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Investigation of Low-Temperature Creep in Two Titanium Alloys Final Report

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Prepared by:

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Denver Division
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INVESTIGATION OF LOW-TEMPERATURE CREEP IN TWO TITANIUM ALLOYS FINAL REPORT

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Authors

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Approved

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FOREWORD

This final report, in accordance with the requirements of Contract NAS9-5842, is submitted to the Manned Spacecraft Center, National Aeronautics and Space Administration. The MSC technical representative for this work was Mr. W. L. Castner.

CONTENTS

I. INTRODUCTION

Titanium alloys were first used primarily for moderate-temperature service where a high strength-to-weight ratio was required. Their use in compressor sections of turbojet engines is a typical example. The normal material properties evaluations included determination of elevated temperature creep. At room temperature, creep was not considered a problem.

Recent applications of titanium alloys have included service at room temperature and at cryogenic temperatures. Because time-dependent deformation was not considered to be a problem at these temperatures, design stresses have been selected at high percentage of the yield strength. For cryogenic service, material composition must be carefully controlled to provide adequate toughness at low temperatures. However, the composition variations also decrease room-temperature strength. The various combinations of controlled chemical composition and high design stresses have led to the recent identification of low-temperature creep as a problem in structures of titanium alloys.

A typical example of an application in which low-temperature creep is a problem is a helium gas pressurization sphere cooled to -423°F. The common alloy selection for this application is 5Aℓ-2.5Sn extra-low-interstitial (ELI) titanium. This composition exhibits excellent strength and toughness at -423°F. However, the room-temperature properties are significantly lower than those obtained with the normal interstitial grade. Although pressurization spheres are not stressed until they are at service temperatures, these vessels must be qualified by proof testing. Hydrostatic testing at room temperature and a maximum permissible stress is a common practice. The 5Aℓ-2.5Sn ELI titanium alloy exhibits time-dependent plastic deformation at stresses below the yield strength; therefore, stress should be cautiously selected for the hydrostatic test.

Data regarding the creep behavior of the two popular alloys, 6Aℓ-4V and 5Aℓ-2.5Sn titanium, are very meager. The objective of this program was to evaluate both alloys in a variety of conditions to obtain valid characterization of their low-temperature creep behavior.

II. TEST PLAN

The test plan for this program was designed to evaluate the creep characteristics of two titanium alloys at room and low temperatures.

The principal test parameters considered for this evaluation were:

1) Time;
2) Temperature;
3) Stress level;
4) Chemical composition;
5) Metallurgical characteristics.

These parameters are defined in the following paragraphs.

Time - Sustained load testing will be terminated after 100 hr if no measurable creep* occurs in that period of time. If measurable creep does occur during the 100-hr period, the test will be extended until rupture occurs or 500 hr.

Temperature - Testing will be conducted at 70°F for all materials and at -110°F for the material exhibiting the most significant creep at 70°F. Testing at -320°F will be considered if the -110°F results warrant such action.

Stress Level - Room temperature creep tests will be performed at stress levels from 50 to 100% of the yield strength of the material. Low temperature creep tests will be performed at stresses from 75 to 100% of the low temperature yield strength.

Chemical Composition - Two alloys will be evaluated, 6Aℓ-4V and 5Aℓ-2.5Sn titanium, in the normal and ELI grades.

*For this program, measurable creep is defined as plastic deformation greater than 200 μin./in. or 0.02% strain.

Metallurgical Characteristics - All alloys will be tested in the longitudinal direction using sheet material in the 0.080 to 0.125-in. thickness range. The sheet material will represent a fine-grained wrought structure. One sheet of 5Aℓ-2.5Sn ELI titanium will be intentionally heat treated to produce a coarse grain structure. The 5Aℓ-2.5Sn material will also be evaluated in the forged condition (fine-grained structure). One sheet on 5Aℓ-2.5Sn ELI fine-grained sheet will also be tested in the transverse direction. The 6Aℓ-4V titanium alloy will be tested in both the annealed, as well as solution-treated and aged conditions.

III. MATERIALS

All sheet material required for this program was supplied by the Titanium Metals Corporation of America (TMCA). It was not possible to procure material in all of the conditions originally desired for the program. As a result, one change, described later, was incorporated into our plan. The forged material was supplied through the courtesy of Cameron Iron Works, Houston, Texas. This material was obtained from a scrap pressure vessel forging that was rejected because of dimensional accuracy. Selection of this type of material rather than a section of billet stock that had merely been forged to provide specimens was made so that our property evaluation would best characterize the forging application of this alloy in aerospace service. Figure III-1 shows the first hemisphere section received from Cameron. Test specimens were removed meridionally as shown in the photograph. A second section from the same forging was supplied by Cameron for the low-temperature testing.

Vendor certification data for chemical composition and mechanical properties are given in Table III-1.

During the course of the material procurement phase of the program, we were unable to obtain normal interstitial 6Aℓ-4V titanium in the STA condition. Actually, material could be obtained that was covered by the normal interstitial specifications; however, the chemistry was identical to that for the ELI grade. As a result, we decided to evaluate a second heat of 5Aℓ-2.5Sn ELI to show the effect of heat-to-heat variations on creep behavior.

All materials were evaluated in the as-received condition. In addition, a portion of the 5Aℓ-2.5Sn ELI sheet material was heat treated to produce a coarse-grained structure. It was desired to merely evaluate the effect of grain size. However, without preparation of special material, grain coarsening of the alpha structure cannot be achieved. The alternative approach, used in this work, is to achieve grain coarsening by heating the material above the beta transus to develop the prior beta grain structure. Care must be exercised in performing this operation because extreme coarsening can occur as temperature is raised in excess of the transus or if the material is maintained at temperature. Although the beta transus temperature range for the alloy is well known, the specific transus temperature can vary sufficiently so that excessive coarsening could result. Therefore, a carefully controlled determination of the beta transus was conducted for

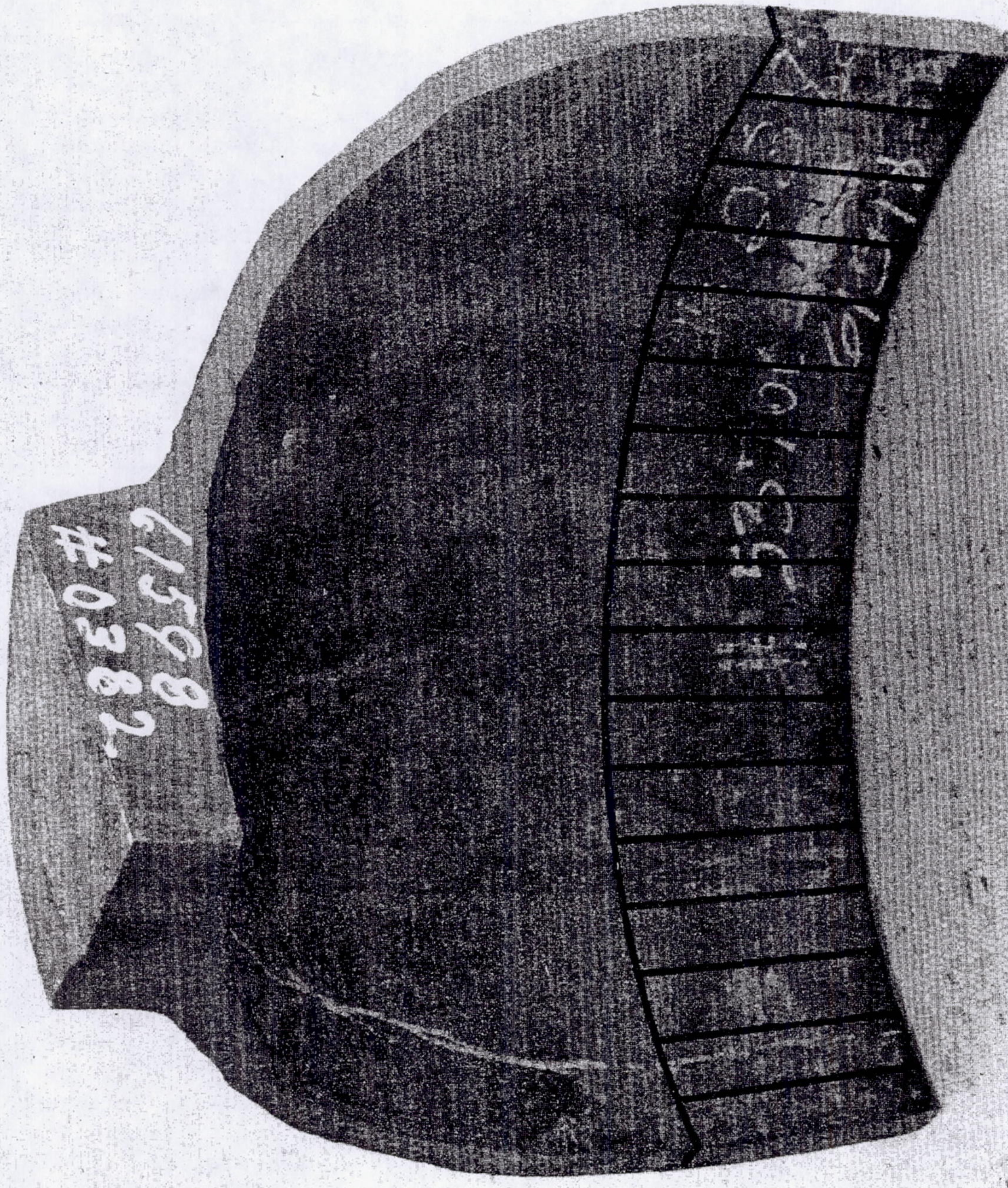

Fig. III-1 Section from Forged 5Aℓ-2.5Sn ELI Titanium Hemisphere

Table III-1 Certifications of Alloy Composition and Mechanical Properties

Alloy	Grade and Condition	Vendor	Heat No.	Form	Chemical Analysis (Wt %)								Mechanical Properties		
					O_2	C	Fe	N	H	Aℓ	V	Sn	Yield Strength, 0.2% offset (ksi)	Ultimate Strength (ksi)	Elongation (%)
5Aℓ-2.5Sn	ELI, Annealed	TMCA	G-28 (Heat A)	0.125-in. Sheet	.09	.025	.15	.009	.006 -.008	5.0		2.2	107.4	115.3	17.0
5Aℓ-2.5Sn	Normal Interstitial, Annealed	TMCA	G-150	0.125-in. Sheet	.17	.025	.29	.012	.007	5.3		2.4	122.8	137.9	16.0
5Aℓ-2.5Sn	ELI, Annealed	TMCA	D-9453 (Heat B)	0.115-in. Sheet	.09	.026	.15	.012	.008	5.0		2.3	115.2	124.0	17.5
5Aℓ-2.5Sn	ELI, Annealed	Cameron Iron Works*	G-24	Hemisphere Forging	.09	.010	.13	.012	.002	5.2		2.6	117.2	124.1	14.0
6Aℓ-4V	Normal Interstitial, Annealed	TMCA	G-784	0.125-in. Sheet	.13	.025	.11	.010	.004 -.006	5.9	4.0		138.1	143.4	16.5
6Aℓ-4V	ELI, Annealed	TMCA	G-738	0.125-in. Sheet	.12	.025	.05	.008	.004 -.005	5.9	4.0		138.7	146.4	15.0
6Aℓ-4V	ELI, STA	TMCA	D-7462	0.091-in. Sheet	.11	.025	.10	.020	.006 -.007	5.8	3.9		154.0	167.9	9.5

*Forging stock supplied by TMCA.

the actual material to be transformed. The transus temperature was found to be 1860 to 1870°F. The resulting grain size determined on small specimens at the beta transus temperature was approximately ASTM 1. However, we were unable to keep this grain size level in transforming the much larger quantity of material required for specimen preparation. The average grain size determined on specimen blanks was ASTM -1 to 0. Figure III-2 shows the microstructure of the transformed alloy.

Metallographic examination was performed for all as-received materials. In addition to determining the grain size (Table III-2), observations with regard to structure were made. The three heats of rolled 5Aℓ-2.5Sn titanium sheet all showed generally fine grained, equiaxed structures. Heat A was the coarser grained of the three and showed a somewhat more equiaxed structure. The normal interstitial material showed grain boundaries that were less well defined than Heat A. The Heat B material exhibited more evidence of prior working than the other two heats. Figures III-3 thru III-5 show the microstructures of the three heats of rolled 5Aℓ-2.5Sn sheet. None of the structures were judged to be abnormal. The 5Aℓ-2.5Sn forging exhibited a coarser grained structure than the sheet material. Grains were moderately equiaxed but showed definite evidence of the prior working above the beta transus temperature. The 500X photomicrograph in Fig. III-6 shows the acicular alpha in the structure resulting from transformation.

The 6Aℓ-4V titanium heats showed an extremely fine-grained structure. Structures for the annealed and fully heat treated (STA) materials were typical for rolled sheet. Figures III-7 thru III-9 show the microstructures for each heat.

