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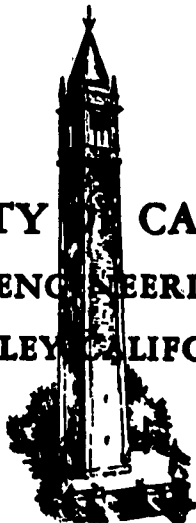
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CREEP CORRELATIONS OF METALS AT
ELEVATED TEMPERATURES

Twenty Fifth Technical Report

By

Oleg D. Sherby, Raymond L. Orr and John E. Dorn

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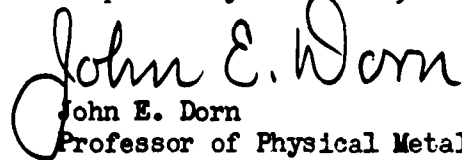
ATTENTION: Dr. O. T. Marzke

Dear Sir:

Attached hereto is the Twenty Fifth Technical Report on
Contract N7-onr-295, Task Order II, NR-031-048, entitled
"Creep Correlations of Metals at Elevated Temperatures".

The wholehearted cooperation of the Office of Naval Research
in making these studies possible is sincerely appreciated.

Respectfully submitted,


John E. Dorn
Professor of Physical Metallurgy

JED:bp

CREEP CORRELATIONS OF METALS AT
ELEVATED TEMPERATURES

By

Oleg D. Sherby ⁽¹⁾, Raymond L. Orr ⁽¹⁾ and John E. Dorn ⁽²⁾

Twenty Fifth Technical Report, Series 22, Issue 25
N7-onr-295, Task Order II, NR-031-048

March 1, 1953

(1) Research Engineer and (2) Professor of Physical Metallurgy, University
of California, Berkeley, California

ABSTRACT

Creep and tensile data of pure metals above 0.45 T_m are correlatable by means of the equations $\epsilon = f(t e^{-\Delta H/RT}, \sigma)$ and $\sigma = f(\dot{\epsilon}_s e^{\Delta H/RT})$. These parameters were applied successfully to creep and tensile data for platinum, nickel, copper, gold, aluminum, lead, iron and zinc as well as to solid solution alloys. The activation energy for creep, ΔH , was found to be a constant for a given metal; the activation energies obtained were found to be about equal to the activation energies for self-diffusion of the various metals. In addition, for the elements investigated, ΔH was found to be a periodic function of their atomic number.

INTRODUCTION

The early recognition that creep is stimulated by thermal activation prompted numerous investigators (1,2) to apply the same laws that are valid for the viscous behavior of liquids to analyses of creep data. To a good first approximation these laws are summarized by the equation

$$\dot{\epsilon} = S' e^{-\Delta H/RT} \sinh \frac{B'\sigma}{RT} \quad (1)$$

where

$\dot{\epsilon}$ = creep rate

T = absolute temperature

R = gas constant

σ = applied stress

ΔH = activation energy

S' = a constant dependent on the entropy of activation, the frequency of activation and the contribution of each activation to the strain.

B' = a constant dependent upon the size of the flow unit that is activated.

Although Equation 1 describes the flow of viscous fluids very accurately, its application to the creep of solids has been disappointing. Two reasons for the failure of Equation 1 for creep are now known: First, the decelerating creep rates during primary creep demand that the substructures of the metals are changing and that these changes are reflected by changes in one or more of the three creep parameters S' , ΔH , and B' . Consequently when the conventional methods of evaluating these parameters are employed by comparing the secondary creep rates at a series of temperatures and at a series of stresses, the true effects of temperature and stress are masked because of simultaneous changes in one or more of the creep parameters.

Secondly, as will be illustrated more fully later, three distinctly different types of investigations have shown that the stress term for high temperature creep enters the analysis as σ and not as σ/T . This rather unexpected result points sharply to a significant fundamental difference between the mechanisms for the viscous behavior of fluids and the high temperature creep of metals.

More recent extensive investigations ^(3,4) on the creep of high purity aluminum and several of its dilute alpha solid solutions have shown that

$$\epsilon = f_1(\theta, \sigma_c) \quad (2a)$$

or

$$\theta = f_2(\epsilon, \sigma_c) \quad (2b)$$

where

ϵ = total creep strain

$\theta = \int_0^t e^{-\Delta H/RT} dt$ = temperature-compensated time = $t e^{-\Delta H/RT}$
for a constant temperature test.

σ_c = initial stress in a constant load test or the constant
true stress in a constant stress test.*

t = duration of test.

The fundamental origin of the validity of Equation 2a must arise from some equivalence of substructures in constant load creep tests at equal values of θ or ϵ . Both x-ray and metallographic examination revealed that identical lattice distortions and subgrain sizes are obtained for the same creep strain under the same load over wide ranges of test temperature ⁽⁴⁾. Furthermore the room temperature tensile properties following equal creep strains at different temperatures

* Equation 2 is valid for either constant stress or constant load tests; but the total creep strain is different (i.e. the function, f_1 , is different) for each test.

under constant loads were also identical, illustrating that identical substructures were indeed obtained (5).

A second type of correlation was obtained by differentiating Equation 2a with respect to time, giving

$$\dot{\epsilon} = \left(\frac{\partial f}{\partial \theta} \right) \frac{d\theta}{dt} = f'_i(\theta, \sigma_c) e^{-\Delta H/RT} \quad (3)$$

For the secondary creep rate, denoted by $\dot{\epsilon}_s$,

$$\dot{\epsilon}_s = f'_i(\theta_s, \sigma_c) e^{-\Delta H/RT}$$

But Equation 2b reveals that θ_s is a function of σ_c alone because the secondary creep rate in a given constant load test is always reached at a fixed value $\dot{\epsilon}_s$.

Therefore

$$\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT}) = f(Z) \quad (4)$$

where Z is the function that was introduced a number of years ago by Zener and Holloman (6). Equation 4 is not only valid for creep but will permit correlations between constant load creep and tensile data where $\dot{\epsilon}_s$ is the rate of tensile straining and σ_c is the engineering ultimate tensile strength.

Investigations on the effect of stress on the creep rate at constant substructures (7) have shown that Equation 3 reduces to

$$\dot{\epsilon} = S e^{-\Delta H/RT} \sinh B\sigma \quad (5)$$

where B is independent of temperature or substructures generated during creep but does depend on alloying.

The evaluation of the activation energy, ΔH , for the creep of aluminum alloys by means of Equations 2a and 4 gave the following conclusions:

1. ΔH is practically a universal constant for aluminum; it is independent of temperature over wide ranges of temperatures (above about 0.45 the melting temperature, T_m), creep stress, creep strain, grain size, substructures developed

during creep and small alloying additions (3,4), as well as cold work (8) and dispersions of CuAl_2 (9).*

2. Although creep takes place at temperatures below about $0.45 T_m$, the correlations suggested by Equations 2 and 4 are valid only above $0.45 T_m$. Perhaps no special meaning can be ascribed to the number $0.45 T_m$ above which the creep laws given previously are valid. But it is significant to note $0.45 T_m$ is that temperature at which the tensile strength of aluminum and its dilute alloys begin to decrease rapidly with increase in temperature due to rapid recovery rates (10). Evidently these laws are only valid in the temperature range where reasonably rapid recovery can occur.

3. Furthermore, the experimentally established validity of Equations 2, 4 and 5 proves that the stress and not the stress divided by the absolute temperature enters the creep equation for high creep temperatures. Since the stress does not enter the creep equation as stress divided by temperature, the stress term cannot enter the free energy of activation term. Consequently the mechanism for creep cannot be that of thermal activation wherein the free energy of activation includes the work term arising from the applied stress as is assumed in the derivation of Equation 1. It is possible that the activation energy is solely that for crystal recovery of barriers, and such recovery is the rate controlling process for high temperature creep. Thus the stress merely moves the dislocation to a new barrier once the former barrier has been removed by recovery. The extent of this motion per activation, of course, would depend upon the substructure developed in the metal.

The success achieved by applying Equations 2 and 4 to the creep of aluminum suggests that they should also be valid for other systems. Since ΔH appears to

* For some as yet unknown reasons the creep behaviors of some commercial aluminum alloys such as 24S-T are not analyzable by the above methods.

be rather insensitive to structural variables and minor alloying additions, it appears to be a fundamental property and should therefore be correlatable with other fundamental properties. It is the purpose of this report to review creep data of various metals already reported in the literature in an attempt to test the general validity of Equations 2 and 4. Furthermore the activation energies for the elements studied will be evaluated in a preliminary attempt to uncover additional correlations.

MATERIALS INVESTIGATED

In order to avoid complications arising from simultaneous phenomena such as precipitation hardening, phase changes, etc., only creep data for pure metals and solid solution alloys were investigated. Since Equations 2 and 4 were found to be valid only above $0.45 T_m$ for aluminum, the temperature at which rapid recovery occurs, special precautions were taken to use only high temperature creep data.

Creep data on high purity metals are indeed meager; the metals and solid solution alloys covered in this report are listed in Table I. All the face centered cubic metals are listed in Section A of the table, the body centered cubic in Section B and the hexagonal close packed materials in Section C.

RESULTS

A. Face Centered Cubic Metals

1. Platinum

Carreker ⁽¹¹⁾ investigated the creep properties of 99.98 + percent platinum wire, containing only traces ($<0.01\%$) of iron and palladium, at temperatures ranging from 78° to 1550°K , under constant stress conditions. The true creep strain - time plots are reproduced in Figure 1 for the temperature range above $0.45 T_m$ (950° to 1550°K).

TABLE I
Metals and Solid Solution Alloys Investigated

A. Face Centered Cubic Metals

Metal	0.45 Tm			Investigator
	[°] K	[°] C	[°] F	
1. Platinum	920	647	1436	Carreker (11), Dushman, Dunbar and Huthsteiner (2)
2. Nickel	777	504	939	Hazlett, Parker and Nathans (12)
3. Solid Solution of 45% Ni, 55% Cu (Constantan)	672	399	750	Dushman, Dunbar and Huthsteiner (2)
4. Copper	610	337	638	Nadai and Manjoine (13)
5. Gold	601	328	622	Alexander, Dawson and Kling (14)
6. Aluminum	420	147	296	Servi and Grant (15) Sherby and Dorn (3,4)
7. Lead	270	-3	27	Smith (16) McKeown (17) Smith and Howe (18) Andrade (19)

B. Body Centered Cubic Metals

1. Iron	488*	215	419	Tapsell and Clenshaw (20)
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C. Hexagonal Close Packed Metals

1. Zinc	312	39	38	Pomp and Länge (21) Graeser, Hanemann and Hofmann (22)
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*Tm for iron was considered to be equal to the phase transformation temperature from alpha to gamma iron, 910°C, instead of the actual melting temperature 1545°C.

