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STATISTICAL ANALYSIS OF HIGH-TEMPERATURE CREEP-RATE DATA FOR ALLOYS OF TANTALUM, MOLYBDENUM, AND COLUMBIUM

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16. Abstract

Empirical creep-rate equations are presented for the refractory-metal alloys T-111, T-222, TZM, TZC, D-43, and Cb-1Zr. These metals are potential structural materials for space power systems. The method of least squares was used to statistically analyze experimental creep data reported by other investigators. The form of the correlating equations is based on the theory that creep rate is a function of material temperature, stress, and structure. The equations cover a temperature range of 1256 to 1922 K (1800° to 3000° F) and a stress range of 3.4×10^{6} to 5.5×10^{8} Nm^{-2} (500 to 80 000 psi). The variability associated with each correlating equation is expressed in terms of its standard deviation.

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SUMMARY

This report presents empirical equations for the high-temperature creep of six refractory-metal alloys that are potential structural materials for space power systems. The materials are the tantalum alloys T-111 (Ta-8W-2Hf) and T-222 (Ta-10W-2.5Hf-0.01C), the molybdenum alloys TZM (Mo-0.5Ti-0.08Zr-0.03C) and TZC (Mo-1.2Ti-0.25Zr-0.15C), and the columbium alloys D-43 (Cb-9W-1Zr) and Cb-1Zr. The method of least squares was used to statistically analyze experimental creep data reported by other investigators. The form of the creep-rate equation is based on the generally accepted theory that creep is a function of time, temperature, stress, and structure. Stress is expressed as a power function and temperature as an exponential function. The empirical constants determined for the stress and temperature terms agreed with those reported by other investigators for similar refractory materials undergoing high-temperature creep.

The correlating equations cover a temperature range of 1256 to 1922 K (1800° to 3000° F) and a stress range of 3.4×10^{6} to 5.5×10^{8} newtons per square meter (500 to 80 000 psi). The variability associated with each equation is expressed in terms of its standard deviation. Since the standard deviation is quite different for each material, it is important that this factor be considered when applying the equations. The large standard deviation for each creep-rate equation reflects the nonuniformity of the refractory-metal alloys at this stage of their commercial development. Some of the reasons for this nonuniformity would include small differences in chemical composition, the type of heat treatment, and the amount of work the test specimens receives. A comparison of the six alloys at 1366 K (2000° F) shows that TZC is the most creep resistant and Cb-1Zr is the least creep resistant.

INTRODUCTION

The combined factors of high temperature, stresses, long operating times, and corrosive environments create very stringent creep-strength requirements for structural materials. Yet, these are the conditions in which equipment for many future processes will operate. Examples would include high-temperature turbines, pumps, heat exchangers, and process piping. Another example, which pertains directly to this investigation, is the nuclear fuel element for space power reactors.

One type of fuel element being investigated for this purpose is in the form of a pin in which the nuclear fuel is contained within a completely enclosed cylindrical cladding. Throughout the operating life of the fuel element, fission products are generated within the fuel. At the high operating temperatures, some of the gaseous fission products are released from the fuel and migrate to void spaces within the cylindrical container, thereby exerting an internal pressure force on the cladding material. The fission products that cannot escape or are not gaseous cause the fuel to swell and eventually exert an additional internal force on the fuel-element cladding. Both forces combine to stress the cladding material.

The combination of stress, high temperature, and long time creates a creep condition that must be considered in the fuel-pin design. The refractory-metal alloys of tantalum (T-111 and T-222), molybdenum (TZM and TZC), and columbium (D-43 and Cb-1Zr) appear to possess good high-temperature strength characteristics that would resist or limit the creep deformation in a fuel-element cladding. Because these materials can be fabricated and possess good corrosion resistance to liquid metals and nuclear fuels, they are candidate materials for space power nuclear reactors (ref. 1).

The structural design of a nuclear fuel pin requires, among other things, that the creep properties of the cladding material be predictable for the stress and temperature conditions of interest. The stresses within the cylindrical cladding are distributed in the tangential, axial, and radial directions of the pin in a manner that can be described by applying plastic flow theory for combined stresses (ref. 2). The directional creep rates corresponding to each principal stress can be calculated from the plastic flow theory if the uniaxial creep properties of the material are known. However, these stresses are continually increasing with time as fissioning continues. For this reason, the creep properties of the cladding material must be expressed in a convenient mathematical form that can be integrated over the operating life of the fuel element. Design strains would normally be less than 1 percent; therefore, rupture should not occur before the limiting strain has been reached.

