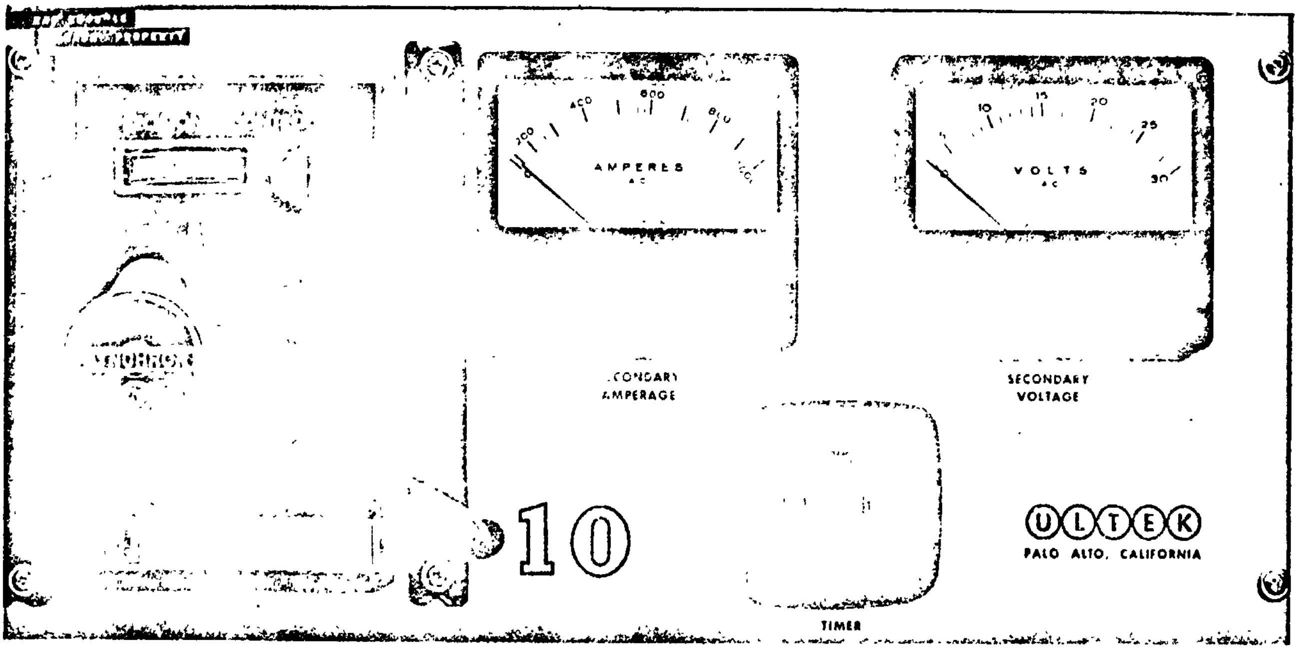

Figure 4. Photograph of temperature control panel as modified by the addition of a drive motor for continuous variation of the temperature setting.

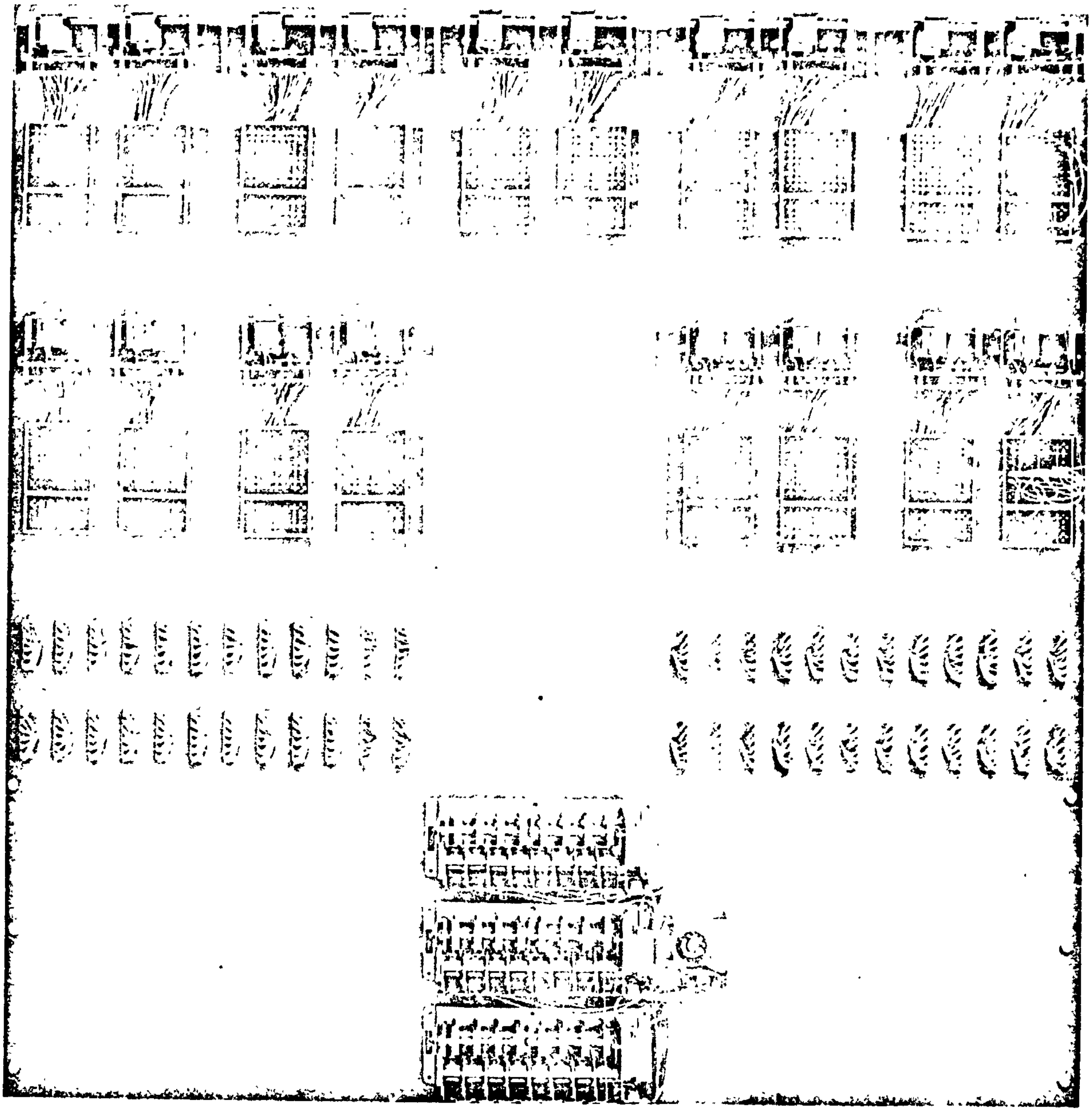

Figure 5. Cam timer system for programming of the temperature variation.

RESULTS AND DISCUSSION

Presentation and discussion of the test results will be divided into four sections concerning the T-111, ASTAR 811C, vapor deposited tungsten, and TZM test materials. A summary of the tests conducted during this report period is presented in Appendix II together with all of the previous tests from the vacuum creep program. Creep curves for each test conducted during the current reporting period are presented in Appendix III.

T-111 Alloy Results

Discussion of the current T-111 test results will be subdivided into sections on conventional test results, parametric studies of the conventional T-111 creep data, and results from the exponentially varying stress and temperature program.

1. Conventional Test Results

Additional conventional creep tests were conducted on T-111 alloy during the current reporting period with the primary purpose of "filling in" areas in the Larson-Miller plot where sufficient data were not available to clearly define a scatter band. The additional data generated are summarized on a Larson-Miller plot in Figure 6 and on a plot of temperature compensated creep rate versus hyperbolic sine of the stress in Figure 7. Both of these plots shown good agreement with the previously published data[6].

A limited amount of creep life data was obtained on T-111 alloy during the current report period at higher creep strains than the previously used 1% value. These results are summarized in Table 2 and in Figure 8, where the available 2% and 5% T-111 creep life data are compared on a Larson-Miller diagram with the average of the 1% creep results from Figure 6. While sufficient results are not available to define a scatter band, the data presented allow an estimate of the 2% and 5% creep strengths relative to the 1% creep strength. Presuming that the inherent data scatter at the higher creep strains is similar to the 1% data scatter, these relative strength increases can be used in conjunction with the low limit of the 1% scatter band to design to 2% and 5% creep in T-111 alloy.

A creep test was performed during the current report period on a specimen of T-111 alloy having a duplex heat treatment (1 hour at 3000°F (1649°C) followed by 1 hour at 2400°F (1316°C)) which was designed to simulate a currently used post weld annealing treatment. Results of this test were not measureably different from the conventional T-111 test results, as indicated in Figure 6.

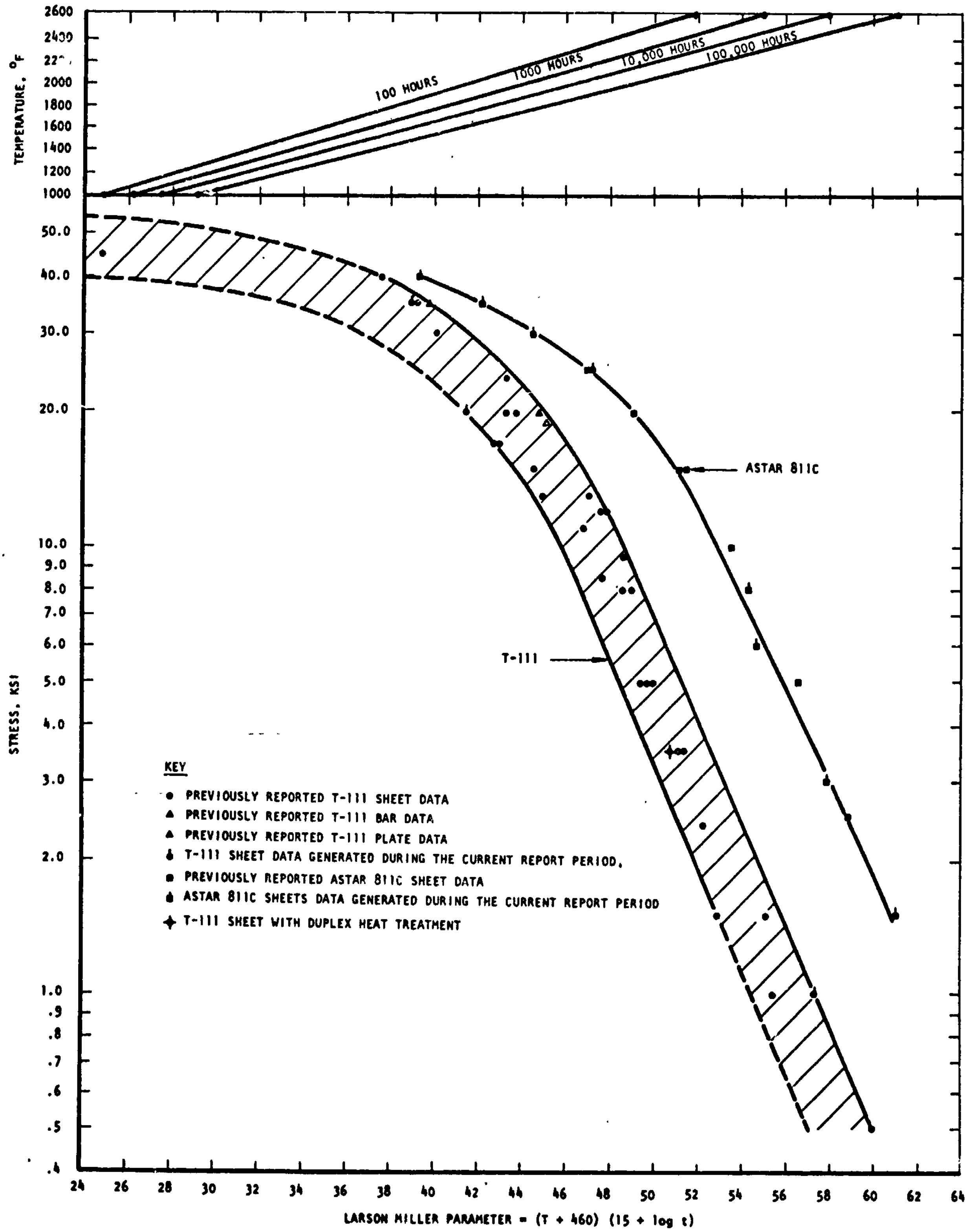

FIGURE 6 PARAMETRIC REPRESENTATION OF 1% CREEP LIFE DATA FOR T-111 ALLOY ANNEALED 1 HOUR AT 3000°F (1649°C) AND FOR ASTAR 811C ALLOY ANNEALED 1/2 HOUR AT 3600°F (1982°C)

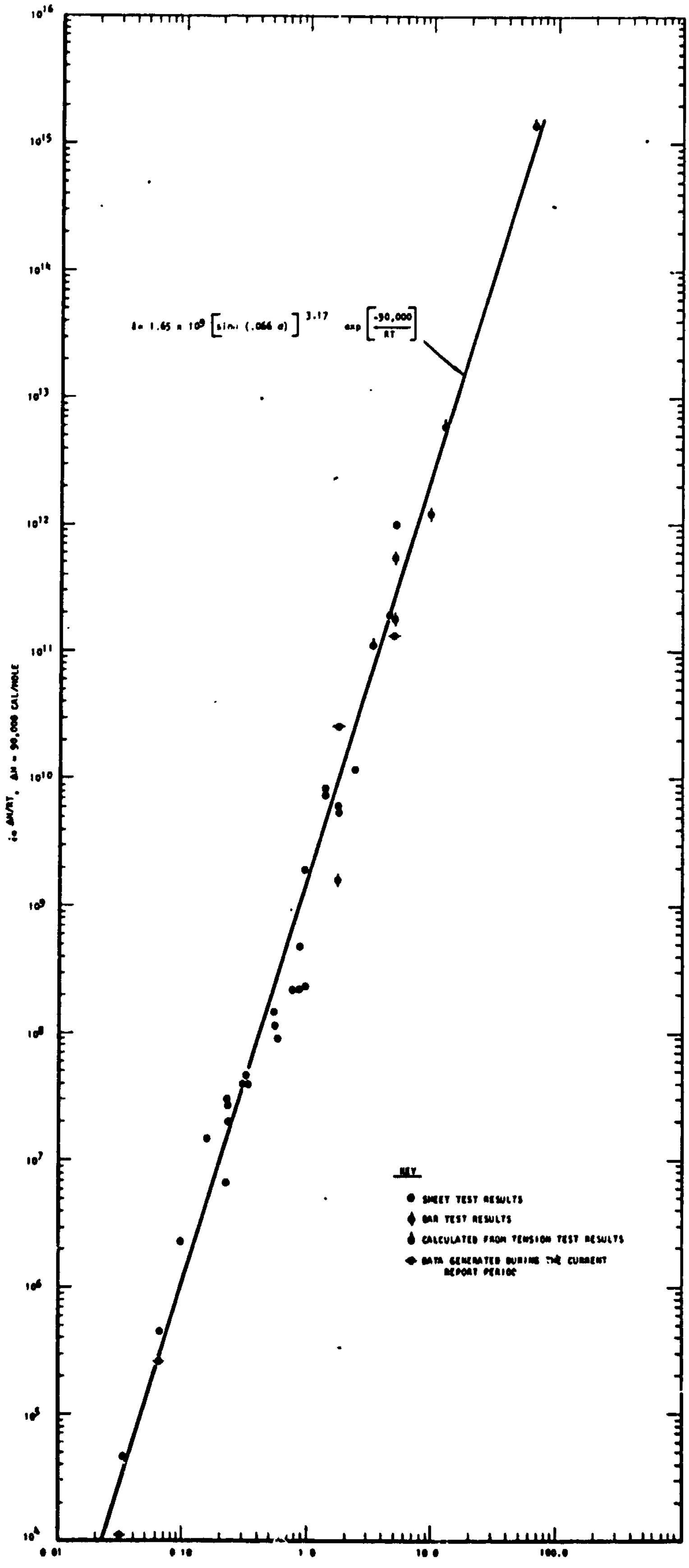

FIGURE 7. VARIATION OF TEMPERATURE COMPENSATED CREEP RATE WITH HYPERBOLIC SINE STRESS FUNCTION IN T-111 ALLOY ANNEALED ONE HOUR AT 3000°F (1649°C).

TABLE 2

CREEP LIFE DATA FOR T-111 ANNEALED 1 HOUR AT 3000°F (1649°C)

Test No.	Heat No.	Stress ksi	Stress mN/m²	Temperature °F	Temperature °C	Creep Life Hours	LMP T°R (15 + log T)
Two Percent Extension							
S-19	70616	8	55.1	2200	1204	3325	49.3
S-21	70616	12	82.6	2200	1204	1800	48.6
S-22	70616	20	138.0	2000	1093	1095	44.4
S-27	D-1102	13	89.5	2000	1093	3350	45.6
S-30	65079	3.5	24.1	2400	1316	1760	52.2
S-47	65079	24	165.0	1750	954	28,000*	43.0
S-60	D-1183	35	241.0	1600	870	10,000	39.1
S-68	650028	1	6.9	2560	1403	24,000*	58.5
B-44	650038	35	241.0	2000	1093	26	40.4
P-1	8049	19	131.0	2000	1093	3475	45.6
S-84	650028	1.5	10.4	2400	1316	7500*	54.0
S-107	848001	20	138.0	1900	1038	790	42.2
Five Percent Extension							
S-19	70616	8	55.1	2200	1204	6300*	50.0
S-21	70616	12	82.6	2200	1204	3235	49.2
S-30	65079	3.5	24.1	2400	1316	5000	53.5
S-60	D-1183	35	241.0	1600	870	13,000	39.4
B-44	650038	35	241.0	2000	1093	43	40.9
S-107	848001	20	138.0	1900	1038	2000	43.2

* Extrapolated

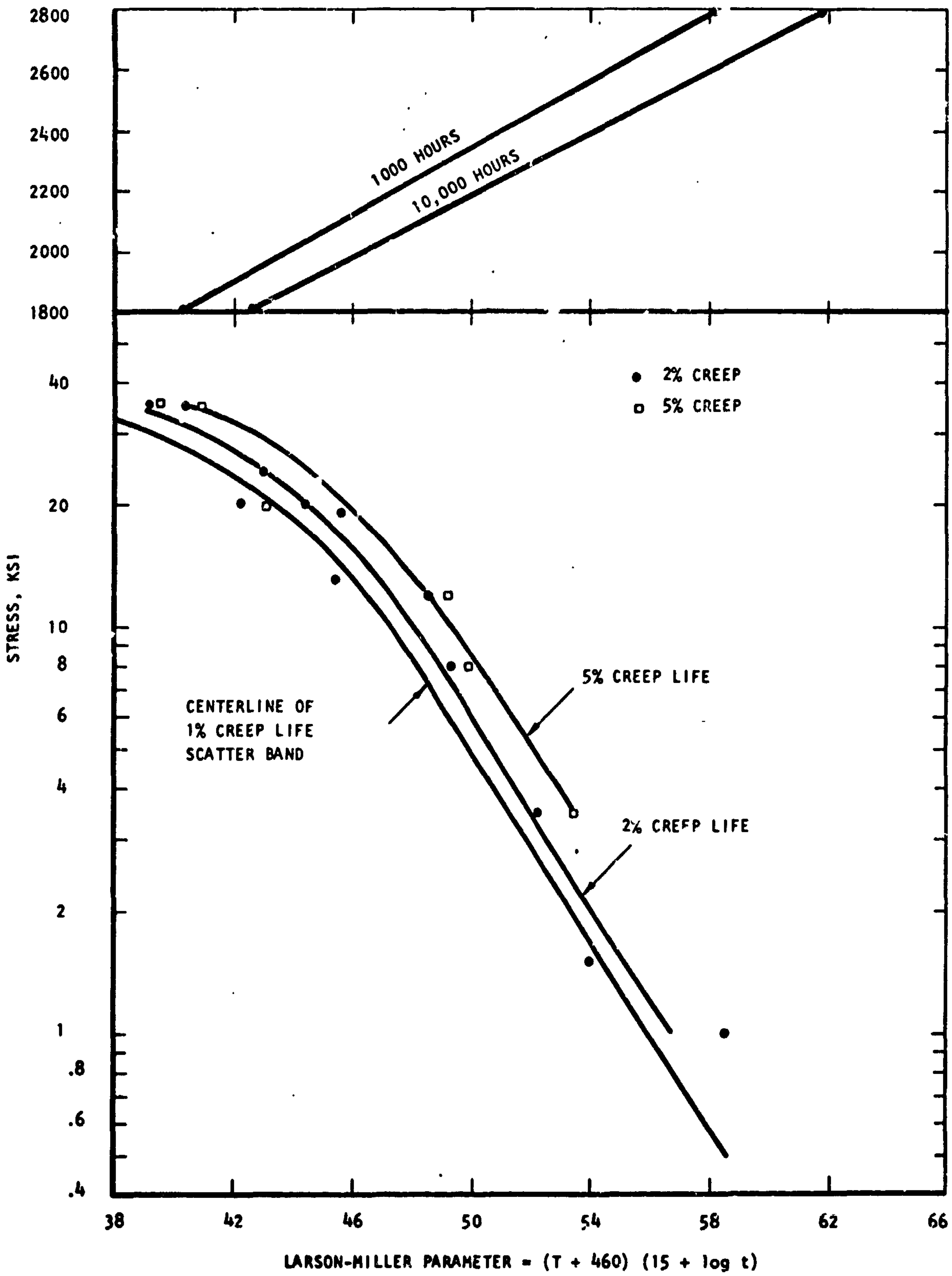

FIGURE 8. PARAMETRIC REPRESENTATION OF CREEP LIFE DATA FOR T-111 ALLOY ANNEALED 1 HOUR AT 3000°F (1649°C).

