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FINAL REPORT

COOPERATIVE INVESTIGATION OF RELATIONSHIP BETWEEN
STATIC AND FATIGUE PROPERTIES OF HEAT-RESISTANT
ALLOYS AT ELEVATED TEMPERATURES

By

SPECIAL PANEL OF NACA SUBCOMMITTEE
ON HEAT-RESISTING MATERIALS

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SUMMARY

Extensive data were obtained relating properties of a heat-resistant alloy under static, combined static and dynamic, and completely reversed dynamic stress conditions. Time periods for fracture ranged from 50 to 500 hours at room temperature, 1000°, 1200°, 1350°, and 1500°F. Correlation of the data showed:

1. Increasingly higher percentages of superimposed dynamic stress on the steady loads for rupture in 50, 150, and 500 hours were required to change appreciably rupture strength as the temperature increased. At 1500°F the dynamic stresses approached the completely reversed fatigue strength before a substantial reduction in fracture time occurred.
2. A given amount of superimposed dynamic stress had decreasingly less effect on the rupture time as the steady stress was reduced to increase rupture time.
3. Completely reversed stress tests show fatigue strengths which are of the order of 40 to 60 per cent of the static tensile strength. As the temperature and time period considered was increased, the fatigue strengths increased relative to static rupture strengths to values twice the rupture strength for 500 hours at 1500°F. This means that the material can tolerate a cyclic load of larger magnitude than a steady load under conditions where creep occurs.

4. Limited data indicated that under combined stresses up to 67 per cent of the steady load at 1350° and 1500°F, the fatigue stress did not appreciably alter the creep characteristic through the second stage of creep. Apparently superimposed fatigue stresses exert their main influence during the third stage of creep.
5. Properties evaluated on the basis of number of cycles to failure differed from those evaluated on a time basis only when the properties were time-dependent. Thus two fatigue machines operating at different cyclic speeds gave differing values on a cyclic basis when a fatigue limit was not attained. This was particularly evident in combined stress tests at 1350° and 1500°F.
6. Increasing amounts of fatigue loading decreased elongation in the rupture test progressively to very low values in completely reversed stress tests.
7. Bending tests gave slightly higher fatigue strengths than completely reversed axial stress tests. The difference decreased with increasing test temperature so that the two types of tests gave comparable results at 1500°F. There seemed to be little definite effects from variation in cyclic speed. Axial tests did not show the "knee" typical of S-N curves. The knee also tended to disappear with increasing temperatures in all tests.
8. Surface-finish effects decreased with increasing temperature. Apparently residual stress variation was the main variable. Polished specimens gave higher strengths than ground specimens at low temperatures. This may have been a factor in the difference between bending and axial stress tests.

Limited data are reported on dynamic stress-strain properties, damping characteristics, and the influence of notches in rotating cantilever beam tests.

INTRODUCTION

Data are presented and correlated to relate the fatigue and static properties of a heat-resistant alloy over a wide range of temperatures. The work was undertaken on a cooperative basis to help clarify the principles governing load-carrying ability of heat-resistant alloys at temperatures and conditions where both creep and fatigue can occur simultaneously. In view of the uncertainty in interpreting the results of various types of fatigue tests, duplicate data were obtained from as many types of fatigue testing machines as could be arranged.

In the major part of the program, extensive efforts were used to eliminate variations in test specimens as a factor. One cooperator did study surface-finish effects in reversed bending. Another cooperator obtained creep data under static tension and combined dynamic axial loading. This cooperator also measured damping and dynamic elasticity properties and carried out reversed bending tests on notched specimens.

The program was undertaken by the NACA Subcommittee on Heat-Resisting Materials in view of the uncertainties of the principles involved at high temperatures where materials are subjected to fatigue or fatigue and creep simultaneously. A Special Panel was appointed by the Subcommittee to investigate the relationships between static and fatigue properties of heat-resistant alloys at high temperatures. The fragmentary nature of available fatigue data at high temperatures made it nearly impossible to develop such relationships. The panel decided the best procedure was to organize a cooperative testing program to obtain reasonably complete data for one representative alloy.

Cooperation was obtained from the following organizations.

1. The Elliott Company
2. General Motors Corporation, Research Division
3. National Advisory Committee for Aeronautics by contract with Battelle Memorial Institute.
4. National Advisory Committee for Aeronautics, Lewis Flight Propulsion Laboratory
5. National Advisory Committee for Aeronautics by contract with the Engineering Research Institute, University of Michigan
6. Office of Naval Research, U. S. Navy, by contract with Battelle Memorial Institute
7. Rolls-Royce Company, Research Laboratories, England
8. United States Naval Engineering Experiment Station
9. Westinghouse Electric Corporation, Research Division
10. Wright Air Development Center, Materials Laboratory, by contract with the Institute of Industrial Research, Syracuse University
11. Wright Air Development Center, Materials Laboratory, by contract with the Institute of Technology, University of Minnesota.

PROCEDURE

A Special Panel of the NACA Subcommittee on Heat-Resisting Materials arranged the cooperative program. The general objective was to obtain data which would define load-carrying ability of a typical heat-resistant alloy at high temperatures as a function of mean and alternating stresses from static rupture tests to completely reversed fatigue tests. The temperatures selected were 1000°, 1200°, 1350°, and 1500°F to cover a wide range of temperature effects. In addition, some data were established at room temperature for comparative purposes. In general, tests were aimed to cover time periods for fracture of 50 to 500 hours so that the results could be expressed in terms of both time and cycles to failure. An attempt was made to obtain data from as many types of test machines as possible and particularly to have as much data as possible duplicated by two types of machines.

A procedure was adopted to reduce variations from test material and surface finish to a minimum because the program was set up to obtain objective data on the relation between static and dynamic properties at elevated temperatures. Low-carbon N-155 alloy bar stock solution-treated for 1 hour at 2200°F, water-quenched, and then aged for 16 hours at 1400°F was selected because it met two requirements. One was that this material treated in this manner had the most uniform properties at high temperatures of any representative "super-alloy" known to the Panel. Secondly, it was metallurgically similar to several forged alloys of the type of interest for application in the gas turbines of jet engines. An additional factor in the choice was that there was more experimental metallurgical background available for this alloy than for any other choice. The NACA purchased 271 feet of 1-inch round bar stock for the test program.

In order to insure uniformity of test specimens, the NACA sponsored the preparation of the specimens at the Engineering Research Institute of the University of Michigan. A system of sampling was set up so that any lot of specimens sent to a cooperator was made from material representative of the complete length of the original ingot. This avoided misleading trends which might have occurred from segregation effects in specimens taken from one hot-rolled length of bar stock. The bar stock was cut to the lengths required for specimens and heat-treated. All specimens were prepared using elaborate procedures to keep the surface of the gage sections constant regardless of shape.

Arrangements were made to have all fractured specimens examined. Westinghouse, Syracuse University, University of Minnesota, and the Lewis Laboratory of the NACA elected to examine the specimens which they tested. All others except those tested by Rolls-Royce were returned to the University of Michigan for visual and metallographic examination under sponsorship of the NACA.

Under sponsorship of the NACA, the University of Michigan served as secretary to the Panel to compile data and issue reports.

TEST MATERIAL

Two hundred and seventy-one feet of 1-inch round bar stock from one ingot of heat A-1726 were supplied as twenty-six mill length bars in the as-rolled condition.

The chemical analysis of heat A-1726 was as follows:

Chemical Composition										
(Weight percent)										
C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N	
0.13	1.64	0.42	21.22	19.00	19.70	2.90	2.61	0.84	0.13	Suppliers' heat analysis
0.14	1.43	0.35	20.80	18.80	19.65	3.00	2.00	0.99	0.135	U.M. check on bar stock

The manufacturing conditions were reported to be as described in table I.

Coupons about 1 inch long were cut from both ends and the center of each bar, heated at 2200°F for 1 hour, water-quenched, and then aged at 1400°F for 16 hours. The Brinell hardness was then determined on the surface of each coupon and at the center of the cross section. The hardness values shown in table II indicate good uniformity. Metallographic examination of specimens cut from the top, middle, and bottom bars of the ingot had similar structures after the heat treatment.

COOPERATING LABORATORIES AND TESTING METHODS

1. Static Tests

The NACA sponsored short-time tensile tests and rupture tests at the University of Michigan. Testing temperatures were 1000°, 1200°, 1350°, and 1500°F. In addition, tensile tests were also run at room temperature. All tests were conducted in accordance with ASTM Recommended Practices on standard 0.505-inch-diameter specimens. Tensile specimens were held at temperature one hour before testing. The rupture specimens were brought to temperature over a 24-hour period before loading. Stress-strain data for the tensile tests and creep data from the rupture tests were measured with an optical lever extensometer system attached to the specimens.

2. Dynamic Axial Stress Fatigue and Creep Tests

The Materials Laboratory, WADC, sponsored dynamic creep tests at 1350° and 1500°F at Syracuse University. Specimens having an equivalent uniform diameter gage length of 2 inches (fig. 1(a)) were tested under combinations of steady axial stress with superimposed axial dynamic stress. Loads were applied by a constant-force spring mechanism, the alternating stress being applied at 3600 cpm. Temperatures were measured and controlled from thermocouples attached to the specimens.

Creep data were measured during the tests. In order to use the uniform-diameter gage length specimens, the stresses had to be kept in tension. Consequently creep data were limited to ratios of alternating-to-mean stress of 0, 0.25, and 0.67. Combinations of stress were used to give fracture times out to several thousand hours.

The Materials Laboratory, WADC, also sponsored high alternating-to-shear stress ratio tests, at Syracuse University and later at the University of Minnesota. Tests were carried out in the same machines at ratios of alternating to mean stress of 1.64 and ∞ at 1350° and 1500°F; and at ratios of 2 and ∞ at room temperature and 1000°F. A profile specimen (fig. 1(b)) was used to prevent buckling. The gage section was made the same as the specimens tested at Battelle Institute in Krause machines at high alternating stresses. Creep data could not be obtained from this type of specimen.

Difficulty was encountered from heating of the specimen by damping during the application of the load in the tests at room temperature and 1000°F. Attempts were made to control this by using an air blast to cool the specimens and by loading the specimens before they were brought to temperature. The most successful procedure, however, was to load the specimens at reduced cyclic speed and then gradually bring the specimen up to 3600 cpm as a function of temperature.

In addition to the tests carried out on specimens prepared and furnished by the NACA through the University of Michigan, completely reversed stress tests were made at 1500°F on specimens heat-treated and made at the University of Minnesota. The stock for the specimens was obtained from the producer in the form of bars rolled from the same ingot at the same time as those furnished to the NACA. Similar specimens were also used for part of the tests at 1000°F.

The testing machine and details of procedure are described in detail in references 2, 3, and 4.

3. Krause Axial Fatigue Tests

The Office of Naval Research and the NACA sponsored axial fatigue tests at Battelle Memorial Institute. Profile specimens (fig. 1(c)) were tested at 1200°, 1350°, and 1500°F with varying mean stresses for constant superimposed axial fatigue loads of ± 7500 , ± 15000 , ± 25000 psi. A modified specimen (fig. 1(d)) was used for tests going into compression and for completely reversed stress tests at 1350° and 1500°F.

Constant axial loads are applied by the Krause machine through a load maintainer, and constant-amplitude alternating axial loads at 1500 cpm are applied through a crank mechanism. Special adapters had to be developed for the tests going into compression. Some difficulty in obtaining axially for the tests going into compression was encountered; but was corrected by redesigning grips.

4. Sonntag SF4 Axial Fatigue Tests

The Elliott Company carried out tests in which combinations of steady axial and alternating axial stresses were applied. The alternating stresses were restricted to values which did not go into compression. The testing program was selected to provide the following data:

- (a) Establish the alternating stresses to cause fracture at room temperature for a mean stress of ± 75000 psi.
- (b) Obtain curves of alternating stress versus rupture time out to 500 hours at 1000°F for mean stresses of 75000, 60000, 45000, and 40000 psi.
- (c) Establish the influence of superimposed alternating stress on the rupture time for tests with the mean stress equal to the static rupture strength for 175 hours at 1350°F (28000 psi).

The Sonntog SF⁴ machine applies constant force loads through a spring mechanism. It operates at 3600-cpm. Temperatures were measured and controlled by thermocouples in the furnace adjacent to the specimen. Eccentricity difficulties required new grips for the higher stress tests at 1000°F.

The test specimen (fig. 1(e)) is profiled to a minimum diameter. A few of the specimens tested at 1000°F were machined by the Elliott Company from blanks heat-treated at Michigan.

5. Rupture Tests with Superimposed Alternating Bending Stress

The Research Laboratories of the General Motors Corporation conducted tests at 1350°F with combined rotating bending and steady axial tension stresses. A uniform-diameter gage length specimen (fig. 1(f)) was loaded in steady axial tension under 28000 psi (stress to cause rupture in 175 hours) and then rotating bending stress was applied at 10,800-cpm by causing one end of the system to rotate in a circle. The specimen was heated by gas flames. Temperatures were measured by thermocouples welded to the gage length of the specimen.

6. Westinghouse Reversed Bending Fatigue Tests

The Research Laboratories of the Westinghouse Electric Corporation conducted completely reversed bending tests at room temperature, 1000°, 1200°, 1350°, and 1500°F. Round-profile specimens (fig. 1(g)) were tested in the Westinghouse 7200-cpm electronic fatigue machine. The specimens are vibrated electrically at resonance in one plane so that maximum stress occurred on the surface at two diametrically opposite points. Temperatures were measured and controlled by thermocouples welded to the specimens.

In addition to a complete set of tests on specimens machined at Michigan with the controlled machining procedure, check tests were made on specimens simply turned and hand polished at Michigan. The object of these tests were to obtain some information regarding the influence of surface finish.

7. Effect of Surface Finish on Westinghouse Reversed Bending Fatigue Tests

The Lewis Laboratory of the NACA investigated the influence of surface finish on fatigue properties at room temperatures and 1350°F in the Westinghouse reversed bending fatigues machine described previously. A smaller specimen (fig. 1(h)) was used by the NACA. Three types of finish were utilized for the main tests: (1) ground and polished, (2) a plain ground surface, and (3) ground, partly polished, and then deliberately roughened with emery cloth. The influence of a stress relief for 4 hours at 1400°F on the fatigue properties at room temperatures was also established. In addition, tests were carried out at 1350°F on specimens

turned and polished. The polished specimens had about the same surface roughness as the specimens machined at Michigan. The specimens were machined at the Lewis Laboratory from blanks heat-treated by Michigan.

Temperatures were measured and controlled from thermocouples welded to the specimen.

8. Fatigue, Damping, Elasticity Properties from Rotating Cantilever Beam Tests on Unnotched and Notched Specimens.

The Materials Laboratory, WADC, sponsored tests at Syracuse University which provided fatigue, damping, and dynamic modulus data for room temperatures, 1350°, and 1500°F. A special testing machine rotated specimens under cantilever beam loads. Targets mounted on the rotating extension arm - loading weight - specimen assembly were used to measure vertical and horizontal deflections from which the damping and elastic values were calculated. Tapered specimens (fig. 1(i)) resulted in equal maximum bending stresses along the gage length.

All tests were conducted under variable speeds of rotation. A speed of 20 rpm was used for the first 500 cycles. In general, the speed was then increased to 50 rpm until several thousand cycles were imposed, after which the highest speed between readings was about 400 rpm for the elevated temperature tests and various speeds up to 1500 rpm for the tests at room temperature. All deflection readings were taken at 20 rpm. Temperatures were measured and controlled from thermocouples attached to the specimens.

Tests were made on notched specimens (fig. 1(i)) as well as the unnotched specimens. The theoretical stress concentration factor was 2.6 by Neuber's method. Approximate damping and dynamic elasticity properties were measured (ref. 5) but have not been included in this report.

The unnotched specimens were prepared at Michigan with the controlled surface finish procedures. The notched specimens were prepared by the John Stuhlen Company for Syracuse.

The testing machine and procedures are described in detail in reference 5.

9. Rolls-Royce Rotating Cantilever Beam Tests

The Rolls-Royce, Limited, of Derby, England, conducted rotating cantilever beam tests at their Research Laboratory. Tests were made at 1200°, 1350°, and 1500°F. The testing machine was of their own design and operated at 5500 rpm.

Temperatures were measured by thermocouples located $1/32$ inch from the critical section of the test specimen. Data were submitted which showed that the maximum difference between specimen and the measuring thermocouple was 3.25°C ; temperatures were reproducible to 1°C ; and at any instance during the test the error in temperature measurement due to heat produced in the specimen from damping was less than 0.50°C .

The specimens used (fig 1(j)) were profiled to a minimum diameter. They were machined by Rolls-Royce from heat-treated stock supplied to them. Their specimen was small enough so that they quartered the bar stock in making specimens.

10. NEES Rotating Cantilever Beam Fatigue Tests

The Engineering Experimental Station, U. S. Navy, conducted completely reversed fatigue tests at 1350°F in a rotating cantilever beam machine of their own design.

Tapered gage length specimens (fig. 1(k)) were loaded at one end and rotated at 1700 cpm.

SPECIMEN PREPARATION

In an effort to keep surface finish constant, all the specimens except as noted later were prepared by the NACA at the Production Engineering Department of the University of Michigan. Procedures were developed which would meet requirements of constant surface roughness and constant surface cold-work for all types of specimens included in the program. The objective was to avoid variable surface finish effects influencing the results from the various types of tests. A third variable arising from specimen preparation (surface stresses) should also have been constant since the surface preparation was duplicated regardless of the shape and size of the specimen.

The surface roughness was maintained at 2 to 4 microinches rms. This quality of surface finish was established to meet the most severe specification of the several cooperators.

The amount of cold-work on the surface after finishing was not measured. Extreme precautions, however, were taken to reproduce the method of metal removal on all specimens in order to keep surface cold-work constant. This requirement imposed severe restrictions because the very close dimensional tolerances of the specimens had to be met with a fixed procedure for metal removal. The result was that the specimen preparation was very time-consuming and expensive. Because emphasis was placed on reproducibility of surface finish on the various specimens and not on minimizing cold-work or surface roughness, the following details of machining and finishing operations should not be accepted as the most desirable for preparing fatigue specimens for testing at high temperatures.

Machining Procedure

All of the several types of test specimens submitted to the University of Michigan for machining were processed by substantially traditional methods. All gage sections were turned on a lathe with the exception of the Krause specimen for tests in compression (fig. 1(a)). This specimen was turned on a milling machine in a setup wherein the specimen was mounted between centers in the spindle and the cutting tool was mounted on a rotary table in turn mounted on the table of the milling machine; the rotary table was rotated manually through a worm gearset for the feeding motion. All turning tools were 18-4-1 high-speed steel machine ground to the following shape: 10° back rake angle, 15° side rake angle, 10° relief angle, and 0.010-inch nose radius. All cutting speeds were confined to the range 30 to 40 fpm; the depth of cut was selected in a descending sequence ranging from the maximum of 0.030 inch to a minimum of 0.005 inch, while the feed rate was held constant at 0.005 inch per revolution in every case except for manual feed where an attempt was made to keep the feed above a minimum of 0.005 inch per revolution.

The above conditions were set up in the belief that the amount of cold flow was directly proportional to the size of cut. Consequently, it was expected that the progressively decreasing series of depth of cut used consistently would establish a degree of control as well as lead to a minimum of cold flow. The unique characteristics of the specimen material make it unusually susceptible to burnishing and related effects resulting from dull cutting edges which behave even duller at light feed rates. This latter reason was the basis for establishing a minimum feed rate.

Finishing Procedure

The original finishing setup was on a Kent-Owens 2-20 milling machine. The milling-machine setup was characterized by a continuous belt and was unique in that a system of counterbalances was used in an attempt to minimize and control the pressure between the cloth-backed abrasive and the specimen. However, irregularities developed and the mass of the counterbalance system made it impossible to achieve control over the pressure between the abrasive and the specimen.

The Krause machine specimens in figure 1(c) were finished on the Kent-Owens setup using only cloth-backed abrasives as belts down through 500 grit, wherein the final step involved the use of chrome-oxide polishing stick rubbed on thoroughly worn 500-grit belts. Irregularities of the belts and the light pressures used made it impossible to improve the accuracy of the machined specimens and it is probable in some cases that the runout and out-of-roundness increased as a consequence of the finishing process.

The Westinghouse specimens were finished on a special setup wherein strips of cloth-backed abrasive were fastened to the surface of an oscillating sector while the specimen was mounted between centers and rotated. By this time all attempts to control finishing pressure by counterbalancing had been abandoned in favor of precision positioning of the specimens relative to the abrasive so that greater accuracy could be obtained. Pressure control was achieved somewhat arbitrarily by holding back on the rate of cutting so that the specimen did not heat. The finishing procedure used on the Westinghouse specimens is considered to be the most satisfactory in terms of the original objective although it was very slow and very expensive as a consequence of the relatively small amount of abrasive available during each setup.

All subsequent specimens were finished by one of two arrangements of a final setup shown schematically in figure 2. The specimen was mounted between centers and rotated. A continuous belt was operated over a system of driving and idler pulleys with the motion of the belt oriented longitudinally to the specimen. When the longitudinal section of the specimen was a radius, a pulley or wheel with a corresponding radius was mounted in place of the form block shown in the sketch although a form block could be used for these

specimens. The pulley or wheel was substituted for the form block in this case so as to reduce the heat arising from friction between the belt and the form block. Control of both pressure and size, to the extent that it was achieved, was obtained through screw adjustments of the position of the axis of the specimen relative to the form block or wheel.

The procedure for finishing specimens involved the use of continuous abrasive belts used in sequence of decreasing grain size with the following grain sizes: 60, 120, 240, 320, 400, and 500. This was followed by a final step wherein a standard tallow stick such as is used for grease polishing was smeared on a well-worn 500-grit belt to inhibit further its cutting action. It is vitally important to use this belt at highly specific operating conditions.

It is possible with such a combination to produce a highly burnished surfaced by exerting considerable pressure between the belt and the specimen to be finished. However, much less cold flow and an even smoother finish can be obtained by using a very light pressure between the belt and the specimen. So far as is known now this is a unique property of the type of specimen material.

It is significant that, as mentioned earlier in this report, chrome oxide was first used for this final step although tallow is now being used. By experimentation it became apparent that there was little or no value in the chrome-oxide stick as an abrasive, but rather that the beneficial effects arose from the ability of the stearate base or bond to inhibit the abrasive and cutting action of the belt. It was this experience which led to the final practice of using tallow on a well worn 500-grit belt for the final finishing step.

The belts were made from commercial rolls of Behr-Manning clothbacked abrasive. Appropriate lengths were cut on a bias and the belt was formed with a butt joint backed up with a manila paper of about 0.006-inch thickness and cemented with a commercial grinding disc cement (Gardner No. 2 Disc Wheel cement).

Specimens Prepared by Cooperators

Certain cooperators prepared their own specimens from stock heat-treated at the University of Michigan. In general, such specimens were for special purposes.

1. The Lewis Laboratory of the NACA prepared their own specimens because they were interested in studying surface finish effects. The gage section was made by form-grinding in a cylindrical grinder with a 60-grit aluminum oxide, vitrified bonded wheel of grade J and density 5. The grinding wheel speed was maintained between 5000 and 7000 surface feet per minute and the

specimen speed for the finish cut was maintained between 200 and 300 surface feet per minute. The "Polished" finish was prepared by polishing the ground surface with successively finer grades of emery cloth and paper, finishing in the longitudinal direction of the specimen with paper grade 20. The "rough" finish was prepared by simipolishing the ground specimens to remove the grinding scratches and then roughening the surface by holding a strip of 46-grit abrasive cloth against a slowly rotating specimen, causing circumferential finish marks. The "ground" specimens had the finish obtained in grinding, the finish marks being circumferential. One lot of specimens was turned in a lathe which gave the same finish described for the "polished" specimens.

2. The notched specimens for the rotating cantilever beam tests at the University of Minnesota were prepared separately. It seemed impossible to duplicate the surface finish of the other specimens in a notch. The John Stuhlen Company made the specimens for the University of Minnesota using the following procedure:
 - (a) rough turned to 0.070 inch oversize in diameter
 - (b) rough ground to 0.025 inch oversize in diameter, feed, 0.040 inch per minute
 - (c) rough ground to 0.007 inch oversize in diameter, feed, 0.020 inch per minute
 - (d) finish ground to size, feed, 0.010 inch per minute.
3. Part of the specimens used for axial fatigue tests at 1000°F and 1500°F at the University of Minnesota were heat-treated and machined by the University of Minnesota. These specimens are designated in table V by "N ... F" rather than the "J ..." designation used for specimens prepared at Michigan. The specimens were taken from the same stock as those prepared at Michigan but obtained directly from the supplier. Apparently, the machining procedure approximated that used at Michigan (ref. 3).
4. A few specimens were prepared by the Elliott Company from blanks heat-treated at Michigan.
5. The Rolls-Royce Company prepared their own specimens from heat-treated blanks furnished to them.

TEST DATA

Test data for each individual cooperator have been included separately in the report. An effort was made to present the data exactly as reported. In general, the fatigue curves have been drawn as nearly as possible the way the cooperator did in submitting the data. In a few instances, curves were re-drawn to present the data on a time basis rather than a number-of-cycle basis. In such cases, however, care was exercised to maintain the fatigue strength reported by the cooperator.

This procedure has been used because in several cases where there was duplication of tests, it is probable that the curves would have been drawn differently if all the data had been considered. It seemed evident in considering the data that this feature was significant.

The data for each cooperator are explained in the following sections and any significant features recorded.

Static Tensile and Rupture Tests

There was little variation in yield strengths between 1000° and 1500°F (see table III) although the tensile strength decreased appreciably over the same temperature range. Ductility also decreased with temperature. The agreement between check tests was quite close.

The original stress-rupture data obtained are given in table IV and figure 3. The points fell on straight lines of log stress against log rupture time with no more scatter than usual even though the specimens were taken at random from the original mill lengths of bar stock. The curve for 1200°F was unusual in that there was a decrease in slope at about 100 hours and 4500 psi, which is somewhat unusual. There appeared to be more scatter in elongation and reduction-of-area values than in the rupture times. They tended to decrease with time for rupture and were lowest at 1200°F.

When the data for static tests in the dynamic creep test unit at Syracuse University became available, their slightly lower rupture strengths was evident. Certain check tests were made to try to determine the cause (table IV and fig. 3).

Two specimens from the original group heat-treated and machined for Syracuse (fig. 1(a)) were tested at Michigan. One test fell closer to the Syracuse data than the original tests at Michigan (JX4). The other one was closer to the original data (JR5). Two check tests were made on new specimens using a 1-inch-gage length 0.050-in. in diameter to see if specimen size and surface preparation were responsible. The fracture times were

slightly less than the original curve for 0.505-inch-diameter specimens. One additional test was made on a 0.250-inch-diameter specimen with a 2-inch-gage length to see if the 2-inch-gage length of the Syracuse specimens was a factor. A perfect check of the original data on 0.505-inch-diameter specimens was obtained. These results tend to indicate variation in properties of the individual specimens (JX4) could have been a contributing cause and probably was combined with some factor in testing technique. Specimen size or surface finish was apparently not a factor. One possible reason for a consistent variation in specimen properties might have come from all of the original specimens tested at Michigan being taken from the end of the mill lengths, whereas the Syracuse specimens were taken farther along the bars.

Creep data from the rupture tests in the form of curves for 0.5 and 2 per cent deformation against testing time are shown in figure 4. Minimum creep rates measured are included as stress-creep rate curves in figure 5. These data are limited to 1200°, 1350°, and 1500°F because deformation on loading at 1000°F exceeded deformations of interest.

Dynamic Axial Stress Fatigue and Creep Tests

The dynamic creep test machine stresses a specimen axially with combinations of steady and alternating stress ranging from steady-load creep tests with no fatigue load through combinations of fatigue and steady stresses to completely reversed-stress fatigue tests. The test data obtained is given in table V. It will be noted that a series of tests was made at several constant ratios of alternating to mean stress (both alternating and mean stress were varied at a constant ratio). The primary graphical treatment was curves of mean stress against time for fracture for each constant ratio (see fig. 6), or of maximum stress against time for fracture (see fig. 7). The former method is most convenient for low ratios of stress and the latter for high ratios.

Ratios of alternating to mean stress of 2 and ∞ were used at room temperature and 1000°F. At 1350° and 1500°F the ratios were 0, 0.25, 0.67, 1.64, and ∞ . A ratio of ∞ involves completely reversed stress fatigue tests, while a ratio of "0" is a steady-load rupture test.

Creep data were also measured for the tests which did not go into compression (stress ratios of 0, 0.25 and 0.67). The specimens had a 2-inch-gage length of uniform diameter. Figure 6 includes curves of mean stress versus time for total deformations of 0.5 and 2.0 per cent for these stress ratios. Elongations of the fractured specimens are included in table V. Minimum creep rates are compared with those for rupture tests in figure 5.

In the tests in which the alternating stress went into compression (stress ratios of 1.64, 2.0, and ∞), it was necessary to use a profile specimen with a minimum diameter to avoid buckling. Two tests were made at a ratio

of 0.67 and 1500°F to check the results from the two types of specimens. The agreement was quite good (see fig. 6). Creep data could not be obtained from these type specimens, however. By agreement the gage section of these specimens was made identical to the high-alternating-stress specimens in the Krause machine. The following features of the data should be recognized:

1. Rather complete data were obtained for establishing the curves at 1350° and 1500°F.
2. Subsequent to the original curve established with specimens machined by the NACA at Michigan, the University of Minnesota conducted additional tests at 1500°F for stress rates of ∞ on specimens which they heat-treated and machined. The latter data yielded a curve which was of a considerably higher stress level than the original curve. For this reason two curves are included in figure 7 for a ratio of ∞ at 1500°F. The specimens were made from bar stock from the same ingot as that used for specimens made at Michigan but was not part of the stock supplied to Michigan by the producer.
3. Tests were also made at 1000°F on specimens heat-treated and machined at Minnesota. The data, however, are inconclusive as to whether there was a difference in the properties of the two groups of specimens.
4. The data are very sparse at room temperature and 1000°F. The curves shown in figure 7 are very approximate. Both a shortage of specimen and considerable testing difficulty were encountered, as detailed in the notes to table V. The points on figure 7 for which there were extenuating circumstances have been starred. The shortage of specimens led to retesting unbroken specimens after varying times of testing at higher stresses with a consequent uncertainty of the effect of prior history. Secondly a good deal of difficulty from overheating due to damping while the load was being applied was encountered, particularly at 1000°F. Those tests carried out at reduced cyclic speeds during loading to prevent overheating are indicated in table V. It was also noted that stresses below +40000 psi gave no difficulty. A small amount of overheating at 1350°F was also noted for the high-stress tests at zero mean stress.