Table III-2 ASTM Grain Size for Program Materials

Alloy	Grade and Condition	ASTM Grain Size
5Aℓ-2.5Sn	Normal Interstitial, Annealed	8 to 9
5Aℓ-2.5Sn	ELI, Annealed (Heat A)	7 to 8
5Aℓ-2.5Sn	ELI, Annealed (Heat B)	8 to 9
5Aℓ-2.5Sn	ELI, Annealed, Coarse Grained (Heat B)	-1 to 0
5Aℓ-2.5Sn	ELI, Annealed Forging	5 to 6
6Aℓ-4V	Normal Interstitial, Annealed	10
6Aℓ-4V	ELI, Annealed	10
6Aℓ-4V	ELI, Solution Treated and Aged	10

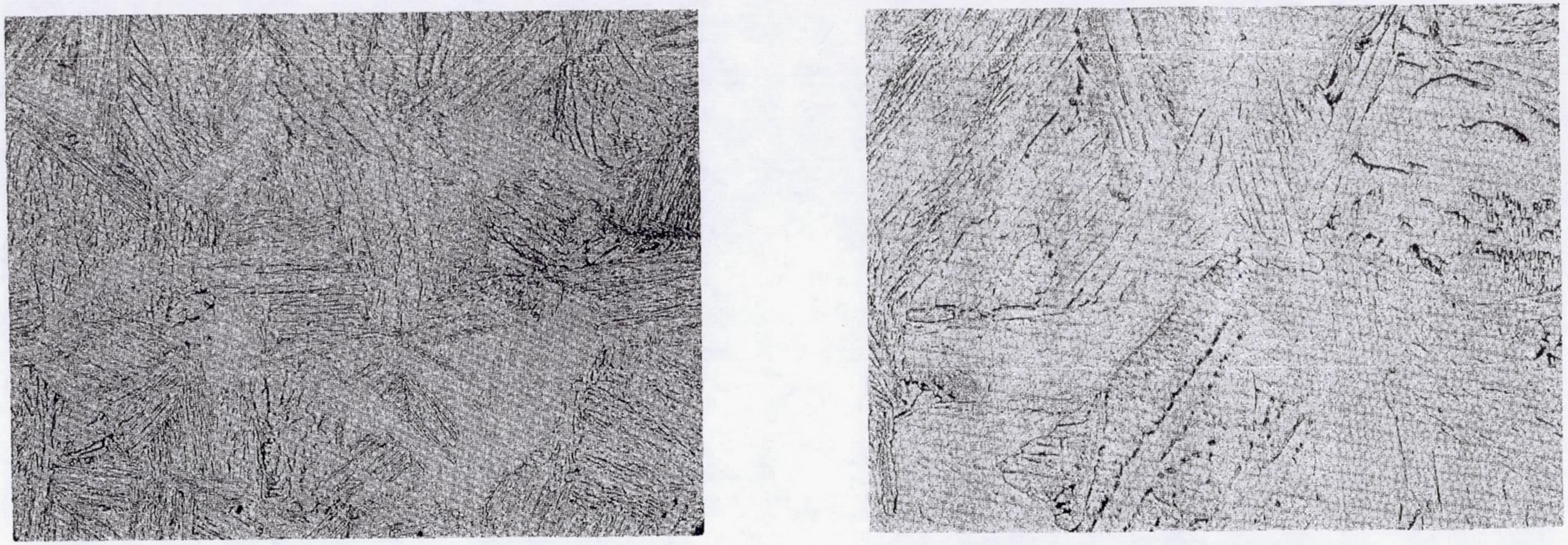

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Fig. III-2 Microstructure of 5Aℓ-2.5Sn (ELI) Titanium (Heat B) after Heating above Beta Transus Temperature

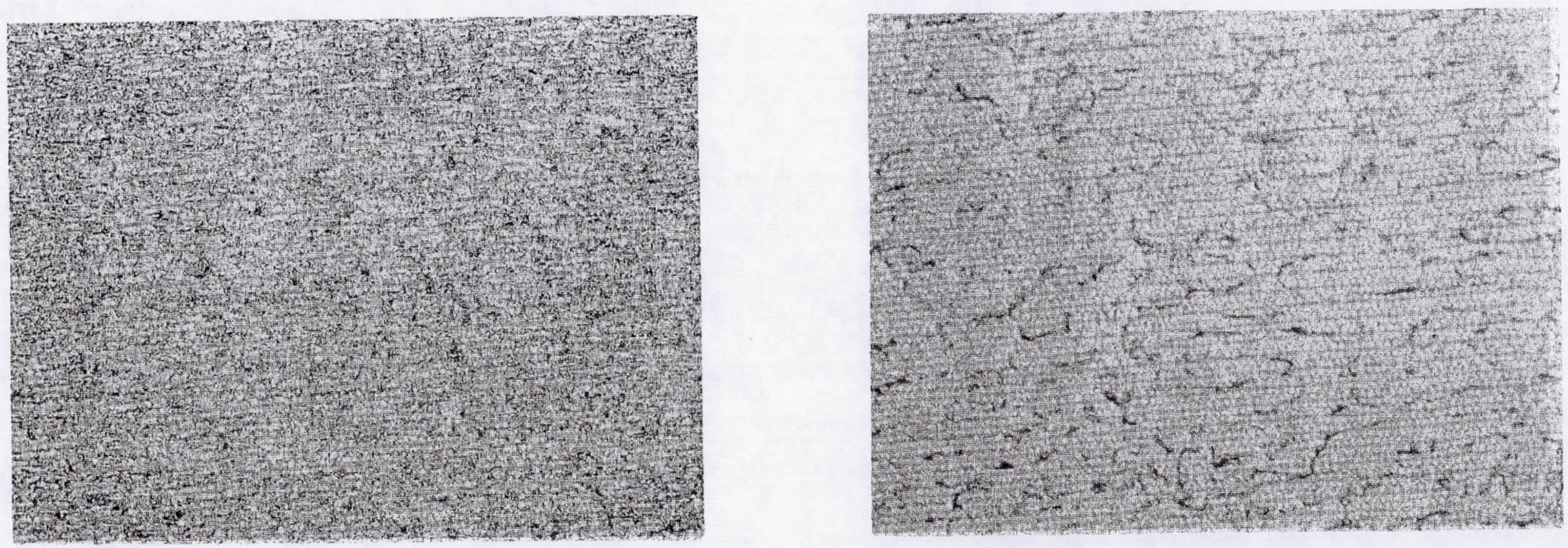

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Fig. III-3 Microstructure of 5Aℓ-2.5Sn (Normal Interstitial) Titanium

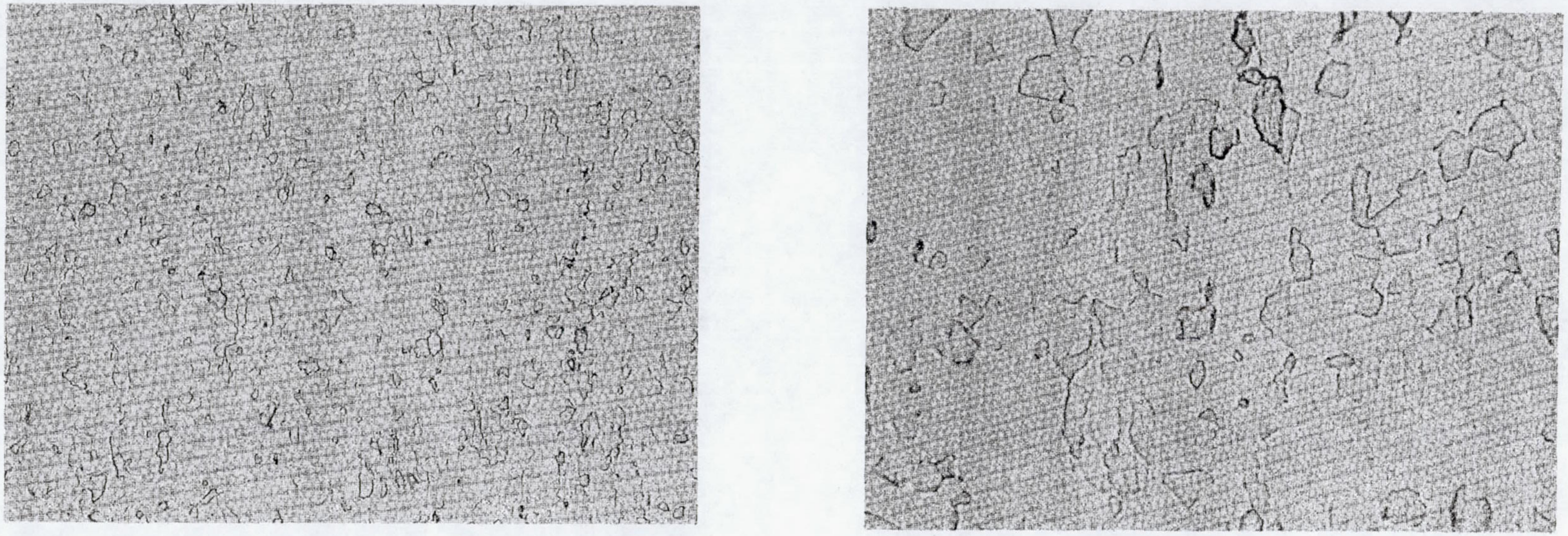

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Fig. III-4 Microstructure of 5Aℓ-2.5Sn (ELI) Titanium (Heat A)

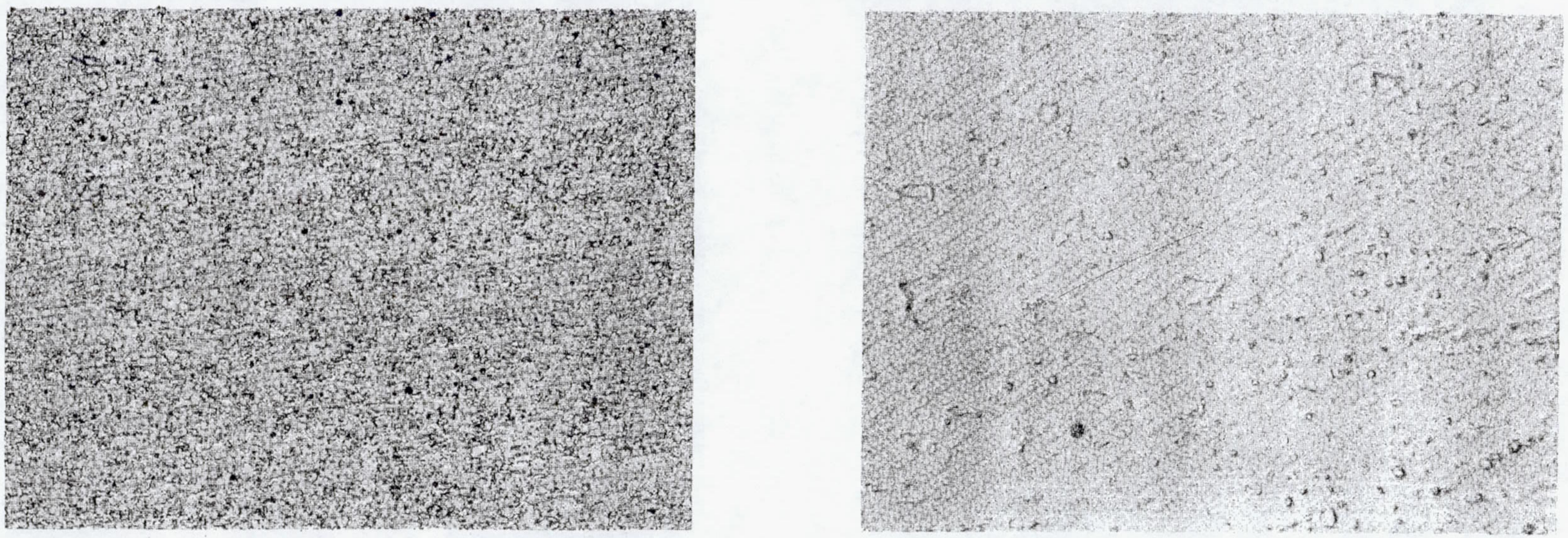

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Fig. III-5 Microstructure of 5Aℓ-2.5Sn (ELI) Titanium (Heat B)

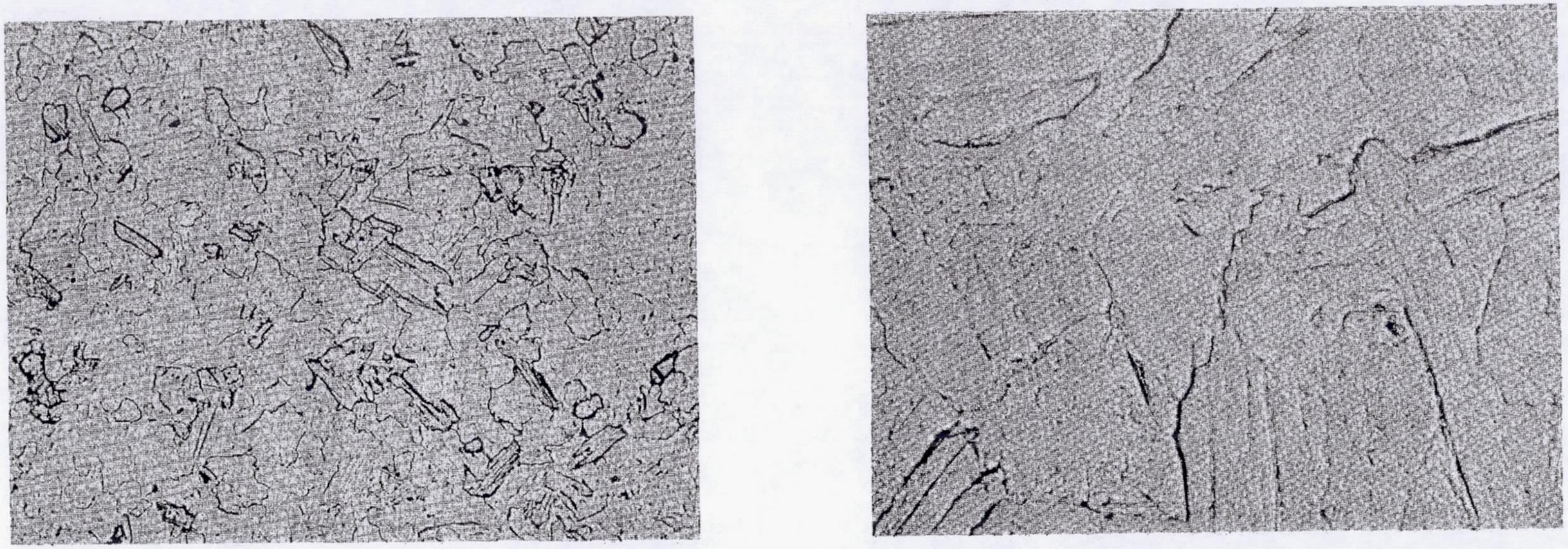

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Fig. III-6 Microstructure of 5Aℓ-2.5Sn (ELI) Titanium Forging

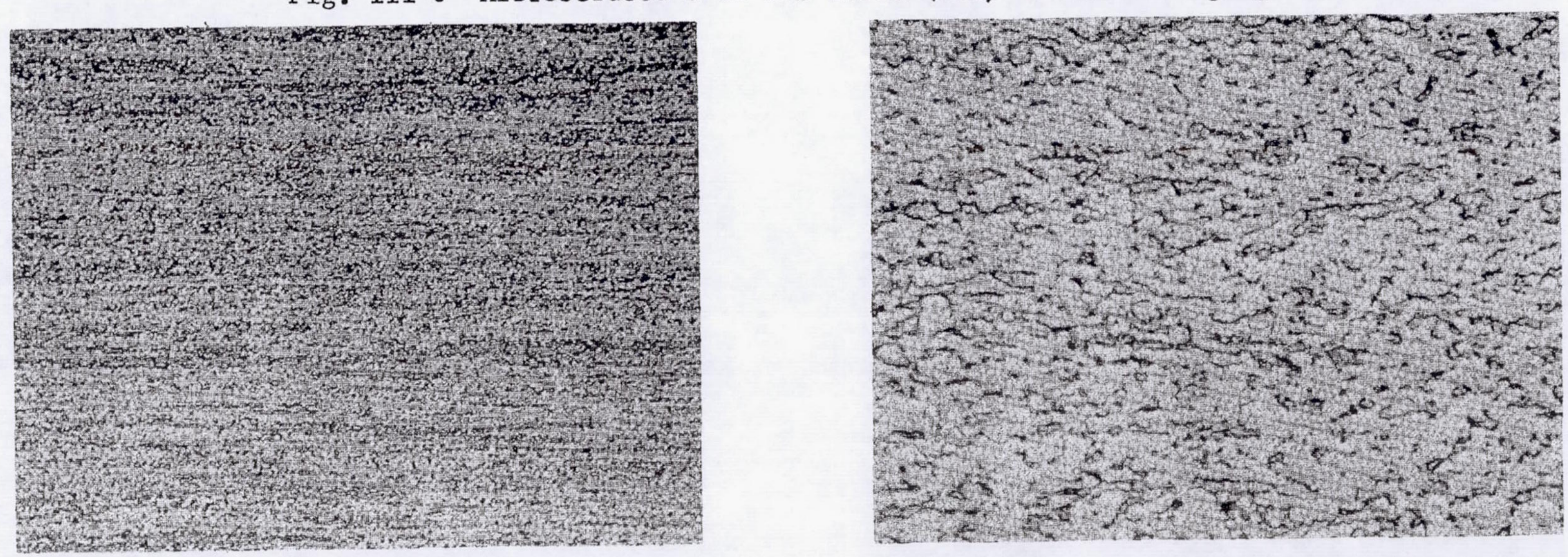

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Fig. III-7 Microstructure of 6Aℓ-4V (Normal Interstitial) Titanium (Annealed Condition)