This report presents empirical equations for the high-temperature creep of six refractory-metal alloys. The correlating equations were determined by analyzing suitable creep-rate data for each alloy by the method of least squares. The form of the

creep-rate equations is based on the generally accepted theory that, for a given material, creep rate is primarily a function of temperature, stress, and structure (ref. 3). Stress is expressed as a power function and temperature as an exponential function, and structure is included in a correlation constant. This form was chosen over the parametric correlations of Larson-Miller and Manson-Haferd in an attempt to arrive at a more readily usable equation for the analytical treatment of multiaxial stress calculations.

Associated with each correlating equation is a standard deviation that reflects the nonuniformity of the refractory-metal alloys at this stage of their commercial development. Reasons for the large deviations from the mean would include small differences in chemical composition, heat treatment, and work. When commercial development is further along, the equation constants can be expected to change slightly, and the standard deviations will be significantly reduced.

METHOD OF ANALYSIS

Theory of Creep

Empirical relations have been developed to define creep rate in terms of stress and temperature. Many hypotheses have been proposed to interpret the empirical parameters in terms of physical changes within the structure of the material. However, no physical laws of creep have yet been determined. The creep hypothesis based on the movement of dislocations through the crystal lattice has received the most acceptance (ref. 4). In this mechanism, dislocations, which are line defects in the lattice arrangement, form in large numbers on each slip plane and move through the crystal under the action of an applied stress until they encounter some obstacle that impedes their progress. At low temperatures, the dislocations trapped within the lattice tend to remain immobile. At high temperatures, they are able to move slowly, by a process associated with the diffusion of vacancies, in a direction away from the slip plane. This process, known as dislocation climb, enables dislocations to move around obstacles and thereby continue the creep mechanism.

The creep-rate equations presented in this report pertain to steady-state creep. Experimental evidence (ref. 4) shows that for the case of constant stress, creep is a thermally activated process that is rate dependent on temperature as expressed by equation (1)

$$\left(\frac{\partial \epsilon}{\partial t}\right)_{\sigma} = (\dot{\epsilon})_{\sigma} = A_1 \exp\left(\frac{-\Delta H}{RT}\right) \tag{1}$$

where ΔH is the activation energy for the controlling creep mechanism. (All symbols

are defined in the appendix.) This relation is the basis for the familiar Larson-Miller (ref. 5) and Manson-Haferd (ref. 6) correlation methods in which a time-temperature parameter is determined as a function of constant stress.

For the case of constant temperature, the stress dependence for steady-state creep can be expressed by the power function

$$\left(\frac{\partial \epsilon}{\partial t}\right)_T = (\dot{\epsilon})_T = A_2 \sigma^n \tag{2}$$

Some investigators (refs. 2 to 4) indicate that at higher stress levels the creep rate may be represented better by either an exponential function

$$\dot{\epsilon} = A_3 \exp(B_1 \sigma) \tag{3}$$

or a hyperbolic sine function

$$\dot{\epsilon} = A_4 (\sinh B_2 \sigma)^n \tag{4}$$

A portion of the data of this investigation was analyzed in these forms, but no significant difference could be observed. Therefore, for reasons of simplicity, it was assumed that the power function (eq. (2)) applies equally well at both high and low stresses.

An empirical equation (ref. 7) for steady-state creep rate that combines the stress and temperature functions of equations (1) and (2) is

$$\frac{d\epsilon}{dt} = \dot{\epsilon} = A \sigma^n \exp\left(\frac{-\Delta H}{RT}\right) \tag{5}$$

The term A is a constant that includes such structural effects as grain size, number and distribution of dislocations, and other microstructural features. The creep of metals and alloys is usually separated into low- and high-temperature behavior (ref. 3). The change from low to high occurs at approximately one-half the melting temperature. High-temperature creep is believed to be diffusion controlled, whereas low-temperature creep is controlled by nondiffusion mechanisms that cannot be specified. The activation energy ΔH for creep increases progressively up to about one-half the melting temperature and then remains almost constant with increasing temperature. For most metals and alloys, this constant creep activation energy value is similar to the energy required for self-diffusion (the movement of atoms through a lattice by interchanging positions with vacancies). The exponent n for the stress term is somewhat dependent on tempera-

ture (ref. 3). In most cases of high-temperature creep, n remains constant, with typical values between 3 and 6. When the temperature nears the melting point of the material, the value of n does not remain constant but approaches a value of 1.