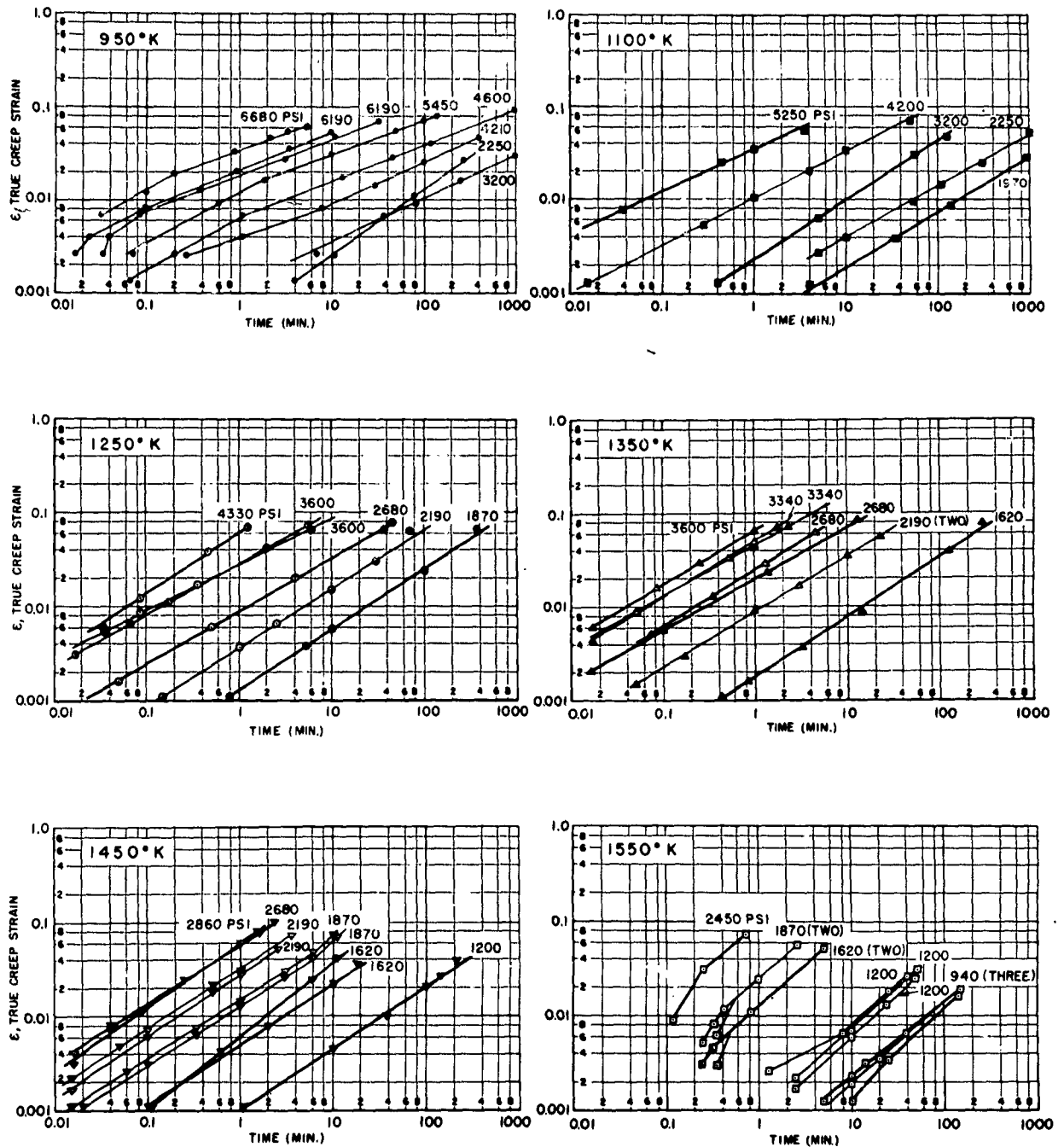


FIG. 1 TRUE CREEP STRAIN - TIME DATA FOR PLATINUM AT VARIOUS TEMPERATURES UNDER CONSTANT STRESS CONDITIONS.
[DATA OF R. P. CARREKER⁽¹⁾]

These data can best be analyzed in terms of Equations 2a and 2b. In order to cover all the creep data shown in Figure 1 it was first decided to use Equation 2b and attempt to correlate the constant stress σ_c with $\theta = t e^{-\Delta H/RT}$ at a given strain. These results are shown in Figure 2 for a given strain of 1%, wherein an activation energy of 56,000 calories per gram atom was found to be valid for all the data with the exception of those obtained at 950°K. It therefore appears that the correlation by means of Equation 2b is valid for platinum somewhat above about 0.50 T_m .

Similarly, Equation 2a should also be valid for the platinum data above 950°K, correlating the whole creep curve. Figure 3 is a replot of three representative stress data at each temperature (shown as the extra dark curves in Figure 1) on a single composite graph of $\dot{\epsilon}$ versus $t e^{-56000/RT}$. These results further justify the validity of Equations 2a and 2b.

Dushman, Dunbar and Huthsteiner ⁽²⁾ investigated the secondary creep rate characteristics of pure platinum at temperatures of 1118°, 1206° and 1285°K under constant load conditions. The chemical composition of the wire used was not given. Their results are plotted in terms of Equation 4 as shown in Figure 4. The correlation obtained was quite good using the same activation energy of 56,000 calories per gram atom obtained previously from the more extensive data of Carreker.

2. Nickel

Hazlett, Parker and Nathans ⁽¹²⁾ in an unclassified AEC Technical Report presented creep data under constant stress for nickel of the following chemical composition: 98.7% Ni, 0.7% Co, 0.015% Fe, 0.35% Si, 0.10% Cu, 0.25% Mn, 0.01% S and 0.05% C. They performed creep tests under a constant stress of 5750 psi in the range from 946° to 1027°K.

Their data correlated very well in terms of the temperature-compensated time concept as shown in Figure 5, wherein an activation energy, ΔH , of 65,400

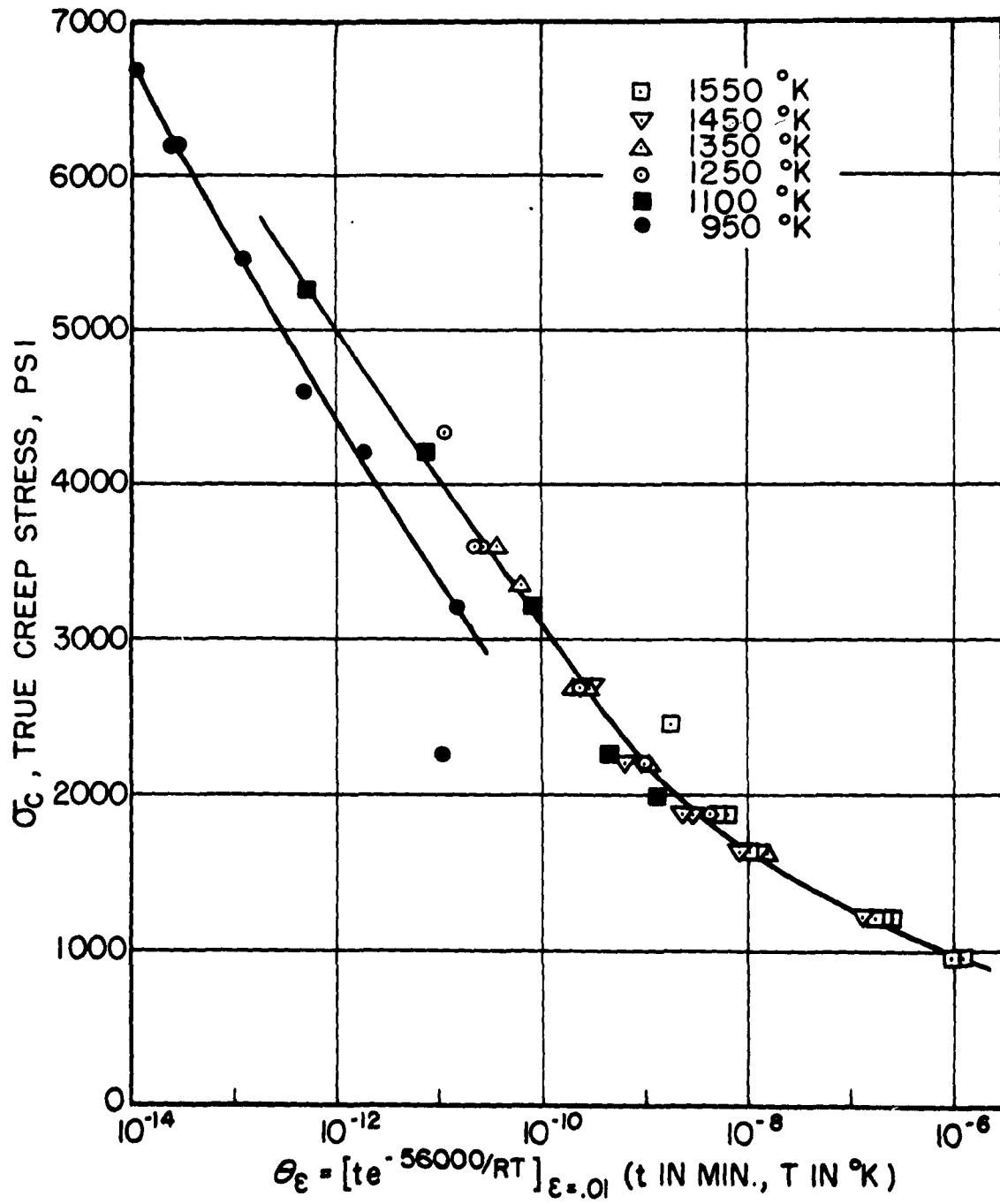


FIG.2 CORRELATION OF CREEP DATA FOR PLATINUM
BY THE RELATION $\theta = f(\epsilon, \sigma_c)$. [DATA OF R. P. CARREKER⁽¹¹⁾]

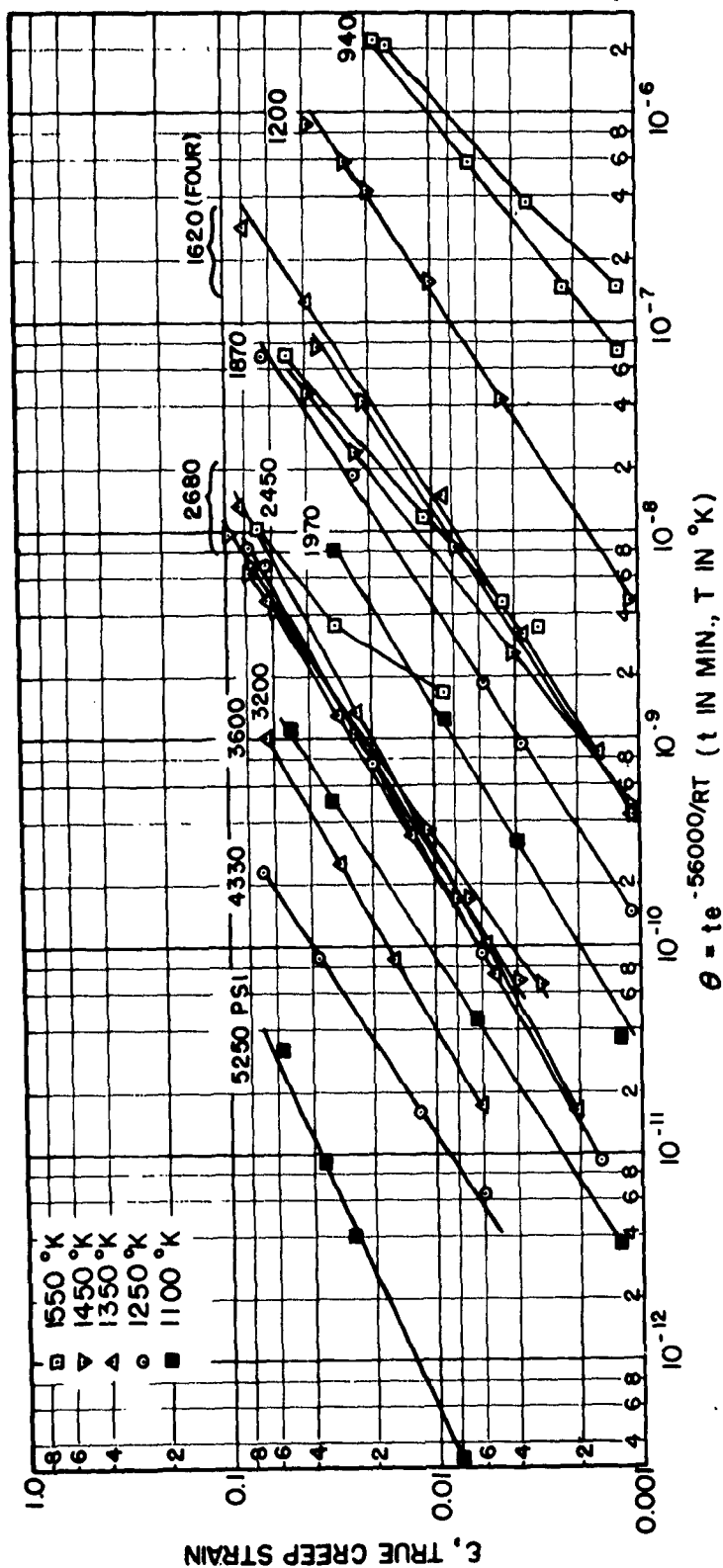


FIG. 3 CORRELATION OF CREEP STRAIN - TIME DATA FOR PLATINUM BY THE
RELATION $\epsilon = f(\theta, \sigma_c)$ AT VARIOUS STRESSES. [DATA OF R.P. CARREKER⁽¹¹⁾]

