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TENSILE, FATIGUE, AND CREEP PROPERTIES OF FORGED ALUMINUM ALLOYS AT TEMPERATURES UP TO 800° F

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SUMMARY

This paper presents data on the tensile strength, fatigue strength, creep properties, and thermal expansion of forged aluminum alloys XB18S, 18S, 24S, and 32S, which are pertinent to the application of these alloys in the temperature range from 70° to 800° F. Included are data taken from published sources, unpublished material made available through the courtesy of the Aluminum Company of America and the National Bureau of Standards, and original data, obtained at Battelle Memorial Institute, which extend this previous information. The work also contains a critical discussion of the data and their application to design of aircraft engines.

INTRODUCTION

Recent advances in the development of aircraft engines have resulted in the use of higher operating temperatures at some locations in the engine. It has been estimated that temperatures from 700° to 800° F are reached in localized spots in pistons and cylinder heads in reciprocating engines. Jet power plants also require high operating temperatures.

In order that developments in materials might keep pace with developments in mechanical design of power plants, the National Advisory Committee for Aeronautics is supporting work with the following objectives:

(1) To obtain reliable data on the pertinent high-temperature properties of aluminum alloys currently available

(2) To develop heat treatments and fabrication procedures to develop the maximum high-temperature properties of currently available alloys

(3) To foster the development of new and improved aluminum alloys for high-temperature service

The present investigation, conducted at Battelle Memorial Institute under the sponsorship and with the financial assistance of the National

Advisory Committee for Aeronautics, was intended to develop information pertinent to the first two of these objectives.

It was recognized that the problem is complex and that, regardless of the care used in planning a program, it was quite likely that in the course of conducting the investigation it might become desirable to obtain other information than that included specifically in the plans. With this in mind, the program summarized as follows was planned:

(1) Work was to be confined to an exploration of the fatigue and creep properties of the forged (or rolled) alloys XB18S, 18S, 24S, and 32S, concentrating particularly on the temperature range from 400° to 800° F. While it was recognized that this series is not a complete cross section of available alloys, and in particular provides no information on castings, it was hoped that base-line information could be obtained which would be useful in cutting down the amount of experimental work necessary to make comparisons between these and other alloys.

(2) It was decided that the creep tests should be conducted by conventional means. It was thought unnecessary to carry the creep tests beyond 500 hours. The fatigue tests were to be direct-stress fatigue tests in which the load was to be varied from a minimum stress, almost zero, to a maximum stress in tension. The type of data obtained from such a test differs from conventional data in that most data obtained previously have been made on reversed-bending tests of one kind or another. It was thought that the direct-stress tests might provide more information on the effect of creep than tests in which the mean stress is zero, as it is in the reversed-bending type.

DESCRIPTION OF MATERIALS AND PREVIOUS DATA

Material

The aluminum alloys studied in this investigation were furnished by the Aluminum Company of America, in the form of 1-inch-round, hot-rolled rods. (A small amount of 7/8-inch-round rod of forged XB18S alloy was also furnished in order that the properties of the forged and the rolled rod could be compared.) Table 1 contains descriptive material about the alloys: their composition, the heat treatment recommended by the Aluminum Company of America for each alloy to produce the T-temper, and the room-temperature mechanical properties to be expected if the alloy is heat-treated according to the specification.

Thermal Treatment

The aluminum rods (1 in. in diameter), from which the tension test, fatigue test, and creep test specimens were made, were cut into bars 7 inches long. These bars were clamped into a 15-bar heat-treating fixture with the surface of each bar not less than 1 inch from the surface of any other bar in the fixture. This spacing ensured adequate room for the circulation of the hot furnace air and the quenching medium. Two of these fixture-bar assemblies could be heat-treated at the same time in a Lindberg Air-Draw Furnace; the heat-treating time and temperature and the quenching medium were as specified by the Aluminum Company of America. Each of the fixture-bar assemblies was quenched separately by plunging it into the quenching medium and vigorously agitating it; the second fixture-bar assembly was allowed to come back to the quenching temperature if the temperature had dropped when the furnace door was opened to quench the first assembly.

Artificial aging, when it was specified, was conducted in the same furnace, and the bars were left undisturbed in the fixtures for this operation.

A dummy specimen, drilled to allow the insertion of a thermocouple, was attached to a pipe and placed (down through the exhaust opening in the top of the furnace) among the specimens that were being heat-treated. Although the furnace-control thermocouple - located in the hot, incoming, air stream - was found to vary approximately ±15° F from the nominal temperature, the thermocouple in the dummy specimen varied less than ±2° F.

A 0.505-inch tension test specimen was made from one bar taken from each group of bars that had been heat-treated together. The results obtained by testing this specimen were compared with tension test data that had been furnished by the Aluminum Company of America; this was a precaution intended to prevent the waste of time and effort that would occur if improperly heat-treated bars were machined and tested. A comparison of the nominal and actual room-temperature tensile properties of several of the alloys studied during this investigation is given in table 2. Tension test results obtained by the Aluminum Company of America and by Battelle Memorial Institute are included in this tabulation. It will be noted from table 2 that the forged test pieces of XB18S-T have somewhat lower strength than the rolled material. The possible significance of this difference is discussed later.

Table 3 summarizes information from the Aluminum Company of America files on the high-temperature tensile properties of XB18S-T, 18S-T, and 32S-T tested after holding for a prolonged period at the testing temperatures (reference 1). Included also are data for 24S-T from a survey by Wyman (reference 2).

Considerable reference is made throughout the present report to the elevated-temperature tensile properties of these alloys that have been held for varying lengths of time at the testing temperature before starting the test. These data were furnished by the Aluminum Company of America and were obtained by testing forged alloys (references 3 and 4 and unpublished data). Table 4 contains a brief description of these particular materials.

The curves in figures 1 to 4 show the effect of the time at the testing temperature before beginning the tension tests on the tensile and yield properties of forged XB18S-T, 32S-T, 24S-T, and 18S-T. In order that some sort of comparison of fatigue and tension properties of these alloys can be made, time in these figures is expressed in two ways: (1) the time as reported in the Aluminum Company of America tests and (2) the time in terms of the average number of cycles that the Krouse machine would run if a fatigue test were in progress. The Krouse machines are operated for 10 hours each day and run 900,000 cycles during the period. The specimens, however, are maintained at temperature for 24 hours each day, so the Krouse machine is considered to have averaged 900,000 cycles for 24 hours at temperature. Thus, a fatigue specimen that has run 9 million cycles would have been at temperature for 10 days, and would be considered comparable with a tension specimen which had been held for 10 days at temperature before testing. The plotted points in figures 1 to 4 represent the results of the direct-stress fatigue tests. These data and their relation to the tensile data are discussed later in the section on fatigue test results.

Figures 5 to 7 show, respectively, the reversed-stress fatigue strength of alloys XB18S-T, 18S-T, and 32S-T at elevated temperatures from Aluminum Company of America tests (reference 1). Figure 8 shows the reversed-stress fatigue strength of 24S-T after "prolonged" heating at the testing temperature (reference 2).

Table 5 summarizes creep test data on XB18S-T, 18S-T, and 32S-T from reference 1. The significance of these data will be discussed in relation to the results obtained at Battelle Memorial Institute.

SHORT-TIME TENSION TESTS AT ELEVATED TEMPERATURES

A few short-time tension tests at elevated temperatures were conducted at Battelle Memorial Institute in order to determine if the properties of the rolled alloys were greatly different from those of the forged alloys. The bars were pulled in accordance with the procedure given in reference 5. The results are tabulated in table 6. Data from Aluminum Company of America and Battelle Memorial Institute short-time tension tests are plotted in figures 9 and 10 for XB18S-T and 24S-T. The Aluminum Company of America results were obtained by testing material described in table 4.

The forged and hot-rolled alloys do not seem to behave exactly alike at elevated temperatures, but, in the case of the 24S-T, the comparison of "typical" with actual values is involved. The difference between the short-time tension properties of the rolled and the forged alloys does not appear to be highly significant.

The values in table 6 for the yield strength, and especially for the modulus of elasticity, are dependent on the slope of the stress-strain curve. The "straight-line" portions of the stress-strain curves were not perfectly straight, and there was some evidence that plastic flow occurred even at relatively low loads. The effect on the modulus of the rate of loading is not quantitatively known. This method of obtaining the modulus is not a very satisfactory one for aluminum alloys at elevated temperatures, and these values should not be regarded as design data.

The effect of longer times at the testing temperature, before testing, has not been determined for the hot-rolled alloys, so they cannot be compared, in this regard, with the forged alloys. The effect of various lengths of time at the testing temperature on the tensile properties of the forged alloys is discussed later in relation to the fatigue test results.

DIRECT-STRESS FATIGUE TESTS AT ROOM TEMPERATURE AND AT ELEVATED TEMPERATURES

Testing Equipment

Fatigue test equipment.- The fatigue tests were conducted on Krouse Direct Repeated Stress Testing Machines which impose an axial load (4000 lb, maximum) at the rate of 1500 cycles per minute. Figure 11 is a photograph of one of the machines that has been modified for testing at elevated temperatures.

The construction and operation of the 4000-pound machine is quite similar to that of the 10,000-pound machine, previously described (reference 6). Like the larger machine, this machine is so designed that two specimens can be tested, independently, at the same time.

A loading lever (A), actuated by the connecting rod (R), adjustable cam (C), and driving pulley (B), applies the variable load. (See fig. 11.) The force is transmitted to the specimen by a member (M), which is guided by a parallelogram system of four steel-plate fulcrums (D), designed to produce straight-line motion and axial loading of the specimen. The mean value of the load is applied by adjusting the loading nuts (F) on the loading screw (E).

The mean load is applied, with the cam throw at zero, to the specimen and is measured by means of the calibrated dial bar (G) in terms of the bending induced in the loading lever. Then the cam throw is so adjusted that, as the cam is slowly rotated by hand, the desired maximum and minimum loads - measured by the dial bar - are applied.

When the machine is running under a variable load, the short steel pin (P) travels in a short arc; for a given cam setting the length of the arc is inversely proportional to the load. If the load decreases sufficiently, the length of the arc increases enough to cause the pin to strike a microswitch (T) - the height of which can be regulated by knob (K) - which actuates a relay that stops the machine.

The specimen-adapter assemblies (the ends of the adapters can be seen projecting from the ends of the furnace in fig. 11) are connected to the machines by means of universal joints (U). At first, rigid connections were used for this purpose, but they complicated the already difficult problem of alinement. It was determined that, if the imposed nominal stresses were equal, the lives of specimens which had been assembled with universal joints were considerably longer than the lives of specimens which had been assembled with the conventional rigid connections. It had been noticed that some force had to be applied when a specimen was assembled into a machine that had the rigid connections, and it was thought that an initial bending stress was being imposed on the specimen. Strain-gage measurements verified this hypothesis and revealed that the initial stress was very high at some points on the circumference of the specimen; both compressive and tensile stresses were present before any of the nominal load had been applied. Strain-gage measurements that were made on specimens which had been assembled into a machine provided with universal joints indicated that the bending stresses had been quite substantially reduced. It seems probable that the use of universal joints would not be desirable if specimens were being tested in compression or in tension-compression; but, since the stresses used in this investigation are all between zero (actually a little above zero) and some higher tension stress, the universal joints appear to be a satisfactory answer to the alinement problem.

A furnace (V) which is used to maintain the specimens at temperature during the elevated-temperature tests is shown in figure 11 attached to the fatigue test machine and in position. This tube furnace is 15 inches long; the furnace-control thermocouple is located midway between the furnace ends and its bead is flush with the inside of the refractory tube. The temperature of the specimen can be measured by a portable potentiometer; the lid (W) can be seen in figure 11. The specimen thermocouple, located inside of the specimen at the base of the threaded section, comes out through an opening in the specimen adapter. Each furnace is controlled by a Foxboro Controller which is shunted with a resistance in order to minimize temperature variations.

When the temperature of a specimen changes, it will either contract or expand, and if a specimen is undergoing a test this expansion or contraction will cause the load on the specimen to be decreased or increased. It is quite important that no increase in load occur because an unknown portion of the life of the specimen would be spent at an unknown stress, higher than the nominal stress. If a predetermined decrease in load occurs, the cut-off is actuated and the machine stops automatically.

Fatigue specimen.- Figure 12 is a drawing of the fatigue test specimen used in this investigation. The reduced section of this specimen is finished by longitudinal polishing with No. 320 abrasive paper. Several specimens were finished by polishing the reduced section with rouge, but, since this operation did not result in longer lives for these specimens, it was discontinued.

Testing Technique

Each fatigue test specimen that was tested in the T-condition at elevated temperatures was held for at least 1 hour at temperature in the fatigue test machine before the load was applied. The mean load was then applied, and if, in the course of an hour or so, no appreciable change in the value of the mean load had occurred, the alternating load was applied to the specimen. If the specimen had not failed by the end of the day, the machine was turned off and the specimen unloaded to prevent damage to it in the case of a power failure during the night. The temperature was maintained both day and night, and the day-to-day temperature variation was never more than ±10° F from the nominal temperature. Even small temperature variations during the running of the tests would have resulted in considerable changes in load, but for the actual testing period the changes in load resulting from temperature changes were probably greater for specimens tested at room temperature than for those tested at elevated temperatures - there being fewer short-time temperature variations in, and more frequent routine load checks made on, specimens that were tested at elevated temperatures.

Considerable difficulty was encountered in deciding upon a criterion for failure for fatigue tests conducted above 400° F because two types of failure apparently occur. The first type is the normal fatigue fracture and can be handled in the conventional manner; the second type is a sort of shear failure, the nature of which is not too well understood. This second type of failure is characterized by the relatively sudden inability of the test piece to sustain the applied load. A loading cycle is applied to the test piece at the start of the test; then after the test has been running for a period of time, the test piece begins to creep rapidly, and the indications are that it will eventually fail with a ductile fracture more nearly resembling a static failure than a fatigue failure.

