

# ACTIVATION ENERGIES FOR CREEP OF HIGH-PURITY ALUMINUM\*

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Activation energies for creep of high-purity aluminum were obtained over the temperature range from 77°K to 880°K by rapidly changing the temperature during creep at constant stress. The experimentally obtained activation energy was shown to be insensitive to stress and strain, and this fact questions the validity of those theories for creep that postulate stress and strain dependent activation energies. From 500°K to 880°K the activation energy for creep was found to be independent of temperature and equal to 35,500 calories per mole which is the same as that for self-diffusion of aluminum. Between 0.25 and 0.40  $T_m$  (250 to 375°K) the activation energy for creep was found to be equal to about 27,500 calories per mole. Below 0.25  $T_m$  the activation energy for creep was found to decrease rapidly with decreasing temperature; it was shown that the presence of at least four discrete activation energies could account for these low temperature results.

## ENERGIES D'ACTIVATION POUR LE FLUAGE DE L'ALUMINIUM DE HAUTE PURETÉ

Les énergies d'activation pour le fluage de l'aluminium de haute pureté ont été obtenues pour la gamme de température de 77 à 880°K par variation rapide de la température au cours du fluage à tension constante. L'énergie d'activation déterminée expérimentalement s'est révélée insensible à la tension et à la déformation et ce fait met en cause la validité des théories du fluage qui postulent une dépendance entre tension et déformation et les énergies d'activation. De 500°K à 880°K, l'énergie d'activation pour le fluage a été trouvée indépendante de la température et égale à 35,500 calories/môle, ce qui correspond à l'énergie d'autodiffusion de l'aluminium. Entre 0,25 et 0,40  $T_m$  (250 à 375°K), l'énergie d'activation pour le fluage vaut environ 27,500 calories/môle. En-dessous de 0,25  $T_m$ , cette énergie décroît rapidement avec la température. On a montré que l'existence d'au moins 4 énergies d'activation discrètes permettraient d'interpréter les résultats à ces basses températures.

## AKTIVIERUNGSENERGIEN BEIM KRIECHEN VON REINSTALUMINIUM

Im Temperaturbereich von 77°K bis 880°K wurden die Aktivierungsenergien des Kriechens von Reinstaluminium durch rasche Veränderung der Versuchstemperatur während des Kriechens unter konstanter Last ermittelt. Dabei wurde nachgewiesen, dass die experimentell bestimmte Aktivierungsenergie unempfindlich gegen die Grösse von Spannung und Dehnung ist. Dieser Befund stellt die Gültigkeit von Kriechtheorien, die spannungs- und dehnungsabhängige Aktivierungsenergien postulieren, in Frage. Zwischen 500°K und 880°K ist nach den vorliegenden Ergebnissen die Aktivierungsenergie des Kriechens unabhängig von der Temperatur; sie ist dieselbe wie die Aktivierungsenergie der Selbstdiffusion von Aluminium und beträgt 35500 cal/Mol. Zwischen 0,25 und 0,40  $T_m$  (250 bis 375°K) wurde für das Kriechen eine Aktivierungsenergie von etwa 27500 cal/Mol gefunden. Unter 0,25  $T_m$  nimmt die Aktivierungsenergie des Kriechens mit sinkender Temperatur rasch ab. Wie gezeigt wird, kann dieses Tieftemperatur-Verhalten durch das Vorhandensein von mindestens vier diskreten Aktivierungsenergien erklärt werden.

## INTRODUCTION

The creep behaviour of pure metals at temperatures above one-half of their melting temperatures can be correlated by the functional relationship<sup>(1-4)</sup>

$$\epsilon = f(\theta), \quad \sigma = \text{const.} \quad (1)$$

where  $\epsilon$  = total plastic strain during creep,

$f$  = a function that depends on the stress,

$\sigma$  = the stress,

$\theta = te^{-\Delta H/RT}$  = a temperature-compensated time.

$t$  = time under test,

$e$  = the base for natural logarithms,

$\Delta H$  = the activation energy for creep,

$R$  = the gas constant, and

$T$  = the absolute temperature.

Since the activation energies for high temperature

creep of pure metals coincide with their activation energies for self-diffusion,<sup>(3)</sup> high temperature creep is believed to be controlled by some type of dislocation climb process.<sup>(5)</sup>

The correlations prescribed by equation (1), however, are invalid for creep at temperatures below about one-half of the melting temperature.<sup>(1)</sup> Undoubtedly, one or more alternate mechanisms for creep predominate at lower temperatures. Several investigations have been made in attempts to identify the mechanism of creep at low temperatures.<sup>(6-8)</sup> But most of these investigations were especially directed toward verifying the exhaustion theory for creep and they therefore emphasized the dependence of creep strain on the time under test. Many possible mechanisms for creep might have about the same dependence of creep strain on time as that predicted by the exhaustion theory; consequently, agreement between the observed time laws for creep and predictions

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based on the exhaustion model are not definitive *per se* for establishing the validity of the exhaustion hypothesis.

