Engineering Research Institute
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FOURTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

by

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SUMMARY

Creep and Relaxation Properties

Results for creep and relaxation properties of S-816 at 1350°F have previously been reported for this joint investigation under Contract No. AF 18(600)-62, Expenditure Order No. R-605-227 SR-3a. For that alloy multiple-stress rupture tests were run, with a fixed stress maintained for a while and then the stress was changed to a new value for another portion of the test. It was found that the portion of the total life expended during a given period of constant stress level was equal to the fraction:

$$\frac{\text{actual time at the stress}}{\text{rupture life at that stress}}.$$

Prior plastic strain was found to increase the rate of stress relaxation for all initial stresses tested with S-816 at 1350°F.

The present report covers investigations for Waspaloy at 1500°F. Relaxation properties were found to be similar to those reported for S-816 except that prior strain had a much less marked effect on residual stress after a like period of relaxation.

Further work is indicated before a quantitative law can be formulated for rupture life under a variable-stress history.

Metallurgical Variables

Active experimentation is in progress with both S-816 and Waspaloy on effects of certain metallurgical variables on notched-bar properties. This phase of the work is continuing and will be covered in a later report.

INTRODUCTION

This report presents results of tests performed in the quarter between March 16 and June 15, 1953 under Contract No. AF 18(600)-62, Expenditure Order No. R-605-227 SR-3a. This work is part of a program designed to study factors affecting notch sensitivity of heat-resistant alloys, with special attention to be given the significance of creep and relaxation, and to the effects of certain metallurgical variables in rupture tests of notched bars.

The rupture life of a notched specimen is assumed to start by failure of fibers near the notch root where stresses are initially high. It is sought to study the rate of relieval of such high stresses by relaxation tests run on smooth bars and to develop a method for predicting time to failure of fibers under a decreasing-stress history of the type expected to be present in a notched bar.

Past reports have included experimental results on pertinent properties of S-816 alloy at 1350°F. Among the findings reported were the following:

(1) For S-816 at 1350°F, in tests where the stress was changed from one steady value to another during the run, the portion of life expended during a given period at constant stress is approximately equal to the fraction:

$$\frac{\text{actual time at the stress}}{\text{rupture life for that stress}} .$$

(2) Prior plastic strain increased the rate of stress relaxation for all initial stresses tested.

The present progress report covers results of similar investigation for the second of three alloys to be tested in the overall program.

CURRENT STATUS OF THE INVESTIGATION

Creep and Relaxation Properties

S-816

All experimental work outlined at the start of the program for this alloy has been completed and the data reported.

Waspaloy

Tests to date have all been confined to a single temperature of 1500°F, where the elongations for smooth bars in the conventional stress-rupture time tests are expected to be of an intermediate magnitude (around 5 to 10 per cent) as compared with the higher values for S-816 at 1350°F.

Relaxation studies are believed complete enough for correlations to be attempted, but a few further tests are indicated before rupture life under variable stress can be predicted with sufficient accuracy.

Inconel X-550

Bar stock of this alloy has finally been received and specimens with conventional heat treatment are being prepared. Experimental work can start as soon as it has been ascertained whether this material will be notch sensitive at one of the temperatures chosen for study by the second laboratory cooperating in the project. (It is desired that at least one condition of marked notch sensitivity be considered in any correlation of notch behavior with material properties.)

Metallurgical Variables Affecting Notch Properties

Approximately twenty-five specimens of Waspaloy and of S-816 with a variety of treatments are in various stages of preparation or testing. It is anticipated that this phase of the program will be ready for reporting in the next progress report.

PROPERTIES OF WASPALOY AT 1500°F

Short-Time Tensile Data

In a notched specimen the critical fibers undergo plastic deformation during loading to stresses of interest in this program. To establish suitable test conditions between the proportional limit and the tnesile strength, a short-time tensile test was conducted for Waspaloy at 1500°F. The following properties were obtained:

Yield strength (0.2 per cent offset)	75,500 psi
Tensile strength	81,000 psi
Elongation in 2 inches	6. per cent
Reduction of Area	7. per cent

Data for this tensile test are plotted in Figure 1, along with a typical curve obtained while applying a high stress to prestrain a relaxation specimen. In this plot the stresses have been corrected for the instantaneous cross section and strains are given in terms of the effective gauge length over which the optical extensometer measured deformations.