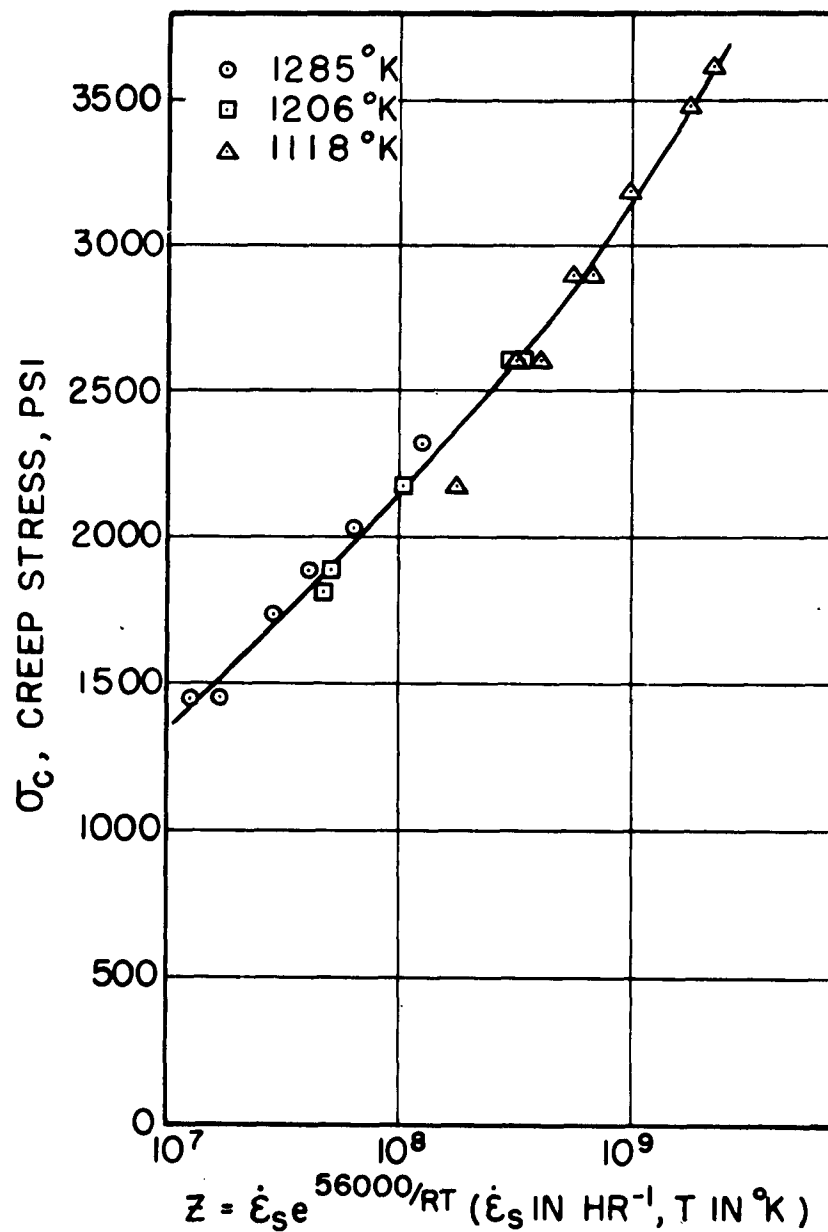


FIG. 4 CORRELATION OF STRESS - SECONDARY CREEP RATE DATA FOR PLATINUM BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$. [DATA OF DUSHMAN, DUNBAR & HUTHSTEINER⁽²⁾]

calories per gram atom was obtained. These investigators also studied the creep curve for a constant stress of 5750 psi under changing temperature conditions, obtaining a typical curve as shown in Figure 6 for the temperature cycling shown above the curve. Actually this experimental curve can be predicted from the $\epsilon - \theta$ data of Figure 5. Thus, knowing the temperature history of the test, one can obtain a value of θ for a given time (the area under an $e^{-\Delta H/RT}$ - time curve), following which the creep strain ϵ can be predicted from the $\epsilon - \theta$ master curve of Figure 5. In this manner the predicted curve was obtained as shown by the dotted creep curve of Figure 6. The actual and predicted curves superimpose extremely well.

3. 45% Ni - 55% Cu Solid Solution Alloy (Constantan)

Dushman, Dunbar and Huthsteiner ⁽²⁾ creep tested constantan at temperatures from 673° to 783°K. The lower limit of creep test temperature used by Dushman et al is just equal to 0.45 T_m . The constantan creep specimens contained only traces of manganese and iron. An annealing treatment of 10 minutes at 773°K was used before creep testing. They studied the effect of the applied creep stress (constant load creep) on the secondary creep rate at various temperatures. Their data are replotted in terms of the Z parameter in Figure 7 wherein an activation energy of $\Delta H = 41,800$ calories per mole was obtained. The correlation by means of this parameter was found to be excellent over the range of creep temperatures studied.

4. Copper

As far as is known to the authors, there are no data available on the creep of high purity copper above 610°K, that is, above 0.45 T_m . Nadai and Manjoine ⁽¹³⁾ however, studied the effect of strain rate on the tensile strength of commercially pure copper over the range 300° to 1273°K. The chemical composition of the copper was not given. The testing rate at high temperatures was

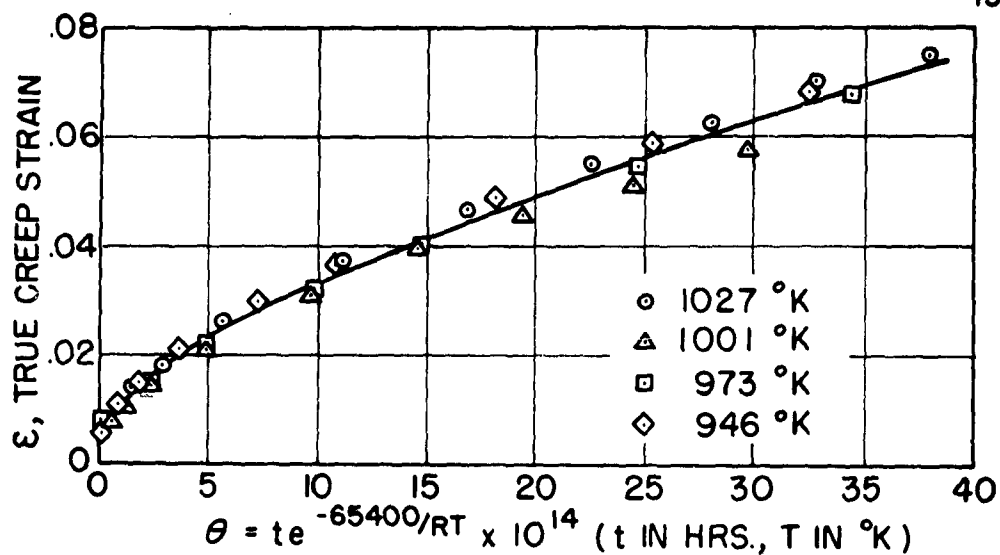


FIG. 5 CORRELATION OF CREEP STRAIN-TIME DATA FOR NICKEL BY THE RELATION $\epsilon = f(\theta, \sigma_c)$ AT A CONSTANT STRESS OF 5750 PSI. [DATA OF HAZLETT, PARKER & NATHANS⁽¹²⁾]

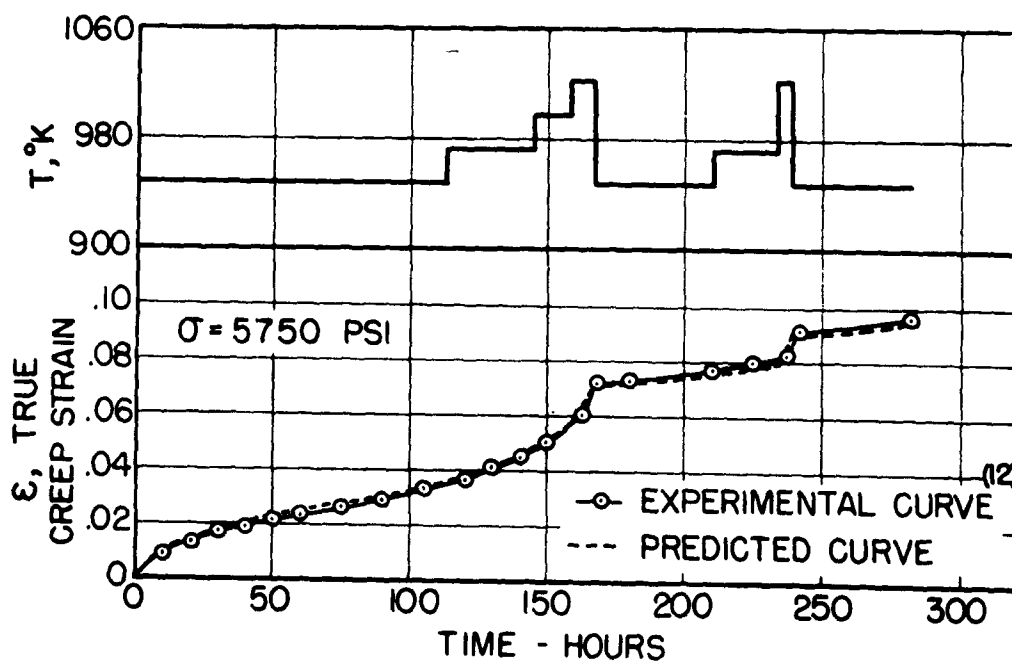


FIG. 6 PREDICTED AND EXPERIMENTAL CREEP CURVES FOR NICKEL WHEN THE TEMPERATURE IS CHANGED AS A FUNCTION OF TIME UNDER CONSTANT STRESS CONDITION.

