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INTERIM ANALYSIS OF LONG-TIME CREEP BEHAVIOR OF COLUMBIUM C-103 ALLOY

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16. Abstract

Analysis of 16 long-time creep tests on columbium C-103 alloy (Cb-10Hf-1Ti-0.7Zr) indicates that the calculated stresses to give 1 percent creep strain in 100,000 hours at 1255 K (1800 F) are 7.93 and 8.96 MPa (1150 and 1300 psi) for fine-grained and course-grained material, respectively. The apparent activation energy and stress dependence for creep of this alloy are approximately 315 KJ/gmol (75,300 cal/gmol) and 2.51, respectively, based on Dorn-Sherby types of relations. However, the 90 percent confidence limits on these values are wide because of the limited data currently available.

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INTERIM ANALYSIS OF LONG-TIME CREEP BEHAVIOR OF COLUMBIUM C-103 ALLOY

by William D. Klopp and Robert H. Titran

SUMMARY

An analysis is presented based on 16 creep tests from an on-going program to evaluate the long-time creep behavior of columbium C-103 alloy. This interim analysis indicates that the calculated stresses to give 1 percent creep strain in 100,000 hours at 1255 K (1800 F) are 7.93 and 8.96 MPa (1150 and 1300 psi) for fine-grained and coarse-grained material, respectively. The alloy exhibits an accelerating creep rate at strains of less than 1 percent which can be differentiated into periods termed early tertiary creep (time dependence of 3/2) and late tertiary creep (time dependence of 5/2). No periods of identifiable primary or secondary creep were observed. The times-to-1-percent-strain and early and late tertiary creep rates were correlated with stress and temperature by Dorn-Sherby types of relations. The apparent activation energy and stress dependence applicable to all three relations are 315±49 KJ/gmol (75,300±11,700 cal/gmol) and 2.51±0.44, respectively. The creep rate for the fine-grained material accelerates more rapidly with time than that for the coarse-grained material.

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INTRODUCTION

The columbium C-103 alloy (Cb-10Hf-1Ti-0.7Zr) was selected as the material of construction for the Heat Source Heat Exchanger of the Mini-Brayton Isotope Power System (ref. 1) in July, 1974. This alloy was subsequently also selected for the turbine scroll of the Mini-Brayton Power System. The basis for these selections was a comparative evaluation of C-103 and Cb-1Zr by the authors of this report. At that time, it was estimated, on the basis of eight creep tests, that C-103 would have a strength of 20 MPa (2900 psi) for a creep strain of 1 percent in 100,000 hours at 1255 K (1800 F).

Since that time, additional creep data have been generated on C-103. A re-analysis with these more extensive data (16 creep tests for times up to 4897 hours) initiated in September, 1975, indicated that the original correlation was erroneous with regard to the activation energy and stress dependence of the creep rate. This re-analysis further indicated that the extrapolated strength for 1 percent creep in 100,000 hours at 1255 K (1800 F) is somewhat less than one-half the 20 MPa (2900 psi) value originally estimated.

In view of the need for accurate long-time creep strength predictions for C-103 for the design and safety margin of the Mini-Brayton Power System, this re-analysis was extended to include detailed stress and temperature effects, grain size effects, and shapes of the creep curves. The results of this analysis are reported herein.

The analysis is termed interim since this characterization of the long-time creep behavior of C-103 is continuing. It is anticipated that the results of the completed study will be reported at a later date.

EXPERIMENTAL PROCEDURE

The C-103 alloy was commercially procured as 0.076-cm (0.030-in.) thick sheet. Principal constituents were determined as follows:

Hafnium	9.75 wt pct
Titanium	1.11 wt pct
Zirconium	0.45 wt pct
Tantalum	0.31 wt pct
Tungsten	0.25 wt pct
Oxygen	214 wt ppm
Nitrogen	62 wt ppm
Carbon	37 wt ppm
Hydrogen	0.8 wt ppm

Creep specimens having a 0.635-cm (0.250-in.) wide by 2.54-cm (1.00-in.) long gage section were machined from the 0.076-cm (0.030-in.) sheet. These specimens were degreased, rinsed in alcohol and distilled water, wrapped in tantalum foil, and annealed in a vacuum of 10^{-8} torr at 1600 to 2023 K (2420 to 3200 F) prior to creep testing. Weight changes which were observed during annealing generally amounted to only a few milligrams, equivalent to compositional changes of a few tens of ppm.

The grain size after annealing for 1 hour at 1600 K (2420 F) averaged 30 micro-meters, while annealing for 1 to 5 hours at 1700 to 2023 K (2600 to 3200 F) gave an average grain size of 90 micro-meters. These two structures are referred to below as fine-grained and coarse-grained, respectively.

Creep tests were conducted in internally loaded high-vacuum creep units described earlier (ref. 2). A tantalum split sleeve resistance heater was employed for heating the specimens. The pressure was generally 10^{-8} torr at the start of a creep test, decreasing into the 10^{-10} torr range after several hundred hours. Strains were measured by frequent telescopic readings of fiducial marks at the ends of the gage sections during creep.

Test temperatures ranged from 1100 to 1366 K (1520 to 2000 F) and stresses from 20.7 to 276 MPa (3 to 40 ksi). Tests were generally terminated after 1 to 3 percent strain. The duration of the longest completed test was 4897 hours.

RESULTS AND DISCUSSION

Analysis of Time-to-1-Percent-Strain Data

The creep data on C-103 currently available from this study are summarized in Table 1. Tests currently in progress are also listed to inform the interested reader of additional data which will soon be available.

Representative creep curves are shown in Figure 1.

The creep behavior is seen to be unusual in comparison to that of pure metals and of many alloys in that only accelerating creep is observed for C-103. Since the anlaysis of C-103 creep was complicated further by slightly differing behavior between fine-grained and coarse-grained materials, a straight-forward analysis of the times to 1 percent creep strain was preferred over analyses of the creep rates for the initial correlation and extrapolation to longer times.

Dorn-Sherby Analysis

For this initial correlation, the times to 1 percent strain from Table 1 were correlated by a Dorn-Sherby type of relationship as expressed by Eq. (1), Table 2 (refs. 3,4).

It is seen in Figure 2 that a linear relationship exists on a log-log basis between the temperature-compensated time-to-1-percent-strain and stress for stresses between 20.7 and 82.7 MPa (3 and 12 ksi); above this stress, the curve deviates upwards. This type of behavior is consistent with that for most other metals and alloys when the temperature-compensated linear creep rate is plotted against stress. The upward curvature of this line above a given stress indicates usually a change from a power stress dependence to an exponential stress dependence (ref. 5).

The apparent activation energy (Q) and stress dependence (n) were determined simultaneously for both the fine-grained and coarse-grained C-103 by a least-squares fitting of the data at 20.7 to 82.7 MPa (3 to 12 ksi) to Eq. (1). These values and their approximate 90 percent confidence limits were determined to be 315±49 KJ/gmol (75,300±11,700 cal/gmol) and 2.51±0.44, respectively, as given in Table 2. The constant K1 is also given in Table 2 for both the fine-grained and coarse-grained materials.

Figure 2 shows that the creep rates for the fine-grained material are about one-third faster than those for coarse-grained C-103. This is equivalent to a strength advantage for the coarse-grained material of about 11 percent over the fine-grained material.