Stress Relaxation Properties

Seven step-down relaxation tests at 1500°F covered a range of initial stresses from below the proportional limit to near the yield strength (30,000, 40,000, 50,000 and 70,000 psi). Of four tests started at 40,000 psi, two were preceded by rapid plastic straining of different amounts, obtained through temporary overloading. A third specimen was held at the 40,000 psi initial stress until a creep strain of 0.0206 in./in. had taken place before the relaxation run proper was started.

The results plotted in Figure 2 show that for all testing conditions studied, for specimens with no extended plastic strain prior to relaxation, the residual stress dropped more rapidly the higher the initial stress. Residual stresses at the end of one hour were substantially equal for all, and at relaxation times greater than ten hours the magnitudes of the residual stresses were in reverse order to the original values.

As was observed for S-816 at 1350°F, so also for Waspaloy at 1500°F, increasing amount of prior strain by momentary overloading appeared to result in slightly more rapid stress reduction by relaxation. Allowing a specimen to creep extensively before a relaxation run was started also resulted in more rapid drop of residual stress. These effects may be seen from Figure 3 to be rather small.

Rupture Time and Creep Data

Four bars run to rupture under constant tensile stresses yielded the results of Table I (A). When these data are plotted on Figure 4, the curve for the higher stresses shows satisfactory agreement with three test points obtained by Simmons and Cross (1) for comparable conditions. However, at stresses below 25,000 psi the final position and slope of the curve is in doubt until further test points have been established. On this figure, reductions in area have been reported for ductility measurements.

Creep curves for the four constant-load tests have been plotted in Figure 5, along with results for creep to rupture under multiple stress levels for five other specimens.

Multiple-Stress Rupture Tests

In the correlation between rupture life of notched bars and material properties as determined with smooth bars, it is anticipated that it will be necessary to specify what portion of the total life of a fiber in a notched bar has been "used up" by being subjected to a given stress for a known period of time.

Five multiple-stress rupture tests were performed on Waspaloy with the results listed in Table I (B). These data, together with the tentative rupture time plot of Figure 4 permit the following calculations:

Specimen Number	Stress (psi)	Ratio: Time at This Stress / Rupture Life at This Stress		
MS-W158	60,000	0.177/0.5	=	0.35
	30,000	34.0/58	=	0.59
				0.94
MS-W164	40,000	3.4/7.8	=	0.44
	30,000	22.4/58	=	0.39
	20,000	164.5/500	=	0.33
				1.16
MS-W166	40,000	5.1/7.8	=	0.65
	20,000	287.3/500	=	0.57
				1.22

Specimen Number	Stress (psi)	Ratio: Time at This Stress / Rupture Life at This Stress		
MS-W165	20,000	107.3/500	=	0.21
	40,000	3.4/7.8	=	0.44
	20,000	177.2/500	=	0.35
				1.00
MS-W168	20,000	165.0/500	=	0.33
	40,000	2.5/7.8	=	0.32
	20,000	182.4/500	=	0.36
				1.01

For these experiments with either two or three discrete stress levels during the specimen's history, the simple method proposed appears ample to handle addition of portions of life in the range from 20,000 to 60,000 psi.

It still seemed desirable, however, to test the effect of a period of relaxation on the life still remaining. In a notched specimen, it is to be expected that the high stress initially present near the notch root will relax, approaching a limiting value of stress. The fibers are then subjected to this residual stress until localized necking or rupture begins.

Specimens previously used to obtain relaxation data were re-loaded to a suitable stress and run until rupture. This stress-time history differs slightly from that of a fiber at a notch, but data of the general type desired were obtained in a minimum of time by this procedure, without needless duplication of specimen preparation.

