Engineering Research Institute
University of Michigan
Ann Arbor

SECOND PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF HEAT RESISTANT ALLOYS AT ELEVATED TEMPERATURES

By

H. R. Voorhees

J. W. Freeman

Project 2024

Air Force Contract No. AF 18(600)-62
Expenditure Order No. R-605-227 SR-3a

December 15, 1952

SUMMARY

This investigation, under contract number AF 18(600)-62, Expenditure Order No. R-605-227 SR-3a, is a study of the significance of notched-bar rupture tests of alloys for high temperature service, and seeks a method of predicting notched-bar behavior from properties obtainable with conventional smooth bars. Assuming rupture life of a fiber of metal is a unique function of the stress-strain-temperature-time history, the history of representative fibers in a notched bar are to be followed and rupture life compared with other fibers in a smooth bar subject to a like history.

A series of tests on relaxation properties of S-816 at 1350°F has been conducted. The results indicate that for bars allowed to relax immediately upon loading the residual stress after 1000 hours should be less than 5,000 psi for all initial stresses between 20,000 and 55,000 psi. Tests started at high stresses show a very rapid fall in stress so that the curves of residual stress as a function of relaxation time cross over those for lower initial stresses. Prior creep before the relaxation process accelerates this initial drop from high stresses. On the other hand, an initial period of creep slows down the rate of relaxation in tests which have initial stresses of 20,000 to 30,000 psi.

It is proposed to extend these studies to include the effect of initial strain added rapidly rather than by a slow creep process.

Comparison of results of single-stress and multiple-stress tests indicates that for S-816 at 1350°F the portion of life expended by being subject to a given stress for a certain period of time is nearly equal to the ratio: $\frac{\text{actual time at the stress}}{\text{rupture life at that stress}}$.

A memorandum was received from another laboratory on variation in notch sensitivity of 16-25-6 alloy wheel rims for a limited range of heat treating and forming conditions. Analysis of these results indicates that this alloy is not made notch sensitive by moderate changes from recommended practice, but that a critical combination of such changes may seriously lower notch and unnotched strength alike.

Further work on metallurgical variables is initially to be centered on attempts to make Waspaloy notch brittle with conventional heat treatment, but with prior cold rolling to a critical degree.

INTRODUCTION

The general purpose of this investigation, as stated in the First Progress Report, (1) of August 15, 1952, is to accumulate and analyze data on the significance of notched-bar rupture tests of alloys for high-temperature service. Experimental work at the University of Michigan is to consist of tests designed to study the role of stress relaxation by creep and the role of metallurgical variables in notched-bar rupture tests. It has been emphasized that these studies are aimed at establishment of fundamental principles, preferably of a quantitative nature.

When available data for alloys and temperatures of interest were assembled and examined, two qualitative results appeared:

(1) For fixed nominal stress, determined as the applied load divided by the area at the minimum original cross section, the life until rupture of notched bars becomes shorter as the notches are made sharper.

(2) With a fixed notch geometry, sensitivity to notch effects seems to be related to ductility of the conventional smooth bar, but no

---

(1) References are listed at the end of the text, page 19, under "Bibliography".

one minimum value of elongation marks onset of notch weakening for different alloys or for different prior heat treatments of the same alloy.

It is sought to explain this behavior as one specific case of the general problem of complex stresses which vary during life of the structure.

A basic postulate put forth in the First Progress Report was that the rupture life of a given fiber of metal should be a unique function of its stress-strain-temperature-time history, no matter how that history came about. It was proposed to follow the history for representative fibers in a notched bar and to compare rupture life with other fibers in smooth bars subjected to a like history. Rupture of any one fiber is taken as the onset of general failure of the entire structure.

Relaxation of Stresses

It is a rather familiar experience when operating high-temperature equipment that bolts originally pulled up tight show a gradual decrease in stress or "relaxation". This decrease of stress occurs as the original elastic strain is replaced by plastic strain (creep). Relaxation characteristics are commonly plotted as a smooth curve of remaining stress versus time for a given initial stress and for continuous reduction of load so as to maintain the total strain constant. In practice the stress reduction is often performed in finite steps (see figure 1). The specimen is loaded to its highest value (S_1 at point A) and the strain measured. Creep is allowed to occur (A-B) until such time that removal of a weight will return the specimen to its original length (Point C) but at a lower stress (S_2). When a large number of small equal weights are used the resulting step-wise curve of remaining stress versus elapsed time approaches the theoretical smooth curve.

There is, however, a practical limit of weight increment below which it is not advisable to go. Accuracy is greatly reduced if the length of time for a relaxation step to occur is of the same order as that for unavoidable small temperature cycles obtained when using conventional controllers or if the strain decrement upon removal of a load is not considerably larger than the sensitivity of the extensometer system used. For instance, a change of temperature of 1°F results in a change in length of approximately 10×10^{-6} in/in which is some two to three times the sensitivity of the extensometer system being used.

For the purpose in hand, the step-wise relaxation tests has the advantage of giving creep curves for material which has been subjected to a strain history of the type expected in a fiber of the notch bar.

After a notched specimen has been loaded in tension and the inital state determined, it appears reasonable to expect a tendency for any high component of stress in some direction to drop as relaxation proceeds. Since high stresses show a greater percentage decrease in a certain time than do lower stresses, the differences between principal stresses might be expected to fall even faster. This raises the question of why some test evidence of others should indicate notch sensitivity in even quite ductile materials when the notch is made sharp enough. In such cases it seems that the relaxation process has not been able to act rapidly enough to reduce the acting stresses before critical fibers have failed.

One reasonable explanation is that perhaps the work hardening on loading has reduced the relaxation rate severely. A second possibility is that the initial load may have brought some fibers to the point of incipient failure due to severe local straining. In any case the effect of prior straining on relaxation properties appears of major interest in experimental work.

Any marked alteration in relaxation properties resulting from metallurgical changes are particularly sought. In both smooth and notched bars similar direct effects on strength and ductility should be found. Indirect effects on relaxation properties should be a function of the stress complexity and of the variation of stress intensity from point to point. An ultimate aim is to learn what effects of metallurgical changes actually bring about notch sensitivity.

CURRENT STATUS OF THE INVESTIGATION

The status of work in progress may be summarized as follows:

1. Compilation of Data; Metallurgical Variables:

During the past quarter a memorandum received from the Thomson Laboratory of the General Electric Company (2) gave data on notch sensitivity of specimens taken from a number of 16-25-6 alloy wheel rims with a limited range of heat treatments and forming conditions. These data which are presented in the following section give no definite indication of a general treatment which gives notch sensitivity. Work originally proposed to investigate metallurgical effects on notch embrittlement of 16-25-6 alloy was held back pending re-evaluation of this phase of the program to insure results of value and to prevent duplication of tests performed satisfactorily elsewhere.

2. Experimental Work on Relaxation Effects:

Tests to date have all been with S-816 at 1350°F.

Thirteen relaxation tests have been completed over a range of stresses from 0.6 to 1.5 times that at the proportional limit and over a range of prior creep strain.

Complete creep curves were run to rupture on four smooth bars. Three multiple-stress creep-rupture tests (step-up; step-down; step-up and then step down) were performed to determine a method of adding portions of life at different stress levels. These curves are all presented in this report.

A further test involved measurement of creep and rupture properties of a smooth bar relaxed from 50,000 psi initial stress to 25,000 psi and then maintained at the latter stress level for the balance of the run.

SUPPLEMENT TO DATA COMPILATION

Test results of the General Electric Company's Thomson Laboratory for 16-25-6 (2) have been re-plotted in figures 2 through 9. On these plots the small numbers inside or immediately adjacent a test point identify the rim from which the specimen was taken. For smooth bars the percent elongation at rupture is indicated by the larger number located on a line drawn to the point.

Specimens were from a number of turbine-wheel-rim forgings made by conventional hammer cold working and by the die-expansion process. Most specimens were sampled in the radial direction, with a few additional bars cut in the tangential direction from material located near the outer surface of the forging.

The circumferential notch used had a 60 degree included angle and 0.005-inch root radius. Full diameter was 0.177-inch; reduced diameter, 0.125-inch.

Data for smooth specimens and for notched specimens from all the conventional rims were separated in figure 2 to determine the range over which the values spread as a result of variation from test to test and rim to rim. The range so obtained for smooth bars is shown on all remaining plots to give a standard of comparison.

In the original Thomson Laboratory report, individual rims were classed as either notch brittle or notch ductile after comparison of lives for corresponding smooth and notched bars taken from that rim. However, when the separate data for the two classes are plotted, as in figure 3, it appears that data for all conventional rims cover the same spread of values. Further, no correlation is evident between notch brittleness and the elongation at rupture of smooth bars.

At 1350°F the two notch brittle rims showed 8 and 12 percent elongations as against the slightly higher values of 11 and 15 percent for the notch ductile rims. At 1200°F, however, if the one exceptional elongation of 29 percent be overlooked, the range of elongation for the four notch brittle rims (10 - 19 percent) is actually higher than the range for the eight remaining notch-ductile rims (6 - 15 percent).

Results for die-expanded rims, presented in figure 4, exhibit a somewhat greater scatter than did those for conventional rims. It is noted that a few of the die-expanded rims give low values of rupture life but no really significant deviation from conventional rims is found for either smooth or notched specimens at either 1200° or 1350°F. Comparing points for individual die-expanded rims, it is found that some are strengthened, some are weakened by a notch with 0.005-inch root radius.

For a wide range of ductilities (1.7 to 30 percent elongation at fracture), the limited number of specimens cut in the tangential direction from die-expanded rims had a consistently longer life until rupture than did those sampled in the radial direction for both smooth and notched bars and at both test temperatures. These tangential specimens are indicated on figure 4 by triangles.

A single rim forged by conventional hammer cold working was given a prior solution treatment at 2000°F instead of 2110°F. Figure 5 shows that life was on the high side of the range for all bars from this rim. Results are also shown for three die-expanded rims with 2000°F solution treatment. For tests run after aging at 1200°F for 10 hours, the specimens appear to be much weaker than with the 2100°F solution treatment alone and show severe notch effects for a single pair of tests at 1350°F from rim number 6.

Effect of aging for increasing lengths of time at 1200° and at 1300°F on specimens from die-expanded rims has been separated for prior solution temperatures of 2100° and 2000°F in figures 6 through 9.

In general, radial specimens appear to vary more with aging time than do bars cut in the tangential direction. The number of test points for each combination of variables is so few as to leave much doubt as to the exact shape of the curves sketched in these plots. There is, however, a general indication that after an initial strengthening, further aging gives first a decrease and then an increase in time to rupture. The combination of treatments previously noted to give embrittled specimens in figure 5 appears to be near the worst condition to be encountered over the range of variables investigated.

EXPERIMENTAL RESULTS OBTAINED WITH S-816 AT 1350°F

The behavior of S-816 at 1350°F in the short-time tensile test determined with a conventional tensile machine with a free head speed of 0.052-0.056 in/in/min. are presented in figure 10 along with data obtained from a typical loading curve for a stress-rupture time test. In both instances axial deformations were measured by a Martens-type optical extensometer with sensitivity of 3 to 4×10^{-6} in/in of strain.

The proportional limit appeared to be just below 35,000 psi, while the yield strength for the 0.2-percent offset was near 47,500 psi and the breaking strength based on final area was 111,000 psi or 74,000 psi based on original area. From all the data plotted for tests run, the average modulus of elasticity was between 24 and $25 \times 10^{+6}$ psi/in/in at 1350°F.

Step-down stress relaxation tests were conducted for a range of initial stress between a low of 20,000 psi and a high of 53,470 psi with the relaxation run started immediately upon loading. Figure 11 shows the results for this series of tests in which the inital plastic strain was only that which was unavoidable due to creep and/or yielding during the short period of loading (approximately 2-4 minutes). In this plot and in figure 12 a change of scale should be noted at the one-hour mark.

For all values of initial stress tested, any bar free to relax without extended prior creep is seen to have a residual stress of 25,000 psi or lower by the end of the first hour at test conditions.

In a notched bar the metal near the notch root is expected to strain as the specimen is loaded. This initial strain may be expected to affect the rate at which localized stress concentrations are relieved. Some preliminary tests have been completed to study the magnitude of changes in relaxation rate brought about by prior creep deformation. Figure 12 (A and B) shows findings to date. In these runs several specimens were loaded to the same initial stress and allowed to creep at this constant stress to different total plastic strains before the relaxation test was initiated.

