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

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for

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

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Contract No. NAS 3-2545

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April 28, 1965

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FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-2545. The purpose of this study is to obtain design creep data on refractory metal alloys for use in space power systems.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager. J. Sawyer is the Principle Investigator. H. Philleo and R. Ebert contributed to the program.

ABSTRACT

Ultra-high vacuum creep data are presented for tungsten, tungsten-25% rhenium, TZM and TZC molybdenum alloys, and AS-30 columbium alloy. TZC alloy exhibits the greatest creep strength of the turbine alloys examined and has been selected for the initial 10,000 hour creep tests.

TABLE OF CONTENTS

	Page No.
INTRODUCTION	1
INTERNATIONAL SYSTEM OF UNITS	1
MATERIALS & PROCEDURE	2
EXPERIMENTAL RESULTS	2
TUNGSTEN AND TUNGSTEN-25% RHENIUM	2
MOLYBDENUM BASE ALLOYS - TZM AND TZC	8
COLUMBIUM ALLOY - AS-30	14
FUTURE WORK	14
APPENDIX I	16
APPENDIX II	18

INTRODUCTION

The object of this program is to obtain long-time creep data on selected refractory alloys which have potential use in advanced space power systems. Earlier reports have described the equipment design and test methods, and have presented creep data on tungsten, tungsten-25% rhenium alloy, TZM molybdenum alloy, and AS-30 columbium alloy. This report presents additional creep data for the above materials and for TZC molybdenum alloy.

International System of Units

Certain of the field centers of the National Aeronautics and Space Administration have followed the National Bureau of Standards in adopting the units of the International System (SI). As a result, in this report the International System of units will be presented along with the more conventional engineering units.

The conversion values for the terms used most frequently in this program are presented in the following table.

TABLE 1

COMMONLY USED CONVERSIONS FROM ENGLISH TO INTERNATIONAL UNITS

Temperature	English		International
	1800°F	=	982° Celsuis (°C)
	2000°F	=	1093°C
	2200°F	=	1204°C
	2850°F	=	1566°C
	3092°F	=	1700°C
	3200°F	=	1760°C
	Stress - 1000 psi	=	6.895×10^6 newtons/meter^2
	Vacuum - 1×10^{-8} Torr (mmHg)	=	1.333×10^{-6} newtons/meter^2

Materials and Procedure

A summary of the material variables being evaluated is presented in Table 2, while the compositions of the specific alloys are summarized in Table 3. A detailed description of the processing history of tungsten, tungsten-25% rhenium, TZM, TZC, and AS-30 was presented in the previous progress report(1)*, and similar data for Sylvania A alloy are given in Appendix 1 of this report.

The geometries for both the rod and sheet specimens are shown in Figures 1 and 2. The test procedure involved obtaining a vacuum of 5×10^{-10} Torr ($6.65 \times 10^{-8} N/m^2$) or better at room temperature, then heating the specimen at a rate so that the pressure never rises above 1×10^{-6} Torr ($1.33 \times 10^{-4} N/m^2$). The specimen is held at temperature for approximately two hours prior to load application. After the first few minutes of load application, specimen contraction can often be observed due to a slight temperature decrease produced by the increased grip contact and the resulting increase in heat conduction. As the test proceeds the vacuum continuously improves and approaches the 10^{-9} to 10^{-10} Torr range (10^{-7} to $10^{-8} N/m^2$ range).

Experimental Results

The general test plan involves conducting 1000 hour screening tests on all the alloys and from these data selecting appropriate materials for long time creep tests. At present, the test end point has been chosen as a total creep of 1% for the materials applicable to turbines (AS-30, Cb132M, TZM, TZC) and 5% creep for the cladding alloys (W, W-25%Re). The basic creep data for all the tests completed or initiated during this quarter are presented in Appendix 2.

Tungsten and Tungsten-25% Rhenium

The creep curves for tungsten and tungsten-25% rhenium tested at 3200°F (1760°C) are presented in Figure 3. The W-25% Re alloy loaded at 1500 psi ($1.03 \times 10^7 N/m^2$) showed a total extension of 2.76% in 800 hours while the tungsten loaded at 1000 psi ($6.9 \times 10^6 N/m^2$) extended 1.02% in 688 hours.

* Numbers in parentheses pertain to references in the Bibliography.

TABLE 2

SUMMARY OF MATERIAL VARIABLES BEING EVALUATED IN CREEP PROGRAM

Material	Form	Test Temperature	Test Condition
Tungsten	Arc-Melted 0.030" Sheet	3200°F (1760°C)	Recrystallized 2 hours, 3200°F (1760°C)
Tungsten-25% Rhenium	Arc-Melted 0.030" Sheet	3200°F (1760°C)	Recrystallized 2 hours, 3200°F (1760°C)
Sylvania A	Powder Metallurgy 0.030" Sheet	3200°F (1760°C)	Recrystallized 2 hours, 3200°F (1760°C)
AS-30	3/4" Plate	2000-2200°F (1093-1204°C)	As-received, stress-relieved condition, (R_c 29)
Cb132M	3/4" Plate	2000°F (1093°C)	Recrystallized 1 hour, 3092°F (1700°C)
TZM	"Pancake" Forging	2000°F (1093°C)	(Cond. 1) As-received, stress-relieved condition (R_c 32) (Cond. 2) Recrystallized 1 hour, 2850°F (1566°C)
TZC	3/4" Plate	1800, 2000, 2200°F (982, 1093, 1204°C)	Recrystallized 1 hour, 3092°F (1700°C)
T-222*	0.030" Sheet	1800, 2000, 2200°F (982, 1093, 1204°C)	As-received

* Originally scheduled to be tested as ST-222 plate material, program plan revised to include material as T-222 grade applicable for tubing.

TABLE 3

CHEMICAL COMPOSITION OF ALLOYS BEING EVALUATED IN CREEP PROGRAM (WEIGHT %)

Material	W	Re	Cb	Mo	Ta	Hf	C	N_2	Ti	Zr	Ni	ppm O_2	ppm H_2
Tungsten	Bal												
Tungsten-25% Rhenium	Bal	24.9											
Sylvania A	Bal					0.52	.030						
AS-30			Bal				.064	.015	.03	.940	.02	145	3
Cb-132M	15.0		Bal	5.07	19.8		.150			2.170		4	4
TZM				Bal			.013	.001	.47	.091			
TZC				Bal			.080	.002	1.02	.130			
ST-222 (T-222)	10.4				Bal	2.47	.0086						

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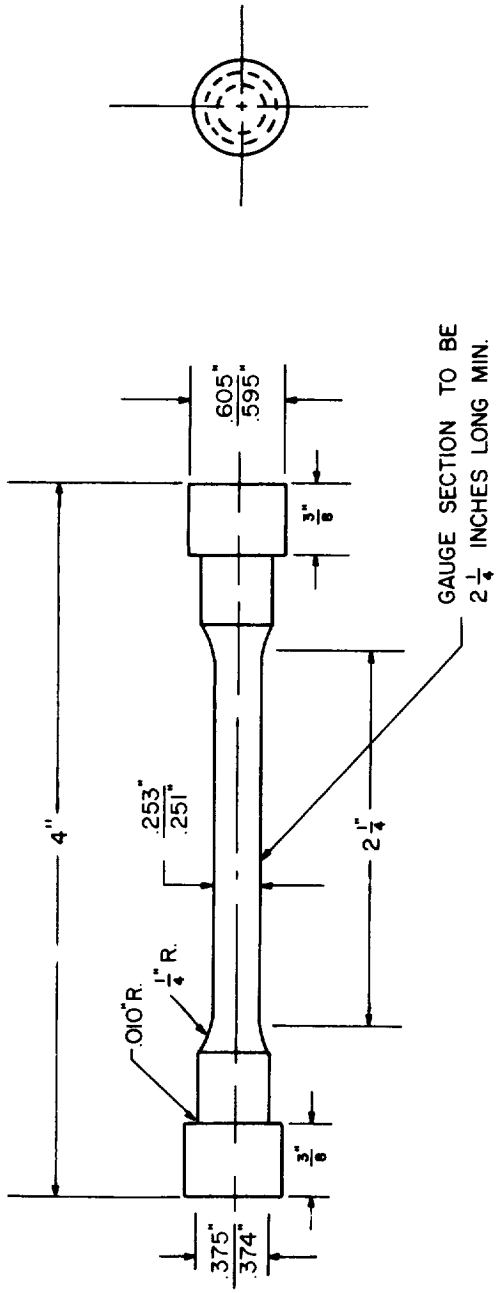


NOTE: ANY TAPER IN GAUGE SECTION MUST BE TOWARDS CENTER

ALL TOLERANCES ± .010" UNLESS OTHERWISE NOTED

FIG. 1: CREEP SPECIMEN USED FOR DISC AND PLATE STOCK.