2. Parametric Analysis of Conventional Creep Test Data

A new approach to the problem of parametric representation of stress, temperature, and creep life data was recently discussed by Manson[5]. An effort is presently being made to apply this new technique, which is called station function analysis, to the T-111 alloy 1% creep life data generated in this program. While the results of the analysis are not yet complete, the following discussion is being presented to document the method and to describe the current state of progress on this effort.

Station function analysis differs from previous methods in that it involves essentially a "minimum commitment" to the form of the correlating parameter. Conventional techniques for creep data correlation require that a correlating parameter (or parameters) first be postulated and then curve-fitting techniques are used to determine how well the parameter describes the experimental data. The station function analysis is a method which permits numerical values of the optimum correlating parameter to be calculated without specifying the analytical form of the parameter. This approach has the significant advantage of providing a convenient means by which the experimental data may be used to determine the best form of parameter for the specific material being tested.

The station function analysis is based on assumption that the creep data can be represented by a generalized parametric equation of the form:

$$g\,(\log \sigma) = p(T) + f(\log t) \tag{3}$$

where t is creep life, T is test temperature, and σ is stress. The well known correlating parameters such as the Larson-Miller, the Manson-Haferd, the Orr-Sherby-Dorn, etc. are included as special cases of this generalized parametric equation. The Larson-Miller parameter, for example, which has the standard form:

$$P(\log \sigma) = (T + 460)(C + \log t) \tag{4}$$

can be transformed by taking logs of both sides:

$$\log P(\log \sigma) = \log(T + 460) + \log(C + \log t) \tag{5}$$

which has the form of (3) with

$$g(\log \sigma) = \log P(\log \sigma)$$

$$p(T) = \log\,(T + 460)$$

$$f(\log t) = \log(C + \log t)$$

Similar transformations can be applied to other standard parameters to achieve the desired form.

Application of the station function analysis requires that specific "stations" or discrete values of the three experimental variables be selected prior to computing the "station functions," which are the numerical values of the p, f, and g parameters at each station. The range of stations selected for each variable must contain the range of the experimental data and the stations must be distributed within that range so that no two adjacent intervals between stations are void of data. The values of the correlating parameters at each station are then calculated by solving a system of simultaneous linear equations in which the discrete values of the station functions are the unknowns. Each equation in the system represents data from a single creep test. In order to have enough equations to solve for all of the station functions, it is necessary that the total number of stations be equal to or less than the number of data points available. The detailed method of applying Equation (3) to each data point is best illustrated by the following example.

The T-111 creep data selected for analysis by the station function method are given in Table 3, while the stations selected for the analysis are shown in Table 4. Ideally, it would be desireable for each station to correspond to an experimental test condition. However, in practice this is difficult to accomplish, particularly in the present case where the experimental test conditions are not arranged at uniform stress and temperature intervals. In this case it was necessary to establish the stations at uniform intervals and to interpolate to obtain the station functions at the experimental data points. This procedure will be illustrated using the data for test S-60 from Table 3. The value of the parameter for this test is easily seen to be p_1, since the test temperature coincides with the 1600°F stati in Table 4. However, the stress and creep life for this test fall between stations and it will therefore be necessary to interpolate to obtain the g and f station functions. The procedure used will be the linear interpolation method suggested by Manson. Simply stated, this procedure says that the value of the station function at a test condition intermediate between two stations will be linearly related to the relative distances of the experimental test condition between the two stations. Thus, for example, if an experimental test condition fell exactly half way between two stations, it would be assumed that the value of the station function for that test condition would be exactly half way between the values of the station functions at the two adjacent stations. If the test condition is 1/4 of the way between one station and the other, the station function will be the sum of three quarters of the value of the closer station function and 1/4 of the value of the farther station function. For the specific case of test S-60, the log of the test stress is 4.544, which falls between stations g_6 and g_7. Linear interpolation thus gives the value of the g function at this test condition:

$$\text{g function at 35 ksi} = \frac{(4.699-4.544)}{(4.699-4.301)} g_6 + \frac{(4.544-4.301)}{(4.699-4.301)} g_7 \qquad (6)$$

$$= .39g_6 + .61g_7$$

TABLE 3

T-111 CREEP TEST DATA USED IN STATION FUNCTION ANALYSIS

Test No.	Temperature °F	Stress psi	Log Stress	1% Creep Life Hours	Log Life
S-60	1600	35,000	4.544	8550	3.932
S-69	1625	30,000	4.477	16,506	4.218
S-47	1750	24,000	4.380	19,896	4.298
S-40	1800	17,000	4.230	8558	3.932
*	1800	17,000	4.230	9000	3.954
S-26	1800	17,000	4.230	9540	3.979
S-24	1860	20,000	4.301	4730	3.675
S-50	2000	8500	3.929	24,000**	4.380
S-34	2000	11,000	4.041	10,800	4.034
S-27	2000	13,000	4.114	1880	3.274
S-59	2000	13,000	4.114	13,350	4.126
S-25	2000	15,000	4.176	1340	3.127
S-22	2000	20,000	4.301	670	2.862
S-23	2120	12,000	4.079	3450	3.538
S-21	2200	12,000	4.079	1140	3.057
S-19	2200	8000	3.903	2000	3.301
S-33	2200	8000	3.903	2850	3.455
S-32	2200	5000	3.699	4050	3.608
S-35	2200	5000	3.699	5400	3.732
S-31	2200	5000	3.699	6160	3.790
S-88	2300	3500	3.544	2565	3.409
S-42	2300	3500	3.544	3810	3.581
S-48	2330	2400	3.380	5500	3.740
S-84	2400	3500	3.544	3250	3.521
S-30	2400	1500	3.176	860	2.934
S-68	2560	1000	3.000	2300	3.362
S-28	2600	500	2.699	55,000**	4.740

* Interpolated data - does not correspond to an actual test

** Extrapolated

TABLE 4

FIRST SET OF STATIONS CHOSEN FOR APPLICATION OF THE STATION FUNCTION ANALYSIS TO T-111 ALLOY

Stress Stations			Temperature Stations		Time Stations		
Stress psi	Log Stress	Station Name	Temperature °F	Station Name	1% Creep Life Hours	Log Life	Station Name
500	2.699	g_1	1600	p_1	562	2.75	f_1
1000	3.000	g_2	1700	p_2	1000	3.00	f_2
2000	3.301	g_3	1800	p_3	1780	3.25	f_3
5000	3.699	g_4	1900	p_4	3160	3.50	f_4
10,000	4.000	g_5	2000	p_5	5620	3.75	f_5
20,000	4.301	g_6	2100	p_6	10,000	4.00	f_6
50,000	4.699	g_7	2200	p_7	17,800	4.25	f_7
			2300	p_8	31,600	4.50	f_8
			2400	p_9	56,200	4.75	f_9
			2500	p_{10}			
			2600	p_{11}			

The creep life function at the 8550 hour creep life for S-60 is obtained similarly as:

$$\text{f function at 8550 hours} = \frac{(4.00-3.932)}{(4.00-3.75)} f_5 + \frac{(3.932-3.75)}{(4.00-3.75)} f_6 \quad (7)$$

$$= .27f_5 + .73f_6$$

The form of Equation (3) for test S-60 is thus

$$.39g_6 + .61g_7 = p_1 + .27f_5 + .73f_6$$

or, rearranging, (8)

$$-39g_6 -.61g_7 + p_1 + .27f_5 + .73f_6 = 0$$

Similar procedures may be used to generate additional equations for each of the remaining tests. The set of equations so generated will constitute a set of simultaneous linear equations.

The next step in the station function analysis is to solve this set of simultaneous equations for the unknowns, which are the numerical values of the correlating functions at each of the preselected stations. In order to do this it is first necessary to rearrange the equations into a format which is suitable for treatment by one of the standard methods for solving simultaneous equations. To make the format more convenient the unknowns will be renamed as X_1 through X_{27} instead of the previously used p, f, and g names. The variables X_1 through X_7 will correspond to g_1 through g_7, X_8 through X_{18} will correspond to p_1 through p_{11}, and X_{19} through X_{27} will correspond to f_1 through f_9. Using these variable names the 27 simultaneous equations may be expressed in the form

$$\begin{array}{llll}
a_{1,1}X_1 + a_{12}X_2 + \text{- - - - - - - - - -} & + a_{1,27}X_{27} & = b_1 & \\
a_{2,1}X_1 + \text{- - - - - - - - - - - - - -} & + a_{2,27}X_{27} & = b_2 & \\
\vdots & \vdots & \vdots & (9) \\
a_{27,1}X_1 + \text{- - - - - - - - - - - - - -} & + a_{27,27}X_{27} & = b_{27} &
\end{array}$$

where the coefficients correspond to the coefficients calculated for each data set using the linear interpolation technique. Again using the S-60 data as an example, inspection of Equation (8) shows that the coefficients in the first row will be:

$a_{1,6} = -.39$

$a_{1,7} = -.61$

$a_{1,8} = 1$

$a_{1,23} = .27$

$a_{1,24} = .73$

and all of the rest of the coefficients in the first row will be zero, as will all of the right hand b terms in Equation (9). In working with the complete system it is generally simpler to speak in terms of the coefficient matrix [A], which is the matrix formed by the individual $a_{i,j}$ coefficients, rather than to write out the complete set of equations. If [A] is defined in this way and if the column vectors [X] and [B] are defined as:

$$[X] = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_{27} \end{bmatrix} \qquad [B] = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ \vdots \\ b_{27} \end{bmatrix} \tag{10}$$

then by the rules of matrix multiplication the system (9) may be expressed in the compact form:

$$[A][X] = [B] \tag{11}$$

Using the assistance of a high speed digital computer, the coefficient matrix shown in Table 5 was developed from the creep data in Table 3. Each row of this matrix is labeled to show the creep test from which the equation was constructed and the columns are labeled to show both the original and the renamed unknowns.

Unfortunately it is not possible to directly solve a system of equations such as the one presently under consideration. The problem is that this is a homogenous system, that is, one where all of the right hand b terms contained in [B] are zero, and as such it does not have a unique solution. This type of system can be solved only by arbitrarily specifying one or more of the unknowns and then solving for the rest of the unknowns in terms of the arbitrarily fixed values.

ROW NO.	PSI							FAHRENHEIT											HOURS									
	500 (g_1) × 1	1000 (g_2) × 2	2000 (g_3) × 3	5000 (g_4) × 4	10,000 (g_5) × 5	20,000 (g_6) × 6	50,000 (g_7) × 7	1600 (P_1) × 8	1700 (P_2) × 9	1800 (P_3) × 10	1900 (P_4) × 11	2000 (P_5) × 12	2100 (P_6) × 13	2200 (P_7) × 14	2300 (P_8) × 15	2400 (P_9) × 16	2500 (P_{10}) × 17	2600 (P_{11}) × 18	562 (f_1) × 19	1000 (f_2) × 20	1780 (f_3) × 21	3160 (f_4) × 22	5620 (f_5) × 23	10,000 (f_6) × 24	17,800 (f_7) × 25	31,600 (f_8) × 26	56,200 (f_9) × 27	
1	0	0	0	0	0	-.39	-.61	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.27	.73	0	0	0	S-60
2	0	0	0	0	0	-.56	-.44	.75	.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.13	.87	0	0	S-69
3	0	0	0	0	0	-.80	-.20	0	.50	.50	0	0	0	0	0	0	0	0	0	0	0	0	0.	0	.80	.20	0	S-47
4	0	0	0	0	-.23	-.77	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	.27	.73	0	0	0	S-40
5	0	0	0	0	-.23	-.77	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	.18	.82	0	0	0	*
6	0	0	0	0	-.23	-.77	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	.08	.92	0	0	0	S-26
7	0	0	0	0	0	-1	0	0	0	.40	.60	0	0	0	0	0	0	0	0	0	0	.30	.70	0	0	0	0	S-24
8	0	0	0	-.23	-.77	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	.48	.52	0	S-50
9	0	0	0	0	-.86	-.14	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	.87	.13	0	0	S-34
10	0	0	0	0	-.62	-.38	0	0	0	0	0	1	0	0	0	0	0	0	0	0	.90	.10	0	0	0	0	0	S-27
11	0	0	0	0	-.62	-.38	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	.50	.50	0	0	S-59
12	0	0	0	0	-.42	-.58	0	0	0	0	0	1	0	0	0	0	0	0	0	.49	.51	0	0	0	0	0	0	S-25
13	0	0	0	0	0	-1	0	0	0	0	0	1	0	0	0	0	0	0	.70	.30	0	0	0	0	0	0	0	S-22
14	0	0	0	0	-.74	-.26	0	0	0	0	0	0	.80	.20	0	0	0	0	0	0	0	.85	.15	0	0	0	0	S-23
15	0	0	0	0	-.74	-.26	0	0	0	0	0	0	0	1	0	0	0	0	0	.77	.23	0	0	0	0	0	0	S-21
16	0	0	0	-.32	-.68	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	.80	.20	0	0	0	0	0	S-19
17	0	0	0	-.32	-.68	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	.18	.82	0	0	0	0	0	S-33
18	0	0	0	-1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	.57	.43	0	0	0	0	S-32
19	0	0	0	-1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	.07	.93	0	0	0	0	S-35
20	0	0	0	-1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	.84	.16	0	0	0	S-31
21	0	0	-.39	-.61	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	.36	.64	0	0	0	0	0	S-88
22	0	0	-.39	-.61	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	.68	.32	0	0	0	0	S-42
23	0	0	-.80	-.20	0	0	0	0	0	0	0	0	0	0	.70	.30	0	0	0	0	0	.04	.96	0	0	0	0	S-48
24	0	-.42	-.58	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	.95	.05	0	0	0	0	S-84
25	0	0	-.39	-.61	0	0	0	0	0	0	0	0	0	0	0	1	0	0	.26	.74	0	0	0	0	0	0	0	S-30
26	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.40	.60	0	0	.55	.45	0	0	0	0	0	S-68
27	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	.04	.96	S-28

TABLE 5 COEFFICIENT MATRIX FOR STATION FUNCTION ANALYSIS

Actually, there is a procedure by which the number of arbitrarily specified variables required for a consistent solution may be determined, using the rank of the coefficient matrix. The rank of a matrix is defined as the order of the largest none-zero detriment which is contained within that matrix. In the general case of a nonhomogenous set of n simultaneous linear equations in n unknowns, a unique solution is possible if and only if the determinant of the coefficient matrix is not zero; that is, for a unique solution the rank of the coefficient matrix must be equal to its order n. In the special case of a homogenous set of n simultaneous linear equations in n unknowns, a solution is possible only if the determinant of the coefficient matrix is zero; that is, the rank of the coefficient matrix must be at least one less than its order n. (If the rank of the coefficient matrix is equal to the order n then the system will be found to be inconsistent.). It can be shown, in fact, that the number of unknowns which must be arbitrarily specified for the system to be solvable is equal to the difference between the order of the coefficient matrix and the rank of the coefficient matrix. Further, it is possible to determine which unknowns can and which cannot be arbitrarily specified by removing from the coefficient matrix the column corresponding to the unknown in question and determining if the removal changes the rank of the resulting (n)x(n-1) matrix. If the rank is not changed by the removal then the unknown may be arbitrarily fixed; if the rank is changed then the unknown may not be arbitrarily specified.

Using the techniques described above a solution was obtained to the system of equations represented by the coefficient matrix in Table 5. Unfortunately, it was found that the results were not physically meaningful; that is, the values calculated for the station functions varied randomly in the range between 1 and 10^{-12} and showed no systematic variation with the corresponding station values of the creep variables. It was felt that this result was caused by the fact that the system as shown in Table 5 was poorly conditioned for a least squares solution. Using computerized techniques, the rank of the matrix shown in Table 5 was found to have a value of 24, meaning that it was necessary to arbitrarily specify three of the station functions. Of more importance, however, was the fact that the value of the largest non-zero determinant contained within the sub-matrix (that is, the 27 x 24 matrix from which the coefficients of the arbitrarily specified unknowns had been removed) had a value on the order of 10^{-7}, meaning that even the solvable system was very poorly conditioned for the least squares solution.

In an effort to determine the cause for the poor conditioning of the codfficient matrix, the data were re-examined to see if any obvious inconsistencies could be detected. It was thought that perhaps the presence of duplicate tests where the creep life results were not identical (e.g., tests S-26 and S-40) might cause difficulty in obtaining a meaningful solution. In an effort to eliminate this situation, the results of all of duplicate tests were averaged, which left a net of 20 unique test results to work with. In order to provide a solution in this case it was necessary to also reduce the number of unknown (stations) to a number near the number of tests. The interval between temperature stations was therefore increased from 100 to 200°F, as illustrated in Table 6. The coefficient matrix for the 20 tests and 22 stations is shown in Table 7. Obviously additional data will have to be generated to solve this (n)x(n-2) system. This will be done during the coming report period by using a fairing procedure on a log stress log-creep life plot, and then selecting one or two "data" points between the actual test points. The procedures discussed above will then be re-applied to the selected data matrix to develop a solution for the 22 station functions.

3. Exponentially Varying Stress and Temperature Results

A previous report[1] has documented the analytical methods available for the prediction of varying stress and temperature test results. The analytical approach to the problem involves the integration with respect to time of a quantity which is dimensionally a strain rate:

$$\varepsilon = \int_0^t \dot{\varepsilon}(t)dt \tag{12}$$

where $\dot{\varepsilon}$ is the time dependent creep rate function, t is time and ε is the total creep strain accumulated between time 0 and time t. Computer assisted numerical integration techniques were used to integrate Equation (12) using a previously developed hyperbolic size creep rate equation for T-111 alloy[6]. By integrating in a step-wise fashion it was possible to plot the value of the integral (which is total creep strain) at successively larger values to t, thereby providing hypothetical variable stress and temperature creep curves for the T-111 alloy. It was found that these curves displayed a unique feature called the "stall strain," which was essentially a peak in the creep curve which occurred at the point in time where the rate of creep extension was just balanced by the rate thermal contraction. Because of the uniqueness of the stall strain it was felt that it would represent a significantly better capsule design parameter than one of the more conventional creep parameters such as rupture life or steady state creep rate.