Creep is possible only because of thermal activation of deformation processes. In the absence of thermal fluctuations, creep could not occur. Consequently, a deeper and more intimate insight into the mechanisms of creep might be obtained from a more complete picture of the activation energies for creep. Each mechanism contributing to creep should eventually be identified with a corresponding characteristic activation energy. It is the purpose of this investigation to determine the activation energies for creep of high-purity aluminum from 77°F to 880°K, in anticipation that this knowledge will provide the basis for a better understanding of the creep process.

The creep rate continually changes during the course of creep at a given stress and temperature. Since the external variables of stress and temperature are maintained constant throughout the test, such changes in creep rate must be attributable to the internal changes in substructure that attend the creep process. Consequently, the standard types of creep tests are not suited for uncovering the fundamental laws of creep, because the structural changes might be unique for each temperature and stress. At elevated temperatures, however, where equation (1) is valid, the same substructures are obtained at identical values of  $\epsilon$  for constant stress creep tests conducted over a range of high temperatures.<sup>(2)</sup> Equation (1) can therefore be used to determine the activation energy for high temperature creep. But in the lower ranges of temperature of major interest in this investigation, equation (1) is no longer valid. Therefore the superior and unambiguous technique of obtaining activation energies by the effect of abrupt changes in temperature on the instantaneous creep rates just before and immediately following the temperature change was adopted for this study.<sup>(9, 10)</sup> The range of temperatures investigated extended from 77°K to 880°K, and therefore included both the high and low temperature ranges for creep.

#### MATERIALS AND TECHNIQUES

High-purity (99.996%) aluminum was selected for this investigation in view of the extensive data already available on its creep behavior at elevated temperatures.<sup>(1, 10)</sup> Creep tests were performed on tensile specimens 0.250 in. wide and 0.100 in. thick machined from rolled sheet. All specimens were annealed for 10 min at 700°K in order to remove the effects of machining and to provide uniform equiaxed grains having a mean grain diameter of 0.33 mm.

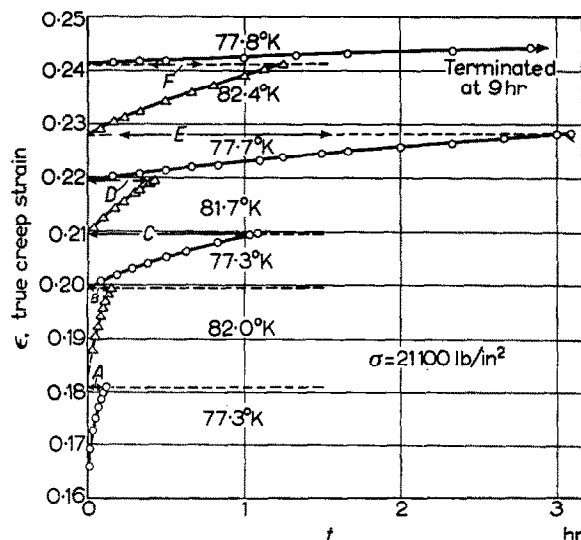


FIG. 1. Creep curve for pure aluminum at constant stress under cyclic temperature conditions.

Creep tests were performed in machines equipped with Andrade-Chalmers type lever arms<sup>(11)</sup> that were contoured so as to maintain the stress constant to within better than  $\pm 1\%$ . Strains were measured by special dial-gage extensometers having a least count of 0.0001 in strain.

Activation energies were calculated from the instantaneous creep rates just preceding and immediately following abrupt small changes in temperature. From 77°K to 500°K, various types of constant-temperature baths were used to maintain steady temperatures. The specimen temperature was determined by means of thermocouples attached directly

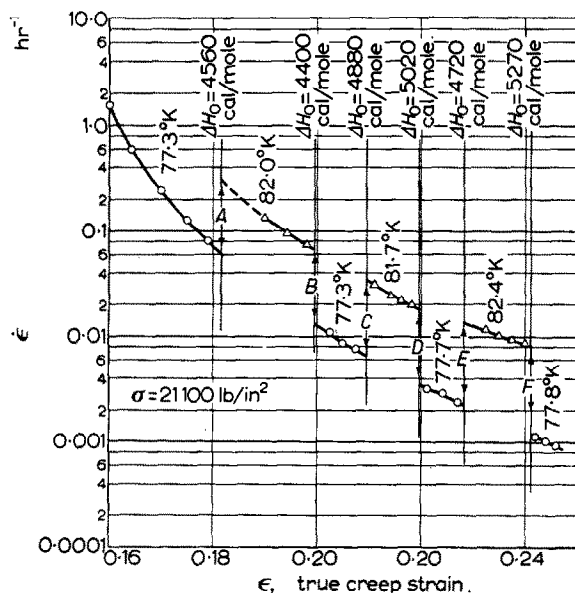


FIG. 2. Creep rate-true creep strain curves for use in evaluation of the activation energy for creep of pure aluminum under cyclic temperature conditions. (Deduced from Fig. 1.)