For low initial stresses the rate of stress relaxation is found to be lowered by prior creep. For high stresses the effect of increasing amounts of creep is less pronounced, but the data seem to indicate that larger amounts of creep give faster initial relaxation than is found in specimens with a minimum of creep.

Four conventional constant-load rupture tests were run on smooth bars for tensile stresses of 35,000, 45,000, 55,000, and 65,000 psi. Results were then compared with those for three multiple-stress tests where one steady load was held for a while and then changed to another load for an additional period. Rupture data are summarized in Table I and in figure 13, while complete creep curves are shown in figure 14.

DISCUSSION

Metallurgical Variables

When the Thomson Laboratory data on 16-25-6 are compared as in figures 2 through 4, it appears that scatter in values between different rims exceeds any general trend of differences between rims formed by conventional hammer working and those formed by die expansion. The few lower values for die expanded rims can probably be attributed to a less standardized practice for this method.

With conventional hammer working, one rim (number 4) with high ductility (29 percent elongation) showed exceptional notch strengthening, but some of the specimens from rims which appeared to be notch brittle had higher elongation at rupture than did some of those from notch ductile rims. Thus, in figure 3, rims number 2 and 1 showed marked brittleness at 1200°F when a smooth specimen had 11 percent and 19 percent elongation, respectively. At the same temperature all notch ductile rims but one had elongations of 6-15 percent.

A combination of solution treatment at 2000°F followed by die expanding and then aging 10 hours at 1200°F gave very low values compared with conventional rims, particularly for the notched bars. In one case the elongation was as low as 4 percent but even rim number 5 with 10 percent elongation showed the same poor strength.

Effects of aging time are rather vague from the meager data of figures 6 to 9. The most noteworthy feature is that bars cut with their length in the tangential direction appear uniformly stronger than are radial bars. It appears that prolonged aging always gives the longest rupture life of both smooth and notched bars after a point of minimum strength for shorter aging times has been exceeded.

Viewed as a whole, the data on 16-25-6 obtained by General Electric confirm the belief expressed in the First Progress Report that commercial alloys now used as jet engine turbine components are not sensitive to notches when given recommended conventional treatments. Further, small variations in heat treatment or forming procedures should not in general drastically lower notch strength.

However, with a critical combination of deviations from conventional practice (as for the rims die expanded after 2000°F solution treat plus later aging for 10 hours at 1200°F) it is possible to get marked deterioration from desired properties. Opposite effects obtained with conventional rims with just the lower solution treatment, together with the few tests on effects of aging time, would seem to show that the aging conditions after forming are the most critical of several factors involved. But much further work is necessary before valid generalizations can be drawn.

Attention is also directed to an apparent anamoly in the results of tests on rims. Extensive experience at the University with bar stock has always shown 16-25-6 to have greatly reduced ductility to fracture in the rupture test at 1200°F as the solution treatment temperature was increased past 2000°F prior to cold working. For this reason the rather high ductility shown for the rims solution treated at 2100°F are difficult to understand. Some factor beyond that apparent in the data must have been present.

Past experimentation at the University of Michigan indicates that Waspaloy, and perhaps others of the alloys of interest in this program, can be caused to show extreme grain growth following critical rolling conditions. Such excessive growth of grains has often been reported to be associated with low ductility to fracture. Since such low ductility has been shown to occur in many cases of notch sensitivity at elevated temperatures, it appears in order to attempt to create this condition of large grains in specimens of the heat of Waspaloy under study and to investigate any changes in notch ductility which result. At the same time any alteration in relaxation characteristics may be studied and some generalized sought.

Relaxation Data

Most of the data then available on relaxation in high-temperature bolting materials were reported by Robinson in a 1948 report of an A. S. M. E.-A. S. T. M. Joint Committee (3). With a few exceptions these results were for tests run at stresses somewhat below the proportional limit.

At such relatively low stresses, the relaxation process is slow enough to permit accurate determination of the time when a weight should be removed in the step-down type of test. In the present investigation the highest stresses employed allowed less exact determination of the proper time for relieval, so that some weights were removed slightly early or late in the first steps where the elapsed time between reliefs was of the order of one minute. The small number of test points obtainable in the early stages made the usual saw-tooth plot of strain versus time on linear coordinates of questionable value since each step of the test had a creep curve of shallower slope than the one preceeding. A plot of strain versus log time (shown in figure 15 for a typical test) proved to be much easier of interpolation or extrapolation since portions of the curve are quite similar and change but gradually in shape as the elapsed time for a given amount of strain to occur becomes longer.

Then when a load was removed too early, as was the case in relieving the specimen shown from a stress of 11,260 to 7,380 psi, the proper time when the weight should be lifted can be closely determined. The corrected time intervals were used in plotting the resulting curves of residual stress as a function of time.

Most relaxation data in the past have been plotted as a family of curves showing rapid decrease of stress with time for high initial stress and more gradual decrease for low initial stresses, with all curves tending to become asymptotic one to another at very long times (4, 5). Moreover, it has been a common experience of workers in this field that bolts relax more slowly after re-tightening from the first relaxation period.

All curves of figure 11 (no extended prior creep) have narrowed to a maximum spread of about 3,000 psi after only 100 hours, and the specimens started at 20,000, 30,000, and 40,000 psi initial stress follow the expected trend. Turning to figure 12(A), it is seen that half a percent of creep prior to the start of relaxation from 20,000 psi or 2 percent prior creep before the start of relaxation from 30,000 psi sharply limits the rate of stress decrease.

Tests at higher stresses (roughly at or above the proportional limit) do not give at all the anticipated result. Starting with an initial stress above 50,000 psi, the residual stress has already dropped below that for the bar with 20,000 psi starting stress before one hour of relaxation time has elapsed. The 35,000 psi run with prior creep drops faster than does the corresponding run where relaxation was started immediately upon loading.

In a matter of 5 hours the curves re-cross so that at long times prior strain does give the higher residual stress.

Relaxation curves for four specimens all starting at 40,000 psi stress are plotted in figure 12 (B) for initial creep strains between 0.03 and 1.24 percent. The closeness of the curves one to another may make conclusions uncertain, but it again appears that above the proportional limit initial plastic strains imparted by creep causes faster relaxation at short times, but that eventually the stresses of unstrained bars drop below those for specimens with no extended prior creep.

It might be well to examine the reported data of others before these somewhat unexpected results are accepted. Robinson (3) reports residual stresses at 1,000 and 10,000 hours for a total of 127 specimens of both low-alloy and high-alloy materials. In most instances short-time results were extrapolated to get the final stresses reported for the longer time. Initial strains are given in only some of the tests. Over half of the data reported are for single runs where no other results are given for the same material and test temperature so that comparisons of value for our purpose are quite limited. Selected tests summarized in Table I I are of interest.

Tabulated data have been grouped so that those in the first part present "normal" behavior. Thus, the data for SAE 4140 steel and for "17-22-A" with different starting stresses show an approach to like final values at long times, with a fast drop of stress for high initial stresses and slower rates for lower starting values. What the same specimen is re-run after a first relaxation test, a wide variety of alloys indicate a greater resistance to relaxation in the second test. This is even true for tests 78 and 79 on 19-9DL where the inital stress greatly exceeds the reported proportional limit. However, the magnitude of plastic strain on loading is not indicated. In the one series on N-155 (tests 84 through 86) where three runs were performed on the same bar the third test showed a somewhat greater improvement in relaxation strength than was evident between the first two tests on the bar.

The second group of four pairs is marked by cross-over of the relaxation curves either when two different initial stresses are used or else when the same bar is subjected to two relaxations in turn. Tests 74 and 77 indicate a radical drop in relaxation strength at 1200°F for 19-9DL after an initial strain of 1.25 percent.

Three single runs on 19-9W Mo, N-155, and 16-25-6 were reported for initial strains in excess of 1 percent. No comparative tests at low starting strain were reported but it is perhaps significant that in all three cases the residual stresses at 1000 hours were among the lowest of all values reported despite relatively high starting stresses. These observations are in complete agreement with the findings of the current investigation for S-816 at 1350°F with high initial creep strain and high starting stress.

The question remains as to whether rapid addition of the same amount of initial strain would have similar effects as does strain introduced by creep. This matter must be studied further before relaxation behavior may be predicted for the fibers near the root of a notch which are strained plastically upon loading.

Prediction of Rupture Life Under Variable Stress

To be able to predict the life of a fiber in a notched tensile bar is not sufficient to know the changing pattern of stress with time. It must also be known what fraction of the total life is expended by a given sojourn at one of these stress levels.

In a study of periodic overstressing and its effects on creep and rupture properties Guarnieri and Yerkovich (6) suggest a method which amounts to adding for each stress the fraction $\frac{\text{actual creep elongation at the stress}}{\text{elongation to rupture at the stress}}$. Their data on sheet stock of annealed low-carbon N-155 and of annealed A. I. S. I. type 347 stainless steel, as well as precision cast HS 21 alloy show considerable deviation from this rule. (Discrepancies between observed and calculated rupture life average 25-50 percent with a few as high as 100 percent). For many of these tests equally good or better correlation resulted when the fraction added was simply the ratio of actual time at a given stress to the rupture life at that stress in the conventional constant-load test.

These two methods of addition portions of life become the same for a material with uniform elongation at rupture over the range of stresses of concern. For S-816 between 35,000 and 65,000 psi the elongation at rupture was found to be uniformly high (34.1 - 52 percent of the effective gauge length). This is in agreement with the data of the General Electric Company reported in figure 1(B) of the First Progress Report where elongations were given as 27 to 47 percent. The data obtained for S-816 at this laboratory also agree extremely closely with the average curve for the alloy as reported by General Electric.

Three multiple-stress rupture curves may not be enough to give a rigorous test of validity to any rule deduced from them, but appear to be sufficient for our immediate purpose. Using the experimental data of Table I, the following calculations can be obtained:

(see following page)

Specimen No.	Stress (psi)	Ratio: $\frac{\text{Time at this stress}}{\text{Rupture life at this stress}}$	
MS-8	45,000	9.8/25.2 =	0.39
	35,000	93.9/180.6 =	0.52
			0.91
MS-12	55,000	1.33/4.25 =	0.31
	45,000	8.42/25.2 =	0.34
	35,000	80.05/180.6 =	0.44
			1.09
MS-16	35,000	68.0/180.6 =	0.38
	45,000	10.0/25.2 =	0.40
	35,000	56.2/180.6 =	0.31
			1.09

The indicated magnitude of 10 percent error is completely satisfactory when one considers the usual scatter of rupture data is of this same order. To check these findings a single test was run to rupture following relaxation from 50,000 to 30,000 psi. The decline to 40,000 psi was but a matter of a few minutes and the final stress level of 30,000 psi was attained in three-quarters of an hour. These times were so short compared to the constant-stress rupture lives that a negligible portion of total specimen life should have been expended. This is confirmed by the plot of log stress versus log time to rupture in figure 13 (B) where the point for the specimen previously relaxed lies on the curve for the bars without prior relaxation. Further tests of this type with the S-816 appear to be unwarranted unless results of an unusual nature arise in the future.

It should be pointed out that the method found to be satisfactory for adding portions of life for S-816 at 1350°F may not be applicable to other temperature or alloys. Where an alloy shows a marked difference in elongation to rupture from high to low stress, it is expected that some account of the elongation might have to be included in the law expressing rupture life under variable stress. The law for S-816 should then develop to be a special case of the more general rule.

FUTURE WORK

A limited number of further tests appears desirable with S-816 at 1350°F:

(1) Relaxation after initial rapid plastic straining such as would occur in certain fibers of a notched bar on loading. This initial strain could be accomplished by overloading with immediate unloading to the stress from which the relaxation is to start.

(2) Relaxation from stresses below the proportional limit after a very small amount of creep strain. Such a test would permit one to establish behavior between the extremes of zero and large prior creep tested to date.

Once the above tests have been completed and information has been obtained as to any changes in shape of a notch on loading, it will be attempted to predict the life of a notched bar of S-816 under conditions actually being tested by the second contractor to this overall program.