A number of experiments were performed in an attempt to obtain a clear-cut criterion for this "ductile" failure. In one set of experiments SR-4-type strain gages were mounted on the load-applying mechanism of the testing machine ((M) fig. 11). The idea was that the onset of ductile failure could be measured by a definable rate of decrease of load. It was found, however, that when ductile failure was about to occur, the rate of decrease of load was too rapid to measure by the method indicated. In some experiments it was demonstrated that the major portion of the decrease in load would occur when the machine was turned 1 or 2 revolutions by hand.

From experiments of the type described, it was finally decided that a ductile failure had occurred if either of the two following conditions existed:

(1) The cut-off was actuated every 5000 cycles or less.

(2) After stopping the machine, the test pieces failed to sustain the mean load to within 100 psi for at least 10 minutes.

The fracture type of fatigue failure was defined by conventional methods. While the criterion for failure apparently produces a reproductible end point, neither the effect of creep alone nor the effect of fatigue alone has been measured in this test.

The direct-stress type of fatigue test is really a combined creep and fatigue test, and the behavior of the direct-stress specimens was analogous to that of creep specimens. At first the rate of creep was relatively rapid, and then the specimen had a low rate of creep for a relatively long time before the rate of creep increased as the ductile failure became imminent. No quantitative measure of creep was made during the fatigue testing, but some work along this line has been done by other investigators (references 7 and 8).

Fatigue Test Results And Discussion

The results of room-temperature and elevated-temperature direct-stress fatigue tests on XB18S-T are presented in table 7. These results are plotted in figure 13. The results of room-temperature and elevated-temperature direct-stress fatigue tests on 18S-T, 32S-T, and 24S-T are presented in table 8. These alloys were tested at stress-temperature combinations which had resulted in relatively long lifetimes for the XB18S-T alloy. Fatigue test results for all four alloys at these stress-temperature combinations are plotted in figure 14. There is some scatter in the results, which is to be expected with materials of which the properties change rapidly in the first day and less rapidly during subsequent days.

In the past, the static property most consistently related to the fatigue performance of a material has been the tensile strength. At room temperature the tensile strength and endurance limit of most of the "stable" alloys are usually thought to be relatively unaffected by the passage of time alone. Above 350° F the tensile strengths of these aluminum alloys decrease as the testing temperature increases. Furthermore, the tensile strength of each alloy is affected by the length of time that a specimen is held at the testing temperature before beginning the test. Some data concerning the effect of time at temperature on the tensile and yield strengths of XB18S-T, 18S-T, 32S-T, and 24S-T are available (references 3, 4, and unpublished data of the Aluminum Company of America). The curves in figures 1 to 4 were drawn from these data. As previously mentioned, time in these figures is expressed in days or hours, as reported by Aluminum Company of America, and in the average number of cycles that the Krouse machine would run during the holding period if a fatigue test were in progress. From these curves, it is possible to determine the approximate tensile and yield strengths of these alloys for a number of lifetime-temperature combinations. The plotted points in figures 1 to 4 represent the results of the direct-stress fatigue tests and show the relation of those results to the tensile properties at the completion of each test.

Table 9 contains a tabulated comparison of the direct-stress fatigue data with the tensile data for the four alloys at the elevated temperatures. The ratios in table 9 were obtained by dividing the maximum fatigue stress, endured for a certain lifetime, by the tensile or yield strength that the alloy would have had if it had been held, before testing, at temperature for a period equal to that required to produce the fatigue failure. It is important to remember that the tensile data were obtained by testing forged materials and the fatigue data were obtained by testing hot-rolled materials. If the possible variations that are influenced by the different methods of reduction – hot-rolling and forging – are assumed to be insignificant, it can be said that in no case was the ratio of maximum fatigue stress to tensile strength less than 0.60 and that the ratio of maximum fatigue stress to yield strength was always greater than 0.70 in the lifetime range that was tested. When the relative performance of the four hot-rolled alloys is evaluated using the averages of these ratios as the criterion, the "best" alloy is 32S-T, followed by the XB18S-T, 24S-T, and 18S-T.

Table 10 contains results of direct-stress fatigue tests on the four alloys and is arranged for easy comparison of the alloys. When the relative direct-stress fatigue performance of the hot-rolled alloys are evaluated on the basis of lifetimes for given stress-temperature combinations, the following tabulation results:

Stress-temperature combination			Relative direct-stress fatigue performance, based on lifetimes of from 200,000 to 10,000,000 cycles			
(psi)	(°F)		1	2	3	4
30,000	400		32S-T	XB18S-T	24S-T	18S-T
15,000	500		XB18S-T	24S-T	18S-T	32S-T
7,000	600		18S-T	32S-T	[a]XB18S-T	[b]24S-T
6,000	700		24S-T	32S-T	18S-T	XB18S-T

[a] Forged XB18S-T.

[b] 24S-T exhibited both shortest and longest life at 600° F.

If the results of the two methods of fatigue testing are compared, it will be noticed that the fatigue test specimens tested by the direct-stress method exhibit somewhat longer lifetimes, at given stresses, than those tested by the reversed-bending method (figs. 5 to 8). However, since the two methods of testing are so different, their results could not be considered comparable even if the materials had had identical mechanical and thermal histories. The stress range in the direct-stress method was roughly one-half that in the reversed-bending method. The mean stress in the direct-stress method is about one-half the maximum stress, but the mean stress in the reversed-bending method is, nominally, zero; therefore, the effect of creep would be expected to be more significant in the direct-stress method. The speed of testing can also be an important factor, inasmuch as the strength of these precipitation-hardening alloys decreases with time at temperature. These present tests, however, were conducted at speeds of about the same order of magnitude as those at which aircraft engines operate.

The relative performance of the alloys tested in reversed bending is tabulated as follows (references 1 and 2):

Temperature (°F)	Relative reversed-bending fatigue performance, based on lifetimes of from 1 to 5 million cycles			
	1	2	3	4
400	XB18S-T	18S-T	32S-T	[a]24S-T
500	XB18S-T	18S-T	[a]24S-T	32S-T

[a] Tested after prolonged heating at testing temperature (reference 2). The fact that the 24S-T had been stabilized at the testing temperature undoubtedly accounts for its apparent inferiority in the table.

The results of the direct-stress fatigue tests show that these alloys are quite weak at 600°, 700°, and 800° F. Failure would occur very rapidly if parts made from these alloys were highly stressed at these elevated temperatures. It seems likely that when these high temperatures occur in service they occur in localized spots, and the high stresses are borne by surrounding material which is cooler.

CREEP TESTS AT ELEVATED TEMPERATURES

Creep Test Equipment

A group of four creep units is shown in figure 15. The furnaces are wound with Chromel wire and insulated with Sil-O-Cel. The temperature gradient in each furnace is controlled by external shunts on the furnace windings. The temperature variations are kept below the maximum allowed by the requirements of reference 5. Each furnace has a small window in the front and in the back so that deformation can be measured by optical means. The load is applied to the test specimens with a lever arm having a ratio of 9:1.

A calibration specimen and a creep test specimen are shown in figure 16. Deformation is measured by the change in distance between cross marks ruled on the two platinum strips (shown in position in fig. 16) as they slide apart. A filar micrometer eyepiece and microscope is used to make the deformation readings. Calibration has shown that the smallest division on the filar eyepiece is equivalent to 0.00002 inch per inch, about 0.002 percent, on a gage length of about 2.3 inches. Deformation readings are usually made daily by two observers.

Creep Test Results and Discussion

The creep test data obtained during this investigation are reported in table 11. These data, and data obtained from the Aluminum Company of America on the properties of forged alloys, are plotted in figure 17. Each specimen was held 1 hour at the testing temperature before starting the test. The grain size of the hot-rolled XB18S-T, 32S-T, 24S-T, 18S-T, and the forged XB18S-T used in this investigation is given in table 12.

There are only a few places that the data obtained during this investigation overlap those resulting from previous investigations. The data are not nearly complete enough to evaluate the subsequent effects of forging or of hot-rolling on the creep rates of these alloys. It appears that the XB18S-T tested at Battelle Memorial Institute, both hot-rolled and forged, has much higher creep rates than those previously reported. It is also apparent that, at 600° F and between 1000 psi and 2000 psi, the hot-rolled 18S-T has a lower creep rate than the wrought alloy tested by the Aluminum Company of America. That grain-size differences may explain these apparent discrepancies seems to be a possibility. The effect of grain size on creep is very significant, as has been previously reported (reference 1, p. 8):

> It should be emphasized that comparisons of resistance to creep are apt to lead to false conclusions if the structures of the materials being compared are not similar. The following figures show the effect of grain size on the creep characteristics of 18S alloy, solution treated and aged.
>
> PER CENT CREEP OF 18S ROD (10 HRS. 960°F, BWQ - 12 HRS. 340°F) AT 400°F AND AT END OF 50 HOURS
>
> | 18S, 3/4 in. rod structure | 15000 psi | 20000 psi |
> |---|---|---|
> | Coarse grain | 0.056 | 0.10 |
> | Medium grain | 0.10 | 0.20 |
> | Fine grain | 0.32 | 0.81 |

Unfortunately, the grain size is not specified for the material reported on in the literature, but it does seem reasonable to believe that differences in grain size could be responsible for the apparent discrepanies. The grain size of these alloys is determined by their composition and thermal and mechanical history.

"Average" grain size has been found to be misleading as far as predicting creep performance is concerned. In copper, it has been discovered that fine grains exert a deleterious influence that is greater than would be indicated by the proportion in which they occur.

THERMAL-EXPANSION TESTS

Determinations were made of the linear thermal expansion of 11 samples of the rolled aluminum alloys used in the present investigation. Each sample was 300 millimeters in length and 25 millimeters in diameter. A precision micrometric method was used for these determinations. (See white furnace shown in fig. 1 of reference 9.)

The observations obtained on heating and cooling the samples of aluminum alloys to various temperatures between room temperature and 800° F were plotted as expansion and contraction curves. The expansion curves indicated that the linear thermal expansion of the samples increased with temperature. Table 13 gives coefficients of expansion and coefficients of contraction determined by the National Bureau of Standards. These coefficients were derived from the expansion and contraction curves. The average difference between the coefficient of expansion of the samples aged at 700° and 800° F compared with the corresponding coefficients of the samples aged at lower temperatures is $\pm 0.6 \times 10^{-6}$ per degree centigrade, but the average difference between the coefficients of contraction of the samples aged at 700° and 800° F compared with the corresponding coefficients of the samples aged at lower temperatures is only $\pm 0.2 \times 10^{-6}$ per degree centigrade. The coefficients of expansion of alloy 32S are nearly 15 percent less than those for alloys 18S, XB18S and 24S. The dimensional changes of the samples at room temperature after heating and cooling during the thermal-expansion determinations were less for the samples aged at 700° and 800° F than for those aged at lower temperatures. These data are given in the last column of table 13.

CONCLUDING REMARKS

Results of an investigation of forged aluminum alloys XB18S, 18S, 24S, and 32S show that, although it seems obvious that the tensile, creep, and fatigue properties of these alloys at elevated temperatures are interrelated, there seems to be no simple correlation between any of these properties. The reason for this may be that an attempt has been made to correlate the properties of two general classes of materials, hot-rolled and forged, which are not fundamentally comparable owing to the particular, and different, histories of the materials from which the different sets of data were obtained.

The effect of grain size on the creep rate has been discussed, and the grain size, or microstructure, determined by the composition and the previous fabrication and thermal history of the alloy. Unfortunately, very little information is available concerning the effects of the various mechanical and thermal treatments on the structure and mechanical properties of these alloys at elevated temperatures. Practically, these factors are of considerable importance because the aircraft engine manufacturers are influenced in their choice of thermal and mechanical treatments by fabrication and tolerance considerations, as well as by strength requirements.

Battelle Memorial Institute,
Columbus, Ohio, March 31, 1946

REFERENCES

1. Kempf, L. W., Dean, W. A., and Wrege, R. B.: Investigation of Aluminum Alloys for Application at Elevated Temperatures. Rep. 4-45-6, Cl-257 and Cl-258, Cleveland Res. Div., Aluminum Res. Lab., Aluminum Co. of Am., Sept. 12, 1945.

2. Wyman, L. L.: High Temperature Properties of Light Alloys (NA-137). I - Aluminum. OSRD No. 3607, Serial No. M-251, War Metallurgy Div., NDRC, April 15, 1944.

3. Howell, F. M.: Tensile Properties of XB18S-T at Elevated Temperatures. Rep. 9-45-2, Aluminum Res. Lab., Aluminum Co. of Am., March 23, 1945.

4. Bogordus, K. O.: Tensile Properties of Forged 18S-T and 32S-T at Elevated Temperatures. Rep. 9-46-4, Aluminum Res. Lab., Aluminum Co. of Am., Feb. 12, 1946.

5. Anon.: Recommended Practice for Short-Time Elevated-Temperature Tests of Metallic Materials. Designation: E21-43. A.S.T.M. Standards, 1943 Supplement, Part I - Metals.

6. Russell, H. W., Jackson, L. R., Grover, H. J., and Beaver, W. W.: Fatigue Characteristics of Spot-Welded 24S-T Aluminum Alloy. NACA ARR No. 3F16, 1943.

7. Hempel, Max, and Krug, P.: Tension Compression Fatigue Tests on Steel at High Temperatures and Their Evaluation According to Various Methods. Mitteilungen a.d. Kaiser Wilhelm Inst. f. Eisenforschung, vol. 24, no. 7, 1942, pp. 71-95.

8. Hempel, Max, and Krug, P.: Fatigue Diagrams for Steels at High Temperatures. Archiv. fur das Eisenhuttenwesen, vol. 16, no. 7, 1943, pp. 261-268.

9. Souder, Wilmer, and Hidnert, Peter: Measurements on the Thermal Expansion of Fused Silica. Sci. Paper No. 524, Nat. Bur. of Standards, April 13, 1926.