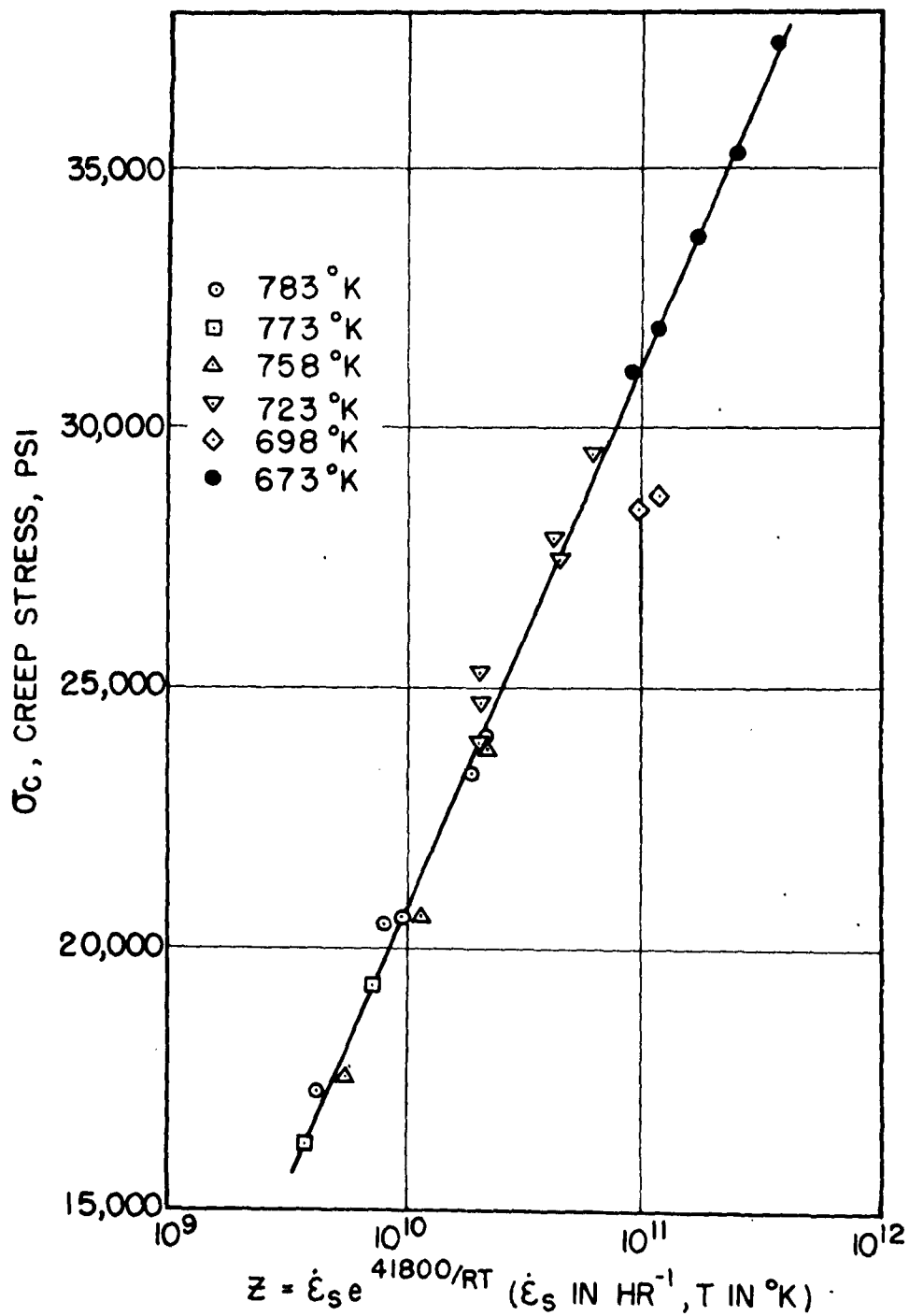


FIG. 7 CORRELATION OF STRESS-SECONDARY CREEP RATE DATA FOR CONSTANTAN (45 % Ni, 55 % Cu) BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$.

[DATA OF DUSHMAN, DUNBAR & HUTHSTEINER (2)]

at speeds ranging from $\dot{\epsilon}_s = 3.6 \times 10^6/\text{hr}$ to $\dot{\epsilon}_s = 3.6/\text{hr}$. In order to correlate all of Nadai and Manjoine's data, Equation 4 was used where σ_c refers to the ultimate tensile strength or true stress at ultimate and $\dot{\epsilon}_s$ refers to the rate of straining of the specimen. The good correlation by this equation is shown in Figure 8. ΔH was found to be a constant of about 44,000 calories per gram atom for copper over the wide temperature range from above 0.45 T_m to almost the melting point.

5. Gold

Alexander, Dawson and Kling ⁽¹⁴⁾ performed creep tests on pure gold near the melting point. Unfortunately, they were primarily interested in the so-called microcreep range wherein an apparent viscous behavior of the metal was obtained. The data are therefore quite limiting; furthermore, at very low stresses they obtained negative creep rates due to surface tension effects. If these very low stress tests are eliminated their data can be correlated by means of the Z parameter of Equation 4. Figure 9 is a plot of their results wherein an activation energy of 50,000 calories per gram atom was found valid for the creep of gold.

6. Aluminum

The correlation of creep data for aluminum and its solid solution alloys has been extensively studied in terms of Equations 2a and 4 and therefore will not be covered here. An activation energy of 36,000 calories per gram atom was obtained independent of dilute alpha solid solution alloying ^(3,4) and grain size ⁽³⁾ as well as independent of stable precipitates of CuAl_2 ⁽⁹⁾.

7. Lead

Only limited data are available on the creep of high purity lead at various elevated temperatures. Smith ⁽¹⁶⁾ studied the creep of 99.9998 percent lead at three temperatures, 303°, 328° and 373°K, under constant load conditions. Unfortunately, the tests were conducted up to only slightly over 3% strain and

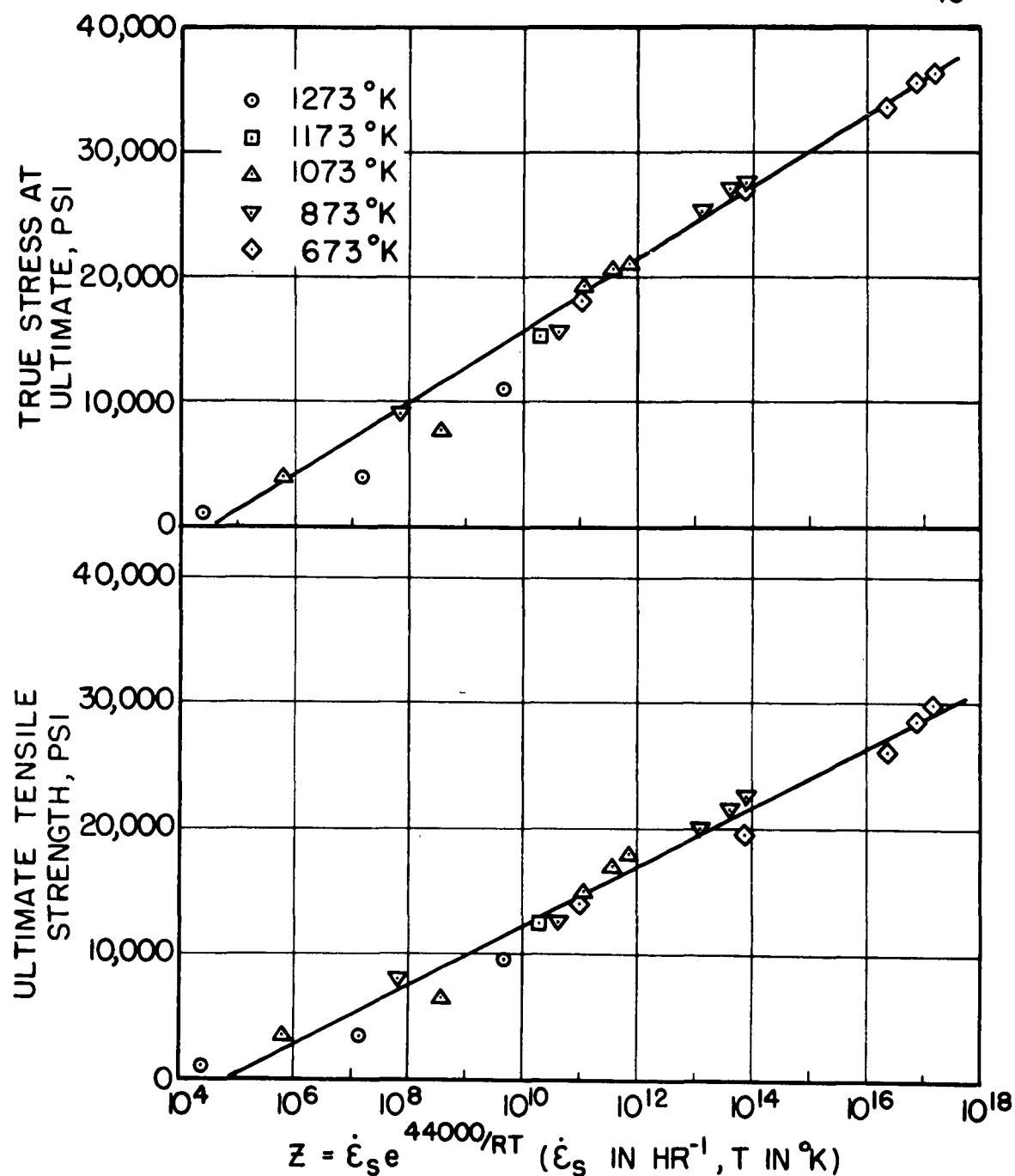


FIG. 8 CORRELATION OF TENSILE DATA FOR COPPER AT VARIOUS STRAIN RATES AND TEMPERATURES BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$ [DATA OF NADAI & MANJOINE⁽¹³⁾]

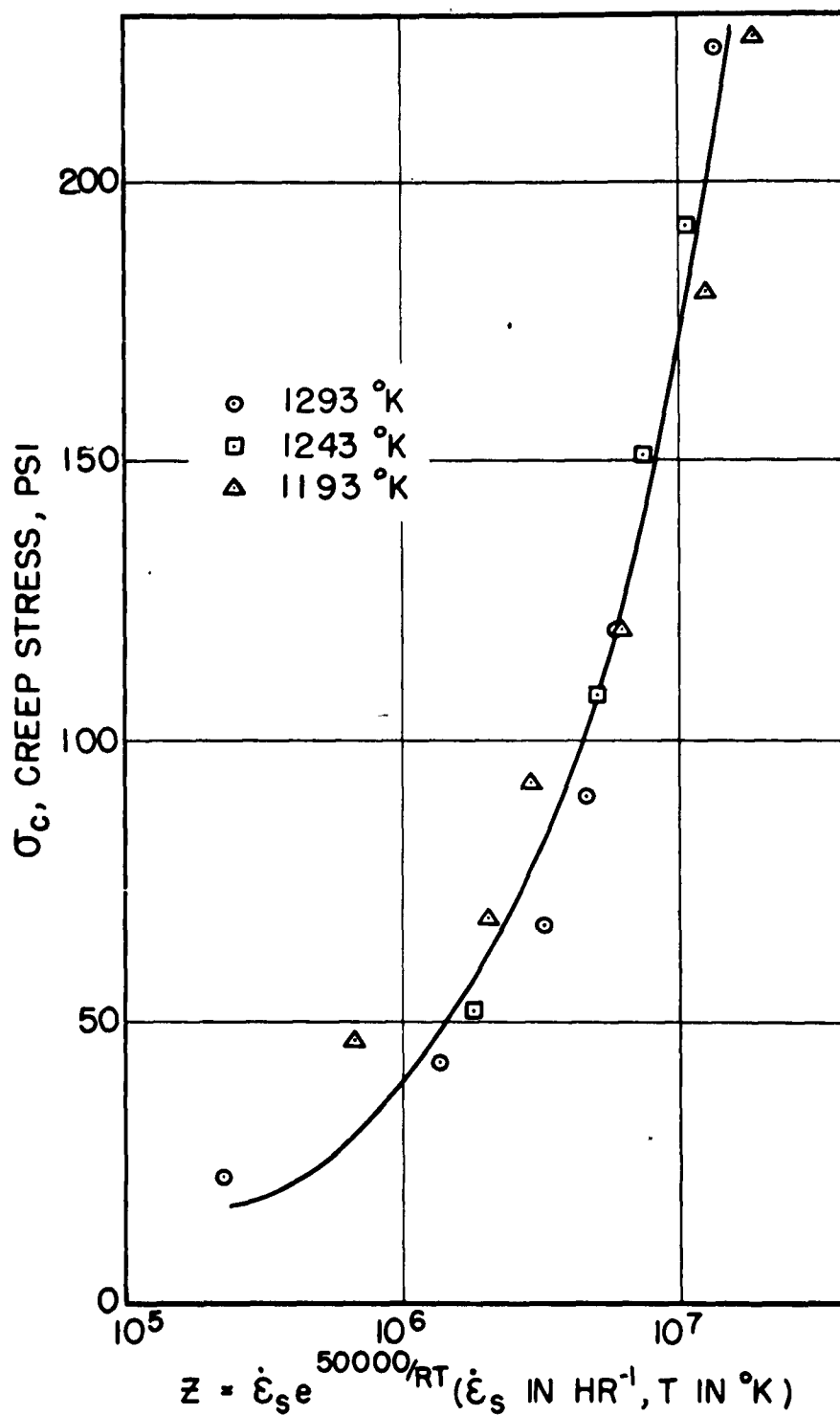


FIG. 9 CORRELATION OF STRESS-INITIAL CREEP RATE DATA FOR GOLD BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$. [DATA OF ALEXANDER, DAWSON & KLING (14)]