The creep strength of C-103 for selected times and temperatures of interest to the Mini-Brayton Power System were predicted using Eq. (1) and the appropriate constants from Table 2. These predicted strength values and their approximate 90 percent confidence limits are given in Table 3. Figure 3 shows the predicted strength for 1 percent creep in 100,000 hours as a function of temperature. These new predicted 1255 K (1800 F) strength values of 7.93 to 8.96 MPa (1150 to 1300 psi) are 40 to 45 percent of the 20 MPa (2900 psi) predicted from the earlier analysis of C-103 creep data. The wide confidence limits (i.e., a spread of nearly a factor of 2) reflect the very limited amount of long-time creep data currently available for C-103 and the consequent high level of uncertainty in these predicted values.

Larson-Miller ~~Analysis~~

The time-to-1-percent-strain data were also analyzed by the Larson-Miller method (ref. 6). This correlation is shown in Figure 4. Here, T is expressed in t in hours, and the constant is given its usual value of 20. The best curve through these data extrapolates to a creep strength for 1 percent strain in 100,000 hours at 1255 K (1800 F) of 21 MPa (3050 psi), significantly higher than those predicted by the Dorn-Sherby method.

Comparison of Dorn-Sherby and Larson-Miller Analyses

It is obvious that the Dorn-Sherby and Larson-Miller analyses give widely differing results for the extrapolated long-time strength of C-103.

We consider that, at least for the present analysis, the Dorn-Sherby approach provides a more accurate relationship between creep rate, stress, and temperature and thus is better suited for data correlation and extrapolation than the Larson-Miller method for the following reasons:

1. The Dorn-Sherby type of relationship includes terms for activation energy and stress dependence which can be correlated with theoretical expressions for the rate-determining dislocation reactions (at least for linear creep). In contrast, the Larson-Miller relationship is strictly empirical.
2. The Dorn-Sherby relationship can simultaneously correlate the creep behavior of a wide variety of pure metals when diffusivity and modulus corrections are included. The Larson-Miller relation, in contrast, must be individually fitted to each data set.
3. The Dorn-Sherby relationship provides a much better correlation of the present data at 20.7 MPa (3 ksi), near the region of greatest interest, than does the Larson-Miller relation.
4. The Dorn-Sherby approach allows distinction between the fine-grained and coarse-grained material while the Larson-Miller does not.
5. Strength values derived from the Dorn-Sherby analysis are more conservative than those derived from the Larson-Miller analysis.

Thus, we recommend that data extrapolated by the Dorn-Sherby relation, Eq. (1), be employed for design of those portions of the Mini-Brayton Power System made of C-103.

Analysis of Creep Curve Shapes

Correlation of Early and Late Tertiary Creep Rates

As mentioned earlier, analysis of the creep behavior of C-103 is more complicated than that for most pure metals by the absence of periods of identifiable primary (parabolic or cubic) or secondary (linear) creep. The creep rate instead accelerates with time at strains of less than 1 percent in a manner normally referred to as tertiary creep.

Similar accelerating creep has been observed previously in high vacuum for many columbium and tantalum alloys (refs. 2,7-12). Analysis of the curves for Ta-10W (ref. 11) showed that creep strain was proportional to time (3/2) for strains up to several percent.

The data from the present study were analyzed to determine the time dependence of creep using the method of finite differences as described by Crussard (ref. 13). The time dependence (m) of C-103 creep was determined on six specimens to range from 2.10 to 2.83, as indicated in Table 1. The average value was 2.41, which was rounded off to 5/2.

We define creep which proceeds proportional to the 5/2 power of time as "late tertiary creep" to distinguish it from "early tertiary creep", which proceeds according to the 3/2 power of time. The late tertiary creep rate, expressed in dimensions of strain (2/5) sec(-1) is termed $\dot{\gamma}$, while the early tertiary creep rate, with dimensions of strain (2/3) sec(-1), is termed $\dot{\beta}$.

The term tertiary creep here refers to the shape of the creep curve and not to the imminence of failure. Although the mechanisms which cause accelerating tertiary creep are not well understood at present, it is known that grain boundary voids nucleate and grow during this period of creep. Thus, early and late tertiary creep behavior may be associated with reactions involving grain boundary voids.

Both early and late tertiary creep rates as well as the strain intercepts at zero time for early tertiary creep were determined for each creep curve and are included in Table 1. These rates were correlated by Dorn-Sherby type relations, Eqs. (2) and (4) in Table 2. The activation energies and stress dependencies determined for early tertiary and late tertiary creep were very similar to those determined earlier for the time-to-1-percent-strain correlations. In order to improve intercorrelations among the early ($\dot{\beta}$) and late ($\dot{\gamma}$) tertiary creep rates and the time-to-1-percent-strain data, the activation energy and stress dependence determined for the time-to-1-percent-strain data were employed also for correlating the early and late creep rates. This approach precluded the determination of separate confidence limits for the constants in Eq. (2) and (4). These correlations are shown in Figures 5 and 6, respectively, and the derived constants are given in Table 2. The early and late tertiary creep rates are seen to correlate fairly well by these relationships and to exhibit an upswing at stresses greater than 82.7 MPa (12 ksi) as also observed for the time-to-1-percent-strain data in Figure 2.

Reconstruction of Creep Curves

It is desireable to reconstruct as well as possible the average creep curves for fine-grained and coarse-grained C-103 in order to illustrate the effects of grain size on the shapes of the creep curves and to allow extrapolation of the curves to creep strains greater than 1 percent. In order to reconstruct the creep curves, the strain intercept at zero time (which represents strain on loading and any traces of primary and secondary creep) is needed as well as the "transition time" from early to late tertiary creep. It is also necessary to assume that the shapes of the creep curves are unchanged (except for the effects of grain size) over the time, temperature, and stress ranges of interest here. Although this assumption is not true over wide ranges of conditions, it is necessary here in view of the limited available data and ~~is useful~~ for the purposes of this study.

The strain intercept at zero time is obtained by correlation of these data for early tertiary creep from Table 1. Assuming that the creep represented by this strain has the same activation energy as that for the other creep rates for C-103, 315±48 KJ/gmol (75,300±11,700 cal/gmol), a stress dependence of 1.85 was obtained by least-squares analysis of the early tertiary creep, zero-time strain intercept data. This stress dependence is similar to the value of 2 previously observed between stress and initial creep strain (ref. 14). This correlation is seen in Figure 7 to be fair at best, probably reflecting the scatter inherent in the extrapolation to zero time of experimental measurements of very small creep strains.

The transition time from early to late tertiary creep is needed since the two rates must be employed sequentially to reconstruct the creep curve. This transition time is defined as that time at which the instantaneous early and late tertiary creep rates are equal. The early tertiary creep relation and its differential with respect to time (the instantaneous creep rate) are:

$$e - e_o = (\dot{\beta}t)^{3/2} \tag{5}$$

$$de/dt = (3/2)\dot{\beta}^{3/2}t^{1/2} \tag{6}$$

The equivalent relations for late tertiary creep are:

$$e - e_o = (\dot{\beta}t)^{5/2} \tag{7}$$

$$de/dt = (5/2)\dot{\gamma}^{5/2}t^{3/2} \tag{8}$$

The transition time is derived from Eqs. (6) and (8) as:

$$t = \frac{3\ \dot{\beta}^{3/2}}{5\ \dot{\gamma}^{5/2}} \tag{9}$$

The transition times and strains calculated from the experimentally observed early and late tertiary creep rates are given in Table 1.

