ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICH.

NINTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

by

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Project 2024

Air Force Contract No. AF 18(600)-62
Task No. 73605

March 31, 1955

SUMMARY

Work under Contract AF 18(600)-62 has been extended to check generality of past findings relating notched-bar rupture behavior at elevated temperature to creep-relaxation properties. Past studies on cylindrical specimens of three heat-resistant alloys are to be expanded to include two new materials (a Cr-Mo-V low alloy steel and an age-hardening aluminum alloy) and to study notch effects in flat specimens.

Prior studies indicated that notch preparation methods have a major effect on rupture life of notched specimens, presumably as a result of variable residual machining stresses. An experimental ultrasonic method will be investigated in search of a method of preparing notch specimens with minimum residual machining stresses.

Studies are in progress with material from three different heats of Waspaloy seeking other factors than creep and relaxation which affect notch sensitivity.

Specimen geometry for both round and flat notched bars for future tests has been standardized to give the same two values of theoretical stress concentration factor for each shape. (K_t about 3.1 and 1.85).

Experimentation in the coming quarter is to emphasize obtaining extensive data at 1100°F for the low-alloy steel, so that notched-bar rupture life may be analyzed in terms of creep properties for this material of different type from alloys considered previously. Correlations are to be sought for notches in flat, as well as cylindrical, specimens of this alloy.

INTRODUCTION

This report covers tests completed in the first quarter of 1955 under Contract AF18(600)-62 in a study of factors affecting notch sensitivity of alloys at elevated temperatures.

Past experimental work was restricted to smooth and notched cylindrical specimens of three heat-resistant alloys. For the materials and conditions studied notch weakening in rupture tests was found to be associated with high resistance to creep, with consequent slow relaxation of concentrated stresses near the notch root. Notch strengthening occurred under conditions of relatively rapid stress relaxation by a creep mechanism.

A mathematical analysis was developed which successfully explained results for two particular examples with quite different notch behavior. The range of validity of the proposed analysis will be examined for other conditions already studied and by new tests covering other types of metals. Experiments with a flat specimen notched at its edges are also planned to supplement past tests using cylindrical notched bars.

The summary report covering tests for calender year 1954 (See Ref. 1) mentioned two phases of the past work calling for clarification:

(1) Effects of notch preparation methods on experimental notched-bar rupture life.

(2) Influence of other factors on notch behavior besides creep and relaxation properties.

Though neither of the studies on these topics is complete, progress up to March 31, 1955 will be covered below:

CURRENT STATUS OF THE EXPERIMENTAL PROGRAM

Effects of Notch-Preparation Methods on Test Results

Three specimens of Inconel X-550 with a notch prepared by grinding showed no evidence of surface alteration or preferential grain orientation when heat treated in vacuum after notching. These specimens should be quite free from residual stresses and if notches prepared by another means give the same rupture results as do these, the results are probably quite close to the true values for stress-free notches.

Of the available methods for notching specimens with minimum residual machining stresses, an experimental ultrasonic method under development by the Sheffield Corporation of Dayton, Ohio is being considered first. Specimen blanks have been forwarded to their laboratory but actual finishing of these trial specimens has not yet begun. Other techniques will be investigated should ultrasonic methods prove unsatisfactory.

Meanwhile, notches for routine testing are being finished by grinding, followed by form lapping to final size.

Effect on Notch Behavior of Other Factors than Creep and Relaxation

Material from one vacuum-melted and two air-melted heats of Waspaloy was obtained and rolled to a common bar size. Specimens from all three heats were given either of two heat treatments, and short-time tensile and creep-rupture properties determined. Notched-bar rupture tests for the same materials and treatments are in progress. It is planned to compare notched-bar and smooth-bar results in search for possible correlations involving properties other than creep or relaxation.

New Test Materials and Specimen Types

Two additional alloys were chosen for study after conferences between the University of Michigan and the Materials Laboratory, WADC:

(1) An air-hardening Cr-Mo-V low-alloy steel (Timken "17-22-A"S).

(2) An age-hardening aluminum alloy (2024-T4).

The alloy steel stock has been received and initial tests scheduled. Delivery of the aluminum alloy is expected in the coming quarter.

Specimen dimensions have been established to give theoretical stress concentration factors in flat specimens machined from round stock equal to the factors for cylindrical bars used in this program. To date the only data obtained with flat notched specimens are for a few odd-sized specimens finished in the course of machine-shop trials of grinding and lapping techniques.

EXPERIMENTAL RESULTS

Rupture Life of Inconel X-550 Specimens Heat-Treated in Vacuum After Notching

Three notched specimens of Inconel X-550 were finished by grinding in the as-received condition to a nominal gauge diameter of 0.600-inch, 0.424-inch diameter at the notch, and 0.005-inch notch root radius. The specimens then received a conventional heat treatment after being sealed in individual Vycor glass tubes under high vacuum. The Vycor tubing collapsed around the specimen and showed pronounced devitrification during the four-hour solution treatment at 2150°F, but the vacuum was retained throughout the treatment.

Rupture data obtained at 1350°F follow :

Spec. No.	Stress (psi)	Rupture Life (Hr.)
NX-569	60,000	3.4
NX-571	50,000	7.6 (± 0.2)
NX-570	40,000	55.9

These rupture times fall near, but slightly lower than, the values previously found for similar specimens treated in a raw helium atmosphere after turning the notch on a lathe. In the present specimens no evidence was seen of the surface alteration and preferential orientation of grain boundaries perpendicular to machined surfaces noted in the earlier specimens.

Comparison of Properties for Three Heats of Waspaloy

Limited amounts of material was found to be available from one heat of Waspaloy melted under vacuum and from two different heats melted in air. Chemical analyses are listed in Table 1.

It was anticipated from results reported by Carlson, et al. (pages 9 and 11 of reference 2) that notched-bar properties for the several heats might differ one from another, especially when the intermediate aging step (1550°F, 4 hr, Air Cool) was omitted from some specimens. These differences were to be examined in terms of any corresponding differences to be found in the smooth-bar properties.

To minimize effects of different prior treatments, and to stretch the short supply of stock, all three materials were rolled to one-half inch squares at the University. Initial break-down to one-inch squares was at 2150°F. All further rolling was at 1950°F. Reduction to 5/8-inch squares was in 10 steps, with reheat after each step. The final 14 percent reduction (5/8-inch to 1/2-inch squares) was from 1950°F in four steps without reheat.

Test results are presented in Figures 1 through 6. Five pages were used to cover the different creep plots of Figure 1 to permit more convenient comparisons between curves and easy determination of creep rates. The most evident finding is a considerable higher creep strength for the vacuum-melted heat tested compared with the air-melted materials.

TABLE 1.

CHEMICAL COMPOSITIONS OF THREE HEATS OF WASPALOY TESTED

Melting Atmosphere:	Vacuum	Air	Air
Heat Number:	3-260	44,036	63,613
Element	Chemical Composition, Percent by Weight		
C	0.08	0.08	0.04
Mn	0.27	0.80	0.73
Si	0.60	0.61	0.66
P		0.01	0.014
S	0.005	0.017	0.014
Cr	19.7	18.72	20.16
Ni	Bal.	Bal.	Bal.
Co	14.0	13.44	14.25
Mo	3.90	2.93	3.15
Fe	0.74	1.17	1.33
Al	1.11	1.29	1.00
Ti	3.10	2.29	2.54
Cu	0.1	0.1	0.06
Mg	0.1		

Figures 2 and 3 show a similar high yield strength and rupture strength for heat 3-260, compared with results for the remaining two heats. The short-time tensile and rupture data for these tests are listed in Tables 2 and 3. Notch weakening occurred in all cases for a notch with 0.004-inch root radius in a bar with shank and notch diameters of 0.50 and 0.350-inch, respectively. These specimens were heat treated in an atmosphere of raw helium after turning on a lathe. For all three heats, effects on rupture life of omitting the 1550°F aging step were small and the relative position of rupture curves for notched and unnotched specimens was about the same for the three heats.

TABLE 2

SHORT-TIME TENSILE PROPERTIES AT 1350°F FOR THREE HEATS OF WASPALOY

	Heat 3-260		Heat 44,036		Heat 63,613	
	[a]Conv. H. T.	[b]No 1550° Age	Conv. H. T.	No 1550° Age	Conv. H. T.	No 1550° Age
0.2% Y. S. (psi)	112,500	118,000	91,400	91,000	95,000	90,200
Tensile Strength (psi)	135,000	135,000	115,000	102,000	117,000	106,200
Proportional Limit (psi)	92,000	85,000	67,500	77,000	75,000	73,000
Elongation (%/1.4 in.)	16.	16.	4.5	3.5	7.5	4.5
Reduction of Area (%)	17.5	16.	7.5	11.5	9.	9.