TABLE 1.- CHEMICAL COMPOSITION, HEAT TREATMENT, AND MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

[Data furnished by the Aluminum Company of America]

Alloy designation	Chemical composition										
	Si	Fe	Cu	Mg	Mn	Ni	Zn	Cr	Pb	Bi	Ti
XB18S	0.58	0.31	3.89	1.43	0.01	2.14	0.02	0.01	0.01	0.01	0.03
18S	.58	.45	3.98	.64	.05	2.01	.02	.01	.01	.01	.01
24S	.10	.25	4.41	1.41	.67	.01	.02	.01	.01	.01	.01
32S	12.18	.41	.89	1.20	.01	.87	.02	.01			.01

Alloy designation	Heat treatment to produce T-temper
XB18S	Hold at 960° F for 1 hour, water quench, temper at 340° F for 10 hours
18S	Do.
24S	Hold at 920° F for 1 hour, water quench, temper at room temperature for 4 days
32S	Hold at 960° F for 1 hour, water quench, temper at 340° F for 12 hours

Alloy designation	Nominal room-temperature mechanical properties in T-temper				
	Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Brinell hardness number
[a]XB18S	45,600	61,200	14.5	28.4	117
18S	47,000	63,000	17.0	----	115
24S	46,000	68,000	22.0	----	120
32S	46,000	56,000	8.0	----	125

[a] Actual properties.

TABLE 2.- RESULTS OF T-TEMPER HEAT TREATMENT ON ALLOYS.
HEAT TREATMENT AT ALCOA LABORATORIES
COMPARED WITH TREATMENT AT BATTELLE

Alloy	Original condition	Laboratory	Yield strength, 0.2 percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction in area (percent)	Brinell hardness number
XB18S-T	Hot-rolled	Alcoa	45,600	61,200	14.5	28.4	117
	Forged	Alcoa	40,625	59,600	15.0	16.1	118
	Hot-rolled	Battelle	46,250	60,250	15.3	29.8	---
	Forged	Battelle	44,700	59,900	16.0	----	---
32S-T	Forged	Alcoa	44,500	52,800	6.0	10.0	126
	Hot-rolled	Alcoa	47,400	61,500	9.5	15.7	126
	Hot-rolled	Battelle	47,000	55,100	9.0	17.4	---
24S-T	Hot-rolled	Alcoa	40,500	67,850	22.3	32.7	114
	Hot-rolled	Battelle	41,000	68,900	25.0	35.4	---
18S-T	Forged	Alcoa	47,600	61,600	14.5	21.2	---
	Hot-rolled	Alcoa	54,800	66,500	12.3	27.3	130
	Hot-rolled	Battelle	55,000	65,500	16.0	28.9	---

TABLE 3.- HIGH-TEMPERATURE TENSILE PROPERTIES OF ALUMINUM ALLOYS

Alloy	Condition	Test temperature (°F) (1)	Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Brinell hardness number
XB18S-T Forged[2]	12 hr, 960° F[3] 10 hr, 340° F	75	40,625	59,600	15.0	118
		300	36,000	41,620	10.5	104
		400	19,250	26,390	14.0	79
		500	7,400	12,150	27.0	50
		700	1,850	4,080	118.0	59
18S-T Rolled and drawn rod[2]	10 hr, 960° F[3] 12 hr, 340° F	75	54,850	66,730	12.8	128
		212	53,000	61,360	12.5	136
		300	38,500	44,220	13.5	111
		400	18,000	23,420	21.5	75
		500	12,000	15,650	24.0	65
32S-T Forged slab[2]	Heated to 960° F[3] 8 hr, 340° F	75	44,500	52,800	6.0	126
		300	32,500	36,800	6.5	99
		400	10,700	15,080	25.5	54
		500	6,100	8,930	39.0	49
		600	3,300	5,600	44.0	43
		700	3,025	3,415	94.0	42
24S-T[4]	(5)	75	45,000	68,000	22	---
		300	35,000	42,000	21	---
		400	21,000	28,000	25	---
		500	9,000	14,000	40	---
		600	5,000	7,500	65	---
		700	3,500	5,000	100	---

[1] All alloys heated for a prolonged period at testing temperature before testing.

[2] Testing speed, 0.107 in. per min. Data from reference 1.

[3] Boiling-water quench.

[4] Data from reference 2.

[5] Testing speed and heat treatment not reported.

TABLE 4.- THERMAL AND MECHANICAL HISTORY OF ALUMINUM ALLOYS FROM WHICH DATA FOR VARIATION OF TENSILE PROPERTIES WITH TIME AT TESTING TEMPERATURE WERE OBTAINED

Alloy	Fabrication method	Thermal treatment	Remarks
XB18S-T	Specimens made from forged 3/4-in. rounds	12 hr, 960° F, water quench, aged 10 hr at 340° F	(1)
18S-T	Specimens machined from forgings	10 hr, 960° F, caustic quench, aged 10 hr at 340° F	"Data represent tests of... single lots" and "should not be interpreted as 'typical values'"[2]
32S-T	Specimens machined from forged slab	12 hr, 960° F, followed by quenching, aged 8 hr at 340° F	Do.[2]
24S-T	----------------------	T-temper	Data "... considered typical for various commercial forms," sheet, plate, bar, rod, and wire[3]

[1] See reference 3.

[2] See reference 4.

[3] Unpublished information from Aluminum Company of America.

TABLE 5.- PERCENT CREEP PER 1000 HOURS FOR WROUGHT ALUMINUM ALLOYS

[Data from reference 1.]

Alloy	Test temperature (°F)	Stress (psi) -							
		1300	1900	2500	5000	7500	10,000	15,000	20,000
XB18S-T	400	----	----	----	----	----	----	0.11	----
	600	----	----	0.69	----	----	----	----	----
18S-T	400	----	----	.03	0.09	0.12	----	----	----
	600	0.40	1.17	----	----	----	----	----	----
32S-T	400	----	----	----	.06	.09	0.15	----	----
	600	.21	----	----	----	----	----	----	----

TABLE 6.- SHORT-TIME TENSILE PROPERTIES OF ALUMINUM ALLOYS XB18S-T, 24S-T, AND 32S-T AT ELEVATED TEMPERATURES

[All bars held 1 hr at temperature before pulling. Bars pulled 0.02 in./min to 0.02-percent offset yield, then 0.10 in./min to rupture. Bars pulled in accordance with procedure given in reference 5.]

Alloy	Specimen	Test temperature (°F)	Tensile strength (psi)	Yield strengths (psi) -		Elongation in 2 in. (percent) (a)	Reduction of area (percent)	Apparent modulus of elasticity (psi)
				0.1-percent offset	0.2-percent offset			
XB18S-T	A6J	400	47,400	40,000	41,500	14.4	29.3	[b]9.65 × 10^6
	A6K	400	48,300	39,200	40,800	15.9	33.4	[b]9.10
	A4J	500	30,500	28,500	30,000	24.0	55.3	9.5
	A4K	500	27,900	22,800	24,300	12.0	35.7	9.7
	A4L	600	14,000	12,000	12,250	41.0	74.7	9.0
	A4M	600	14,700	11,600	12,200	33.0	74.9	8.4
	A8F	700	7,250	5,500	6,000	55.0	83.0	5.5
	A8G	700	7,650	6,100	6,300	64.0	86.0	3.5
	A5L	800	2,940	1,340	1,430	----	----	[c]1.6
	A8H	800	2,700	1,700	1,800	----	----	1.45
24S-T	G1H	400	51,700	44,000	45,000	19.0	46.0	9.8
	G1J	400	52,500	32,500	34,500	26.0	46.0	9.8
	G1K	500	28,700	23,900	24,600	28.0	75.0	8.4
	G1L	500	27,400	22,900	23,800	20.0	82.0	8.7
	G1M	600	17,700	15,140	[d]15,300	25.0	81.0	9.6
	G2A	600	18,700	16,000	16,500	29.0	81.0	8.3
	G2B	700	10,800	9,300	9,500	36.0	84.0	9.1
	G2C	700	9,550	8,200	8,400	54.0	92.0	4.9
32S-T	L1P	500	27,200	24,200	25,000	9.0	18.0	9.6
	L1Q	500	27,200	24,500	25,800	10.0	28.0	7.4

[a] Specimens were not broken. Elongation is greater than stroke of machine under normal conditions.

[b] Bars pulled 0.02 in./min to 0.02-percent offset yield, then 0.06 in./min to rupture.

[c] Held for 2 hr at temperature.

[d] Estimated.

TABLE 7.- DIRECT-STRESS FATIGUE TEST RESULTS FOR XB18S-T AT ROOM TEMPERATURE AND ELEVATED TEMPERATURES

Temperature (°F)	Maximum stress (psi)	Life cycles	Specimen	Remarks
400	30,000	1,754,800	A5C	Fatigue fracture
400	30,000	3,299,500	[a]F1K	Fatigue fracture
400	25,000	6,941,000	A5F	Fatigue fracture
400	20,000	10,496,800	A5B	Unbroken, stress raised
400	30,000	143,200	A5B	Fatigue fracture
500	20,000	----------	A5D	Failed to hold load
500	15,000	3,826,000	A5E	Ductile failure
500	15,000	86,000	[a]F1H	Ductile failure
500	15,000	5,931,800	[a]F1L	Ductile failure
500	10,000	10,477,400	A3R	No failure, stress raised
500	15,000	28,000	A3R	Ductile failure
---	15,000	10,000,000	[a]F1L	No failure, test discontinued
600	10,000	215,000	A5G	Ductile failure
600	7,000	4,200,600	[a]F1G	Ductile failure
600	5,000	6,282,500	A3M	Ductile failure
600	4,000	5,790,400	A3P	Ductile failure
700	3,000	2,986,400	A3L	Ductile failure
700	3,000	241,000	[a]F1J	Ductile failure
700	2,000	8,422,500	A3N	Ductile failure
800	2,000	----------	[a]F1F	Failed to hold load
Room	45,000	172,300	A3H	Fatigue fracture
Room	45,000	52,800	A2H	Fatigue fracture
Room	43,000	1,596,900	[a]F1B	Fatigue fracture
Room	35,000	4,399,000	A1G	Fatigue fracture
Room	33,000	2,517,000	[a]F1E	Fatigue fracture
Room	30,000	10,563,500	[a]F1C	Unbroken, stress raised
Room	45,000	151,900	[a]F1C	Fatigue fracture
Room	30,000	12,445,500	A5H	Unbroken, stress raised
Room	57,500	34,800	A5H	Fatigue fracture

[a] Forged XB18S-T.

TABLE 8.- DIRECT-STRESS FATIGUE TEST RESULTS FOR 18S-T, 32S-T, AND 24S-T AT ROOM TEMPERATURE AND ELEVATED TEMPERATURES

Alloy	Temperature (°F)	Maximum stress (psi)	Life cycles	Specimen	Remarks
18S-T	Room	35,000	11,737,700	J1H	Unbroken, stress raised
	Room	45,000	3,898,200	J1H	Fatigue fracture
	Room	45,000	328,400	J1G	Fatigue fracture
	400	30,000	233,500	J1D	Fatigue fracture
	400	30,000	236,700	J1F	Fatigue fracture
	500	15,000	793,000	J1A	Ductile failure
	600	7,000	7,973,000	J1C	Ductile failure
	700	3,000	3,000,000	J1E	Ductile failure
32S-T	Room	35,000	2,101,700	L2A	Fatigue fracture
	400	30,000	3,447,460	L2C	Fatigue fracture
	500	15,000	791,200	L2D	Ductile failure
	600	7,000	5,103,500	L2E	Ductile failure
	700	3,000	4,155,900	L2F	Ductile failure
24S-T	Room	35,000	690,100	G3F	Fatigue fracture
	400	30,000	476,300	G3C	Cracked and necked down
	400	30,000	432,900	G3G	Cracked and necked down
	500	15,000	1,760,000	G3H	Ductile failure
	600	7,000	1,866,000	G3A	Ductile failure
	600	7,000	18,433,300	G3E	No failure[1]
	700	3,000	19,101,100	G3B	No failure
	700	4,000	9,470,500	G3D	Ductile failure

[1] Test discontinued; failed to hold load at 10,000 psi.

TABLE 9.- COMPARISON OF FATIGUE AND TENSILE DATA FOR HOT-ROLLED ALUMINUM ALLOYS AT ELEVATED TEMPERATURES

[See figs. 1 to 4.]

Stress-temperature combination		Ratio - maximum stress in fatigue cycle to yield strength (a)			
(psi)	(°F)	XB18S-T	18S-T	32S-T	24S-T
30,000	400	0.83	----	1.13	[b]0.91
15,000	500	1.00	0.70	.94	.91
7,000	600	----	----	1.46	.80, 1.08
3,000	700	1.15	1.00	1.20	----

Stress-temperature combination		Ratio - maximum stress in fatigue cycle to tensile strength (a)			
(psi)	(°F)	XB18S-T	18S-T	32S-T	24S-T
30,000	400	0.75	----	1.03	0.71
15,000	500	.79	0.60	.81	.71
7,000	600	----	----	1.00	.69, .83
3,000	700	.67	.65	.77	----

[a] The maximum stress in the fatigue cycle used in this table is one that will produce a failure in less than 10,000,000 cycles. The data were obtained by determining the life of the fatigue test piece at the stress cycle indicated and then using the yield or tensile strength which would have been obtained by holding the test piece at temperature for the same time to compute the ratios shown.

[b] Two tests.

TABLE 10.- COMPARISON OF DIRECT-STRESS FATIGUE TEST RESULTS
FOR HOT-ROLLED XB18S-T, 32S-T, 24S-T, AND 18S-T
AT ELEVATED TEMPERATURES

Temperature (°F)	Stress (psi)	Cycles for failure			
		XB18S-T	32S-T	24S-T	18S-T
400	30,000	1,754,800 [a]3,299,500	3,447,460	476,300 432,900	233,500 236,700
500	15,000	3,826,000 [a]86,000 [a]10,000,000	791,200	1,760,000	793,000
600	7,000	[a]4,200,600	5,103,500	1,866,000 18,433,300	7,973,000
700	3,000	2,986,400 [a]241,000	4,155,900	[b]19,101,100	3,000,000

[a] Forged specimen.