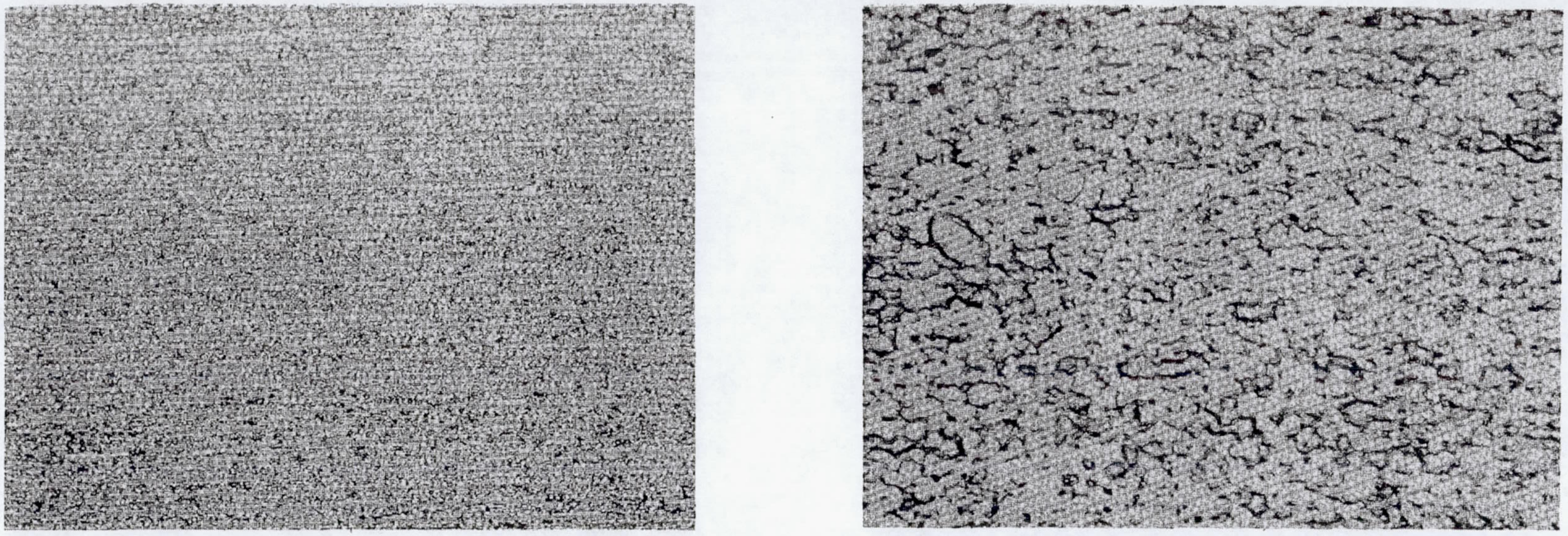

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Fig. III-8 Microstructure of 6Aℓ-4V (ELI) Titanium (Annealed Condition)

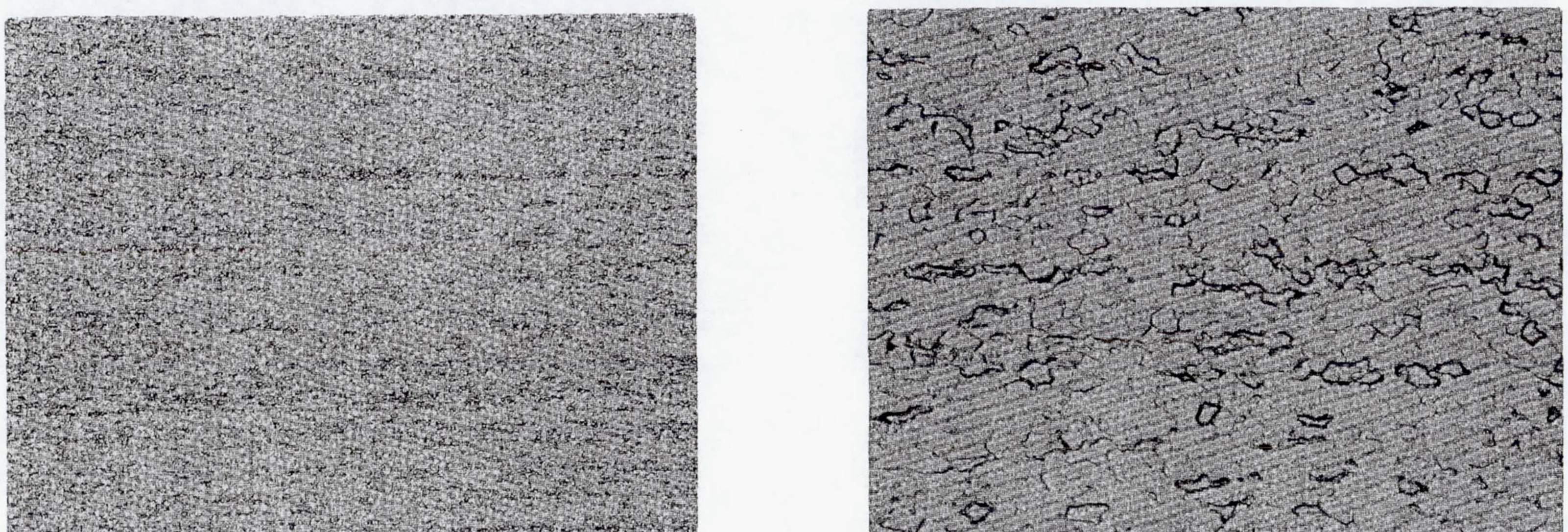

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Fig. III-9 Microstructure of 6Aℓ-4V (ELI) Titanium (Solution Treated and Aged)

IV. EXPERIMENTAL PROCEDURES AND TECHNIQUES

This section describes the procedures and techniques used for tensile and creep testing at both 70 and -110°F.

A. TENSILE TESTING

Room temperature sheet specimens were machined according to the requirements for the standard rectangular tension specimen with a 2-in. gage length, as specified in ASTM E8-61T.

Round bar threaded-end specimens were used for evaluation of forged materials at both 70 and -110°F. Specimen design was the standard 0.350-in. gage diameter bar specified in ASTM E8-61T.

Tensile testing was performed according to the specifications given in ASTM E8-61T. A 50,000-lb Baldwin-Lima-Hamilton (BLH) Model FGT screw-driven machine equipped with an SRA-7 strain gage autographic recorder was used to record load-versus-strain curves. Strain was measured using bonded constantan resistance strain gages. The error of strain measurements using this technique is estimated to be within ± 50 μin./in. exceeding the requirements for qualification as a Class B-1 extensometer. The testing machine load accuracy is within $\pm 1.0\%$. Testing was performed at a strain rate of 0.005 in./in./minute to yield and 0.05 in./in./minute from yield to fracture. A minimum of triplicate specimens were tested for each material and condition; however, in most cases, five replicate determinations were performed.

The same equipment with a suitable cryostat was used for testing at -110°F. Strain instrumentation used for low temperature testing was essentially the same as that used for room temperature testing. Bridge balancing without the necessity for external compensating resistors was accomplished with a bridge consisting of a strain gage mounted on a titanium board and immersed in the liquid bath. Using this technique, all arms of the bridge are accurately matched for resistance. Temperature was controlled with a constant temperature bath of dry ice and alcohol.

B. CREEP TESTING

Creep specimens for sheet materials were machined according to the configuration given in Fig. IV-1. Specimens of the forged material were machined according to the same specifications used for the round bar tension specimens. Figure IV-2 shows both types of specimens instrumented with resistance strain gages.

Creep testing was performed in accordance with the general specifications required by ASTM E139-61T. A variety of commercial machines were used. These included Satec deadweight, BLH folded arm deadweight, and BLH dynamometer creep testers. Figure IV-3 shows four of the machines used for this investigation.

Strain instrumentation was provided using bonded resistance strain gages as the primary system. For strain levels above the capability of bonded resistance gages, mechanical extensometers were used. This provided good accuracy up to 1.5% total deformation. The mechanical extensometers were not as sensitive as strain gages, but provided sufficient accuracy to characterize plastic behavior in the 1 to 5% strain range. The extensometers, which were built specially for this program, were of the strain gage spring beam type. The beams, shown in Figure IV-4, clip into spring clamping blocks attached to the specimen. Figure IV-5 shows a series of three loaded specimens with extensometers attached. Specimens are also strain gage instrumented. By virtue of the simple clamping system, the extensometers cannot be expected to give accuracy comparable to that obtained with bonded resistance gages. However, calibration and actual testing have shown that the extensometers were excellent for the objectives of this program.

Strain readout for the bonded resistance gages was accomplished manually using a BLH Model N strain indicator. Strain determinations were performed on an as-needed basis depending on the rate at which creep was occurring so that accurate characterization of the creep behavior could be determined. An autographic system was used for the mechanical extensometers. This system consisted of a controlled voltage power supply and precision meter, an automatic stepping relay (spring loaded, solenoid operated, with gold contacts), individual bridge and balancing networks for each channel, and a strip chart recorder. A total of 12 strain channels were incorporated in this unit. In addition, another 12 reference signals were used so that system operation could be checked between each strain recording. The switching rate was adjustable. For this program, strain was monitored for each channel for 11 minutes every 4 hr.