(a) 1975°F, 4 Hr., Air Cool + 1550°F, 4 Hr., Air Cool + 1400°F, 16 Hr., Air Cool

(b) 1975°F, 4 Hr., Air Cool + 1400°F, 16 Hr., Air Cool

TABLE 3.

RUPTURE DATA AT 1350°F FOR THREE HEATS OF WASPALOY

SMOOTH SPECIMENS

Stress (psi)	Heat 3-260 Rupt. Life (Hr.)	Heat 3-260 Red. of Area(%)	Heat 3-260 Elong. (%)	Heat 44,036 Rupt. Life (Hr.)	Heat 44,036 Red. of Area(%)	Heat 44,036 Elong. (%)	Heat 63,613 Rupt. Life (Hr.)	Heat 63,613 Red. of Area(%)	Heat 63,613 Elong. (%)
A. Conventional Heat Treatment (1975°F, 4 Hr., AC + 1550°F, 4 Hr., AC + 1400°F, 16 Hr., AC).									
100,000	2.32	11.	7.5	-	-	-	-	-	-
90,000	5.25	6.5	4.	-	-	-	-	-	-
80,000	21.7	9.	5.5	1.23	8.5	3.	2.48	6.5	3.5
70,000	36.6	7.5	3.	5.35	7.	2.5	7.0	7.	3.
60,000	155.4	6.5	4.	42.9	5.5	3.5	11.4	6.5	2.5
50,000	-	-	-	108.5	3.	3.5	189.9	4.5	1.5
40,000	-	-	-	820.95	5.	4.	550.8	4.	4.
B. 1550°F Aging Step Omitted (1975°F, 4 Hr., AC + 1400°F, 16 Hr., AC).									
100,000	1.28	8.	2.	-	-	-	-	-	-
90,000	2.75	8.5	3.	-	-	-	-	-	-
80,000	16.1	5.5	3.5	0.55	-	-	3.15	11.	2.5
70,000	46.4	6.	5.5	4.0 (±0.2)	10.5	2.5	7.0	8.	3.
60,000	49.1	6.5	3.5	25.05	8.5	2.	11.3	6.5	3.
50,000	-	-	-	41.9	1.5	1.5	142.5	4.	3.
40,000	-	-	-	865.6	5.	4.5	634.5	7.	4.5

TABLE 3. (continued)

[a]NOTCHED SPECIMENS

Stress (psi)	Heat 3-260		Heat 44,036		Heat 63,615	
	Conv. H. T.	No. 1550° Age	Conv. H. T.	No 1550° Age	Conv. H. T.	No. 1550° Age
	(Rupture Lives - Hours)					
70,000	1.0	--	--	--	--	--
60,000	--	2.6	--	--	--	--
55,000	11.3	--	--	--	--	--
50,000	--	2.2	0.45	--	0.6	1.5
45,000	9.0	--	--	--	--	--
40,000	--	[b]1038+	1.2	1.3	1.25	29.6
35,000	--	--	--	2.6	--	1477.8
32,500	--	--	[b]853+	--	[b]894+	--
30,000	--	--	--	[b]1320+	--	--

(a) Notch geometry: Shank diameter, D = 0.500 inch
Diameter at notch, d = 0.350 inch
Notch root radius, r = 0.004 inch
Notch Angle, 60°

Heat treated in raw helium atmosphere after notch machined on lathe.

(b) In progress.

Preliminary Studies With Flat Specimens

The extension of the contract for this investigation calls for tests on flat specimens notched on the edges to develop biaxial stressing. Studies are planned to include the same two values of theoretical stress concentration to be used in further tests on cylindrical test bars.

As is explained in Reference 1, calculation of actual stress levels in notched specimens is uncertain for notches with extremely-small root radii. For this reason, future notch tests on round specimens are to use a root radius of either 0.020 or 0.080 inch. The corresponding theoretical stress concentration factors (K_t) are, respectively, about 3.1 and 1.85 when the shank diameter is 0.600 inch and the notch cross section half that of the shank.

Design of suitable flat specimens with these theoretical stress concentration factors involves compromise among several often-conflicting factors:

(1) In the interest of uniformity of material, it is highly desirable that all types of specimens come from the same heats of metal and that all specimen blanks have a common history prior to machining or heat treatment. In particular, it is possible that differences in fabrication of sheet and round stock would cause variable response to later treatments.

Machining of flat specimens from round stock would eliminate many difficulties often encountered with gripping and alignment of strip specimens.

(2) For biaxial stressing, specimen thickness should be small in comparison to its width: a width/thickness ratio of 4/1 is considered to be about the minimum acceptable value, with 8/1 preferred. For the 3/4-inch diameter round stock on hand for this program, the resulting flat specimen must be quite thin. However, a thickness less than about 0.100-inch appears impractical to machine.

(3) Tooling would be simplified if the same two root radii were used for both round and flat specimens.

(4) It might be desirable from the standpoint of later interpretations if the notched cross section cover the same fraction of the shank area in both round and flat notched bars.

Starting with 3/4-inch diameter round stock, a flat 0.100-inch thick and 0.740-inch wide can be obtained. The most critical remaining dimension is the width at the notch. A change to a shallow notch would permit somewhat greater width/thickness ratio, but the resultant localization of the stress concentration makes the shallow notch more prone to variability from minor deviations in specimen geometry and makes analysis of stress changes more critical. Using the borderline width/thickness ratio of 4/1, a 0.031-inch root radius is required for $K_t = 3.1$, and 0.098-inch for $K_t = 1.85$. The convenience of only two root radii will be sacrificed for the other considerations involved, and the above dimensions adopted as "standard" for the present series of tests.

Before the specifications for flat notched specimens had been settled, a few specimens with varying geometry were prepared while machining techniques for flat bars were being perfected. Test results obtained to date with these specimens are listed in Table 4.

TABLE 4

RUPTURE PROPERTIES AT 1350°F FROM PRELIMINARY TESTS ON FLAT SPECIMENS

Spec. No.	Alloy	Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (inches) W	w	t	r	K_t	How Notch was Finished
				SMOOTH SPECIMENS					
FS-S(B)27	S-816	40,000	83.5	0.400	--	0.100	--	--	
FS-X562	Inconel X550	65,000	19.2	0.400	--	0.100	--	--	
				NOTCHED SPECIMENS					
FN-S92	S-816	45,000	40.7	0.730	0.470	0.125	0.005	7.2	Shaped
FN-S91	S-816	40,000	119.3	0.730	0.470	0.125	0.005	7.2	Shaped
FN-S93	S-816	42,000	110.6	0.730	0.470	0.125	0.060	2.45	Shaped
FN-S94	S-816	50,000	37.9	0.620	0.310	0.100	0.025	3.1	Ground, lapped
FN-X560	Inconel X550	61,400	9.2	0.620	0.310	0.100	0.025	3.1	Ground, lapped
FN-X561	Inconel X550	50,000	32.5	0.620	0.310	0.100	0.025	3.1	Ground, lapped

(a) W = Width of unnotched gauge length
w = Minimum width (at notch)
t = Thickness of bar
r = Notch root radius
K_t = Theoretical stress concentration factor (in axial direction).

DISCUSSION OF TEST RESULTS

Properties of Three Heats of Waspaloy

The several plots of Figure 1 show little effect on creep properties when the intermediate (1550°F) aging step is omitted from the conventional heat treatment. Where differences are found, the conventional heat treatment results in the higher creep for any given stress level. For the same stress levels, and with conventional heat treatment, heat 44,036 showed more creep than heat 63,613 at 80,000 and 70,000 psi (Fig. 1(B) and 1(C)), but the reverse was noted at 60,000 and 40,000 psi (Fig. 1(E) and 1(D)). Possible tendency for a more prominent primary creep stage was noted for heat 63,613 compared with heat 44,036.

Comparative creep properties for the three Waspaloy heats are more easily visualized from Figures 4 through 6, where the creep rates are shown as a function of stress level. Besides the minimum creep rate, initial creep rate and creep rates at different percentages of the rupture life are shown by separate curves on these figures.

The 1550°F aging step had no apparent effect on the creep rate for heat 3-260 at any portion of the tests, from initial loading until rupture (Fig. 4A). For the other two heats, omitting the intermediate age had no effect early in the test, but near the end of life a slower creep rate resulted at high stress levels (Fig. 4, B and C). Even in this case, variation in creep rates for the two heat treatments is probably too small to have recognizable effects on results calculated by the analysis proposed in Reference 1.