7637

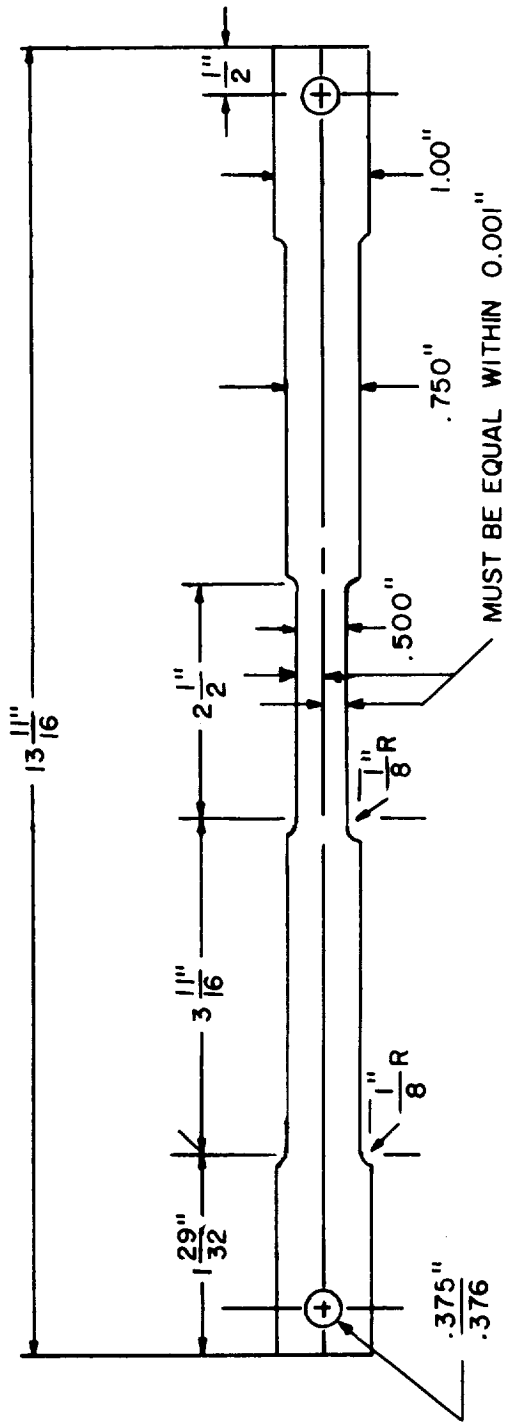


FIG. 2: CREEP SPECIMEN USED FOR SHEET STOCK

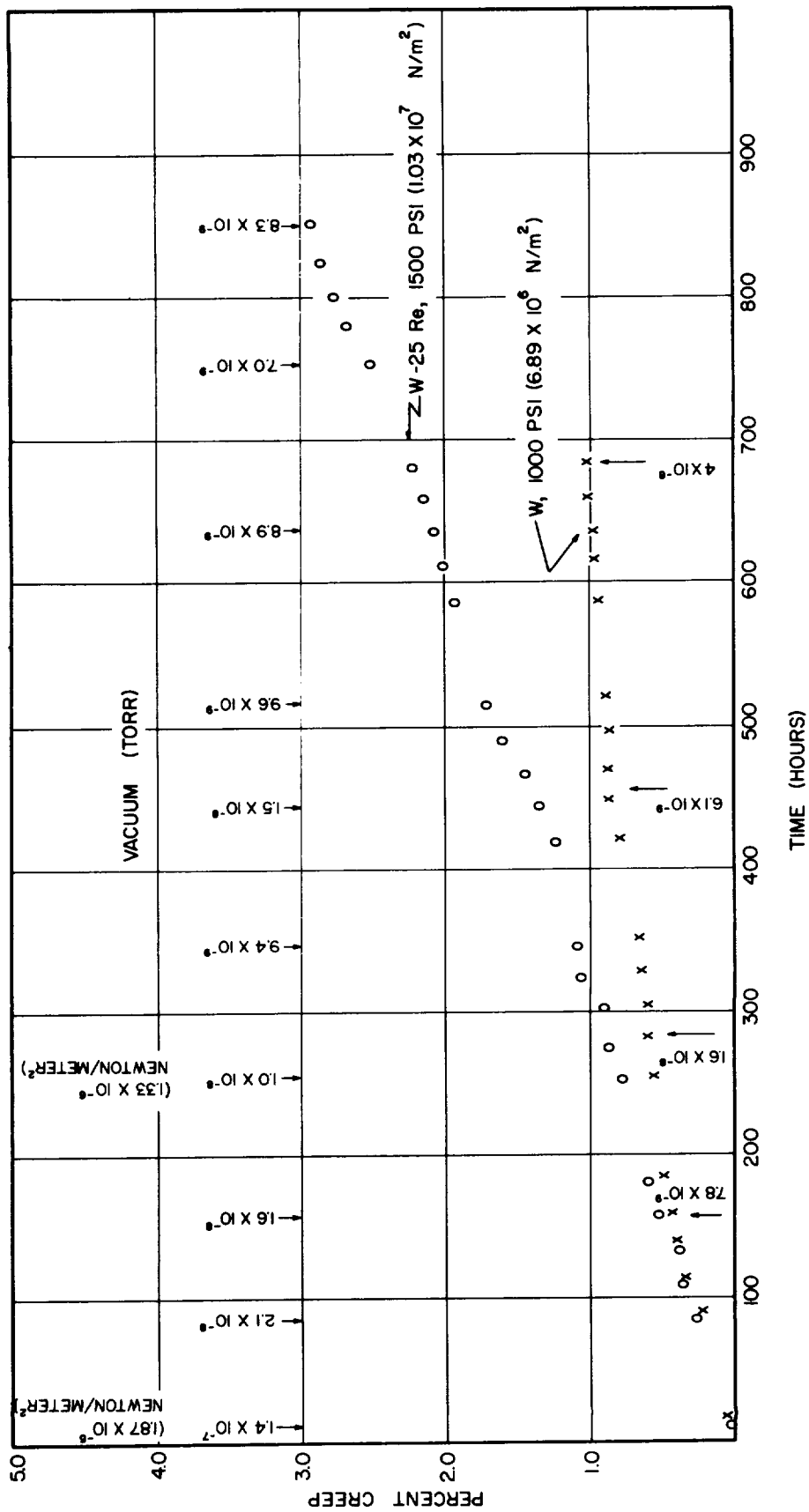


FIG. 3: CREEP OF TUNGSTEN AND TUNGSTEN-25% RHENIUM ALLOYS TESTED AT 3200°F, (1760°C).

For purposes of initially comparing the available data, the Larson-Miller plot was employed with a value of 15 for the constant (see Figure 4). Using this method of presentation, no significant difference between the creep properties of the tungsten and tungsten-25% rhenium was apparent at the lower levels of applied stress.

In general, when published data obtained at higher temperatures on powder metallurgy tungsten in an argon atmosphere were analyzed, they indicated a higher stress capability for a given value of the Larson-Miller parameter.

Molybdenum Base Alloys -- TZM and TZC

The test data obtained on TZM at 2000°F (1093°C) under an applied stress of 10,000 psi (6.89 x 107 N/m^2) are presented in Figures 5 and 6. Two material conditions are being evaluated. The variable representing the as-received, stress-relieved condition (Figure 5) indicates a relatively constant creep rate over the 2000 hour test period, while the specimens from the recrystallized material exhibited creep behavior that was considerably different. At approximately 325 hours a significant discontinuity in the creep curve was apparent in the recrystallized material followed by an extended period where no creep and even some specimen contraction was measured. In many of the creep curves, obvious discontinuities have been noted and considerable effort has been devoted to determining whether these variations can be attributed to experimental problems or to real material behavior. A check of the temperature measurements using both the thermocouples contained in the system and the optical pyrometer have indicated that temperature fluctuations are not the cause. Variations in extensometer readings are also not believed to be the primary contributing factor, since all measurements are performed on the same instrument and the observed fluctuations are greater than differences noted between various observers. On this basis, the discontinuities are believed to be a material effect associated with some type of phase change which is occurring during testing. Analysis of specimens after testing will be performed in an effort to define the variations in material which may be occurring during the test exposure.

Since the TZM is being tested as pancake forgings, a question exists as to whether significant variations are present in the degree of working throughout the forging and their possible influence on creep properties. The variation in microstructure as a function of position from the outer edge of the forging is shown in Figure 7. The structures are reasonably consistent and comparable to those found in the specimen gage sections. The structure of the cross-section of the TZM is shown in Figure 8, which illustrates the typical flow pattern. The results indicate that variations in grain pattern can exist between the gage section and the specimen button-head; however, over the 2" gage length the structure is reasonably reproducible and should not introduce a wide degree of scatter in test results.

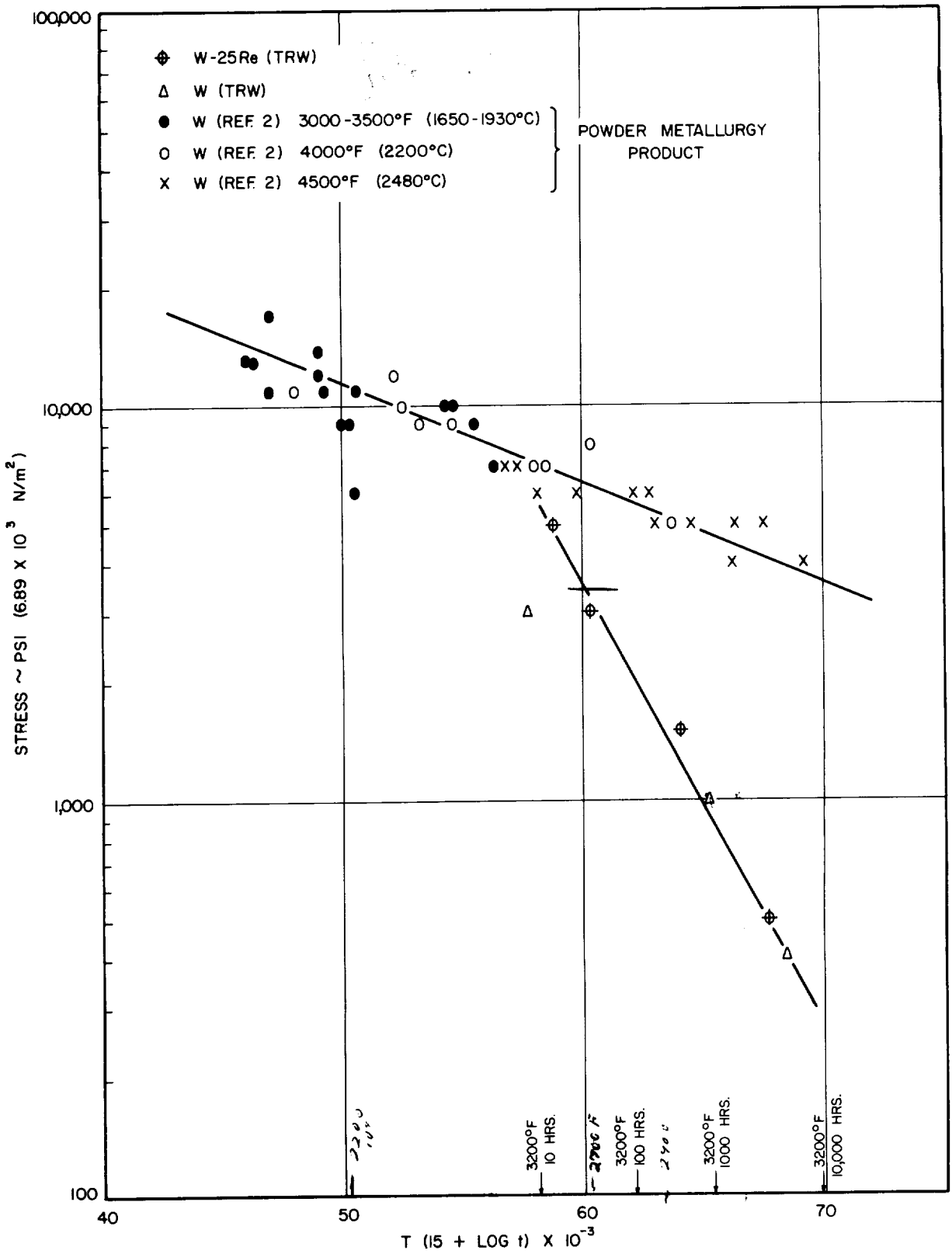


FIG. 4: LARSON-MILLER PLOT OF TUNGSTEN AND TUNGSTEN-25% RHENIUM 1% CREEP DATA, (T = TEST TEMPERATURE °R, t = TEST TIME, HOURS).