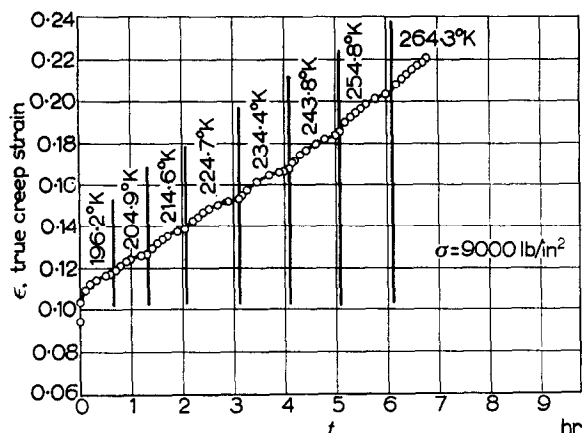


FIG. 3. Creep curve for pure aluminum at constant stress under increasing temperature conditions.

to the gage section. In this range, rapid changes in temperature were obtained by quickly removing one bath from the specimen and immediately substituting a second bath at the new controlled temperature. With this technique, the specimen acquired the new temperature in slightly less than 2 min. The instantaneous creep rate immediately following a temperature change was obtained by extrapolating through the 2 min transient temperature interval. Above 500°K the specimens were tested in air in a low heat capacity resistance-type furnace. Temperature changes were obtained by resetting the temperature controller. Although about 10 min. was required before the specimen reached the new temperature by

this technique, no difficulty was experienced in extrapolating over the transient temperature interval, inasmuch as the creep rate did not change rapidly with time for the stress levels that were investigated.

## RESULTS

A typical example of a cyclic-temperature creep curve is given in Fig. 1. Creep was started at 77.3°K. At *A* the temperature was changed rapidly to 82.0°K. In order to represent the entire curve on a single graph, the creep curve from *A* to *B* at 82.0°K is shown on a folded time scale, the time being taken as zero the instant the temperature was changed at *A*. At *B* the temperature was reduced to 77.3°K, etc.

Creep rates were obtained from Fig. 1 by graphical differentiation and were plotted as shown in the example of Fig. 2. Over the complete range of conditions that were covered in this investigation no spurious transients could be detected following small abrupt changes in temperature. Consequently, the instantaneous creep rates just preceding and immediately following a change in temperature were easily obtained by appropriate extrapolations of the  $\dot{\epsilon}$  versus  $\epsilon$  curves as illustrated in Fig. 2.

In order to provide detailed coverage over wide ranges of temperatures, a number of tests were made under progressively increasing temperatures, as shown by the typical example of Fig. 3. The creep rates, obtained by graphical differentiation of the creep strain-time curves, were again plotted, as

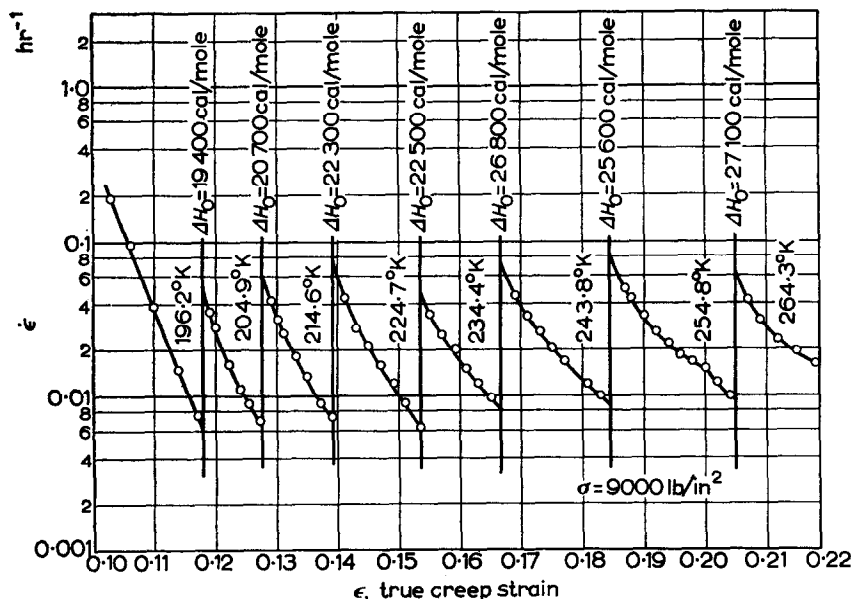


FIG. 4. Creep rate-true creep strain curves for use in evaluation of the activation energy for creep of pure aluminum under increasing temperature conditions. (Deduced from Fig. 3.)

shown in the typical example of Fig. 4, as a function of the strain. It is significant that results from both techniques gave identical activation energies for the same temperature, in spite of differences in stress and strain and temperature histories.