The first of a series of experimental tests to confirm this predicted creep behavior was conducted during the current report period. The experimental conditions for this test (No. S-109), which were discussed in the experimental details section of this report, are shown in Appendix V and in Figure 3. A hypothetical creep curve calculated for these test conditions is compared with the experimental creep data from this test in Figure 9. The shapes of these two curves are quite similar, and the experimental curve does indeed exhibit a "stall" phenomenon as predicted. Furthermore, the experimental stall strain of 2.83% agrees quite well with the predicted value of 2.95%. The only significant difference between these curves is that the experimental values fall somewhat below the predicted curve in the steepest (highest creep rate) area of the curves. It is not possible to evaluate from the limited data available to date whether this difference is the result of the inherent scatter in creep test results, or is the result of a systematic deviation of the prediction technique from the real behavior. Additional

TABLE 6

REVISED LIST OF TEMPERATURE STATIONS CHOSEN FOR STATION FUNCTION ANALYSIS FOR T-111 ALLOY

Temperature °F	Station Name
1600	P_1
1800	P_2
2000	P_3
2200	P_4
2400	P_5
2600	P_6

	g_1 x_1	g_2 x_2	g_3 x_3	g_4 x_4	g_5 x_5	g_6 x_6	g_7 x_7	P_1 x_8	P_2 x_9	P_3 x_{10}	P_4 x_{11}	P_5 x_{12}	P_6 x_{13}	f_1 x_{14}	f_2 x_{15}	f_3 x_{16}	f_4 x_{17}	f_5 x_{18}	f_6 x_{19}	f_7 x_{20}	f_8 x_{21}	f_9 x_{22}	
1	0	0	0	0	0	-.39	-.61	1	0	0	0	0	0	0	0	0	0	.27	.73	0	0	0	S-60
2	0	0	0	0	0	-.56	-.44	.88	.12	0	0	0	0	0	0	0	0	0	.13	.87	0	0	S-69
3	0	0	0	0	0	-.80	-.20	.25	.75	0	0	0	0	0	0	0	0	0	0	.81	.19	0	S-47
4	0	0	0	0	-.23	-.77	0	0	1	0	0	0	0	0	0	0	0	.18	.82	0	0	0	Avg. S-40 & S-26
5	0	0	0	0	0	-1	0	0	.70	.30	0	0	0	0	0	0	.30	.70	0	0	0	0	S-24
6	0	0	0	-.23	-.77	0	0	0	0	1	0	0	0	0	0	0	0	0	0	.48	.52	0	S-50
7	0	0	0	0	-.86	-.14	0	0	0	1	0	0	0	0	0	0	0	0	.87	.13	0	0	S-34
8	0	0	0	0	-.63	-.38	0	0	0	1	0	0	0	0	0	0	.59	.41	0	0	0	0	Avg. S-27 & S-59
9	0	0	0	0	-.42	-.58	0	0	0	1	0	0	0	0	.49	.51	0	0	0	0	0	0	S-25
10	0	0	0	0	0	-1	0	0	0	1	0	0	0	.70	.30	0	0	0	0	0	0	0	S-22
11	0	0	0	0	-.74	-.26	0	0	0	.4	.6	0	0	0	0	0	.85	.15	0	0	0	0	S-23
12	0	0	0	0	-.74	-.26	0	0	0	0	1	0	0	0	.77	.23	0	0	0	0	0	0	S-21
13	0	0	0	-.32	-.68	0	0	0	0	0	1	0	0	0	0	.46	.54	0	0	0	0	0	Avg. S-19 & S-33
14	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0	.07	.93	0	0	0	0	Avg. S-32 & S-35, S-31
15	0	0	-.39	-.61	0	0	0	0	0	0	.50	.50	0	0	0	0	.98	.02	0	0	0	0	Avg. S-88, S-42
16	0	0	-.80	-.20	0	0	0	0	0	0	.35	.65	0	0	0	0	.04	.96	0	0	0	0	S-48
17	0	-.42	-.58	0	0	0	0	0	0	0	0	1	0	0	0	0	.95	.05	0	0	0	0	S-84
18	0	0	-.39	-.61	0	0	0	0	0	0	0	1	0	.26	.74	0	0	0	0	0	0	0	S-30
19	0	-1	0	0	0	0	0	0	0	0	0	.2	.8	0	0	.55	.45	0	0	0	0	0	S-68
20	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	.04	.96	S-28
21																							
22																							
	500	1,000	2,000	5,000	10,000	20,000	50,000	1,600	1,800	2,000	2,200	2,400	2,600	562	1,000	1,780	3,160	5,620	10,000	17,800	31,600	56,200	
	PSI							DEG. F						LIFE, HOURS									

TABLE 7 REVISED COEFFICIENT MATRIX FOR STATION FUNCTION ANALYSIS

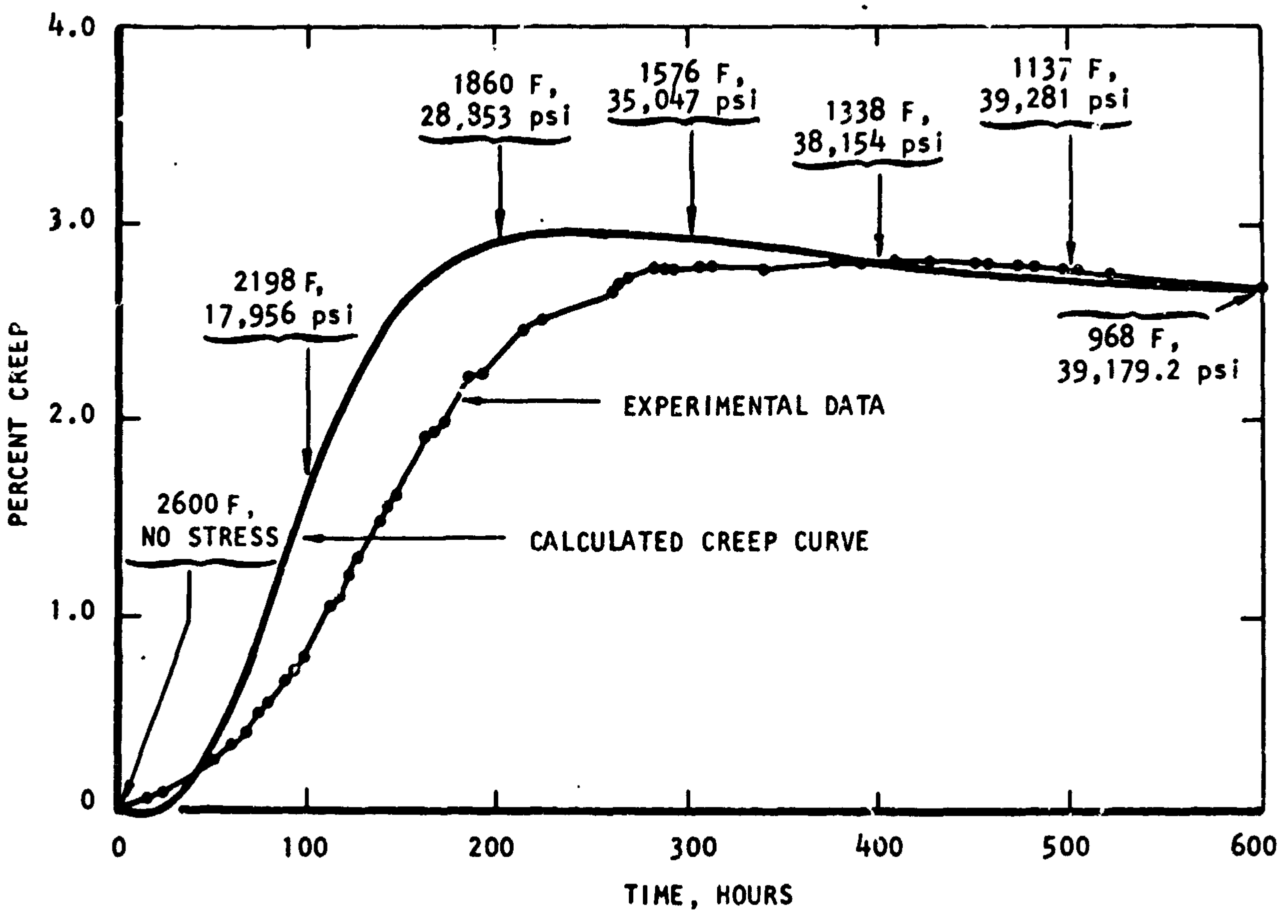

FIGURE 9. COMPARISON OF CALCULATED AND EXPERIMENTAL CREEP CURVES FOR EXPONENTIALLY VARYING STRESS AND TEMPERATURE TEST S-109

tests will be performed during the coming report period, and the results from these tests should indicate whether a systematic deviation exists. These tests will also provide additional stall strain data for evaluation of a stall strain correlating parameter which has been proposed for this type of data[1].

ASTAR 811C Alloy

During the past report period, the primary emphasis of the effort on the ASTAR 811C alloy was directed to the development of additional 1% creep life design data on specimens annealed 1/2 hour at 3600°F. A significant number of design characterization tests were conducted and more design tests are planned. Also, as with the T-111 alloy, some effort was made to obtain creep life data for the ASTAR 811C alloy at larger strain levels.

The 1% results of the current design tests on the ASTAR 811C alloy are plotted in Figure 6 together with earlier test results on this material. The limited amount of creep life data which are available for the higher strain levels are presented in Table 8 and are compared with the 1% data in Figure 10. Results of the commercial heat of this alloy continue to show strengths which are slightly better than the earlier laboratory heats, although the difference does not appear as great at the higher stress levels as it did at the lower stress levels. Another interesting observation is that this alloy appears to be significantly weaker in the high stress-low temperature range than it is at lower stresses and higher temperatures. This is an important point, as will be shown by the following discussion of structural creep effects in the ASTAR 811C alloy.

Previous reports have discussed the influence of heat treatment on the structure and creep strength of the ASTAR 811C alloy. The influence of creep exposure on the structure of this alloy has also been evaluated. Results of these studies have shown that the annealing treatment can significantly influence the creep strength of the ASTAR alloy. For example, the 1% creep life at 2400°F (1316°C) and 15,000 psi (103 mN/m^2) ranges from about 6000 hours for specimens annealed 1/2 hour at 3600°F (1982°C) to about 150 hours for material annealed 1 hour at 3000°F (1649°C). The previous studies have indicated that this variation includes the effects of both grain size and carbide morphology on the creep process. Examination of the post-test microstructure adds another puzzling note to these somewhat confusing observations. It has been found that regardless of what the pretest microstructure may be, the carbides in the post-test material are located predominantly at the grain boundaries. The puzzling thing about this observation is that this sometimes drastic change in carbide morphology occurs without the appearance of any significant change of creep rate during the tests.

TABLE 8

CREEP LIFE DATA FOR ASTAR 811C ANNEALED 1/2 HOUR AT 3600°F (1982°C)

Test No.	Heat No.	Stress ksi	Stress mN/m2	Temperature °F	Temperature °C	Creep Life Hours	LMP T°R (15 + log T)
Two Percent Extension							
S-74	650056	15	103.0	2400	1316	1370	51.9
S-76	650056	25	162.0	2175	1191	1450	47.9
S-85	650056	20	138.0	2175	1191	8650*	49.9
S-86	650056	15	103.0	2300	1263	7900*	52.2
S-90	650056	35	241.0	1850	1010	3814	42.9
S-91	650056	30	207.0	1950	1066	6500*	45.3
S-92	650056	25	162.0	2050	1121	14,000*	48.1
S-93	650056	3	20.7	2700	1482	3125	58.4
S-95	650056	8	55.1	2500	1371	3575	54.9
S-96	650056	2.5	16.2	2750	1510	3670	59.6
S-97	650056	1.5	10.3	2900	1593	2680	61.9
Five Percent Extension							
S-76	650056	25	162.0	2175	1191	2950	48.7
S-97	650056	1.5	10.3	2900	1593	4600*	62.7
Ten Percent Extension							
S-76	650056	25	162.0	2175	1191	4250	49.1
Fifteen Percent Extension							
S-76	650056	25	162.0	2175	1191	4950	49.3

* Extrapolated

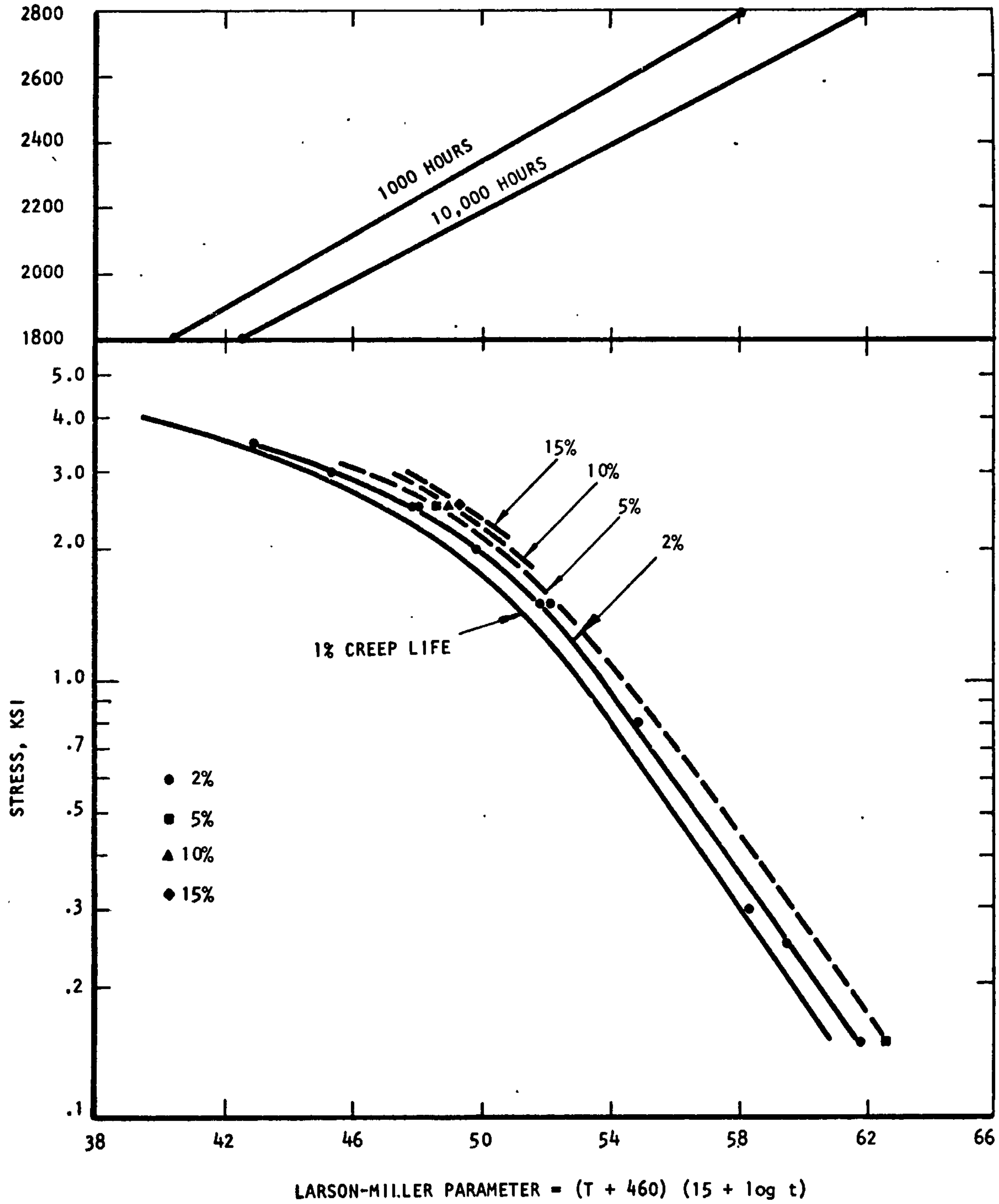

FIGURE 10. PARAMETRIC REPRESENTATION OF CREEP LIFE DATA FOR ASTAR 811C ALLOY ANNEALED 1/2 HOUR AT 3600°F (198?°C).

Another interesting observation which was made during the current report period concerns the previously noted reduction in the relative creep strength of the ASTAR 811C alloy at the higher stress levels. It would appear, in fact, that at very high stresses the strength of this material may be approaching that of the normally weaker T-111 alloy. One of the reasons for this observation is that it may relate to the results of Harrod, Ammon, and Buckman, presented recently by Buckman[7], which showed a distinct shift in creep mechanisms in this alloy in going from the low stress range at 2600°F, where the creep life appeared to be strongly grain size dependent, to the higher stress range at 2000°F, where the creep life appeared to be essentially independent of grain size. This would indicate that the ASTAR alloy is markedly superior to the solid solution strengthened T-111 alloy only at temperatures and stresses where grain boundary sliding is the predominant deformation mechanism. It cannot be stated, however, that grain size is the only factor controlling the creep strength of this alloy, since it was clearly shown that the presence of the carbide is necessary to achieve the improved strength over the non-carbide containing material. To prove this point, Buckman tested a non-carbon containing analog which had a composition essentially identical to the ASTAR 811C alloy except that it did not contain carbon. Results of these tests showed that the carbon free analog was significantly weaker than the ASTAR 811C alloy, thereby demonstrating the pronounced effect of the carbide on the creep strength of this material.

Analysis of the observations presented above has led to the development of a theory concerning creep strengthening mechanisms in the ASTAR 811C alloy which might explain all of the observed effects. The key observations which led to the development of this hypothesis are that:

a) The presence of carbides appears to improve the creep strength only in the temperature range where grain boundary sliding is an important creep mechanism.

b) The bulk of the carbides in the post-test microstructure appear to be concentrated at grain boundaries, irrespective of the pretest microstructure.

The hypothesis is that the carbides provide their strengthening effects not in the classical dispersion hardening way, but instead as grain boundary strengtheners. If a classical dispersion hardening effect were present, the strengthening effect should not disappear at the lower temperatures. On the other hand, a grain boundary strengthening effect is consistent with the observation that the strengthening is effective only at temperatures where grain boundary sliding is a significant creep mechanism. These observations are consistent with commonly observed effects in the nickel and cobalt base superalloys, where carbide pinning is a widely utilized grain boundary strengthening mechanism[8,9]. A true carbide dispersion strengthening effect is also inconsistent with the observation that the carbide has migrated to the grain boundaries during testing, with no detectable influence on the creep curve. Unfortunately, there is no information available at the present time concerning how quickly this migration takes place. It would be useful to know this, because if the period of migration occupies a significant fraction of the test duration, then it would be expected that the grain boundary strengthening would increase slowly, which would be reflected in the creep curves as a continuously decreasing creep rate. Such an effect is not observed and the microstructural information would therefore be useful in determining whether or not the proposed hypothesis is correct. During the coming report period efforts will be made to determine how soon after the start of a creep test the change in carbide microstructure occurs.

In another phase of the ASTAR 811C test program, a study was made of the influence of liquid metal exposure on the creep strength of the ASTAR 811C alloy. Four specimens were obtained for these tests from the General Electric Company at Evendale, Ohio. All four specimens were taken from the original Westinghouse NASV-20 heat and were annealed at 1 hour at 3000°F (1649°C) prior to exposure. Two of these specimens were then exposed at G.E. to liquid lithium for 5000 hours at 2400°F (1316°C), thereby providing duplicate pre- and post exposure samples. After exposure all four specimens were delivered to TRW for creep testing in the UHV creep laboratory.

The four specimens from the G.E. corrosion loop program were creep tested at a temperature of 2400°F (1316°C) and at stress levels of 15 and 8 ksi (103 and 55.1 mN/m^2). The testing was complicated by the fact that the specimens were very small and therefore required special grips and pull bars. Another complication of the small size was that the standard optical cathetometer, which has a minimum working distance of 1-1/2", could not be used for these tests. It was therefore necessary to use a traveling telescope having the same accuracy as the cathetometer, which essentially doubled reading errors because of the fact that two readings (one at each end of the gauge section) were made instead of one. This problem, coupled with the fact that the gauge section was only 1/2" (which is 1/4 of the usual 2") meant that the scatter on the creep curves for these tests was about eight times the usual amount. Despite this problem, it has been possible to obtain reliable 1% creep life data from these tests.

Results of the four tests from the G.E. corrosion loop program are summarized in Table 9, which shows a significant reduction of the 1% creep life as a result of the liquid metal exposure. During the coming report period efforts will be made to examine the pre- and post-liquid metal exposure specimens to determine if some structural difference can be detected which would account for the observed reduction of creep life.

TABLE 9

SUMMARY OF CREEP LIFE DATA FROM G.E. CORROSION LOOP SPECIMENS CREEP TESTED AT 2400°F (1316°C)

Test Stress		1% Creep Life, Hours	
psi	mN/m^2	Not Exposed	Exposed
15	103.0	152	68
8	55.1	2600*	1575

* Extrapolated

CVD Tungsten

A program was undertaken during this report period to characterize the creep behavior of chemically vapor deposited tungsten creep specimens. Thus far only one test has been conducted in this series at a temperature of 2912°F (1600°C) and a stress of 500 psi (3.5 mN/m^2). This test exhibited a steady state creep rate of 7.5×10^{-7} hr^{-1} and had an extrapolated 1% creep life of 14,000 hours. Additional tests will be run during the coming report period so that a Larson-Miller plot can be constructed for this material and compared with previous tungsten test results.

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 ([illegible]71°C) range to produce an improved carbide dispersion. This test at 2000°F (1093°C) and 22 ksi (15.1×10^7 mN/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.

CONCLUSIONS

Analysis of ultrahigh vacuum creep test data obtained during the current report period has led to several significant conclusions. The current 1% creep life results for the tantalum base T-111 alloy have been found to agree well with previously obtained results from this program and Manson's recently developed station function analysis has been applied in an effort to correlate all of the T-111 alloy 1% creep data obtained to date. The current state of progress of the analysis has been described in this report. In addition, a limited amount of 2% and 5% creep life data have been presented for this alloy. In another phase of the T-111 test program, a specimen was tested which had a duplex heat treatment (1 hour at 3000°F (1649°C) followed by 1 hour at 2400°F (1316°C)) which was designed to simulate post-weld heat treatments applied to T-111 alloy. Results of this test showed no measurable difference from the conventional T-111 test data.

A test conducted on T-111 alloy with exponentially varying stress and temperatures has shown that the creep behavior under these test conditions can be predicted with reasonable accuracy using previously described analytical techniques.

Creep test results obtained on ASTAR 811C alloy during the current reporting period have been shown to agree with previous test results on this material. However, it has also been shown that at relatively high stresses and low temperatures this alloy loses some of the strength advantage which it has over T-111 alloy in the intermediate stress and temperature range. A hypothesis has been advanced in this report to explain the previously observed influence of heat treatment on the creep strength of ASTAR 811C alloy. The theory proposes that the carbide strengthening in this material occurs primarily at the grain boundaries rather than through a classical dispersion strengthening effect. An experimental approach to obtain additional data concerning this mechanism has been suggested.

In another phase of the program, a study has been conducted to evaluate the influence of high temperature liquid metal exposure on the 1% creep life of ASTAR 811C at 2400°F (1316°C). Results of this study showed that at both 15 and 8 ksi (103 and 55.1 mN/m^2) an exposure of 5000 hours to liquid lithium at 2400°F (1316°C) caused a significant reduction of the 1% creep life.

Results of the first in a series of creep tests on CVD tungsten annealed 100 hours at 3272°F (1800°C) and tested at 2912°F (1600°C) and 500 psi (3.5 mN/m^2) showed this material to have an extrapolated 1% creep life of 14,000 hours and a steady state creep rate of 7.15×10^{-7} hr^{-1} at these test conditions.