Findings may be tabulated as follows:

Specimen Number	Stress-Time History	Summation of Fractions: Time at given stress / Rupture life at stress	Reduction of Area at Rupture (%)
OR+S-W159	1) Overload to 81,600 psi; unload to 40,500 psi	0.58 (±0.3)	
	2) Relax to 6,400 psi (81 hrs)	0.05	
	3) Rupture at 30,200 psi (10.7 hrs)	0.19	
		0.82 (±0.3)	5.5
OR+S-W154	1) Overload to 63,100; unload to 40,000 psi	0.08	
	2) Relax to 10,000 psi (151.7 hrs)	0.09	
	3) Rupture at 30,000 psi (26.3 hrs)	0.45	
		0.62	10.
R+S-W156	1) Load to 70,000 psi	0.09	
	2) Relax to 3,800 psi (176 hrs)	0.17	
	3) Rupture at 40,250 psi (2.73 hrs)	0.37	
		0.63	11.
R+S-W153	1) Relax 50,000 psi to 9,810 psi (259 hrs)	0.15	
	2) Rupture at 35,000 psi (10.5 hrs)	0.53	
		0.68	[a](13.5)
R+S-W151	1) Relax 40,000 to 4,820 psi (538 hrs)	0.18	
	2) Rupture at 30,000 psi (30.5 hrs)	0.51	
		0.69	14.5
S+R+S-W152	1) Creep 4.37 hrs at 40,000 psi	0.56	
	2) Relax to 4,850 psi (227.4 hrs)	0.07	
	3) Rupture at 35,000 psi (7.2 hrs)	0.36	
		0.99	[a](13.5)

[a] Broke in fillet; estimated from elongation.

From these data it appears that after a relaxation period of the order of 100-200 hours, the material retains less than half of the rupture life normally found for a given high stress level. Secondly, the total life was apparently reduced considerably below that expected in at least four cases. This seems to be contrary to the findings in the multi-stress rupture tests described previously.

DISCUSSION

In the tests conducted at 1500°F, Waspaloy relaxed rather rapidly. The stresses and time periods involved were similar to those previously found for S-816 at 1350°F. Calculations summarized earlier showed that unless stresses were very high, approaching the tensile strength, only a very small percentage of rupture life was used up during rapid relaxation of stress.

It would seem, therefore, that the Waspaloy material being tested should not be notch sensitive in the rupture test at 1500°F, unless the stress concentrations reached very high values during loading. This should be a function of the notch and of the applied load. If this should not prove to be correct, then the explanation must lie in some other factor not yet considered. The possibility of undue reduction in life associated with relaxation suggested by some of the tests could, for instance, be a factor.

The evident ability to add rupture life as a function of percentage of total life at each given stress for multiple-stress tests was most encouraging for arriving at an analysis of behavior of fibers in notched specimens. The disparity in results for constant-load tests performed on specimens after relaxation tests had been completed does, however, indicate possible complications.

The calculations of the probable part of the total life expended during loading for high-stress relaxation tests are subject to considerable error because of the variable rate inherent to hand loading. An error of 100 per cent would not, however, explain the low life after relaxation. Other uncertainties also exist.

Computations were based on extrapolations of the stress - rupture time curve. This was probably most serious at high stresses where test points for very short times were not available. Incidentally, rather minor variations of individual specimens could cause considerable error in this range. At low stress, computations were again based on extrapolations, this time to long times where the curve is not yet well established. Additional data should help to clear up this matter.

Exposure to temperature and stress for relative long time periods during the relaxation tests may have altered structures, and thus rupture properties. Subjecting relaxation specimens to high initial stresses may have been the source of such changes rather than damage from creep.

FUTURE WORK

The future work will concentrate first on clearing up factors affecting the addability of rupture life for Waspaloy at 1500°F under variable-stress conditions.

Work on metallurgical variables affecting notch sensitivity of S-816 and Waspaloy will be carried on simultaneously.

The temperature at which Inconel X-550 is to be investigated should be one at which definite notch sensitivity will be obtained. As soon as this has been established by the laboratory cooperating on this program, the work will be started.

BIBLIOGRAPHY

(1) W.F. Simmons and H.C. Cross, Third Quarterly Progress Report on Investigation on Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures, Battelle Memorial Institute, April 8, 1953.

TABLE I

RESULTS OF SMOOTH-BAR TESTS WITH WASPALOY AT 1500°F

A) Conventional Constant-Load Tests

Specimen Number	Stress (psi)	Time at Stress (hours)	Elongation at Rupture (% in 2.1-2.2 in. gage lth)	Reduction of Area (%)
S-W157	60,000	0.5	7.5	10.5
S-W163	40,000	10.15	7.5	9.5
S-W162	30,000	65.6	9.	[a](3.)
S-W161	20,000	498.9	12.	13.