The technique of determining activation energies from the effects of abrupt changes in temperature on the instantaneous creep rates has a number of advantages. First, the activation energy is determined with one specimen, thereby reducing materially the sampling scatter so generally prevalent in most types of creep tests. Secondly, the activation energy can be determined for a wide range of strains on a single sample. Thirdly, the effect of stress on the activation energy is easily evaluated by running a series of tests over a range of several stresses. Furthermore, the absence of transients following small abrupt changes in temperature suggests that the structure is the same just preceding and immediately following the change in temperature. Consequently, the change in creep rate attending a change in temperature is exclusively attributable to the change in temperature alone.

If creep were due to a single thermally activated process, the temperature dependence of the creep rate for a given structure and stress could be represented by the relationship

$$\dot{\epsilon} = Ae^{-\Delta F/RT} \quad (2)$$

where  $A$  is a constant and  $\Delta F$  is the free energy of activation. Both  $A$  and  $\Delta F$  might depend on the instantaneous values of the structure and the stress. Consequently, the creep rates,  $\dot{\epsilon}_1$  and  $\dot{\epsilon}_2$ , just preceding and immediately following an abrupt change in temperature from  $T_1$  to  $T_2$  would be related by

$$\frac{\dot{\epsilon}_1 e^{\frac{\Delta F(T_1)}{RT_1}}}{\dot{\epsilon}_2 e^{\frac{\Delta F(T_2)}{RT_2}}} = 1 \quad (3)$$

Since  $T_2$  was selected to be only slightly different from  $T_1$ , equation 3 can be rewritten as

$$R \ln \frac{\dot{\epsilon}_1}{\dot{\epsilon}_2} = \frac{\Delta F(T_2)}{T_2} - \frac{\Delta F(T_1)}{T_1} = \frac{d\left(\frac{\Delta F}{T}\right)}{d\left(\frac{1}{T}\right)} \Delta\left(\frac{1}{T}\right) \\ = \Delta H \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \quad (4)$$

from which the activation energy for creep,  $\Delta H$ , can be calculated from the known temperatures  $T_1$  and  $T_2$  and the measured creep rates  $\dot{\epsilon}_1$  and  $\dot{\epsilon}_2$ . All of the reported activation energies were obtained by means of equation (4). If creep is due to a series of processes, however, the activation energies given by the application of equation (4) are not necessarily real or attributable to one unique process. Consequently, it is desirable to refer to such activation energies as apparent activation energies,  $\Delta H_0$ , unless it can be established that they are uniquely associated with a single process. Typical examples of the apparent activation energies are recorded in Figs. 2 and 4 immediately above the data points that were employed in their evaluation.

The variation of the apparent activation energy with the mean test temperature is summarized in Fig. 5. The mean test temperature was calculated from the obvious relationship

$$\frac{1}{T_m} = \frac{1}{2} \left( \frac{1}{T_1} + \frac{1}{T_2} \right) \quad (5)$$

The numbers adjacent to each point of Fig. 5 give the number of independent experimental determinations of the apparent activation energy that were averaged for that point.

In Fig. 6 are shown a series of typical examples of the effect of strain and stress on the apparent

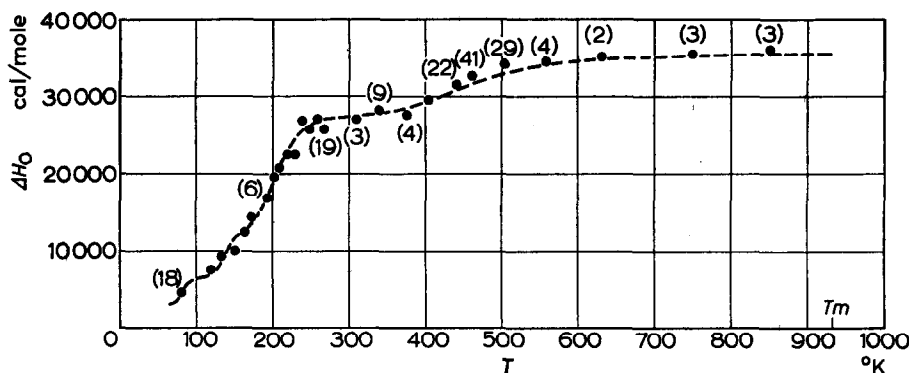


FIG. 5. Activation energies for creep of pure aluminum as a function of the absolute temperature. — — — Calculated curve using six discrete activation energies.  
● Experimental data. (Numbers in parentheses refer to number of determinations made; only one determination made on all other points.)

