TR 58-440
Part II

WADC TECHNICAL REPORT 58-440
PART II
ASTIA DOCUMENT NO. 213834
ADO

TENSILE PROPERTIES OF AIRCRAFT-STRUCTURAL METALS AT VARIOUS RATES OF LOADING AFTER RAPID HEATING

J. ROBERT KATTUS
SOUTHERN RESEARCH INSTITUTE

20081006 194

MAY 1959

WRIGHT AIR DEVELOPMENT CENTER

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

- - - - -

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, (ASTIA), Arlington Hall Station, Arlington 12, Virginia.

- - - - -

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C., for sale to the general public.

- - - - -

Copies of WADC Technical Reports and Technical Notes should not be returned to the Wright Air Development Center unless return is required by security considerations, contractual obligations, or notice on a specific document.

WADC TECHNICAL REPORT 58-440
PART II
ASTIA DOCUMENT NO. 213834

TENSILE PROPERTIES OF AIRCRAFT-STRUCTURAL METALS AT VARIOUS RATES OF LOADING AFTER RAPID HEATING

J. ROBERT KATTUS
SOUTHERN RESEARCH INSTITUTE

AD- 213834

MAY 1959

MATERIALS LABORATORY
CONTRACT NO. AF 33(616)-3996
PROJECT NO. 7360

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

McGregor & Werner Midwest Corp., Dayton, O.
38-782 & 783-500-6-11-59

FOREWORD

This report was prepared by Southern Research Institute under USAF Contract No. AF 33(616)-3996. The contract was initiated under Project No. 7360, "Material Analysis and Evaluation Techniques," Task No. 73605, "Design and Evaluation Data for Structural Metals." It was administered under the Direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Mr. Richard Klinger acting as project engineer.

This report covers work conducted from January 1953 through June 1958.

In addition to the author, the following personnel at Southern Research Institute were major contributors to the work:

1. F. R. O'Brien, Assistant Director
2. J. B. Preston, Engineer
3. H. E. Dedman, Associate Metallurgist
4. D. E. Rice, Technician

ABSTRACT

In this report, a summary and an analysis are presented of the results of five years of investigation of the short-time tensile properties of structural metals. The specimens that were tested in this investigation were heated to various elevated test temperatures within 10 sec, were held at test temperature for periods of time from 10 sec to 30 minutes, and were then loaded to failure at strain rates from 0.00005 to 1.0 in. /in. /sec.

The strength properties of all of the test metals tended to decrease with increasing temperatures. Variations in holding time at test temperature had no significant effect upon the tensile properties of the structurally stable metals. The tensile properties of the unstable alloys changed with variations in holding time at certain temperatures as a result of time-temperature-dependent structural changes. In general, increasing strain rate produced increased strength in the test metals, the percentage increases in strength being relatively small in the temperature ranges of low-temperature behavior and quite large in the temperature ranges of high-temperature behavior. Under certain conditions, the effects of time-temperature-dependent and strain rate-temperature-dependent structural changes were superimposed upon, and sometimes obscured, the inherent effects of temperature and of strain rate.

An evaluation of time-temperature and rate-temperature parameters indicated that short-time tensile properties cannot be expressed with a high degree of accuracy as invariant functions of such parameters. Nevertheless, illustrations of short-time tensile properties as functions of the Larson-Miller parameter are quite useful for general comparisons of the strength levels of various materials over wide ranges of conditions. A duplex method that was developed for the presentation of tensile-strength data is useful primarily for the accurate condensation of tensile data over wide ranges of conditions into simple one-page plots. Such presentations, however, are not particularly useful for comparisons among different materials or for extrapolations of tensile data beyond the experimental conditions.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Richard R. Kennedy

RICHARD R. KENNEDY
Chief, Metals Branch
Materials Laboratory

TABLE TO CONTENTS

Section		Page
I.	INTRODUCTION	1
	1.1 History	1
	1.2 Purpose	1
	1.3 Scope	2
II.	COMPARATIVE PROPERTIES	8
	2.1 Contents	8
	2.2 Strength	9
	2.3 Elongation	21
	2.4 Modulus of Elasticity	23
III.	GENERALIZATION OF DATA	24
	3.1 Purpose	24
	3.2 Parameters	26
	3.3 Application of Parameters to Tensile Data	29
	3.4 Duplex Generalizations	36
IV.	CONCLUSIONS	41
	BIBLIOGRAPHY	44

LIST OF ILLUSTRATIONS

Figure No.		Page
1	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of thirteen metals tensile tested at a strain rate of 0.00005 in./in./sec	47
2	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of twelve metals tensile tested at a strain rate of 0.00005 in./in./sec	48
3	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of fifteen metals tensile tested at a strain rate of 1.0 in./in./sec	49
4	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of ten metals tensile tested at a strain rate of 1.0 in./in./sec	50
5	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of twelve metals tensile tested at a strain rate of 0.00005 in./in./sec	51
6	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of thirteen metals tensile tested at a strain rate of 0.00005 in./in./sec	52
7	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of fifteen metals tensile tested at a strain rate of 1.0 in./in./sec	53
8	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of ten metals tensile tested at a strain rate of 1.0 in./in./sec	54

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
9	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of thirteen metals tensile tested at a strain rate of 0.00005 in. /in. /sec	55
10	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of twelve metals tensile tested at a strain rate of 0.00005 in. /in. /sec	56
11	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of thirteen metals tensile tested at a strain rate of 1.0 in. /in. /sec	57
12	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of twelve metals tensile tested at a strain rate of 1.0 in. /in. /sec	58
13	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of thirteen metals tensile tested at a strain rate of 0.00005 in. /in. /sec	59
14	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of twelve metals tensile tested at a strain rate of 0.00005 in. /in. /sec	60
15	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of twelve metals tensile tested at a strain rate of 1.0 in. /in. /sec	61
16	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of thirteen metals tensile tested at a strain rate of 1.0 in. /in. /sec	62

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
17	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec	63
18	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec	64
19	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec	65
20	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec.....	66
21	Effect of temperature, after 10-sec heating time and 1800-sec holding time on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec	67
22	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec	68
23	Schematic representation of the effects of a wide range of strain rates on one alloy in which strength is sensitive and another alloy in which strength is not sensitive to changes in strain rate	69
24	Effect of temperature, at the 1.0 in./in./sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	70

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
25	Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	71
26	Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	72
27	Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	73
28	Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	74
29	Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature	75
30	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy illustrating that a time-temperature-dependent structural change—precipitation hardening—at 450° F improves strength more at the slow strain rate than at the rapid strain rate	76
31	Effects of temperature, after 10-sec heating time and 30-min holding time, on the ultimate strength and 0.2%-offset yield strength of carbon steel and of low-alloy steel at two strain rates	77
32	Effect of temperature, after 10-sec heating time and 30-min holding time, on the ultimate strength and 0.2%-offset yield strength of three test alloys	78

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
33	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of fifteen metals tensile tested at a strain rate of 0.00005 in. /in. /sec	79
34	Effect of temperature, after 10-sec heating time and 1800-sec holding time on the percent total elongation of ten metals tensile tested at a strain rate of 0.00005 in. /in. /sec	80
35	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of fifteen metals tensile tested at a strain rate of 1.0 in. /in. /sec	81
36	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of ten metals tensile tested at a strain rate of 1.0 in. / in. /sec	82
37	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of fourteen metals tensile tested at a strain rate of 0.00005 in. /in. /sec	83
38	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of eleven metals tensile tested at a strain rate of 0.00005 in. /in. /sec	84
39	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of fourteen metals tensile tested at a strain rate of 1.0 in. /in. /sec	85
40	Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of eleven metals tensile tested at a strain rate of 1.0 in. /in. /sec	86

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
41	Tensile-test variables for annealed A 110-AT titanium alloy sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn, and Linear parameters	87
42	Tensile-test variables for full-hard Type 301 stainless steel sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn, and Linear parameters	88
43	Tensile-test variables for alclad 2024-T3 aluminum alloy sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn, and Linear parameters	89
44	Relationship between strain-rate/temperature parameter and ultimate tensile strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	90
45	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	91
46	Relationship between strain-rate/temperature parameter and ultimate tensile strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	92

Figure No.		Page
47	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	93
48	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of, annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec	94
49	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated fromtwo parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec	95
50	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec	96
51	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec	97

Figure No.		Page
52	Relationship between strain-rate/temperature parameter and ultimate tensile strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperatures. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	98
53	Relationship between strain-rate/temperature parameter and ultimate tensile strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	99
54	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	100
55	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperatures. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	101
56	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in./in./sec	102

Figure No.		Page
57	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. / sec	103
58	Relationship between strain-rate/temperature parameter and ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	104
59	Relationship between strain-rate/temperature parameter and ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec.....	105
60	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	106
61	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	107
62	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 alloy aluminum sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.....	108

LIST OF ILLUSTRATIONS (Cont'd)

Figure No.		Page
63	Effect of strain rate, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain in in. /in. /sec	109
64	Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rate (r) from 0.00005 to 1.0 in. /in. /sec	110
65	Relationship between strain-rate/temperature parameter and ultimate tensile strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	111
66	Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800-sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	112
67	Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	113
68	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in. /in. /sec	114

Figure No.		Page
69	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	115
70	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of five metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	116
71	Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of six metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec	117
72	Schematic representation of the linear variation of strength with the log of the strain rate at various constant temperatures in an alloy	118
73	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constant K_1 and K_2 for the determination of the 0.2%-offset yield strength and the ultimate tensile strength of annealed A 110-AT titanium alloy sheet by the formula, Strength= $K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	119
74	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, UTS = $K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	120

Figure No.		Page
75	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	121
76	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $UTS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	122
77	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	123
78	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determinations of the 0.2%-offset yield strength and ultimate tensile strength of full-hard 301 stainless steel sheet by the formula, Strength $= K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	124
79	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	125

Figure No.		Page
80	Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec.	126
81	Effect of temperature, after 10-sec heating time and various holding times on constants K_1 and K_2 for the determination of the ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet by the formula, $UTS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	127
82	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	128
83	Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	129
84	Effect of strain rate, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec	130

Figure No.		Page
85	Effect of holding time, after 10-sec heating time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures and at a strain rate of 1.0 in./in./sec. Both experimentally determined curves and curves calculated from the formula, YS = $K_1 + K_2$ (log r + 4.3) are shown. K_1 and K_2 are temperature- and holding-time-dependent constants and r is the strain rate in in./in./sec	131
86	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of alclad 2014-T6 aluminum alloy sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	132
87	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of alclad 2014-T6 aluminum alloy sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	133
88	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of alclad 7075-T6 aluminum alloy sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	134
89	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of alclad 7075-T6 aluminum alloy sheet by the formula YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	135

Figure No.		Page
90	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of hard-rolled AZ-31 magnesium alloy sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	136
91	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of hard-rolled AZ-31 magnesium alloy sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	137
92	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constant K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of annealed A 70 titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	138
93	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed C 110-M titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	139
94	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of annealed 321 stainless steel sheet by the formula, Strength=$K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	140

Figure No.		Page
95	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed Stellite-25 sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	141
96	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of heat-treated Inconel X alloy sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	142
97	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of 301 half-hard stainless steel sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	143
98	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed 17-7 PH stainless steel sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	144
99	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of 17-7 PH stainless steel sheet (TH 1050 condition) by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	145

Figure No.		Page
100	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of normalized AISI 4130 steel sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	146
101	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of heat-treated AISI 4130 steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	147
102	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of hot-rolled SAE 1020 steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	148
103	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed 140 A titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	149
104	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of Type ZH 62-T5 magnesium casting alloy by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	150

Figure No.		Page
105	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of Type 356-T6 aluminum casting alloy by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	151
106	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of Type 356-T6 aluminum casting alloy by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	152
107	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated Chro-Mow die steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	153
108	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated Chro-Mow die steel sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	154
109	Effect of temperature, after 10-sec heating time and various holding times on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated Thermold-J die steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	155
110	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated Thermold-J die steel sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	156

Figure No.		Page
111	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated Peerless-56 die steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	157
112	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated Peerless-56 die steel sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	158
113	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of heat-treated AM-350 stainless steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	159
114	Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of heat-treated AM-350 stainless steel sheet by the formula, YS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	160
115	Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of heat-treated 6Al-4V titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec	161

LIST OF TABLES

Table No.		Page
I	Test Alloys	3
II	Chemical Composition of Test Alloys	6
III	Temperatures at Which Sharp Increases in Strain-Rate Sensitivity Started in Various Alloys	12

TENSILE PROPERTIES OF AIRCRAFT-STRUCTURAL METALS AT VARIOUS RATES OF LOADING AFTER RAPID HEATING[1]

SECTION I. INTRODUCTION

1. 1 History

During a time period of five years beginning in 1953 and ending in 1958, Southern Research Institute carried out a series of investigations of the tensile properties of structural metals under conditions of rapid heating, short times at temperature, and moderate to rapid rates of loading. The purpose of the work was to provide design data on the mechanical properties of metals under short-time conditions similar to those to which certain structural components in missiles and in high-speed aircraft are subjected in service.

As the work progressed during the five-year period, the detailed results were presented in a series of yearly summary reports identified as WADC Technical Reports 55-199 Parts I, II, and III and 58-440 Part I. These reports also included discussions of the accuracy of the data and discussions of the effects on tensile properties of the test variables—temperature, time at temperature, and strain rate. Complete descriptions were given of the testing equipment that was specially designed and developed for the work.

1. 2 Purpose

Since each previous report covered only one segment of the work, the purpose of this report is to present an analysis of the combined results from all of the work. It is felt that such an analysis will lead to a better perception of the significance of the work and to more generalized conclusions than could be obtained in the previous segments.

Two approaches to the analysis of the short-time tensile data are presented in this report:

---

1. Manuscript copy released by author February 1959, for publication as a WADC Technical Report

1. Simple comparisons of the effects of temperature, of strain rate, and of time at temperature on the tensile properties of all of the alloys that were tested.

2. An exploration of methods for generalizing and correlating the effects on short-time tensile data of temperature, strain rate, and time at temperature in simple concise presentations.

This second approach was suggested by a number of reviewers of the previous reports (24, 25)[1]. Although these reviewers confirmed the need for short-time data in the design of aircraft and missiles, they suggested that the data should be presented in a more condensed form than the numerous plots of properties as functions of the different test variables that were shown in previous reports.

1.3 Scope

The materials that are included in this analysis, all of which have been previously tested, are identified in Table I. Also shown in Table I are abbreviated designations that will be used to identify the alloys in subsequent illustrations. The chemical analyses are given in Table II, whereas details concerning the histories of these test materials are included in the previous reports pertaining to this work. As shown in Table I, twenty-two different alloys were included in the work. The Type 301 stainless steel was tested in both the half-hard and the full-hard conditions; the AISI 4130 steel and the 17-7 PH stainless steel were each tested in two different heat-treated conditions. In all, therefore, it may be considered that twenty-five different materials were investigated.

The test conditions for all of the test alloys included a heating time of 10 sec or less to each elevated test temperature. At the various constant test temperatures, specimens of each test material were held for different time intervals of 10 sec, 100 sec, and 1800 sec, after which they were tensile loaded to failure at various strain rates of 0.00005, 0.01, and 1.0 in./in./sec. Tests were not run in conjunction with the intermediate holding time of 100 sec or with the intermediate strain rate of 0.01 in./in./sec when tests at the extreme conditions showed very little effects of these variables on the tensile properties. In general, the ranges of test temperatures were from room temperature to 600° F for aluminum and magnesium alloys, to 1000° F for titanium alloys, and to 1200° F for steel alloys, nickel alloys, and cobalt alloys. For the five of the

---

1. The numbers in parentheses refer to the bibliography.

Table I

Test Alloys

Alloy	Abbreviated Designation[1]	Form[2]	Condition
Alclad 2024 aluminum alloy	2024-T3 Al	0.062-in. sheet	T3-quenched only
Alclad 7075 aluminum alloy	7075-T6 Al	0.064-in. sheet	T6-quenched and tempered
Alclad 2014 aluminum alloy	2014-T6 Al	0.064-in. sheet	T6-quenched and tempered
RC-A70 titanium alloy	A70 Ti	0.040-in. sheet	annealed
RC-C110M titanium alloy	C-110M Ti	0.040-in. sheet	annealed
AZ-31 magnesium alloy	AZ-31 Mg	0.064-in. sheet	hard-rolled
Type 321 stainless steel	321 SS	0.040-in. sheet	annealed
Stellite-25 cobalt alloy	Stellite-25	0.040-in. sheet	annealed
Inconel X nickel alloy	Inconel X	0.040-in. sheet	aged 20 hours at 1300° F
Type 301 stainless steel	301 1/2 H	0.040-in. sheet	half-hard
Type 301 stainless steel	301 F. H.	0.040-in. sheet	full-hard
17-7 PH stainless steel	17-7 PH (An.)	0.040-in. sheet	annealed
17-7 PH stainless steel	17-7 PH (TH 1050)	0.040-in. sheet	TH 1050

Table I (continued)

Test Alloys

Alloy	Abbreviated Designation[1]	Form[2]	Condition
AISI 4130 steel	4130 (Nor.)	0.040-in. sheet	normalized
AISI 4130 steel	4130 (Q and T)	0.040-in. sheet	Oil quenched from 1570° F, tempered at 1000° F
SAE 1020 steel	1020	0.064-in. sheet	hot-rolled
A 110-AT titanium alloy	A 110-AT Ti	0.040-in. sheet	annealed
Ti-140 A titanium alloy	140 A Ti	0.040-in. sheet	annealed
ZH-62 magnesium alloy	ZH-62-T5 Mg	cast	T5-artificially aged
356 aluminum alloy	356-T6 Al	cast	T6-quenched and tempered
Chro-Mow die steel	Chro-Mow	0.040-in. sheet	oil quenched from 1850° F, double tempered at 950° F
Thermold-J die steel	Thermold-J	0.050-in. sheet	oil quenched from 1850° F, double tempered at 950° F
Peerless-56 die steel	Peerless-56	0.050-in. sheet	oil quenched from 1950° F, double tempered at 950° F

Table I (continued)

Test Alloys

Alloy	Abbreviated Designation[1]	Form[2]	Condition
AM-350	AM-350	0.040-in. sheet	water quenched from 1725° F, -100° F 3 hr, tempered at 850° F 3 hr
6Al-4V titanium alloy	6Al-4V Ti	0.040-in. sheet	Water quenched from 1750° F, tempered at 1000° F

1. Designations used in subsequent illustrations.
2. Sheet-metal test specimens oriented in the direction of lower room-temperature tensile strength as follows:
   Longitudinal—AZ-31 Mg, C-110 M Ti, A 70 Ti, 321 SS, Inconel X, 301 F. H., 4130 (Nor.), 4130 (Q and T), 140 A Ti, A 110 AT Ti, Chro-Mow, Thermold-J, Peerless-56, AM-350.
   Transverse—2014-T6 Al, 2024-T3 Al, 7075-T6 Al, Stellite-25, 301 1/2 H, 17-7 PH (An.), 17-7 PH (TH 1050), 1020, 6Al-4V Ti.

Table II

Chemical Composition of Test Alloys

Alloy	Major Constituents
2024-T3 Al	1.5% Mg, 4.5% Cu, 0.6% Mn, 92% Al
7075-T6 Al	2.5% Mg, 0.3% Cr, 1.6% Cu, 5.6% Zn, 89% Al
2014-T6 Al	0.6% Mg, 0.9% Si, 4.5% Cu, 0.8% Mn, 92% Al
A 70 Ti	< 0.1% C, 0.04% N, 0.168% O_2, 106 ppm H_2, 99 + % Ti
C-110 M Ti	< 0.1% C, 0.02% N, 8.5% Mn, 0.117% O_2, 180 ppm H_2, 91% Ti
AZ-31 Mg	3% Al, 0.2% Mn, 1.0% Zn, 95.5% Mg
321 SS	0.07% C, 1.6% Mn, 9.7% Ni, 17.5% Cr, 0.6% Ti, 70% Fe
Stellite-25	1.3% Mn, 2.7% Fe, 10.2% Ni, 19.9% Cr, 14.8% W, 50% Co
Inconel X	0.7% Mn, 6.5% Fe, 0.4% Si, 16% Cr, 0.9% Al, 2.6% Ti, 0.8% Ta + Cb, 72% Ni
301 (1/2 H and F. H.)	0.1% C, 17.8% Cr, 7.3% Ni, 0.2% Mo, 74% Fe
17-7 PH	0.06% C, 17.3% Cr, 7.2% Ni, 1.14% Al, 73% Fe
4130	0.33% C, 0.48% Mn, 0.84% Cr, 0.16% Mo, 98% Fe
1020	0.22% C, 0.48% Mn, 99% Fe
A 110-AT Ti	0.1% C, 0.02% N, 5.7% Al, 2.7% Sn, 91% Ti
140 A Ti	0.024% C, 0.024% N, 1.8% Fe, 1.8% Cr, 1.5% Mo, 0.009% H_2, 93.7% Ti
ZH 62-T5 Mg	6.2% Zn, 0.9% Zr, 2.1% Th, 90.5% Mg
356-T6 Al	6.9% Si, 0.3% Mg, 92.5% Al

Table II (continued)

Chemical Composition of Test Alloys

Alloy	Major Constituents
Chro-Mow	0.3% C, 0.4% Mn, 1.0% Si, 5% Cr, 1.4% Mo, 1.3% W, 90% Fe
Thermold-J	0.5% C, 0.4% Mn, 1.1% Si, 5% Cr, 1.3% Mo, 1.5% Ni, 1% V, 89% Fe
Peerless-56	0.4% C, 0.6% Mn, 1.0% Si, 3.2% Cr, 2.5% Mo, 0.26% V, 92% Fe
AM-350	0.07% C, 0.7% Mn, 16.8% Cr, 4.3% Ni, 2.6% Mo, 0.07% N_2, 75% Fe
6Al-4V	0.02% C, 4.1% V, 0.014% N_2, 6.1% Al, 0.12% Fe, 89% Ti

test alloys, however, as originally reported in WADC Technical Report 55-199 Part III, the test-temperature range was extended to higher temperatures as follows: to 2250° F for Stellite-25, to 2250° F for Inconel X, to 2250° F for full-hard 301 stainless steel, to 2770° F for A 110-AT titanium alloy, and to 900° F for alclad 2024-T3 aluminum alloy. At each test temperature, triplicate tests were run at the extreme conditions of strain rate and holding time, and duplicate tests were run at the intermediate conditions.

Full stress-strain curves were recorded for each material at all test conditions. All test specimens contained a 2-in. gage length. In the design of the test equipment and in the performance of the tests, major emphasis was placed on the accurate determination of the 0.2%-offset yield strength and ultimate strength, which were determined to an accuracy of $\pm$ 2.5%. The modulus of elasticity, percent elongation, proportional limit, and full stress-strain curves were determined with somewhat less accuracy but, nevertheless, with sufficient accuracy to establish trends.

SECTION II. COMPARATIVE PROPERTIES

2.1 Contents

In this section of the report, illustrations are given of the tensile properties of the 25 test materials at different temperatures, times at temperature, and strain rates. Rather than to present an exhaustive review of all of the tensile properties that were determined, the illustrations are intended to afford simple comparisons of the properties of the different alloys and to show the inherent effects of temperature, holding time at temperature, and strain rate on the properties of the alloys.

For comparative purposes, it would have been desirable to have individual properties of all of the test materials included on single plots, but because of the large number of test materials, such plots were excessively muddled and confusing. For clarity, therefore, it was necessary to divide the comparative plots of the different properties into four or five separate sections, each section containing curves for a few test materials in a lucid arrangement. Unless otherwise noted, the ordinate and abscissa scales for all sections of each type of plot are constant so that visual comparisons can quickly be made between different sections.

2.2 Strength

Fig. 1, 2, 3, and 4 show the effects of temperature upon the ultimate tensile strength of the test alloys after a holding time at test temperature of only 10 sec, Fig. 1 and 2 pertaining to a strain rate of 0.00005 in./in./sec and Fig. 3 and 4 to a strain rate of 1.0 in./in./sec. Similar information is presented in Fig. 5, 6, 7, and 8 for the 0.2%-offset yield strength of the same alloys. For most of the test materials, the strength levels at the fast strain rate are higher than those at the slow strain rate.

The hot-work die steels—Thermold-J, Peerless-56, and Chro-Mow—are the strongest of all of the test alloys at temperatures up to 1200° F. At the slow strain rate, the curves indicate that the strengths of the Inconel X and the Stellite-25 exceed those of the die steels at temperatures above about 1200° F; at the fast strain rate; however, the superior strengths of the die steels would, apparently, be maintained to much higher temperatures. The high strength stainless steels—full-hard Type 301 and heat-treated Types 17-7 PH and AM-350—are quite similar in strength properties, slight advantages in strength being exhibited by each at different test conditions. The stainlesses with lower room-temperature strengths—half-hard Type 301, annealed Type 321—approached or exceeded the strength levels of the high-strength stainlesses at temperatures of 1000° F and above.

The 6Al-4V titanium alloy, which is lower in strength than the high-strength stainlesses at temperatures up to 1000° F, is the strongest of all titanium alloys that were tested. In general, the aluminum and magnesium alloys are lower in strength than the other test alloys. The wrought alclad aluminum alloys, however,—2024-T3, 2014-T6, and 7075-T6—are appreciably stronger than the wrought magnesium alloy and the cast aluminum and magnesium alloys—AZ-31, 356-T6, and ZH-62-T5. Over most of the test-temperature range, the quenched and tempered 4340 steel is stronger than the same material in the normalized condition; but as the temperature approaches 1200° F, the strength of the heat-treated material decreases rapidly to the level of the normalized material.

Additional comparisons of the relative strengths of the various alloys as functions of temperature are shown in Fig. 9 through 16. In these plots, however, the strength properties are expressed as strength-weight ratios. These ratios are shown for ultimate strengths at a strain rate of 0.00005 in./in./sec in Fig. 9 and 10 and at a strain rate of 1.0 in./in./sec in Fig. 11 and 12. The yield strength-density ratios are given in Fig. 13 and 14 for the 0.00005 in./in./sec strain rate and in Fig. 15 and 16 for the 1.0 in./in./sec strain rate.

On the basis of strength-weight ratios, the die steels—Thermold-J, Peerless-56, and Chro-Mow—remain among the strongest of the test alloys, but they are approached and under some conditions exceeded by the strength-weight ratio of the 6Al-4V titanium alloy. Again, at the slow strain rate and at temperatures above 1200° F, the curves indicate that the Inconel X and to some extent the Stellite-25 are superior in strength-weight ratio to the die steels and to 6Al-4V titanium alloy; this superiority of the Inconel X and Stellite-25 at high temperatures, apparently, does not apply at the fast strain rate.

On the basis of strength-weight ratio, the titanium alloys—A 110-AT, 140 A, and C-110M—compare favorably with the high-strength stainless steels; under some conditions—primarily at low temperatures and at high strain rates—the titanium alloys are superior. At room temperature, the strength-weight ratios of the wrought aluminum alloys and wrought magnesium alloy—2024-T3, 2014-T6, and AZ-31—are roughly equivalent to those of the high-strength stainlesses and of most of the titanium alloys and exceed those of the carbon steels and anhealed stainlesses. As temperatures are increased to 600 or 800° F, however, the strength-weight ratios of the aluminum and magnesium alloys decrease rapidly to levels lower than those of the other materials.

Although Fig. 1 through 16 show that, under most conditions, the strength properties of the various alloys increase with increasing strain rate, more vivid illustrations of the effects of strain rate on strength properties are presented in Fig. 17, 18, 19, 20, 21, and 22. Fig. 17, 18, and 19 show, as functions of test temperature, the relative changes in ultimate tensile strength of the test metals as a result of an increase in strain rate from 0.00005 to 1.0 in./in./sec; similar illustrations for 0.2%-offset yield strength are given in Fig. 20, 21, and 22. The change in strength at each temperature is expressed as a percentage of the strength at the lower strain rate. The scales for Fig. 19 and 22 were modified somewhat to include the larger ranges of temperature effects and strain-rate effects required for some alloys.

These illustrations show that, in all of the test materials, increasing strain rate has relatively minor effects on strength properties at room temperature, approximately 35% being the maximum increase in strength associated with an increase in strain rate from 0.00005 to 1.0 in./in./sec. At higher temperatures, the relative effects of strain rate become much greater, the strength properties of most materials increasing markedly with increasing strain rate. In most of the alloys, the marked increases in the effects of strain rate occur rather abruptly at a certain temperature. Below this temperature, the effects of strain rate on strength are relatively small and constant, whereas at higher temperatures they increase at a rapid rate with increasing temperature.

The critical temperatures at which the sharp increases in strain-rate sensitivity started, which for this report are chosen as the temperatures at which the curves in Fig. 17, 18, and 19 crossed the 50% level, are shown in the order of increasing temperature in Table III. These temperatures, it is believed, correspond roughly to the temperatures at which most of the alloys undergo transitions from low-temperature to high-temperature behavior. In addition to increased strain-rate sensitivity, high-temperature behavior is characterized by a breakdown of low-temperature strengthening mechanisms as a result of an increased rate of self diffusion. Poor resistance to creep and an inability of metals to work harden are invariably associated with high-temperature behavior; therefore, the temperature of transition from low-temperature to high-temperature behavior is normally the maximum temperature for long-time load-carrying applications of structural metals.

Tensile strength properties at slow rates of strain deteriorate considerably as a result of the transition to high-temperature behavior. At high rates of strain under high-temperature conditions, however, much higher strength properties are maintained because, it is believed, the plastic flow occurs more rapidly than some of the diffusion mechanisms that contribute to low strength. Since diffusion is a much less important factor in low-temperature strength, the effects of strain rate on strength are much less pronounced at low temperatures.

The only exception to the correlation between strain-rate sensitivity and the transition from low-temperature to high-temperature behavior occurred in the unalloyed titanium, A70. Although this material has relatively low strength for titanium alloys, its transition to high-temperature behavior would be expected to occur at a higher temperature than 130° F, which is its temperature for increased strain-rate sensitivity. For four of the alloys—6Al-4V titanium and Types 321, half-hard 301, annealed 17-7 PH stainlesses—the test-temperature ranges were not extended high enough to obtain increases in strain-rate sensitivity. For the remaining alloys, the temperatures for increased strain-rate sensitivity in Table III correspond roughly to the maximum temperatures for which the various alloys are normally used for long-time load-carrying applications. As shown in Table III, these temperatures are highest in the heat-resisting alloys—Stellite-25, Inconel X, and the austenitic stainless steels—; they are lowest in the magnesium alloys and aluminum alloys, which materials are not normally classed as "heat resisting." Of the titanium alloys listed in Table III, A 110-AT and 6Al-4V are known to retain useful creep properties to higher temperatures than the A70, C-110M, and 140 A alloys. Correspondingly, decided increases in sensitivity to changes in strain rate were found in the A70, C-110M, and 140 A alloys at considerably lower temperatures than in the A 110-AT and the 6Al-4V alloys. A similar correlation is shown in Table III for the steel alloys. The austenitic stainlesses—Types 301, 321, and annealed 17-7 PH—, which normally retain useful creep properties to higher maximum

Table III

Temperatures at Which Sharp Increases in Strain-Rate Sensitivity Started in Various Alloys

Alloy	Condition	Temp., ° F
RC-A70 titanium	annealed	130
AZ-31 magnesium	hard-rolled	225
ZH-62 magnesium	T5	260
2024 aluminum (alclad)	T3	475
7075 aluminum (alclad)	T6	515
356 aluminum	T6	565
2014 aluminum (alclad)	T6	600
C-110M titanium	annealed	680
140A titanium	annealed	820
1020 steel	hot rolled	825
4130 steel	quench and tempered	930
4130 steel	normalized	960
Peerless-56 tool steel	quenched and tempered	960
Thermold-J tool steel	quenched and tempered	970
Chro-Mow tool steel	quenched and tempered	980
A 110-AT titanium	annealed	1100
17-7 PH stainless	TH 1050	1100
AM-350 stainless	heat treated	1150
301 stainless	full-hard	1280

Table III (continued)

Temperatures at Which Sharp Increases in Strain Rate Sensitivity Started in Various Alloys

Alloy	Condition	Temp., ° F
Inconel X	aged at 1300° F	1450
Stellite-25	annealed	1530
6Al-4V Titanium	quenched and tempered	>1000
321 stainless	annealed	>1200
301 stainless	half-hard	>1200
17-7 PH stainless	annealed	>1200

temperatures than the ferritic and martensitic steels, become strain-rate sensitive at higher temperatures than the ferritic and martensitic materials—1020, 4130, 17-7 PH (TH 1050), heat-treated AM-350, and the die steels. It is interesting and in keeping with these correlations that two different crystallographic modifications of 17-7 PH stainless steel exhibit appreciably different sensitivities to changes in strain rate. Although the annealed, austenitic structure has poorer strength at lower temperatures, the heat-treated, martensitic structure becomes strain-rate sensitive at a lower temperature.

Good creep properties have generally been the main criteria for the selection of alloys for elevated-temperature applications since these applications often involve long exposures under load. As stated previously, the maximum temperatures at which alloys are serviceable for these applications are the temperatures of transition from low-temperature to high-temperature behavior. The results of tensile tests with rapid heating and rapid loading indicate that the same criteria for selection and the same temperature limitations do not necessarily apply to structural metals for aircraft and missiles when loads are applied rapidly and only for short periods of time. Under these conditions many metals, e. g. the heat-treated die steels, retain considerable load-carrying capacity in the usual temperature range of high-temperature behavior. In other words, under short-time, fast-strain-rate conditions, metals tend to retain low-temperature characteristics to higher temperatures than they do under long-time, slow-strain-rate conditions; therefore, the structural metals can safely be used to higher temperatures under rapid conditions of heating and loading than under long-time conditions. Furthermore, alloys that would be selected for high-temperature applications on the basis of good creep properties may not provide the best structural strength in missiles and aircraft at these temperatures when loads are applied rapidly and only for short periods of time. This point is illustrated schematically in Fig. 23, which shows the effects of strain rate on the strength of two alloys at constant temperature. The temperature is in the range of high-temperature behavior for one of the alloys, which, therefore, is highly strain-rate sensitive and has poor creep strength. The other alloy, however, exhibits low-temperature behavior and as a result is not highly strain-rate sensitive and has good creep strength. Under conditions of rapid tensile loading or impact loading, however, the strain-rate-sensitive alloy is stronger than the insensitive, creep-resistant alloys. The conclusion should not be drawn that strain-rate sensitive alloys are invariably superior to creep-resistant alloys when loads are applied very rapidly. The absolute level of strength is also important. In comparing the two types of alloys, in many instances the general level of the curve for the strain-rate sensitive alloy would be relatively lower than shown in Fig. 23. In these instances the strength of the sensitive alloy may be inferior to that of the insensitive alloy at all strain rates.

The effects of variations in holding time from 10 sec to 30 minutes at test temperature on the strength of the test metals are, in general, not as pronounced or consistent as the effects of strain rate. In most of the test metals, the effects of this variation in holding time are insignificant at all test temperatures; in the remaining test metals, the strength properties vary upward or downward with increasing holding time at certain temperatures.

These relative effects of holding time are illustrated in Fig. 24, 25, and 26, which show the percentage change in ultimate tensile strength in all of the test alloys resulting from an increase in holding time from 10 sec to 30 minutes at the various test temperatures. Fig. 27, 28, and 29 show similar effects for the 0.2%-offset yield strength. The strength properties upon which these illustrations are based were determined at the fast strain rate of 1.0 in./in./sec so that holding times are long relative to loading time. At the fast strain rate, the loading time to failure, which is less than one second, is negligible in comparison to holding time and, therefore, does not contribute any supplementary holding-time effects. At slow strain rates, however, loading time, which varies up to one-half hour, must be added to holding time in considering the effects of holding time.

Although no studies were made of the metallurgical structures of the test alloys, existing knowledge of the metallurgy of most of the alloys indicates that holding-time effects are significant only under conditions that promote time-temperature-dependent structural changes. As shown in Fig. 24 through 29, the following alloys, which are believed to be relatively stable under all of the conditions of high temperature and short-times employed in the test program, are affected negligibly or only to minor degrees by variations in holding time:

ZH 62-T5 magnesium

annealed 321 stainless steel

half-hard 301 stainless steel

normalized 4130 steel

quenched and tempered 4130 steel

6Al-4V titanium alloy

A70 titanium alloy

hot-rolled 1020 steel

C-110M titanium alloy

140 A titanium alloy

annealed 17-7 PH stainless steel

17-7 PH (TH 1050) stainless steel

Inconel X

Stellite-25

Most of the small variations in strength with variations in holding time in these alloys are believed to be a result of a combination of natural nonuniformities in the test materials and of experimental error. It is probable, however, that some of these small holding-time effects are caused by minor structural changes. For example, the 17-7 PH (TH 1050) and the half-hard Type 301 stainless steels tend to lose strength slightly with increasing time at 1200° F. It is possible that these losses of strength are a result of recovery in half-hard Type 301 and of overaging in the 17-7 PH (TH 1050), which previously had been precipitation hardened at 1050° F.

As shown in Fig. 24 through 29 much more pronounced effects of holding time were found at certain temperatures in the following alloys:

2014-T6 aluminum (alclad)

7075-T6 aluminum (alclad)

2024-T3 aluminum (alclad)

356-T6 aluminum

hard-rolled AZ-31 magnesium

A110-AT titanium alloy

full-hard 301 stainless steel

AM-350 stainless steel

Chro-Mow tool steel

Thermold-J tool steel

Peerless-56 tool steel

Almost invariably, the time-temperature conditions that promoted holding-time effects in these alloys would also be expected to promote structural changes. The precipitation-hardening 2024-T3 alclad aluminum alloy, for example, had been quenched only. At 300° F, its structure is relatively stable for short periods of time because precipitation is extremely slow; therefore, holding-time effects are negligible. Precipitation progresses at a moderate rate at 450° F and causes an increase in strength as holding time increases from 10 sec to 30 minutes. At 600° F and at 800° F, precipitation occurs much more rapidly so that overaging and associated decreases in strength occur as the holding time is increased from 10 sec to 30 minutes. At 900° F, precipitation occurs so rapidly that considerable overaging probably occurs during the first 10 seconds of exposure to temperature. The decrease in strength with further exposure up to 30 minutes, therefore, is not as severe as it is at 600° F and at 800° F. The 356 and alclad 7075 and 2014 aluminum alloys had all been heat treated to the T6 condition, which should have produced the optimum precipitate dispersion for high strength. With the exception of the 356-T6 alloy at 450° F, these alloys show little or no increase in strength with increasing holding time at elevated temperatures because no benefits from additional precipitation were possible. The decrease in strength in the 356-T6 and 2014-T6 at 600° F and in the 7075-T6 at 450° F and at 600° F are a result of overaging. It is interesting to note that the alclad 7075-T6 alloy overaged at a lower temperature than the other aluminum alloys. The small increase in strength in the 356-T6 alloy with increasing time at 450° F is believed to be a result of the failure of the structure to attain the optimum degree of precipitation during the T6 heat treatment. Additional dispersion hardening, therefore, was developed during the 30-minute exposure at 450° F.

In the hard-rolled AZ-31 magnesium alloy, the decrease in strength with increasing holding time at 500° F is probably a result of recrystallization.

Since the die steels—Chro-Mow, Thermold-J, and Peerless-56—had been tempered at 950° F, their structures were relatively stable at lower temperatures. At 1200° F, however, the degree of carbide precipitation and coagulation in the structure probably increased with increasing holding time resulting in a decrease in strength. Although the AM-350 and 17-7 PH (TH 1050) alloys are both precipitation-hardening stainless steels, overaging at 1200° F resulted in a greater decrease in strength in the AM-350 than in the 17-7 PH (TH 1050). This difference in the two alloys in response to variations in holding time at 1200° F is probably a result of greater stability in the 17-7 PH (TH 1050) alloy as a result of its higher tempering temperature.

At 2250° F, the full-hard Type 301 stainless steel exhibited unusual holding-time effects; the ultimate strength decreased whereas the yield strength increased with increasing holding time. At this temperature, the strength level of the Type 301 is very low so that the percentage changes shown in Fig. 26 and

29 represent only minor and probably insignificant differences in properties. The reason for the increase in strength of the A110-AT titanium alloy with increasing time at 2350° F is not clear; it is conceivable that absorbed atmospheric gases may have contributed to increased strength at that temperature. In absolute terms, this increase in strength in the A110-AT is very small and is probably insignificant.

In the discussion of the effects of holding time at various test temperatures on the strength of the test metals, it was mentioned that at slow strain rates an appreciable time elapses during loading, whereas loading time is negligible at a fast strain rate of 1.0 in./in./sec. In unstable metals, time-temperature-dependent structural changes that affect properties can occur during the loading time at slow strain rates as well as during the holding time; therefore, holding-time effects are accentuated at slow strain rates. With rapid heating and very short holding times, time-temperature-dependent structural changes may occur to an appreciable extent during slow loading but to a negligible extent during rapid load. The effects of the structural changes would, therefore, influence the properties at slow strain rates but not at rapid strain rates.

This point is illustrated in Fig. 30, which shows the effect of temperature on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy at two strain rates after rapid heating and only 10 sec at temperature. As mentioned previously, precipitation hardening occurs at a moderate rate in this alloy at 450° F. At the rapid strain rate, time at temperature is not sufficient for appreciable precipitation hardening, but at the slow strain rate the additional time at temperature permits appreciable hardening. As shown in Fig. 30, this precipitation hardening at 450° F outweighs the inherent strengthening effect of increased strain rate, so that the strength is higher at the slow strain rate than at the rapid strain rate. Conversely, of course, if the time-temperature-dependent structural change happens to be weakening—such as overaging—rather than strengthening, the inherent strengthening effect of increased strain rate is supplemented rather than counteracted. The alclad 2024-T3 aluminum alloy, for example, overages rapidly at temperatures of 600° F and above. At these temperatures, therefore, the structure is weakened during the loading time as well as during the holding time. As a result, the strength determined at the slow strain rate is representative of a weaker structure than that determined at the rapid strain rate. The effects of this difference in structure are added to the inherent effects of strain rate to produce the large differences in strength at temperatures above 600° F in Fig. 30.

In general, strengthening time-temperature-dependent structural changes, which occur under certain service or test conditions, tend to counteract the inherent strengthening effects of increased strain rate, whereas weakening structural changes accentuate the inherent strengthening effects of increased strain rate.

It is well known that the tensile strength of low-alloy steels and carbon steels tend to increase in the temperature range 400° F to 800° F. Such increases in strength are a result of a phenomenon called strain aging or blue brittleness. Strain aging is believed to be caused by the diffusion of carbon and nitrogen atoms to dislocations in the lattice structure as the metal is plastically strained. The carbon and nitrogen atoms in these positions have a strengthening effect because they interfere with the movement of dislocations. Since strain aging is dependent upon plastic strain as well as upon temperature and time, it is strain-rate dependent. At the slow strain rates ordinarily associated with tensile testing, strain aging is most pronounced at about 400° F in steels. As strain rate is increased, the testing time is not sufficient for carbon and nitrogen atoms to diffuse to dislocations at 400° F; consequently, the maximum effects of strain aging on tensile strength occur at higher temperatures, which are associated with higher rates of diffusion. Strain aging has a much greater effect upon ultimate strength than upon yield strength because ultimate strength normally occurs at much higher degrees of plastic strain.

The effects of strain aging on the strength properties of 1020 carbon steel and of 4130 low-alloy steel, both normalized and hardened, are illustrated in Fig. 31. As a result of strain aging at 400° F, these materials developed higher ultimate strength at the slow strain rate than at the fast strain rate. Also as a result of strain aging, the ultimate strengths at the rapid strain rate tended to rise slightly or to remain constant as the temperature was increased from 400° F to 800° F; whereas, at the slow strain rate, the ultimate strengths decreased sharply in the same temperature range. The effects of strain aging as shown in these illustrations are superimposed upon the effects of strain rate. At 400° F, the strengthening effect of strain aging at the slow strain rate exceeded the inherent strengthening effect of increased strain rate so that the ultimate strength decreased with increasing strain rate. Since at 800° F strain aging was effective only at the fast strain rate, the inherent strengthening effects of increased strain rate were augmented by strain aging.

Fig. 31 also shows that, for the reasons discussed above, the strain-aging effects on yield strength were much less pronounced than on ultimate strength. The absence of strong strain aging effects on yield strength are demonstrated by two facts:

1. The yield strength of each material increased with increasing strain rate at all test temperatures showing that the effects of strain aging were not sufficient to obscure the inherent effects of increasing strain rate.

2. The yield strength decreased continuously with increasing temperature showing that the effects of strain aging were not sufficient to obscure the inherent effects of increasing temperature.

Since plastic strain is a requisite for strain aging, the effects of strain aging are not developed by variations in holding time at test temperature under no load. The strain-aging effects illustrated in Fig. 31 were the same for both the 10-sec and the 30-min holding times.

In general, strain aging, which is a temperature- and strain-rate-dependent structural change in steel, tends to counteract the inherent strengthening effect of increased strain rate in the lower temperature range of strain aging and to augment the inherent strengthening effect of increased strain rate in the upper temperature range of strain aging.

Although strain aging has been most widely investigated in carbon steels and low-alloy steels, it is quite probable that analogous temperature- and strain-rate-dependent structural changes also occur in other materials. In a number of the test alloys, the test results showed abnormal behavior similar to that produced by strain aging in the steels. This abnormal behavior, which is illustrated for three test alloys in Fig. 32, consisted of certain limited temperature ranges within which the ultimate strength decreased while the yield strength increased with increasing strain rate. The behavior of the 17-7 PH (TH 1050) stainless steel in this regard was exactly the same as that of the 1020 and 4130 steels. Since this material has a martensitic structure similar to that of the quenched and tempered 4130, it is possible that a similar strain-aging phenomenon occurs. Strain aging is not normally associated with Stellite-25 and annealed 17-7 PH stainless, which is austenitic, but it is probable that the abnormal relationships between strain rate and ultimate strength in these alloys at certain temperatures are a result of similar structural changes that are dependent upon temperature and strain rate.

An analysis of the effects of temperature and of strain rate on the ratio of yield strength to ultimate strength in the test alloys showed that the relationships between these variables are not consistent. At the slow strain rate, for example, the yield-strength to ultimate-strength ratio increased with increasing temperature in nine of the test metals; whereas just the opposite effect occurred in three of the test metals. In the remaining thirteen test metals at the slow strain rate, the ratio of yield strength to ultimate strength varied erratically with increasing temperature. At faster strain rates, the effects of temperature on this ratio were quite similar except that the tendency for the ratio to increase with increasing temperature was slightly less and the tendency for it to decrease slightly more than at the slower strain rates. The effects of strain rate on the yield-to-ultimate ratios were just as erratic as those of temperature.

2.3 Elongation

Of all the tensile properties measured in the test program, total percent elongation reacted most erratically to variations in temperature and in strain rate. No generalizations, therefore, can be made regarding the effects of temperature and of strain rate on the total elongation of structural metals except that these effects are inconsistent and unpredictable. Fig. 33 and 34 show the variations in total elongation in the test metals with increasing temperature at a slow strain rate of 0.00005 in./in./sec, and Fig. 35 and 36 show similar information for a fast strain rate of 1.0 in./in./sec. In some of the alloys, such as AZ-31 magnesium, elongation increased, and in others, such as 321 stainless, the total elongation decreased with increasing temperature at all strain rates. In other alloys, the effects of increasing temperature on elongation changed with changes in strain rate; e. g. the total elongation of A70 titanium alloy tended to decrease with increasing temperature at slow strain rates and to increase with increasing temperature at rapid strain rates. The total elongation of many of the alloys varied erratically with increasing temperature at all strain rates. The effects of increasing strain rate on total elongation were equally as erratic as those of increasing temperature. Under certain conditions, the elongation tended to increase with increasing strain rate and under other conditions it decreased, but these conditions varied with the different alloys.

The effects of variations in holding time at test temperature on total elongation were somewhat more consistent and predictable. These effects were negligible in the stable alloys. Under conditions that produced structural changes in the unstable alloys, corresponding variations in elongation occurred. When strengthening structural changes, such as precipitation hardening, occurred, elongation tended to decrease; when weakening structural changes, such as overaging or tempering, occurred, elongation tended to increase.

Some of the inconsistencies in the total-elongation determinations are probably a result of an inherent error introduced by the resistance-heating method that was used. With this method of heating, a hot spot tends to develop in the gage length when the specimen necks down prior to rupture. Since this reduced section does not start to form until the ultimate load is reached, the hot spot does not affect the determinations of modulus of elasticity, yield strength, or ultimate strength, but it does affect total elongation. Whether the hot spot increases or decreases elongation probably depends upon the test material and the temperature. For the following reasons, it is believed that error introduced by the hot spot is not a major contributing factor to the erratic characteristics of total elongation:

1. At a strain rate of 1.0 in./in./sec, sufficient time is not available for a hot spot to develop, yet total elongation is just as erratic as at slow strain rates.

2. In metals with poor ductility very little reduction of area occurs, yet total elongation varies inconsistently.

3. Other work carried out with uniform furnace heating has demonstrated the erratic characteristics of total elongation.

In general, it is believed that the inconsistent responses of total elongation to variations in temperature and in strain rate are an inherent characteristic of structural metals.

Total elongation values are not ordinarily used directly in design. They are used primarily as a comparative measure of the ability of metals to absorb shock loading and stress concentrations. For some applications, minimum allowable elongation values have been established within some organizations through long experience with each application. These minimum values, of course, vary with the type of application and with the conditions. Universally accepted minimum elongation requirements for applications in aircraft and in missiles have not been established. Furthermore, no method has been developed for predicting accurately the minimum elongation values that are needed for new applications. Some competent authorities have seriously questioned the significance of total elongation measurements (21). It is generally agreed, however, that some minimum amount of ductility is desirable in structural materials, but it is not generally agreed that a material with very high elongation is in any way superior to one with lower elongation provided both values exceed some minimum. In view of the foregoing facts, no general conclusions can be drawn regarding the relative merits of the various test materials insofar as ductility is concerned. For those applications for which minimum elongation values have been set, the acceptable test materials can readily be selected from Fig. 33, 34, 35, and 36.

For certain types of fabrication methods, the amount of uniform elongation, which is the elongation that occurs before the test specimen begins to neck down, is an important consideration. Since tensile specimens begin to neck down at approximately the ultimate load, the uniform-elongation values for the test metals were determined by measurement, from the full stress-strain curves, of the degree of plastic strain up to the ultimate load. These uniform elongation values are illustrated as functions of temperature in Fig. 37 and 38 for tests conducted at a slow strain rate and in Fig. 39 and 40 for tests conducted at a fast strain rate.

The variations in uniform elongation with increasing temperature were considerably more consistent than the variations in total elongation. Both at the slow strain rate and at the fast strain rate, the uniform elongation of most of the test metals decreased with increasing temperature. These decreases in uniform elongation with increasing temperature are probably a result of decreasing ability to work harden with increasing temperature. Uniform elongation in some of the test metals, however, varied erratically or increased with increasing temperature as shown in Fig. 37, 38, 39, and 40, these variations being more prevalent at the fast strain rate than at the slow strain rate.

The effects of increasing strain rate upon uniform elongation were quite inconsistent. In many of the test metals increasing strain rate caused an increase in uniform elongation at certain temperatures and a decrease in uniform elongation at other temperatures, but the temperatures at which these variations occurred varied with different alloys.

2.4 Modulus of Elasticity

As mentioned previously, modulus-of-elasticity values were not determined with a high degree of precision in this work, ± 10% being the approximate level of accuracy for these determinations. Furthermore, modulus of elasticity is not as sensitive to changes in the test variables as are the other tensile properties. For these reasons no detailed analysis is given of the modulii of elasticity of the test metals.

In general, the modulus values of all of the test alloys decrease with increasing temperature, but the decreases are relatively smaller than those of the strength properties. Variations in strain rate have no significant effects on modulus of elasticity at temperatures up to the temperature of transition from low-temperature to high-temperature behavior in the various alloys. At higher temperatures, modulus values appear to decrease as the strain rate is decreased. Rather than true variations in elastic properties, these "apparent" decreases in modulus are believed to be a result of a small amount of plastic (creep) deformation that occurs during the initial portion of the tensile tests as the specimens are loaded slowly through the "elastic" region. This plastic deformation, of course, decreases the slope of the stress-strain curve thereby causing an apparent decrease in modulus of elasticity. Since creep is time dependent, the modulus values determined at the most rapid strain rate are probably representative of true elasticity. The lower values obtained at the slower strain rates represent the true slope of the stress-strain curves at those strain rates but do not indicate true elastic properties. In the temperature range of low-temperature behavior, modulus

values that are determined from stress-strain curves are not affected by variations in strain rate because creep is insignificant in that temperature range.

Variations in holding time at test temperature have no significant effects upon modulus values of the test metals except under very special conditions. These conditions include temperatures in the range of high-temperature behavior, slow strain rates, and time-dependent structural changes in the test material. Under these conditions, creep resistance may change appreciably with variations in holding time, thereby changing the amount of plastic deformation during the initial stages of loading. This change in the plastic deformation, of course, results in a change in the apparent modulus values. For example, at 1200° F the creep resistance of the Thermold-J and Peerless-56 die steels decreased with increasing holding times because of increased tempering. When the holding time at 1200° F was increased from 10 sec to 30 minutes, increased plastic deformation occurred during the initial stages of loading at slow strain rates, and lower apparent modulus values were obtained. At the fastest strain rate, the modulus determinations are not affected by creep resistance and, therefore, are not affected by structural changes that occur with increasing holding time.

SECTION III. GENERALIZATION OF DATA

3.1 Purpose

Since three variables—temperature, strain rate, and holding time at temperature—were investigated, three different types of plots were employed in the previous reports to illustrate the effects of the three variables:

1. Tensile properties as functions of temperature at various constant strain rates and holding times.

2. Tensile properties as functions of strain rate at various constant temperatures and holding times.

3. Tensile properties as functions of holding time at various constant temperatures and strain rates.

The presentation and usefulness of the data might be improved if means could be developed to show the effects of all of the test variables for individual metals on single plots.

In this section of the report, two possible methods are explored for accomplishing such generalizations of the more important tensile properties—0.2%-offset yield strength and ultimate strength. These generalizations are intended to serve some or, if possible, all of the following purposes:

1. To condense a large volume of data on each alloy into simple and meaningful plots, thus simplifying the presentation of the data.

2. To afford an easy and quick method of comparison of the strengths of different alloys over wide ranges of conditions. Such comparisons are quite useful since the effects of a number of variables are included on a single curve.

3. To afford a better means of interpolation between data points.

4. To afford a reliable method for extrapolating data beyond the ranges of temperature, strain rate, and time covered by the test program.

5. To provide a means of defining the characteristics of a material over wide ranges of conditions with a minimum amount of testing.

For application to short-time tensile data, the first three objectives listed above are most important. The fifth objective is, of course, very desirable in any test program but is of greater advantage in long-time creep-testing programs. Actually, objectives No. 3 and 5 are supplementary since the development of more reliable methods for interpolation tends to minimize the amount of testing required to define the characteristics of a material. Objective No. 4 is not of prime importance in the development and use of short-time data since the temperatures, strain rates, and times that are of interest in this work can be adequately covered quite practically and efficiently. The development of improved methods for extrapolating short-time tensile data to long-time conditions would, of course, be very useful in the design of structures for long-time load-carrying applications.

One method for generalization of the data that will be explored involves the use of time-temperature or rate-temperature parameters of the types that have been applied primarily to long-time creep data (1, 3-7, 11-15, 17, 19,

20, 22). Such parameters have also been applied to a limited extent to such phenomena as tempering of steel (2) and short-time tensile properties under both rapid-heating and constant-temperature conditions (8, 9, 10, 18). The other method that will be evaluated for generalizing the strength data is a new method based on the fact that in most of the test metals the strength tends to vary linearly with the log of the strain rate. This method is called the "duplex" method of generalization because it required two curves for adequate presentation.

3.2 Parameters

The rate-temperature and time-temperature parameters that have been applied to certain types of metallurgical data in the past are based upon the observation that many characteristics of metals, such as creep strength, tensile strength, and tempered hardness, are rate- or time-dependent as well as temperature-dependent. Creep strength and tensile strength, for example, are functions of strain rate and of temperature, a decrease in strain rate usually affecting strength in the same manner as an increase in temperature or vice versa. In the parameters, temperature and rate or its reciprocal, time, are combined into a single mathematical expression, which is an invariant function of the appropriate property of a material—creep strength, tensile strength, tempered hardness. In other words, each numerical value of the parameter, which is derived from a formula that includes temperature and rate or time, is supposed to be associated with only one value of the pertinent property of each material. A plot of the property as a function of the parameter yields a curve showing the combined effects of temperature and rate or time on the property. Past experience has shown that the various properties are not necessarily perfectly invariant functions of the rate-temperature or the time-temperature parameters that have been developed. The parametric methods of presentation, therefore, are not entirely accurate; nevertheless, they afford very useful approximations.

Most of the parameters (1, 14, 19) that have been developed for the presentation of creep-strength data are based upon the classical Arrhenius rate-process equation expressed as

$$r = Ae^{-\frac{Q}{RT}}$$

where r is strain rate, A is a constant, Q is the activation energy, R is the gas constant, T is the absolute temperature, and e is the base of the natural system of logarithms, 2.71828. The parameters developed by Larson and

Miller (1) and by Dorn (14) are representative and commonly used methods for applying this expression to the presentation of creep data. Larson and Miller reduced the rate-process equation to the form

$$T (\log A - \log r) = \frac{Q}{2.3\,R} = \text{constant} \qquad (a)$$

for constant stress. They further modified the expression to the form

$$T (C - \log r) = f (S) \qquad (b)$$

where S is stress and C is constant equal to log A. Although the value of C varies somewhat with different materials, Larson and Miller stated that the use of a universal value of 20 introduces very little error when r is strain rate in %/hr and T is absolute temperature in ° R. The Larson-Miller parameter is used in the following manner: When creep tests on a particular material have been conducted at a number of stresses and a number of temperatures, the parameter for each test is calculated using the test temperature and the minimum creep rate. The corresponding stresses are plotted as functions of the parameter values, the individual points ordinarily falling on a single curve that shows decreasing stress with increasing parameter value. Thus a large amount of creep data on one material are reduced to a single master curve. For interpolation or extrapolation, the stress for any combination of creep rate and temperature can be determined (with varying degrees of accuracy) from the master curve. When the same value of the constant, C, is used for different materials, curves of this type are quite useful for comparisons of their creep properties—the higher the curve for a particular material on the stress scale the better the creep resistance. When the value of C is varied properly for different materials, more precise interpolation and extrapolations are obtained, but the curves are not comparative among different materials.

Dorn and his co-workers reduced the rate-process equation to the form

$$re^{\frac{Q}{RT}} = A = \text{constant} \qquad (c)$$

for constant stress. Furthermore, this expression is a function of stress, S:

$$re^{\frac{Q}{RT}} = f (S) \qquad (d)$$

When this parameter is used, a different value of the activation energy, Q, is determined for each metal to which it is applied. The parameter is employed in the same manner as the Larson-Miller parameter, i.e., parameter values are determined from creep data and plotted against stress to form master curves for individual materials. These master curves can be used for interpolation and extrapolation (again with varying degrees of accuracy) in the same manner as the Larson-Miller master curves. Since one of the constants—the activation energy, Q—in Dorn's parameter varies appreciably among different materials, the master curves based on this parameter are not very useful for direct comparisons of the creep properties of different materials.

In the use of Dorn's parameter, equations c and d, the activation energy, Q, is mathematically constant for a given material regardless of the strain rate or the temperature. In the use of the Larson-Miller parameter, equations a and b, the activation energy of a given material is a function primarily of stress, being independent of temperature and of strain rate at each constant stress. Recent work by Dorn (23), however, indicates that the activation energy of different materials is a function of temperature, the activation energy increasing with increasing temperature in the range of low-temperature behavior and being constant at higher temperatures. The mathematical independence of activation energy from temperature in the parameters, undoubtedly, is a source of error in the use of the parameters.

Very little is known about the factors that control the value of the constant A in the rate-process equation. In the use of the Larson-Miller parameter, A is mathematically independent of stress, temperature, and strain rate. As mentioned previously A varies somewhat among different materials, but Larson and Miller stated that only a small amount of error is introduced by the use of a universal value of C, which is equal to log A. The use of such a universal value makes possible the employment of Larson-Miller master curves for direct comparisons among different materials. In the Dorn parameter, A is a function primarily of stress for a given material and is independent of temperature and of strain rate at each constant stress.

A third very useful time-temperature or rate-temperature parameter was developed by Manson and Haferd (4) and is called the "Linear" parameter. Although this parameter was developed primarily for the presentation of creep data, it has also been applied to short-time data (8, 9, 10, 18). Since this parameter was developed empirically, it is not based upon the Arrhenius rate-process relationship. It is based, rather, upon the observed linear relationship between temperature (T) and the log of rupture time (t) or between temperature (T) and the log of creep rate (r) at constant nominal

creep stress and upon the tendency for the lines that represent these relationships to converge at a point (Ta, log ta or Ta, log ra). The Linear parameter can be expressed as follows:

$$\frac{T - Ta}{\log r - \log ra} = f(S) \qquad (e)$$

Any consistent units can be used for temperature, strain rate, and stress. In the use of this parameter for a given material, values of Ta and log ra are determined first as explained by Manson and Haferd (4). These values are constant for each material but vary among different materials. For each creep test on a given material a value of the parameter can be determined. When a number of values representing various creep-test conditions are plotted against stress, a single master curve is obtained. This curve can be used for interpolation or for extrapolation since the stress for any combination of temperature and creep rate can be determined (again with varying degrees of accuracy) from the corresponding parameter value. Since the constants, Ta and ra vary with different materials, the master curves for this parameter cannot be used for direct comparisons among different materials.

3.3 Application of Parameters to Tensile Data

Although the parameters discussed above were developed primarily for application to long-time creep data, the variables involved—temperature (T), strain rate (r), and stress (S)—are also involved in tensile tests. An investigation was made, therefore, of the applicability of the various temperature-strain rate parameters to the short-time tensile data covered by this report.

One of the variables—holding time at temperature under no load—that was included in the tensile test program is not included as one of the variables in any of the existing parameters. The time factor that is included in the time-temperature parameters refers to time under load, which is ordinarily considerably different from holding time under no load in its effects upon strength properties. In the temperature-strain rate parameters, the time factor in strain rate (strain per unit time) also refers to time under load. In metals, the influence of time under no load on strength properties is dependent entirely upon time-temperature-dependent changes in the metallurgical structure. When structural changes do not occur, strength properties are not affected by prolonged holding times at temperature; when structural changes do occur, corresponding changes in strength properties take place. When metals are held at elevated temperatures under load, they

tend to flow plastically (creep). This plastic deformation normally has a damaging effect on strength; as a result, the strength of metals tends to decrease with increasing exposure times at elevated temperatures under load. Under these conditions, the effects of time-temperature-dependent structural changes are superimposed upon the effects of the plastic flow, but the plastic flow usually has the predominant influence on strength.

In the investigation of the applicability of temperature-strain rate parameters to short-time tensile data, efforts were made to incorporate the additional variable of holding time under no load into the parameters that were studied. For those test metals in which strength was not affected by holding time, of course, a holding-time term need not be incorporated into the parameter since the parameter values corresponding to various combinations of temperature and strain rate would not be affected by changes in holding time. For those materials that were affected by variations in holding time, the incorporation of a holding-time term into the parameters leads to a great increase in the complexity of the parameters. No suitable method was found for incorporating a holding-time term into the existing temperature-strain rate parameters or into other types of parameters that were investigated. One of the main obstacles to the development of convenient and accurate holding-time terms is the narrow temperature ranges in which holding time has significant effects in some of the test alloys. For example, over the range of holding times investigated—10 sec to 30 minutes—the alclad 2024-T3 aluminum alloy continuously increases in strength at 450° F and continuously decreases in strength at 600° F. Such effects of holding time are difficult to represent mathematically in the parameters since they must be superimposed upon the strain-rate and temperature terms. The lack of a single parameter to express holding-time effects as well as strain-rate and temperature effects is not a serious detriment since most of the test alloys were not affected by variations in holding time. For the other alloys, the qualitative effects of holding time are illustrated by the difference in two master curves—one representing strength obtained after a 10-sec holding time and the other representing strength obtained after a 30-minute holding time.

From the equations expressing the Larson-Miller parameter, a and b, it is seen that, for a given material at constant stress, a plot of log r versus $1/T$ should be a straight line. The slope of the line will be equivalent to $-Q/2.3\ R$. Since the value of $-Q/2.3\ R$ varies with stress, a different straight line will represent each value of stress. Since the value of C, which is the same as log A, does not vary with stress, all of the straight lines should intercept at the point C on the log r axis ($1/T = 0$).

The equations for the Dorn parameter, also require that, for a given material at constant nominal stress, a plot of log r against 1/T be a straight line. In this case, again, a different straight line is associated with each stress level, but the slope, Q/R, does not vary with stress. Therefore, the straight lines should be parallel, and their intercepts on the log r axis (1/T = 0) should be stress dependent.

The Linear parameter indicates mathematically that at constant temperature a plot of log r against temperature should be a straight line. The slope of the straight line is stress dependent, and all straight lines representing various constant stresses should converge at a point Ta, log ra.

With the tensile data for three representative test alloys—A110-AT titanium, full-hard Type 301 stainless steel, and alclad 2024-T3 aluminum alloy—curves of log r versus 1/T and log r versus T were plotted for various constant yield stresses. The points for each of these curves, which are shown in Fig. 41, 42, and 43, were taken at constant stress levels, from curves of yield strength as a function of temperature at three strain rates—0.00005, 0.01, and 1.0 in./in./sec. The plots in Fig. 41, 42, and 43 are intended to aid in the evaluation of the applicability of the three types of existing parameters—Larson-Miller, Dorn, and Linear—to short-time tensile data. The plot that conforms most closely to the mathematical requirements discussed above should indicate the most suitable parameter. For none of the materials are all constant-stress curves of 1/T versus log r parallel, nor do they all converge at a point on the log r axis; therefore, the data do not fulfill the mathematical requirements of either the Dorn or the Larson-Miller parameters. It is interesting that, for each of the test metals, the 1/T versus log r curves for data obtained at low temperature levels have markedly smaller negative slopes than the curves for data obtained at high temperatures. Since the negative value of the slope is proportional to the activation energy, these results are consistent with the findings of Dorn (23) that the activation energy increases as the temperature of a material is increased from the range of low-temperature behavior to the range of high-temperature behavior. As shown on the right-hand side of Fig. 41, 42, and 43, the constant-stress curves of T versus log r do not converge at a point; therefore, the data do not fulfill the mathematical requirements of the Linear parameter.