Inital work on Waspaloy in the coming quarter is to center around attempts to make this alloy notch sensitive by adverse handling prior to the final heat treatment. It is proposed to follow the recommended solution and aging practice in initial experiments. If it is found impossible to create notch brittleness under these limitations, deviations from accepted heat treat practice will next be considered.

BIBLIOGRAPHY

(1) Voorhees, H.R. and J.W. Freeman, "First Progress Report to Air Research and Development Command On Notch Sensitivity of Heat Resistant Alloys at Elevated Temperatures", University of Michigan Engineering Research Institute Project 2024, Aug. 15, 1952.

(2) Thomson Laboratory, General Electric Company, "Memorandum on Smooth and Notched Bar Rupture Testing of Timken 16-25-6 Alloy Wheel Rim Forgings", October 22, 1952.

(3) Robinson, E.L., "High Temperature Bolting Materials", Proc. A.S.T.M., 48, pp. 214-238 (1951).

(4) Roberts, I., "Prediction of Relaxation of Metals from Creep Data", A.S.T.M. Preprint No. 37 (1951)

(5) Robinson, E.L., "The Resistance to Relaxation of Materials at High Temperature", Trans., A.S.M.E., 61, pp. 543-550 (1939).

(6) Guarnieri, G.J. and L.A. Yerkovich, "The Influence of Periodic Overstressing on the Creep Properties of Several Heat Resistant Alloys", A.S.T.M. Preprint No. 72, (1952).

TABLE I

RESULTS OF SMOOTH-BAR RUPTURE TESTS FOR S-816 AT 1350°F

Specimen No.	Stress (psi)	Time at Stress (hours)	Elongation at Rupture (% of effective gauge length)	Reduction of Area at Rupture (%)
S-10	65,000	1.2	37.2	39.4
S-17	55,000	4.25	34.1	49.5
S-13	45,000	25.2 (± 0.8)	52.	58.0
S-9	35,000	180.6	38.1	51.6
MS-8[1]	45,000 35,000	9.8 93.9	46.5	45.1
MS-12[1]	55,000 45,000 35,000	1.33 8.42 80.05	50.2	43.6
MS-16[2]	35,000 45,000 35,000	68.0 10.0 56.2 (± 0.4)	35.1	46.3
R+S-7[3]	30,000	675.7	35.5	48.0

---

[1] - Step-down test.

[2] - Step-up, step-down test.

[3] - Run as relaxation test 50,000 to 30,000 psi in 0.77 hours; then kept at constant load to rupture.

TABLE II

SELECTED DATA FROM A PAPER BY ROBINSON, Proc. A. S. T. M., 48, pp. 214-238 (1948)

Test No.	Material	Lab. No.*	Temp. (°F)	Initial Strain (in/in)	Initial Stress (psi)	Calculated Residual Stress (psi)		Test Duration (hours)	Remarks
						1000 hrs.	10,000 hrs.		
11	SAE 4140	1	850		30,000	17,500	12,800		Elastic limit 55,000
12	SAE 4140	2	850		50,000	21,500	15,300		
56	"17-22-A"	3	1000	0.0016	35,800	22,400	16,200		Prop. limit 110,000
57	"17-22-A"	3	1000	0.0015	33,645	19,200	14,500		
58	"17-22-A"	3	1000	0.0015	29,220	16,600	12,600		
31	DM-45, 1st str.	4	1000		25,000	11,000	9,800	523	Prop. limit 72,000
32	DM-45, 2nd str.	4	1000		25,000	15,300	13,800	598	
46	A193-B14(446) 1st str.	1	930		30,000	18,600	14,500	2,880	Y. P. 100,250 psi
47	A193-B14(446) 2nd str.	1	930		30,000	19,700	15,500	1,056	
52	A193-B14 CrMoV 1st str.	5	900		44,000	19,000	11,700	13,579	Prop. limit 116,900
53	A193-B14 CrMoV 2nd str.	5	900		30,000	17,000	11,600	6,700	
61	"17-22-A", 1st str.	3	950	0.0018	36,300	22,600	20,000		Prop. limit 110,000
62	"17-22-A", 2nd str.	3	950	0.0018	38,700	27,000	24,000		
63	"17-22-A", 1st str.	4	950		25,000	18,500	17,500		Prop. limit 87,000
64	"17-22-A", 2nd str.	4	950		25,000	23,600	23,000		
65	"17-22-A", 1st str.	4	1000		25,000	16,000	15,000		Prop. limit 87,000
66	"17-22-A", 2nd str.	4	1000		25,000	17,200	16,400		
78	19-9DL, 1st str.	4	1100		30,000	19,500	18,500	1,752	Prop. limit 21,300
79	19-9DL, 2nd str.	4	1100		30,000	23,000	21,000	475	
84	N-155, 1st str.	4	1500		16,000	5,000		428	Y. P. 57,100 psi
85	N-155, 2nd str.	4	1500		16,000	5,400		116	
86	N-155, 3rd str.	4	1500		16,000	7,250		260	
99	6059(ZW), 1st str.	4	1500		15,000	3,900	3,700	964	
100	6059(ZW), 2nd str.	4	1500		15,000	4,600	4,300	2,136	

(concluded on the following page)

Table II (concluded)

Test No	Material	Lab. No.*	Temp. (°F)	Initial Strain (in/in)	Initial Stress (psi)	Calculated Residual Stress (psi)		Test Duration (hours)	Remarks
						1000 hrs.	10,000 hrs.		
40	A193-B14 CrMoV	4	950		30,000	19,400	16,000	700	Prop. limit 81,000
41	A193-B14 CrMoV	4	950		45,000	19,700	14,800	1,300	
18	A193-B7, 1st str.	1	850		30,000	13,200	10,000	1,920	
19	A193-B7, 2nd str.	1	850		30,000	14,300	8,600	4,900	
67	A193-B16, 1st str.	1	1000		30,000	14,000	9,300	2,640	Y. P. 125,100 psi
68	A193-B16, 2nd str.	1	1000		50,000	13,000	7,000	3,840	
74	19-9DL	6	1200	0.00173	21,680	15,200	13,055	695	
77	19-9DL	7	1200	0.01232	32,000	5,000	2,850	1,012	Y. P. 79,000 psi
80	19-9 W. Mo	7	1200	0.01424	40,000	3,900	2,200	260	
87	N-155	7	1200	0.0124	35,000	5,600	2,645	1,1012	
103	16-25-6	7	1200	0.01245	43,000	5,900	3,200	250	

---

* Key to Laboratories:

1 - The Crane Company
2 - Westinghouse Electric Co.
3 - Timken Steel and Tube Co. (University of Mich.)
4 - U.S. Naval Engineering Experiment Station
5 - Babcock and Wilcox Co. (M. I. T.)
6 - Battelle Memorial Institute
7 - International Nickel Company

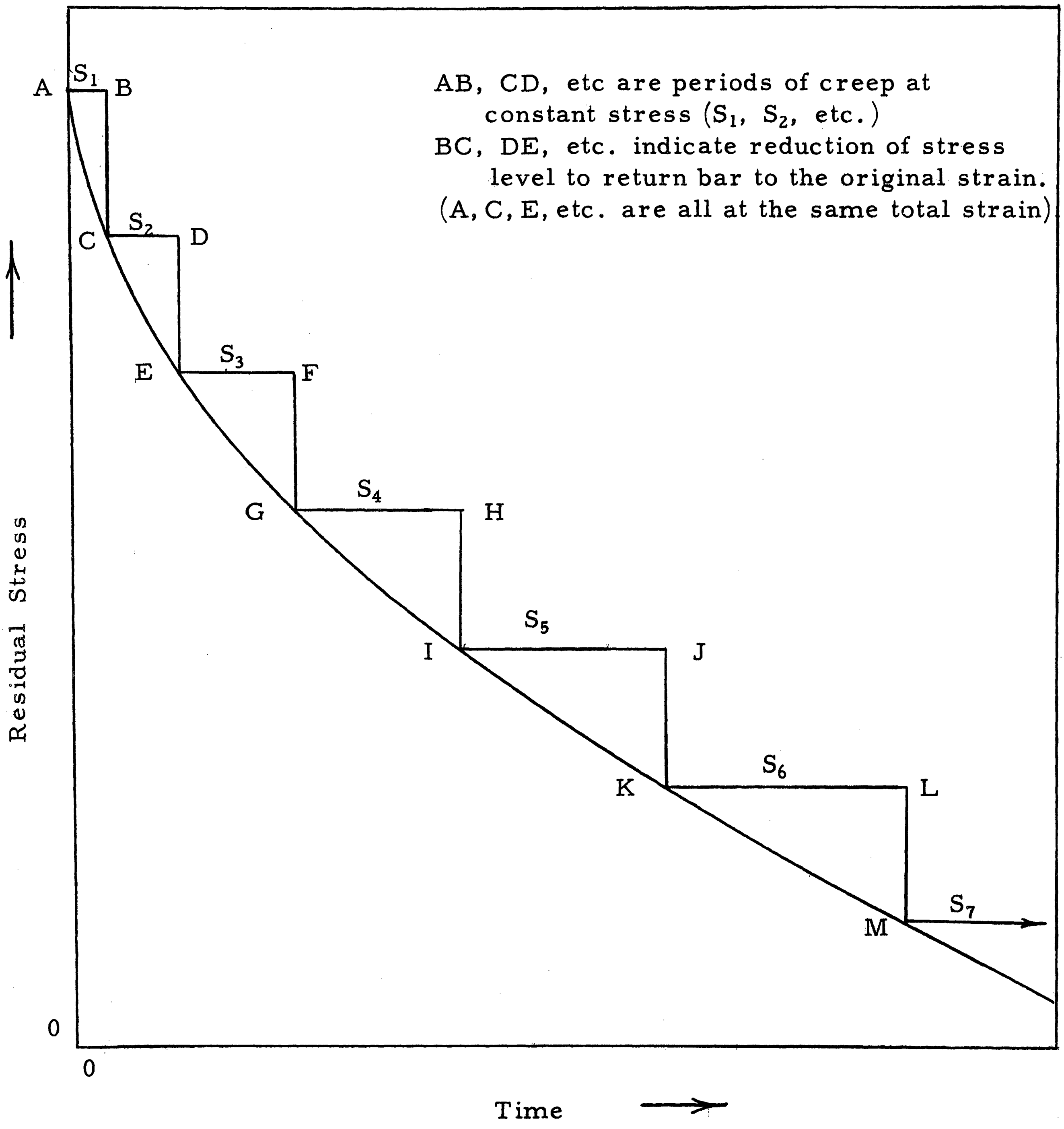


Fig. 1 - STEP-WISE RELAXATION TEST OF SMOOTH SPECIMEN IN PURE TENSION.