Data Correlation

Creep data generally have appreciable scatter because of many unpredictable factors that are difficult to analyze, and which affect the test results. Such factors include small variations in chemical composition, different heat treatments, and the amount of work the material receives prior to creep testing. The latter two factors are referred to as thermomechanical history and result in changes in the microstructure of the material. When the amount of data is limited, as is the case for the refractory alloys, it is very difficult to specify these effects on creep properties. If differences in chemical and thermomechanical history of the test specimens are assumed to be random and representative of the material, the creep data are amenable to statistical analysis.

These assumptions may not strictly apply to the newer refractory-metal alloys at this stage of their commercial development because optimum composition and processing may not yet have been achieved. However, if determining the general creep properties of a designated alloy is the goal, these assumptions must be made. For each analysis, it was assumed that the creep data represented one designated alloy and not a series of chemically similar alloys, each possessing its own peculiar properties.

The application of statistics results in the establishment of a correlating equation by analytical procedures, rather than by graphical methods. This report analyzes the data by the method of least squares. Since it is a least-squares procedure, it statistically gives the most probable values of the desired constants in the mathematical model (ref. 8). By changing equation (5) into logarithmic form, the model for the analysis becomes an equation of a plane

$$\log \dot{\epsilon} = \log A + n \log \sigma - \frac{\Delta H}{2.303\ RT} \tag{6}$$

where stress σ and temperature T are the independent variables. Equation (6) can be considered a linear equation for use in the method of least squares (ref. 9). The estimates of A, n, and ΔH are determined such that the sum of the squares of the differences between the observed values (data points) and the calculated values (the correlating plane) in the dependent variable direction is minimized. Since equation (6) defines the correlating plane, the summation of the squares of the differences may be expressed as follows:

$$\sum_{I}^{N} (\log \dot{\epsilon} - \log \dot{\epsilon}_c)^2 = \left(\log \dot{\epsilon}_1 - \log A - n \log \sigma_1 + \frac{\Delta H}{2.303\, RT_1}\right)^2 + \ldots$$

$$\ldots + \left(\log \dot{\epsilon}_N - \log A - n \log \sigma_N + \frac{\Delta H}{2.303\, RT_N}\right)^2 \quad (7)$$

The summation is minimized when its derivatives with respect to A, n, and ΔH are each set equal to zero. Taking these derivatives and equating them to zero yields three equations which are solved to give the optimum values, from a least-squares standpoint, for A, n, and ΔH. The correlating plane for each material, therefore, represents the data such that the sum of the squares of the deviations of the data from the correlating plane in the creep-rate direction is less than that from any other plane through the data. The equation of the plane fitted in this manner is considered to be the best means of predicting dependent variable (creep rate) changes, with variations in independent variables (stress and temperature).

Once the correlating equation has been established, it is pertinent to have some measure of the scatter of the actual data from the correlating plane. One such measure is the standard deviation calculated by

$$S = \sqrt{\frac{\sum (\log \dot{\epsilon} - \log \dot{\epsilon}_c)^2}{N - 3}} \quad (8)$$

The denominator, N - 3, in equation (8) is the number of degrees of freedom. The degrees of freedom for this case are the number of data points minus the number of constants in the correlating equation. One standard deviation above and below the correlating plane (±1 standard deviation) represents a region within which about two-thirds of the experimental data would be expected to fall, assuming the data are representative, random, and normally distributed. Thus, it is a measure of the reliability of the correlating equation.

DATA SELECTION

The amount of creep data for refractory metals and alloys is limited. The experimental uniaxial creep data used in this investigation, along with the sources, are presented in table I. The criteria used for selecting data were (1) the data were obtained

under similar, carefully controlled test conditions, (2) the chemical composition of the materials adhered to standard specifications and did not change appreciably during the creep test, and (3) the test temperatures were somewhere within the range of 1256 to 1922 K (1800° to 3000° F), which represents the temperature range of interest for space power applications.

The majority of creep data for the refractory alloys was obtained under high-vacuum ($<1\times10^{-6}$ torr) test conditions in order to minimize chemical reactions with the environment. Data that were obtained in a gaseous environment were included only if the compositional changes during testing were minimal. As far as can be determined, the creep data represent arc-melted material. No attempt was made to segregate the data on the basis of thermomechanical history because there was insufficient data to specify these effects on creep rate at this time. Therefore, the standard deviation for each correlation reflects the inherent variation of thermomechanical history and chemical composition on the creep properties of the alloys at this stage of their commercial development.