Creep curves calculated for both fine-grained and coarse-grained C-103 using Eqs. (2), (3), (4), and (9) are compared in Figure 8 to representative experimental data. Here, the experimental times are compensated for creep stress and creep temperature so that the differences between the two curves represent only the effects of grain size. It is coincidental that the experimental points lie below the calculated curves for both tests shown here; scatter both above and below the calculated curves was observed for other tests. It is noted that the curve for the fine-grained material accelerates more rapidly than that for the coarse-grained material. This difference reflects the transition to late tertiary creep at a lower strain in the fine-grained than in the coarse-grained material, as seen from the calculated transition strains in Table 1.

The calculated creep strengths for strains up to 5 percent at various times and temperatures of interest are given in Table 4. For example, relaxing the allowable strain in coarse-grained C-103 at 1255 K (1800 F) and 100,000 hours from 1 percent to 5 percent increases the allowable stress from 9.17 to 12.7 MPa (1.33 to 1.84 ksi), an increase of 38 percent. For fine-grained material, the allowable stress increase is 29 percent. The sharper acceleration of creep in the fine-grained material is responsible for the lesser increase in allowable stress relative to the coarse-grained material. Similarly, the allowable stress increases with higher allowable strains are less for C-103 in general than they would be for materials exhibiting linear creep because of the accelerating creep exhibited by C-103.

SUMMARY OF RESULTS

Major results from this interim analysis of the long-time creep behavior of the columbium C-103 alloy are summarized as follows:

1. The stresses for 1 percent creep in 100,000 hours at 1255 K (1800 F) are calculated as 7.93 and 8.96 MPa (1150 and 1300 psi) for fine-grained and coarse-grained C-103, respectively. These strengths are both substantially lower than the 20 MPa (2900 psi) predicted from an earlier analysis on fewer data. Confidence limits on these new strength values are wide because of the few data currently available.
2. At 1100 to 1366 K (1520 to 2000 F) and stresses from 20.7 to 276 MPa (3 to 40 ksi), C-103 exhibits accelerating creep which can be differentiated into one period where strain is proportional to time (3/2) and a second period where strain is proportional to time (5/2). These two periods are termed early and late tertiary creep, respectively. No periods of identifiable primary or secondary creep were observed.
3. The times-to-1-percent-strain and early and late tertiary creep rates currently appear best correlated with stress and temperature by Dorn-Sherby types of relations. The apparent activation energy and stress dependence applicable to all three relations are 315±49 KJ/gmol (75,300±11,700 cal/gmol) and 2.51±0.44, respectively.
4. Analysis of creep curves indicates that the creep rate accelerates more rapidly with time for fine-grained than for coarse-grained C-103.

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TABLE 1. - LONG-TIME CREEP DATA FOR C-103

Test no.	Annealing conditions			Creep test data						Analytical results						
	Time, hr	Temperature, K	(F)	Test temperature, K	(F)	Stress, MPa	(ksi)	Test duration: Time, hr	Test duration: Strain, %	$\dot{\delta}\times10^{9}$, sec^{-1}	$\epsilon_o(E)$, %	$\dot{\gamma}\times10^{8}$, sec^{-1}	Time to 1% strain, hr	Time dependence, m, dimensionless	Calculated $\dot{\epsilon}$-$\dot{\gamma}$ transition: Time, hr	Calculated $\dot{\epsilon}$-$\dot{\gamma}$ transition: Strain, %
Fine-grained C-103																
7	1	1600	(2420)	1100	(1520)	138	(20)	4867	1.81	2.74	0.06	1.03	3960	2.23	2220	0.38
8	1	1600	(2420)			276	(40)	<22.5	>4.36	574	3.99	690	(a)	——	[illegible]	3.99
2	1	1600	(2420)	1150	(1610)	120	(17.4)	192	2.01	95.4	0.36	27.5	99	——	124	1.24
5	1	1600	(2420)	1200	(1700)	55.2	(8)	4897	3.37	2.24	0.02	1.45	2980	1.33	653	0.05
6	1	1600	(2420)			82.7	(12)	2034	3.17	5.13	0.02	3.44	1260	2.48	279	0.06
18	1	1600	(2420)	1250	(1790)	41.4	(6)	2493	1.24	5.63	0.01	1.77	2210	——	1690	0.64
3	1	1600	(2420)			50	(7.27)	982	1.28	7.96	0.03	4.92	876	1.32	[illegible]	0.08
4	1	1600	(2420)			60	(8.71)	960	1.30	4.73	0.03	5.03	867	[illegible]	93	0.03
17	1	1600	(2420)	1300	(1850)	20.7	(3)	3016	1.10	3.65	0.01	1.43	2930	——	[illegible]	0.29
23	1	1600	(2420)			41.4	(6)	1294	3.35	20.3	0.21	5.05	545	——	[illegible]	1.73
9	1	1600	(2420)			55.2	(8)	433	3.55	50.1	-0.01	16.[illegible]	229	[illegible]	[illegible]	0.54
Coarse-grained C-103																
T-29	3	1922	(3000)	1144	(1600)	89.6	(13)	5879	0.63	(b)						
T-28	3	1922	(3000)	1200	(1700)	62.1	(9)	3861	1.67	4.35	0.08	1.20	2790	——	3030	1.11
T-30	3	1866	(2900)	1228	(1750)	34.5	(5)	3407	0.39	(b)						
T-33	3	1866	(2900)	1255	(1800)	34.5	(5)	3025	0.68	(b)						
T-27	3	1922	(3000)			41.4	(6)	2275	1.18	5.66	0.15	1.78	2030	——	1680	0.78
13	5	1700	(2600)			48.3	(7)	1387	1.42	(b)						
14	1	1811	(2800)			48.3	(7)	2353	2.59	9.45	0.04	2.51	1330	——	1530	1.23
16	1	2033	(3200)			48.3	(7)	2541	2.12	7.88	0.04	1.96	1600	——	2170	1.56
T-32	3	1566	(2900)	1366	(2000)	13.8	(2)	2756	0.47	(b)						
T-26	3	1922	(3000)			20.7	(3)	1676	1.57	10.1	0.15	2.80	1170	——	1290	1.17
T-34	3	1866	(2900)	1422	(2100)	10.3	(1.5)	1699	0.75	(b)						

(a) Strained 3.99 percent on loading.

(b) Test in progress as of December 11, 1975.

TABLE 2. - CREEP RELATIONSHIPS AND CONSTANTS FOR C-103

$$1/t = K_1\sigma^n e^{-Q/RT} \tag{1}$$

$$\dot{\beta} = K_2\sigma^n e^{-Q/RT} \tag{2}$$

$$\epsilon_0(\beta) = K_3\sigma^{n'} e^{-Q/RT} \tag{3}$$

$$\dot{\gamma} = K_4\sigma^n e^{-Q/RT} \tag{4}$$

	K_1	$\ln K_1$	K_2	K_3	K_4
Fine-grained material	2.01x10^2	5.304±4.063	5.96	2.87x10^6	2 [illegible]x10^1
Coarse-grained material	1.49x10^2	5.001±4.073	6.50	8.07x10^6	1 [illegible]9x10^1

	n	n'
Fine-grained material	2.51±0.44	1.85
Coarse-grained material	2.51±0.44	1.85

t = time to 1 percent strain, seconds
$\dot{\beta}$ = early tertiary creep rate, strain$^{2/3}$second^{-1}
$\epsilon_0(\beta)$ = strain intercept at zero time for β creep
$\dot{\gamma}$ = late tertiary creep rate, strain$^{2/5}$second^{-1}
σ = stress, MPa
n = stress dependency
Q = apparent activation energy for creep
= 315±49 KJ/gmol
R = gas constant = 8.314 J/K-gmol
T = temperature, K
K = creep constant, (MPa)$^{-n}$(sec)$^{-1}$or(MPa)$^{-n}$