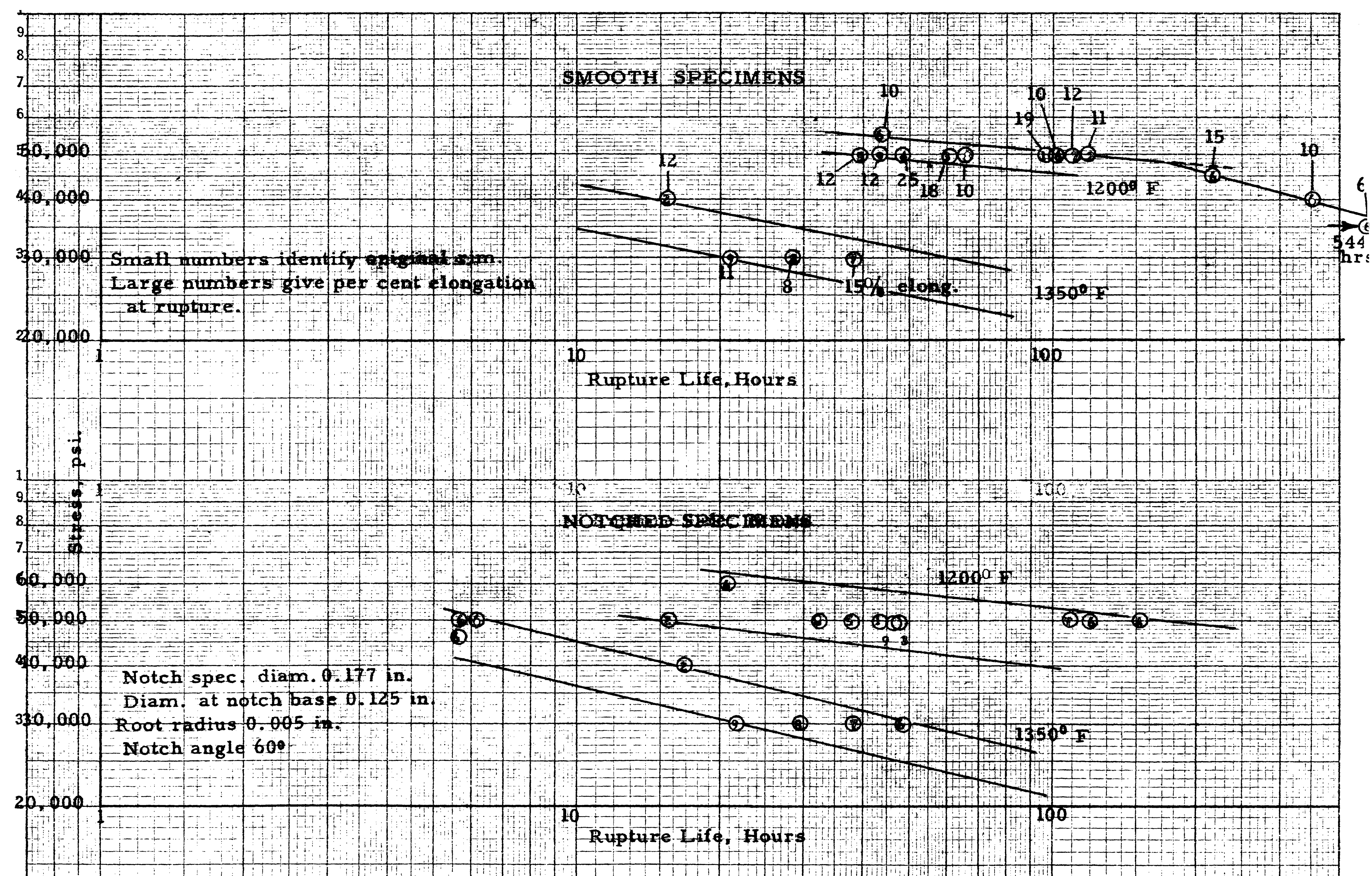


Fig. 2 - STRESS-RUPTURE TIME CURVES FOR SMOOTH AND NOTCHED SPECIMENS FROM COMMERCIAL COLD WORKED △16-25-6 RIMS (Data from Thomson Laboratory, General Electric Company).

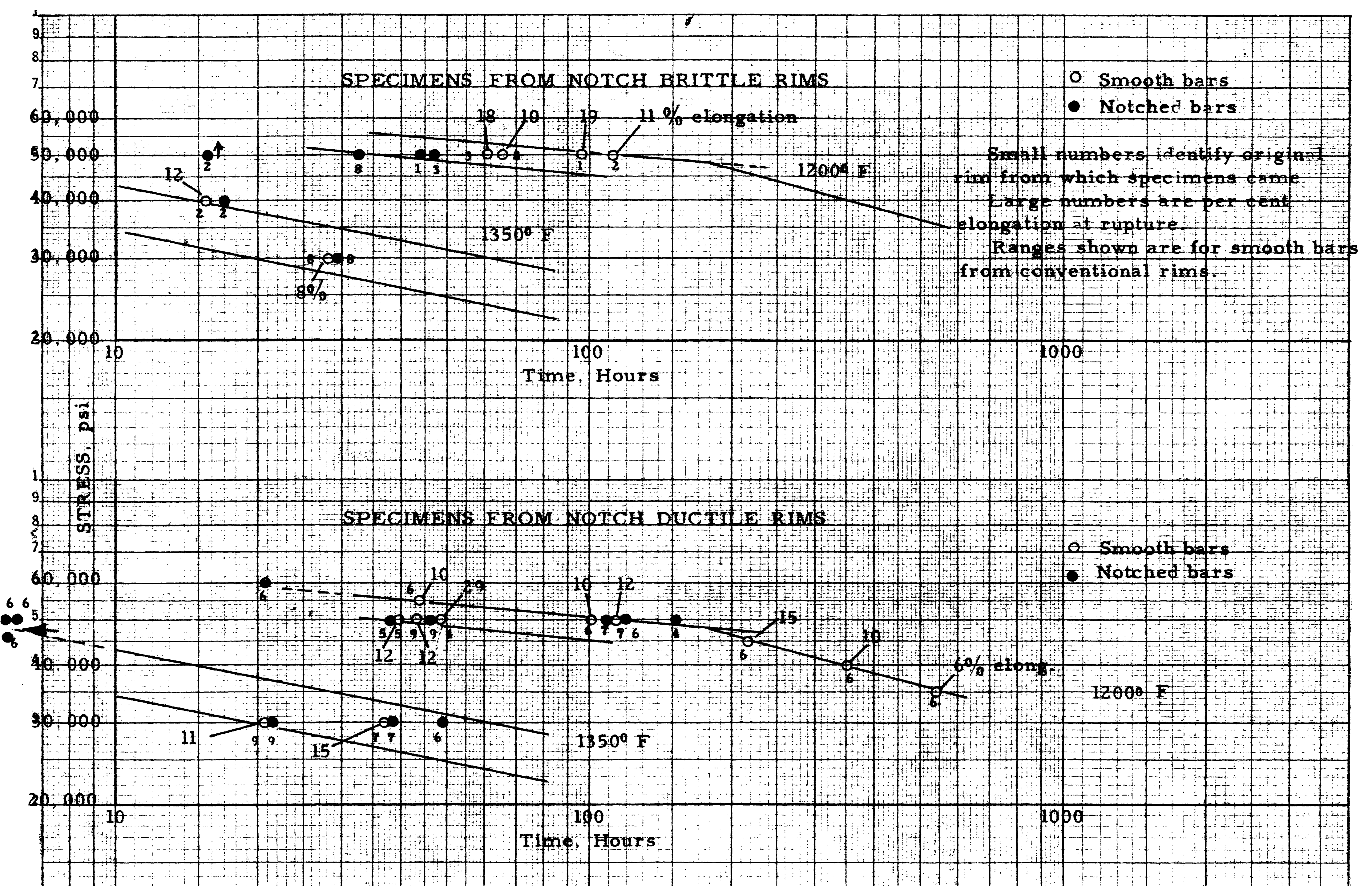


Fig. 3: STRESS - RUPTURE TIME DATA FOR 16-25-6 SPECIMENS FROM NOTCH BRITTLE AND NOTCH DUCTILE CONVENTIONAL COLD WORKED RIMS (Data from Thomson Lab., General Electric Company).

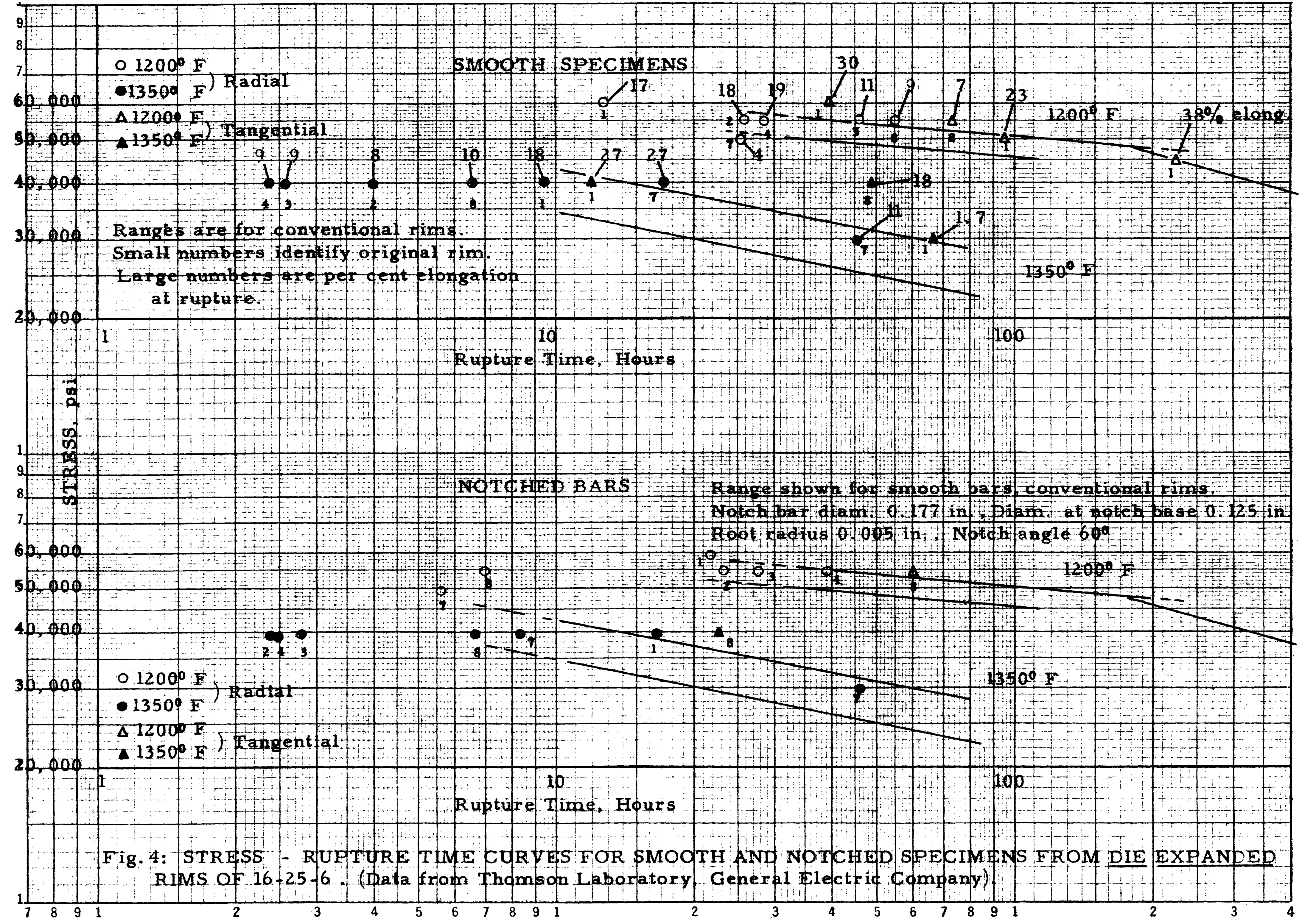


Fig. 4: STRESS - RUPTURE TIME CURVES FOR SMOOTH AND NOTCHED SPECIMENS FROM DIE EXPANDED RIMS OF 16-25-6. (Data from Thomson Laboratory, General Electric Company).