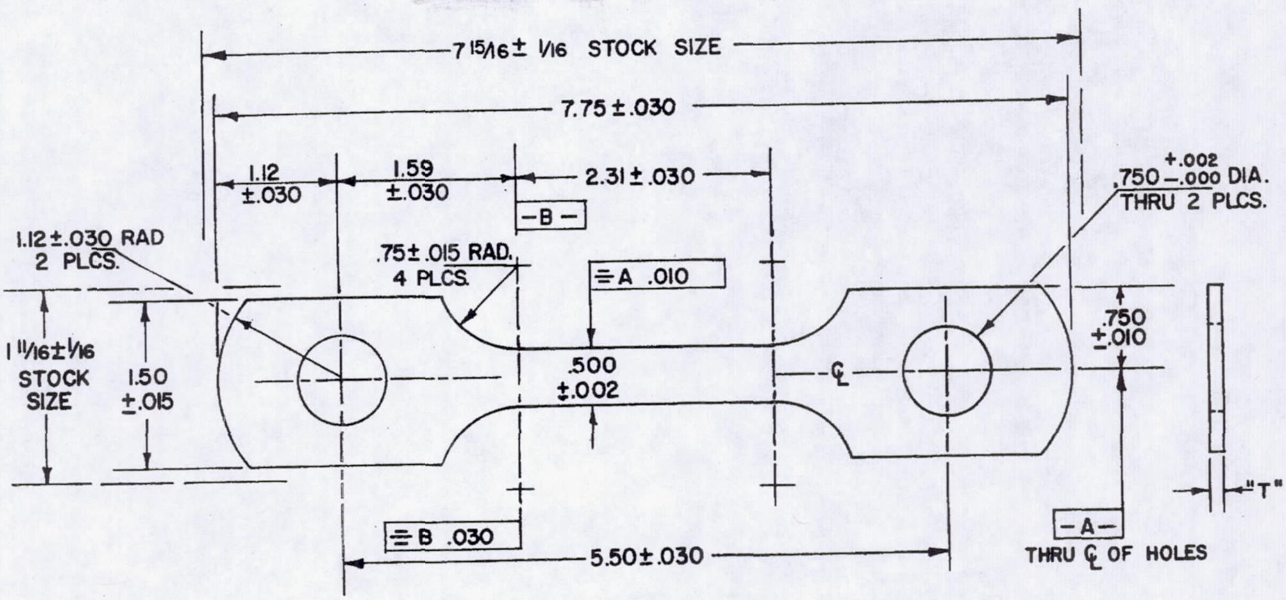

Fig. IV-1 Configuration for Creep Specimen

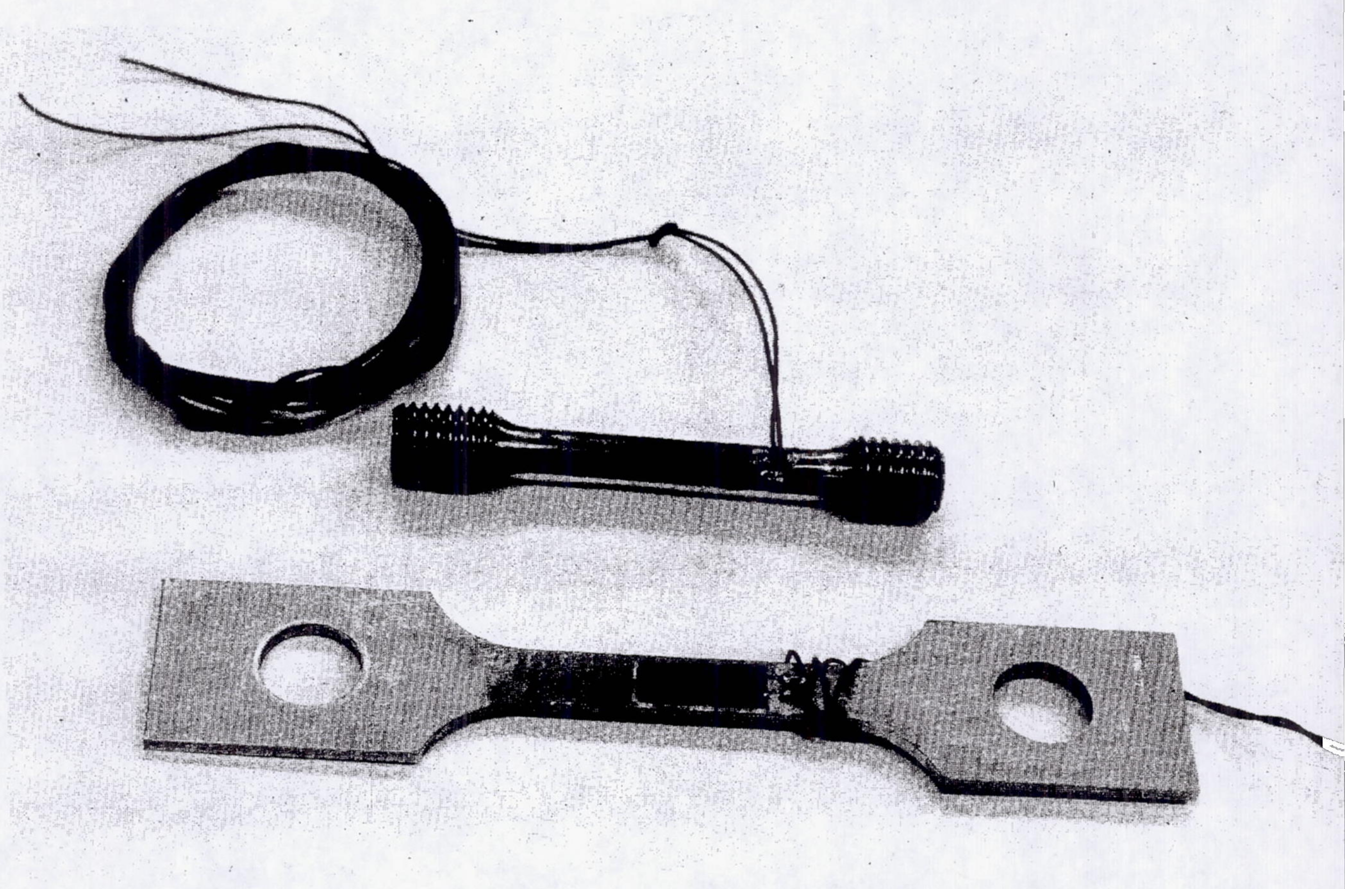

Fig. IV-2 Sheet and Round Bar Creep Specimens

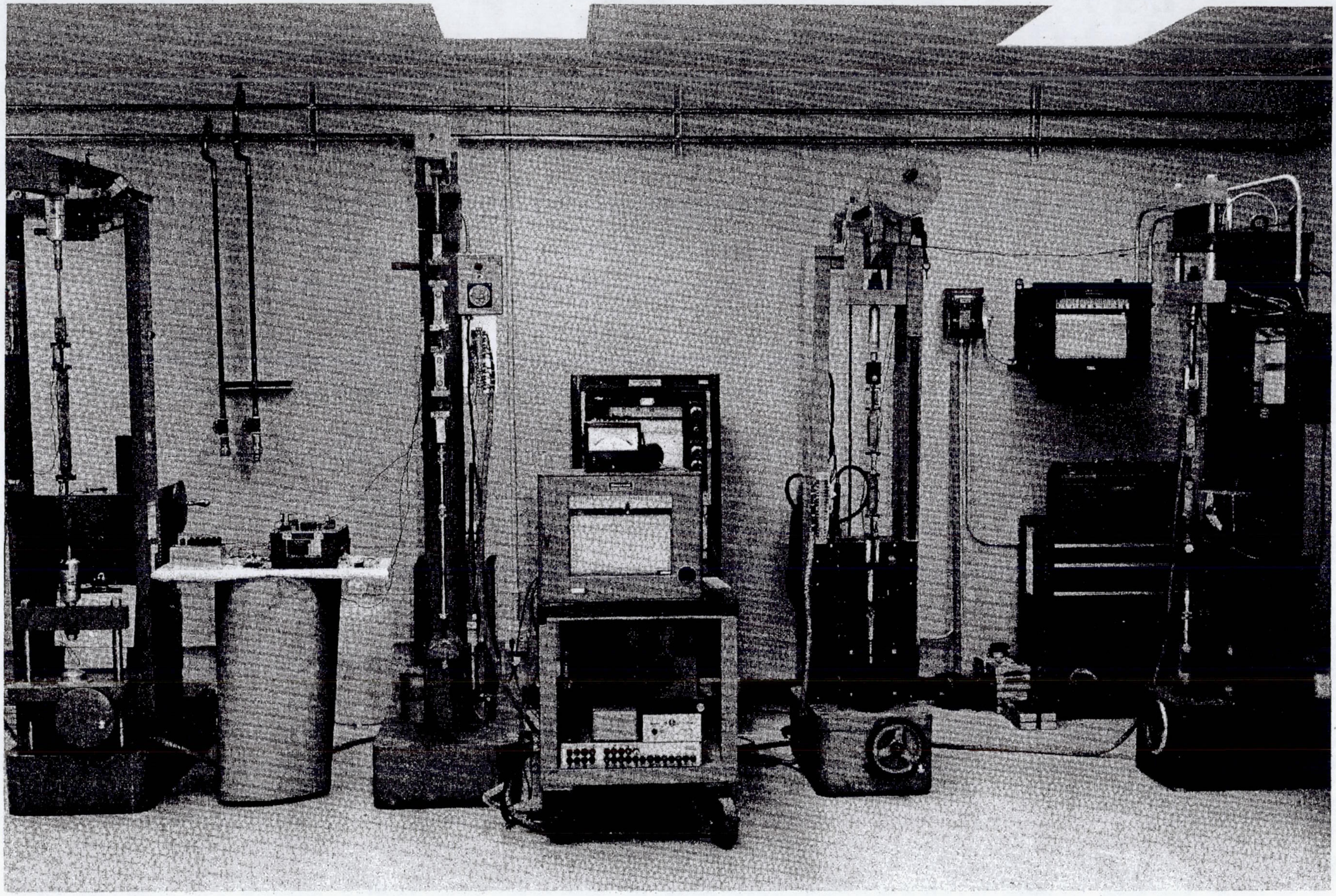

Fig. IV-3 View of Various Creep Testing Machines Used in This Program

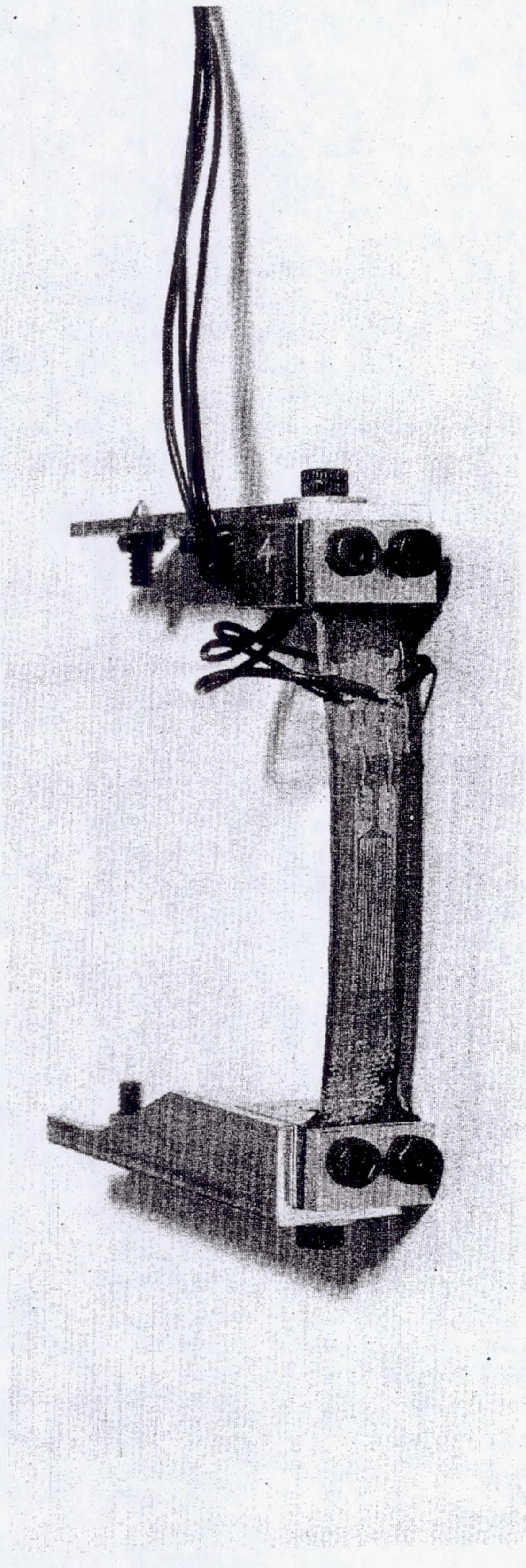

Fig. IV-4 Extensometer Beam

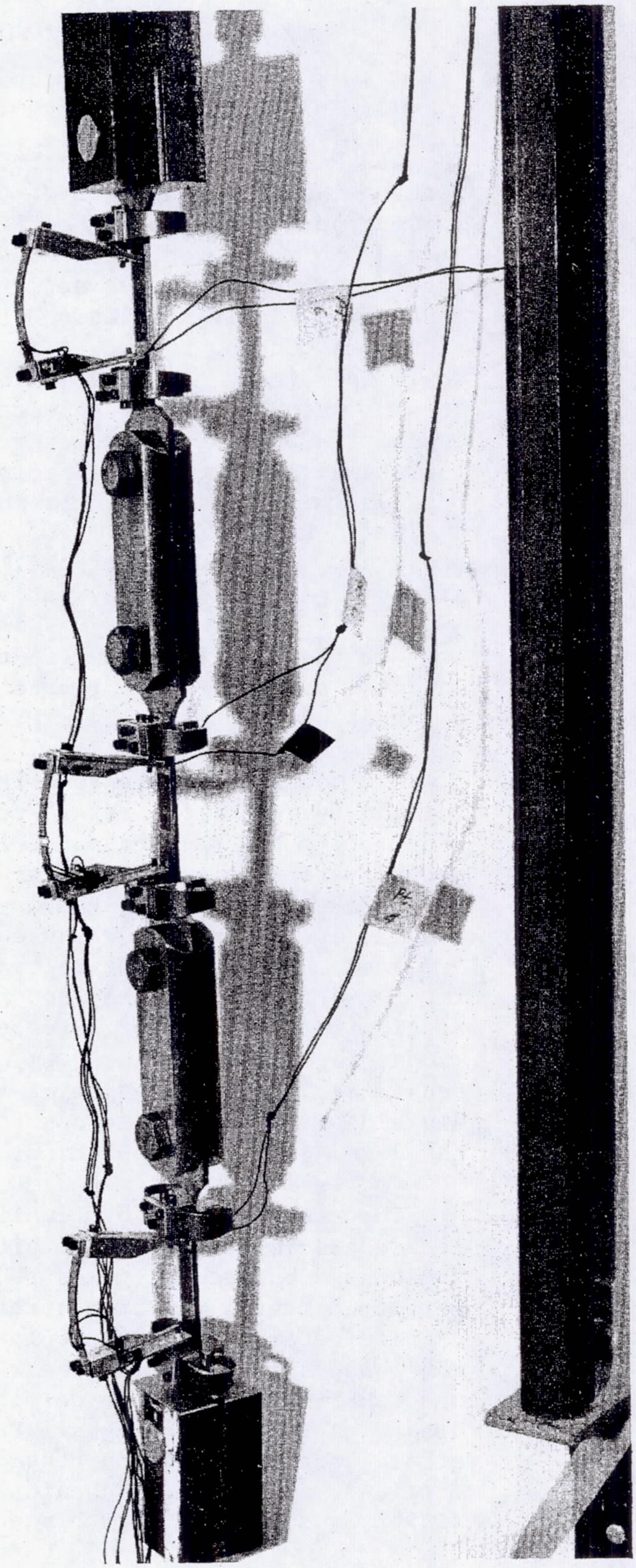

Fig. IV-5 Typical Creep Testing Setup Using Bonded Strain Gages and Mechanical Extensometer

BLH FAB-50 constantan strain gages were chosen for the 70°F work on the recommendation of the manufacturer as the best choice for extended time use. The EPY-400 adhesive was used to apply the gages. No waterproofing was used. To confirm that the strain gage-adhesive system was satisfactory for the proposed titanium testing, a simple evaluation was conducted. This evaluation consisted of bonding the gages to a high-strength titanium alloy which would not creep, and determining whether loading and unloading strains were equal. We selected 13V-11Cr-3Aℓ titanium for this evalaution because of its extremely high strength and freedom from room temperature creep. Specimens were strained to various levels between 1.0 and 2.0%. The results indicated that no slipping of the gage occurred up to 1.5%. At 2.0% strain, occasional slipping occurred. As a result of this evaluation we concluded that the strain gage technique was satisfactory to 1.5% total strain.

For the -110°F creep testing, nichrome gages (BLH FNH-100) were selected because of their greater low temperature stability when compared with constantan. EPY-400 was selected for gage bonding.

The mechanical extensometers were calibrated by first adjusting the length of the strain beam arms for each unit to give approximately the same output for a given deflection. The extensometer was then calibrated to give deflection versus strain output data and deflection versus strip chart displacement data. The latter information was used to provide the calibration factor for each channel so that test data could be converted to strain. The former data were used to provide a backup for manual data collection in the event of a recording system malfunction or for periodic checking of the system operation. Deflection of the extensometer was achieved using a micrometer graduated in 0.0001-in. divisions. This corresponds to 0.005% or 50 μin./in. strain for the 2-in. gage length used for testing.

The testing procedure consisted of loading the three series loaded specimens and determining the initial loaded strain with the bonded resistance gages as soon as possible. Since this was performed manually with a strain indicator, it took several minutes to determine the three loading strains. For the tests at the lower stress levels, the strains at completion of testing were sufficiently low to permit the unloading strains to be measured with the strain gages. For those tests that exceeded the strain capability of the bonded gages, unloading data were not obtained because the mechanical extensometer system was not sufficiently sensitive for this purpose.

Note that the loading data for the higher stress levels reflects the time required to take three consecutive readings. Whereas the readings for each of the three specimens tested at the lower stress levels show excellent agreement; the higher level data often show an increasing strain for each specimen in the sequence of reading the strain instrument. This is indicative of the higher creep rates at higher stress levels.

V. EXPERIMENTAL RESULTS

Presentations of experimental results for both tension and creep tests are given in this chapter.

A. TENSION TESTS

Tension data for the room temperature tests are given in Table V-1. Low temperature tensile test data for the 5Aℓ-2.5Sn titanium forging are given in Table V-2.

B. CREEP TESTS

Strain versus time data for these stress levels for which measurable creep occurred are presented graphically as log-log plots in Fig. V-1 thru V-10. Tabular presentations of data for each alloy give additional information not included in the graphical presentation (Tables V-3 thru V-12). Typical additional data are loading and unloading strains, minimum creep rate, and total creep strain at completion of test.

