TENSILE PROPERTIES OF SOME STRUCTURAL SHEET MATERIALS UNDER RAPID-HEATING CONDITIONS

By George J. Heimerl

NACA Langley Aeronautical Laboratory
Langley Field, Va.

For Presentation at the
Fourth Sagamore Ordnance Materials
Research Conference

Raquette Lake, New York
August 21-23, 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TENSILE PROPERTIES OF SOME STRUCTURAL SHEET MATERIALS UNDER RAPID-HEATING CONDITIONS

By George J. Heimerl

NACA Langley Aeronautical Laboratory

SUMMARY

The results of the NACA tests to determine the tensile strength of some structural sheet materials heated to failure at temperature rates from 0.2° F to 100° F per second under constant load conditions are reviewed. Yield and rupture stresses obtained under rapid-heating conditions are compared with the results of conventional elevated-temperature tensile tests. The relation between rapid-heating tests, short-time creep tests, and conventional creep tests is discussed. The application of a phenomenological theory for calculating rapid-heating curves is shown. Methods are given for predicting yield and rupture stresses and temperatures from master curves and temperature-rate parameters.

INTRODUCTION

Aerodynamic heating of aircraft and missiles has led to considerable research on the strength of materials under rapid-heating conditions. In order to provide data on the strength of materials under such conditions, three procedures have been employed so far. In the rapid-heating test, the material is loaded and then heated at various constant temperature rates until failure occurs. In the short-time creep test, the material is loaded, heated quickly to some predetermined temperature, and then allowed to creep. In the stress-strain test, the material is heated rapidly to temperature, and after various holding periods, loaded to failure at some constant strain rate.

This paper is concerned chiefly with the results of the NACA program to determine the tensile properties of some aluminum, magnesium, titanium, and nickel-base alloy sheet materials under rapid-heating conditions (refs. 1 to 5). These results are reviewed briefly and comparisons are made with the conventional tensile properties. The relation between rapid-heating, short-time creep, and conventional creep tests is discussed. In addition, theoretical and empirical methods for predicting the strength of materials under rapid-heating conditions are included.

Review of Test Results (CAPS)

In order to heat the material rapidly, the general practice has been to pass an alternating or direct current through the specimen. The specimen is usually loaded by weights and a lever system. The main differences in practice are in the specimen design and strain-gage system. The system used by the NACA is illustrated in figure 1. The specimen has a reduced section 1/2-inch wide and 11-inches long which is sufficiently long to give fairly uniform temperatures over the middle 1-inch gage-length region. For materials having low conductivities, this reduced section was still further reduced over the middle 3-inch region by grinding off about $1\frac{1}{2}$ thousandths of an inch from each edge. If this was not done, the maximum temperature sometimes occurred near an end instead of in the middle of the specimen. The strain-gage system consisted of two pairs of strain-gage frames mounted opposite each other and one inch apart, and two strain-transfer units, each of which actuated a variable linear differential transformer-type gage. Each strain-gage frame consisted of a two-point knife edge and a stabilizer arm which kept the knife edge normal to the surface. Each end of each strain-transfer arm was in point contact with the flat horizontal surface of a strain-gage frame. The arms of the strain-transfer unit were mounted on flexure plates about at their midposition. Temperatures were measured with No. 30 chromel-alumel thermocouples which were spot welded to the specimen whenever possible; otherwise, they were peened or clamped on the specimen.

Strain-temperature curves for 7075-T6 aluminum-alloy sheet (fig. 2) illustrate the characteristic effects of rapid heating on a material which behaves in an orderly fashion. The strains, which include the elastic, thermal, and plastic strains, are plotted against the instantaneous temperatures for different stresses and for temperature rates from about 0.2° F to 100° F per second. A regular family of curves is obtained at each stress for the different temperature rates when the material becomes plastic. As long as the material is elastic, however, a single curve is obtained at each stress regardless of the temperature rate. This single curve coincides with the calculated strain curves (dashed lines) representing the sum of the thermal and elastic strains. The thermal expansion curve obtained from these tests is also shown. Yield temperatures, defined as temperatures at which 0.2-percent plastic strain occurs are indicated by tick marks offset 0.2 percent from the calculated strain curve. For materials such as 7075-T6 aluminum alloy, a linear relation between yield temperatures and the logarithm of the temperature rate is obtained (fig. 3). An approximately linear relation is also obtained for the rupture temperatures which occur at failure of the specimen (fig. 3).

Not all materials behave in such a consistent manner as 7075-T6 aluminum alloy. Some examples of variations in the pattern will now be cited. The effect of aging on the strain-temperature curves for 2024-T3 aluminum-alloy sheet at 50 ksi is shown in figure 4. In this case, all of the curves band more or less together up to yield, after which the curves fall into the characteristic pattern. Another example of aging is shown for RS-120 titanium-alloy sheet at 75 psi (fig. 5). In this case, the test results follow the usual pattern up to yield, but at higher temperatures, the order of the curves is almost completely changed. Another example shows the discontinuous plastic flow of Inconel at 28 ksi (fig. 6). At this stress, plastic flow occurs at irregular intervals after periods of elastic straining. Even though discontinuous plastic flow occurs, yield temperatures increase with the temperature in a normal fashion. This type of plastic flow is probably caused by the development of Luders' lines.

Comparisons can be made between the strength of materials under rapid-heating conditions and the conventional elevated-temperature tensile strength, even though rapid-heating tests and stress-strain tests are distinctly different kinds of tests. Comparative results for the tensile yield stress for 7075-T6 and 2024-T3 aluminum-alloy sheet are shown in figure 7. The yield stress for a temperature rate of 100° F per second is appreciably greater in the high-temperature region than the tensile yield stress obtained from the stress-strain test for 1/2-hour exposure and a strain rate of 0.002 per minute. The yield stress for 0.2° F per second may be about the same or less than the yield stress from the stress-strain test. The effect of increase in temperature rate levels off rapidly for rates above about 60° F to 100° F per second.

A summary of the comparative yield strengths under rapid-heating and stress-strain conditions for seven sheet materials is shown in figure 8 for temperature rates of 100° F and 0.2° F per second. At 100° F per second, the ratio of the yield stress for the rapid-heating test to the yield stress for the stress-strain test varies from about 1 in the low temperature region to as high as about 4 in the high-temperature region for the material. This high ratio was obtained for the thorium magnesium-alloy HK31XA-H24. At 0.2° F per second, the yield stress ratio decreases somewhat from about 1 with temperature. The greatest decrease was obtained for the same magnesium alloy which showed the greatest increase in the ratio at 100° F per second.

RELATION BETWEEN RAPID-HEATING AND CREEP TESTS

The strain rates which occur under given stress and temperature conditions provide a basis for relating rapid-heating, conventional-creep, and short-time creep tests. The creep rate from the rapid-heating test may be compared with the minimum creep rate from the conventional and short-time creep tests.

In rapid-heating tests, elastic, thermal, and plastic strains occur. The plastic strain rate $\dot{\epsilon}_{pl}$ may be determined for a given stress and temperature from the relation

$$\dot{\epsilon} = \dot{\epsilon}_{th} + \dot{\epsilon}_{pl} \tag{1}$$

in which $\dot{\epsilon}$ and $\dot{\epsilon}_{th}$ are the total and thermal strain rates, respectively. Both $\dot{\epsilon}$ and $\dot{\epsilon}_{th}$ can be obtained directly from the data. The relatively small change in the elastic strain with temperature is neglected in equation (1).

The variation of the plastic strain rate with temperature for the rapid-heating tests of 7075-T6 aluminum-alloy sheet is shown in figure 9 for two stresses. Within the scatter of the data, the individual curves for the various strain rates roughly follow a single curve for each stress. The plastic strain rate thus appears to be more or less independent of the rate at which the material is heated. If this is the case, the mechanical equation of state concept may be valid under rapid-heating conditions. The plastic strain rates for this material increase by a factor of about 5 over a 200° F temperature range at each stress level. The strain rates are very high compared with those encountered in conventional creep tests.

Plastic strain rates for 7075-T6 aluminum-alloy sheet obtained from the rapid-heating tests (fig. 9) are compared with the minimum creep rates obtained from short-time creep tests (data from ref. 6) and conventional creep data in figure 10 at 300° F, 400° F, and 500° F. Creep rates from the rapid-heating tests are about the same magnitude as those obtained from the short-time creep test. Creep rates for rapid-heating and short-time creep tests are much greater in general than those obtained from conventional creep tests at the same temperature and stress. The high creep rates from the rapid-heating and short-time creep tests, however, tie in fairly well with the conventional creep data. The theoretical curves follow the general trend of the data, and were calculated from a phenomenological relation which will be discussed in the next section.

METHODS OF PREDICTING STRENGTH

Application of a Phenomenological Relation

A phenomenological relation between stress σ (ksi), strain rate $\dot{\epsilon}$ (per hr), and temperature T (°K) for metals given in reference 7 is

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{d}{dt}\left(\frac{\sigma}{E}\right) + \alpha\left(\frac{dT}{dt}\right) + 2sTe^{-\frac{\Delta H}{RT}} \sinh \frac{\sigma}{\sigma_0} \qquad (2)$$

In equation (2), ϵ is the total strain, t is the time (hr), E is Young's modulus (ksi) at the temperature T, α is the linear coefficient of expansion (per °K), s is a constant (per hr per °K), R is the gas constant (taken as 2 cal per mole per °K), ΔH is the activation energy (cal per mole), and σ_0 is a constant (ksi). This theory is based upon conventional steady or viscous creep conditions, and its extension to the high-strain rate region of the short-time and rapid-heating tests gives a reasonable approximation of the actual creep rates involved (fig. 10).

Further conformation will be shown later in more direct comparisons with results of rapid-heating tests for two other materials. The solution of equation (2) for the total strain under constant load and temperature-rate conditions has been obtained by the author of reference 7. This solution is

$$\epsilon = \frac{\sigma}{E} + \alpha(T - T_0) + \frac{s\left(\frac{\Delta H}{R}\right)^2 e^{\frac{\sigma}{\sigma_0}}}{\dot{T}_0}\left[\frac{e^{-\frac{\Delta H}{RT}}}{\left(\frac{\Delta H}{RT}\right)^3}\left(1 - \frac{3}{\frac{\Delta H}{RT}} + \ldots\right)\right] \tag{3}$$

In equation (3), T_0 is the ambient temperature ($^{\circ}$K), $\dot{T}_0$ is the known temperature rate ($^{\circ}$K per hr), and the other quantities are as previously defined. Values of the constants used in equations 2 and 3 for the various applications are given in table 1. These constants also hold for creep and some of the other applications covered by the relation in reference 7.