therefore in some cases true secondary creep rates were not obtained; in addition, at very low stresses Smith reported anomalous creep behavior wherein the material would creep intermittently. If these latter tests are omitted from consideration, the good correlation shown in the lower curve of Figure 10 is obtained by means of the Z parameter. In this plot the minimum creep rate reported by Smith is used in the $\dot{\epsilon}_s e^{\Delta H/RT}$ parameter wherein an activation energy of 19,000 calories per gram atom was obtained.

McKeown (17) also studied the creep of high purity lead. The chemical composition was 0.00002% Cd, 0.0005% Bi, < 0.002% Sb, and < 0.0005% Cu and Ag, remainder lead. He covered rather large creep extensions, under constant load stressing, and was able to obtain good secondary creep rates for most of the tests with the exception of three very low stress conditions. His results are plotted in terms of the Z parameter on the same graph as Smith's data on 99.9998 percent lead shown in Figure 10. It will be observed that the same activation energy of 19,000 calories per gram atom was obtained for McKeown's lead.

Smith's and McKeown's data were also analyzed in terms of Equation 2a. Figure 11 shows the nominal validity of this method of correlation, wherein all the data obtained by these two investigators are used, even in cases where the secondary creep rate was not reached.

The only other usable data on the creep of pure lead at various temperatures are those presented by Smith and Howe (18) and Andrade (19). These investigators studied commercially pure lead. Smith and Howe creep tested 99.92 percent lead at 303° and 373°K under constant load conditions, whereas Andrade tested lead of unreported composition at 290° and 433°K under constant stress conditions. The data are too limited to make an exact determination of ΔH . The most reasonable value (primarily based on Smith and Howe's data) was 23,000 calories per gram

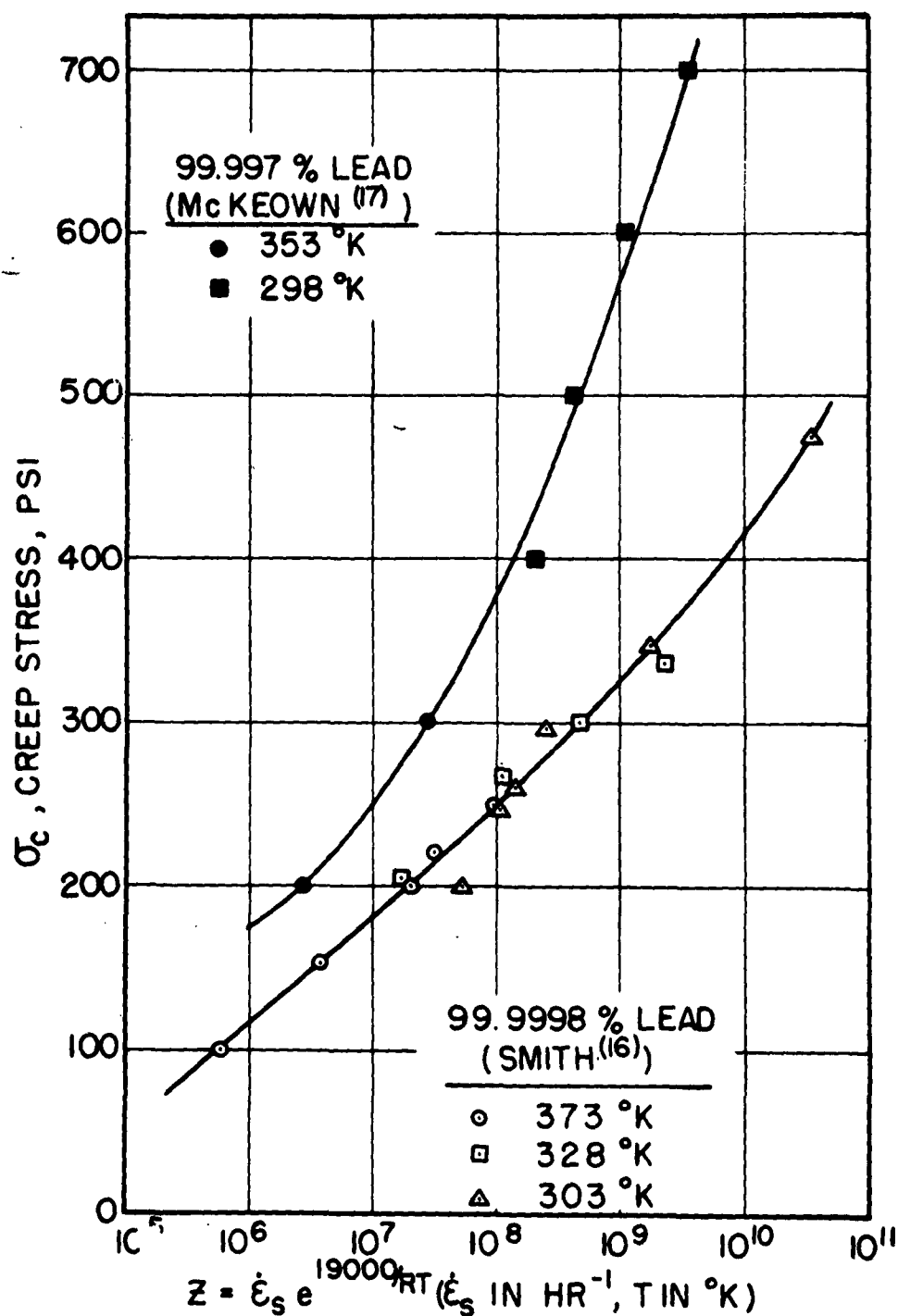


FIG. 10 CORRELATION OF STRESS - MINIMUM CREEP RATE DATA FOR HIGH PURITY LEAD BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$ [DATA OF SMITH (16) & Mc KEOWN (17)]

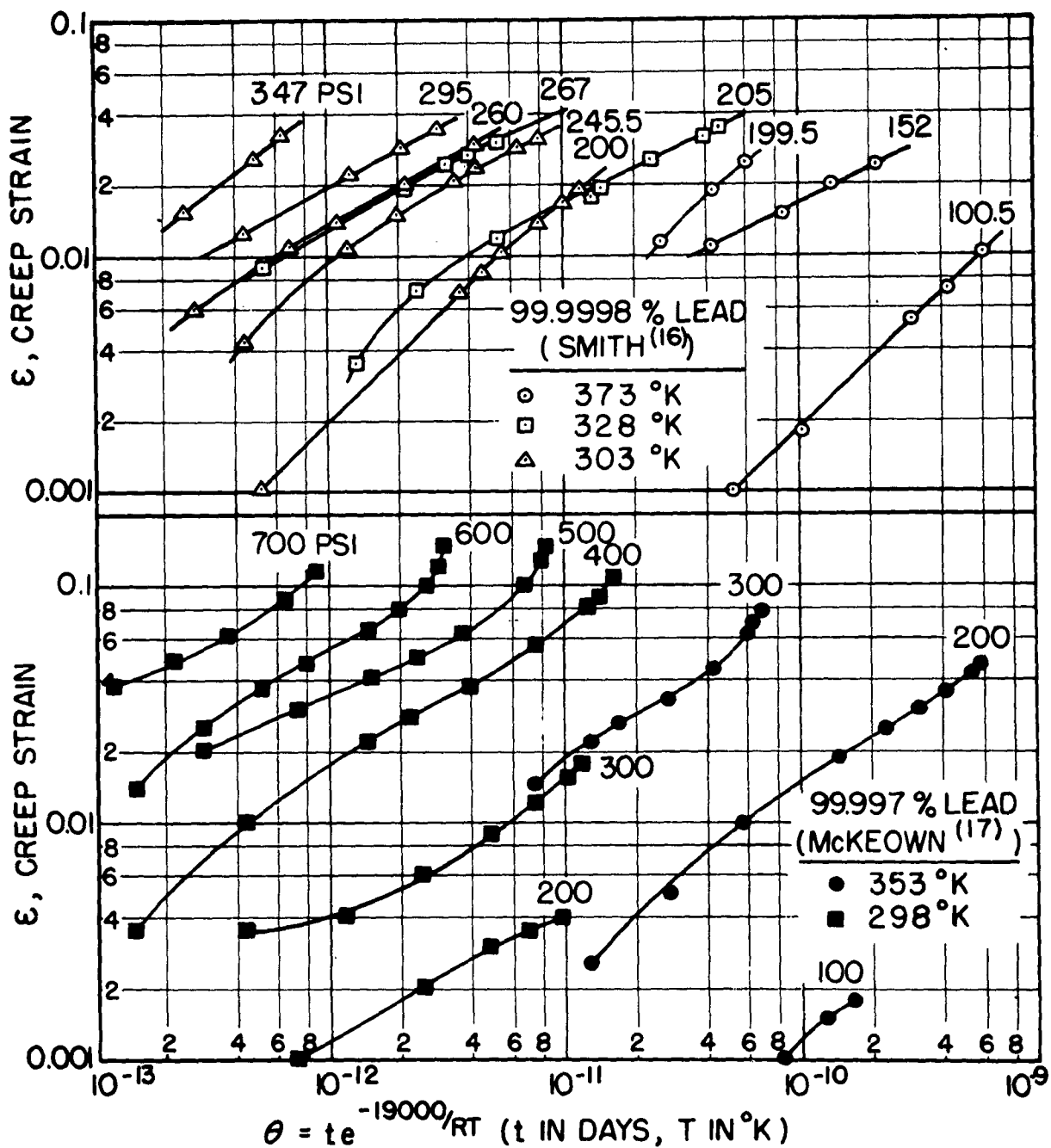


FIG. II CORRELATION OF CREEP STRAIN - TIME DATA FOR HIGH PURITY LEAD BY THE RELATION $\epsilon = f(\theta, \sigma_c)$ AT VARIOUS STRESSES. [DATA OF SMITH⁽¹⁶⁾ AND McKEOWN⁽¹⁷⁾]

atom. The data are analyzed on the basis of the Z parameter as shown in Figure 12 where $\dot{\epsilon}_s$ refers to the minimum creep rate observed during testing.