RESULTS AND DISCUSSION

Figure 1 visually summarizes the results of this analysis for each of the alloys investigated. The curves represent the straight-line equation

$$\log \frac{\dot{\epsilon}}{\sigma^n} = \log A - \frac{\Delta H}{2.303\ R}\left(\frac{1}{T}\right) \tag{10}$$

which is a rearrangement of equation (5). This permits showing the three variables on a two-dimensional plot. The data points represent the measured values of temperature $1/T$ and creep rate and stress $\dot{\epsilon}/\sigma^n$. However, the exponent n is the calculated value determined from the least-squares analysis. The dashed lines are located ±1 standard deviation from the correlating line and form a region within which approximately two-thirds of the experimental data will fall. The deviation pertains only to the dependent variable $\dot{\epsilon}$ as expressed by equation (8). The distance between the dashed lines gives a visual measure of the data scatter and the reliability of the correlating equation. The scatter is similar for each investigator's data. This is significant because each investigator heat treated and worked his test specimens differently. The fact that these effects are not discernible indicates that the assumption of random and representative data is valid. Type 316 stainless steel (316 SS) is included so that a comparison can be made with a standard commercial material whose composition and physical properties are carefully controlled and reproducible.

The creep-rate equations resulting from the least-squares analysis are as follows:

$$\text{T-111:}\quad \dot{\epsilon} = 3.776\times10^{-20}\,\sigma^{3.692}\exp\left(\frac{-397\,075}{RT}\right)$$

$$\text{T-222:}\quad \dot{\epsilon} = 1.094\times10^{-28}\,\sigma^{4.995}\exp\left(\frac{-458\,902}{RT}\right)$$

$$\text{TZM:}\quad \dot{\epsilon} = 7.083\times10^{-20}\,\sigma^{3.333}\exp\left(\frac{-321\,475}{RT}\right)$$

$$\text{TZC:}\quad \dot{\epsilon} = 1.036\times10^{-55}\,\sigma^{7.880}\exp\left(\frac{-402\,628}{RT}\right)$$

$$\text{D-43:}\quad \dot{\epsilon} = 3.863\times10^{-35}\,\sigma^{5.549}\exp\left(\frac{-353\,944}{RT}\right)$$

$$\text{Cb-1Zr:}\quad \dot{\epsilon} = 4.333\times10^{-35}\,\sigma^{5.988}\exp\left(\frac{-370\,856}{RT}\right)$$

$$\text{316 SS:}\quad \dot{\epsilon} = 1.944\times10^{-32}\,\sigma^{6.307}\exp\left(\frac{-418\,218}{RT}\right)$$

Table II summarizes the range of temperatures and stresses encompassing the experimental data, the number of data points in the statistical sample, and the standard deviations for each analysis. The ratio of maximum to minimum creep rate for ±1 standard deviation is a measure of the variation of the experimental data from values given by the correlating equation. For example, if this ratio were equal to 1, the correlation would be perfect. The larger this value is, the more scatter appears in the data and the less reliable is the correlating equation. A value of 10 means that approximately two-thirds of the data fall within a region that encompasses 1 order of magnitude in creep rate, while a value of 100 corresponds to 2 orders of magnitude.

In comparing materials, it is apparent that the creep-rate equation for the 316 SS is much more reliable than the equations for the refractory alloys. This is to be expected for a standard commercial material, and it represents the degree of accuracy that is possible with a well-developed alloy. The columbium alloys D-43 and Cb-1Zr have the best correlations of the refractory metals tested. However, the data used for each of these alloys represent only a small sample primarily from one investigator, thereby minimizing the effects of variable chemical composition and thermomechanical history. The equations representing the tantalum alloys (T-111 and T-222) are next best in terms of reliability, while the molybdenum alloys (TZM and TZC) produced the least reliable correlations. The creep properties of the molybdenum alloys seem to be particularly susceptible to the

amount of work the material receives (ref. 15) and this may be a significant factor for the low reliability of their correlating equations.