On the basis of this mathematical analysis, none of the existing parameters appear to be promising for the accurate condensation and presentation of short-time tensile data. Attempts to modify the parameters for better conformance with short-time tensile data resulted in no significant improvements. Nevertheless, further analyses are given below of the

accuracy and usefulness of condensed presentations of short-time ultimate- and yield-strength data as functions of the Larson-Miller parameter. This parameter was chosen in preference to the others for the following reasons:

1. Fig. 41, 42, and 43 show that the conformance of short-time tensile data to the mathematical requirements of the Larson-Miller parameter is no poorer than their conformance to the requirements of the other parameters.

2. The use of a universal value of C in the Larson-Miller parameter for all test materials affords the great advantage that the master curves can be used for direct comparisons of the strengths of various materials. The error introduced by the use of the universal value for all materials is probably comparatively minor in view of the fact that the scatter in the intercept of the 1/T versus log r curves on the log r axis indicates that there is no one precise value of C for each material.

Fig. 41, 42, and 43 show that the 1/T-versus-log r curves intercept the log r axis—which intercept is mathematically equivalent to C in the Larson-Miller parameter—at values ranging from 4 to more than 35. The lower values are associated with low-temperature behavior and the higher values with high-temperature behavior. The intercepts for the high-temperature data for A 110-AT titanium alloy are considerably lower than those for the full-hard Type 301 stainless and the alclad 2024-T3 aluminum alloy. Because of the wide scatter in these intercepts and the resulting uncertainty concerning the best value of C, Larson-Miller master curves were determined for the ultimate and yield strengths of these three alloys with two values of C—14 and 25. An analysis of the accuracy with which these curves represent the experimental data will then indicate the better value of C.

Fig. 44 and 45 show the ultimate and yield strengths of A 110-AT titanium alloy plotted as functions of the Larson-Miller parameter with a C value of 14. The plots in Fig. 46 and 47 are similar except that a C value of 25 was used. Each individual data point in these plots represents the average of two or three tensile tests. Since variations in holding time from 10 sec to 30 minutes at test temperature have no significant effects upon the strength of this alloy, data representative of all holding times employed in the test program are included in each plot. At temperatures up to about 1200° F, the data points conform very closely to master curves that are drawn through them. At higher temperatures, the data become more scattered, the scatter apparently being somewhat greater when a C value of 25 is used in preference to a C value of 14.

As a check on the accuracy with which the master curves represent the properties of A 110-AT titanium alloy, yield-strength and ultimate-strength values were determined from the curves with the use of parameter values representing a number of temperatures and strain rates. These strength values for strain rates of 0.00005 and 1.0 in./in./sec in comparison with precise experimental data are shown as functions of temperature in Fig. 48 and 49. Additional strength values determined from the two master curves for strain rates of 0.0001, 0.005, and 0.5 are shown in comparison with experimental data as functions of strain rate at various constant temperatures in Fig. 50 and 51. These comparisons show that the data derived from both parameters follow the general form of the experimental data. Although the accuracy of representation of ultimate strength for the two parameters is about equal, the yield-strength data for this material is more accurately represented by the parameter that contains a C value of 14. This greater accuracy associated with the C value of 14 is to be expected for the A 110-AT alloy since Fig. 41 shows that this value is more representative of an average experimentally determined C value for this alloy. In general, Fig. 48 through 51 indicate that the data derived from the master curves represent the general levels of strength properties but that they are not sufficiently accurate for precise design purposes.

Master curves similar to those previously presented for A 110-AT titanium alloy are shown for full-hard Type 301 stainless steel in Fig. 52 through 55. As in the case of the titanium alloy, the stainless steel is not significantly affected by variations in holding time; therefore, data representing all holding times are included on individual plots. Yield-strength data derived from the master curves are compared with experimental yield-strength data as functions of temperature in Fig. 56 and as functions of strain rate in Fig. 57. Although the scatter in the data points about the master curves is greater when a C value of 25 is used for this alloy, Fig. 56 and 57 show that the yield-strength values derived from the parameter with the C value of 25 correspond more closely to the experimental data. This finding is consistent with the fact that, as shown in Fig. 42, the average experimentally determined C value is closer to 25 than to 14. Fig. 56 and 57 show that, although the values derived from the master curves indicate general levels of strength and general trends associated with variations in temperature and in strain rate, they are not sufficiently accurate and reliable for design purposes.

The yield-strength and ultimate-strength data for alclad 2024-T3 aluminum alloy are plotted as functions of the parameters in Fig. 58 through 61. Since variations in holding time have an appreciable effect upon the strength of this alloy at certain temperatures, master curves are shown both for the minimum holding time of 10 sec and the maximum holding

time of 30 minutes. The effects of holding time are rather poorly defined by the master curves obtained with a C value of 14 because the arbitrary scatter in the data points is equal to the real differences caused by holding-time effects. The master curves associated with a C value of 25 show the effects of holding time more consistently and clearly. Interpolation to intermediate holding times between those represented by the master curves can only be estimated quite roughly. Yield-strength values derived from the master curves for the alclad 2024-T3 aluminum alloy are shown in comparison with accurate experimental data as functions of temperature in Fig. 62 and as functions of strain rate in Fig. 63. These comparisons show that for this alloy the strength values obtained with a C value of 25 and its associated parameter are usually more accurate than those obtained with a C value of 14.

Fig. 62 and 63 show that unusual effects of the test variables may not be adequately represented or even indicated by the Larson-Miller master curves. In the alclad 2024-T3 alloy, a strengthening time-temperature dependent structural change at 450° F entirely counteracts the strengthening effect of increased strain rate, resulting in a decrease in strength with increasing strain rate. As shown in Fig. 62 and 63, however, the data obtained with the use of the master curves does not show this abnormal fluctuation in the data.

On the basis of the foregoing analysis of the application of Larson-Miller temperature-strain rate parameters to the presentation of short-time tensile data, it is concluded that, of the five possible purposes of such presentations listed in Section 3.1, the first two purposes are served quite adequately. Certainly, the Larson-Miller master curves serve as condensations of a large amount of test data, a single master curve showing the ultimate or yield strength of an alloy over any desired range of temperature and strain rate. Since each Larson-Miller master curve indicates the general level but not precise values of the tensile strength of a material over wide ranges of conditions, the curves can be used for general comparisons of the strengths of different materials, but they cannot be used for very fine distinctions between two materials that are quite similar in strength. The tensile-strength values derived from the Larson-Miller master curves are not sufficiently accurate for precise interpolation between or extrapolation beyond the experimental conditions. Such interpolation or extrapolation, however, might be used to obtain rough estimates of tensile-strength values at temperatures, strain rates, and holding times that have not been investigated. Since the master curves do not represent the tensile strength of materials with a high degree of accuracy, they cannot be used to minimize the amount of testing required to define the short-time design properties of a material. However, the master curves,

which are recommended for use only for comparative purposes, can be adequately defined with a smaller number of tests than were performed in this test program. For example, the test data obtained at the intermediate strain rate—0.01 in./in./sec—and the intermediate holding time—100 sec—are probably not necessary for the construction of the master curves.

The ultimate strengths of all of the test alloys are presented in Fig. 64, 65, 66, and 67 as functions of the Larson-Miller time-strain rate parameter. Similar presentations of yield strength are given in Fig. 68, 69, 70, and 71. For these comparative curves, a C value of 25 is used in the parameter because the analysis presented above indicates that this value is probably more accurate than the value of 14 for most of the test alloys. In these plots, the materials that are not significantly affected by variations in holding time are represented by a single master curve; whereas, two master curves—one representing the 10-sec holding time and the other representing the 30-minute holding time—are presented for the alloys in which strength changes with increasing holding time.

Fig. 64 through 71 show that the die steels—Peerless-56, Chro-Mow, and Thermold-J—are the strongest of the test metals at lower parameter values. As the parameter values increase, the strengths of the die steels decrease, the decreases being sharper after the 30-minute holding time than after the 10-sec holding time as a result of the increased tempering associated with the longer holding time. The master curves indicate that the Inconel X and Stellite-25 are the strongest of the test alloys at high parameter values. The precipitation-hardened stainlesses—17-7 PH (TH 1050) and AM-350—and the full-hard Type 301 are the strongest of the stainless steels, whereas the annealed stainlesses and half-hard Type 301 are lower in strength as shown on the curves. The 6Al-4V is shown to be the strongest of the titanium alloys, approaching in strength the high-strength stainlesses at the higher parameter values. At low values of the parameter, the strength of the quenched and tempered 4130 steel is higher than that of the normalized material, but the master curves indicate that the strength of the normalized structure approaches or exceeds that of the hardened structure as the parameter values are increased. As shown on the master curves, the strengths of the aluminum and magnesium alloys are near the low end of the scale. The cast Type 356-T6 aluminum, which is shown to be the weakest of the aluminum alloys at low parameter values, approaches the wrought alloys in strength at higher parameter values. Although the alclad 7075-T6 is the strongest aluminum alloy at low parameter values, the alclad 2024-T3 aluminum alloy has higher strength at higher values of the parameter. At low parameter values, the strength of the wrought magnesium alloy—hard-rolled AZ-31—is greater than that of the cast magnesium alloy—

ZH62-T5—but this order of increasing strength is reversed in favor of the cast alloy at higher parameter values.

3.4 Duplex Generalizations

Since more accurate condensations of the short-time tensile data would be much more useful for design purposes, additional concise methods for presenting the data were investigated. A method that affords a combination of brevity and reasonable accuracy is based upon the fact that at constant temperature, the strength of individual metals tends to increase linearly with the log of the strain rate. This relationship is shown schematically in Fig. 72, the range of log strain rate from -4.3 to 0 corresponding to the range of strain rates from 0.00005 to 1.0 in./in./sec employed in the test program. Mathematically, the linear relationship between strength and the log of strain rate can be expressed as follows:

$$\text{Strength} = K_1 + K_2 (\log r + 4.3)$$

at constant temperature, K_1 and K_2 being constants and r the strain rate in in./in./sec. Referring to Fig. 72, K_1 is the strength level of individual constant-temperature lines at log strain rate of -4.3. These strength levels are equal to the strength of the material at a strain rate of 0.00005 in./in./sec. K_2 is the slope of the individual constant-temperature lines, these slopes being equivalent to the change in strength per unit change in log strain rate. If the values of K_1 and K_2 are known for a particular metal at any temperature, the strength at that temperature and at any strain rate can be calculated by means of the formula given above.

Values of K_1 and of K_2 were determined for the ultimate and yield strengths of all of the test metals throughout their test-temperature ranges and were plotted as functions of temperature. The values of K_1 and K_2 were determined from plots of the type shown in Fig. 72, which had been previously constructed from the test data for each test material and shown in WADC Technical Reports 55-199 Parts I, II, and III and WADC Technical Report 58-440 Pt I. Under some conditions, of course, the constant-temperature plots of log r versus strength were not perfectly straight lines. In these cases, the best possible straight lines were drawn among the data points, and the K_1 and K_2 values were determined from the line. For those alloys in which strength is not significantly affected by variations in holding time at test temperature, individual values of K_1 and K_2 at each temperature apply to all holding times at that temperature, at least within the range from 10 sec to 30 minutes covered by this investigation. When strength properties

are appreciably affected by changes in holding time, different K_1 and K_2 values are obtained for different holding times. For those test alloys that are sensitive to changes in holding time, separate curves are presented of K_1 and K_2 as functions of temperature for the three holding times that were employed in the test program—10 sec, 100 sec, and 30 min. K_1 and K_2 values for intermediate holding times can be determined, at least roughly, by visual interpolation between these curves.

Fig. 73 shows K_1 and K_2 as functions of temperature for both the ultimate strength and the yield strength of annealed A110-AT titanium alloy sheet. Since the properties of this alloy were not significantly affected by changes in holding time, at the test temperatures covered by these presentations, these curves apply to all holding times within the range investigated. For an evaluation of the accuracy with which these curves represent the experimental data, yield-strength and ultimate-strength values at various temperatures and strain rates were calculated by means of the formula, $S = K_1 + K_2 (\log r + 4.3)$. Calculated ultimate- and yield-strength values as functions of temperature and at strain rates of 0.01 and at 1.0 in./in./sec are shown in comparison with accurate experimental values in Fig. 74 and 75. It is shown in these illustrations that the calculated curves correspond very closely with the experimental curves. Fig. 76 and 77 show comparisons of the experimental and calculated data as functions of strain rate at various constant temperatures. Since the duplex method of data presentation is based upon a linear relationship between log r and strength, the only appreciable errors in the calculated data occur at temperatures where this relationship departs appreciably from linearity.

Fig. 78 shows the K_1 and K_2 values for full-hard Type 301 stainless steel sheet as functions of temperature. The close agreement between yield strengths calculated from these values of K_1 and K_2 and the experimental data are shown in Fig. 79 and Fig. 80, Fig. 79 showing strength as a function of temperature at two constant strain rates and Fig. 80 showing strength as a function of strain rate at six constant temperatures. The only appreciable error occurred at 85° F because the relationship between log r and strength departed somewhat from linearity, but, even so, the maximum percentage error was less than 10%.

The K_1 and K_2 values for a material that is sensitive to variations in holding time at test temperature, i.e. alclad 2024-T3 aluminum alloy, are shown as functions of temperature in Fig. 81 and 82. Ultimate- and yield-strength data are shown on separate plots because a number of extra curves are required to illustrate the effects of holding time. Yield strength values, calculated by means of the K_1 and K_2 values for the 10-sec holding time in Fig. 82, are compared with experimental data as functions of temperature in

Fig. 83 and as functions of strain rate in Fig. 84. These illustrations show very close agreement between the experimental and the calculated data throughout the entire ranges of temperature and strain rate. Both Fig. 83 and 84 show that the abnormal increase in strength with decreasing strain rate at 450° F, which was not shown by the parameter method of data presentation, was closely followed in the data calculated from the duplex method of presentation.

The accuracy with which holding-time effects are recorded by the duplex method of data presentation is shown in Fig. 85, which shows calculated and experimental values of yield strength as functions of holding time at various constant temperatures and at a strain rate of 1.0 in./in./sec. The K_1 and K_2 values for the calculated data points representing the 10-sec, 100-sec, and 1800-sec holding times were taken directly from the curves representing these holding times in Fig. 82. For the calculation of the strength values representing the 30-sec and 400-sec holding times, it was necessary to obtain interpolated values of K_1 and K_2 since no experimental data for these holding times were available. These interpolations, which were made visually, are represented by the dotted and dashed lines in Fig. 82. Interpolations for other holding times could, of course, be made by appropriate shifts in the dotted and dashed lines. Fig. 85 shows that the effects of holding time on strength are very accurately recorded by the duplex method of data presentation.

The foregoing discussion indicates that the duplex method of presentation of short-time tensile data is superior to the Larson-Miller parameter method for some purposes but is inferior for other purposes. Both methods afford means of condensing a large amount of data into simple one-page plots. The Larson-Miller master curves are useful chiefly for general comparisons of the strength levels of many materials over wide ranges of temperature and of strain rate, whereas the duplex presentations do not afford such direct general comparisons. On the other hand, the strength values derived from the duplex presentations are much more consistently accurate and reliable than those from the Larson-Miller master curves. It is believed, therefore, that the duplex method affords an acceptable means for obtaining accurate strength values by interpolation between the experimental conditions of temperature, strain rate, and holding time, whereas the Larson-Miller master curves are not suitable for accurate interpolations. As in the case of the Larson-Miller master curves, the duplex presentations are not recommended for accurate extrapolations of strength beyond the experimental conditions because the values of K_1 and K_2 cannot be predicted with certainty beyond these conditions. In other words, accurate strength values can be calculated from the duplex presentations only for temperatures, strain rates, and holding time that are within the limits

employed in establishing the K_1 and K_2 values. It is probable, however, that reasonable estimates of strength at higher or lower strain rates than those employed experimentally can be made with the assumption that K_2— the slope of the log r versus strength curve at a particular temperature— is constant over a wider range of strain rates. It is believed that, for accurate duplex data presentations over the wide ranges of temperature, strain rate, and holding time covered in this test program, the number of test conditions could not be reduced.

It can be concluded that the Larson-Miller master curves are useful primarily as rough but direct comparisons of the strength levels of a number of materials over wide ranges of conditions, whereas the duplex presentations provide accurate condensations of the strength properties of materials over wide ranges of conditions.

For design purposes and for purposes of comparison, the parameter method and the duplex methods for data presentation have two disadvantages that are not associated with the previous presentations of properties as functions of the individual test variables:

1. A calculation is required to determine a property for a set of test conditions from the parameter and duplex presentations, whereas properties are read directly from the plots of properties as functions of individual test variables.

2. The parameter presentations and duplex presentations do not illustrate directly the trends in properties produced by changes in the individual test variables, whereas such trends are clearly shown in the presentations used previously.

The main advantage of the parameter presentations and duplex presentations is their brevity. It is questionable, in view of the disadvantages mentioned above, that they should replace or would be more useful than the more voluminous plots of properties as functions of the individual test variables.

The duplex presentations for the ultimate and yield strengths of the remaining test materials are shown in Fig. 86 through 115 in the following order:

Material	Fig. No.
2014-T6 aluminum (alclad)	86-87
7075-T6 aluminum (alclad)	88-89
AZ-31 magnesium	90-91
A 70 titanium alloy	92
C-110 M titanium alloy	93
321 Stainless steel	94
Stellite-25	95
Inconel X	96
Half-hard 301 stainless steel	97
Annealed 17-7 PH stainless steel	98
17-7 PH (TH 1050) stainless steel	99
Normalized 4130 steel	100
Quenched and tempered 4130 steel	101
1020 steel	102
140 A titanium alloy	103
ZH62-T5 magnesium	104
356-T6 aluminum	105-106
Chro-Mow die steel	107-108
Thermold-J die steel	109-110
Peerless-56 die steel	111-112
AM-350 Stainless steel	113-114
6Al-4V titanium alloy	115

SECTION IV. CONCLUSIONS

The following conclusions are based upon the results of short-time tensile tests conducted on twenty-five metallic materials after they had been heated within ten seconds to various elevated test temperatures:

1. Variations in holding time from 10 sec to 30 minutes at elevated test temperatures had no significant effects upon the tensile properties of the structurally stable alloys. In certain temperature ranges in the unstable alloys, marked changes in strength and ductility occurred during the same holding-time interval. These variations in properties were a result of time-temperature-dependent structural changes such as precipitation, recrystallization, overaging, and tempering. The direction of the changes in properties—increasing or decreasing—depended upon the temperature and upon the type of structural change.

2. The strength properties and modulii of elasticity of the test materials tended to decrease with increasing temperature. In a few alloys within certain limited temperature ranges, time-temperature-dependent or strain rate-temperature-dependent structural changes completely counteracted the inherent weakening effect of increasing temperature and caused an increase in strength with increasing temperature. The total percent elongation of the test metals reacted erratically to increasing temperature. The uniform percent elongation, i.e. the percent elongation up to the ultimate load, tended to decrease with increasing temperature in the great majority of the alloys that were investigated. This effect of increasing temperature on uniform elongation, however, was not entirely consistent in all of the test alloys.

3. In general, the strength properties of the test metals tended to increase with increasing strain rate. The relative increases in strength were moderate in the temperature ranges of low-temperature behavior but increased sharply and continuously as the temperatures were increased into the ranges of high-temperature behavior. At certain temperatures in some unstable alloys, the effects of structural changes—which are dependent upon time, temperature, and plastic strain or upon time and temperature only—were superimposed upon and sometimes

obscured the inherent strengthening effect of increasing strain rate. Modulus-of-elasticity values were not affected by variations in strain rate in the temperature ranges of low-temperature behavior. In some of the alloys in their ranges of high-temperature behavior, modulus values, which were determined from the stress-strain curves, decreased with decreasing strain rate. Rather than true changes in elastic properties, such decreases in "apparent" modulus are believed to be a result of a small amount of creep deformation that occurred during the elastic portion of the tests at slow strain rates. The effects of increasing strain rate on total elongation and on uniform elongation were quite inconsistent.

4. An investigation of time-temperature and rate-temperature parameters indicated that short-time tensile properties of individual alloys cannot be expressed with a high degree of accuracy as invariant functions of such parameters. It is believed that, at the present state of the art, the dependence of tensile properties on temperature, strain rate, and time is too complex and nonuniform for such expression. Nevertheless, illustrations of strength properties as functions of the Larson-Miller parameter are quite useful for general comparisons of the strength levels of various materials over wide ranges of conditions. They cannot be used with confidence, however, for the presentation of accurate design data or for fine distinctions between alloys of nearly equal strength.

5. A duplex method that was developed for the presentation of tensile-strength data is useful primarily for the accurate condensation of tensile data over wide ranges of conditions into simple one-page plots. An analysis of this method of data presentation indicates that it affords a method of data interpolation that is accurate enough for design purposes. It is not particularly useful for comparisons of various materials, nor is it recommended for accurate extrapolations of tensile properties to conditions beyond those covered by the tests used in establishing the duplex presentations.

6. It is questionable that any condensed method of data presentation—such as the duplex method or the parameter method—that requires a calculation for the determination of

a property under specific conditions will be more acceptable for design purposes than the more voluminous plots that show properties directly as functions of the different individual test variables.

7. The service conditions of temperature, time at temperature, time under load, and strain rate must all be considered when a choice is made of an alloy for structural applications. For long-time load carrying applications, alloys are ordinarily useful only in their temperature ranges of low-temperature behavior, where they are not highly sensitive to changes in strain rate. Conditions of rapid loading and short times at temperature have the effect of extending the usefulness of alloys into their normal temperature ranges of high-temperature behavior where they are highly sensitive to changes in strain rate. In certain temperature ranges under very short-time conditions, alloys that are inferior for long-time creep-type applications may have higher strength than creep-resisting alloys.

BIBLIOGRAPHY

1. Larson, F. R., and Miller, James, "A Time-Temperature Relationship for Rupture and Creep Stresses." Transactions ASME, Vol 74, July 1952, pp 765-771.

2. Hollomon, J. H., and Jaffee, L. D., "Time-Temperature Relationships in Tempering Steel," Transactions AIME, Vol 162, 1945, pp 223-249.

3. LaRocca, E. W., "Time-Temperature Relationships for Rupture of Metals in Combustion Atmospheres." Jet Propulsion, Vol 27, June 1957, pp 674-675.

4. Manson, S. S., and Haferd, A. M., "A Linear Time-Temperature Relation of Creep and Stress-Rupture Data," NACA TN 2890. Lewis Flight Propulsion Laboratory, Cleveland, Ohio, March 1953.

5. Stowell, Elbridge Z., "A Phenomenological Relation Between Stress, Strain Rate, and Temperature for Metals at Elevated Temperatures," NACA TN 4000. Langley Aeronautical Laboratory, Langley Field, Va., May 1957.

6. Heimerl, George J., "Time-Temperature Parameters and an Application to Rupture and Creep of Aluminum Alloys," NACA TN 3195, Langley Aeronautical Laboratory, Langley Field, Va., June 1954.

7. Heimerl, George J., and McEvily, Arthur J., "Generalized Master Curves for Creep and Rupture," NACA TN 4112, Langley Aeronautical Laboratory, Langley Field, Va., Oct. 1957.

8. Krug, Ivo M., "Tensile Properties of Inconel-X Sheet under Rapid-Heating and Constant-Temperature Conditions," NACA TN 4065. Langley Aeronautical Laboratory, Langley Field, Va., Aug. 1957.

9. Krug, Ivo M., "Tensile Properties of AZ31 A-O Magnesium-Alloy Sheet under Rapid-Heating and Constant-Temperature Conditions," NACA TN 3752, Langley Aeronautical Laboratory, Langley Field, Va., Aug. 1956.

10. Heimerl, George J., "Tensile Properties of Some Structural Sheet Materials under Rapid-Heating Conditions," Proceedings of Fourth Sagamore Ordnance Materials Research Conference, Ordnance Materials Research Office and Office of Ordnance Research, U. S. Army, 1957.

11. Sherby, Oleg D., and Dorn, John E., "Creep Correlations in Alpha Solid Solutions of Aluminum," Transactions AIME, Vol 194, Sept. 1952, pp 959-964.

12. Sherby, Oleg D., and Dorn, John E., "Some Observations on Correlations Between Creep Behavior and the Resulting Structures in Alpha Solids Solutions," Transactions AIME, Vol 197, Feb. 1953, pp 324-330.

13. Grant, N. J., and Bucklin, A. G., "Extrapolation of Short-Time Stress-Rupture Data," Transactions ASM, Vol 42, 1950, pp 720-751.

14. Orr, R. L., Sherby, O. D., and Dorn, J. E., "Correlations of Rupture Data for Metals at Elevated Temperatures," Transactions ASM, Vol 46, 1954, pp 113-128.

15. Frenkel, R. E., Sherby, O. D., and Dorn, J. E., "Effect of Cold Work on the High Temperature Creep Properties of Dilute Aluminum Alloys," Transactions ASM, Vol 47, 1955, pp 632-644.

16. Hollomon, J. H., and Zener, C., "Effect of Strain Rate upon Plastic Flow of Steel," Journal of Applied Physics, Vol 15, Jan. 1944, pp22-32.

17. Garofalo, F., Smith, G. V., and Royle, B. W., "Validity of Time-Compensated Temperature Parameters for Correlating Creep and Creep-Rupture Data," Transactions ASME, Vol 78, 1956, pp 1423-1434.

18. 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, Langley Aeronautical Laboratory, Langley Field, Va., July 1955.

19. Fisher, J. C. and MacGregor, C. W., "A Velocity-Modified Temperature for the Plastic Flow of Metals," Jr. of Applied Mechanics, Transactions ASME, Vol. 68, 1946, p A-11.

20. Trozera, T. A., Sherby, O. D., and Dorn, J. E., "Effect of Strain Rate and Temperature on the Plastic Deformation of High Purity Aluminum," Transactions ASM, Vol 49, 1957, pp 173-184.

21. Gillett, H. W., "The Limited Significance of the Ductility Feature of the Tension Test," Symposium on Significance of the Tension Test of Metals in Relation to Design, American Society of Testing Materials, 1940.

22. Manson, S. S., Succop, G., and Brown, W. F., Jr., "The Application of Time-Temperature Parameters to Accelerated Creep-Rupture Testing," 1958, ASM Preprint No. 106.

23. Dorn, John E., "A Survey of Recent Experimental Determinations of Activation Energies for Creep," Proceedings of the Fourth Sagamore Ordnance Materials Research Conference, Ordnance Materials Research Office and Office of Ordnance Research, U. S. Army, 1957.

24. Mar, James W., Unpublished Report to Wright Air Development Center, Oct. 15, 1956, Contract No. AF 33(616)-2729.

25. Needham, Robert A. "A Study of the Tensile Properties of Aircraft Structural Materials Subject to Rapid Heating," Unpublished Report to WADC, March 18, 1957, Contract No. AF 33(616)-2729.

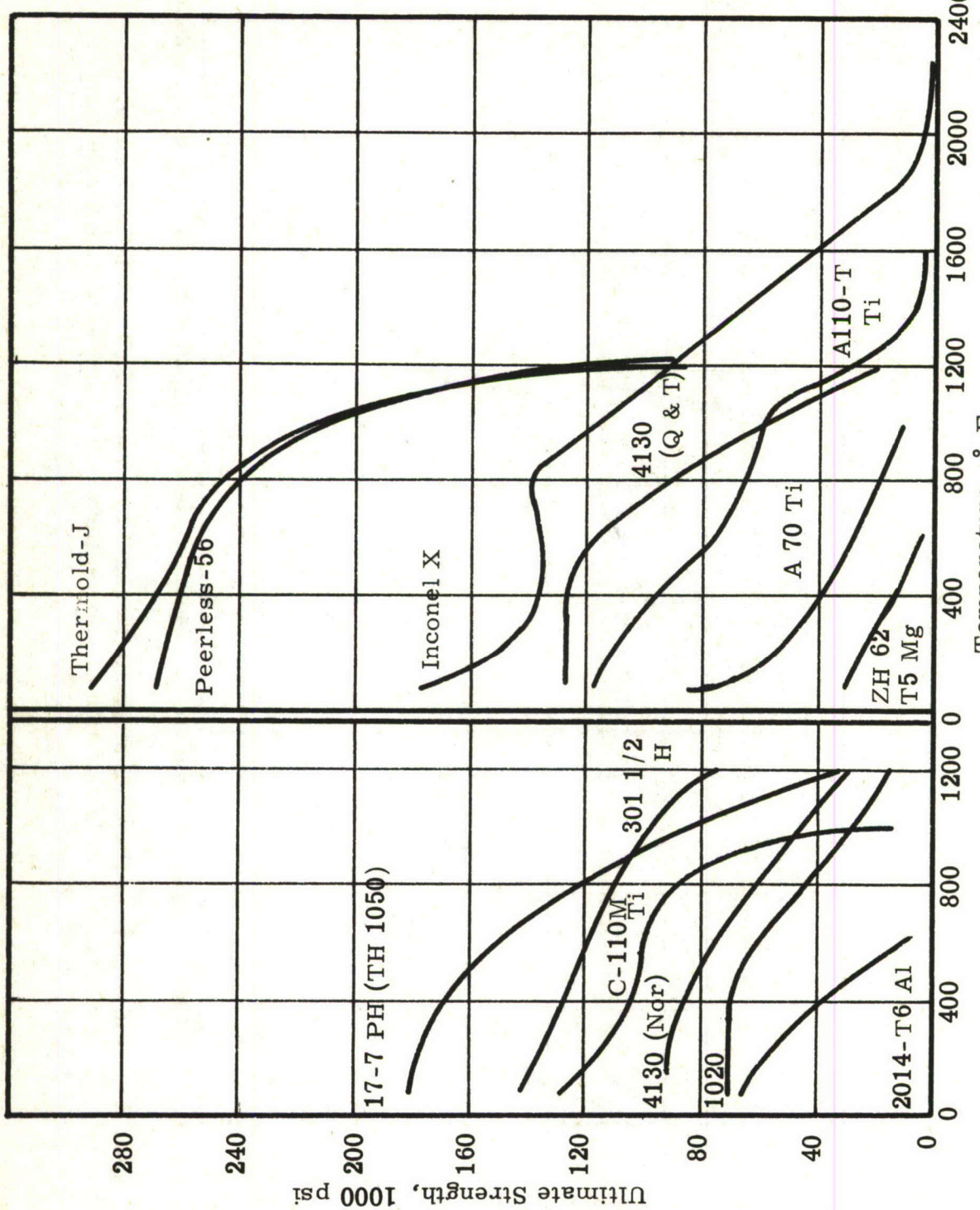

Figure 1. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of thirteen metals tensile tested at a strain rate of 0.00005 in./in./sec

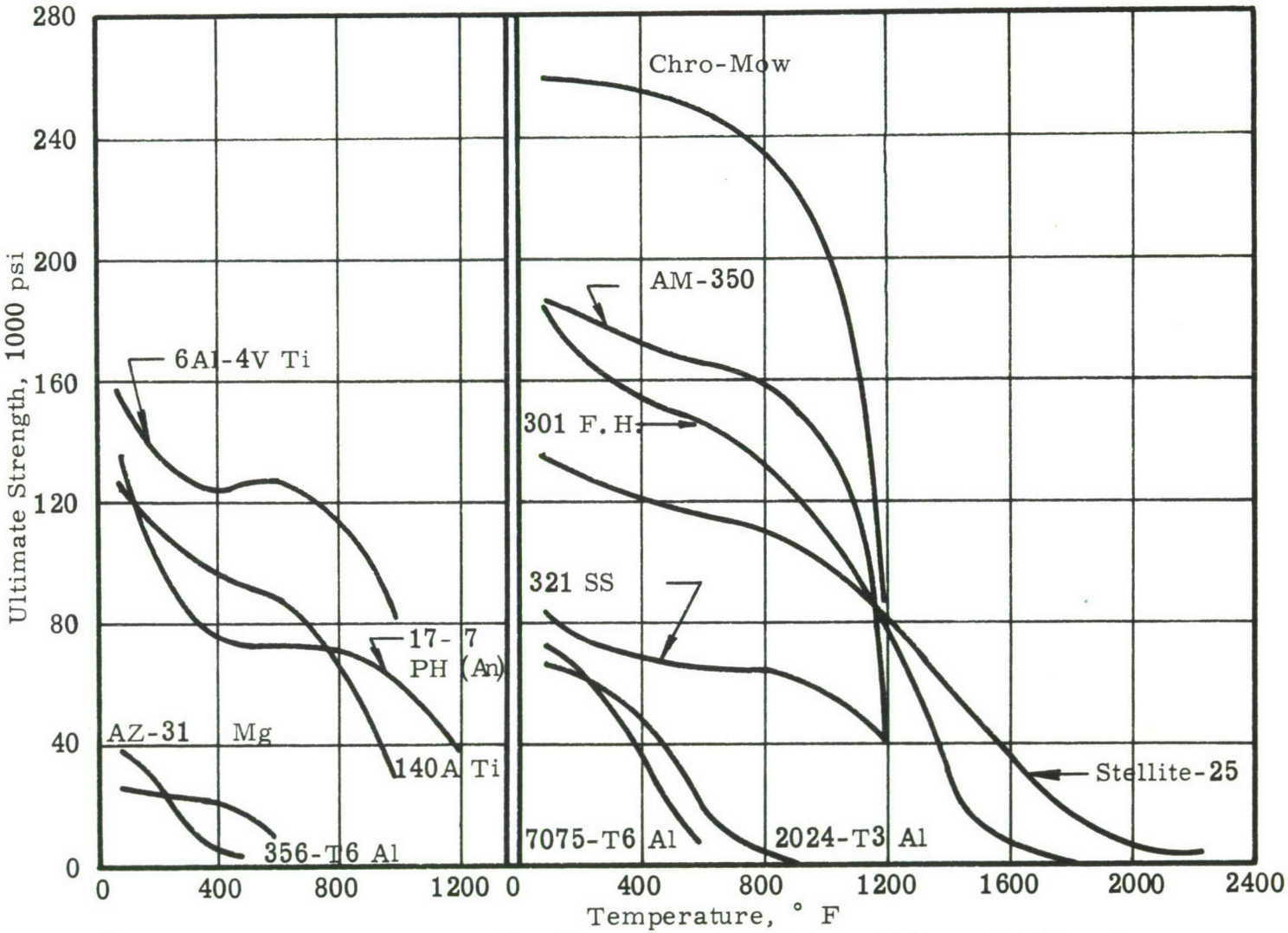

Figure 2. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of twelve metals tensile tested at a strain rate of 0.00005 in./in./sec.

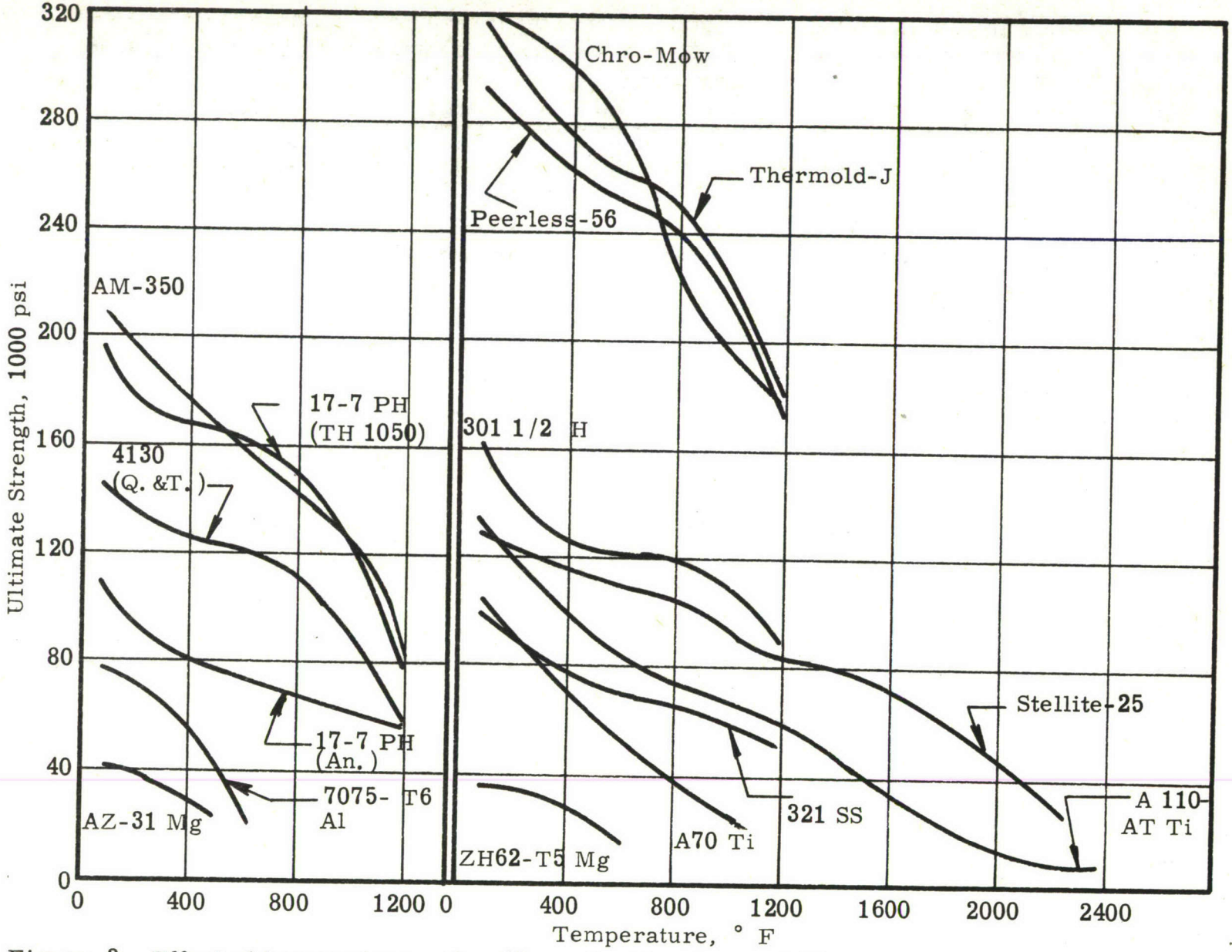

Figure 3. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of fifteen metals tensile tested at a strain rate of 1.0 in. / in. /sec.

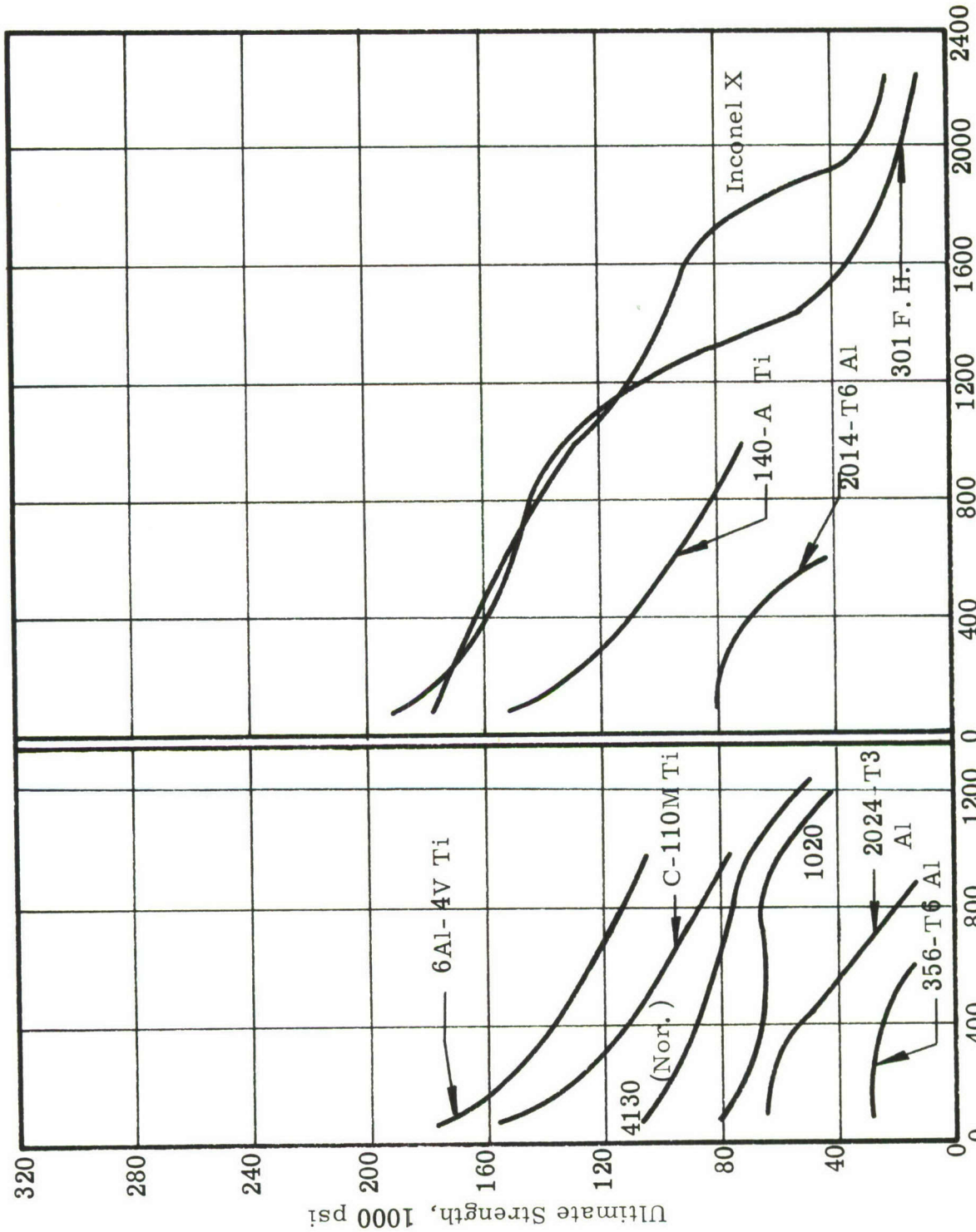

Figure 4. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ultimate tensile strength of ten metals tensile tested at a strain rate of 1.0 in./in./sec

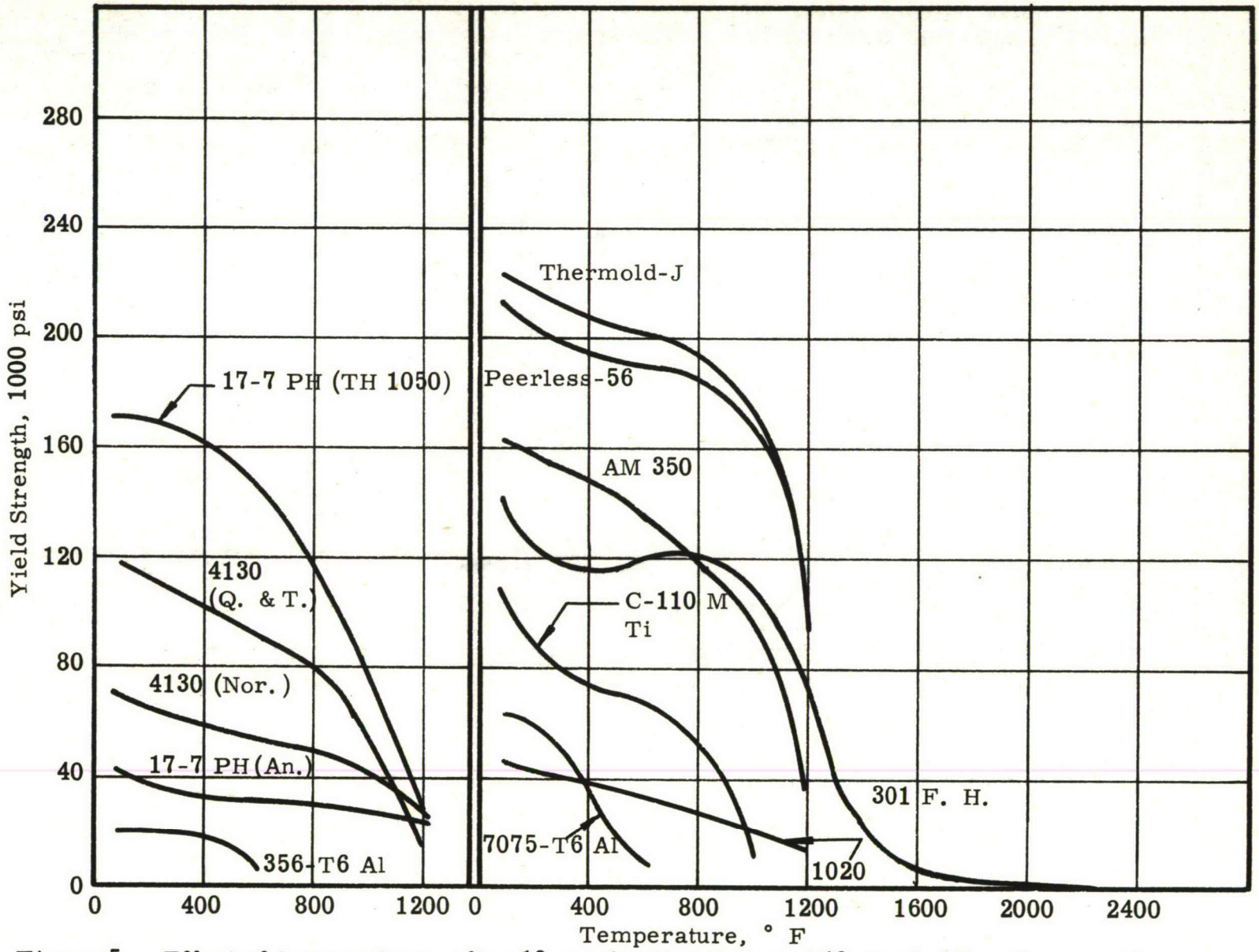

Figure 5. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of twelve metals tensile tested at a strain rate of 0.00005 in./in./sec.

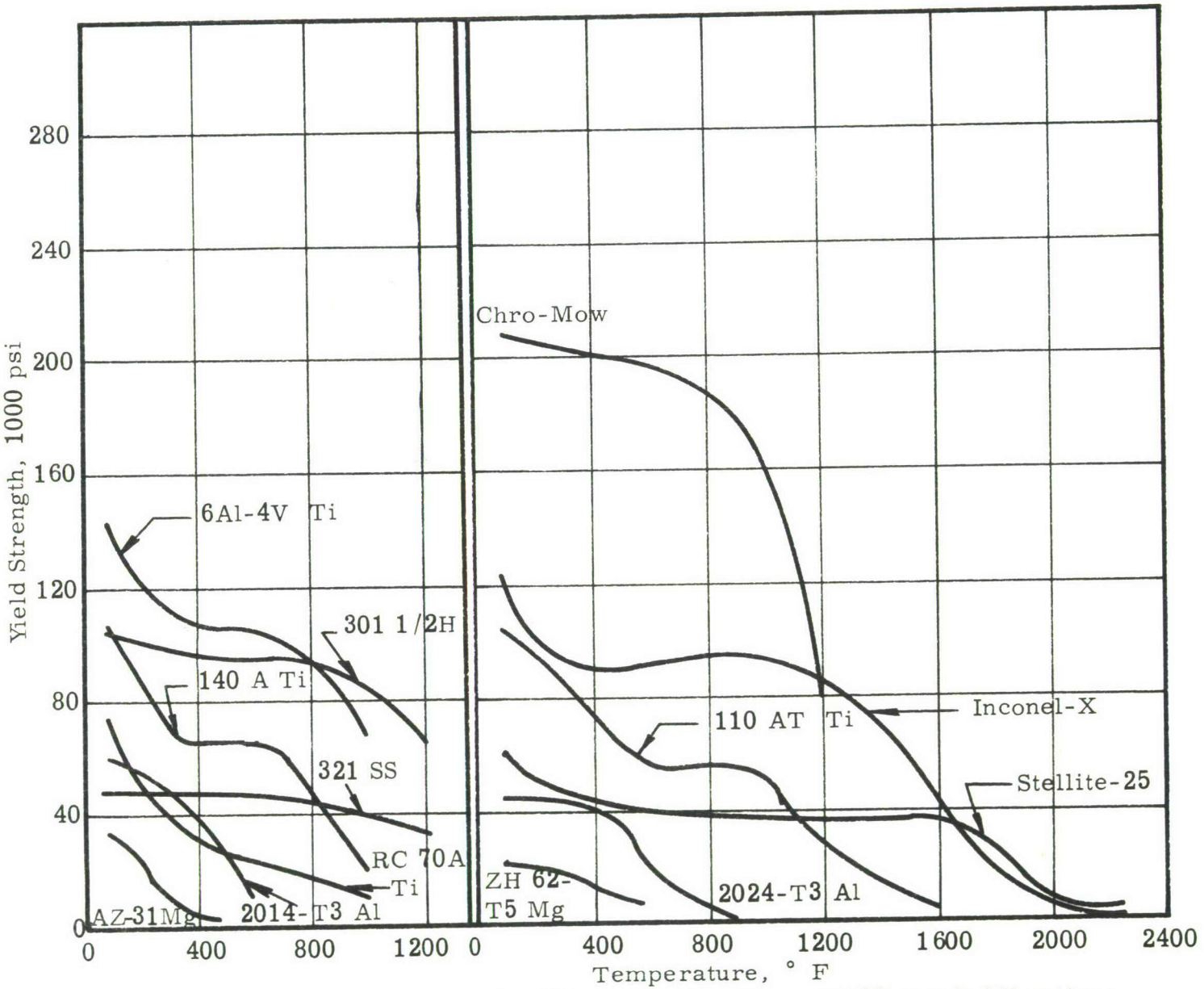

Figure 6. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of thirteen metals tensile tested at a strain rate of 0.00005 in./in./sec.

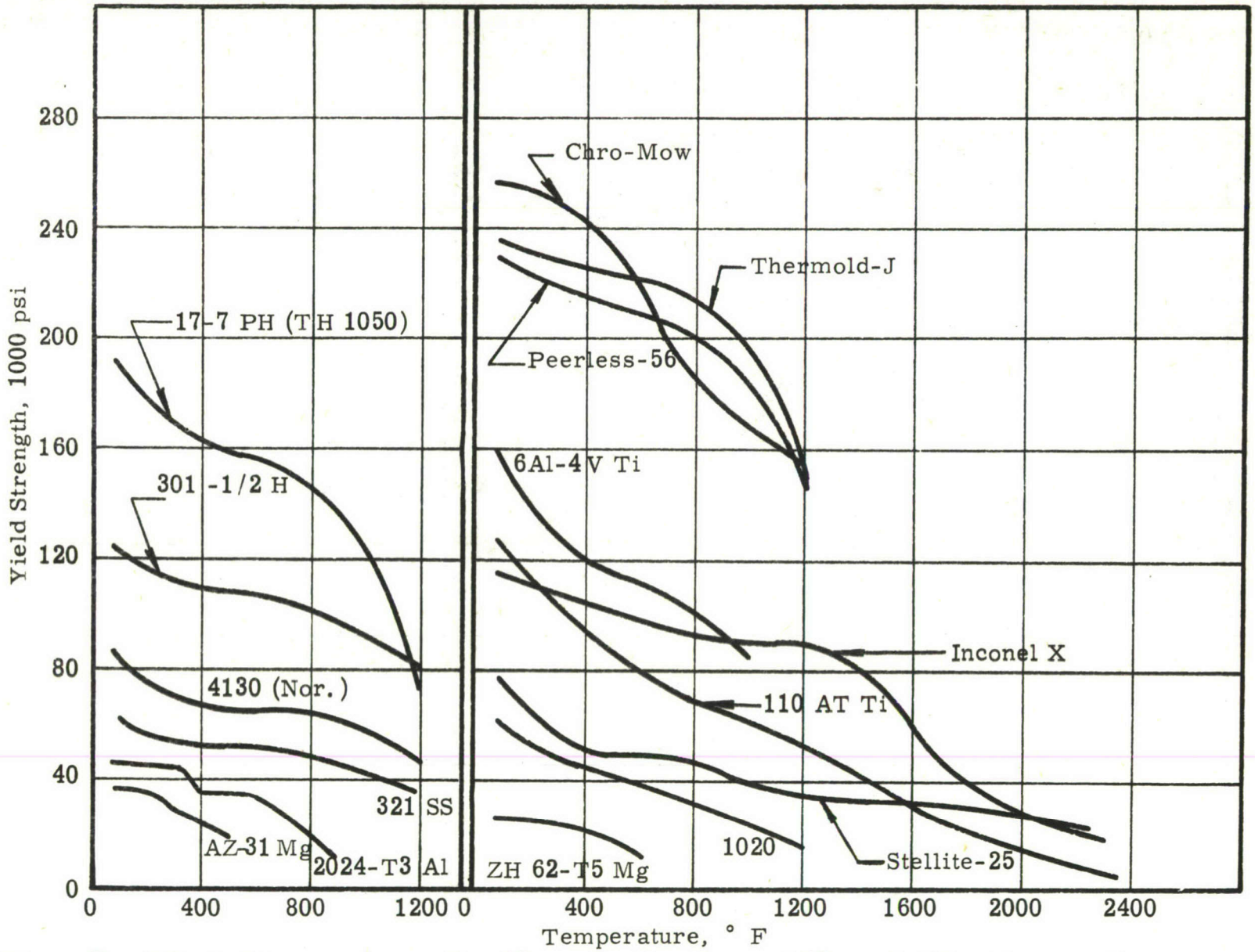

Figure 7. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of fifteen metals tensile tested at a strain rate of 1.0 in./in./sec.

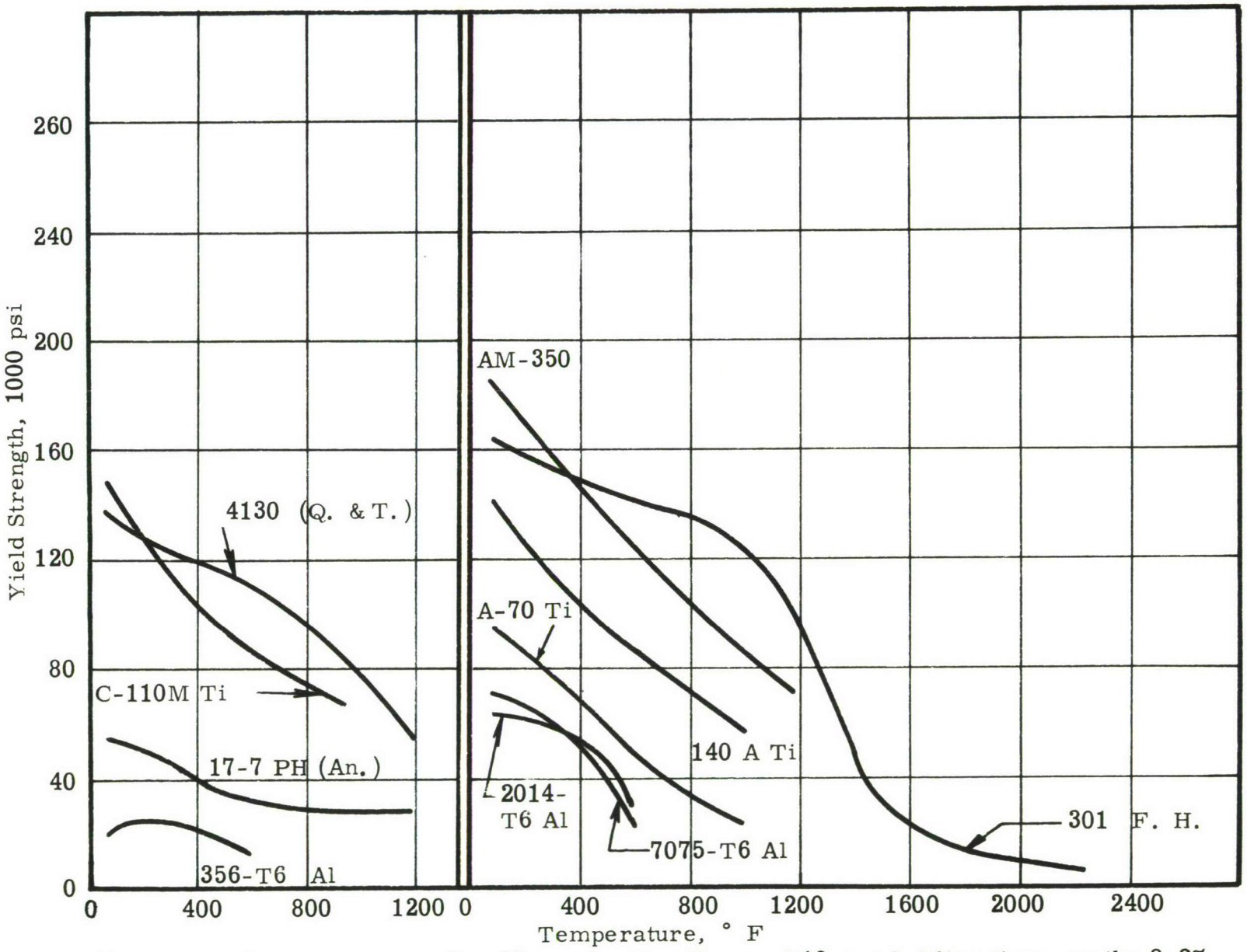

Figure 8. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of ten metals tensile tested at a strain rate of 1.0 in./in./sec.

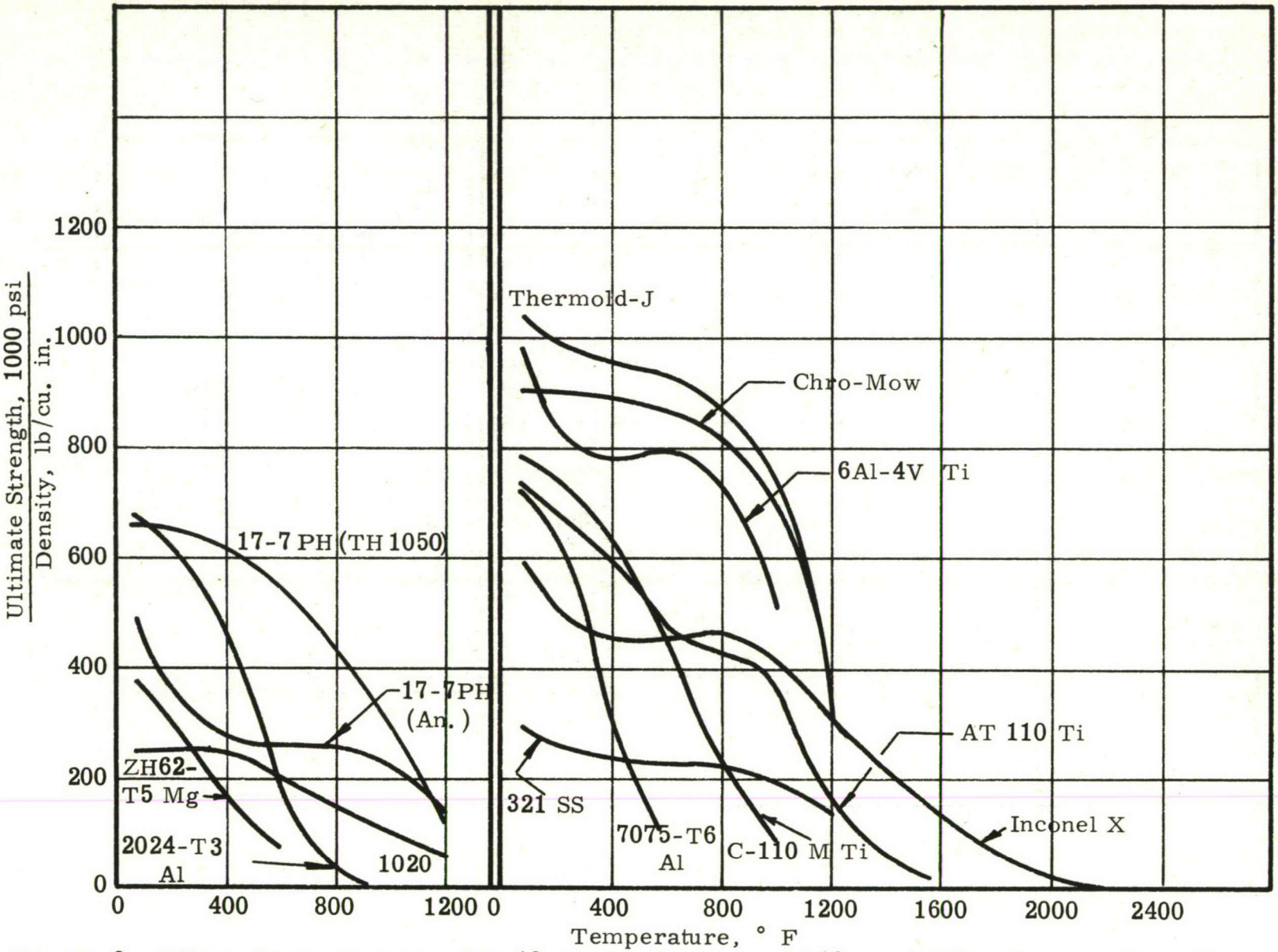

Figure 9. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of thirteen metals tensile tested at a strain rate of 0.00005 in. /in. /sec.

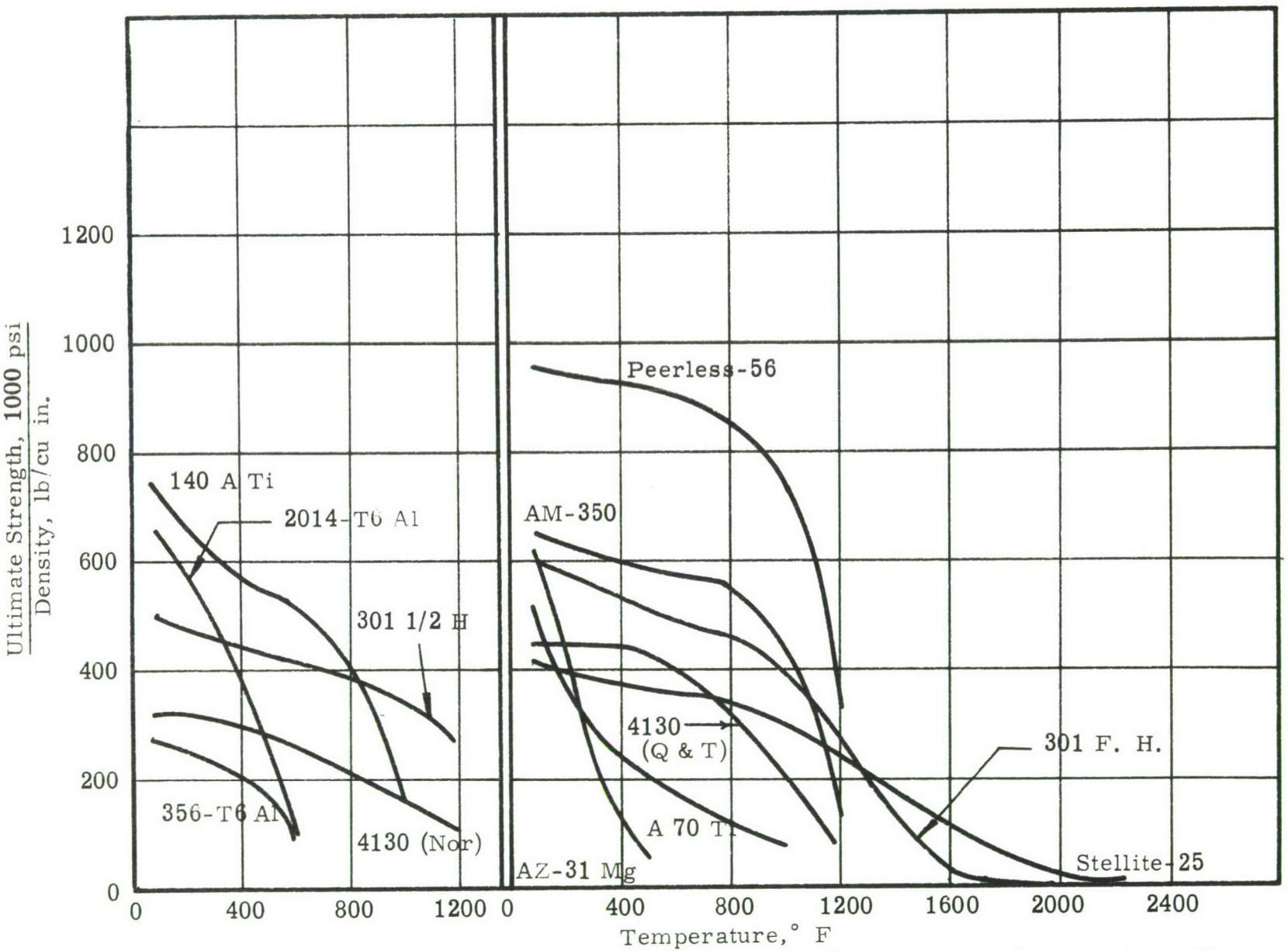

Figure 10. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of twelve metals tensile tested at a strain rate of 0.00005 in. /in. /sec

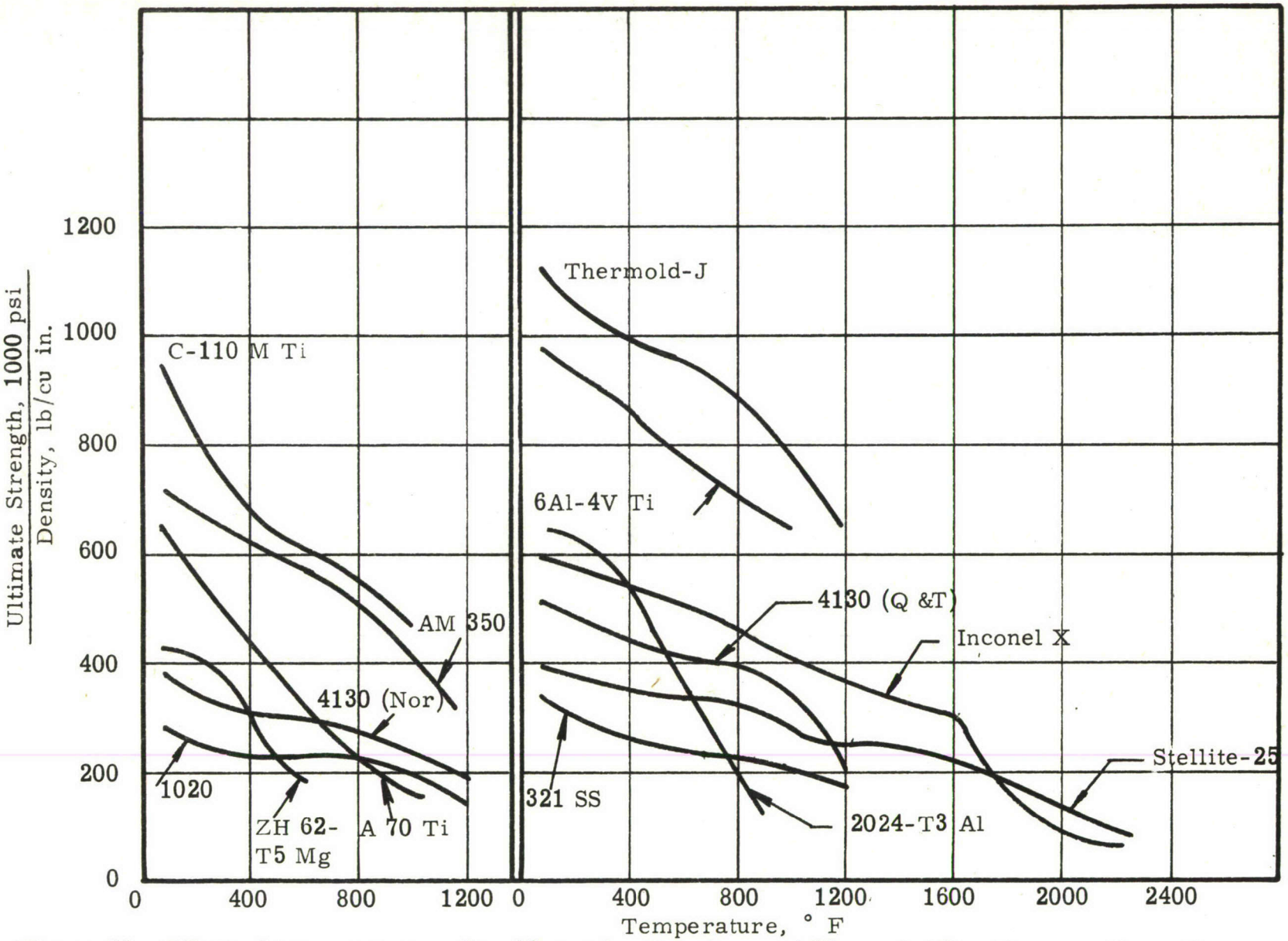

Figure 11. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of thirteen metals tensile tested at a strain rate of 1.0 in. /in. /sec.