The data presented are published and discussed in detail in references 3 and 4 except for the ∞ stress ratio tests at 1500°F for specimens heat-treated and machined at Minnesota.

Krause Axial Fatigue Tests

Data were obtained for combinations of steady axial stress and superimposed axial dynamic stress at 1200°, 1350°, and 1500°F (see table VI and fig. 8). A series of tests was made with varying mean stress with constant amounts of alternating stress, which led to stress-rupture time curves for the various constant alternating stress value. The tests at 1200°F were stopped at ± 25000 psi due to load limitations of the test machine. Tests were carried out at increasing alternating stress values at 1350° and 1500°F to completely reversed "0" mean stresses.

Most of the curves with varying mean stress were reasonably well established in the range of 50 to 500 hours and were fairly consistent. The completely reversed-stress curves are, however, based on very meager data. There was no evident effect from changing the dimensions of the specimens for the high-dynamic-stress tests. Some difficulty in alignment from grips was encountered for the high-stress tests. This was corrected and only the successful tests have been plotted in figure 8. No overheating during application of the loads was reported.

It will be noted that increasing amounts of alternating stress reduced strength as measured by mean stress. The reduction, however, decreased with increasing temperature so that there was little effect at 1500°F.

The curves for completely reversed-stress tests at 1350° and 1500°F were very nearly horizontal. Apparently in this type of test there is a characteristic maximum stress above which fracture occurs immediately and below which fracture is prolonged indefinitely.

Sonntag SF₄ Axial Fatigue Tests

The influence of varying alternating axial stresses on the time for fracture under constant mean stresses was established at room temperature, 1000°, and 1350°F (see table VII and fig. 9). The data show:

1. For time periods of 10 hours or less at 1000°F, the magnitude of the alternating stress rather than the mean stress in the range from 40000 to 60000 psi appeared to govern fracture. The approach to a common value of ± 30000 psi for fracture for these mean stresses suggests that the fatigue load governed fracture.

As the alternating stress was reduced, the curves diverged, indicating that mean stress became increasingly important in governing fracture time.

The necessity for the curves to drop rather abruptly to the rupture time from rather high levels of alternating stress indicates that there is a range of low alternating stresses which have little effect on fracture time. Thus, there appear to have been three types of response to the test conditions:

- (a) nearly pure fatigue at high values of alternating stress
 - (b) Fatigue and creep both governing life at intermediate values of alternating stress
 - (c) Nearly pure creep, at low values of alternating stress and prolonged times for fracture.
2. The tests at 75000 psi mean stress indicate that when there is a high level of mean stress, small amounts of alternating stress result in an excessive maximum stress and short life.
 3. The data at 1350°F follow the pattern of other tests in that as the temperature increased, larger amounts of alternating stress were required to shorten life from a given static rupture time.
 4. The data at room temperature are sparse, but suggest approach to a fatigue limit at 75000 psi \pm approximately 27000 psi.
 5. Fairly extensive testing problems were encountered for tests at high mean-stress values. The combination of this factor together with correction of eccentricity part way through the testing program makes it difficult to analyze causes for abnormal test results. These factors masked any effect, if one was present, from specimens machined at Michigan and the Elliott Company. It is suggested that the combined influence of both fatigue and creep at intermediate alternating stress values could in itself have been a source of erratic data.
 6. The measuring and control of temperature by thermocouples measuring furnace temperature could have masked overheating effects. This could have been responsible for apparently low strengths at high alternating stresses, as will be discussed later.

Rupture Tests with Superimposed Rotating Bending Stress

A series of tests was carried out at 1350°F with 10800 cpm rotating bending stresses superimposed on a steady axial stress of 28000 psi (see table VIII and fig. 10).

All the combined stress tests had less than one third the life of the rupture test alone. The three lowest alternating stress tests failed by rupture at points remote from the point of maximum stress. Only the highest alternating stress gave fracture at the point of maximum stress, and this was a fatigue failure.

The pronounced reduction in life from as small an alternating stress as ± 5000 psi was considerably different from behavior of specimens in axial combined stress tests. The axial tests either showed no reduction or an increase in life from small alternating stresses. The reason for the effect as well as the fracturing at points other than those of maximum stress is uncertain. The most likely explanation points to some material and testing-machine effect rather than to the presence of rotating bending stresses.

Superimposed alternating stresses of small magnitude can increase strength for a given mean stress, as indicated by other tests. This does not appear to be an adequate explanation of the abnormal fractures because it is difficult to see how the point of maximum stress could have been strengthened while the life could have been lowered by one third in other parts of the gage length, where the bending stresses were less. It was reported that other materials had always fractured at the point of maximum stress, so that some material characteristic apparently entered into the abnormal results.

Creep data obtained during the test and included in figure 10 as total deformation curves were apparently influenced less than the rupture time by the bending stresses. The much longer times required for fracture than for total deformations of 2 per cent was rather striking.

Westinghouse Reversed Bending Fatigue Tests

The Westinghouse machine bends a specimen in one plane at 7200 cpm. The results of the tests carried out at room temperature, 1000° , 1200° , 1350° , and 1500° F are given in table IX and shown as S-N curves in figure 11.

Fatigue limits were established by 5×10^6 cycles at room temperature, 1000° , 1200° , and 1350° F. A fatigue limit was not established in 10^8 cycles at 1500° F. There was no apparent difference in fatigue life between specimens finished by the specially controlled practice and those simply turned and hand polished.

Effect of Surface Finish on Reversed Bending Fatigue Properties at Room Temperature and 1350° F

Plain ground specimens were found to have considerably lower fatigue strength than polished or roughened specimens at room temperature

in the Westinghouse reversed bending fatigue machine (see table X and figure 12). The difference was considerably reduced at 1350°F, although the polished specimens were still slightly stronger.

Stress-relieving at 1400°F for 4 hours did not reduce the strength of the polished specimens at room temperature and may have increased it slightly at high stress values (see table X and fig. 12). Repolishing after stress-relieving did not alter the strength. The strength of the roughened specimens was, however, reduced to that of the ground specimens, and the ground specimens were not affected.

The turned and polished specimens had the same fatigue characteristics at 1350°F as the ground and polished specimens. (See table X and fig. 12.) The values reported for fatigue strength of polished specimens at room temperature were slightly lower than reported by Westinghouse, although it is doubtful if the difference is justified in view of scatter of data. There was no difference in reported strength between the two laboratories for 1350°F.

Fatigue, Damping, and Elasticity Properties
from Variable Speed Rotating Cantilever Beam Tests
on Notched and Unnotched Specimens

The fatigue data are given in table XI and plotted in figure 13. Figure 13 also shows curves for the "first-evidence-of-crack" for the notched specimens as obtained from changes in damping and stiffness behavior. It was not possible to obtain evidence of cracking prior to fracture from the damping and deflection data for the unnotched specimens. Such values would, however, be so close to the fracture curve as to nearly coincide with it.

The fatigue curves were considered approximate due to the small number of points. The approximate fatigue strengths were:

Type Specimen	Temp °F	Stress, psi for failure in indicated cycles		Effective Stress Concentration Factor at 3×10^7 Cycles ⁽¹⁾
		10^7	3×10^7	
unnotched	room	<u>+53000</u>	<u>+53000</u>	
	1350	<u>+40000</u>	<u>+40000</u>	
	1500	<u>+29000</u>	<u>+29000</u>	
notched	room	<u>+25000</u>	<u>+23500</u>	2.2
	1350	<u>+22000</u>	<u>+21500</u>	1.85
	1500	<u>+19500</u>	<u>+19000</u>	1.50

(1)theoretical stress-concentration factor according to Neuber's method was 2.6.

It is evident from these data and the curves of figure 13 that the notch drastically reduced strength. In fact, the notched specimens at room temperature were weaker than the unnotched at 1500°F for stresses below +31500 psi. Also there was very little difference in strength of notched specimens from room temperature to 1500°F for 10^7 cycles. The difference in cycles for the first evidence of a crack and actual failure for the notched specimens was amazingly large.

Because the cyclic speeds were so nonuniform in these tests, the significance of the times for fracture (table XI and fig. 14) is uncertain. It would seem that considerable information ought to be available from these data regarding influence of cyclic-speed effects. However, the data are so few and scatter so much that any possible conclusions are masked. It is evident that cyclic speed variations caused two points for notched specimens to deviate far more widely than on the basis of number of cycles. Observations other than this are masked by data scatter.

In addition to the fatigue data, damping and dynamic modulus-of-elasticity data were obtained by the cooperator. These data are thoroughly presented and analyzed in reference 2. For this reason such data are not presented in this report. The more important trends discernable from the data were:

1. Damping increased with stress and temperature in a complex manner, depending on the stress level, number of cycles, and temperature. Figure 15 shows the specific damping (in lb of energy absorbed per cu. in. of metal per cycle for uniform stress) as a function of stress for the three test temperatures.
2. The greater damping with increasing temperature for the temperatures considered at a given stress is evident.
3. The increase in damping with stress became sensitive to the number of cycles above certain limiting stresses at each temperature:
 - (a) room temperature - The damping decreased with number of cycles at stresses between +34000 and +60000 psi. Above +60000 psi the damping increased with number of cycles.
 - (b) 1350°F - Damping decreased with number of cycles above +26000 psi.
 - (c) 1500°F - There was little effect from number of cycles.

4. The rather high damping capacity at high stresses is noteworthy. The values are much higher for the engineering stress range than would be indicated from the low stress measurements and the usually accepted value of 3 for the exponent of the damping capacity-stress curves.

Data on damping for notched specimens did not show cyclic stress sensitivity. Perhaps the most important point to be noticed from the damping data from the notched specimens is the very small volume of metal absorbing energy and the consequent low energy-absorbing capacity in the presence of a notch.

The results of the measurements of dynamic modulus are summarized in figure 16. As in the damping measurements, dynamic modulus values change with stress and number of cycles, the major change being above some limiting value of stress. The changes in modulus were generally opposite to those for damping.

Determinations of dynamic stress-strain relationships are compared with static values and the fatigue limits in figure 17. The values reported are the deflections for the individual tests at 100 cycles of reversed bending. In addition to the static tension curves shown by the dashed lines, data from one static bending test are shown at room temperature by the small solid points. The bending data checked the dynamic values above the proportional limit rather than the static tension curves. It will be noted that:

1. The dynamic proportional limit was above the static-tension values. This might have been influenced by the sensitivity of the strain measurements and the use of separate specimens for each point.
2. At room temperature and 1350°F the fatigue strength was above the dynamic proportional limit and was very close at 1500°F

Rolls-Royce Rotating Cantilever Beam Test

Completely reversed stress tests were conducted on small specimens rotated at 5500 rpm with a cantilever beam load. The specimens were profiled to a minimum diameter. The heat-treated bar stock furnished to Rolls-Royce was quartered and the specimens machined from the quarters. Due to this procedure and due to the short length of the specimens, a number of tests were obtained from a single bar furnished to them with the coding system established by Michigan.

The data obtained from the tests at 1200°, 1350°, and 1500°F are recorded in table XII and shown as S-N curves in figure 18. The following observations should be recognized:

1. Fatigue limits were apparently attained by 10^7 cycles at 1200° and 1350°F . Apparently, a limit was not reached in 10^8 cycles at 1500°F .
2. There appeared to be two distinct curves at 1500°F . The higher curve was defined mainly by specimens from bars JP14 and JS15. The lower curve was based mainly on specimens from bar JR16, although there were test points on this curve from JP14 and JS15. Rolls-Royce suggested that this was evidence of appreciable variation along the length of the bars. Comparison of the data with those obtained in the Westinghouse machine, however, shows that the total scatter was about the same. Thus, there may have been an appreciable contribution to the scatter from bar-to-bar variations.

Bar JR came from a point in the ingot intermediate to JP and JS, so that this does not appear to be a cause of variation. Also, all three bars involved were taken from about the same location along the length of the original mill length.

3. The quartered specimens used by Rolls-Royce gave the same fatigue strengths as those obtained from other reversed bending tests in which the gage section was in the center of the original bar.

NEES Rotating Cantilever Beam Fatigue Tests

Tapered specimens having uniform stress in the gage length were tested in the 1700-cpm rotating cantilever machine of the Engineering Experiment Station, U. S. Navy, at 1350°F . (See table XIII and fig. 19.) The S-N curve of figure 19 indicates a lower fatigue strength than the other reversed stress tests. Actually, however, the scatter of points is the same as in the other tests. Thus, the fatigue results in this test checked other machines even though the EES preferred to report a curve at the lower range of the test points. As with other reversed stress tests at 1350°F , a fatigue limit was attained at 10^6 cycles.

Fracture Characteristics

The results of extensive studies of fractured specimens are summarized as follows:

1. Fatigue nuclei can appear in fractures of specimens tested at 1350° and 1500°F when an alternating stress of approximately 67 per cent of the mean stress is applied. (See fig. 20.)

The appearance of nuclei under combined stress apparently increases with alternating stress to a limit where the maximum stress (at a given mean stress) exceeds the limit the material can withstand for even a short time, and a tensile-type fracture results. This occurred in the 1 and 2 minute tests for dynamic creep with completely reversed axial stresses at 1350°F and accounts for those specimens at the outer range of alternating stress in combined tests which did not show fatigue nuclei.

For the lower values of alternating stress, the mean stress, at least, can be reduced to values where no nucleus appears and failure occurs entirely by creep rupture. This is equivalent to saying that as the time for fracture is increased by decreasing the mean stress, fatigue nuclei tend to disappear and the failure is characteristic of a creep-rupture test.

At 1000°F fatigue nuclei apparently occur at lower ratios of combined stress than at the higher temperatures. On the other hand, tests at 1200°F in the Krause machine did not show fatigue nuclei when the alternating stress was nearly equal to the mean stress.

All completely reversed stress tests showed fatigue nuclei, except a few very high stress tests of very short duration which appeared to have failed entirely by excessive tensile deformation.

2. The longer time tests at 1350°F had more of a tendency to fracture with a fatigue nucleus than tests at 1500°F at the same ratios of alternating to mean stress. Apparently at higher temperatures there is more of a tendency for fracture by creep-rupture than by fatigue for the same times for fracture.
3. The fractures in the fatigue nuclei were straight, transgranular, and showed no evidence of deformation.

In those specimens which failed in a short time with a fatigue nucleus, the remaining area of fracture outside the nuclei resembled short-time tensile fractures. As the time for fracture increased, the fracture area outside the nucleus tended to resemble rupture-test fractures at the same time period, that is, the fractures became increasingly intergranular. Even the completely reversed axial fatigue specimens showed substantial amounts of intergranular fracture at the

longer time periods at 1350° and 1500°F. Low mean stresses and high alternating stresses reduced the tendency for creep-rupture type of failure and often resulted in what appeared to be a combination of fatigue nuclei, creep-rupture, and rapid tensile-type fractures. High mean stresses and low alternating stresses favored creep-rupture type fractures even for the same time for fracture.

4. Fatigue nuclei appeared both internally and at the surface of axial fatigue specimens.
5. Creep-rupture specimens normally show intergranular cracks adjacent to the main fracture, particularly at the surface. This tendency normally increases with both temperature and time for fracture. This tendency was reduced by high alternating stresses, although intergranular cracking at the surface was found even in the longer-duration completely reversed axial stress tests at 1350° and 1500°F. A longer time for fracture or a higher temperature seems to be required to produce a given state of crack formation under fatigue loading.
6. No evidence was found to show that an intergranular creep-rupture crack initiated a fatigue nucleus. In fact, it was not possible to determine whether the fatigue nucleus or the creep-rupture type of fracture occurred first or if they developed simultaneously in the combined stress tests.
7. There is some scatter in the data relating fatigue nuclei to stress in figure 20. The scatter, however, seems related to some extent to the type of test machine. This is mainly evident in the comparison of the dynamic creep-test data and the Krause machine data at 1350° and 1500°F. While the data are very few, it appears that alternating stresses for fatigue need to be slightly higher for the Krause specimens to develop fatigue nuclei. This may have been related to the use of profiled specimens, as compared to uniform-diameter specimens, in the dynamic creep specimens. It seems possible, however, that the higher cyclic speed may have been a factor in the greater nuclei-forming tendency of the dynamic creep specimens. This is partially supported by the one good test in the 10800-cpm General Motors machine at 1350° showing a fatigue nucleus whereas the tests in the 3600-cpm dynamic creep test and Sonntag SF-4 machines did not. Again however, this might have been due to the rotating bending in the high-speed machine instead of axial fatigue loading in the slower machines.

8. A very detailed study of fractures was carried out at Syracuse and Minnesota on their test specimens. (See references 6, 7, and 8.) In general, their findings agreed with those of others. It was found, however, that a prohibitive amount of work would have been necessary to duplicate their quantitative measurements of percentage intergranular fracture in all specimens. As they found, it is difficult to estimate such values reliably. For this reason this report has been restricted to qualitative observation and is nowhere as detailed in description of fractures.

Typical microstructures for the original material, fracture at a fatigue nucleus, and a rupture fracture are included as figure 21. The reader is, however, referred to the remarkable composite photographs of complete fracture profiles in reference 8 for more complete pictures of fracture.

Reference 8 also indicates that structural changes are slightly increased in rate by stress. High alternating stress was reported to increase the rate of breakdown of an intergranular precipitate which occurs in the test alloy at prolonged times at 1350° and 1500°F.

DISCUSSION

The data obtained show the relationships between static and fatigue properties of the test material over a wide range of temperatures. Test conditions ranged from ordinary tensile and creep-rupture tests through combinations of steady and fatigue loads to completely reversed fatigue tests. The features of the relationships between steady and fatigue loads will be correlated in the following sections.

Rupture and Fatigue Strengths

The influence of superimposed fatigue loads on stress-rupture time curves was as follows:

1. As the temperature increased, larger amounts of fatigue loading could be added without appreciably affecting the stress-rupture time curve. (See figures 6 and 8.) At a high temperature for the alloy (1500°F) fatigue stresses as large as 67 per cent of the steady stress did not change the stress-rupture time curve appreciably.
2. As temperature was lowered, less and less fatigue load could be tolerated without reducing strength. At 1350°F fatigue loads up to +15,000 psi had little effect, while at 1200°F loads above +7500 psi reduced strength. (See figure 6.)
3. The reduction in strength due to superimposed fatigue loads tends to be greater at short time periods than at long time periods. This is evident in the tendency of the stress-rupture time curves for the higher superimposed alternating stresses to converge at long time periods in figures 6 and 8.
4. At high ratios of alternating to steady stress, the curves of mean stress against rupture time tend to flatten out. This behavior would be expected inasmuch as the completely reversed stress curve would necessarily have to be horizontal at zero mean stress. The major influence of temperature is to control the alternating-stress level at which the flattening occurs and the resulting degree of strength is evident in the curves of figures 6 and 8.

5. Completely reversed stress and high ratios of alternating-to-mean stress are more realistically presented in terms of maximum stress, as in figures 7 and 8. It is evident that these high-stress fatigue curves based on maximum stress cross or lie above the lower-stress curves at the longer true periods when both are considered on a maximum stress basis.

These trends in the relationship between static and dynamic rupture-strength characteristics are summarized by the curves of alternating stress versus mean stress for fracture in 50, 150, and 500 hours in table XIV and figure 22. The tendency for the decreasing influence of **alternating stress with increasing temperature** is evident. The decreasing influence of alternating stress with increasing time for fracture is also evident, though it is not as striking as in the stress-rupture time curves previously discussed. Perhaps the most significant feature of figure 22 is the fact that at 1500°F, superimposed alternating stresses had to be increased to the nearly completely reversed level to change strength appreciably. The indication of slight strengthening from small superimposed fatigue loads apparently was real.

The relative strengths under static and fatigue loads are further compared in figure 23. This figure shows the influence of temperature on static tensile, 0.2 per cent offset yield strength and the 50-, 150-, and 500-hour rupture strengths, as compared to the completely reversed fatigue strengths and the mean stresses for superimposed fatigue loads of ± 7500 , $\pm 15,000$, $\pm 25,000$, and $\pm 35,000$ psi for the time periods of 50, 150, and 500 hours. These curves show clearly the temperatures for the various time periods where the controlling property shifts from fatigue-to-static stresses. It is interesting to note that insofar as static strength is concerned, the yield strength would govern allowable stress up to 1325°F for 50 hours and up to 1225°F for 500 hours. Some of the ratios involved are also of interest:

		Room Temp.	1000°	1200°	1350°	1500°F
<u>Fatigue Strength</u>	Axial	0.38	0.48	---	0.58	0.54-0.68
Tensile Strength	bending	.46	.52	.58	.65	.57- .66
<u>Fatigue Strength</u>	Axial	---	.54	---	1.09	1.3 -1.56
50-hr rupture strength	bending	---	.59	.86	1.22	1.5
<u>Fatigue Strength</u>	Axial	---	.61	---	1.23	1.5 -1.8
150-hr rupture strength	bending	---	.66	1.05	1.38	1.7
<u>Fatigue Strength</u>	Axial	---	.67	---	1.43	1.7 -2.0
500-hr rupture strength	bending	---	.73	1.13	1.6	1.9

The ratio of completely reversed strength to tensile strength tended to increase from about 0.4 to 0.68 with temperature. The ratios of fatigue strength to static rupture strength also remained at about 0.6 at 1000°F. However, at the higher temperatures, the fatigue strengths were higher than the static rupture strength, the ratios ranging up to the maximum value of 2 for 1500°F and 500 hours. There were variations in the data from different tests, which will be discussed later. The general trends, however, appear valid for the data and should not be confused by the small difference due to test machines.

The relationships between static and dynamic properties appear to be controlled by the relative predominance of creep or fatigue damage as influenced by temperature, stress level, and time. At high stress levels rapid repetitions of a given stress were more damaging than a steady stress from a static load. At temperatures where creep occurred, a static stress eventually became more damaging than the same stress repeatedly applied. Consequently, conditions were reached at which the static strength was less than the fatigue strength. This was true at shorter time periods and increasingly higher stresses as the temperature was increased. For these reasons, fatigue strengths were always lower than static strengths where creep was not involved and for all except relatively short time periods were higher at high temperatures where creep did occur.

Fatigue Strengths Based on Cycles to Failure

The fatigue strengths based on cycles to failure were the same as these based on time to failure when fatigue limits were established. The two differ due to variation of cyclic speed in different test machines when the time periods involved were less than those required to establish a fatigue limit, or when a definite fatigue limit was not involved. The stresses for fracture established for the arbitrarily selected values of 10^7 , 3×10^7 , and 10^8 cycles (table XIV and fig. 24) show such deviations. The features of figure 24 are:

1. At 1350° and 1500°F the 3600-cpm dynamic creep test unit and the 1500-cpm Krause machine gave considerably different values at low superimposed fatigue stresses. The strengths were time-dependent under these conditions due to the predominating effect of creep, so that higher values were obtained in the ~~3600-cpm~~ unit than in the slower, 1500-cpm, machine.
2. The agreement for the two axial-type units, was improved at high values of superimposed stresses; but it was not perfect. The reason for this is not apparent from the data.

Influence of Superimposed Fatigue Loads on Creep

Fatigue stresses superimposed on steady static loads appear to have the same effects on total deformation as they do on rupture properties. (See figures 6 and 25.) The data do not cover as wide a range of combinations of stresses as for rupture; but up to ratios of alternating to mean stress of 0.67 the behavior had the same general characteristics. The most significant difference was the substantial decrease in time for the total deformation curves of figure 6 to converge at 1350°F, where the stress ratio was high enough to reduce strength at the shorter time periods. The following tabulation gives the time periods beyond which there was no appreciable effect from superimposed stress at 1350°F:

	Time to Reach Equal Strengths at Alternating-to-Steady Stress Ratios of 0, 0.25 and 0.67 (hr)
Rupture	2000
2.0% total deformation	800
0.5% total deformation	100

This illustrates strikingly the degree to which the effects of fatigue loads were reduced for limited amounts of creep. Superimposed alternating loads must have less effect on creep than on fracture characteristics. Another way of expressing this effect would be to state that superimposed fatigue loads probably have little effect until third-stage creep occurs.

The lack of an appreciable effect of superimposed fatigue loads on creep prior to third-stage is emphasized by the almost complete absence of any effect on minimum creep rates for stress ratios up to 0.67. (See figure 26.) In reference 3 it was shown that there was no effect of alternating stress on total creep up to the start of third-stage creep for the same data.

The data for total deformations reported for the General Motors rupture tests with superimposed rotating bending (fig. 10) differ from those established by the dynamic axial creep tests. The main difference is that the General Motors tests show appreciable times for limited deformations at 28,000 \pm 18,800 psi whereas the dynamic creep tests show that 0.5 per cent deformation was exceeded by this stress on loading and 2 per cent was reached in a very short time period. The two sets of data agree very well at 28,000 \pm 7000 psi and for static tests. It will be noted that at the high mean stress of 28,000 psi, a small amount of superimposed fatigue loading reduced total deformation strength. The General Motors data

indicate no effect from substantial further increases in fatigue stress while the dynamic creep tests indicate continued decrease in time to reach the deformation. The General Motors tests tend to follow the trend of the Krause data more than the dynamic-creep test data.

Influence of Superimposed Fatigue Stress on Elongation in the Rupture Test

Elongations were reduced from those exhibited by static tests in increasing amounts (table V and Fig. 26) by fatigue loading:

1. At 1350°F when dynamic-to-static stress ratios were 0.67, 1.64, and ∞ .
2. At 1500°F when stress ratios were 1.64 and ∞ .

There was also some tendency for the elongations to be reduced at shorter time periods for the smaller dynamic loadings.

As would be expected, there was very little elongation in completely reversed stress tests. The values of 2 per cent of 1500°F were, in fact, surprisingly high. It is uncertain if this latter effect was due to error in measuring matched fractures or represents a real effect from more creep in tension than in compression.

It was interesting to note that the high values of superimposed stress apparently eliminated the time dependency of elongation characteristic of static tests. There was also a slight tendency for improved elongation at the longer time periods for the lowest dynamic loads (stress ratio of 0.25).

This influence of alternating stress on total elongation contrasts sharply with the absence of an effect for limited creep deformations or total creep through second-stage creep discussed in the previous section. While it is true that the limited total-creep effects were restricted to stress ratios of 0.25 and 0.67, it appears that for these ratios, at least, superimposed dynamic stress effects are largely limited to third-stage creep.

Stress-Strain Characteristics under Fatigue Loading

Completely reversed stress tests (fig. 17) in a rotating cantilever beam type test indicated that static tensile proportional limits fell below the dynamic bending proportional limits. Apparently this is not necessarily a characteristic result inasmuch as data for mild steel showed the opposite effect (ref. 5).

Static bending tests gave load-deflection curves at room temperature, which coincided with those for the dynamic bending tests. The more gradual deviation from proportionality for the bending curves is related to the restriction of plastic yielding to the higher-stressed surface layers in the bending tests. The reason for the higher proportional limit under bending conditions is not as clear. Possibly testing technique, particularly sensitivity of strain measuring equipment, could be involved.

Perhaps the most important point from the dynamic modulus data regarding the relationship between static and dynamic properties, is that static or low-stress modulus data can be very misleading in computing resonance effects. At least for the material tested the tendency for dynamic moduli to decrease with stress is reduced by increasing temperature and also with increased numbers of cycles. Variations of dynamic moduli of the type shown by figure 16 could be a source of considerable shift in vibration response on both a stress and a number-of-cycle basis. Such variations are, however, considerably less for stresses below the fatigue limit than for those above the fatigue limit.

Damping Effects

The actual data on specific damping (fig. 15) were discussed previously from the viewpoint of actual stress and stress history. In addition, damping characteristics as evidenced in heating of test specimens was mentioned for several of the axial-stress-type tests.

From the viewpoint of the relationship between static and fatigue properties, damping characteristics probably alter the relationships between static and fatigue properties in a manner that is not evident from this investigation.

Insofar as actual fatigue is concerned either in practice or in testing, one important feature of the data is the very evident excessive temperatures which can be induced by high damping under high fatigue loads. For the test material involved damping can be much higher at engineering stress levels than would be expected from low-stress data. It may also increase or decrease with the number of cycles of applied stress. The surprising large damping at high stress levels is probably related to the overheating problem encountered in a number of the tests in axial-stress machines, since the energy absorbed where the whole specimen is being stressed can be quite large. This effect seems to be critically influenced by cyclic speed and stress level in a nonuniform manner. This observation is based on the reported extremely rapid temperature increases reported for axial tests at room temperatures and 1000°F above certain stress levels. Further it seemed that the machines operated at 3600-cpm were more subject to such heating than the 1500-cpm machine. In fact, reduction of cyclic speed during loading seemed

necessary to control the heating. Apparently, these critical effects diminish with temperature since no one reported overheating at 1500°F even though damping increased with temperature.

High damping tends to reduce notch sensitivity. A notch is very detrimental, however, when material damping is important because the volume of metal at high stress in the notch is too small to absorb much energy.

Apparently damping characteristics can vary in different alloys to a considerable extent (ref. 5).

Influence of Cyclic Speed on Fatigue Properties

The major emphasis in this report has been placed on properties from a time viewpoint. The main problem has been to relate fatigue properties to the rupture properties which are expressed in terms of the static stress for rupture in a specified time.

Cyclic speed effects in the fatigue tests would be expected to:

1. Show a difference in strength for a given number of cycles where the speeds of the machines differ and the fatigue properties are time-dependent (i.e., no fatigue limit as at high temperatures or at stresses above fatigue limit).
2. Show a difference in fatigue strength where the cyclic speed itself influences properties.

The data obtained show the following regarding cyclic speed effects:

1. Tests carried out at low values of superimposed alternating stress and at high temperature where creep occurs show differences in strength between the 3600-cpm and 1500-cpm machine tests on the basis of number of cycles. There was little difference in strength on a time basis (compare figures 22 and 24) at 1350° and 1500°F.
2. Comparisons based on number of cycles did not eliminate the differences between the two axial tests at high alternating stress values. (See figures 22 and 24 at 1350° and 1500°F.) Both machines indicated fatigue limits, so that there was little difference between comparison based on time or cycles. The 1500-cpm machine gave the higher strengths although it is doubtful that cyclic speed differences were responsible.