The application of equation (3) to rapid-heating tests for low carbon-steel (data from ref. 8) is shown in figures 11 and 12. Plastic strain-temperature curves at 10 ksi for temperature rates of 50° F and 400° F per second, obtained from the rapid-heating tests and calculated from short-time creep tests (ref. 8) are compared with the theoretical results in figure 11. The theoretical and rapid-heating test results are in good agreement. The curves calculated from the special short-time creep tests are in poor agreement with both the test and theoretical results. The effect of prior creep in reducing plastic flow under rapid-heating conditions was given as a possible explanation for the difference between the test results and those calculated from the short-time creep tests (ref. 8). Creep strains and creep rates, obtained from the short-time creep test, are greater in this case than those obtained in the rapid-heating tests.

Yield temperatures for low-carbon steel calculated from equation (3) for 0.2-percent plastic strain, are compared with the test results (ref. 8) in figure 12 for temperature rates from about 20° F to $1,000^{\circ}$ F per second. Good agreement between experimental and theoretical results is evident. Consequently for this material, both the shape of the plastic-strain curves (fig. 11) and the yield temperatures (fig. 12) can be predicted satisfactorily by the theory.

The application of equation (3) to the rapid-heating tests for Inconel X sheet is shown in figures 13 and 14 (data from ref. 5). The calculated strain-temperature curves (fig. 13) are in close agreement with the experimental results at 40 and 80 ksi. Calculated and experimental yield temperatures (fig. 14) are also in close agreement at 60 and 80 ksi, but at 20 ksi and 40 ksi, the experimental and theoretical results do not follow the same slope. Rapid-heating results for Inconel X, however, can be predicted by this method, provided that the constants in equation (3) are known.

Application of Experimental Rate-Temperature Parameters

For cases in which the theory cannot be readily applied, an engineering approach for predicting yield and rupture temperatures and stresses under rapid-heating conditions may be employed which is based upon the use of master curves and temperature-rate parameters derived from the data.

An approximately linear relation was found between yield and rupture temperatures and the logarithm of the temperature rate for the various materials (refs. 1 to 5, 8). Examples of this linear relation may be found in figures 3, 12, and 14. From such relationships, linear or reciprocal rate-temperature parameters may be derived. The derivation of the parameters for 7075-T6 aluminum-alloy sheet will be given as an example.

When the linear and reciprocal yield temperatures are plotted against the logarithm of the temperature rate on an enlarged scale (fig. 15), each stress level can be approximated by straight lines which intersect at a point. In the linear-temperature plot, the slopes m of the curves can be given as

$$m = \frac{T - T_a}{\log h - \log h_a} \qquad (4)$$

where T is the yield temperature ($^{\circ}F$), h is the temperature rate ($^{\circ}F$ per sec), and T_a and h_a are the temperature and rate constants for the intersection point. The right-hand side of equation (4) is a parameter which is a function of stress. Consequently, a single curve should be obtained in plots of stress against the parameter. Inasmuch as $T_a = -200$ and $\log h_a = -17$, the linear rate-temperature parameter for this material is

$$\frac{T + 200}{\log h + 17} \qquad (5)$$

Parameter (5) has the same form as the linear rate-temperature parameter of Manson and Haferd (ref. 9) which has been applied to creep tests, the only difference being the substitution of the temperature rate for the minimum creep rate.

In the reciprocal-temperature plot (fig. 15), the intersection at zero reciprocal temperature of the constant stress lines gives the constant in the parameter

$$T(24 - \log h) \qquad (6)$$

In parameter (6), T is the absolute temperature ($^{\circ}R$) and h is the temperature rate ($^{\circ}F$ per sec). This parameter has the same form as the Larson-Miller parameter (ref. 10). In the case of 7075-T6 aluminum-alloy sheet, parameters (5) and (6) hold for rupture as well as for yield temperatures.

Parameters such as (5) and (6) take into account both the effect of temperature and temperature rate at a given stress level and can thus be used to construct master curves. Master curves for yield and rupture for 7075-T6 and 2024-T3 aluminum-alloy sheet, employing the linear rate-temperature parameters, are shown in figure 16 for illustrative purposes. The validity of the parameter is shown by the correlation of the data with the master curves. Yield and rupture temperatures, calculated from the master curves are in general in close agreement with the test results.

CONCLUDING REMARKS

The characteristic behavior of materials heated at constant temperature rates under constant tensile load conditions has been fairly well established for a number of structural materials. Theoretical and empirical methods are available for predicting the strength of materials for such relatively simple loading and heating conditions. For the case in which loading and heating occur simultaneously, however, data are completely lacking, and the need for further research is evident.

REFERENCES

1. Heimerl, George J., and Inge, John E.: Tensile Properties of 7075-T6 and 2024-T3 Aluminum-Alloy Sheet Heated at Uniform Temperature Rates Under Constant Load. NACA TN 3462, 1955.

2. Heimerl, George J., Kurg, Ivo M., and Inge, John E.: Tensile Properties of Inconel and RS-120 Titanium-Alloy Sheet Under Rapid-Heating and Constant-Temperature Conditions. NACA TN 3731, 1956.

3. Gibbs, Thomas W.: Tensile Properties of HK31XA-H24 Magnesium-Alloy Sheet Under Rapid-Heating Conditions and Constant Elevated Temperatures. NACA TN 3742, 1956.

4. Kurg, Ivo M.: Tensile Properties of AZ31A-0 Magnesium-Alloy Sheet Under Rapid-Heating and Constant-Temperature Conditions. NACA TN 3752, 1956.

5. Kurg, Ivo M.: Tensile Properties of Inconel X Sheet Under Rapid-Heating and Constant-Temperature Conditions. NACA TN 4065, 1957.

6. Van Echo, John A., Gullotti, Damian V., Bibler, James R., and Simmons, Ward R.: Short-Time Creep Properties of Structural Sheet Materials for Aircraft and Missiles. AF Technical Report 6731, Part 4, Jan. 1956.

7. Stowell, Elbridge Z.: A Phenomenological Relation Between Stress, Strain Rate, and Temperature for Metals at Elevated Temperatures. NACA TN 4000, 1957.

8. Smith, W. K.: Relation of High-Heating-Rate Tests to Very-Short-Time Creep Tests NAVORD Rep. 3403 (NOTS 995), U. S. Naval Ordnance Test Station (China Lake, Calif.), March 15, 1955.

9. Manson, S. S., and Haferd, A. M.: A Linear Time-Temperature Relation for Extrapolation of Creep and Stress-Rupture Data. NACA TN 2890, 1953.

10. Larson, F. R., and Miller, James: A Time-Temperature Relationship for Rupture and Creep Stresses. Trans. ASME, vol. 74, no. 5, July 1952, pp. 765-775.

TABLE 1.- VALUES OF CONSTANTS IN STRESS, STRAIN RATE,

TEMPERATURE RELATION FOR VARIOUS APPLICATIONS

Figure	Application	Constants		
		ΔH, cal per mole	σ_0, ksi	s, per hour per $^{\circ}K$
10	Conventional creep	34,700	4.3	1.5×10^8
11, 12	Rapid heating	72,000	1.3	7.7×10^{10}
13, 14	Rapid heating	115,000	8	10^{16}

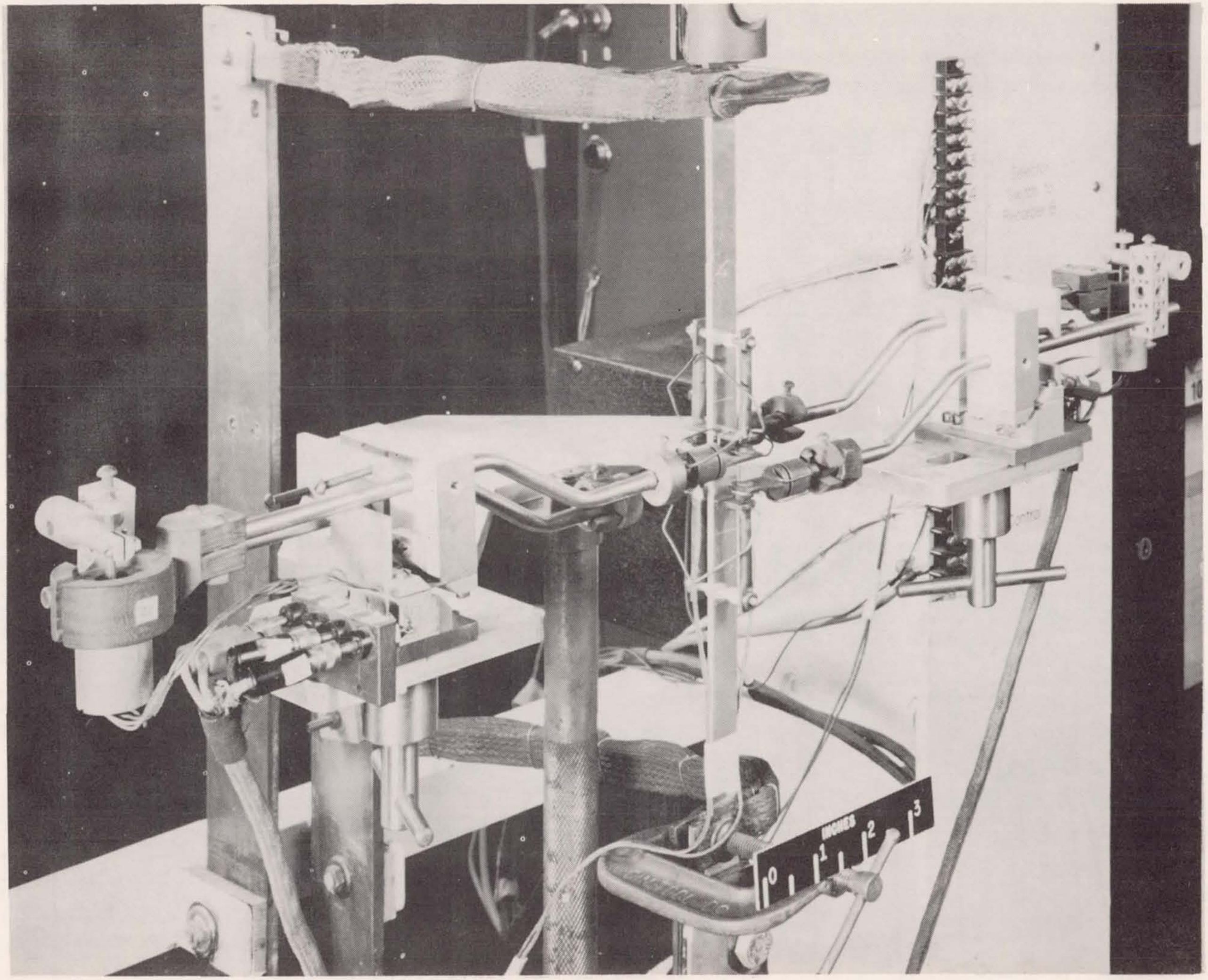

Figure 1.- Rapid-heating test specimen and strain-gage system.