Comparison of Figures 5 and 6 shows that the minimum creep rate for heat 3-260 occurred rather early (from 5 to 15 percent of the life) and that the creep rate after about 50 percent of the life exceeded the initial rate. For both air-melted heats, the minimum rate occurred somewhat later (12 to 25 percent of life expired) and the creep rate remained below the initial rate until very near rupture.

The consistently-higher tensile and rupture strengths exhibited by the vacuum-melted material may be due to higher titanium content but may be at least partly the result of different prior history. Heat 3-260 was rolled to final size directly from a 10-pound ingot, whereas, the other materials were from large commercial heats and had been submitted to a rolling and annealing schedule before final rolling at the University of Michigan.

The magnitude of effect to be expected from this difference in prior history is hard to estimate, but one producer of Waspaloy has stated in a private communication that he has observed occasional changes in notch behavior when material from a given heat was rerolled to another size of bar stock.

It should be noted that the notch used in the tests to date on these three heats of Waspaloy gave a high stress concentration factor (7.2), so that localized plastic deformation should be expected near the notch root in all cases. Future tests will use a notch with more moderate stress concentration factor. The fact remains that the lack of marked change in notch rupture strength with omission of the 1550°F aging step agrees perfectly with the corresponding lack of differences in any other property measured for the two heat treatments involved.

A short length of the 1-3/4 inch diameter bar stock of heat 63,613, supplied by the manufacturer, is still on hand. It is possible that specimen blanks cut from this "as received" material may exhibit an effect of the intermediate aging step on its notched-bar behavior. If such an effect is found, smooth bars in this same condition can be examined for corresponding differences in other test properties.

Preliminary Results for Flat Specimens

The 83.5-hour rupture life at 40,000 psi for the flat strip specimen of S-816 compares with about 80 hours for round specimens (See Fig. 1, Ref. 1), while Fig. 6 of the same reference gives a life of about 13 hours for Inconel X-550 at 65,000 psi, compared with the 19.2 hours found for the flat strip of this alloy. Deviations in rupture life between round and flat unnotched specimens for the two tests are within normal scatter. Unless conflicting findings arise in two remaining tests in progress, it appears that the curves already established from round specimens can be applied directly to unnotched flats. This result should be expected for conditions where surfaces deterioration during testing is slight, as is the case at 1350°F for the superalloys under study.

Data on flat notched specimens are too sparse for general conclusions. The S-816 was still strengthened, but to a smaller extent than for round specimens. Three flat bars notched on the shaper showed only a few thousand psi higher strength than for smooth specimens, which result may reflect the probable high degree of cold working in this method of finishing.

Results for the two completed tests on flat notches of Inconel X-550 fell near those reported by Carlson, et al (Ref. 2) in their Figure 5 for round bars with ground notches having a like stress concentration factor (0.020-inch root radius).

FUTURE WORK

During the coming quarter, experimental work is to continue with the limited remaining stocks of the original three alloys in efforts to clear up effects of machining methods, rupture strength of flat versus round notched specimens, and differences between the three Waspaloy heats with and without an intermediate aging step in the heat treatment.

Major emphasis, however, will be devoted to getting extensive test results for the "17-22-A"(S) alloy at 1100°F so that the analysis developed for the original three alloys may be checked for validity with this different type of material.

Once rupture curves for flat notched specimens have been firmly established for any of the metals under study, experimental results will be used to test the applicability of the analysis proposed in earlier work for round notched bars.

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2. Carlson, R. L., MacDonald, R. J., and Simmons, W. F. Investigation on Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperature, (Rupture Strength of Notched Bars at High Temperatures). WADC TR 54-391, October 1954.