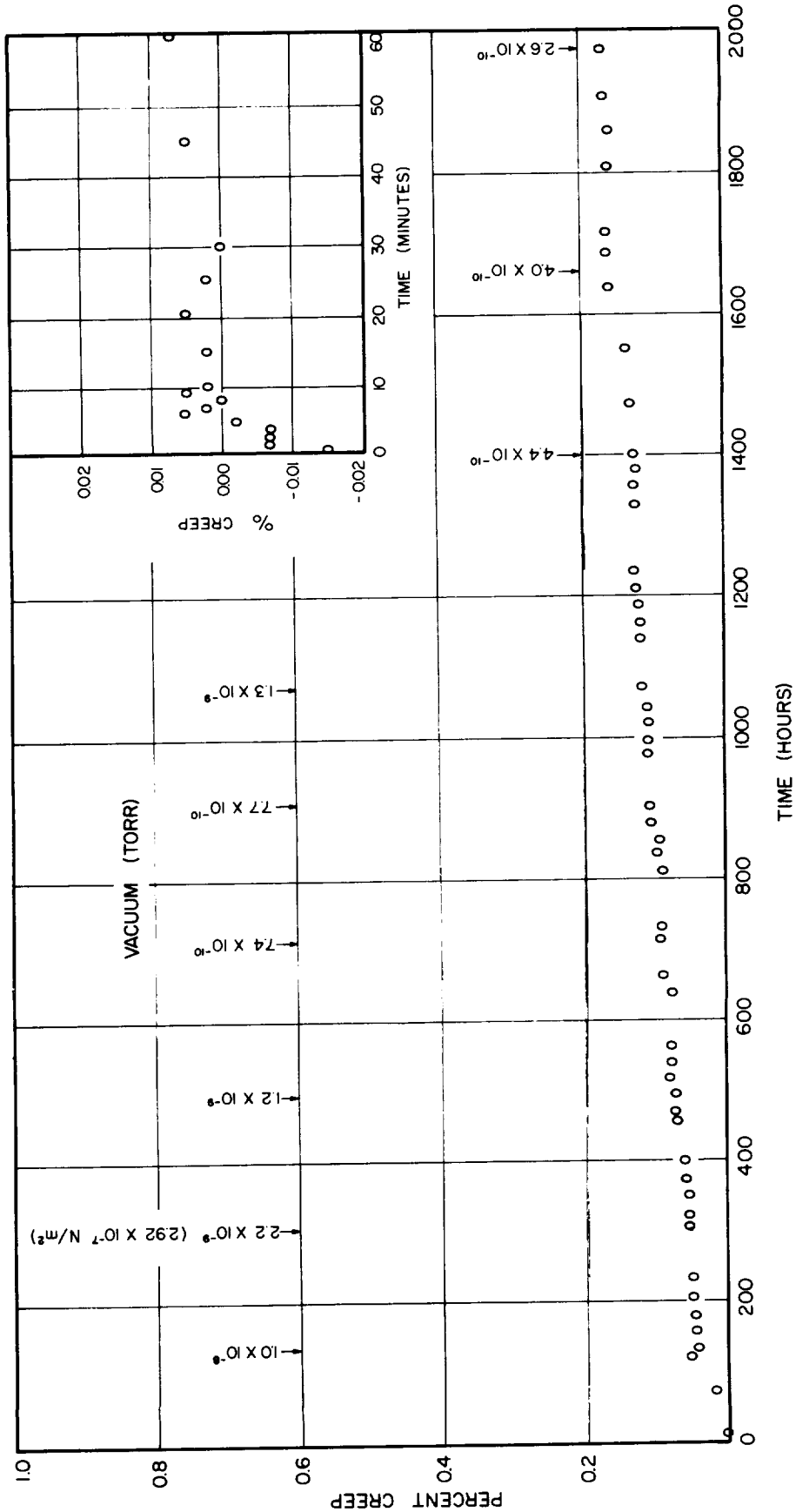


FIG. 5: CREEP OF STRESS-RELIEVED TZM TESTED AT 2000°F (1093°C), 10,000 PSI (6.89×10^7 N/m^2).

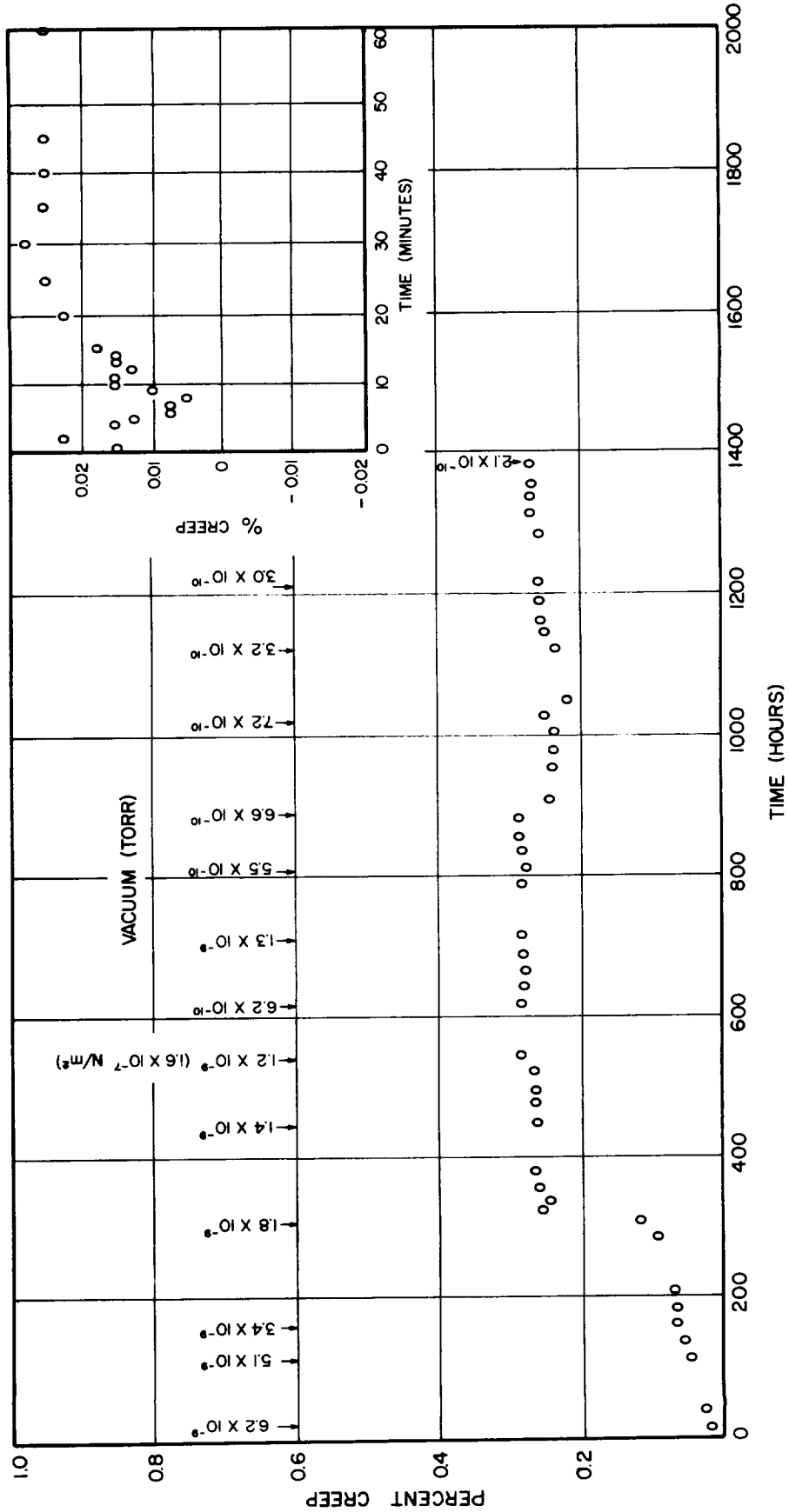
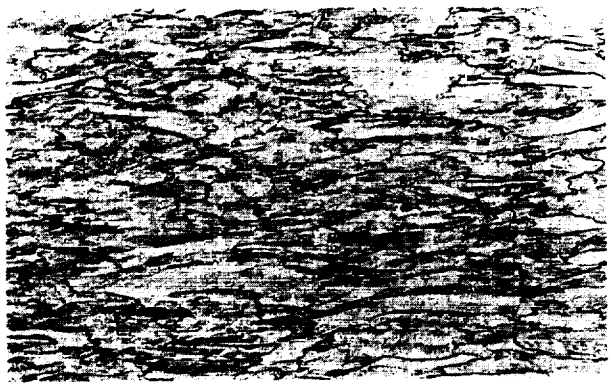
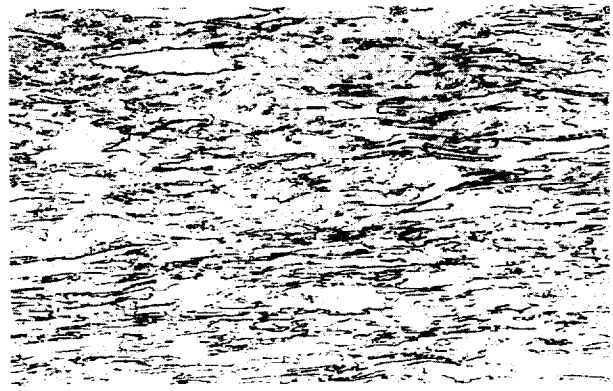