[b] Unbroken.

TABLE 11.- CREEP TEST DATA FOR ROLLED ALUMINUM-BASE ALLOYS XB18S-T, 18S-T, 24S-T, 32S-T AND FOR FORGED ALLOY XB18S-T

Alloy	Specimen	Temperature (°F)	Stress (psi)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Final creep rate (percent/hr)	Total deformation (percent)	Contraction on release of load (percent)	Duration (hr)
XB18S-T	A6L	400	10,000	0.069	0.000160	0.000160	0.240	-----	478
	A6M	400	15,000	.406	.000900	.002200	1.440	0.120	697
	A3K	500	5,000	.052	.000360	.001250	.636	.064	501
	A3J	500	10,000	.138	.022000	(a)	(a)	(a)	(a)
	A8C	600	1,000	.017	.000310	.000310	.365	.009	618
	A8B	600	2,500	.017	.006100	(b)	(b)	(b)	(b)
24S-T	G1B	400	10,000	.117	.000025	.000025	.148	.117	524
	G1C	400	15,000	.175	.000130	.000140	.304	.181	572
	G1F	600	1,200	.013	.000040	[c].000040	.035	.023	526
	G1E	600	2,000	.015	.000080	[c].000080	.076	.018	553
	G1G	600	3,000	.030	.000120	.000120	.152	.023	528
32S-T	L1B	400	10,000	.119	.000300	.000470	.443	.122	722
	L1C	400	8,000	.062	.000120	.000140	.195	.077	528
	L1D	600	1,500	.041	.000270	.000270	.240	.019	497
	L1F	600	2,500	.021	.002200	(d)	(d)	(d)	(d)
	L1E	600	3,000	.047	.006000	(e)	(e)	(e)	(e)
18S-T	J1N	600	1,000	.017	.000090	.000090	.076	-----	498
	J1L	600	2,000	.024	.000330	.000330	.295	.021	500
[f]XB18S-T	F4C	400	15,000	.170	.000450	.000720	.506	.180	502
	F3B	600	1,000	.015	.000350	.000350	.212	.009	503

[a] Broke at 96.8 hr; 38.8-percent elongation; 61.2-percent reduction area.

[b] Broke at 257.8 hr; 84.7-percent elongation; 90.9-percent reduction area.

[c] Average creep rate between 100 and 500 hr. The rate varied somewhat during test (alternately higher and lower).

[d] Broke at 552 hr; 48.5-percent elongation; 81.3-percent reduction area.

[e] Broke at 244 hr; 38.9-percent elongation; 78.0-percent reduction area.

[f] Forged. All other specimens from rolled alloy. These specimens were run at the same temperatures and stresses as rolled XB18S-T specimens A6M and A8C, so that a direct comparison of the results of rolled and forged fabrications could be made.

TABLE 12.- GRAIN SIZES OF XB18S-T, 32S-T, 24S-T, AND 18S-T USED IN THE INVESTIGATION

Alloy	Fabrication	Solution treatment		Average grain diameter (in.) (1)	Range of grain size (in.)
		Time (hr)	Temperature (°F)		
XB18S-T	Hot-rolled	1	960	0.0006	Fairly uniform
XB18S-T	Forged	1	960	.0020	0.00165 to 0.00236
XB18S-T	Hot-rolled	10	960	.0013	Fairly uniform
32S-T	Hot-rolled	1	960	.0011	0.00079 to 0.00118
24S-T	Hot-rolled	1	920	.0027	0.00158 to 0.00315 Some very large grains
18S-T	Hot-rolled	1	960	.0013	0.00099 to 0.00197

[1] Average of 25 to 40 measurements.

TABLE 13.- COEFFICIENTS OF EXPANSION AND CONTRACTION OF ROLLED ALUMINUM ALLOYS

[Unpublished data from the National Bureau of Standards]

NBS sample number	Alloy	Average coefficients of expansion per degree Fahrenheit				Average coefficients of contraction per degree Fahrenheit				Change in length after heating and cooling (percent) (a)
		68° to 200° F	68° to 400° F	68° to 600° F	68° to 800° F	800° to 68° F	600° to 68° F	400° to 68° F	200° to 68° F	
1776	[b]18S-T	12.8 × 10^{-6}	13.1 × 10^{-6}	14.1 × 10^{-6}	14.4 × 10^{-6}	14.0 × 10^{-6}	-----------	13.0 × 10^{-6}	12.4 × 10^{-6}	0.03
1776A	[c]18S-T	12.5	12.9	13.4	13.9	14.1	-----------	13.0	12.3	-.01
1776B	[d]18S-T	12.7	13.1	13.7	14.2	14.1	-----------	13.0	12.3	.01
1777	[b]XB18S-T	12.8	13.0	13.7	14.6	14.0	-----------	13.1	12.5	.04
1777A	[c]XB18S-T	12.5	13.1	13.6	-----------	-----------	13.6 × 10^{-6}	-----------	12.4	.00
1778	[b]24S-T	12.8	13.0	13.3	14.0	14.7	-----------	13.1	12.4	-.05
1778A	[c]24S-T	12.7	13.1	13.7	14.6	14.6	-----------	13.2	12.6	.00
1778B	[d]24S-T	12.6	13.2	13.6	14.3	14.4	-----------	13.3	12.6	-.01
1779	[b]32S-T	11.1	11.7	12.5	13.0	12.1	-----------	11.0	10.3	.06
1779A	[c]32S-T	10.9	11.3	11.6	12.2	12.0	11.4	-----------	-----------	.02
1779B	[d]32S-T	10.8	11.4	11.7	12.2	11.9	-----------	10.9	10.3	.02

[a] Determined at 20° C from the expansion curve on heating and the contraction curve on cooling. Positive values indicate an increase in length; negative values, a decrease in length.

[b] T-temper.

[c] T-temper and aged at 700° F for 100 hr.

[d] T-temper and aged at 800° F for 500 hr.

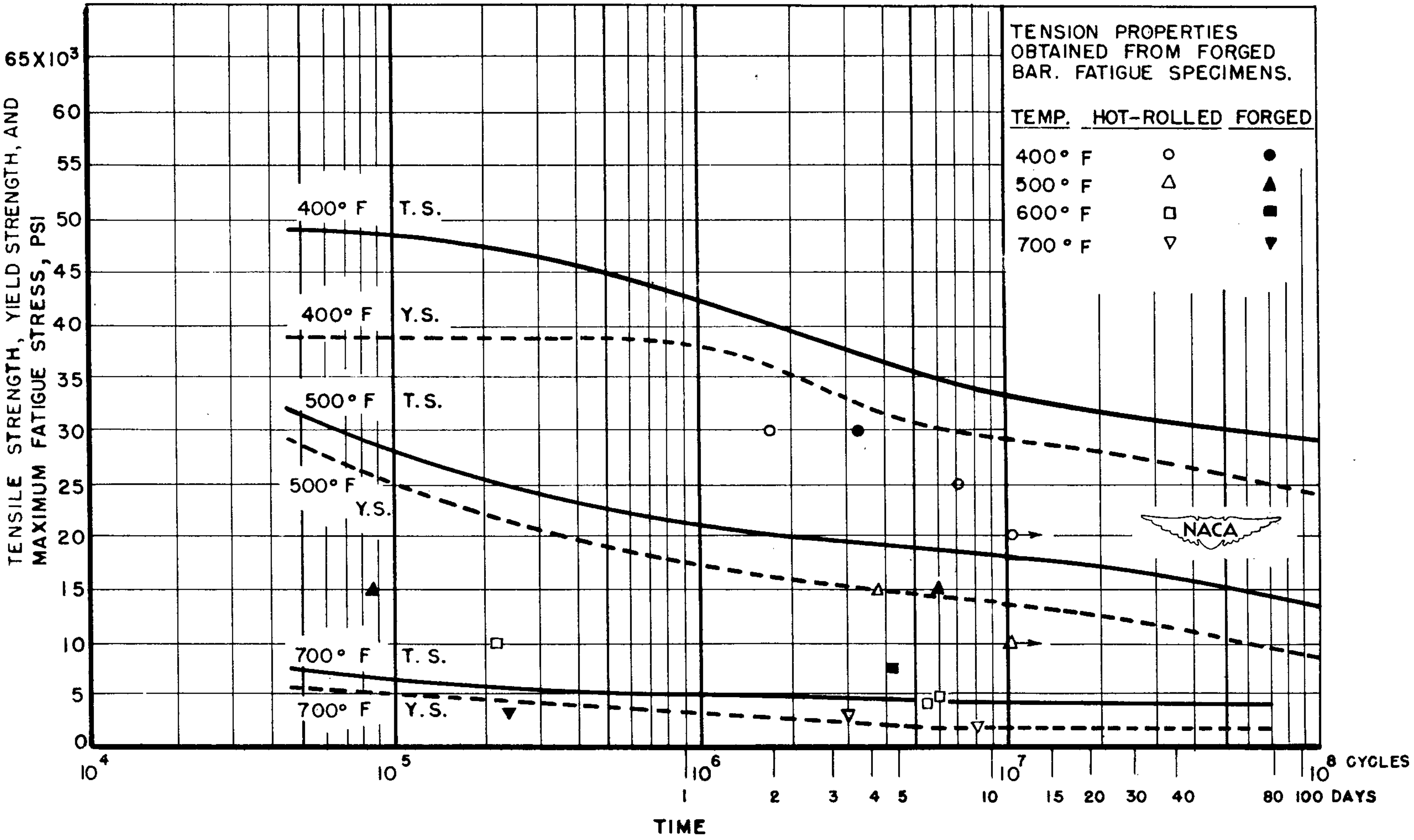

Figure 1.- Tension and direct-stress fatigue properties of XB18S-T, at elevated temperatures, on comparable time scales. (Tensile data from reference 3.)

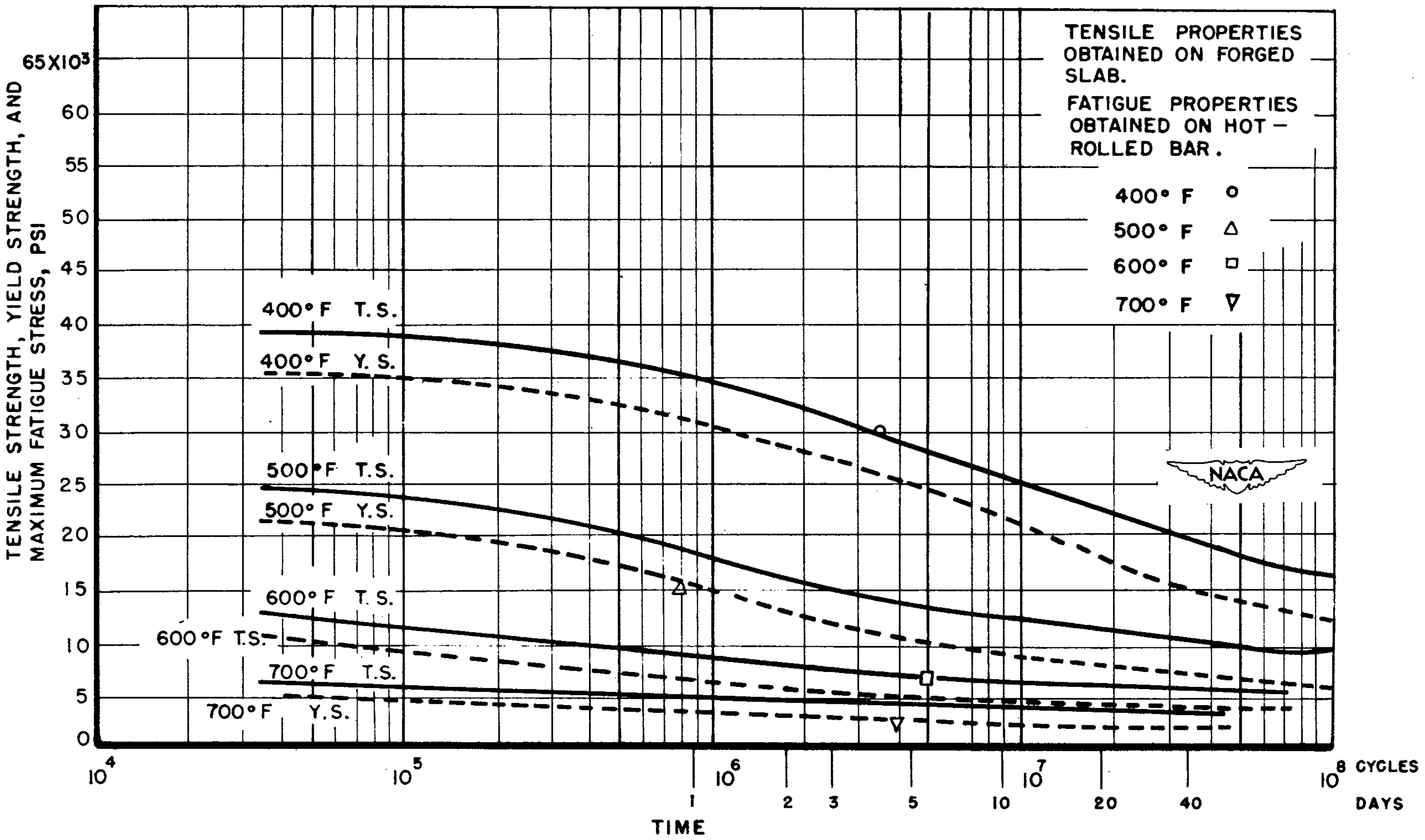

Figure 2.- Tension and direct-stress fatigue properties of 32S-T, at elevated temperatures, on comparable time scales. (Tensile data from reference 4.)