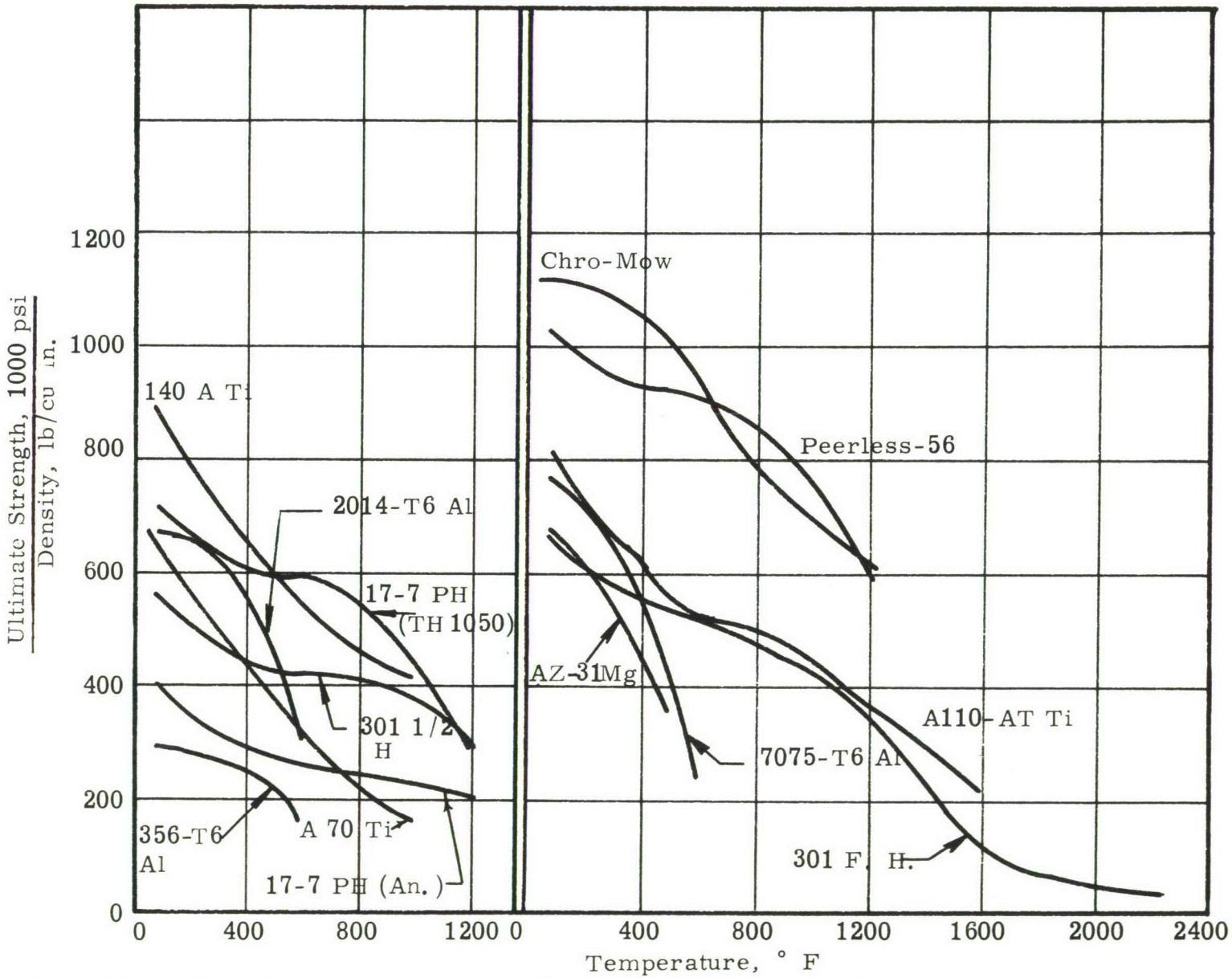

Figure 12. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of ultimate tensile strength to density of twelve metals tensile tested at a strain rate of 1.0 in. /in. /sec.

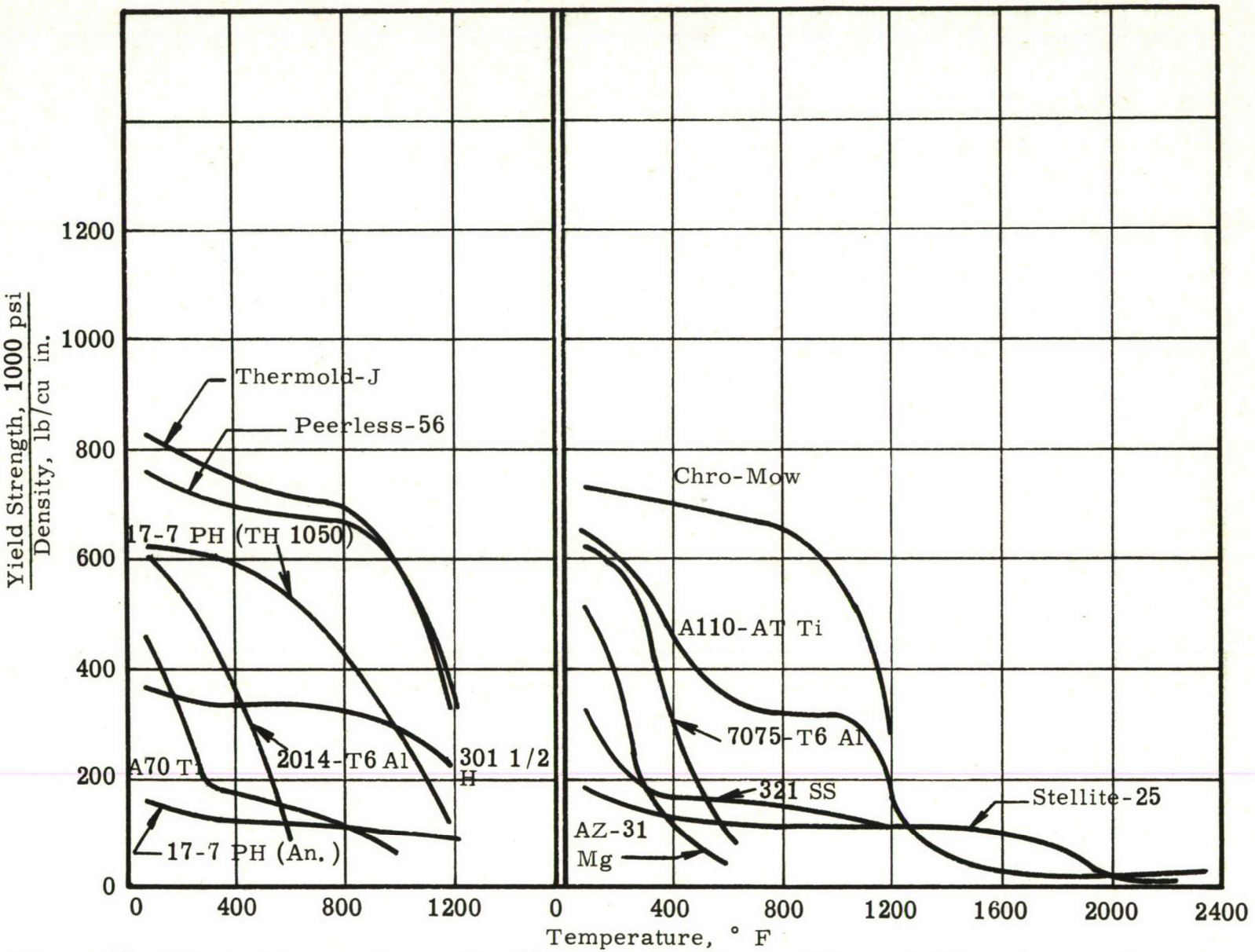

Figure 13. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of thirteen metals tensile tested at a strain rate of 0.00005 in./in./sec.

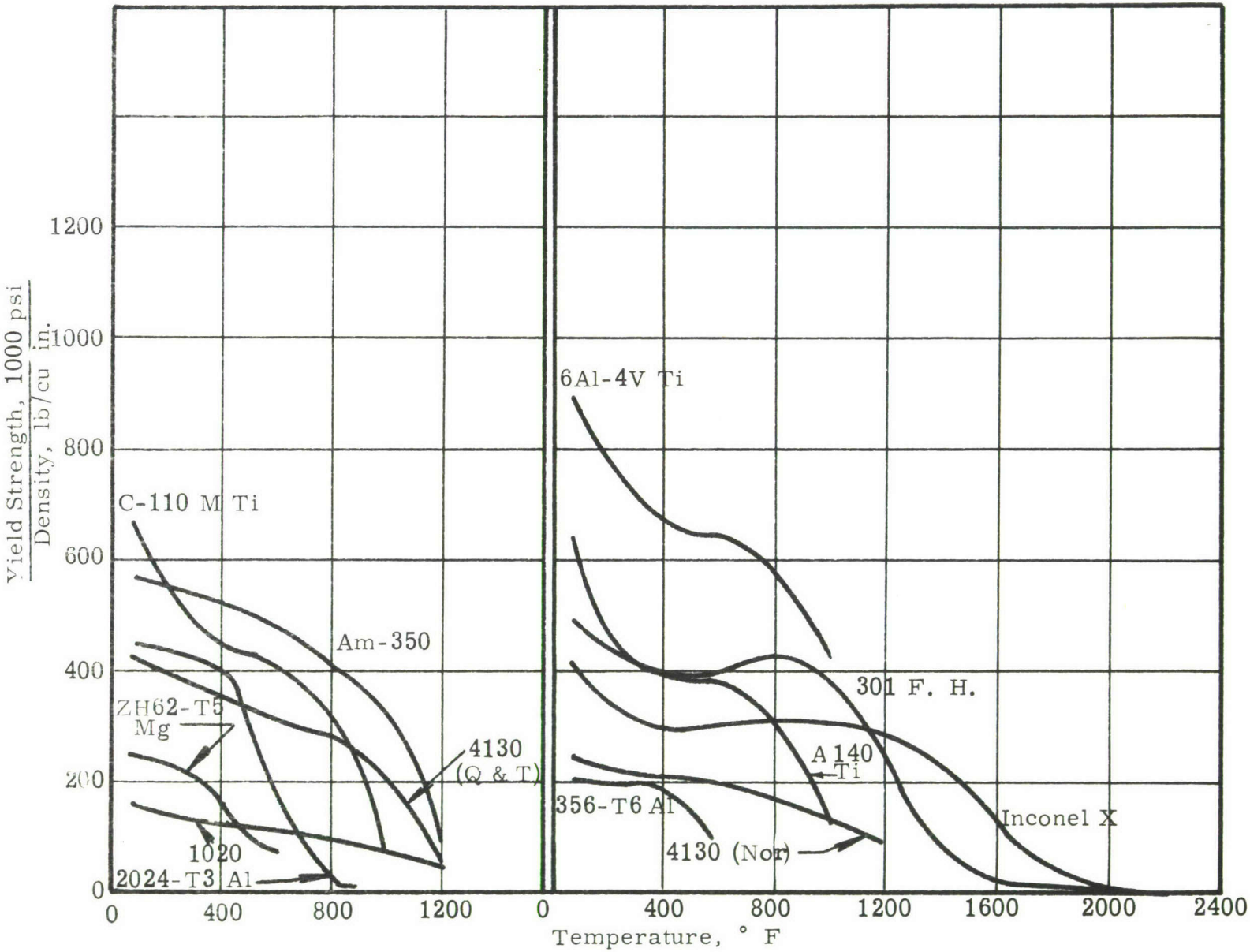

Figure 14. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of twelve metals tensile tested at a strain rate of 0.00005 in./in./sec.

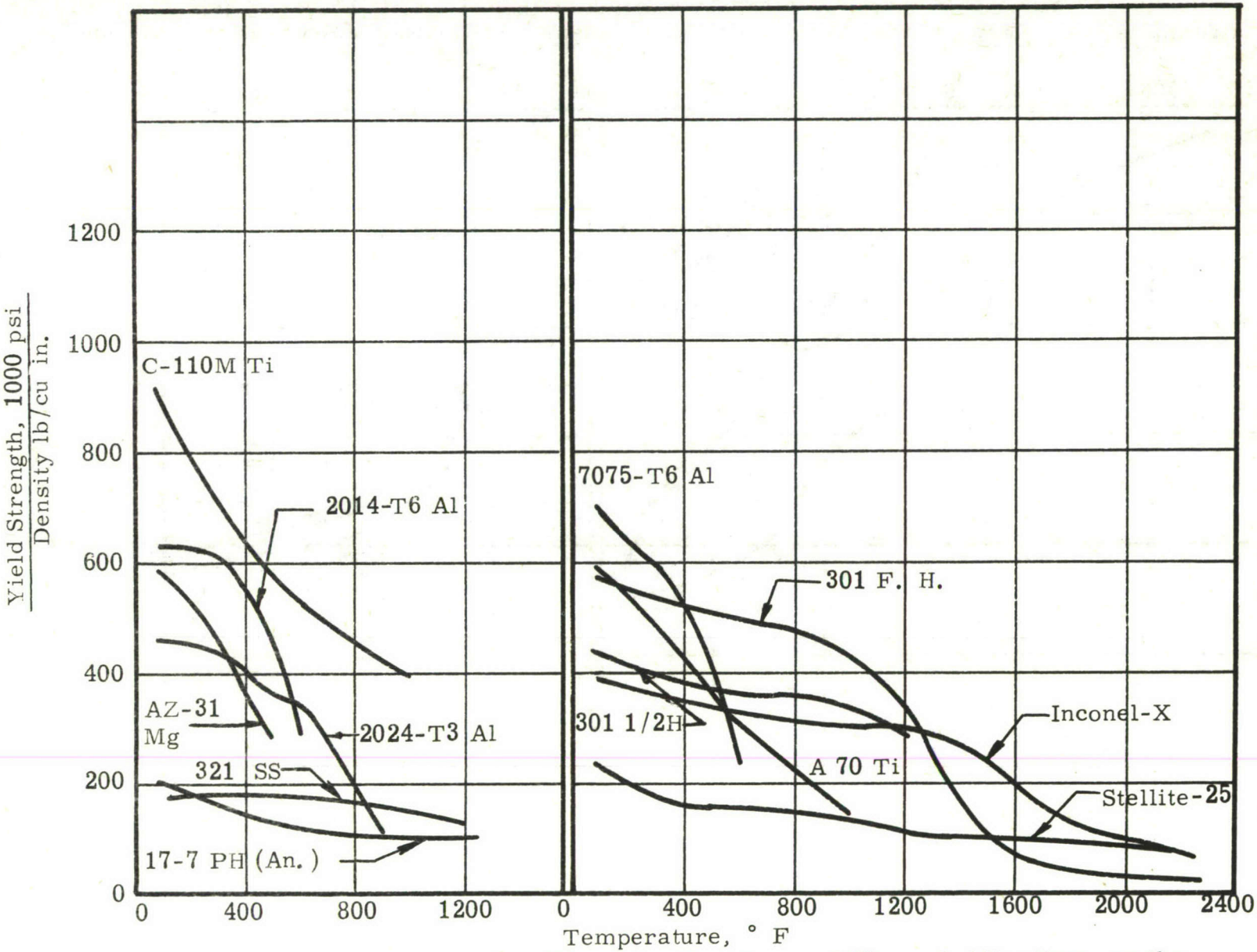

Figure 15. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of twelve metals tensile tested at a strain rate of 1.0 in./in./sec.

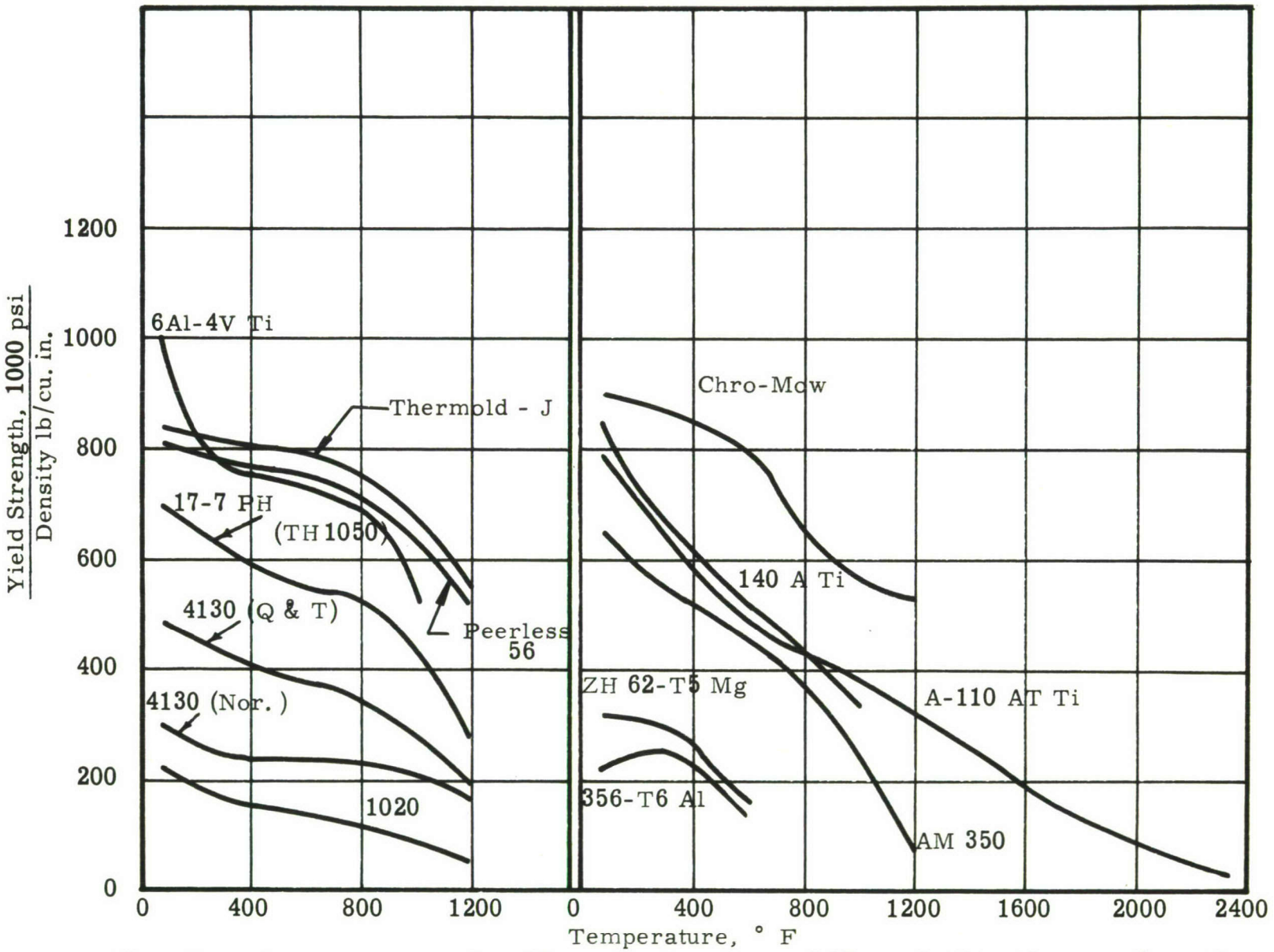

Figure 16. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the ratio of 0.2%-offset yield strength to density of thirteen metals tensile tested at a strain rate of 1.0 in./in./sec.

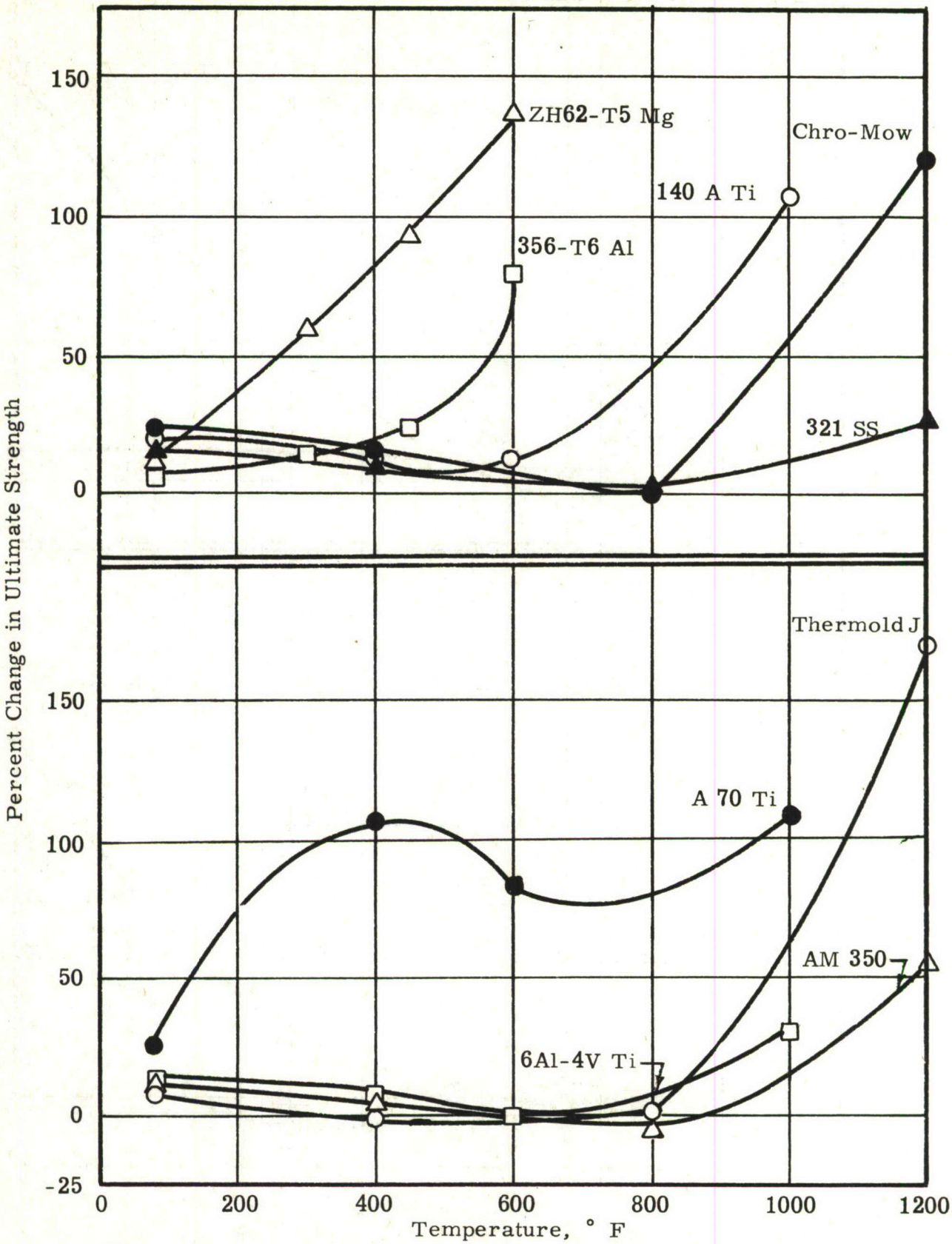

Figure 17. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec

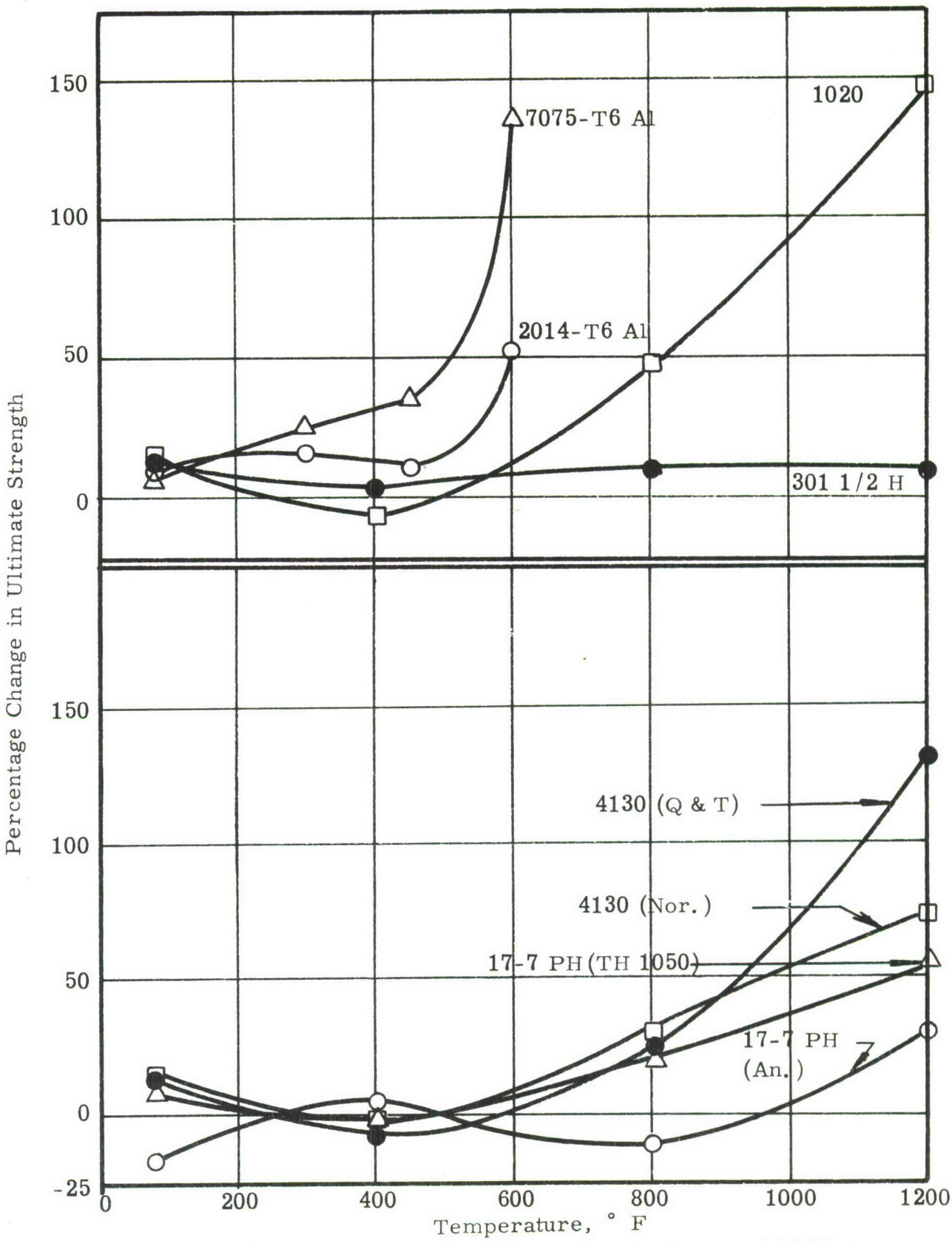

Figure 18. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec.

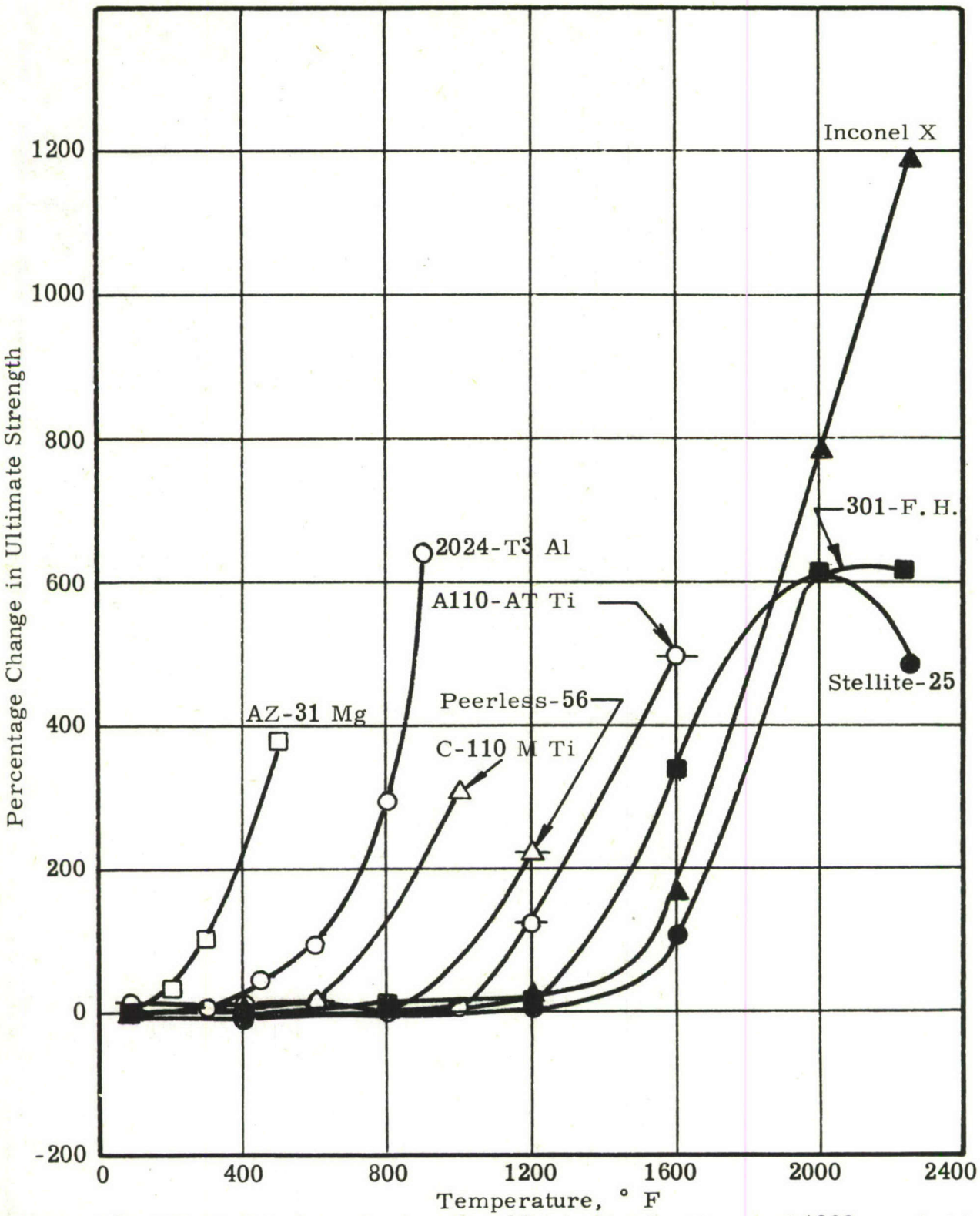

Figure 19. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in ultimate tensile strength resulting from an increase in strain rate from 0.00005 to 1.0 in. / in. /sec.

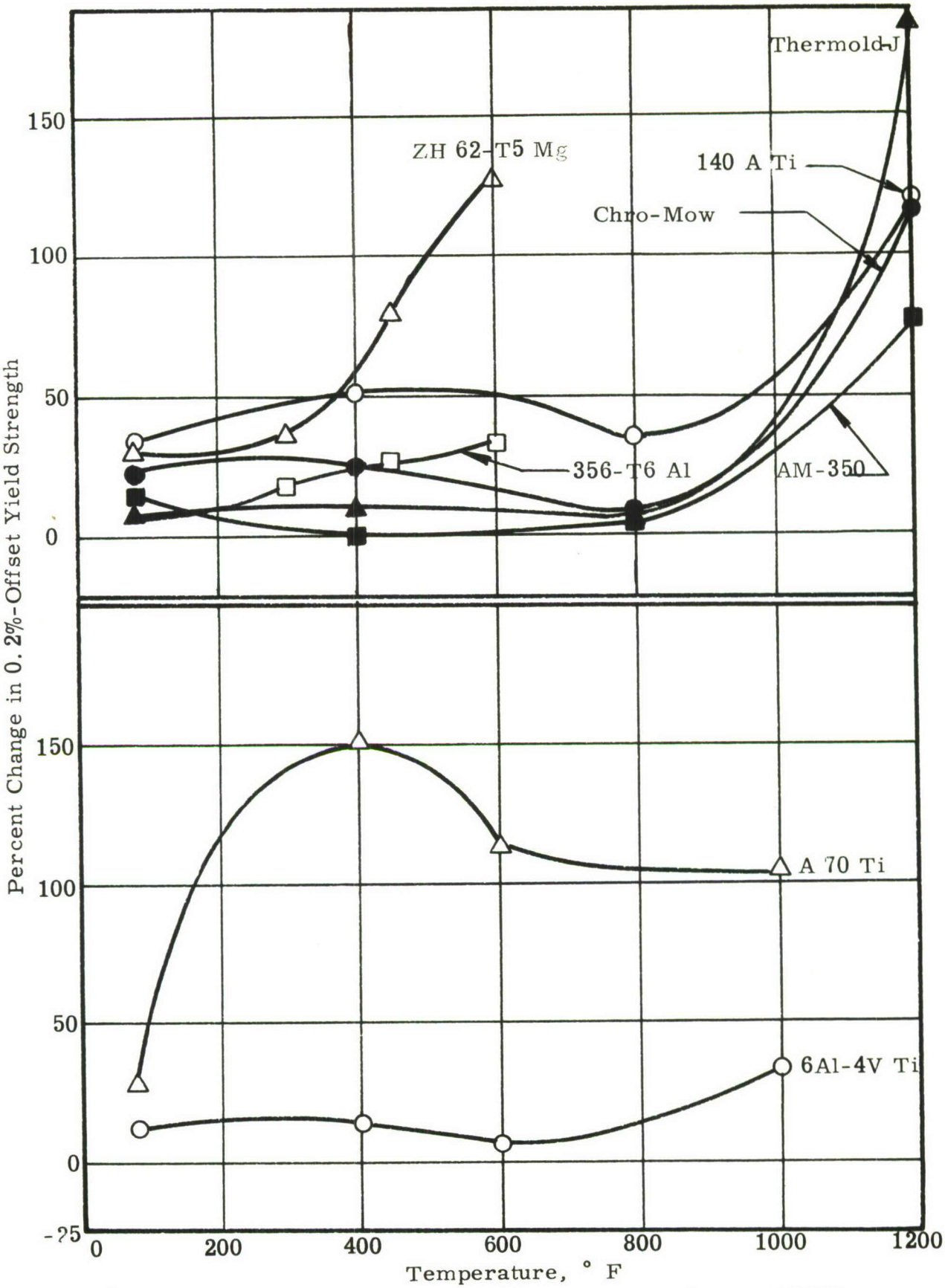

Figure 20. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec

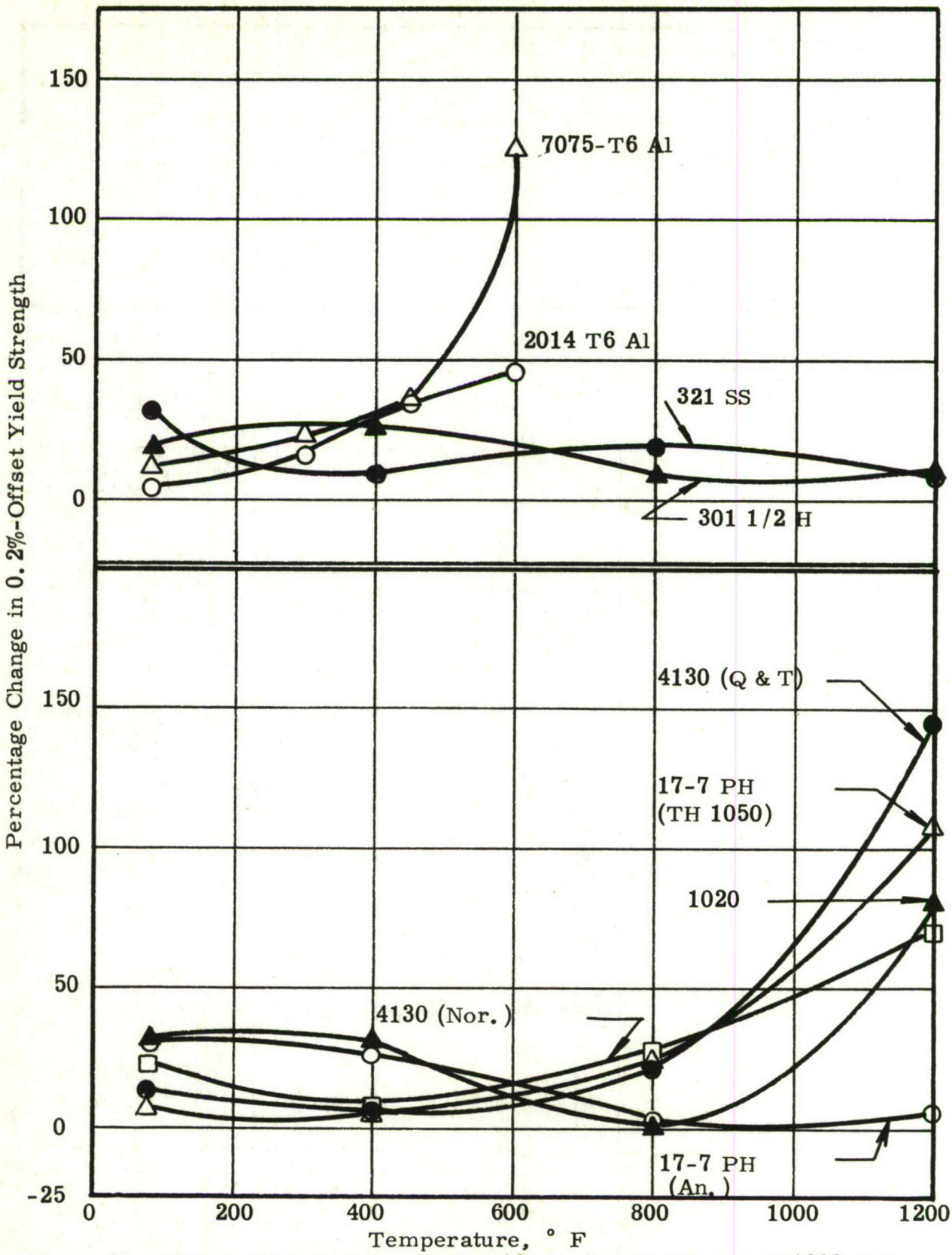

Figure 21. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec.

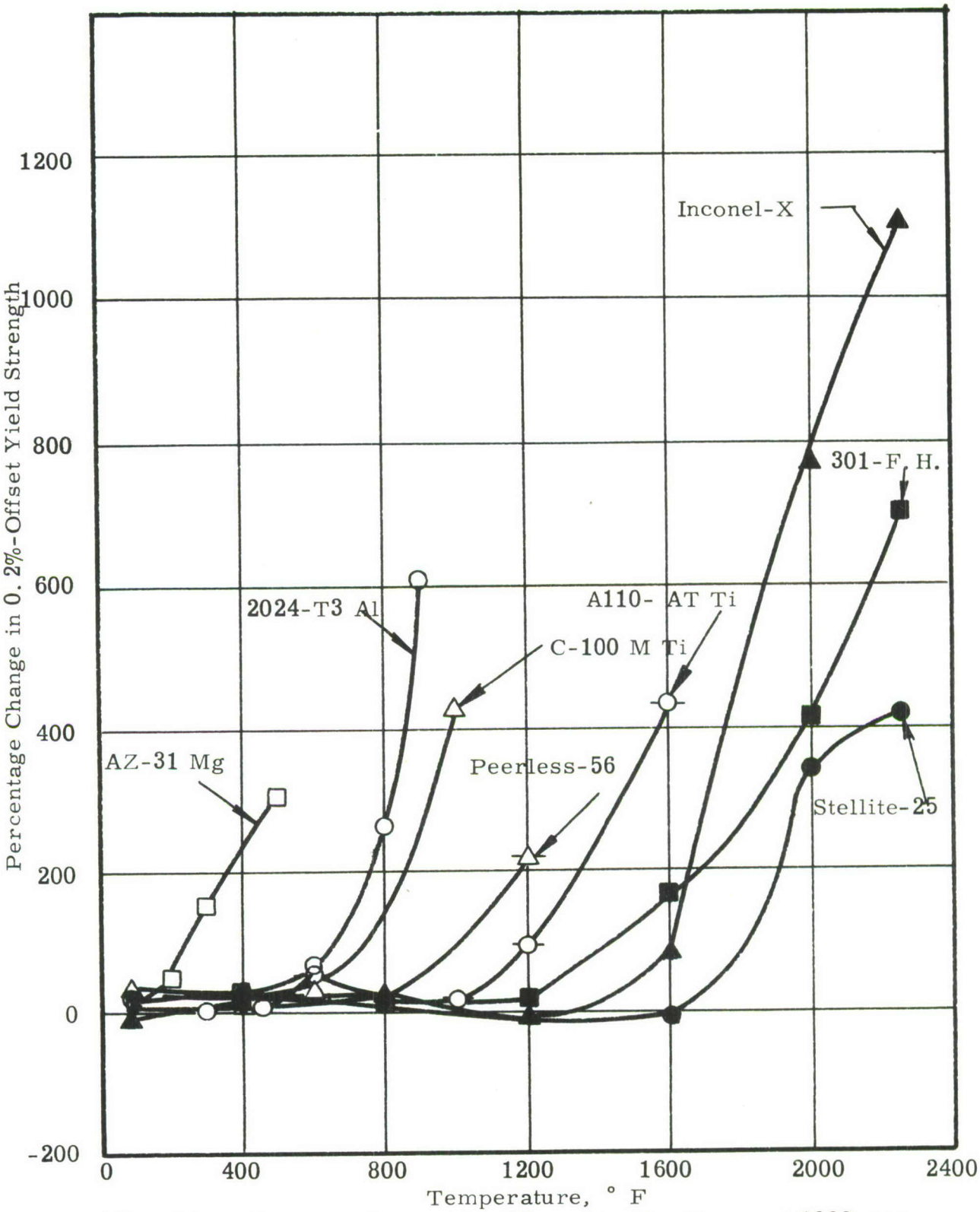

Figure 22. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percentage change in 0.2%-offset yield strength resulting from an increase in strain rate from 0.00005 to 1.0 in./in./sec.

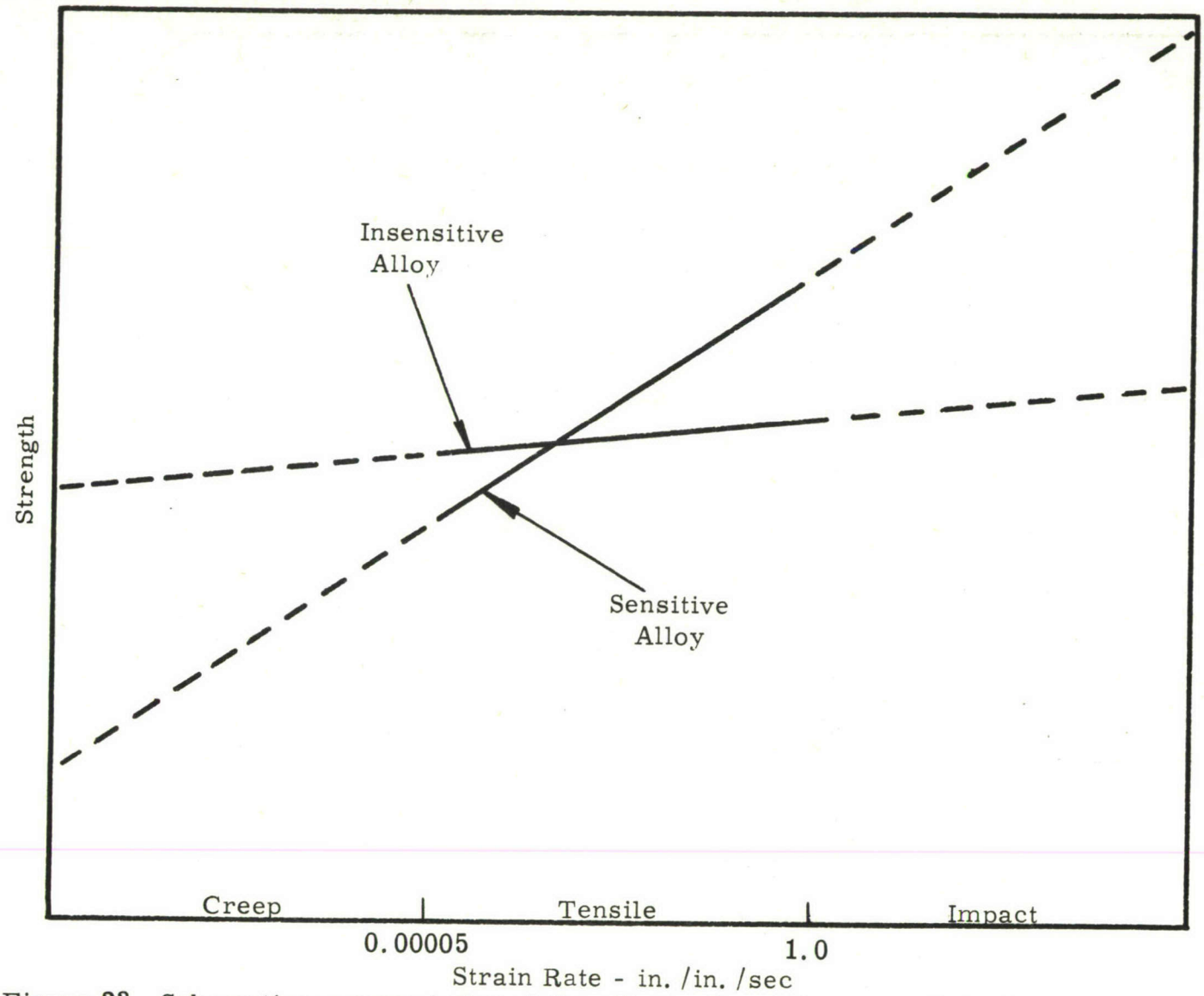

Figure 23. Schematic representation of the effects of a wide range of strain rates on one alloy in which strength is sensitive and another alloy in which strength is not sensitive to changes in strain rate.

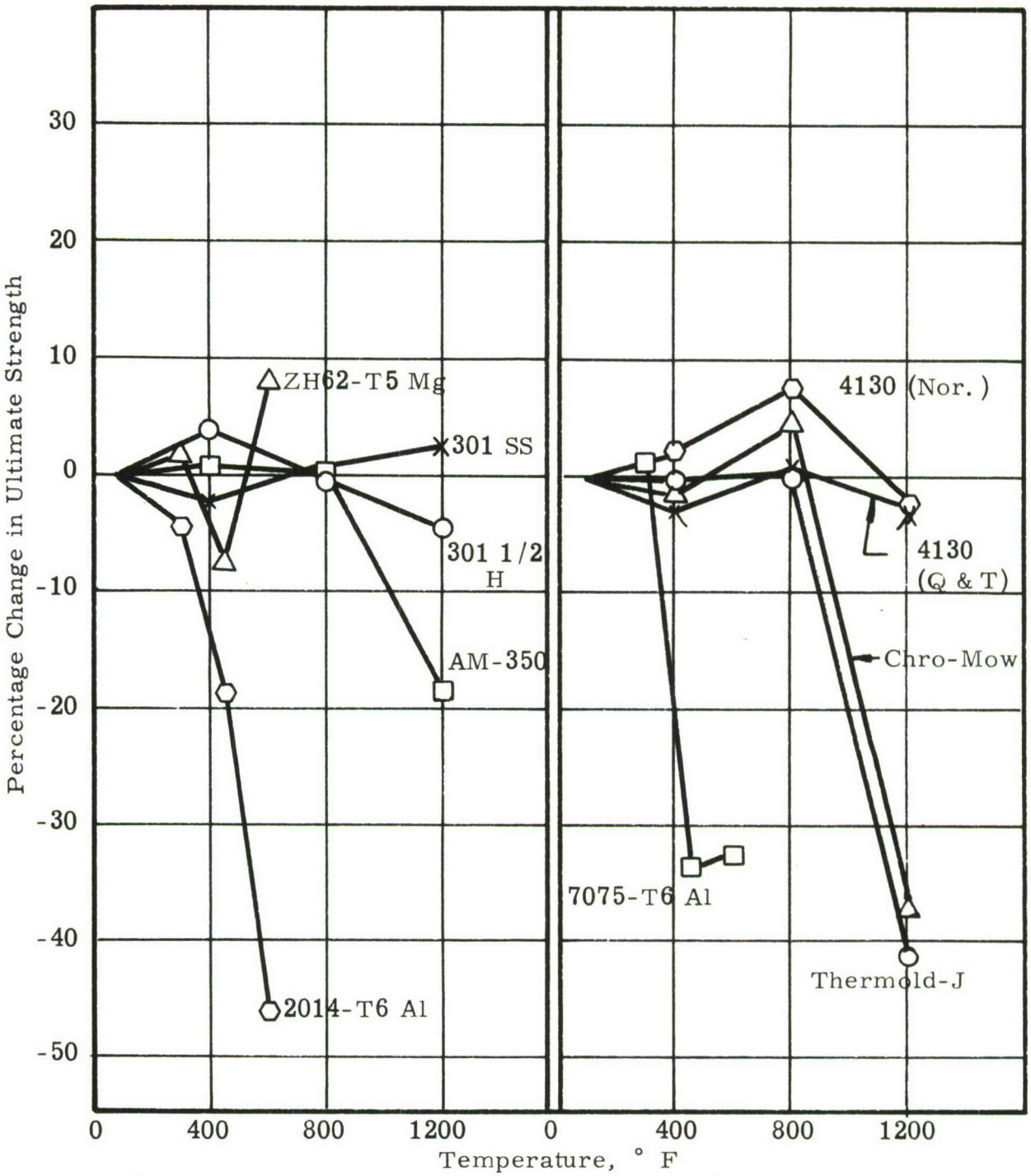

Figure 24. Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

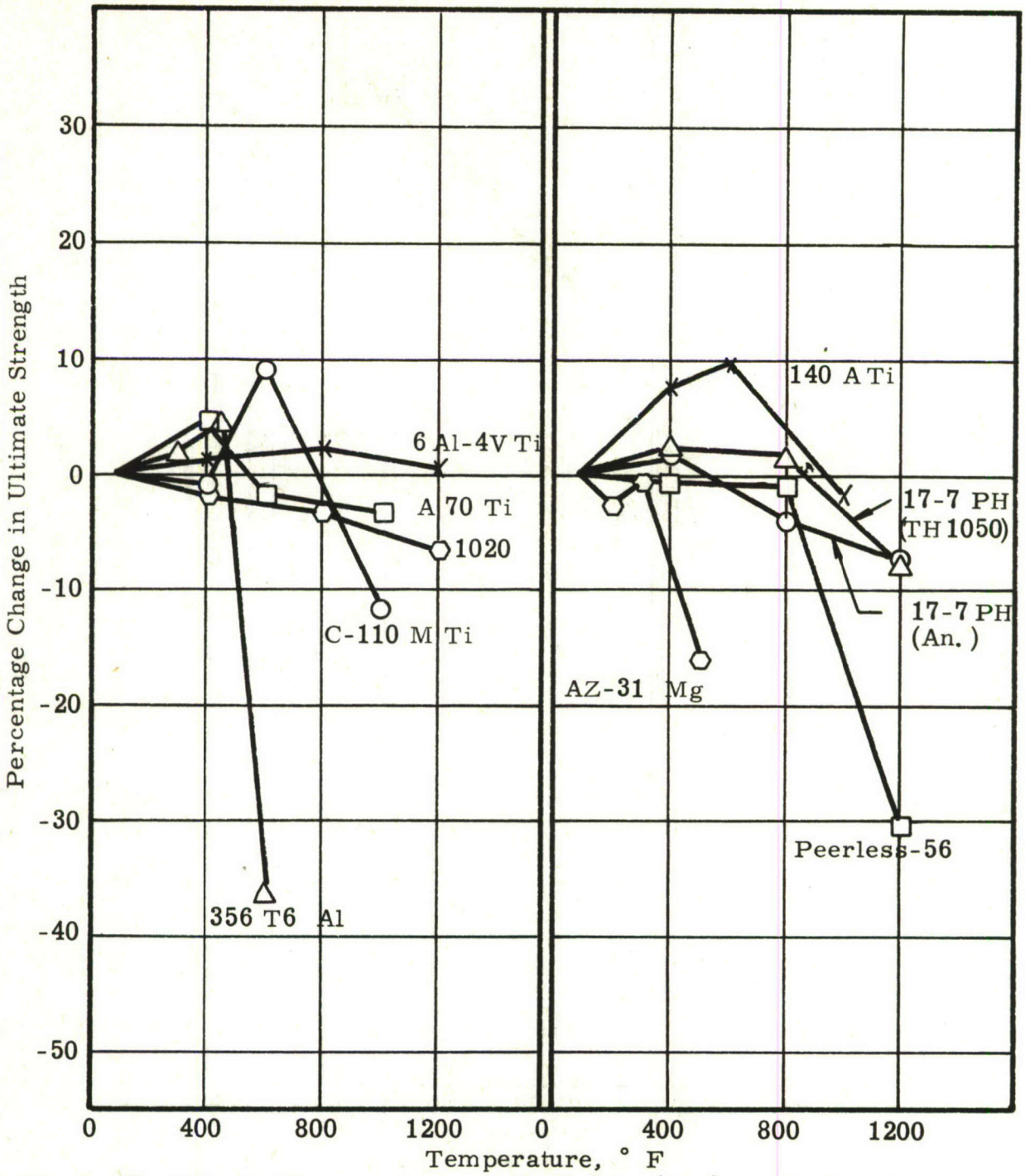

Figure 25. Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

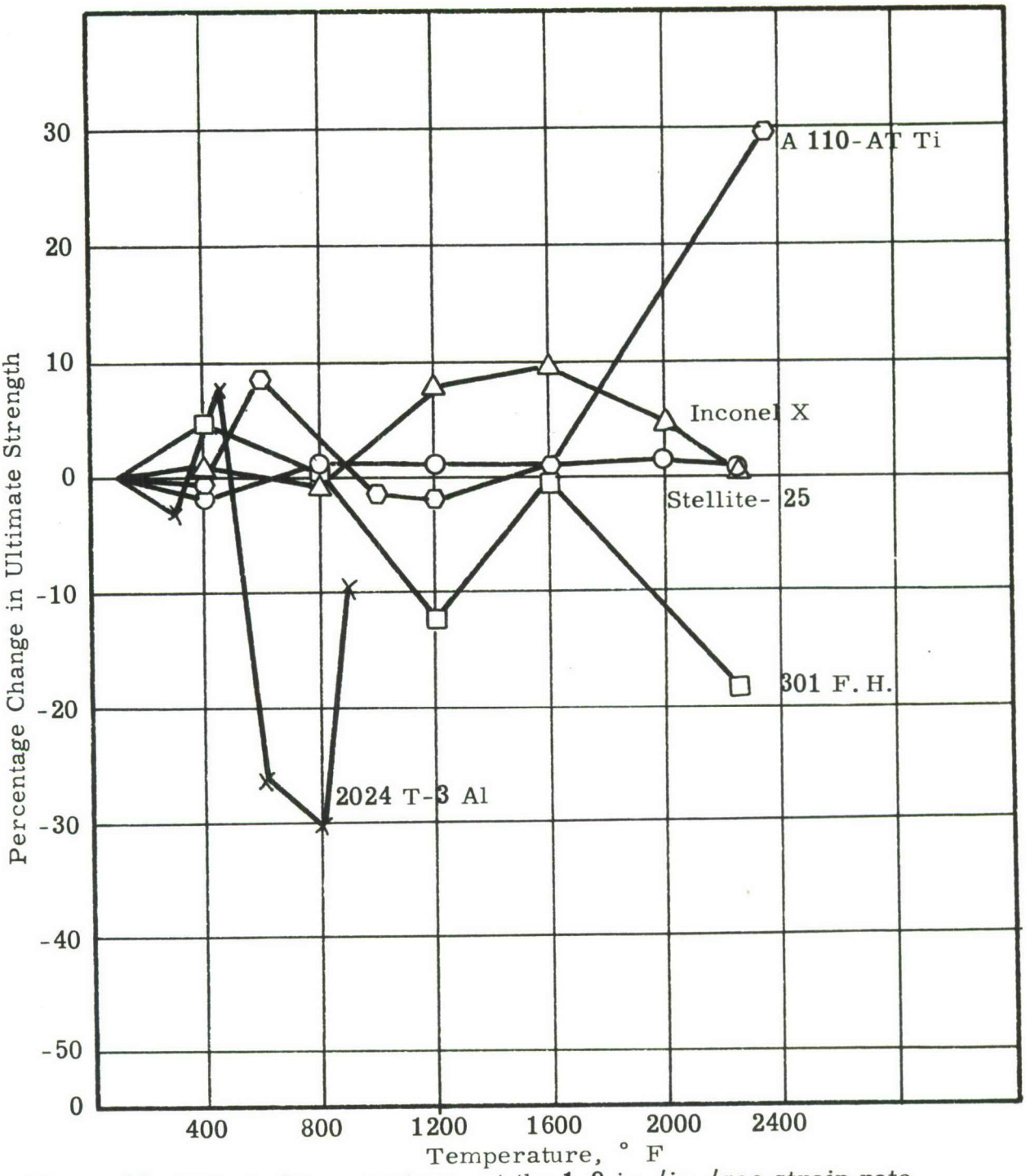

Figure 26. Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in ultimate tensile strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

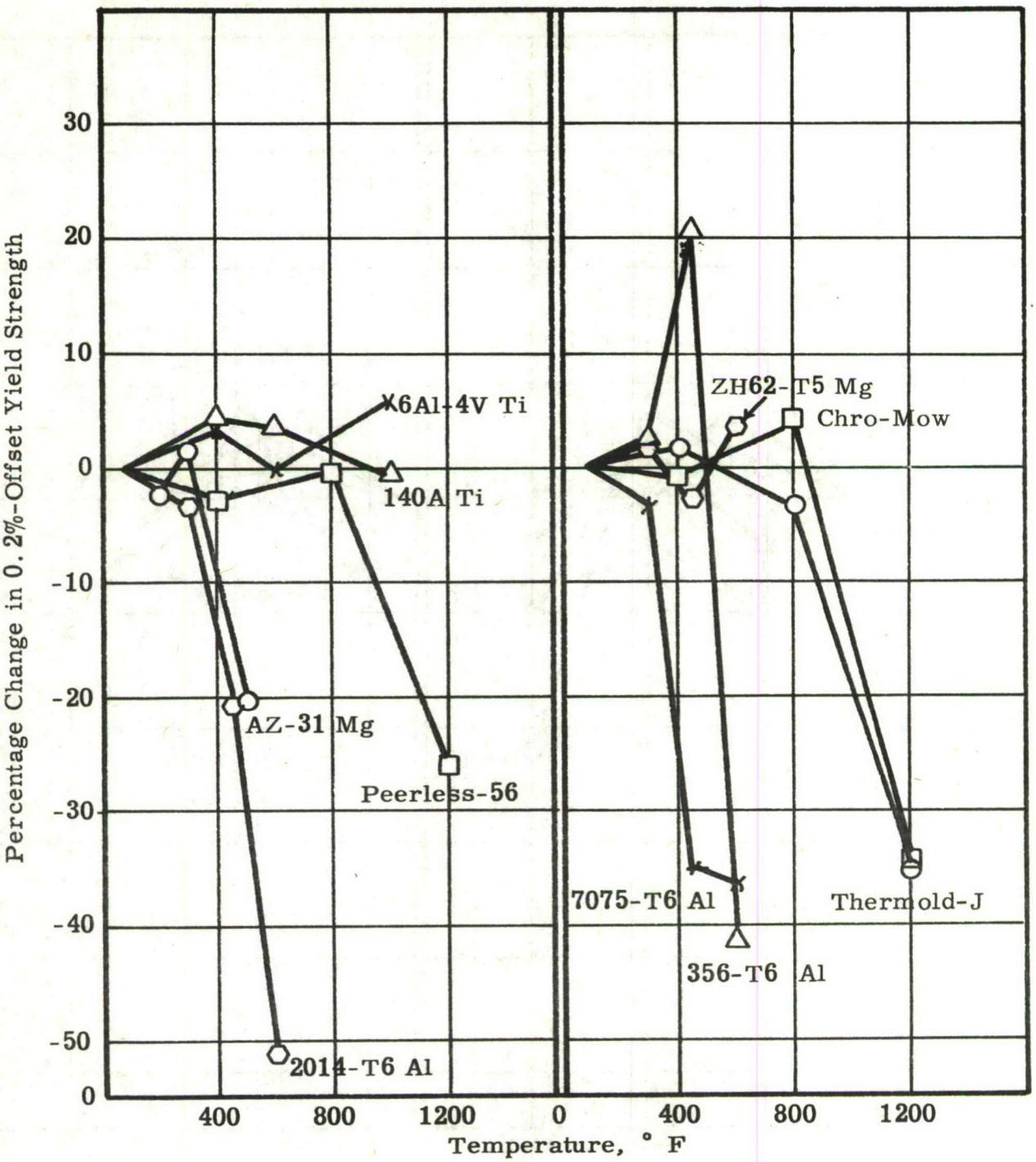

Figure 27. Effect of temperature, at the 1.0 in./in./sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

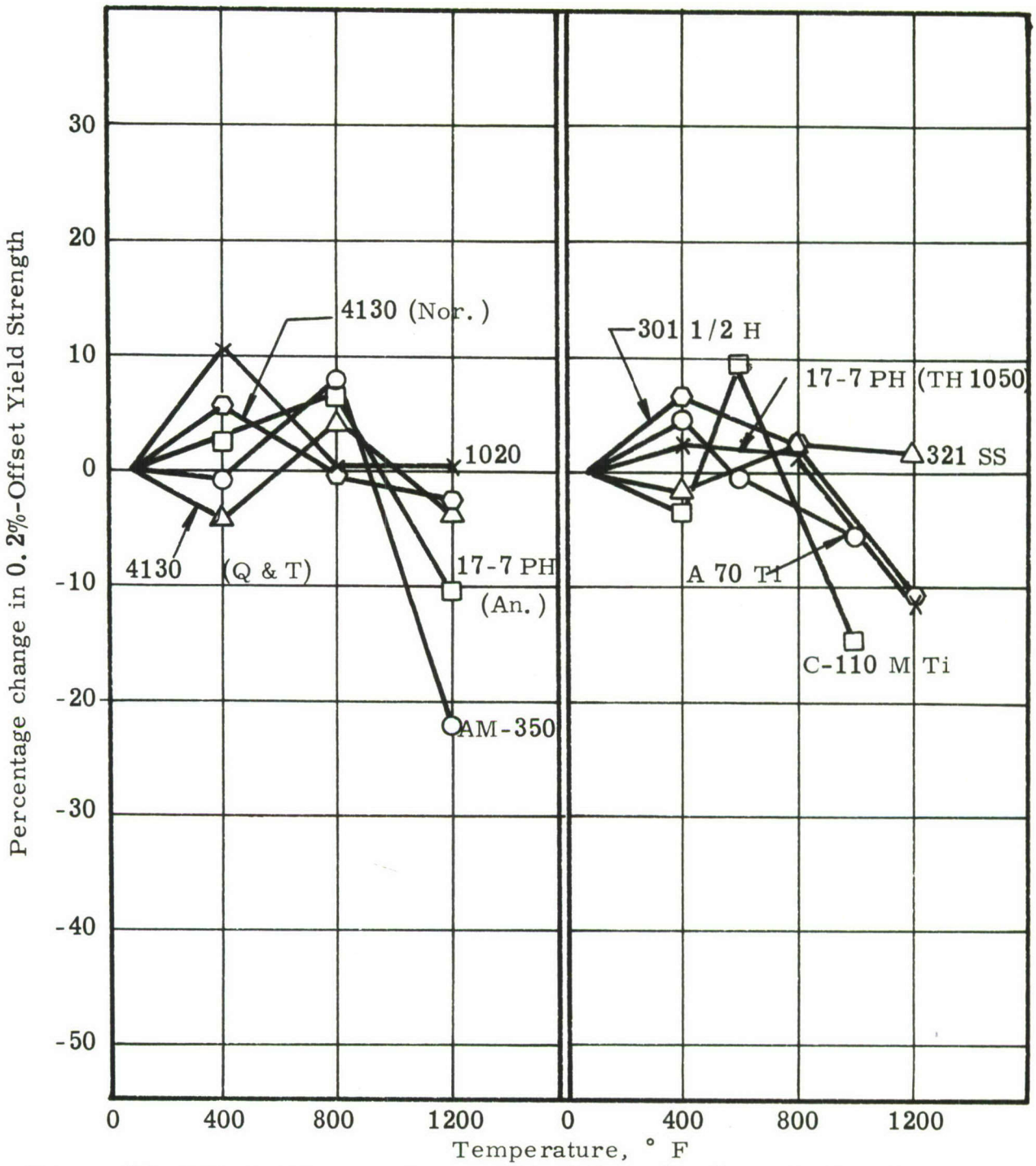

Figure 28. Effect of temperature, at the 1.0 in./in./sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

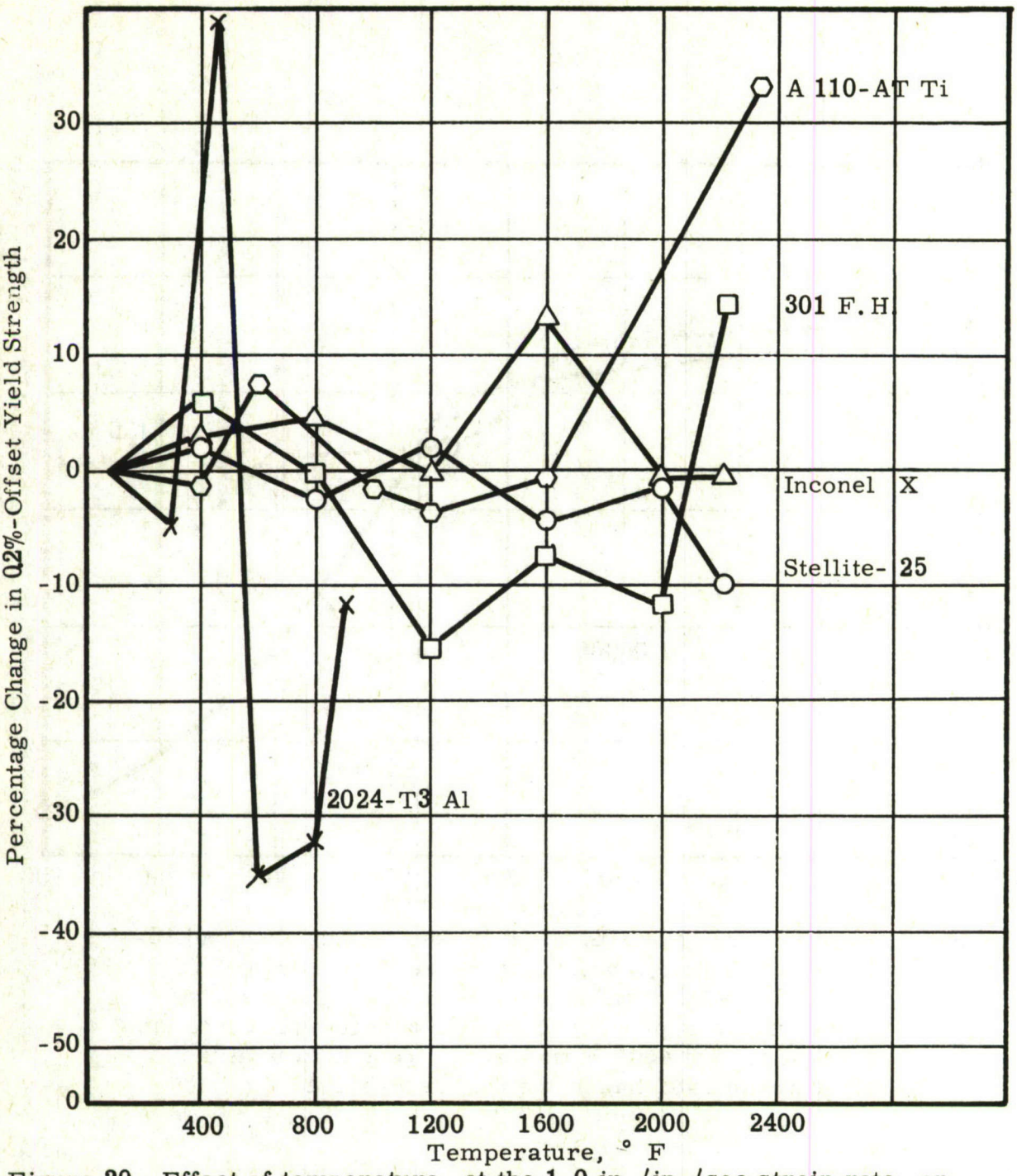

Figure 29. Effect of temperature, at the 1.0 in. /in. /sec strain rate, on the percentage change in 0.2%-offset yield strength resulting from an increase in holding time from 10 sec to 1800 sec at test temperature.