Table V-1 Room Temperature Tensile Properties

Alloy	Grade and Condition	Grain Direction	Yield Strength, 0.2% Offset (ksi)	Ultimate Strength (ksi)	Elongation, (%)	Reduction of Area (%)
5Aℓ-2.5Sn	Normal Interstitial, Annealed	Long.	122.6	135.1	15.0	
			121.7	135.2	15.5	
			121.9	135.5	15.5	
			121.6	134.5	15.5	
			123.4	136.3	15.5	
			122.2 Avg	135.3 Avg	15.4 Avg	
5Aℓ-2.5Sn	ELI, Annealed (Heat A)	Long.	103.7	115.8	19.0	
			104.5	116.8	18.5	
			105.0	116.6	18.5	
			104.1	116.2	18.5	
			105.8	116.3	18.0	
			104.6 Avg	116.3 Avg	18.3 Avg	
5Aℓ-2.5Sn	ELI, Annealed (Heat A)	Trans	106.2	114.2	19.0	
			109.4	114.2	18.5	
			106.5	114.6	18.0	
			107.5	115.5	19.0	
			105.8	113.8	18.5	
			107.1 Avg	114.5 Avg	18.6 Avg	
5Aℓ-2.5Sn	ELI, Annealed (Heat B)	Long.	113.2	122.4	16.7	
			108.6	121.8	15.5	
			108.9	122.4	16.7	
			110.2 Avg	122.2 Avg	16.3 Avg	
5Aℓ-2.5Sn	ELI, Annealed, Coarse Grained (Heat B)	Long.	96.5	110.8	14.1	
			98.9	112.7	9.9	
			95.8	110.4	11.5	
			97.1 Avg	111.3 Avg	11.8 Avg	
5Aℓ-2.5Sn	ELI, Annealed, Forging	Meridional	104.0	113.5	14.0	33.2
			107.9	114.7	12.0	32.5
			105.6	113.0	13.5	34.2
			105.8 Avg	113.7 Avg	13.2 Avg	33.3 Avg
6Aℓ-4V	Normal Interstitial, Annealed	Long.	131.9	139.3	16.5	
			132.2	140.0	16.0	
			134.0	140.7	16.0	
			133.3	141.4	15.0	
			132.1	139.5	16.0	
			132.7 Avg	140.2 Avg	15.9 Ave	
6Aℓ-4V	ELI, Annealed	Long.	134.9	142.0	16.0	
			138.0	142.0	15.0	
			131.1	141.8	15.5	
			137.2	144.7	15.5	
			133.4	142.3	15.5	
			134.9 Avg	142.6 Avg	15.5 Avg	
6Aℓ-4V	ELI, Solution Treated and Aged	Long.	149.6	163.9	10.5	
			149.2	164.0	12.0	
			149.4	164.4	9.5	
			149.2	163.9	10.0	
			149.9	164.1	11.0	
			149.5 Avg	164.1 Avg	10.6 Avg	

Table V-2 Tensile Properties of 5Aℓ-2.5Sn Forging* at -110°F

Yield Strength, 0.2% Offset (ksi)	Ultimate Strength (ksi)	Elongation, (%)	Reduction of Area (%)
126.5	132.3	9.0	33.0
126.0	132.3	9.9	31.9
128.6	135.1	8.5	32.4
127.0 Avg	133.2 Avg	9.1 Avg	32.4 Avg

*Meridional direction.

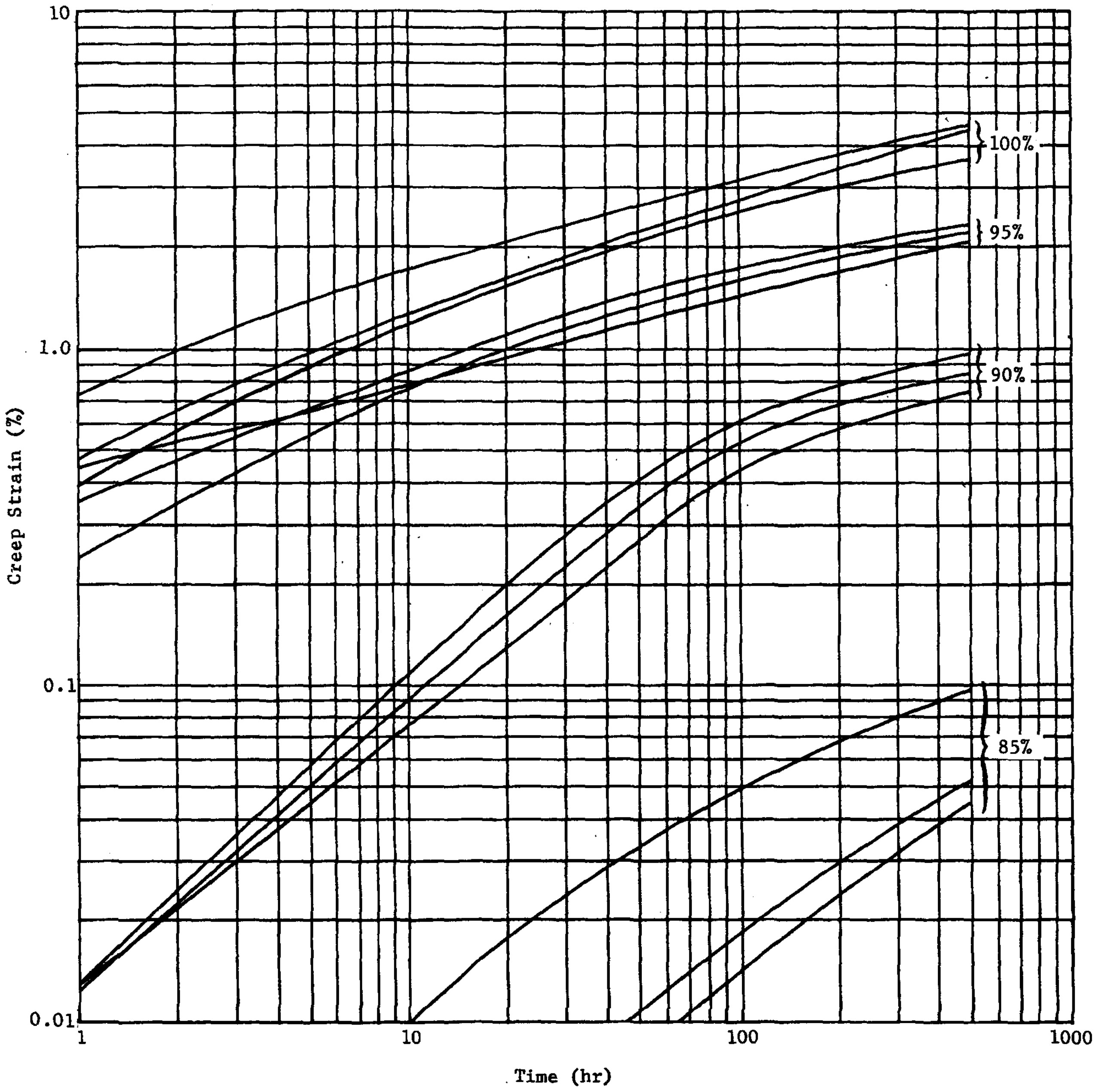

Fig. V-1 Strain vs Time for 5Aℓ-2.5Sn (Normal Interstitial) Titanium at 70°F

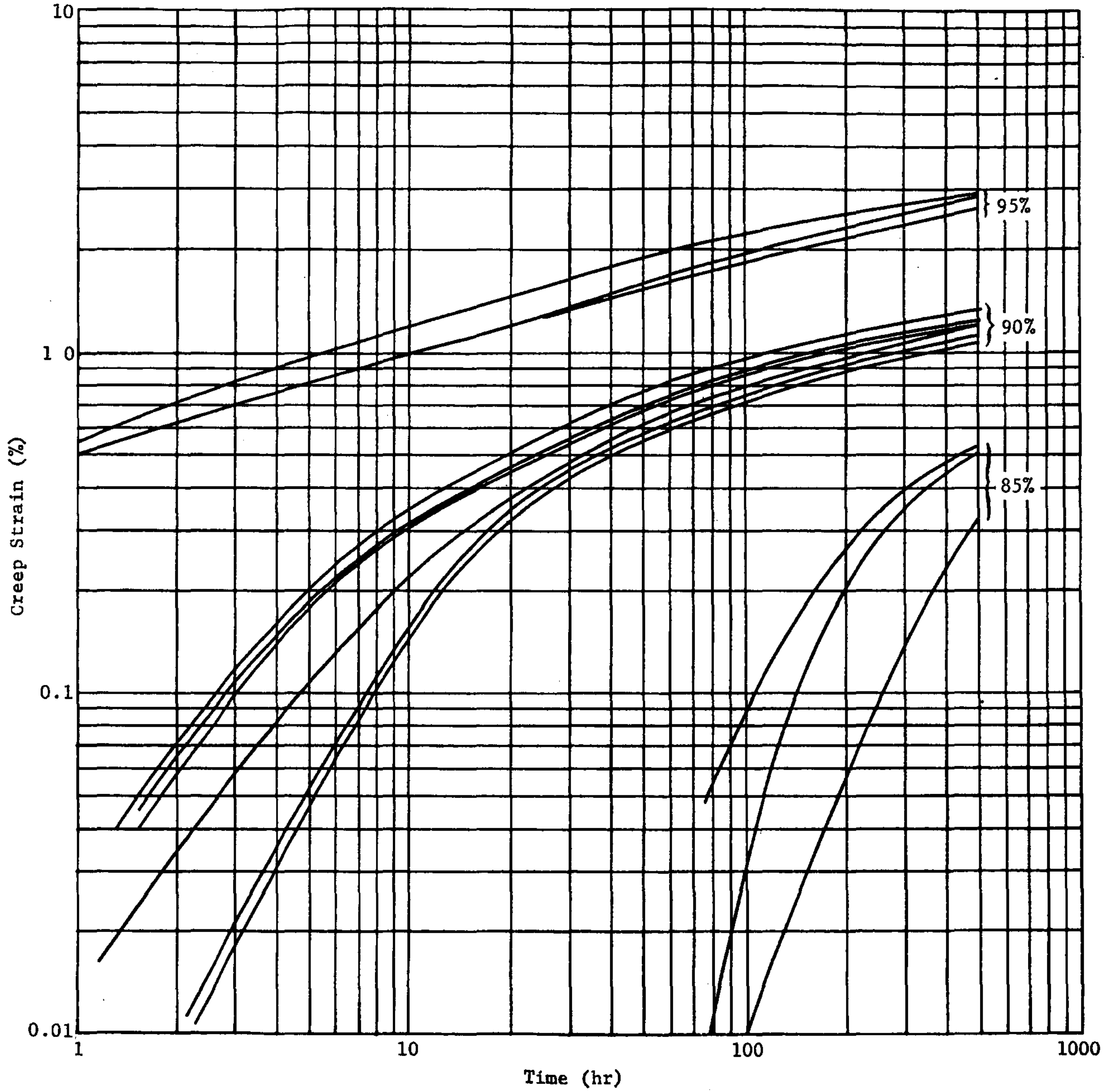

Fig. V-2 Strain vs Time for Longitudinal 5Aℓ-2.5Sn (ELI) Titanium (Heat A) at 70°F