TABLE 3. - PREDICTED CREEP STRENGTHS FOR C-103
(BASED ON DORN-SHERBY ANALYSIS)

Temperature, K	Temperature, (F)	Time	Stress for 1 percent strain in indicated time and approximate 90 percent confidence limits MPa	(ksi)
Fine-grained C-103				
1116	(1550)	5 yr	49.0±13.5	(7.11±1.96)
		7 yr	42.9±12.4	(6.22±1.81)
		100,000 hr	35.3±11.1	(5.12±1.61)
1228	(1750)	5 yr	14.4± 4.1	(2.09±0.60)
		7 yr	13.3± 3.8	(1.83±0.56)
		100,000 hr	10.4± 3.4	(1.51±0.50)
1255	(1800)	5 yr	11.0± 3.2	(1.60±0.47
		7 yr	9.7± 3.0	(1.40±0.43)
		100,000 hr	7.9± 2.6	(1.15±0.38)
Coarse-grained C-103				
1116	(1550)	5 yr	55.3±14.4	(8.02±2.09)
		7 yr	48.3±13.3	(7.01±1.93)
		100,000 hr	39.9±11.9	(5.78±1.72)
1228	(1750)	5 yr	16.3± 4.3	(2.36±0.62)
		7 yr	14.2± 4.0	(2.06±0.58)
		100,000 hr	11.7± 3.6	(1.70±0.52)
1255	(1800)	5 yr	12.4± 3.3	(1.80±0.48)
		7 yr	10.8± 3.1	(1.57±0.45)
		100,000 hr	9.0± 2.7	(1.30±0.39)

TABLE 4. - PREDICTED STRESSES TO GIVE VARIOUS CREEP STRAINS IN C-103
(BASED ON DORN-SHERBY ANALYSES)

Temperature, K	(F)	Time	Stress for creep to indicated strain, MPa (ksi)				
			1%	2%	3%	4%	5%
			Fine-grained C-103				
1116	(1550)	5 yr	50.7 (7.35)	56.8 (8.24)	60.7 (8.80)	63.6 (9.22)	[illegible]
		7 yr	44.3 (6.43)	49.7 (7.21)	53.1 (7.70)	55.6 (8.07)	[illegible]
		100,000 hr	36.5 (5.29)	41.0 (5.94)	43.7 (6.34)	45.8 [illegible]	[illegible] (6.88)
1228	(1750)	5 yr	14.9 (2.16)	16.8 (2.43)	17.9 (2.59)	[illegible]	19.4 (2.81)
		7 yr	13.0 (1.89)	14.6 (2.12)	15.7 (2.27)	[illegible] (2.37)	17.0 (2.46)
		100,000 hr	10.8 (1.56)	12.1 (1.75)	12.9 (1.87)	13.4 (1.95)	14.0 (2.03)
1255	(1800)	5 yr	11.4 (1.65)	12.8 (1.85)	13.6 (1.97)	14.3 (2.07)	14.8 (2.14)
		7 yr	9.9 (1.44)	11.2 (1.62)	11.9 (1.73)	12.5 (1.81)	13.0 (1.88)
		100,000 hr	8.2 (1.19)	9.2 (1.33)	9.8 (1.42)	10.3 (1.49)	10.6 (1.54)
			Coarse-grained C-103				
1116	(1550)	5 yr	56.6 (8.21)	66.4 (9.63)	71.8 (10.41)	75.6 (10.96)	78.6 (11.40)
		7 yr	49.6 (7.19)	58.1 (8.42)	62.7 (9.10)	66.1 (9.59)	68.7 (9.97)
		100,000 hr	40.8 (5.92)	47.8 (6.93)	51.6 (7.49)	54.4 (7.89)	56.6 (8.21)
1228	(1750)	5 yr	16.7 (2.42)	19.5 (2.83)	21.1 (3.06)	22.3 (3.23)	23.2 (3.36)
		7 yr	14.6 (2.12)	17.1 (2.48)	18.5 (2.68)	19.4 (2.82)	20.3 (2.94)
		100,000 hr	12.0 (1.74)	14.1 (2.04)	15.2 (2.21)	16.0 (2.32)	16.7 (2.42)
1255	(1800)	5 yr	12.7 (1.84)	14.9 (2.16)	16.1 (2.33)	17.0 (2.46)	17.7 (2.56)
		7 yr	11.1 (1.61)	13.0 (1.89)	14.1 (2.04)	14.8 (2.15)	15.4 (2.24)
		100,000 hr	9.2 (1.33)	10.8 (1.56)	11.6 (1.68)	12.2 (1.77)	12.7 (1.84)