3. There were differences in fatigue strength for completely reversed stress tests. It is difficult to determine if this was due to cyclic speed variation or to other causes. Data scatter tended to obscure such effects. There were a few trends which may be due to cyclic speed:

- (a) The Westinghouse 7200-cpm machines tended to require higher stresses than the other machines to fracture in a given number of cycles. (See figures 22 and 23.) This was not as evident at room temperature as at temperatures of 1200°F and higher.
- (b) The short-time tests in the variable-speed rotating cantilever tests tended to fracture at shorter times than did the tests in the Westinghouse machines. The short-time tests were run at very slow cyclic speeds. This, however, is not a definitely established effect, inasmuch as some of the other tests also tended to show the same behavior.
- (c) In view of the relatively small differences between the fatigue strengths for the variable-speed cantilever tests and the other higher-speed machines, it seems doubtful the cyclic speed alone had much effect, possibly the very slow speeds resulted in low strength for short time periods.

The lowest fatigue strengths were obtained in axial stress test machines. This, however, is apparently due to other causes than cyclic speed.

A possible relation between cyclic speed and overheating was discussed under damping effects. High cyclic speeds unquestionably increase overheating from damping.

The possibility exists that fatigue nuclei may be expected in fractures from combined stress at somewhat lower stress ratios for higher-speed machines. This may be the reason for the slight overlap of the stress conditions for the appearance of nuclei in figure 20. This does not seem unreasonable because the slower-speed machines require longer times for fracture and there is a time-depending effect on the time of fracture at 1350° and 1500°F.

Influence of Notches on Fatigue

No data were accumulated for notched specimens under static stresses. The variable-speed rotation cantilever beam fatigue tests indicate the very pronounced reduction of fatigue strength which can result from a notch. (See figures 13 and 14.) The indications that there is little difference in the fatigue strength for notched material over a wide range of temperatures were somewhat surprising. Notch weakening was reduced by increasing temperature, although there still was a substantial difference between notched and unnotched specimens even at 1500°F.

The very much longer time required for fracture of notched specimens after the first evidence of a crack was also surprising. This is particularly true in view of the very short time difference for unnotched specimens. This should be an interesting phenomenon for both stress analysis and fracture study.

Surface Finish

The most important general result of the NACA Lewis Laboratory studies of the effect of surface finish is the evidence that such effects decrease with increasing temperature. Very little effect remained at 1350°F, in spite of the fact that there was a substantial effect at room temperature. This checks the cooperators results on another heat of low-carbon N155 alloy (ref. 9) although the other heat showed lower strengths and lower temperatures of disappearance of the effect of surface finish.

The influence of surface finish seems to be related more to the procedure used in finishing the specimens than to surface roughness (ref. 9). Polished surfaces apparently have higher strength than plain ground specimens at low temperatures. This, however, does not appear to be related to less surface roughness inasmuch as the rough surface was even stronger. Reference 9 attributed the main effect to the compressive stresses induced by polishing or by the roughening procedure, offsetting the fatigue stresses and requiring higher applied stresses for fracture. The reduced effect of increasing temperature was attributed to stress relief.

The data obtained for this report do not substantiate the stress-relief theory as definitely as the previous work on the same alloy with a lower fatigue strength. Heating at 1400°F did not change the fatigue strength at room temperature for either the ground or polished specimens. The rough specimens were, however, reduced to the level of the ground specimens.

All surfaces were cold-worked by the finishing procedures. Cold-working definitely alters strength at both low and high temperatures and ductility characteristics as well. It seems improbable, therefore, that residual stress effects alone control the effect of surface finish. The ground surface should have had the least cold-work and particularly a very shallow depth of penetration. The polished and rough surfaces should have had increasing effects. A 4-hour treatment at 1350°F would not be expected to remove the effects of such cold-work, although it should considerably decrease the strength and increase the ductility. It is probable that a complete evaluation will show a complex relation between residual stress, strength, and ductility, as reflected in fatigue properties. Thus different alloys, different heat treatments of the same alloy, or different response at the same alloy to treatment (see low fatigue strength of N-155 alloy in reference 9) all probably alter surface finish effects.

Polished specimens of the material used for this investigation prepared by different laboratories showed no significant difference in fatigue characteristics at 1000°, 1200°, 1350°, or 1500°F. It would appear, therefore, that there was either little difference in surface finishes or that fatigue properties of the alloy at these temperatures were not sensitive to variations in polishing. The NACA Lewis Laboratory data suggested that there ought to have been an effect at 1000° and 1200°F if there were differences in surface finish. Their data show slight effects at 1350°F, and if true they would indicate greater effects at lower temperatures. Possibly their data at 1350°F were not outside the scatter band and here actually was no great effect even at 1000°F, as was indicated by their data in reference 9.

The indication of an absence of surface-finish effects on fatigue at high temperatures should not be accepted as general until a much wider range of response of alloys to cold-work and stress-concentration effects have been studied. In view of the known sensitivity of other properties of heat-resistant alloys at high temperatures to cold-work, it seems unlikely that all alloys will be free of such effects. This seems particularly true for bending fatigue, where stresses are a maximum on the surface.

There is one very interesting feature of the NACA Lewis Laboratory data. The ground specimens had a fatigue strength about 5000 psi less than the polished specimens. This is the same order of magnitude as the difference between axial and reversed bending fatigue tests. Axial fatigue tests would probably be much less sensitive to surface finish effects. The ground specimens were considered to have low strength because they were relatively free of surface-finish effects. This suggests that a major contributing cause for the difference between the two types of tests was the increased strength imparted to bending tests by polishing. The decrease in difference with increasing temperature also parallels the influence of surface finish found by the Lewis Laboratory.

Types of Testing Machines

There were four general types of stress applied by the various testing machines:

1. Axial with Superimposed Axial Fatigue Load

In general, this type of test gave lower results than the bending type tests for completely reversed stresses. This is shown by the data of table XIV and figures 22, 23, and 24. The actual S-N curves of figure 27 show clearly the tendency to be lower. As was pointed out in the surface finish studies, this difference may have largely been due to high compression stresses in the surface of the bending specimens. The general absence of a "knee" in the S-N curves for axial tests was also evident.

The difference between the two types of tests tends to disappear at the longer times at the higher temperatures. This is more evident on a time than on a cyclic basis.

As discussed elsewhere, the two axial-type test machines did not agree too well over the range of superimposed stresses from static to completely reversed stress tests. Apparently, some variable in the characteristics of the two machines is the most logical reason. Differences in cyclic speed do not seem to be the answer.

The curves of alternating-versus-mean stress for fracture in 50, 150, and 500 turns (fig. 22) at 1000°F were irregular and approached closer to the 1200°F curves than would be expected. No evident reason was found to explain the difference. It was noted that the tests at 1000°F showed fatigue nuclei at rather low stress ratios whereas those tested at 1200°F showed the opposite effect. It also should be noted that the Krause tests tended to give higher strengths than the dynamic creep machine. It is possible that the Sonntag machine gives lower strengths than the Krause machine pulling the curves together at 1000° and 1200°F.

2. Axial with Superimposed Rotating Bending Fatigue Loads

Only a few tests were made with this type of machine and only one specimen fractured at the point of maximum stress. This one test agreed very well with those made in the axial fatigue machines. The very little evidence indicates agreement between the two types of stressing. The reason for part of the tests fracturing away from the point of maximum stress in this test remains unexplained.

3. Cantilever Beam Tests, Vibrating in One Plane with Completely Reversed Stress

Only one machine of this type was involved, although it was used by two laboratories. Different-sized specimens were used in the two laboratories. While there were minor variations in the reported fatigue strength it is doubtful that the differences were outside the normal scatter of the data.

4. Rotating Cantilever Beam Tests

Some variation in reported fatigue strengths existed between the various rotating beam tests and with the fixed bending tests. (See table XIV and figures 23, 24, and 27.) It is difficult to determine whether such variations were real or reflected data scatter. There was a slight tendency for the rotating tests to give lower strengths than the fixed Westinghouse machine tests. The low curve at 1350°F reported for the NEES tests was largely due to the cooperator drawing the curve on the low side of sparse data. The test points (fig. 27) agree reasonably well with the other tests.

The very slow variable-speed rotating tests tended to fracture at short time periods at the higher stress (fig. 27). This suggests a possible reduction in strength at low cyclic speeds. Otherwise the variable speed tests agreed reasonably well with the other tests.

Limitations of Findings

The major limitation of the relationships developed in this report are their limitation to one alloy with one heat treatment. It is expected that the trends are characteristic of static and fatigue tests. It is, however, reasonably certain that the characteristic effects will vary in temperature, time period, and magnitude for various alloys or the same alloy with varying heat treatments. The data in this report indicate that increased creep resistance will increase the temperatures and time periods to which fatigue will control properties. This, however, will probably be altered by fracture characteristics at least and probably by other characteristics not immediately evident. For instance, factors which minimize third-stage creep ought to minimize the effects of superimposed fatigue or steady loads. Alloys may differ considerably in sensitivity to surface-finish effects. Likewise, the detrimental effect of large grain size on fatigue resistance is reported to be important.

Many of the fatigue-strength values reported, particularly for the high alternating-stress axial tests, are based on very limited data and are only approximate. The reported difficulties from overheating by damping in these types of tests also raises the question as to how much influence from this source is reflected in the data.

The Rolls-Royce data suggest **that** an appreciable amount of scatter in the data may have been due to variations from specimen to specimen. The substantial difference in fatigue strength for completely reversed axial stress tests at 1500°F on specimens prepared at Michigan and those prepared at **Minnesota** also points to the possibility of some contribution to scatter **from** variations in heat treatment.

There are minor differences in data due to peculiarities of test machines, although presumably they applied the same combinations of stresses. These do not, and should not, complicate the overall trends. They simply point out that there are characteristics of different machines which alter the results of the tests to a minor degree. These could **at least** be related to the actual shape of the stress pattern, the way the stresses are applied, or to some of the evident difficulties of calibration.

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TABLE I. PROCESSING OF LOW-CARBON N-155 1-INCH ROUND BAR STOCK

(Reported by the Universal-Cyclops Steel Corporation)

An ingot was hammer-cogged and then rolled to bar stock under the following conditions:

1. Hammer-cogged to 13-inch square from 15-1/2-inch ingot
Furnace temperature, 2210° - 2220°F
Three heats - Starting temperature on die, 2050° - 2070°F
Finish temperature on die, 1830° - 1870°F
2. Hammer-cogged to 10-3/4-inch square
Furnace temperature, 2200° - 2220°F
Three heats - Starting temperature on die, 2050° - 2070°F
Finish temperature on die, 1790° - 1800°F
3. Hammer-cogged to 7-inch square
Furnace temperature, 2200° - 2220°F
Three heats - Starting temperature on die, 2050° - 2070°F
Finish temperature on die, 1790° - 1890°F
Billets ground to remove surface defects.
4. Hammer-cogged to 4-inch square
Furnace temperature, 2190° - 2210°F
Three heats - Starting temperature on die, 2040° - 2060°F
Finish temperature on die, 1680° - 1880°F
Billets ground to remove surface defects.
5. Hammer-cogged to 2-inch square
Furnace temperature, 2180° - 2210°F
Three heats - Starting temperature on die, 2050° - 2065°F
Finish temperature on die, 1730° - 1870°F
Billets ground to remove surface defects.
6. 1-inch rounds were rolled from 2-inch square billets in one heat. The 2-inch bars were heated in a furnace at 2100° to 2115°F; the temperature at the start of rolling was 2050° to 2060°F; and the finishing temperatures were from 1820° to 1840°F. The bars were numbered in order of their position in the ingot.
7. Bars were assigned letters from A through Z, Bar A representing the extreme bottom of the ingot and Bar Z the extreme top position.

All billets were kept in number sequence throughout all processing, so that ingot position of any bar could be determined by its letter.
8. All bars were cooled on the bed and no anneal or stress relief was applied after rolling.

TABLE II. BRINELL HARDNESS RANGES OF TEST STOCK

HEAT TREATMENT: 2200°F for 1 hour - W.Q. - 16 hours at 1400°F

(NACA Data from University of Michigan)

Bar*	Surface	Cross Section	Range
JA	207-220	217-218	207-220
JB	197-212	207-214	197-214
JC	210-212	214-216	210-216
JD	207-208	210-214	207-213
JE	204-216	212-217	204-217
JF	199-214	212-214	199-214
JG	198-215	201-216	198-216
JH	203-212	205-212	203-212
JI	192-215	201-213	192-215
JJ	209-212	210-211	209-212
JK	203-208	205-213	203-213
JL	211-214	211-215	211-215
JM	203	200	200-203
JN	205-208	213-214	205-214
JO	206-208	212-214	206-214
JP	201-213	211-211	201-213
JQ	201-215	213-216	201-216
JR	211-215	212-216	211-216
JS	206-211	208-212	206-212
JT	205-211	206-210	205-211
JU	204-208	213-215	204-215
JV	205-207	211-212	205-212
JW	208-208	210-216	208-216
JX	203-211	210-214	203-214
JY	211-212	211-216	211-216
JZ	202-205	209-211	202-211
Over-all Range	192-220	200-218	192-220

* Specimens taken from 26 bars marked A through Z. "A" represents the bottom bar from the ingot and "Z" the top bar from the ingot, with the others lettered consecutively in between.

Note: Hardness values were taken on samples cut from the center and each end of every bar.

TABLE III. TENSILE-TEST DATA

(NACA Data from University of Michigan)

Specimen	Test Temp. (°F)	Tensile Strength (psi)	Proportional Limit (psi)	Offset Yield Strengths (psi)			Elongation (% in 2 in.)	Reduction of Area (%)	
				0.01%	0.02%	0.10%			
JM1	Room	119,100	41,000	46,000	48,700	56,100	59,500	45.0	46.2
JY1	Room	119,000	40,000	47,600	50,500	58,500	61,500	42.5	45.5
JF1	1000	91,250	26,750	31,750	32,500	34,800	35,800	44.5	49.3
JW1	1000	93,900	26,000	31,750	34,000	38,750	40,000	39.5	45.7
JM4	1000	94,250	26,250	32,500	33,800	37,000	37,750	42.0	47.1
JP1	1200	81,200	25,750	29,500	30,500	34,250	35,250	35.0	38.0
JG1	1200	79,600	26,000	29,500	31,000	34,900	35,800	33.0	34.5
JX1	1350	60,250	22,250	27,500	29,750	34,750	36,500	27.5	28.5
JN1	1350	60,125	23,500	28,750	30,750	35,250	37,200	26.0	28.5
JE1	1500	45,600	20,000	26,250	28,500	33,800	35,800	19.5	26.8
JR1	1500	43,625	20,500	26,800	28,500	33,200	35,800	25.5	27.1

TABLE IV

RUPTURE-TEST DATA

(NACA Data from University of Michigan)

Specimen	Test Temp. (°F)	Stress (psi)	Rupture time (hr)	Elongation (% in 2 in.)	Reduction of area (%)
J110	1000	85,000	36	24	28
JT9		80,000	70	25	25
JH9		75,000	128	17	17
JP10		70,000	345	14	13
JL9		63,000	790	12	13
JX8	1200	65,000	26	12	14
JB12		55,000	47	10	11
JA1		50,000	61	10	11
JM2		47,000	83	16	10
JQ1		43,000	195	15	8.5
JM8		40,000	668	10	16
JD1		38,000	1107	20	18
JS1	1350	32,000	55	20	23
JC1		29,000	112	37	40
JB1		28,000	248	25	35
JJ1		26,000	336	30	43
JT1		24,000	665	20	30
J11		22,000	1361	12	20
JU1	1500	20,000	51	34	37
JK1		18,000	108	28	32
JO1		16,000	203	25	37
JH1		14,000	575	26	33
JS10		12,500	1361	13	20
^a JX4	1500	14,000	358	13	17
^a JR5		14,000	502		
^b JA21		14,000	484	25	24
^b JA16		14,000	470	22	26
^c JR17		14,000	554	18	26

a. Specimens made for dynamic creep tests at Syracuse.

b. 0.250-in.-dia. specimens with 1-inch gage length.

c. 0.250-in.-dia. specimen with 2-inch gage length.

TABLE V(a) - AXIAL FATIGUE DATA FROM 3600-CPM DYNAMIC CREEP
 TEST MACHINE FOR ROOM TEMPERATURE AND 1000°F
 (Materials Laboratory, WADC, data from Syracuse University and University
 of Minnesota)

Specimen	Temp. (°F)	Stress Ratio	Stress (psi)	Cycles to Failure	Time for Fracture (hours)
Profile Specimens					
JU-23	Room	2.0	21,000 + 41,200	5.3 x 10 ⁶	* ^a 24.6
JB-23			21,500 + 42,200	32.8	152.0
JE-21			22,100 + 43,200	0.3	^b 1.5
JF-20			22,000 + 43,400	3.9	18.2
* ^a JT-22	Room	∞	0 + 44,200	108.5	^c 502.0
JW-21			0 + 47,000	15.0	32.5
^b JT-22			0 + 47,200	57.6	^d 267.5
JP-19			0 + 52,900	0.02	^e 0.08
^c JT-22			0 + 52,900	0.07	^f 0.35
^a N1231F	1000	2.0	19,300 + 38,700	25.3	^g 117.0
N1230F	1000	1.8	21,000 + 37,900	0.004	^h 0.018
JL19	1000	2.0	19,700 + 39,300	0.65	3.0
N1233F			19,700 + 39,300	0.04	ⁱ 0.17
N1234F			19,700 + 39,300	10.6	48.1
^b N1231F			20,000 + 40,000	1.1	^j 5.1
N1232F			20,000 + 40,000	0.95	4.4
^a JC20	1000	∞	0 + 39,000	58.5	^k 270.9
^a JJ18			0 + 41,000	40.4	^l 187.4
J122			0 + 41,000	0.03	^m 0.13
JS-21			0 + 43,400	0.002	ⁿ 0.008
^b JC20			0 + 43,400	0.005	^o 0.025
^b JJ18			0 + 43,500	0.003	^p 0.13
N1226F			0 + 43,500	0.01	^q 0.05
^a N1227F			0 + 43,500	30.7	^r 142.0
N1228F			0 + 45,000	0.03	^s 0.15
^b N1227F			0 + 46,000	36.3	^t 168.0
N1235F			0 + 46,500	0.03	^u 0.15
N1227F			0 + 48,500	0.14	^v 0.65

Note: Specimen numbers with "J" prefix prepared by Michigan.
 Specimen numbers with "N" prefix prepared by Minnesota.

*These elevated letters indicate notes on the following page.

(Continued on following page)

TEST DATA FOR N-155 (CONTINUED)

Notes:

- a. Flex-plate (machine part) failed which bent specimen and stopped test.
- b. Specimen fractured in the threads.
- c. Test stopped before specimen ruptured.
- d. Previous stress history. See JT-22(1).
- e. Test section of specimen attained dull red-heat color with consequent elongation of specimen, which stopped test.
- f. Previous stress history. See JT-22(1) and (2). Specimen temperature rose from 75° to approximately 400°F during time of test.
- g. Test stopped before specimen ruptured. Variable rpm start-up procedure used to control damping heat.
- h. Specimen ruptured before machine attained 3600 rpm. Stress calculated on basis of maximum rpm attained. Variable rpm start-up procedure used to control damping heat.
- i. Specimen temperature rose 20°F from 1000°F within 20 seconds after machine attained 3600 rpm. Variable rpm start-up procedure used to control damping heat.
- j. Previous stress history. See N1231F (1).
- k. Test stopped before specimen ruptured.
- l. Test stopped before specimen ruptured. Air blast used to control specimen heating at approximately 825°F.
- m. Specimen rupture before machine attained 3600 rpm. Stress calculated on basis of maximum rpm attained. Variable rpm start-up procedure used to control damping heat.
- n. Specimen temperature rose from 800° to approximately 1130°F within 30 seconds after machine attained 3600 rpm.
- o. Previous stress history. See JC20 (1). Specimen temperature rose from 900° to approximately 1126°F within 90 seconds after machine attained 3600 rpm.
- p. Previous stress history. See JJ18 (1). Specimen temperature rose from 900° to approximately 1150°F after machine attained 3600 rpm. The thermocouple failure occurred 2 minutes after starting test. Air blast used.
- q. Specimen temperature rose from 950° to approximately 1040°F in about 20 seconds. Air blast used.
- r. Variable rpm start-up procedure used to control damping heat.
- s. Specimen temperature rose from 1000° to 1100°F in approximately 30 seconds. Variable rpm start-up procedure used; specimen ruptured before machine attained 3600 rpm. Stress calculated on basis of maximum rpm attained.
- t. Previous stress history. See N1227F (1). Variable rpm start-up procedure used to control specimen damping heat.
- u. Specimen temperature rose from 1000° to 1030°F at time of rupture. Variable rpm start-up procedure used.
- v. Previous stress history. See N1227F (1) and (2). Specimen temperature rose from 1000° to 1030°F at time of rupture. Variable rpm start-up procedure used.

TABLE V(a) - AXIAL FATIGUE DATA FROM 3600-CPM DYNAMIC CREEP
 TEST MACHINE FOR ROOM TEMPERATURE AND 1000°F
 (Materials Laboratory, WADC, data from Syracuse University and University
 of Minnesota)

Specimen	Temp. (°F)	Stress Ratio	Stress (psi)	Cycles to Failure	Time for Fracture (hours)
Profile Specimens					
JU-23	Room	2.0	21,000 + 41,200	5.3 x 10 ⁶	^a 24.6
JB-23			21,500 + 42,200	32.8	152.0
JE-21			22,100 + 43,200	0.3	^b 1.5
JF-20			22,000 + 43,400	3.9	18.2
[*] a JT-22	Room	∞	0 + 44,200	108.5	^c 502.0
JW-21			0 + 47,000	15.0	32.5
^b JT-22			0 + 47,200	57.6	^d 267.5
JP-19			0 + 52,900	0.02	^e 0.08
^c JT-22			0 + 52,900	0.07	^f 0.35
^a N1231F	1000	2.0	19,300 + 38,700	25.3	^g 117.0
N1230F	1000	1.8	21,000 + 37,900	0.004	^h 0.018
JL19	1000	2.0	19,700 + 39,300	0.65	3.0
N1233F			19,700 + 39,300	0.04	ⁱ 0.17
N1234F			19,700 + 39,300	10.6	48.1
^b N1231F			20,000 + 40,000	1.1	^j 5.1
N1232F			20,000 + 40,000	0.95	4.4
^a JC20	1000	∞	0 + 39,000	58.5	^k 270.9
^a JJ18			0 + 41,000	40.4	^l 187.4
J122			0 + 41,000	0.03	^m 0.13
JS-21			0 + 43,400	0.002	ⁿ 0.008
^b JC20			0 + 43,400	0.005	^o 0.025
^b JJ18			0 + 43,500	0.003	^p 0.13
N1226F			0 + 43,500	0.01	^q 0.05
^a N1227F			0 + 43,500	30.7	^r 142.0
N1228F			0 + 45,000	0.03	^s 0.15
^b N1227F			0 + 46,000	36.3	^t 168.0
N1235F			0 + 46,500	0.03	^u 0.15
N1227F			0 + 48,500	0.14	^v 0.65

Note: Specimen numbers with "J" prefix prepared by Michigan.
 Specimen numbers with "N" prefix prepared by Minnesota.

*These elevated letters indicate notes on the following page.

(Continued on following page)

TABLE V(b) - AXIAL FATIGUE DATA FROM 3600 CPM DYNAMIC CREEP
TEST MACHINE AT 1350° AND 1500°F

(Materials Laboratory, WADC, data from Syracuse University
and University of Minnesota)

Specimen	Test Temp. (°F)	Ratio of Alternating to Mean Stress	Stress (psi)	Cycles to Failure	Time for Fracture (hours)	Elongation (%)
Uniform-diameter gage length, 2-inchs long						
JJ-6	1350	0	40,000 ± 0	--	4.0	18.4
JY-6			35,000 ± 0	--	22.8	31.4
JM-22			30,000 ± 0	--	58.3	24.7
JA-20			25,000 ± 0	--	208.8	28.5
JC-5			22,000 ± 0	--	1114.7	17.9
JZ-16			17,500 ± 0	--	3185.0	15.0
JN-6	1350	0.25	37,000 ± 9,200	1.64x10 ⁶	7.6	18.5
JB-13			33,000 ± 8,250	5.88	27.2	17.4
JK-13			30,000 ± 7,500	11.3	52.2	19.0
JC-10			27,500 ± 6,875	35.8	165.7	24.9
JF-11			25,000 ± 6,250	112	518.3	20.8
JG-5			23,200 ± 5,800	147.2	682.2	22.3
JV-13			19,000 ± 4,750	580	2683	25.8
JQ-5			17,500 ± 4,400	817	3783	14.0
JK-5	1350	.67	29,000 ± 19,332	2.44	11.3	12.6
JZ-19			27,000 ± 18,000	4.97	23.0	8.7
JO-4			26,000 ± 17,332	12.96	60.0	14.5
JP-5			24,000 ± 16,000	60.0	278.0	8.0
JM-20			25,000 ± 16,666	23.55	109.0	9.8
JZ-20			24,000 ± 16,000	65.5	303.6	7.5
JY-4			22,800 ± 15,200	85.75	397.2	11.9
JA-19			21,600 ± 14,400	114.5	530.0	7.9
JI-12			19,000 ± 12,600	456.0	2107	12.0
JD-13			18,000 ± 12,000	540.0	--	--
JX-6			17,500 ± 11,700	609.0	2821	11.0
JQ-14			17,500 ± 11,700	724.0	3349	8.0
Profile specimens						
JN-5	1350	1.64	15,500 ± 25,400	17.16	^a 795.0	---
JW-10			16,000 ± 26,200	66.5	308.0	2.4
JO-9			16,500 ± 27,100	14.6	67.7	4.8
JP-11			17,000 ± 27,900	9.55	44.2	4.8
JV-15			18,000 ± 29,500	5.08	23.5	8.0
JX-10	1350	∞	0 ± 33,600	68.0	^a 315.0	0.2
JO-5			0 ± 37,900	.024	4 min.	0.2
JT-14			0 ± 38,800	.012	2 min.	0.4
JV-14			0 ± 39,700	.005	1 min.	1.0

(Continued on following page)

TABLE V(b) (Cont.)

Specimen	Test Temp. (°F)	Ratio of Alternating to Mean Stress	Stress (psi)	Cycles to Failure	Time for Fracture (hours)	Elongation (%)
Uniform-diameter gage length, 2-inches long						
JP-12	1500	0	7,000 + 0		Discont unbroken at 5000 hr	
JI-5			11,000 + 0		1004.6	11.6
JE-5			13,000 + 0		398.5	11.7
JH-10			15,000 + 0		^a 221.2	^a 17.0
JV-8			17,500 + 0		67.2	25.2
JA-16			19,000 + 0		47.9	28.0
JO-6			20,000 + 0		24.9	34.4
JB-5			22,500 + 0		20.7	36.4
JR-10	1500	0.25	8,800 + 2,200	889.0x10 ⁶	4117.0	11.1
JH-5			10,000 + 2,500	603.0	2790.0	11.9
JF-5			14,000 + 3,500	88.8	410.9	15.4
JT-5			15,200 + 3,800	82.6	^a 382.3	^a 9.6
JE-12			16,800 + 4,200	45.2	209.5	21.3
JL-5			19,200 + 4,800	18.0	83.4	19.9
JM-21			22,000 + 5,500	3.2	14.9	30.0
JW-4			24,000 + 6,000	1.7	8.0	28.1
JS-5	1500	0.67	8,000 + 5,300	880.0	4066.0	5.9
JT-11			12,000 + 8,000	138.0	640.0	10.2
JW-6			15,000 + 10,000	49.0	226.5	15.8
JD-5			16,800 + 11,200	18.4	85.1	18.3
JL-10			18,600 + 12,400	78.4	36.3	21.8
JG-12			21,000 + 14,000	4.3	^c 19.7	^c 13.7
JV-13			22,200 + 14,800	2.4	10.9	19.9
Profile specimens						
JL-8	1500	0.67	12,000 + 8,000	181.0	837.5	11.4
JI-14			16,800 + 11,200	27.0	125.1	16.8
JY-9	1500	1.64	9,000 + 14,800	275.0	1273.0	--
JK-11			11,000 + 18,000	74.1	343.7	5.0
JY-10			12,000 + 19,700	32.4	150.0	7.0
JS-13			13,000 + 21,800	10.9	50.7	8.0
JW-9			14,000 + 23,000	3.2	14.7	6.5
JR-14			15,000 + 24,600	.08	0.4	6.0
JX-9	1500	∞	0 + 21,800	226.0	1048.0	2.8
JU-14			0 + 24,300	115.6	536.1	--
JI-15			0 + 24,600	22.9	106.1	3.4
^d JH-15			0 + 25,300	^d 23.0	^d 106.9	2.4
JS-14			0 + 25,300	1.8	8.3	1.6

(Concluded on following page)

TABLE V(b) (Cont.)

Specimen	Test Temp. (°F)	Ratio of Alternating to Mean Stress	Stress (psi)	Cycles to Failure	Time for Fracture (hours)	Elongatic (%)
Uniform-diameter gage length, 2-inches long						
N1236F	1500	∞	0 + 25,300	^a 24.1x10 ⁶	^a 111.5	--
N1236F			0 + 28,000	^e 3.39	^e 15.7	
N1248F			0 + 28,000	16.1	74.5	
N1240F			0 + 28,500	.80	3.7	
N1238F			0 + 29,000	2.18	10.1	
N1237F			0 + 30,000	.048	0.2	

- (a) Test stopped before failure, either due to too long time for fracture or experimental difficulties.
- (b) Controller failure at 2126 hr. Established rupture time was 2500 hr.
- (c) Temperature 20° low for 2 hours at beginning of test.
- (d) Statically loaded for 100 hours at 14,000 psi prior to dynamic loading.
- (e) Previously tested for 111.5 hours at + 25,300 psi before this test.

Note 1. Elongations for uniform-diameter specimens were measured over a 2-inch gage length. For profile specimens, elongations were obtained by a suitable factor to give equivalent percentage of values. (See reference 3.)

Note 2. Specimens marked N-F were heat-treated and machined at Minnesota.