B. Body Centered Cubic Metals

1. Iron

Tapsell and Clenshaw (20) investigated the creep properties of Armco iron from 500° to 773°K, determining the secondary creep rates over wide ranges of stresses. Their iron contained 0.02% C, 0.034% S, 0.017% P and traces of Si and Ni. The results, in terms of the Z parameter, are shown in Figure 13; the correlation is seen to be excellent yielding an activation energy of 78,000 calories per gram atom.

C. Hexagonal Close Packed Metals

1. Zinc

The investigation of the creep of zinc under constant load conditions by Pomp and Lange (21) includes data at three temperatures above 0.45 T_m : 313°, 328° and 343°K. The zinc studied had a purity of about 99.0%, containing 0.93% Pb, 0.016% Fe, 0.004% Cu and 0.06% Cd. The complete creep curves correlate very nicely by means of the relation $\dot{\epsilon} = f(\theta, \sigma_c)$, as is shown in Figure 14, yielding an activation energy of 26,000 calories per gram atom. The minimum creep rates obtainable from these data were also analyzed by means of the relation $\sigma_c = f(\dot{\epsilon}_s e^{\frac{\Delta H}{RT}})$ using the value of ΔH obtained above. The resulting correlation is shown in the upper curve of Figure 15.

Graeser, Hanemann and Hofmann (22) studied the creep of pre-annealed zinc under constant load conditions at two temperatures above 0.45 T_m , 323° and 348°K. The zinc had a purity of 99.99% and was annealed at 473°K prior to testing. Their data, presented in the form of minimum creep rates observed under various stresses at each temperature, have been correlated in terms of the Z parameter as is shown in the lower curve of Figure 15. The correlation of these data, using the

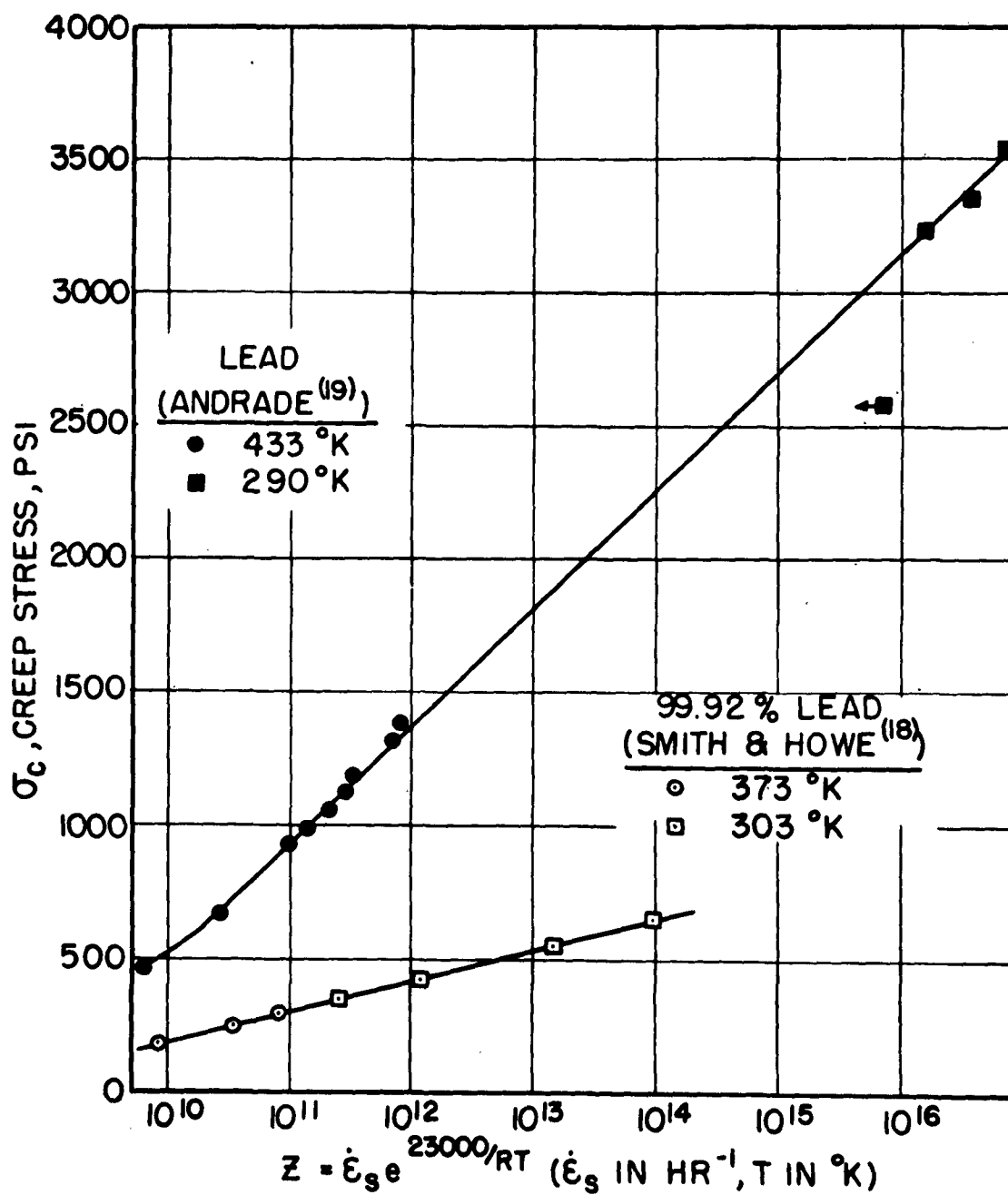


FIG. 12 CORRELATION OF STRESS-MINIMUM CREEP RATE DATA FOR COMMERCIAL PURE LEAD BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\Delta H/RT})$ [DATA OF SMITH & HOWE (18) AND ANDRADE (19)]

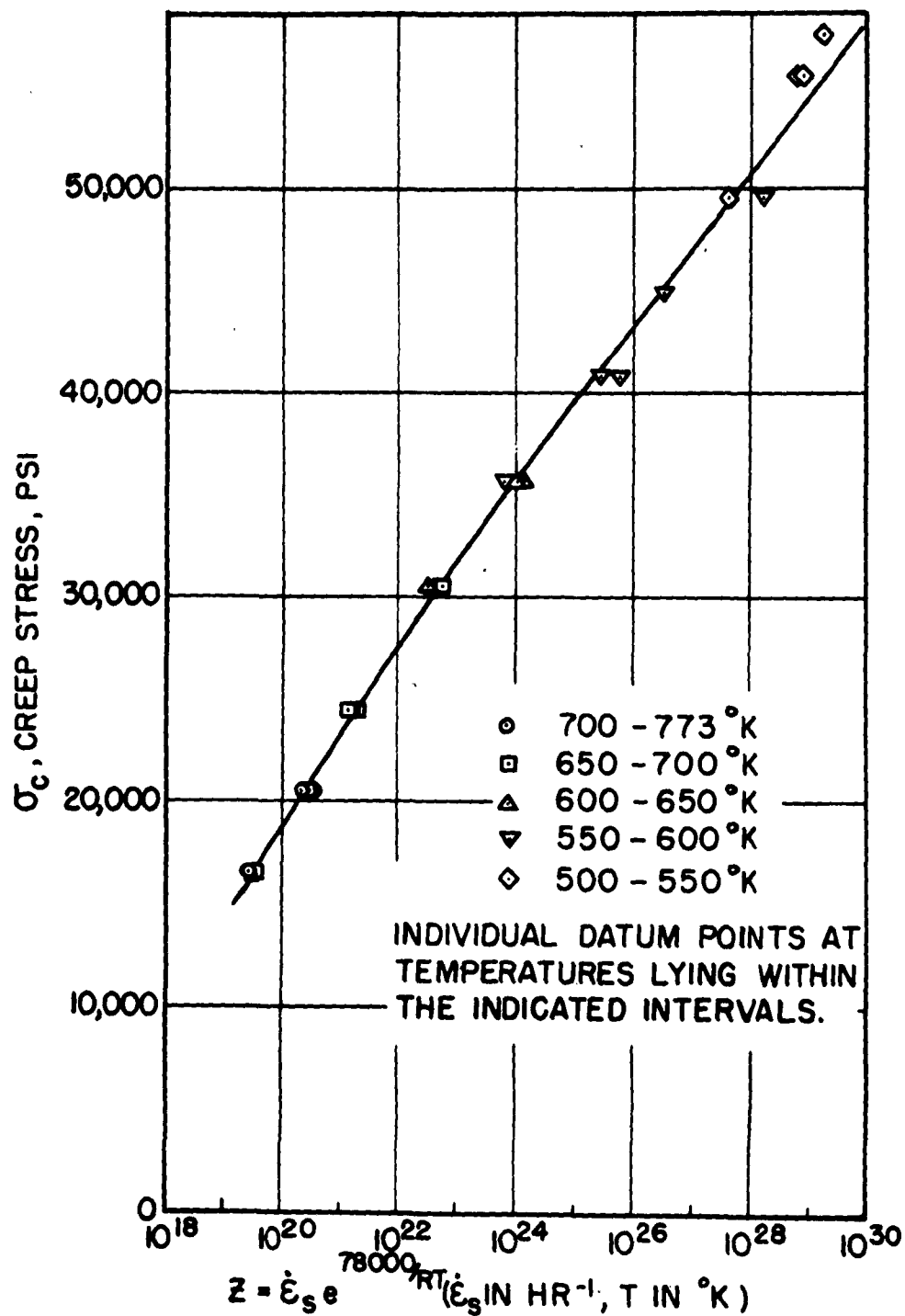


FIG. 13 CORRELATION OF STRESS-SECONDARY CREEP RATE DATA FOR IRON BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_s e^{\frac{\Delta H}{RT}})$ [DATA OF TAPSELL & CLENSHAW(20)]