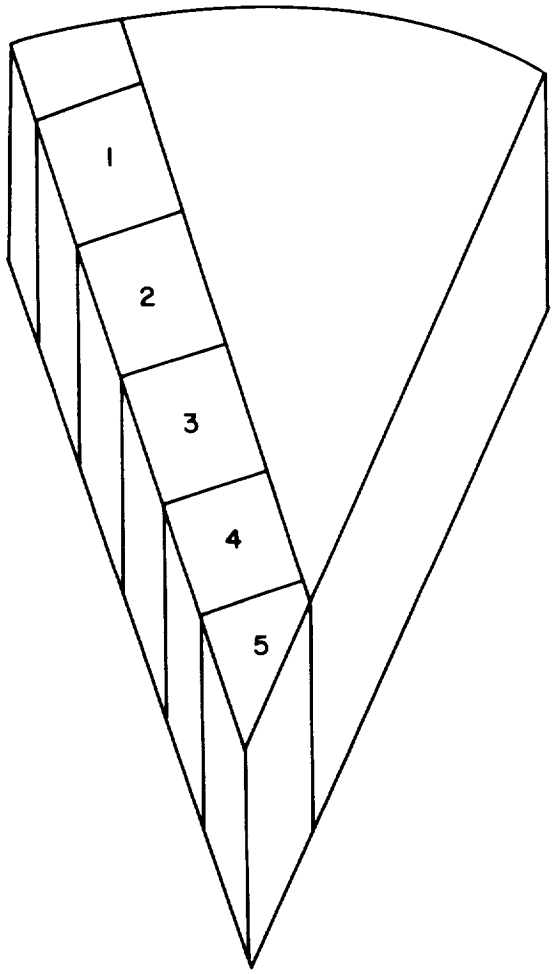
FIG. 6: CREEP OF TZM RECRYSTALLIZED AT 2850°F (1560°C), TESTED AT 2000°F (1093°C), 10,000 PSI (6.89 X 10^7 N/m^2).

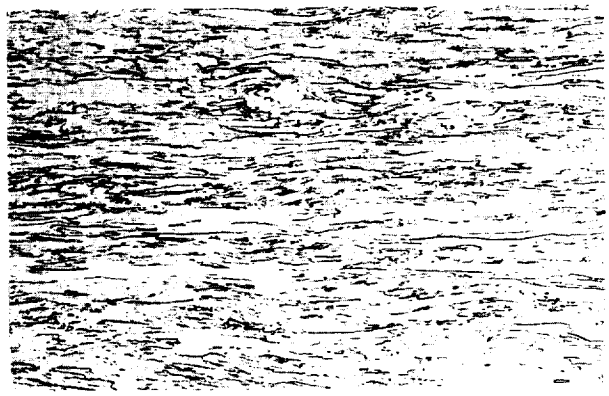


1 AN 866



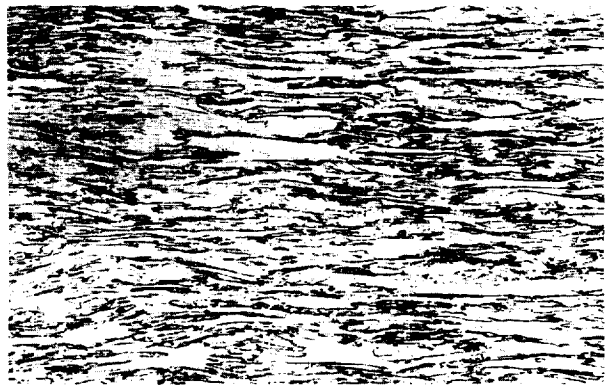
2 AN 865





3 AN 864

4 AN 863



5 AN 862

FIG. 7: PHOTOMICROGRAPHS SHOWING ETCHED SECTIONS OF TZM PANCAKE FORGING. 100X, MURAKAMI'S ETCH. AS RECEIVED.

8553

CENTER OF FORGING

08305

OUTER EDGE OF FORGING

FIG. 8: PHOTOGRAPH OF MACROETCHED SECTION OF TZM PANCAKE - FORGED DISC. SHOWING FLOW LINES DUE TO FORGING. 1 1/2 X.

The initial test on TZC was performed at 2000°F (1093°C) at a load of 14,000 psi (9.65×10^7 N/m^2). No measurable amount of creep was observed after 520 hours. In order to save set-up time and obtain an approximation of a suitable stress for the TZC alloy at this temperature, a "staircase" loading technique was employed. Thus the specimen was reloaded at 20,000 psi (1.38×10^8 N/m^2) for 259 hours, and 22,000 psi (1.52×10^8 N/m^2) for 572 hours. Between each of these tests the load was removed, the specimen was heated to 3092°F (1700°C) for 1 hour, and cooled to room temperature prior to retesting. A summary of the results obtained on the sequentially loaded specimen is shown in Figure 9. The repeated loading and heating of the specimen appeared to have improved the creep properties relative to the initial recrystallized TZC material.

On the basis of these preliminary data, stresses were selected for long-time tests on TZC at 2200°F (1204°C) and 2000°F (1093°C) and the current results are presented in Figure 10.

A comparison of the TZM and TZC data on the basis of the Larson-Miller parameter is given in Figure 11, along with previously published data obtained under less stringent vacuum conditions(3). The creep resistance of the TZM alloy used in the current program is substantially less than that previously reported. However, at present this difference cannot be associated with either material processing, composition, or test conditions.

Columbium Alloy – AS-30

The creep data obtained during this quarter on AS-30 are summarized in Figure 12. At the specific test temperatures, the material has less creep resistance than the molybdenum-base alloys. A presentation of the data on a Larson-Miller plot is shown in Figure 13 for various degrees of creep extension.

Future Work

During the next report period, additional 10,000 hour tests will be initiated with the TZC alloy. These tests will be at 1800°F (982°C) and 2200°F (1204°C).

The ST-222 tantalum alloy plate has been received; and, in agreement with NASA, this alloy was returned to the vendor to be rolled into T-222 sheet material since the actual composition of the as-received ST-222 was within the T-222 alloy specification. The reworked alloy should be received during the next report period, and long-time tests will be initiated.

The Sylvania "A" sheet received contained a number of defects; however, it was possible to obtain suitable test specimens. This material will be tested on a limited basis during the next report period, along with the Cb132M columbium alloy which is scheduled for delivery early in April.

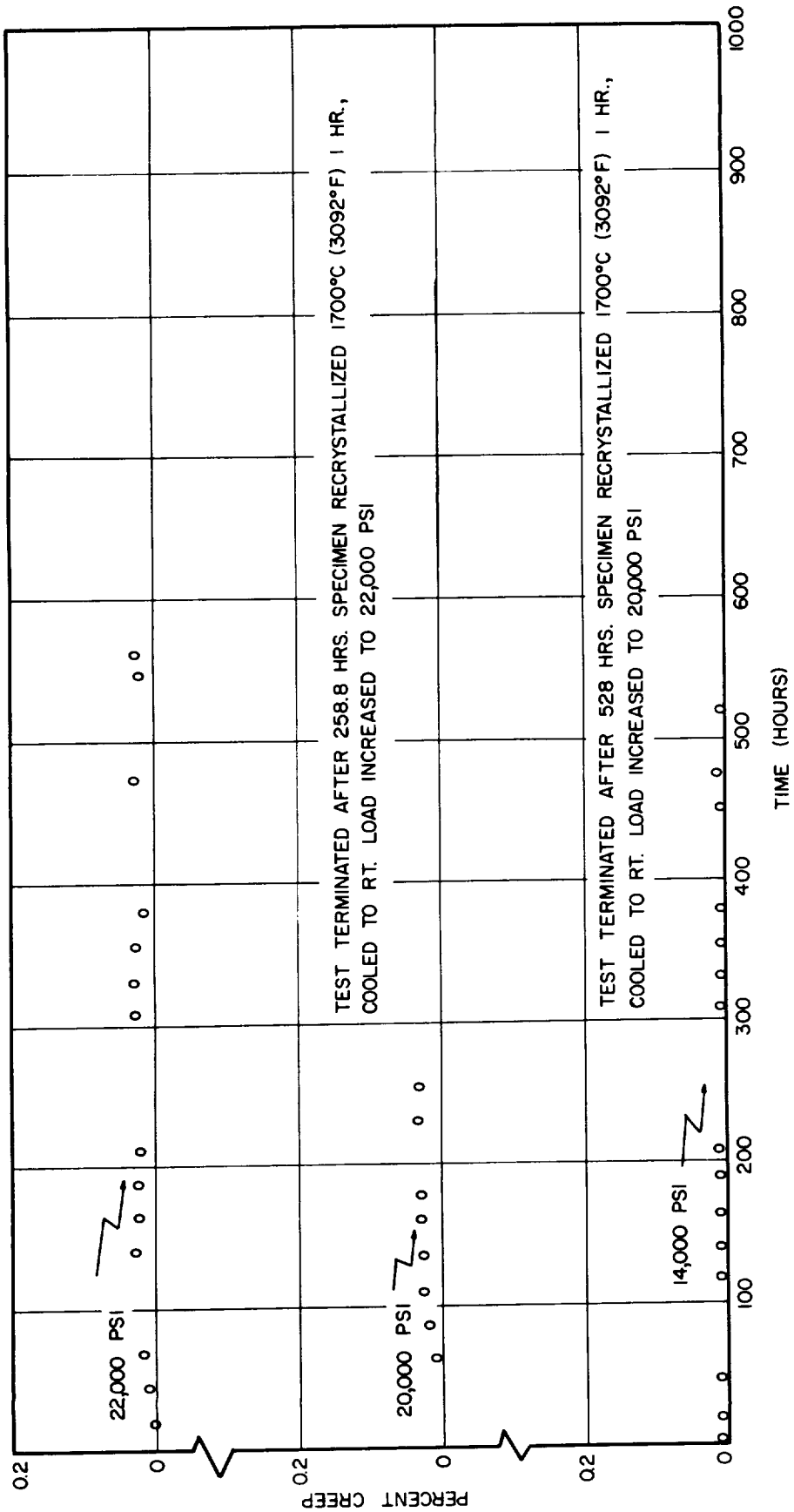


FIG. 9: CREEP OF RECRYSTALLIZED TZC SPECIMEN TESTED AT 2000°F (1093°C) AND STRESSES OF 14,000 PSI (9.65×10^7 N/m^2); 20,000 PSI (1.38×10^8 N/m^2), 22,000 PSI (1.52×10^8 N/m^2) VACUUM ENVIRONMENT (< 10^{-8} TORR).