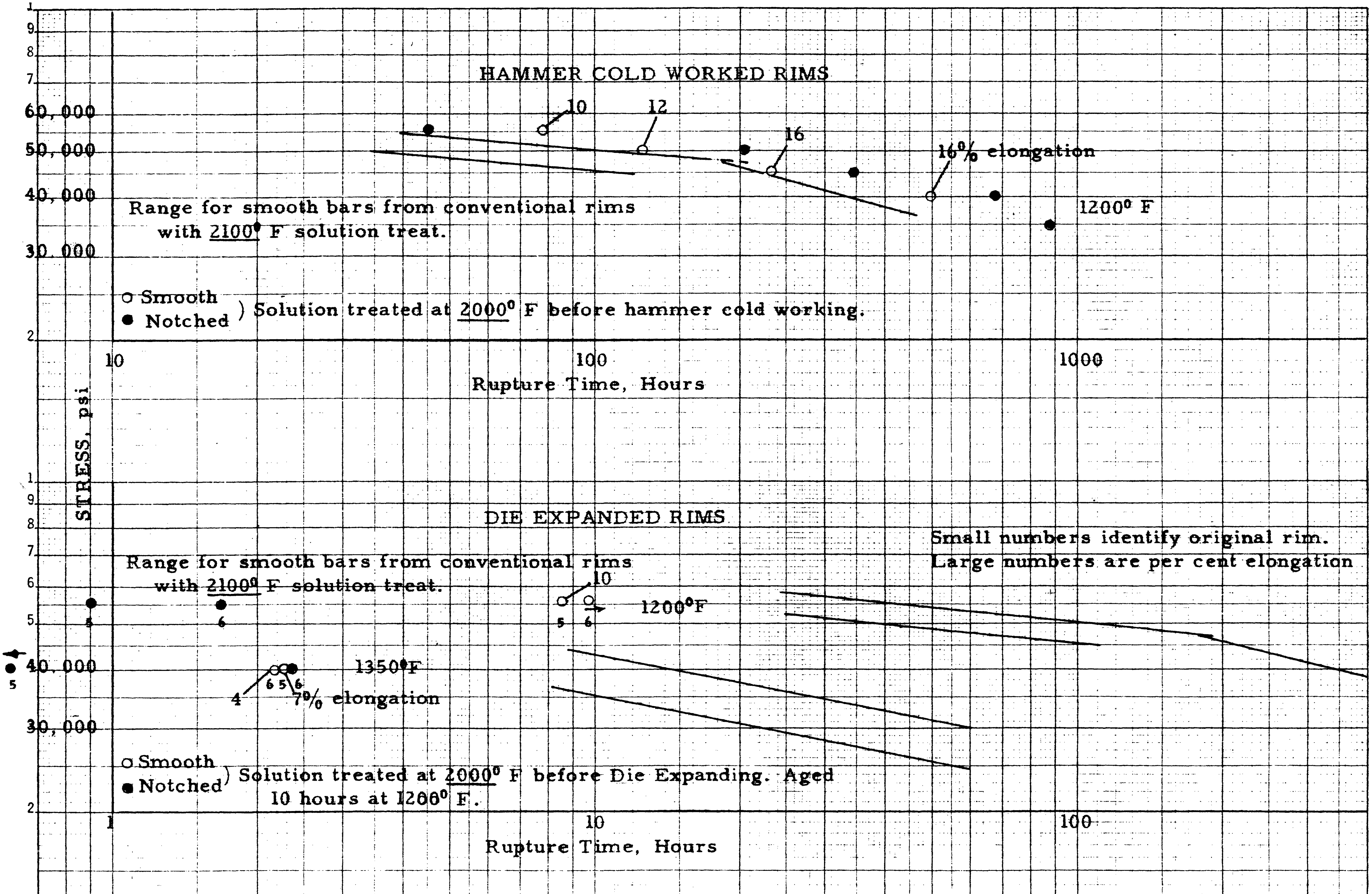


Fig. 5: INFLUENCE OF 2000° F SOLUTION TREAT BEFORE COLD WORK, INSTEAD OF 2100° F. (Data from Thomson Laboratory, General Electric Company).

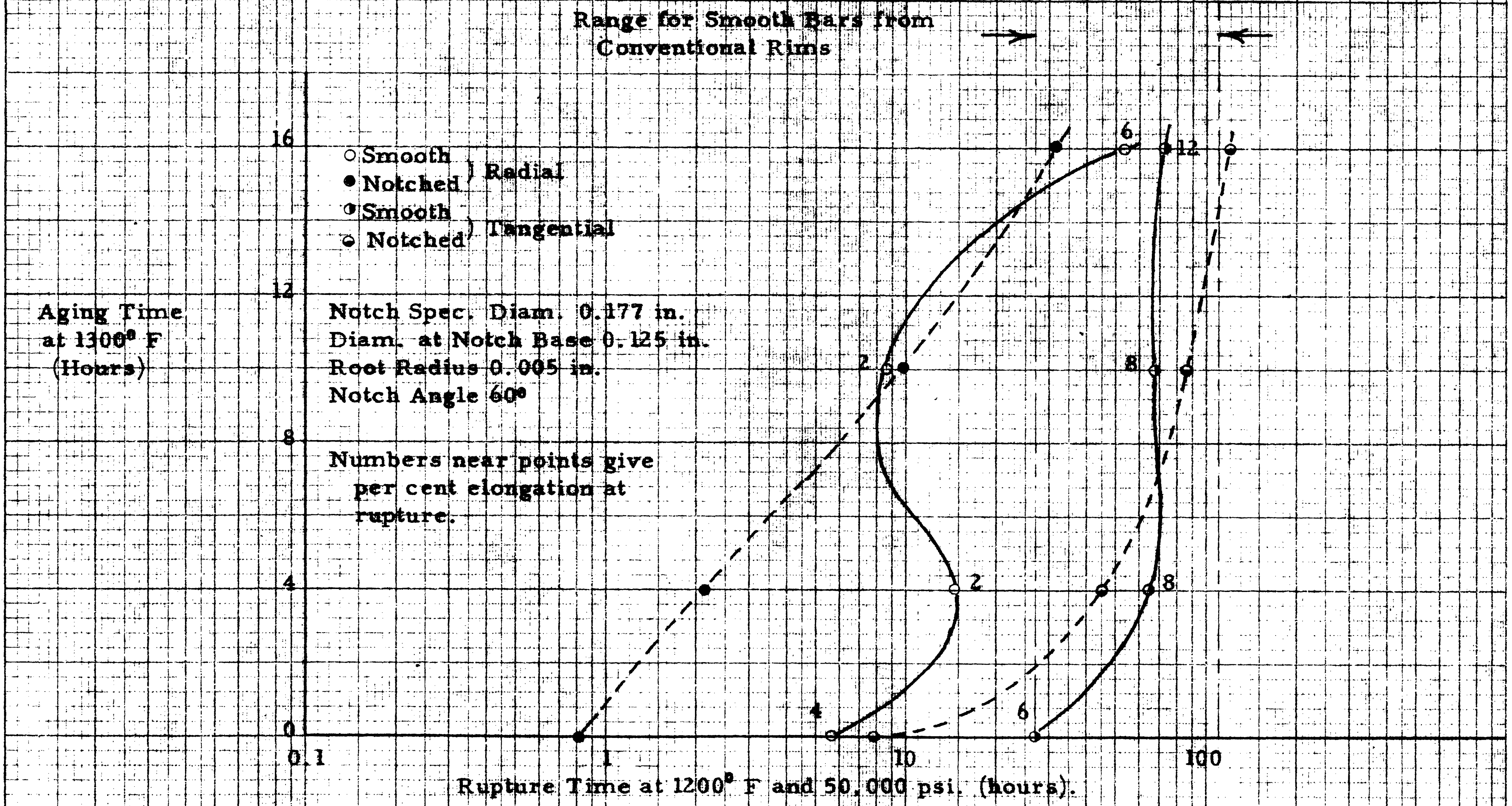


Fig. 6: EFFECT OF TIME OF AGING AT 1300°F ON RUPTURE LIFE AT 1200° F OF 16-25-6 RIMS, DIE-EXPANDED AFTER SOLUTION TREATMENT AT 2100°F (Data of Thomson Laboratory, General Electric Company).

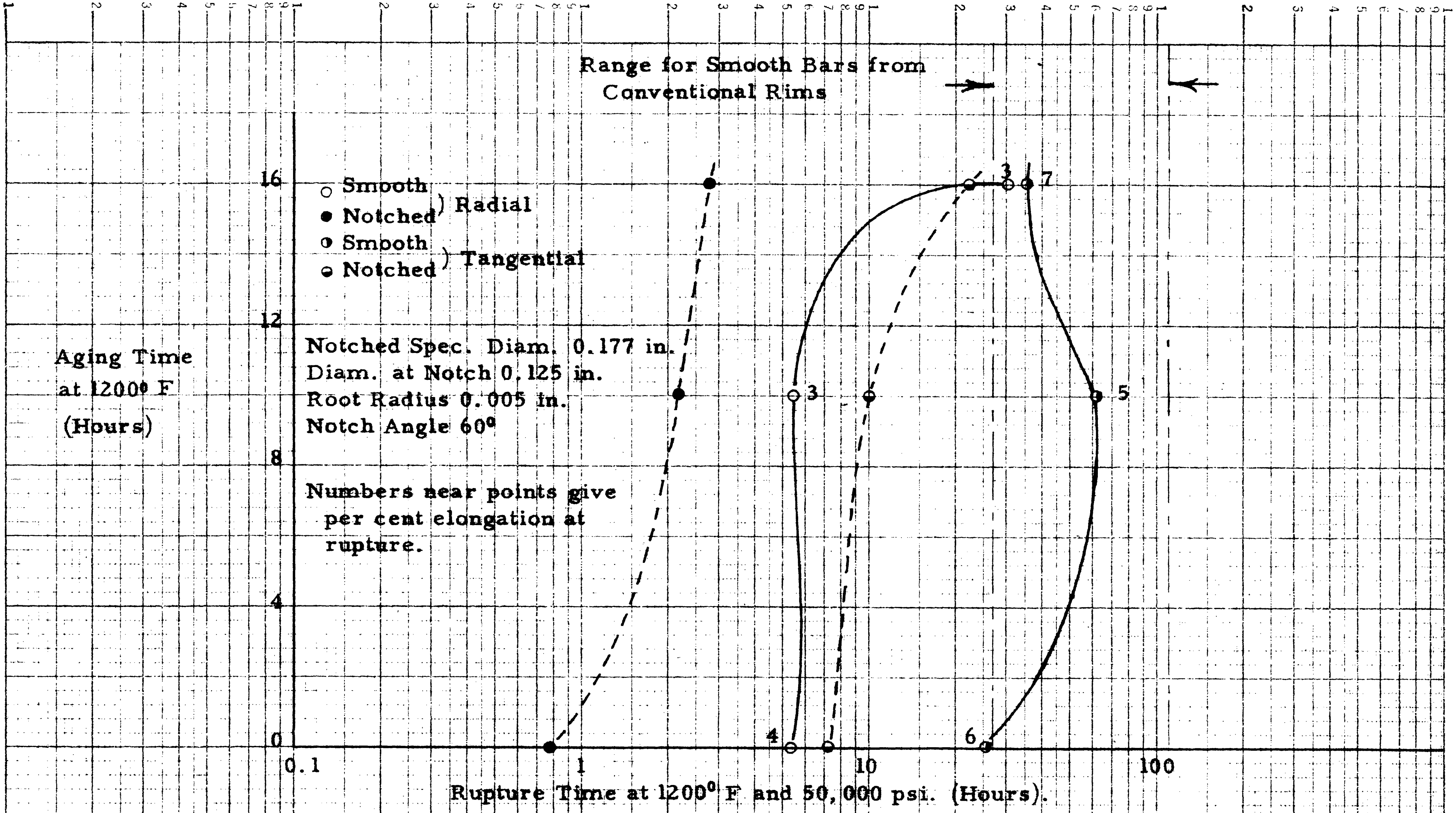


Fig. 7 : EFFECT OF TIME OF AGING AT 1200° F ON RUPTURE LIFE AT 1200° F OF 16-25-6 RIMS, DIE EXPANDED AFTER SOLUTION TREATMENT AT 2100° F (Data from Thomson Laboratory, General Electric Company).