B) Multiple-Stress Rupture Tests

Specimen Number	Stress (psi)	Time at Stress (hours)	Elongation at Rupture (% in 2.1-2.2 in. gage lth)	Reduction of Area (%)
[b]MS-	60,000	0.177	6.5	7.5
W158	30,000	34.0		
[b]MS-	40,000	3.4		
W164	30,000	22.4	5.5	[a](0.5)
	20,000	164.5		
[b]MS-	40,000	5.1	7.	9.5
W166	20,000	287.3		
[c]MS-	20,000	107.3		
W165	40,000	3.4	8.5	8.
	20,000	177.2		
[c]MS-	20,000	165.0	7.5	9.5
W168	40,000	2.5		
	20,000	182.4		

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a Broke near fillet.
b Step-down test.
c Step-up, step-down test.

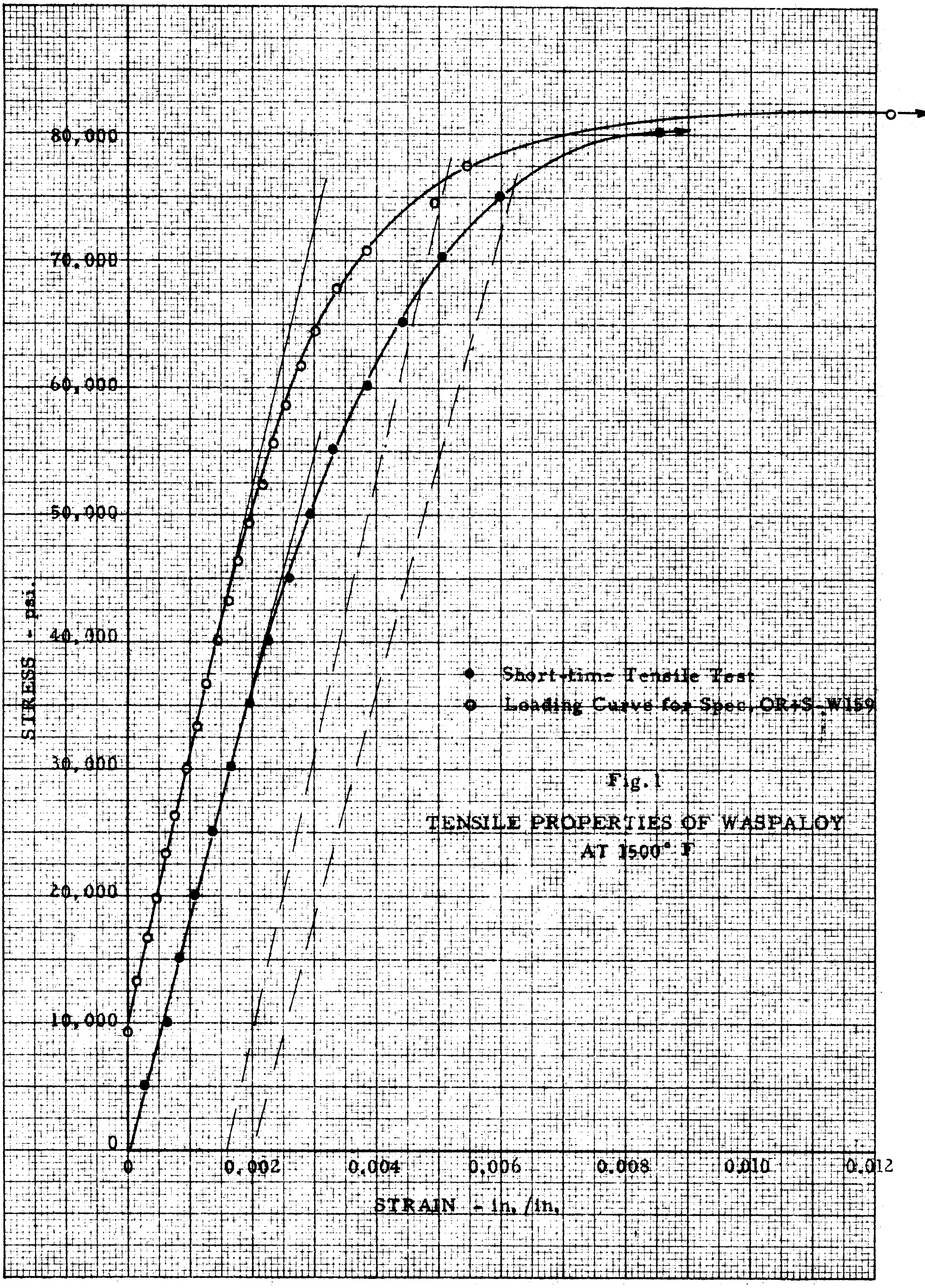


Fig. 1

TENSILE PROPERTIES OF WASPALOY AT 1500° F

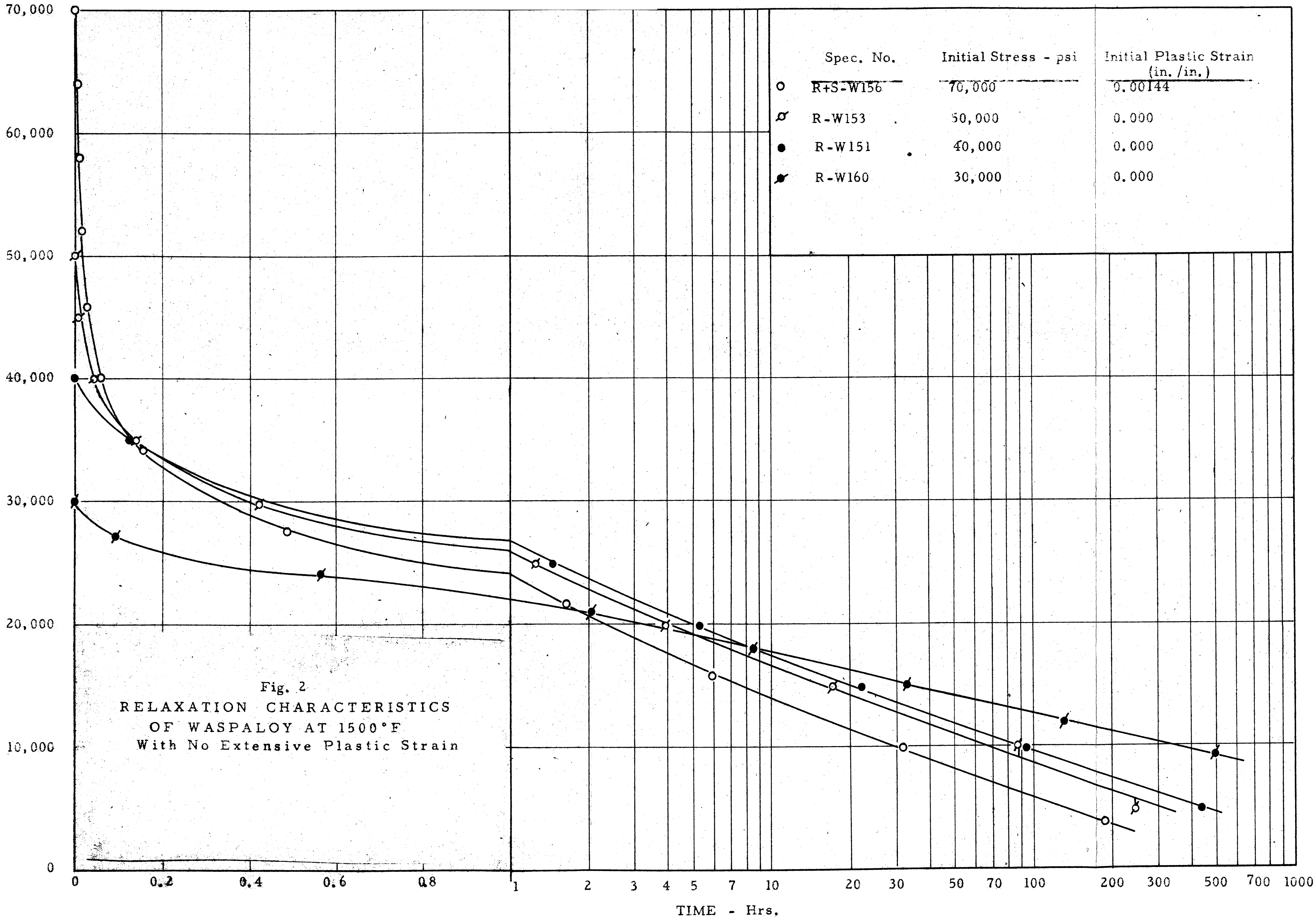


Fig. 2
RELAXATION CHARACTERISTICS
OF WASPALOY AT 1500°F
With No Extensive Plastic Strain