The large standard deviation for each correlating equation is most probably caused by differences in thermomechanical history and chemical composition. An example of the effect of heat treatment is illustrated by the first two data points of table I. These two points represent the same material from the same ingot and were tested at the same temperature and stress. They differ only by the prior heat treatment each received, the first having been treated for 1 hour at 1700 K (2600° F) and the second for 1 hour at 1922 K (3000° F). Their measured creep rates differ by a factor of 2.8. Reference 20 presents a creep-rate correlation for T-111 material that has been heat treated 1 hour at 1922 K (3000° F).

An example of the effect of a slight change in chemical composition is illustrated by the KDTZM data included in table I and figure 1 but not used in the statistical analysis. This material was not considered typical TZM because its carbon content was 0.035 weight percent as compared to 0.020 weight percent for normal TZM. This slight change in composition resulted in much greater creep strength, as indicated by figure 1.

With the exception of these two specific examples, the remaining data for each alloy represent varying heat treatments, chemical composition, and amounts of work. Because these effects cannot be accurately separated and specified, the variations listed in table II must be considered real and indicative of the variability in creep properties of the refractory alloys at this stage of their commercial development.

The values determined for the stress exponent n and the creep activation energy ΔH appear reasonable when compared to other investigations. As stated previously, the typical value of n for high-temperature creep is between 3 and 6, which agrees reasonably well with the calculated values of this analysis. Table III compares the calculated creep activation energy values of this investigation with the reported high-temperature activation energies for creep and self-diffusion in similar materials. A direct comparison is not possible because the temperatures for which the referenced values apply were not reported. However, there is sufficient agreement to indicate that the creep mechanism described by equation (5) is reliable. The comparison substantiates the hypothesis stated under METHOD OF ANALYSIS that diffusion is the controlling mechanism for high-temperature creep.

These equations can be used to determine the most creep resistant material for a given set of operating conditions. Figure 2 illustrates such a comparison for a temperature of 1366 K (2000° F) and a stress of 6.9×10^{7} newtons per square meter (10 000 psi). The calculated creep rate for each alloy is given by the vertical line. The dark band on both sides of the calculated value represents ±1 standard deviation. For these refractory metals, the molybdenum alloy TZC is the most creep resistant, even when the variability is considered. The other molybdenum alloy, TZM, possesses such a wide range of possible creep rates that it is difficult to evaluate it. The tantalum alloys T-111 and T-222 have similar

creep properties when the variability of each is considered. The columbium alloys possess the poorest creep resistance, with Cb-1Zr being much inferior to D-43.

SUMMARY OF RESULTS

The statistical analysis by the least-squares method of high-temperature creep data for six refractory-metal alloys resulted in the following equations:

$$\text{T-111: } \dot{\epsilon} = 3.776\times10^{-20}\,\sigma^{3.692}\exp\left(\frac{-397\,075}{RT}\right)$$

$$\text{T-222: } \dot{\epsilon} = 1.094\times10^{-28}\,\sigma^{4.995}\exp\left(\frac{-458\,902}{RT}\right)$$

$$\text{TZM: } \dot{\epsilon} = 7.083\times10^{-20}\,\sigma^{3.333}\exp\left(\frac{-321\,475}{RT}\right)$$

$$\text{TZC: } \dot{\epsilon} = 1.036\times10^{-55}\,\sigma^{7.880}\exp\left(\frac{-402\,628}{RT}\right)$$

$$\text{D-43: } \dot{\epsilon} = 3.863\times10^{-35}\,\sigma^{5.549}\exp\left(\frac{-353\,944}{RT}\right)$$

$$\text{Cb-1Zr: } \dot{\epsilon} = 4.333\times10^{-35}\,\sigma^{5.988}\exp\left(\frac{-370\,856}{RT}\right)$$

The uncertainty in the creep rates predicted by these equations is quite different for each alloy and must be considered when using the correlations. The range of uncertainty expressed as the ratio of maximum to minimum creep rates for ±1 standard deviation, from the correlating equation, is 2.9 for D-43, 4.4 for Cb-1Zr, 6.7 for T-111, 20.8 for T-222, 30.4 for TZC, and 163.7 for TZM. The greater this ratio, the less reliable is the correlation. For comparison, the ratio for a standard commercial stainless steel is 2. The large variation reflects the inherent nonuniformity of the refractory metals at this stage of their commercial development. The reasons for this nonuniformity would include small differences in chemical composition, the type of heat treatment, and the amount of work the test specimen receives.

A comparison of the creep properties of the six alloys indicated that TZC is significantly superior in creep resistance, followed by T-222, T-111, and TZM which have similar creep properties, D-43 which is less creep resistant, and Cb-1Zr which has very poor creep resistance.