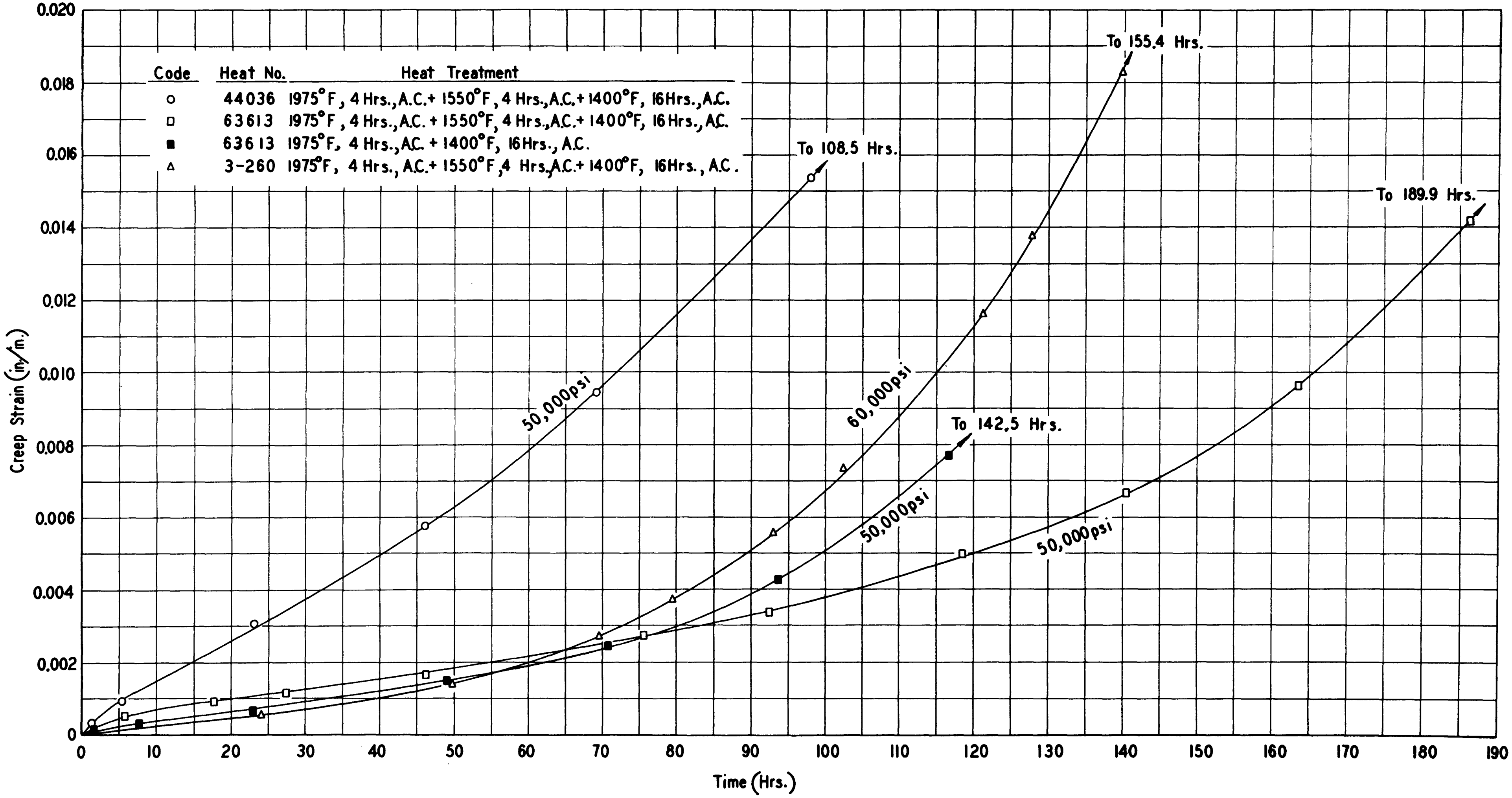

FIG. 1 (A)— CREEP CURVES AT 1350°F FOR SPECIMENS FROM THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

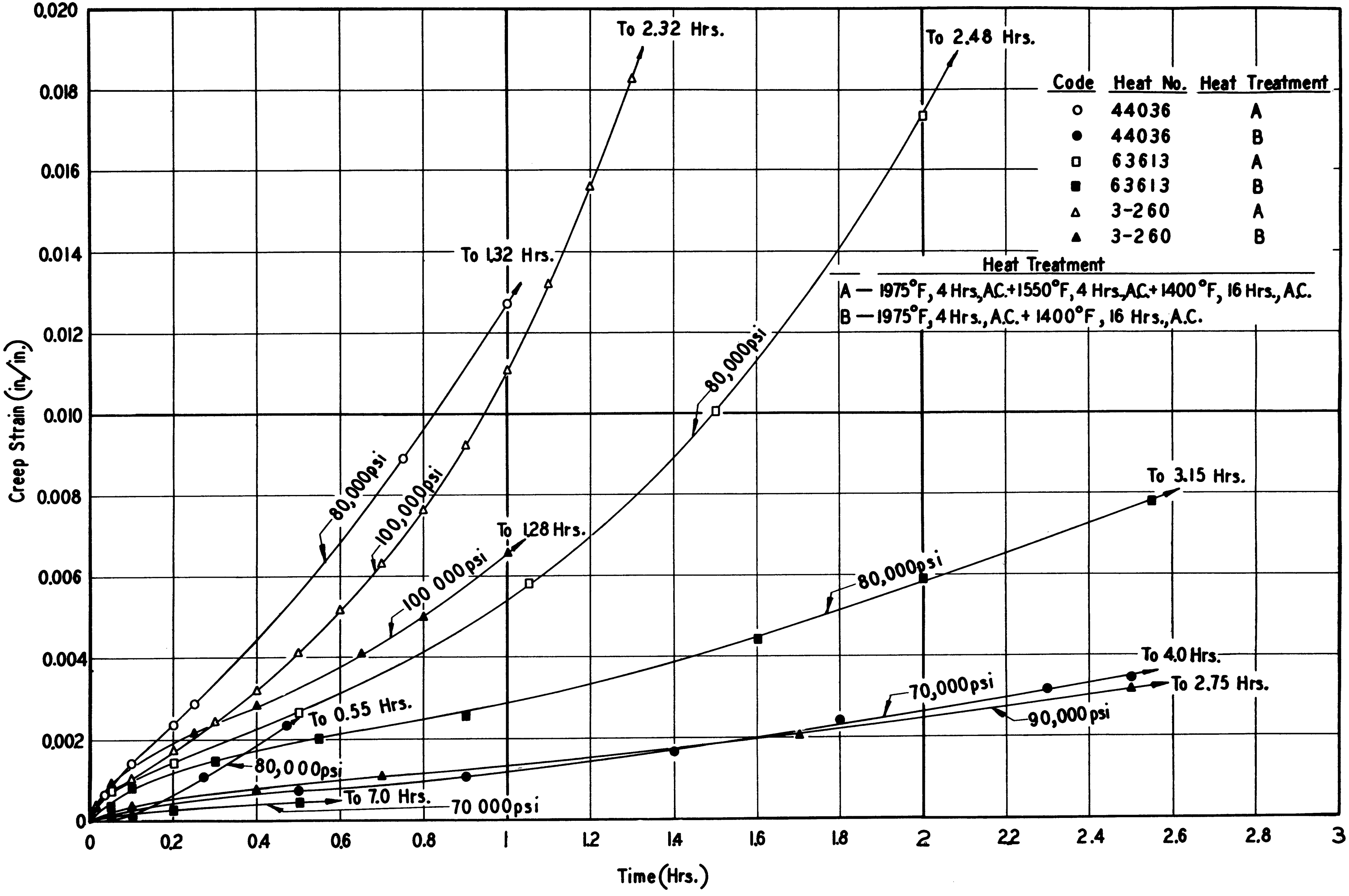

FIG. 1(B) — CREEP CURVES AT 1350°F FOR SPECIMENS FROM THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

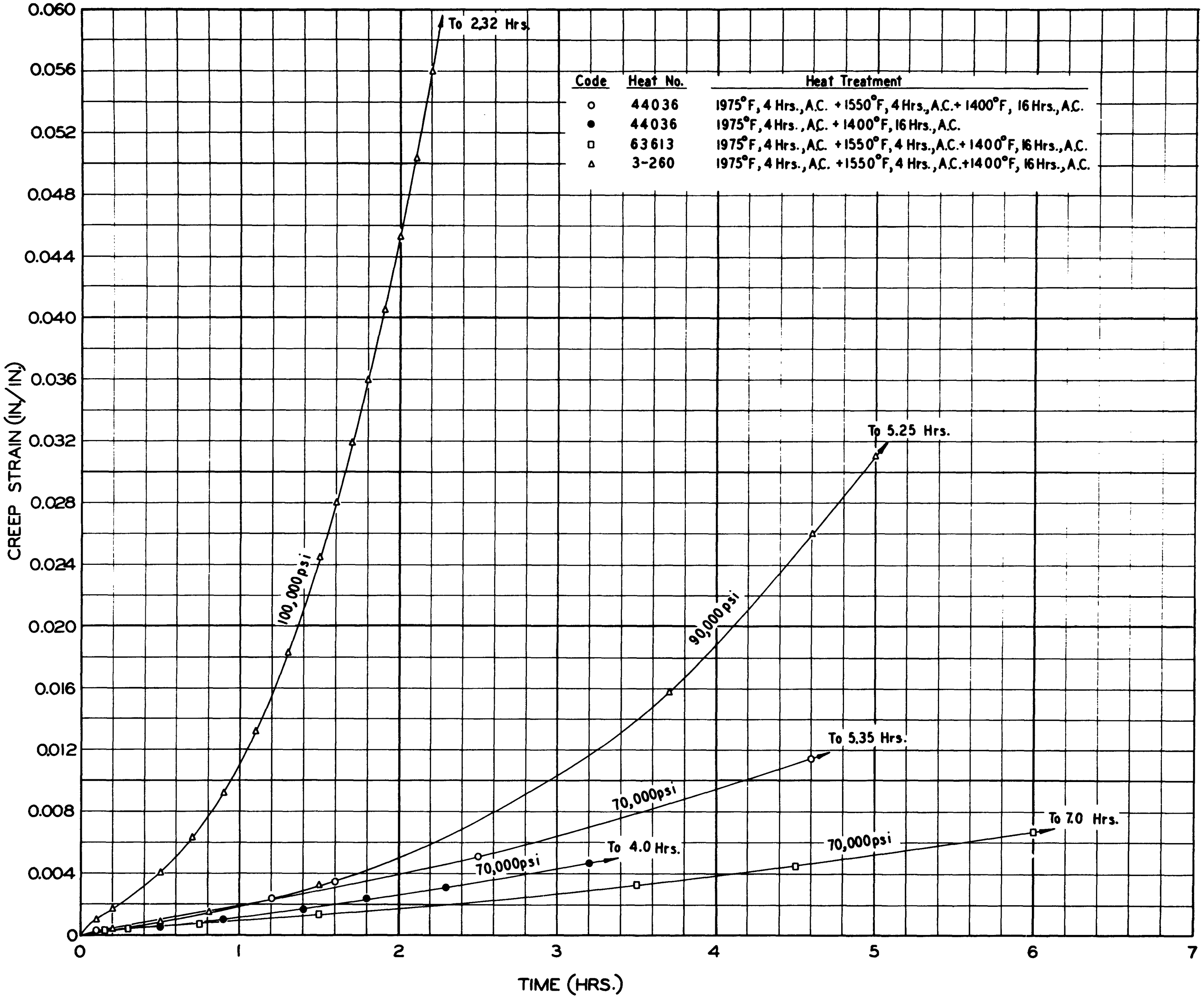

FIG. 1(C) - CREEP CURVES AT 1350°F FOR SPECIMENS FROM THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