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

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APPENDIX I

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APPENDIX II

SUMMARY OF ULTRAHIGH 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/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-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	Termination of Test Time, Hours	Termination 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	2671	1.570	66.0
B-24	--	1	2800	1538	2.0	13.8	2800	1538	1500	6812	3.708	59.2
S-102	--	100	3272	1800	0.5	3.5	2912	1600	14,000*	**	**	64.5

*Extrapolated
**In Progress

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/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-12	--	2	3200	1760	5.0	34.4	3200	1760	35	170	5.25	60.6	13
S-15	--	2	3200	1760	3.0	20.7	3200	1760	250	907	5.862	63.7	16

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/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-2	C5	As-Rolled			12.0	82.7	2000	1093	390	806	1.020	43.3	14
B-6	C5	As-Rolled			11.0	75.8	2000	1093	450	1192	1.016	43.5	17
B-7	C5	As-Rolled			8.0	55.1	2200	1204	115	230	1.025	45.4	20

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+log t) x10^{-3}	
B-13	KC-1454	1	3092	1700	20.0	138.0	2056	1125	275	568	1.170	43.8	14
B-14	KC-1454	1	3092	1700	16.3	82.3	2056	1125	340	691	1.026	44.0	17
B-15	KC-1454	1	3092	1700	7.4	51.0	2256	1236	250	596	1.100	47.2	20

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-30	KDTZM-1175	1	2300	1260	22.0	151.0	2000	1093	16,293	**	**	47.1
B-[illegible]	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-90	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	14
S-14	AL-TA-43	1	3000	1649	19.2	132.0	2056	1124	890	1314	1.685	45.1	17
S-20	AL-TA-43	1	2800	1538	12.0	82.7	2200	1204	405	1389	5.060	46.9	2?

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	138.0	2100	1148	3600*	983.4	0.342	47.5
S-71	VAM-95	.15	3600	1982	20	138.0	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	1.360	50.5
S-74	650056	.33	3600	1982	15	103.0	2400	1316	825	1466.0	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	4962.5	15.088	47.0
S-77	650056	.5	3600	1982	10	69.0	2400	1316	5287	5907.9	1.150	53.6
S-78	650056	.5	3600	1982	5	35.0	2550	1399	5611	6210.4	1.210	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
S-85	650056	.5	3600	1982	20	138.0	2175	1191	4410	5346.7	1.240	49.1
S-86	650056	.5	3600	1982	15	103.0	2300	1263	4390	5206.1	1.240	51.1

*Extrapolated

TABLE II-11. Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results (Continued)

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-87+	NASV-20	1	3000	1649	15	103.0	2400	1316	68	329	11.470	48.1
S-100++	NASV-20	1	3000	1649	15	103.0	2400	1316	152	330.9	10.750	49.1
S-104+	NASV-20	1	3000	1649	8	55.1	2400	1316	1575	1777.0	1.206	52.1
S-108++	NASV-20	1	3000	1649	8	55.1	2400	1316	2600*	**	**	52.7
S-90	650056	0.5	3600	1982	35	241.0	1850	1010	1858	4323.6	2.402	42.2
S-91	650056	0.5	3600	1982	30	207.0	1950	1066	2656	**	**	44.5
S-92	650056	0.5	3600	1982	25	162.0	2050	1121	6500*	**	**	47.2
S-93	650056	0.5	3600	1982	3	20.7	2700	1482	2064	4364.0	3.798	57.9
S-94	650056	0.5	3600	1982	40	276.0	1600	871	12,500*	**	**	39.3
S-95	650056	0.5	3600	1982	8	55.1	2500	1371	2266	3963.8	2.392	54.3
S-96	650056	0.5	3600	1982	2.5	16.2	2750	1510	2270	**	**	58.9
S-97	650056	0.5	3600	1982	1.5	10.3	2900	1593	1580	**	**	61.1
S-101	655056	1	3000	1649	15	103.0	2400	1316	230	673.9	12.182	49.6
S-106	655056	0.5	3600	1982	6	41.4	2500	1371	3200*	**	**	54.7

*Extrapolated
**Test In Progress

+Post Exposure Samples From G.E. Alkali Metal Exposure Program
++Pre-Exposure Samples From G.E. Alkali Metal Exposure Program

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
S-37	65080	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

*Extrapolated
**Test in progress

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results (Continued)

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-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	19,896	22,476.2	1.298	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	13,350	15,219.0	1.192	47.1
S-60	D-1183	1	3000	1649	35.0	241.0	1600	870	8550	17,794.5	11.218	39.0
S-68	650028	1	3000	1649	1.0	6.9	2560	1403	2300	14,783.9	1.660	55.5
S-69	650028	1	3000	1649	30.0	207.0	1625	885	16,625	18,120.7	1.312	40.1
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	1093	16	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	***

*Extrapolated

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results (Continued)

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-82A	650028	-	--	--	50.0	34.4	900	482	***	5610.8	0.075	***
S-83	650028	1	3000	1649	45.0	31.0	1100	593	7	1177.1	2.945	24.8
S-84	650028	1	3000	1649	1.5	10.4	2400	1316	3250	5273.6	1.502	52.9
S-41	65080	15	3000	1649	8.0	55.1	2200	1204	234	259	1.380	46.2
S-98	848001	1	3000	1649	1	6.9	2560	1404	12,000*	**	**	57.4
S-99	650028	1	3000	1649	0.5	3.5	2700	1482	250,000*	**	**	64.5
S-103	650028	1	3000	1649	40	276.0	1500	816	16,000*	**	**	37.6
S-105	650028	1	3000	1649	35	241.0	1700	927	1060	**	**	39.0
S-107	848001	1	3000	1649	20	138.0	1900	1038	380	1197.6	3.042	41.5

*Extrapolated
***Insufficient to extrapolate

TABLE II-13. Summary of T-111 Linearly Increasing 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	0.225
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	1596	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
***Insufficient creep to extrapolate
+Welded
++Linearly increasing stress

TABLE II-14. Summary of Pure Ta Ultra-High Vacuum Creep Test Results (Continued)

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	2175.4	3.372	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	2712.0	4.412	29.8
B-52	60C65	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	12,000*	6930.9	0.858	34.5
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	6096.2	3.168	30.4
P-4	B-1960	++	++	++	6.5	44.8	1350	732	30	5689.4	4.230	29.8
P-5 **	B-1960	++	++	++	6.5	44.8	1350	732	110,000*	4900.5	0.155	36.3

*Extrapolated
**Pre-strained 30% in tension prior to testing

+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/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-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 Linearly Decreasing 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	14
S-72	650028	1	3000	1649	7	48.2	2400	1316	370	1322.1	1.282	0.3	17
S-82	650028	1	3000	1649	31	214.0	1900	1038	235	2013.8	1.180	0.5	20

TABLE II-17. Summary of T-111 Exponentially Varying Stress and Temperature Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress Level (Dimensionless)	Starting Temperature °F	Starting Temperature °F	Half Life (Hours)	Stall Strain Percent	Termination of Test Time, Hours	Termination of Test Percent Creep	
S-109	650028	1	3000	1649	1	2600	1427	400	2.830	**	**	15

APPENDIX III

CREEP CURVES

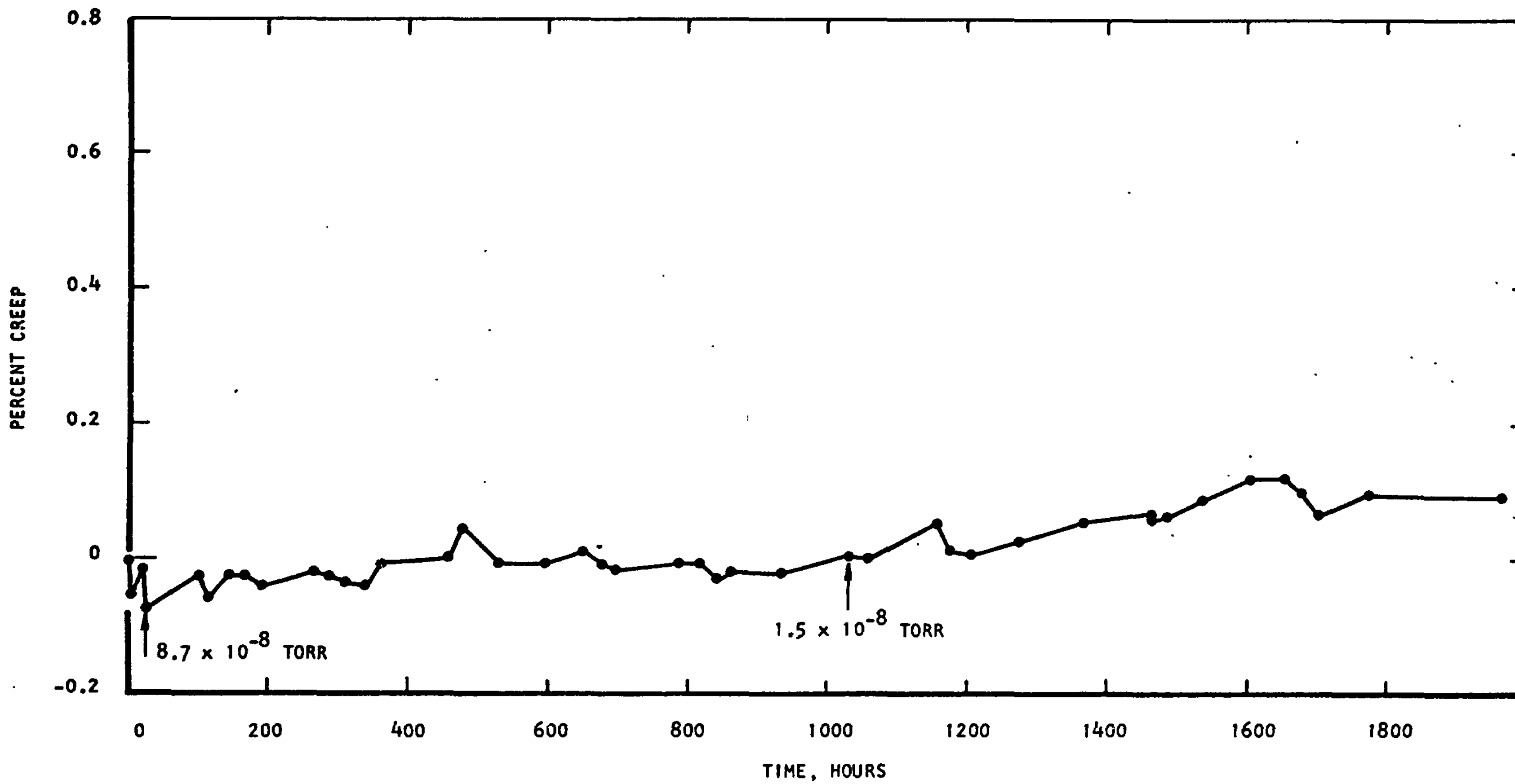

FIGURE III-1. CREEP TEST DATA, CVD TUNGSTEN ANNEALED 100 HOURS AT 3272°F (1800°C), TESTED AT 2912°F (1600°C) AND 0.5 KSI (3.5 mN/m^2), TEST NO. S-102, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS CURING THE TEST.

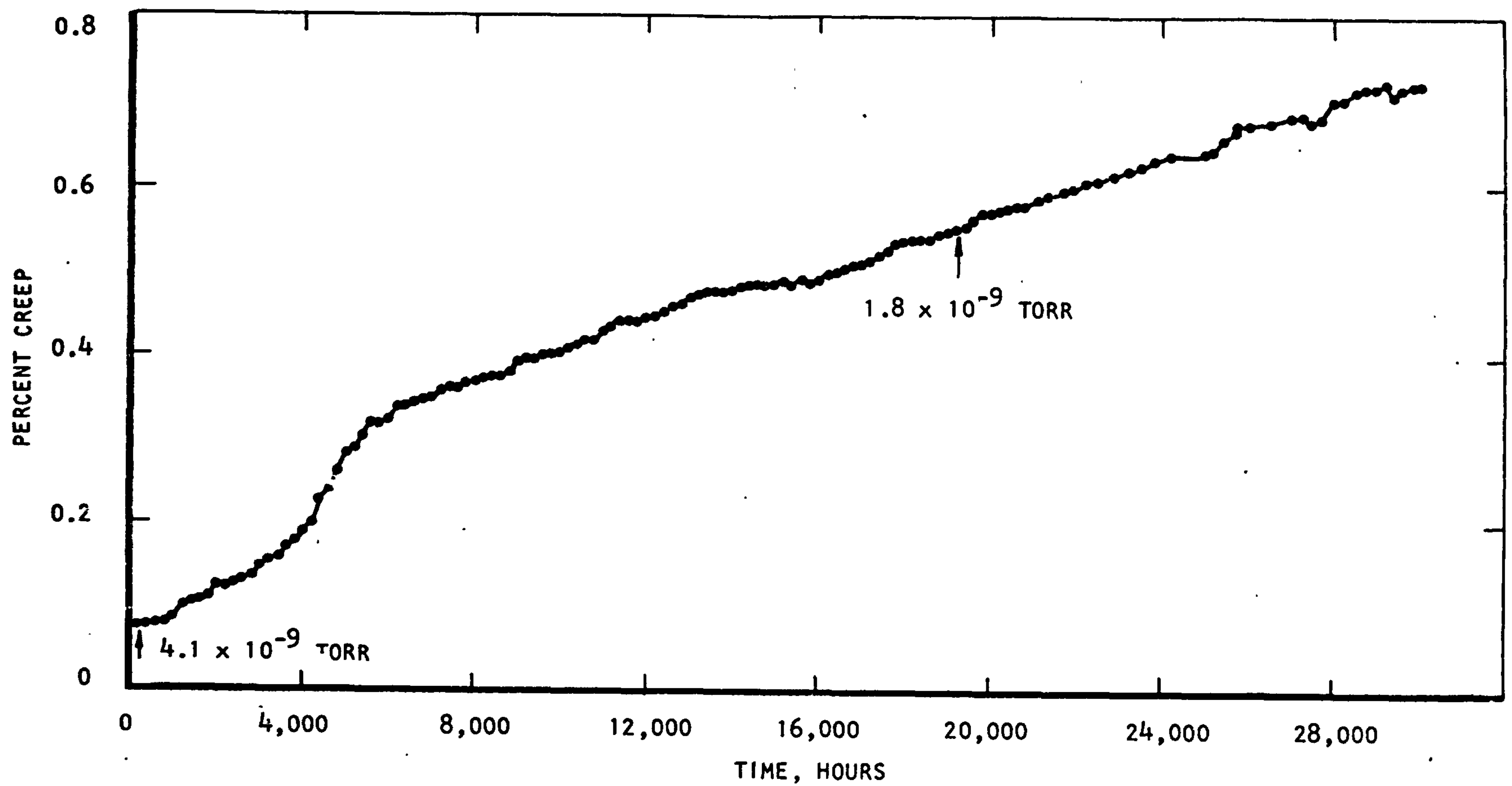

FIGURE III-2. CREEP TEST DATA, TZM HEAT NO. KDTZM-1175 STRESS RELIEVED 1 HOUR AT 2300°F (1260°C), TESTED AT 2000°F (1093°C) AND 22 KSI (151 mN/m^2), TEST NO. B-38, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

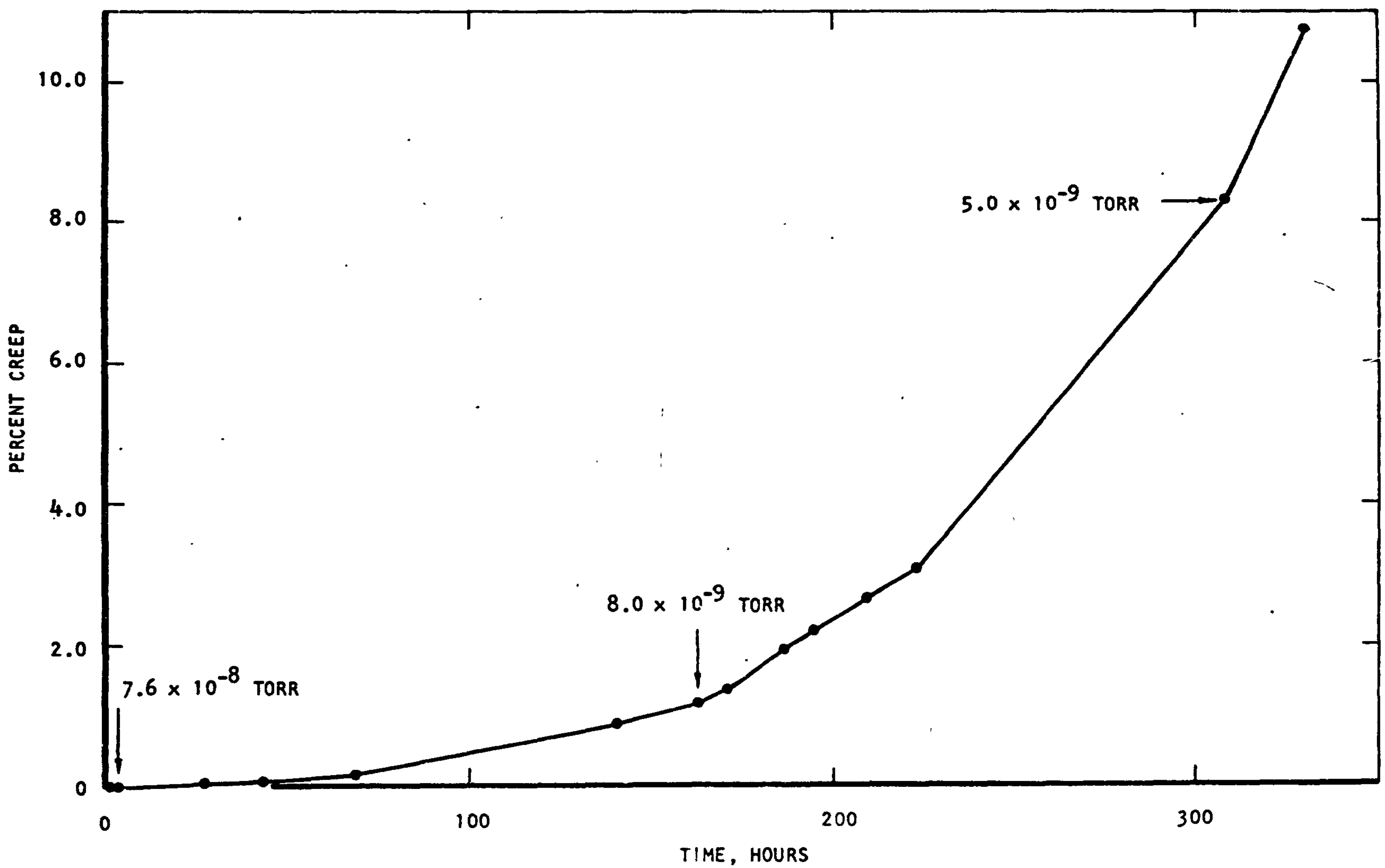

FIGURE III-3. CREEP TEST DATA, ASTAR 811C HEAT NO. NASV-20, ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2400°F (1316°C) AND 15 KSI (103 mN/m^2), TEST NO. S-100, PRE-EXPOSURE SPECIMEN FROM G.E. CORROSION LOOP PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

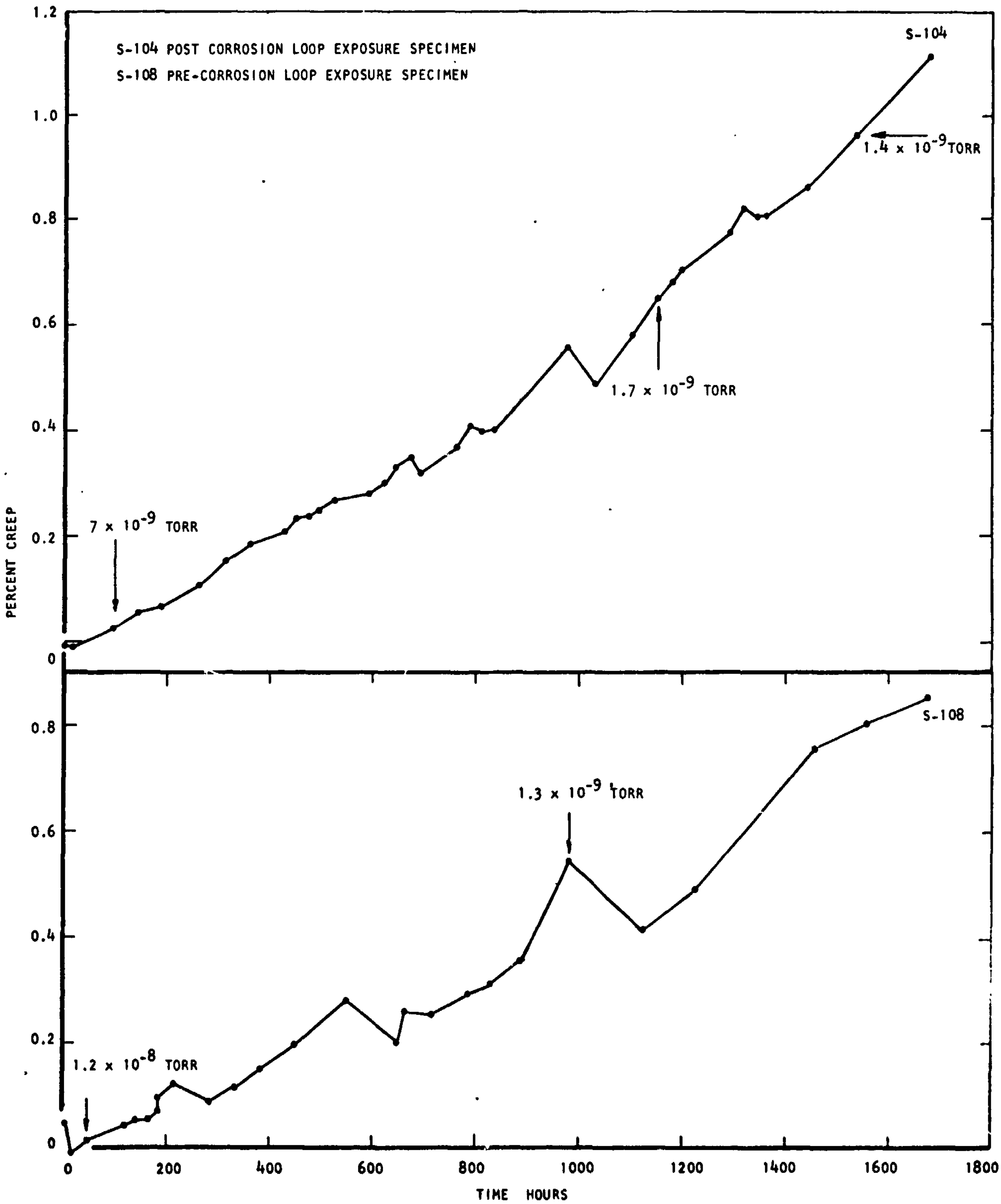

FIGURE III-4. CREEP TEST DATA, ASTAR 811C HEAT NO. NASV-20 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2400°F (1316°C) AND 8 KSI (55.1 mN/m^2), TESTS NO. S-104 AND S-108 FROM G.E. CORROSION LOOP PROGRAM, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