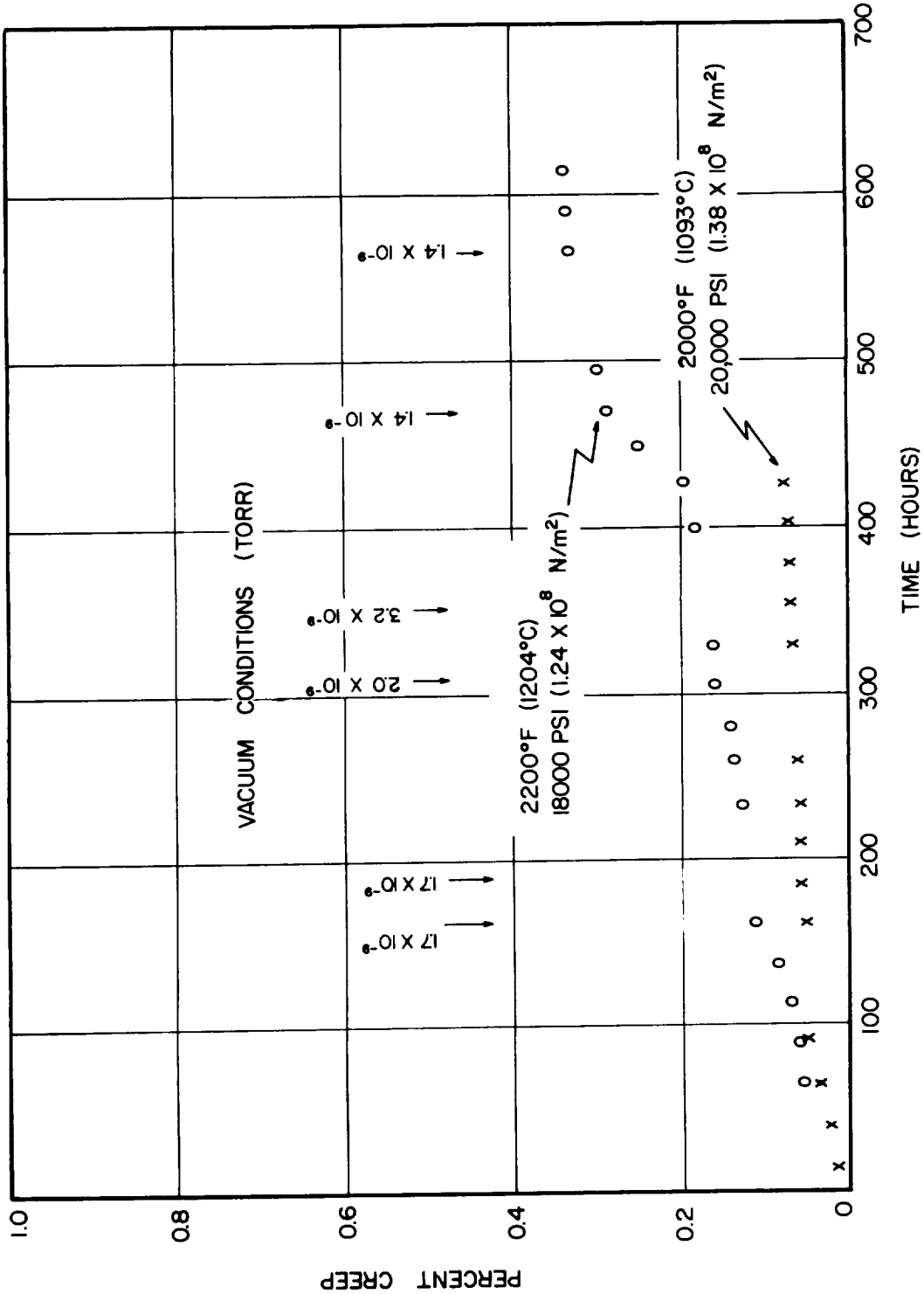


FIG. 10: CREEP OF RECRYSTALLIZED TZC ALLOY, VACUUM ENVIRONMENT $< 10^{-8}$ TORR (1.33×10^{-6} N/m²).

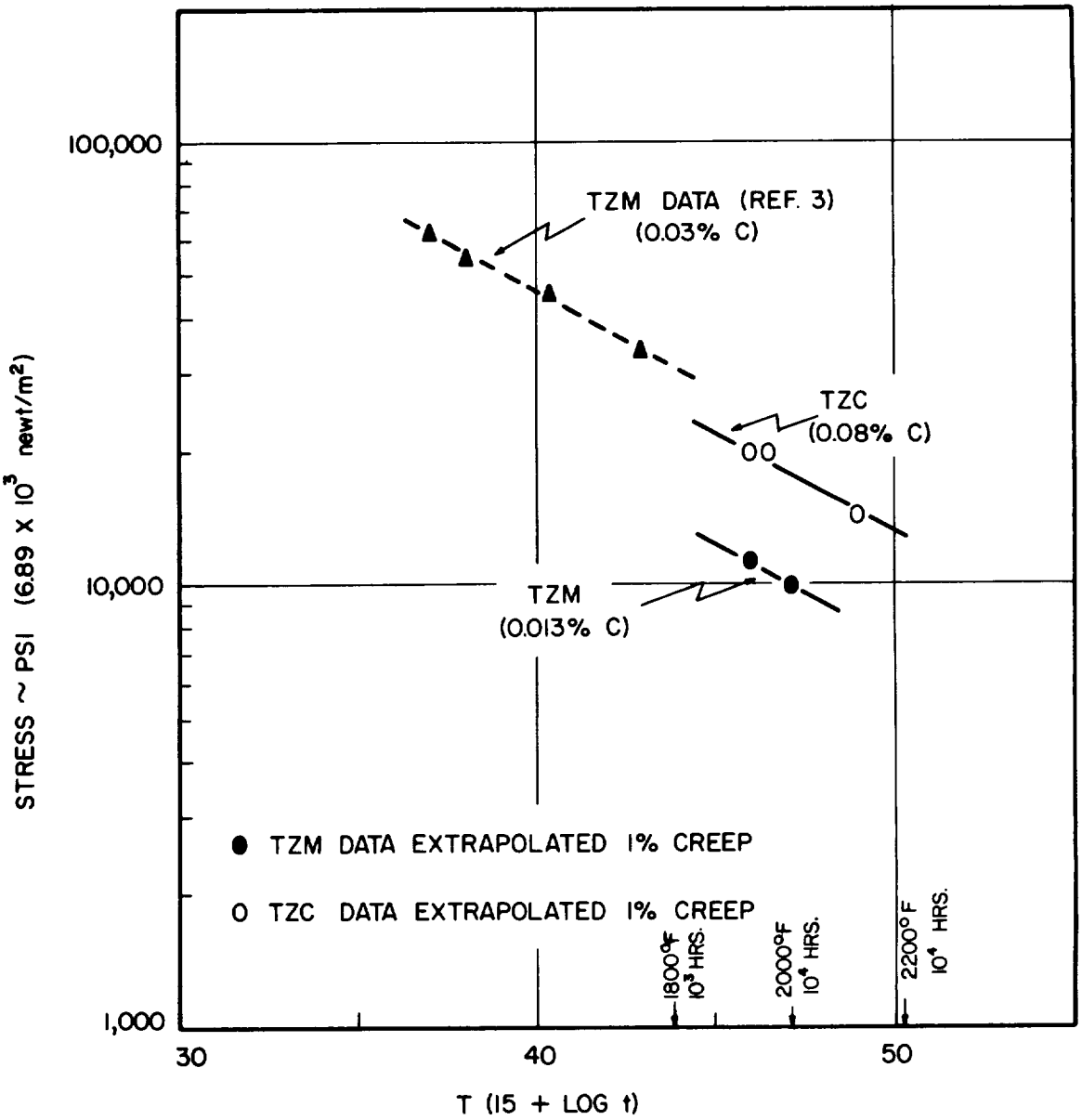


FIG. 11: COMPARISON OF 1% CREEP DATA FOR MOLYBDENUM ALLOYS OBTAINED UNDER ULTRA HIGH VACUUM CONDITIONS WITH PREVIOUSLY PUBLISHED DATA.