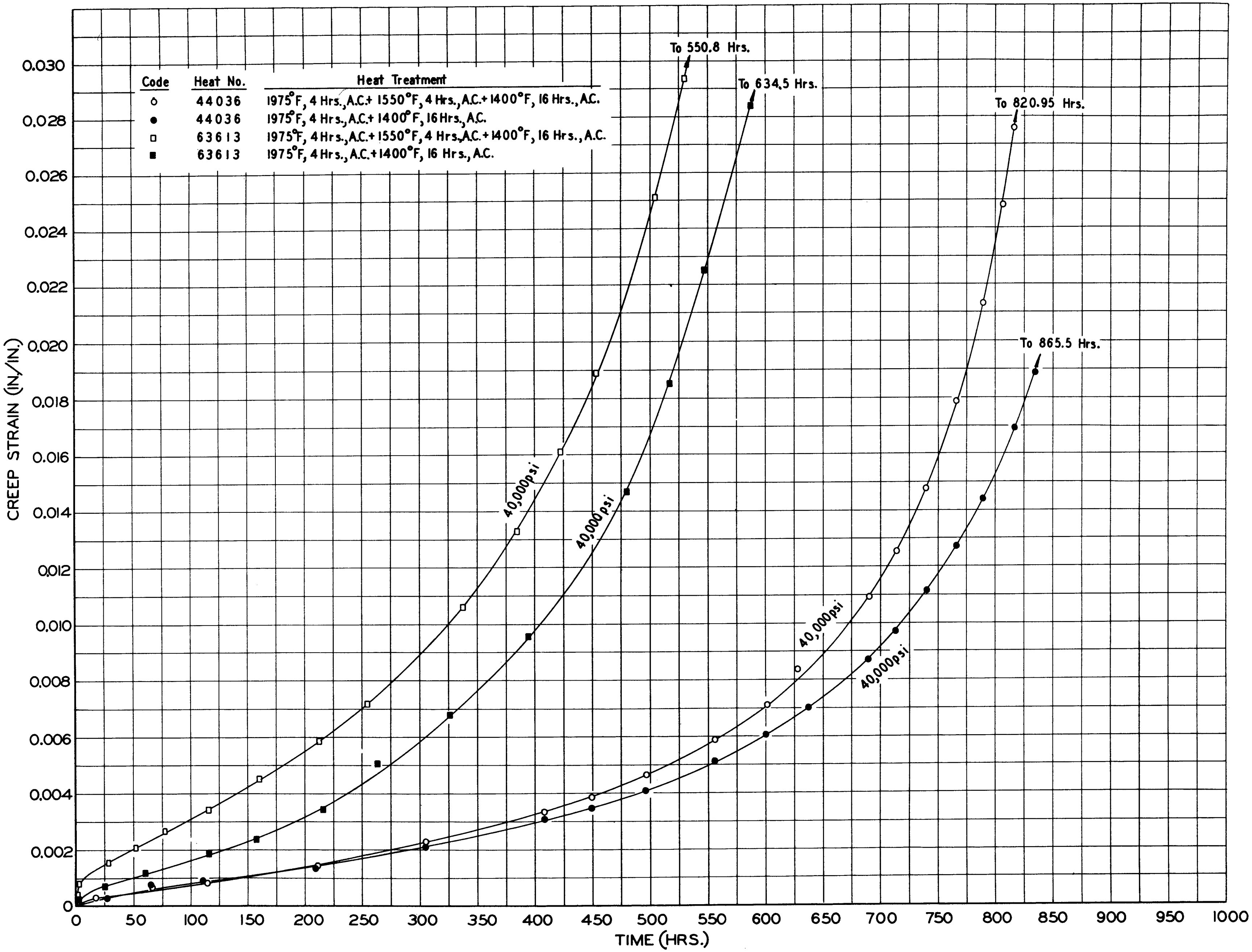

FIG. 1(D)— CREEP CURVES AT 1350°F FOR SPECIMENS FROM THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

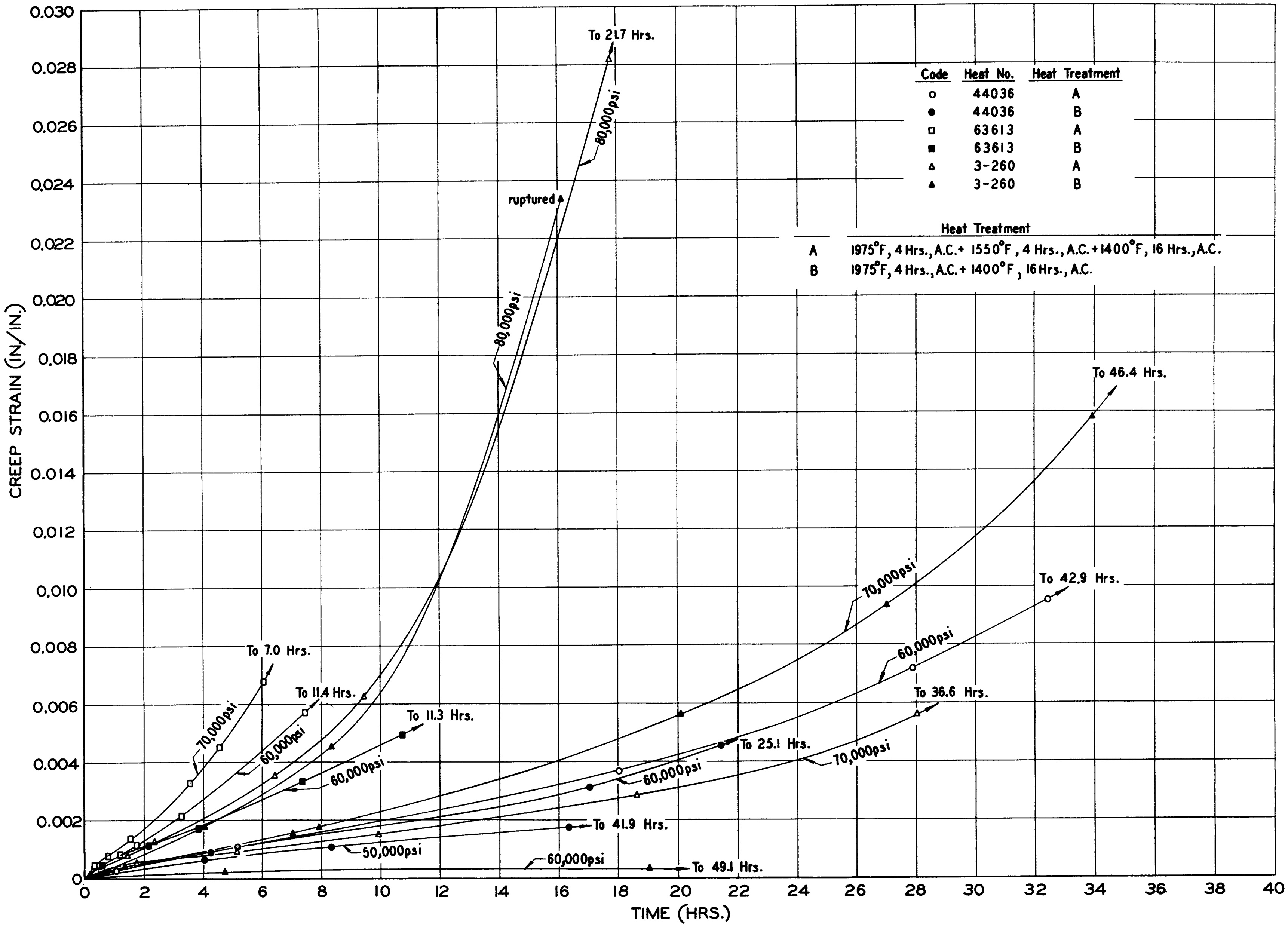

FIG. 1(E)—CREEP CURVES AT 1350°F FOR SPECIMENS FROM THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

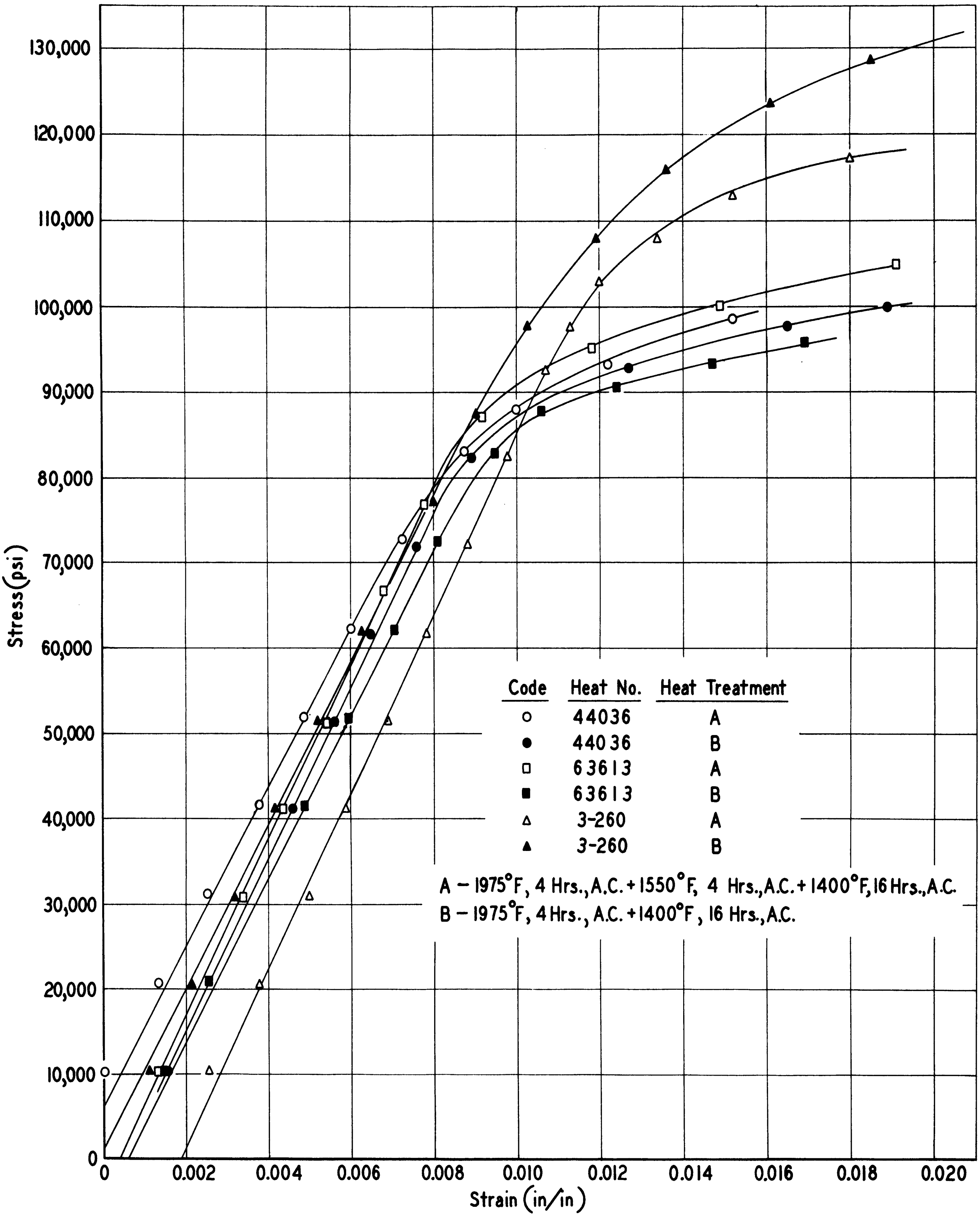

FIG. 2 – INITIAL PORTION OF STRESS–STRAIN CURVES AT 1350°F FOR THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