NACA
L-57-2303.1

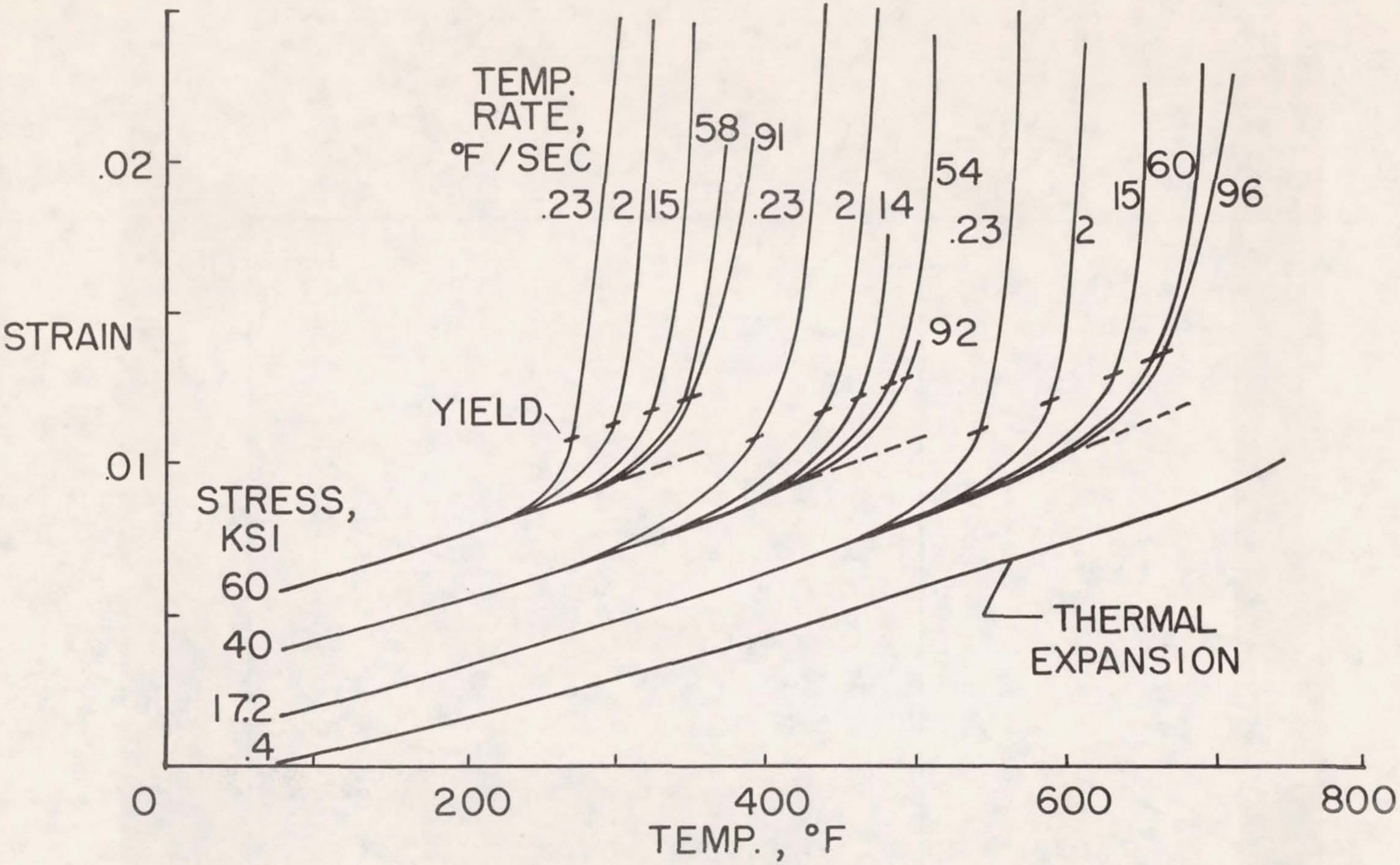

Figure 2.- Strain-temperature curves for 7075-T6 aluminum-alloy sheet for temperature rates from 0.2° F to 100° F per second for various stresses. (Data from ref. 1.)

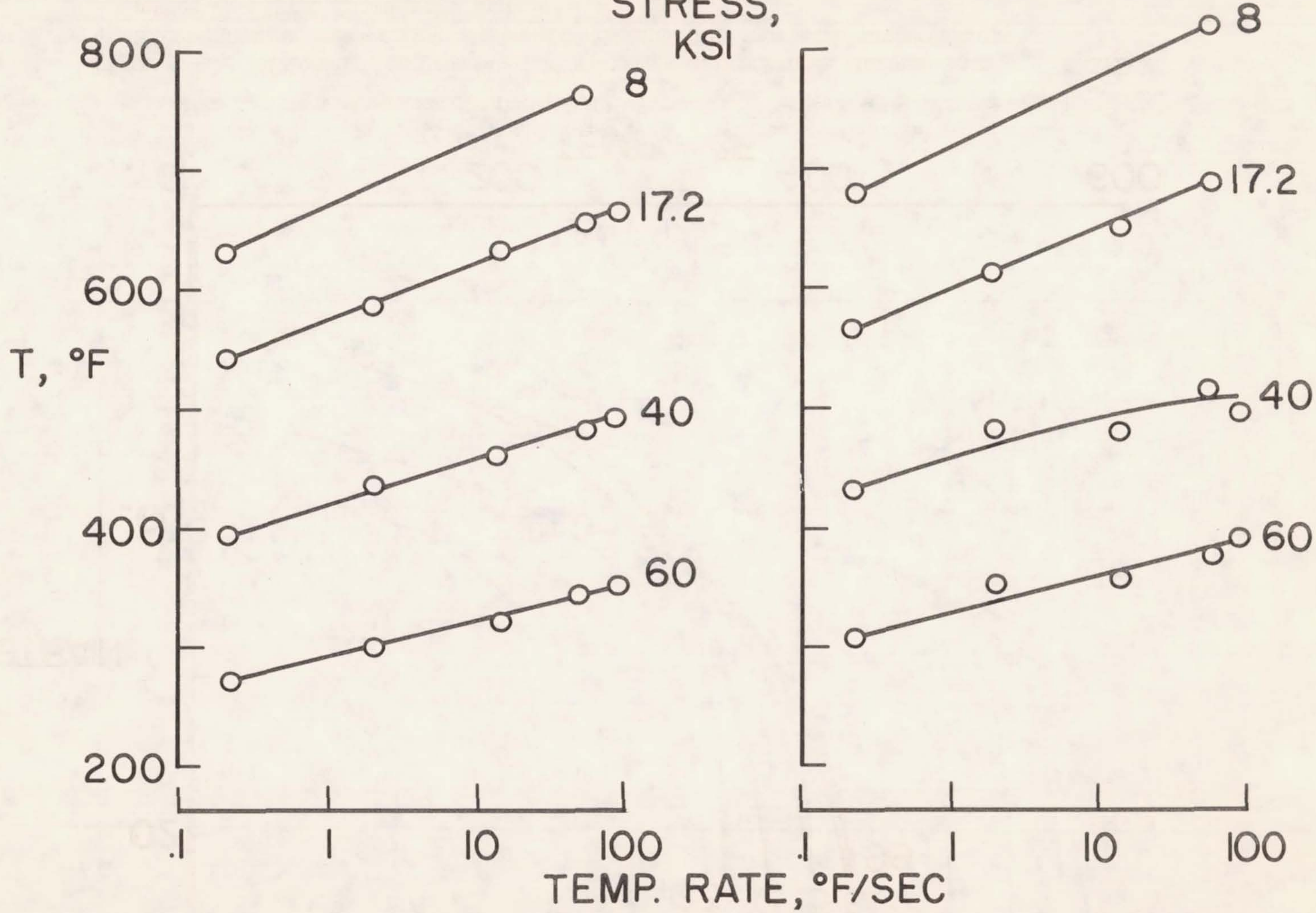

Figure 3.- Yield and rupture temperatures for 7075-T6 aluminum-alloy sheet for temperature rates from 0.2° F to 100° F per second for various stresses. Yield temperatures are for 0.2-percent plastic strain. (Data from ref. 1.)