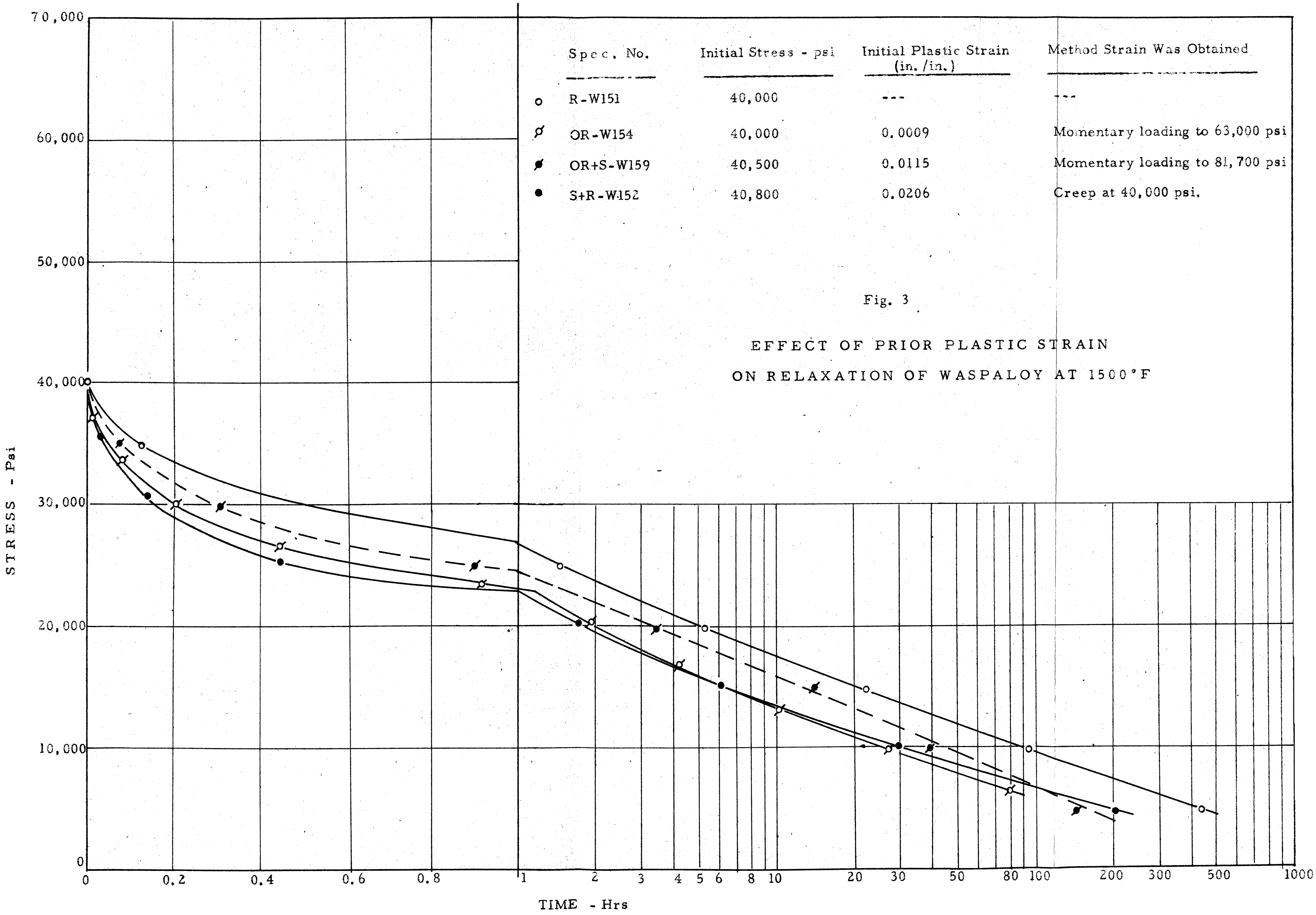