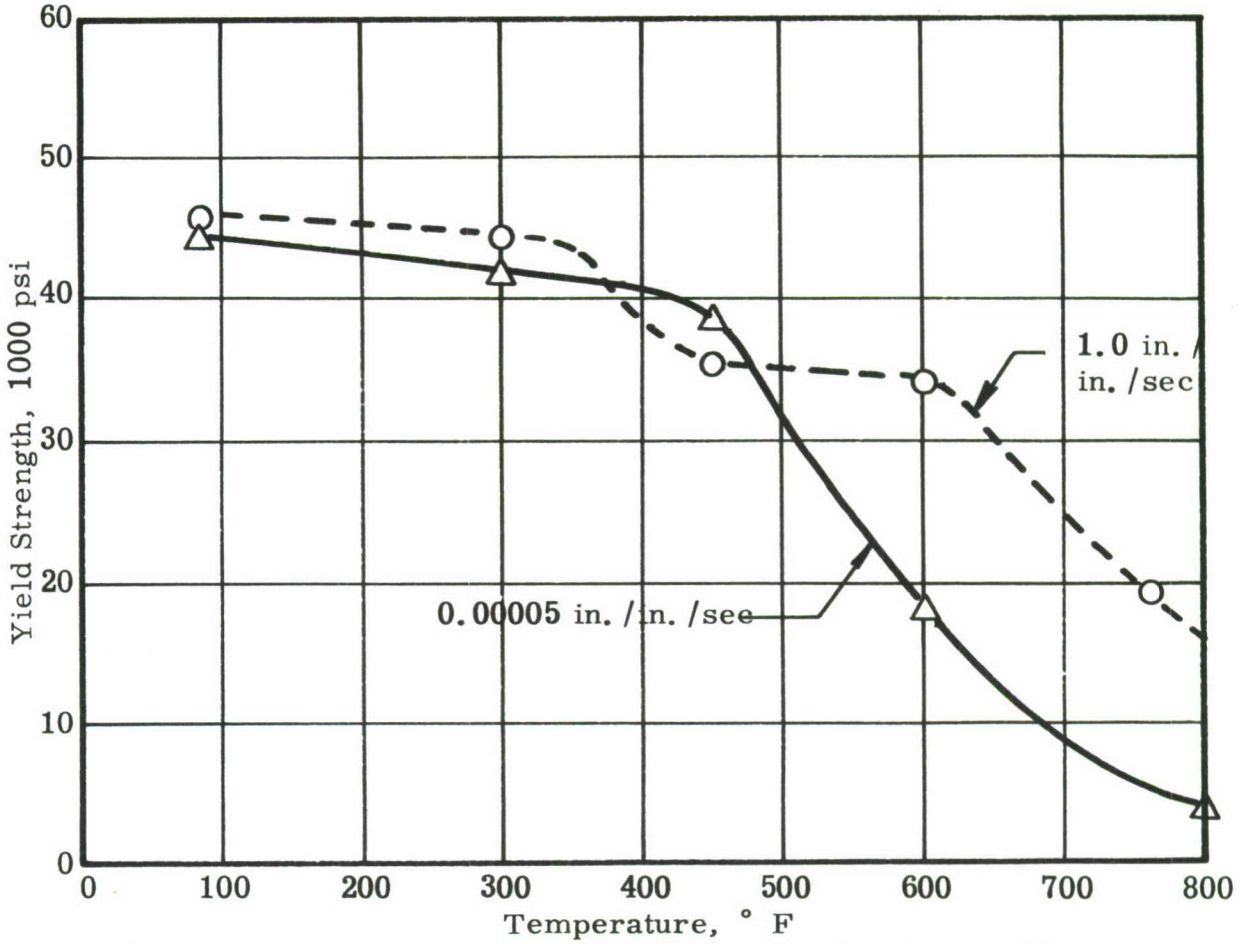

Figure 30. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy illustrating that a time-temperature-dependent structural change—precipitation hardening—at 450° F improves strength more at the slow strain rate than at the rapid strain rate.

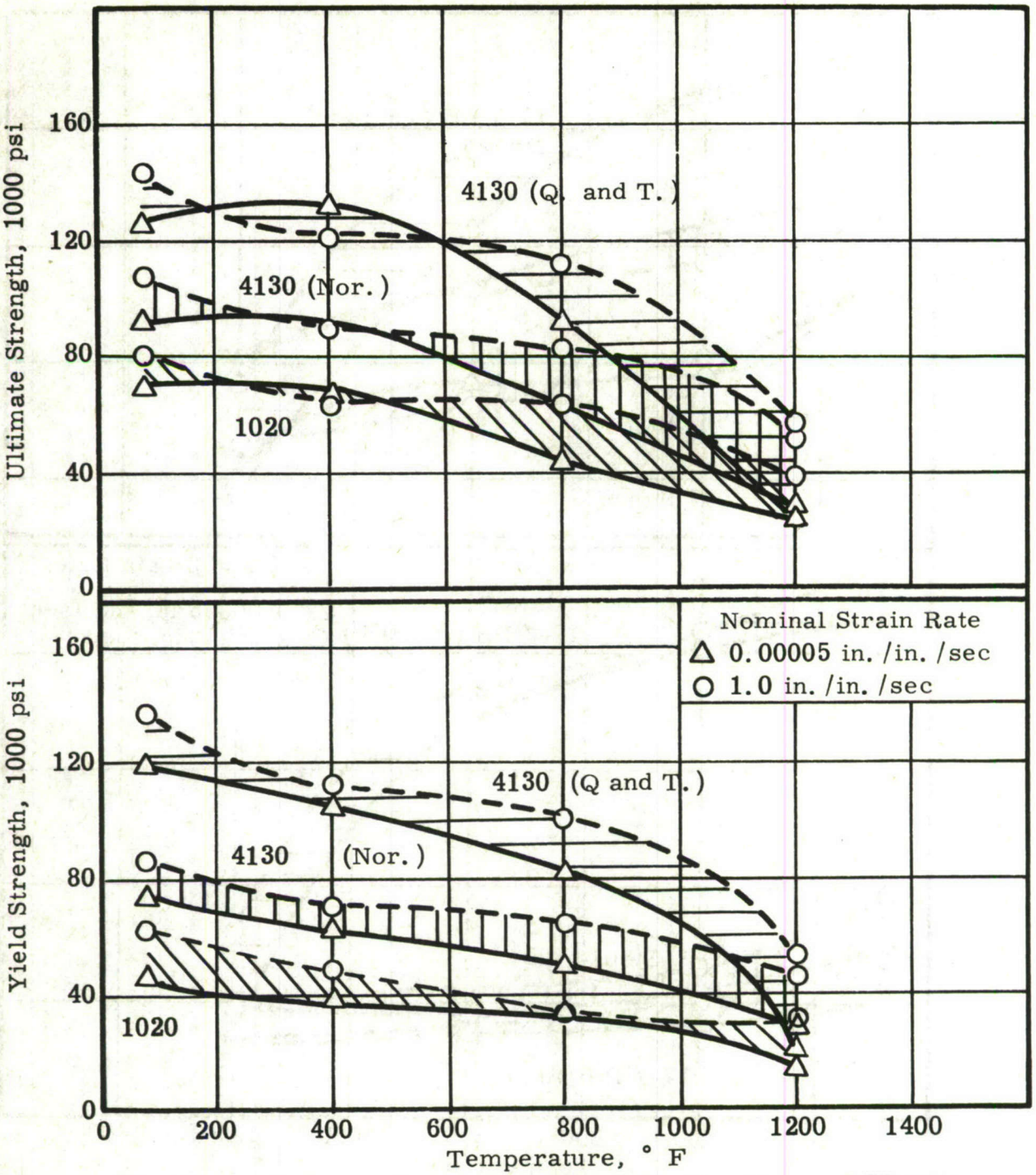

Figure 31. Effects of temperature, after 10-sec heating time and 30-min holding time, on the ultimate strength and 0.2%-offset yield strength of carbon steel and of low-alloy steel at two strain rates.

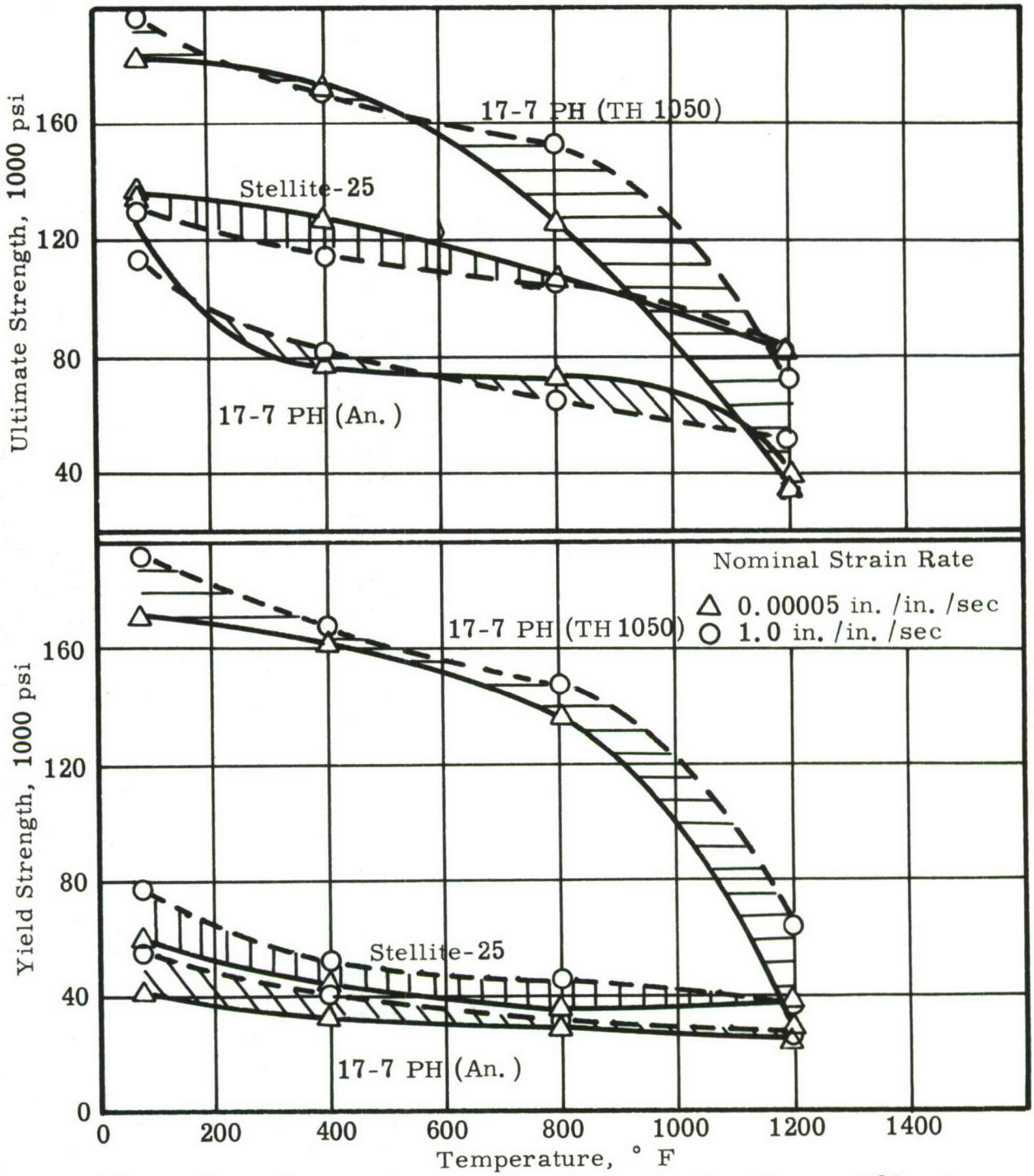

Figure 32. Effect of temperature, after 10-sec heating time and 30-min holding time, on the ultimate strength and 0.2%-offset yield strength of three test alloys.

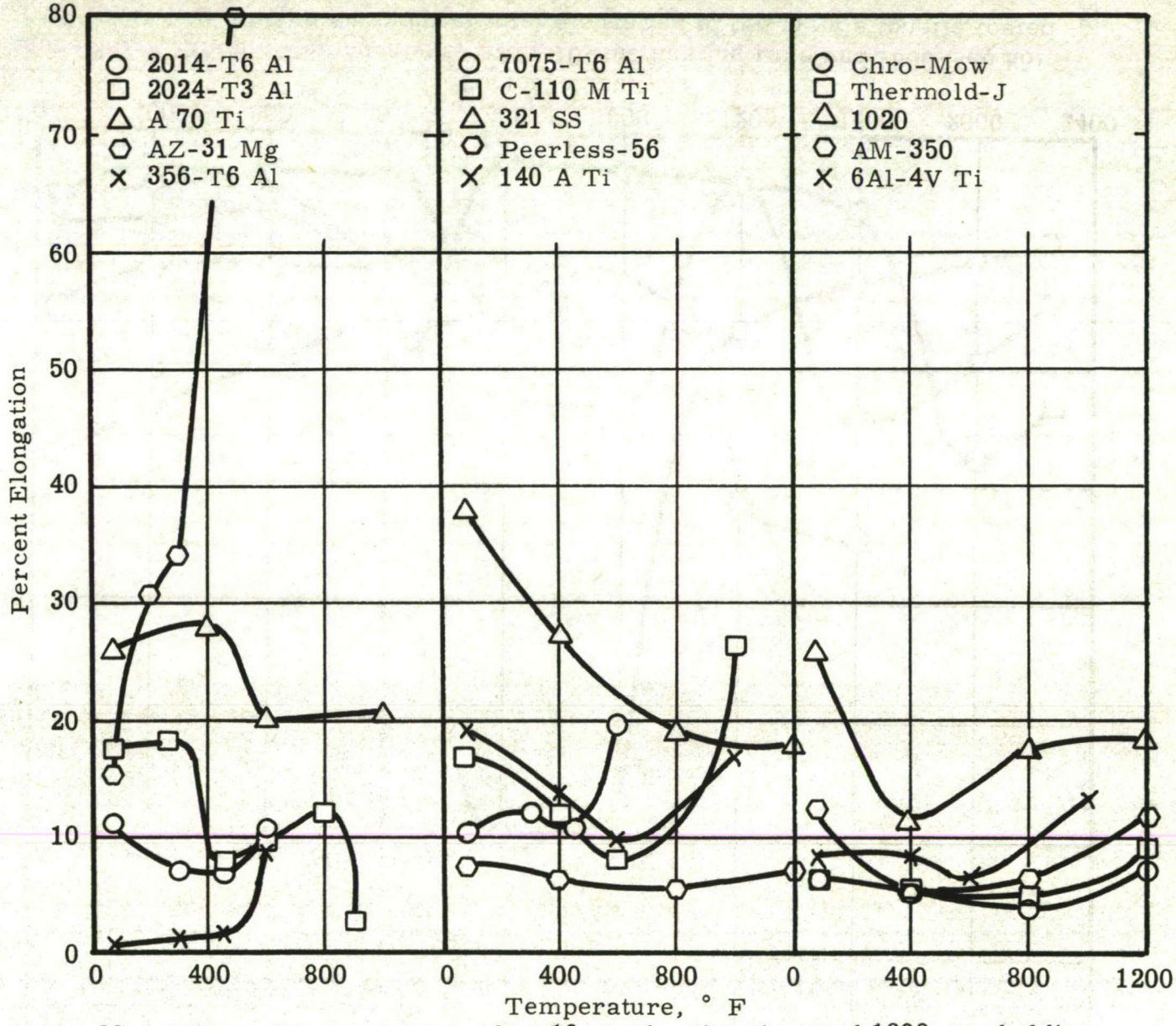

Table 33. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of fifteen metals tensile tested at a strain rate of 0.00005 in./in./sec.

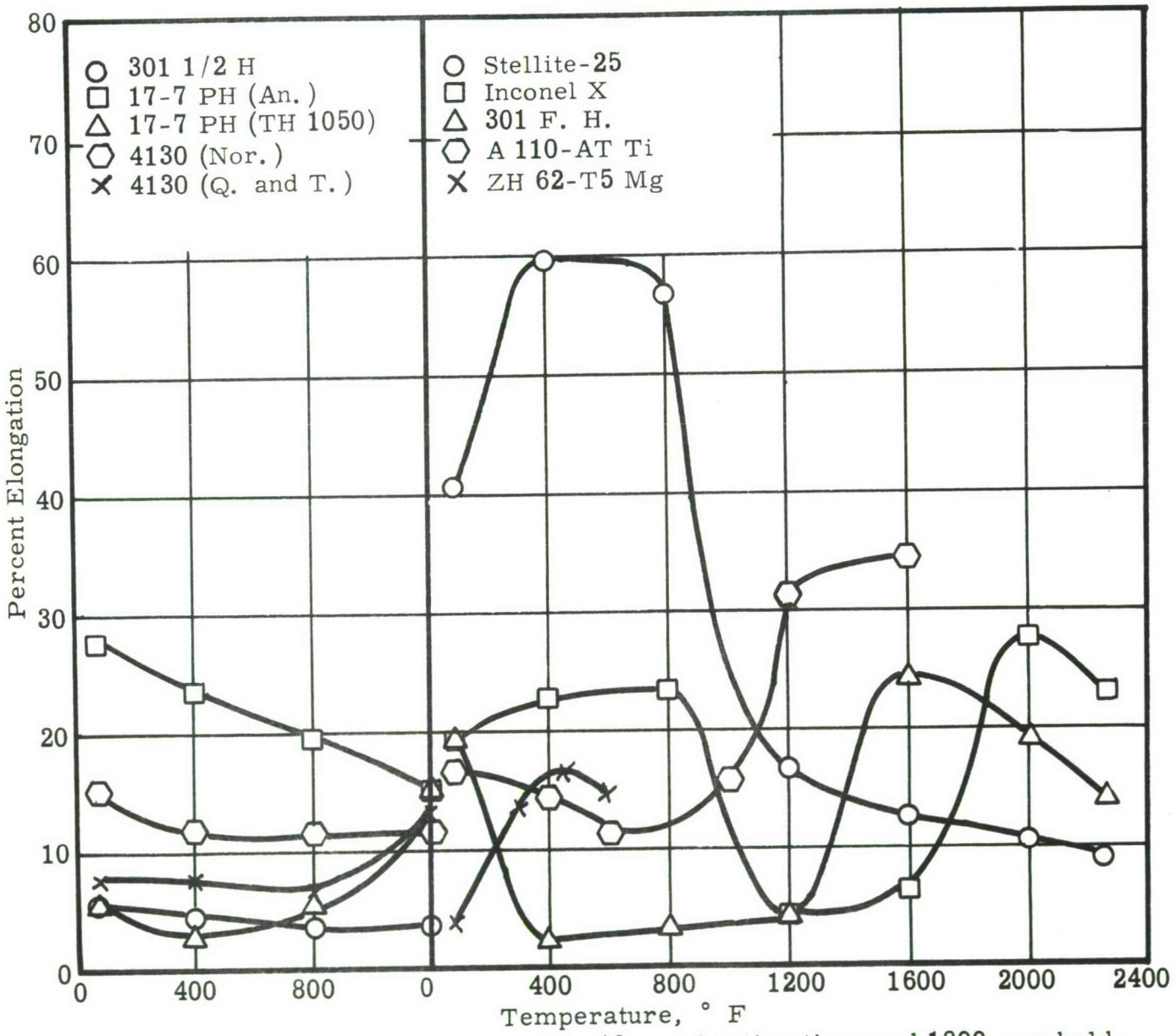

Figure 34. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of ten metals tensile tested at a strain rate of 0.00005 in./in./sec.

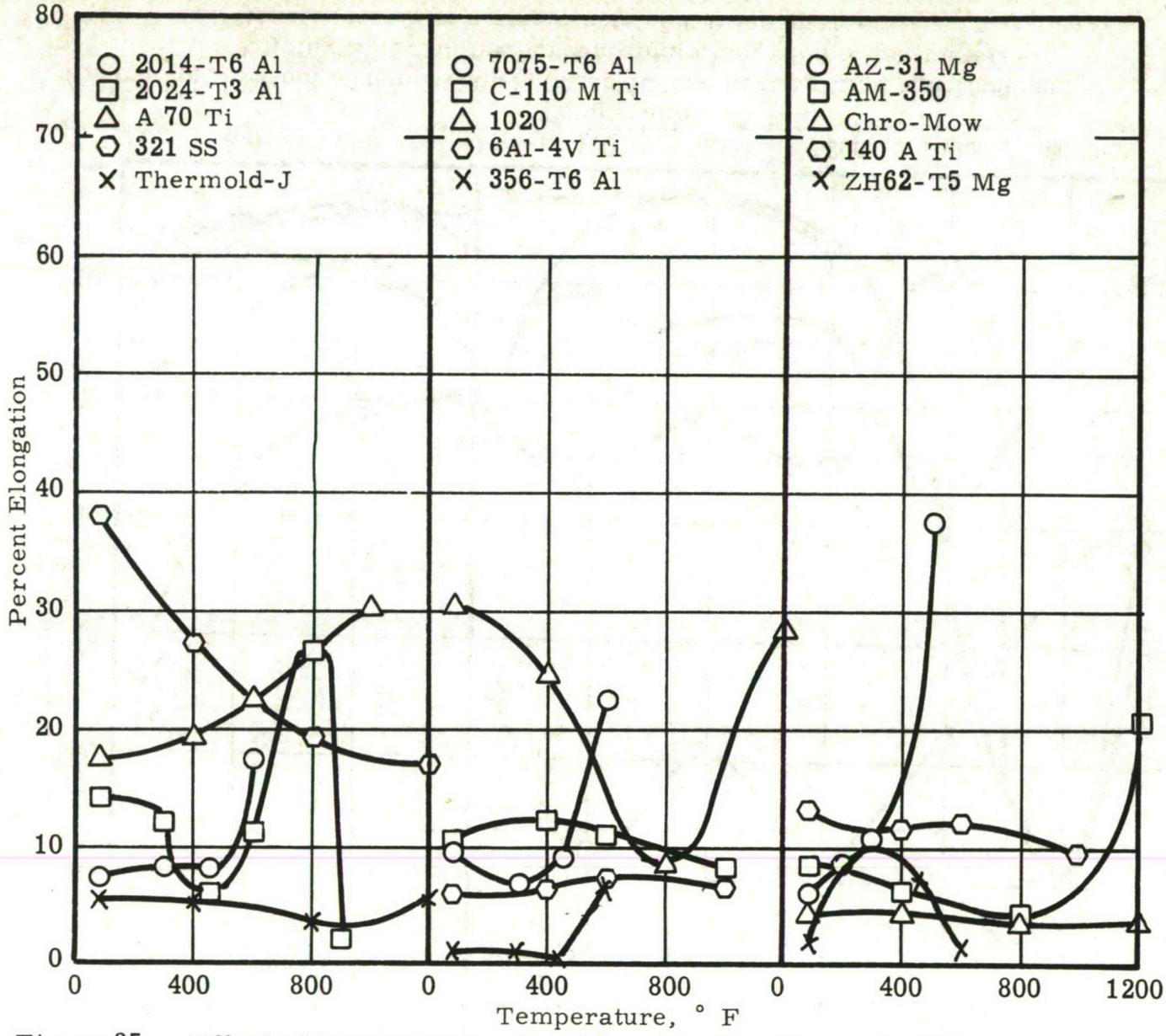

Figure 35. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of fifteen metals tensile tested at a strain rate of 1.0 in. /in. /sec

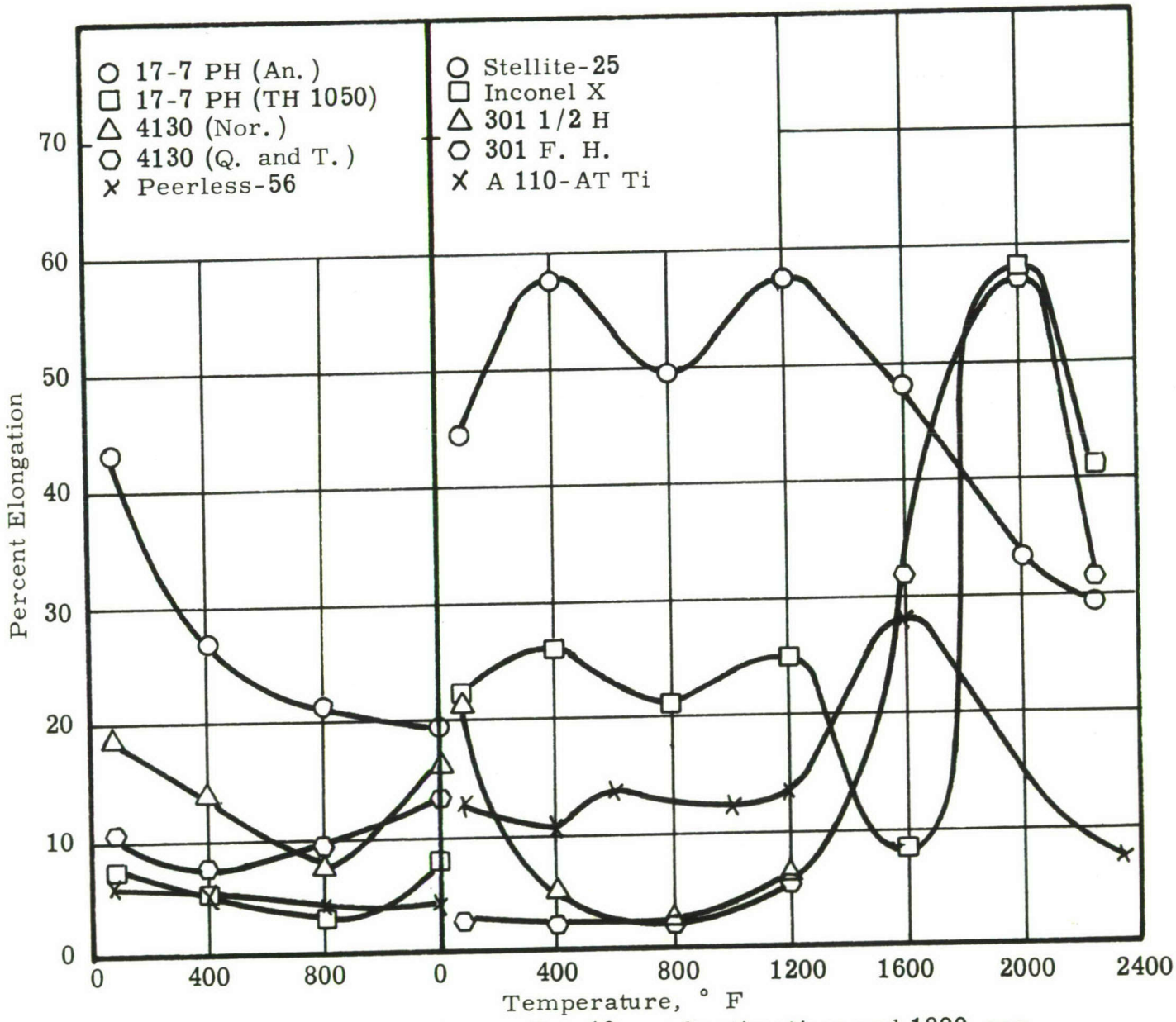

Figure 36. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent total elongation of ten metals tensile tested at a strain rate of 1.0 in./in./sec.

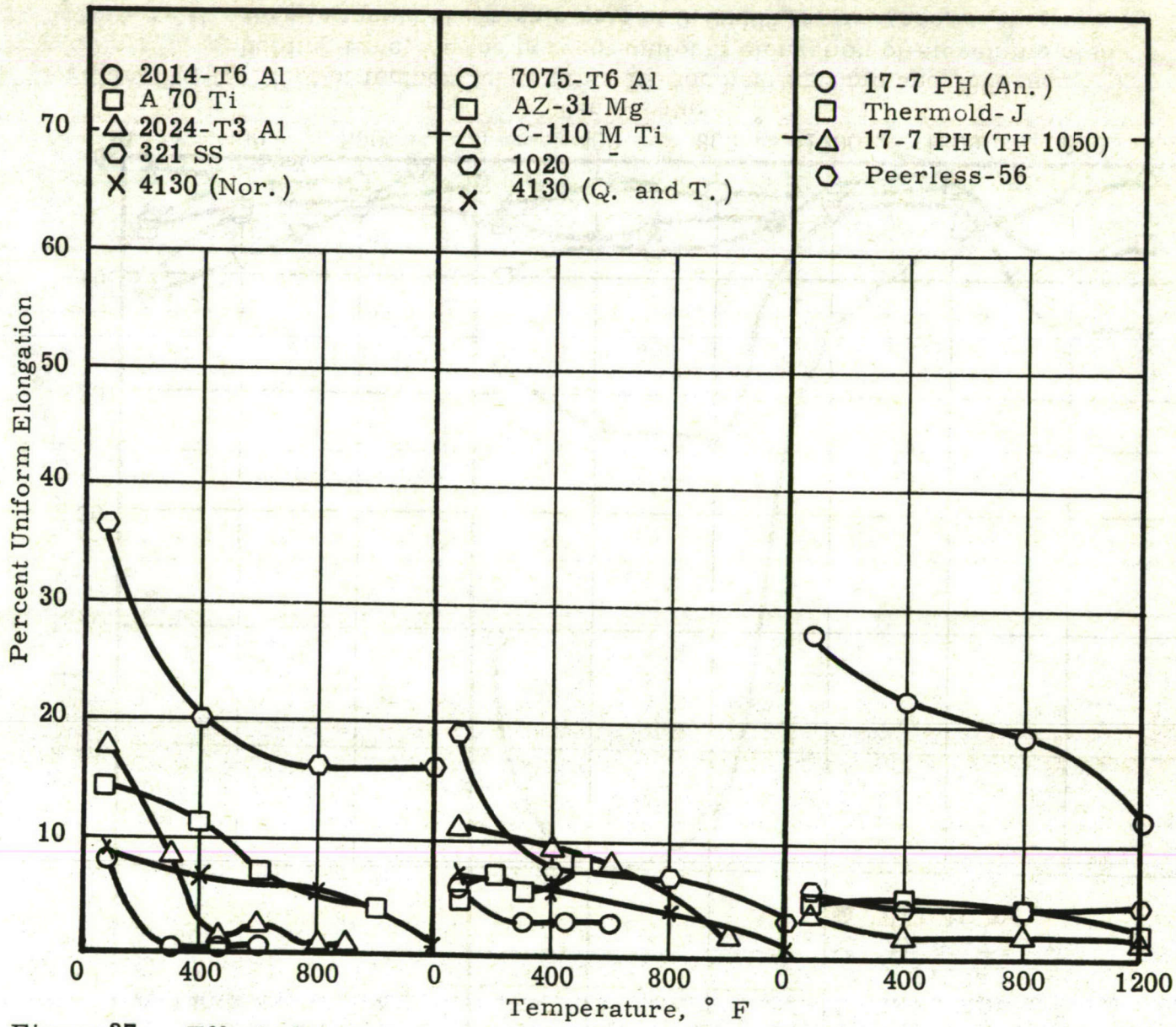

Figure 37. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of fourteen metals tensile tested at a strain rate of 0.00005 in./in./sec.

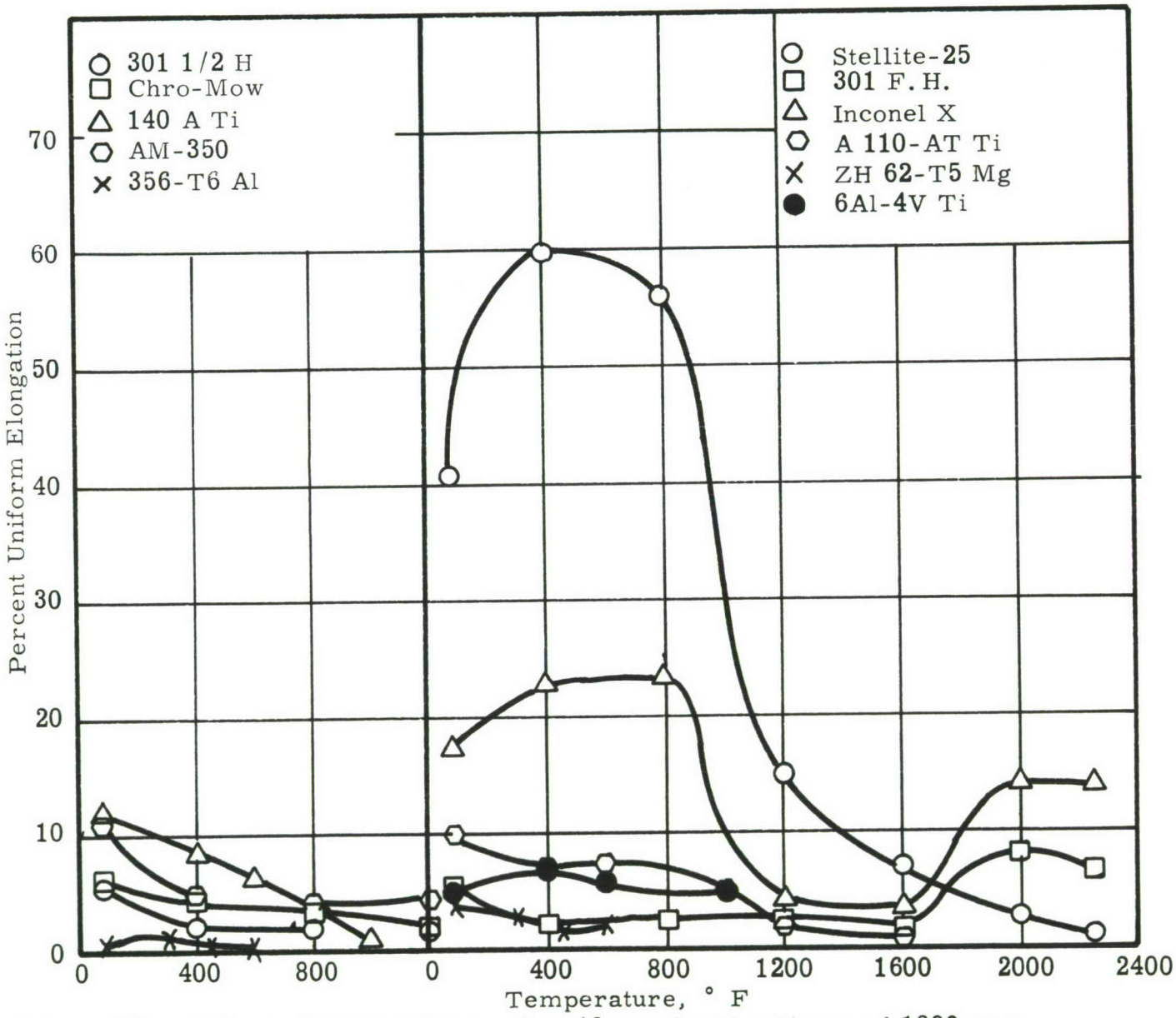

Figure 38. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of eleven metals tensile tested at a strain rate of 0.00005 in./in./sec.

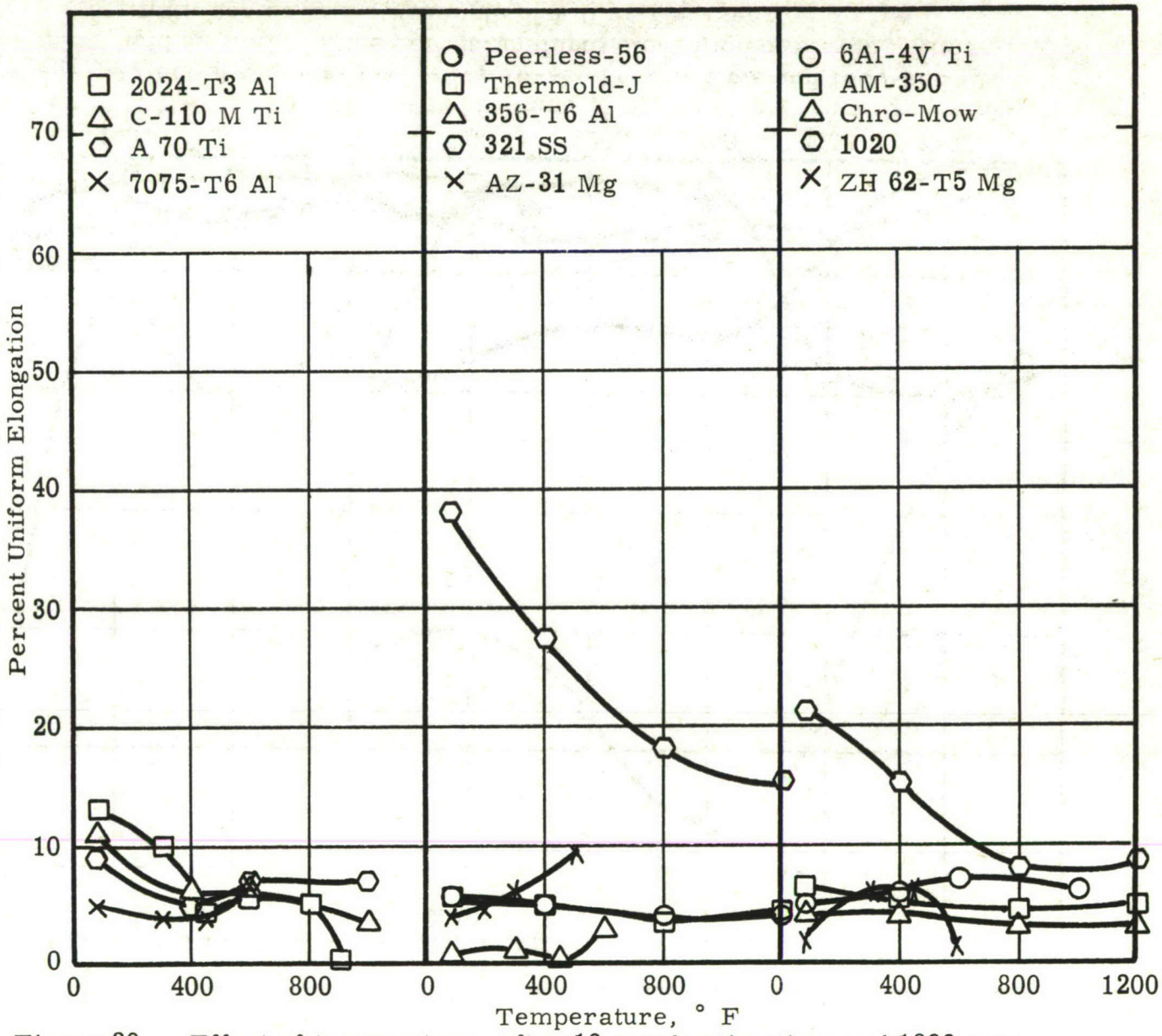

Figure 39. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of fourteen metals tensile tested at a strain rate of 1.0 in./in./sec.

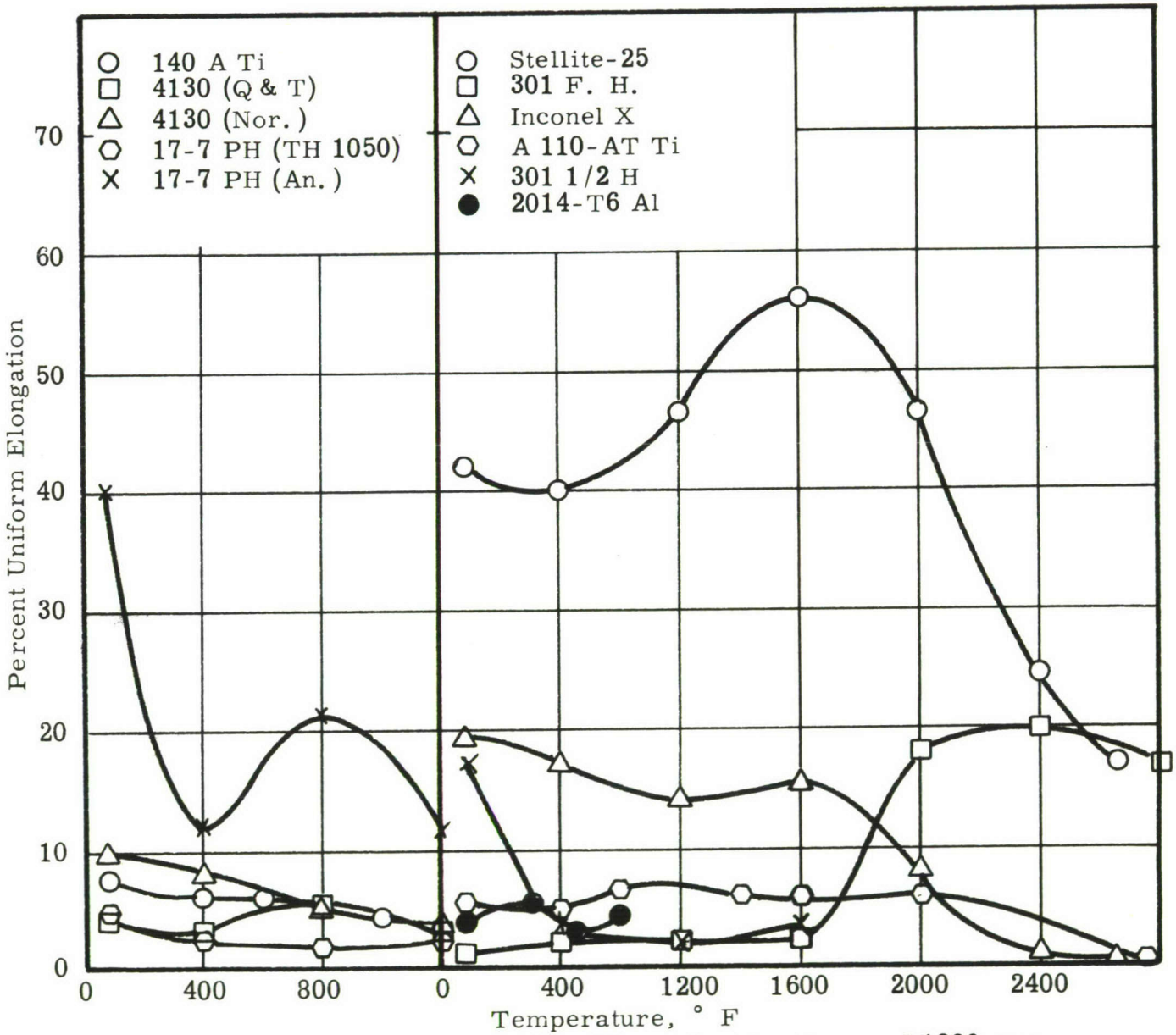

Figure 40. Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the percent uniform elongation of eleven metals tensile tested at a strain rate of 1.0 in./in./sec.

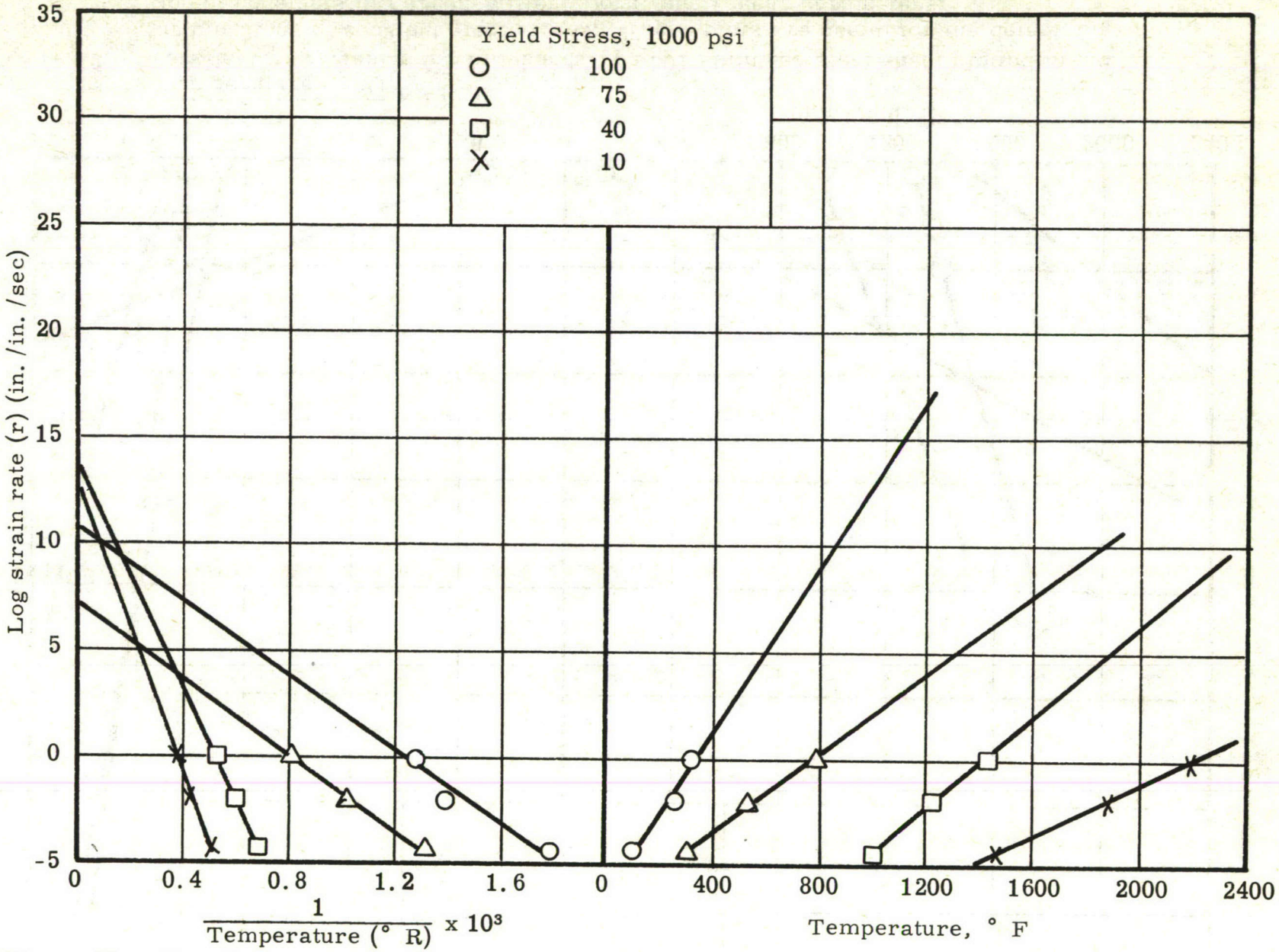

Figure 41. Tensile-test variables for annealed A110-AT titanium alloy sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn, and Linear parameters.

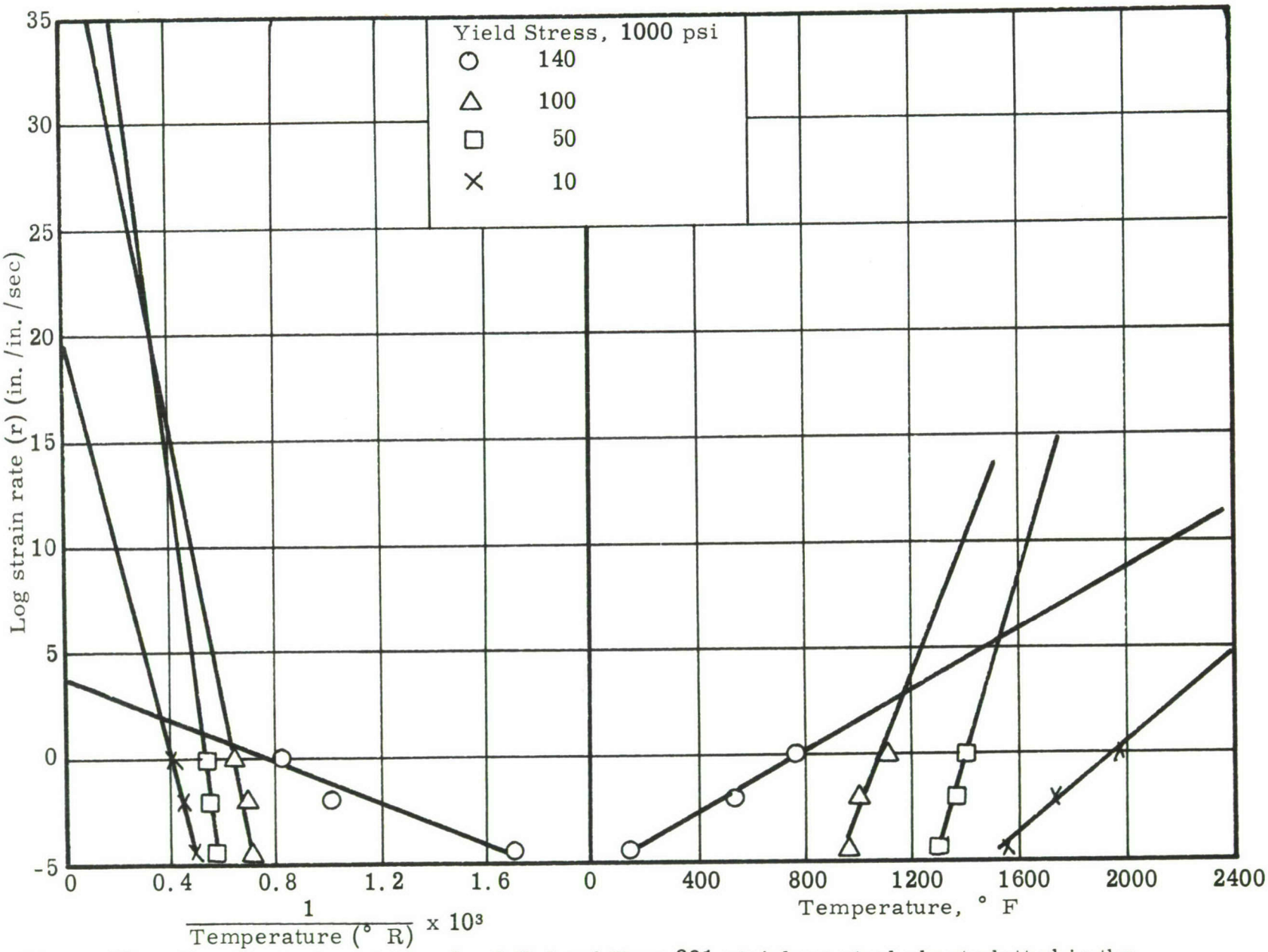

Figure 42. Tensile-test variables for full-hard Type 301 stainless steel sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn, and Linear parameters.

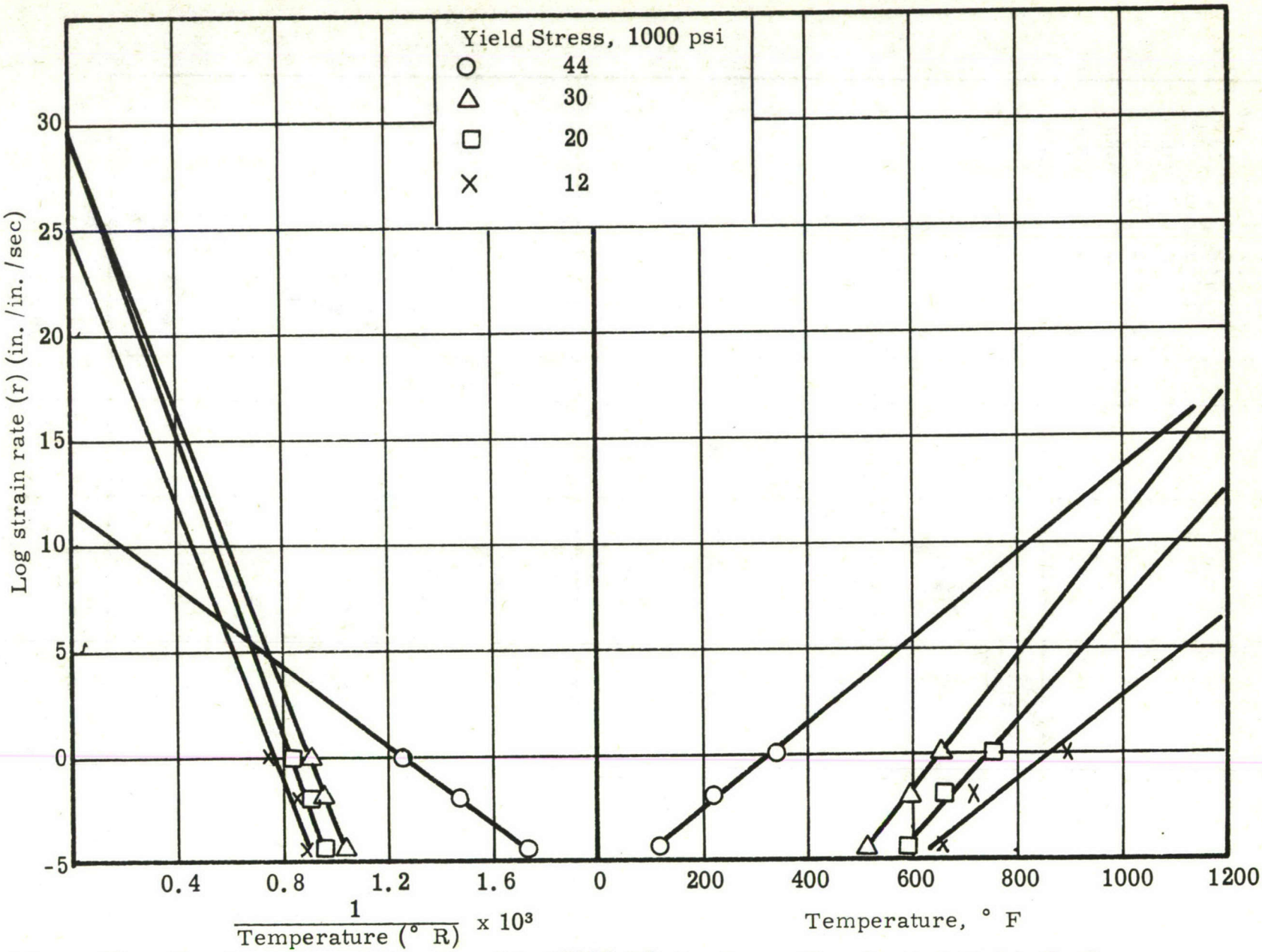

Figure 43. Tensile-test variables for alclad 2024-T3 aluminum alloy sheet plotted in the form of lines of constant yield stress. These plots are useful for the determination of constants in Larson-Miller, Dorn and Linear parameters.