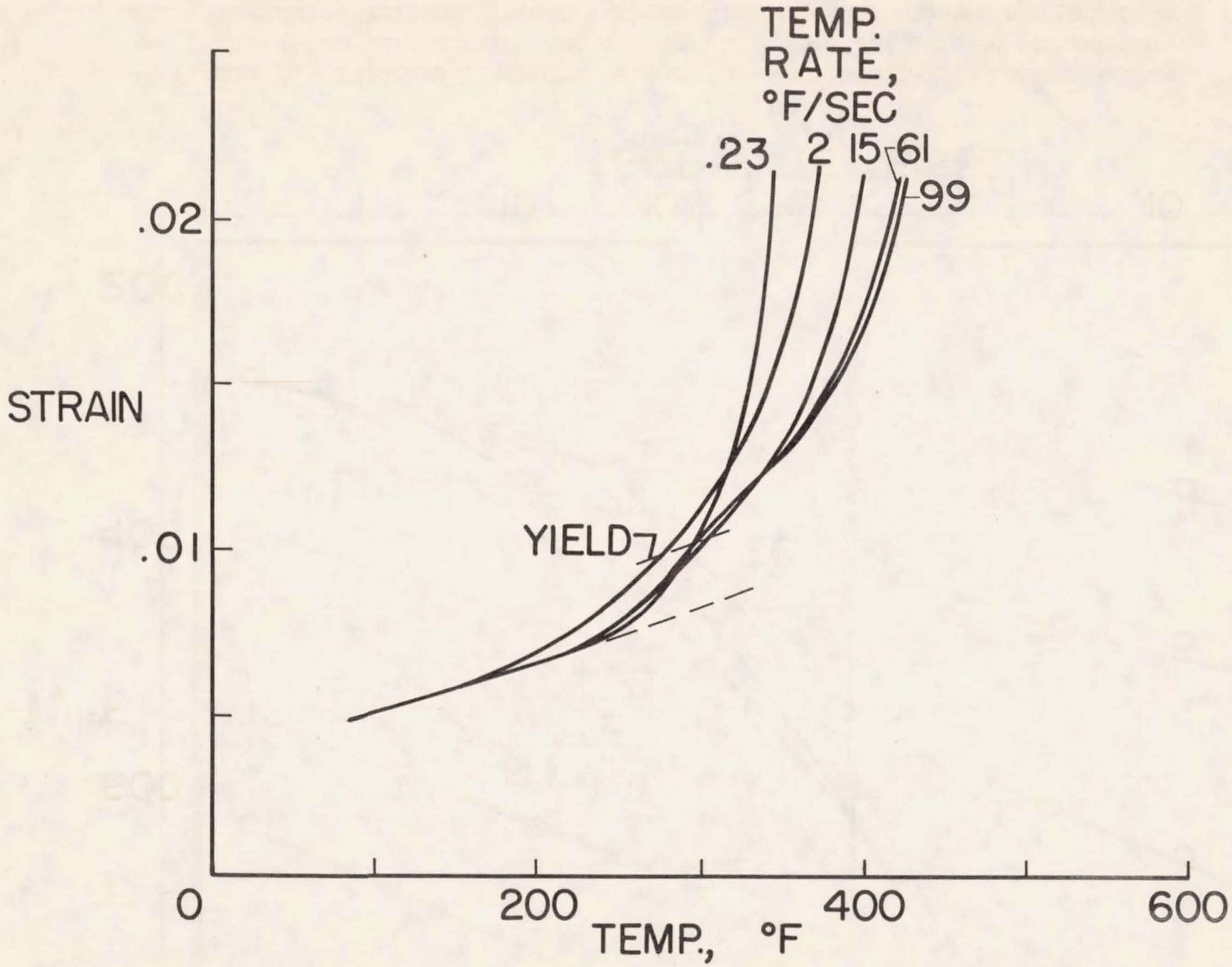

Figure 4.- Effect of aging on the strain-temperature curves for 2024-T3 aluminum-alloy sheet at 50 ksi for various temperature rates. (Data from ref. 1.)

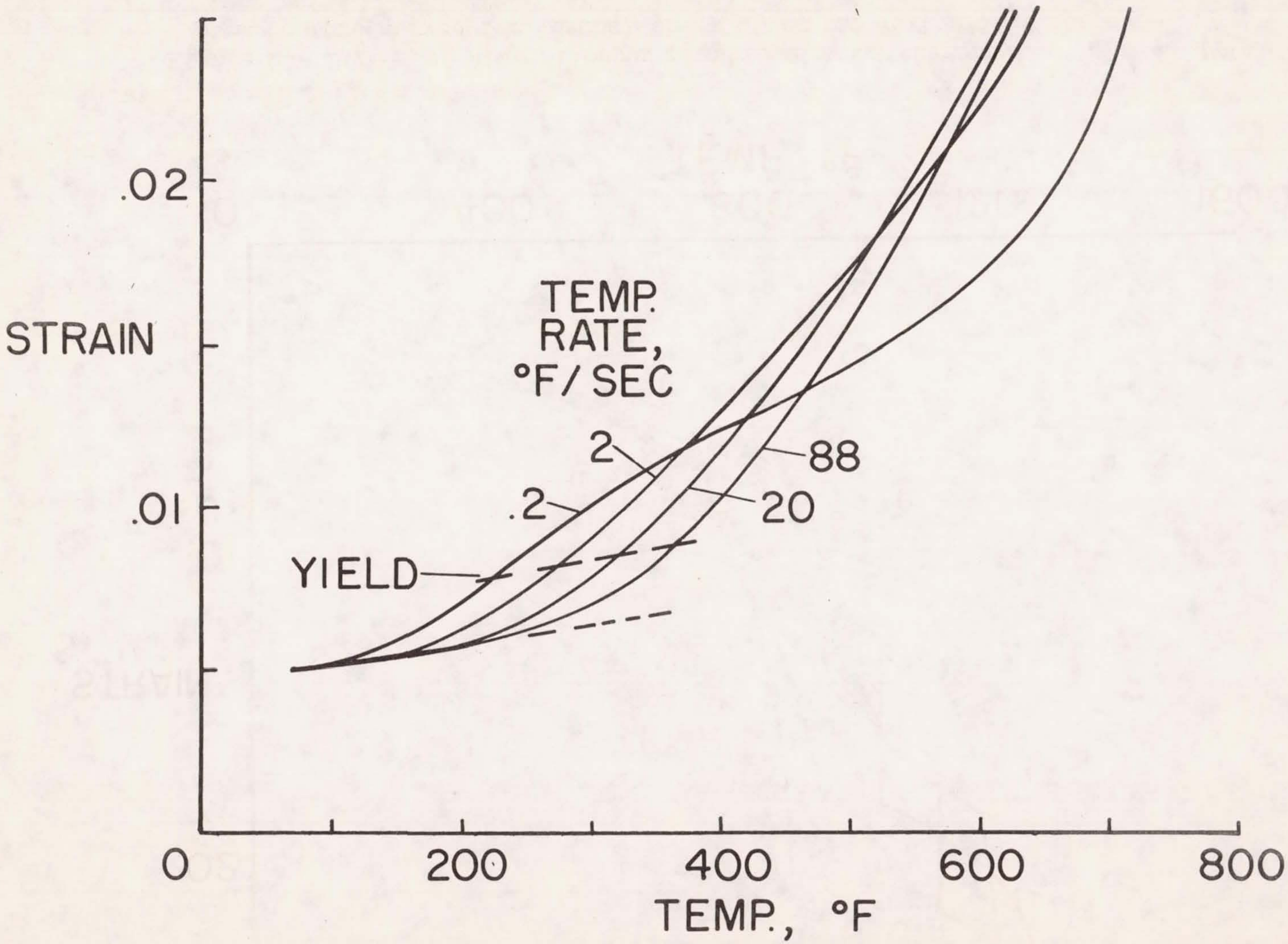

Figure 5.- Effect of aging on the strain-temperature curves for RS-120 titanium-alloy sheet at 75 ksi for various temperature rates. (Data from ref. 2.)

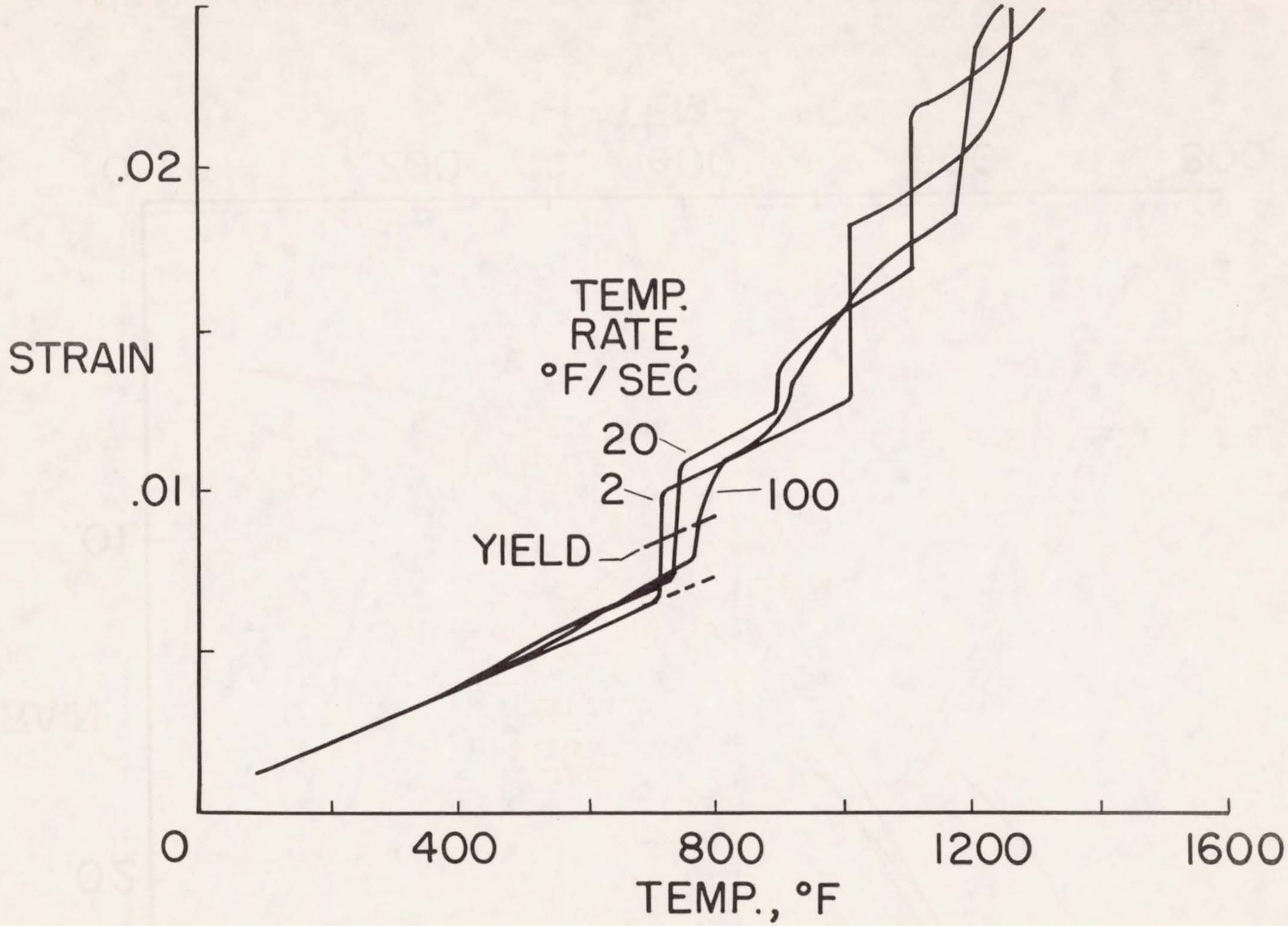

Figure 6.- Effect of discontinuous plastic flow on the strain-temperature curves for Inconel sheet at 28 ksi for various temperature rates. (Data from ref. 2.)