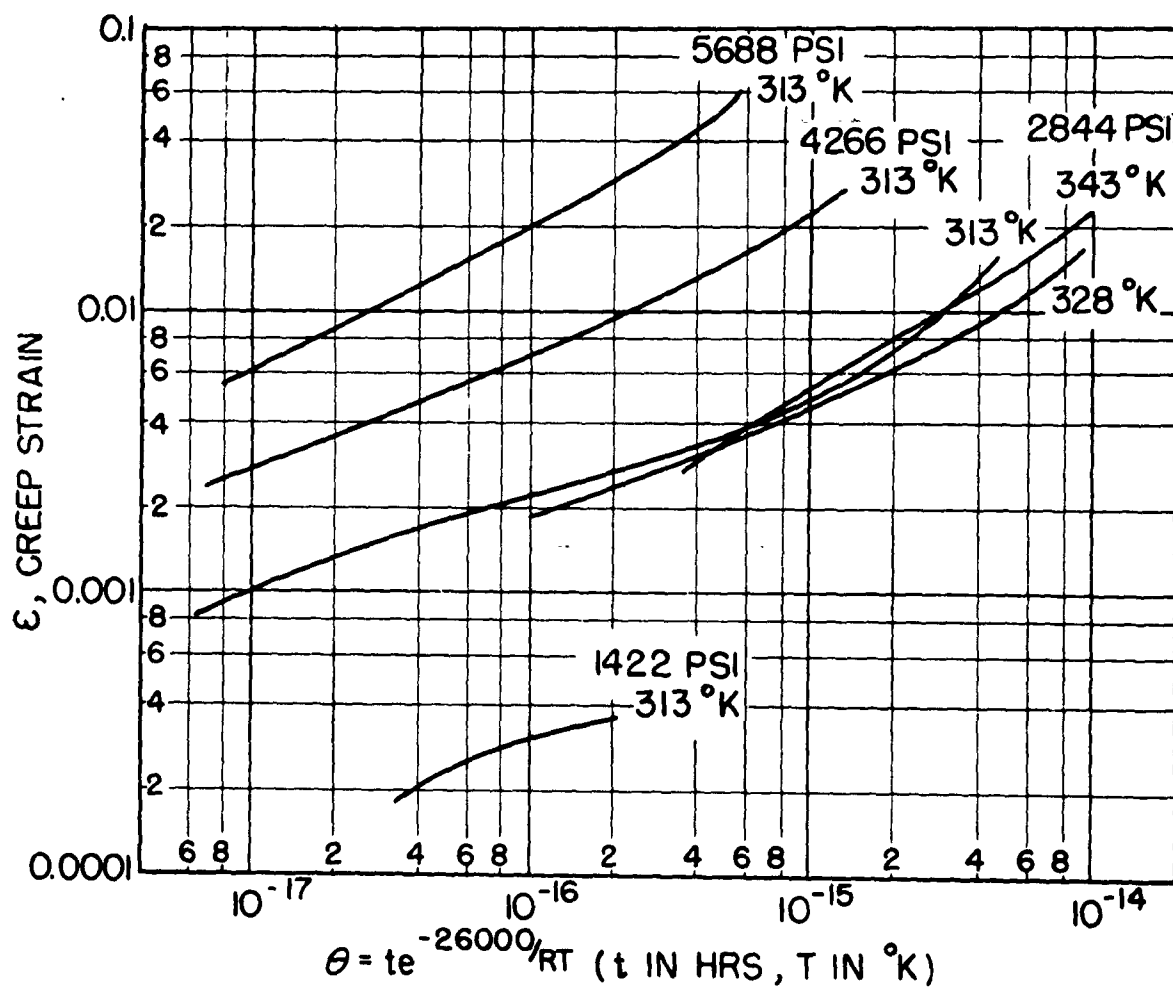


FIG. 14 CORRELATION OF CREEP STRAIN-TIME DATA FOR ZINC BY THE RELATION $\epsilon = f(\theta, \sigma_c)$ AT VARIOUS STRESSES. [DATA OF POMP & LÄNGE⁽²¹⁾]

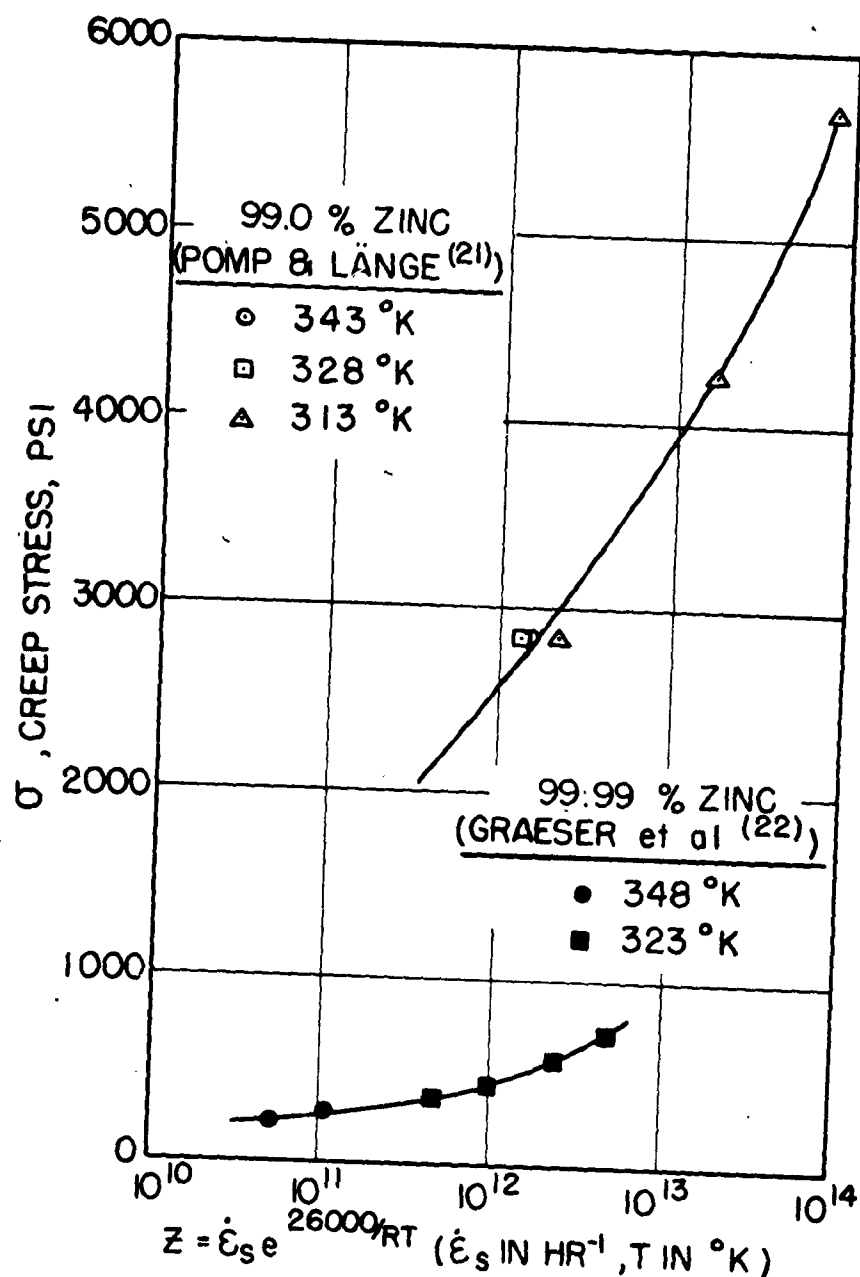


FIG. 15 CORRELATION OF STRESS-MINIMUM CREEP RATE DATA FOR ZINC BY MEANS OF THE RELATION $\sigma_c = f(\dot{\epsilon}_{se}^{\Delta H/RT})$.
[DATA OF POMP & LÄNGE (21) AND GRAESER, HANEMANN & HOFMANN (22)]

value for ΔH obtained from the data of Pomp and Lange, is very good, supporting the validity of 26,000 calories per gram atom as the activation energy for zinc.

DISCUSSION OF RESULTS

The previously outlined analyses of all pertinent data currently available in the literature confirm the general validity of Equations 2 and 4 for the creep of simple metal systems at temperatures above 0.45 of the melting temperature. Since this is probably the temperature at which recovery first becomes pronounced, it appears as if Equations 2 and 4 are valid only at temperatures of rapid recovery.

The good agreement obtained for the activation energies from data by different investigators for a given metal confirms that the rate controlling process is rather insensitive to minor differences in metal preparation, purity and structure. Thus, the activation energies determined in the context of this report for relatively pure metals should approach those of the elements.

The confirmation of the general validity of Equations 2 and 4 further emphasizes the previously discussed suggestion that the free energy of activation term for the rate controlling process in high temperature creep cannot be stress dependent; for if this were the case the stress would enter the equations as the stress divided by the absolute temperature which is contrary to the facts. Consequently high temperature creep appears to occur due to removal of barriers to the motion of dislocations by means of some recovery processes. Perhaps once a barrier is removed the dislocations (or other deformation units) migrate under the stress to a new barrier which the stressed dislocations cannot surmount. The extent of this motion would therefore depend on the substructure and also the magnitude of the applied stress. This would suggest that the activation energy for creep obtained herein is the activation energy for removal of barriers to

the motion of dislocations. It might be supposed that the motion of these barriers is controlled by atomic diffusion processes and therefore the activation energy for creep might be closely associated with the activation energy for self-diffusion. A comparison of the activation energies for these two processes is made in Figure 16.* As shown in this figure, the correlation appears exceptionally good. In fact, the almost exact equality between these two activation energies suggests that the rate controlling process for self-diffusion might also be the rate controlling process for creep.

It might be anticipated that the activation energy for creep of the elements should be a periodic function of atomic number. The activation energy data recorded in Figure 17 begin to reveal a periodic variation. (In the cases of elements for which the activation energies for creep have not yet been evaluated, the known activation energies for self-diffusion have been used). Undoubtedly the first members of each series (i.e. the alkali and alkaline earth elements) exhibit low activation energies for creep. Furthermore, the possible effects of crystal structure on the activation energies for creep are neglected in this periodic correlation. Consequently, the data of Figure 17 are yet too incomplete to select those elements that exhibit the highest activation energies and therefore might be most creep resistant for this reason.

The suspected periodic variation of the activation energy for creep with atomic number suggests that the activation energy for creep should correlate with other properties that exhibit periodic variation. Two such correlations are shown in Figures 18 and 19. Evidently the activation energy for creep does not correlate

* Table II, appearing in the appendix to this report, lists the values of the activation energy for self-diffusion for various metals that have been published in the literature. The average or "best" value is listed for each metal using only data that appear reliable, and this value was used for comparison with the activation energy for creep.

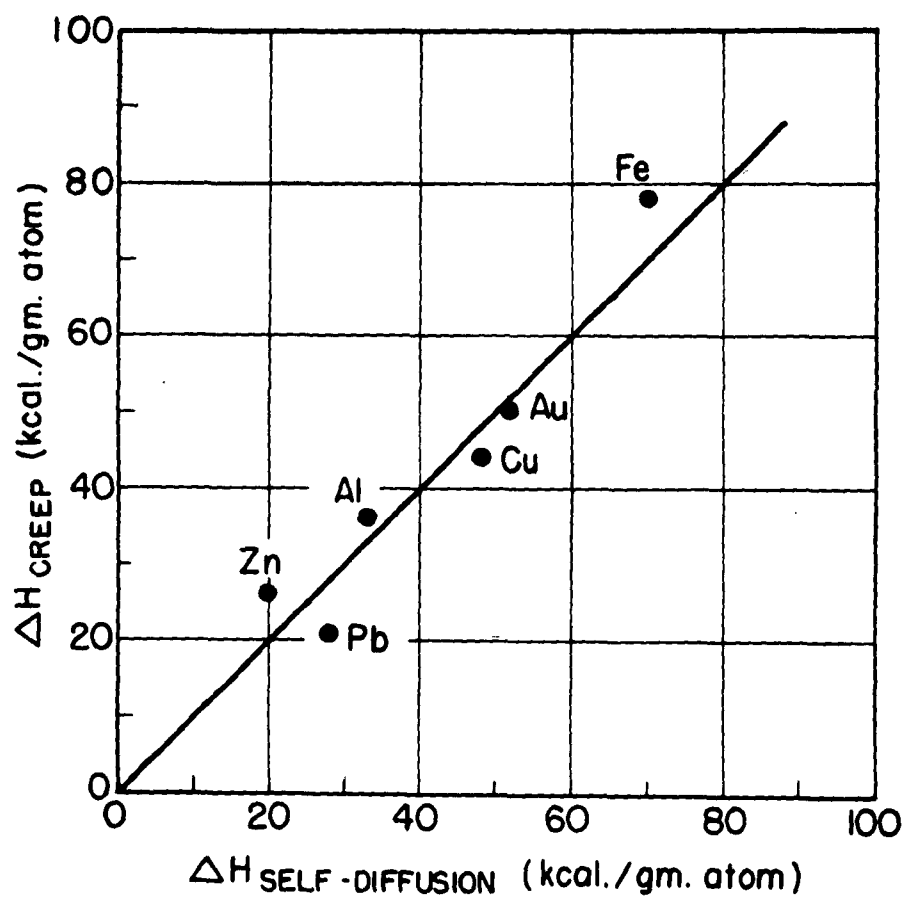


FIG. 16 CORRELATION BETWEEN THE
ACTIVATION ENERGY FOR CREEP AND THE
ACTIVATION ENERGY FOR SELF-DIFFUSION.