TABLE VI - KRAUSE AXIAL 1500-CPM FATIGUE TEST DATA

(Office of Naval Research and NACA Data from Battelle Memorial Institute)

Specimen	Test Temp. (°F)	Stress (psi)	Cycles to Failure	Time to Failure (hours)
JL 7	1200	40,000 ± 25,000	1.32x10 ⁶	14.7
JD 2		38,000 ± 25,000	6.16	68.5
JP 2		35,000 ± 25,000	5.27	58.6
JG 7		35,000 ± 25,000	5.63	62.5
JI 2		32,500 ± 25,000	11.90	132.
JT 7		30,000 ± 25,000	37.10	412.
JE 7	1200	55,000 ± 15,000	0.31	3.45
JV 6		45,000 ± 15,000	2.63	29.2
JJ 2		39,000 ± 15,000	27.04	300.5
JC 3	1200	50,000 ± 7,500	4.18	46.4
JQ 2		45,000 ± 7,500	11.79	131.
JQ 6		39,000 ± 7,500	69.01	767.
^a JD 12	1350	0 ± 45,000	.005	.055
^a JC 9		0 ± 42,500	.022	.244
^a JV 12		0 ± 41,000	.016	.18
^a JK 12		0 ± 40,000	13.19	146.5
JJ 14		0 ± 37,500	.023	.25
JT 16		0 ± 35,000	28.021	311.3
JO8	1350	15,000 ± 35,000	0.8	8.8
JB 15		12,500 ± 35,000	10.638	118.2
JQ 11		10,000 ± 35,000	17.94	197
JU 8		8,000 ± 35,000	67.436	749
JP 7	1350	30,000 ± 25,000	.378	4.2
JC 7		28,000 ± 25,000	.66	7.3
JG 2		26,000 ± 25,000	5.23	58.2
JF 14		22,000 ± 25,000	24.441	271.6
JM 18	1350	32,500 ± 15,000	2.25	25
JN 2		27,500 ± 15,000	5.10	56.6
JR 2		25,000 ± 15,000	22.0	244
JD 8		22,500 ± 15,000	55.0	611
JZ 6	1350	32,500 ± 7,500	5.62	62.4
JZ 8		30,000 ± 7,500	9.04	100.3
JK 2		25,000 ± 7,500	36.67	408
JV 19	1500	0 ± 30,000	7.702	85.6
JW 9		0 ± 29,000	18.247	202.6
JW 16		0 ± 27,000	^b 8.752	^b 97.2
Jo 14		0 ± 20,000	^c 84.59	^c 940

(Concluded on following page)

TABLE VI (Cont.)

Specimen	Test Temp. (°F)	Stress (psi)	Cycles to Failure	Time to Failure (hours)
JY 15	1500	18,000 \pm 22,500	^d 0.28 x 10 ⁶	^d 3.12
JK 16		18,000 \pm 22,500	3.639	40.0
JH 16		17,000 \pm 22,500	^e 11.320	^e 125.9
JK 15		15,000 \pm 22,500	9.318	103.5
JL 14		13,000 \pm 22,500	15.979	177.5
JM 6	1500	20,000 \pm 15,000	2.15	23.9
JS 2		17,500 \pm 15,000	11.58	128.7
JA 12		16,000 \pm 15,000	18.72	208
JK 7		16,000 \pm 15,000	13.63	151.5
JT 2	1500	20,000 \pm 7,500	4.0	44.4
JH 7		17,500 \pm 7,500	11.8	131
JV 3		16,000 \pm 7,500	21.91	244
JZ 13		14,500 \pm 7,500	39.78	442

- a. Tests not plotted because results could not be checked by subsequent tests.
- b. Result of test appears to have been affected by bearing failure and replacement during the test.
- c. Test discontinued due to the probable fracture time being excessive.
- d. Defective bearing.
- e. Test discontinued due to test-machine failure.

Note: Tests at \pm 7500, \pm 15,000, and \pm 25,000 psi were made with specimen having configuration shown by figure 1(c); all other tests were made on specimens shown by figure 1(d).

TABLE VII - SONNTAG SF-4 3600 CPM AXIAL FATIGUE TEST DATA

(Elliot Company Data)

Specimen	Test Temp. °F	Stress psi	Cycles to Failure x 10 ⁶	Time to Failure hr
JL21*	75	75,000 \pm 39,350	0.13	0.60
JC22*		75,000 \pm 33,880	0.0279	1.30
JY23*		75,000 \pm 27,880	3.85	17.8
JX5	1000	75,000 \pm 14,470	1.646	7.63
JV11		75,000 \pm 4,840	51.504	239.0
JT10	1000	60,000 \pm 29,880	.421	1.95
aJB24*		60,000 \pm 27,350	1.49	6.90
aJJ19*		60,000 \pm 23,350	12.176	56.3
JS11		60,000 \pm 19,910	17.156	79.5
bJI24*		60,000 \pm 19,910	130.8	605.0
a,cJY22*		60,000 \pm 17,410	77.818	360.0
a,dJS22*		60,000 \pm 17,410	62.341	288.0
a,dJP20*		60,000 \pm 17,410	53.886	249
JW5		60,000 \pm 16,430	53.707	249
JY5		1000	45,000 \pm 26,880	6.181
JP21*	45,000 \pm 25,840		2.230	10.3
JN9	45,000 \pm 21,410		151.249	701
dJC21*	45,000 \pm 21,170		94.708(disc)	439(disc)
dJR8	45,000 \pm 19,410		77.242	357
JF21*	1000	40,000 \pm 28,880	3.824	17.7
JL20*		40,000 \pm 27,380	6.993	32.4
JJ20*		40,000 \pm 26,380	316.761(disc)	1460(disc)
JE23*		40,000 \pm 25,380	203.402	980
JE11	1350	28,000 \pm 24,000	broke on starting	
JG11		28,000 \pm 24,000	excessive creep on starting	
JI11		28,000 \pm 19,080	12.844	59.5
JC8		28,000 \pm 15,039	11.667	54
JD11		28,000 \pm 7,469	33.878	157
JH8		28,000 \pm 7,469	25.751	119
JF10		28,000 \pm 3,969	46.938	217

*Tests run after reducing eccentricity of grips.

aSpecimen machined by Elliot Company.

bTest considered probably to be untrustworthy; only known difficulty was slight reductions of alternating stress for two hours due to slippage in a flexible coupling.

cTemperature found 60°F low just prior to fracture.

dTests interrupted two or three times due to power failures or machine shut-downs.

TABLE VIII - STRESS-RUPTURE TESTS WITH SUPERIMPOSED ROTATING BENDING STRESS

(Research Laboratories Division, General Motors Corporation, Machine and Data)

Specimen	Test Temp °F	Steady Axial Stress psi	10,800 cpm Bending Stress - psi	Cycles to Failure	Time to Fracture hr	Elongation %
JV17	1350	28,000	+19,250	24.6 x 10 ⁶	^a 38.0	6.78
JX14		28,000	+12,800	35.3	^b 54.5	11.75
JW12		28,000	+5,100	34	^c 52.5	13.05
JO11		28,000	+7,250	33	^b 51.0	13.95
JW14		28,000	+0	0	^d (>180)	15.37

^aFatigue failure at point of maximum stress ($\frac{3}{8}$ inch above lower shoulder of specimen).

^bRupture failure at thermocouple strap weld remote from point of maximum stress (1- $\frac{3}{16}$ inches from upper shoulder of specimen).

^cRupture failure remote from point of maximum stress and thermocouple welds.

^dSpecimen deformation reached limit of machine at 180 hours - creep data indicated failure before 200 hours.

TABLE IX - REVERSED BENDING FATIGUE DATA FROM WESTINGHOUSE 7200- CPM MACHINE

(Westinghouse Data for 0.550-Inch Diameter Specimens)

Test Temp. °F	Alternating Stress psi	Cycles to Failure	Time to Fracture hr
room	+69,000	0.195 x 10 ⁶	0.45
	64,000	.37	0.86
	59,500	1.1	2.55
	57,000	1.1	2.55
	56,000	0.69	1.6
	55,500	a711	1645
	54,500	a150	347
	1000	59,000	.19
51,000		.85	1.97
50,500		.90	2.08
49,000		1.22	2.82
48,500		a210	487
1200		51,000	.55
	47,000	2.35	5.44
	46,500	.79	1.8
	46,000	200	463
	48,500*	1.77	4.1
	46,500*	2.05	4.75
	45,000*	508	1175
	1350	46,000	1.5
44,000		1.75	4.05
43,500		1.88	
41,500		4.4	10.17
39,500		64	148
39,500		a430	994
39,000		115.8	268
38,500		52	120
1500		35,000	.43
	33,500	5.9	13.7
	31,500	4.9	11.3
	30,500	20.5	47.5
	28,000	12.8	29.6
	26,500	109	252
	25,500	190	440
	b30,500	7.2	16.7
	b27,000	138	320
	b26,000	33.45	77.4

^aDiscontinued

^bSpecimens machined by ordinary shop practice.

TABLE IX - REVERSED BENDING FATIGUE DATA FROM WESTINGHOUSE 7200- CPM MACHINE

(Westinghouse Data for 0.550-Inch Diameter Specimens)

Test Temp. °F	Alternating Stress psi	Cycles to Failure	Time to Fracture hr
room	+69,000	0.195 x 10 ⁶	0.45
	64,000	.37	0.86
	59,500	1.1	2.55
	57,000	1.1	2.55
	56,000	0.69	1.6
	55,500	a711	1645
	54,500	a150	347
1000	59,000	.19	.44
	51,000	.85	1.97
	50,500	.90	2.08
	49,000	1.22	2.82
	48,500	a210	487
1200	51,000	.55	1.27
	47,000	2.35	5.44
	46,500	.79	1.8
	46,000	200	463
	48,500*	1.77	4.1
	46,500*	2.05	4.75
	45,000*	508	1175
1350	46,000	1.5	3.47
	44,000	1.75	4.05
	43,500	1.88	
	41,500	4.4	10.17
	39,500	64	148
	39,500	a430	994
	39,000	115.8	268
	38,500	52	120
1500	35,000	.43	.99
	33,500	5.9	13.7
	31,500	4.9	11.3
	30,500	20.5	47.5
	28,000	12.8	29.6
	26,500	109	252
	25,500	190	440
	b30,500	7.2	16.7
	b27,000	138	320
	b26,000	33.45	77.4

^aDiscontinued

^bSpecimens machined by ordinary shop practice.

TABLE X - EFFECT OF SURFACE FINISH ON REVERSED BENDING
FATIGUE DATA FROM WESTINGHOUSE 7200-CPM MACHINE

(Lewis Laboratory, NACA, data for 0.333-inch diameter specimen)

Specimen	Test Temp. (°F)	Stress (psi)	Cycles to Failure	Time to Failure (hr)
Polished finish 4-5 microinch rms				
JB20	Room	+ 65,000	0.39x10 ⁶	0.90
JS20		+ 58,800	2.76	6.4
JC19		+ 57,100	1.60	3.7
JK21		+ 55,700	1.64	3.8
JI20		+ 54,100	1.25	3.0
		+ 52,700	18.14	42.6
		+ 52,500	6.0	13.9
JT20	1350	+ 46,400	.17	.4
JI20		+ 44,100	1.77	4.1
JL17		+ 42,200	4.36	10.1
JE20		+ 40,700	43.3	100.2
		+ 39,500	13.0	30.1
		+ 39,500	92. (unbroken)	212.
Ground finish: 20-25 Microinch rms				
	Room	+ 58,500	0.31x10 ⁶	0.72
		+ 49,700	1.92	4.45
		+ 47,500	40.0	92.5
	1350	+ 43,500	.13	.3
		+ 41,300	1.07	2.47
		+ 39,800	40.0	92.5
		+ 39,500	82. (unbroken)	190.
Rough finish: 70-80 microinch rms				
	Room	+ 62,000	1.08x10 ⁶	2.5
		+ 58,200	1.55	3.6
		+ 57,000	1.60	3.7
		+ 55,700	30.0	69.4
		+ 52,800	30.0	69.4
	1350	+ 43,000	.215	.28
		+ 42,000	.77	.41
		+ 39,200	7.1	16.4
		+ 38,200	8.0	18.5
		+ 36,200	55.0	115.5

(Continued on following page)

TABLE X (Cont.)

Specimen	Test Temp. (°F)	Stress (psi)	Cycles to Failure	Time to Failure (psi)
Specimens turned to shape and polished				
JY11	1350	+ 49,700	0.108x10 ⁶	0.25
JK14		+ 45,000	.95	2.2
J116		+ 44,000	1.21	2.8
JW11		+ 41,500	5.57	12.8
JO10		+ 41,700	17.58	40.7
JP17		+ 40,600	22.12	51.2
JU16		+ 39,700	30.15	69.8
JV16		+ 38,900	24.62	57.0
JJ13		+ 38,100	123.85 (unbroken)	286.7
Polished and stress-relieved for 4 hours at 1400°F				
Room		+ 62,700	1.25x10 ⁶	2.9
		+ 60,600	1.20	2.8
		+ 58,900	0.88	2.0
		+ 55,500	6.4	14.8
		+ 52,900	13.	30.1
		+ 52,900	52. (unbroken)	120.
Polished, stress-relieved for 4 hours at 1400°F, and repolished				
Room		+ 60,000	1.45x10 ⁶	3.35
		+ 55,500	3.35	7.75
		+ 53,700	5.2	12.0
		+ 51,700	24.5	56.8
Ground and stress-relieved for 4 hours at 1400°F				
Room		+ 52,700	1.45x10 ⁶	3.35
		+ 48,500	6.9	16.0
		+ 47,000	44.	102.
Roughened and stress-relieved after 4 hours at 1400°F				
Room		+ 54,000	0.82x10 ⁶	1.9
		+ 52,500	1.65	3.8
		+ 50,500	2.1	4.8
		+ 47,300	19.	44.
		+ 44,500	83. (unbroken)	192.

TABLE XI - FATIGUE DATA FROM VARIABLE SPEED ROTATING CANTILEVER BEAM TESTS
ON UNNOTCHED AND NOTCHED SPECIMENS

(Materials Laboratory, WADC, Data from University of Minnesota)

Specimen	Test Temp. °F	Stress psi	Cycles to Failure	Time to Failure hr	Average Cyclic Speed cpm
Unnotched Specimens					
J119	room	^a +76,600	^a 3,650	---	----
JE15		+73,500	62,000	18	5.73
JH19		+64,600	386,500	50	122.5
JJ15		+59,500	761,500	62	205
JE17		+54,900	2,028,000	90	451
JT18		+51,400	46,000,000	1,032	7500
JY16	1350	+47,400	9,750	9	18
JY17		+44,100	890,000	64	241.5
JT17		+41,250	296,000	26	190
JW18		+37,200	^b 6,470,000	^b 288	375
JX20		+34,450	8,500,000	287	493
JP16	1500	+35,600	^c 43,950	^c 9	81.7
J119		+32,700	945,000	123	127.5
JF17		+29,500	781,000	48	272
JS17		^a +29,800	^a 172,000	216	133
Notched Specimens					
JH20	room	+55,700	55,850	29	32.1
JC16		+47,400	84,500	14	100.5
JF16		^a +45,900	^a 114,900	^a 22	87
J015		^a +39,700	^a 213,500	^a 76	46.8
JL15		+36,100	342,500	23	248
JV19		+30,000	2,112,000	121	291
JX21		+28,600	1,926,000	80	400
JC17		+26,500	1,656,000	95	291
JF16		+22,600	^d 20,300,000	^d 358	945
J118	1350	+35,100	6,600	3	36.7
JU21		+30,000	15,500	6	43
JN10		+25,000	218,000	27	135
JE16		+22,500	4,970,000	548	151.5
J016		+19,960	^e 1,086,000	^e 163	111
JF15	1500	+29,900	9,700	5	32.3
JL16		+25,000	52,200	13	66.8
JL15		+19,960	4,166,000	311	223

^aPreviously run at lower stresses

^bController difficulties

^cBent suddenly

^dTest discontinued

^eTest difficulties

TABLE XII - ROTATING CANTILEVER BEAM FATIGUE DATA
FROM ROLLS-ROYCE 5500-CPM MACHINE

(Rolls-Royce Data for 0.160-Inch-Diameter Ground Specimens
from Quartered 1-Inch-Diameter Bars)

Specimen	Temp. °F	Stress psi	Cycles to Fracture hr	Time to Fracture hr
JX15	1203 \pm 3	+49,200	*0.062 x 10 ⁶	0.79
JX15	1203	48,600	*0.086	.26
JS15	1203	48,100	4.60	13.9
JX15	1203	47,000	*0.040	.12
JX15	1203	47,000	*0.024	.07
JX15	1203	45,200	0.740	2.24
JX15	1203	44,700	34.24+	104+
JX15	1203	44,700	145.97+	441+
JX15	1203	43,600	11.56+	35+
JX15	1203	38,600	24.00+	73+
JP14	1355 \pm 3	+42,500	0.47 x 10 ⁶	1.42
JR16	1355	42,500	0.77	2.33
JR16	1355	40,200	1.68	5.09
JP14	1355	40,200	2.15	6.51
JR16	1355	39,100	3.43	10.4
JS15	1355	38,600	2.23	6.76
JR16	1355	38,000	2.73	8.27
JP14	1355	38,000	96.27	292
JR16	1355	35,750	24.2+	73+
JP14	1355	35,750	34.00+	103+
JP14	1504 \pm 3	+35,750	1.15 x 10 ⁶	3.48
JP14	1504	35,750	0.80	2.42
JP14	1504	33,500	0.96	2.91
JP14	1504	32,400	9.24	28
JS15	1504	31,800	19.27	64
JR16	1504	31,400	2.45	7.45
JS15	1504	31,300	21.35	61
JP14	1504	31,300	1.93	5.85
JP14	1504	31,300	11.72+	35+
JS15	1504	30,700	41.0	124
JS15	1504	30,200	2.41	7.3
JS15	1504	30,200	33.12	100
JR16	1504	29,600	7.63	23
JR16	1504	27,900	15.02	46
JR16	1504	26,800	71.36	216

*Preliminary tests - endurance only approximate due to motor overrun at failure.

+Specimen unfractured.

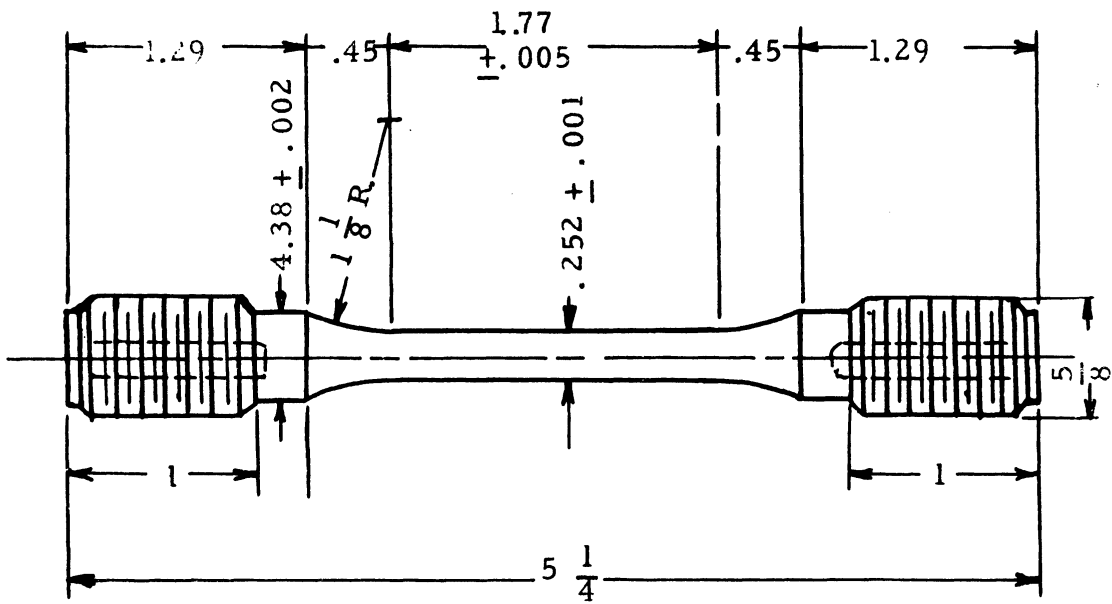
TABLE XIII - NEES ROTATING CANTILEVER BEAM FATIGUE TEST DATA

(U. S. Naval Engineering Experiment Station 1700-cpm Machine and Data)

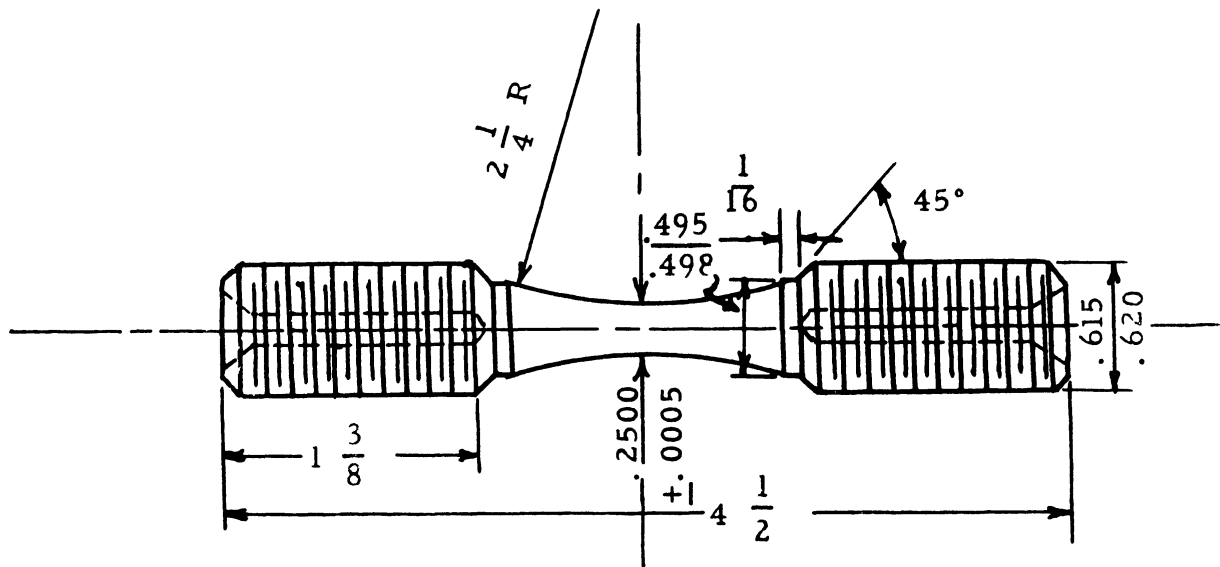
Specimen	Test Temp. °F	Alternating Stress psi	Cycles to Failure	Time for Fracture hr
JX12	1350	43,000	0.09×10^6	0.88
JJ15		40,000	37.69	369
JY13		38,000	7.79	76.3
JW12		37,000	5.22	51.1
JX13		35,000	56.75	556.4

TABLE XIV. COMPARATIVE STRESSES FOR FRACTURE IN FIXED TIMES OR AFTER FIXED NUMBERS OF CYCLES FOR THE VARIOUS TESTS

Type of Test	Test Machine	Test Temp. (°F)	Stress (psi) for fracture in:			Stress (psi) for fracture in:		
			50 hours	150 hours	500 hours	10 ⁷ cycles	3 x 10 ⁷ cycles	10 ⁸ cycles
Axial	3600-cpm "Dynamic creep"	75	± 46,500	± 46,500	± 46,500	± 46,500	± 46,500	± 46,500
Reverse bending	7200-cpm Westinghouse	75	± 55,500	± 55,500	± 55,500	± 55,500	± 55,500	± 55,500
Reverse bending	7200-cpm NACA-Westinghouse	75	± 54,800	± 52,900	± 52,500	± 52,600	± 52,500	± 52,400
Rotating beam	Variable-speed	75	± 62,500	± 54,300	± 52,600	± 53,000	± 53,000	± 53,000
Axial	3600-cpm "Dynamic creep"	75	21,200 ± 42,400	21,200 ± 42,400	21,200 ± 42,400	21,200 ± 42,400	21,200 ± 42,400	21,200 ± 42,400
Axial	3600-cpm Sonntag	75	75,000 ± 25,000	75,000 ± 25,000	75,000 ± 25,000	75,000 ± 25,000	---	---
Rupture	-----	1000	82,500	74,000	67,000	---	---	---
Axial	3600-cpm "Dynamic creep"	1000	± 45,000	± 45,000	± 45,000	± 45,000	± 45,000	± 45,000
Reverse bending	7200-cpm Westinghouse	1000	± 49,500	± 49,200	± 49,000	± 49,500	± 49,300	± 49,200
Axial	3600-cpm "Dynamic creep"	1000	19,700 ± 39,300	19,700 ± 39,300	19,700 ± 39,300	19,700 ± 39,300	19,700 ± 39,300	19,700 ± 39,300
		1000	75,000 ± 12,000	75,000 ± 10,000	---	75,000 ± 13,000	75,000 ± 10,500	---
Axial	3600-cpm Sonntag	1000	60,000 ± 22,000	60,000 ± 19,000	60,000 ± 16,000	60,000 ± 22,000	60,000 ± 19,500	60,000 ± 16,000
		1000	45,000 ± 25,500	45,000 ± 23,500	45,000 ± 22,000	45,000 ± 25,500	45,000 ± 24,000	45,000 ± 22,000
		1000	40,000 ± 28,000	40,000 ± 27,000	40,000 ± 26,000	40,000 ± 28,000	40,000 ± 27,000	40,000 ± 26,000
Rupture	-----	1200	54,000	44,000	41,000	---	---	---
Reverse bending	7200-cpm Westinghouse	1200	± 47,000	± 46,900	± 46,800	± 47,000	± 47,000	± 46,800
Rotating beam	5500-cpm	1200	± 45,000	± 45,000	± 45,000	± 45,000	± 45,000	± 45,000
		1200	49,000 ± 7,500	45,000 ± 7,500	40,600 ± 7,500	46,400 ± 7,500	42,000 ± 7,500	37,700 ± 7,500
Axial	1500-cpm Krause	1200	44,800 ± 15,000	41,000 ± 15,000	36,900 ± 15,000	41,900 ± 15,000	38,100 ± 15,000	33,900 ± 15,000
		1200	36,800 ± 25,000	33,400 ± 25,000	29,900 ± 25,000	34,500 ± 25,000	31,000 ± 25,000	27,500 ± 25,000
Rupture	-----	1350	32,000	28,500	25,000	---	---	---
		1350	32,000	28,000	23,750	---	---	---
Axial	3600-cpm "Dynamic creep"	1350	± 35,000	± 34,000	± 33,000	± 35,000	± 34,500	± 33,500
Axial	1500-cpm Krause	1350	± 35,000	± 35,000	± 35,000	± 35,000	± 35,000	± 35,000
Reverse bending	7200-cpm Westinghouse	1350	± 40,000	± 39,800	± 39,500	± 40,000	± 39,800	± 39,700
Reverse bending	7200-cpm NACA-Westinghouse	1350	± 43,600	± 42,500	± 41,300	± 42,000	± 41,000	± 39,500
Rotating beam	Variable-speed	1350	± 42,300	± 39,700	± 37,000	± 40,400	± 40,000	---
Rotating beam	5500-cpm	1350	± 38,000	± 38,000	± 38,000	± 38,000	± 38,000	± 38,000
Rotating beam	1700-cpm	1350	± 36,000	± 36,000	± 36,000	± 36,000	± 36,000	± 36,000
		1350	31,250 ± 7,800	28,000 ± 7,000	24,000 ± 6,000	31,200 ± 7,800	28,000 ± 7,000	24,000 ± 6,000
Axial	3600-cpm "Dynamic creep"	1350	26,500 ± 17,700	24,500 ± 16,400	22,000 ± 14,700	26,500 ± 17,750	24,500 ± 16,400	22,000 ± 14,750
		1350	17,000 ± 28,000	16,500 ± 27,000	16,000 ± 26,000	17,200 ± 28,200	16,700 ± 27,300	15,900 ± 26,100
Axial	3600-cpm Sonntag	1350	28,000 ± 17,500	28,000 ± 5,000	---	28,000 ± 18,000	28,000 ± 7,500	---
		1350	33,100 ± 7,500	28,900 ± 7,500	24,400 ± 7,500	30,000 ± 7,500	26,000 ± 7,500	21,000 ± 7,500
		1350	30,000 ± 15,000	26,500 ± 15,000	23,000 ± 15,000	27,500 ± 15,000	24,300 ± 15,000	20,600 ± 15,000
Axial	1500-cpm Krause	1350	25,900 ± 25,000	23,200 ± 25,000	20,200 ± 25,000	24,100 ± 25,000	21,200 ± 25,000	18,000 ± 25,000
		1350	12,000 ± 35,000	10,300 ± 35,000	8,300 ± 35,000	11,000 ± 35,000	9,000 ± 35,000	7,200 ± 35,000
Rupture	-----	1500	20,000	17,000	14,500	---	---	---
		1500	19,000	16,250	12,750	---	---	---
Axial	3600-cpm "Dynamic creep"	1500	± 25,900	± 25,500	± 24,500	± 25,500	± 25,500	± 24,800
Axial	1500-cpm Krause	1500	± 30,500	± 28,900	± 28,000	± 29,500	± 28,400	± 27,500
Reverse bending	7200-cpm Westinghouse	1500	± 29,500	± 28,000	± 26,000	± 31,000	± 29,000	± 27,000
Rotating beam	5500-cpm	1500	± 31,200	± 30,400	± 30,000	± 31,700	± 30,700	± 29,900
		1500	± 28,100	± 27,400	± 27,000	± 28,500	± 27,700	± 27,000
Rotating beam	Variable-speed	1500	± 31,500	± 30,000	---	± 29,300	---	---
		1500	19,750 ± 4,900	17,250 ± 4,300	14,500 ± 3,600	20,000 ± 5,000	17,500 ± 4,400	14,500 ± 3,600
Axial	3600-cpm "Dynamic creep"	1500	18,500 ± 12,300	15,500 ± 10,400	13,000 ± 8,700	18,500 ± 12,300	16,000 ± 10,700	13,000 ± 8,700
		1500	13,100 ± 21,400	12,000 ± 19,600	10,500 ± 17,100	13,200 ± 21,600	11,900 ± 19,600	10,600 ± 17,400
		1500	19,750 ± 7,500	16,500 ± 7,500	14,300 ± 7,500	18,000 ± 7,500	15,200 ± 7,500	14,000 ± 7,500
Axial	1500-cpm Krause	1500	18,500 ± 15,000	15,500 ± 15,000	13,500 ± 15,000	17,000 ± 15,000	14,400 ± 15,000	13,300 ± 15,000
		1500	17,000 ± 22,500	13,000 ± 22,500	11,000 ± 22,500	15,100 ± 22,500	11,800 ± 22,500	10,300 ± 22,500

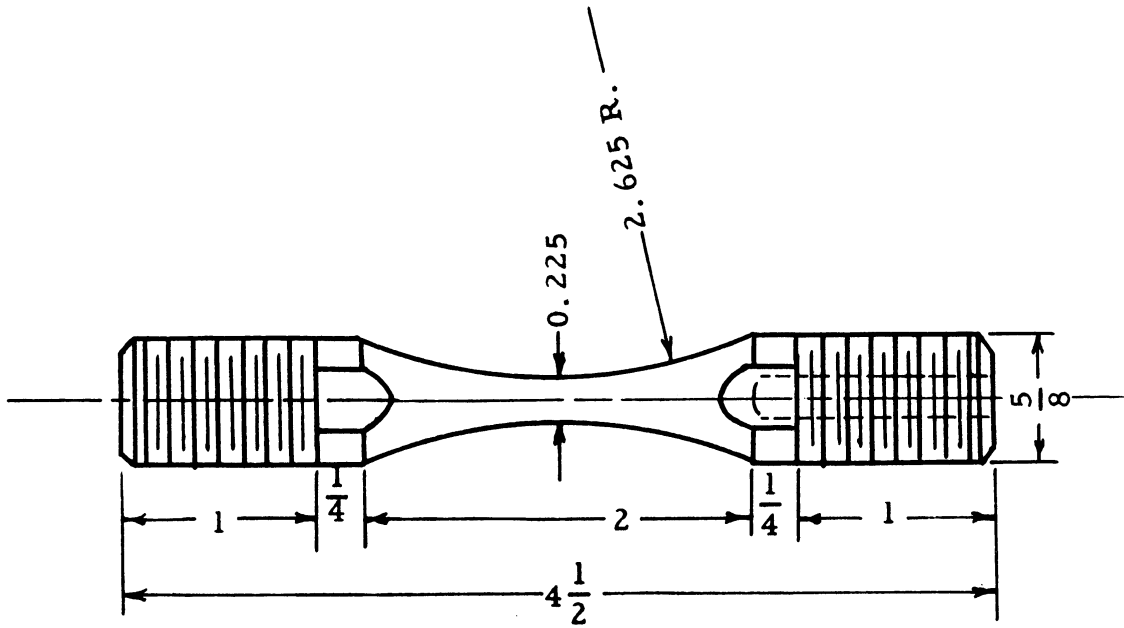


(a) Axial stress dynamic creep test specimen .