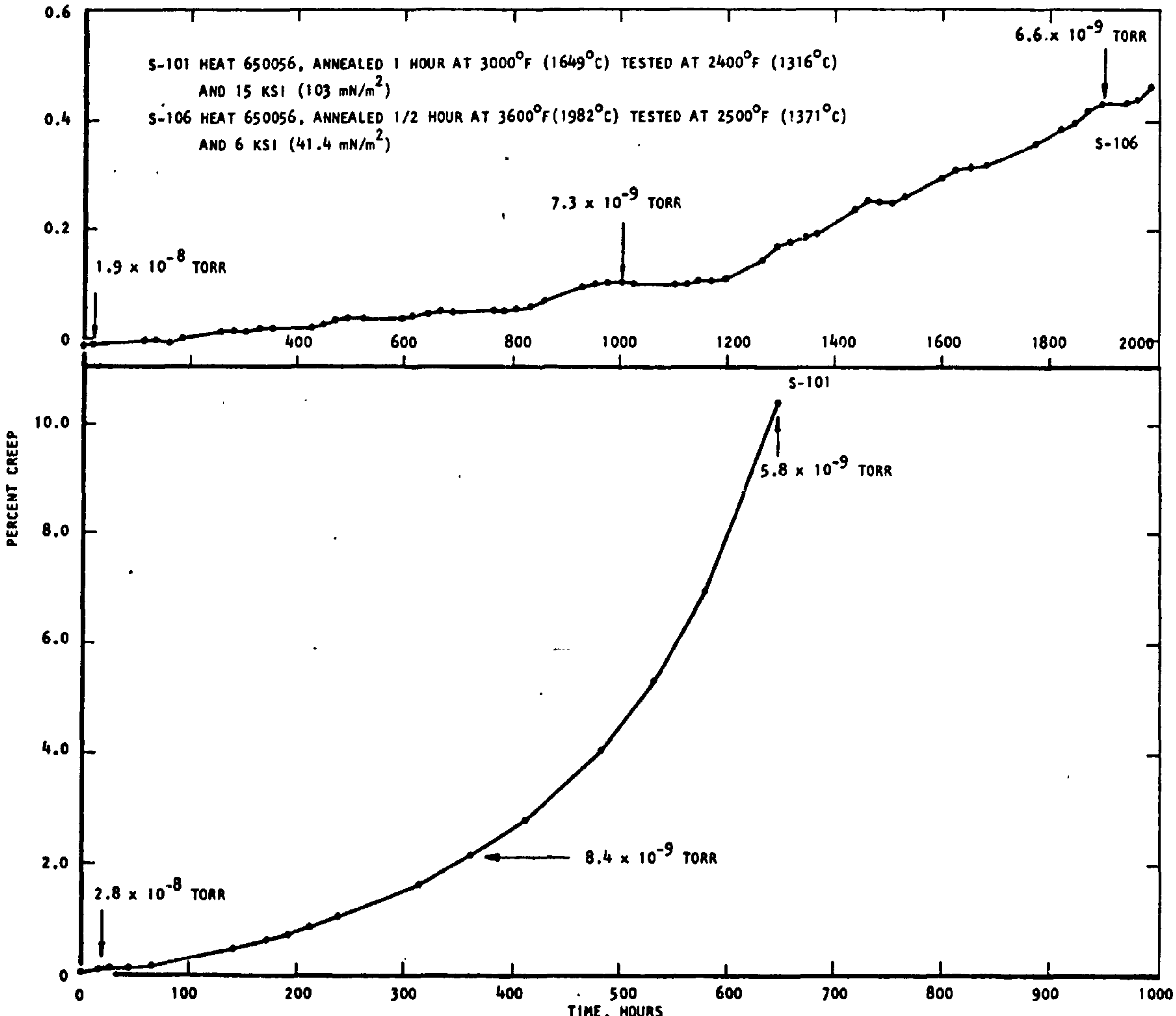

FIGURE III-5. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056. TESTS NO. S-101 AND S-106, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

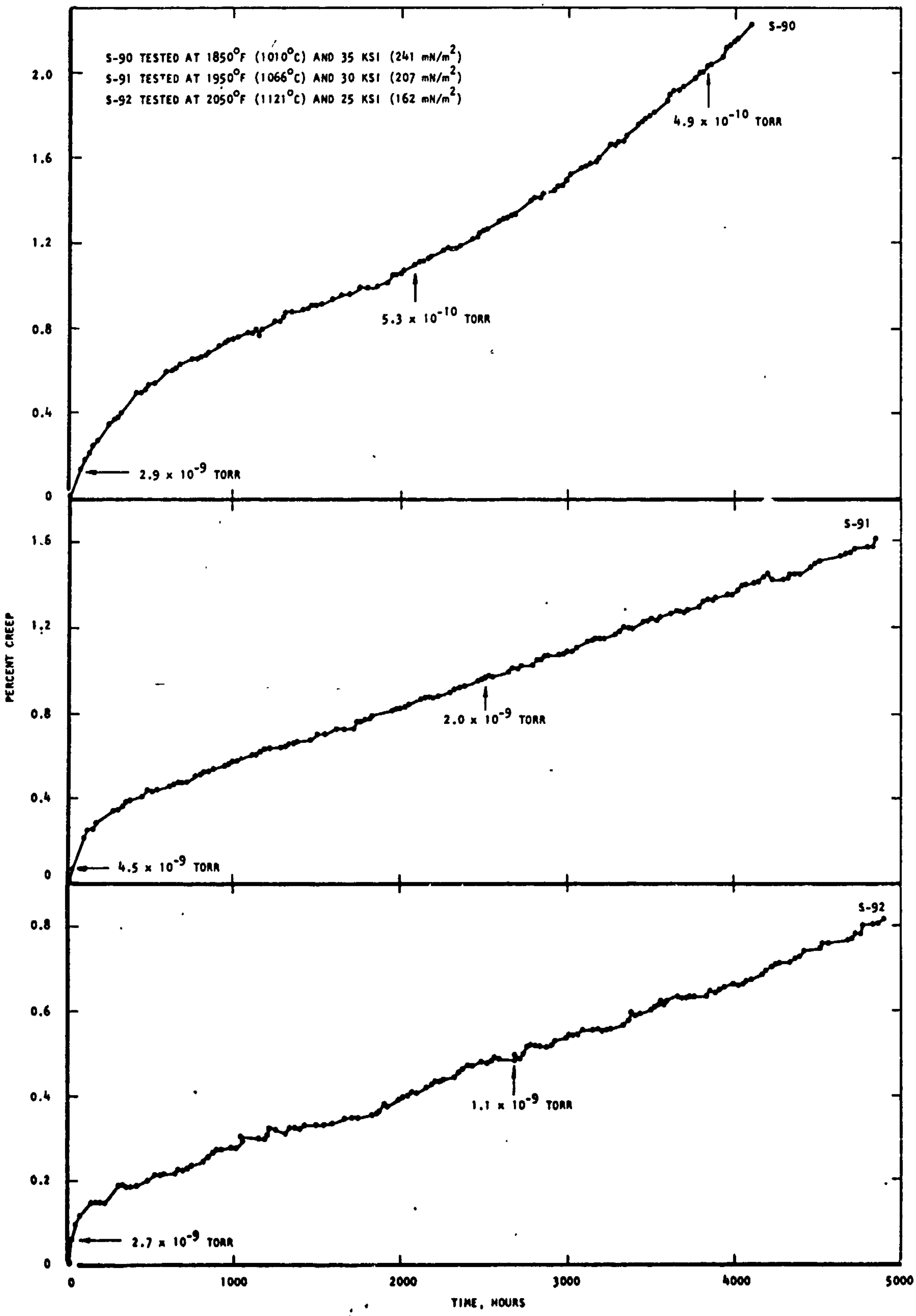

FIGURE III-6. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 1/2 HOUR AT 3600°F (1982°C), TESTS NO. S-90, S-91, AND S-92, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

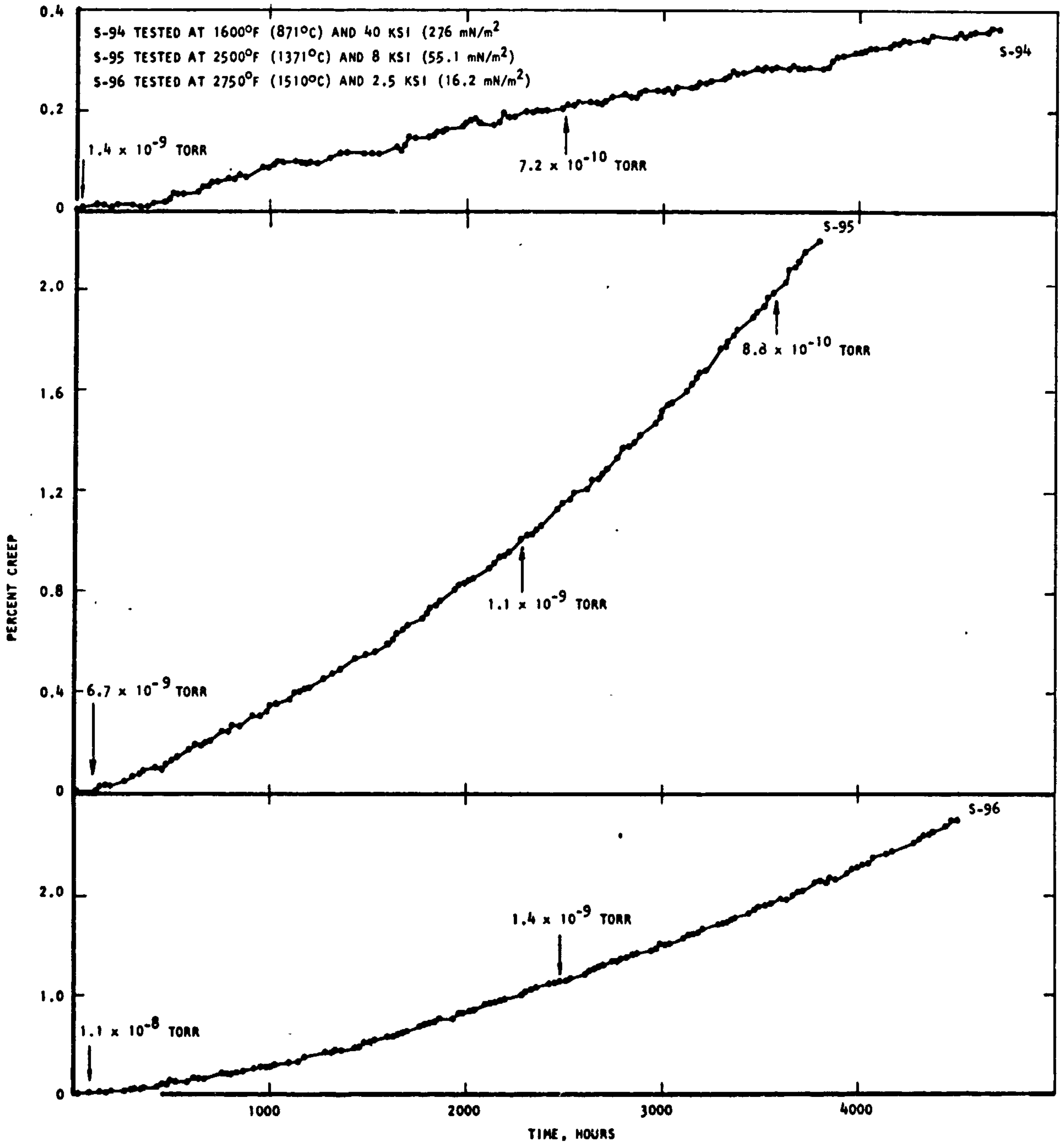

FIGURE III-7. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 1/2 HOUR AT 3600°F (1982°C), TESTS NO. S-94, S-95, and S-96, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

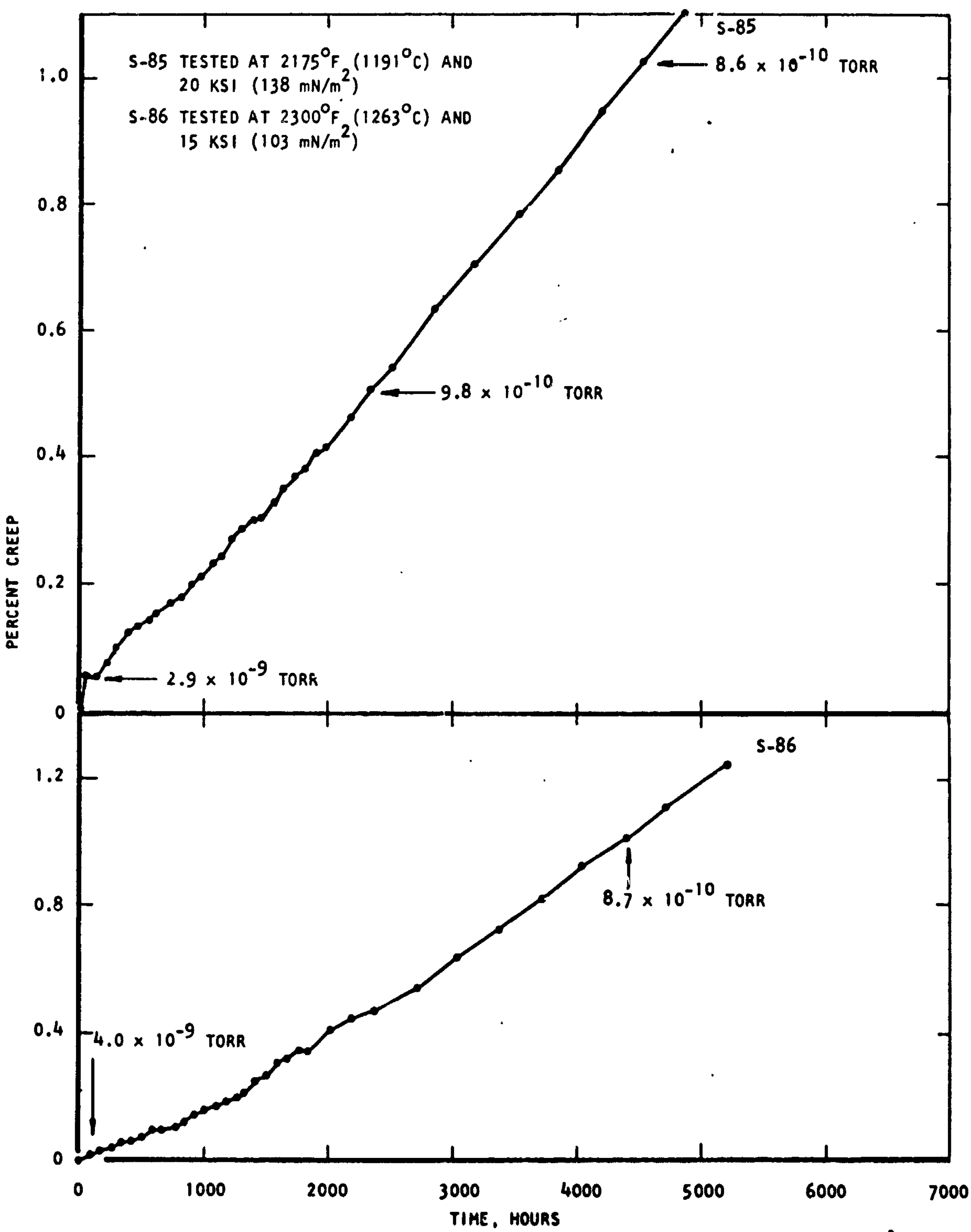

FIGURE III-8. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 1/2 HOUR AT 3600°F (1982°C), TESTS NO. S-85 AND S-86, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

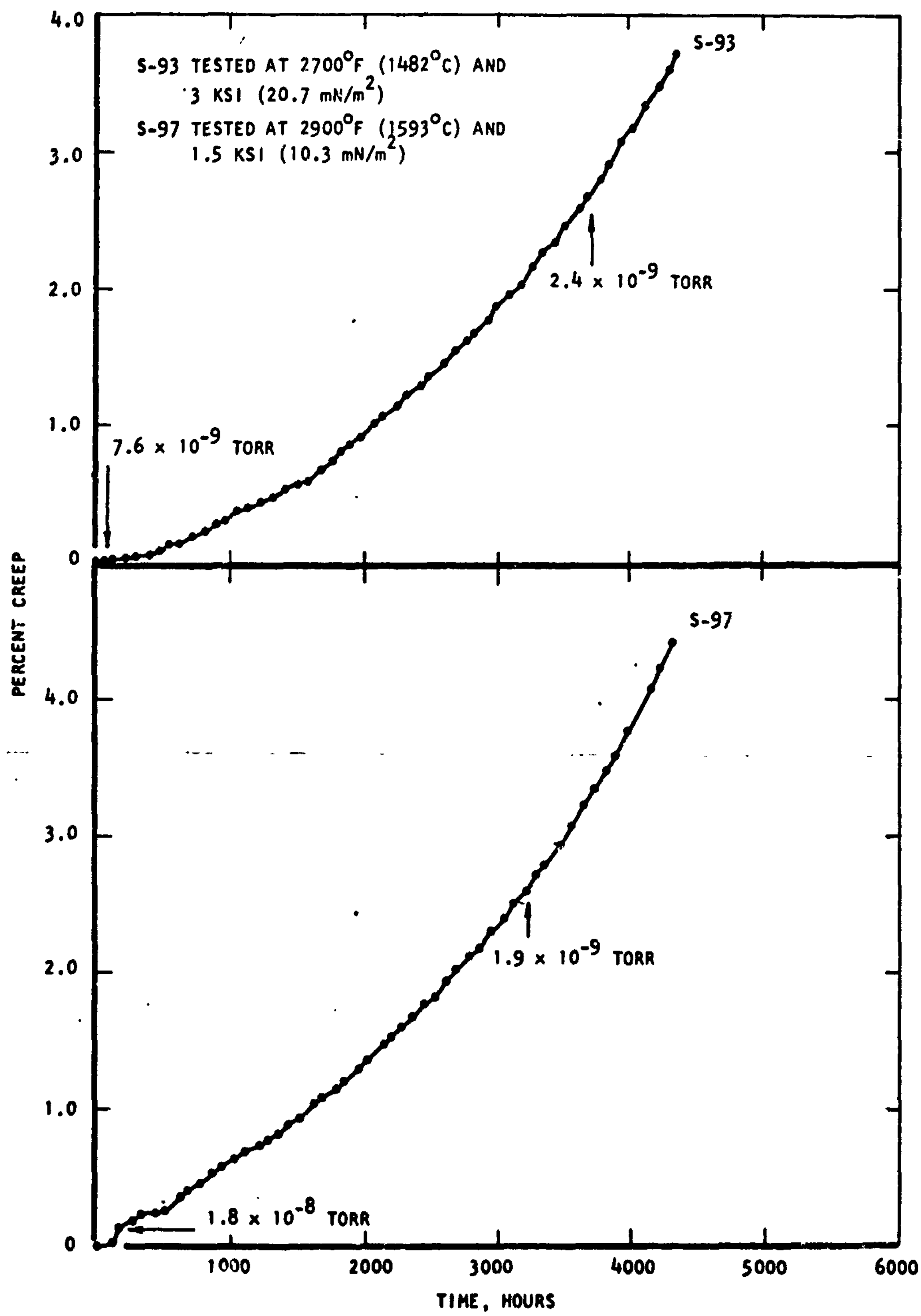

FIGURE III-9. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 1/2 HOUR AT 3600°F (1982°C), TESTS NO. S-93 AND S-97, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