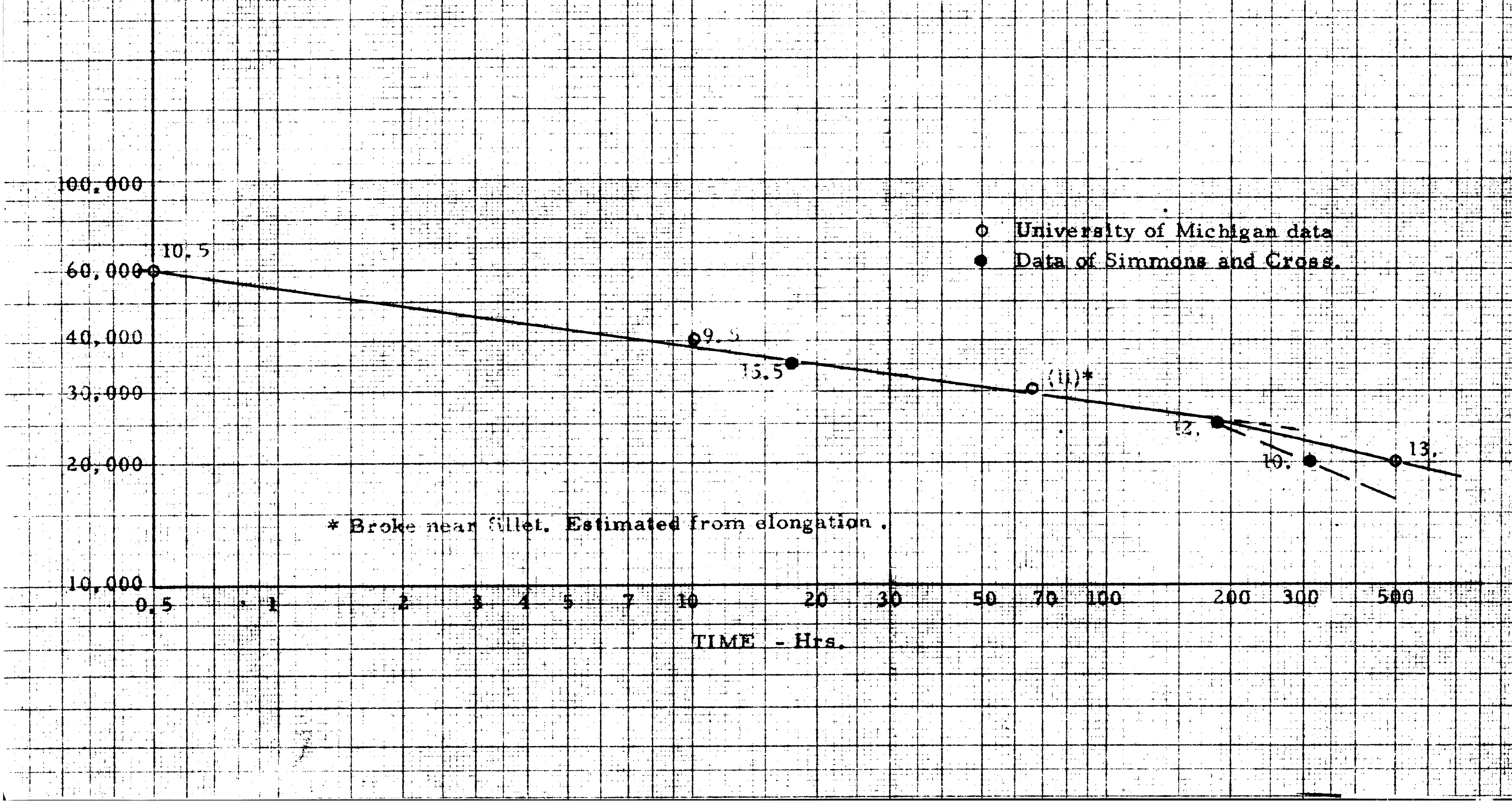