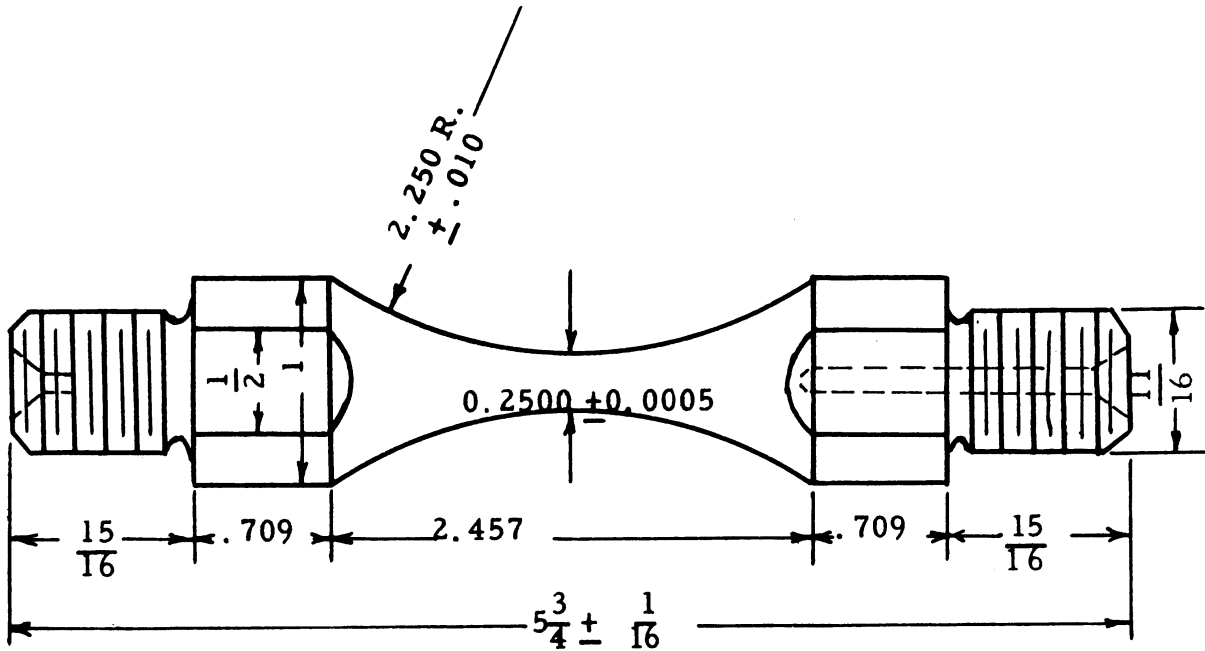


(b) Axial stress radius fatigue specimen.

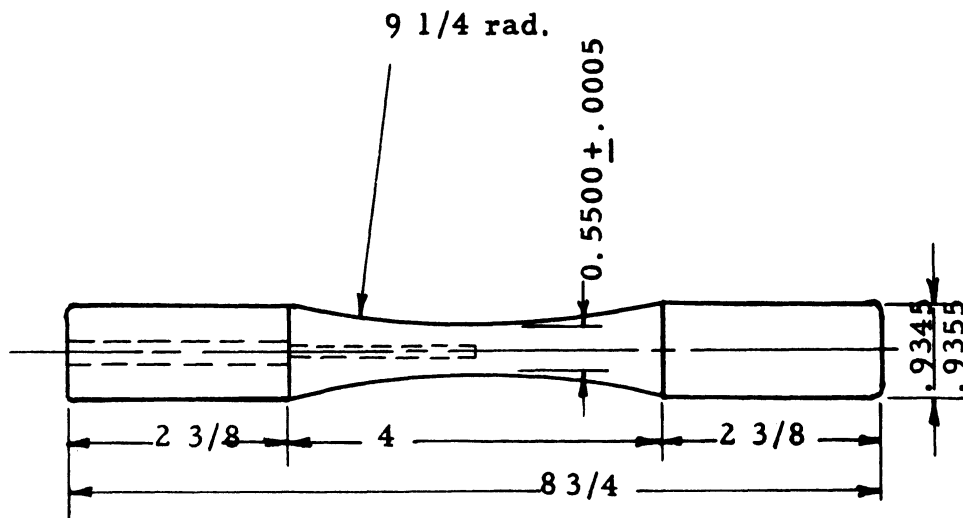
Figure 1. - Fatigue specimens used by cooperators
(All dimensions in inches)



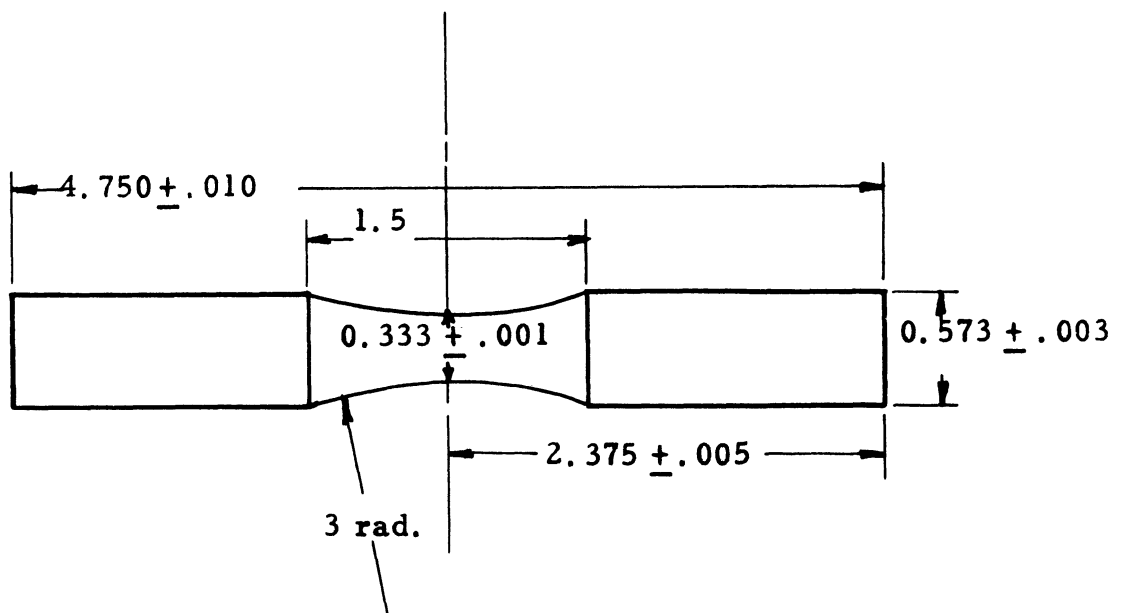
(c) Krause machine axial stress fatigue specimen.



(d) Krause machine axial stress fatigue specimen for tests in compression.

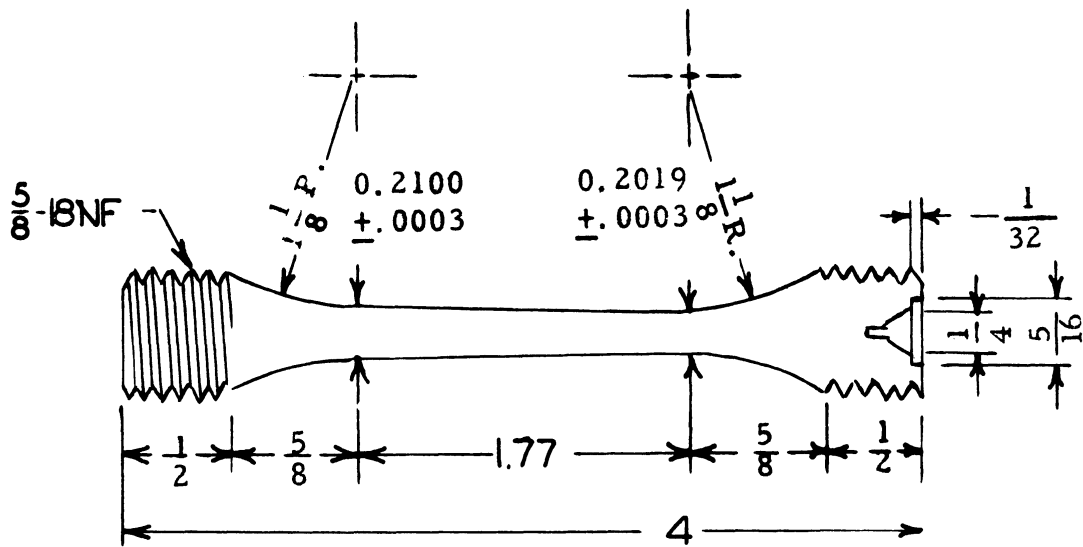


(g) Westinghouse reversed bending fatigue specimen.

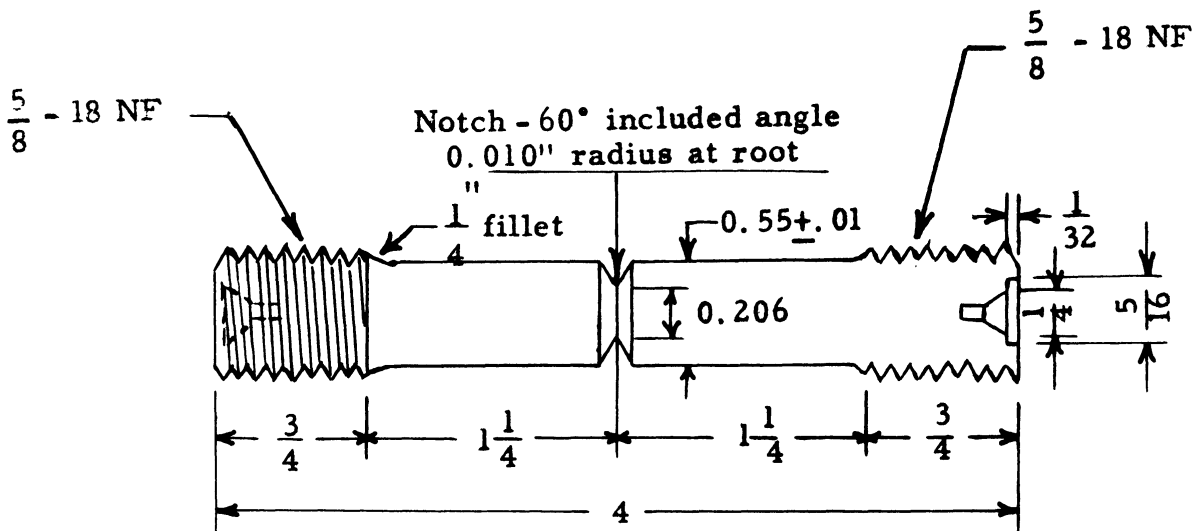


(h) NACA modified Westinghouse reversed bending fatigue specimen.

Figure 1. - Continued.

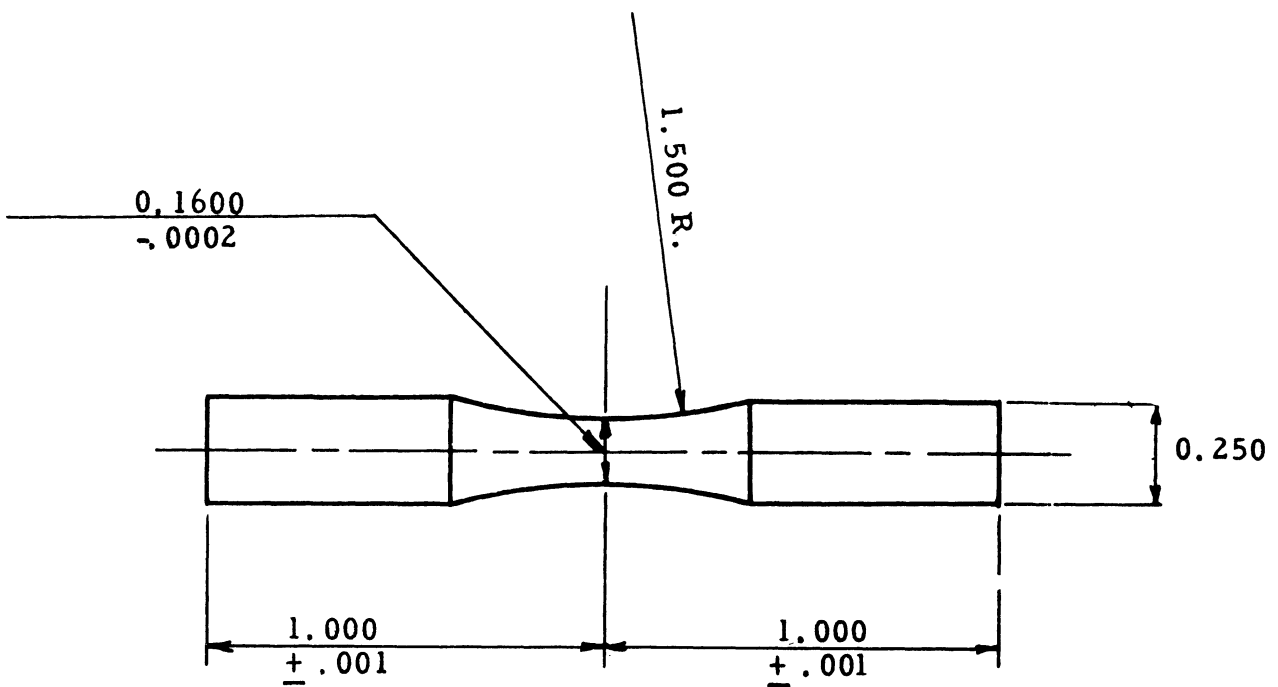


(i) Rotating cantilever beam specimen for fatigue, damping, and elasticity tests.



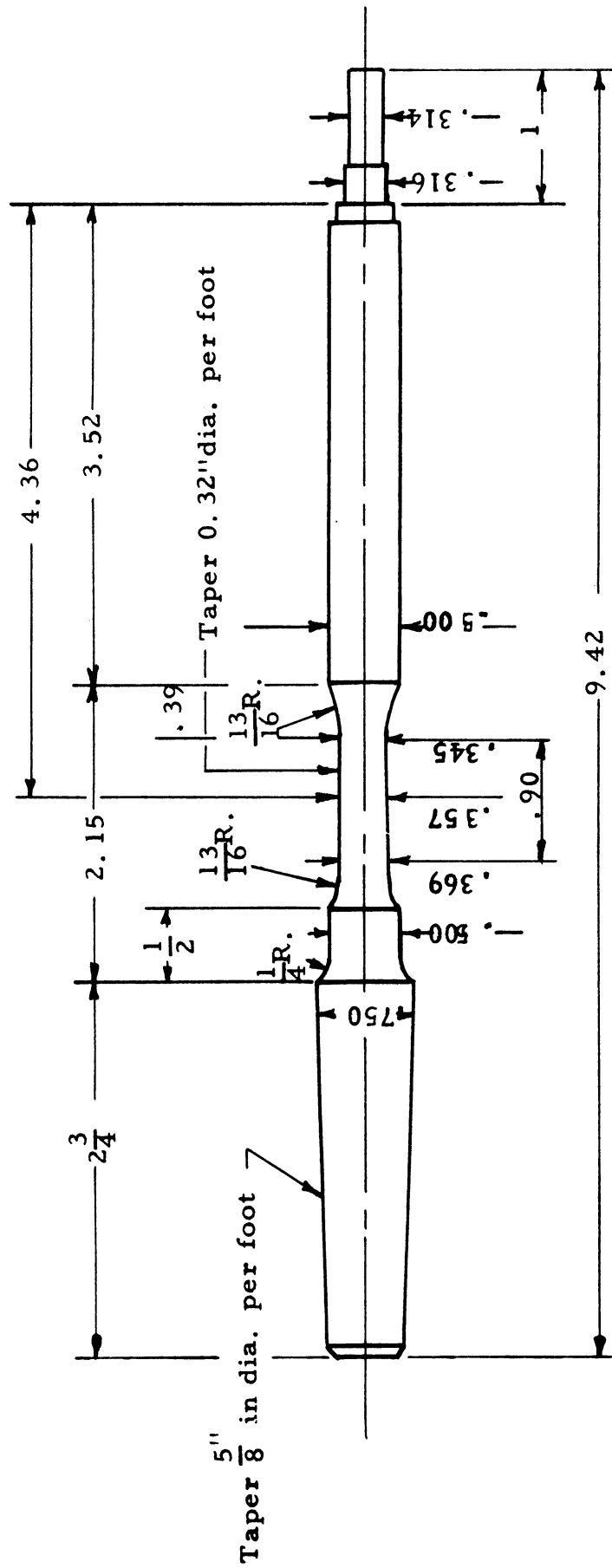
(j) Notched rotating cantilever beam specimen for fatigue, damping, and elasticity tests.

Figure 1. - Continued.



(k) Rolls-Royce rotating cantilever beam fatigue specimen

Figure 1. - Continued.



(1) NEES rotating cantilever beam fatigue specimen.

Figure 1. - Concluded.

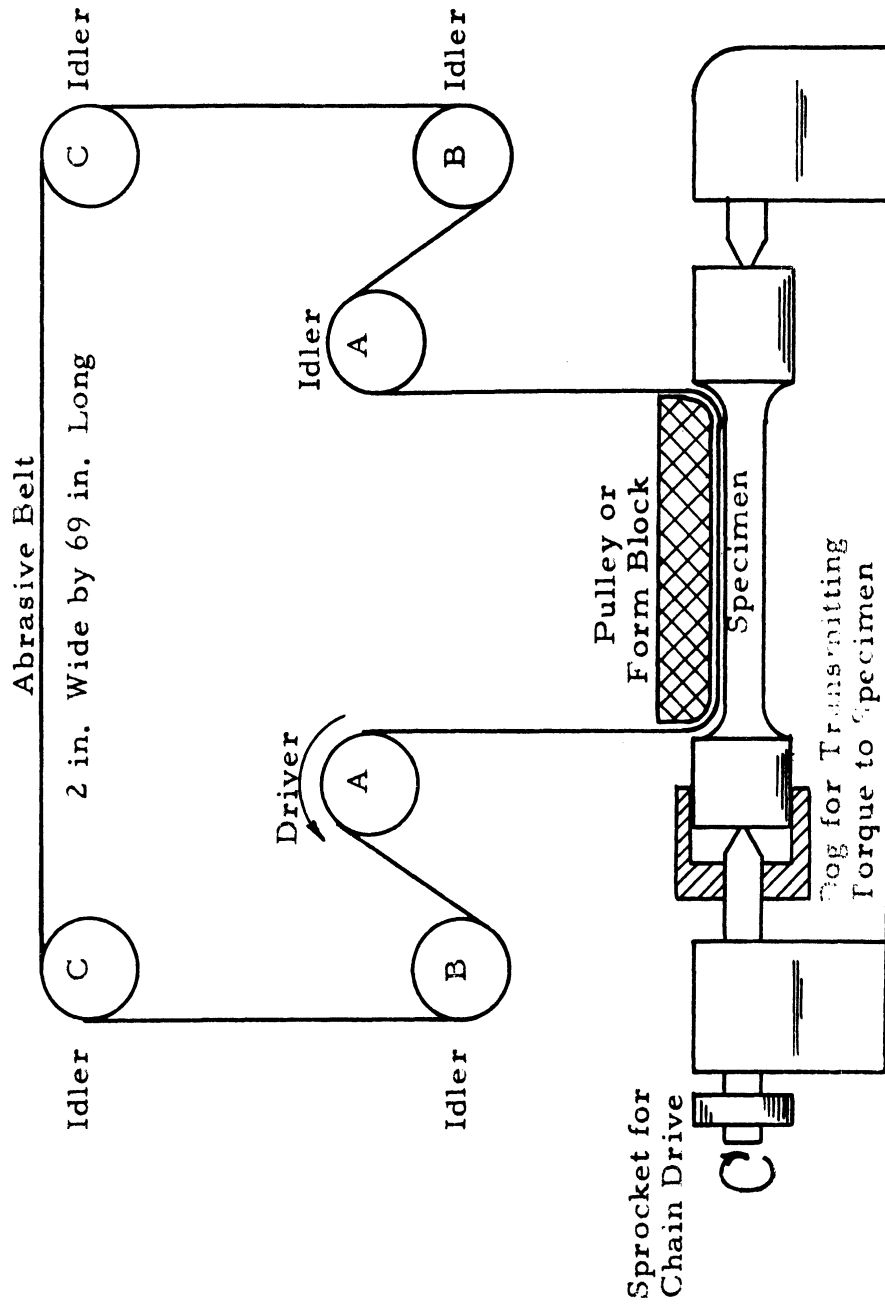


Figure 2. - Polishing machine.

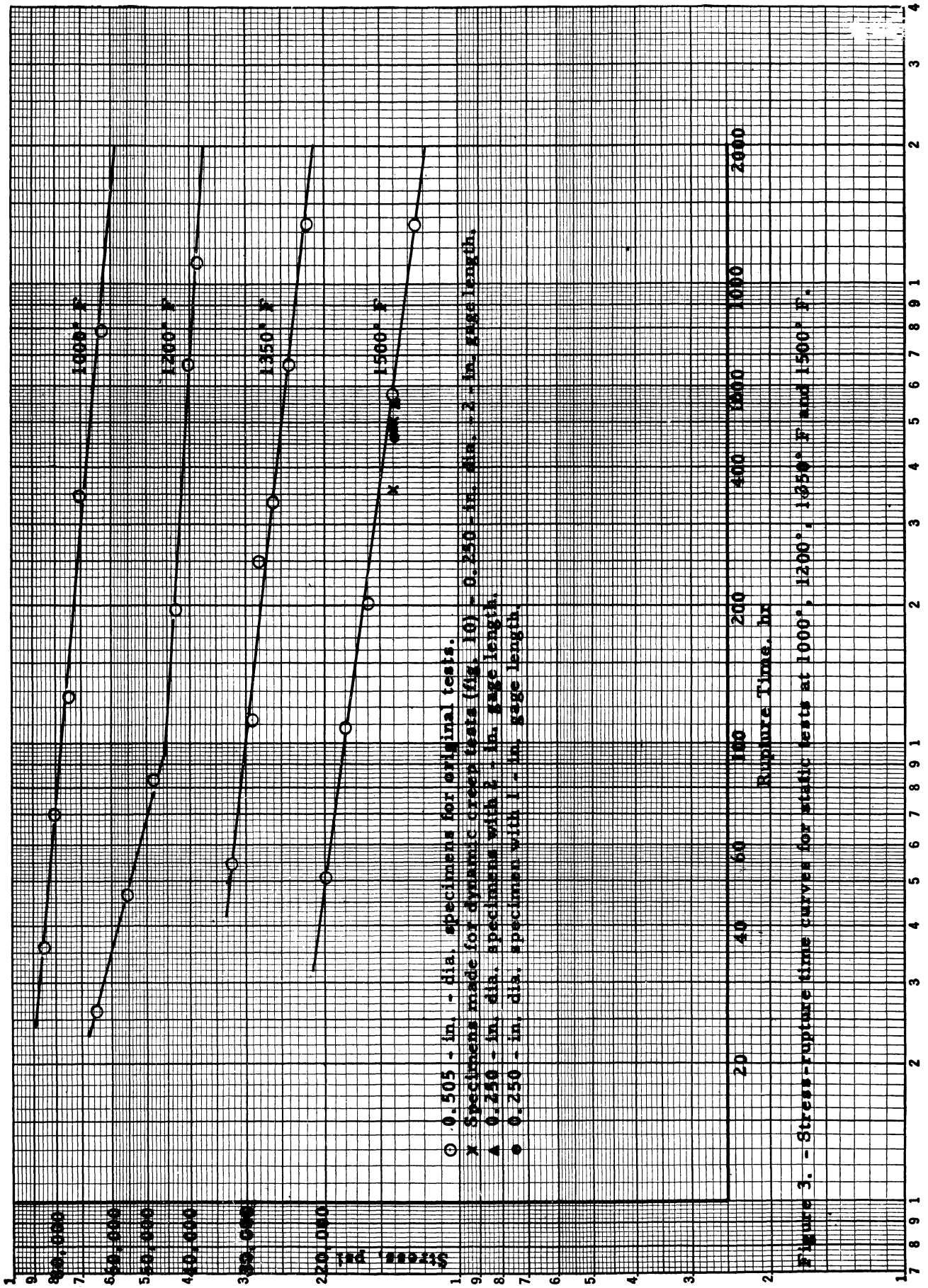


Figure 3. - Stress-rupture time curves for static tests at 1000°, 1200°, 1350° F and 1500° F.

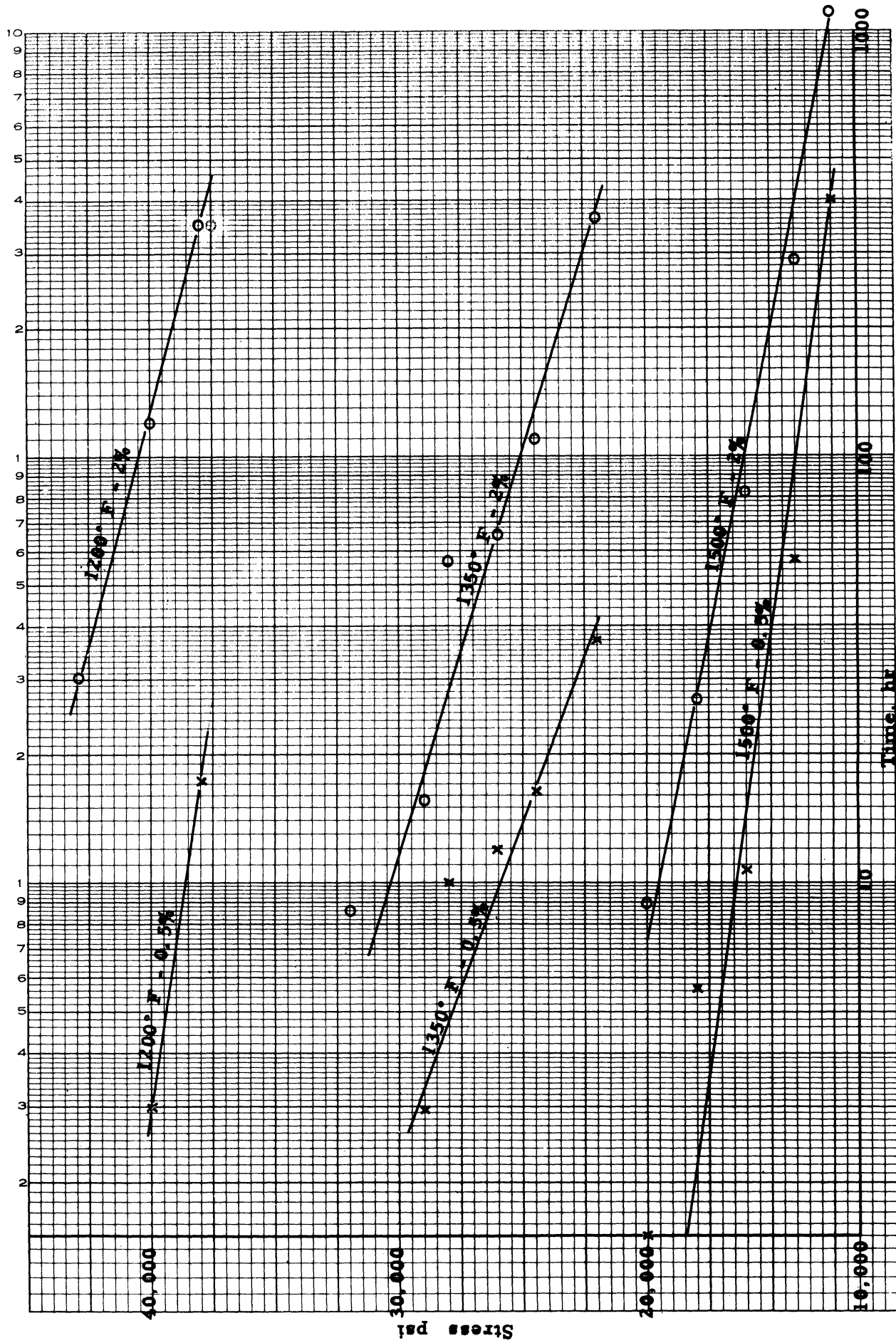


Figure 4. - Curves of stress - time for total deformation of 0.5 - and 2 - per cent from static rupture tests at 1200°, 1350° and 1500° F

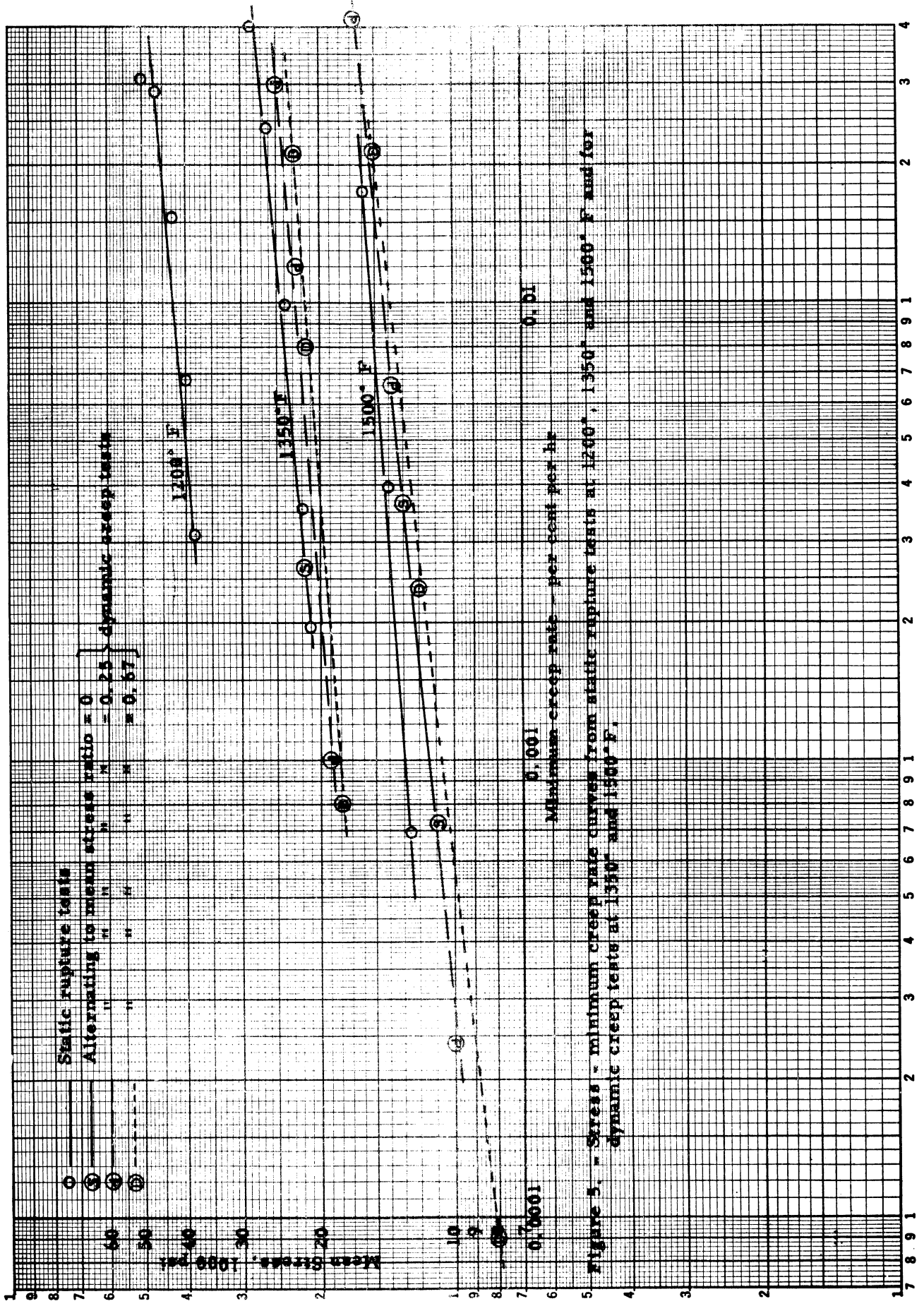


Figure 5 - Stress - minimum creep rate curves from static rupture tests at 1200°, 1350° and 1500° F and for dynamic creep tests at 1350° and 1500° F.