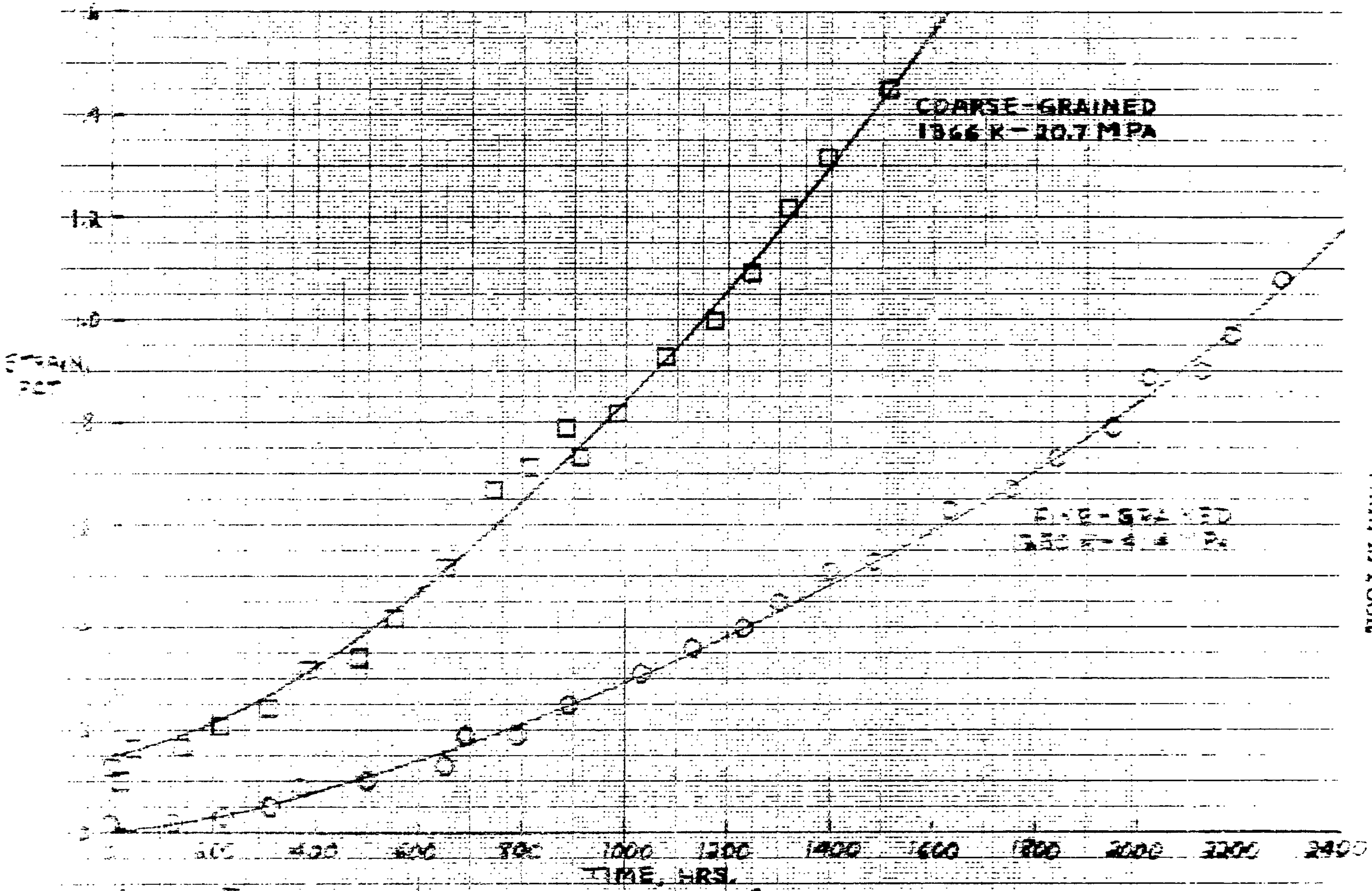


FIG. 1 REPRESENTATIVE CREEP CURVES FOR C-103

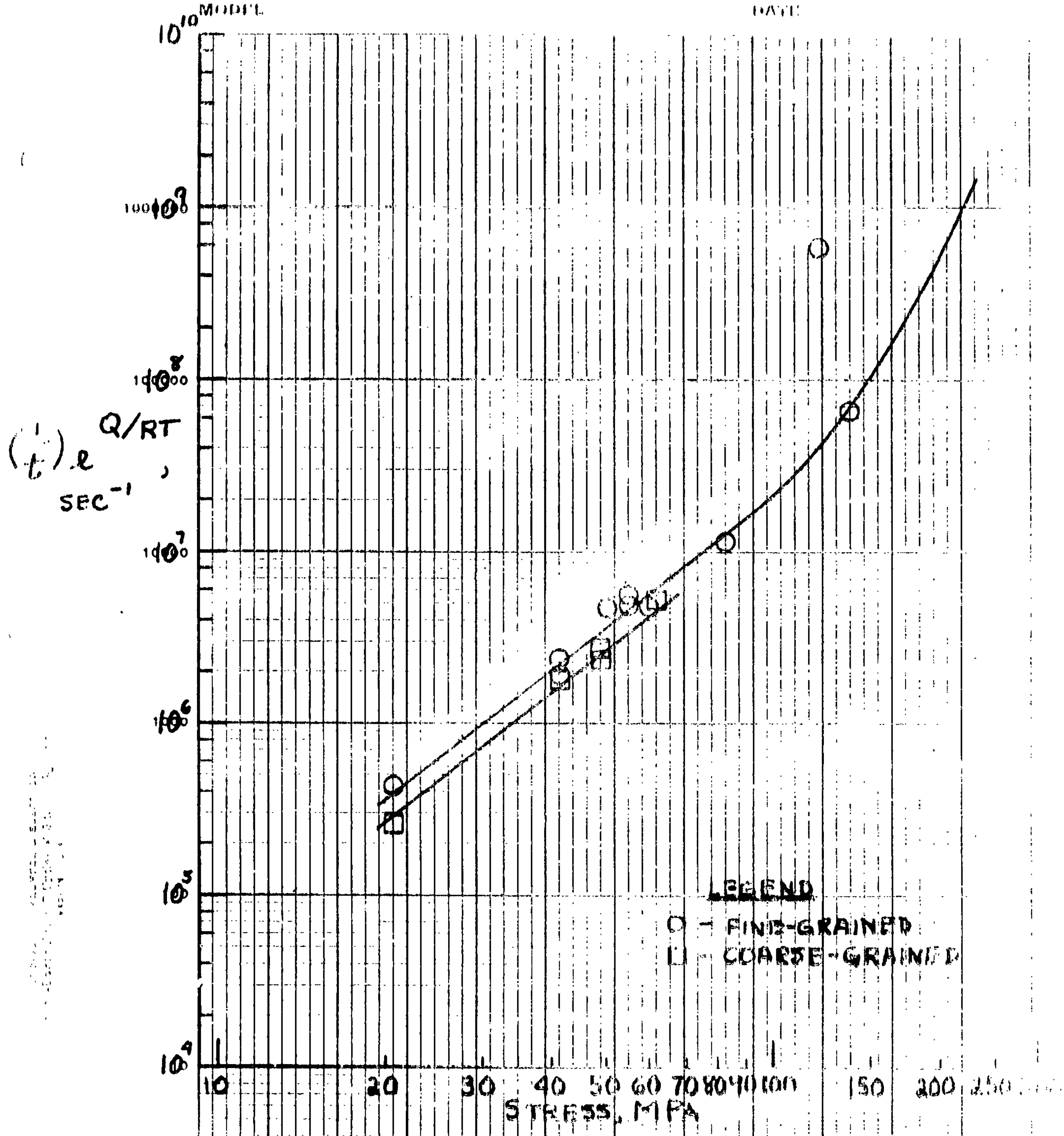


FIG. 2. STRESS DEPENDENCE OF TEMPERATURE-COMPENSATED CREEP TIMES FOR C-103.