Lewis Research Center,
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APPENDIX - SYMBOLS

A, A_2	constant, $hr^{-1} (Nm^{-2})^{-n}$
A_1, A_3, A_4	constant, hr^{-1}
B_1, B_2	constant, $(Nm^{-2})^{-1}$
ΔH	activation energy, $(J)(g\text{-}mole^{-1})$
N	number of data points
n	stress dependency constant
R	gas constant, 8.3143 $(J)(g\text{-}mole^{-1})(K^{-1})$
S	standard deviation from correlating plane in creep-rate direction, $\log hr^{-1}$
T	absolute temperature, K
t	time, hr
ϵ	strain, m
$\dot{\epsilon}$	creep rate, hr^{-1}
$\dot{\epsilon}_c$	calculated creep rate from correlating plane
σ	stress, Nm^{-2}

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TABLE I. - EXPERIMENTAL CREEP-RATE DATA REPORTED BY OTHER INVESTIGATORS

Material	Temperature, K	Stress, Nm^{-2}	Steady-state creep rate, hr^{-1}	Test duration, hr	Reference
T-111 (Ta-8W-2Hf)	1478	5.52×10^{7}	1.4×10^{-5}	1 600	1
	1478	5.52	5.0×10^{-6}	5 000	
	1478	8.27	8.8	4 000	
	1366	1.38×10^{8}	1.7×10^{-5}	1 100	
	1433	8.27×10^{7}	3.2×10^{-6}	3 800	
	1289	1.38×10^{8}	2.1	5 000	
	1589	2.41×10^{7}	1.2×10^{-5}	2 100	
	1478	3.44	1.8×10^{-6}	5 600	10
	1478	3.44	2.2	3 600	10
	1366	1.03×10^{8}	7.5	1 500	1
	1700	1.03×10^{7}	9.1	500	1
	1256	1.17×10^{8}	1.2	10 000	10
	1700	3.44×10^{6}	1.1×10^{-7}	7 500	10
	1366	8.96×10^{7}	5.3×10^{-6}	3 400	1
	1478	3.44	2.6	4 500	10
	1256	1.17×10^{8}	4.6×10^{-7}	1 000	
	1478	5.52×10^{7}	3.3×10^{-6}	3 000	
	1366	7.58	7.8×10^{-7}	4 500	
	1478	5.51	3.4×10^{-5}	300	
	1256	8.96	7.1×10^{-7}	1 100	
	1366	1.09×10^{8}	3.8×10^{-5}	1 400	11
	1478	5.45×10^{7}	1.1	1 400	11
		1.03×10^{8}	1.7×10^{-4}	2 000	12
		1.38	3.2	1 000	
		1.21	3.4	500	
		1.55	1.6×10^{-3}	100	
		1.72	2.5	70	
		2.07	5.8	25	
		2.41	1.3×10^{-2}	8	
	1700	2.07×10^{7}	2.0×10^{-5}	1 000	
		5.17	2.7×10^{-4}	600	
		6.90	4.9	170	
		8.62	3.1×10^{-3}	28	
		8.62	4.9	25	
		1.03×10^{8}	1.4×10^{-2}	20	
		1.21	4.7	5	
	1922	2.41×10^{7}	7.3×10^{-4}	500	
		3.10	9.7	180	
		6.90	3.2×10^{-2}	2	
		9.65	4.4×10^{-1}	1	
T-222 (Ta-10W-2.5Hf-0.01C)	1478	8.27×10^{7}	1.6×10^{-5}	1 900	1
	1398	1.32×10^{8}	1.1	1 200	1
	1478	8.27×10^{7}	2.4	1 400	1
	1256	4.83	7.5×10^{-4}	43	13
	1256	4.14×10^{8}	3.7	83	
	1256	3.45	1.1	561	
	1366	3.45	5.1×10^{-3}	18	
		2.90	1.3	102	
		2.41	8.9×10^{-4}	188	
		2.07	2.4	1 053	
		1.93	2.6	780	
	1477	2.07	4.5×10^{-3}	35	
		1.72	1.2	161	
		1.38	4.6×10^{-4}	541	
		1.21	1.9	1 443	