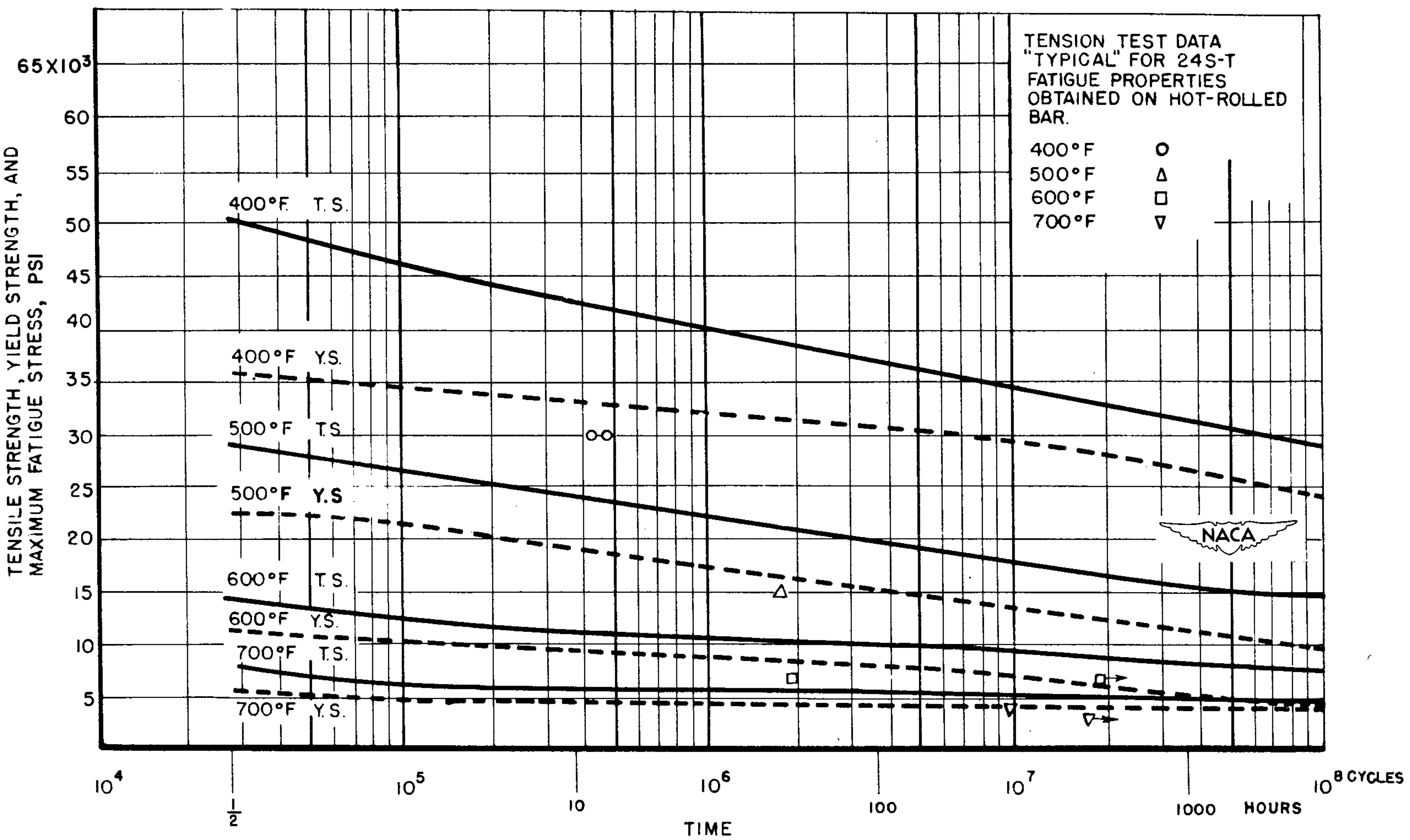

Figure 3.- Tension and direct-stress fatigue properties of 24S-T, at elevated temperatures, on comparable time scales. (Tensile data from unpublished material of the Aluminum Company of America.)

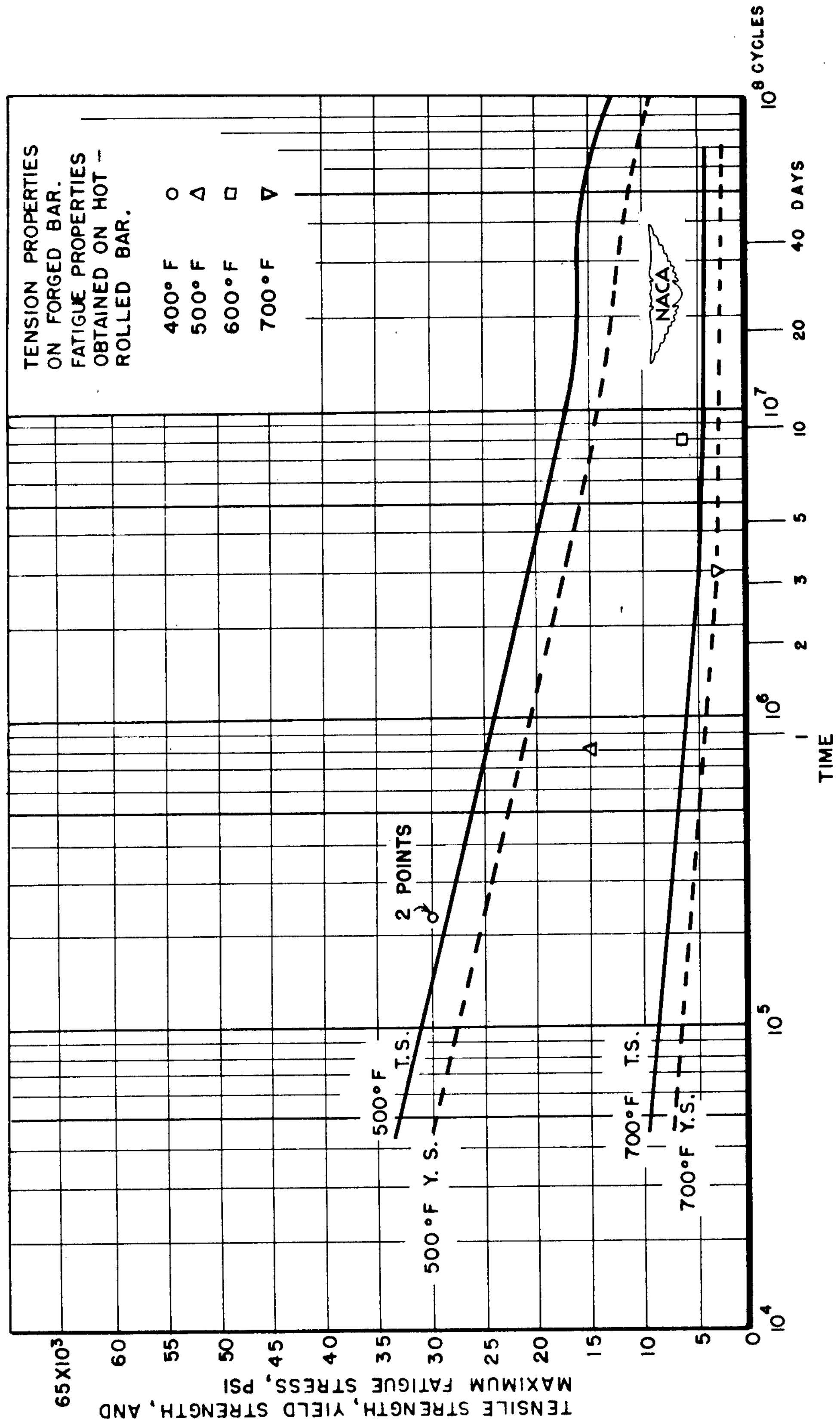

Figure 4.- Tension and direct-stress fatigue properties of 18S-T, at elevated temperatures, on comparable time scales. (Tensile data from reference 4.)

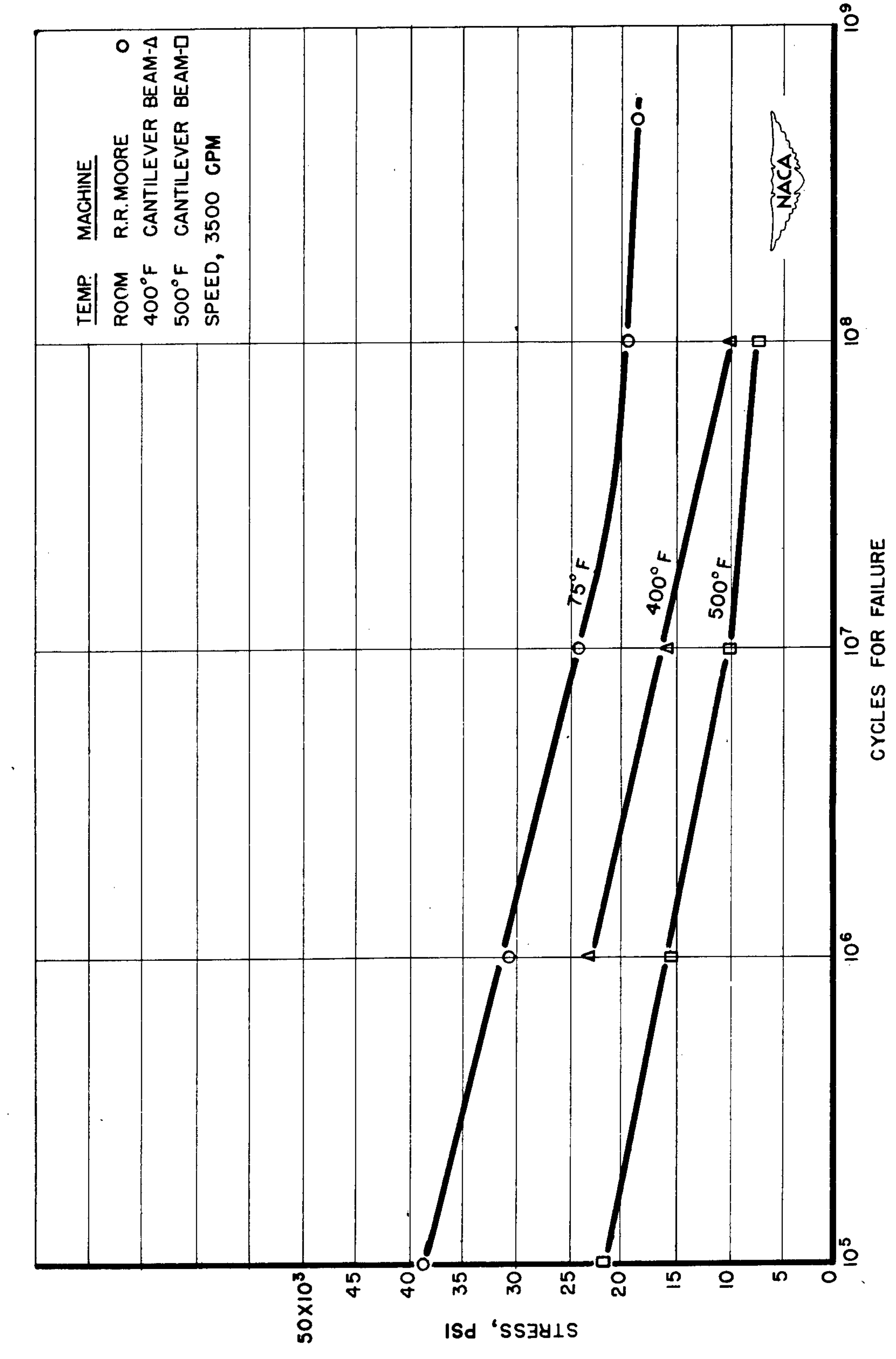

Figure 5.- Fatigue data reported by the Aluminum Company of America for XB18S-T. (See reference 1.)

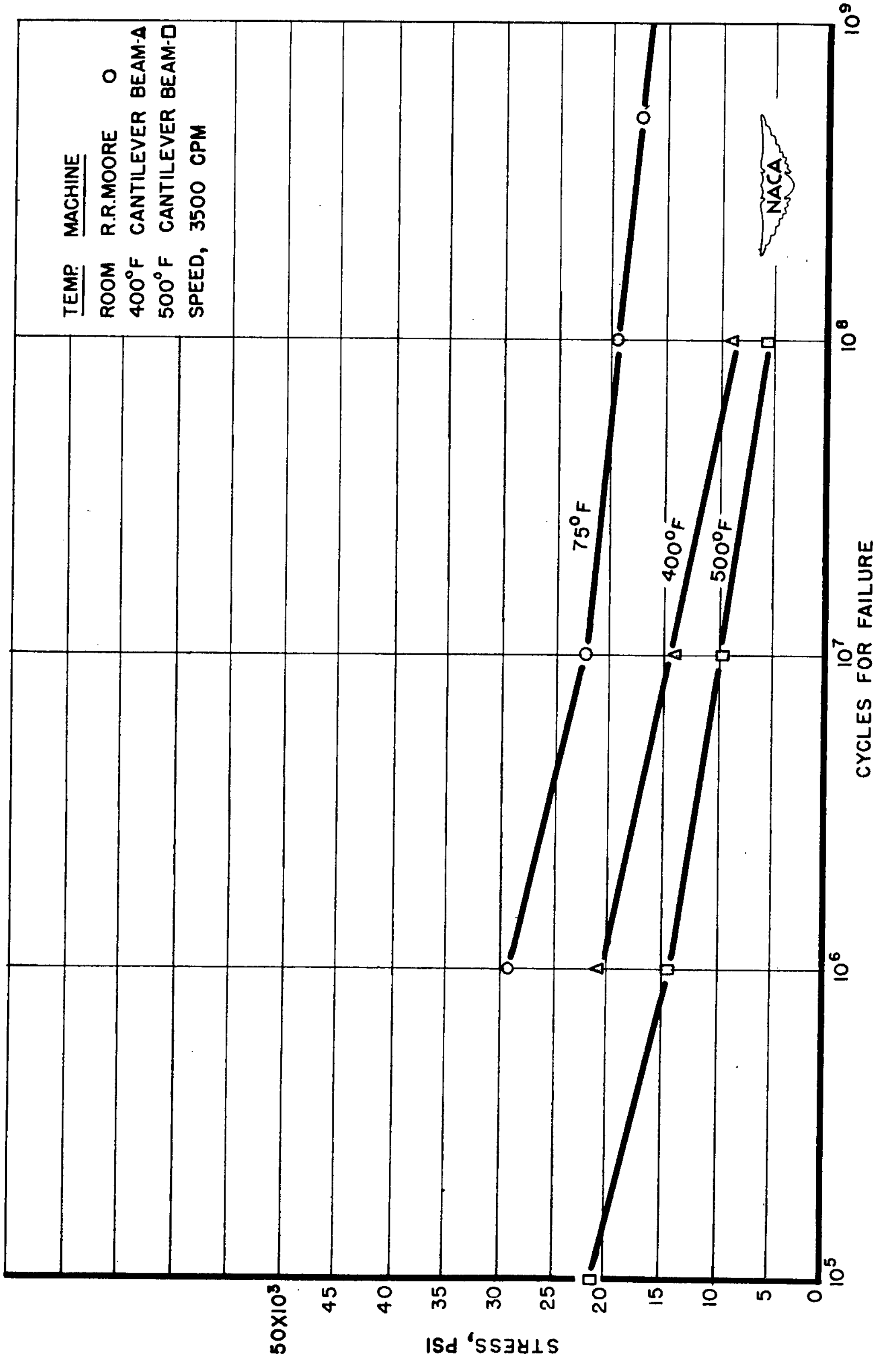

Figure 6.- Fatigue data reported by the Aluminum Company of America for 18S-T. (See reference 1.)