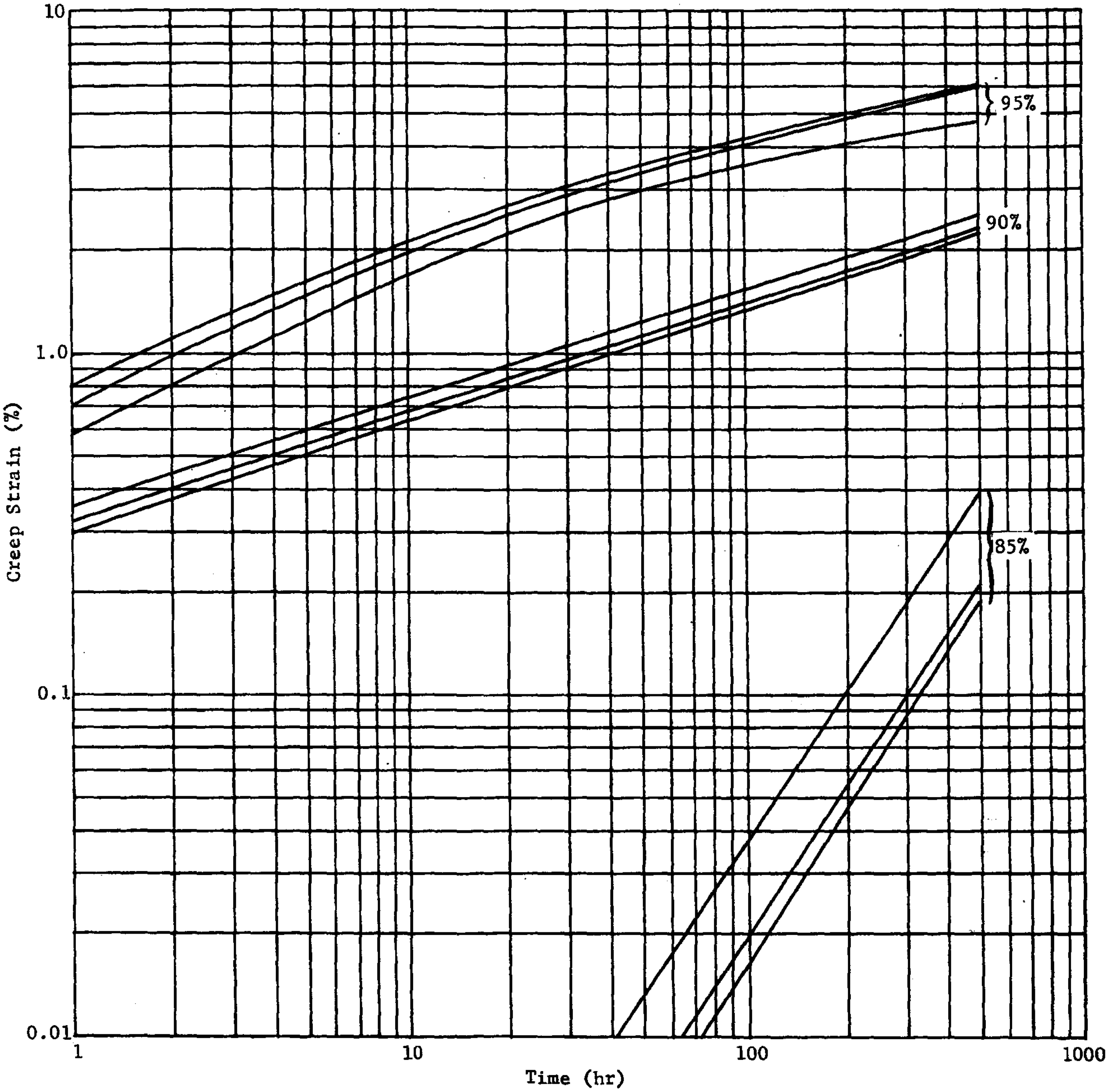

Fig. V-3 Strain vs Time for Transverse 5Aℓ-2.5Sn (ELI) Titanium (Heat A) at 70°F

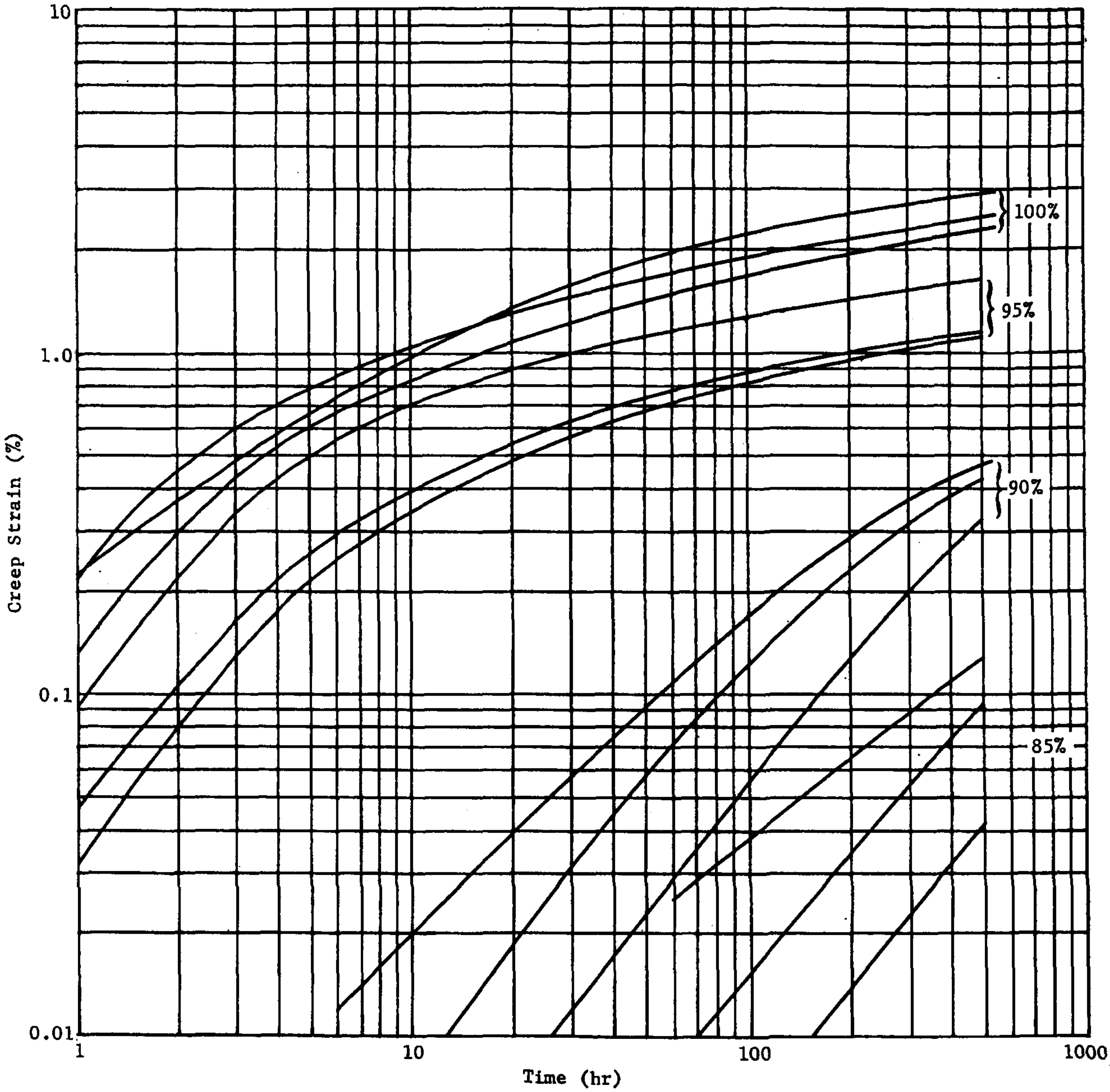

Fig. V-4 Strain vs Time for 5Aℓ-2.5 Sn (ELI) Titanium (Heat B) at 70°F

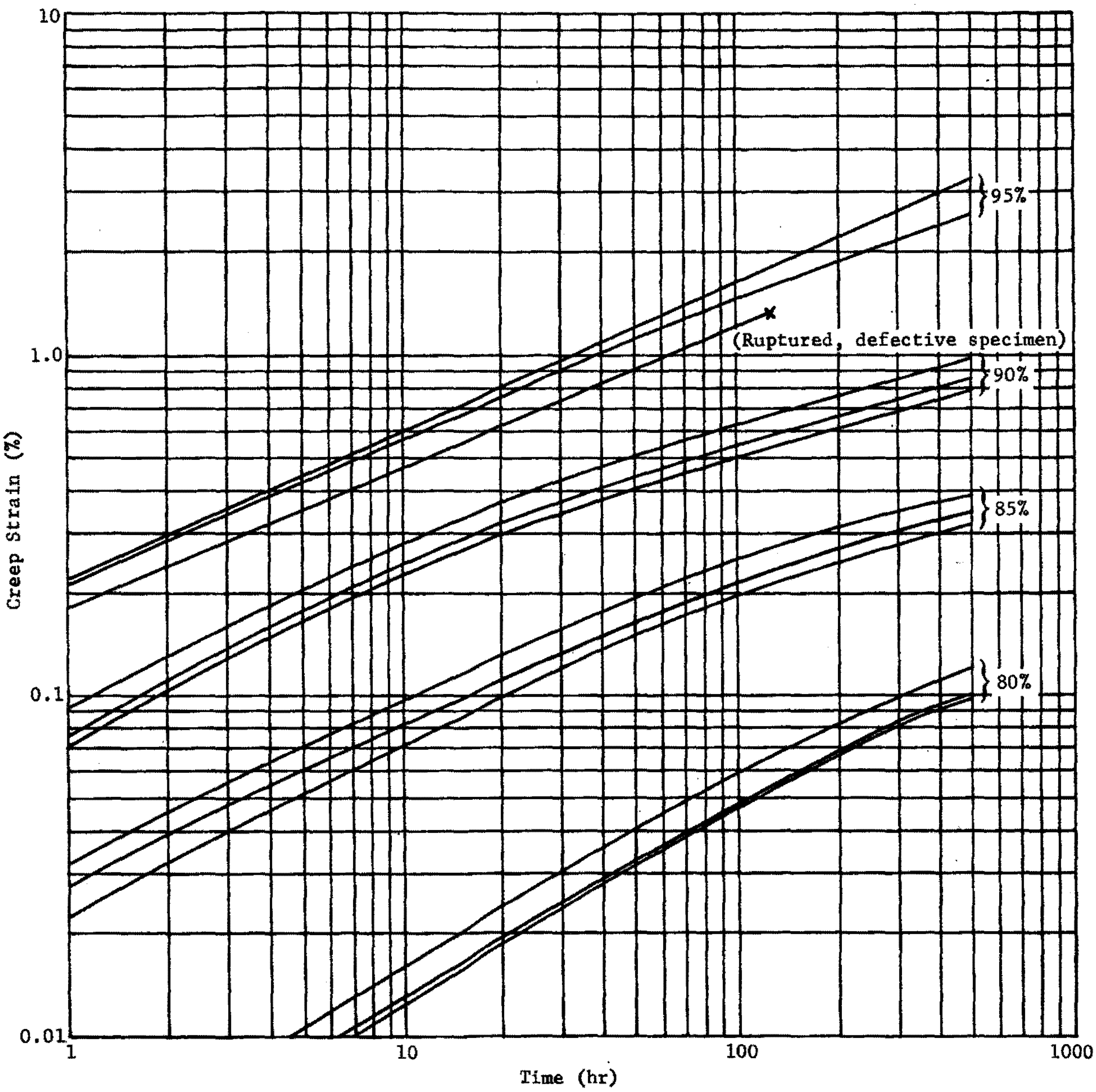

Fig. V-5 Strain vs Time for 5Aℓ-2.5Sn (ELI) Titanium (Coarse Grained, Heat B) at 70°F