8555

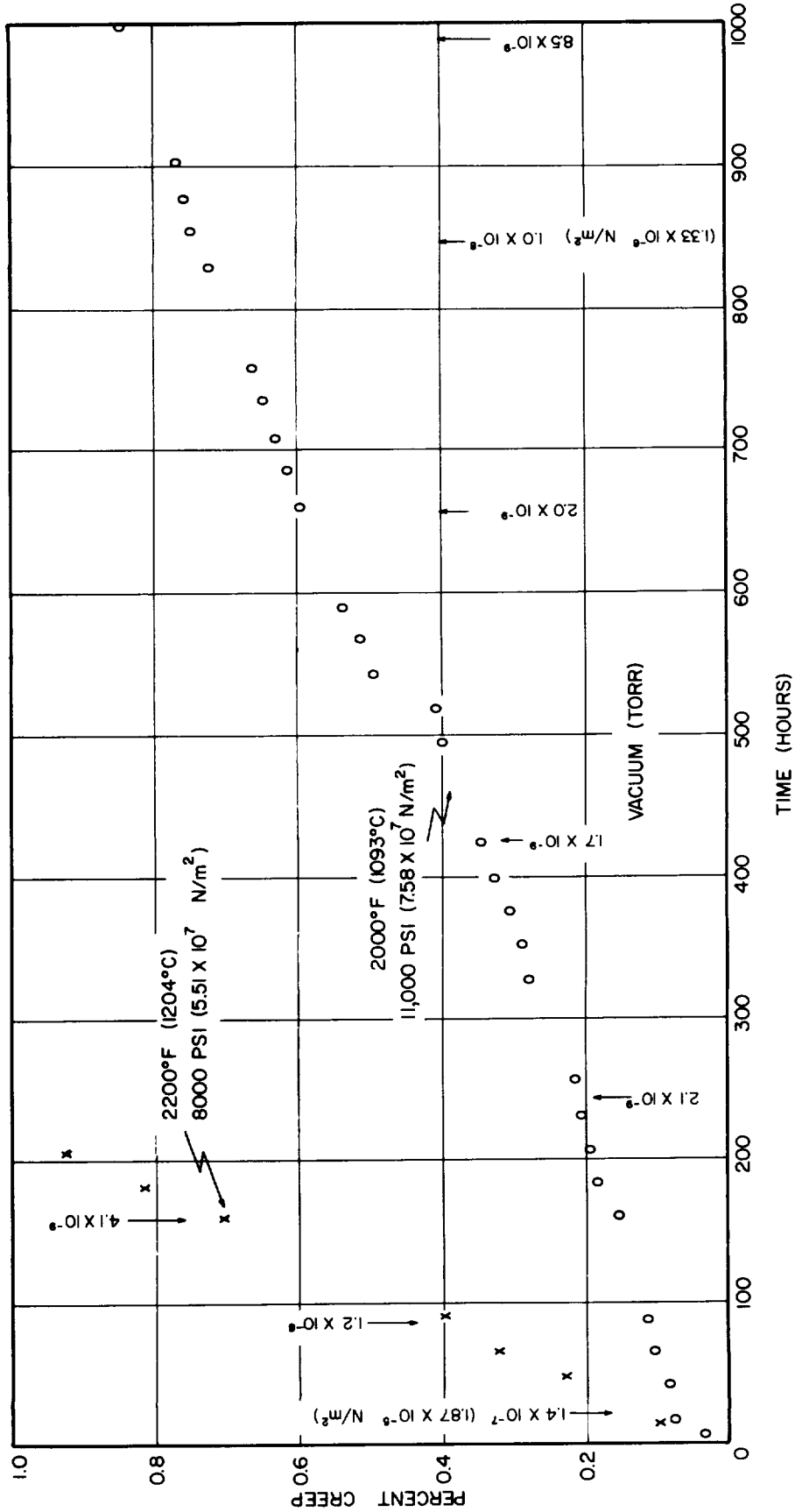


FIG. 12: CREEP OF STRESS-RELIEVED AS-30 PLATE.

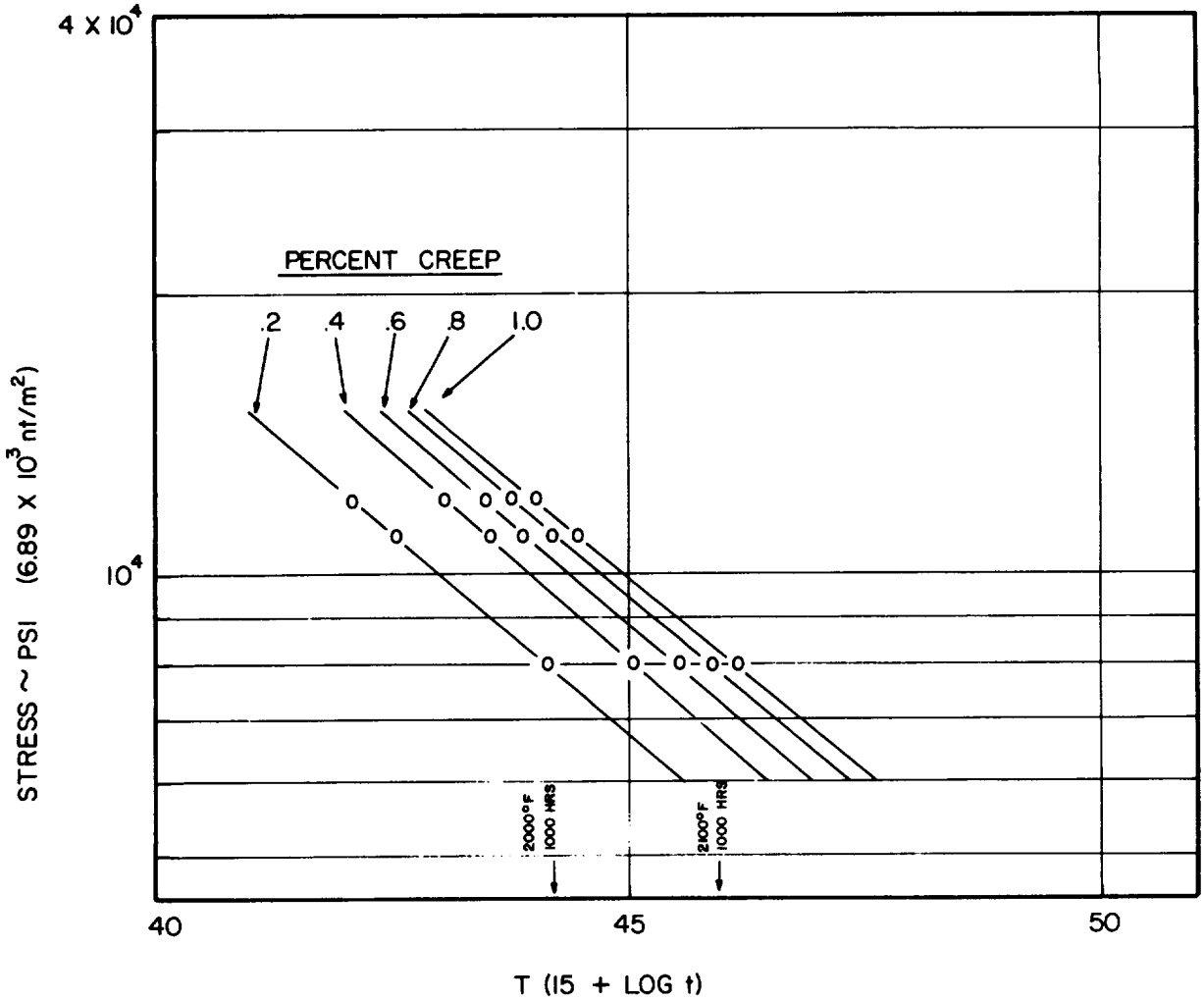


FIG. 13: LARSON MILLER PLOT OF CREEP DATA FOR AS-30 STRESS-RELIEVED PLATE TESTED UNDER ULTRA-HIGH VACUUM.

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1. J. C. Sawyer, and C. H. Philleo, "Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures", Sixth Quarterly Report CR 54287, NASA Contract NAS 3-2545, (January 15, 1965).

2. F. F. Schmidt and H. R. Ogden, "The Engineering Properties of Tungsten Alloys", DMIC Report 191, (September 27, 1963).

3. Creep Rupture Properties of Stress Relieved TZM Alloy - SNAP 50/SPUR Program Part 1. Report No. PAL TDR-64-116, October 1964.

TABLE I

PROCESSING OF SYLVANIA "A" SHEET

Vendor: Sylvania Electric Products Inc.
Chemical and Metallurgical Division
Towanda, Pennsylvania

Processing History:

1. Rolling slabs were made by isostatically pressing powder
2. Slabs rolled at 1500-1900°C to 0.032". Total reduction 90%
3. Intermediate annealing - None
4. Final stress relief - five minutes at 1500°C
5. Sheet trimmed with an abrasive saw and chemically cleaned.

Hardness: 738 DPH
62 R_c

APPENDIX II

CREEP DATA

TABLE I

CREEP TEST DATA, W-25%Re SHEET, TESTED AT 3200°F (1760°C), 1500 PSI (1.03×10^7 N/m^2)

Time (Minutes)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
5	.00005	.0025	3.5×10^{-7}
10	.00010	.005	
15	.00010	.005	
20	.00010	.005	
30	.00010	.005	
45	.00010	.005	
60	.00010	.005	

Specimen S-8

Time (Hours)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
10.6	.00005	.0025	1.4×10^{-7}
82.7	.00450	.225	2.1×10^{-8}
106.6	.00700	.350	2.0×10^{-8}
130.6	.00735	.3675	1.6×10^{-8}
154.6	.01065	.5325	1.6×10^{-8}
178.8	.01170	.585	1.4×10^{-8}
250.6	.01535	.767	1.0×10^{-8}
274.5	.01730	.865	9.8×10^{-9}
298.6	.01795	.897	1.0×10^{-8}
322.5	.02135	1.067	9.6×10^{-9}
346.7	.02195	1.097	9.4×10^{-9}
418.5	.02480	1.24	8.5×10^{-9}
442.9	.02700	1.35	1.5×10^{-8}
466.7	.02910	1.455	8.4×10^{-9}
490.7	.03225	1.612	1.0×10^{-8}
515.0	.03345	1.672	9.6×10^{-9}
586.7	.03870	1.935	1.0×10^{-8}
611.1	.04010	2.005	9.2×10^{-9}
634.6	.04140	2.07	8.9×10^{-9}
658.7	.04300	2.15	1.2×10^{-8}
682.7	.04490	2.245	7.9×10^{-9}
754.7	.05065	2.532	7.0×10^{-9}
781.3	.05385	2.692	7.5×10^{-9}
802.6	.05525	2.762	7.2×10^{-9}
826.6	.05700	2.85	7.2×10^{-9}
850.5	.05835	2.917	8.3×10^{-9}