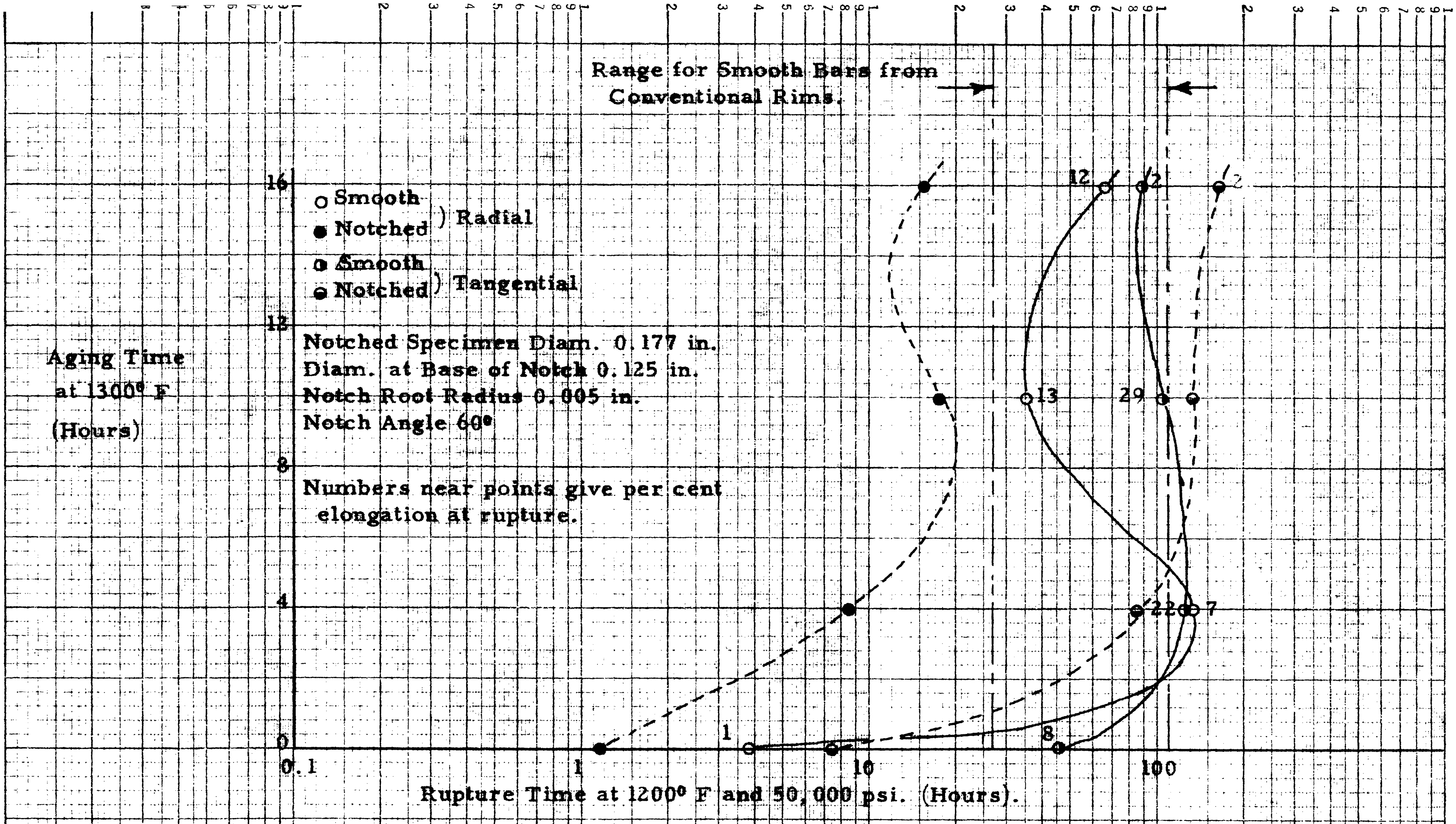


Fig. 8: EFFECT OF TIME OF AGING AT 1300° F ON RUPTURE LIFE AT 1200° F OF 16-25-6 RIMS, DIE EXPANDED AFTER SOLUTION TREATMENT AT 2000° F (Data from Thomson Laboratory, General Electric Company).

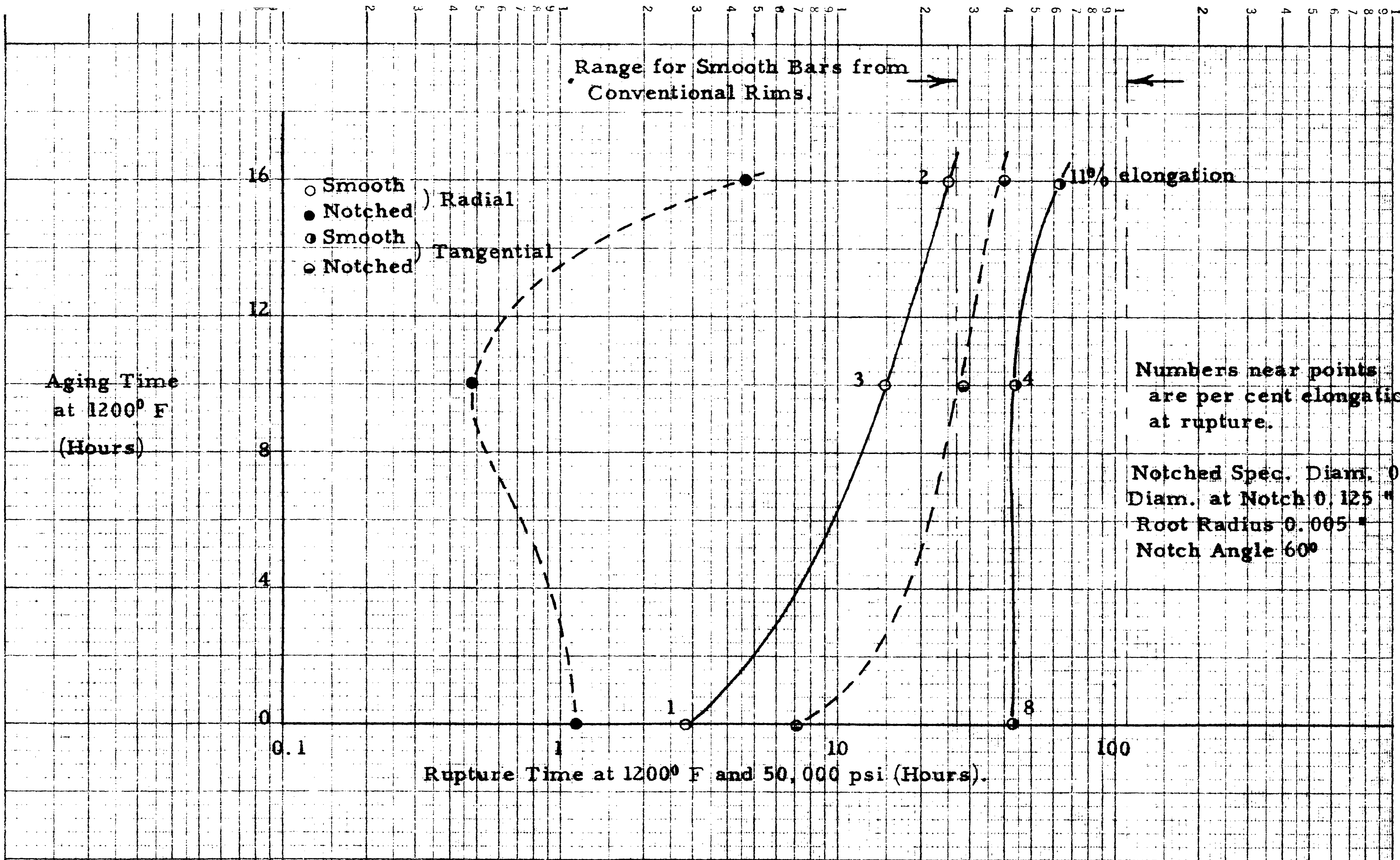
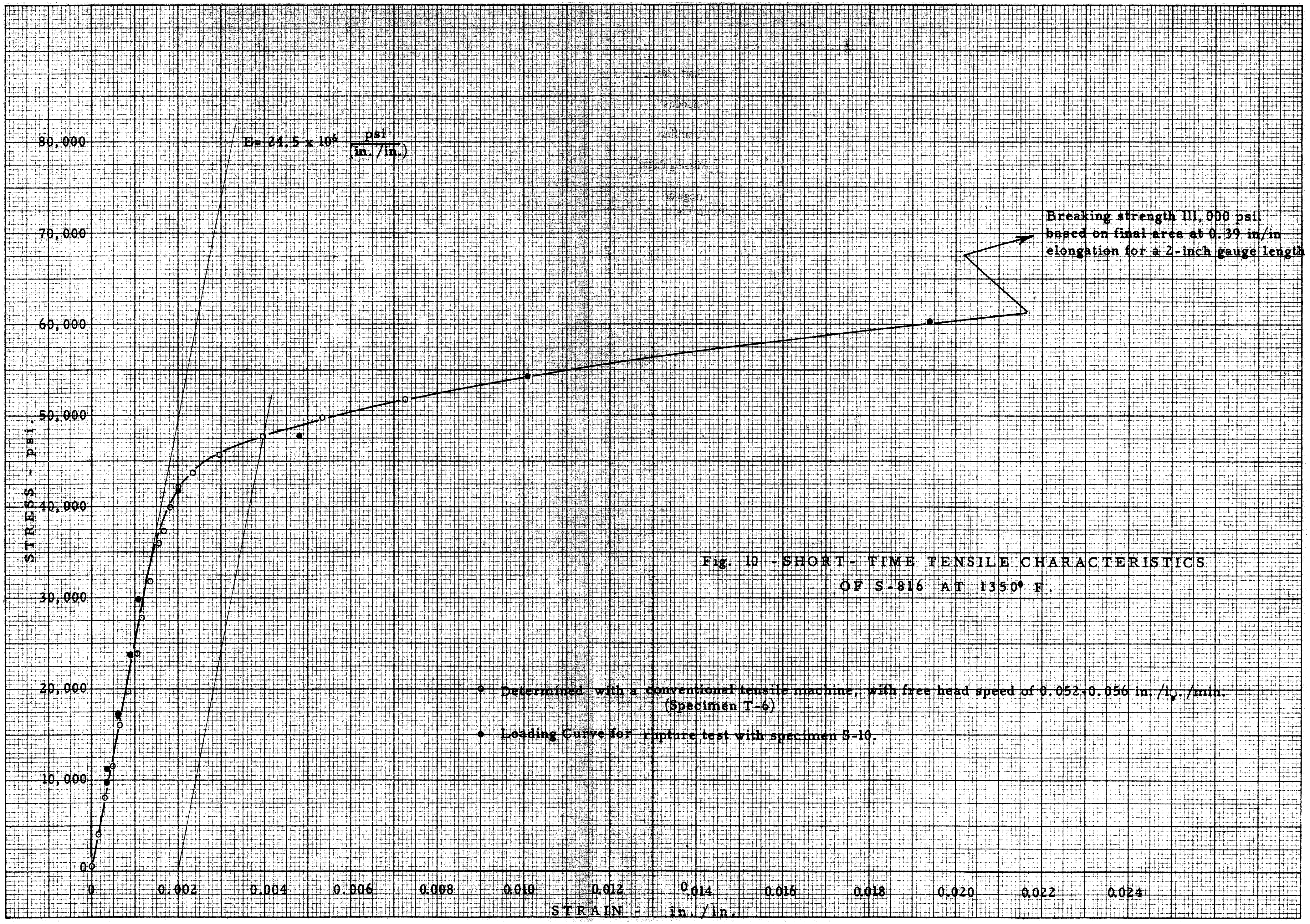


Fig. 9: EFFECT OF TIME OF AGING AT 1200° F ON RUPTURE LIFE AT 1200° F OF 16-25-6 RIMS, DIE EXPANDED AFTER SOLUTION TREATMENT AT 2000° F (Data from Thomson Laboratory, General Electric Company).



Breaking strength 111,000 psi, based on final area at 0.39 in/in elongation for a 2-inch gauge length

Fig. 10 - SHORT-TIME TENSILE CHARACTERISTICS OF S-816 AT 1350° F.