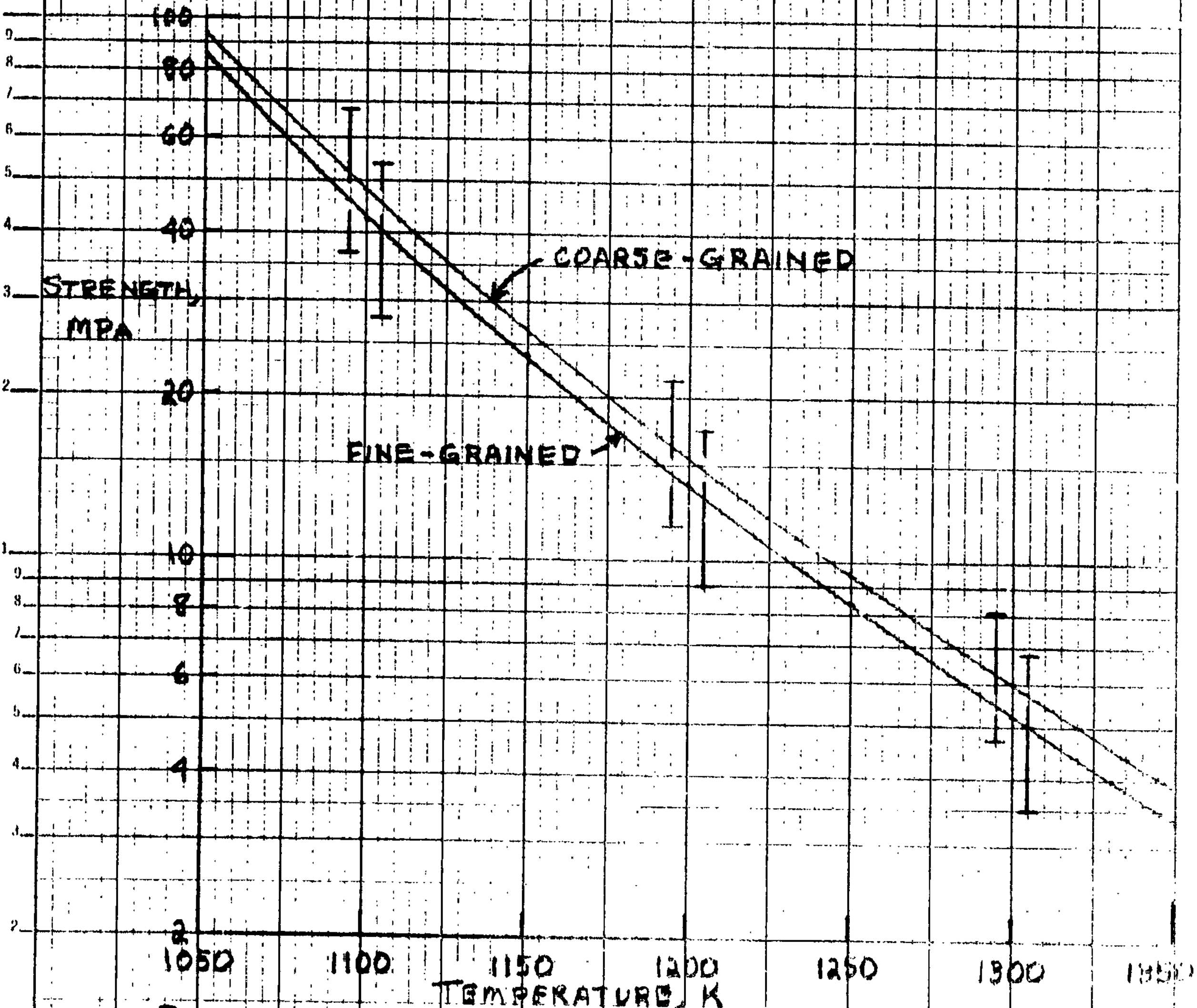


FIG. 3. PREDICTED CREEP STRENGTHS AND APPROXIMATE 90 PCT CONFIDENCE LIMITS FOR 1 PCT STRAIN IN 100,000 HOURS AT 1050 TO 1350 K FOR C-103.

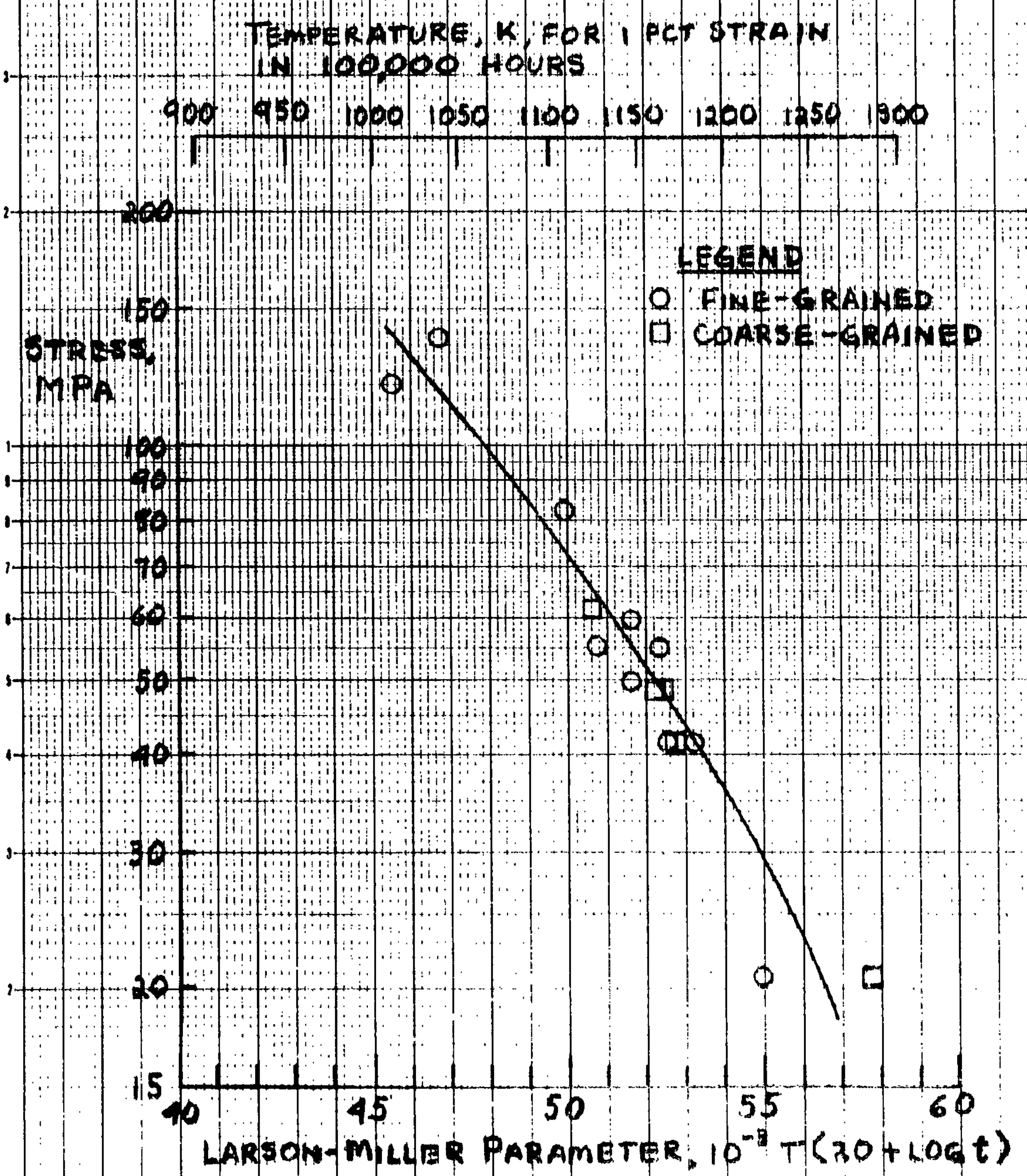


FIG. 4. LARSON-MILLER PLOT OF TIME-TO-1-PCT-STRAIN DATA FOR C-103.