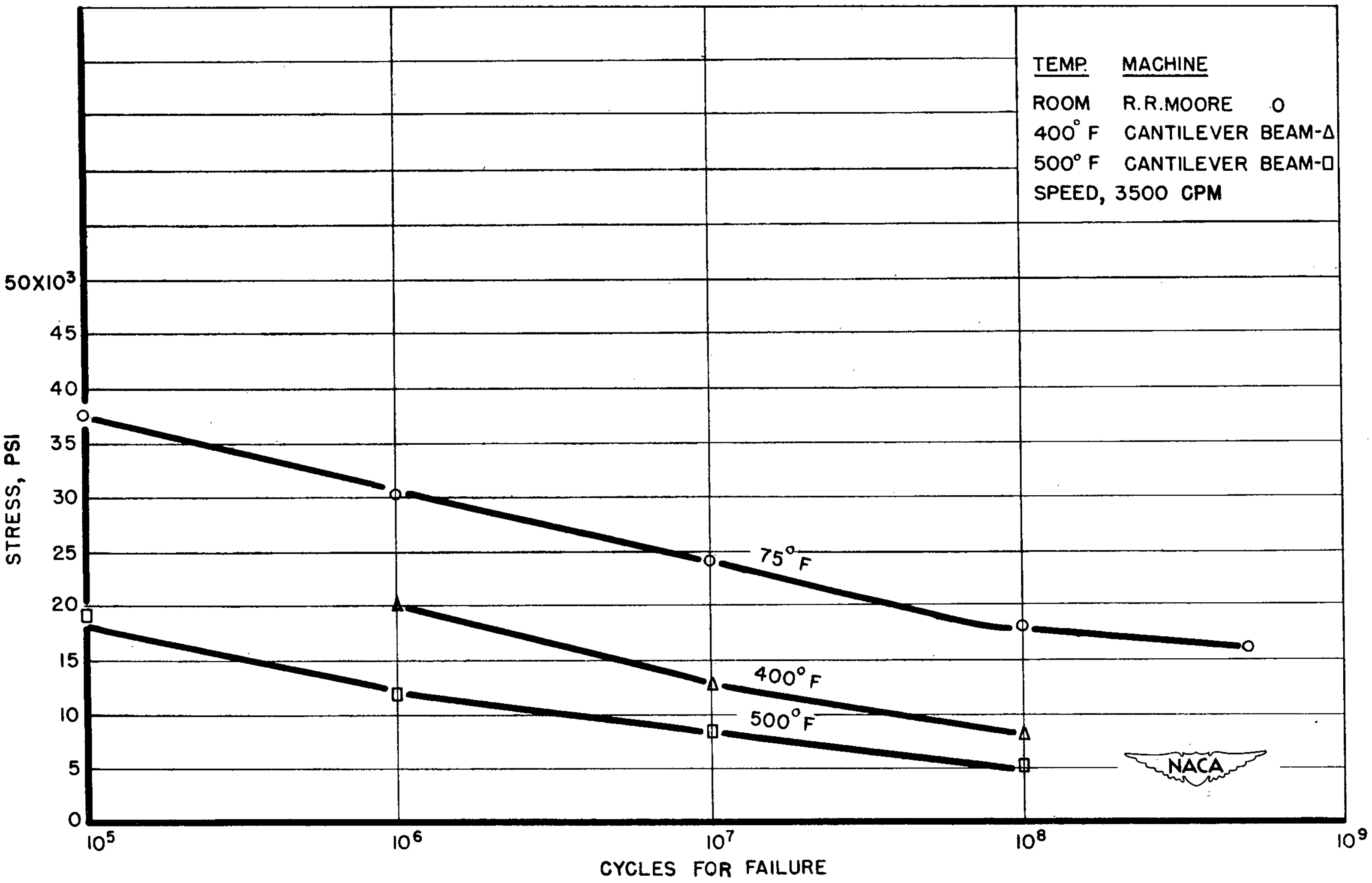

Figure 7.- Fatigue data reported by the Aluminum Company of America for 32S-T. (See reference 1.)

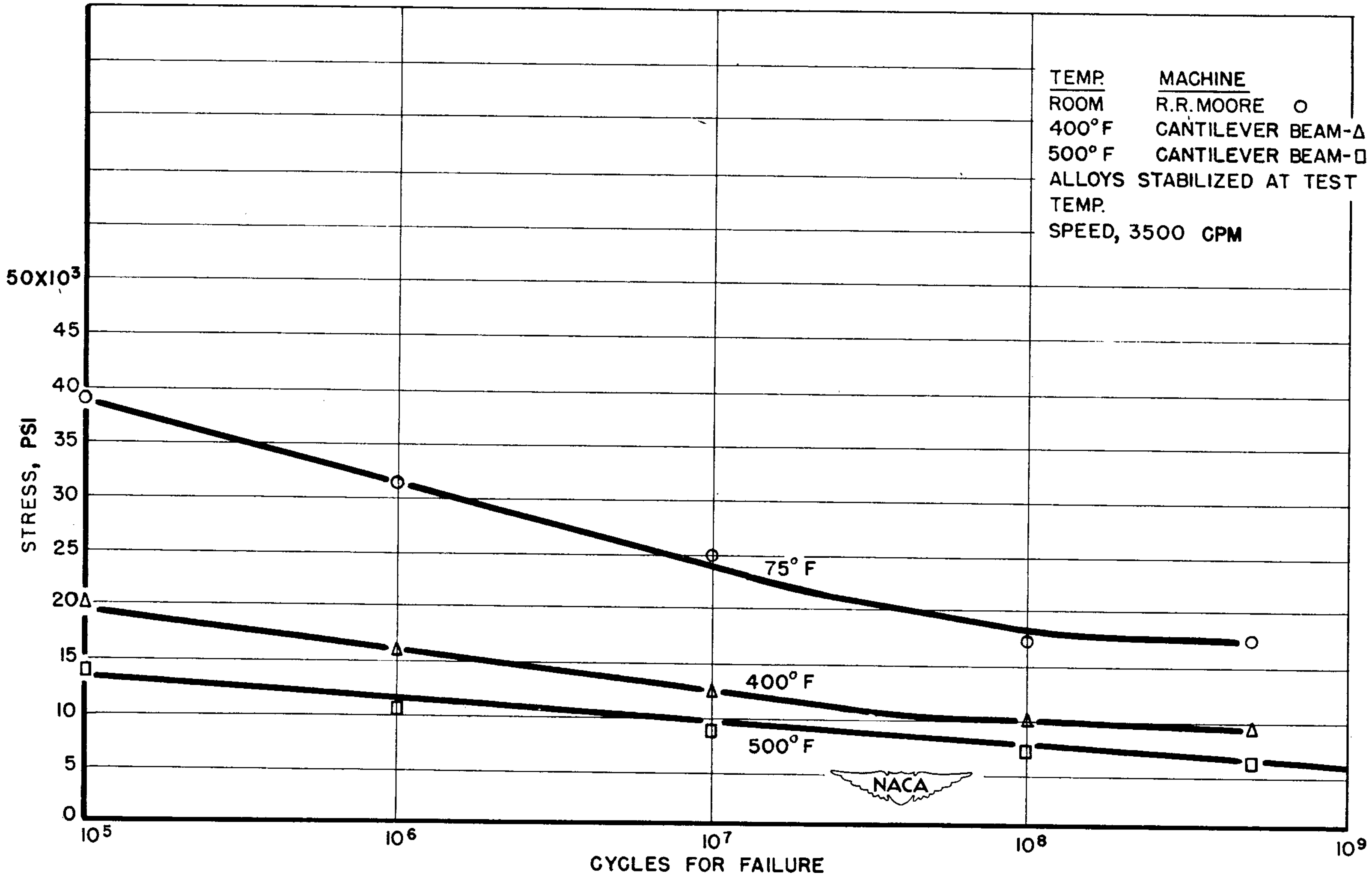

Figure 8.- Fatigue data reported by Wyman for 24S-T rolled and drawn rod. (See reference 2.)

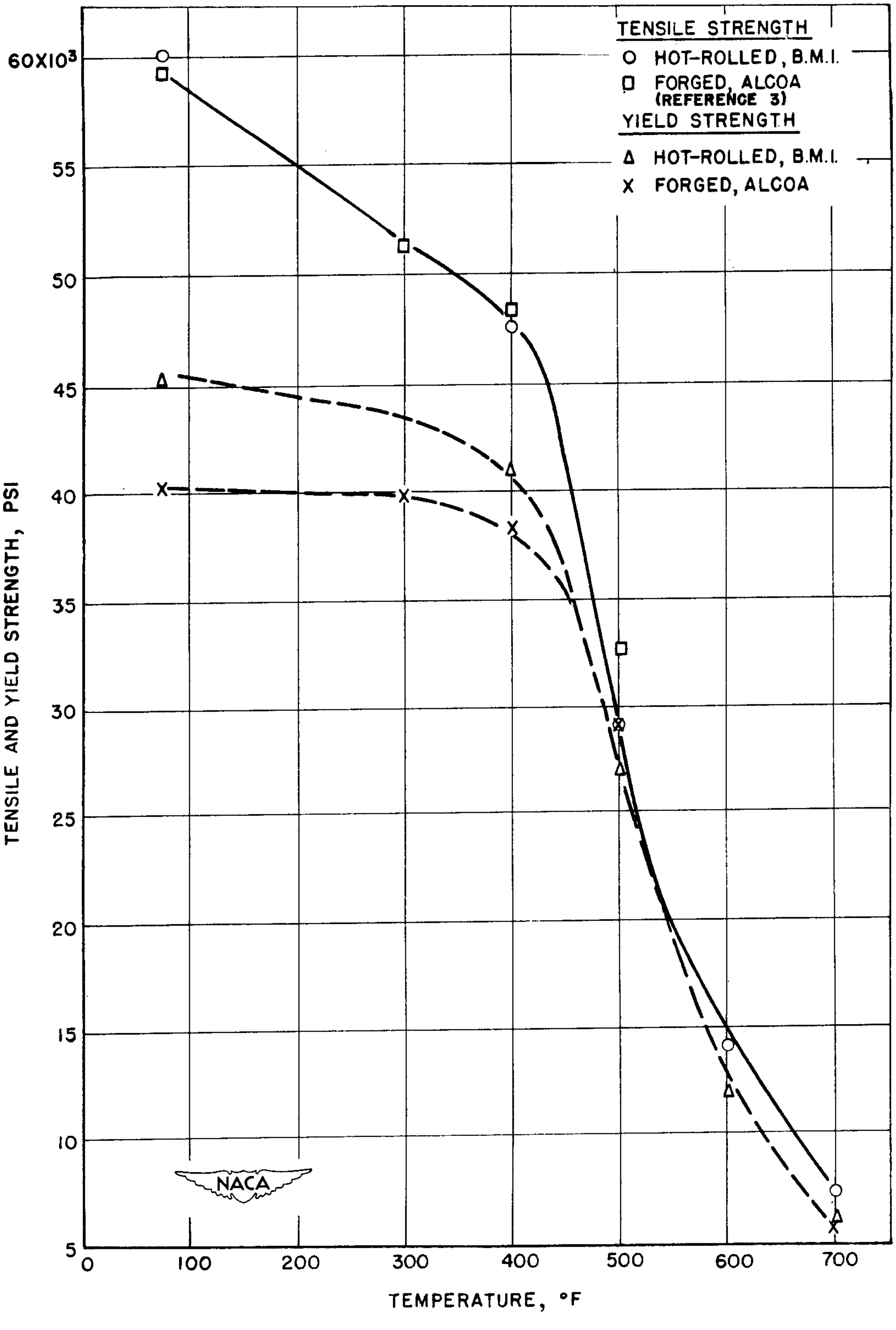

Figure 9.- Short-time tensile tests on XB18S-T.