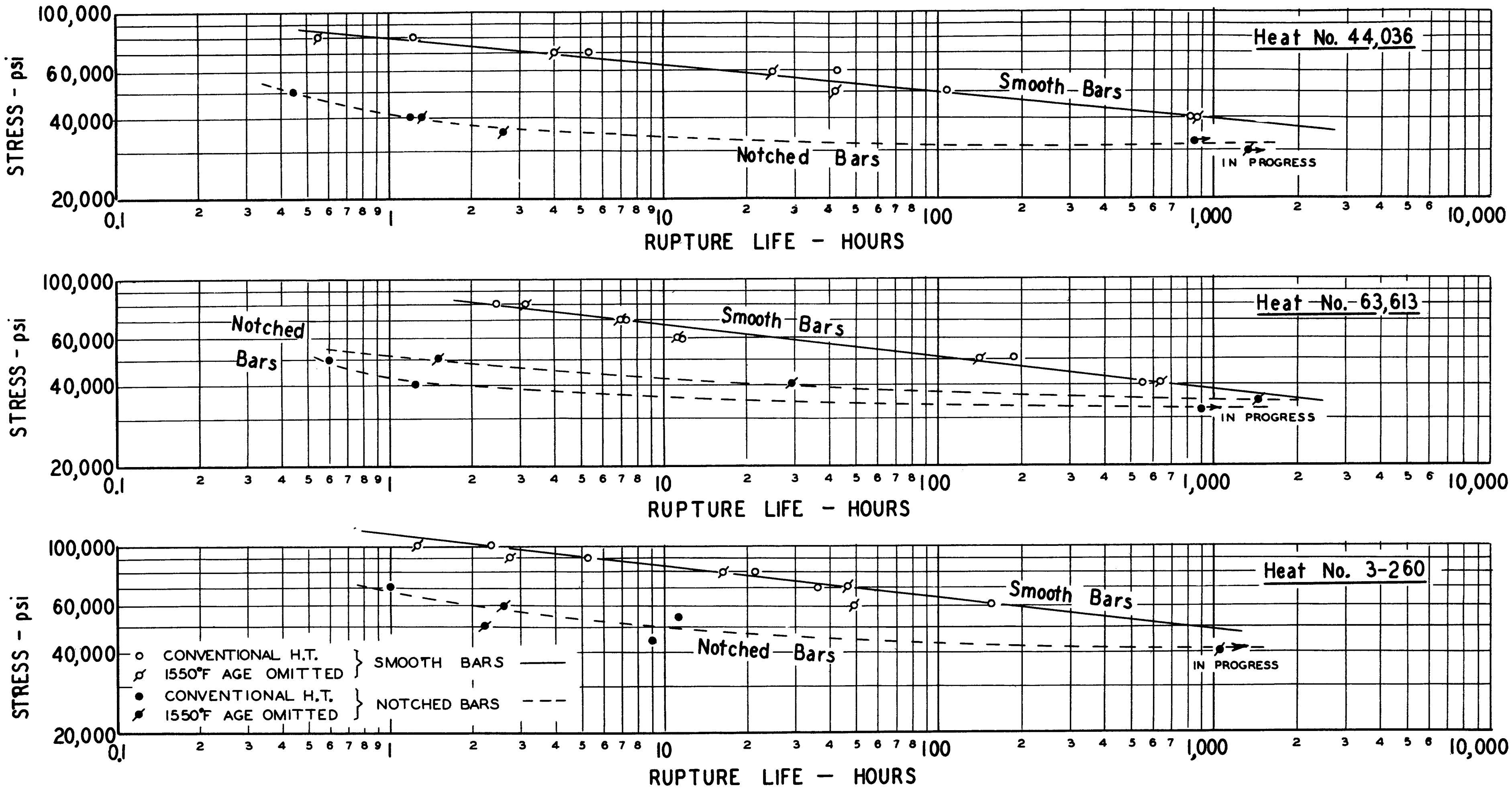

FIG.3 – STRESS VERSUS RUPTURE LIFE AT 1350°F FOR SMOOTH CYLINDRICAL SPECIMENS AND SPECIMENS WITH A CIRCUMFERENTIAL NOTCH FOR THREE HEATS OF WASPALOY.

Notch Geometry: D = 0.500 d = 0.350 r = 0.004 inch

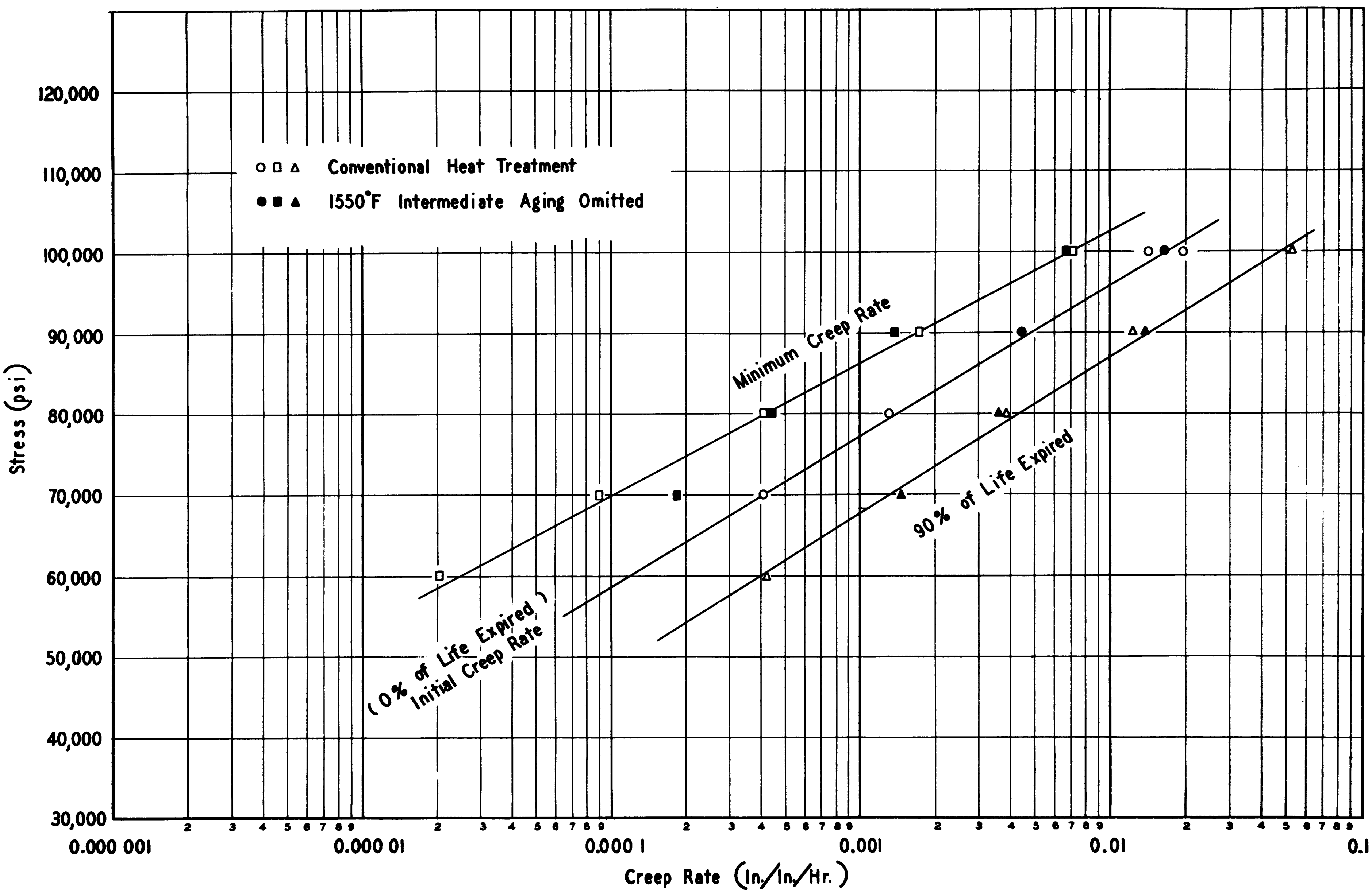

FIG. 4(A) — EFFECT OF INTERMEDIATE (1550°F) AGING TREATMENT ON CREEP RATE AT 1350°F OF WASPALOY (HEAT NO. 3-260)