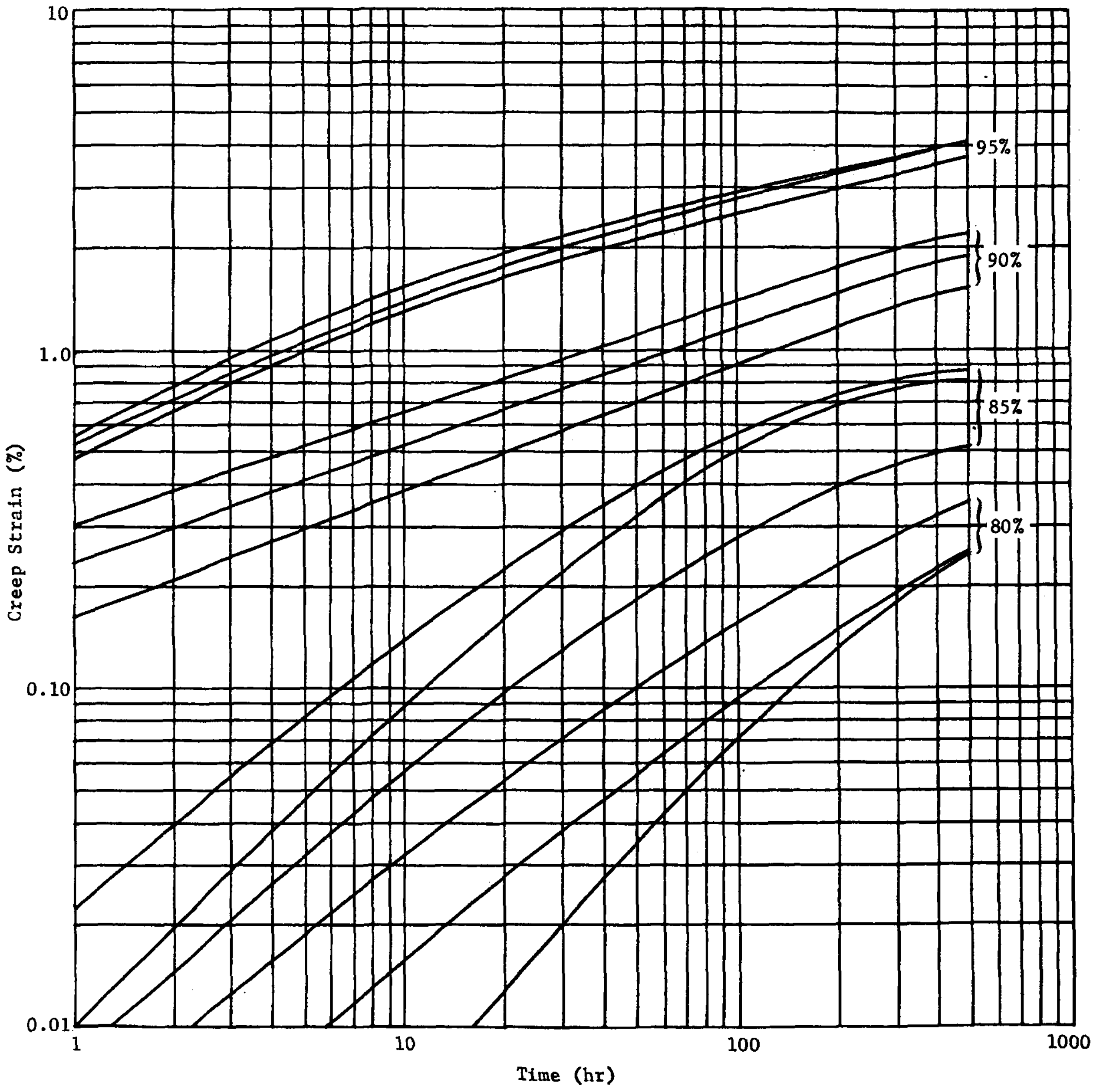

Fig. V-6 Strain vs Time for 5Aℓ-2.5Sn (ELI) Titanium Forging at 70°F

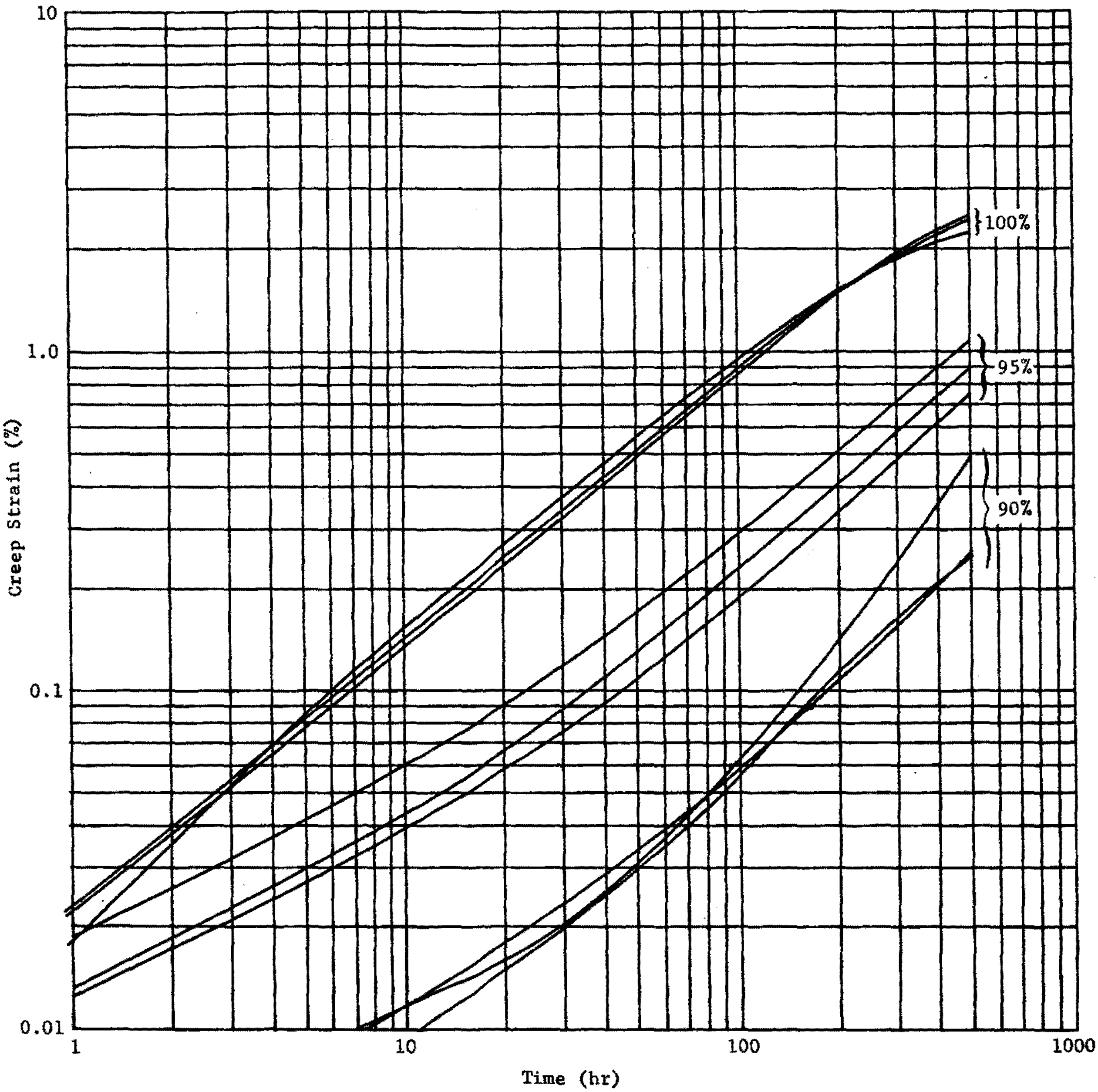

Fig. V-7 Strain vs Time for 5Aℓ-2.5Sn (ELI) Titanium Forging at -110°F

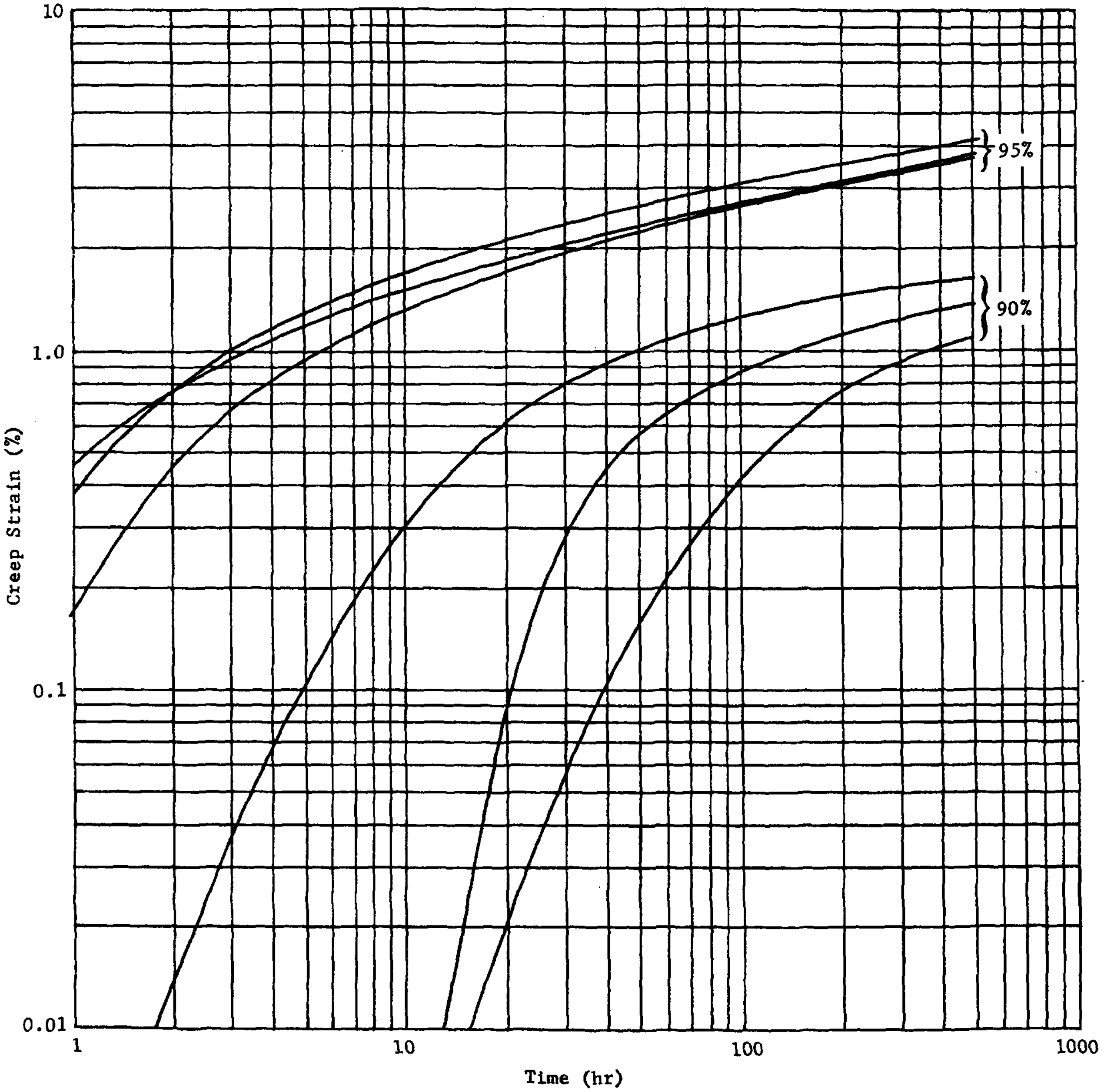

Fig. V-8 Strain vs Time for 6Aℓ-4V (Normal Interstitial) Titanium (Annealed) at 70°F

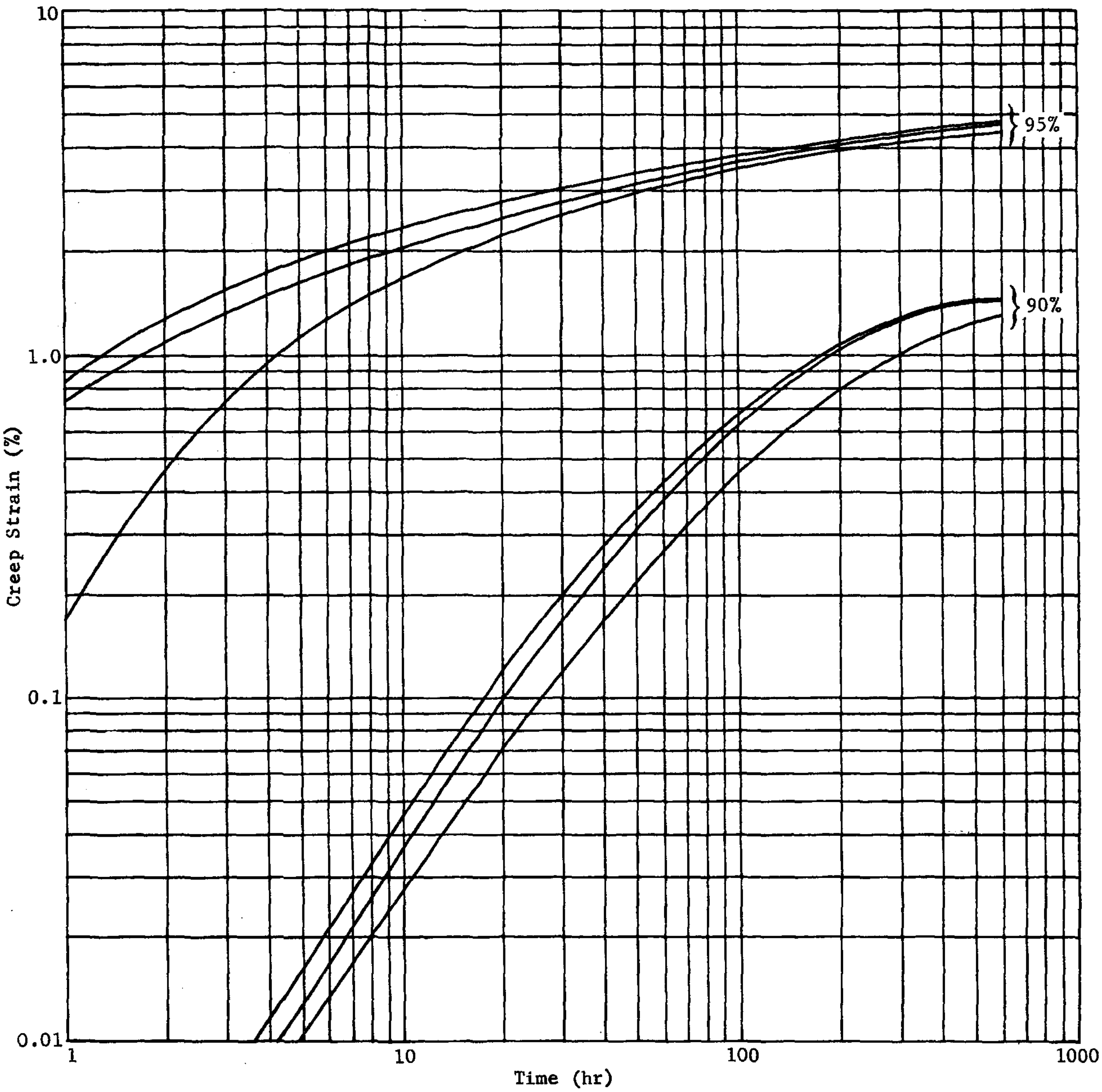

Fig. V-9 Strain vs Time for 6Aℓ-4V (ELI) Titanium (Annealed) at 70°F

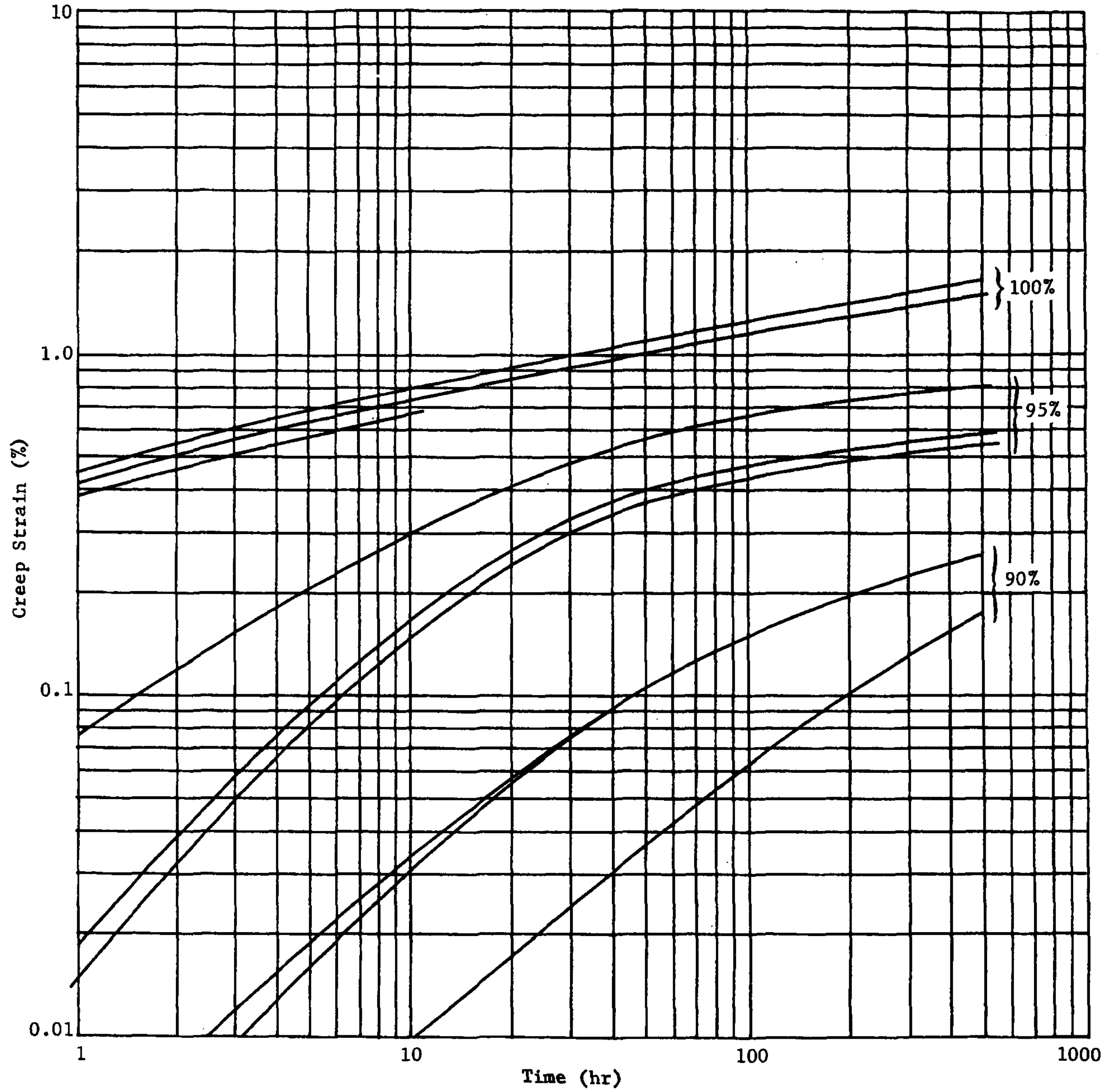

Fig. V-10 Strain vs Time for 6Aℓ-4V (ELI) Titanium (Solution Treated and Aged) at 70°F

Table V-3 Creep Behavior of 5Aℓ-2.5Sn (Normal Interstitial) Titanium at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
85	SG	0.62	110	450	--	--	--	--	--	0.7 Avg	503	0.05	0.62
		0.62	153	--	--	--	--	--	--		503	0.05	0.62
		0.62	23	102	--	--	--	--	--		503	0.10	0.62
90	SG	0.68	2	5	11	26	90	--	--	4.7 Avg	503	0.85	0.70
		0.68	2	6	14	35	130	--	--		503	0.76	0.69
		0.72	2	4	9	20	68	--	--		503	0.98	0.71
95	Ext	0.73	--	--	--	--	2	15	212	13.3 Avg	550	2.40	--
		0.73	--	--	--	--	2	20	278		550	2.43	--
		0.78	--	--	--	--	4	25	400		550	2.22	--
100	Ext	0.82	--	--	--	--	--	2	18	20.3 Avg	495	4.67	--
		0.89	--	--	--	--	1	6	37		495	3.61	--
		--	--	--	--	--	2	7	44		495	4.33	--

*SG = strain gage; Ext = extensometer.

Table V-4 Creep Behavior of 5Aℓ-2.5Sn (ELI) Titanium (Heat A, Long.) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
85	SG	0.55	--	77	107	158	--	--	--	--	525	0.36	0.56
		0.56	--	113	139	187	468	--	--	--	525	0.54	0.57
		0.56	--	187	260	357	424	--	--	--	525	0.56	0.57
90	SG	0.65	--	5	8	14	37	290	--	4.5 Avg	504	1.12	0.61
		0.65	--	5	7	14	41	355	--		504	1.08	0.61
		0.66	--	3	5	9	33	225	--		504	1.22	0.62
90	SG	0.53	--	2	3	6	25	175	--	2.7 Avg	500	1.20	0.60
		0.59	--	2	3	5	19	118	--		500	1.33	0.61
		0.64	--	2	3	5	23	150	--		500	1.22	0.61
95	Ext	0.63	--	--	--	--	--	6	60	3.2 Avg	501	2.97	--
		0.64	--	--	--	--	--	10	135		501	2.64	--
		0.65	--	--	--	--	--	10	113		501	2.83	--

*SG = strain gage; Ext = extensometer.

Table V-5 Creep Behavior of 5Aℓ-2.5Sn (ELI) Titanium (Heat A, Trans) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
85	SG	0.54	102	172	310	485	--	--	--	--	525	0.23	0.55
		0.54	113	220	318	467	--	--	--	--	525	0.24	0.55
		0.54	66	125	198	307	--	--	--	--	525	0.40	0.56
90	SG	0.60	--	--	--	--	4	35	320	--	507	2.36	0.56
		0.59	--	--	--	--	5	41	360	--	507	2.54	--
		0.60	--	--	--	--	3	25	220	--	507	2.60	0.44
95	Ext	0.60	--	--	--	--	--	3	15	20.2 Avg	528	4.94	--
		0.60	--	--	--	--	--	2	11		528	6.12	--
		0.61	--	--	--	--	--	2	9		528	6.07	--

*SG = strain gage; Ext = extensometer.