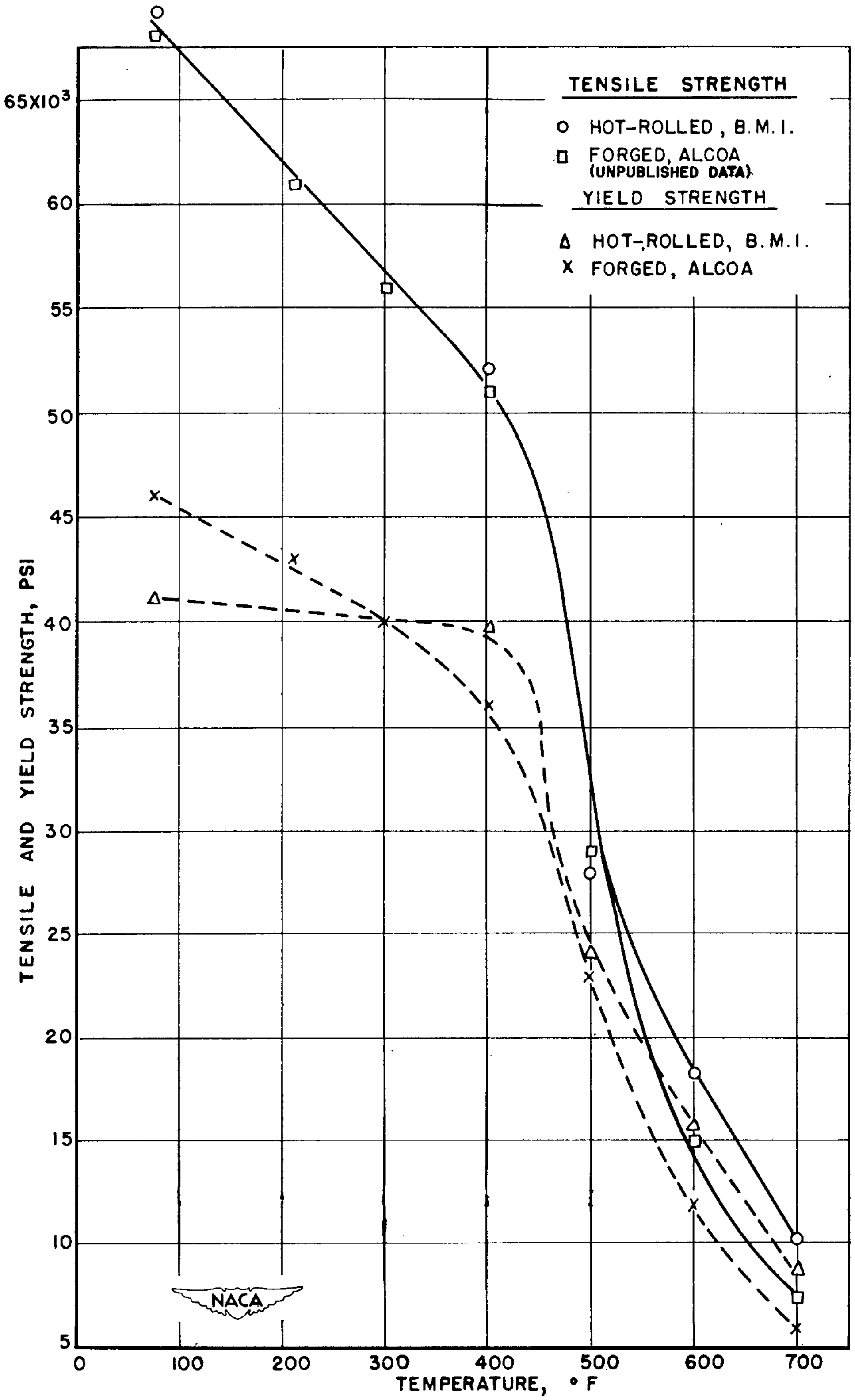

Figure 10.- Short-time tensile tests on 24S-T.

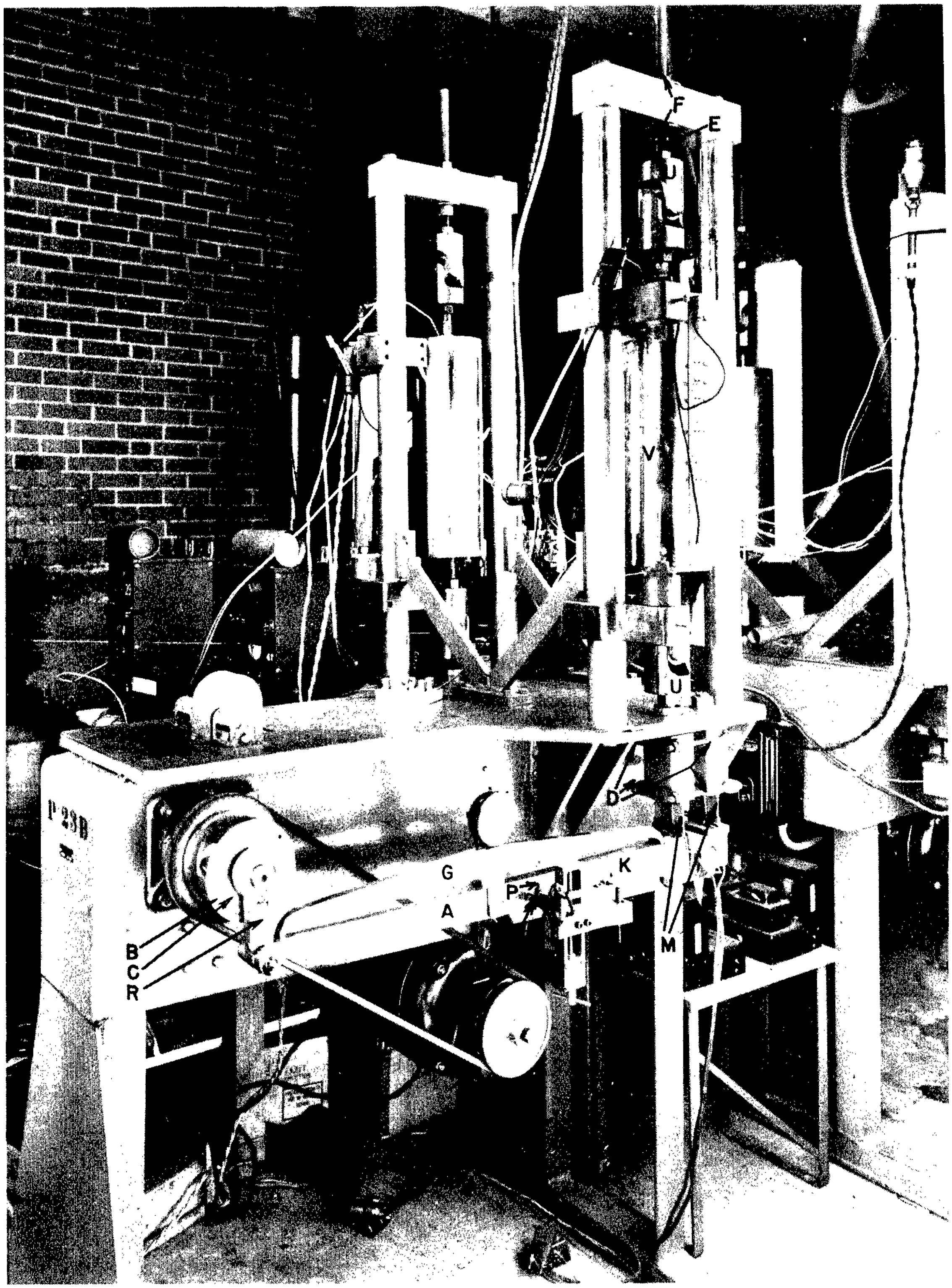

Figure 11.- Krouse machine modified for testing at elevated temperatures.

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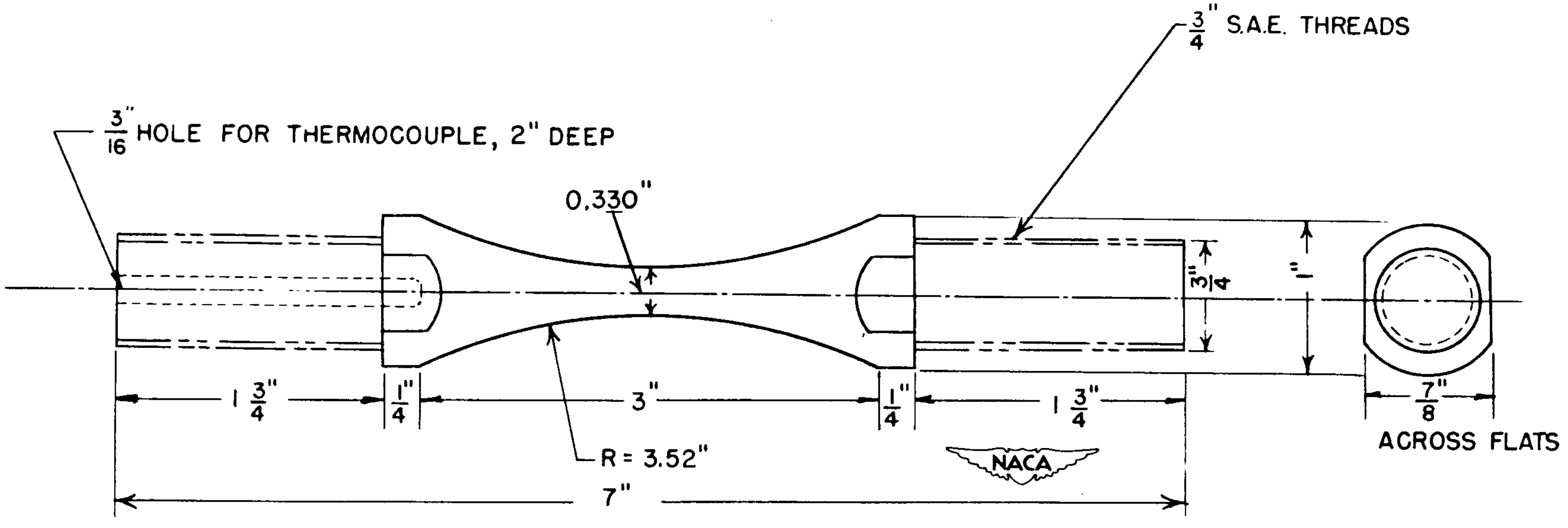

Figure 12.- Aluminum fatigue test specimen for elevated temperatures.

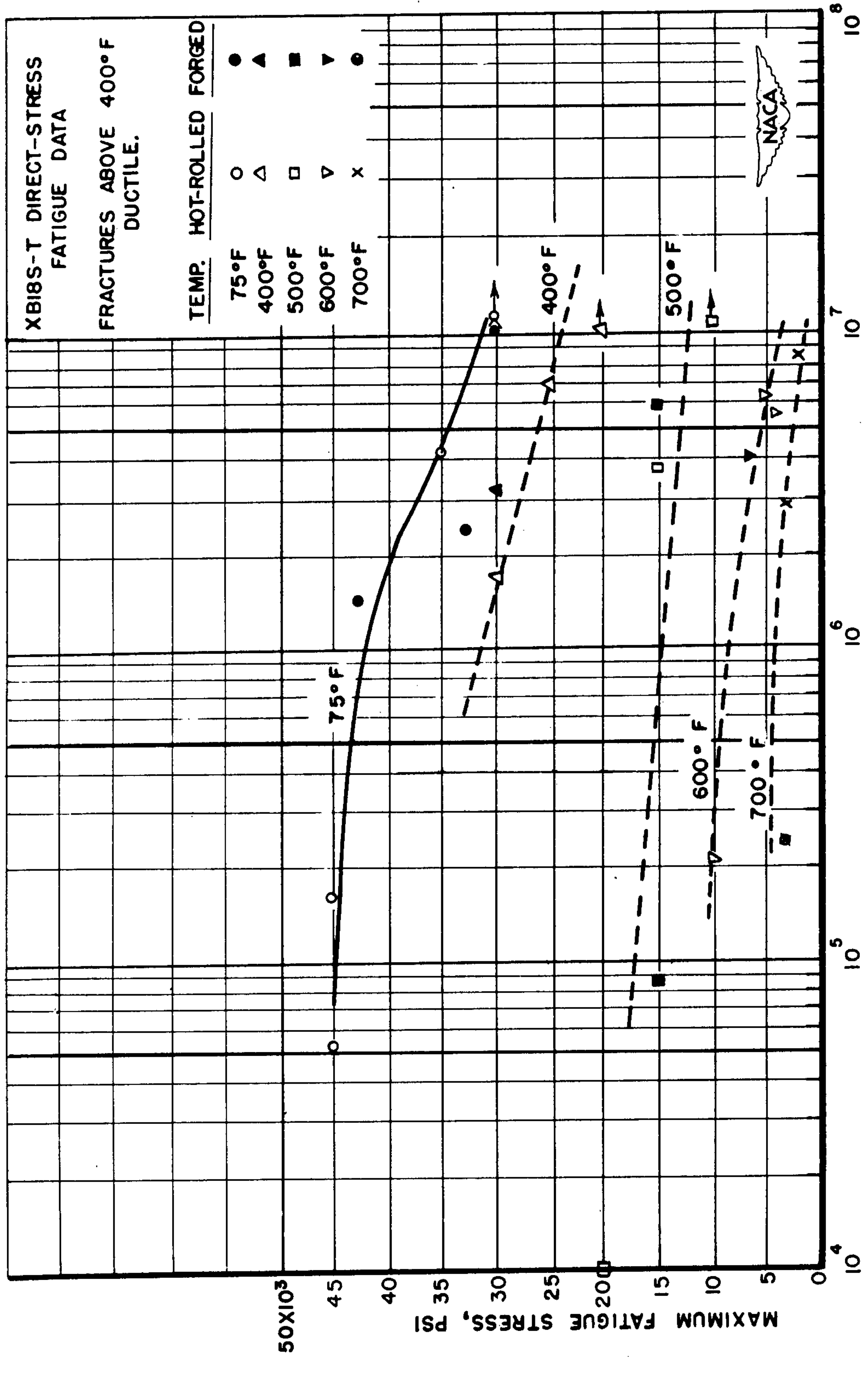

Figure 13.- S-N curves for room-temperature and elevated-temperature direct-stress fatigue tests on XB18S-T.