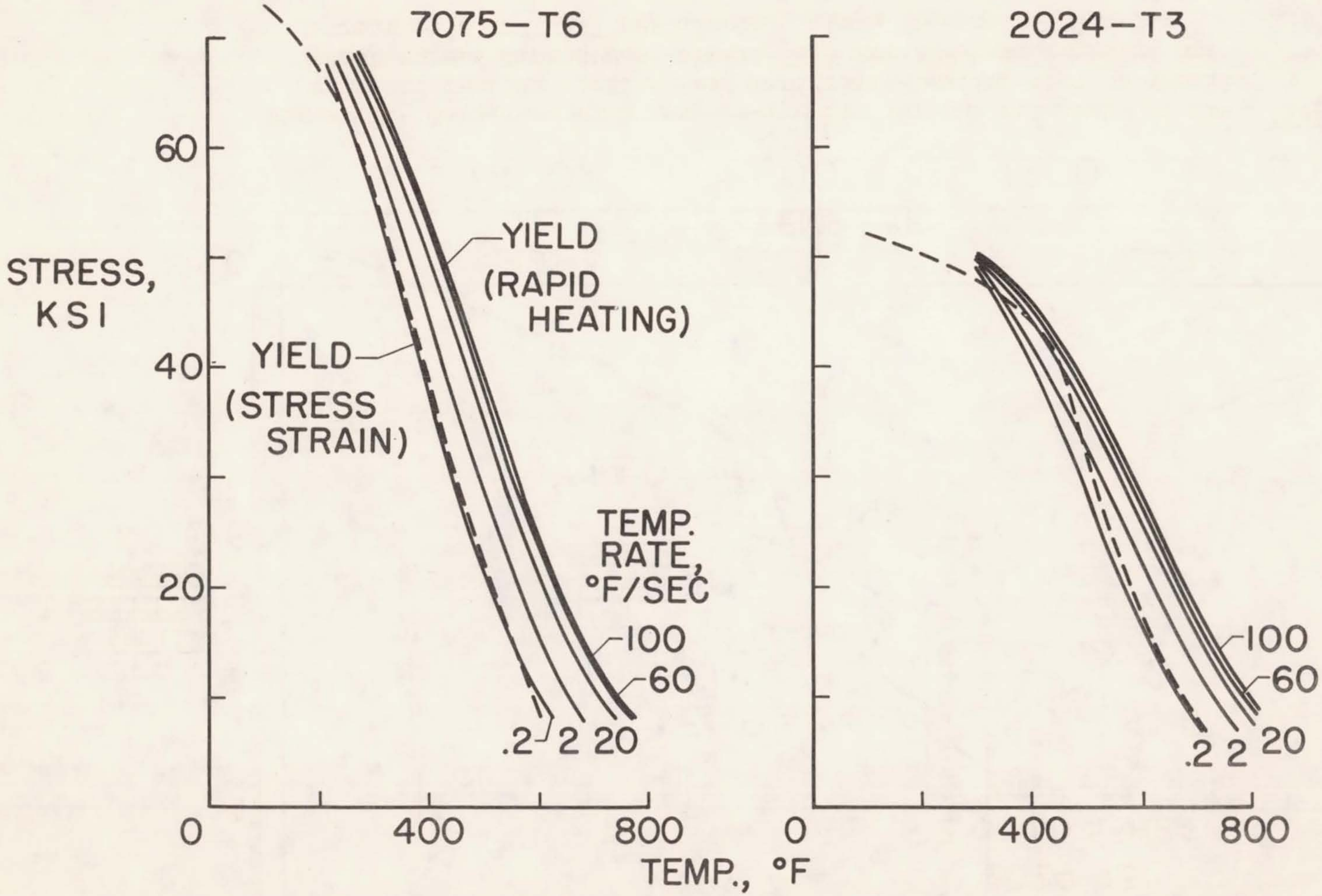

Figure 7.- Tensile yield stress for rapid-heating tests from 0.2° F to 100° F per second and for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute for 7075-T6 and 2024-T3 aluminum alloys. (Data from ref. 1.)

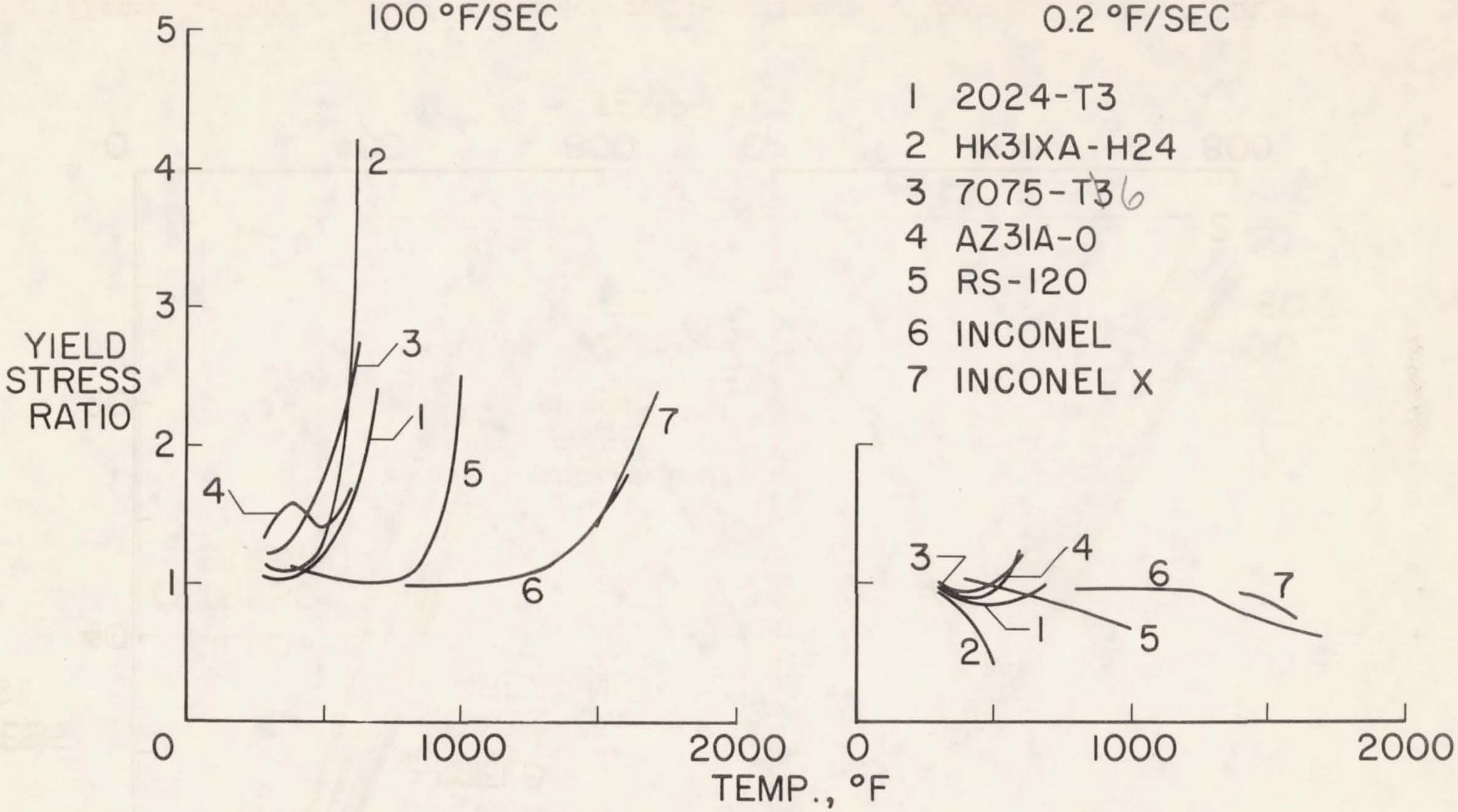

Figure 8.- Variation with temperature for various materials of the ratio of tensile yield stress from rapid-heating test to tensile yield stress from stress-strain test for 1/2-hour exposure and strain rate of 0.002 per minute. (Data from refs. 1 to 5.)