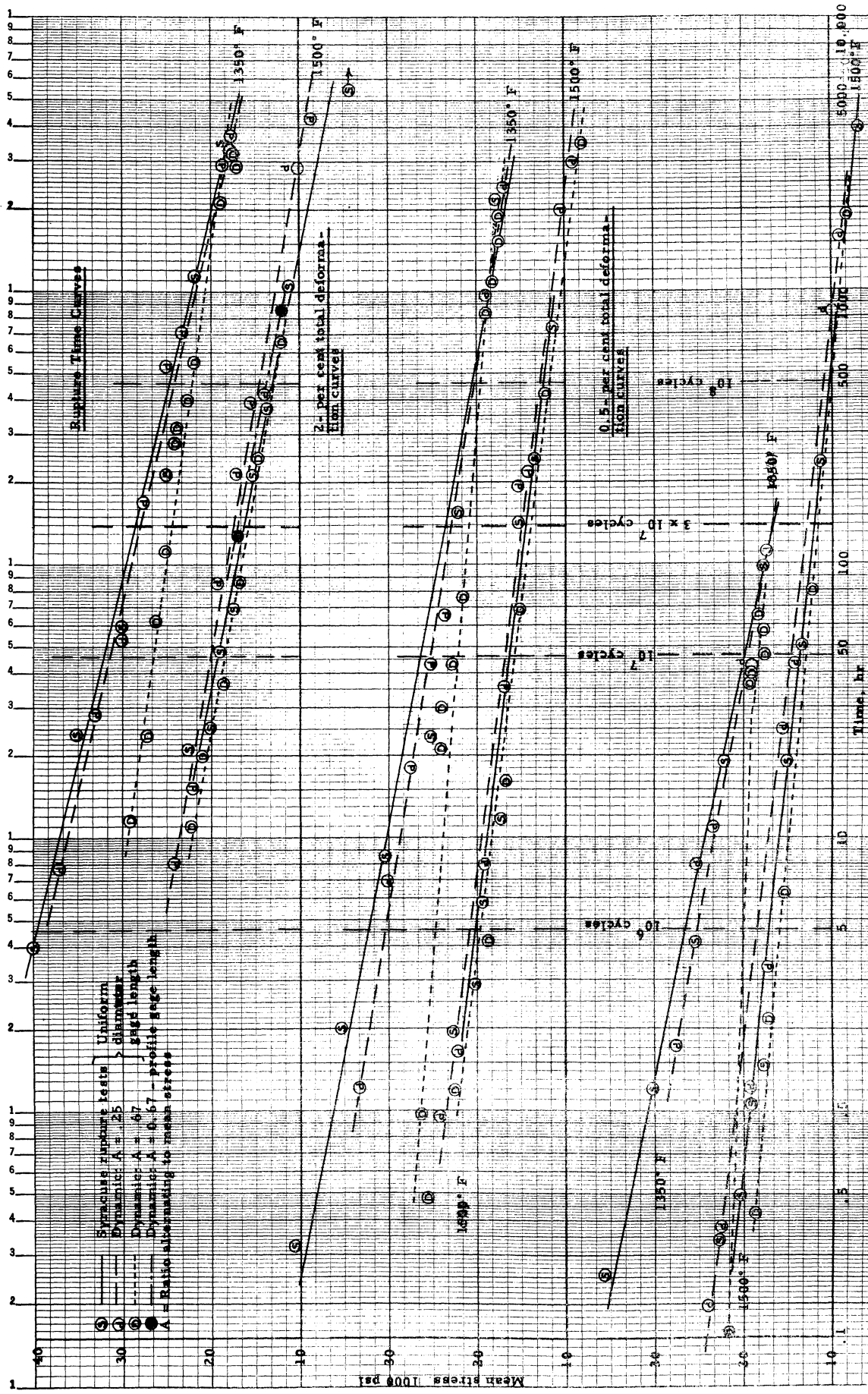
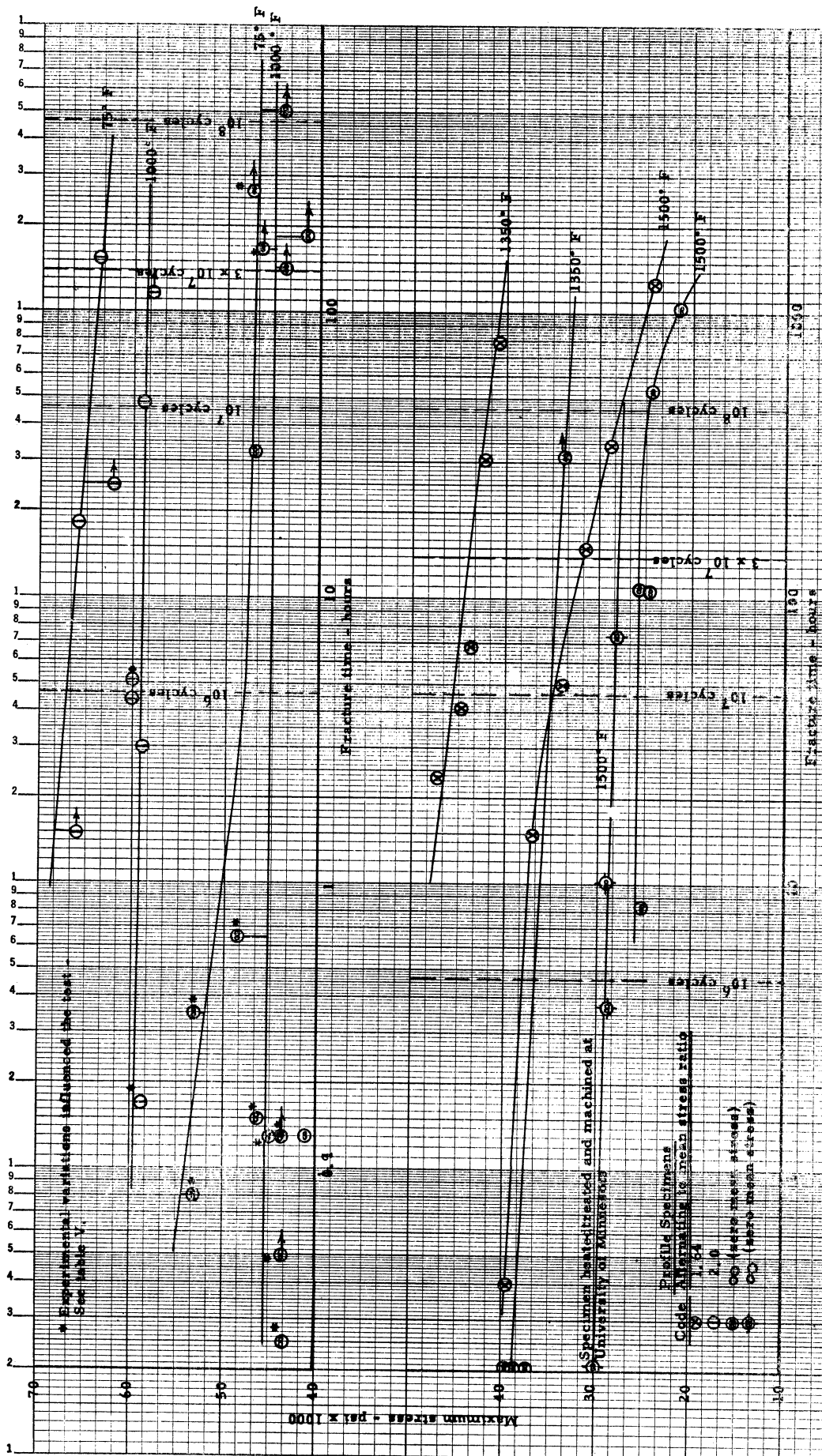


Figure 6. - Curves of mean stress against time for rupture and time for total deformations of 0.5 and 2.0 per cent at 1350° F and 1500° F for axial stress dynamic creep tests.



Figures 1 and 2 - Curves of maximum stress against fracture time for indicated ratios of alternating to mean stress at room temperature. 1000° and 1500° F. are from dynamic stress (stress) testing machine.

* Experimental variations influenced the test. See Table V.

80 Specimen heat-treated and machined at University of Minnesota

Public Specimens
 Code Alternating to mean stress ratio
 1.24
 2.0
 OO (zero mean stress)
 CC (zero mean stress)

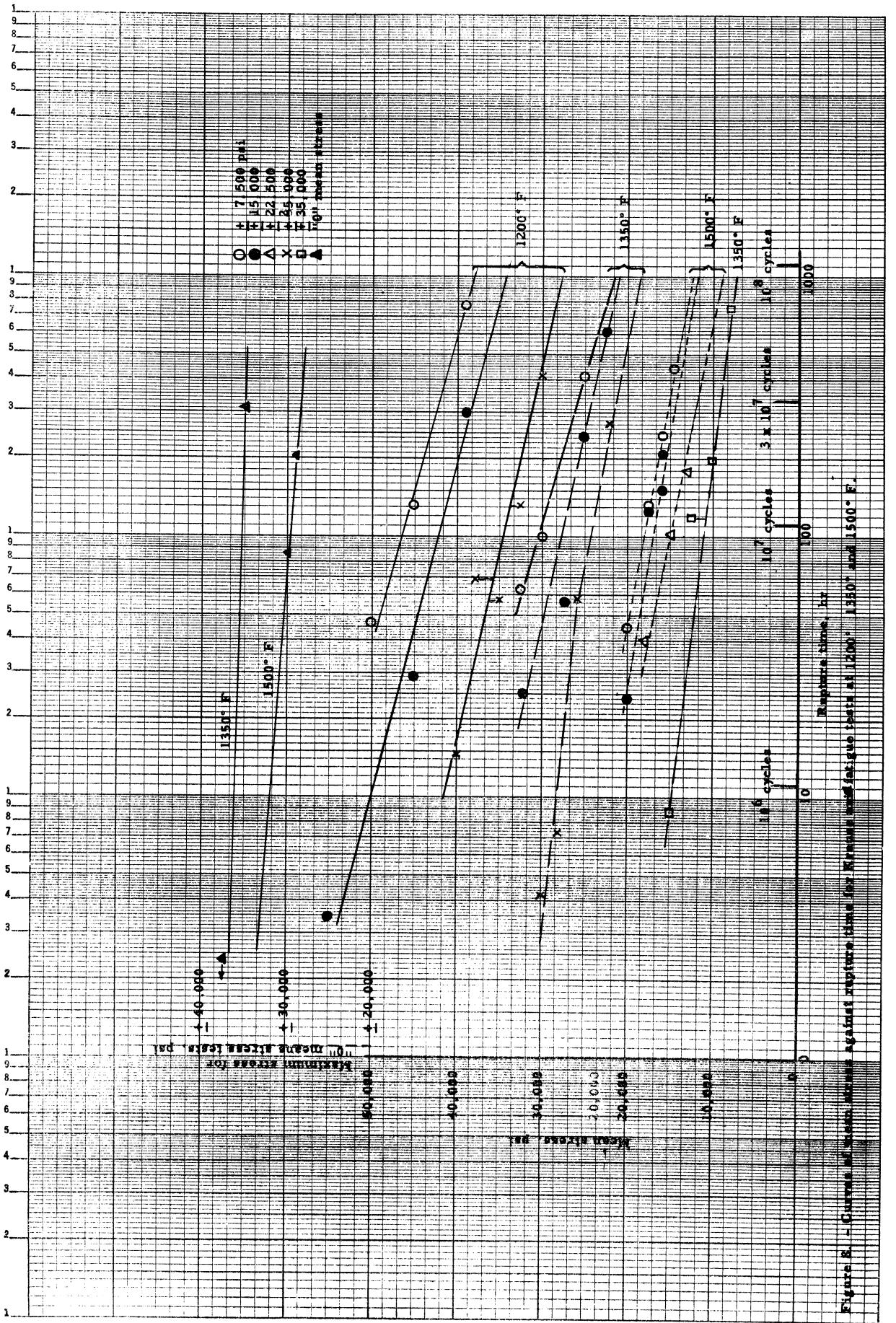


Figure 8. - Curves of mean stress against rupture time for Kirsch fatigue tests at 1200°, 1350°, 1500° and 1550° F.

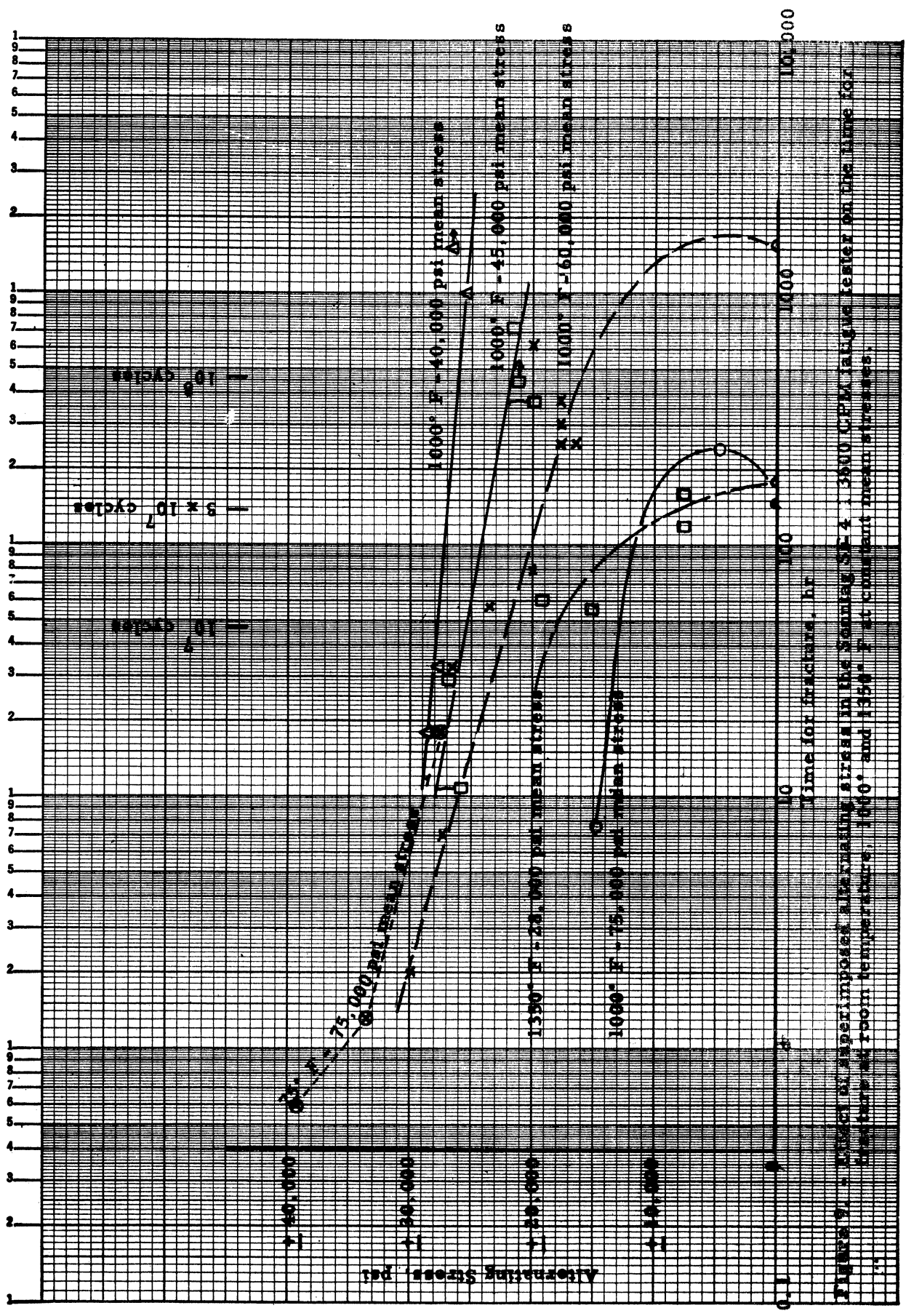


Figure 2. Effect of superimposed alternating stress in the Sealing SS-4 390U CPM titanium alloy on the time for fracture at room temperature, 10,000' and 18,000' F at constant mean stresses.

Alternating Stress, P S I

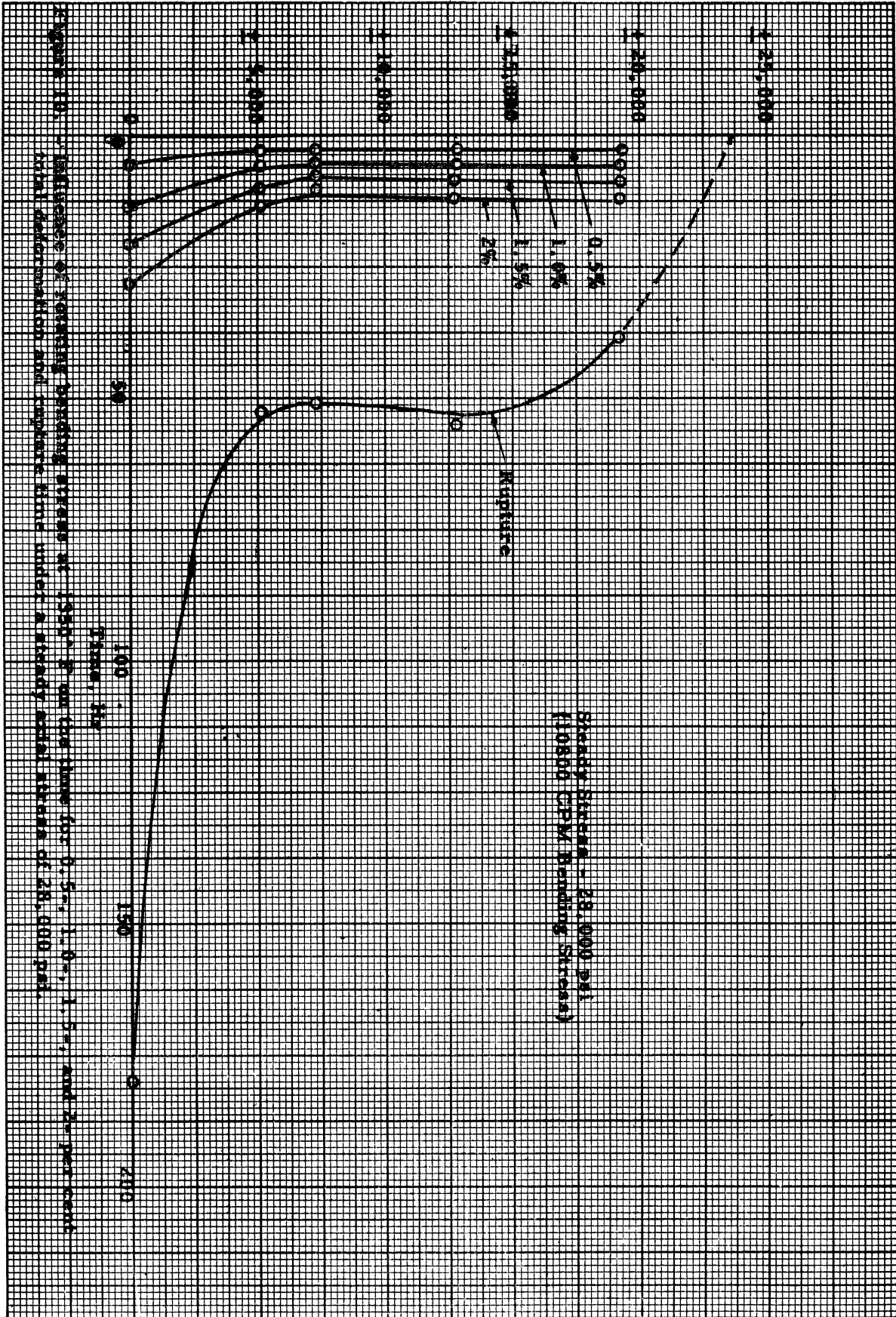
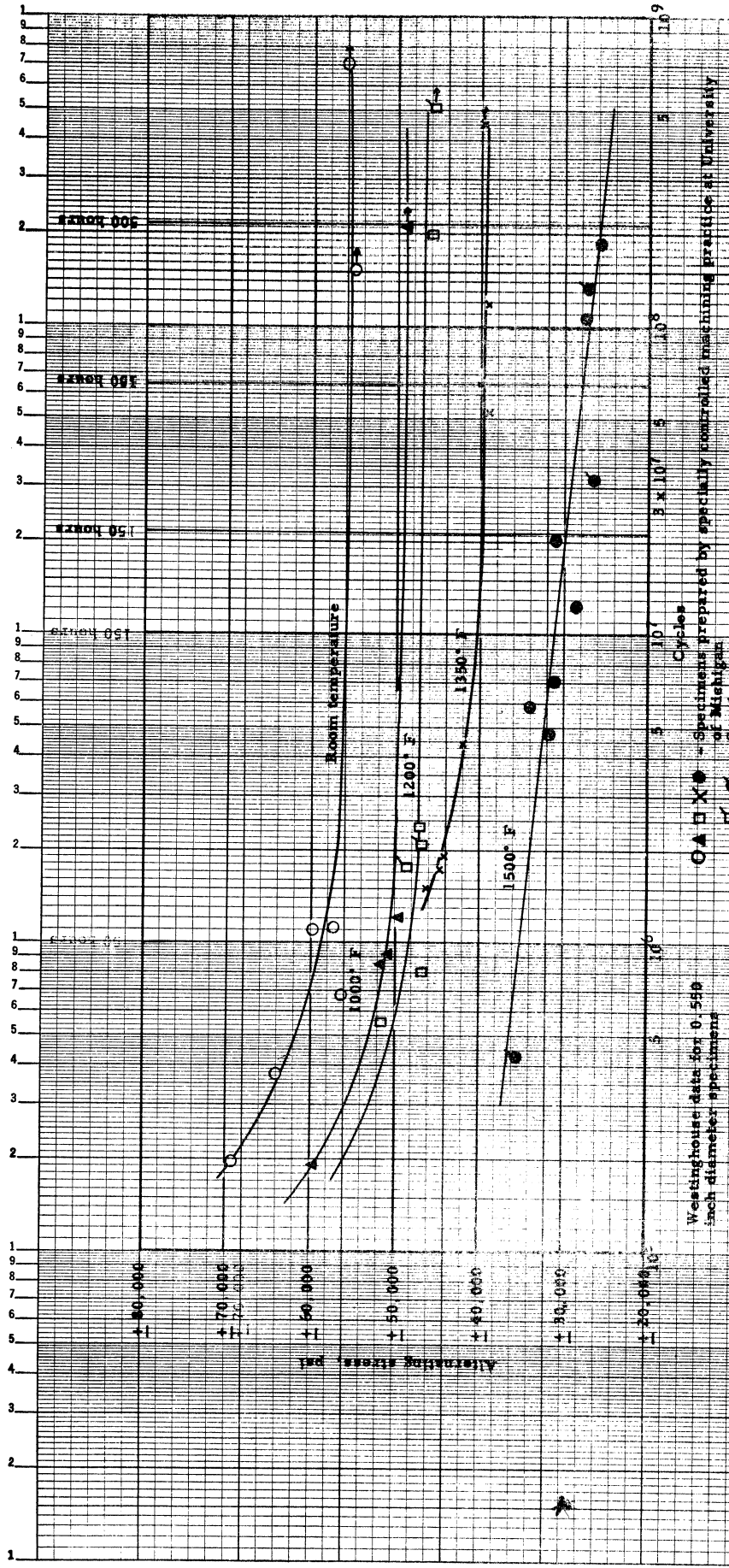


Figure 10 - Influence of rotating operating stress at 1,500 R.P.M. on the time for 0.5%, 1.0%, 1.5% and 2% per cent total deformation and rupture time under a steady axial stress of 28,000 psi.

Steady Stress - 28,000 psi
(10,000 CPM Bending Stress)



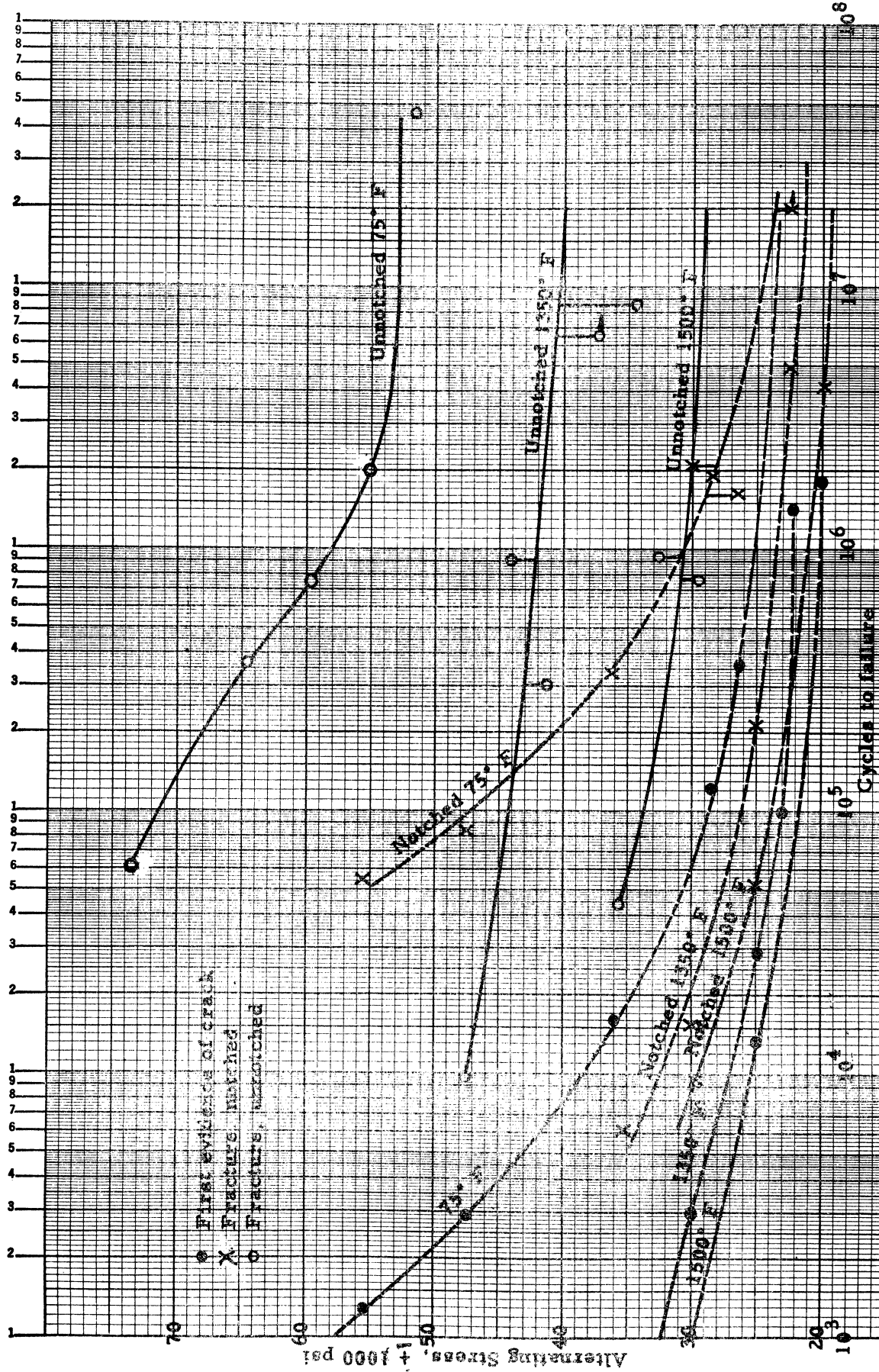


Figure 13 - S-N curves for fracture of unnotched and notched specimens and for first evidence of crack for notched specimens at room temperature, 1350° F and 1500° F in variable speed rotating cantilever beam tests.