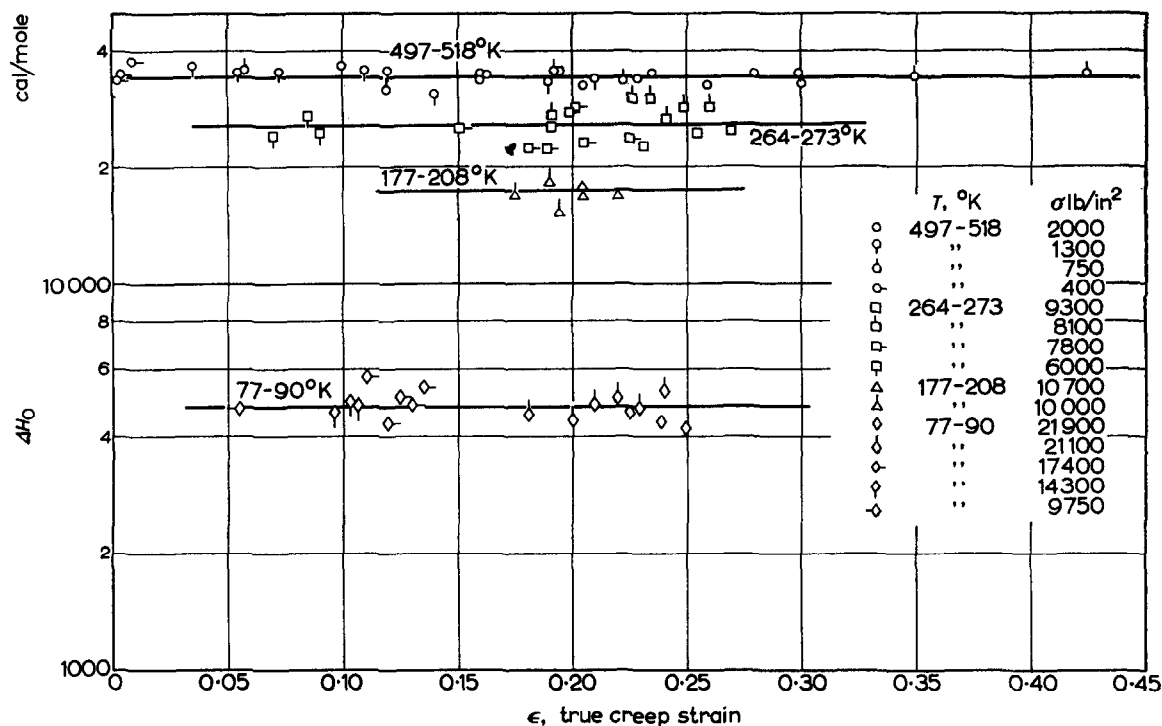


FIG. 6. Activation energies for creep of pure aluminum at various temperatures as a function of the true creep strain.

activation energy for creep at several especially selected temperatures.

#### DISCUSSION

The data presented in Fig. 6 reveal that the apparent activation energy obtained at any one of a series of temperatures is insensitive to either stress or strain. Over the high temperature range, where creep is believed to be controlled by a dislocation climb process, the present observation on the insensitivity of the activation energy to either stress or strain coincides precisely with that previously obtained by the application of equation (1).<sup>(1, 3)</sup> And the fact that the same activation energies are obtained by the progressive increase in temperature technique as those obtained by the cyclic-temperature technique, justifies the conclusion that over the entire range of conditions that were investigated, the activation energies for creep are insensitive to the variables of stress, strain and the preceding strain-temperature history. In fact, the apparent activation energy for creep of aluminum appears to depend exclusively on the instantaneous test temperature.

When the rapid change in temperature technique that was adopted here is used for evaluating the activation energy for creep of polymethyl methacrylate,<sup>(12)</sup> the apparent activation energy decreases in the expected linear manner with increasing stress. Consequently, the observed insensitivity of the

apparent activation energy for the creep of aluminum must be real and cannot be attributed to insensitivity of the technique that was employed.