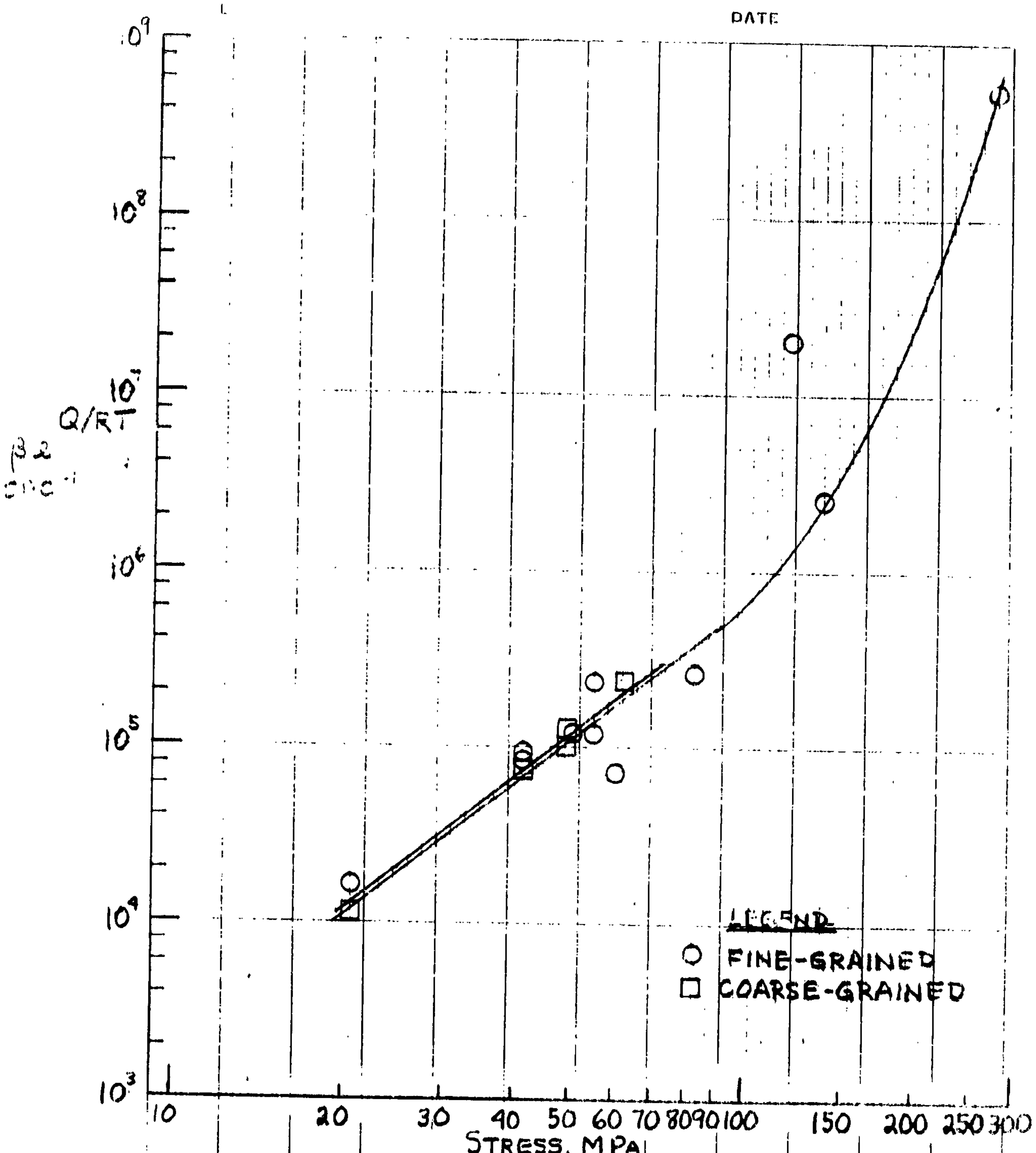


FIG. 5. STRESS DEPENDENCY OF TEMPERATURE-COMPENSATED EARLY TERTIARY CREEP RATES FOR C-103.