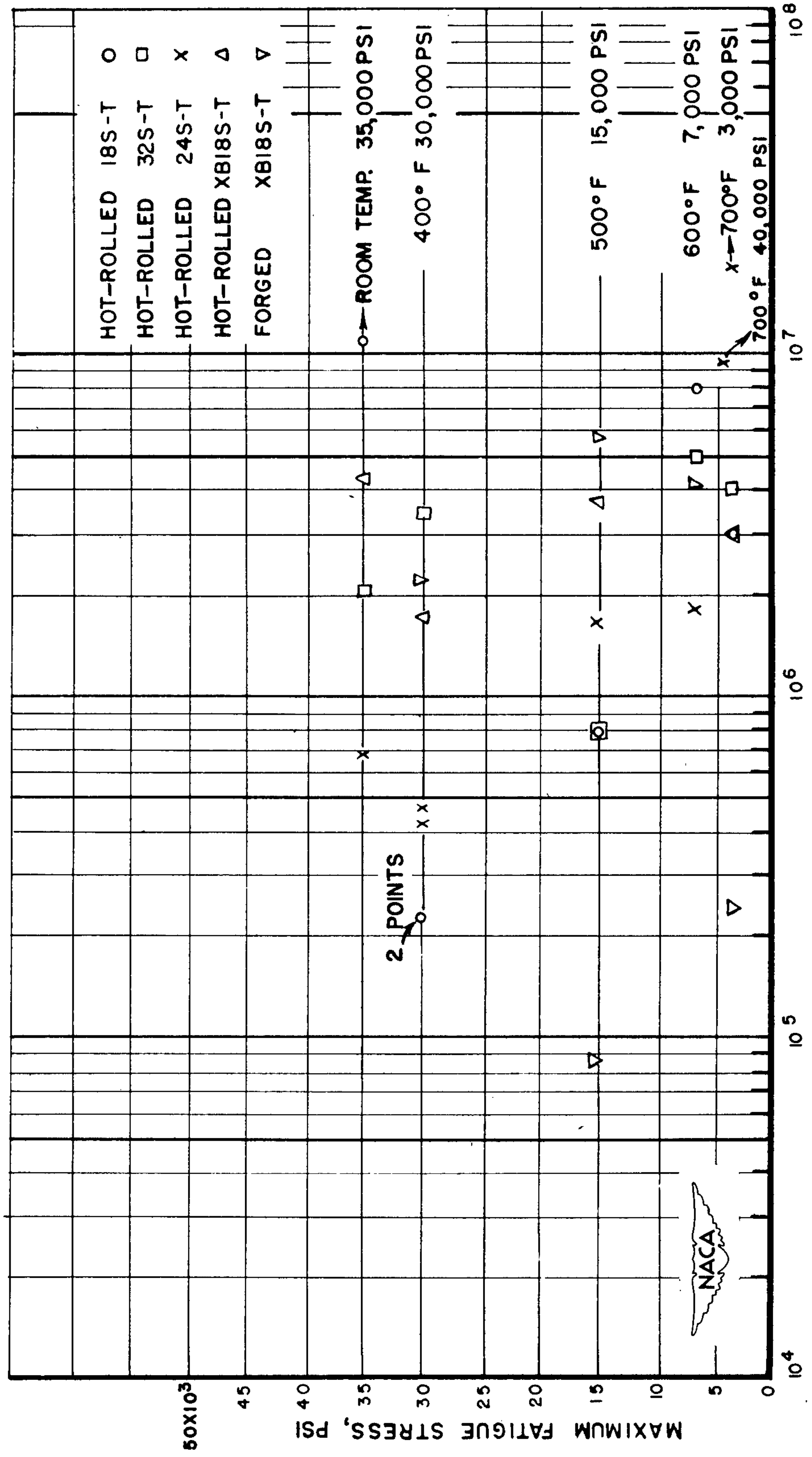

Figure 14.- Comparison of direct-stress fatigue test results.

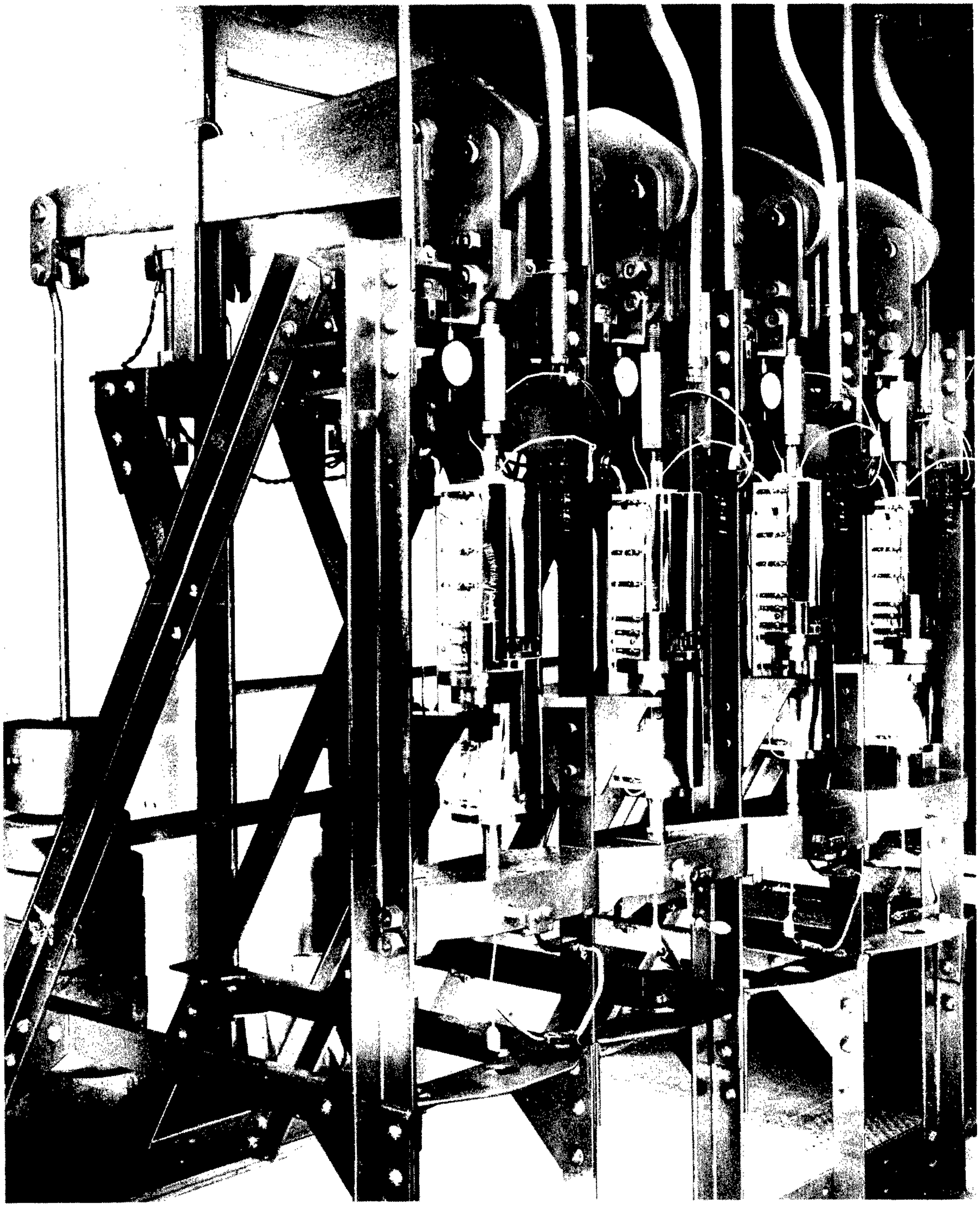

Figure 15.- Creep test equipment.

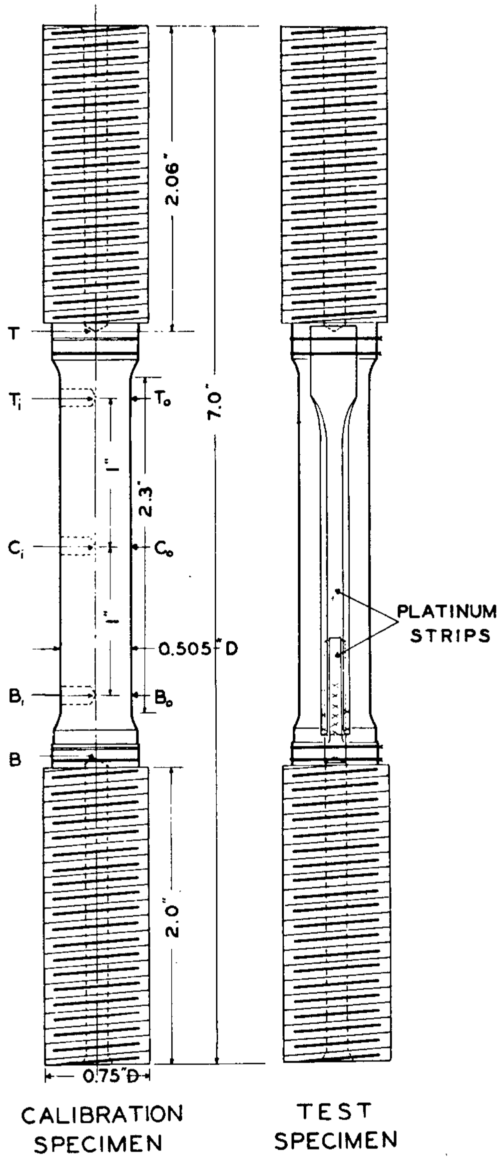

Figure 16.- Calibration and creep test specimens.

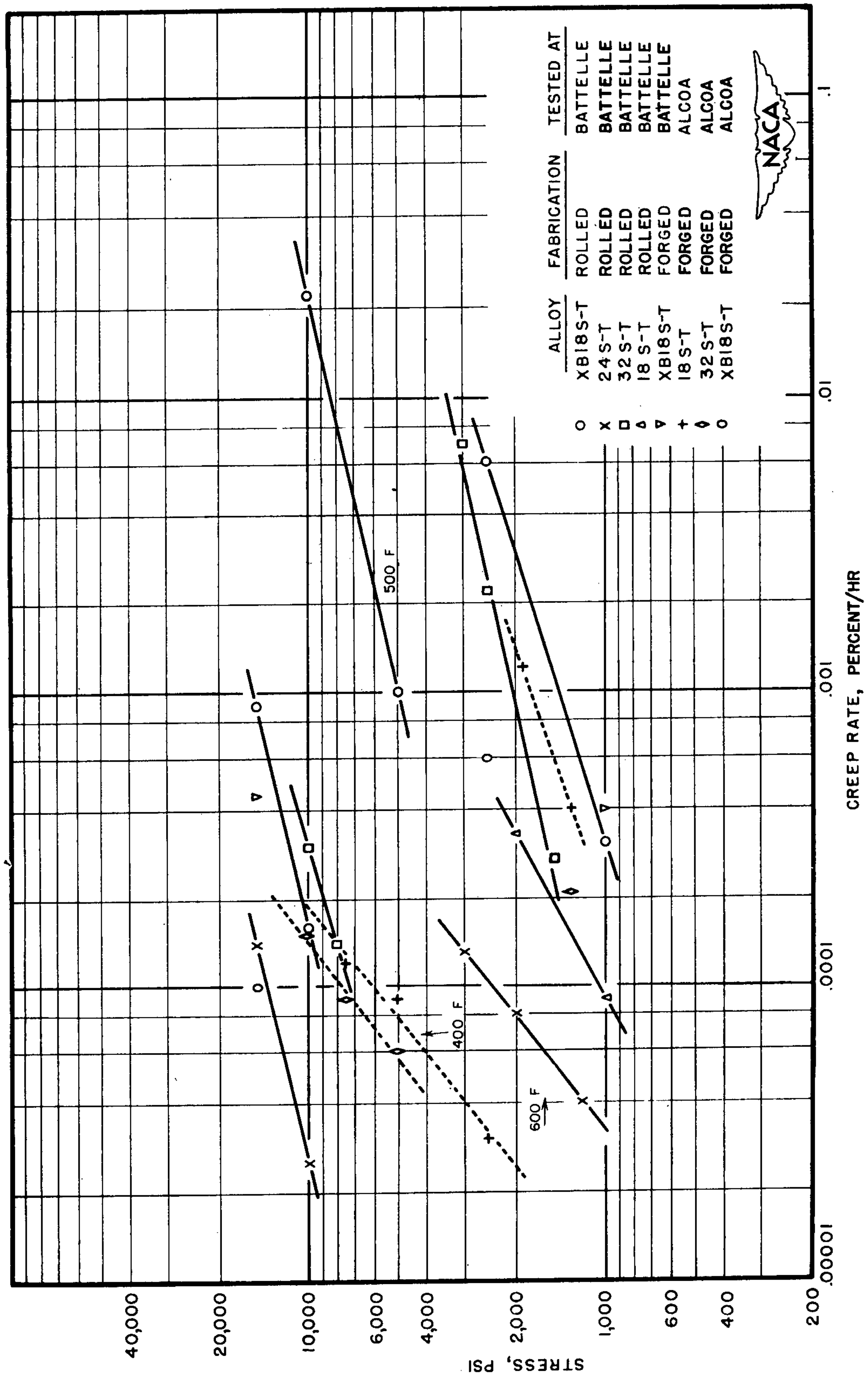

FIGURE 17.–SUMMARY OF AVAILABLE CREEP DATA ON ALLOYS XB18S-T, 32S-T, 18S-T, AND 24S-T.