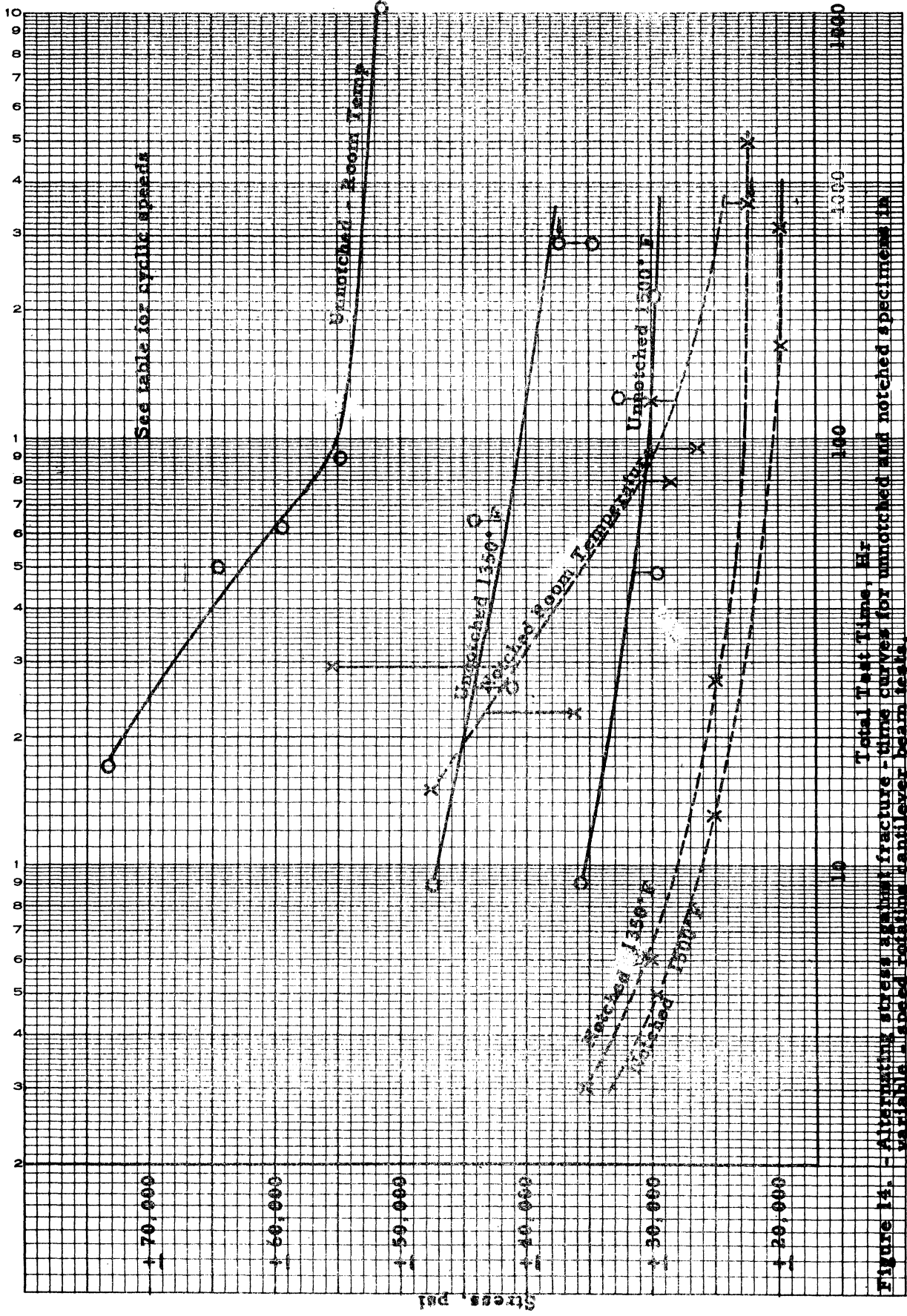


Figure 14. - Alternating stress against fracture - time curves for unnotched and notched specimens in variable speed rotating cantilever beam tests.

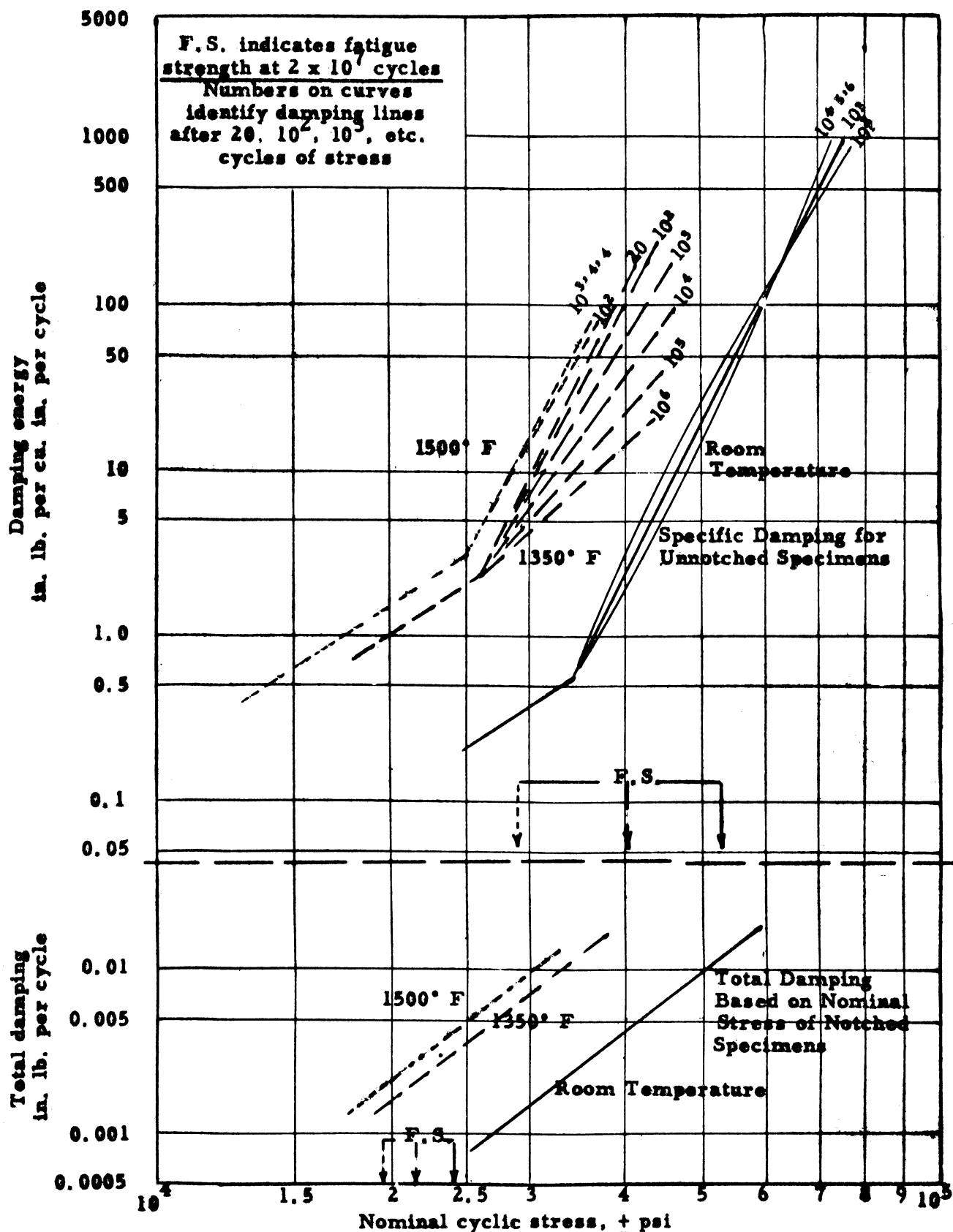


Figure 15. - Effect of stress magnitude and constant cyclic stress history on damping energy for unnotched and notched specimens at room temperature, 1350° and 1500° F.

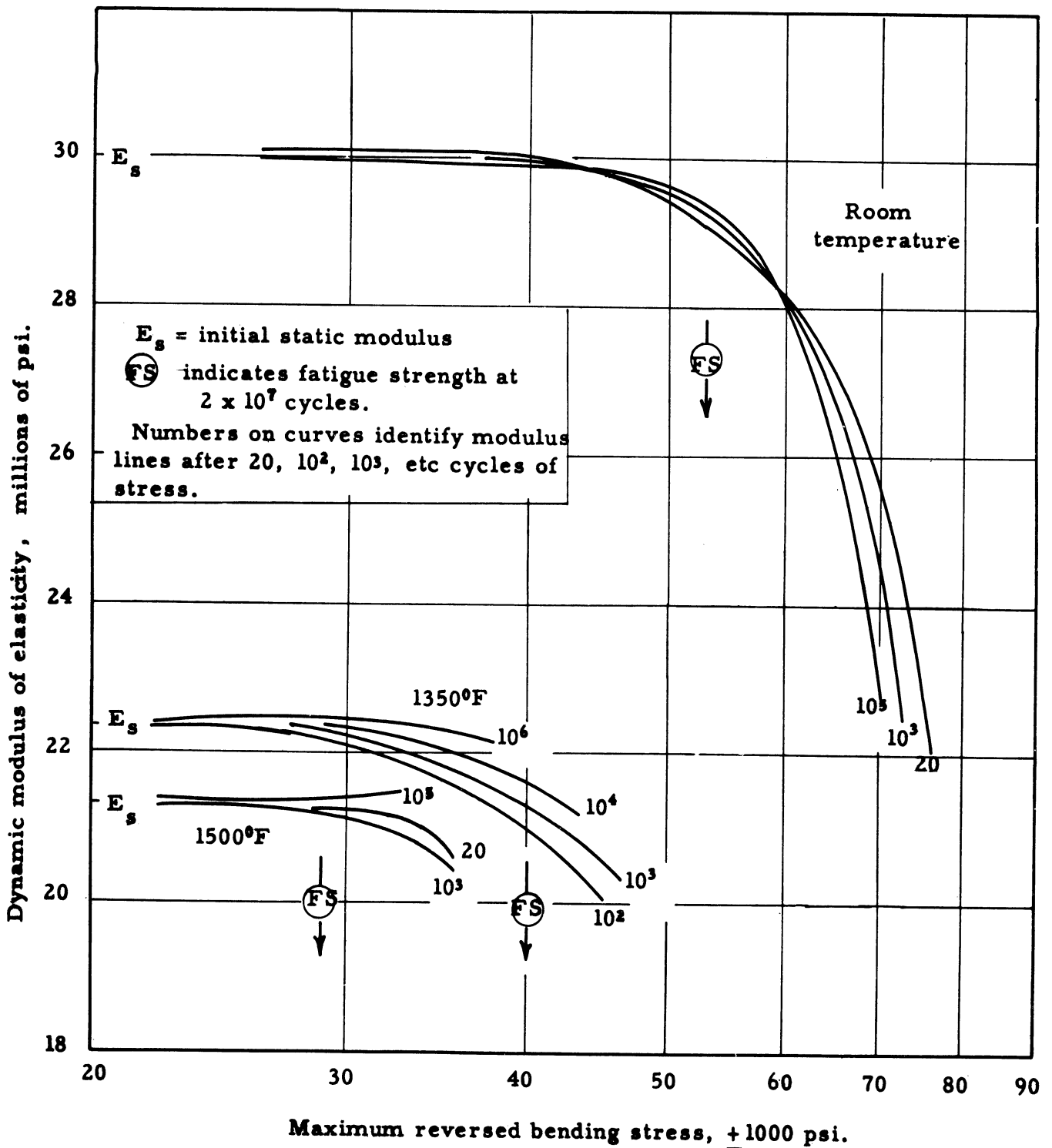


Figure 16. - Dynamic moduli of elasticity at room temperature, 1350° and 1500°F after different numbers of cycles of reversed bending stress.

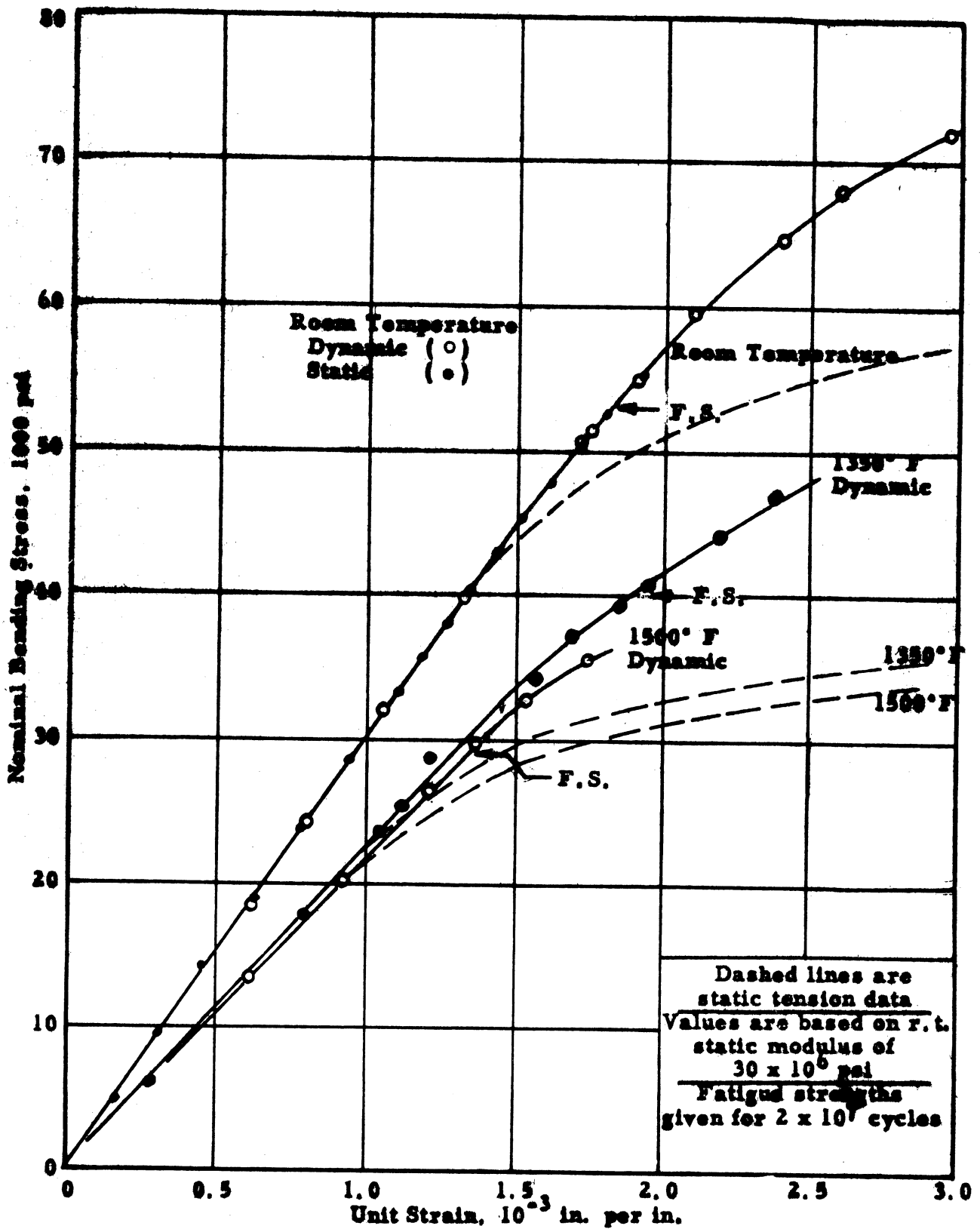
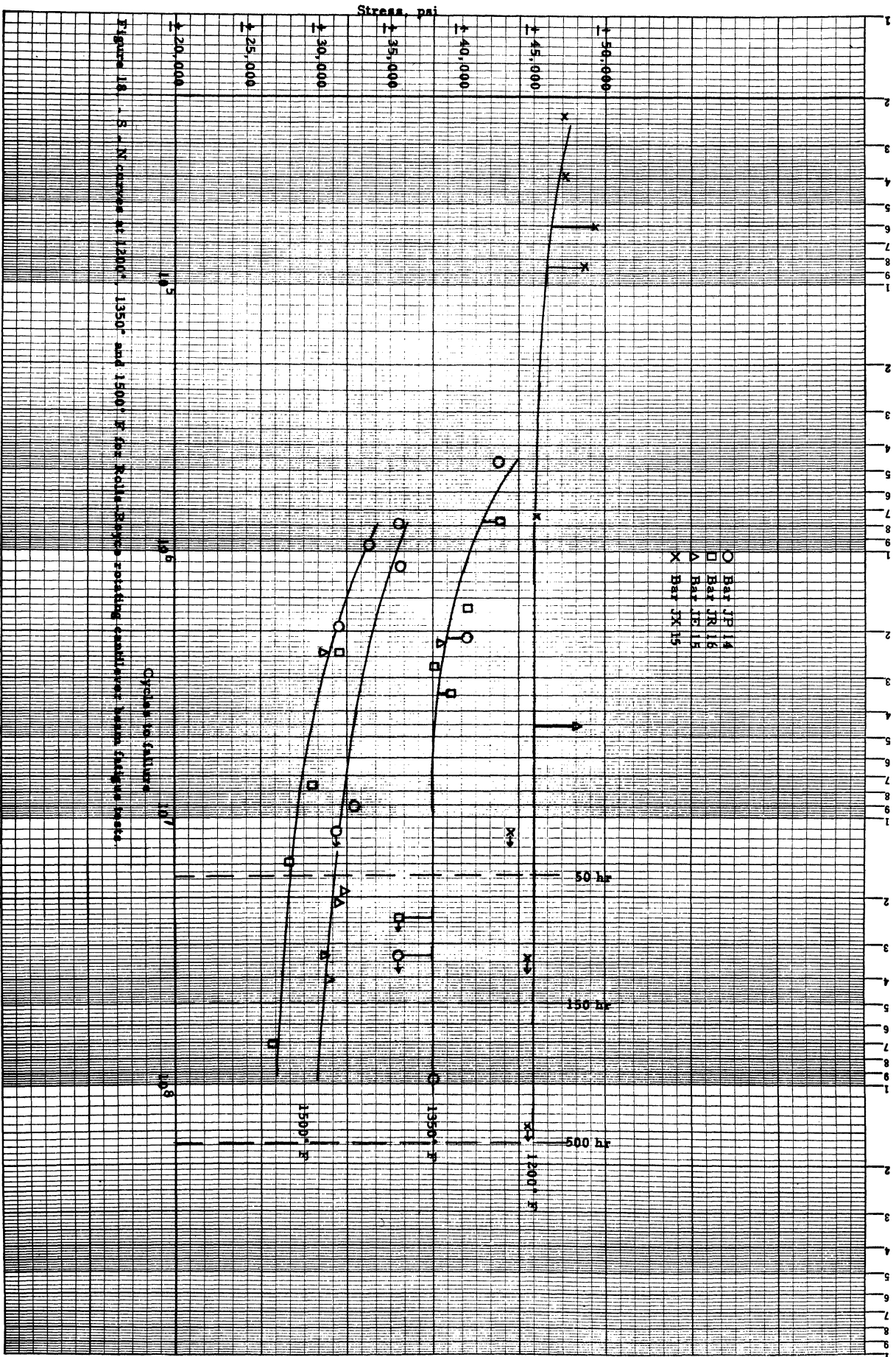


Figure 17. - Static and dynamic stress - strain curves in bending for unnotched specimens.



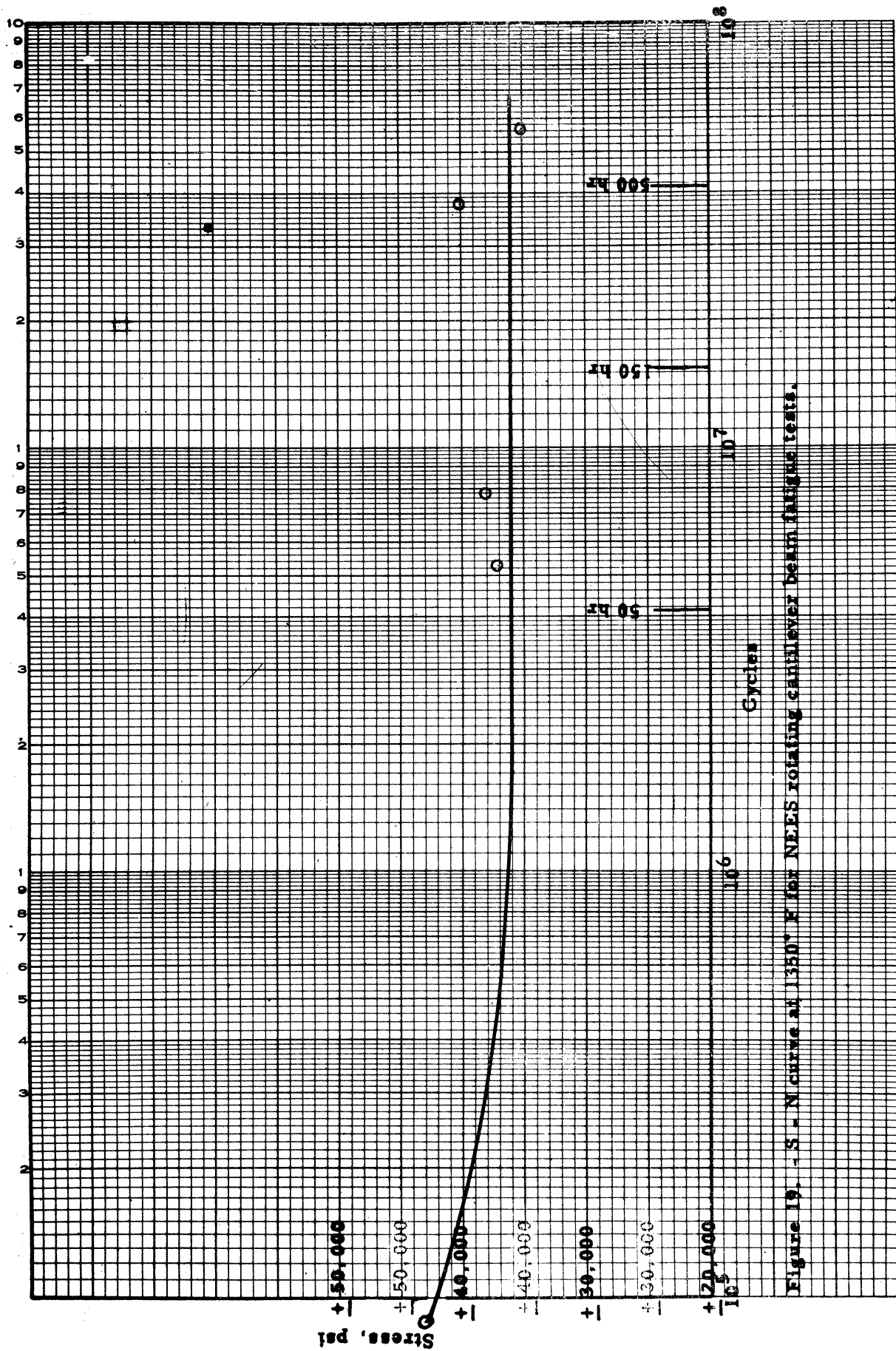
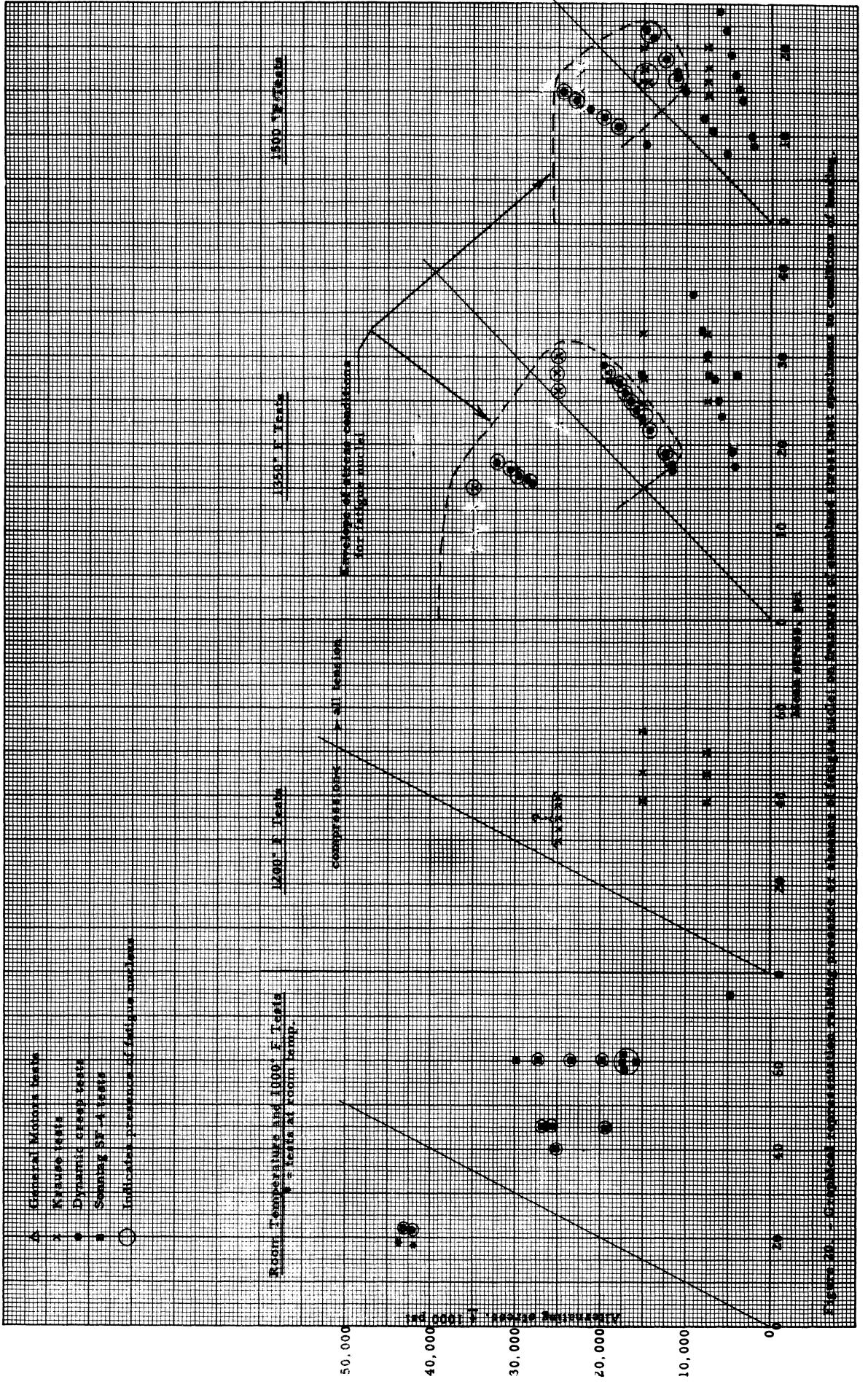
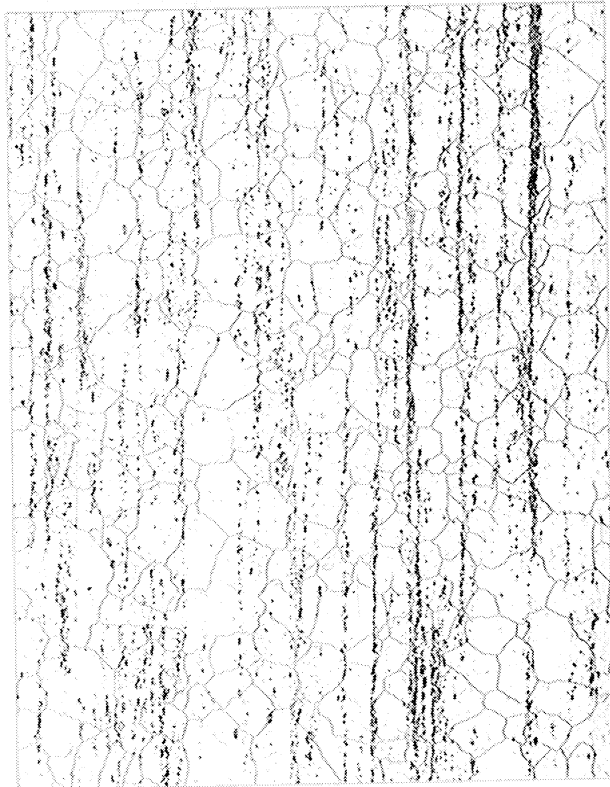
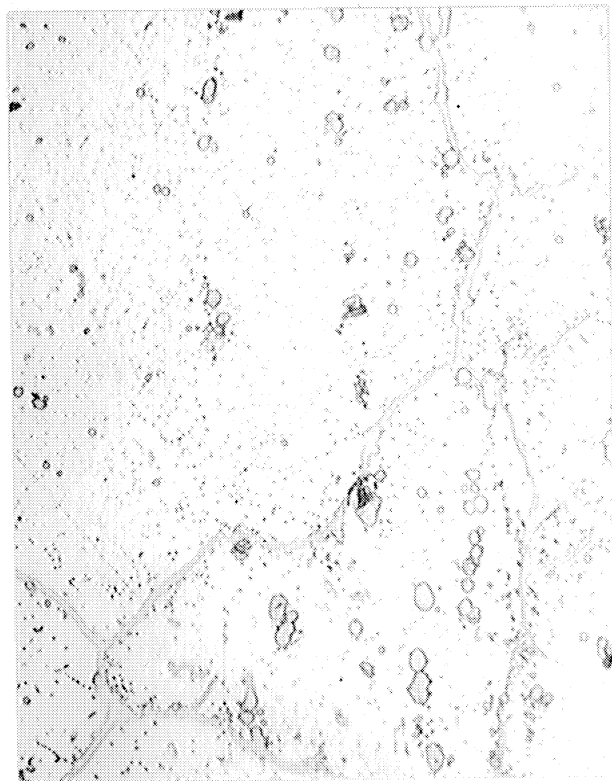


Figure 19. - S - N curve at 13500 F for NEES rotating cantilever beam fatigue tests.