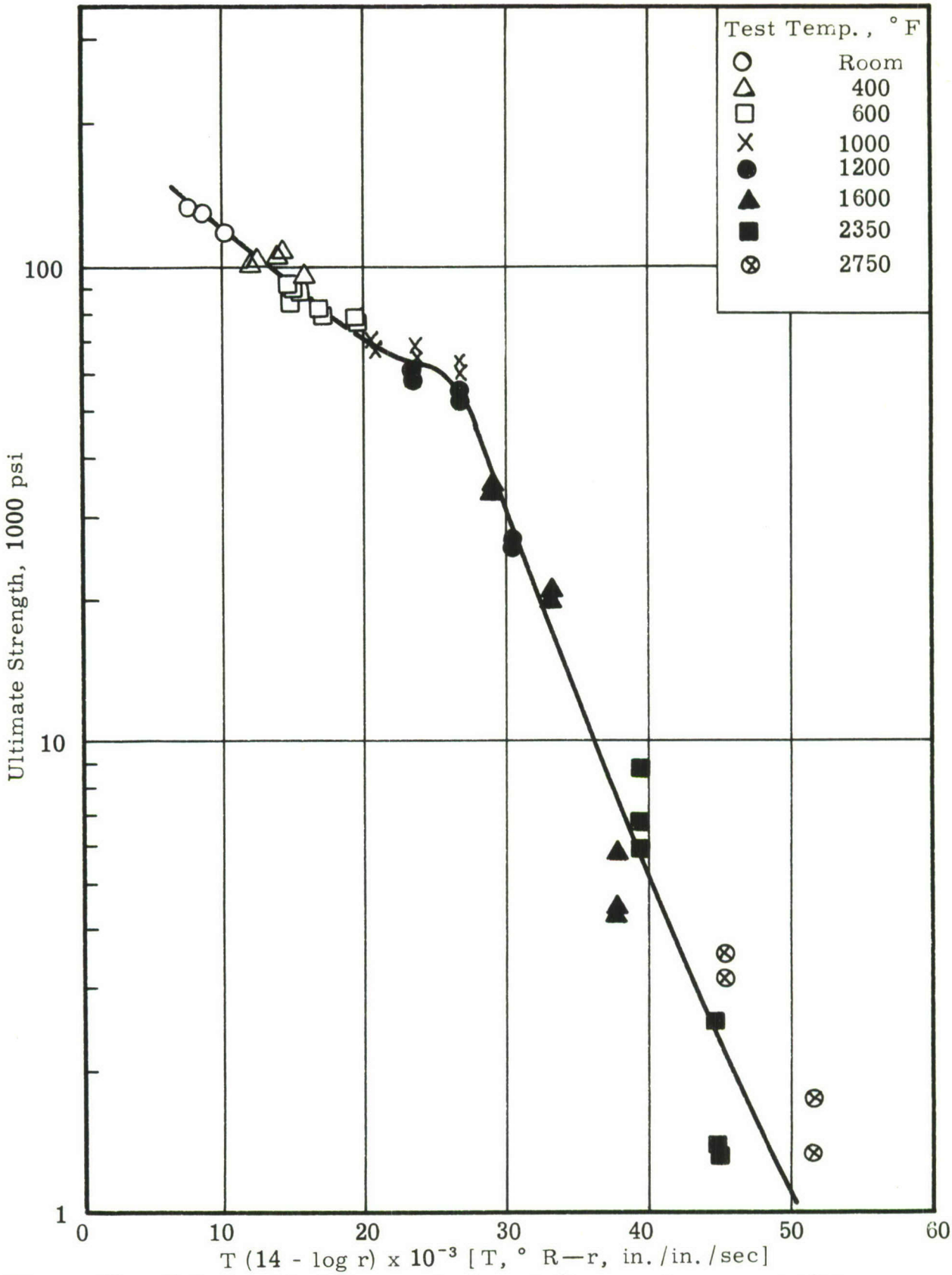

Figure 44. Relationship between strain-rate/temperature parameter and ultimate tensile strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

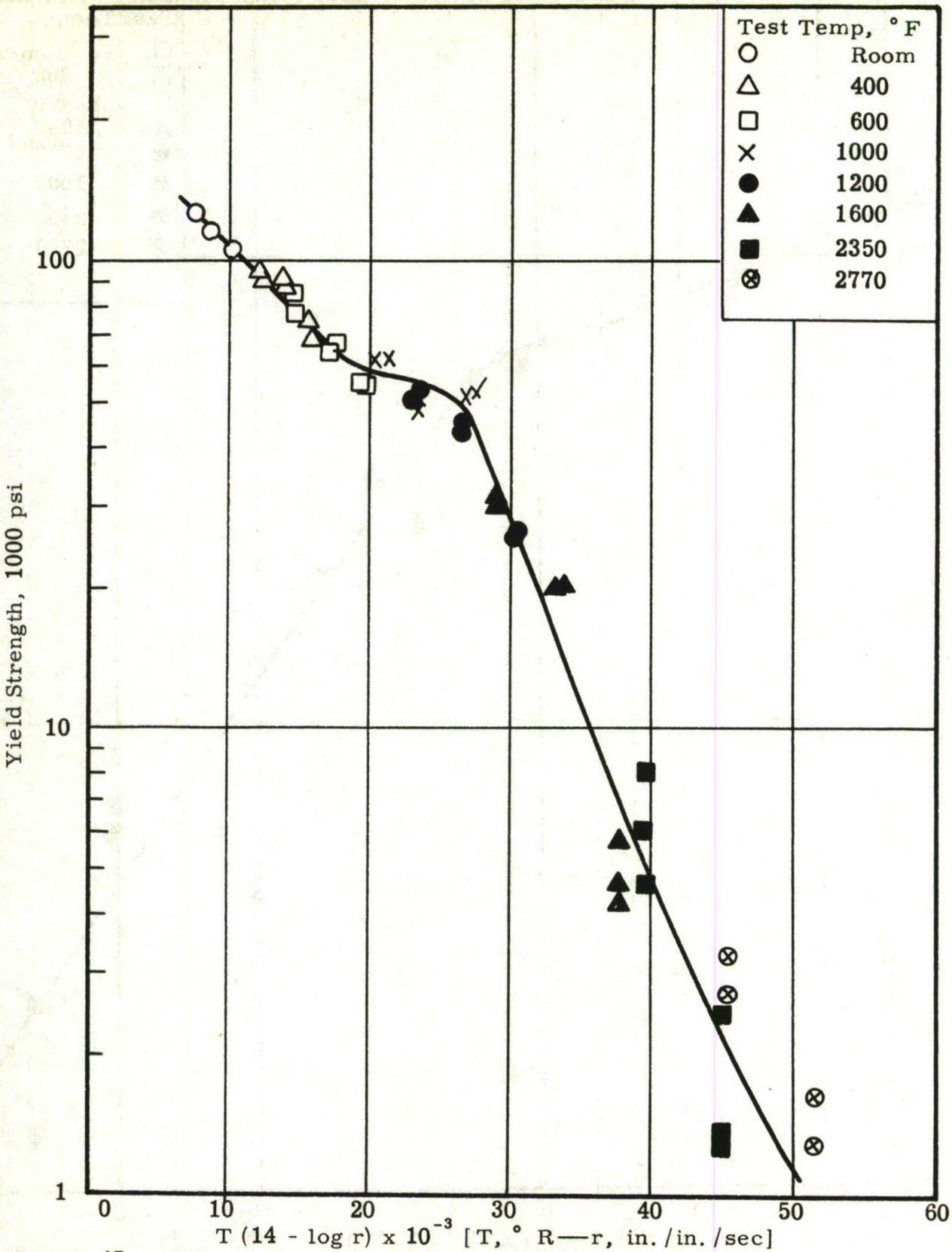

Figure 45. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of annealed A110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

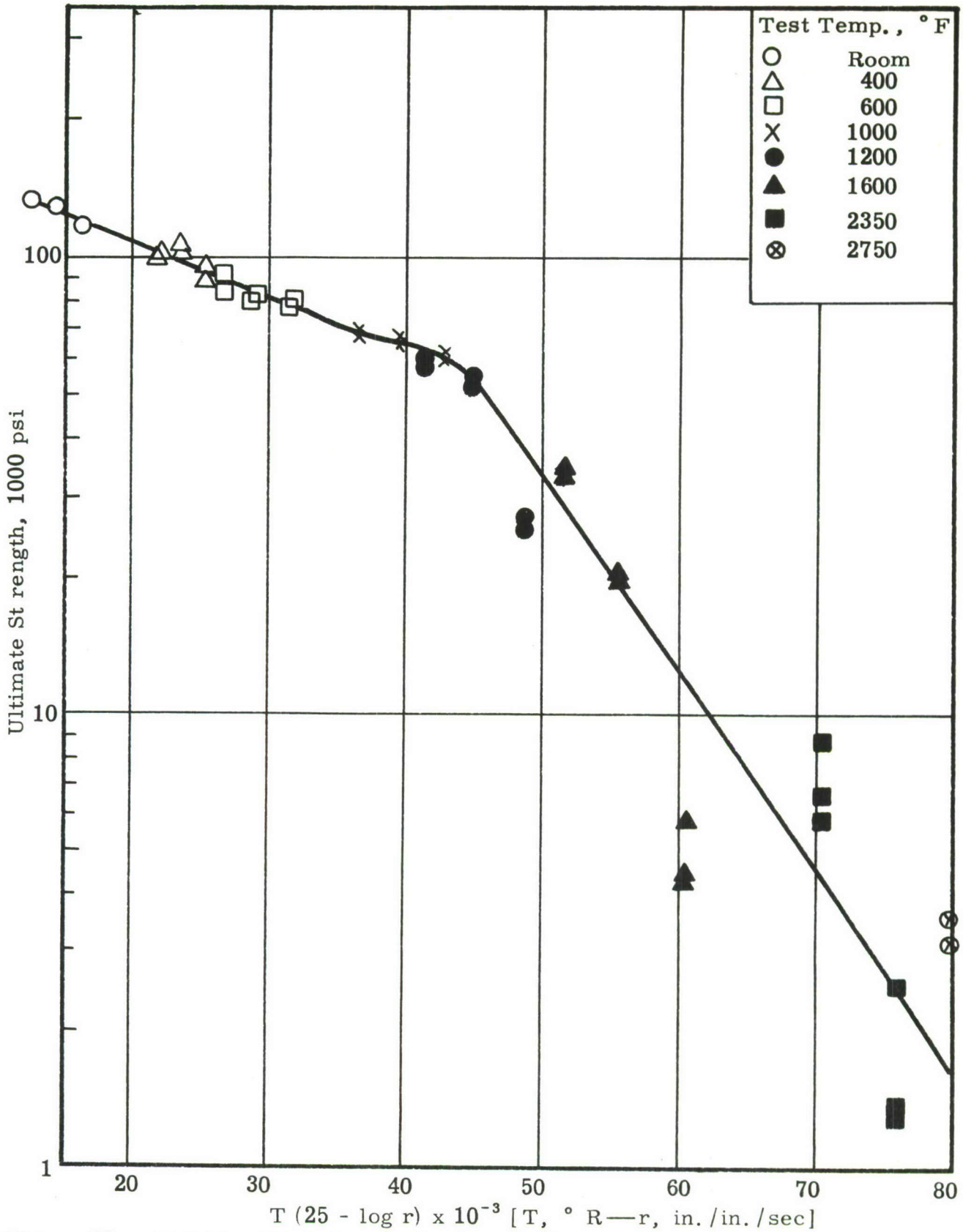

Figure 46. Relationship between strain-rate/temperature parameter and ultimate tensile strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

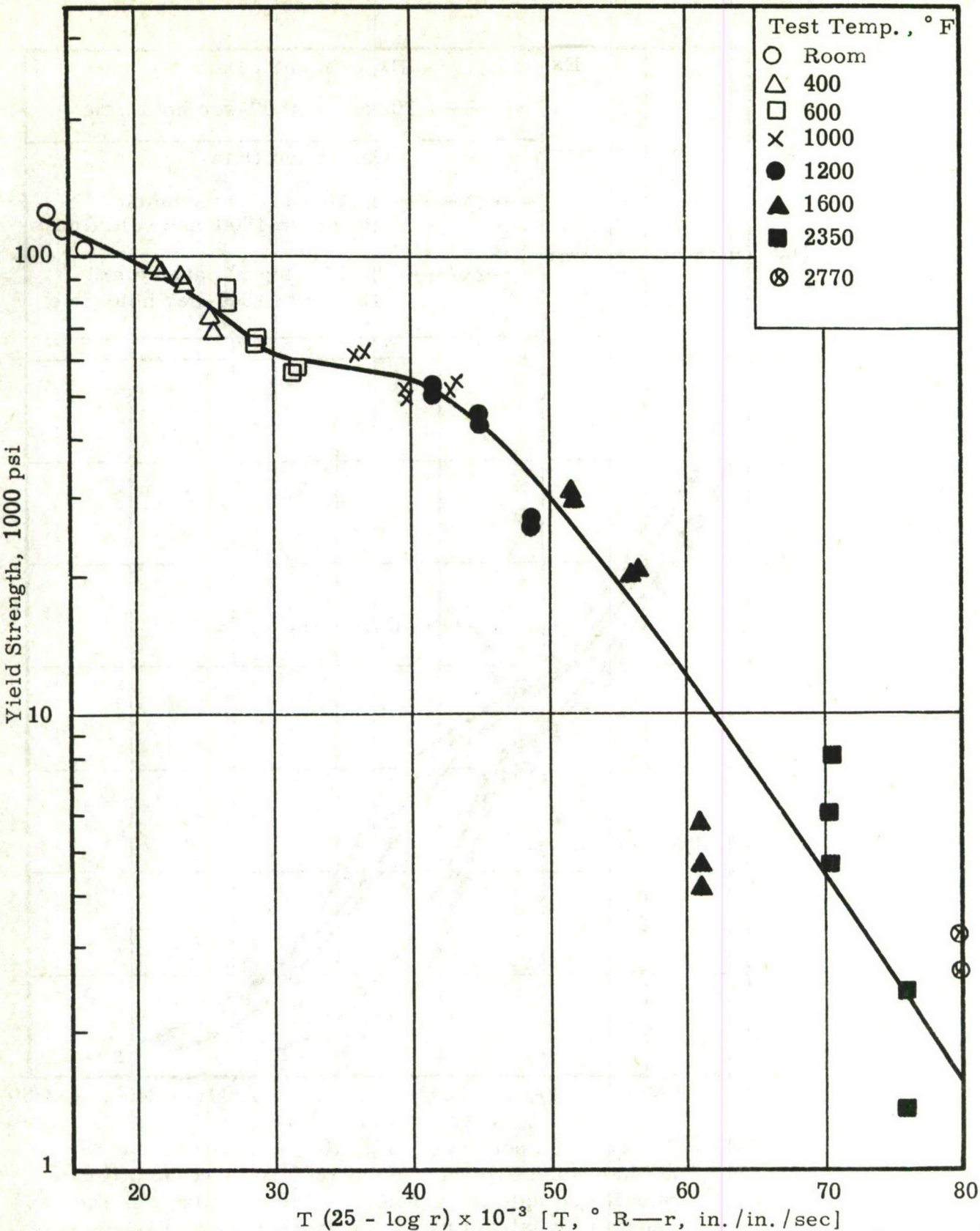

Figure 47. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

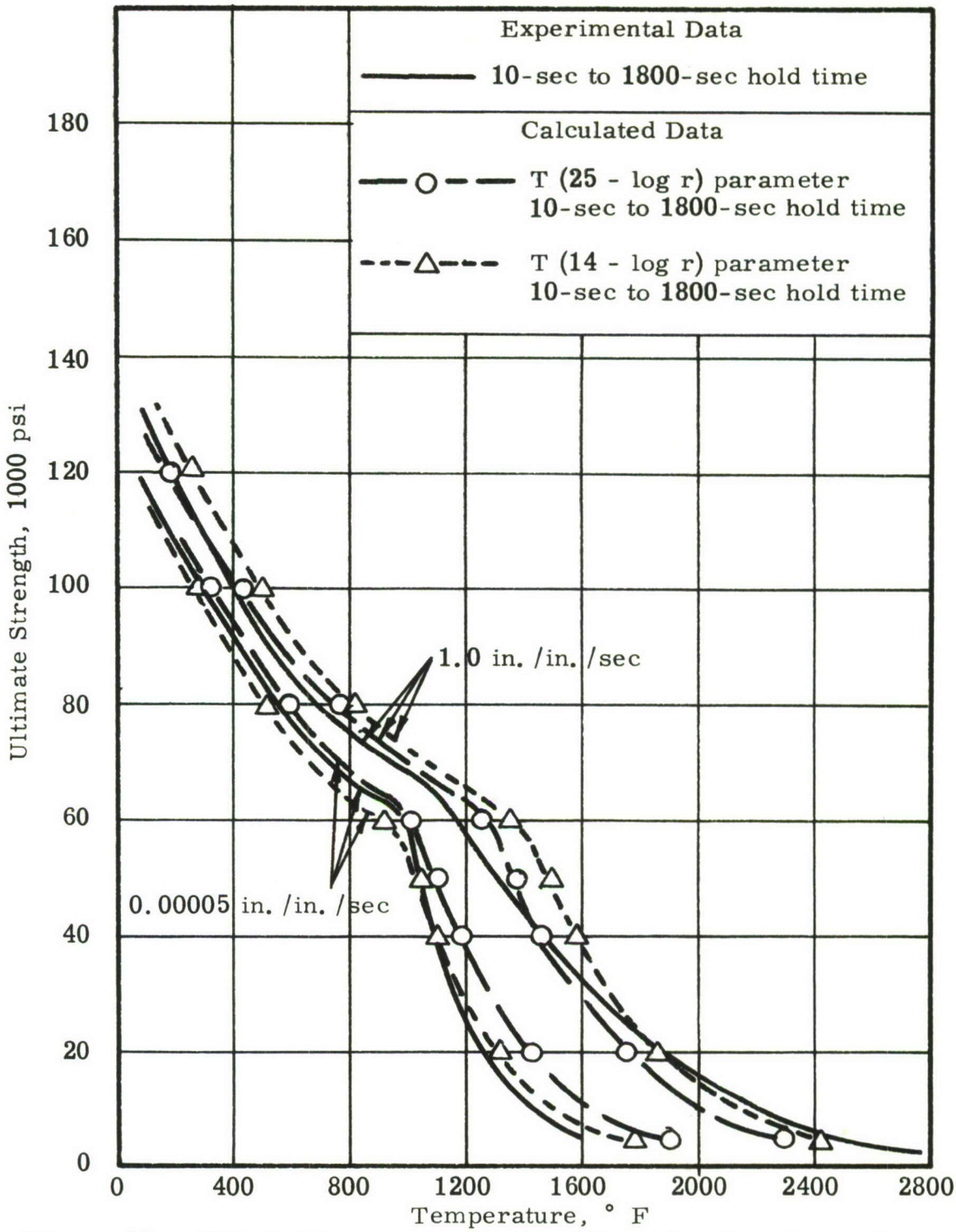

Figure 48. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of, annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T(c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.

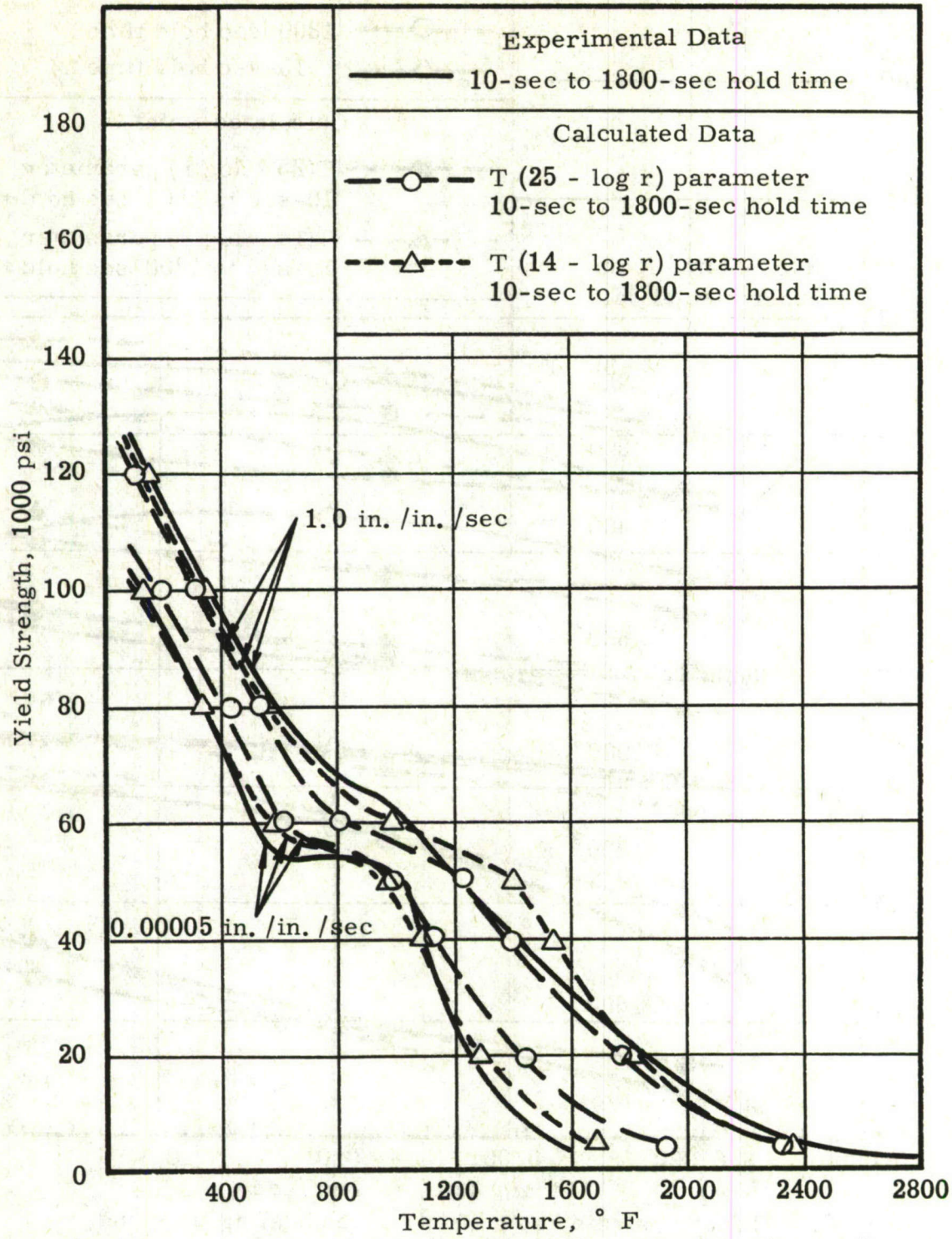

Figure 49. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.

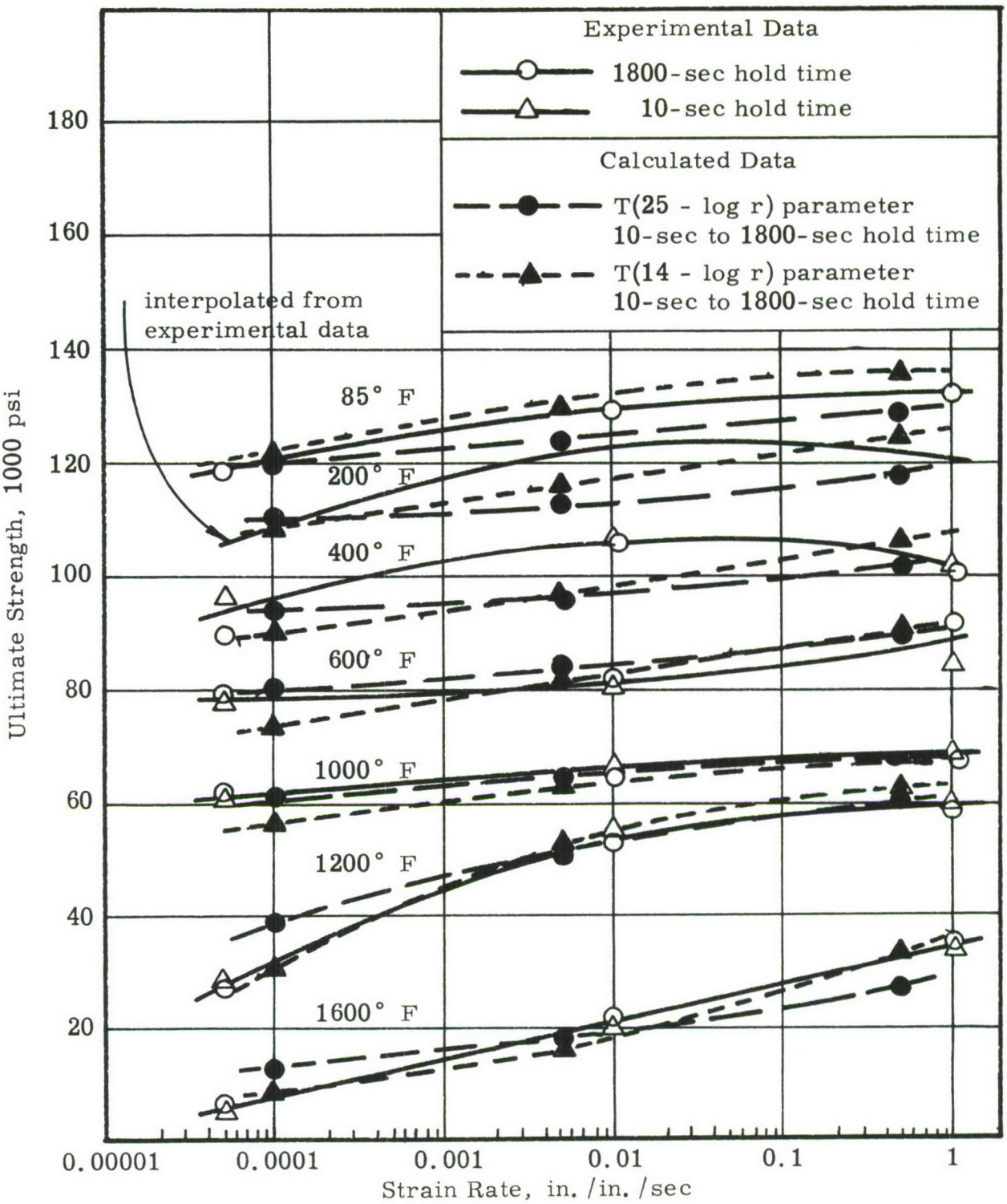

Figure 50. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in./in./sec.

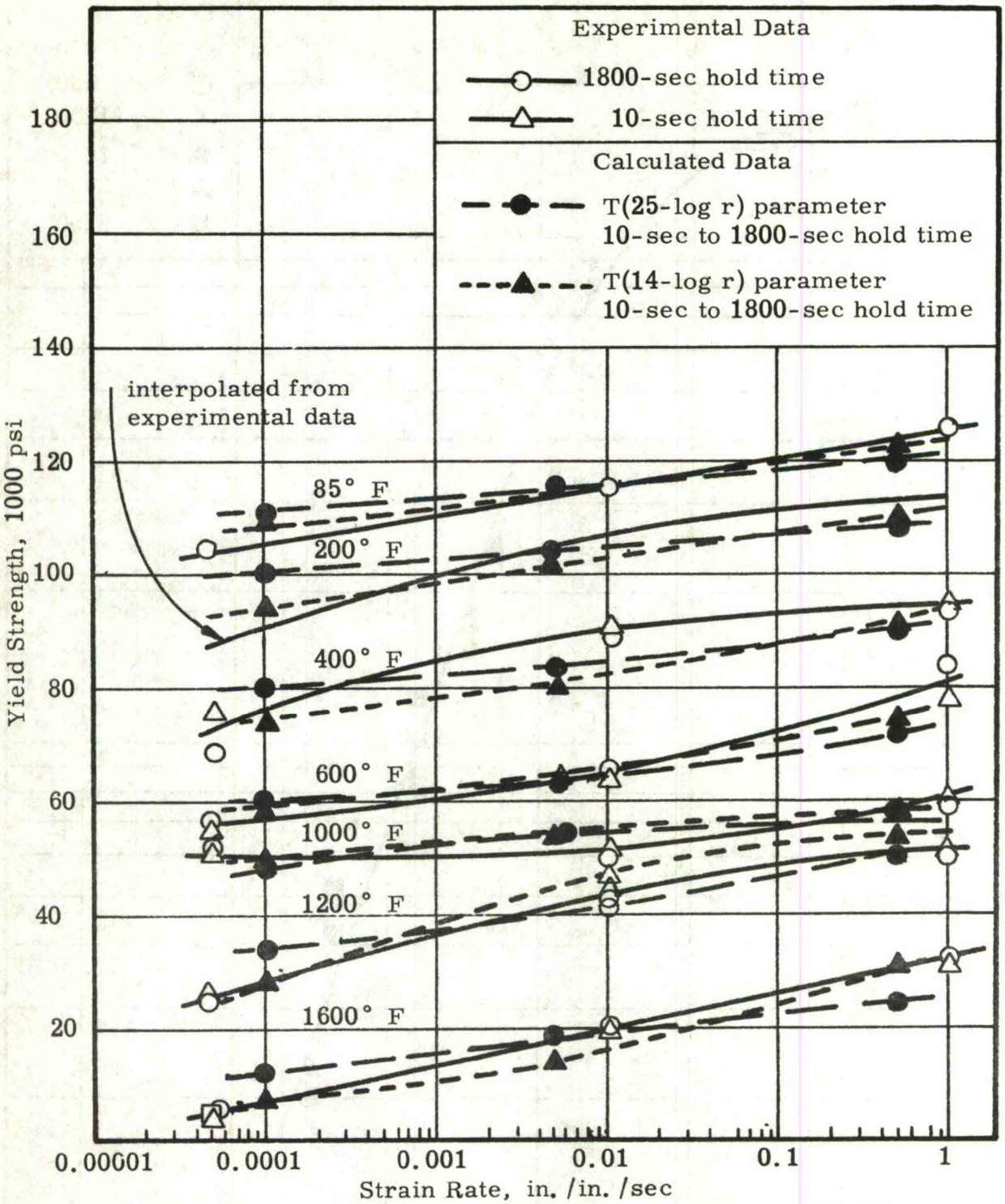

Figure 51. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.

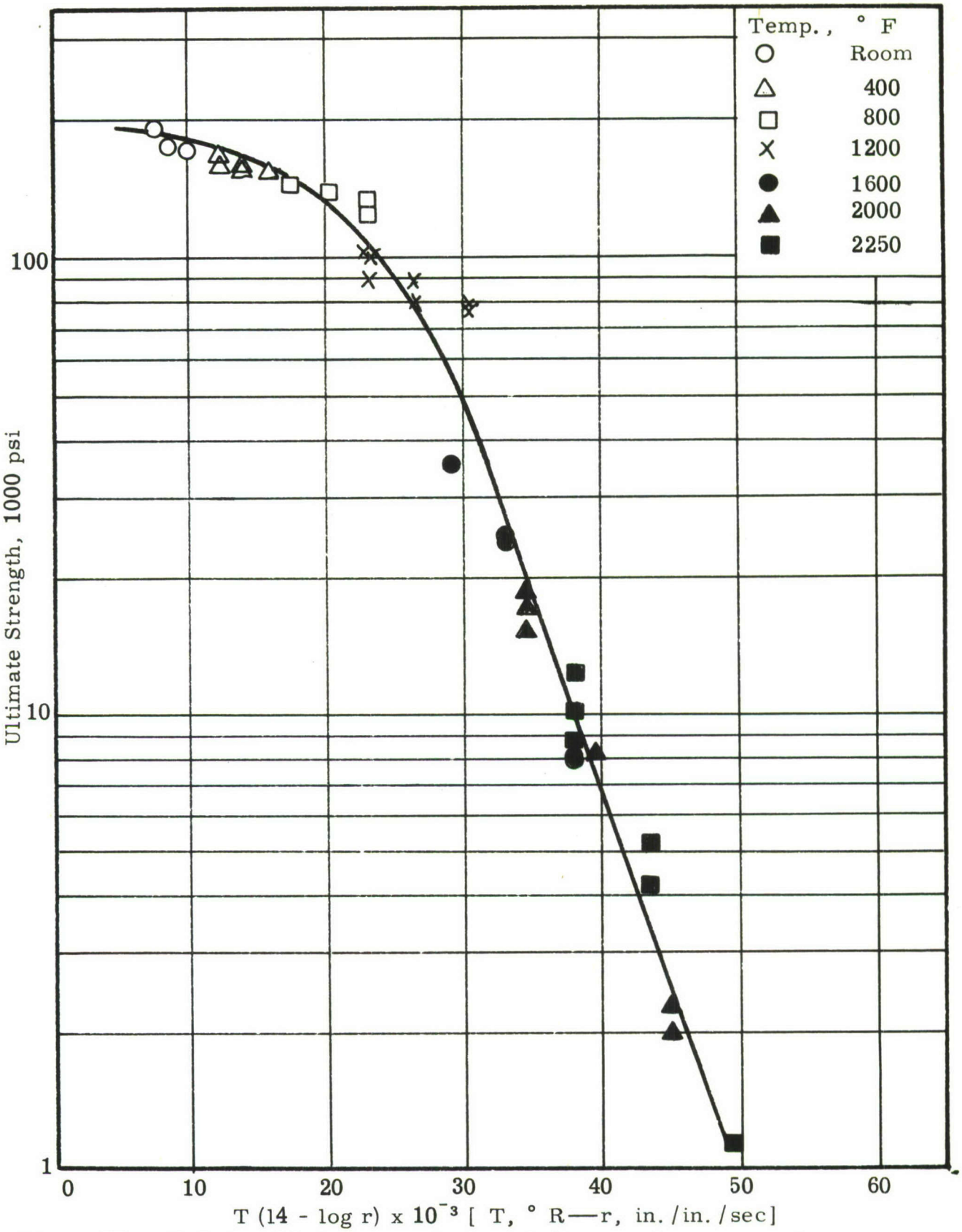

Figure 52. Relationship between strain-rate/temperature parameter and ultimate tensile strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperatures. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

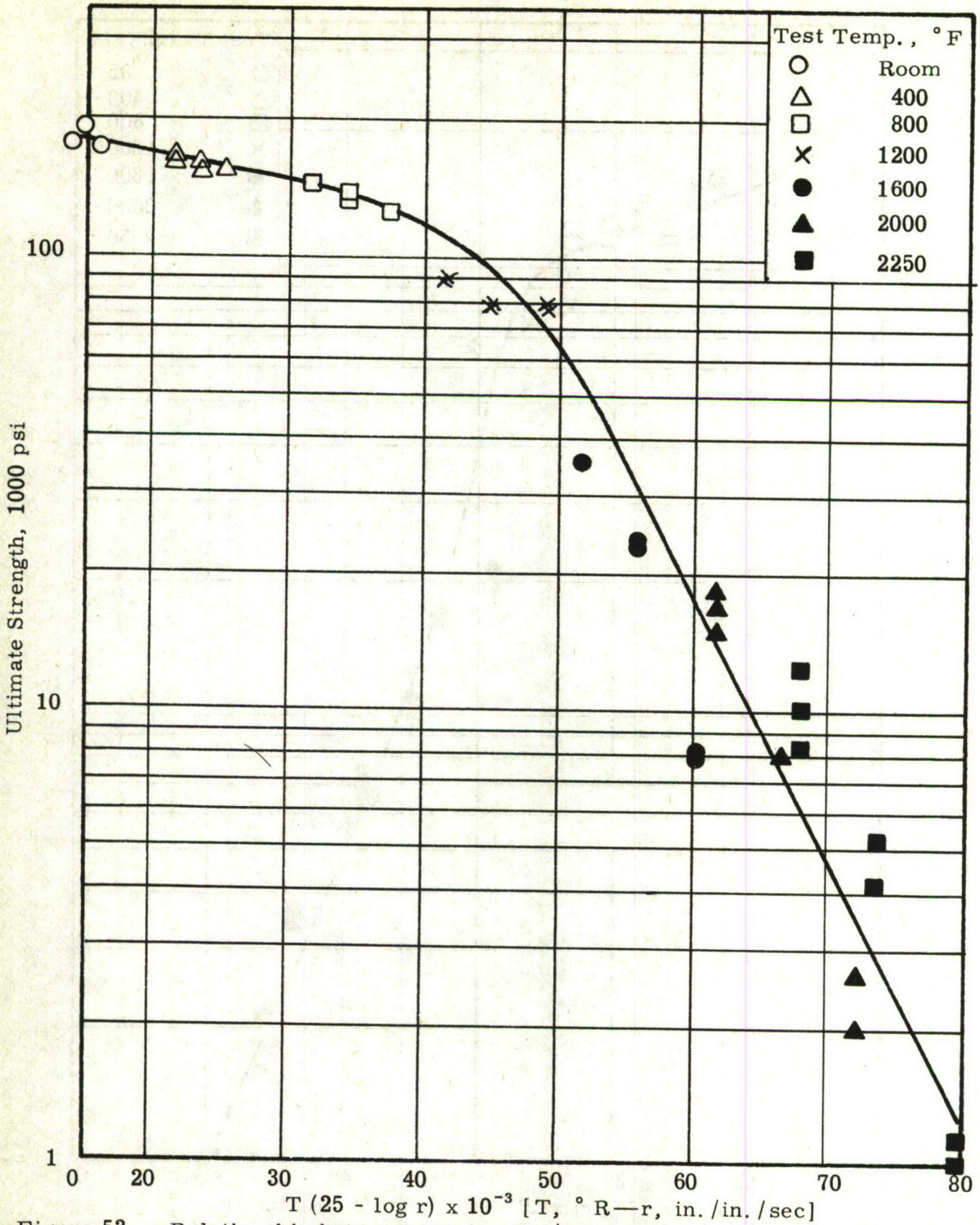

Figure 53. Relationship between-strain-rate/temperature parameter and ultimate tensile strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

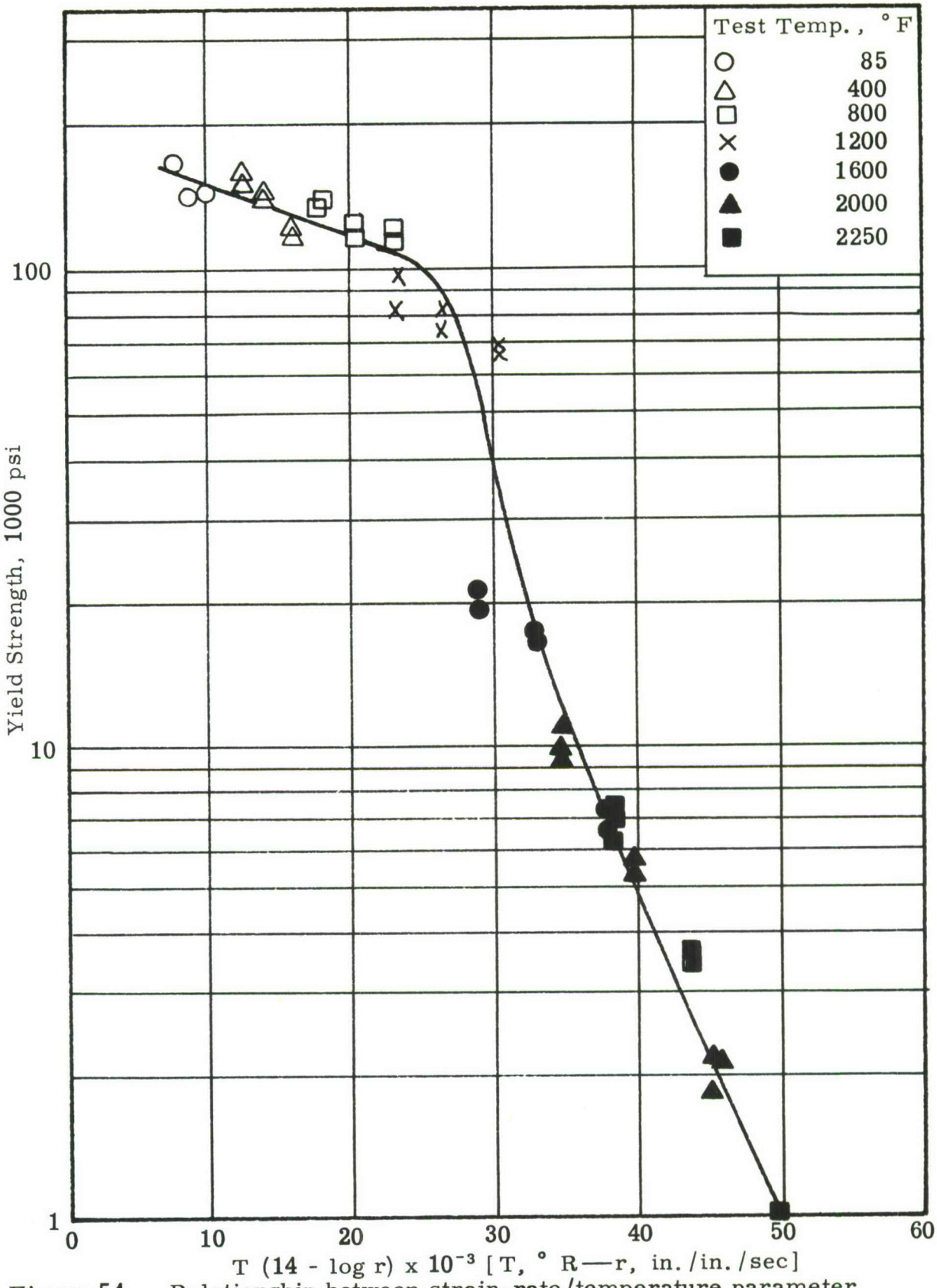

Figure 54. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

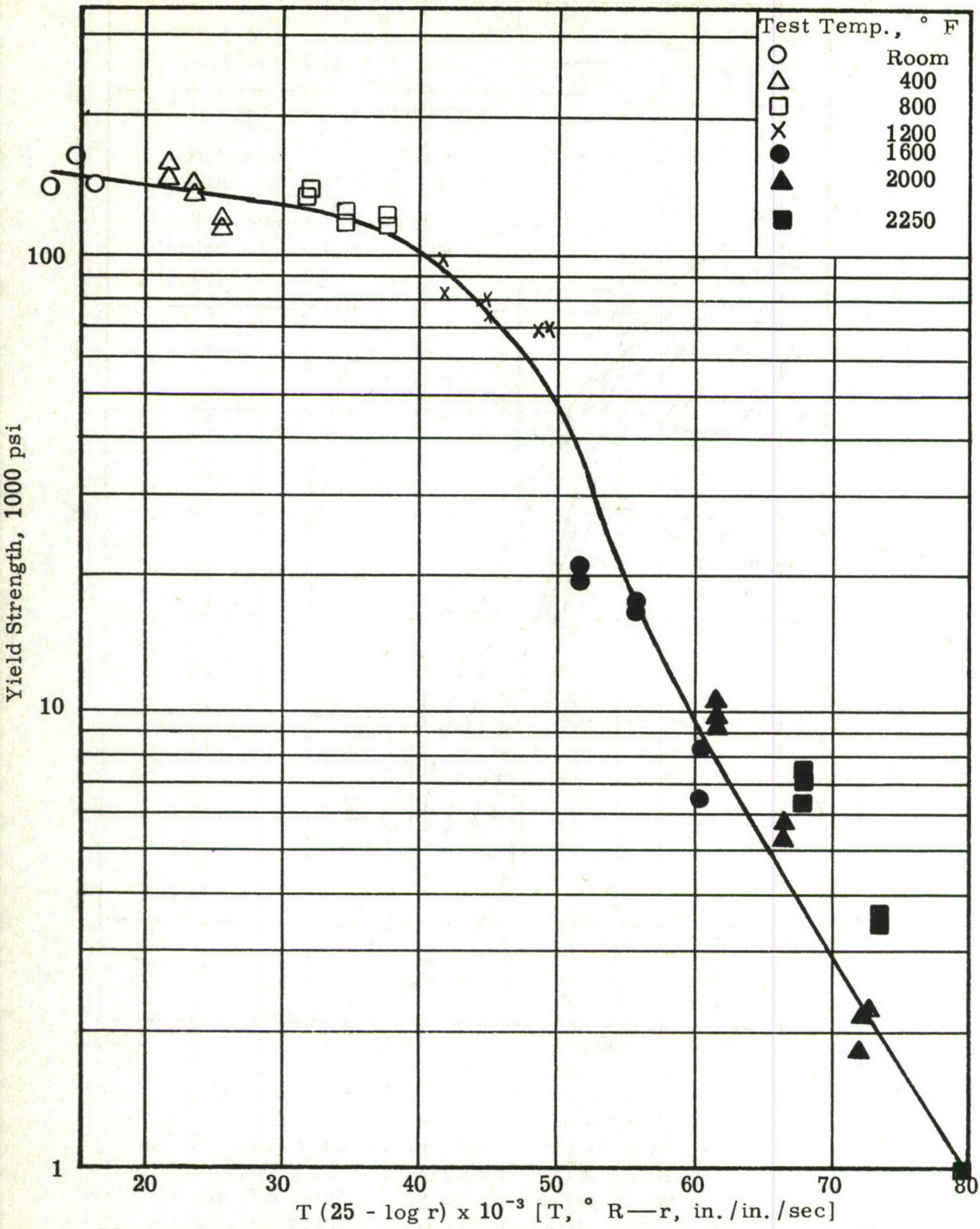

Figure 55. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of full-hard 301 stainless steel sheet after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperatures. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

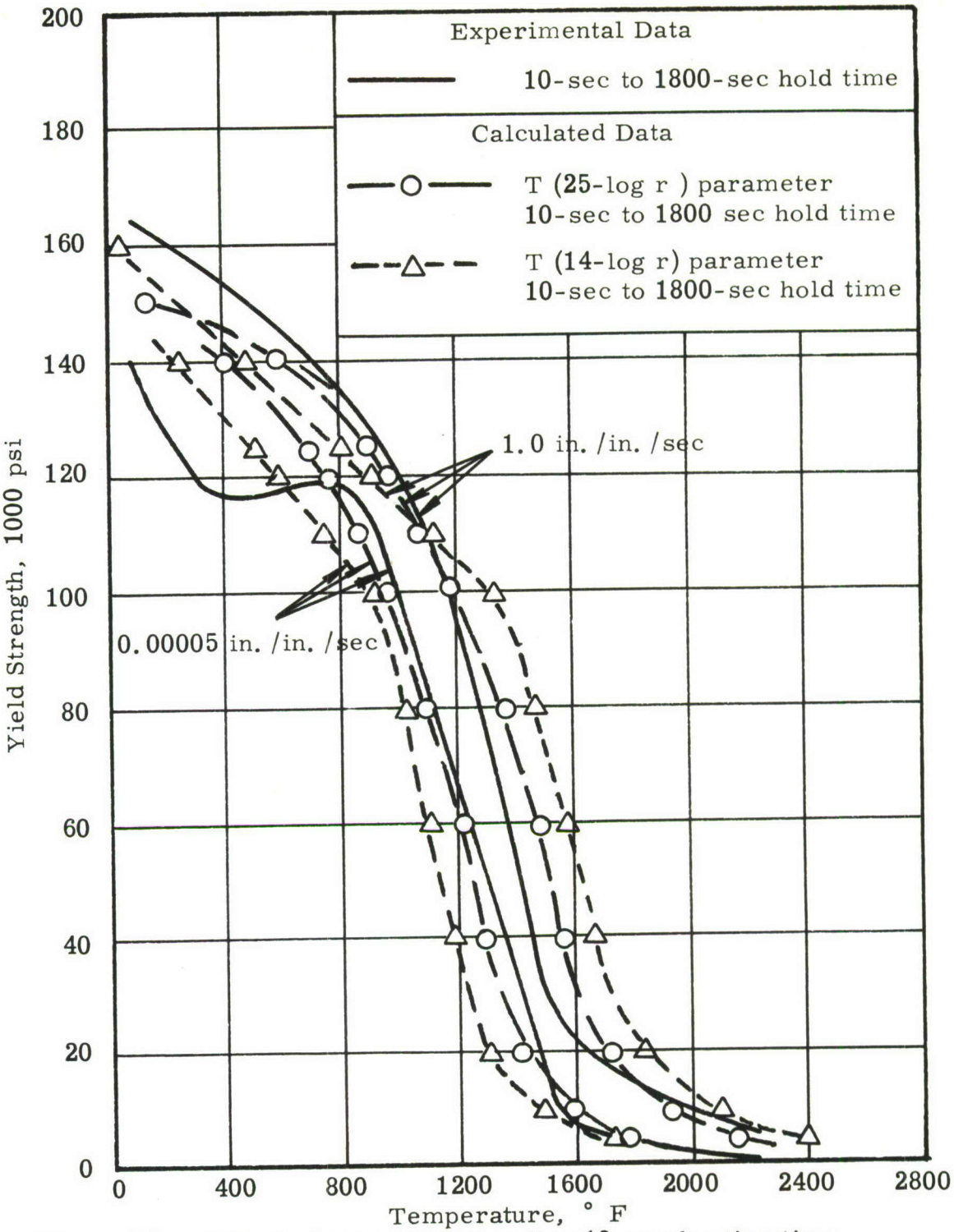

Figure 56. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. / sec.

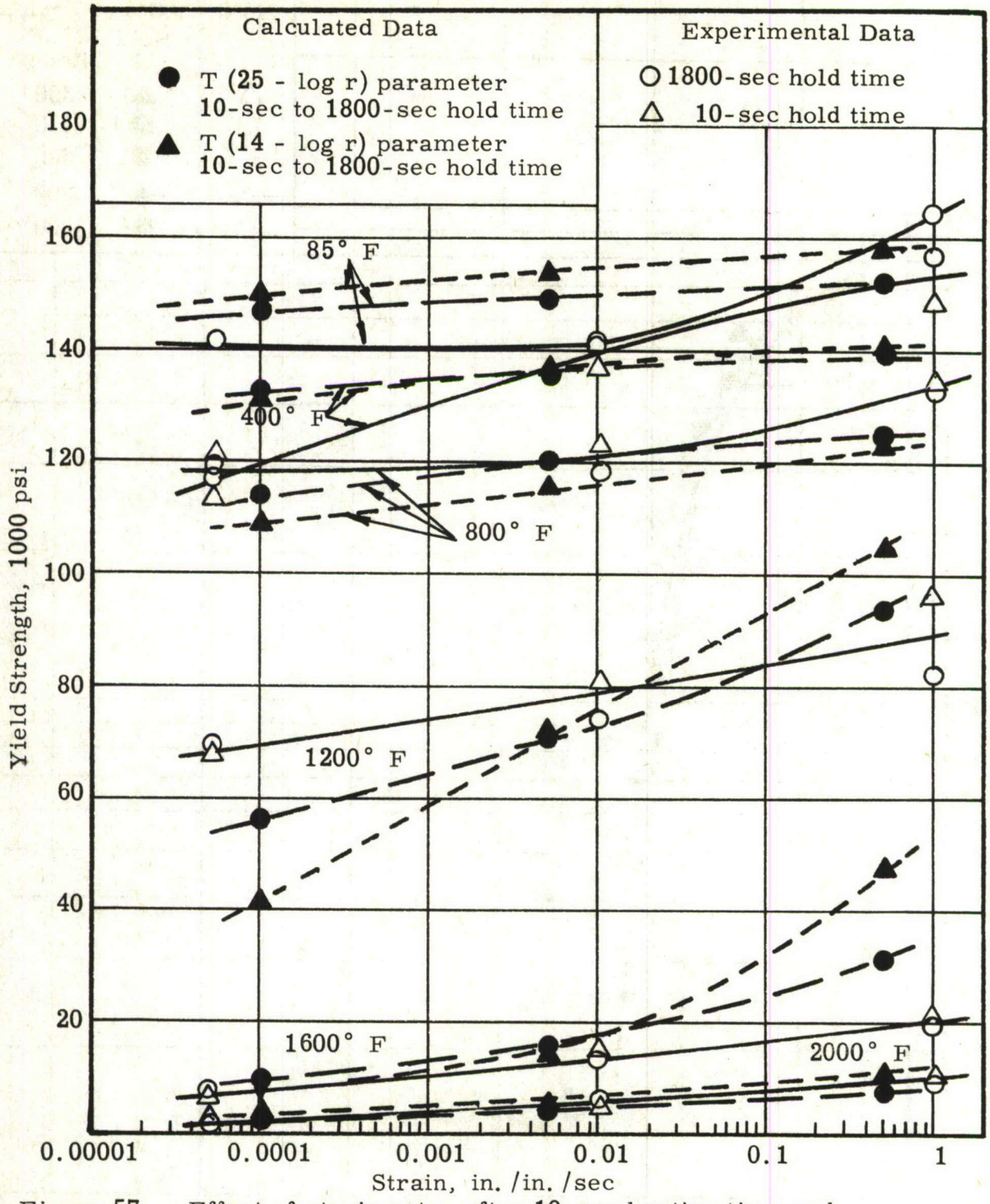

Figure 57. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.

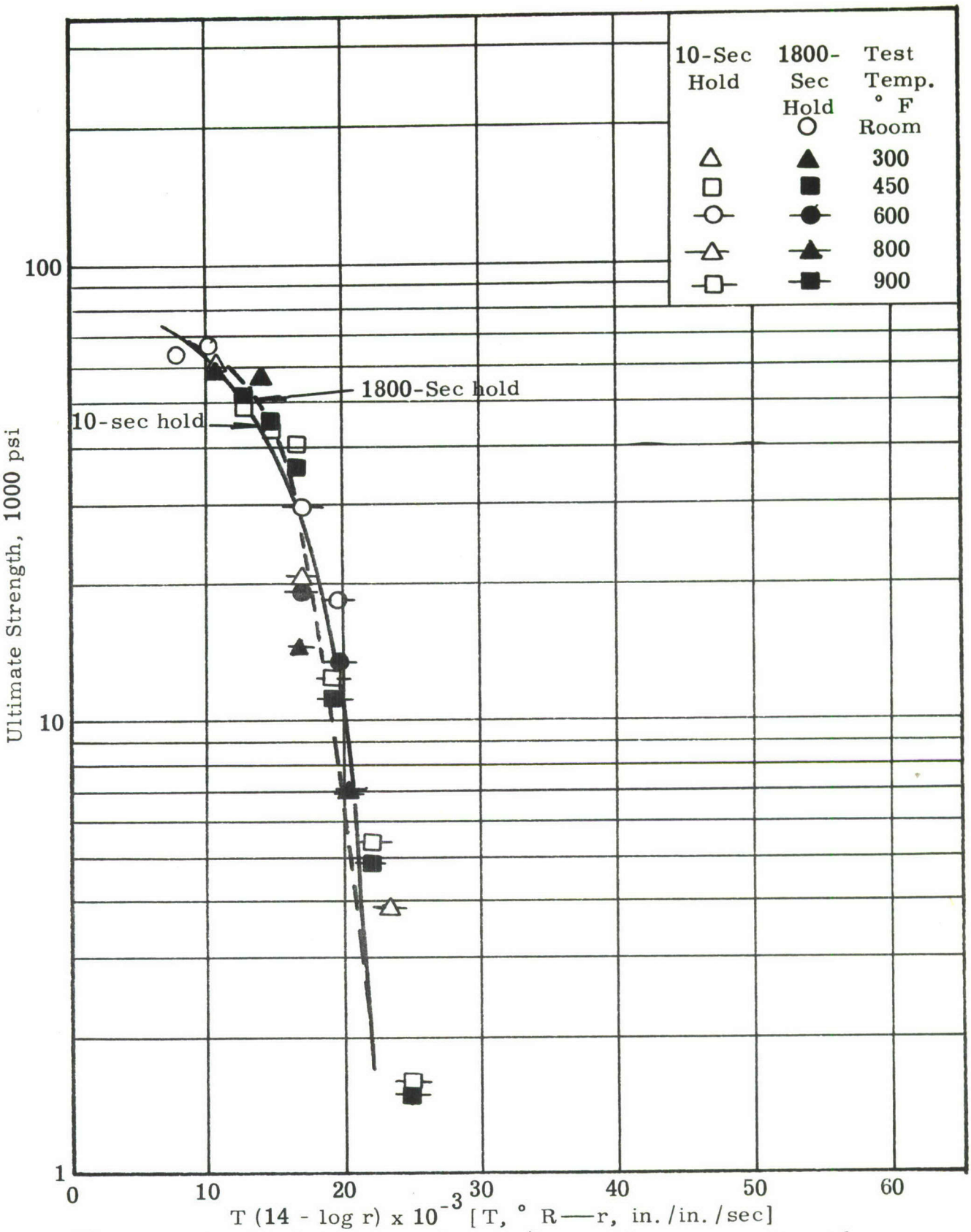

Figure 58. Relationship between strain-rate/temperature parameter and ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

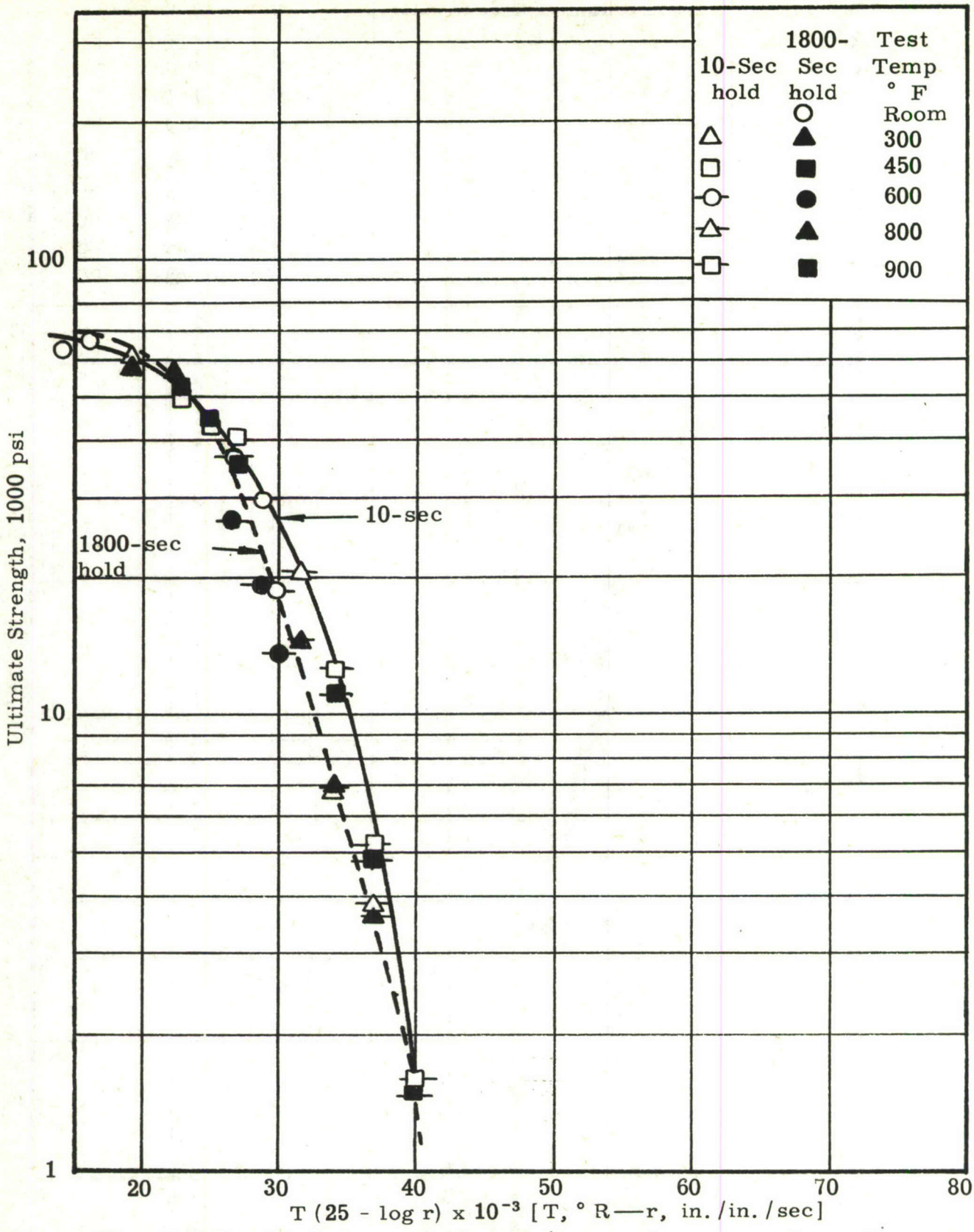

Figure 59. Relationship between strain-rate/temperature parameter and ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

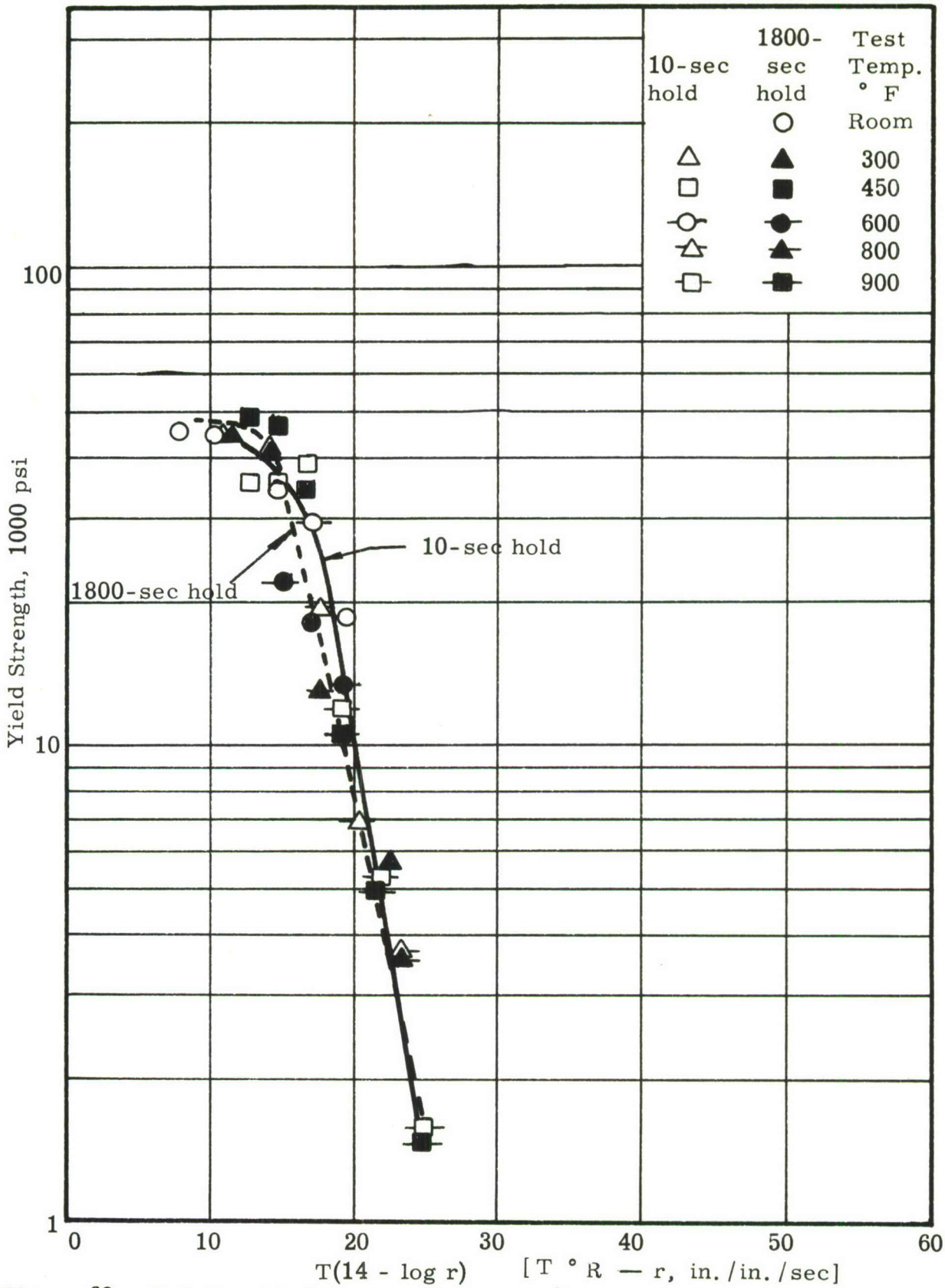

Figure 60. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

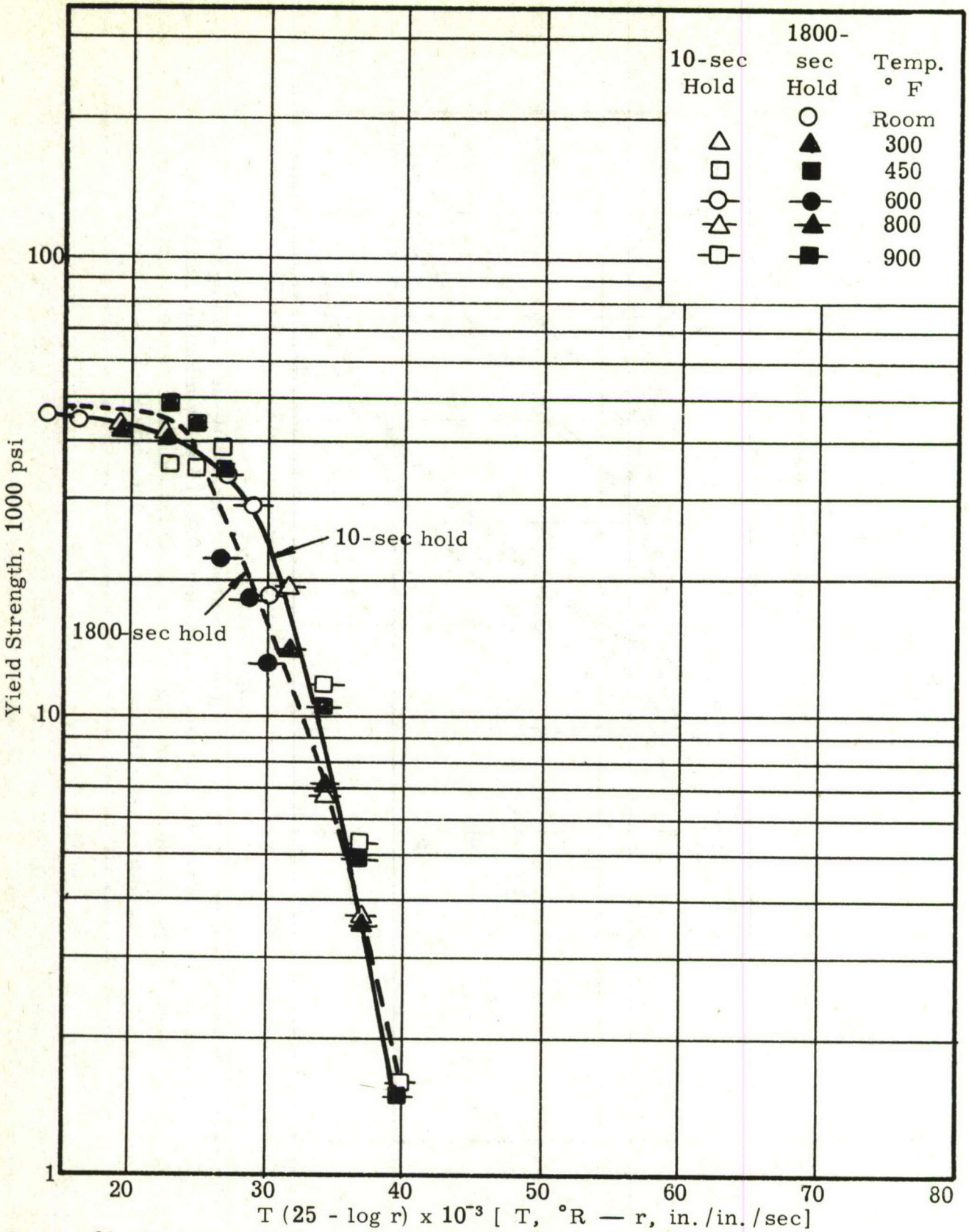

Figure 61. Relationship between strain rate/temperature parameter and 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet after 10-sec heating time and two different holding times at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

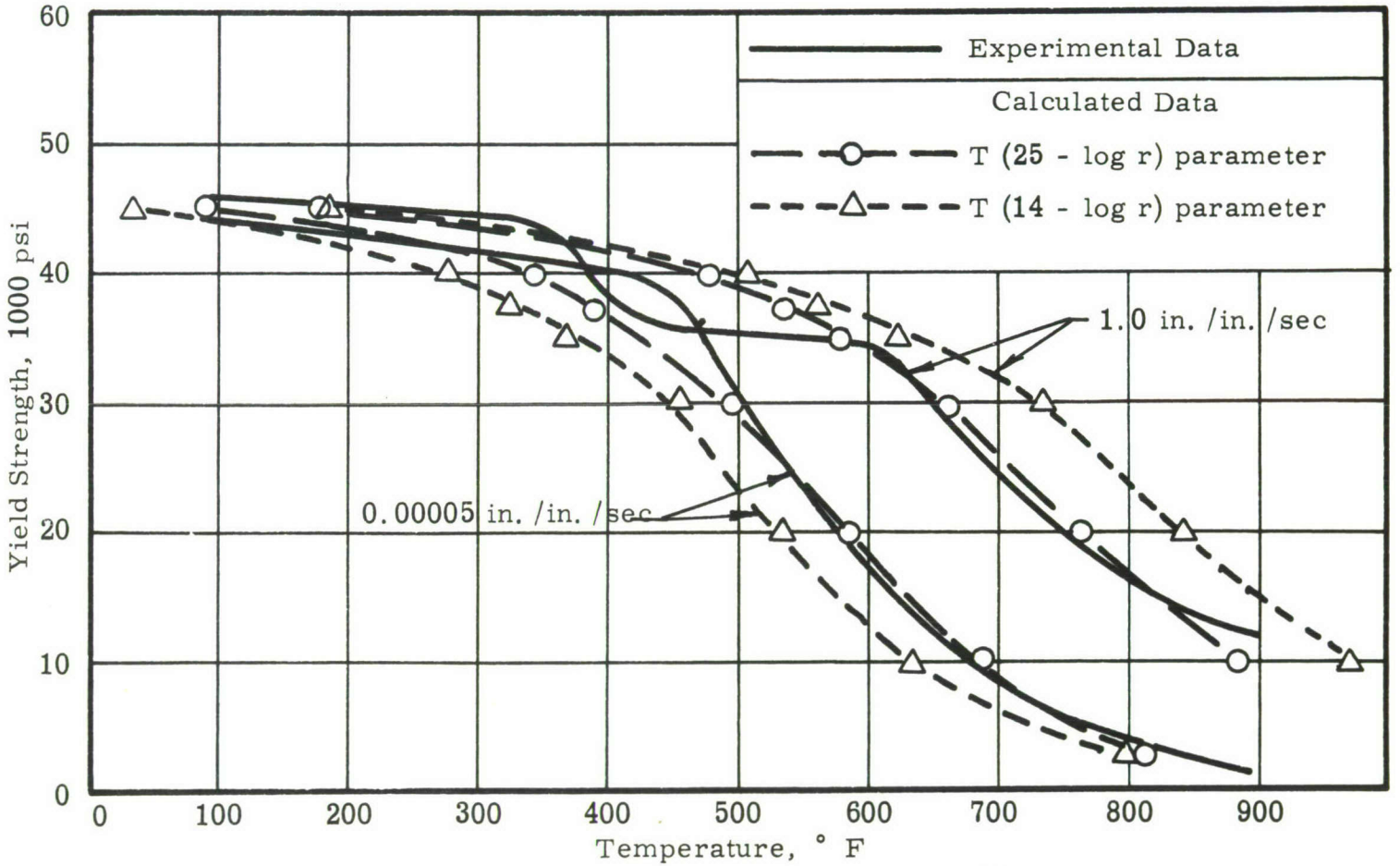

Figure 62. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 alloy aluminum sheet at two strain rates. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain rate in in. /in. /sec.

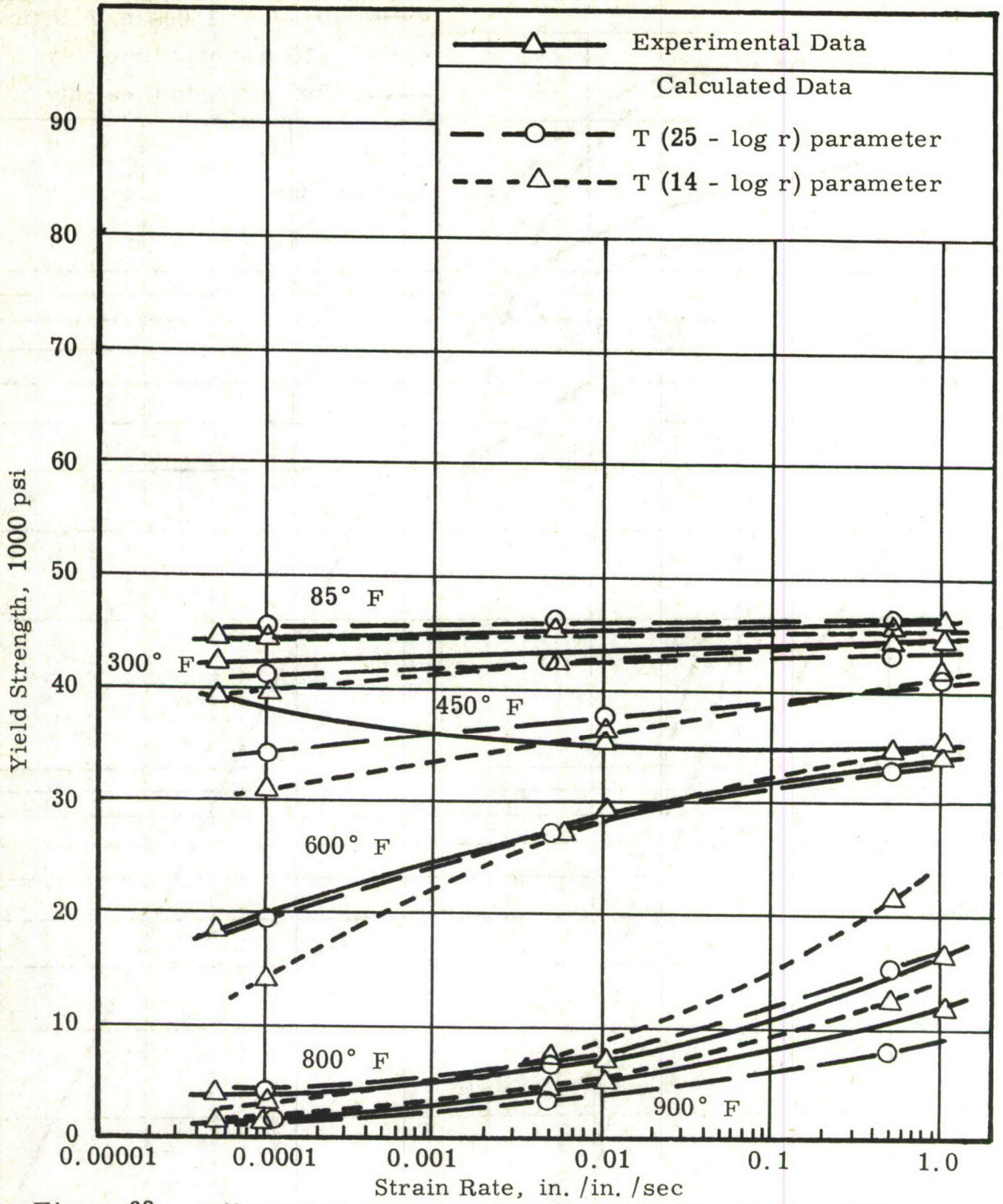

Figure 63. Effect of strain rate, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from two parameters of the form T (c - log r) are shown. T is temperature in ° R and r is strain in in. /in. /sec.