NACA

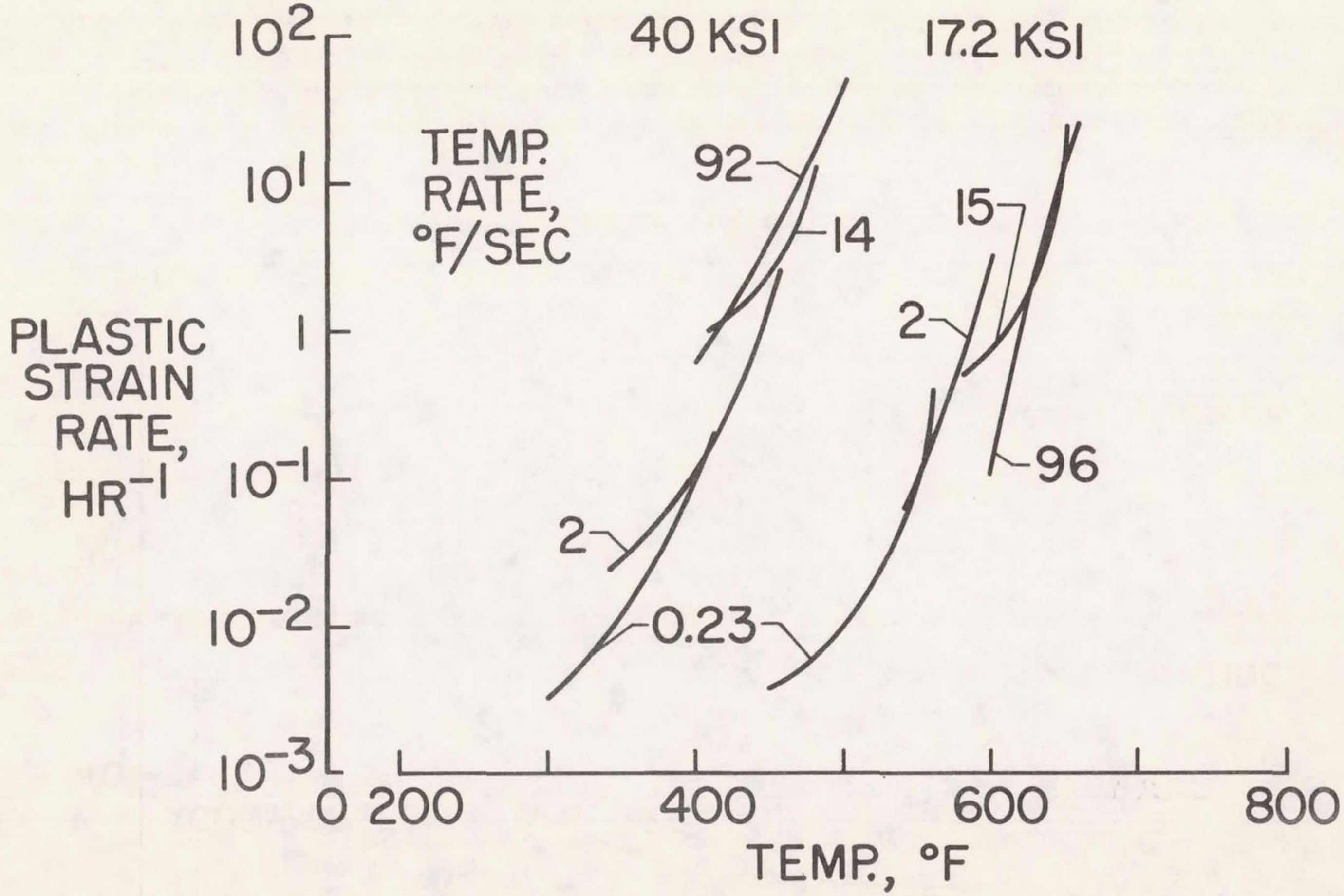

Figure 9.- Plastic strain rates for 7075-T6 aluminum-alloy sheet obtained in rapid-heating tests at temperature rates from 0.2° F to 100° F per second. (NACA unpublished data.)

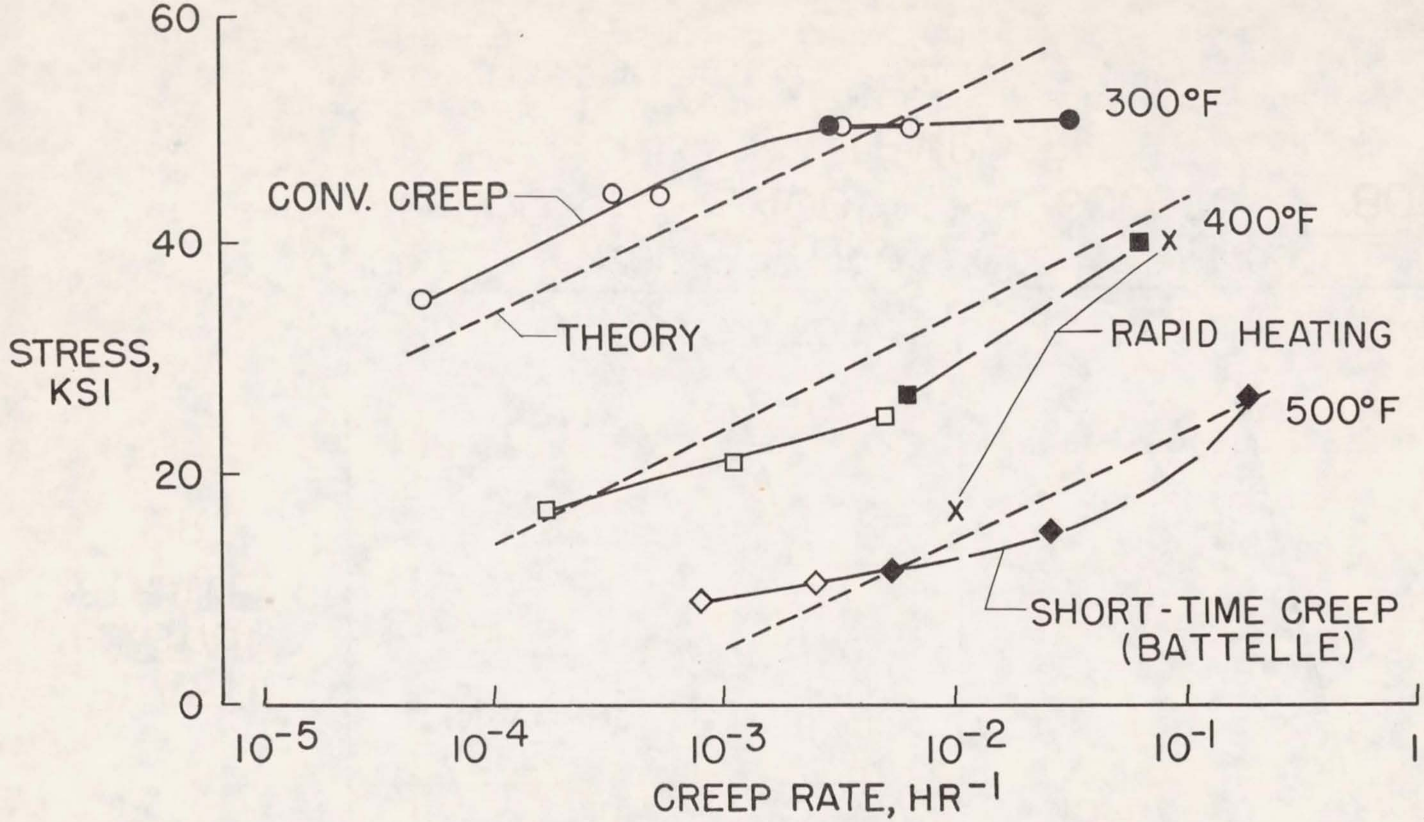

Figure 10.- Creep rates for various stresses for 7075-T6 aluminum-alloy sheet from rapid-heating tests, and from short-time and conventional creep tests. (Battelle data from ref. 6; NACA unpublished data.)

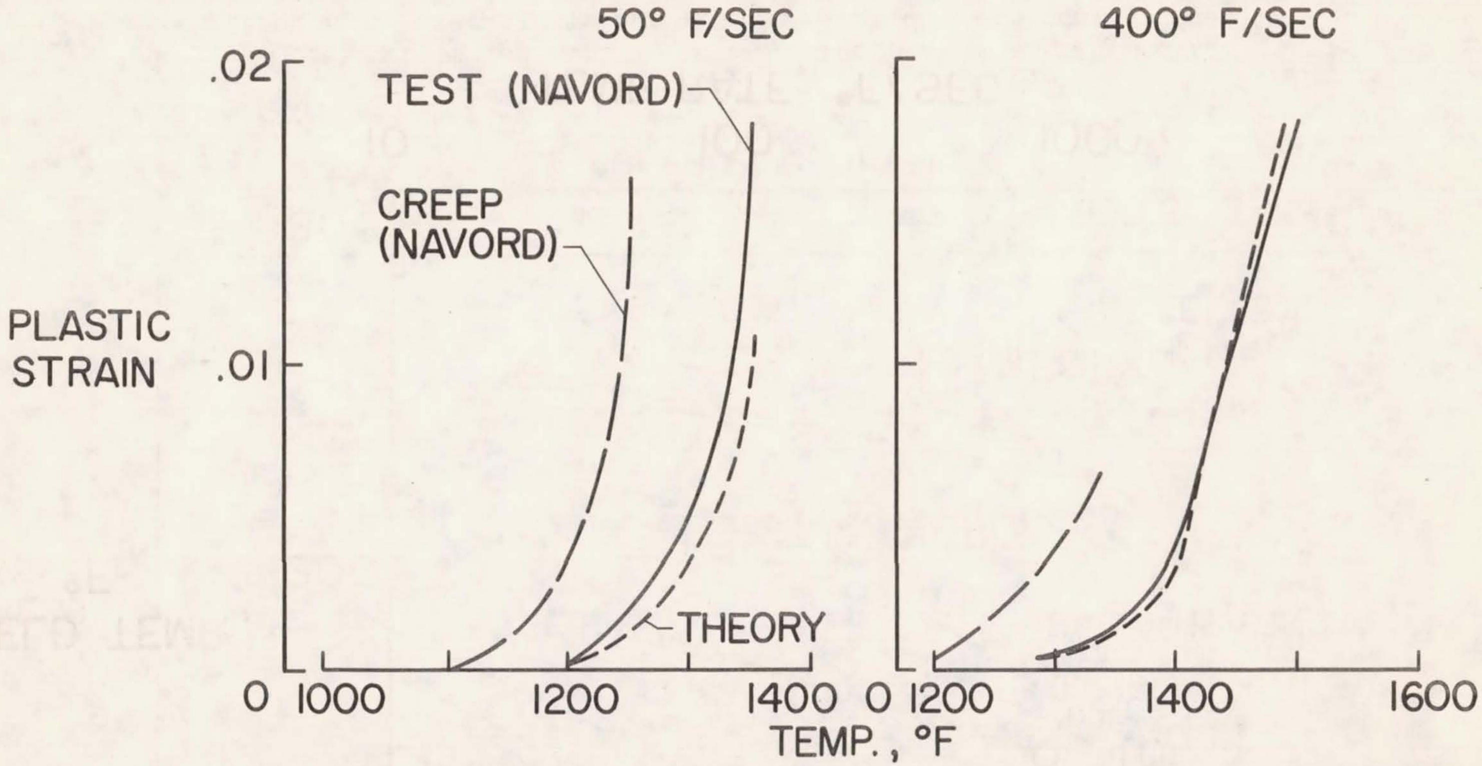

Figure 11.- Plastic strain-temperature curves for low-carbon steel sheet for temperature rates of 50° F and 400° F per second. (Data from ref. 8.)