A brief review of various proposed theories for creep, as given below, will reveal that most of the previously considered mechanisms for creep demand that the activation energy be dependent on the stress or the strain:

1. *Becker theory.* Metals can be deformed at the absolute zero of temperature in the complete absence of thermal fluctuations. Becker<sup>(13)</sup> assumed that slip was nucleated when the elastic shear strain energy in a localized volume  $V$  exceeded some critical value given by  $\frac{V\sigma_y^2}{2G}$ , where  $G$  is the shear modulus of elasticity and  $\sigma_y$  is the yield strength at the absolute zero. If a stress  $\sigma$  less than  $\sigma_y$  were applied, the mechanical strain energy would be less than that required for slip by  $\frac{V(\sigma_y - \sigma)^2}{2G}$ . This missing shear strain energy can be supplied by thermal fluctuations. Applying the Boltzmann principle, the creep rate should be related to the temperature and stress according to

$$\dot{\epsilon} \sim e^{-\frac{V(\sigma_y - \sigma)^2}{2GkT}} \quad (6)$$

where  $k$  is the Boltzmann constant. Orowan's

improvement of the Becker equation<sup>(7)</sup> by the introduction of a stress concentration factor does not alter the general tenet that increasing the stress reduces the activation energy for creep. Furthermore, the decreasing creep rate over the primary stage of creep was ascribed to an increase in  $\Delta H$  resulting from strain hardening.

The Becker theory for creep must be discarded as inadequate for three significant reasons:

(a) The observed activation energy for creep is insensitive to the stress in contrast to the prediction based on the Becker equation.

(b) The observed activation energy for creep is insensitive to strain in contrast to the implications that  $\Delta H$  increases with strain.

(c) The energy to nucleate a Frank-Read source is so great<sup>(14)</sup> that the creep rate based on nucleation of slip bands would be immeasurably small even at the highest test temperatures.

2. *Kauzmann, Dushman, Seitz theories.*<sup>(15-17)</sup> A series of somewhat equivalent creep theories have been proposed, based on the thermal activation of "flow units" over free energy barriers. In metals, such flow units are usually identified with dislocations moving in their slip planes. In general, such theories prescribe that the dislocations are arrested at barriers which they must then surmount in order to have continued creep. If  $\Delta f$  is the free energy the dislocation must achieve in order to surmount the barrier, the energy that must be supplied by a thermal fluctuation is  $\Delta f - B\sigma$ , since the applied stress also contributes to work done in moving the dislocation to the top of the barrier. Neglecting the possible effect of reversed activation, the creep rate suggested by these theories can be related to the stress and temperature by the expression

$$\dot{\epsilon} \sim e^{-\frac{(\Delta f - B\sigma)}{kT}} = e^{\frac{\Delta s}{k}} e^{-\frac{(\Delta h - B\sigma)}{kT}} \quad (7)$$

where  $\Delta s$  is the entropy and  $\Delta h$  is the energy of activation. Consequently, the apparent activation energy for such mechanisms decreases with increasing stress. It is also possible that  $\Delta h$  might increase with increasing creep straining due to the introduction of higher barriers. In any event, however, the dictates of equation (7) are not in accord with the experimental facts, since neither the stress nor the strain appears to influence the observed apparent activation energies for creep.

The general model expressed by equation (7) can be particularized in terms of various detailed dislocation mechanisms:

(a) In fine slip, dislocation arrays issuing from Frank-Read sources on two closely spaced parallel

slip planes will interact with each other and thereby restrain further slip. In this case the activation energy should be equal to the work required to free the interacting dislocations.

(d) Dislocations on intersecting slip planes will intersect each other, thereby producing jogs. Here the activation energy will be the energy to form a jog.

(c) A jogged screw dislocation must leave a trail of interstitials or vacancies in its wake. Consequently, the activation energy to move a jogged screw dislocation is the energy to produce interstitials or vacancies. If the interstitials and the vacancies do not diffuse away, the jogged screw dislocation might return to its original site. Therefore, the activation energy for moving a jogged screw dislocation might include the energy to move an interstitial or a vacancy.

(d) Dislocations can be locked by solute atoms. In one case, locking can occur by a Cottrell mechanism and in the other case by a Suzuki mechanism.

(e) Dislocations are also arrested at inclusions and dispersed secondary phases. Undoubtedly, other processes could be appended to this listing. Consequently, a number of different processes occur during creep and therefore the apparent activation energy for creep could vary with temperature. But all of the above mechanisms predict activation energies that depend on the stress, suggesting that, although they may be possible mechanisms, some other yet undefined mechanisms actually predominate during creep.

3. *Exhaustion creep.* Various types of exhaustion-creep theories have been formulated.<sup>(18)</sup> In general, they are predicated on the hypothesis that dislocations arrested at the lower barriers escape more rapidly than those arrested at higher barriers. Thus the creep rate decreases with time, due to the rapid exhaustion of the lightly restrained dislocations. According to these theories, as creep continues, the average activation energy for creep increases. This theoretical deduction is obviously contrary to the observations presented here.