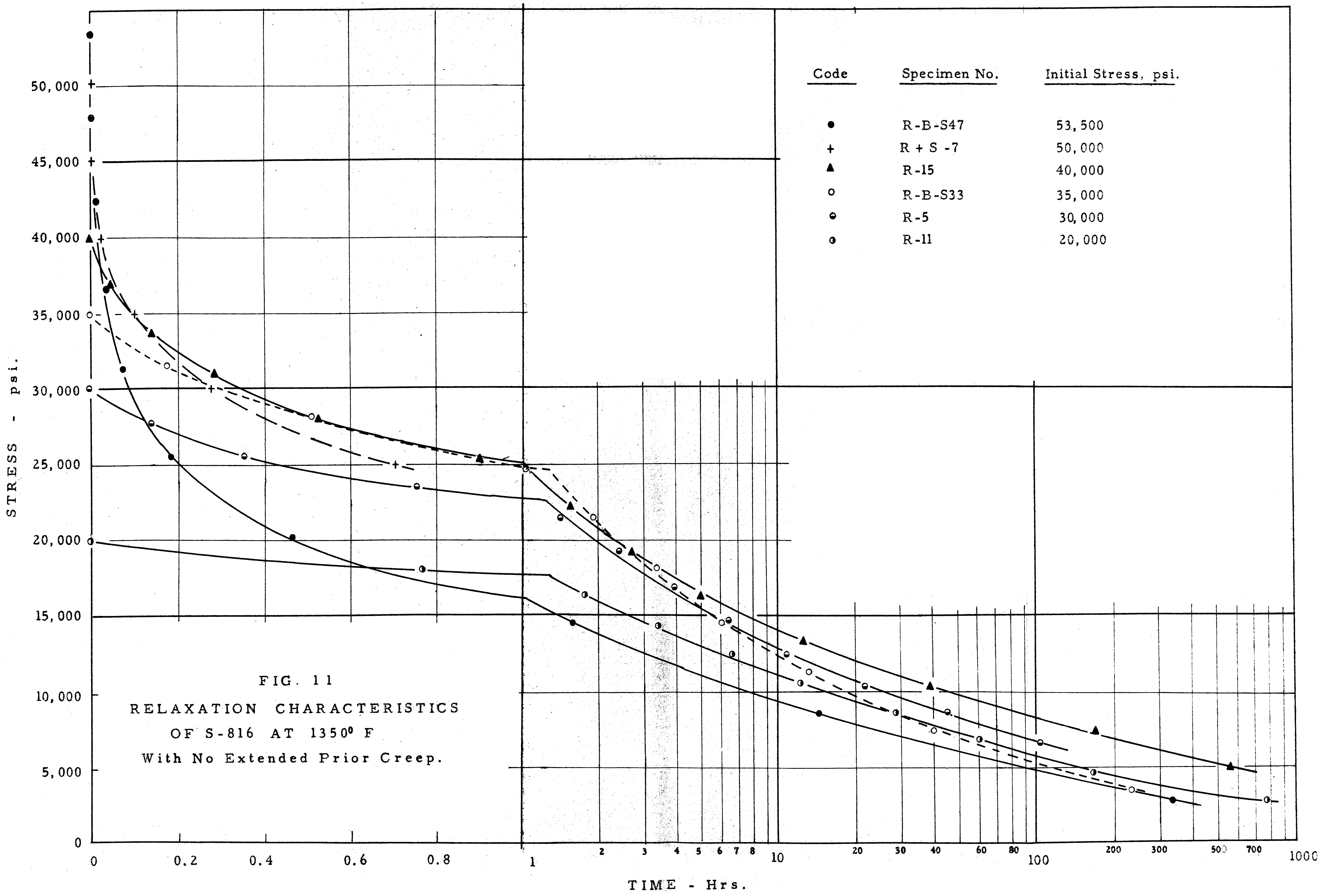


FIG. 11
RELAXATION CHARACTERISTICS
OF S-816 AT 1350° F
With No Extended Prior Creep.

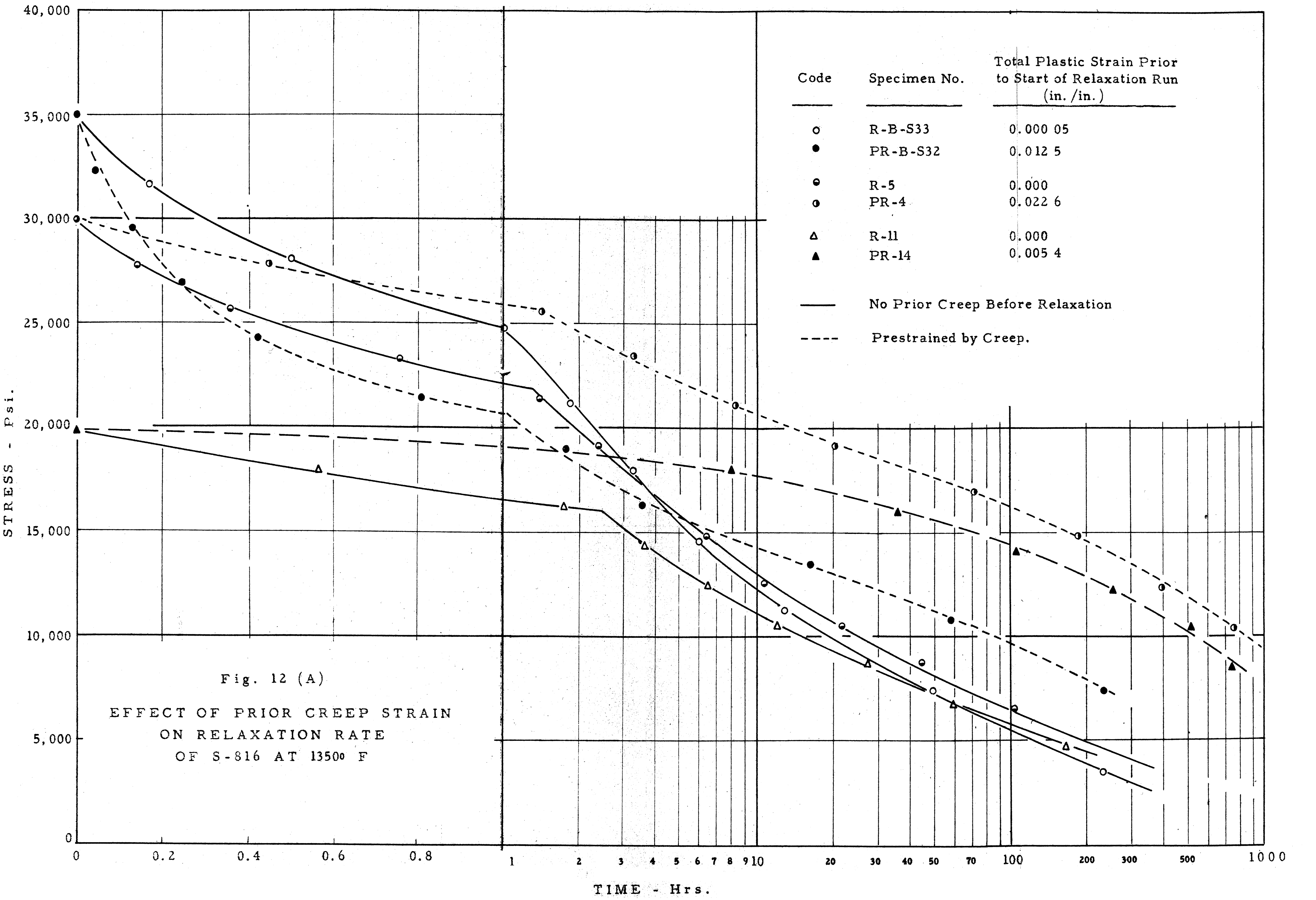


Fig. 12 (A)

EFFECT OF PRIOR CREEP STRAIN
ON RELAXATION RATE
OF S-816 AT 1350° F

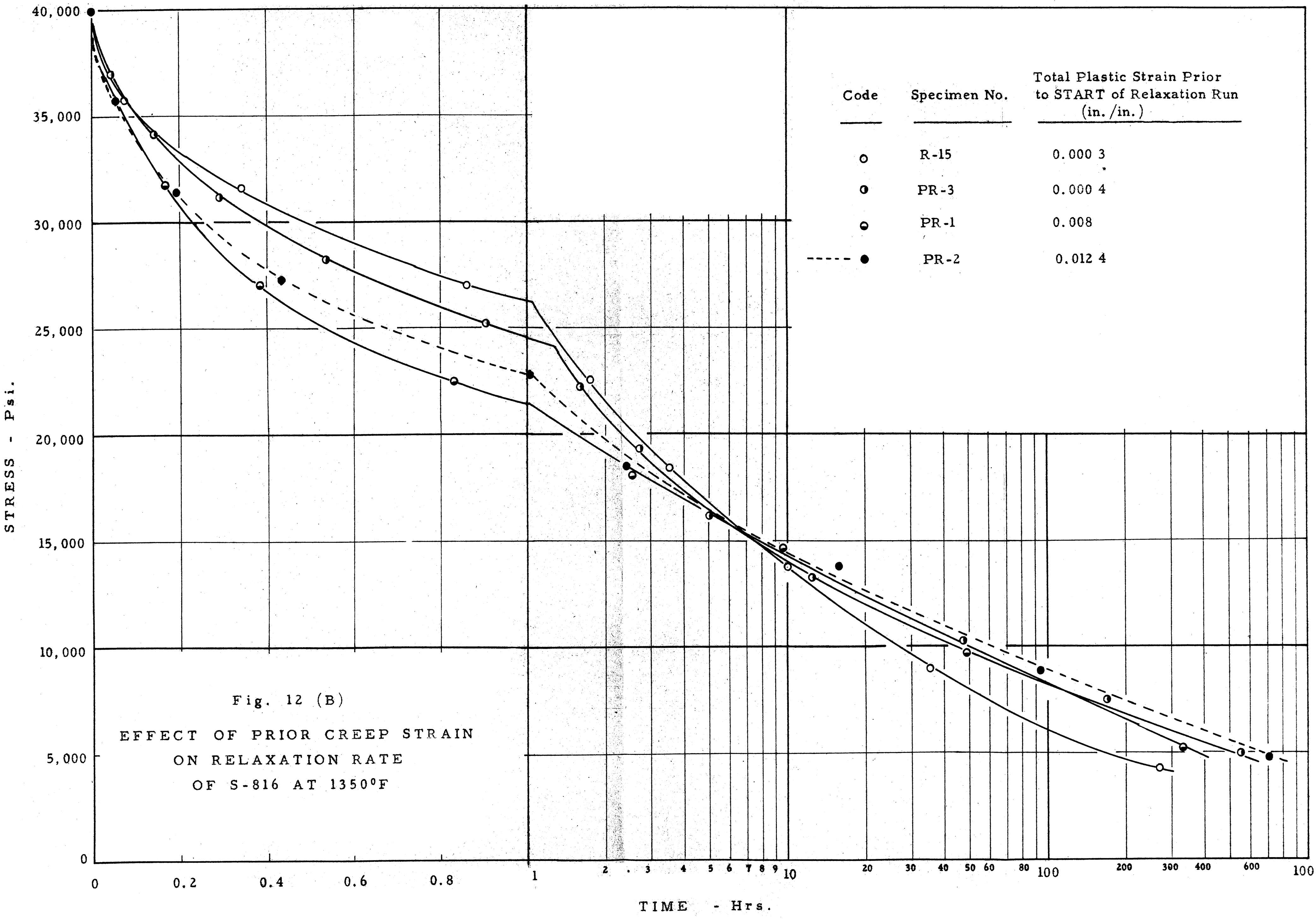


Fig. 12 (B)

EFFECT OF PRIOR CREEP STRAIN
ON RELAXATION RATE
OF S-816 AT 1350°F

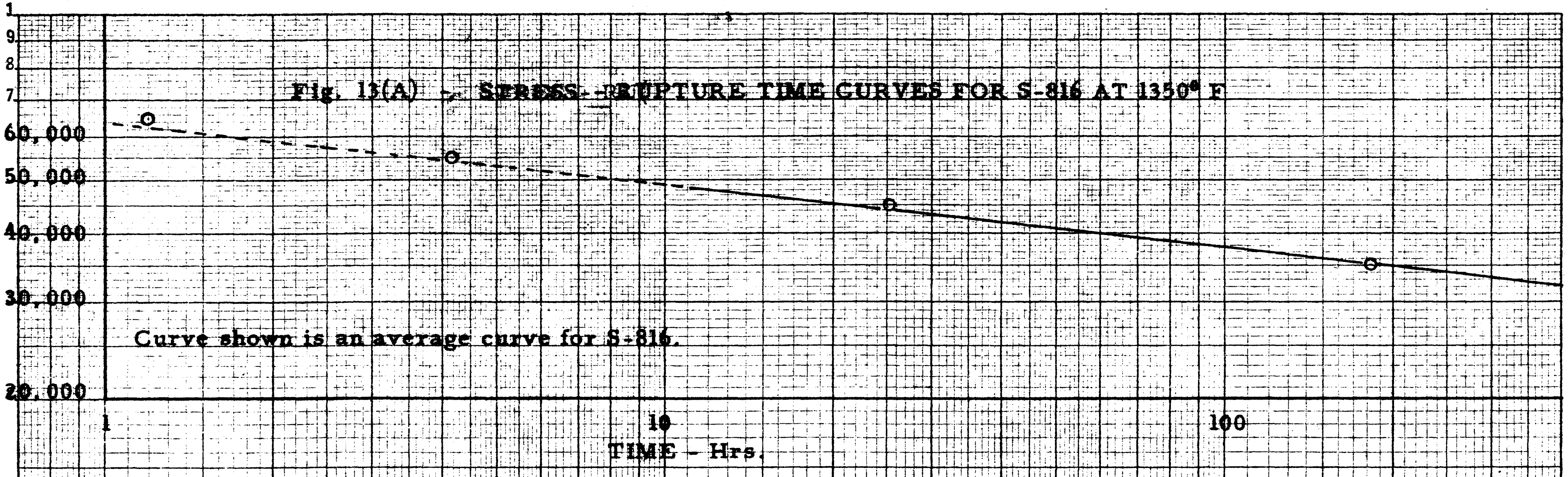


Fig. 13(A) - STRESS-RUPTURE TIME CURVES FOR S-816 AT 1350° F

Curve shown is an average curve for S-816.