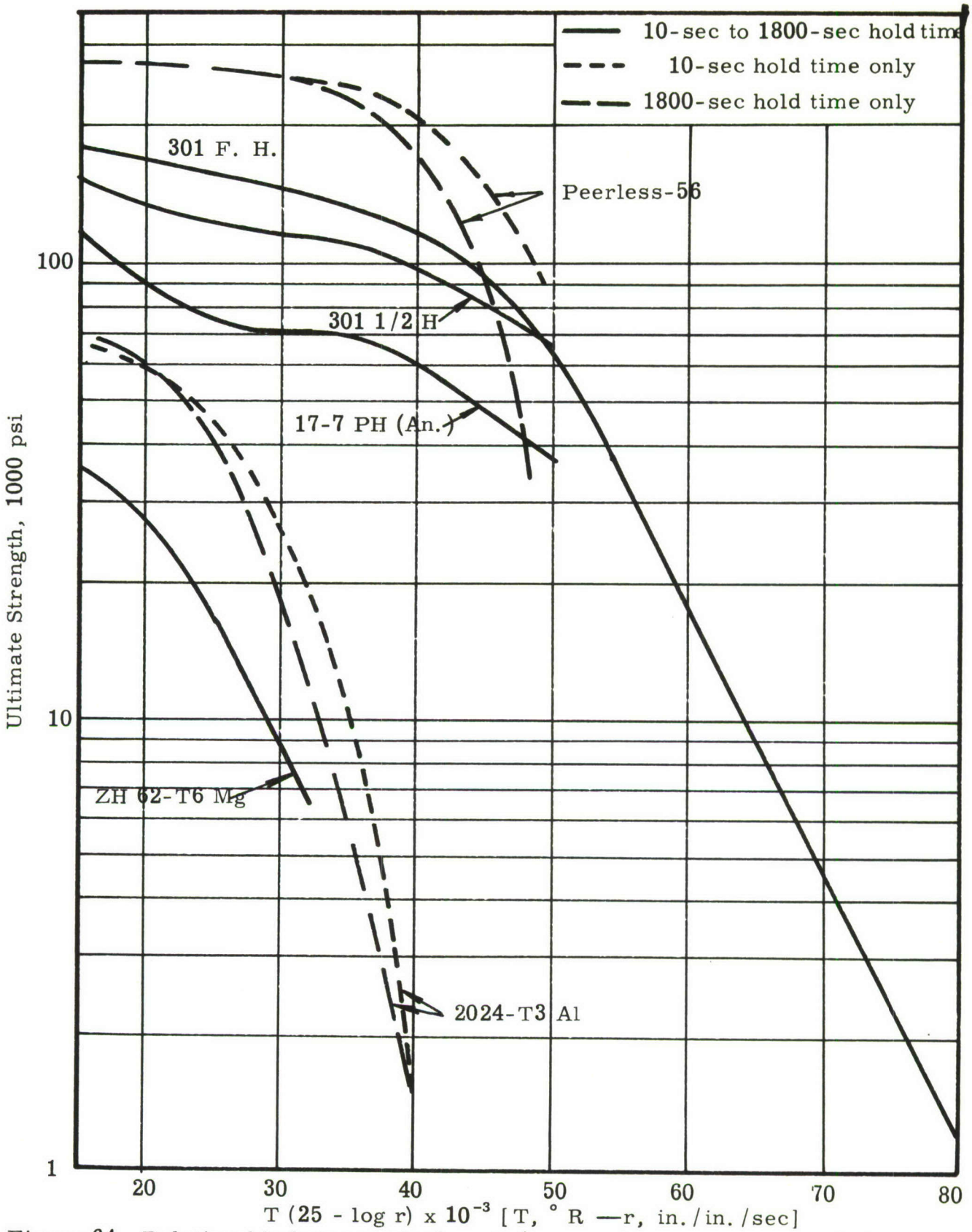

Figure 64. Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800-sec at test temperature. Data applies to strain rates(r) from 0.00005 to 1.0 in./in./sec.

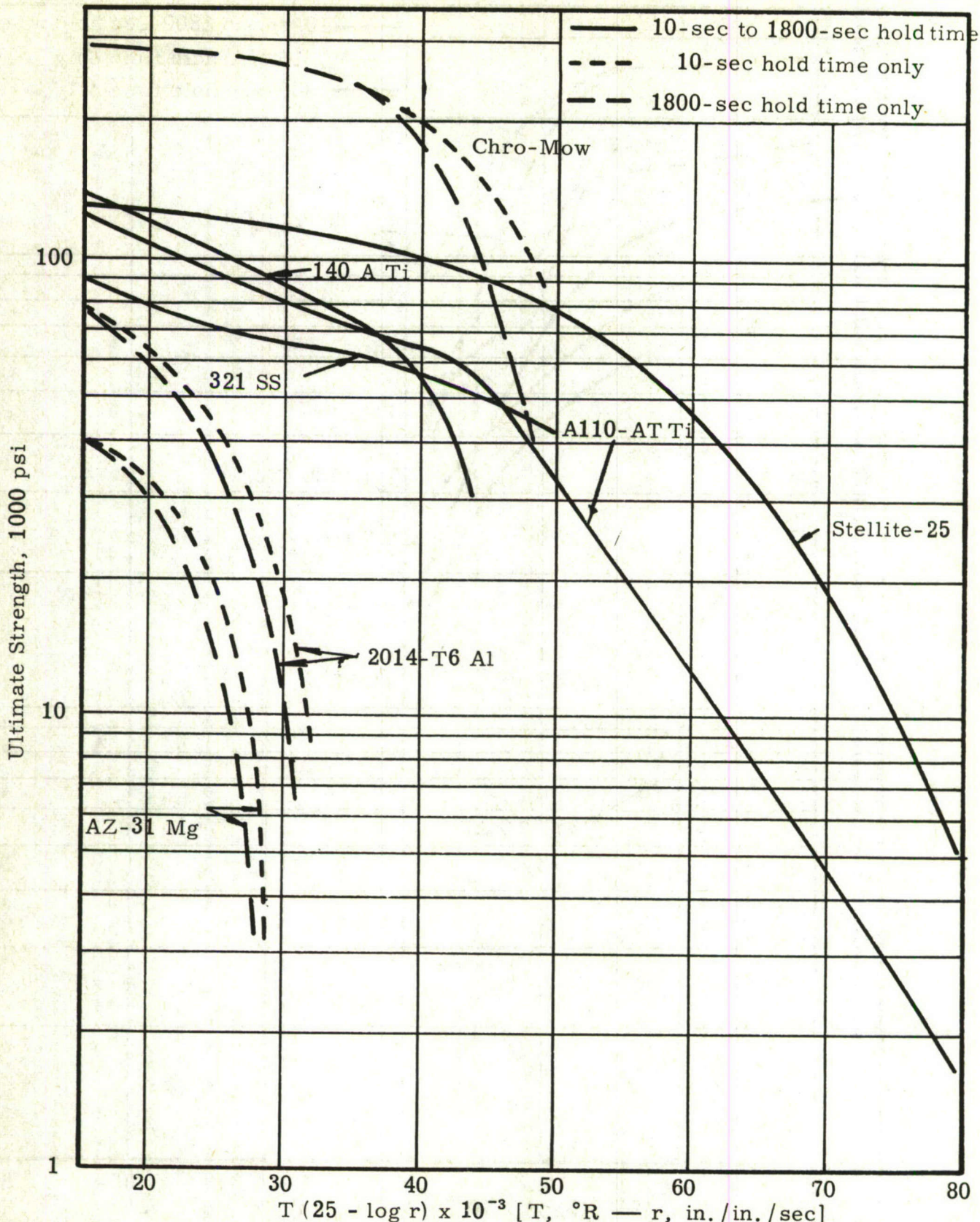

Figure 65. Relationship between strain-rate/temperature parameter and ultimate tensile strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

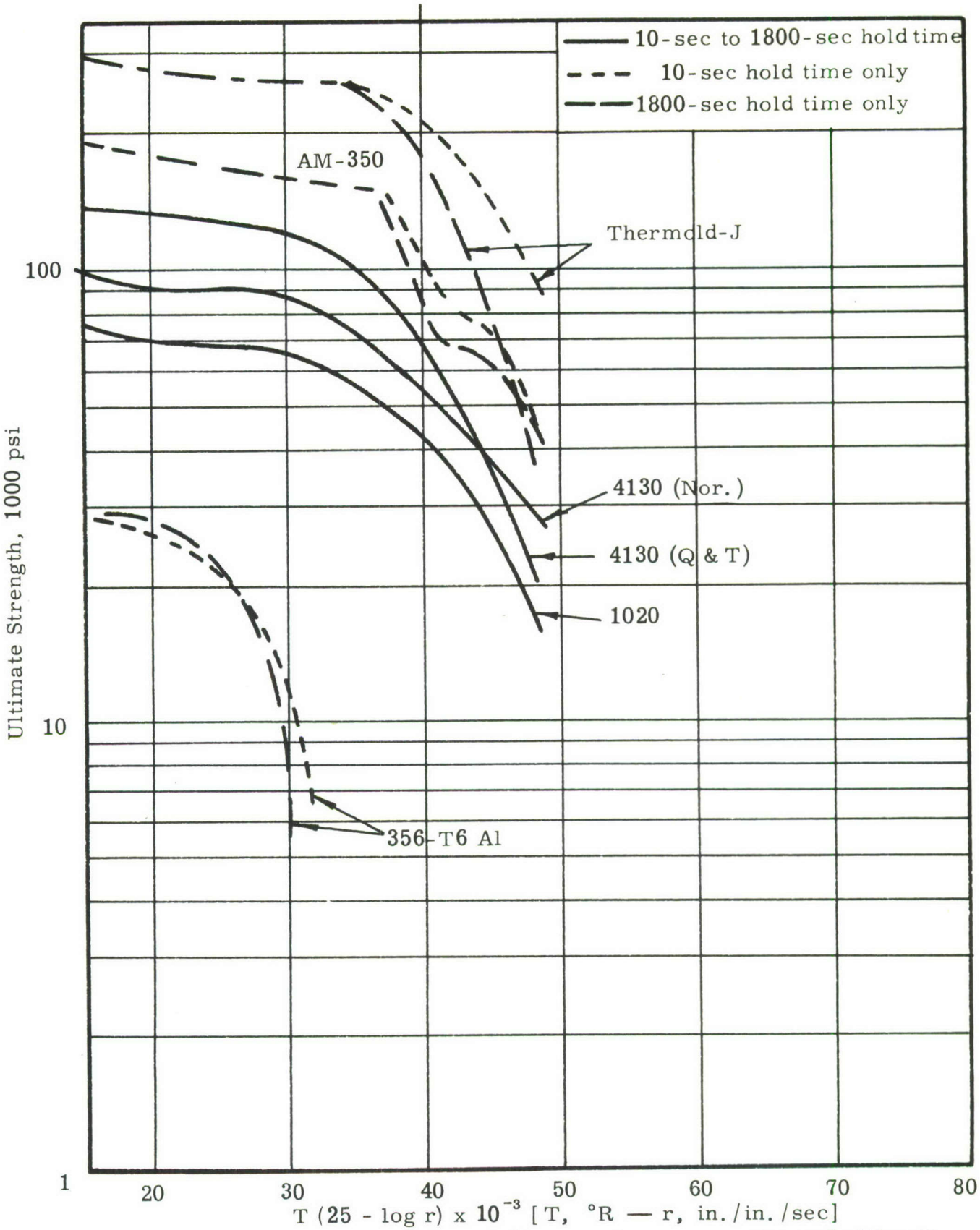

Figure 66. Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800-sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

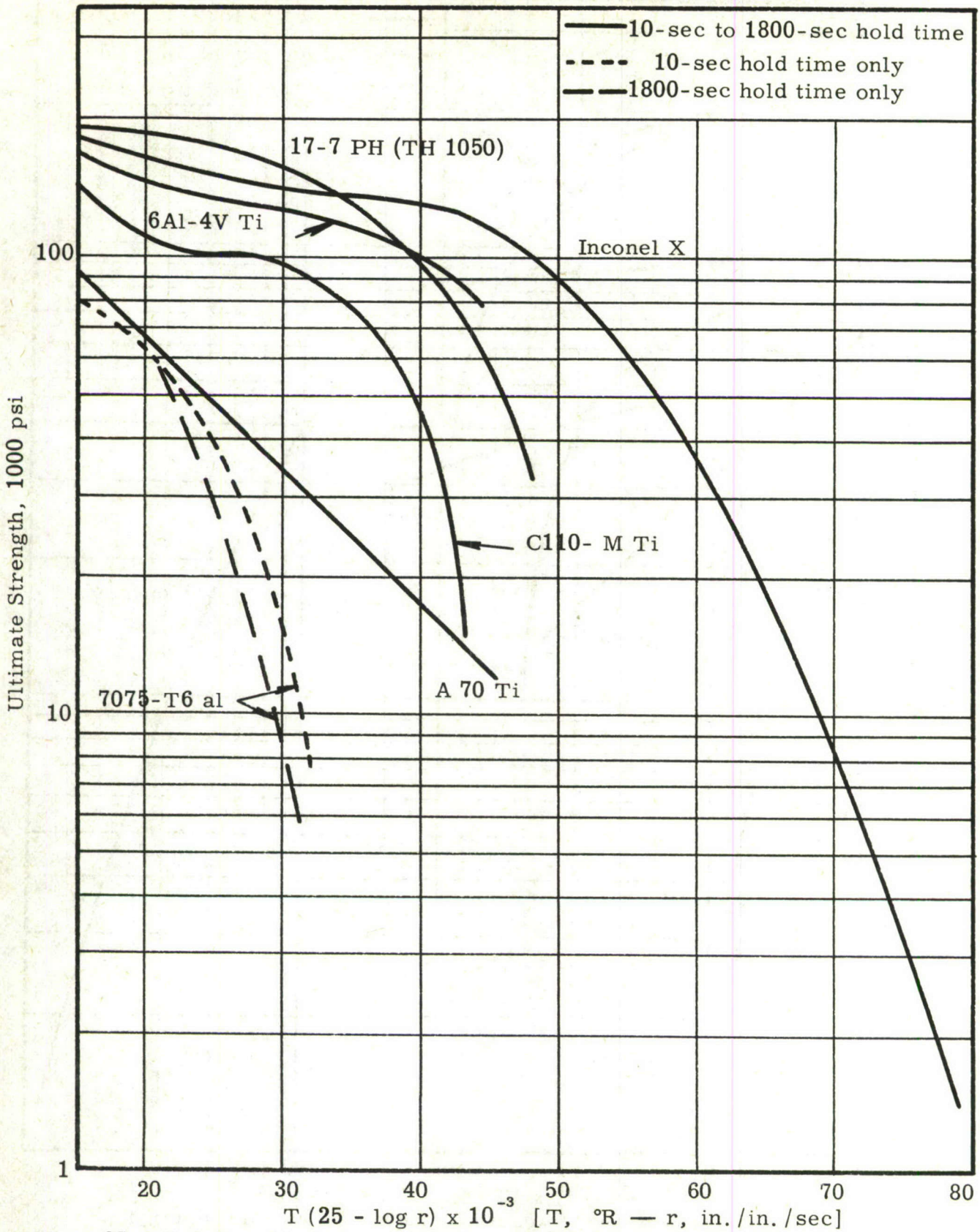

Figure 67. Relationship between strain-rate/temperature parameter and ultimate tensile strength of six metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

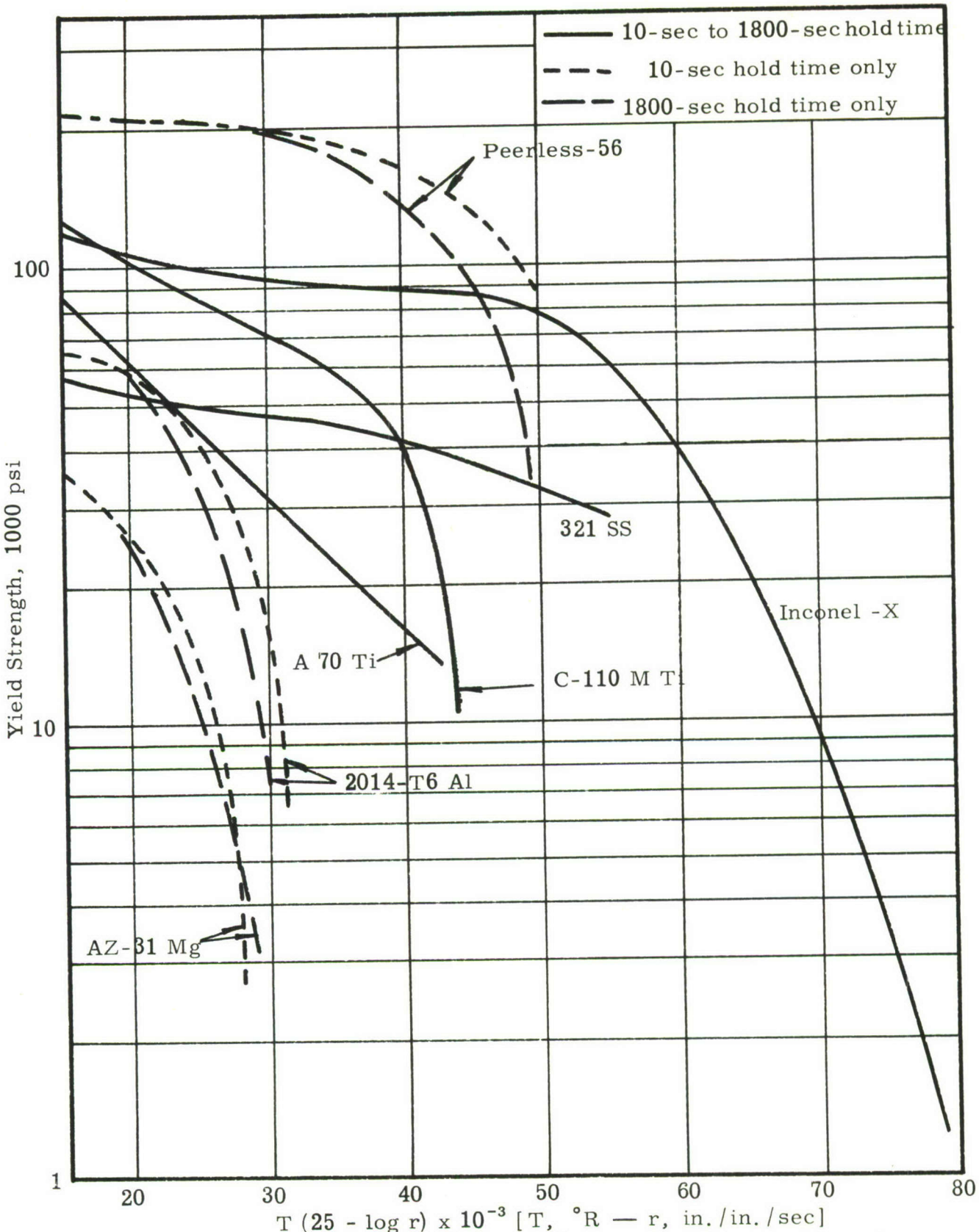

Figure 68. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

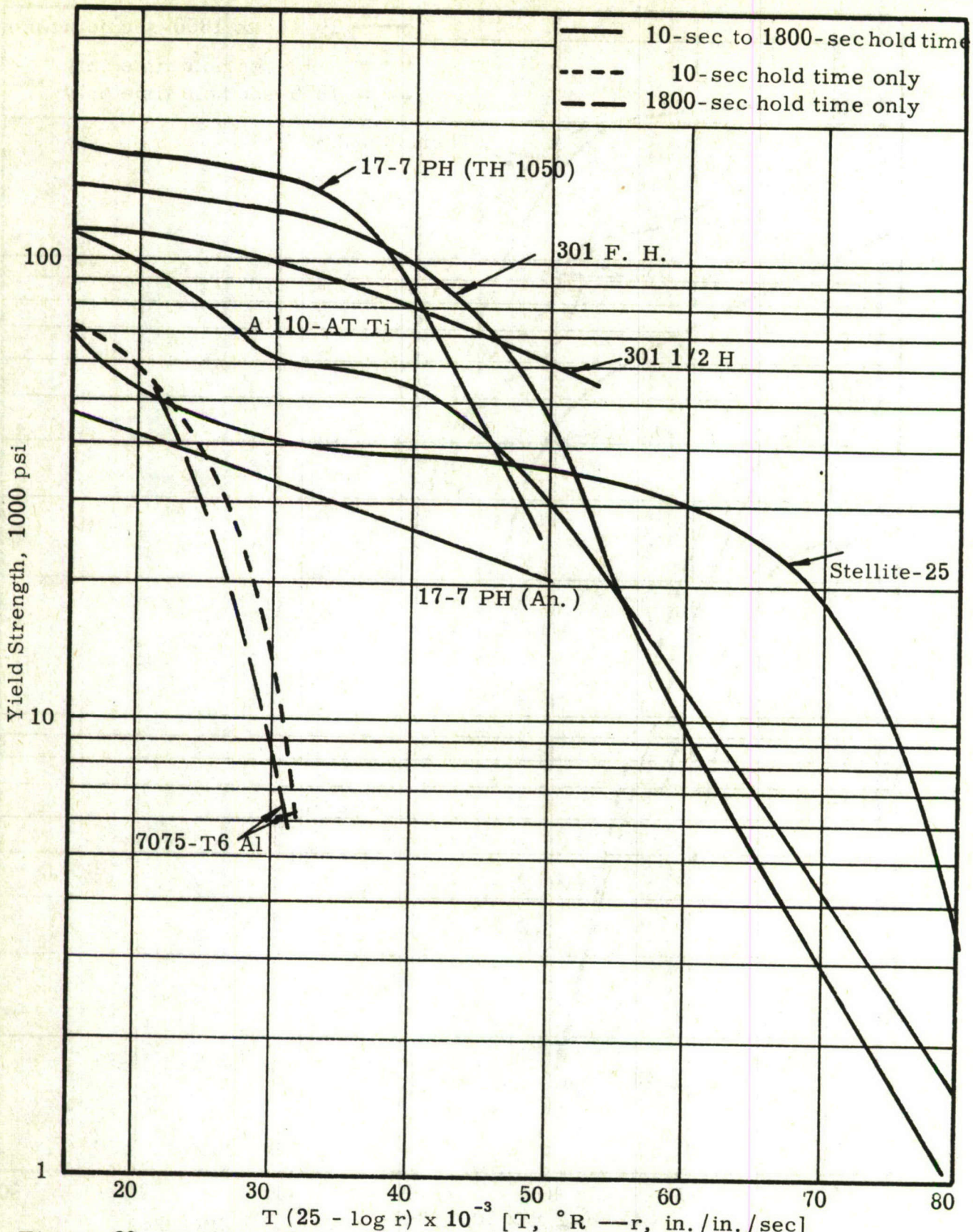

Figure 69. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of seven metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

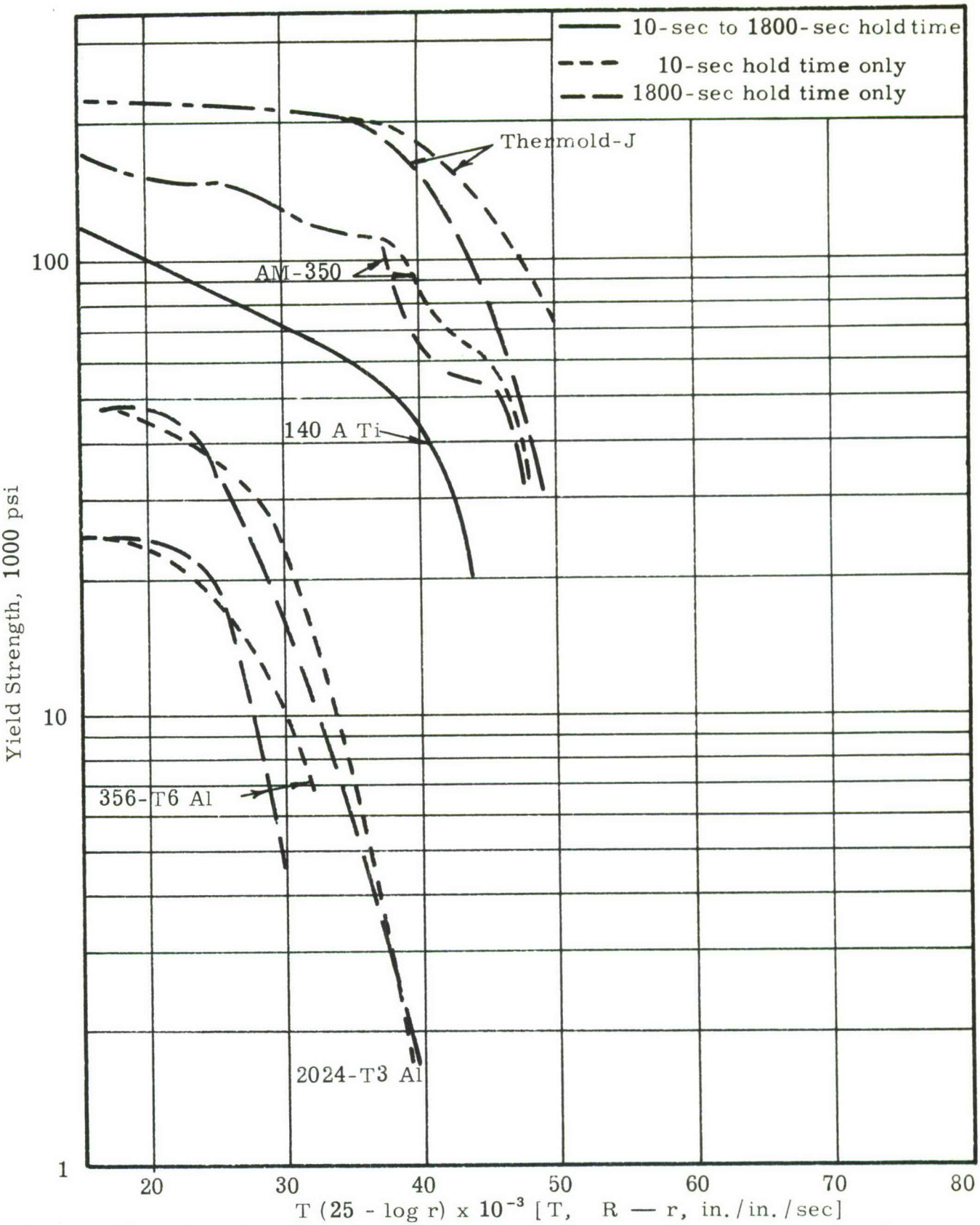

Figure 70. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of five metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

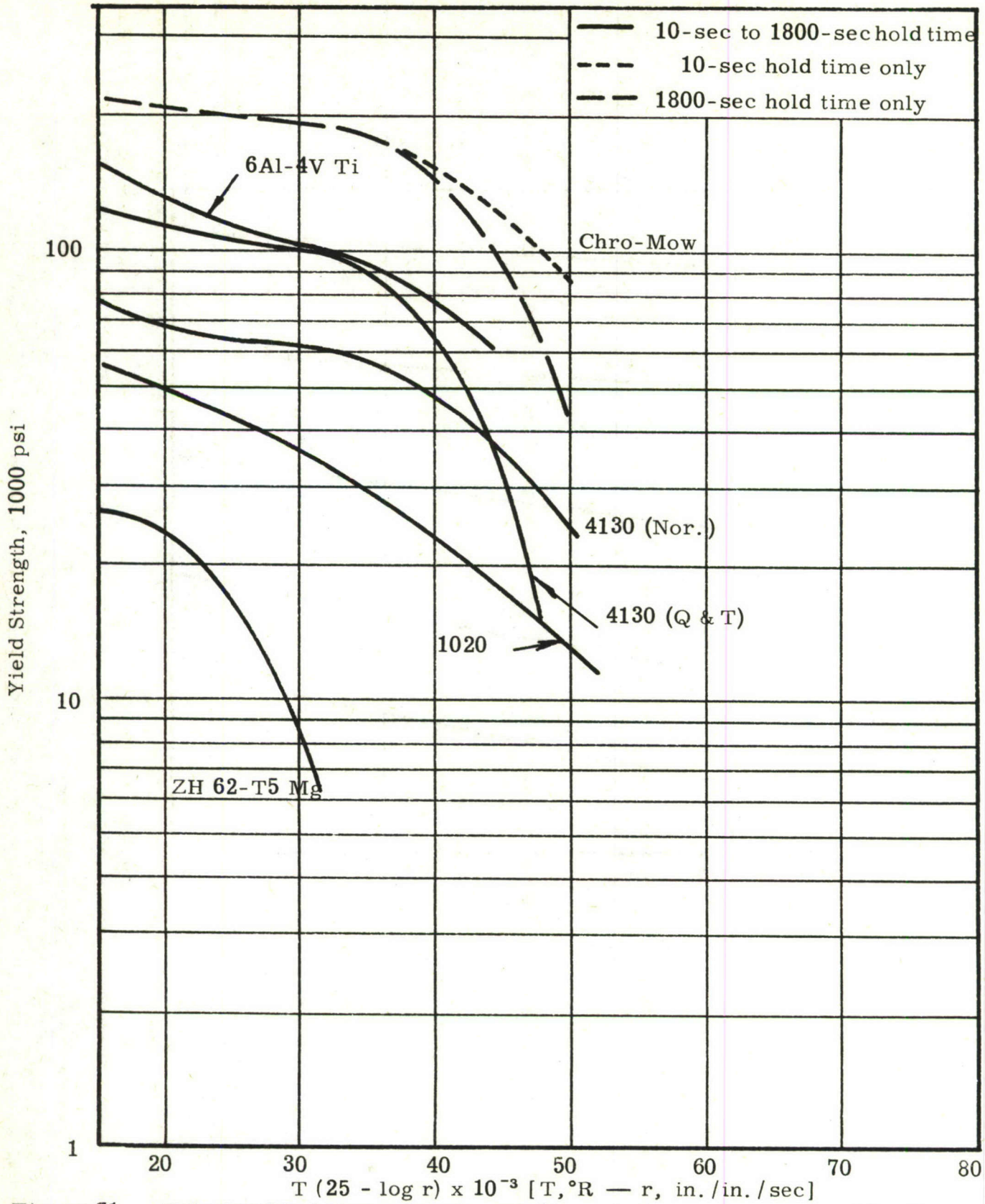

Figure 71. Relationship between strain-rate/temperature parameter and 0.2%-offset yield strength of six metals after 10-sec heating time and holding times from 10 sec to 1800 sec at test temperature. Data applies to strain rates (r) from 0.00005 to 1.0 in./in./sec.

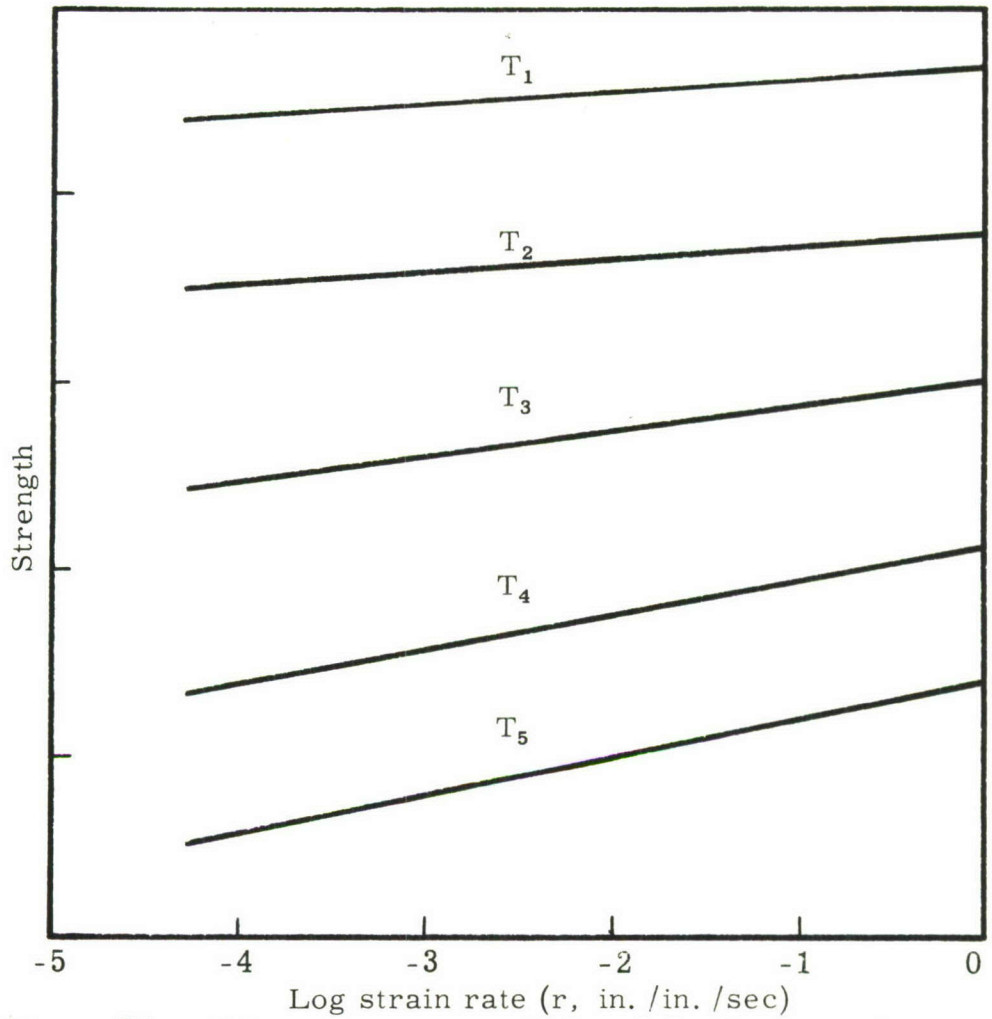

Figure 72. Schematic representation of the linear variation of strength with the log of the strain rate at various constant temperatures in an alloy

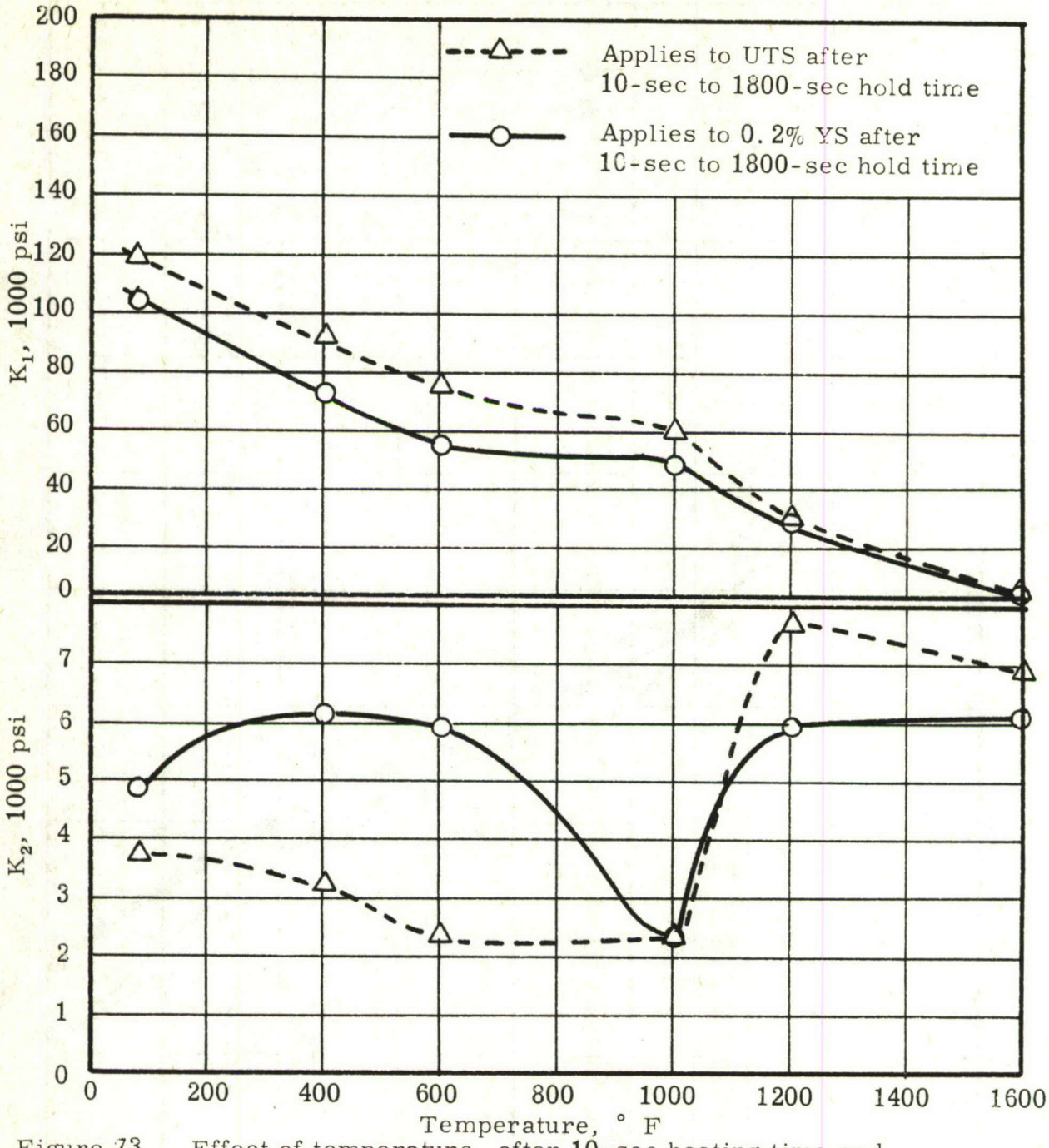

Figure 73. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constant K_1 and K_2 for the determination of the 0.2%-offset yield strength and the ultimate tensile strength of annealed A 110-AT titanium alloy sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

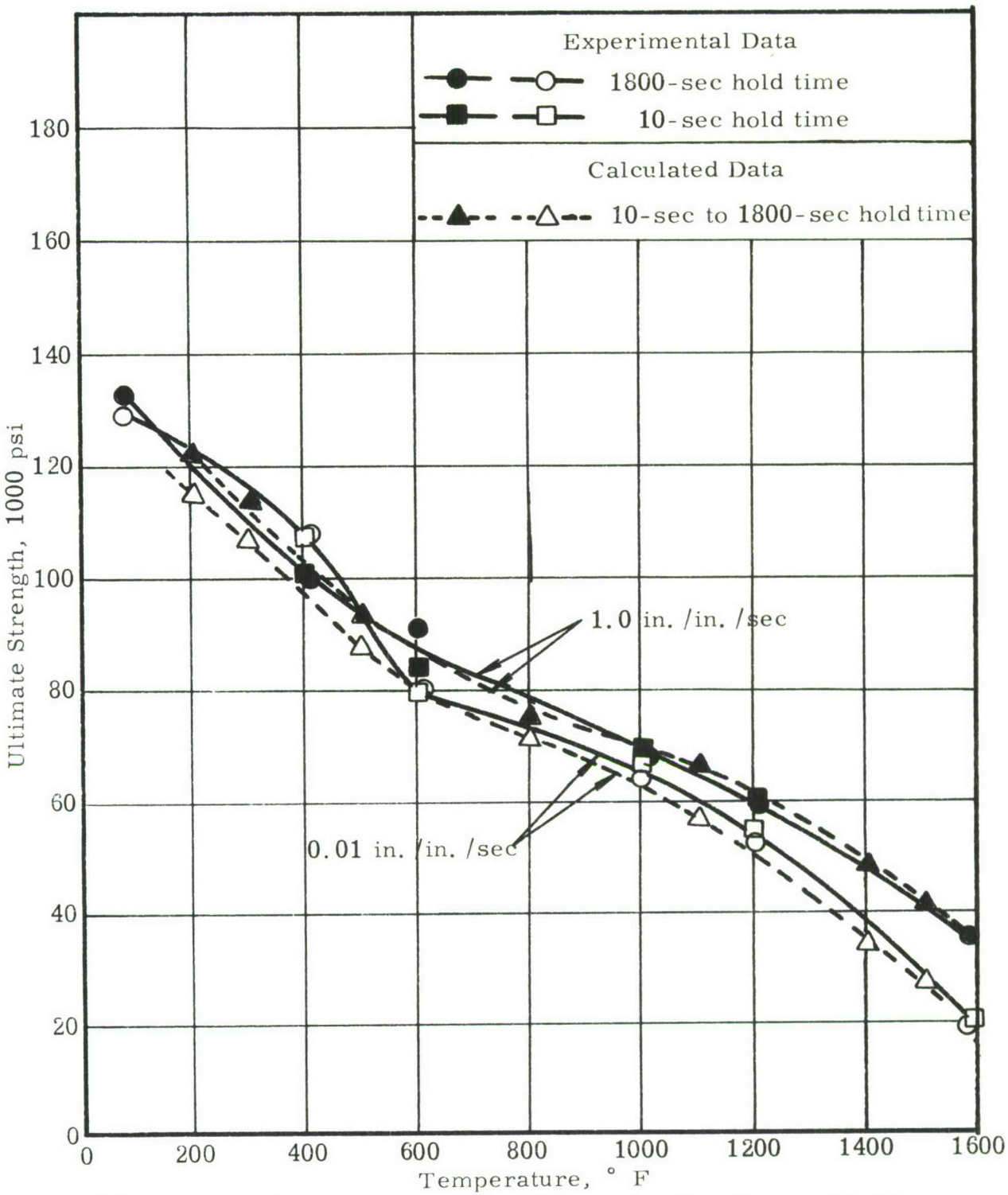

Figure 74. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, UTS = $K_1 + K_2$ (log r + 4.3) are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

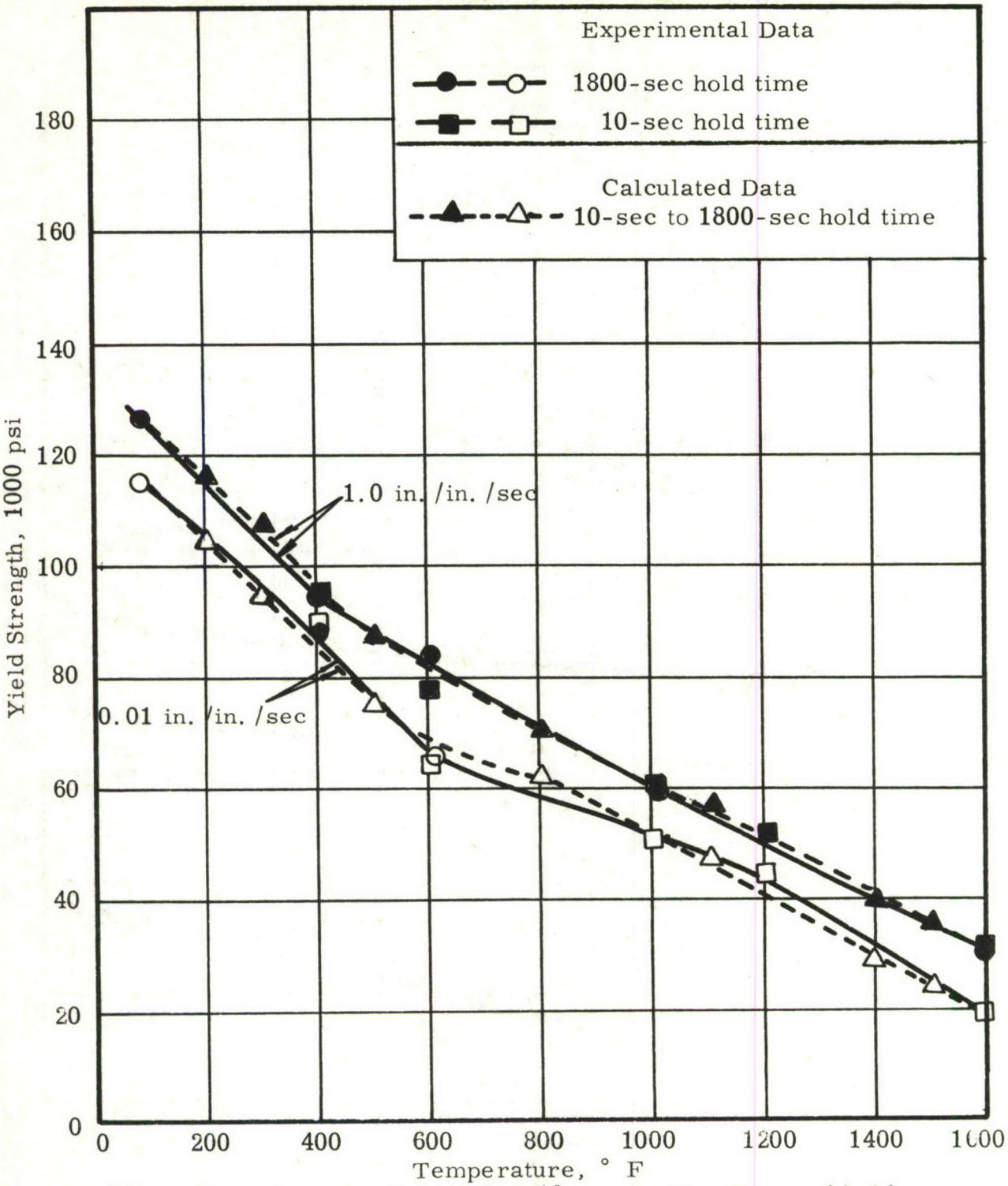

Figure 75. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

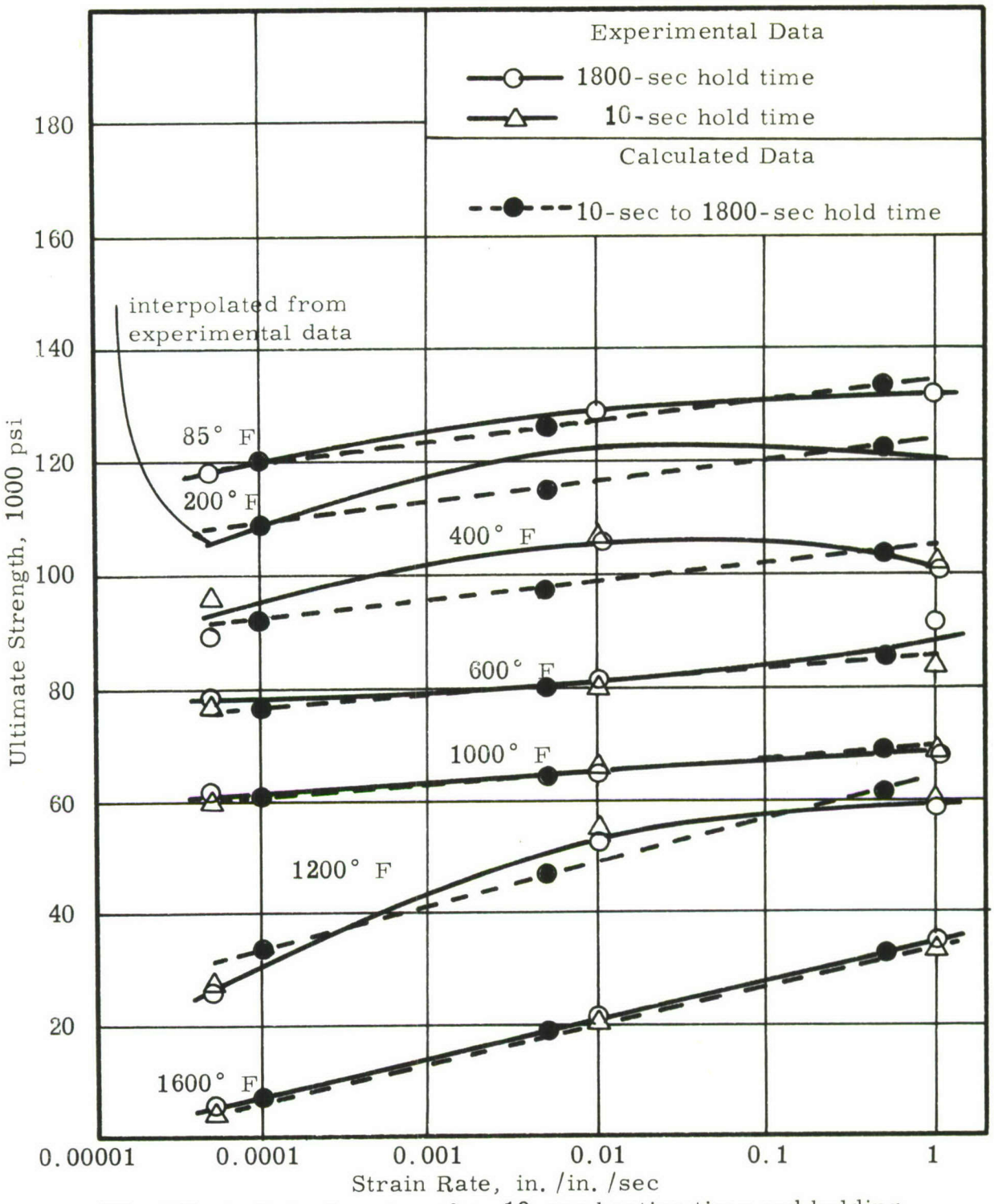

Figure 76. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the ultimate tensile strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, UTS = $K_1 + K_2$ (log r + 4.3) are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

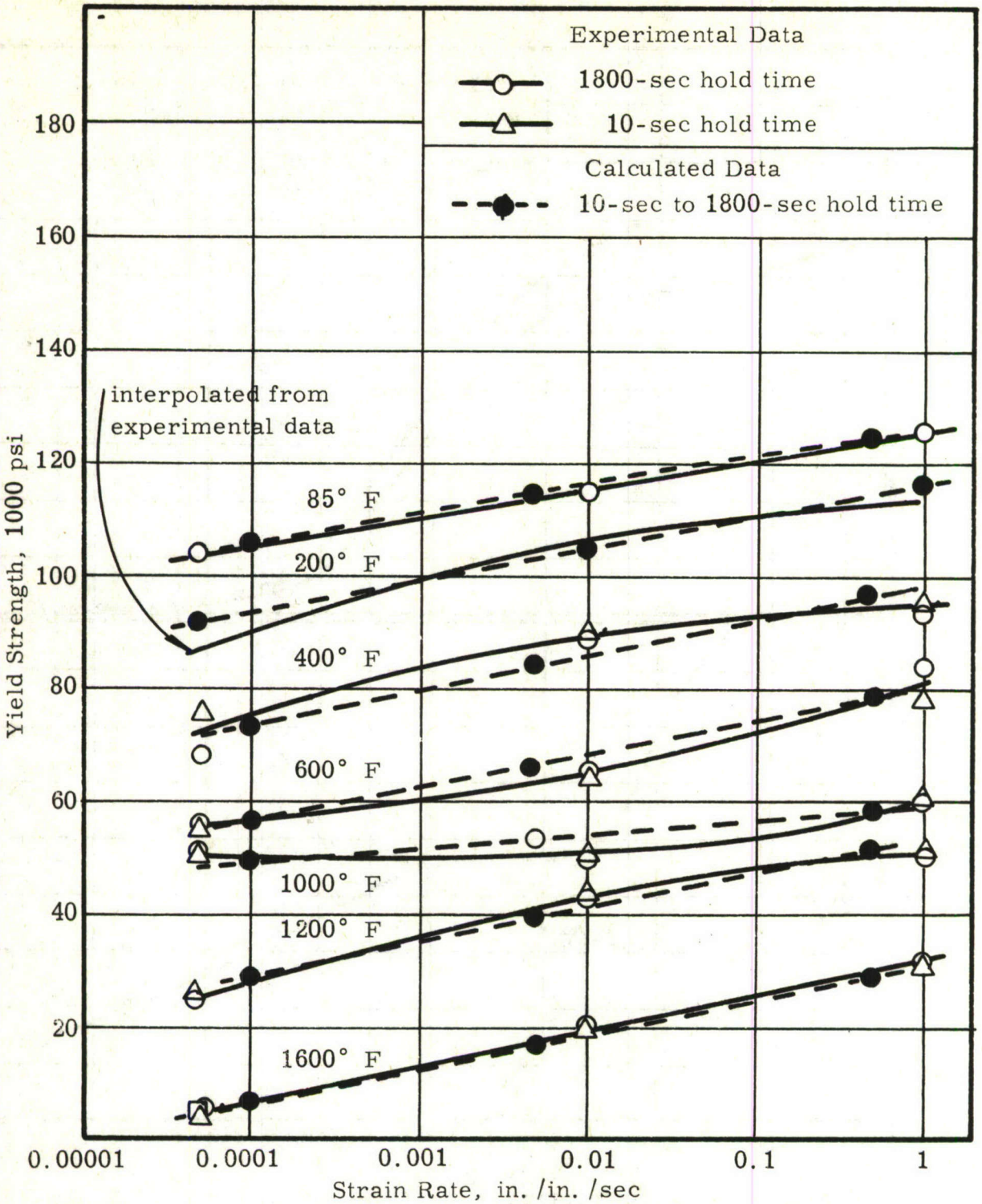

Figure 77. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of annealed A 110-AT titanium alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, YS = $K_1 + K_2$ (log r + 4.3) are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in./in./sec.

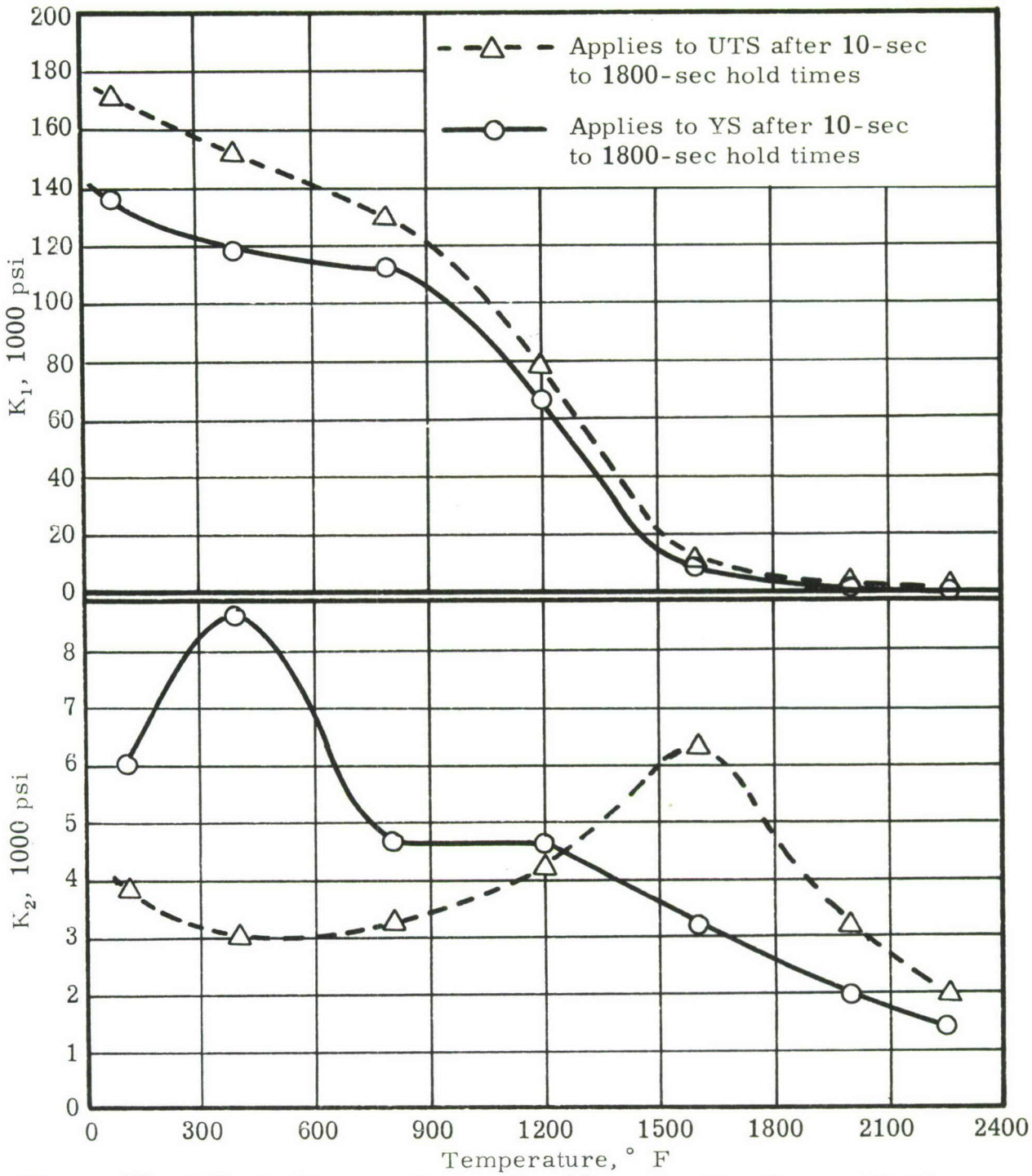

Figure 78. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determinations of the 0.2%-offset yield strength and ultimate tensile strength of full-hard 301 stainless steel sheet by the formula, Strength = $K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

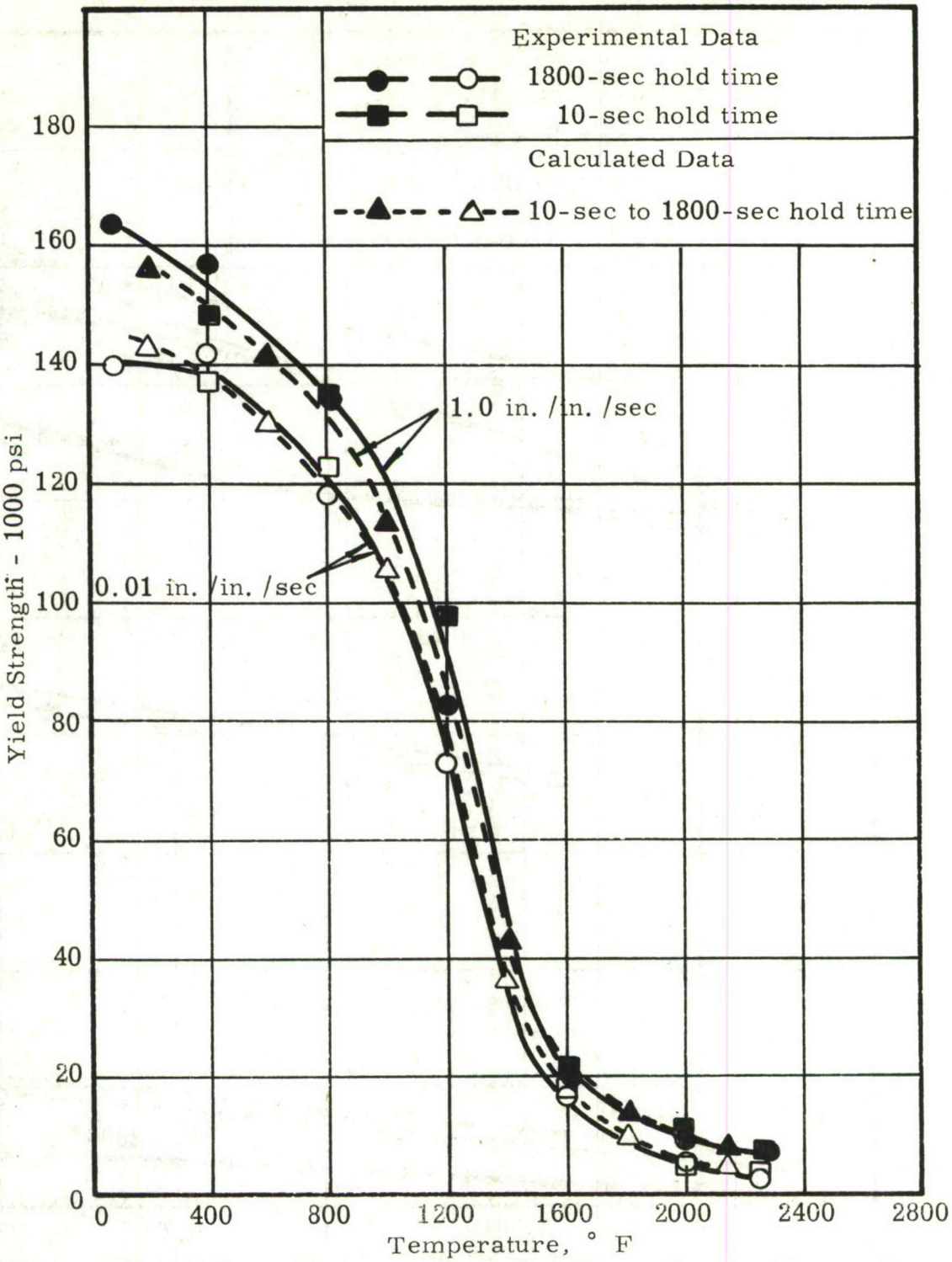

Figure 79. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

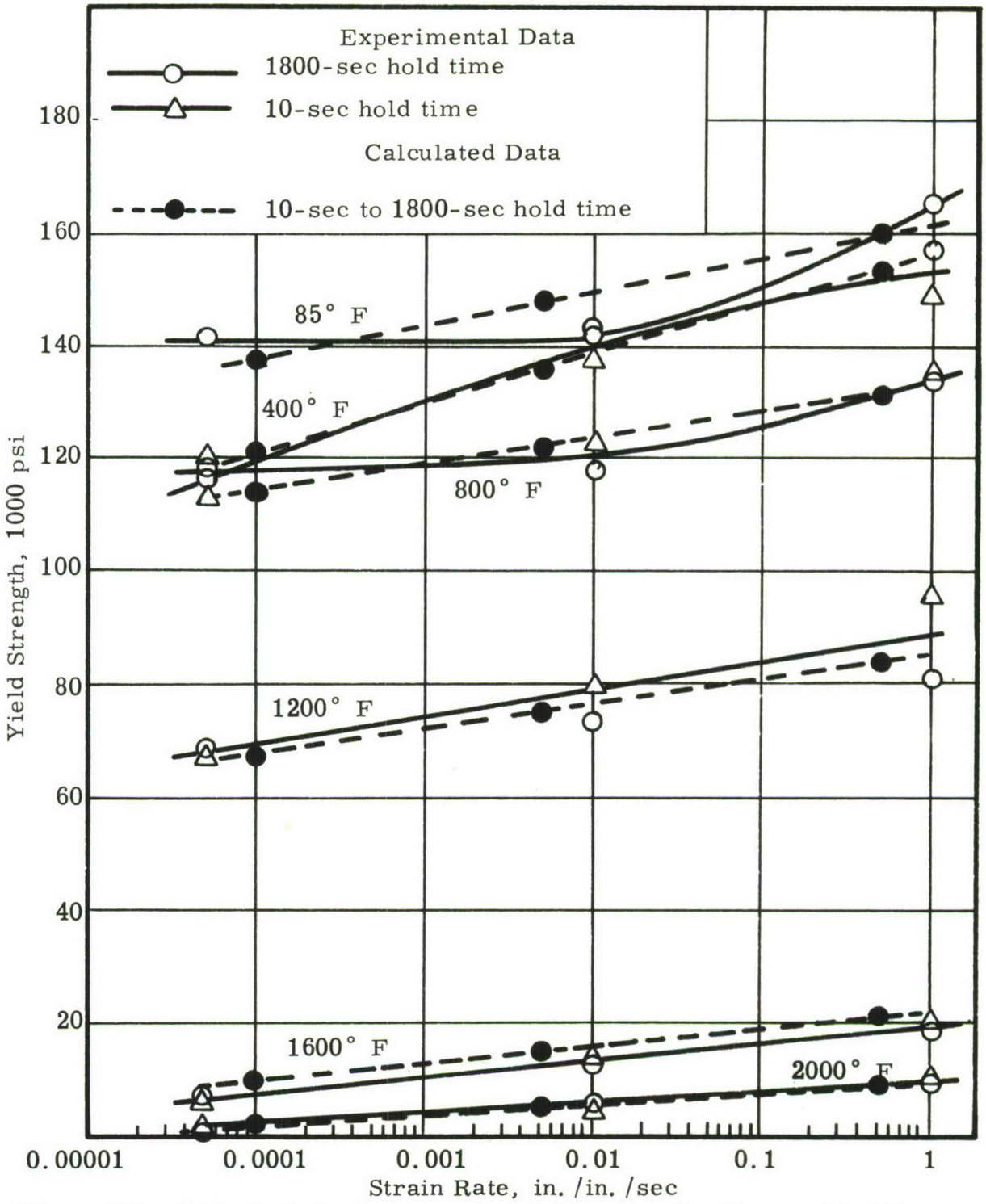

Figure 80. Effect of strain rate, after 10-sec heating time and holding times from 10 sec to 1800 sec, on the 0.2%-offset yield strength of full-hard 301 stainless steel sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

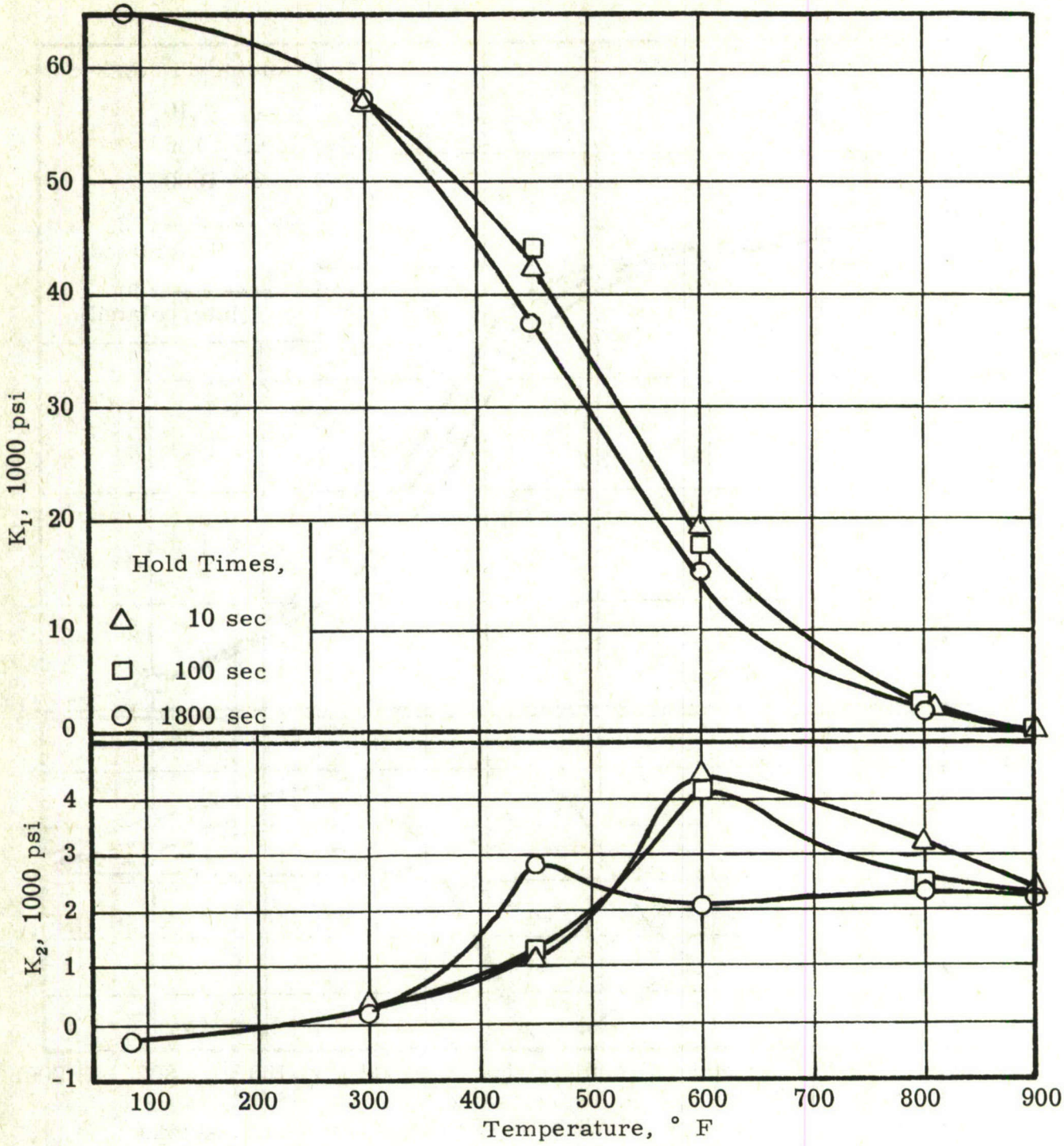

Figure 81. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of alclad 2024-T3 aluminum alloy sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. /in. /sec.