Test in progress

TABLE II

CREEP TEST DATA, TUNGSTEN SHEET, TESTED AT 3200°F (1760°C), 1000 PSI ($6.89 \times 10^6 N/m^2$)

Time (Minutes)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
1	.00005	.0025	4.4×10^{-8}
2	.00015	.0075	
3	.00015	.0075	
4	.00010	.005	
5	.00015	.0075	
6	.00020	.010	
7	.00020	.010	
8	.00020	.010	
9	.00020	.010	
10	.00015	.0075	
15	.00020	.010	
20	.00010	.005	
25	.00020	.010	
30	.00020	.010	
60	.00020	.010	

Specimen S-9

Time (Hours)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
16.6	.0018	.090	2.2×10^{-8}
88.4	.0048	.240	1.0×10^{-8}
112.4	.00615	.307	1.1×10^{-8}
136.3	.00750	.375	9.2×10^{-9}
160.3	.00880	.440	7.8×10^{-9}
184.4	.00960	.480	6.9×10^{-9}
256.3	.01115	.557	5.6×10^{-8}
280.7	.01190	.595	1.6×10^{-8}
304.5	.01215	.607	3.9×10^{-9}
328.4	.01265	.632	6.8×10^{-9}
352.7	.01330	.665	6.5×10^{-9}
424.5	.01575	.787	7.2×10^{-9}
448.9	.01725	.862	6.1×10^{-9}
472.3	.01705	.852	6.3×10^{-9}
496.4	.01725	.862	9.0×10^{-9}
520.4	.01740	.870	4.6×10^{-8}
592.4	.01810	.905	5.0×10^{-8}
619.1	.01930	.965	3.6×10^{-8}
640.3	.01960	.980	4.9×10^{-8}
664.3	.02010	1.005	4.7×10^{-8}
688.2	.02040	1.02	4.0×10^{-8}

Test in progress

TABLE III

CREEP TEST DATE, STRESS-RELIEVED TZM FORGED DISC, TESTED AT 2000°F (1093°C), 10,000 PSI ($6.89 \times 10^7 N/m^2$)

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)	Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	-.00030	-.015	1.6×10^{-7}	352.3	.00105	.0525	1.9×10^{-9}
2	-.00015	-.0075		376.6	.00105	.0525	1.3×10^{-9}
3	-.00015	-.0075		400.8	.00110	.055	2.1×10^{-9}
4	-.00015	-.0075		457.5	.00130	.065	1.3×10^{-9}
5	-.00005	-.0025		472.6	.00135	.0675	1.2×10^{-9}
6	.00010	.005		497.0	.00140	.070	1.2×10^{-9}
7	.00005	.0025		520.2	.00145	.0725	1.2×10^{-9}
8	.0000	.000		544.1	.00145	.0725	1.2×10^{-9}
9	.00010	.005		568.2	.00150	.075	1.2×10^{-9}
10	.00005	.0025		640.2	.00155	.0775	1.5×10^{-9}
15	.00005	.0025		664.3	.00170	.085	9.2×10^{-10}
20	.00010	.005		712.3	.00175	.0875	7.4×10^{-10}
25	.00005	.0025		736.3	.00170	.085	7.6×10^{-10}
30	.00000	.0000		810.2	.00175	.0875	1.3×10^{-9}
45	.00010	.005		832.2	.00185	.0925	9.0×10^{-10}
60	.00015	.0075		856.1	.0018	.090	9.2×10^{-10}
75	.00005	.0025		880.1	.0020	.100	7.5×10^{-10}
90	.00010	.005		904.0	.00205	.1025	7.7×10^{-10}
(Hours)				982.8	.00210	.105	8.1×10^{-10}
20.0	-.00005	-.0025	6.7×10^{-8}	1000.2	.00210	.105	7.6×10^{-10}
74.7	.00030	.015	1.0×10^{-8}	1024.2	.00210	.105	8.2×10^{-10}
125.7	.00100	.05	1.4×10^{-8}	1048.3	.00220	.110	8.0×10^{-10}
136.5	.00080	.04	1.0×10^{-8}	1072.1	.00220	.110	1.3×10^{-9}
160.3	.00085	.0425	5.7×10^{-9}	1144.0	.00230	.115	6.9×10^{-10}
184.4	.00085	.0425	4.4×10^{-9}	1168.3	.00235	.1175	6.9×10^{-10}
208.5	.00090	.045	4.0×10^{-9}	1192.2	.00240	.120	6.6×10^{-10}
232.2	.00090	.045	3.4×10^{-9}	1216.4	.00250	.125	6.4×10^{-10}
304.4	.00100	.05	2.2×10^{-9}	1240.2	.00250	.125	5.8×10^{-10}
328.3	.00100	.05	2.0×10^{-9}	1336.2	.00250	.125	5.9×10^{-10}

Specimen B-3

TABLE III (Cont.)

	Time (Hours)	Length Change L (in) (2" G. L.)	Creep (%)	Pressure (Torr)
	1360.3	.00250	.125	5.8×10^{-10}
	1384.3	.00250	.125	5.2×10^{-10}
	1408.5	.00250	.125	4.4×10^{-10}
	1480.3	.00260	.13	4.6×10^{-10}
	1552.2	.00270	.135	4.6×10^{-10}
	1648.3	.00320	.16	4.0×10^{-10}
	1696.4	.00320	.16	3.8×10^{-10}
	1720.6	.00320	.16	4.4×10^{-10}
Specimen B-3	1816.4	.00320	.16	5.7×10^{-10}
	1864.2	.00315	.157	3.8×10^{-10}
	1912.3	.00325	.162	4.0×10^{-10}
	1984.3	.00330	.165	2.6×10^{-10}
	2032.2	.00335	.167	3.6×10^{-10}
	2080.1	.00340	.17	3.1×10^{-10}

Test in progress

TABLE IV

CREEP TEST DATA, TZM FORGED DISC, RECRYSTALLIZED AT 2850°F (1566°C), FOR 1 HOUR, TESTED AT 2000°F (1093°C) 10,000 PSI (6.89×10^7 N/m^2)

Time (Minutes)	Length Change ΔL (in) 2" G. L.	Creep (%)	Pressure Torr
1	.00030	.015	6.0×10^{-10}
2	.00045	.0225	
3	.00040	.020	
4	.00030	.015	
5	.00025	.0125	
6	.00015	.0075	
7	.00015	.0075	
8	.00010	.005	
9	.00020	.010	
10	.00030	.015	
11	.00030	.015	
12	.00025	.0125	
13	.00030	.015	
14	.00030	.015	
15	.00035	.0175	
20	.00045	.0225	
25	.00050	.025	
30	.00055	.0275	
35	.00050	.025	
40	.00050	.025	
45	.00050	.025	
60	.00050	.025	

Time (Hours)	Length Change ΔL (in) 2" G. L.	Creep (%)	Pressure (Torr)
16.6	.00040	.020	6.2×10^{-9}
40.7	.00055	.0275	3.1×10^{-9}
114.5	.00095	.0475	5.1×10^{-9}
136.5	.00105	.0525	3.0×10^{-9}
160.4	.00120	.060	3.4×10^{-9}
184.4	.00130	.065	2.4×10^{-9}
208.3	.00140	.070	2.3×10^{-9}
287.5	.00180	.090	2.2×10^{-9}
304.7	.00235	.1175	1.8×10^{-9}
328.7	.00505	.2525	1.6×10^{-9}
336.5	.00485	.2425	
352.6	.00515	.2575	1.6×10^{-9}
374.4	.00525	.2625	2.2×10^{-9}
448.3	.00525	.2625	1.4×10^{-9}
472.7	.00525	.2625	1.0×10^{-9}
496.6	.00530	.265	1.0×10^{-9}
520.8	.00535	.2675	1.6×10^{-9}
544.6	.00565	.2825	1.2×10^{-9}
616.6	.00560	.280	6.2×10^{-10}
640.5	.00555	.2775	7.2×10^{-10}
664.6	.00560	.280	7.2×10^{-10}
688.7	.00560	.280	7.3×10^{-10}
712.8	.00565	.2825	1.3×10^{-9}
784.6	.00560	.280	5.6×10^{-10}
808.7	.00555	.277	5.5×10^{-10}
832.6	.00565	.282	5.8×10^{-10}
856.6	.00575	.287	5.8×10^{-10}
880.6	.00580	.290	6.6×10^{-10}
952.6	.00480	.240	4.3×10^{-10}
977.0	.00485	.242	1.4×10^{-9}
1000.7	.00485	.242	4.2×10^{-10}
1025.0	.00505	.252	7.2×10^{-10}
1049.3	.00440	.220	4.6×10^{-10}
1120.8	.00465	.232	3.2×10^{-10}
1145.2	.00485	.242	4.3×10^{-10}
1168.5	.00505	.252	5.0×10^{-10}
1192.7	.00515	.257	8.0×10^{-10}
1216.6	.00515	.257	3.0×10^{-10}
1288.6	.00510	.255	1.6×10^{-10}
1315.5	.00525	.262	2.2×10^{-10}
1336.5	.00525	.262	1.5×10^{-10}
1360.7	.00520	.260	1.6×10^{-10}
1384.5	.00525	.262	2.1×10^{-10}

Test in progress

TABLE V

CREEP TEST DATA, TZC PLATE, RECRYSTALLIZED AT 3092°F (1700°C) FOR 1 HOUR

TESTED AT 2000°F, 14,000 PSI

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	-.00005	-.0025	5.3×10^{-9}
2	-.00020	-.01	
3	-.00020	-.01	
4	-.00020	-.01	
5	-.00015	-.0075	
6	-.00015	-.0075	
7	-.00010	-.005	
8	-.00010	-.005	
9	-.00005	.0025	
10	.00005	.0025	
11	.00010	.005	
12	.00005	.0025	
13	.00010	.005	
14	.00005	.0025	
15	.00005	.0025	
20	.00005	.0025	
25	.00005	.0025	
30	.00010	.005	
35	.00010	.005	
40	.00005	.0025	
45	.00010	.005	
60	.00010	.005	

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
2	.00005	.0025	5.3×10^{-8}
19	.00010	.005	2.8×10^{-8}
43.3	.00010	.005	2.0×10^{-8}
117.1	.00005	.0025	1.4×10^{-8}
139.1	.00005	.0025	9.6×10^{-10}
162.9	.00010	.005	9.1×10^{-10}
187.0	.00010	.005	7.7×10^{-10}
210.8	.00015	.0075	7.3×10^{-9}
307.3	.00005	.0025	6.0×10^{-9}
331.1	.00015	.0075	5.7×10^{-9}
355.1	.00015	.0075	4.7×10^{-9}
378.9	.00005	.0025	3.2×10^{-9}
450.8	.00005	.0025	4.4×10^{-9}
475.2	.00015	.0075	2.4×10^{-9}
523.3	.00010	.005	2.8×10^{-9}

Test discontinued due to low creep rate.