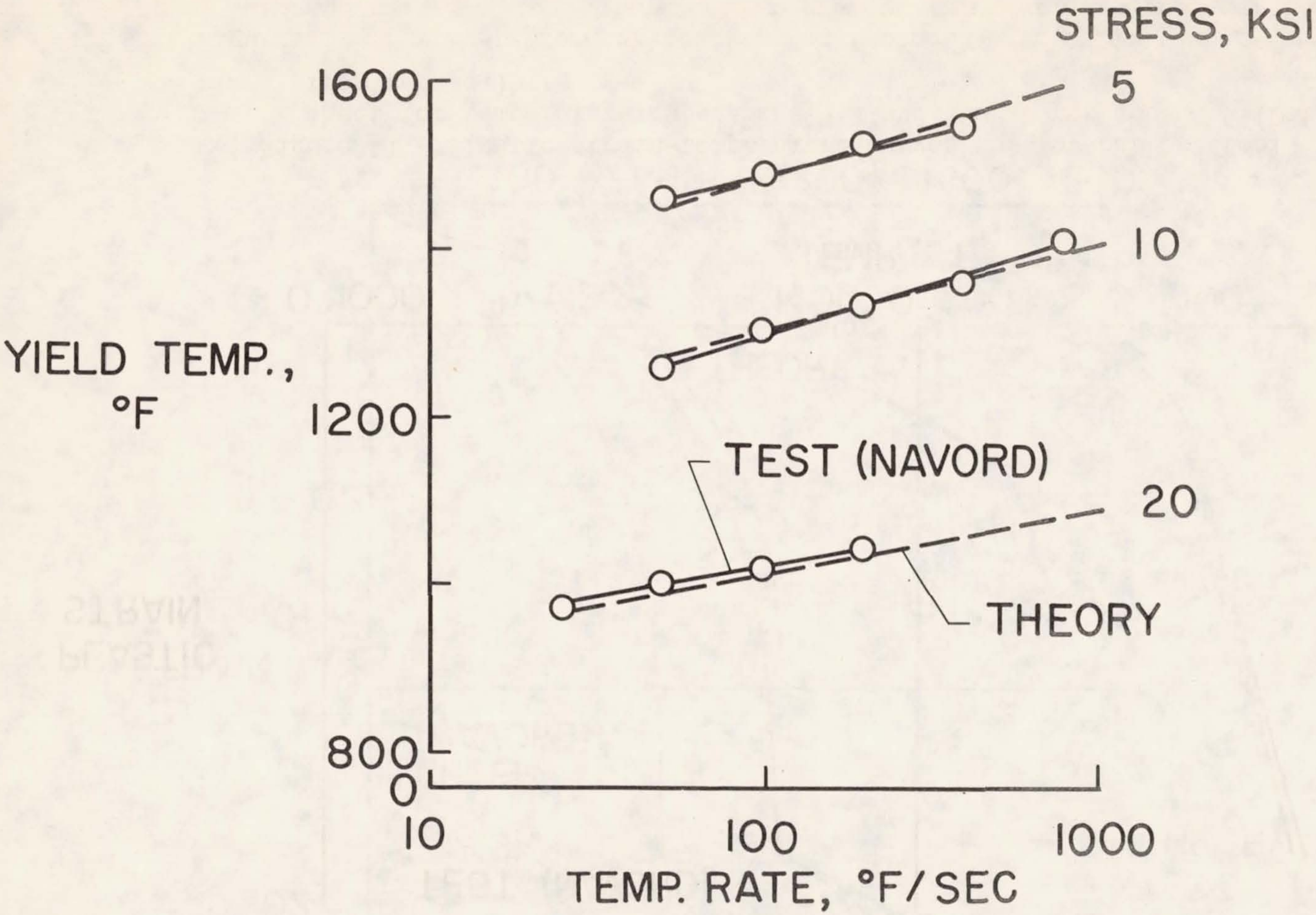

Figure 12.- Yield temperatures for low-carbon steel sheet for temperature rates from 20° F to 1000° F per second for various stresses. Yield temperatures are for 0.2-percent plastic strain. (Data from ref. 8.)

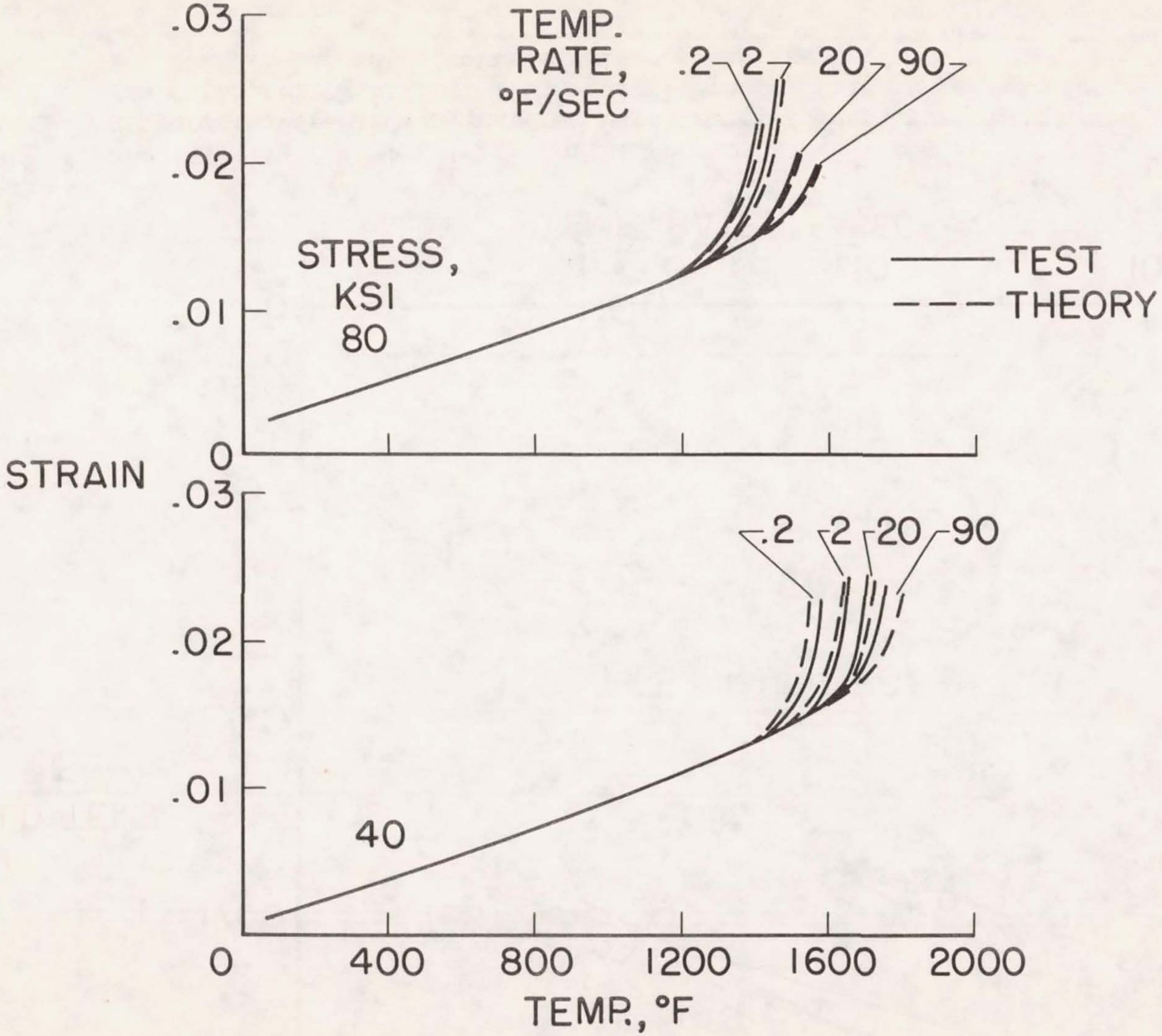

Figure 13.- Strain-temperature curves for Inconel X sheet for temperature rates from 0.2° F to 100° F per second for various stresses. (Data from ref. 5.)