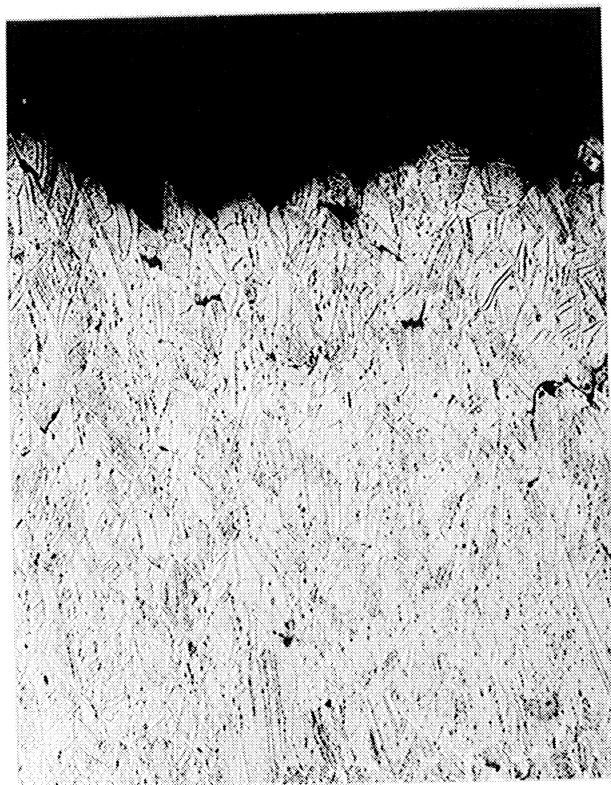


X100D



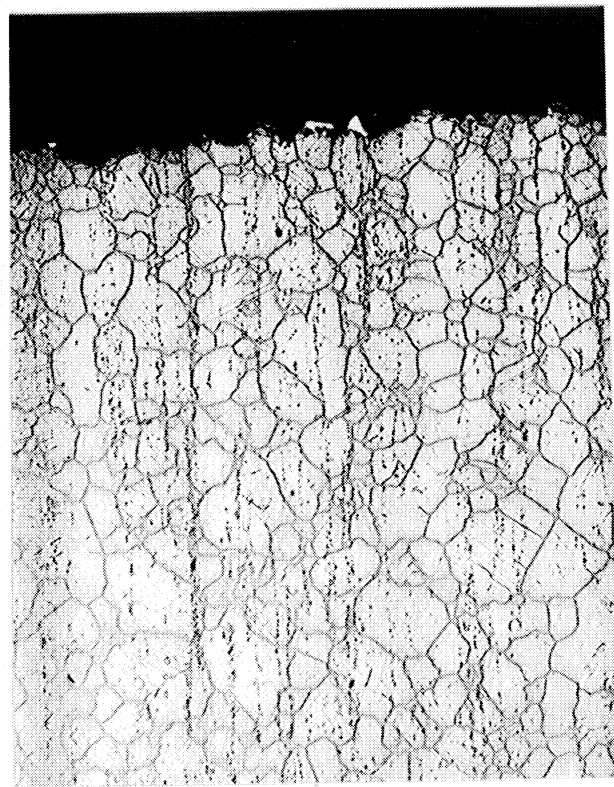
X1000D

(a) Original material



X100D

(b) Typical creep-rupture fracture - 248 hrs. at 1350°F under 28,000 psi.



X100D

(c) Typical fatigue nucleus - 369 hrs. at 1350°F under + 40,000 psi.

Figure 21. - Typical Microstructures of Original Test Material and Fractures of Test Specimens.

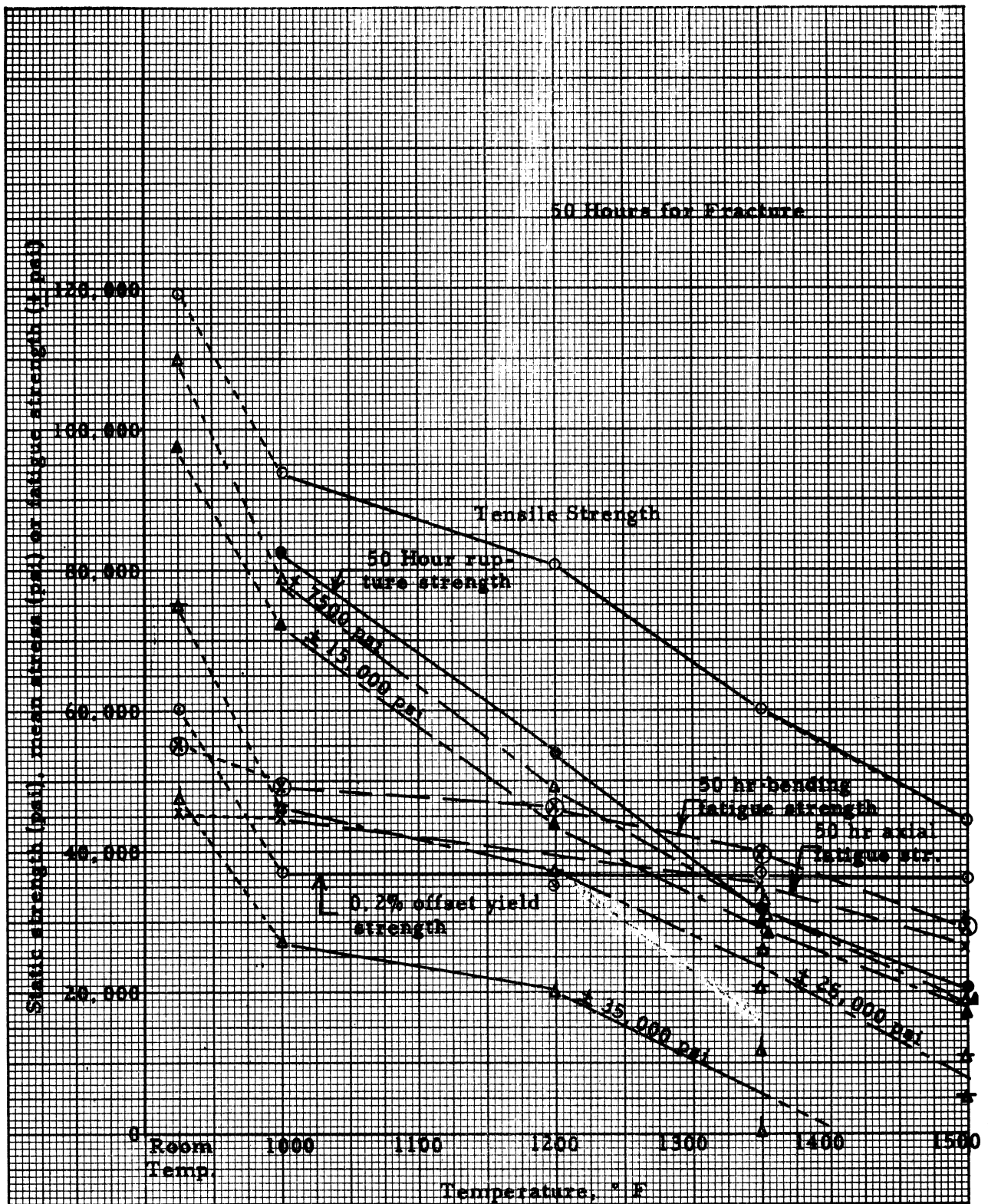


Figure 23. - Comparative static and fatigue strengths for fracture in 50, 150 and 500 hours from room temperature to 1500° F

Note: Curves designated with + 7500, + 15,000, + 25,000 or + 35,000 psi show the mean stress for rupture with the indicated alternating stress superimposed.

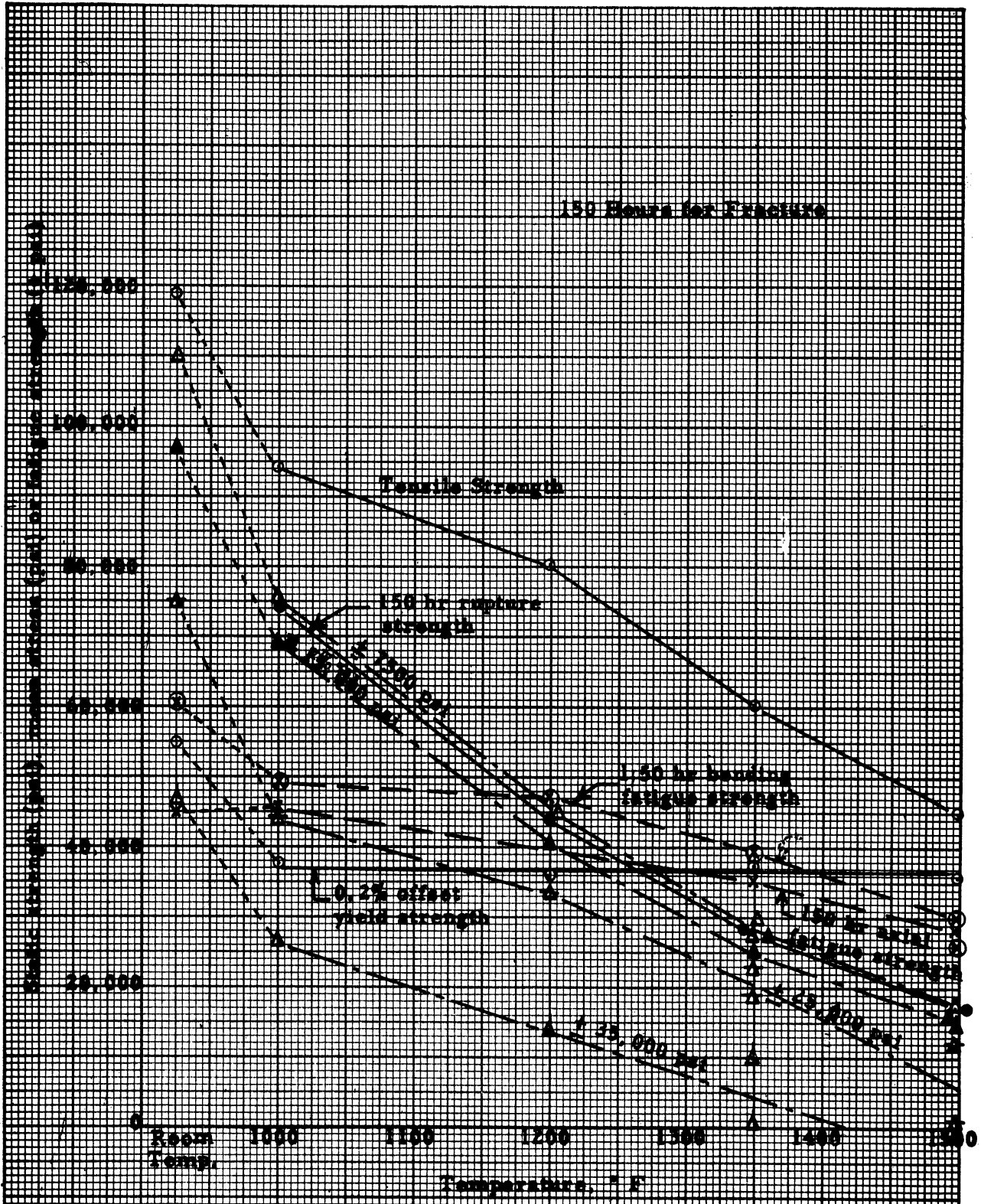


Figure 22. - Continued.

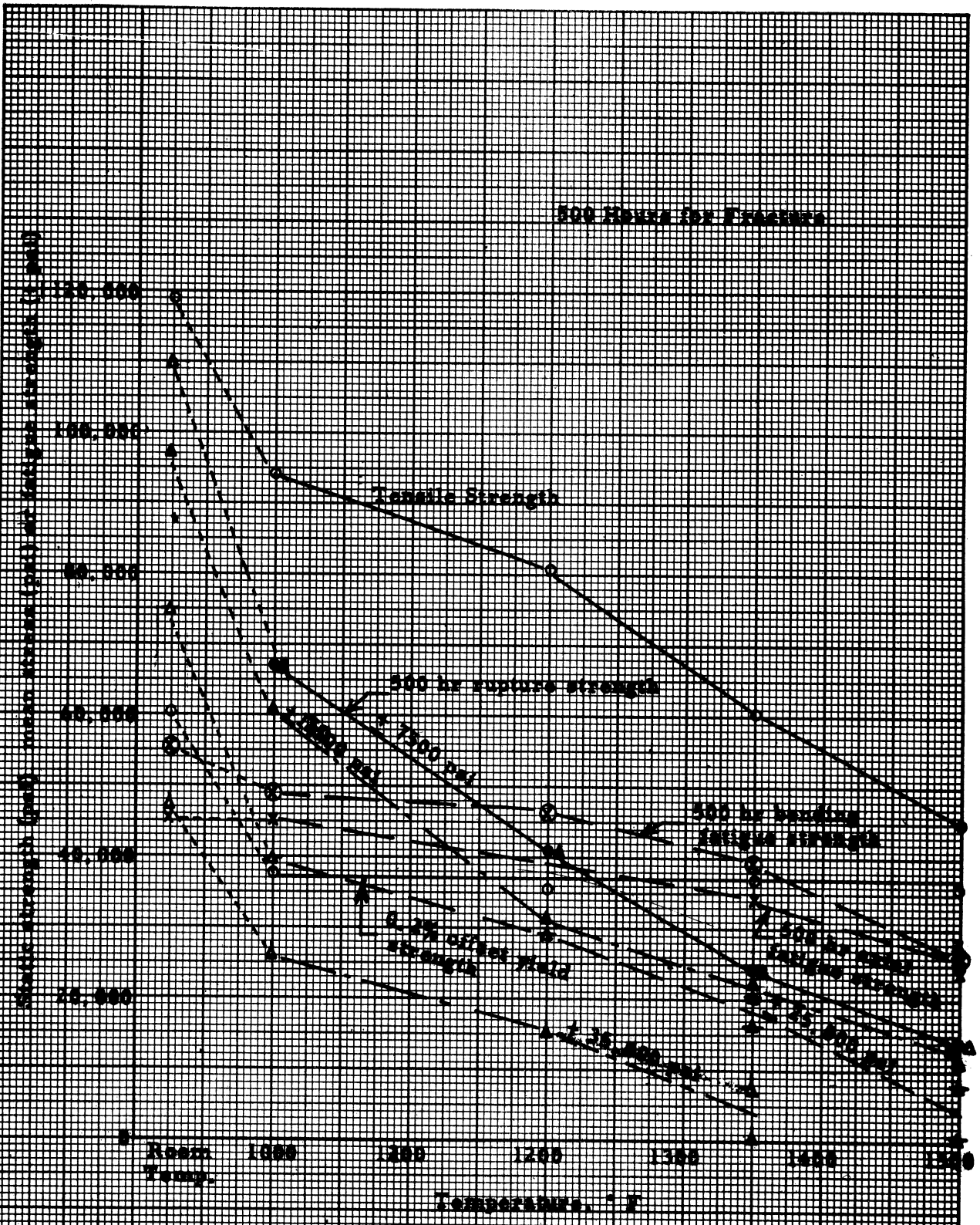


Figure 22 - Continued

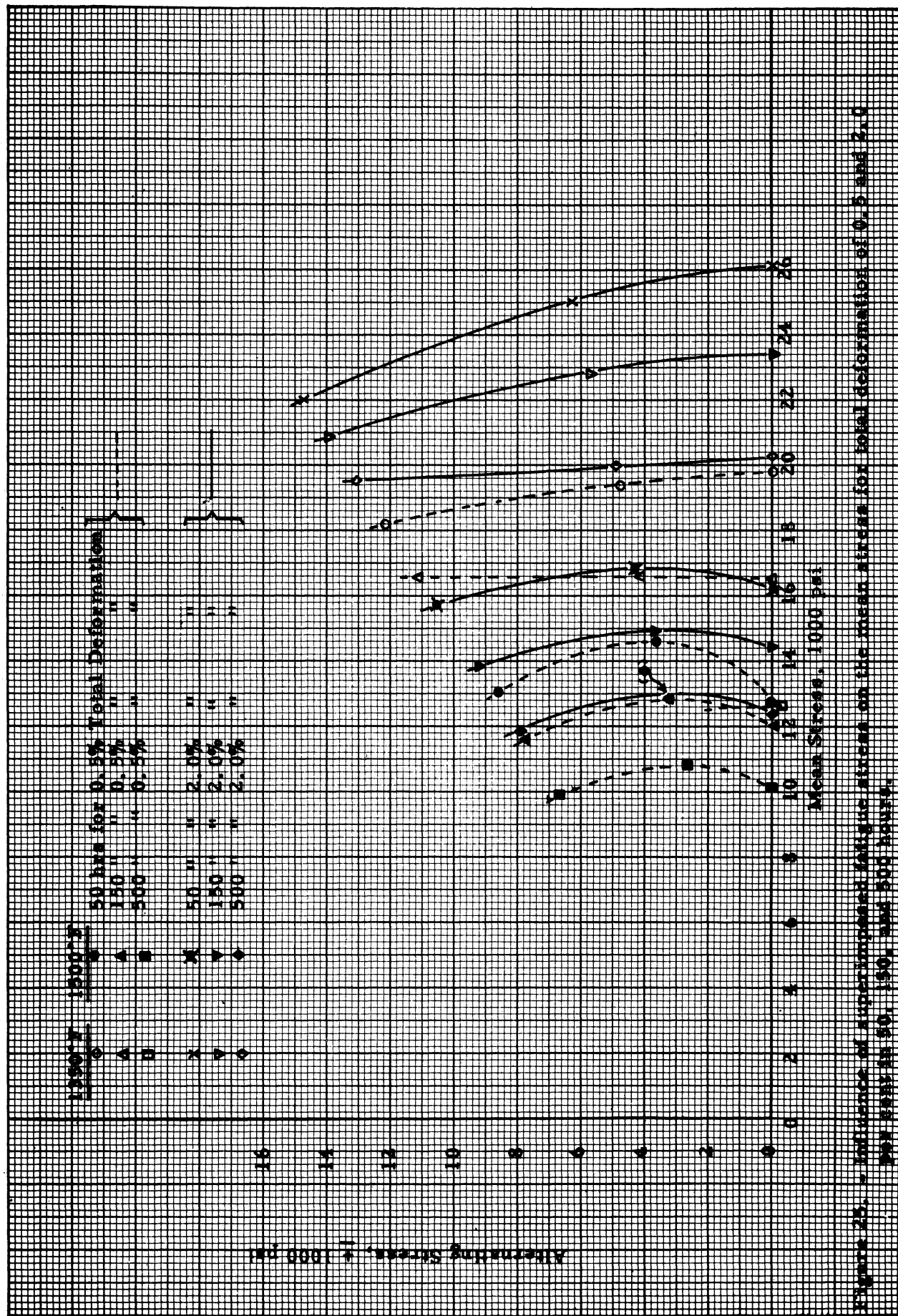


Figure 25. Influence of superimposed fatigue stress on the mean stress for total deformation of 0.5 and 2.0 per cent in 50, 150, and 500 hours.

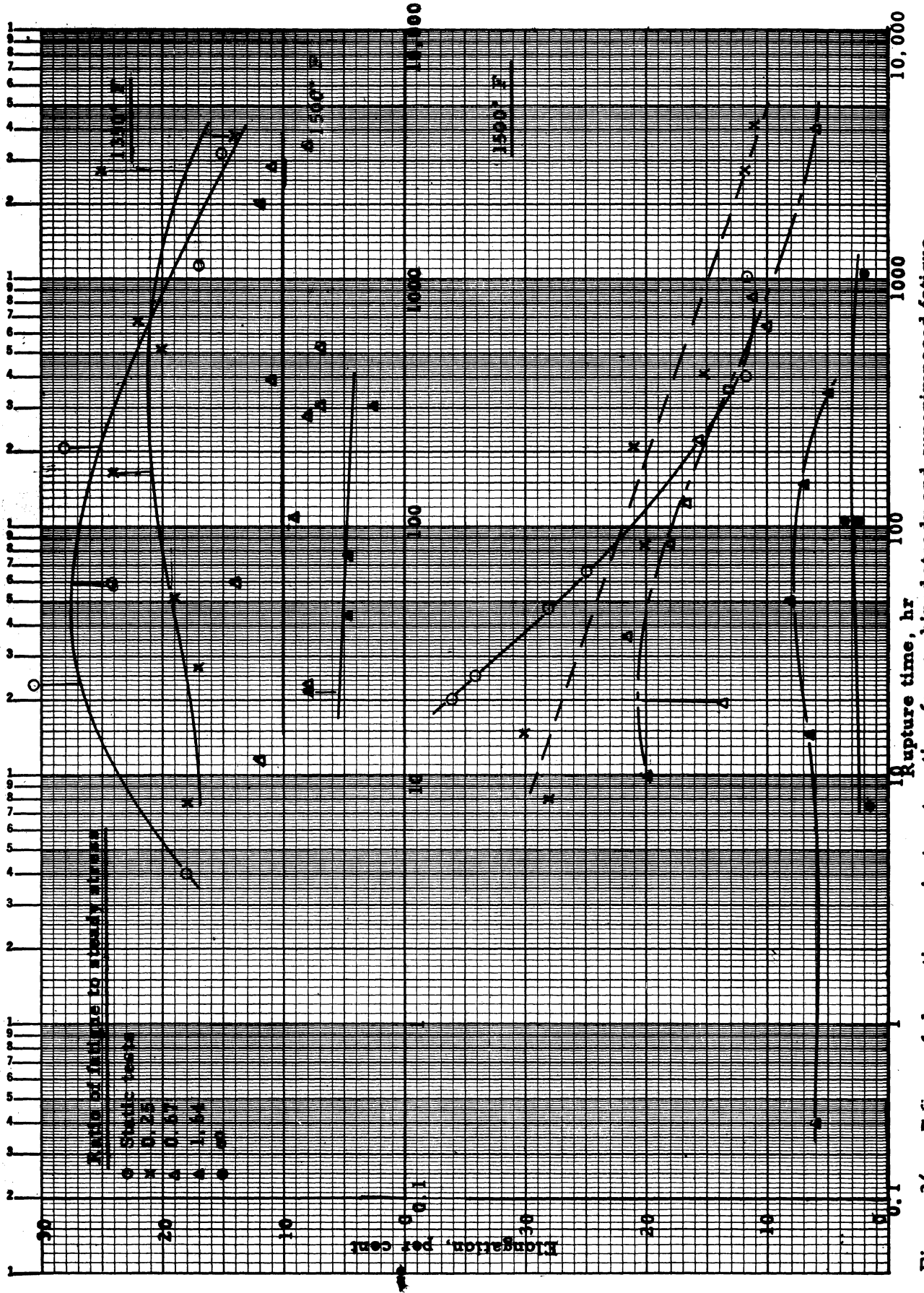


Figure 26. - Curves of elongation against rupture time for combined steady and superimposed fatigue.

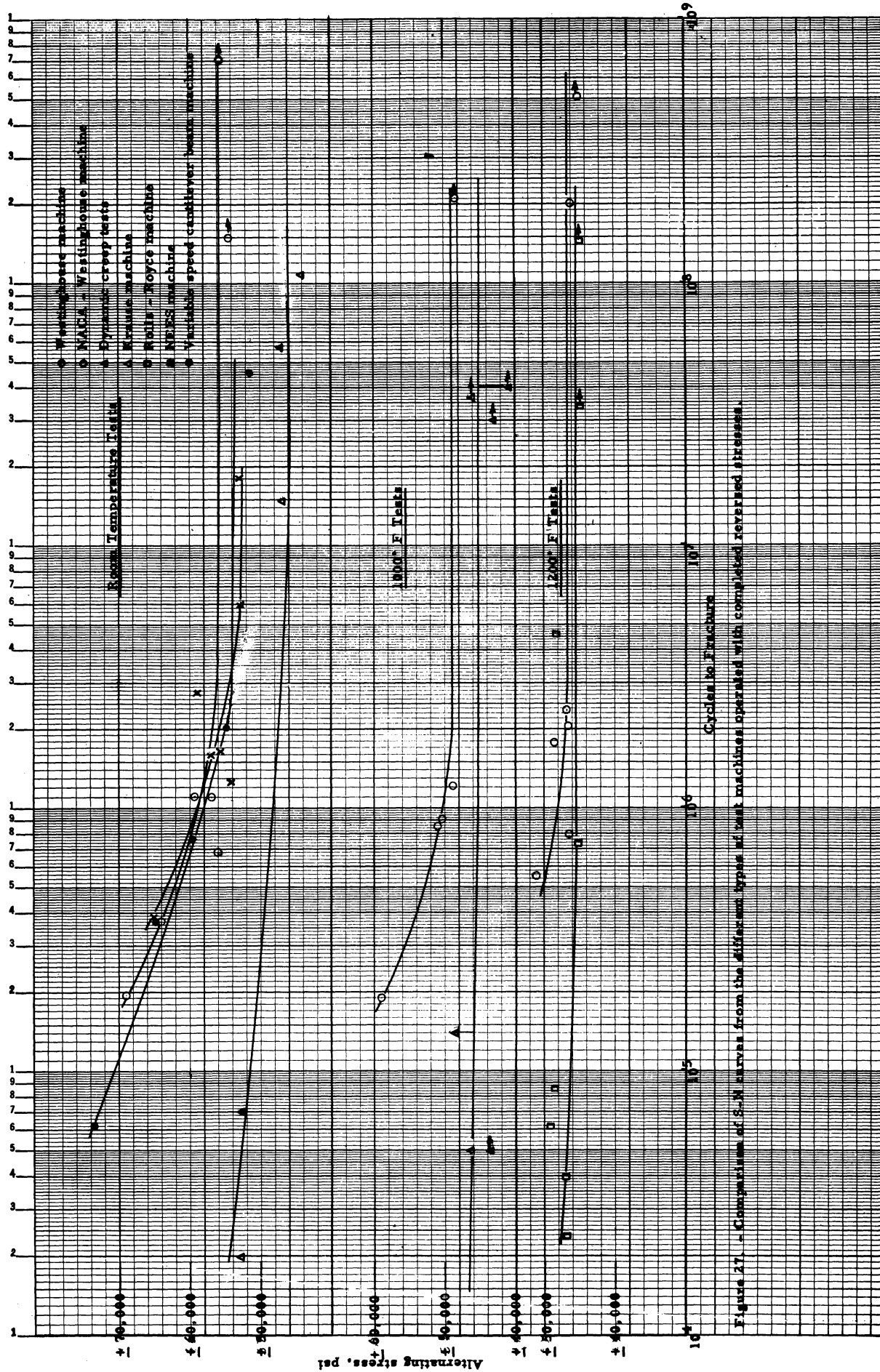


Figure 27 - Comparison of S-N curves from the different types of test machines operated with completed reversed stresses.

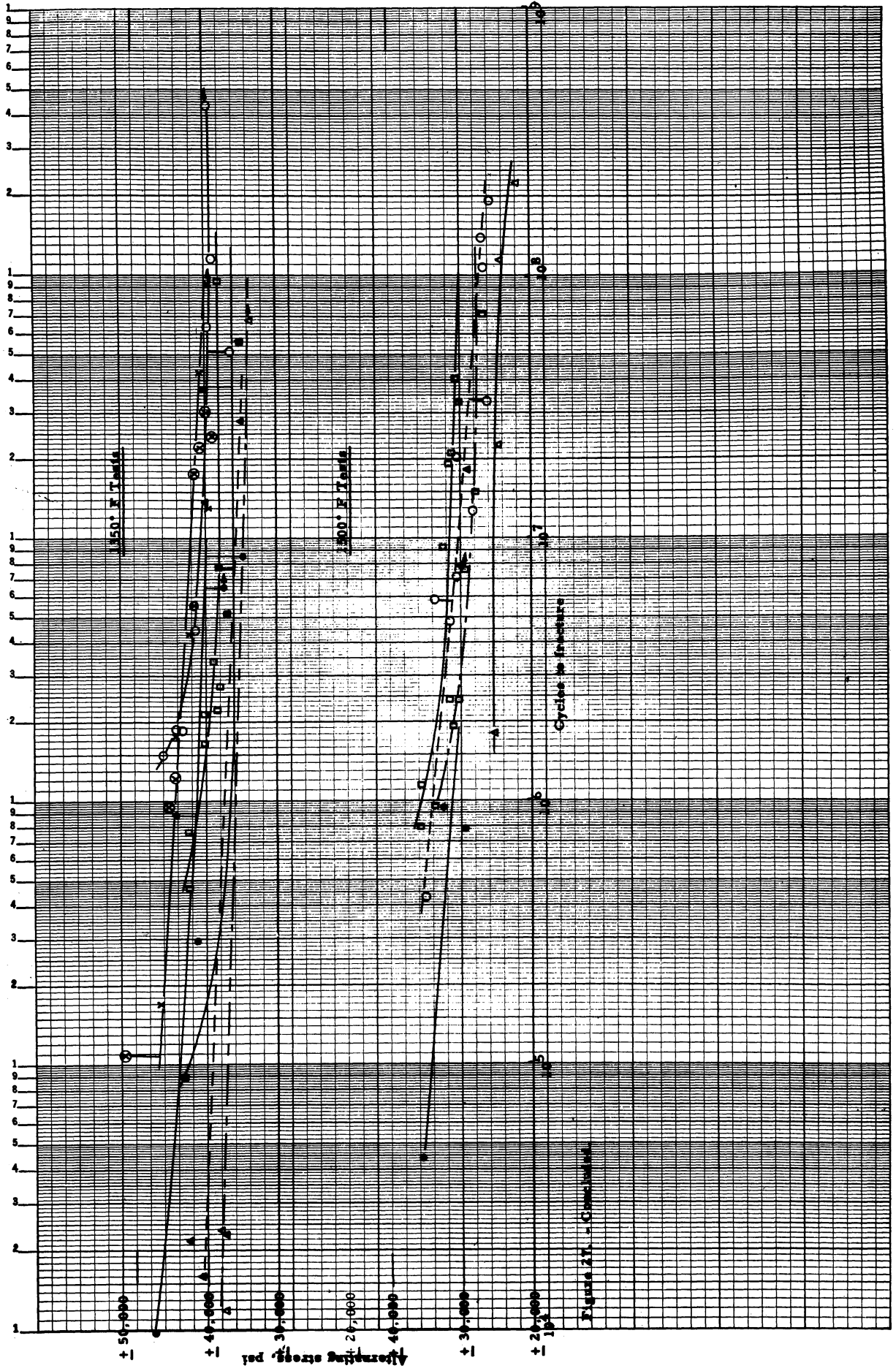


Figure 21 - Continued