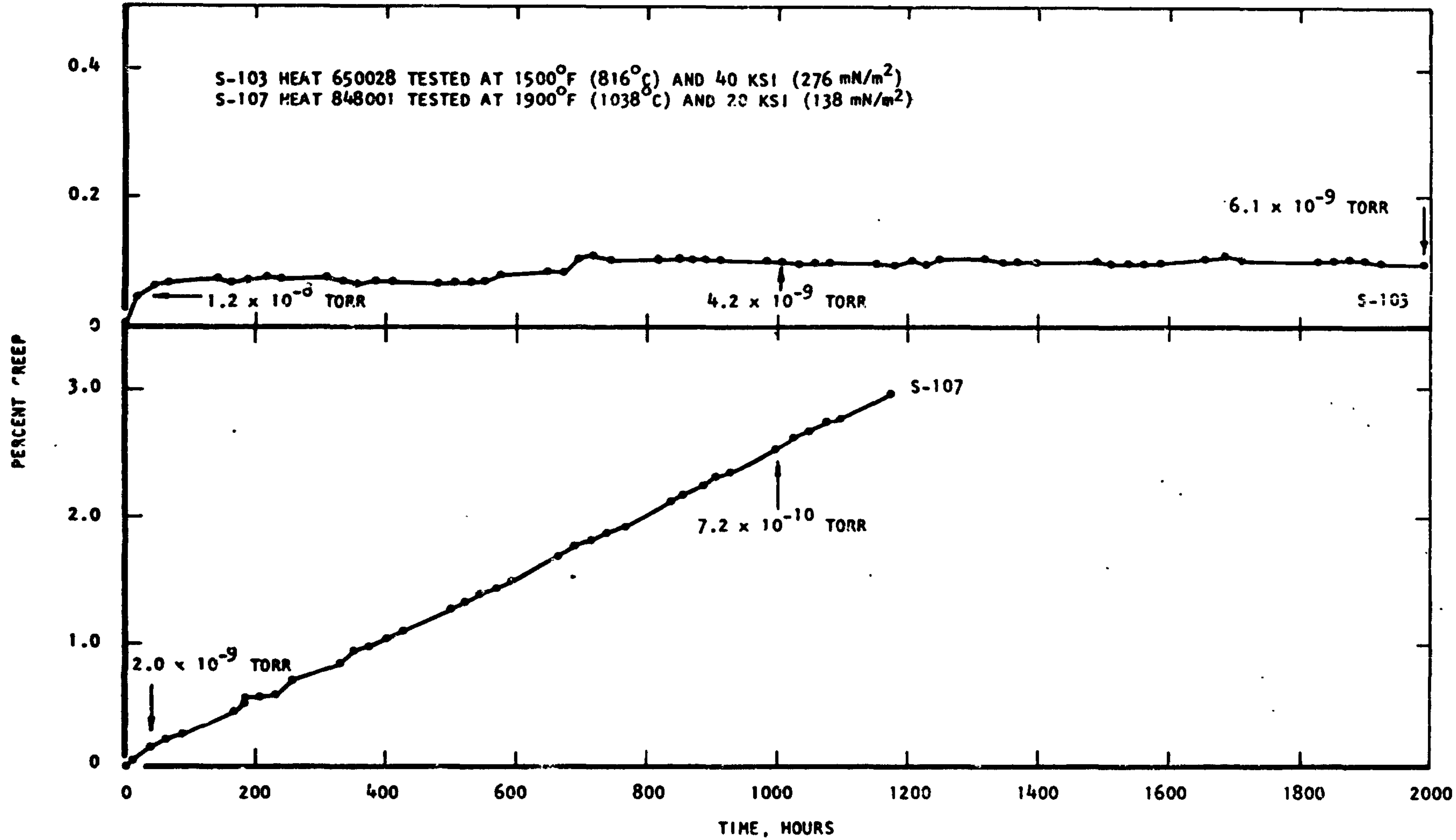

FIGURE III-10. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTS NOS. S-103 AND S-107, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

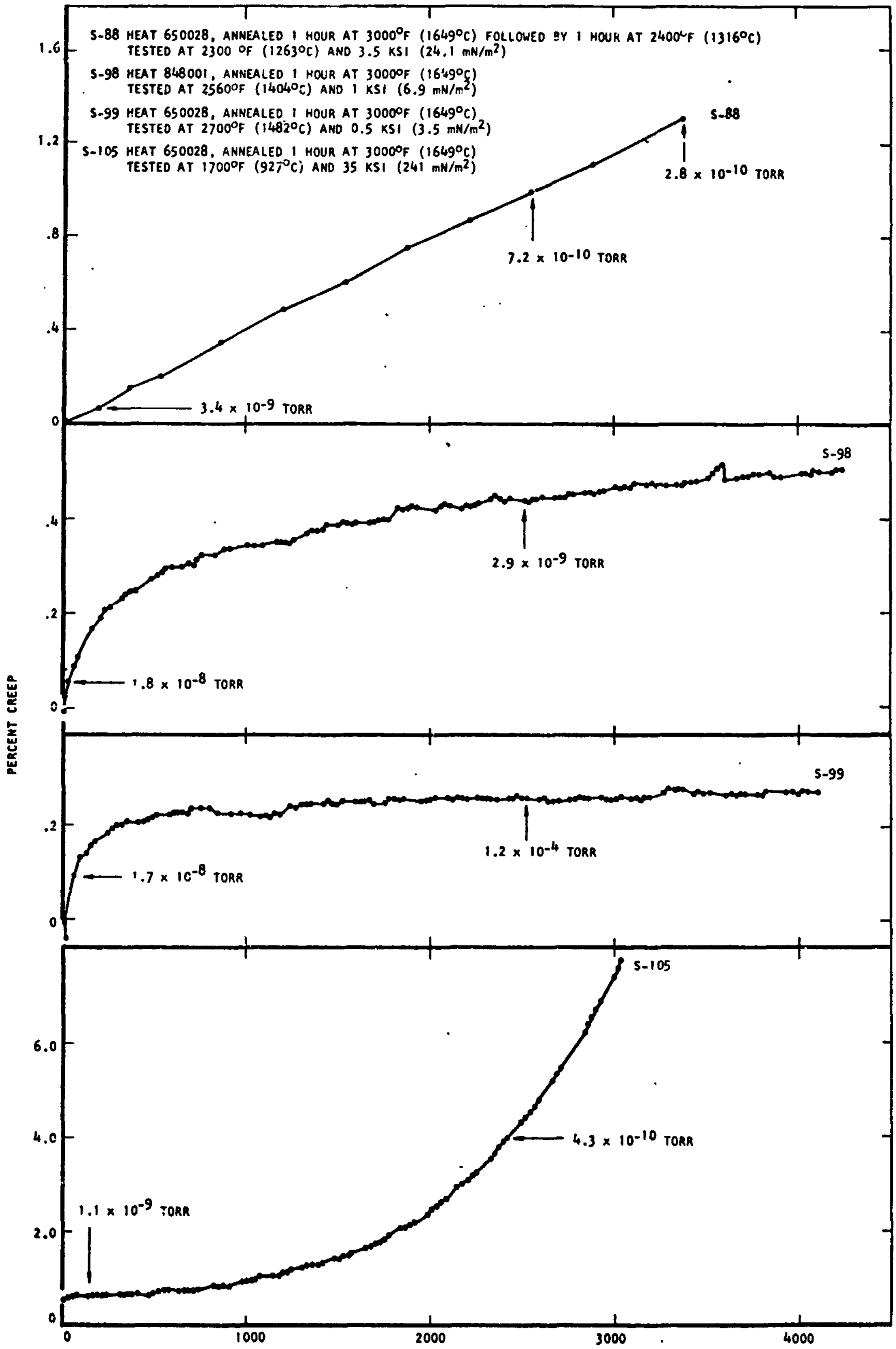

FIGURE III-11. CREEP TEST DATA, T-111, TESTS NO. S-88, S-98, S-99, AND S-105, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

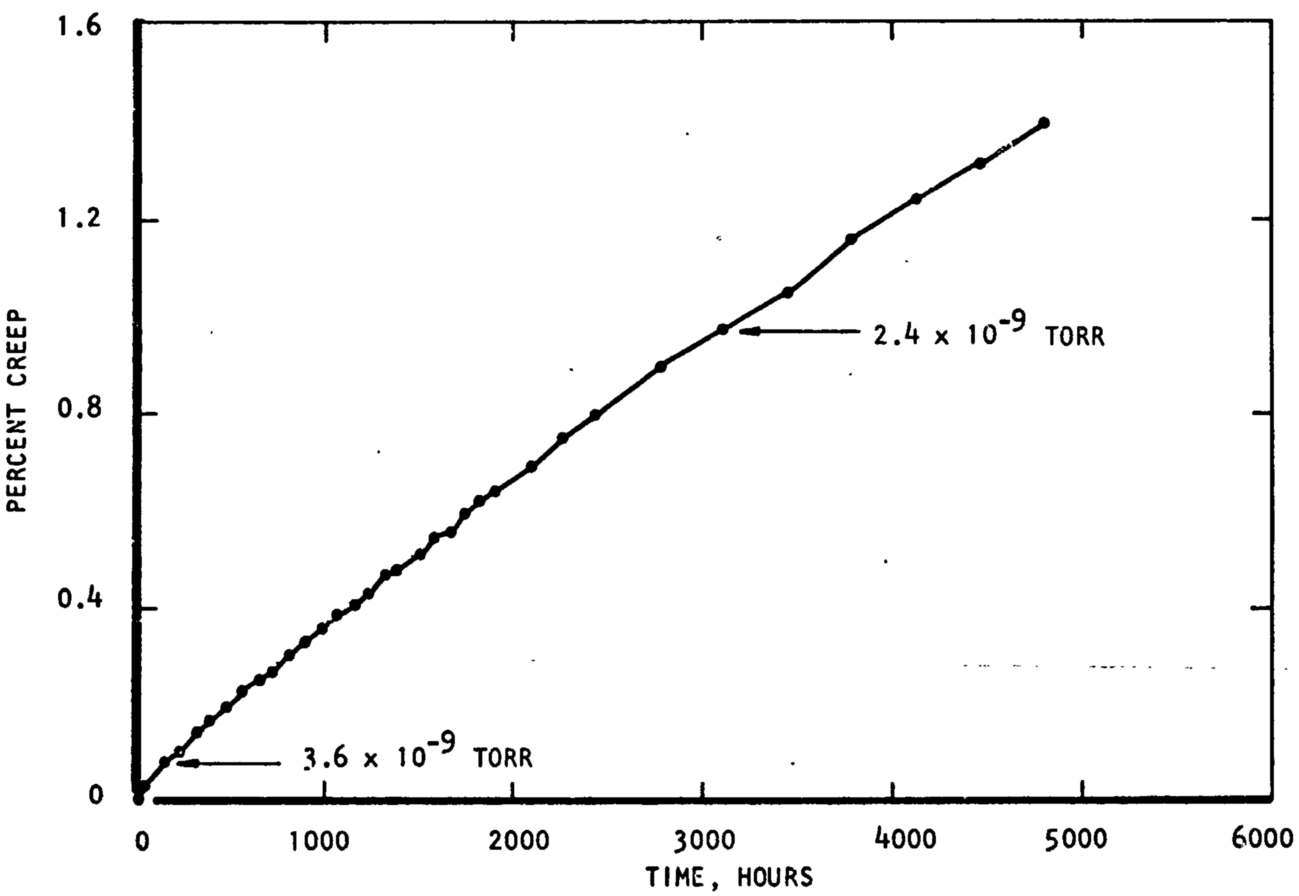

FIGURE III-12. CREEP TEST DATA, T-111, HEAT NO. 650028 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2400°F (1316°C) AND 1.5 KSI (10.4 mN/m^2), TEST NO. S-84, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

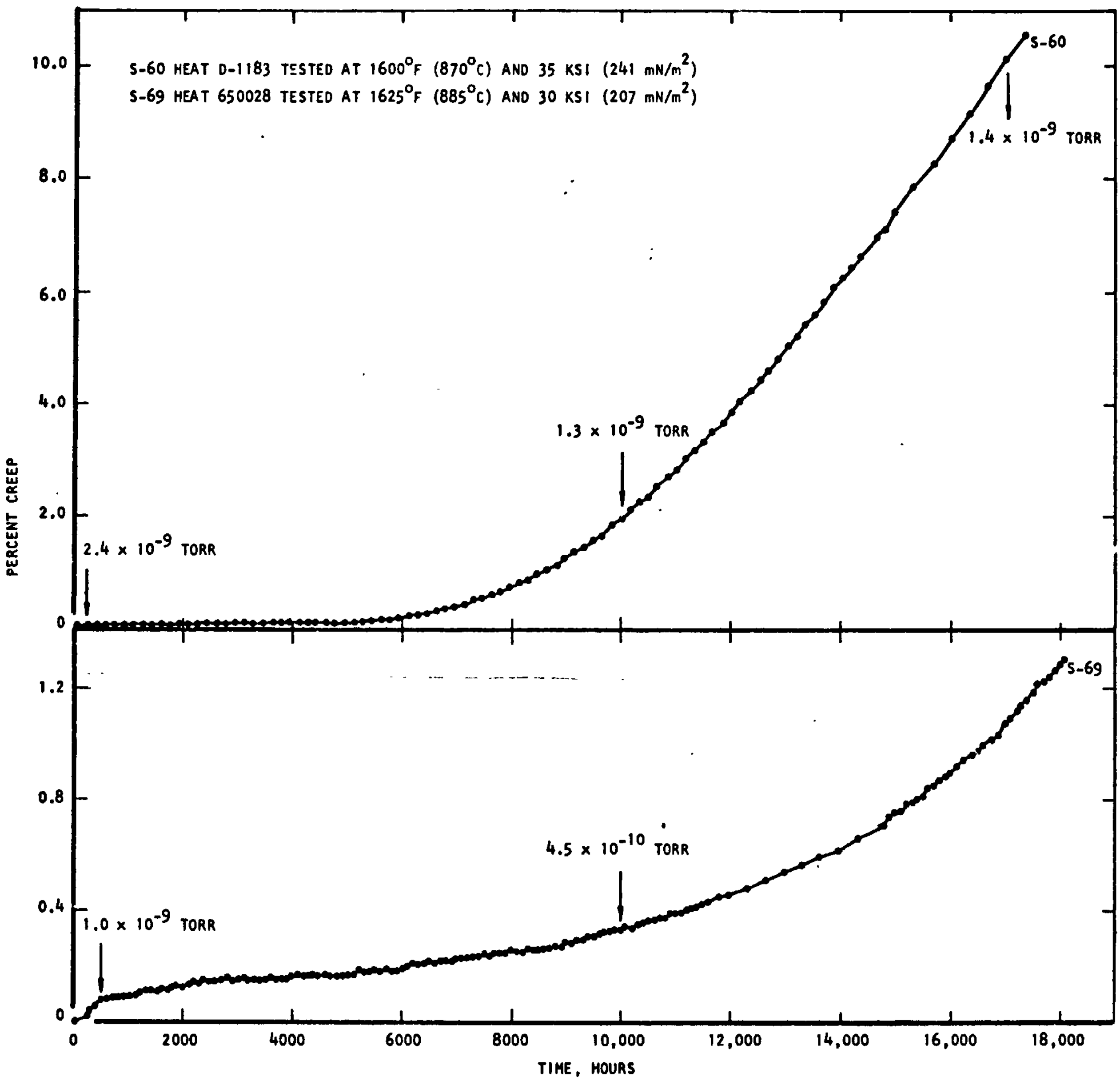

FIGURE III-13. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTS NO. S-60 AND S-69, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

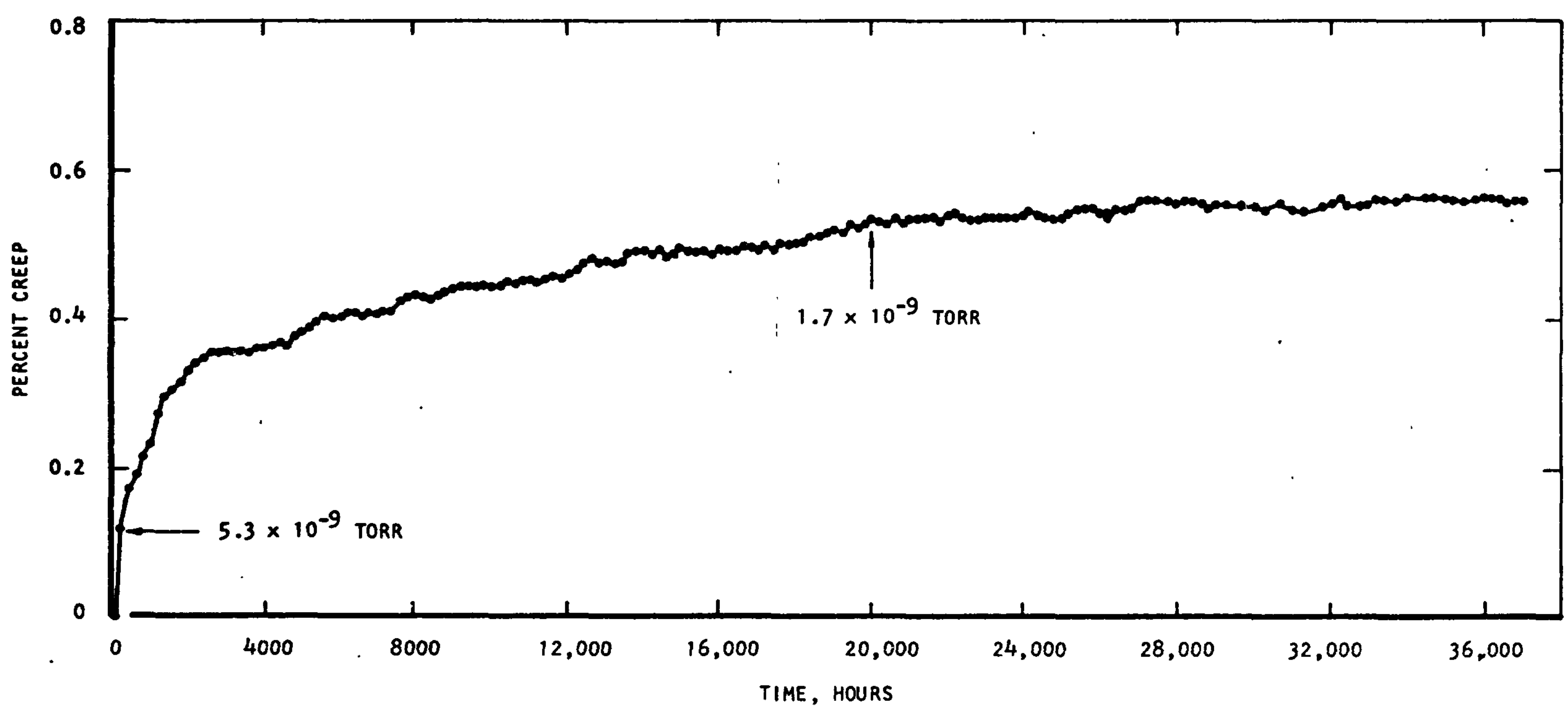

FIGURE III-14. CREEP TEST DATA, T-111 HEAT NO. D-1670 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2600°F (1427°C) AND 0.5 KSI (3.4 mN/m^2), TEST NO. S-28, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