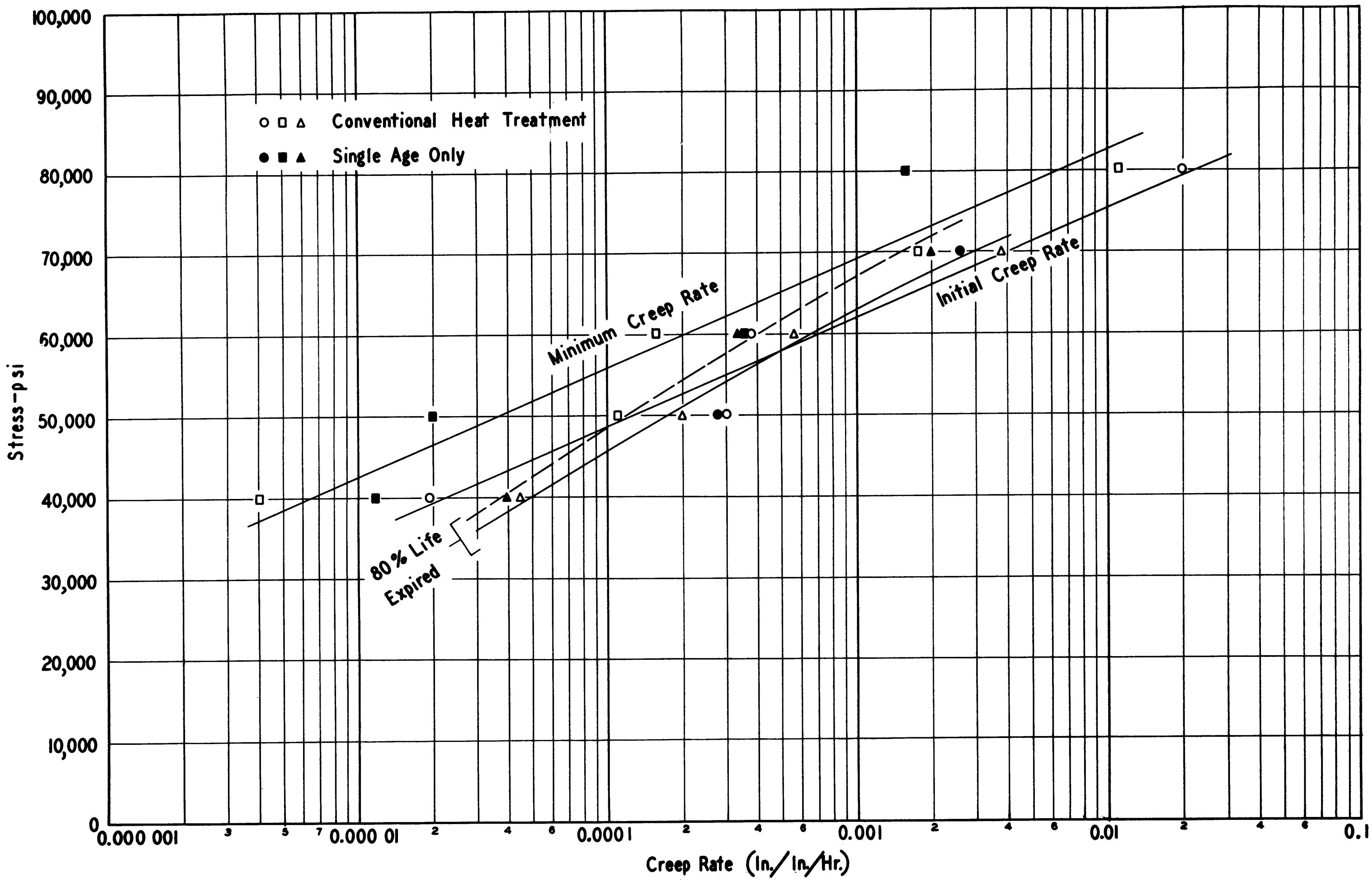

FIG. 4(B)— EFFECT OF INTERMEDIATE (1550°F) AGING TREATMENT ON CREEP RATE AT 1350°F OF WASPALOY (HEAT NO. 44036)

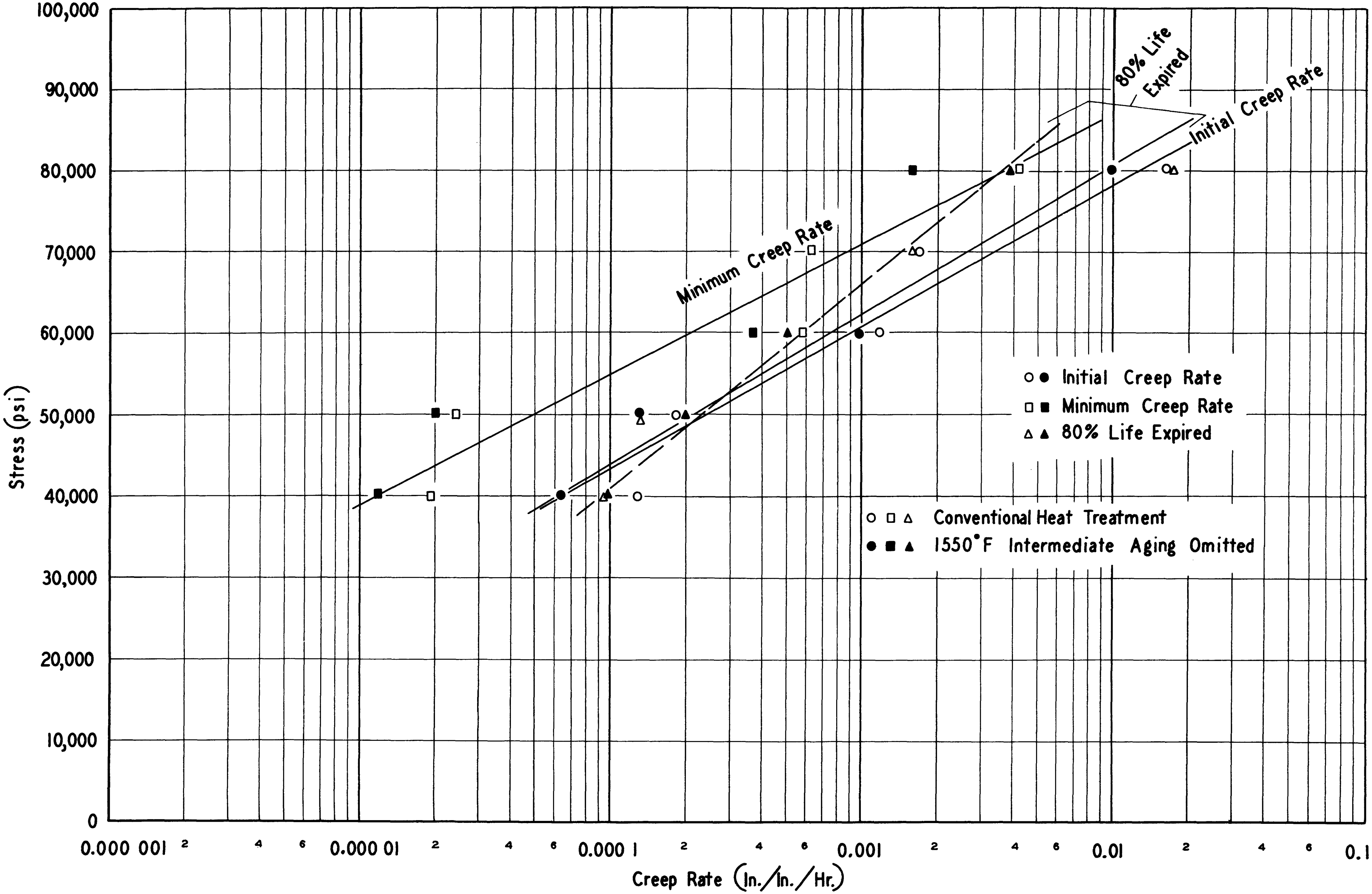

FIG. 4(C) — EFFECT OF INTERMEDIATE (1550°F) AGING TREATMENT ON CREEP RATE AT 1350°F OF WASPALOY (HEAT NO. 63613)