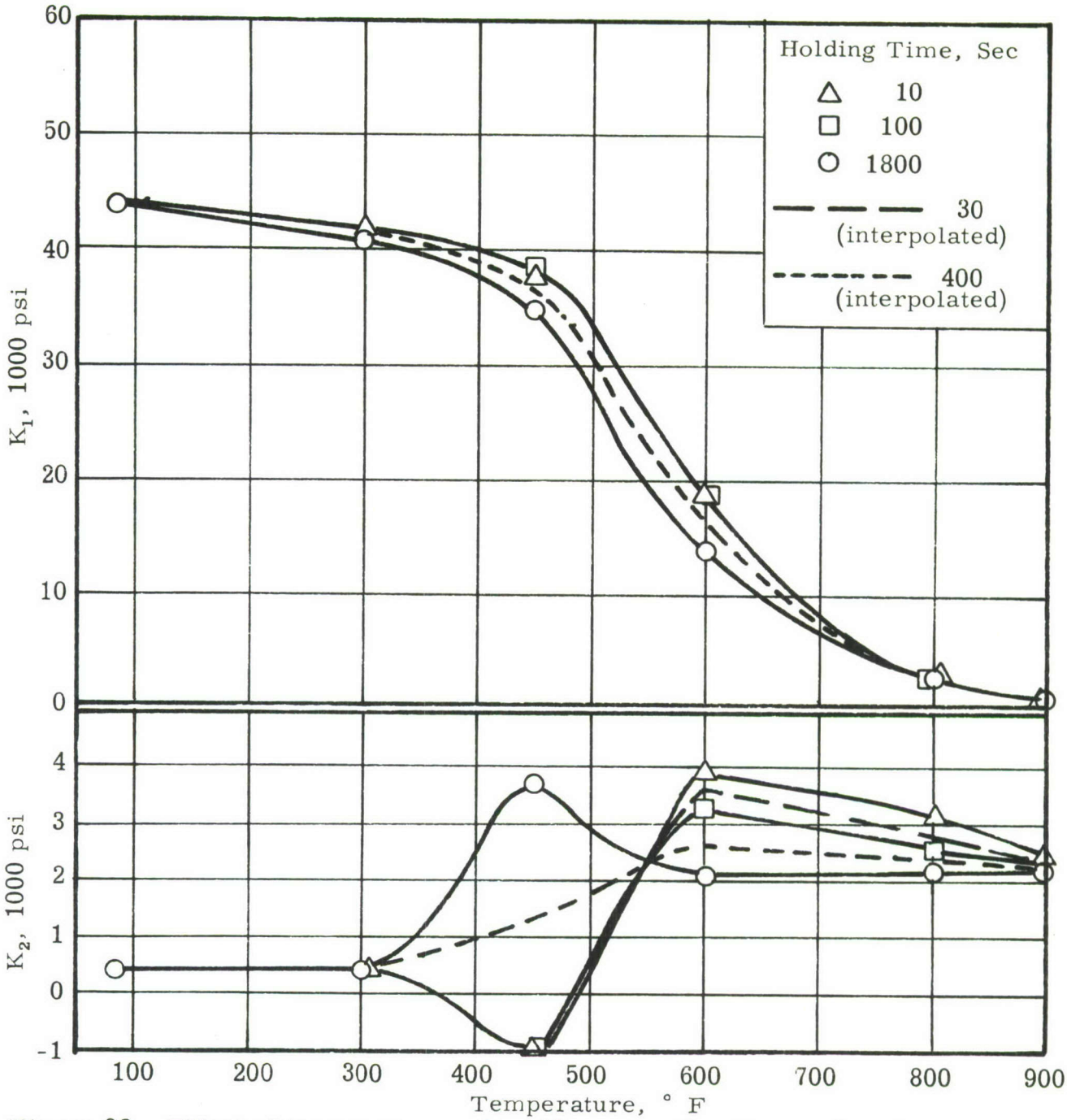

Figure 82. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

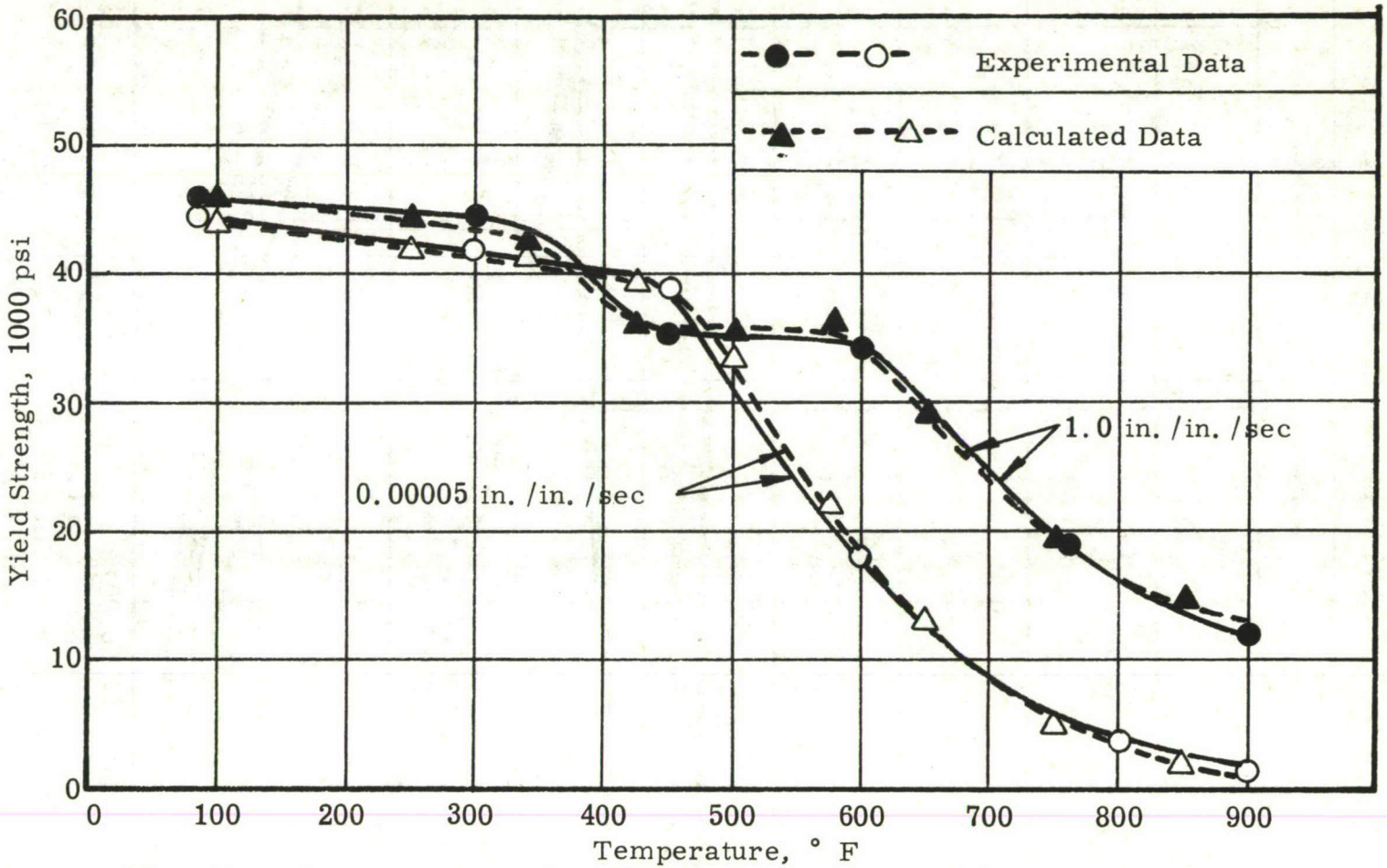

Figure 83. Effect of temperature, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at two strain rates. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

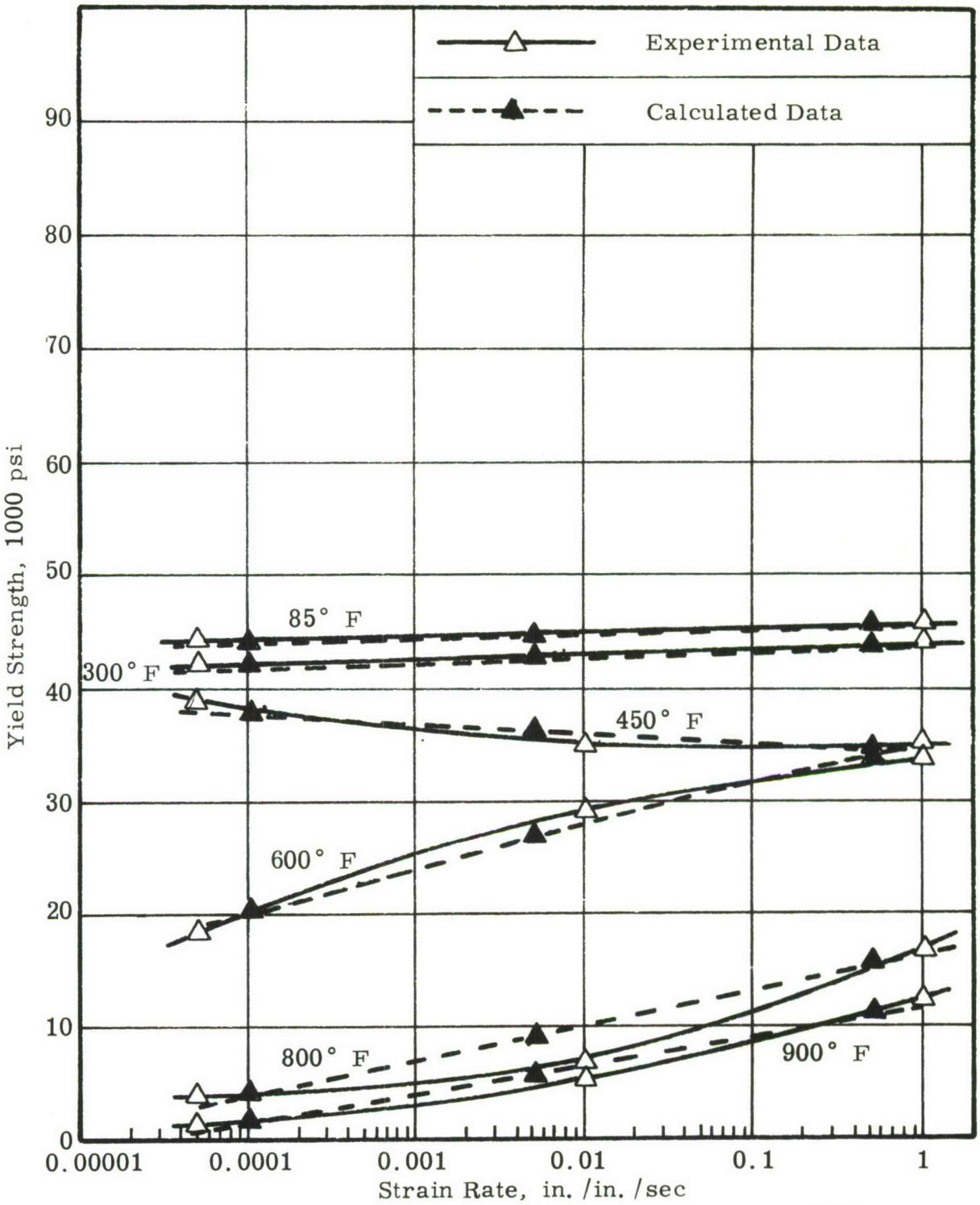

Figure 84. Effect of strain rate, after 10-sec heating time and 10-sec holding time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature-dependent constants and r is the strain rate in in. /in. /sec.

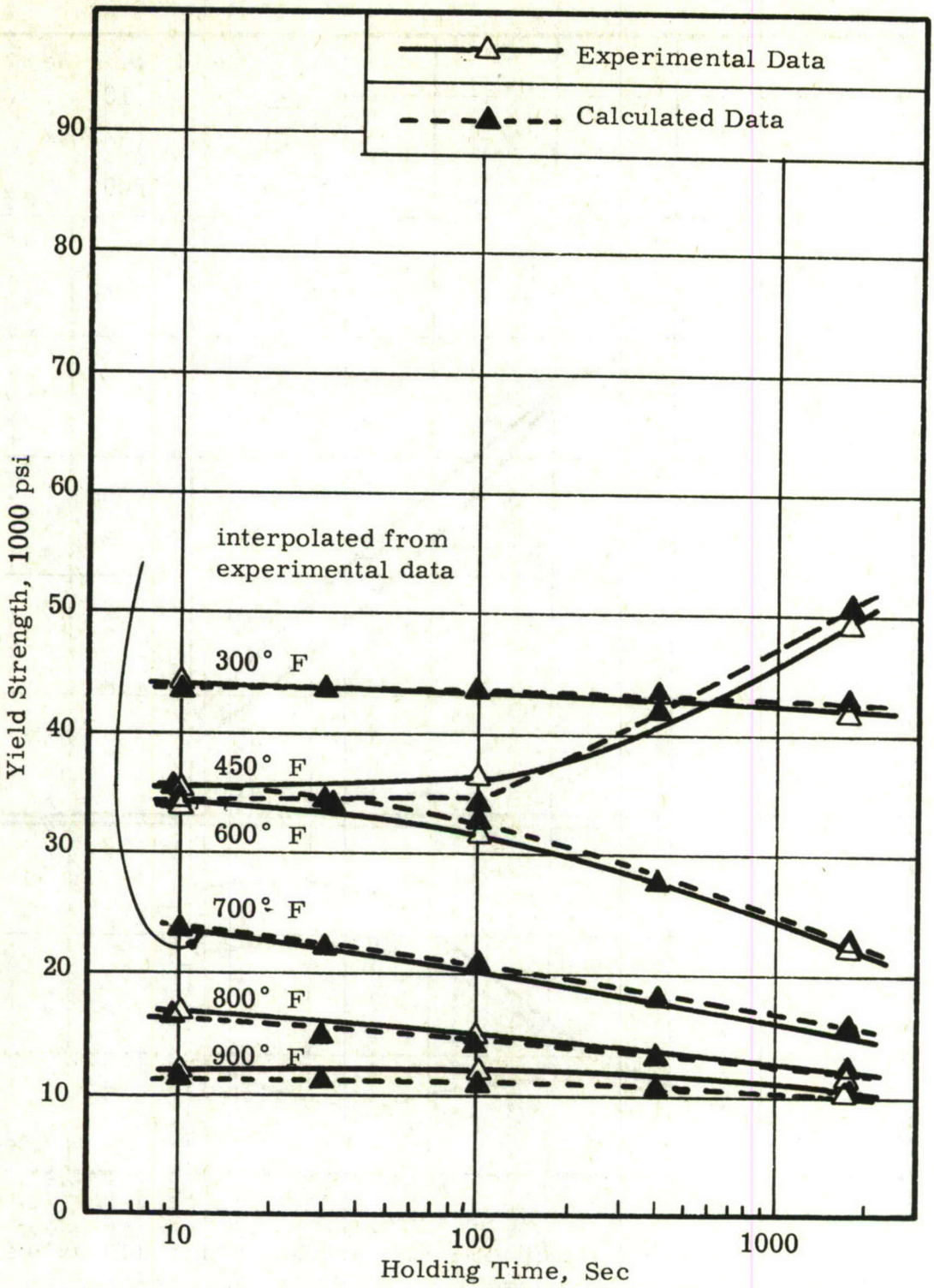

Figure 85. Effect of holding time, after 10-sec heating time, on the 0.2%-offset yield strength of alclad 2024-T3 aluminum alloy sheet at various temperatures and at a strain rate of 1.0 in./in./sec. Both experimentally determined curves and curves calculated from the formula, $YS = K_1 + K_2 (\log r + 4.3)$ are shown. K_1 and K_2 are temperature- and holding-time-dependent constants and r is the strain rate in in./in./sec.

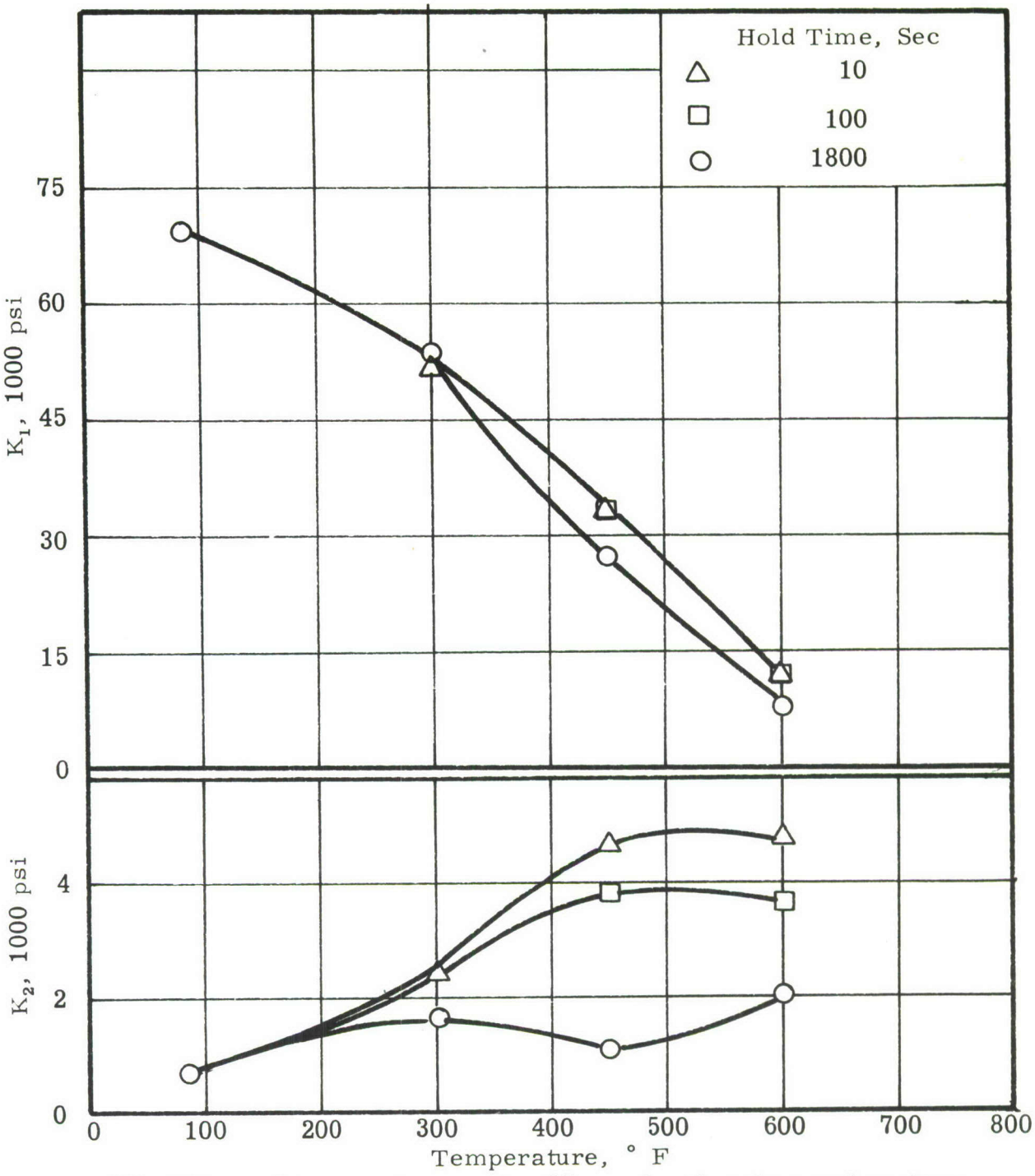

Figure 86. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of alclad 2014-T6 aluminum alloy sheet by the formula, UTS = $K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

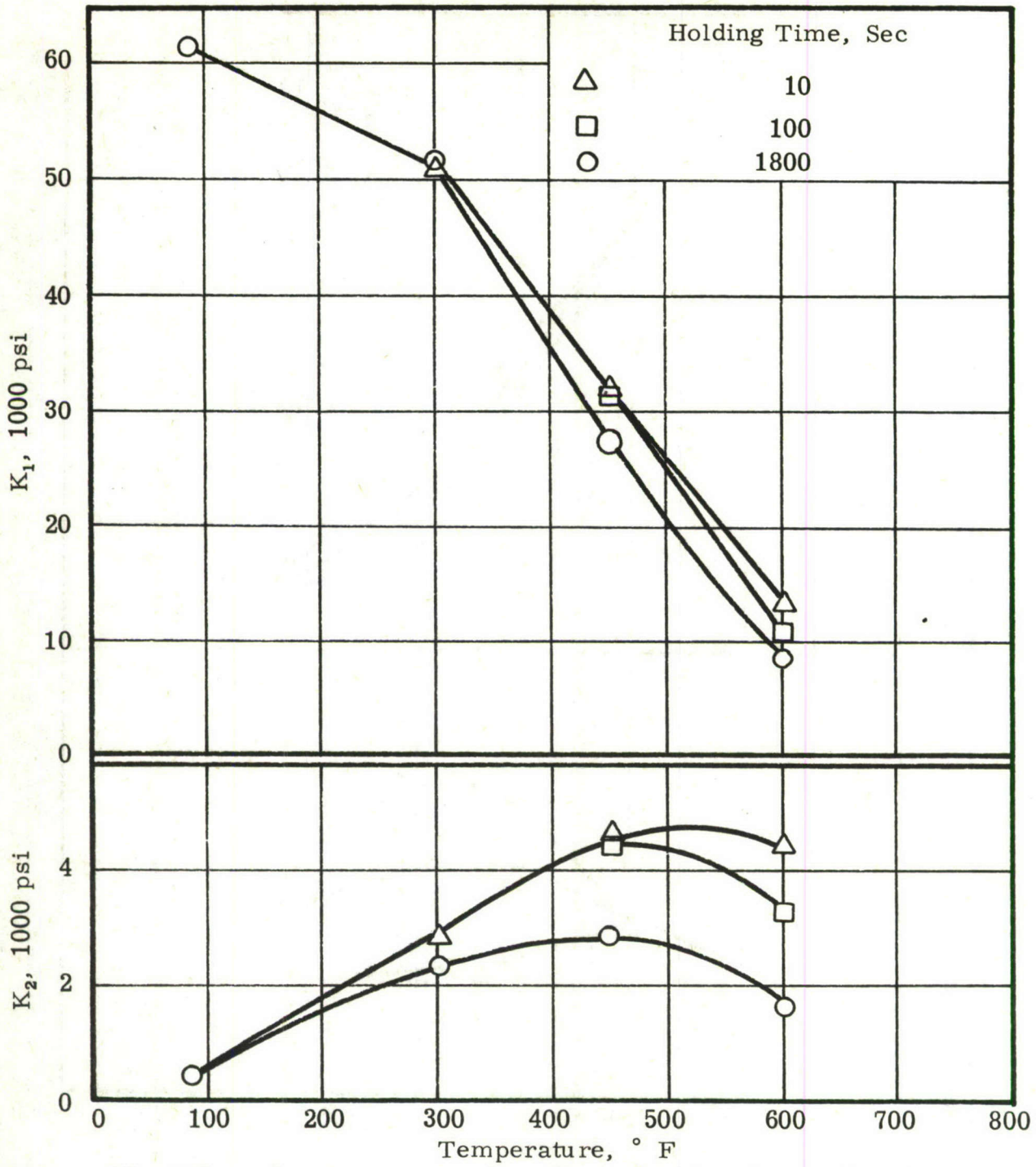

Figure 87. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of alclad 2014-T6 aluminum alloy sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

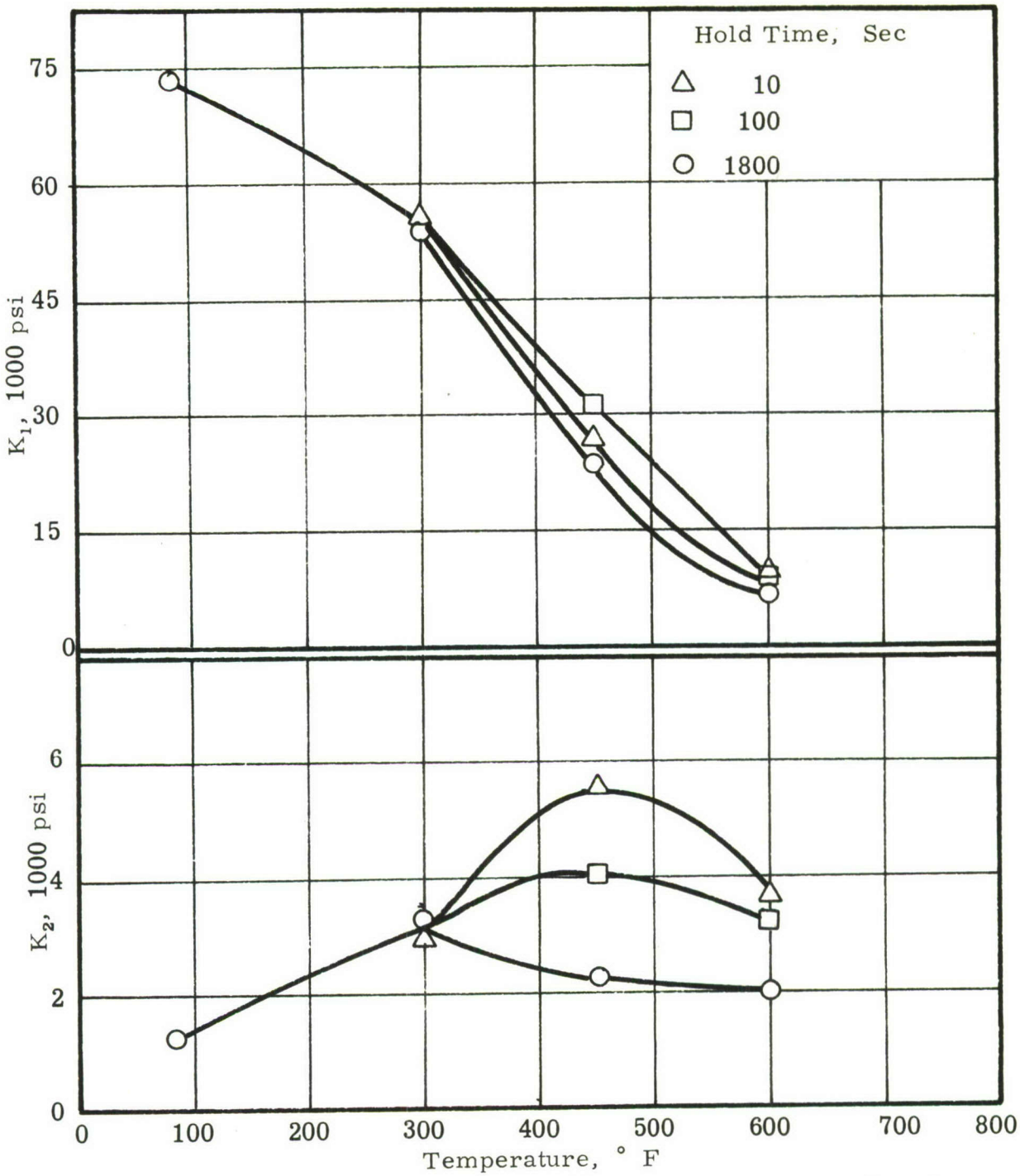

Figure 88. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of alclad 7075-T6 aluminum alloy sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

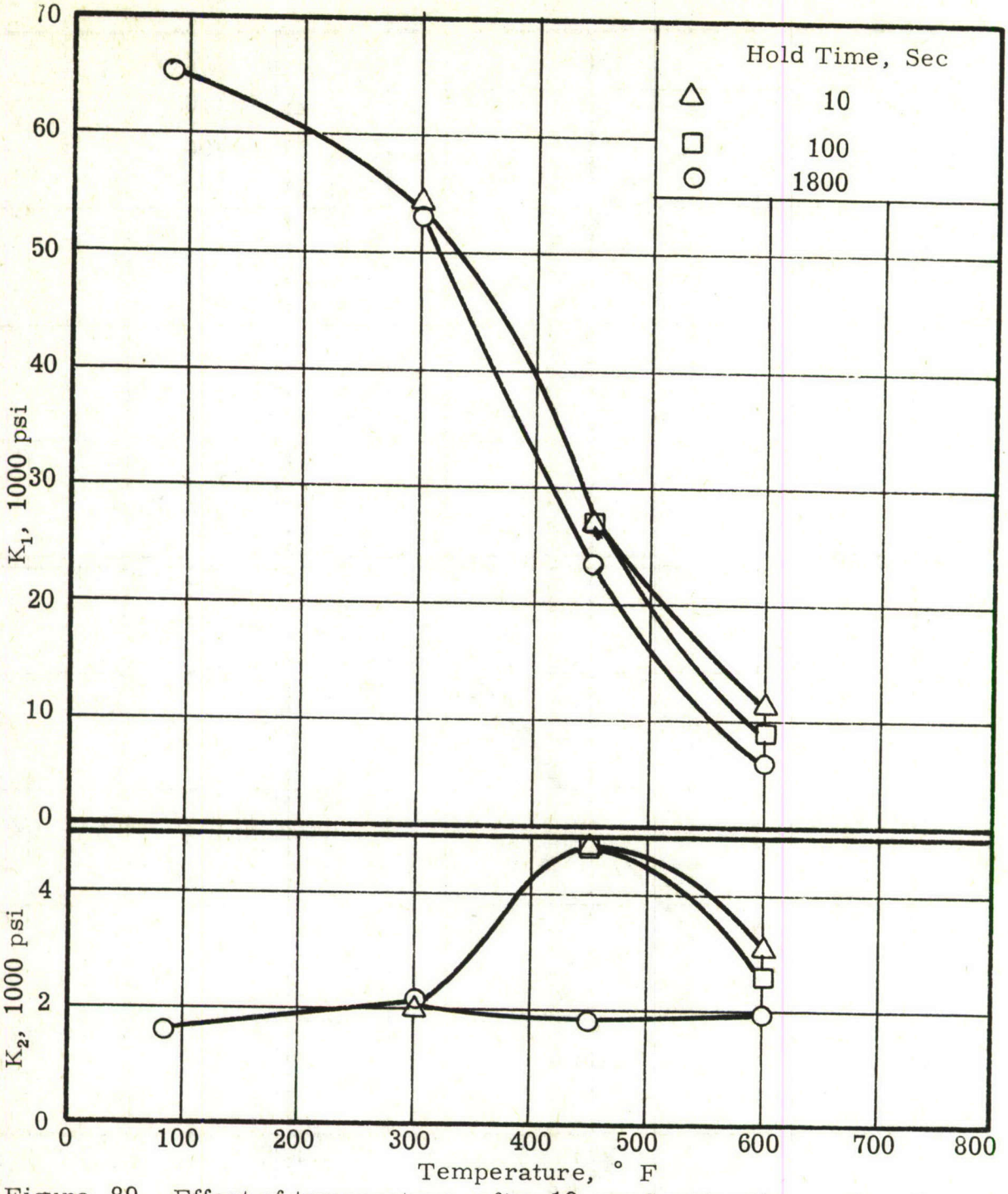

Figure 89. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of alclad 7075-T6 aluminum alloy sheet by the formula $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

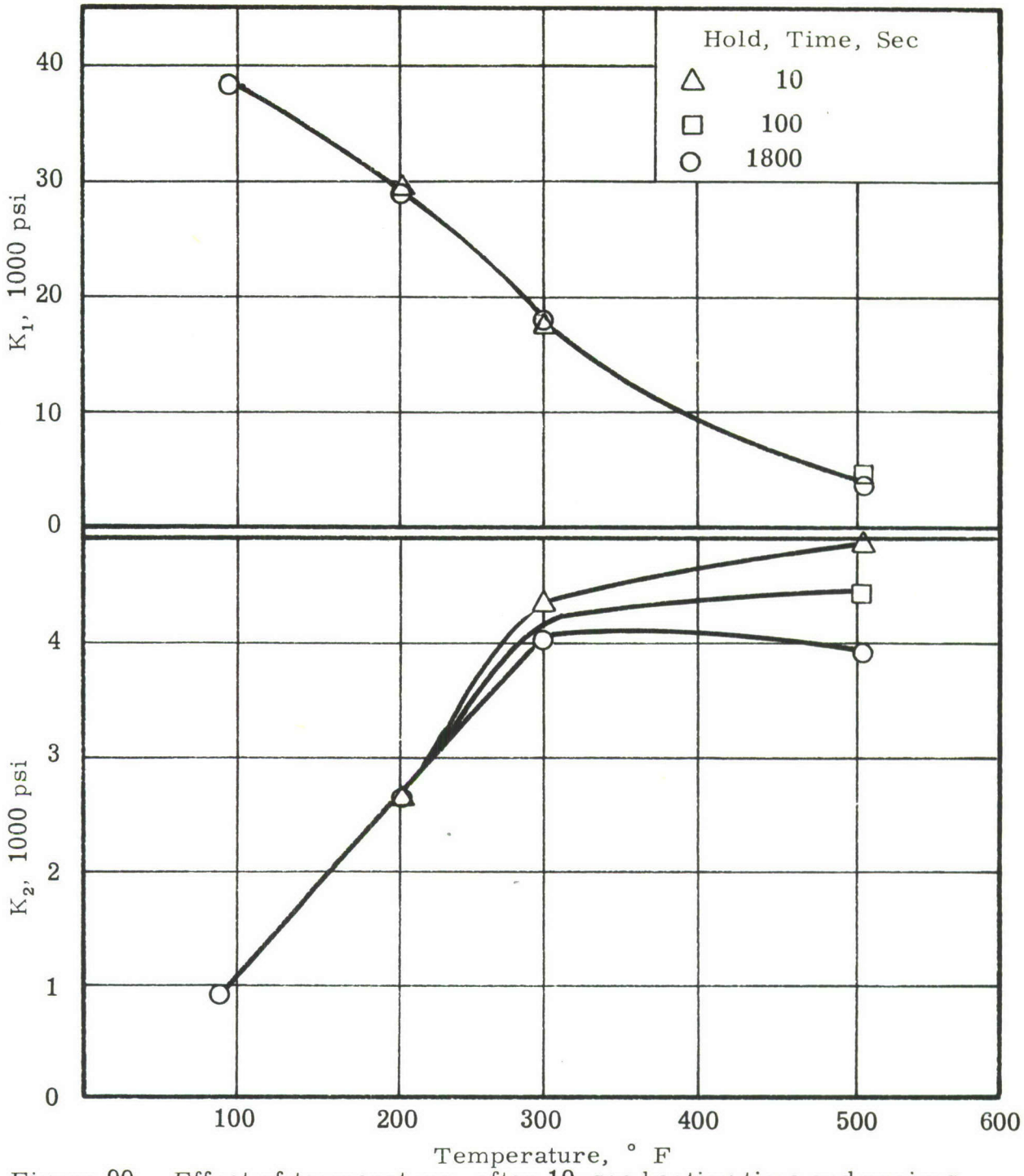

Figure 90. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of hard-rolled AZ-31 magnesium alloy sheet by the formula, $UTS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

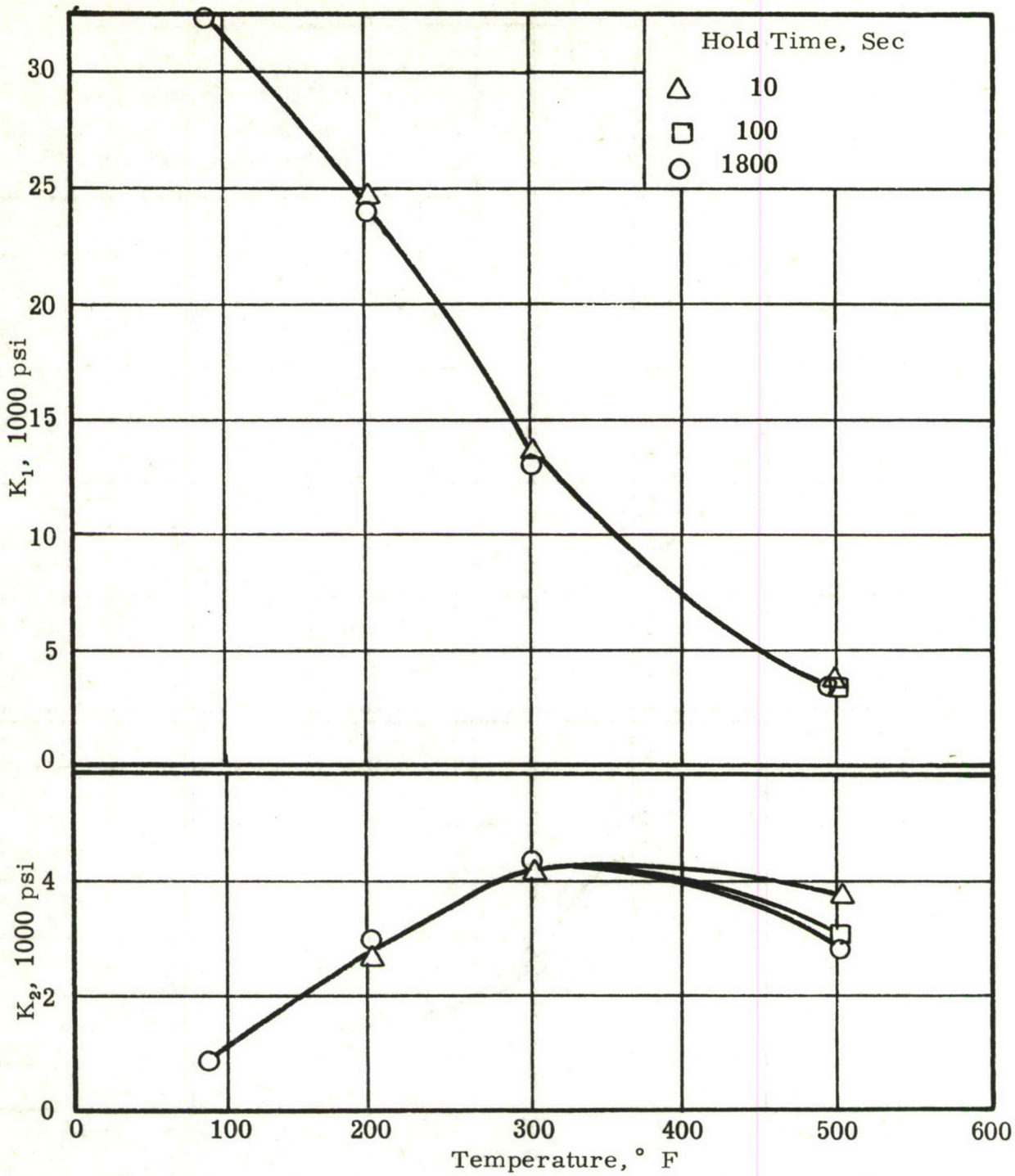

Figure 91. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of hard-rolled AZ-31 magnesium alloy sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in. /in. /sec.

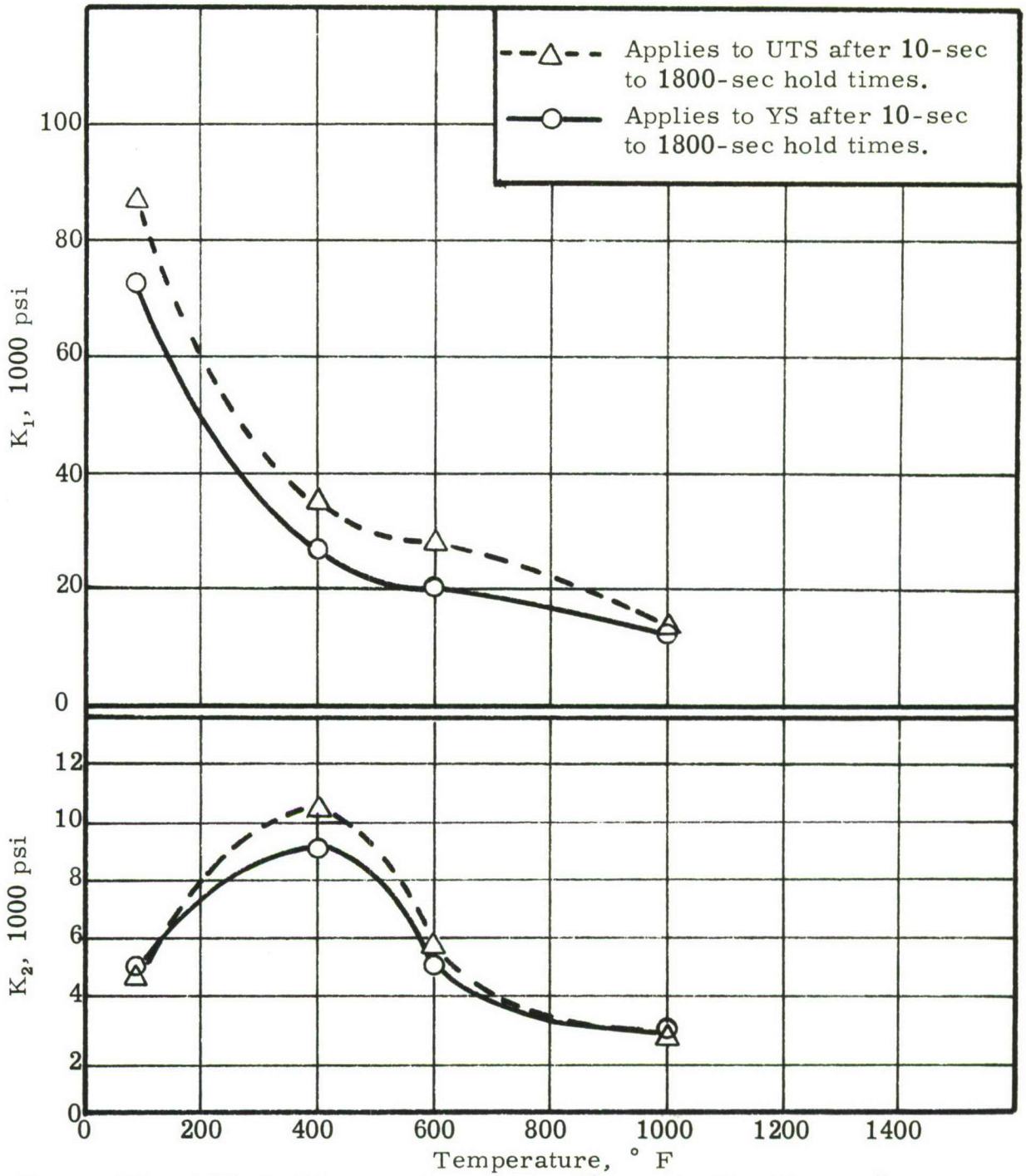

Figure 92. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constant K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of annealed A 70 titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

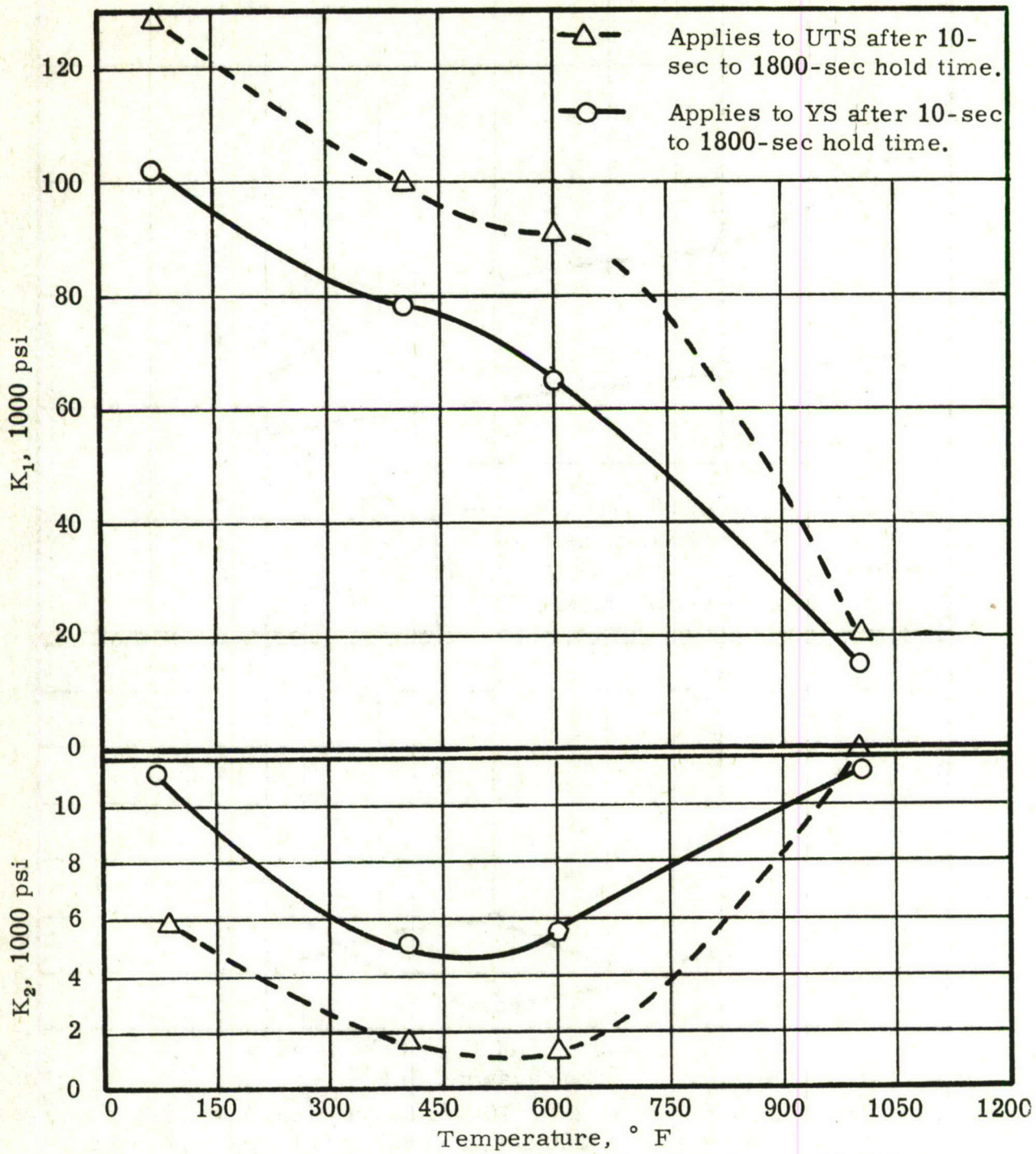

Figure 93. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed C 110-M titanium alloy sheet by the formula, Strength = $K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

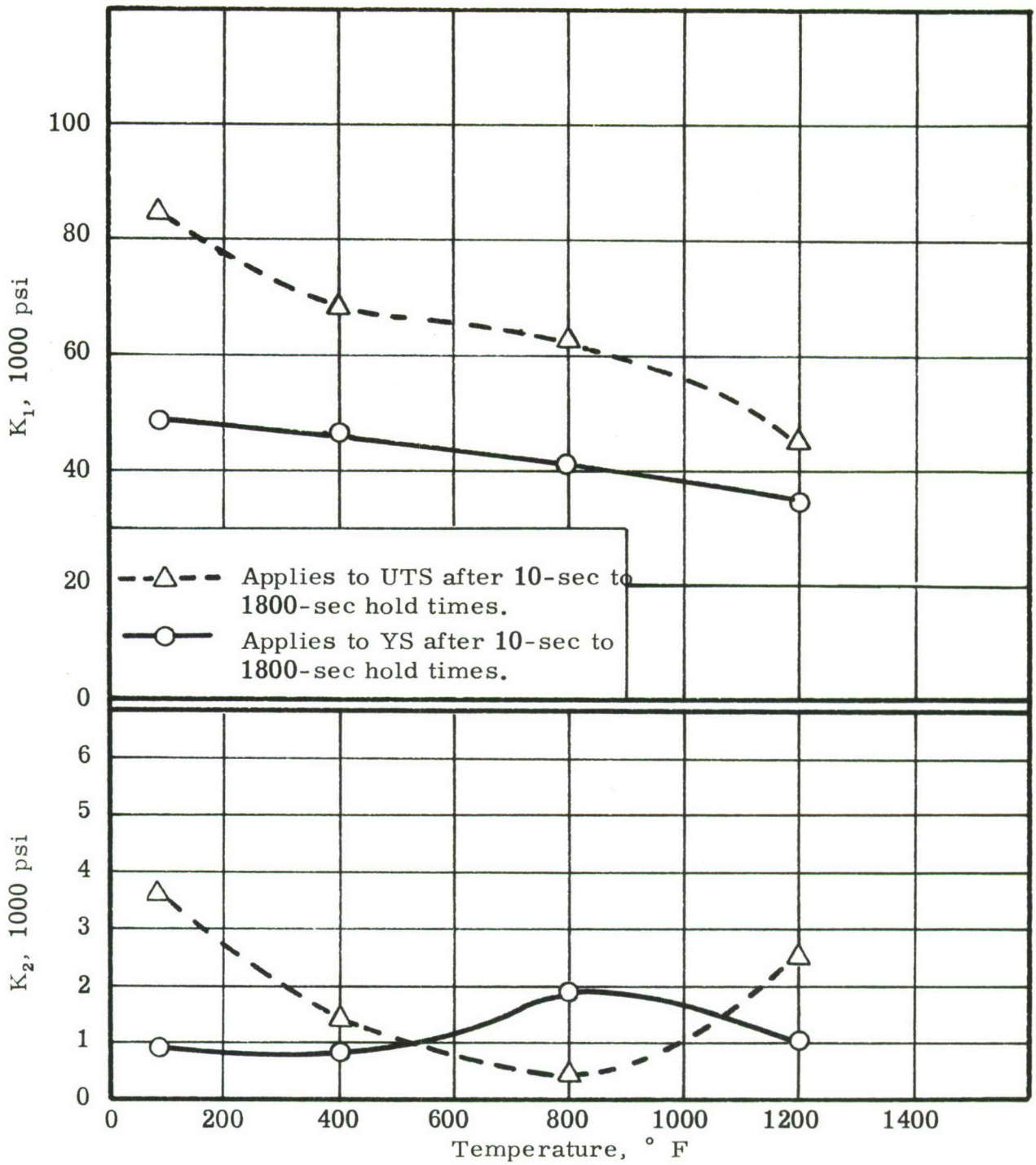

Figure 94. Effect of temperature, after 10-sec heating time and holding times from 10-sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of annealed 321 stainless steel sheet by the formula, Strength=$K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

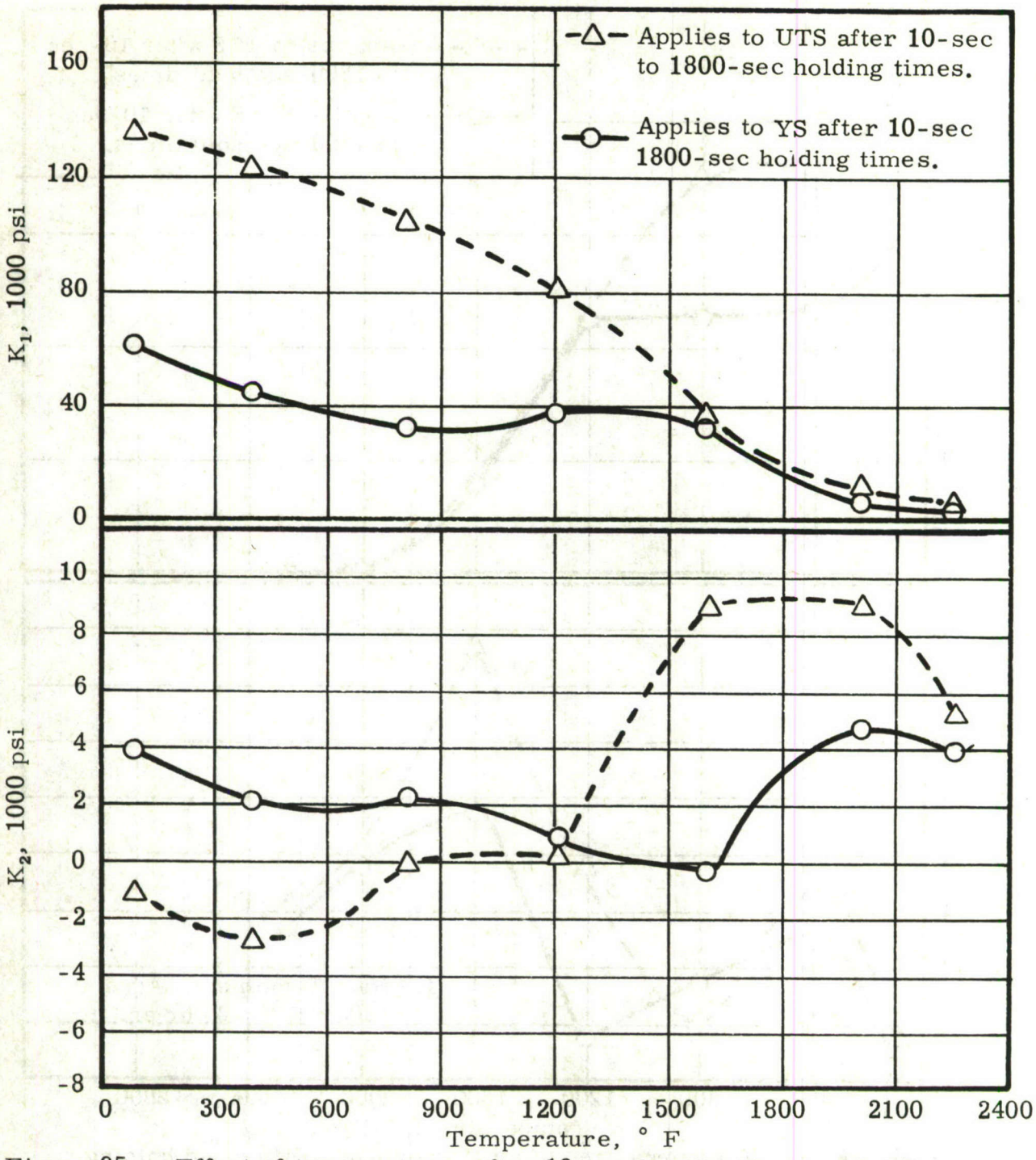

Figure 95. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset strength and ultimate tensile strength of annealed Stellite-25 sheet by the formula, Strength= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

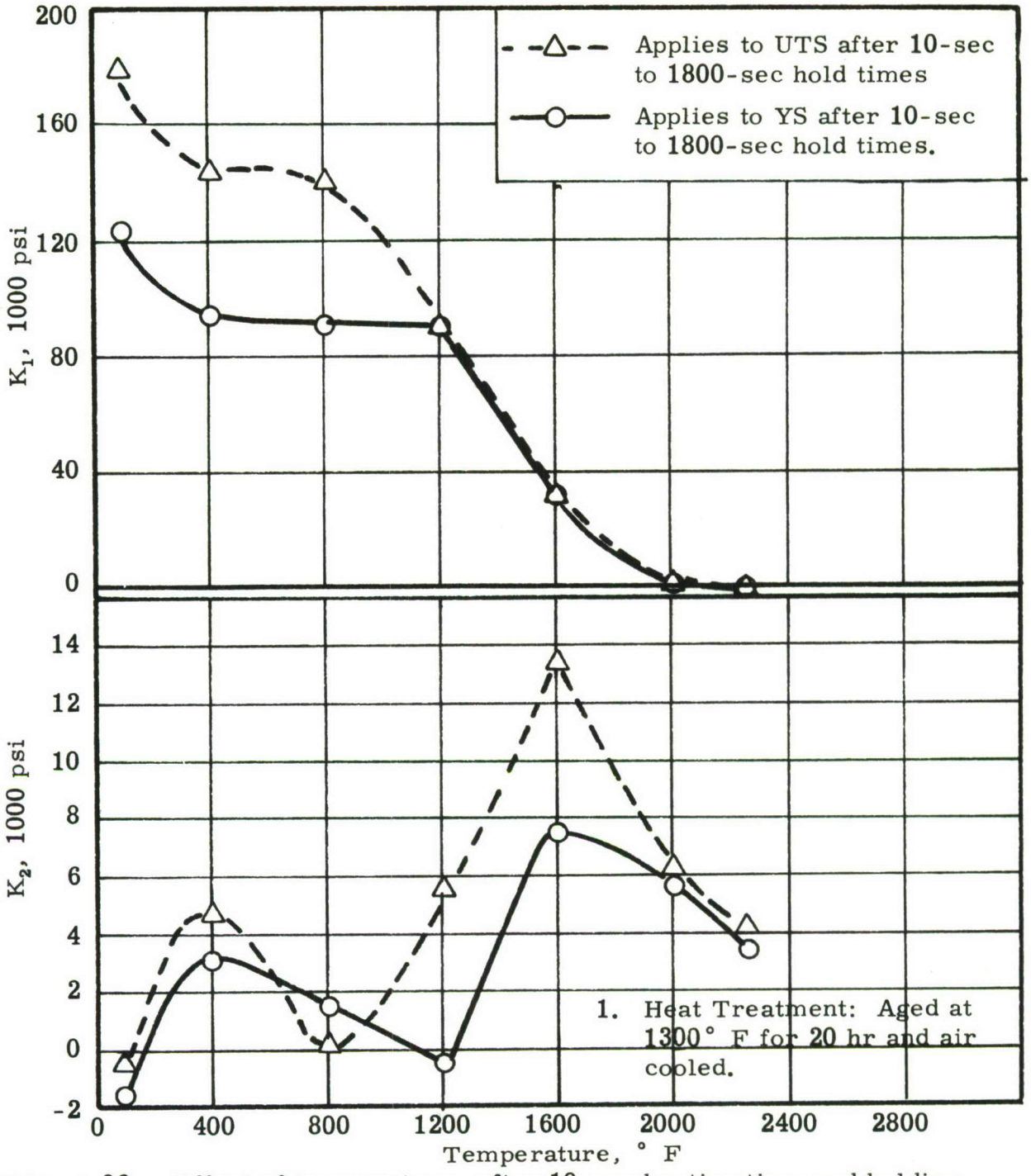

Figure 96. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of heat-treated[1] Inconel-X alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

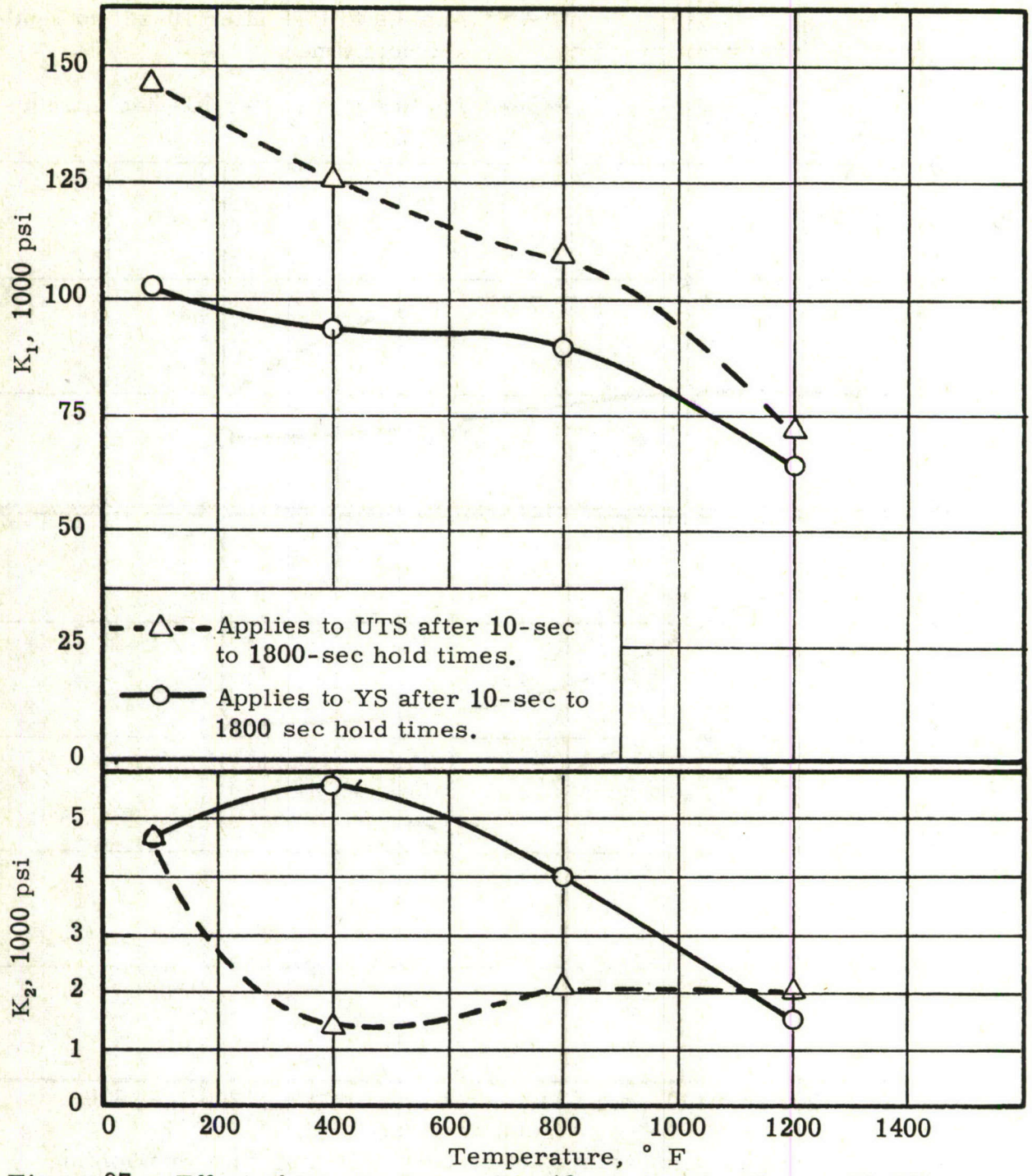

Figure 97. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of 301 half-hard stainless steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

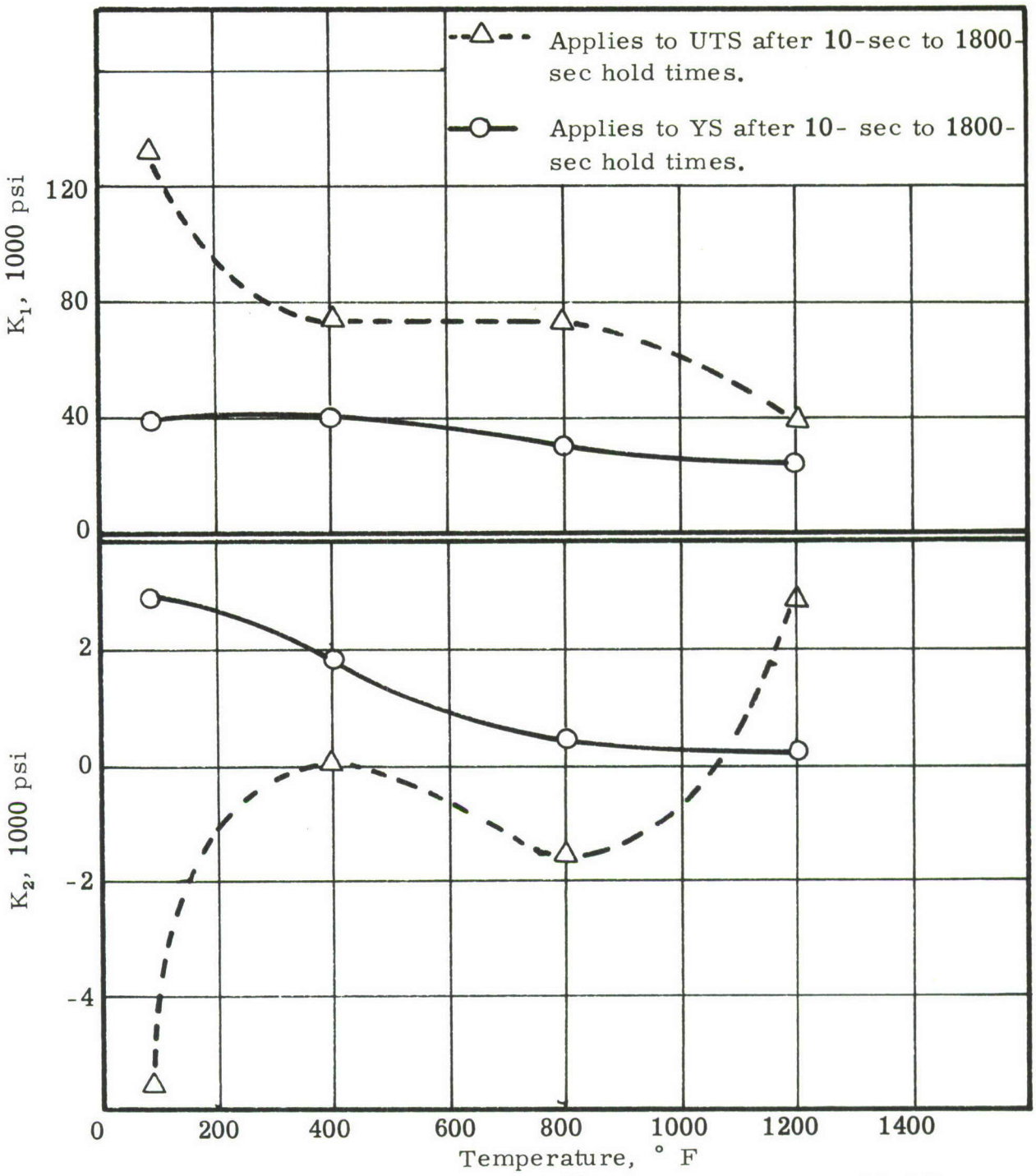

Figure 98. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed 17-7 PH stainless steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

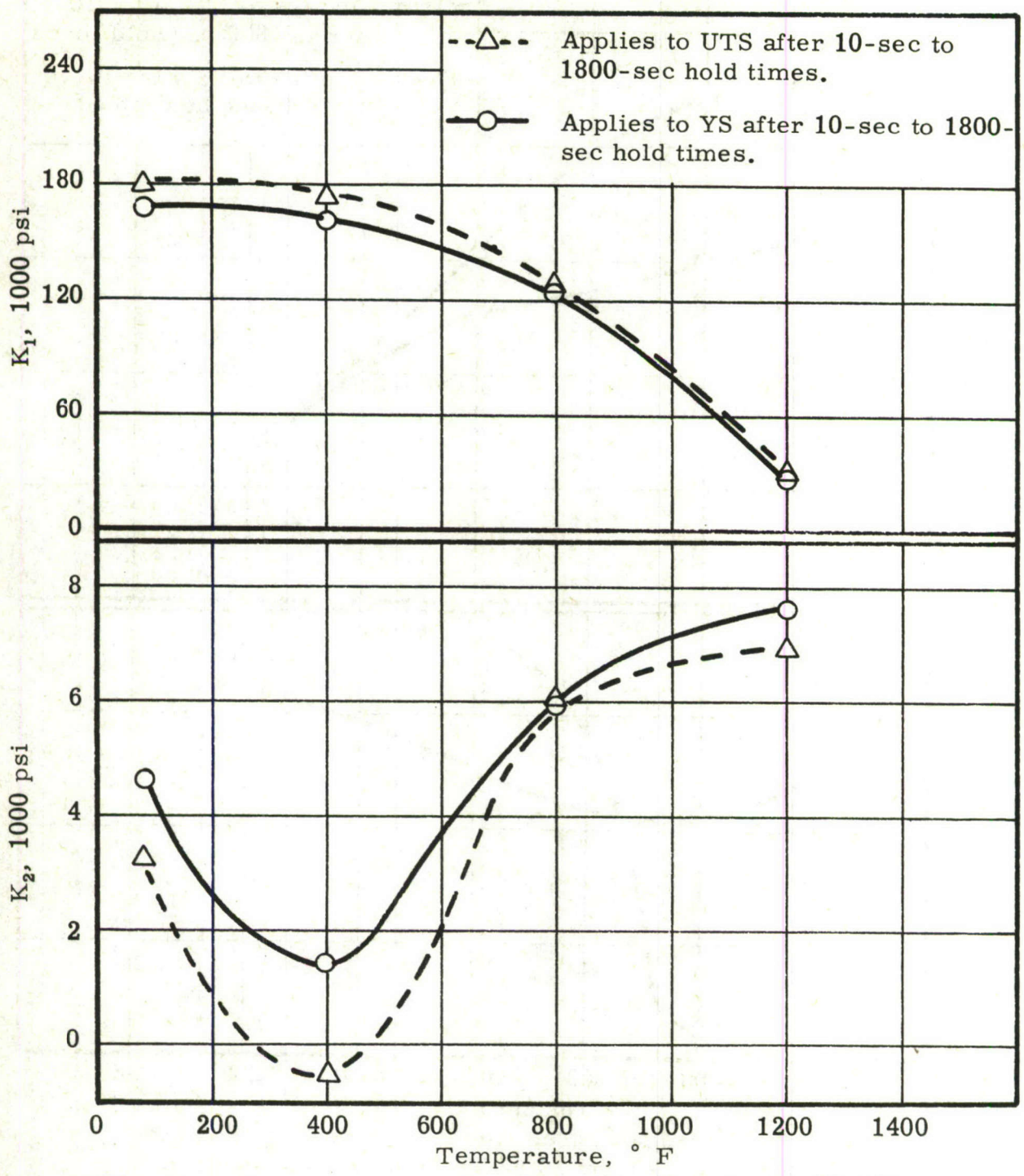

Figure 99. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of 17-7 PH stainless steel sheet (TH 1050 condition) by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. /in. /sec.