APPENDIX IV

LISTING OF BASIC COMPUTER PROGRAM TO CALCULATE STRESS AND TEMPERATURE SET-UP DATA FOR EXPONENTIALLY VARYING STRESS AND TEMPERATURE TESTS

```
100 REM PRØGRAM TØ CALCULATE LØAD AND TEMPERATURE FØR VARIABLE
110 REM STRESS AND TEMPERATURE CREEP TEST
120 REM DATA ARE ENTERED IN LINES 1410 THRØUGH 1510 AS FØLLØWS:
130 REM     1410 THERMØCØUPLE CALIBRATIØN FACTØR,TEMPERATURE CØNTRØLLER
140 REM          DRIVE MØTØR SPEED (HØURS PER REVØLUTIØN)
150 REM     1420 TEST NUMBER
160 REM     1430 STARTING TIME,TIME INCREMENT
170 REM     1440 AMBIENT TEMPERATURE
180 REM     1450 CØNSTANTS FØR YIELD PØLYNØMIAL
190 REM     1460 STARTING TEMPERATURE,STRESS LEVEL,HALF LIFE
200 REM     1470 SPECIMEN WIDTH AND THICKNESS
205 REM     1480 THRØUGH 1510 CØNTAIN PATCHBØARD SETUP INFØRMATIØN
210 REM THE PRØGRAM CALCULATES THE STRESS FACTØR FØR A YIELD KISS
220 REM AND THEN CALCULATES THE STRESS,TEMPERATURE, AND LØAD USING
230 REM THE EQUATIØNS:
240 REM TEMP=TA+(TØ-TA)*EXP(-LAMBDA*TIME)
250 REM STRESS=F*SL*TEMP*(1-EXP(-LAMBDA*TIME))
260 REM LØAD=STRESS*AREA
270 DIM Z(100),G$(100),R(50),V(50),U(50),E(50)
280 READ V2,R6
290 READ B$
300 READ S9,D1,T8,A0,A1,A2,T2,L,H,W,T5
310 FØR I=4 TØ 96 STEP 2
320 READ G$(I)
330 NEXT I
340 LET TO =(T2-32)*5/9 +273.16
350 LET T9 = (T8-32)*5/9 + 273.16
360 LET L9 = LØG(2)
370 LET D = LØG((1-T9/(TO-T9))/2)
380 LET E5 = EXP(D)
390 LET T1 = T9+(TO-T9)*E5
400 LET F = A0+A1*T1+A2*T1*T1
410 LET F = F/T1/(1-E5)
420 LET Z(1) = -A0-A1*TO-A2*TO*TO
430 FØR C = 1TØ10
440 FØR N = 2TØ100
450 LET T = D*(N-1)/100
460 LET E5 = EXP(T)
470 LET T1 = T9+(TO-T9)*E5
480 LET Z(N) = F*T1*(1-E5)-A0-A1*T1-A2*T1*T1
490 IF Z(N)<Z(N-1) GØ TØ 520
500 LET X= Z(N)
510 LET K1 = N
520 NEXT N
530 LET T =K1*D/100
540 LET E5 =EXP(T)
550 LET T1 = T9 +(TO-T9)*E5
560 LET Y = A0+A1*T1+A2*T1*T1
570 IF ABS(X/Y)<.0001 GØ TØ 620
580 LET F = F*(1-X/Y)
590 NEXT C
```

```
600 PRINT "KISS SUBRØUTINE FAILED TØ CØNVERGE"
610 STØP
620 LET L1 = L9/H
630 LET A = W*T5
640 PRINT
650 PRINT
660 PRINT
670 PRINT
680 PRINT"LØAD AND TEMPERATURE DATA FØR VARIABLE STRESS AND TEMPERATURE"
690 PRINT"----------------------------------------------------------------"
700 PRINT
710 PRINT
720 PRINT"TEST NUMBER..................... ";B$
730 PRINT"STARTING TEMPERATURE............";T2;"F"
740 PRINT "STRESS LEVEL....................";L
750 PRINT"HALF LIFE.......................";H;"HØURS"
760 PRINT"STRESS FACTØR...................";F;"PSI/C DEG."
770 PRINT"WIDTH...........................";W;"INCHES"
780 PRINT"THICKNESS.......................";T5;"INCHES"
790 PRINT"AREA............................";A;"SQ. IN."
800 PRINT"THERMØCØUPLE CØRRECTIØN FACTØR..";V2;"MILIVØLTS"
810 PRINT"DRIVE MØTØR SPEED...............";R6;"HØURS/REVØLUTIØN"
820 PRINT
830 PRINT
840 PRINT"          TEMP    DSIRED  ACTUAL  PTCH   STRESS    LØAD     DELTA"
850 PRINT"HØURS   DEG. F  MILVLT  MILVLT  HØLE    PSI     PØUNDS     LB. "
860 PRINT"=====   ======  ======  ======  ====   ======   ======    ====="
870 PRINT
880 LET P9 = 0
890 FØR T =S9TØH STEP D1
900 LET E = EXP(-L1*T)
910 LET T1 = T9+(T0-T9)*E
920 LET T5 = (T1-273.16)*9/5 + 32
930 LET V5=-1.74754+1.12811E-2*T5-3.24975E-6*T5↑2+4.37152E-9*T5↑3
940 LET V5=V5-2.30307E-12*T5↑4+5.38581E-16*T5↑5-4.79086E-20*T5↑6
950 LET V5=V5-.56+V2
960 IF T<>S9 THEN 980
970 LET V1=V5
980 LET V6=V1-V5
990 LET R5=50*V6*R6/D1
1000 LET R(1)=INT(R5/2+.5)*2
1010 FØR I=1 TØ 50
1020 LET U(I)=R(I)*D1/R6/50
1030 LET V(I)=V1-U(I)
1040 LET E(I)=V5-V(I)
1050 IF ABS(E(I))<=.01 THEN 1180
1060 IF I=1 THEN 1120
1070 IF SGN(E(I))=SGN(E(I-1)) THEN 1120
1080 IF ABS(E(I))<=ABS(E(I-1)) THEN 1180
1090 LET V1=V1-U(I-1)
1100 LET R5=R(I-1)
```

```
1110 GØ TØ 1200
1120 IF E(I)>.01 THEN 1150
1130 R(I+1)=R(I)+2
1140 GØ TØ 1160
1150 R(I+1)=R(I)-2
1160 NEXT I
1170 PRINT I
1180 LET V1=V1-U(I)
1190 LET R5=R(I)
1200 LET S = F*L*T1*(1-E)
1210 LET P = S*A
1220 LET D6 =P-P9
1230 LET D7=D6*453.6
1240 LET P9 = P
1250 LET T5=INT(10*T5+.5)/10
1260 LET V5=INT(1000*V5+.5)/1000
1270 LET V8=INT(1000*V1+.5)/1000
1280 LET R5=INT(100*R5+.5)/100
1290 LET D6=INT(100*D6+.5)/100
1300 IF T=S9 THEN 1320
1310 GØ TØ 1340
1320 LET V6=0
1330 LET R5=0
1340 PRINT T;TAB(6);T5;TAB(14);V5;TAB(22);V8;TAB(31);G$(R5);TAB(37);S;
1350 PRINT TAB(46);P;TAB(55);D6;TAB(62);D7
1360 NEXT T
1370 PRINT
1380 PRINT
1390 PRINT
1400 PRINT
1410 DATA .014,24
1420 DATA S-109
1430 DATA 0,2
1440 DATA 75
1450 DATA 97584.97846,-81.77844242,.02342763
1460 DATA 2600,1,400
1470 DATA .49943,.02986
1480 DATA E-7,E-6,E-5,E-4,E-3,E-2,E-1,D-10,D-9,D-8,D-7,D-6,D-5,D-4
1490 DATA D-3,D-2,D-1,C-10,C-9,C-8,C-7,C-6,C-5,A-1,C-4,C-3,C-2,C-1
1500 DATA B-10,B-9,B-8,B-7,B-6,B-5,B-4,B-3,B-2,B-1,A-10,A-9,A-8,A-7
1510 DATA A-6,A-5,A-4,A-3,A-2
1520 END
```

APPENDIX V

TYPICAL OUTPUT OF COMPUTER PROGRAM TO CALCULATE STRESS AND TEMPERATURE SET-UP DATA FOR EXPONENTIALLY VARYING STRESS AND TEMPERATURE TESTS

LOAD AND TEMPERATURE DATA FOR VARIABLE STRESS AND TEMPERATURE TEST

TEST NUMBER...................... S-109
STARTING TEMPERATURE............. 2600 F
STRESS LEVEL..................... 1
HALF LIFE........................ 400 HOURS
STRESS FACTOR.................... 76.4269 PSI/C DEG.
WIDTH............................ 0.49943 INCHES
THICKNESS........................ 0.02986 INCHES
AREA............................. 0.01491 SQ. IN.
THERMOCOUPLE CORRECTION FACTOR.. 0.014 MILIVOLTS
DRIVE MOTOR SPEED................ 24 HOURS/REVOLUTION

HOURS	TEMP DEG. F	DSIRED MILVLT	ACTUAL MILVLT	PTCH HOLE	STRESS PSI	LOAD POUNDS	DELTA LB.	DELTA GRAMS
0	2600	25.849	25.849		0	0	0	0
2	2591.3	25.762	25.763	C-4	448.18	6.69369	6.68	3031.72
4	2582.6	25.674	25.673	C-3	892.255	13.3062	6.62	3003.96
6	2573.9	25.587	25.586	C-4	1332.26	19.868	6.56	2974.42
8	2565.2	25.5	25.499	C-4	1768.22	26.3695	6.5	2949.09
10	2556.6	25.413	25.413	C-4	2200.18	32.8112	6.44	2921.97
12	2548	25.326	25.326	C-4	2628.15	39.1936	6.38	2895.06
14	2539.5	25.24	25.239	C-4	3050.18	45.5171	6.32	2868.36
16	2531	25.153	25.153	C-4	3472.3	51.7823	6.27	2841.87
18	2522.5	25.067	25.066	C-4	3888.52	57.9895	6.21	2815.58
20	2514	24.981	24.983	A-1	4300.9	64.1392	6.15	2789.5
22	2505.6	24.895	24.896	C-4	4709.44	70.2318	6.09	2763.62
24	2497.1	24.81	24.809	C-4	5114.15	76.2679	6.04	2737.95
26	2488.8	24.725	24.726	A-1	5515.18	82.2477	5.98	2712.47
28	2480.4	24.639	24.639	C-4	5912.42	88.1719	5.92	2687.19
30	2472.1	24.554	24.556	A-1	6305.96	94.0407	5.87	2662.11
32	2463.8	24.47	24.469	C-4	6695.83	99.8547	5.81	2637.23
34	2455.5	24.385	24.386	A-1	7082.04	105.614	5.76	2612.54
36	2447.3	24.301	24.299	C-4	7464.63	111.32	5.71	2588.04
38	2439.1	24.216	24.216	A-1	7843.62	116.972	5.65	2563.74
40	2430.9	24.132	24.133	A-1	8219.06	122.571	5.6	2539.62
42	2422.8	24.048	24.047	A-1	8590.95	128.117	5.55	2515.69
44	2414.6	23.965	23.966	A-1	8959.34	133.61	5.49	2491.95
46	2406.5	23.881	23.883	A-1	9324.24	139.052	5.44	2468.4
48	2398.5	23.798	23.799	A-1	9685.69	144.442	5.39	2445.03
50	2390.4	23.715	23.716	A-1	10043.7	149.782	5.34	2421.85
52	2382.4	23.632	23.633	A-1	10398.3	155.07	5.29	2398.84
54	2374.4	23.549	23.549	A-1	10749.6	160.308	5.24	2376.02
56	2366.5	23.467	23.466	A-1	11097.5	165.496	5.19	2353.38
58	2358.6	23.385	23.386	C-5	11442.1	170.635	5.14	2330.91
60	2350.7	23.302	23.303	A-1	11783.3	175.725	5.09	2308.62
62	2342.8	23.22	23.219	A-1	12121.4	180.766	5.04	2286.51
64	2334.9	23.139	23.139	C-5	12456.1	185.758	4.99	2264.57
66	2327.1	23.057	23.056	A-1	12787.7	190.702	4.94	2242.8
68	2319.3	22.976	22.976	C-5	13116	195.599	4.9	2221.21
70	2311.6	22.895	22.896	C-5	13441.2	200.449	4.85	2199.78
72	2303.8	22.814	22.813	A-1	13763.3	205.252	4.8	2178.52
74	2296.1	22.733	22.733	C-5	14082.2	210.008	4.76	2157.44
76	2288.4	22.652	22.653	C-5	14398.1	214.718	4.71	2136.52
78	2280.8	22.572	22.573	C-5	14710.8	219.382	4.66	2115.76
80	2273.1	22.491	22.493	C-5	15020.6	224.001	4.62	2095.17
82	2265.5	22.411	22.413	C-5	15327.3	228.575	4.57	2074.74
84	2258	22.332	22.333	C-5	15631	233.104	4.53	2054.47
86	2250.4	22.252	22.253	C-5	15931.7	237.589	4.48	2034.36
88	2242.9	22.172	22.173	C-5	16229.5	242.03	4.44	2014.42
90	2235.4	22.093	22.093	C-5	16524.4	246.428	4.4	1994.63
92	2227.9	22.014	22.013	C-5	16816.3	250.782	4.35	1974.99
94	2220.5	21.935	21.936	C-6	17105.4	255.093	4.31	1955.52
96	2213	21.856	21.856	C-5	17391.7	259.361	4.27	1936.2
98	2205.6	21.778	21.779	C-6	17675	263.588	4.23	1917.03
100	2198.3	21.699	21.699	C-5	17955.6	267.772	4.18	1898.01
102	2190.9	21.621	21.623	C-6	18233.4	271.915	4.14	1879.15
104	2183.6	21.543	21.543	C-5	18508.5	276.016	4.1	1860.43
106	2176.3	21.465	21.466	C-6	18780.7	280.077	4.06	1841.87
108	2169	21.388	21.389	C-6	19050.3	284.097	4.02	1823.45
110	2161.8	21.31	21.309	C-5	19317.2	288.076	3.98	1805.18
112	2154.6	21.233	21.233	C-6	19581.3	292.016	3.94	1787.06
114	2147.4	21.156	21.156	C-6	19842.9	295.916	3.9	1769.08
116	2140.2	21.079	21.079	C-6	20101.7	299.777	3.86	1751.24
118	2133.1	21.003	21.003	C-6	20358	303.599	3.82	1733.55
120	2125.9	20.926	20.926	C-6	20611.7	307.382	3.78	1716
122	2118.8	20.85	20.849	C-6	20862.8	311.126	3.74	1698.59
124	2111.8	20.774	20.773	C-6	21111.3	314.833	3.71	1681.31
126	2104.7	20.698	20.699	C-7	21357.4	318.502	3.67	1664.16
128	2097.7	20.622	20.623	C-6	21600.9	322.133	3.63	1647.15
130	2090.7	20.547	20.546	C-6	21841.9	325.727	3.59	1630.33
132	2083.7	20.471	20.473	C-7	22080.4	329.285	3.56	1613.6
134	2076.8	20.396	20.394	C-6	22316.5	332.805	3.52	1597.01
136	2069.9	20.321	20.323	C-7	22550.1	336.29	3.48	1580.56
138	2063	20.246	20.246	C-6	22781.4	339.738	3.45	1564.23
140	2056.1	20.172	20.173	C-7	23010.2	343.151	3.41	1548.04
142	2049.2	20.097	20.096	C-6	23236.7	346.529	3.38	1531.98
144	2042.4	20.023	20.023	C-7	23460.8	349.871	3.34	1516.05
146	2035.6	19.949	19.949	C-7	23682.6	353.178	3.31	1500.24
148	2028.8	19.875	19.876	C-7	23902.1	356.451	3.27	1484.57
150	2022	19.802	19.803	C-7	24119.2	359.69	3.24	1469.02
152	2015.3	19.728	19.729	C-7	24334.1	362.894	3.2	1453.59
154	2008.6	19.655	19.656	C-7	24546.7	366.065	3.17	1438.3
156	2001.9	19.582	19.583	C-7	24757.1	369.202	3.14	1423.12
158	1995.2	19.509	19.509	C-7	24965.3	372.307	3.1	1408.07
160	1988.6	19.436	19.436	C-7	25171.2	375.378	3.07	1393.14
162	1982	19.364	19.363	C-7	25375	378.417	3.04	1378.33
164	1975.4	19.292	19.293	C-8	25576.6	381.423	3.01	1363.64
166	1968.8	19.219	19.219	C-7	25776	384.397	2.97	1349.07
168	1962.2	19.148	19.146	C-7	25973.3	387.339	2.94	1334.62
170	1955.7	19.076	19.076	C-8	26168.5	390.25	2.91	1320.99
172	1949.2	19.004	19.006	C-8	26361.6	393.129	2.88	1306.07
174	1942.7	18.933	18.933	C-7	26552.5	395.978	2.85	1291.97
176	1936.3	18.862	18.863	C-8	26741.5	398.795	2.82	1277.98
178	1929.8	18.791	18.789	C-7	26928.3	401.582	2.79	1264.11
180	1923.4	18.72	18.719	C-8	27113.2	404.338	2.76	1250.36
182	1917	18.649	18.649	C-8	27296	407.065	2.73	1236.71
184	1910.6	18.579	18.579	C-8	27476.8	409.761	2.7	1223.17
186	1904.3	18.509	18.509	C-8	27655.7	412.428	2.67	1209.75
188	1898	18.439	18.439	C-8	27832.5	415.066	2.64	1196.44
190	1891.7	18.369	18.369	C-8	28007.5	417.675	2.61	1183.23
192	1885.4	18.299	18.299	C-8	28180.4	420.254	2.58	1170.14
194	1879.1	18.23	18.229	C-8	28351.5	422.805	2.55	1157.15
196	1872.9	18.161	18.159	C-8	28520.7	425.326	2.52	1144.27
198	1866.6	18.091	18.093	C-9	28687.9	427.822	2.49	1131.49
200	1860.4	18.023	18.023	C-8	28853.3	430.289	2.47	1118.82
202	1854.3	17.954	17.953	C-8	29016.9	432.728	2.44	1106.25
204	1848.1	17.885	17.886	C-9	29178.5	435.139	2.41	1093.79
206	1842	17.817	17.816	C-8	29338.4	437.523	2.38	1081.43
208	1835.9	17.749	17.749	C-9	29496.3	439.88	2.36	1069.17
210	1829.8	17.681	17.683	C-9	29652.7	442.211	2.33	1057.01
212	1823.7	17.613	17.613	C-8	29807.2	444.514	2.3	1044.96
214	1817.7	17.546	17.546	C-9	29959.9	446.792	2.28	1033
216	1811.6	17.479	17.479	C-9	30110.9	449.043	2.25	1021.14
218	1805.6	17.411	17.413	C-9	30260.1	451.268	2.23	1009.38
220	1799.6	17.344	17.346	C-9	30407.6	453.468	2.2	997.72
222	1793.7	17.278	17.279	C-9	30553.4	455.642	2.17	986.155
224	1787.7	17.211	17.213	C-9	30697.5	457.79	2.15	974.686
226	1781.8	17.145	17.146	C-9	30839.9	459.914	2.12	963.312
228	1775.9	17.079	17.0	C-9	30980.6	462.013	2.1	952.032
230	1770	17.013	17.013	C-9	31119.7	464.087	2.07	940.847
232	1764.1	16.947	16.946	C-9	31257.1	466.137	2.05	929.755
234	1758.3	16.881	16.883	C-10	31392.9	468.162	2.03	918.755
236	1752.5	16.816	16.816	C-9	31527.2	470.164	2	907.847
238	1744.7	16.751	16.749	C-9	31659.8	472.141	1.98	897.03
240	1740.9	16.686	16.686	C-10	31790.8	474.095	1.95	886.304
242	1735.1	16.621	16.619	C-9	31920.2	476.026	1.93	875.668
244	1729.4	16.556	16.556	C-10	32048.1	477.933	1.91	865.12
246	1723.6	16.492	16.493	C-10	32174.5	479.817	1.88	854.661
248	1717.9	16.427	16.426	C-9	32299.3	481.679	1.86	844.29
250	1712.3	16.363	16.363	C-10	32422.6	483.517	1.84	834.006
252	1706.6	16.299	16.299	C-10	32544.4	485.333	1.82	823.808
254	1701	16.236	16.236	C-10	32664.6	487.127	1.79	813.696
256	1695.3	16.172	16.173	C-10	32783.5	488.899	1.77	803.669
258	1689.7	16.109	16.109	C-10	32900.8	490.649	1.75	793.727
260	1684.1	16.046	16.046	C-10	33016.7	492.377	1.73	783.869
262	1678.6	15.983	15.983	C-10	33131.1	494.083	1.71	774.093
264	1673	15.92	15.919	C-10	33244.1	495.769	1.69	764.401
266	1667.5	15.858	15.859	D-1	33355.7	497.433	1.66	754.79
268	1662	15.795	15.796	C-10	33465.9	499.076	1.64	745.261
270	1656.5	15.733	15.733	C-10	33574.6	500.698	1.62	735.812
272	1651	15.671	15.673	D-1	33682	502.299	1.6	726.444
274	1645.6	15.61	15.609	C-10	33788	503.88	1.58	717.155
276	1640.1	15.548	15.549	D-1	33892.7	505.441	1.56	707.945
278	1634.7	15.487	15.486	C-10	33996	506.982	1.54	698.814
280	1629.3	15.426	15.426	D-1	34098	508.502	1.52	689.76
282	1623.9	15.365	15.366	D-1	34198.6	510.003	1.5	680.783
284	1618.6	15.304	15.303	C-10	34297.9	511.484	1.48	671.883
286	1613.2	15.243	15.243	D-1	34396	512.946	1.46	663.059
288	1607.9	15.183	15.183	D-1	34492.7	514.389	1.44	654.311
290	1602.6	15.123	15.123	D-1	34588.1	515.812	1.42	645.637
292	1597.3	15.063	15.063	D-1	34682.3	517.216	1.4	637.037
294	1592.1	15.003	15.003	D-1	34775.2	518.602	1.39	628.512
296	1586.8	14.943	14.943	D-1	34866.9	519.969	1.37	620.059
298	1581.6	14.884	14.883	D-1	34957.3	521.317	1.35	611.679
300	1576.4	14.824	14.826	D-2	35044.5	522.648	1.33	603.371
302	1571.2	14.765	14.766	D-1	35134.5	523.96	1.31	595.135
304	1566	14.706	14.706	D-1	35221.2	525.254	1.29	586.969
306	1560.8	14.648	14.649	D-2	35306.8	526.53	1.28	578.874
308	1555.7	14.589	14.589	D-1	35391.2	527.788	1.26	570.849
310	1550.6	14.531	14.533	D-2	35474.4	529.029	1.24	562.894
312	1545.5	14.473	14.473	D-1	35556.5	530.253	1.22	555.007
314	1540.4	14.415	14.416	D-2	35637.4	531.459	1.21	547.188
316	1535.3	14.357	14.356	D-1	35717.1	532.648	1.19	539.437
318	1530.3	14.3	14.299	D-2	35795.7	533.821	1.17	531.754
320	1525.2	14.242	14.243	D-2	35873.2	534.976	1.16	524.137
322	1520.2	14.185	14.186	D-2	35949.6	536.115	1.14	516.587
324	1515.2	14.128	14.129	D-2	36024.8	537.237	1.12	509.102
326	1510.2	14.072	14.073	D-2	36099	538.343	1.11	501.682
328	1505.3	14.015	14.016	D-2	36172.1	539.433	1.09	494.328
330	1500.3	13.959	13.959	D-2	36244.1	540.507	1.07	487.037
332	1495.4	13.902	13.903	D-2	36315	541.565	1.06	479.81
334	1490.5	13.846	13.846	D-2	36384.9	542.607	1.04	472.647
336	1485.6	13.79	13.789	D-2	36453.7	543.633	1.03	465.546
338	1480.7	13.735	13.736	D-3	36521.5	544.644	1.01	458.508
340	1475.8	13.679	13.679	D-2	36588.2	545.639	1	451.531
342	1471	13.624	13.623	D-2	36653.9	546.619	0.98	444.616
344	1466.2	13.569	13.569	D-3	36718.7	547.585	0.97	437.762
346	1461.3	13.514	13.513	D-2	36782.4	548.535	0.95	430.968
348	1456.5	13.459	13.459	D-3	36845.1	549.47	0.94	424.235
350	1451.8	13.405	13.406	D-3	36906.8	550.39	0.92	417.56
352	1447	13.351	13.349	D-2	36967.6	551.296	0.91	410.945
354	1442.3	13.296	13.296	D-3	37027.3	552.188	0.89	404.388
356	1437.5	13.242	13.243	D-3	37086.2	553.065	0.88	397.89
358	1432.8	13.189	13.189	D-3	37144	553.928	0.86	391.449
360	1428.1	13.135	13.136	D-3	37201	554.777	0.85	385.065
362	1423.4	13.082	13.083	D-3	37256.9	555.612	0.83	378.739
364	1418.8	13.028	13.029	D-3	37312	556.433	0.82	372.469
366	1414.1	12.975	12.976	D-3	37366.1	557.241	0.81	366.254
368	1409.5	12.923	12.923	D-3	37419.4	558.034	0.79	360.096
370	1404.9	12.87	12.869	D-3	37471.7	558.815	0.78	353.992
372	1400.3	12.817	12.816	D-3	37523.1	559.588	0.77	347.943
374	1395.7	12.765	12.766	D-4	37573.7	560.336	0.75	341.948
376	1391.1	12.713	12.713	D-3	37623.4	561.077	0.74	336.007
378	1386.6	12.661	12.663	D-4	37672.2	561.804	0.73	330.12
380	1382	12.609	12.609	D-3	37720.1	562.519	0.71	324.285
382	1377.5	12.558	12.559	D-4	37767.2	563.221	0.7	318.503
384	1373	12.506	12.506	D-3	37813.4	563.911	0.69	312.773
386	1368.5	12.455	12.456	D-4	37858.8	564.588	0.68	307.095
388	1364	12.404	12.403	D-3	37903.4	565.253	0.66	301.469
390	1359.6	12.353	12.353	D-4	37947.1	565.905	0.65	295.893
392	1355.1	12.303	12.303	D-4	37990.1	566.545	0.64	290.368
394	1350.7	12.252	12.253	D-4	38032.2	567.173	0.63	284.894
396	1346.3	12.202	12.203	D-4	38073.5	567.789	0.62	279.469
398	1341.9	12.152	12.153	D-4	38114	568.393	0.6	274.093
400	1337.5	12.102	12.103	D-4	38153.7	568.986	0.59	268.767