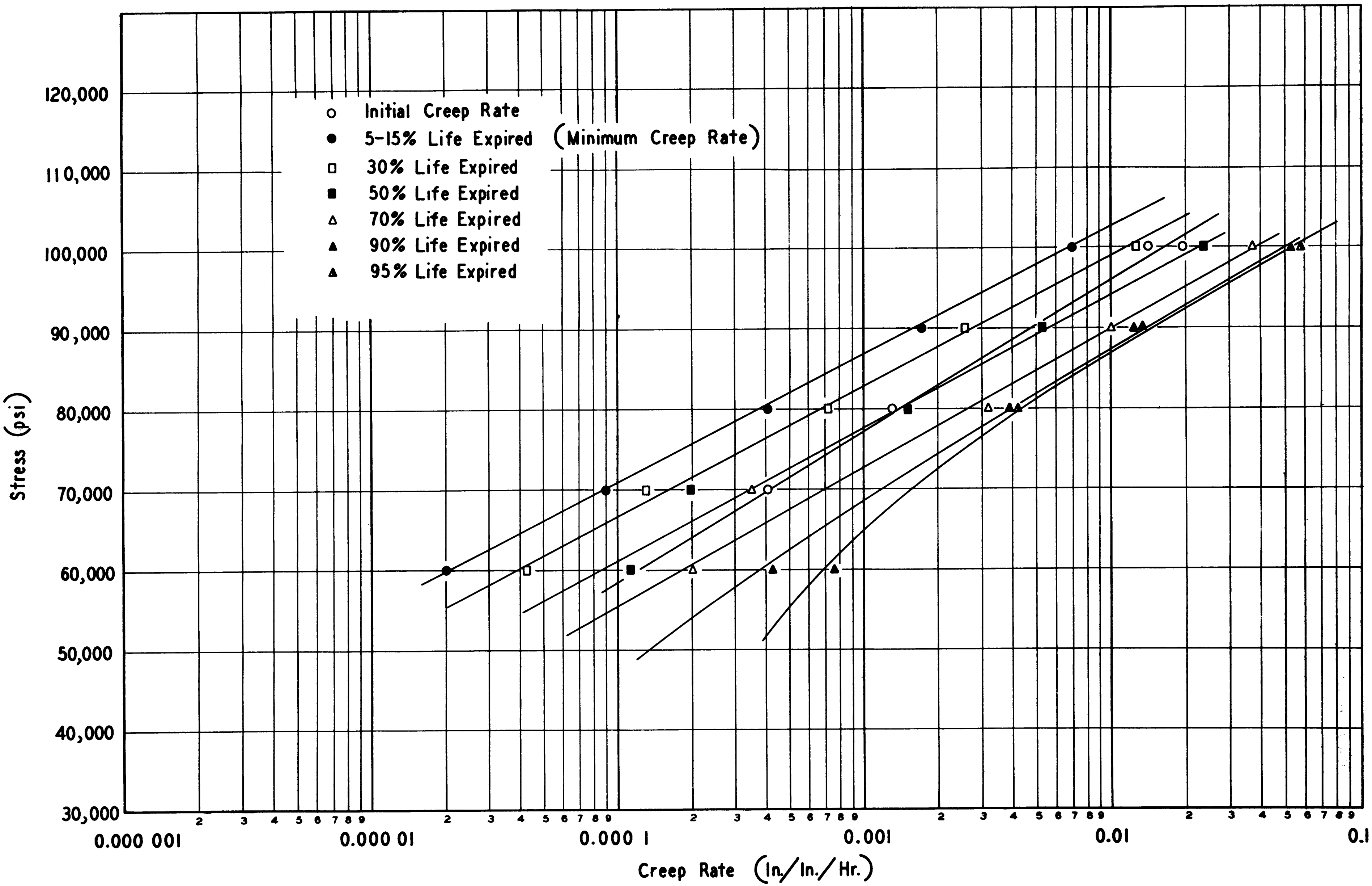

FIG. 5 — STRESS VERSUS CREEP RATE AT 1350°F FOR VACUUM-MELTED WASPALOY HEAT NO. 3-260 WITH CONVENTIONAL HEAT TREATMENT

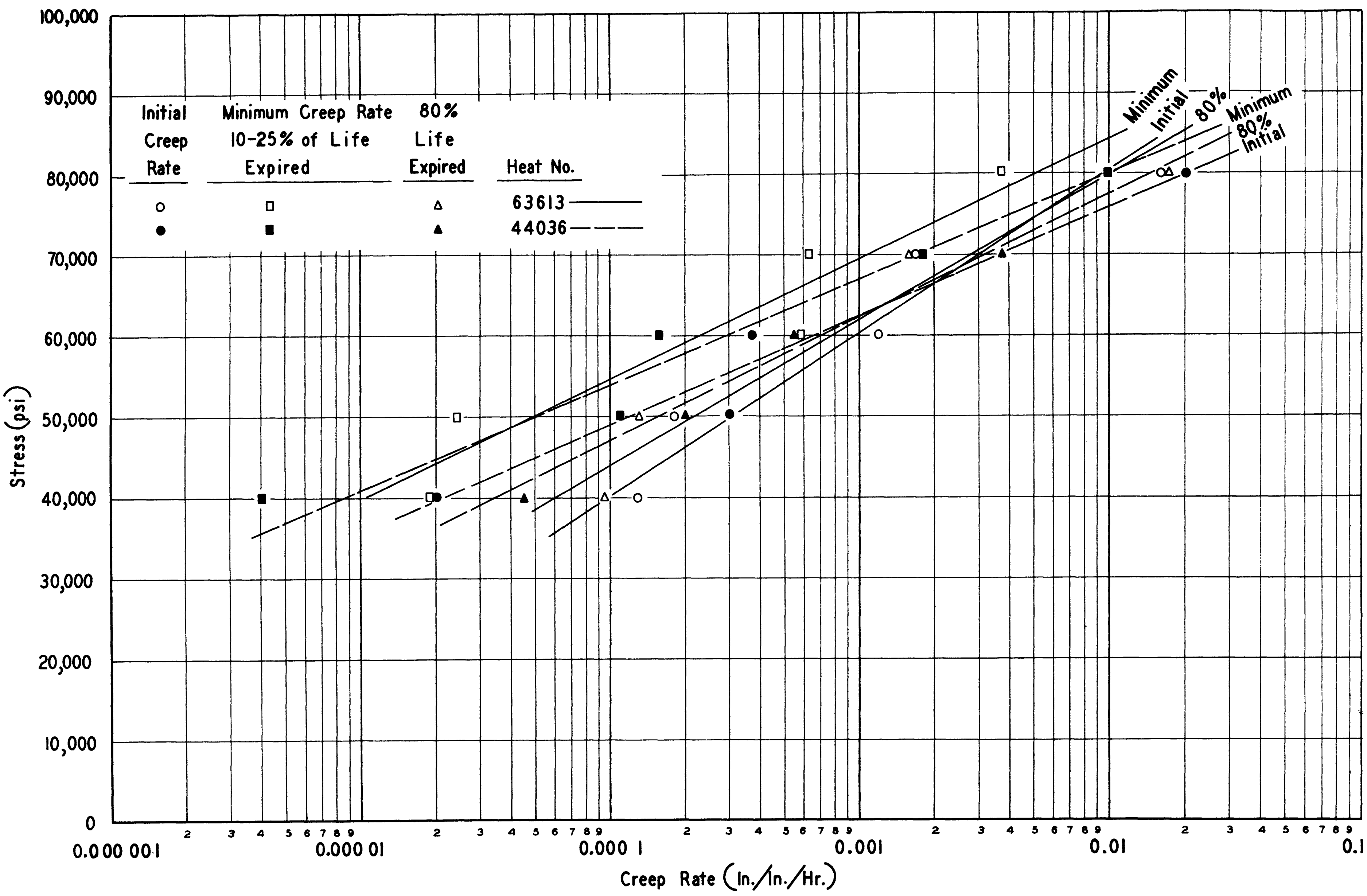

FIG. 6 — STRESS VERSUS CREEP RATE AT 1350°F FOR TWO AIR MELTED HEATS OF WASPALOY WITH CONVENTIONAL HEAT TREATMENT