4. *Dislocation climb.* At high temperatures, edge dislocations can rise to parallel slip planes by a self-diffusion process. Mott<sup>(5)</sup> has suggested that the activation energy for the climb process depends on the applied stress, whereas others<sup>(19, 20)</sup> claim that the applied shear stress along the slip plane cannot introduce a free-energy gradient in the direction of climb. According to the latter viewpoint, the activation energy for dislocation climb should be that for self-diffusion unmodified by the stress. These two alternate viewpoints have not yet been satisfactorily

rationalized in terms of detailed models of creep by dislocation climb processes.

5. *Diffusion model.* It has been suggested that at very high temperatures creep might occur by stress-directed self-diffusion.<sup>(21)</sup> Such theories suggest that the creep rate increases linearly with the stress, and that the activation energy for creep is that for self-diffusion. Although some experimental data<sup>(22, 23)</sup> have been published in the literature supporting this model, it is not valid in the range of stresses employed in the current investigation, since it has been previously shown that the creep rate does not vary linearly with the stress.<sup>(19, 24)</sup>

6. *Recovery model.* Several authors<sup>(7, 25, 26)</sup> have suggested a recovery model for creep where the activation energy is that for recovery of barriers from the path of the moving dislocations. Cottrell and Aytakin<sup>(26)</sup> have developed an interesting model relating steady-state creep and recovery tests; however, their mathematical analyses include a stress-dependent activation energy term which does not seem compatible with the presently known facts. Furthermore, the recovery model, as originally postulated, predicts an initial creep rate of zero if the stress is dropped suddenly from a high stress to a lower stress during primary creep. This arises from the fact that there is a time interval necessary for the internal stress to recover from the high value to a lower one corresponding to the new lower creep stress. This does not appear to be the case for high-temperature creep of pure aluminum, where it has been shown that the creep rate is merely reduced, but not stopped, after a decrease in stress.<sup>(19, 24)</sup> It is nevertheless attractive to consider that creep does take place by some type of a stress-relaxation process. A successful model, however, must yield an apparent activation energy that is independent of the applied creep stress.

Most of the theories for creep described above insist upon activation energies that are stress or strain dependent. In terms of the rather well documented insensitivity of the apparent activation energy with either stress or strain, such theories appear to be incompetent to account for the facts. In most cases the activation energies postulated by these theories are much greater than those which were observed at the lowest temperatures that were investigated. This suggests that creep can occur by easier processes than those thus far taken into consideration in many of the various theories of creep.

The temperature dependence of the apparent activation energy for creep, given in Fig. 5, exhibits two plateaus. The highest one of about 35,500

calories per mole spans a range of temperatures from about 500°K to 850°K. This coincides with the estimated activation energy for self-diffusion in aluminum;<sup>(3)</sup> and, it is equal to the previously reported activation energy for high-temperature creep of aluminum as obtained by the application of equation (1). The next lower plateau, spanning the range from about 250°K to about 375°K, has an apparent activation energy of about 27,500 calories per mole. Between 375°K and 500°K the apparent activation energy increases gradually from 27,500 to 35,000 calories per mole.

Undoubtedly, each plateau represents a region over which a single mechanism for creep predominates. In the intervening region, where the apparent activation energy increases from the lower to the higher plateau, both mechanisms are believed to contribute to the observed creep rates. This rationalization of the data suggests that the structures obtained during creep in the transition zone must depend on the test temperature as well as other test variables. Consequently, it is now clear why equation (1) cannot be rigorously applied in regions where two or more mechanisms of creep are operative.

Within the sensitivity of the techniques employed here, no plateaus of the apparent activation energy were obtained in the range of temperatures from 77°K to 250°K. Either creep occurs by a continuous spectrum of low activation energies in this range or by a number of reasonably closely-spaced characteristic activation energies.

It is possible that each mechanism of creep might be reflected in characteristically different time laws. If this were so, the creep strain versus time curve at various temperatures should reveal significantly different relationships. But, as shown by the typical creep curves reproduced in Fig. 7, there does not appear to be any striking difference in the time laws for creep at different temperatures when appropriate stresses are selected for test. Creep did not exhaust itself even at 77°K, although at lower stresses than those actually employed it might have become immeasurably slow and therefore undetectable in the usual period of a creep test.