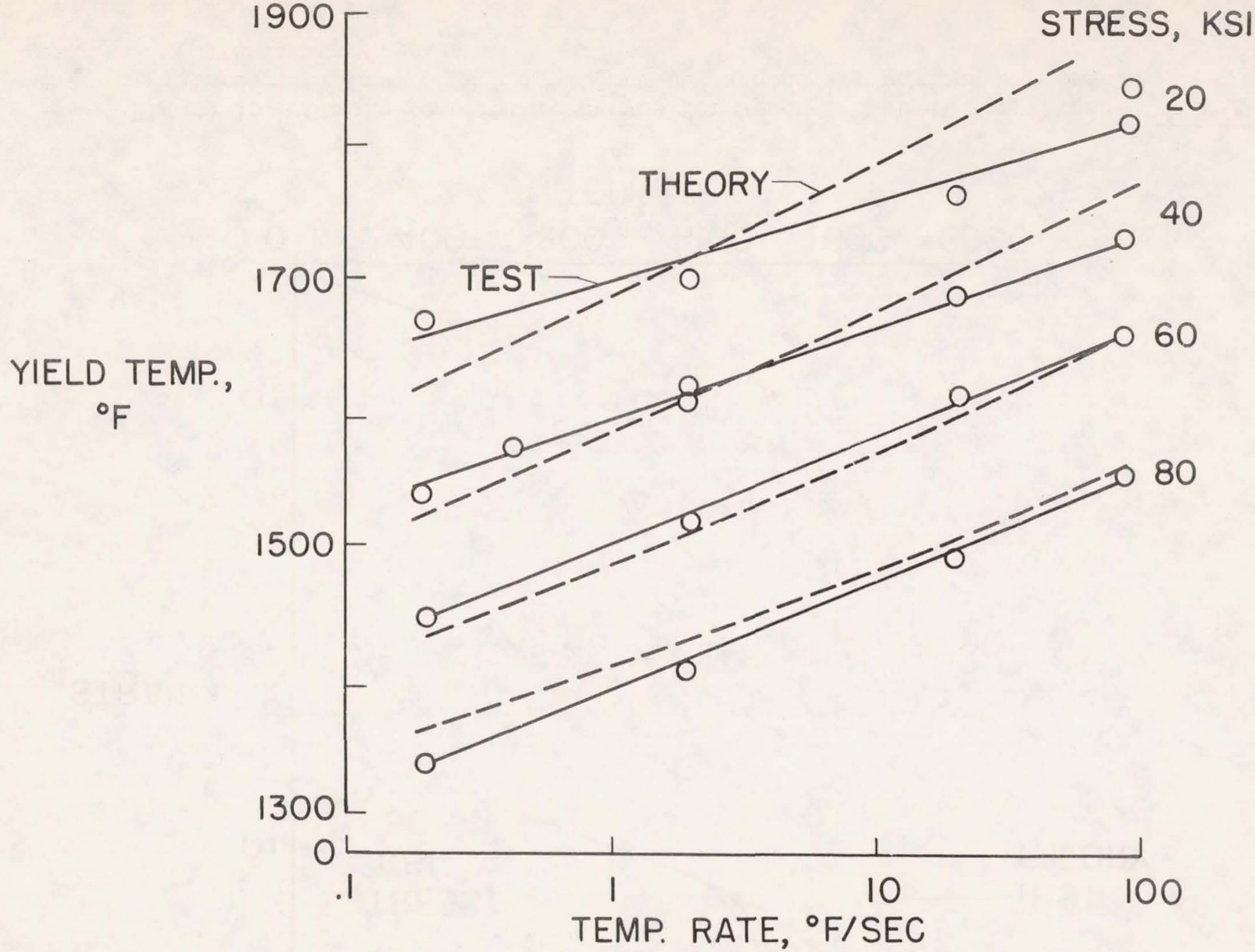

Figure 14.- Yield temperatures for Inconel X sheet for temperature rates from 0.2° F to 100° F per second. Yield temperatures are for 0.2-percent plastic strain. (Data from ref. 5.)

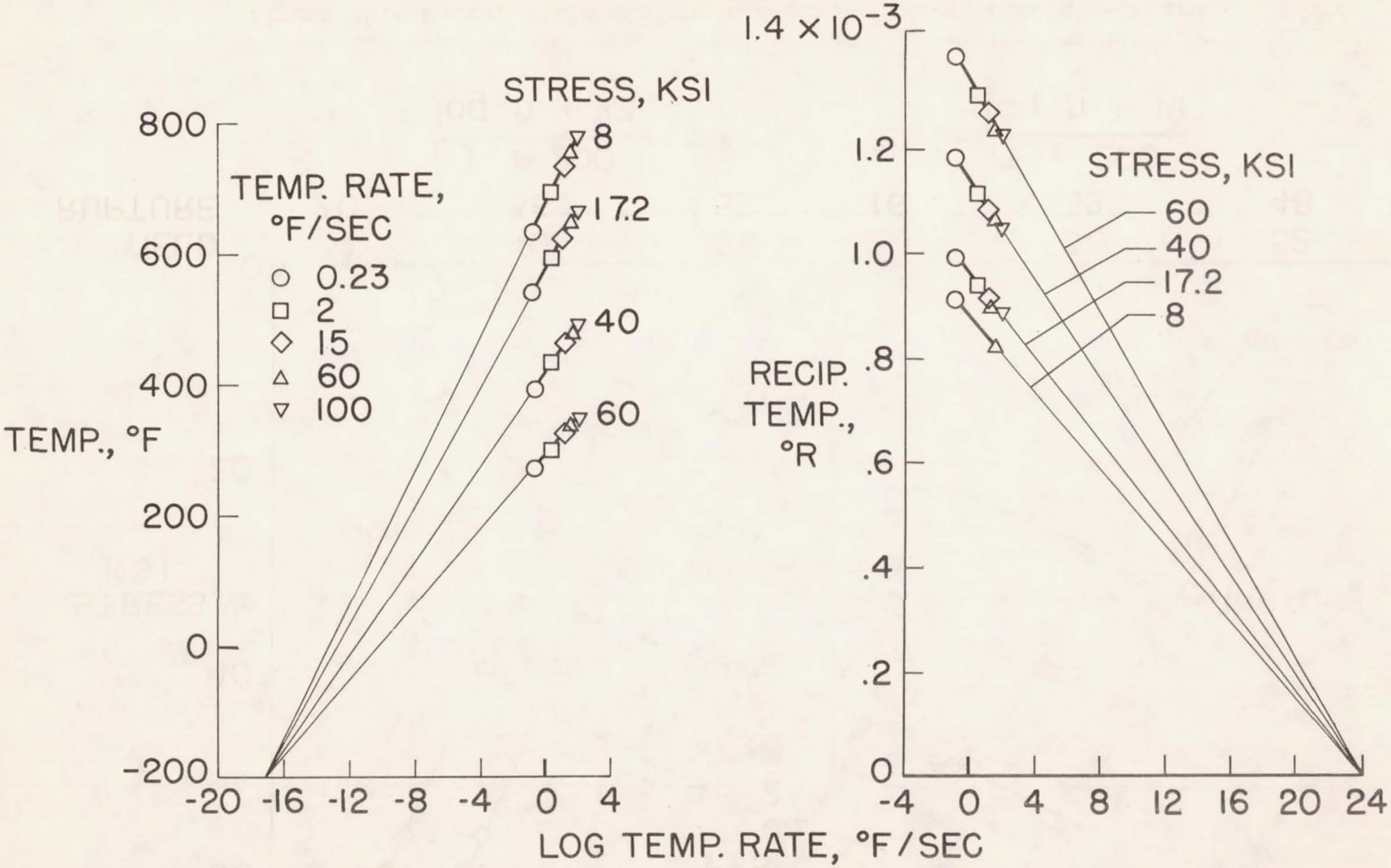

Figure 15.- Variation of yield temperature and reciprocal yield temperature with the temperature rate for 7075-T6 aluminum-alloy sheet. (Data from ref. 1.)

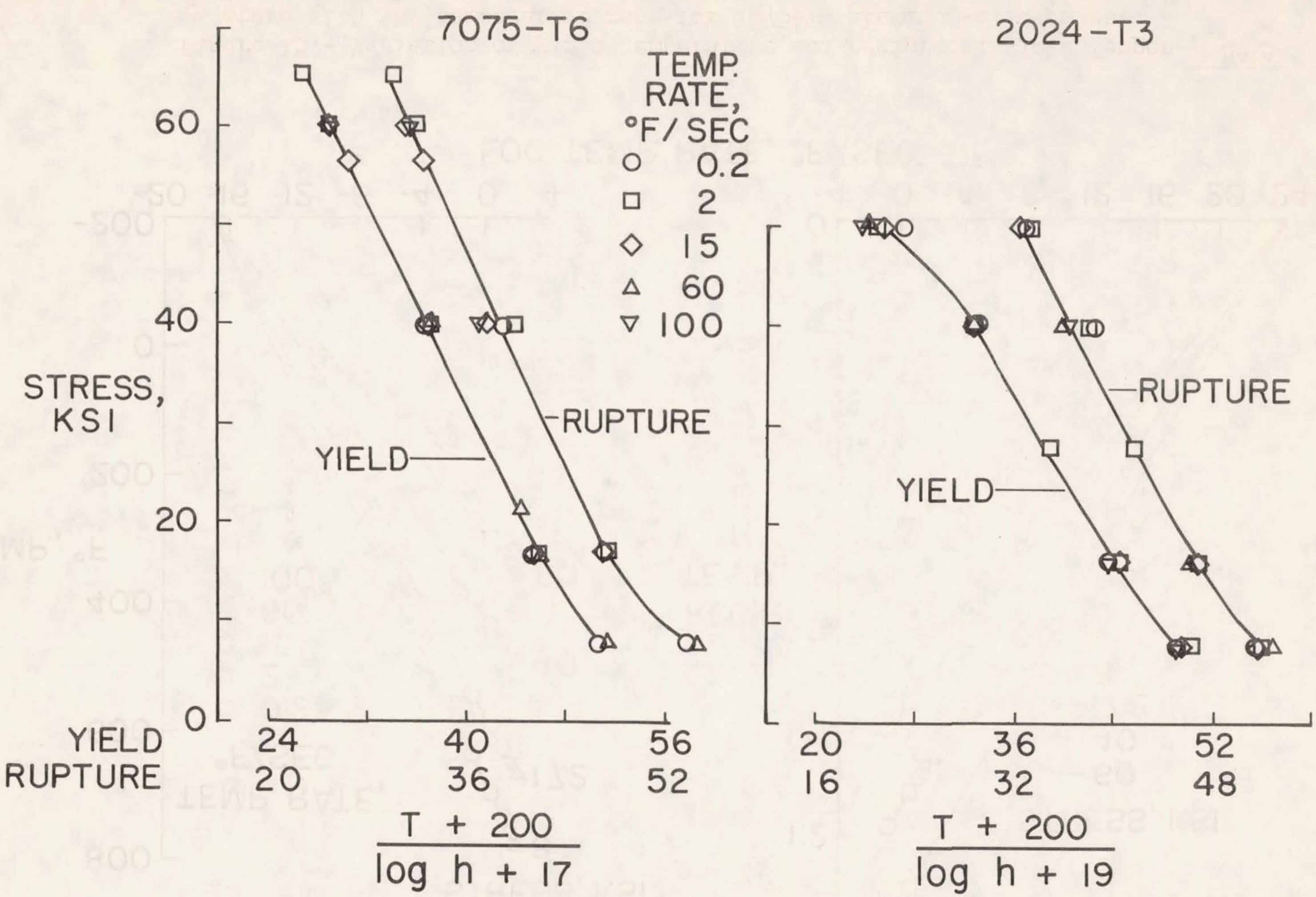

Figure 16.- Master yield and rupture stress curves for 7075-T6 and 2024-T3 aluminum alloys. (T is in °F and h is in °F per second; data from ref. 1.)