Table V-6 Creep Behavior of 5Al-2.5Sn (ELI) Titanium (Heat B) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/\text{hr})$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
85	SG	0.59	125	276	500	--	--	--	--	2.7 Avg	499	0.10	0.59
		0.59	--	140	325	--	--	--	--		499	0.14	0.59
		0.59	265	--	--	--	--	--	--		499	0.04	0.59
90	SG	0.62	44	92	165	282	--	--	--	4.0 Avg	503	0.33	0.62
		0.61	21	44	81	158	--	--	--		503	0.43	0.63
		0.62	10	26	55	121	--	--	--		503	0.47	0.63
95	Ext	0.62	--	--	1	2	5	31	--	3.4 Avg	502	1.60	--
		0.63	--	--	2	4	17	190	--		502	1.14	0.67
		0.62	--	--	2	5	22	233	--		502	1.11	0.66
100	Ext	0.83	--	--	--	1	2	9	135	9.2 Avg	529	2.60	--
		0.75	--	--	--	1	4	15	245		529	2.31	--
		0.73	--	--	--	1	3	11	70		529	2.97	--

*SG = strain gage; Ext = extensometer.

Table V-7 Creep Behavior of 5Al-2.5Sn (ELI) Titanium (Heat B, Coarse Grain) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/\text{hr})$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
80	SG	0.45	13	74	295	--	--	--	--	1.3 Avg	505	0.12	0.45
		0.44	20	110	500	--	--	--	--		505	0.10	0.44
		0.44	20	110	500	--	--	--	--		505	0.10	0.44
85	SG	0.49	--	2	11	52	--	--	--	1.6 Avg	501	0.40	0.48
		0.48	--	3	15	82	--	--	--		501	0.33	0.47
		0.49	--	5	20	100	--	--	--		501	0.36	0.48
90	SG	0.52	--	--	1	5	47	--	--	3.7 Avg	509	0.98	0.50
		0.52	--	--	2	6	74	--	--		509	0.83	0.50
		0.52	--	--	2	8	100	--	--		509	0.78	0.50
95	Ext	0.59	--	--	--	--	12	65	--	20.8 Avg	122	3.5†	--
		0.57	--	--	--	--	7	33	160		503	2.50	--
		0.57	--	--	--	--	8	37	245		503	3.30	--

*SG = strain gage; Ext = extensometer.

†Specimen fractured.

Table V-8 Creep Behavior of 5Al-2.5Sn (ELI) Titanium (Forging) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/\text{hr})$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
80	SG	0.49	30	70	142	352	--	--	--	2.8 Avg	520	0.26	0.49
		0.51	13	43	110	326	--	--	--		520	0.26	0.50
		0.54	6	9	52	158	--	--	--		520	0.37	0.50
85	SG	0.54	--	9	21	57	445	--	--	4.2 Avg	506	0.53	--
		0.49	--	5	12	27	98	--	--		506	0.73	--
		0.49	--	3	7	17	80	--	--		506	0.88	--
90	Ext	0.53	--	--	--	--	21	135	--	17.0 Avg	500	1.50	0.52
		0.61	--	--	--	--	5	37	296		500	2.18	--
		0.54	--	--	--	--	9	66	--		500	1.80	0.45
95	Ext	0.68	--	--	--	--	1	5	41	25.0 Avg	507	4.04	--
		0.67	--	--	--	--	1	5	30		507	3.66	--
		0.75	--	--	--	--	1	4	24		507	4.02	--

*SG - strain gage; Ext = extensometer.

Table V-9 Creep Behavior of 5Al-2.5Sn (ELI) Titanium (Forging) at -110°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/\text{hr})$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
90	SG	0.62	23	82	180	380	--	--	--	3.7 Avg	504	--	--
		0.65	29	83	153	250	--	--	--		504	0.25	--
		0.63	30	89	170	370	--	--	--		504	0.26	0.63
95	SG and Ext	0.69	3	15	45	105	310	--	--	14.0 Avg	494	0.82	--
		0.73	1	7	23	65	182	447	--		494	1.08	--
		0.64	2	13	35	87	252	--	--		494	0.95	--
100	Ext	--	--	3	6	15	43	108	315	6.7 Avg	439	2.24	--
		--	--	3	7	17	51	122	335		439	2.16	--
		--	--	3	6	15	48	115	315		439	2.31	--

*SG = strain gage; Ext = Extensometer.

Table V-10 Creep Behavior of 6Al-4V (Normal Interstitial) Titanium (Annealed) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
90	SG	0.76	--	28	39	58	117	402	--	5.8 Avg	497	1.08	0.82
		0.77	--	3	5	7	16	51	--		497	1.61	0.76
		0.75	--	18	20	26	47	157	--		497	1.34	0.81
95	Ext	0.77	--	--	--	--	1	3	17	17.5 Avg	533	4.15	--
		0.78	--	--	--	--	2	6	35		533	3.65	--
		0.78	--	--	--	--	1	3	28		533	3.80	--

*SG = Strain gage; Ext = extensometer.

Table V-11 Creep Behavior of 6Al-4V (ELI) Titanium (Annealed) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
90	SG	0.71	8	15	25	45	118	288	--	8.7 Avg	627	1.37	0.75
		0.71	6	10	17	30	67	175	--		627	1.50	0.76
		0.71	7	12	20	33	80	185	--		627	1.50	0.76
95	Ext	0.75	--	--	--	--	2	4	16	12.0 Avg	505	4.37	--
		0.75	--	--	--	--	--	2	9		505	4.55	--
		0.75	--	--	--	--	--	1	6		505	4.70	--

*SG = strain gage; Ext = extensometer.

Table V-12 Creep Behavior of 6Al-4V (ELI) Titanium (Solution Treated and Aged) at 70°F

Stress Level (%)	Measurement Technique*	Loading Strain (%)	Time (hr) to Indicated Creep Strain (%)							Minimum Creep Rate $(10^{-4}\%/hr)$	Terminal Data		
			0.02	0.05	0.10	0.20	0.50	1.00	2.00		Test Duration (hr)	Total Creep Strain (%)	Unloading Strain (%)
90	SG	0.81	6	17	46	223	--	--	--	1.5 Avg	502	0.25	0.83
		0.81	6	18	46	241	--	--	--		502	0.26	0.83
		0.79	24	84	202	--	--	--	--		502	0.17	0.81
95	SG	0.89	--	--	2	5	34	--	--	2.8 Avg	545	0.81	0.91
		0.85	1	3	6	15	270	--	--		545	0.56	0.88
		0.87	1	3	6	13	152	--	--		545	0.61	0.88
100	Ext	0.99	--	--	--	--	2	47	--	4.9 Avg	501	1.60	--
		1.04	--	--	--	--	3	--	--		501	1.5†	--
		0.99	--	--	--	--	2	31	--		501	1.44	--

*SG = strain gage; Ext = extensometer.

†Specimen fractured through extensometer clamp marks.

VI. DISCUSSION OF RESULTS

A. TENSION BEHAVIOR

A comparison of the tensile data from the vendor's certifications (Table II-1) with the experimental results of this program (Table V-1) shows excellent agreement for all the as-received sheet materials. Strength results agreed within 5%. The exception was the data for the forging material which our results show to be almost 10% lower than the vendor certification. The difference between our results and the vendor's certification is due to the fact that certification is performed on the forging stock, and not on the finished forging. It is expected that the press forging operation will alter the strength properties.

The two heats of 5Aℓ-2.5Sn (ELI) titanium sheet exhibit a noticeable difference in strength properties. A comparison of the chemistry for the two alloys indicates no basis for different strengths. However, the metallographic examination showed a difference in microstructure. Heat A exhibited a somewhat more equiaxed and coarser grained structure than Heat B. The behavioral trend of the strength properties is in agreement with the expected effect of microstructural variations.

The strength properties of the forging were in close agreement with that of ELI sheet material. The coarse-grained material exhibited the lowest strength properties of the 5Aℓ-2.5Sn ELI titanium.

In general, the strength properties of the 5Aℓ-2.5Sn (ELI) titanium varied with grain size, from lowest strength for the transformed material to highest strength for the fine grained heat B material. The significant difference in strength between the ELI and normal interstitial 5Aℓ-2.5Sn titanium is illustrative of the effect of oxygen in this alloy; the ELI material contained only 0.09% oxygen whereas the normal interstitial alloy contained 0.17% oxygen.

The normal and ELI 6Aℓ-4V titanium (annealed condition) exhibited very similar strength properties. Examination of the chemical compositions showed that these two materials have almost identical chemistries.

B. CREEP TESTS

Creep test results are summarized in Table VI-1. The results are in general agreement with expected behavior based on an understanding of alloy chemistry and microstructural effects. The creep curves obtained were, for the most part, satisfactory. However, it was noted that creep curves obtained on the BLH dynamometer creep racks were frequently subject to abnormal shapes in the initial stages. This is attributed to the loading and control system used in these racks. The load is applied by a motor driven screw. A dynamometer sensing element motor provides the error signal for a servo-system which drives the loading motor. We have discovered that the system response is rather poor and that relaxation can occur in the load train without activating the servo-mechanism. Much of our testing at the 85 and 90% level was performed using these racks. The deadweight racks operated in a much more troublefree manner.

Our predictions regarding expected creep behavior, made at the beginning of the program, were essentially as follows:

1) 5Aℓ-2.5Sn (ELI) titanium would creep more than normal interstitial material;
2) Coarse grained material would have much less creep resistance than fine grained material;
3) 6Aℓ-4V titanium would be more resistant to creep than 5Aℓ-2.5Sn titanium;
4) Solution treated and aged 6Aℓ-4V titanium would be much more resistant to creep than annealed material.

These predictions were generally satisfactory.

The following paragraphs discuss creep behavior of the various materials in detail.

The fine grained 5Aℓ-2.5Sn titanium sheet materials exhibited measurable creep at the 85% stress level. The normal interstitial material did not show the highest creep resistance of those materials tested. Actually, it crept more than Heat B of the ELI material but less than Heat A. There is no obvious explanation for this anomaly based on chemistry and metallographic structure. The transverse grain direction of Heat A exhibited less resistance to creep than the longitudinal direction.

Table VI-1 Summary of Titanium Creep Data

Alloy	Grade and Condition*	Grain Direction	Creep Strain (%) at Indicated Stress Level (%)†								
			50	60	70	75	80	85	90	95	100
5Aℓ-2.5Sn	Normal Interstitial, Annealed	Long.	NC	NC	NC	NC	NC	0.07	0.86	2.28	4.28
5Aℓ-2.5Sn	ELI, Annealed (Heat A)	Long.	NC	NC	NC	NC	NC	0.47	1.22	2.83	--
5Aℓ-2.5Sn	ELI, Annealed (Heat A)	Trans	NC	NC	NC	NC	NC	0.27	2.50	5.71	--
5Aℓ-2.5Sn	ELI, Annealed (Heat B)	Long.	NC	NC	NC	NC	NC	0.09	0.41	1.30	2.56
5Aℓ-2.5Sn	ELI, Annealed, Coarse Grained (Heat B)	Long	NC	NC	NC	NC	0.11	0.36	0.86	2.90	--
5Aℓ-2.5Sn	ELI, Annealed Forging	Meridional (70°F)	NC	NC	NC	NC	0.29	0.71	1.83	3.91	--
		Meridional (-110°F)	--	--	--	NC	NC	NC	0.26	0.95	2.24
6Aℓ-4V	Normal Interstitial, Annealed	Long.	NC	NC	NC	NC	NC	NC	1.34	3.85	--
6Aℓ-4V	ELI, Annealed	Long.	NC	NC	NC	NC	NC	NC	1.36	4.54	--
6Aℓ-4V	ELI, Solution Treated and Aged	Long.	NC	NC	NC	NC	NC	NC	0.23	0.65	1.52

*Sheet material, except as noted.

†Average strain for triplicate specimens after 500 hours.

NC = no creep.

The coarse grained 5Aℓ-2.5Sn titanium exhibited creep starting at 80% of the yield strength. The creep strains after 500 hr were significantly greater than those exhibited by the fine grained material from which they were thermally treated (Heat B). However, the creep strains were similar to those determined in the Heat A tests.

The forging showed creep at 80% of the yield stress. Creep strains after 500 hr at each level were higher than for longitudinal ELI sheet, but lower than that for the transverse ELI sheet.

The 6Aℓ-4V titanium alloy did not show evidence of creep until 90% of the yield strength was reached. However, for the annealed materials, creep strains at 90 and 95% were surprisingly high. The solution treated and aged material showed the most creep resistance of any material tested.

It is interesting to note the levels at which creep was first detected (see Table V-1). The coarse grained 5Aℓ-2.5Sn titanium and 5Aℓ-2.5Sn forging exhibited creep at the 80% level; remaining 5Aℓ-2.5Sn sheet started to creep at 85% of the yield stress; and the 6Aℓ-4V sheet did not creep until the 90% level was reached. The disturbing point is that there appears to be no relationship between the stress level at which creep initiates and the magnitude of creep strain after 500 hr at various stress levels. For example, the creep strains in the 6Aℓ-4V titanium at 95% of the yield stress are greater than many of the final strains for the 5Aℓ-2.5Sn titanium, although the 6Aℓ-4V started to exhibit creep at a higher stress level.

It was surprising to find that the forging material crept at -110°F. In fact it exhibited more creep than the 6Aℓ-4V titanium in the solution treated and aged condition at 70°F.

VII. CONCLUSIONS AND RECOMMENDATIONS

The objective of this work was to characterize the creep behavior of two titanium alloys (5Aℓ-2.5Sn and 6Aℓ-4V) in various conditions at room and low temperatures.

The results of the research led to the following observations:

1) 5Aℓ-2.5Sn appears to be less resistant to the onset of creep than 6Aℓ-4V;
2) Two heats of 5Aℓ-2.5Sn titanium (both fine grained, annealed) exhibited wide variations in creep behavior; this difference does not appear to be related to chemistry, but might result from subtle microstructural variations;
3) Coarse grained titanium appears to be less resistant to creep than fine-grained material;
4) Solution treatment and aging reduces the room temperature creep susceptibility of 6Aℓ-4V titanium;
5) Creep in 5Aℓ-2.5Sn titanium occurs down to -110°F; it is currently unknown whether creep occurs at lower temperatures.

Based on these results, allowable stress levels for these titanium alloys should take into consideration time-dependent plastic deformation. The data obtained in this program are not sufficient to define rigid allowable stress levels for titanium alloys; however, the data suggest that for sustained load conditions a limiting stress of 85% of the yield strength for 6Aℓ-4V and 75 to 80% of the yield strength (depending on form and condition) for 5Aℓ-2.5Sn be imposed.