Specimen B-5

TABLE VI

CREEP TEST DATA, TZC PLATE, RECRYSTALLIZED AT 3092°F (1700°C) FOR 1 HOUR, TESTED AT 2000°F (1093°C), 20,000 PSI (1.38×10^8 N/m2)

Time (Hours)	Length Change Δ L (in) (2" G. L.)	Creep (%)	Pressure (Torr)
62.0	.00015	.0075	2×10^{-9}
85.9	.00035	.0175	1.8×10^{-9}
110.0	.00040	.020	2.2×10^{-9}
134.0	.00045	.022	1.6×10^{-9}
158.1	.00050	.025	2.2×10^{-9}
230.0	.00060	.030	2.2×10^{-9}
254.0	.00050	.025	2.2×10^{-9}

Test discontinued to reload at higher stress

TABLE VII

CREEP TEST DATA, TZC PLATE, RECRYSTALLIZED AT 3092°F (1700°C) FOR 1 HOUR, TESTED AT 2000°F (1093°C), 22,000 PSI (1.52×10^8 N/m^2)

Time (Hours)	Length Change ΔL (in) 2" G. L.	Creep (%)	Pressure (Torr)
19.0	.00005	.0025	2.1×10^{-9}
43.0	.00020	.010	2.2×10^{-9}
67.1	.00035	.017	2.2×10^{-9}
139.0	.00045	.0225	1.6×10^{-9}
163.4	.00045	.0225	1.7×10^{-9}
187.1	.00045	.0225	1.9×10^{-9}
211.4	.00040	.020	2.2×10^{-9}
307.2	.00045	.0225	2.0×10^{-9}
331.5	.00040	.020	1.8×10^{-9}
354.9	.00040	.020	1.8×10^{-9}
379.1	.00025	.0125	1.6×10^{-9}
475.1	.00045	.0225	1.4×10^{-9}
547.1	.00035	.0175	1.3×10^{-9}
570.9	.00050	.025	1.4×10^{-9}

Test discontinued to use unit for another test

TABLE VIII

CREEP TEST DATA, TZC PLATE, RECRYSTALLIZED AT 3092°F (1700°C) FOR 1 HOUR, TESTED AT 2000°F (1093°C), 20,000 PSI (1.38×10^8 N/m^2)

Time (Minutes)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
1	- 0	0	1.2×10^{-9}
2	-.00020	-.010	
3	-.00040	-.020	
4	-.00030	-.015	
5	-.00030	-.015	
10	-.00005	-.0025	
20	+.00005	+.0025	
25	+.00010	+.005	
30	.00010	+.005	
60	.00005	+.0025	

Specimen B-9

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
17.2	.00040	.020	2.6×10^{-9}
41.3	.00060	.030	2.2×10^{-9}
65.2	.00080	.040	2.2×10^{-9}
89.2	.00110	.055	2.0×10^{-9}
161.3	.00105	.0525	1.3×10^{-9}
185.7	.00125	.0625	1.7×10^{-9}
209.1	.00120	.060	1.7×10^{-9}
233.2	.00120	.060	1.7×10^{-9}
257.3	.00125	.0625	1.3×10^{-9}
329.2	.00135	.065	2.0×10^{-9}
353.9	.0014	.070	3.2×10^{-9}
377.0	.0014	.070	3.4×10^{-9}
401.1	.0014	.070	2.4×10^{-9}
425.0	.00145	.0725	1.5×10^{-9}

Test in progress

TABLE IX

CREEP TEST DATA, TZC PLATE, RECRYSTALLIZED AT 3092°F (1700°C) FOR 1 HOUR, TESTED AT 2200°F (1204°C), 18,000 PSI (1.24×10^8 N/m^2)

Time (Minutes)	Length Change L (in) (2" G.L.)	Creep (%)	Pressure (Torr)
1	-.00005	-.0025	3×10^{-9}
2	0	0	
3	0	0	
4	0	0	
5	0	0	
10	.00005	.0025	
20	.00010	.005	
30	.00005	.0025	
40	.00010	.005	
60	.00005	.0025	

Specimen B-8

Time (Hours)	Length Change L (in) (2" G. L.)	Creep (%)	Pressure (Torr)
64.3	.00110	.055	4.1×10^{-9}
88.4	.00120	.060	3.2×10^{-9}
112.5	.00140	.070	2.7×10^{-9}
136.4	.00165	.082	3.4×10^{-9}
160.4	.00215	.107	2.0×10^{-9}
232.5	.00255	.127	2.7×10^{-9}
256.9	.00270	.135	1.8×10^{-9}
280.4	.00280	.140	1.8×10^{-9}
304.3	.00310	.155	9.6×10^{-10}
328.5	.00325	.162	2.0×10^{-9}
400.4	.00365	.182	1.7×10^{-9}
427.1	.00390	.195	5.5×10^{-10}
448.2	.00510	.255	1.8×10^{-9}
472.3	.00580	.290	1.6×10^{-9}
496.3	.00610	.305	1.4×10^{-9}

Test in progress

TABLE X

CREEP TEST DATA, STRESS-RELIEVED AS-30 PLATE, TESTED AT 2000°F (1093°C)
11,000 PSI (7.58×10^7 N/m^2)

Time (Minutes)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
1	-	-	1.6×10^{-7}
2	.00020	.010	
3	.00020	.010	
4	.00000	0	
5	.00005	.0025	
6	.00000	0	
7	.00005	.0025	
8	.00005	.0025	
9	.00005	.0025	
10	.00005	.0025	
11	.00005	.0025	
12	-	-	
13	.00005	.0025	
14	-	-	
15	.00005	.0025	
20	.00005	.0025	
30	.00005	.0025	
45	.00010	.005	
60	.00020	.010	

Specimen B-6

Time (Hours)	Length Change ΔL (in) (2" G.L.)	Creep (%)	Pressure (Torr)
2	.00020	.010	
2.5	.00040	.020	1.1×10^{-7}
15.9	.00165	.0825	1.0×10^{-8}
39.8	.0017	.085	7.8×10^{-9}
63.7	.00210	.105	5.6×10^{-9}
87.4	.00235	.1175	5.5×10^{-9}
159.4	.00315	.1575	3.8×10^{-9}
183.7	.00400	.200	
207.6	.00400	.200	2.4×10^{-9}
231.9	.00410	.205	2.6×10^{-9}
255.7	.00430	.215	2.1×10^{-9}
327.7	.00560	.280	1.6×10^{-9}
351.6	.00575	.287	1.6×10^{-9}
375.6	.00605	.302	1.6×10^{-9}
399.7	.00655	.327	1.2×10^{-9}
423.8	.00685	.342	1.7×10^{-9}
495.7	.00795	.397	5.2×10^{-9}
519.6	.00810	.405	5.8×10^{-9}
543.6	.00985	.492	6.4×10^{-9}
567.7	.01020	.510	7.4×10^{-9}
591.7	.01070	.535	6.5×10^{-9}
663.6	.01195	.597	2.0×10^{-9}
688.0	.01235	.617	3.4×10^{-9}
711.8	.01260	.630	2.5×10^{-9}
736.1	.01285	.642	3.3×10^{-9}
760.3	.01340	.670	8.6×10^{-9}
856.2	.01490	.745	1.0×10^{-8}
879.6	.01510	.755	1.0×10^{-8}
903.7	.01530	.765	3.7×10^{-9}
927.7	.01600	.800	8.5×10^{-9}
999.7	.01685	.842	7.2×10^{-9}
1026.5	.01715	.857	2.4×10^{-9}
1047.6	.01780	.890	7.9×10^{-9}
1071.8	.01795	.897	6.0×10^{-9}
1095.5	.01850	.925	2.8×10^{-9}
1167.7	.02020	1.01	8.6×10^{-9}
1191.9	.02035	1.017	5.5×10^{-9}

Test terminated after reaching 1% creep

TABLE XI

CREEP TEST DATA, STRESS-RELIEVED AS-30 PLATE, TESTED AT 2200°F (1204°C)
8000 PSI (5.51×10^7 N/m^2)

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	.00025	.0125	6.7×10^{-9}
2	-	-	
3	-	-	
4	.00015	.0075	
5	.00025	.0125	
6	-	-	
7	.00025	.0125	
8	.00040	.020	
9	.00035	.0175	
10	.00035	.0175	
11	.00040	.020	
12	.00045	.0225	
13	.00045	.0225	
14	.00045	.0225	
15	.00045	.0225	
20	.00045	.0225	
30	.00040	.020	
45	.00040	.020	
60	.00045	.0225	

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
2.2	.00060	.030	6.7×10^{-9}
13.7	.00195	.0975	1.4×10^{-7}
46.0	.00455	.2275	2.7×10^{-8}
61.8	.00640	.320	1.5×10^{-8}
85.6	.00785	.3925	1.2×10^{-8}
157.7	.01405	.7025	4.1×10^{-9}
181.6	.01620	.810	4.2×10^{-9}
205.6	.01840	.920	3.3×10^{-9}
229.7	.02050	1.025	3.2×10^{-9}

Test discontinued after reaching 1% creep.

Specimen B-7

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