Fig. 3

EFFECT OF PRIOR PLASTIC STRAIN ON RELAXATION OF WASPALOY AT 1500°F

Fig. 4 - STRESS - RUPTURE TIME CURVE FOR WASPALOY AT 1500° F.

(Numbers near points give reduction of area at rupture in per cent).



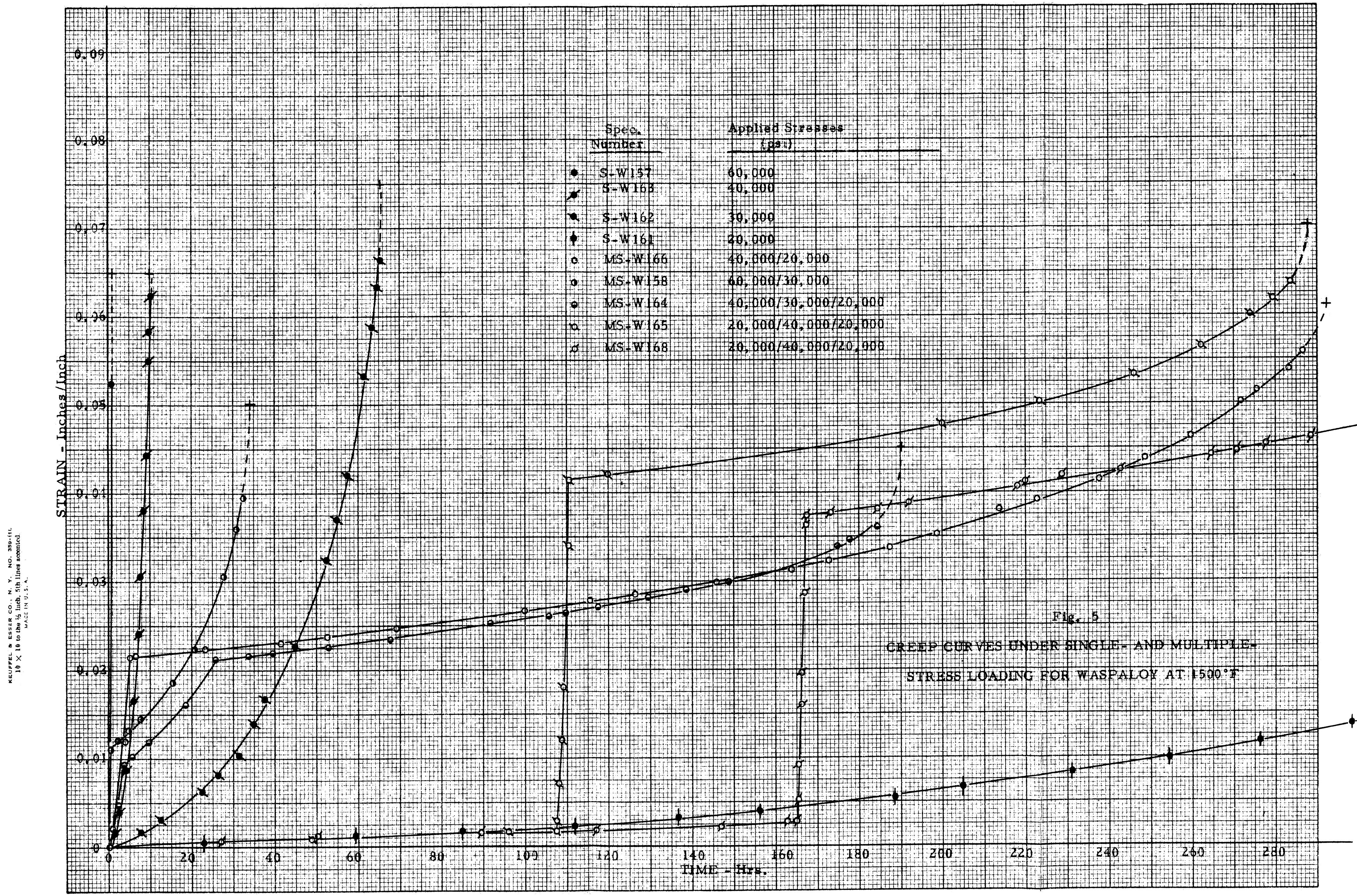


Fig. 5

CREEP CURVES UNDER SINGLE- AND MULTIPLE-STRESS LOADING FOR WASPALOY AT 1500°F