The preceding discussion reveals, in part, the inherent complexity of macroscopically measurable creep. It would indeed be helpful to be able to isolate and study independently each possible mechanism for creep. Lacking the techniques for doing this at present, it is necessary to confine our attention to analyses of macroscopic phenomenological data in anticipation that such analyses might furnish clues to the detailed mechanisms of creep. For this purpose,

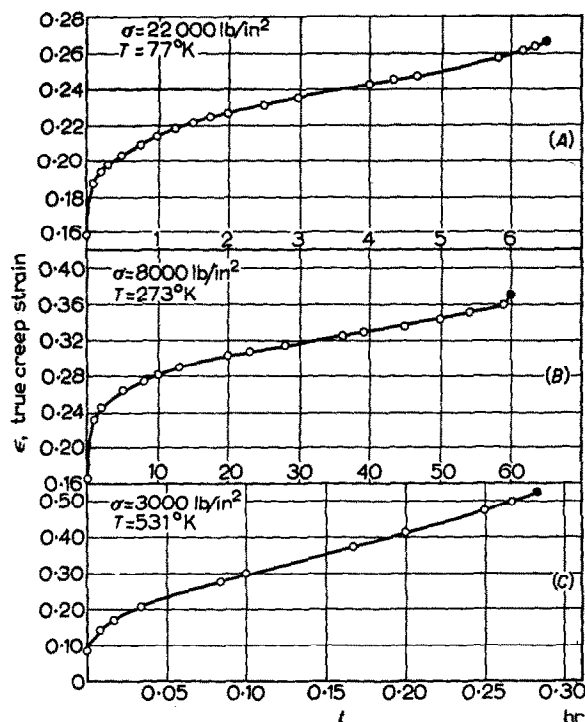


FIG. 7. Typical creep curves for pure aluminum under constant stress at various temperatures.

assume that creep arises from a series of mechanisms. Parallel mechanisms can be discarded, since in such cases creep would be controlled primarily by the slowest unit process in the parallel assemblage. If we insist upon adjusting our model to agree with the experimental results, the model must be so constructed that the apparent activation energy obtained from the model is independent of the stress and the strain. This requirement immediately leads to the unorthodox assumption that

$$\dot{\epsilon} = \left\{ \sum w_i e^{-\Delta H_i/RT} \right\} \varphi(\sigma, s) \quad (8)$$

where  $\Delta H_i$  = a constant equal to the activation energy of the  $i$ th process,

$w_i$  = the weight factor for the  $i$ th process,

$\varphi$  = a function of the instantaneous stress and structure,

and  $S$  = the structure which varies in a yet undefined way with the preceding creep history.

By introducing equation (8) into (4), the apparent activation energy for the assumed model becomes

$$\Delta H_0 = - \frac{R d(\ln \dot{\epsilon})}{d\left(\frac{1}{T}\right)} = \frac{\sum w_i \Delta H_i e^{-\Delta H_i/RT}}{\sum w_i e^{-\Delta H_i/RT}} \quad (9)$$

where  $\Delta H_0$  is independent of the stress and strain,

as revealed by the absence of stress and structure in the expression to the right of the last equality sign in equation (9). The usual assumption that each of the series of processes contributes strain rates that are unique functions of the stress and structure to the total creep rate would have resulted in apparent activation energies that would have been functions of the stress and strain. As yet, the separation of the function  $\varphi(\sigma, s)$  as a single independent multiplying factor of the sums of the series of activation energy terms can only be justified on heuristic grounds and *a posteriori* correlations.

Two activation energies, namely 35,500 and 27,500 calories per mole, of the total series appear to be fairly well established. In order to compare the concept of a series of activation energies with the actual experimental results, four additional activation energies were arbitrarily selected, as shown in Table I. A weight factor of  $w = 1$  was assigned to the highest activation energy of 35,500 calories per mole. The remaining weight factors were then calculated by applying equation (9) to the experimental data. It is interesting to note that according to these assumptions the weight factors must show an unexpectedly large increase with increasing activation energies in order to account for the experimental results. Using the data in Table I, the calculated apparent activation energy curve given by the broken line of Fig. 5

TABLE I. Weight factors

$\Delta H$ (cal/mole)	$w$
35,500	1
27,500	$1.57 \times 10^{-4}$
20,000	$6.90 \times 10^{-12}$
12,500	$1.57 \times 10^{-20}$
6,500	$5.08 \times 10^{-30}$
3,000	$5.04 \times 10^{-39}$

was obtained; this agrees reasonably well for all apparent activation energies. When a similar comparison was made, using the two upper activation energies plus only three lower activation energies, a series of plateaus were obtained over the lower temperature range that gave larger deviations from the experimental facts than the experimental scatter. This suggests that at least four low activation energy processes for creep must be assumed in addition to the two highest activation energies.

## CONCLUSIONS

1. The activation energy for creep of high-purity aluminum is independent of both stress and strain over the range of temperatures from 77°K to 880°K.



2. The activation energy for creep above about 500°K is independent of the temperature and equal to 35,500 calories per mole, the activation energy for self-diffusion of aluminum.

3. Between 250°K and 375°K, the activation energy for creep remains constant at about 27,500 calories per mole.

4. But over the range from 77°K to 250°K and from 350°K to 500°K, the activation energy increases with increasing temperature.

5. These data seriously question the validity of those theories for creep that postulate stress- or strain-dependent activation energies for creep.

#### ACKNOWLEDGMENTS

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