DATE

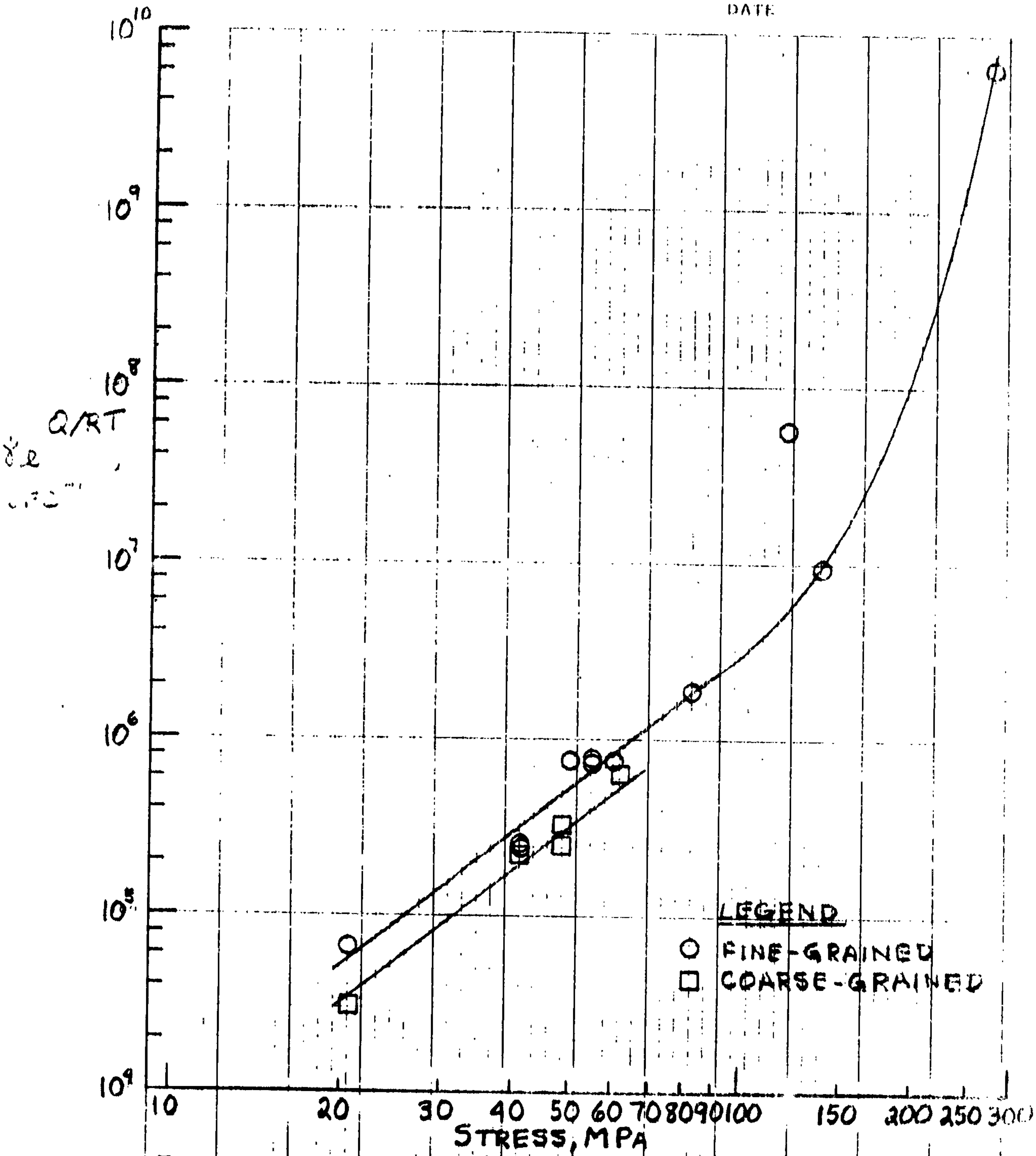


FIG. 6. STRESS DEPENDENCY OF TEMPERATURE-COMPENS
LATE TERTIARY CREEP RATES FOR C-103

DATE

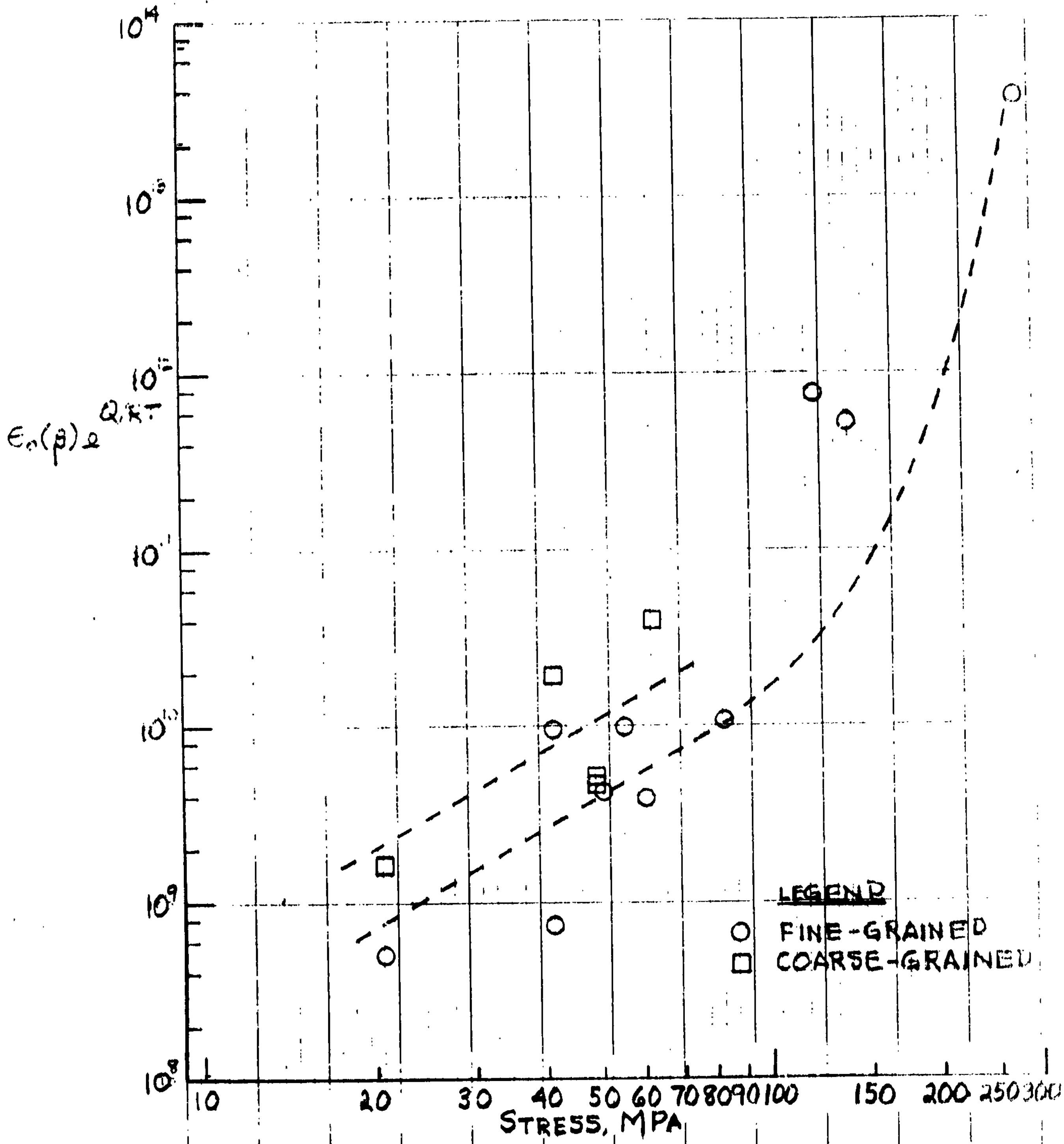
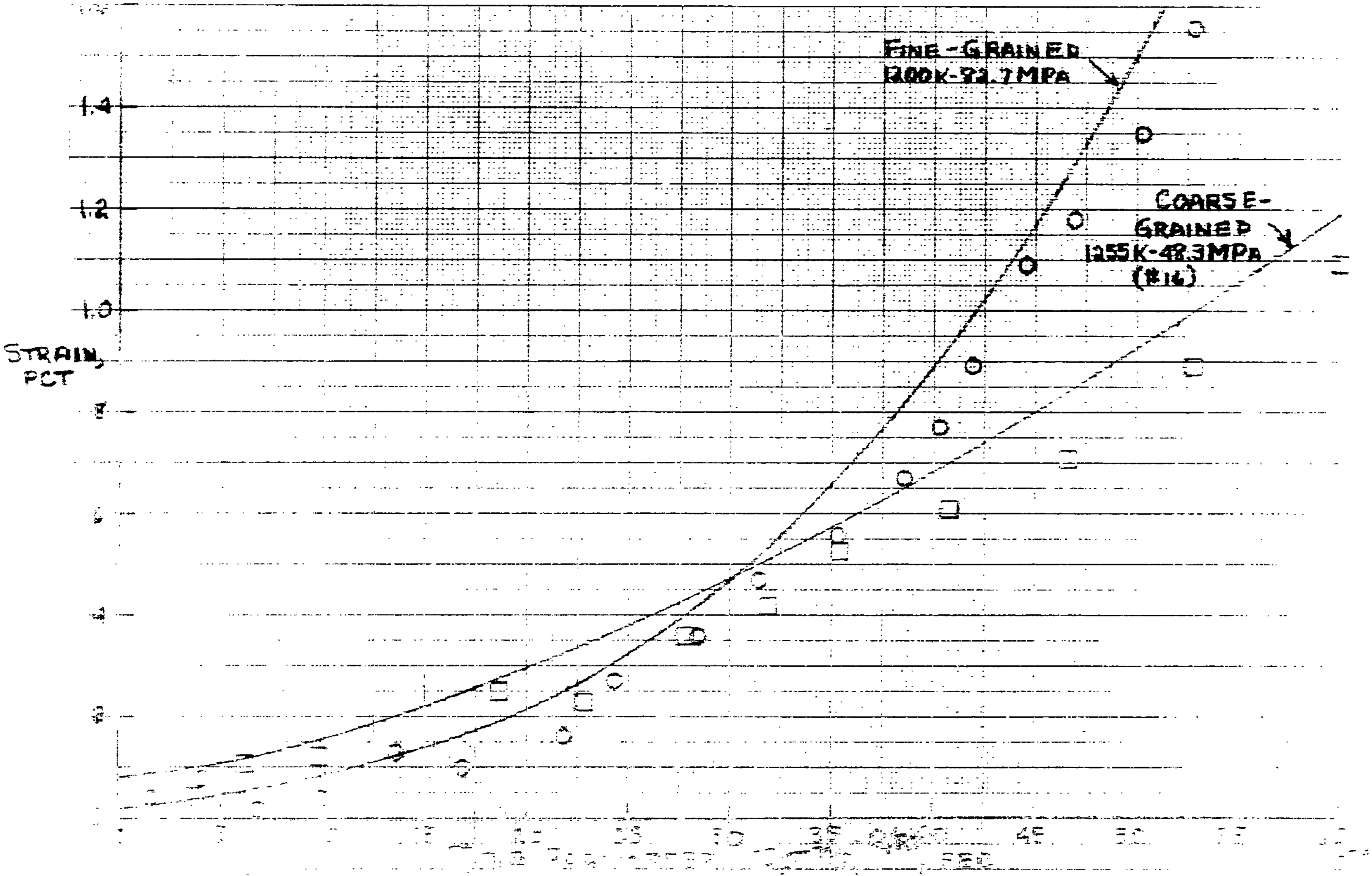


FIG. 7. STRESS DEPENDENCY OF TEMPERATURE-COMPENSA
EARLY TERTIARY CREEP STRAIN INTERCEPTS
FOR C-103



FINE-GRAINED
1200K-82.7MPA
COARSE-
GRAINED
1255K-48.3MPA
(#14)
STRAIN, PCT
1.4
1.2
1.0
.8
.6
.4
.2
25
30
35
45
50