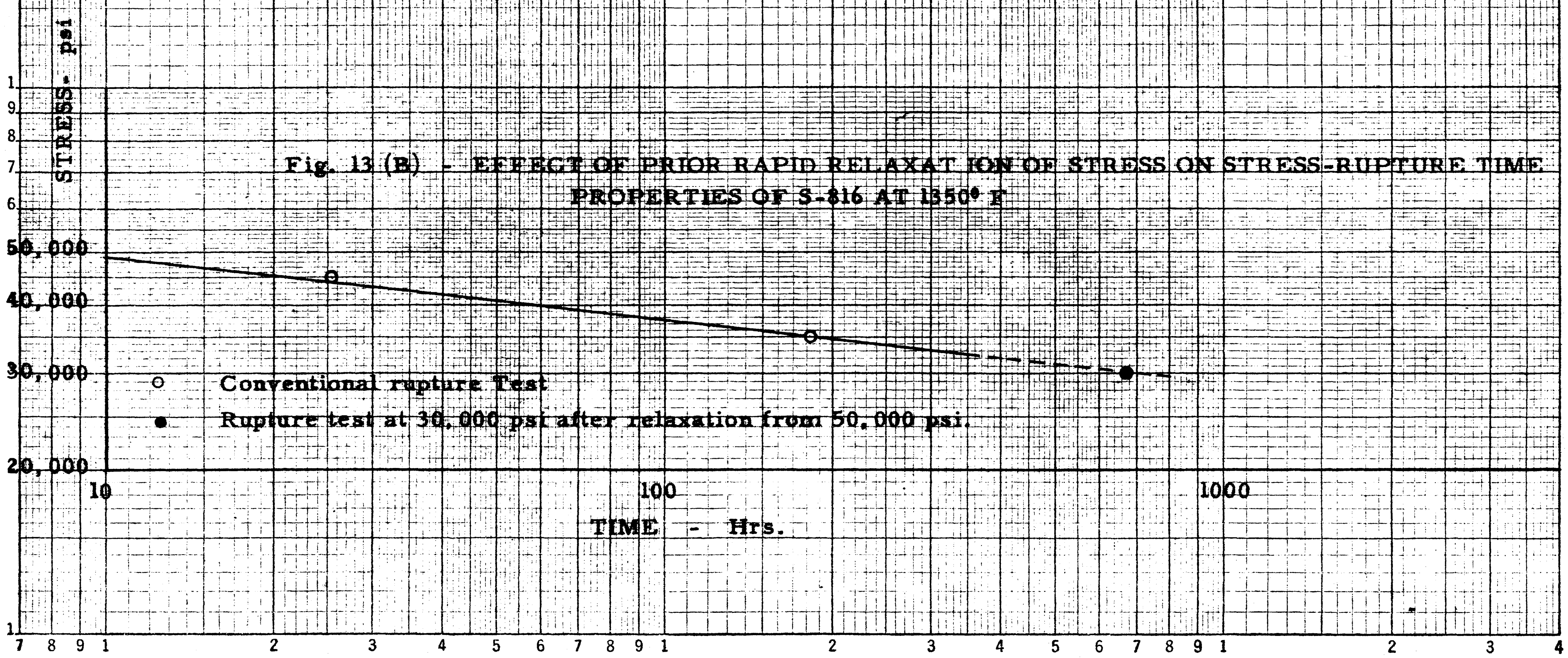


Fig. 13 (B) - EFFECT OF PRIOR RAPID RELAXATION OF STRESS ON STRESS-RUPTURE TIME PROPERTIES OF S-816 AT 1350° F

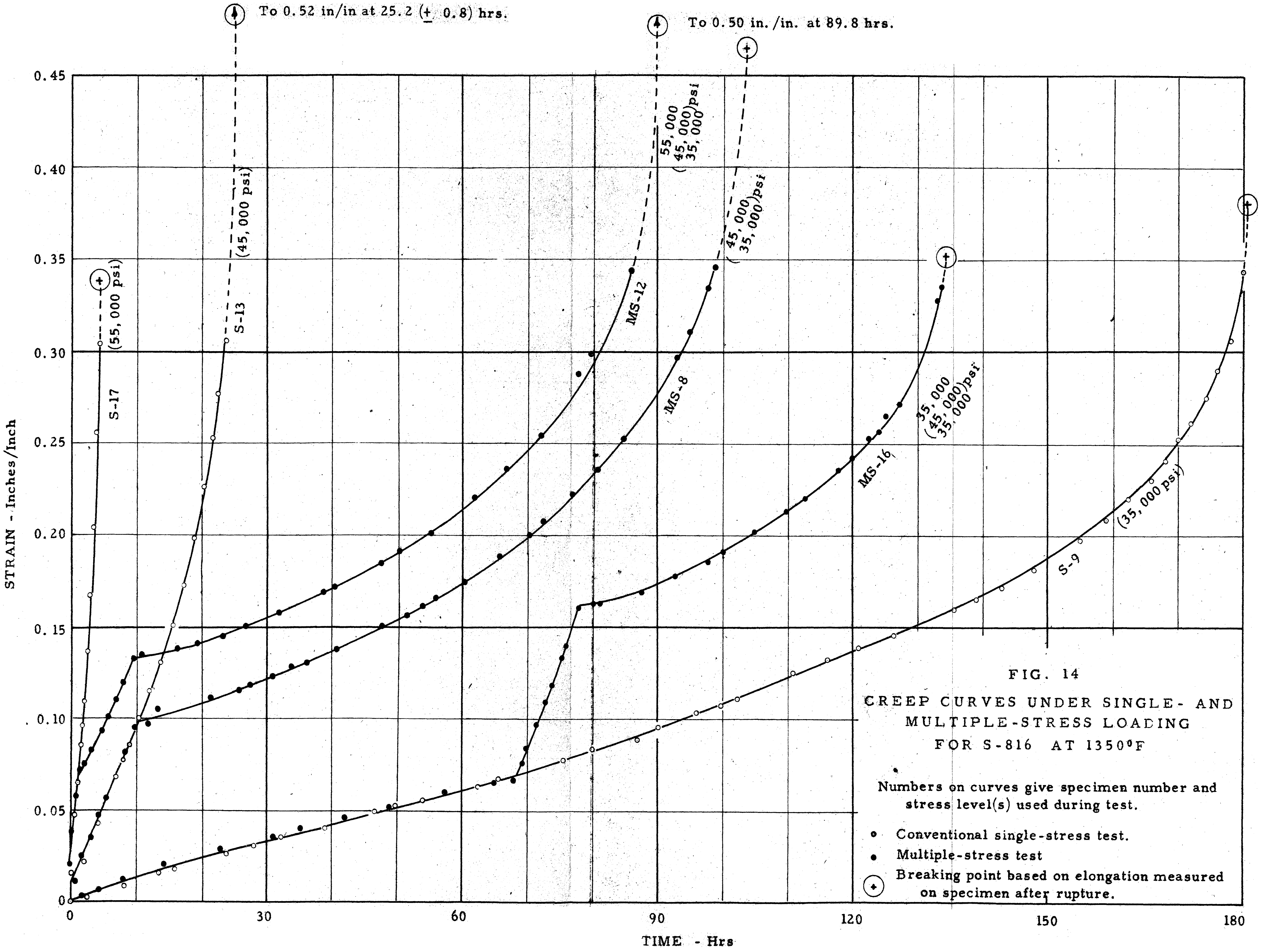
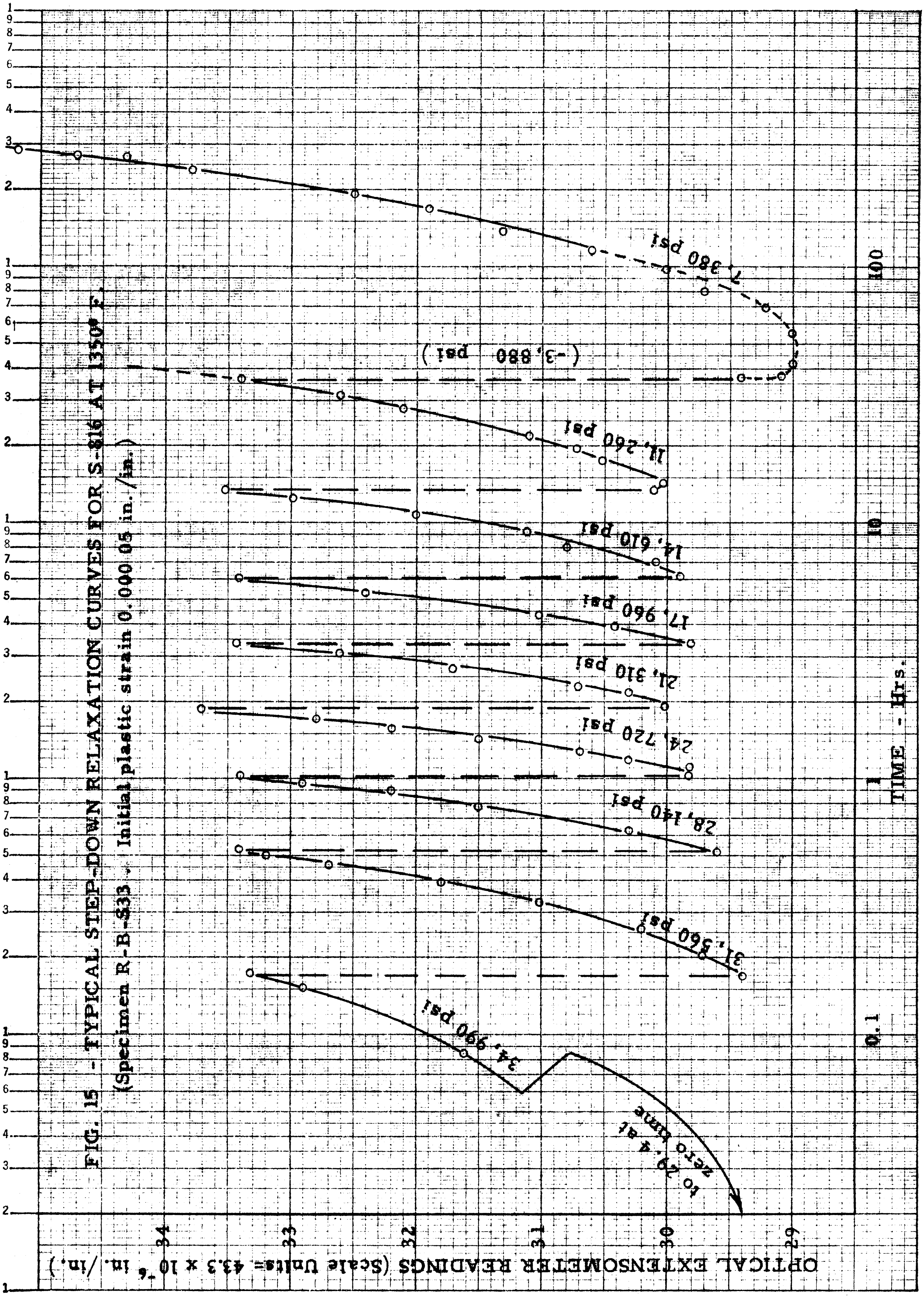


FIG. 14

CREEP CURVES UNDER SINGLE- AND MULTIPLE-STRESS LOADING FOR S-816 AT 1350°F

 FIG. 15 - TYPICAL STEP-DOWN RELAXATION CURVES FOR S-816 AT 1350° F.

(Specimen R-B-533 - Initial plastic strain 0.000 05 in. /in.)