402	1333.1	12.052	12.053	D-4	38192.7	569.567	0.58	263.489
404	1328.8	12.002	12.003	D-4	38230.9	570.136	0.57	258.259
406	1324.4	11.953	11.953	D-4	38268.3	570.694	0.56	253.078
408	1320.1	11.904	11.903	D-4	38304.9	571.241	0.55	247.944
410	1315.8	11.855	11.856	D-5	38340.8	571.776	0.54	242.857
412	1311.5	11.806	11.806	D-4	38376	572.3	0.52	237.817
414	1307.2	11.757	11.756	D-4	38410.4	572.814	0.51	232.823
416	1303	11.709	11.709	D-5	38444.1	573.316	0.5	227.876
418	1298.7	11.66	11.659	D-	38477.1	573.808	0.49	222.974
420	1294.5	11.612	11.613	D	38509.3	574.289	0.48	218.118
422	1290.3	11.564	11.563	D-4	38540.8	574.759	0.47	213.306
424	1286.1	11.516	11.516	D-5	38571.7	575.219	0.46	208.54
426	1281.9	11.469	11.469	D-5	38601.8	575.668	0.45	203.817
428	1277.7	11.421	11.423	D-5	38631.2	576.107	0.44	199.139
430	1273.5	11.374	11.373	D-4	38660	576.536	0.43	194.504
432	1269.4	11.327	11.326	D-5	38688.1	576.954	0.42	189.912
434	1265.3	11.28	11.279	D-5	38715.5	577.363	0.41	185.364
436	1261.1	11.233	11.233	D-5	38742.2	577.762	0.4	180.858
438	1257	11.186	11.186	D-5	38768.3	578.151	0.39	176.394
440	1253	11.14	11.139	D-5	38793.7	578.53	0.38	171.973
442	1248.9	11.094	11.093	D-5	38818.5	578.899	0.37	167.593
444	1244.8	11.048	11.049	D-6	38842.6	579.259	0.36	163.254
446	1240.8	11.002	11.003	D-5	38866.1	579.61	0.35	158.956
448	1236.7	10.956	10.956	D-5	38889	579.951	0.34	154.699
450	1232.7	10.91	10.909	D-5	38911.2	580.282	0.33	150.482
452	1228.7	10.865	10.866	D-6	38932.9	580.605	0.32	146.305
454	1224.7	10.82	10.819	D-6	38953.9	580.918	0.31	142.168
456	1220.7	10.774	10.776	D-6	38974.3	581.223	0.3	138.07
458	1216.8	10.73	10.729	D-5	38994.1	581.518	0.3	134.012
460	1212.8	10.685	10.686	D-6	39013.3	581.805	0.29	129.992
462	1208.9	10.64	10.639	D-5	39031.9	582.083	0.28	126.011
464	1205	10.596	10.596	D-6	39050	582.352	0.27	122.068
466	1201.1	10.552	10.553	D-6	39067.5	582.612	0.26	118.162
468	1197.2	10.507	10.506	D-5	39084.3	582.864	0.25	114.294
470	1193.3	10.464	10.463	D-6	39100.7	583.108	0.24	110.464
472	1189.4	10.42	10.419	D-6	39116.4	583.343	0.24	106.671
474	1185.6	10.376	10.376	D-6	39131.7	583.57	0.23	102.914
476	1181.7	10.333	10.333	D-6	39146.3	583.788	0.22	99.1933
478	1177.9	10.29	10.289	D-6	39160.4	583.999	0.21	95.509
480	1174.1	10.246	10.246	D-6	39174	584.201	0.2	91.8606
482	1170.3	10.203	10.203	D-6	39187.1	584.396	0.19	88.2476
484	1166.5	10.161	10.159	D-6	39199.6	584.583	0.19	84.67
486	1162.7	10.118	10.119	D-7	39211.6	584.761	0.18	81.1273
488	1158.9	10.076	10.076	D-6	39223.1	584.933	0.17	77.6193
490	1155.2	10.033	10.033	D-6	39234	585.096	0.16	74.1458
492	1151.5	9.991	9.993	D-7	39244.5	585.252	0.16	70.7064
494	1147.7	9.949	9.949	D-6	39254.4	585.4	0.15	67.3009
496	1144	9.907	9.906	D-6	39263.9	585.541	0.14	63.929
498	1140.3	9.866	9.866	D-7	39272.8	585.675	0.13	60.5904
500	1136.6	9.824	9.826	D-7	39281.3	585.801	0.13	57.285
502	1133	9.783	9.783	D-6	39289.3	585.92	0.12	54.0123
504	1129.3	9.742	9.743	D-7	39296.8	586.032	0.11	50.7723
506	1125.7	9.701	9.699	D-6	39303.8	586.137	0.1	47.5645
508	1122	9.66	9.657	D-7	39310.4	586.235	0.1	44.3887
510	1118.4	9.619	9.619	D-7	39316.5	586.326	0.09	41.2448
512	1114.8	9.579	9.579	D-7	39322.1	586.41	0.08	38.1324
514	1111.2	9.538	9.539	D-7	39327.3	586.487	0.08	35.0512
516	1107.6	9.498	9.499	D-7	39332	586.558	0.07	32.0011
518	1104	9.456	9.459	D-7	39336.3	586.622	0.06	28.9818
520	1100.5	9.418	9.419	D-7	39340.1	586.679	0.05	25.993
522	1096.9	9.378	9.379	D-7	39343.6	586.73	0.05	23.0346
524	1093.4	9.338	9.339	D-7	39346.5	586.774	0.04	20.104[illegible]
526	1089.9	9.299	9.299	D-7	39349.1	586.812	0.04	17.2075
528	1086.4	9.26	9.259	D-7	39351.2	586.843	0.03	14.3384
530	1082.9	9.22	9.219	D-7	39352.9	586.869	0.03	11.4987
532	1079.4	9.181	9.183	D-8	39354.2	586.888	0.02	8.60807
534	1075.9	9.142	9.143	D-7	39355	586.901	0.01	5.9063
536	1072.4	9.104	9.103	D-7	39355.5	586.908	0.01	3.15317
538	1069	9.065	9.066	D-8	39355.6	586.909	0	0.42844
540	1065.5	9.027	9.026	D-7	39355.2	586.904	-0.01	-2.26812
542	1062.1	8.988	8.989	D-8	39354.5	586.893	-0.01	-4.93674
544	1058.7	8.95	8.949	D-7	39353.4	586.876	-0.02	-7.57763
546	1055.3	8.912	8.913	D-8	39351.9	586.854	-0.02	-10.191
548	1051.9	8.874	8.876	D-8	39350	586.826	-0.03	-12.7771
550	1048.5	8.837	8.836	D-7	39347.7	586.792	-0.03	-15.3362
552	1045.2	8.799	8.799	D-8	39345.1	586.752	-0.04	-17.8684
554	1041.8	8.762	8.763	D-8	39342.1	586.708	-0.04	-20.3741
556	1038.5	8.724	8.724	D-8	39338.7	586.657	-0.05	-22.8537
558	1035.1	8.687	8.686	D-7	39335	586.601	-0.06	-25.3063
560	1031.8	8.65	8.649	D-8	39330.9	586.54	-0.06	-27.7333
562	1028.5	8.613	8.613	D-8	39326.4	586.474	-0.07	-30.1346
564	1025.2	8.577	8.576	D-8	39321.6	586.402	-0.07	-32.5103
566	1021.9	8.54	8.539	D-8	39316.4	586.325	-0.08	-34.8607
568	1018.6	8.504	8.503	D-8	39310.9	586.243	-0.08	-37.1859
570	1015.4	8.467	8.466	D-8	39305.1	586.156	-0.09	-39.4862
572	1012.1	8.431	8.433	D-9	39298.9	586.064	-0.09	-41.7618
574	1008.9	8.395	8.396	D-8	39292.4	585.967	-0.1	-44.0128
576	1005.6	8.359	8.359	D-8	39285.4	585.865	-0.1	-46.2395
578	1002.4	8.324	8.323	D-8	39278.4	585.758	-0.11	-48.442
580	999.2	8.288	8.289	D-9	39270.9	585.647	-0.11	-50.6206
582	996	8.253	8.253	D-8	39263.1	585.53	-0.12	-52.7755
584	992.8	8.217	8.216	D-8	39255	585.409	-0.12	-54.9068
586	989.6	8.182	8.183	D-9	39246.6	585.284	-0.13	-57.0147
588	986.5	8.147	8.146	D-8	39237.9	585.153	-0.13	-59.09[illegible]
590	983.3	8.112	8.113	D-9	39228.8	585.019	-0.13	-61.1613
592	980.2	8.077	8.076	D-8	39219.5	584.879	-0.14	-63.2004
594	977.1	8.043	8.043	D-9	39209.8	584.736	-0.14	-65.2168
596	973.9	8.008	8.009	D-9	39199.9	584.587	-0.15	-67.2108
598	970.8	7.974	7.973	D-8	39189.7	584.435	-0.15	-69.1874
600	967.7	7.94	7.939	D-9	39179.2	584.278	-0.16	-71.1323
602	964.6	7.906	7.906	D-9	39168.4	584.117	-0.16	-73.0602
604	961.6	7.872	7.873	D-9	39157.3	583.952	-0.17	-74.9663
606	958.5	7.838	7.839	D-9	39145.9	583.782	-0.17	-76.851
608	955.4	7.804	7.803	D-8	39134.3	583.609	-0.17	-78.7143
610	952.4	7.771	7.769	D-9	39122.4	583.431	-0.18	-80.5565
612	949.4	7.737	7.736	D-9	39110.2	583.25	-0.18	-82.3777
614	946.3	7.704	7.703	D-9	39097.7	583.064	-0.19	-84.1781
616	943.3	7.671	7.669	D-9	39085	582.874	-0.19	-85.9579
618	940.3	7.638	7.639	D-10	39072.1	582.681	-0.19	-87.7172
620	937.3	7.605	7.606	D-9	39058.9	582.484	-0.2	-89.4562
622	934.3	7.572	7.573	D-9	39045.4	582.283	-0.2	-91.1751
624	931.4	7.539	7.539	D-9	39031.6	582.078	-0.2	-92.874
626	928.4	7.507	7.506	D-9	39017.7	581.87	-0.21	-94.5531
628	925.4	7.474	7.476	D-10	39003.4	581.658	-0.21	-96.2126
630	922.5	7.442	7.443	D-9	38989	581.442	-0.22	-97.8527
632	919.6	7.41	7.409	D-9	38974.3	581.223	-0.22	-99.4734
634	916.6	7.378	7.379	D-10	38959.3	581	-0.22	-101.075
636	913.7	7.346	7.346	D-9	38944.2	580.773	-0.23	-102.658
638	910.8	7.314	7.313	D-9	38928.7	580.544	-0.23	-104.221
640	907.9	7.282	7.283	D-10	38913.1	580.31	-0.23	-105.767
642	905.1	7.251	7.249	D-9	38897.2	580.074	-0.24	-107.293
644	902.2	7.219	7.219	D-10	38881.2	579.834	-0.24	-108.801
646	899.3	7.188	7.189	D-10	38864.9	579.591	-0.24	-110.292
648	896.5	7.157	7.156	D-9	38848.3	579.344	-0.25	-111.764
650	893.6	7.126	7.126	D-10	38831.6	579.095	-0.25	-113.218
652	890.8	7.095	7.096	D-10	38814.7	578.842	-0.25	-114.654
654	888	7.064	7.063	D-9	38797.5	578.586	-0.26	-116.073
656	885.2	7.033	7.033	D-10	38780.1	578.327	-0.26	-117.474
658	882.4	7.003	7.003	D-10	38762.6	578.065	-0.26	-118.858
660	879.6	6.972	6.973	D-10	38744.8	577.8	-0.27	-120.225
662	876.8	6.942	6.943	D-10	38726.8	577.532	-0.27	-121.575
664	874	6.912	6.913	D-10	38708.6	577.261	-0.27	-122.908
666	871.2	6.882	6.883	D-10	38690.3	576.987	-0.27	-124.224
668	868.5	6.852	6.853	D-10	38671.7	576.711	-0.28	-125.524
670	865.7	6.822	6.823	D-10	38653	576.431	-0.28	-126.807
672	863	6.792	6.793	D-10	38634	576.149	-0.28	-128.074
674	860.3	6.762	6.763	D-10	38614.9	575.864	-0.29	-129.325
676	857.6	6.733	6.733	D-10	38595.6	575.576	-0.29	-130.56
678	854.9	6.704	6.703	D-10	38576.1	575.285	-0.29	-131.778
680	852.2	6.674	6.676	E-1	38556.5	574.992	-0.29	-132.981
682	849.5	6.645	6.646	D-10	38536.6	574.696	-0.3	-134.169
684	846.8	6.616	6.616	D-10	38516.6	574.398	-0.3	-135.341
686	844.1	6.587	6.586	D-10	38496.5	574.097	-0.3	-136.498
688	841.5	6.558	6.559	E-1	38476.1	573.794	-0.3	-137.639
690	838.8	6.529	6.529	D-10	38455.6	573.488	-0.31	-138.765
692	836.2	6.501	6.499	D-10	38434.9	573.179	-0.31	-139.877
694	833.5	6.472	6.473	E-1	38414.1	572.868	-0.31	-140.973
696	830.9	6.444	6.443	D-10	38393.1	572.555	-0.31	-142.055
698	828.3	6.416	6.416	E-1	38371.9	572.24	-0.32	-143.122
700	825.7	6.387	6.386	D-10	38350.6	571.922	-0.32	-144.175
702	823.1	6.359	6.359	E-1	38329.1	571.602	-0.32	-145.213
704	820.5	6.331	6.333	E-1	38307.5	571.279	-0.32	-146.237
706	817.9	6.304	6.303	D-10	38285.8	570.955	-0.32	-147.248
708	815.4	6.276	6.276	E-1	38263.8	570.628	-0.33	-148.244
710	812.8	6.248	6.249	E-1	38241.8	570.299	-0.33	-149.226
712	810.2	6.221	6.219	D-10	38219.6	569.968	-0.33	-150.195
714	807.7	6.193	6.193	E-1	38197.2	569.635	-0.33	-151.15
716	805.2	6.166	6.166	E-1	38174.8	569.299	-0.34	-152.091
718	802.6	6.139	6.139	E-1	38152.1	568.962	-0.34	-153.019
720	800.1	6.112	6.113	E-1	38129.4	568.623	-0.34	-153.934
722	797.6	6.085	6.086	E-1	38106.5	568.281	-0.34	-154.836
724	795.1	6.058	6.059	E-1	38083.5	567.938	-0.34	-155.724
726	792.6	6.031	6.029	D-10	38060.3	567.593	-0.35	-156.6
728	790.1	6.004	6.003	E-1	38037	567.246	-0.35	-157.463
730	787.7	5.978	5.979	E-2	38013.6	566.897	-0.35	-158.313
732	785.2	5.951	5.953	E-1	37990.1	566.544	-0.35	-159.151
734	782.7	5.925	5.926	E-1	37966.5	566.193	-0.35	-159.976
736	780.3	5.898	5.899	E-1	37942.7	565.839	-0.35	-160.789
738	777.8	5.872	5.873	E-1	37918.8	565.482	-0.36	-161.59
740	775.4	5.846	5.846	E-1	37894.8	565.124	-0.36	-162.378
742	773	5.82	5.819	E-1	37870.7	564.765	-0.36	-163.155
744	770.6	5.794	5.796	E-2	37846.4	564.403	-0.36	-163.919
746	768.2	5.768	5.769	E-1	37822.1	564.04	-0.36	-164.672
748	765.8	5.743	5.743	E-1	37797.7	563.676	-0.36	-165.413
750	763.4	5.717	5.716	E-1	37773.1	563.309	-0.37	-166.142
752	761	5.692	5.693	E-2	37748.4	562.941	-0.37	-166.86
754	758.6	5.666	5.666	E-1	37723.7	562.572	-0.37	-167.567
756	756.3	5.641	5.643	E-2	37698.8	562.201	-0.37	-168.262
758	753.9	5.616	5.616	E-1	37673.8	561.829	-0.37	-168.946
760	751.6	5.591	5.589	E-1	37648.7	561.455	-0.37	-169.618
762	749.2	5.566	5.566	E-2	37623.6	561.079	-0.38	-170.28
764	746.9	5.541	5.539	E-1	37598.3	560.702	-0.38	-170.931
766	744.6	5.516	5.516	E-2	37572.9	560.324	-0.38	-171.571
768	742.2	5.491	5.493	E-2	37547.5	559.945	-0.38	-172.2
770	739.9	5.467	5.466	E-1	37521.9	559.564	-0.38	-172.819
772	737.6	5.442	5.443	E-2	37496.3	559.181	-0.38	-173.427
774	735.3	5.418	5.419	E-2	37470.6	558.798	-0.38	-174.025
776	733.1	5.393	5.393	E-1	37444.7	558.413	-0.38	-174.612
778	730.8	5.369	5.369	E-2	37418.8	558.026	-0.39	-175.19
780	728.5	5.345	5.346	E-2	37392.9	557.639	-0.39	-175.757
782	726.3	5.321	5.323	E-2	37366.8	557.25	-0.39	-176.313
784	724	5.297	5.296	E-1	37340.7	556.86	-0.39	-176.86
786	721.8	5.273	5.273	E-2	37314.4	556.469	-0.39	-177.397
788	719.5	5.249	5.249	E-2	37288.1	556.077	-0.39	-177.925
790	717.3	5.226	5.226	E-2	37261.7	555.684	-0.39	-178.442
792	715.1	5.202	5.203	E-2	37235.3	555.289	-0.39	-178.95
794	712.8	5.178	5.179	E-2	37208.8	554.894	-0.4	-179.449
796	710.6	5.155	5.156	E-2	37182.2	554.497	-0.4	-179.938
798	708.4	5.132	5.133	E-2	37155.5	554.099	-0.4	-180.417
800	706.2	5.108	5.109	E-2	37128.8	553.7	-0.4	-180.888