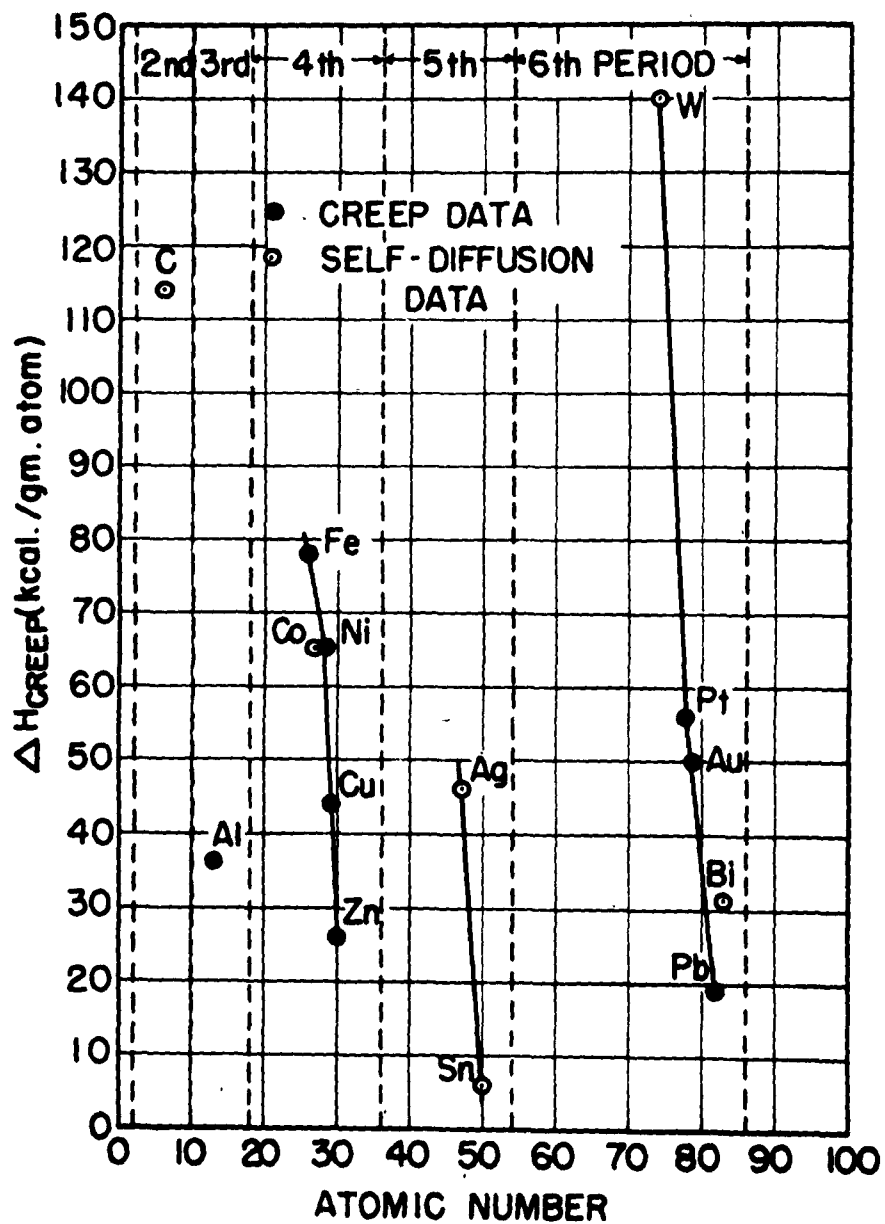


FIG. 17 CORRELATION BETWEEN THE
 ACTIVATION ENERGY FOR CREEP AND
 ATOMIC NUMBER.

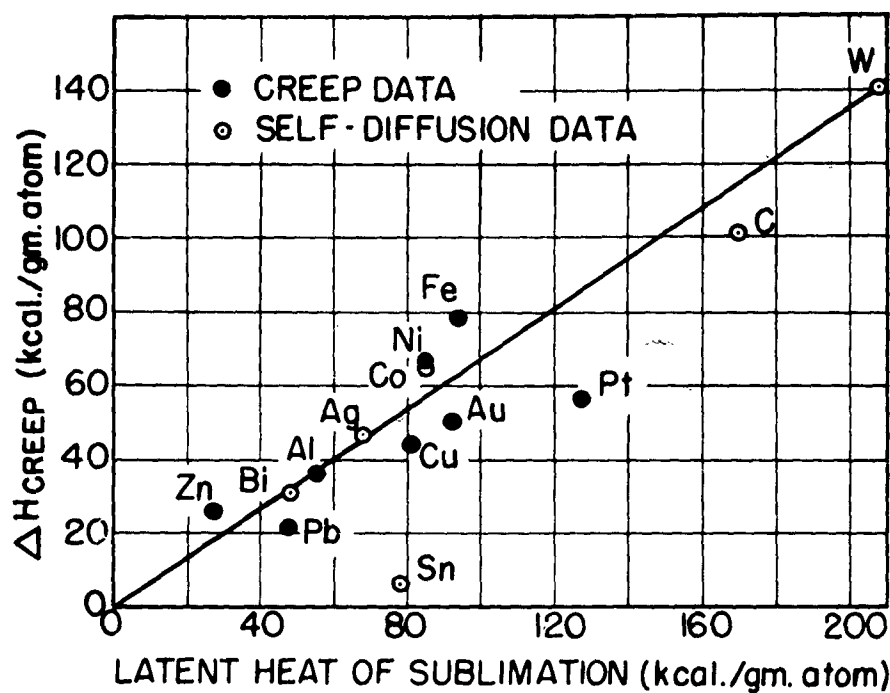


FIG. 18 CORRELATION BETWEEN THE ACTIVATION ENERGY FOR CREEP AND THE HEAT OF SUBLIMATION.

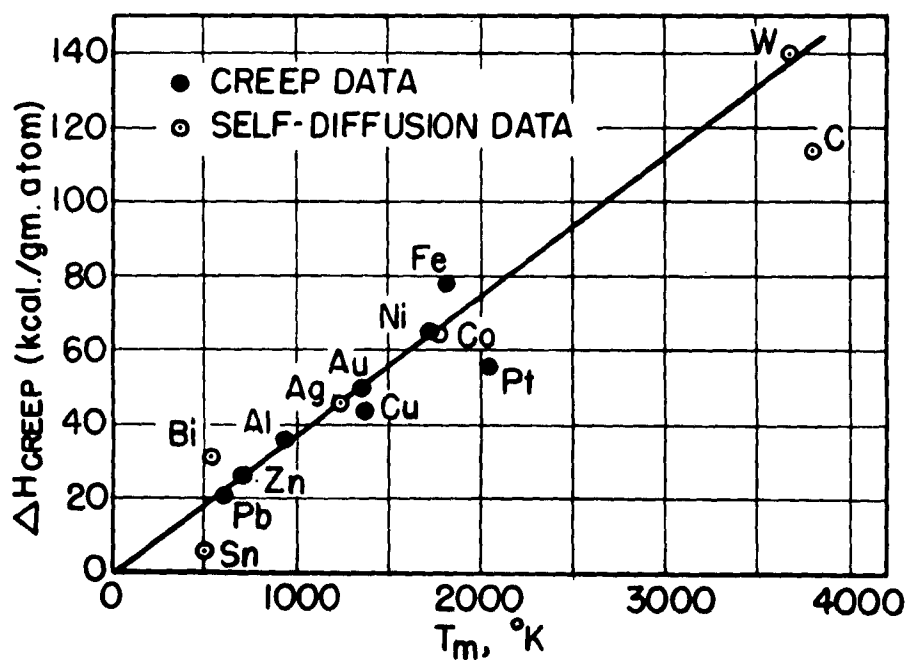


FIG. 19 CORRELATION BETWEEN THE ACTIVATION ENERGY FOR CREEP AND THE MELTING TEMPERATURE.

too well with the latent heat of sublimation, but it does correlate quite well with the melting temperature.

It should be noted that although the activation energy for creep is insensitive to most metallurgical factors, the σ_c versus Z curves obtained from separate investigations on a given metal reveal sensitivity to composition, structure, etc. These effects have been shown to be due to the sensitivity of B of Equation 5 to composition ⁽⁷⁾ and the probable sensitivity of B and S of Equation 5 to structure ⁽⁸⁾. High values of activation energy, ΔH , and low values of B and S favor creep resistance.

CONCLUSIONS

1. Creep and tensile data of pure metals at temperatures above 0.45 of their melting points can be correlated by means of simple equations:

$$\epsilon = f(\theta, \sigma_c)$$

and

$$\sigma_c = f(Z) = f(\dot{\epsilon}_s e^{\Delta H/RT})$$

where ϵ = creep strain

$$\theta = t e^{-\Delta H/RT}$$

where t is the time, T is the absolute temperature, R is the gas constant and ΔH is the experimental energy of activation for creep in calories per gram atom.

σ_c = creep stress (or ultimate tensile strength).

$\dot{\epsilon}_s$ = secondary creep rate (or strain rate of tensile test).

2. Below 0.45 T_m the correlation parameters could not be applied to the creep and tensile properties of metals. These results indicate that the mechanism for plastic flow of metals at temperatures where recovery is rapid might differ fundamentally from low temperature deformation mechanisms.

3. Since the equations given in Conclusion 1 above do not contain the stress

divided by the absolute temperature, the stress does not enter the free energy of activation for the rate controlling process for creep.

4. ΔH was found to be a constant for a given metal at temperatures above $0.45 T_m$. It was shown that the energy of activation for creep is approximately equal to the best known value for the activation energy of self-diffusion. These results suggest that the rate controlling process for high temperature creep might be similar to the rate controlling process for self-diffusion.

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APPENDIX

TABLE II

Data on Activation Energies for Self-Diffusion of Metals			
Metal	$\Delta H_{\text{self-diffusion}}$, cal./gm. atom		Remarks
	Reported Values (Source Indicated)	Best or Average Value	
Copper	45,100 (a)	48,000	Polycrystalline
	49,000 (a)		Single crystal
	46,800 (b)		Based on diffusion of other metals in copper extrapolated to zero concentration
	44,000 (c)		
	57,200 (d)		Incomplete work, based on complete data at two temperatures only. Based on reinterpretation of published data.
	61,400 (e)		
	47,000 (f)		
Gold	51,000 (g) 62,900 (h) 53,000 (i)	52,000	Extensive data, 721°-966°C Data at three temperatures only
Aluminum	33,000 (f)	33,000	Estimated from diffusion data of other metals in aluminum
Lead	27,900 (j) 27,000 (f)	28,000	Single crystal Based on reinterpretation of published data
α -Iron	77,200 (k) 73,200 (l) 59,700 (m)	70,000	Extensive data, 720° - 900°C 800° - 900°C
γ -Iron	48,000 (k) 74,200 (l) 67,900 (m)	71,000	Superseded by later work (1)
Tin	10,500 c (n) 5,900 a (n)		ΔH a used in correlations with creep data.
Zinc	20,400 c (o) 31,000 c (o)		ΔH c used in correlations with creep data.
Cobalt	67,000 (p) 61,900 (q)	65,000	

TABLE II (con't)

Data on Activation Energies for Self-Diffusion of Metals			
Metal	ΔH self-diffusion, cal./gm. atom		Remarks
	Reported Values (Source Indicated)	Best or Average Value	
Silver	45,950 (r) 45,950 (s) 46,000 (f)	46,000	Large grained polycrystals Single crystal Based on reinterpretation of published data.
Bismuth	31,000 $\parallel$ c (t) 140,000 $\perp$ c (t)		$\Delta H \parallel$ c used in correlations with creep data.
Tungsten	140,000 (u)	140,000	Not self-diffusion, but diffusion of Fe extrapolated to zero concentration.
Carbon	114,000 (v)	114,000	

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