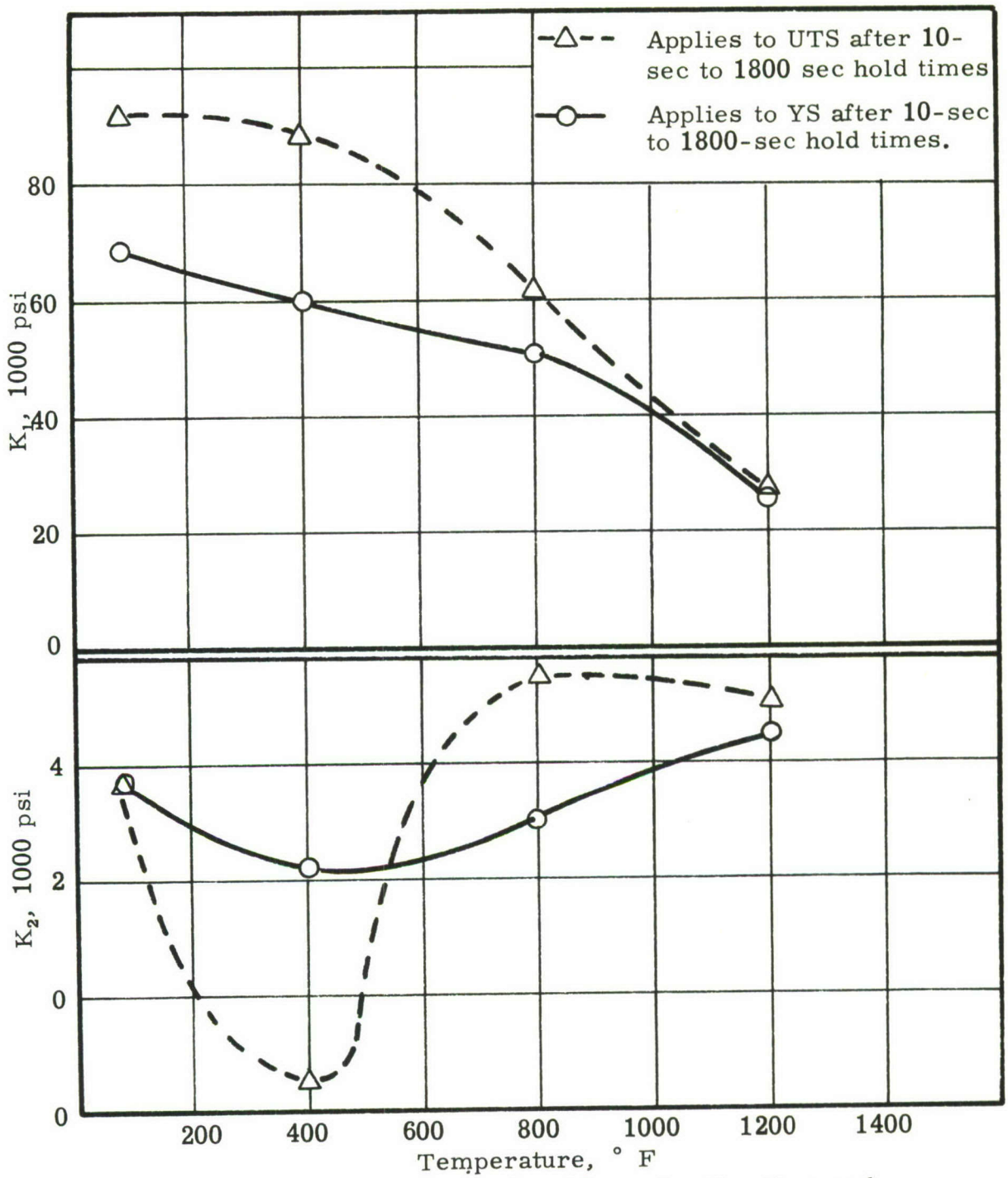

Figure 100. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of normalized AISI 4130 steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

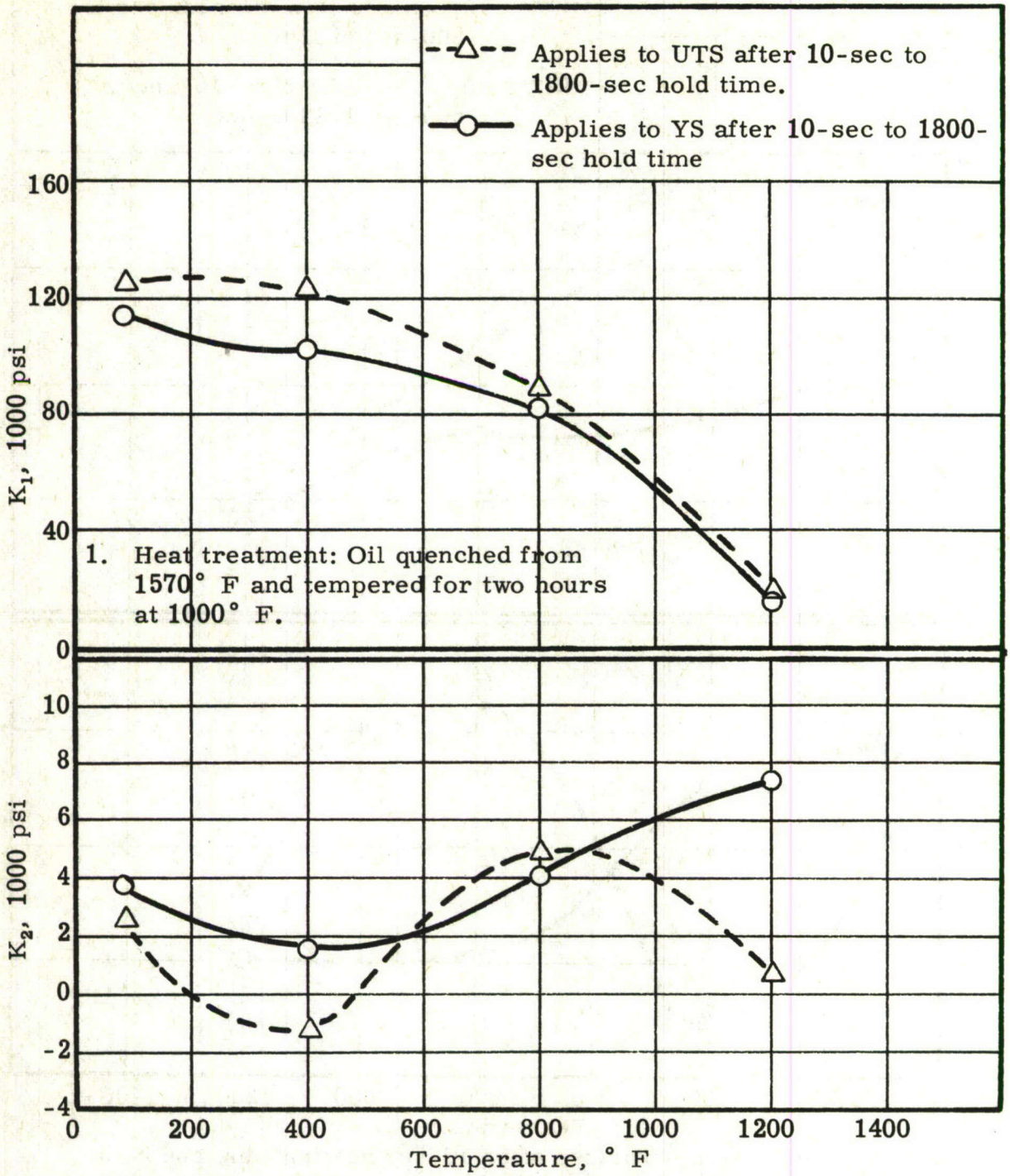

Figure 101. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strengthof heat-treated[1] AISI 4130 steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

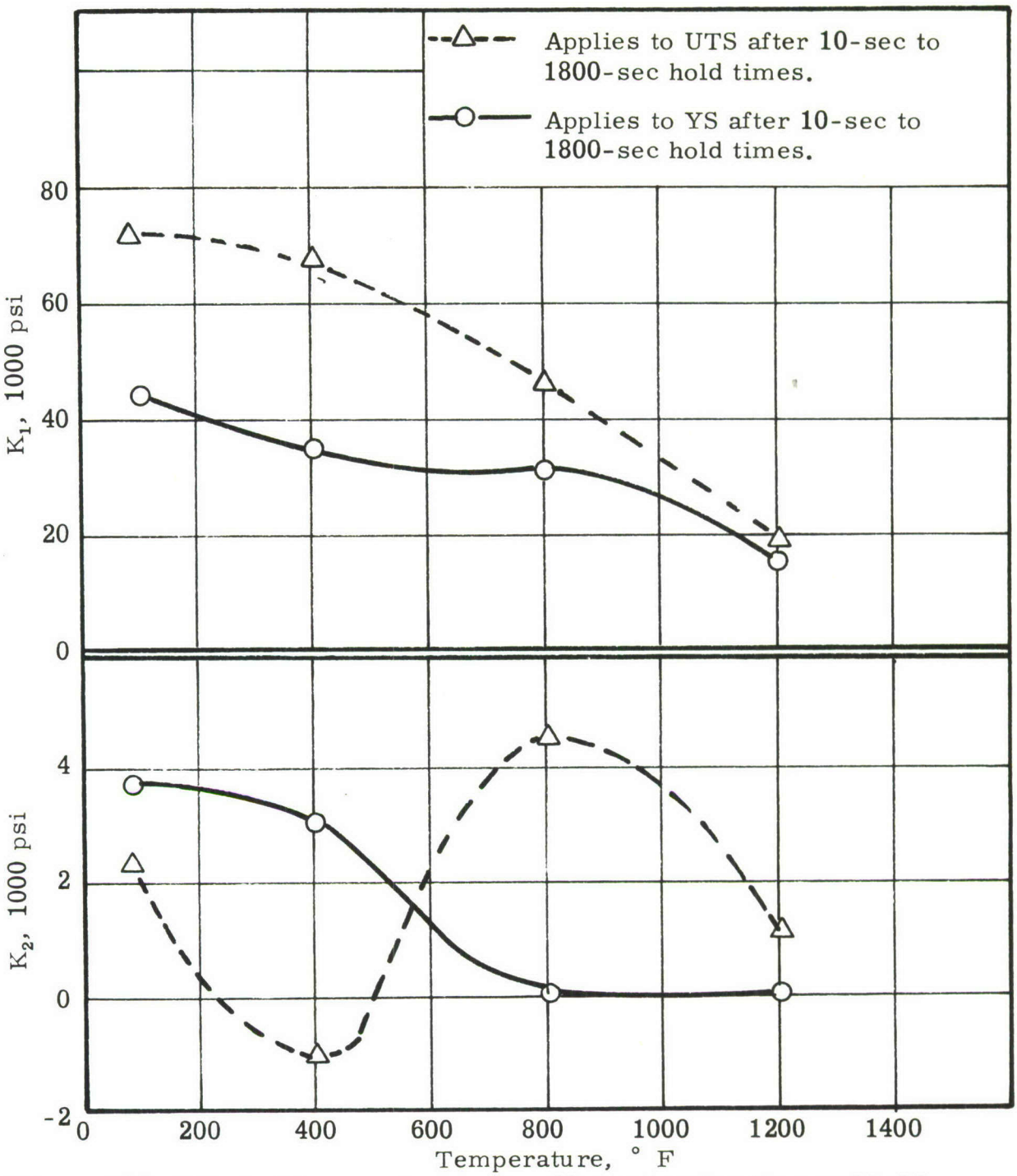

Figure 102. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of hot-rolled SAE 1020 steel sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

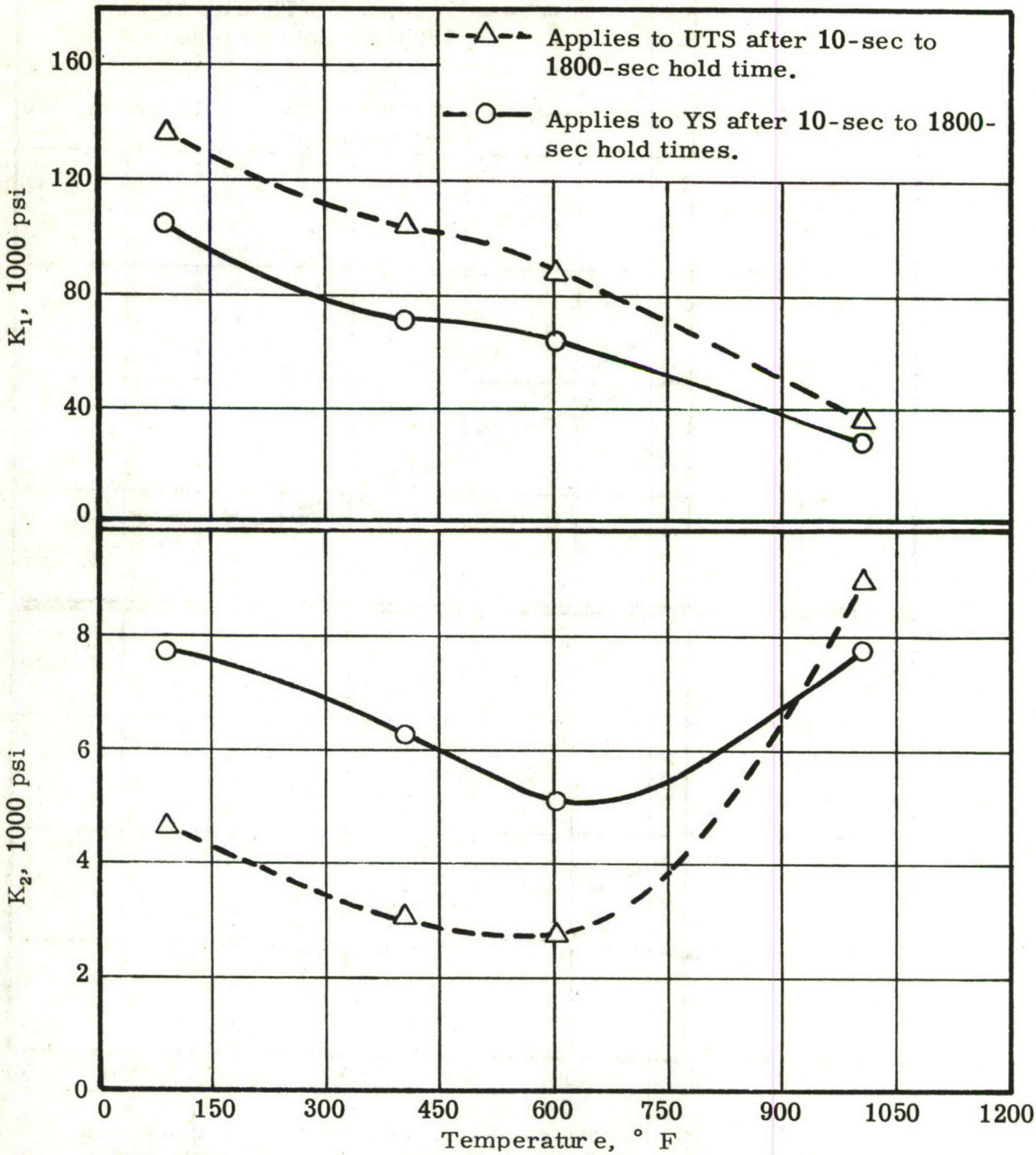

Figure 103. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of annealed 140 A titanium alloy sheet by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

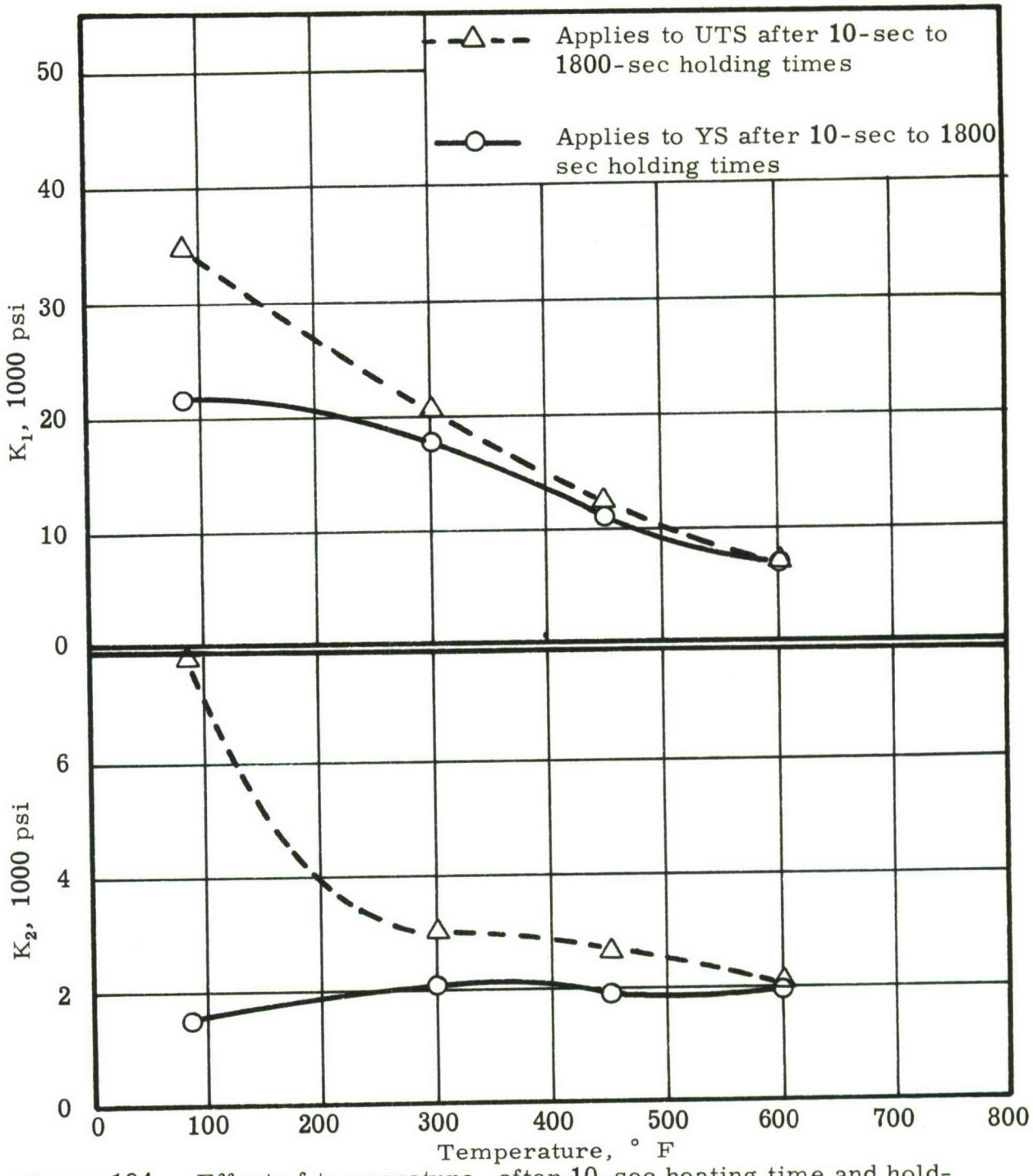

Figure 104. Effect of temperature, after 10-sec heating time and holding times from 10 sec to 1800 sec, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength and ultimate tensile strength of Type ZH 62-T5 magnesium casting alloy by the formula, Strength = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

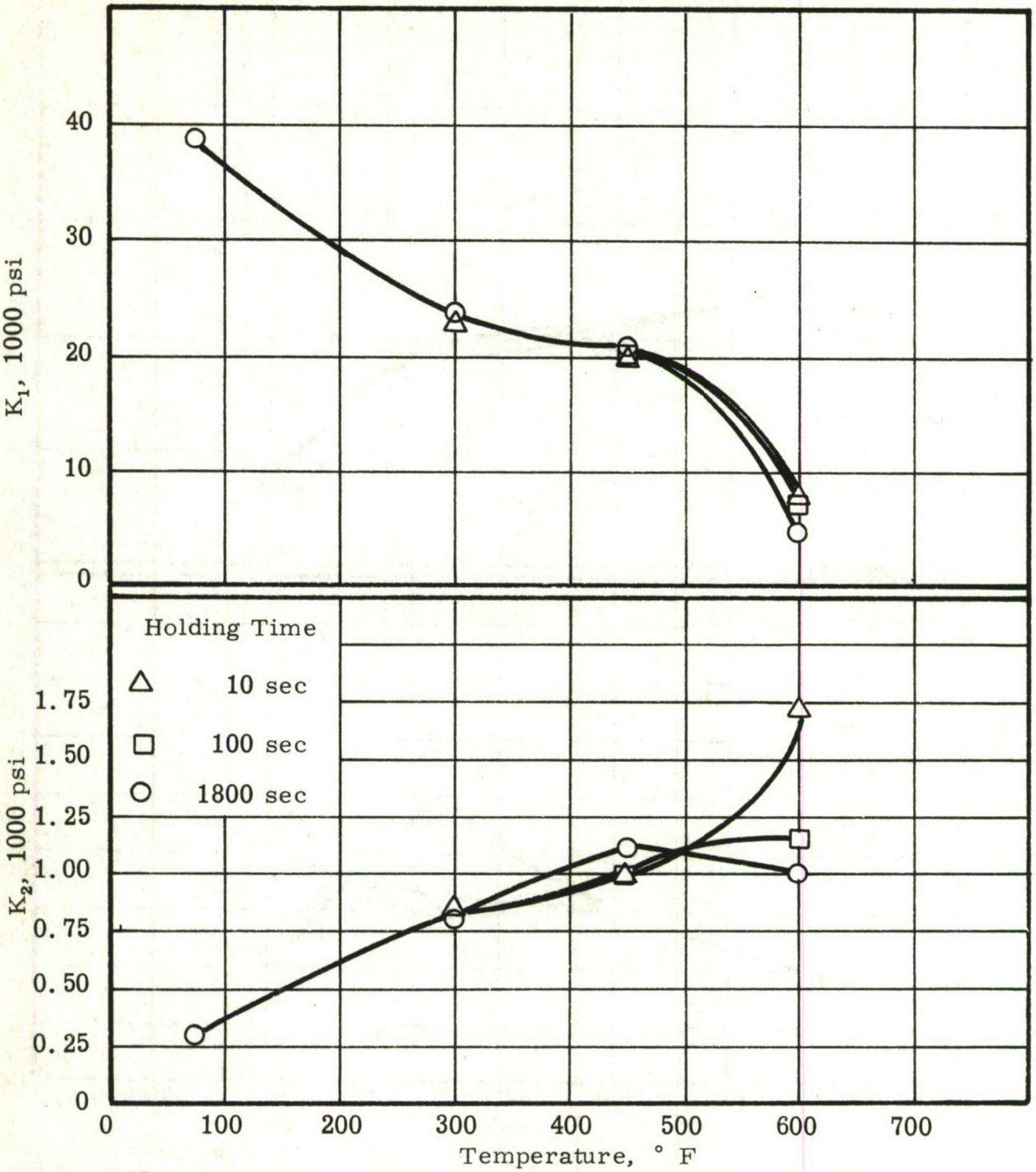

Figure 105. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of Type 356-T6 aluminum casting alloy by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

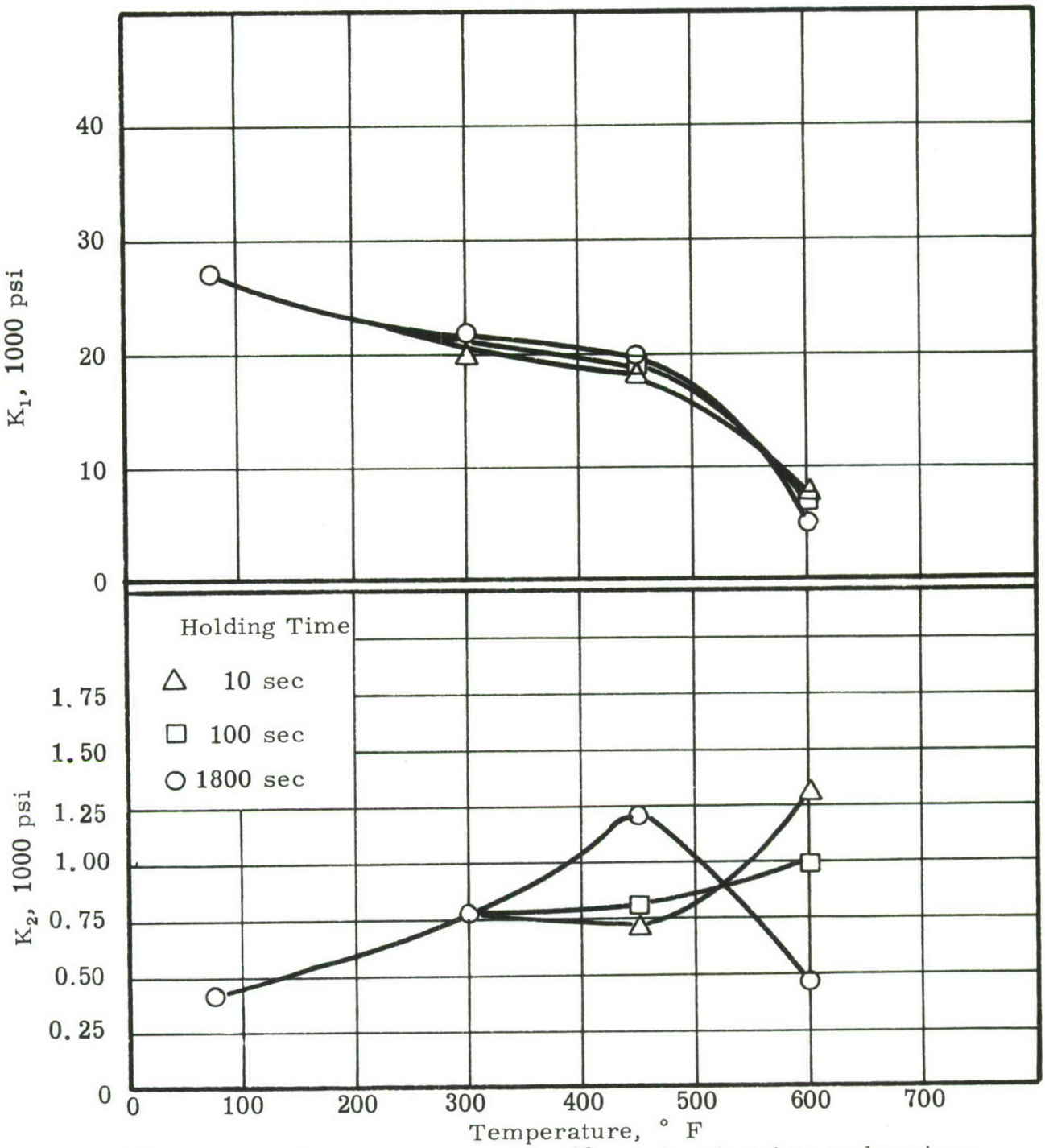

Figure 106. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of Type 356-T6 aluminum casting alloy by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

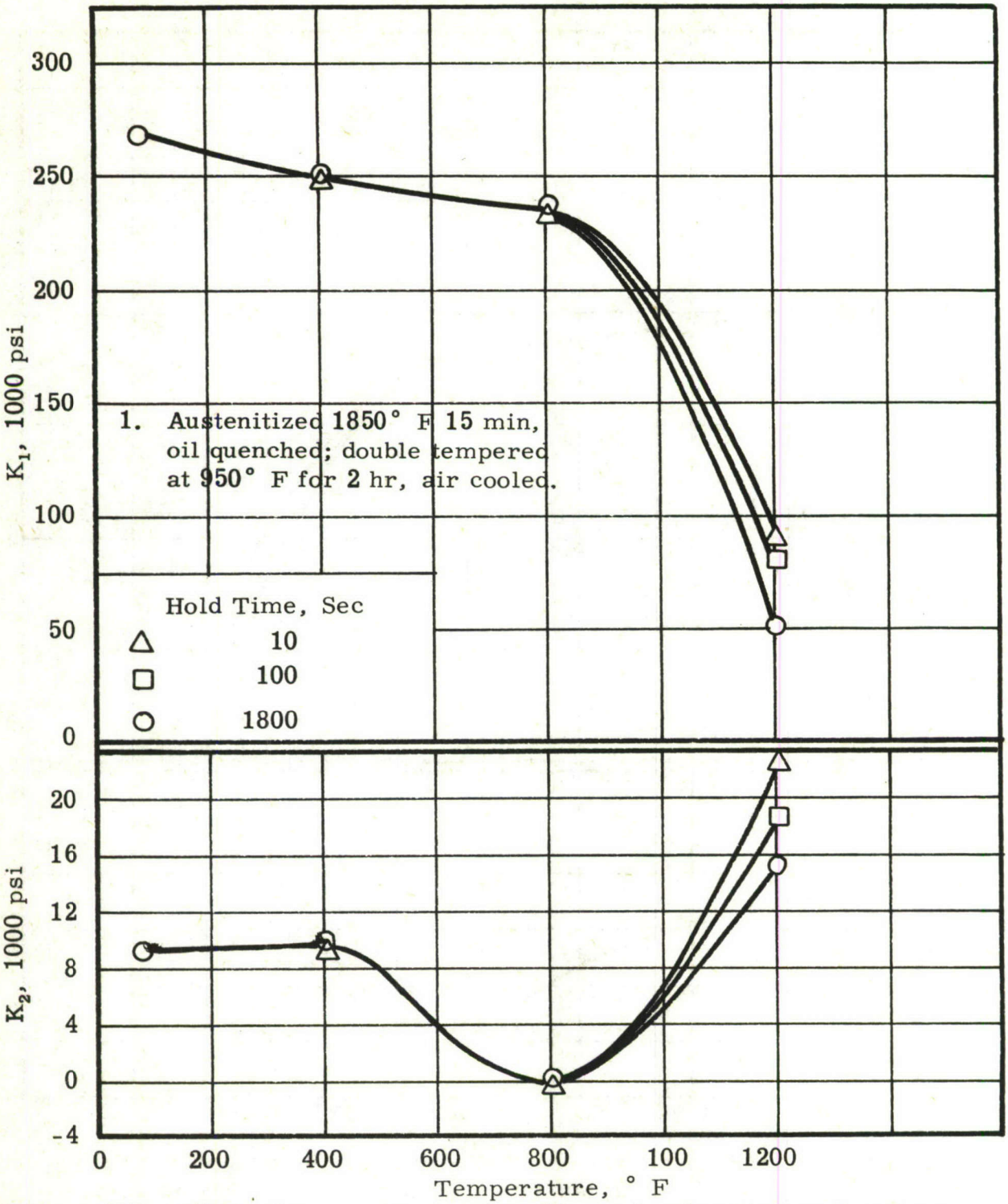

Figure 107. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated[1]Chro-Mow die steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

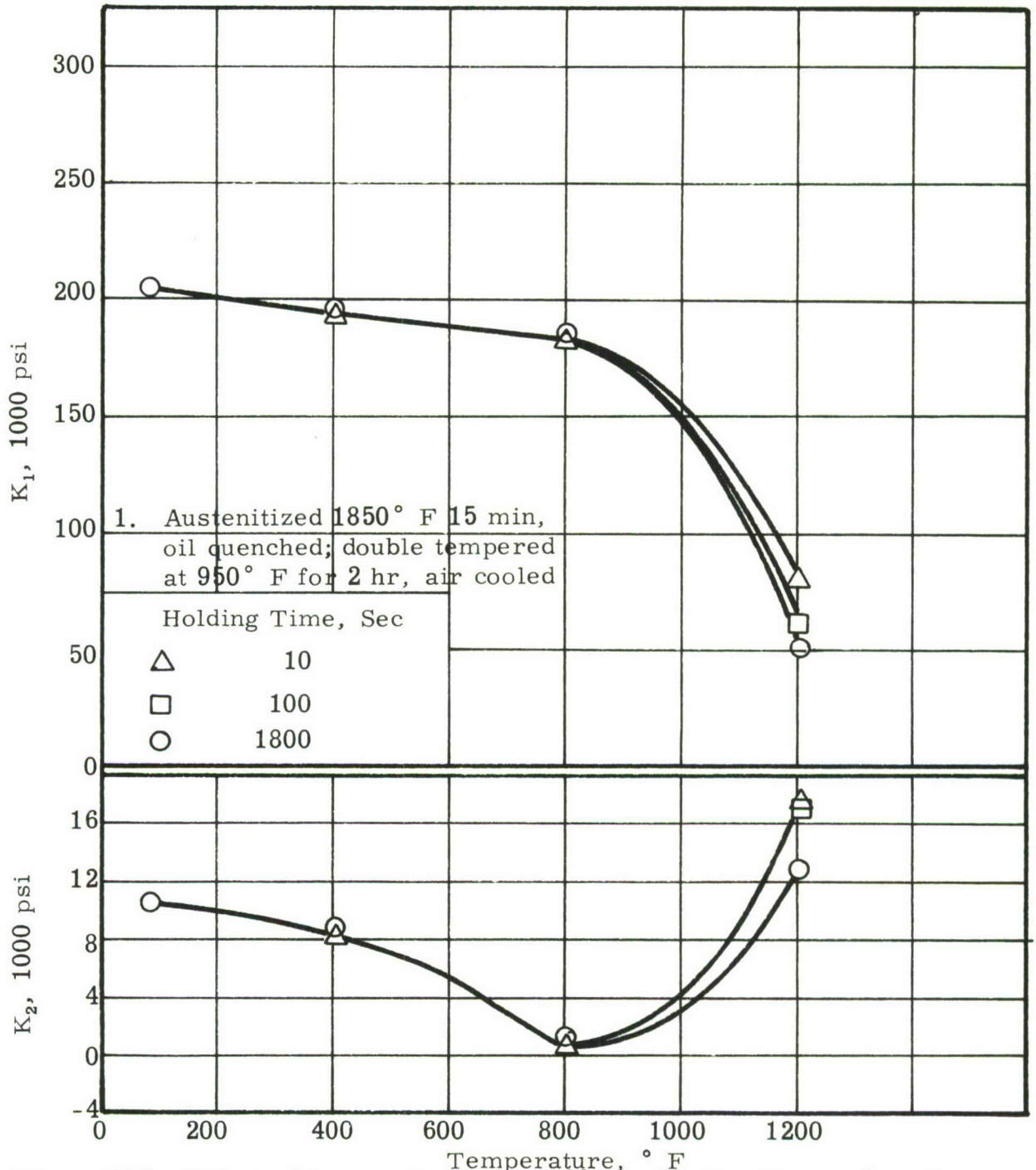

Figure 108. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated[1] Chro-Mow die steel sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

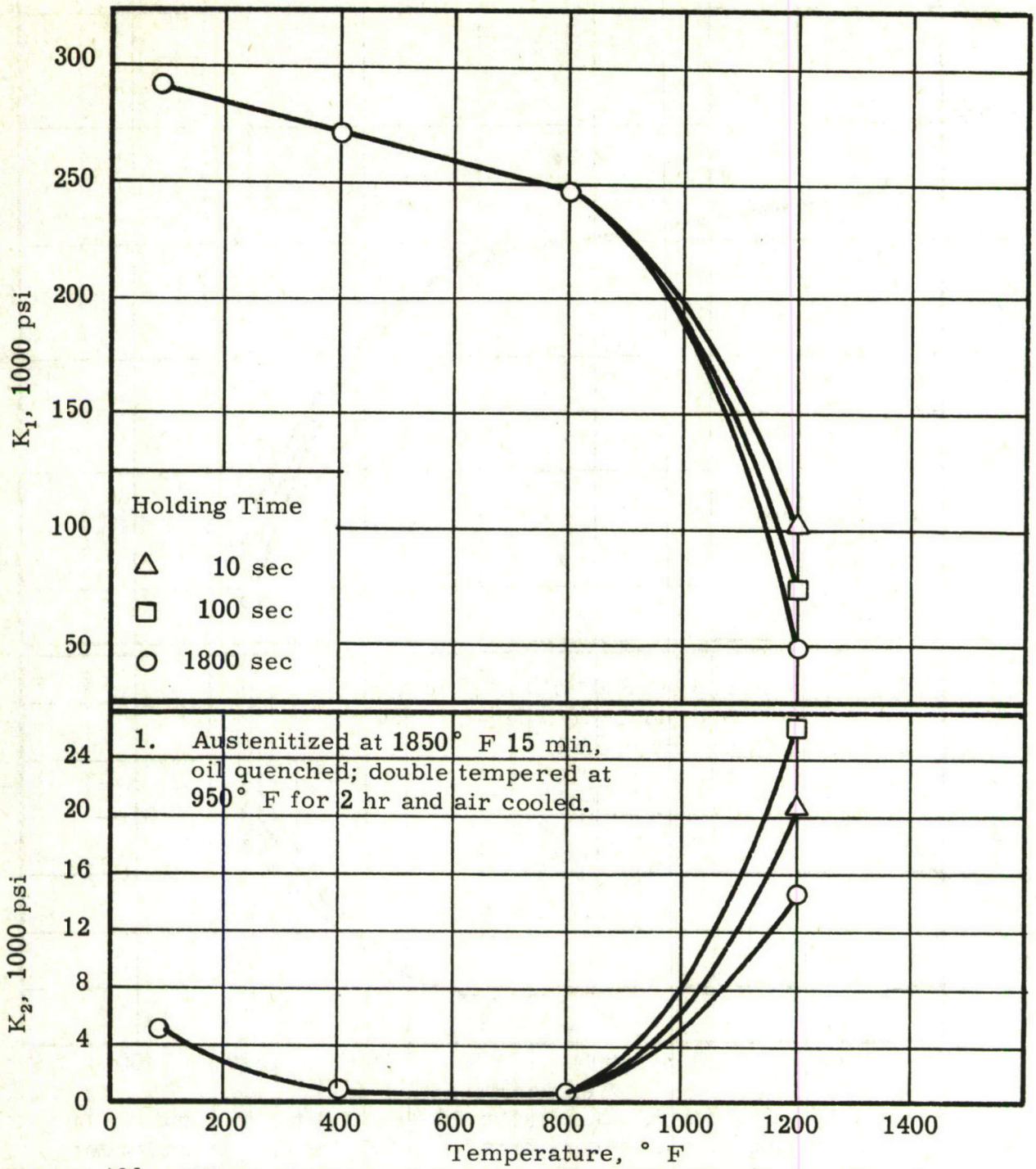

Figure 109. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated[1]Thermold-J die steel sheet by the formula, UTS= $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in. / in. /sec.

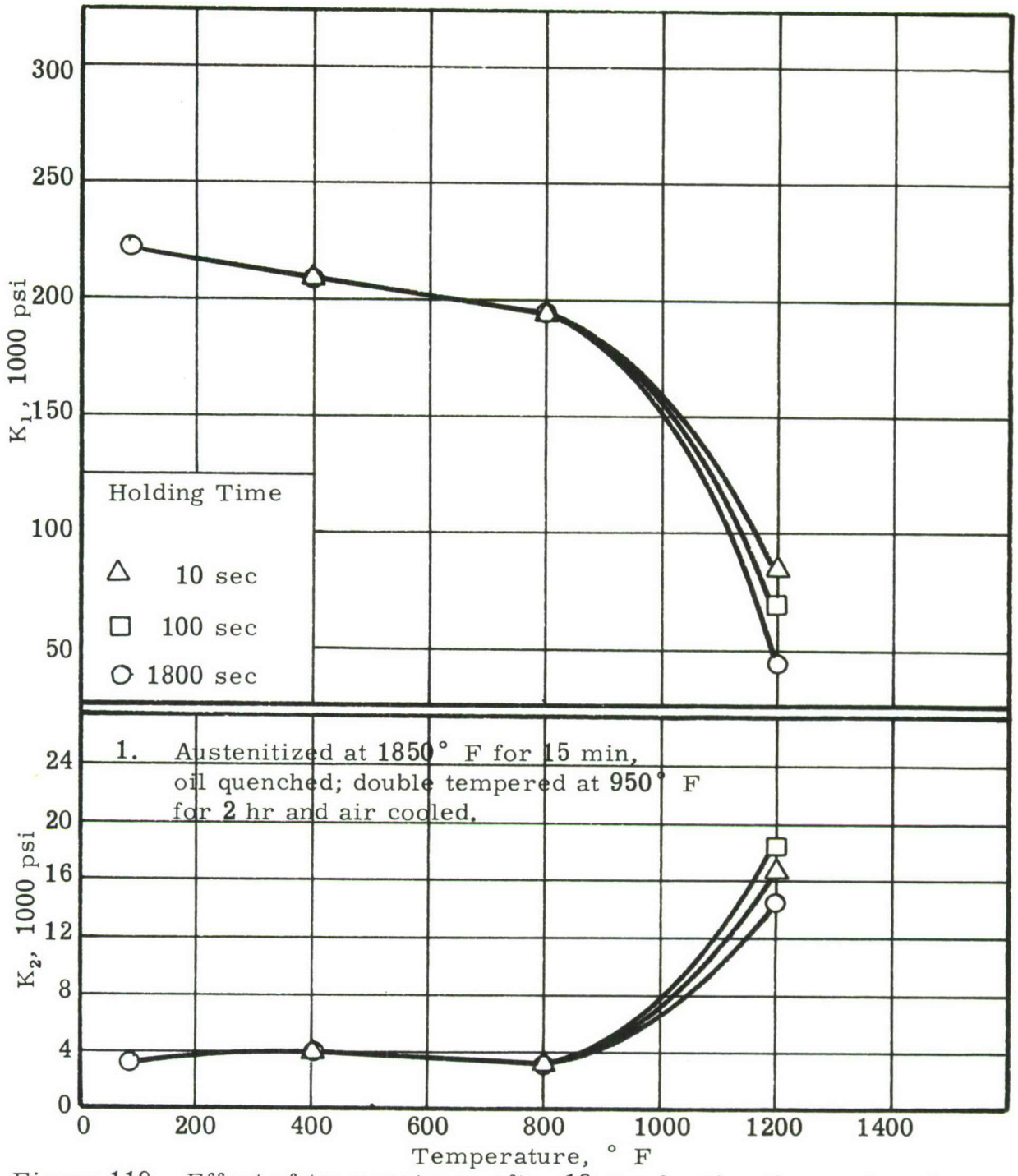

Figure 110. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated[1] Thermold-J die steel sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

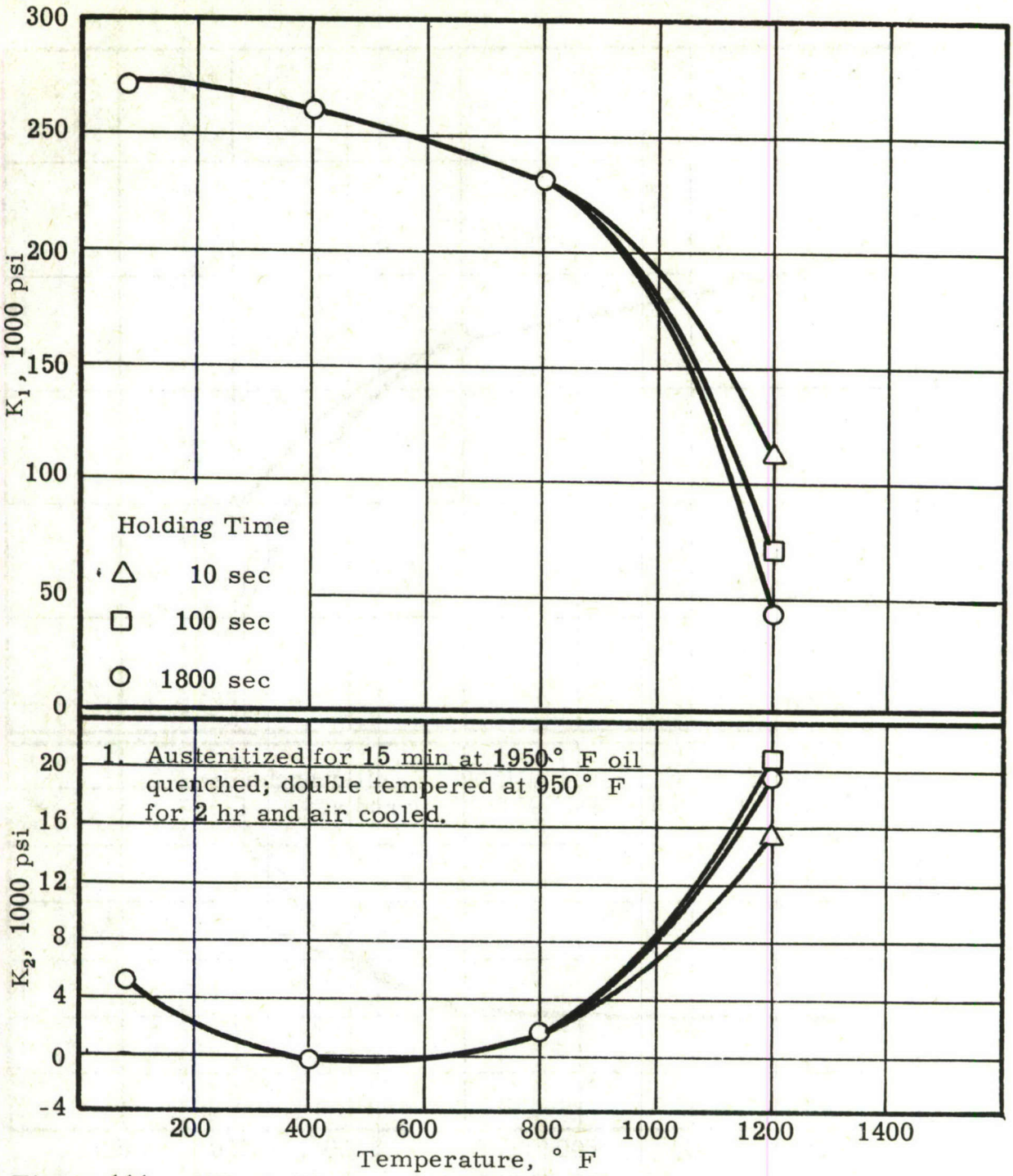

Figure 111. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the ultimate tensile strength of heat-treated[1] Peerless-56 die steel sheet by the formula UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

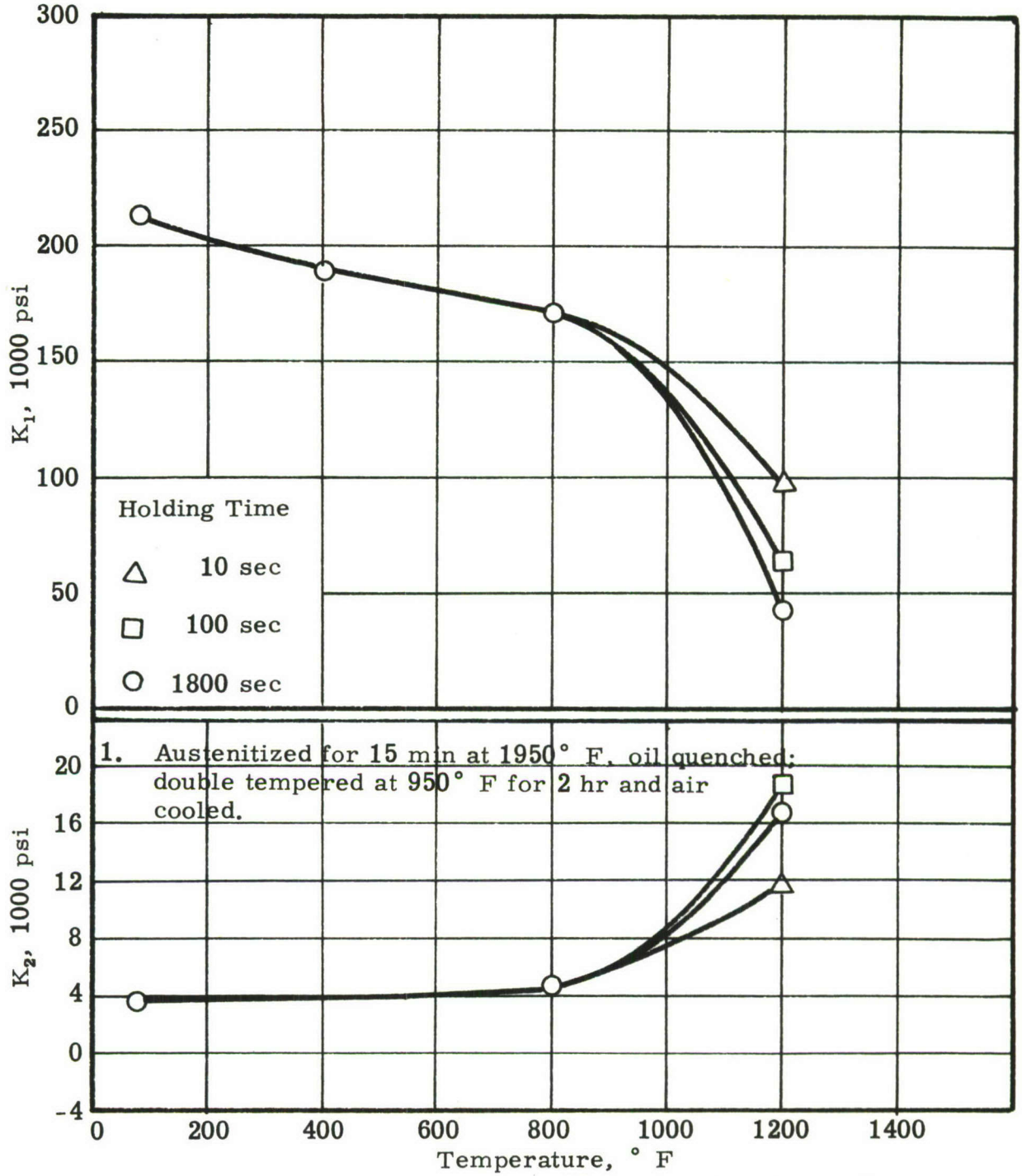

Figure 112. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength of heat-treated[1] Peerless-56 die steel sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

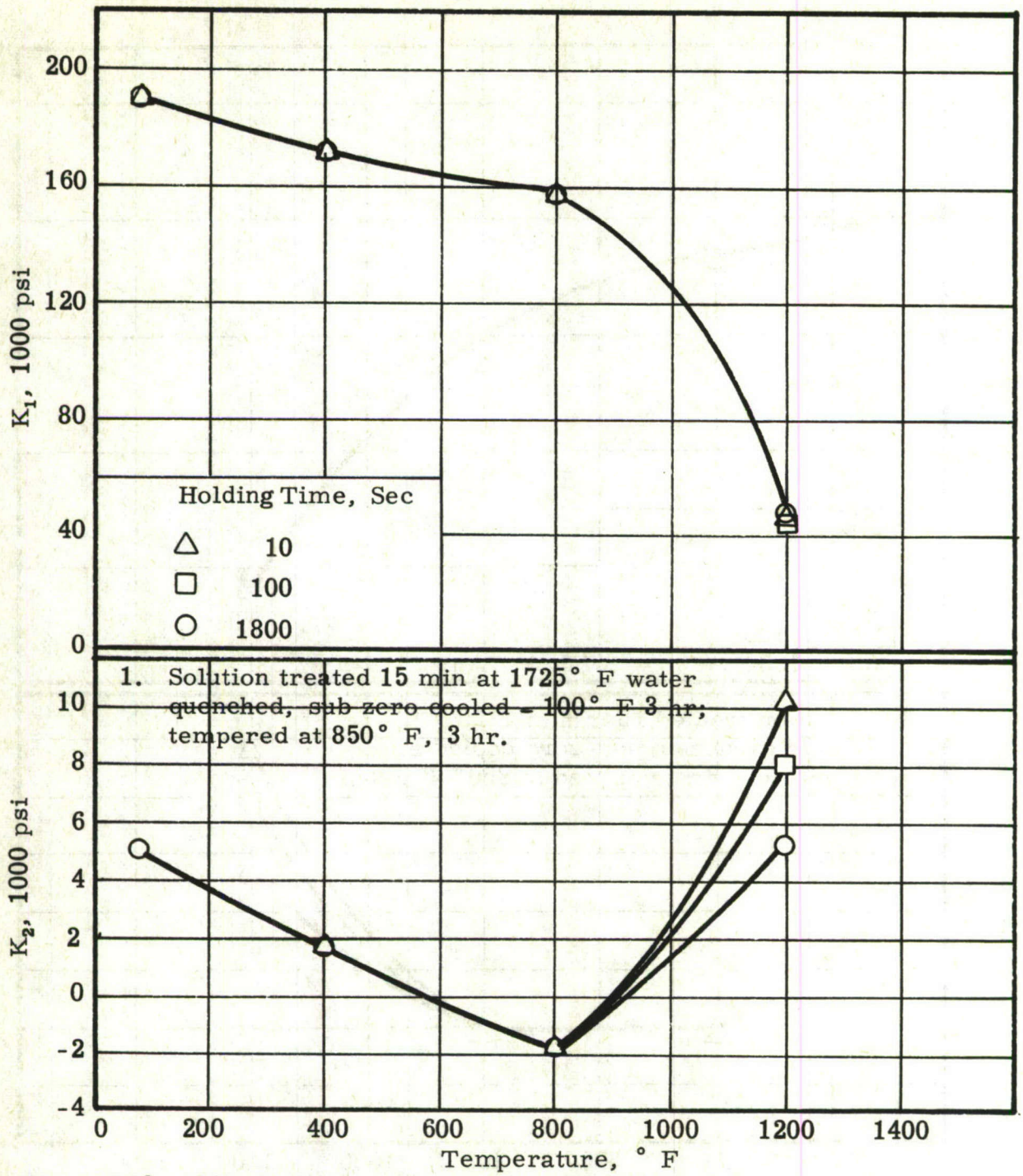

Figure 113. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of ultimate tensile strength of heat-treated[1] AM-350 stainless steel sheet by the formula, UTS = $K_1 + K_2$ (log r + 4.3). Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

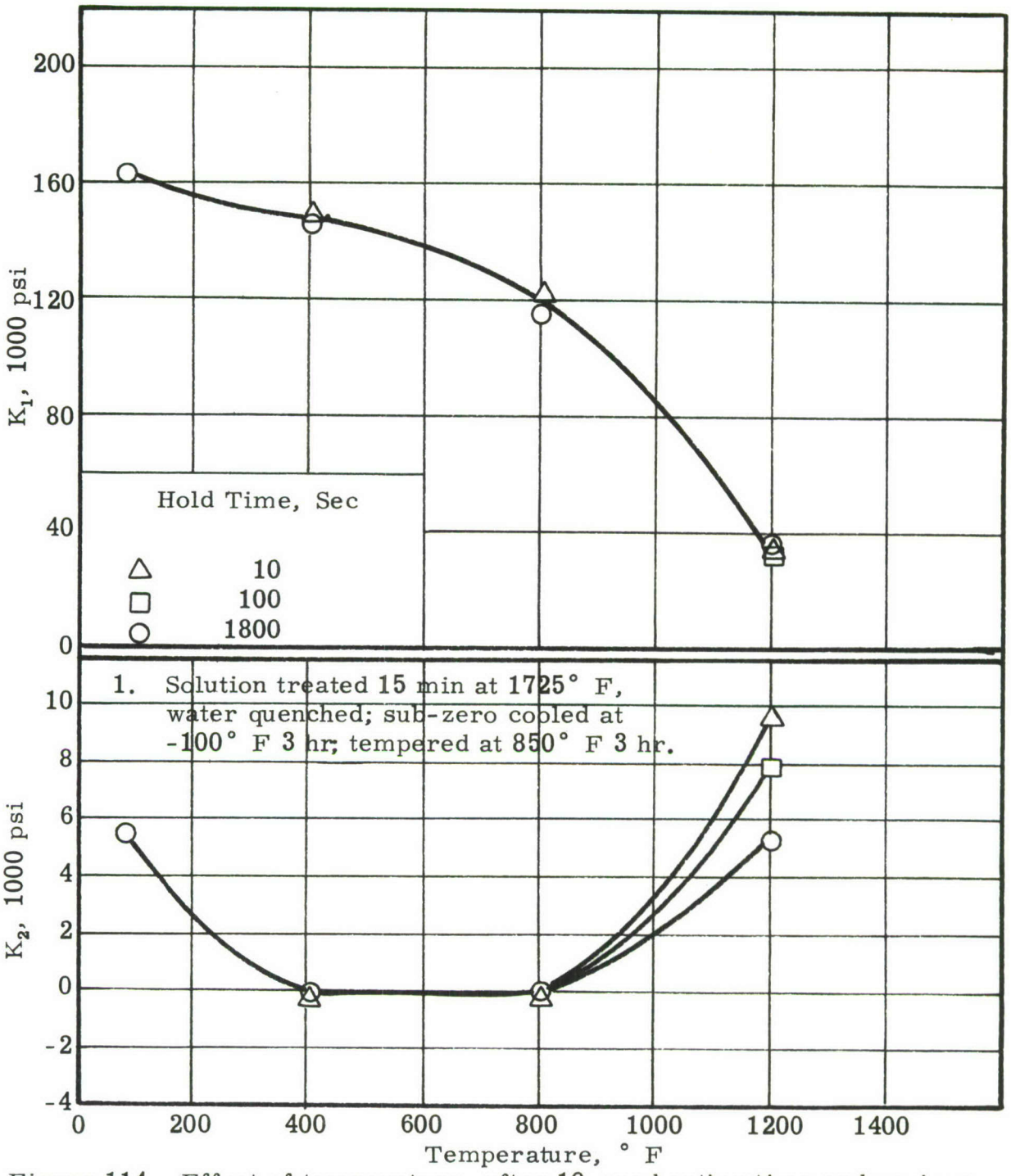

Figure 114. Effect of temperature, after 10-sec heating time and various holding times, on constants K_1 and K_2 for the determination of 0.2%-offset yield strength of heat-treated[1] AM-350 stainless steel sheet by the formula, $YS = K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.

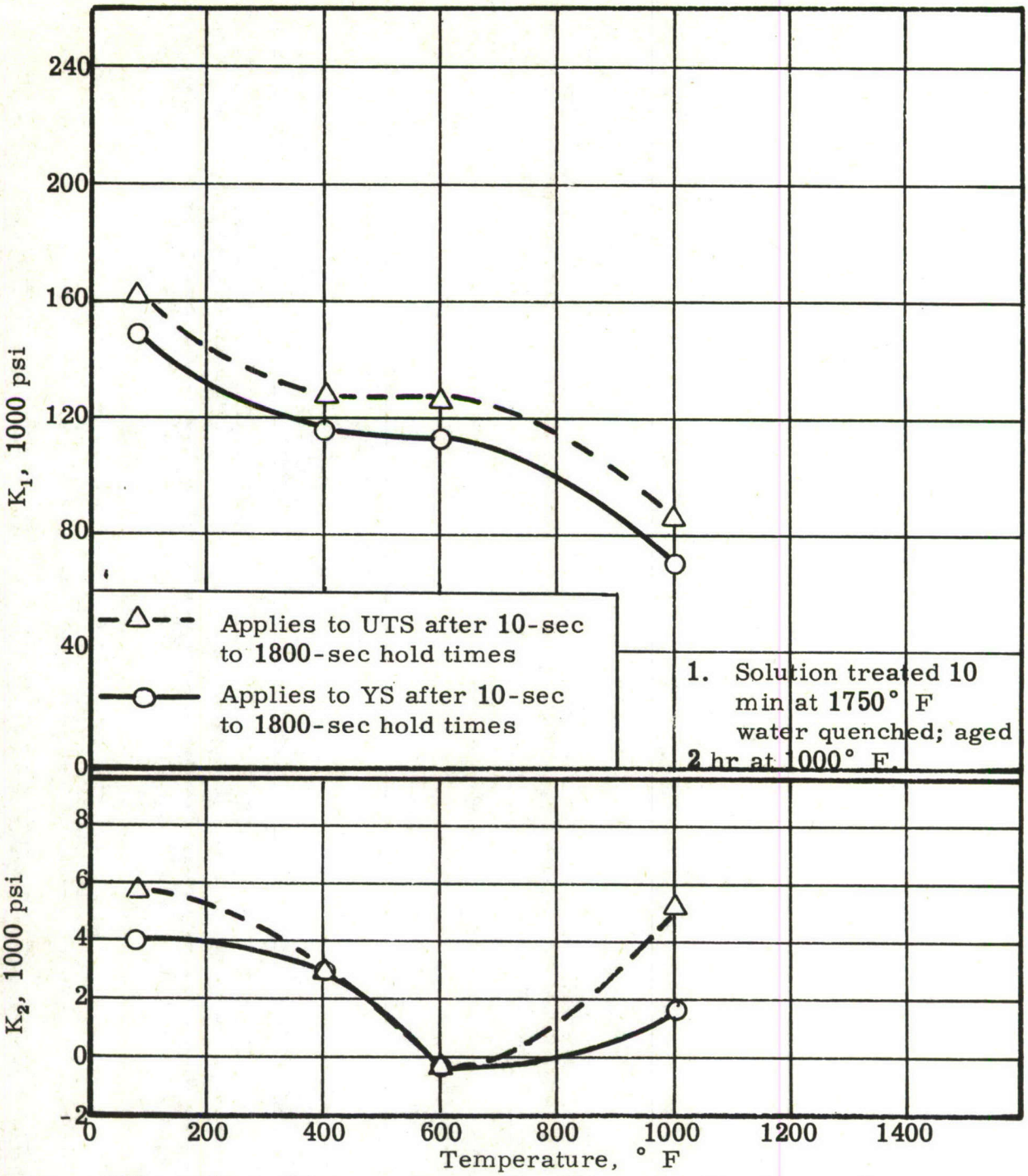

Figure 115. Effect of temperature, after 10-sec heating time and holding times from 10-sec to 1800 sec, on constants K_1 and K_2 for the determination of the 0.2%-offset yield strength and ultimate tensile strength of heat-treated[1] 6Al-4V titanium alloy sheet by the formula, Strength = $K_1 + K_2 (\log r + 4.3)$. Data applies to range of strain rates (r) from 0.00005 to 1.0 in./in./sec.