Material	Temperature, K	Stress, Nm^{-2}	Steady-state creep rate, hr^{-1}	Test duration, hr	Reference
T-222 (Ta-10W-2.5Hf-0.01C)	1700	7.79×10^{7}	2.9×10^{-3}	69	13
	1922	6.90	1.8×10^{-2}	4	
	1922	4.48	8.9×10^{-3}	30	
	1922	3.10	1.2	143	
	1256	4.14×10^{8}	2.3×10^{-4}	161	
	1366	2.41	4.2	296	
	1366	1.93	1.3	1 310	
	1477	1.72	1.2×10^{-3}	175	
	1922	4.48×10^{7}	5.1	51	
	1366	2.90×10^{8}	4.3×10^{-4}	95	
	1477	2.07	3.5	127	
	1700	1.72×10^{7}	2.9×10^{-5}	500	14
	1589	1.72	1.4×10^{-6}	1 400	
		2.41	4.7	1 000	
		2.76	5.9	? 000	
		4.14	1.4×10^{-5}	1 100	
		5.52	2.8	800	
	1477	5.52	1.2×10^{-6}	10 000	
	1477	8.27	4.3	5 000	
	1477	$1.10\cdot10^{8}$	$1.0\cdot10^{-5}$	1 500	
	1366	1.10	1.7×10^{-7}	10 000	
	1366	1.38	3.6	2 000	
	1366	1.09	2.0	6 000	11
	1477	$5.52\cdot10^{7}$	$1.3\cdot10^{-6}$	6 000	11
TZM (Mo-0.50Ti-0.08Zr-0.03C)	1366	8.27×10^{7}	8.3×10^{-6}	500	1
		6.90	$3.5\cdot10^{-7}$	10 000	
		6.90	2.0	10 000	
		$2.83\cdot10^{8}$	$4.4\cdot10^{-5}$	700	
	1256	3.03	$7.1\cdot10^{-7}$	5 000	
	[a]1286	1.61	$8.0\cdot10^{-8}$	4 500	
	[a]1144	3.79	8.3	2 000	
	[a]1144	4.48	5.2	1 500	
	[a]1256	3.03	$1.0\cdot10^{-7}$	10 000	
	1366	2.83	$6.2\cdot10^{-6}$	1 300	
	1256	5.86	$3.4\cdot10^{-3}$	11	15
	1256	5.52	8.0×10^{-4}	65	
	1589	2.41	$1.5\cdot10^{-2}$	3	
	1589	1.86	$4.4\cdot10^{-3}$	4	
	1256	2.76	$5.0\cdot10^{-5}$	334	
	1256	2.41	4.0	471	
	1589	1.38	$9.0\cdot10^{-3}$	15	
	1589	1.10	4.6	33	
	1256	4.83	3.3×10^{-4}	60	
		4.96	3.0	79	
		5.31	9.0	33	
		2.76	3.7	52	
		4.48	1.3×10^{-3}	20	
		2.41	4.5×10^{-4}	95	
		2.76	1.1×10^{-2}	11	
	1366	3.45	1.0×10^{-5}	133	
		4.14	1.8×10^{-4}	24	
		1.86	5.9	214	
		2.28	7.0	44	
	1922	2.41×10^{7}	7.1	24	
	1922	3.45	2.2×10^{-2}	4	

[a]KDTZM.

TABLE I. - Concluded. EXPERIMENTAL CREEP-RATE DATA REPORTED BY OTHER INVESTIGATORS

Material	Temperature, K	Stress, Nm^{-2}	Steady-state creep rate, hr^{-1}	Test duration, hr	Reference
TZC (Mo-1.2Ti-0.25Zr-0.15C)	1478	1.24×10^{8}	4.6×10^{-6}	2 100	1
	1366	1.38	4.8×10^{-7}	16 000	
	1478	1.17	2.0×10^{-6}	2 800	
	1287	1.72	4.2×10^{-8}	14 500	
	1398	1.31	1.1×10^{-7}	14 000	
	1366	1.38	1.4×10^{-6}	11 000	
	1478	9.65	1.5×10^{-5}	800	
	1478	1.52	7.2	200	
	1331	1.38	3.4×10^{-7}	6 500	
	1311	1.52	5.9	6 000	
	1256	3.03	4.7×10^{-6}	4 500	
	1366	1.93	4.6	4 000	
	1366	1.52	6.7×10^{-7}	7 000	10
	1366	1.52	5.4	3 000	10
	1256	5.17	1.1×10^{-2}	2	15
	1589	2.41	1.4	3	15
	1589	2.21	2.3×10^{-4}	55	15
D-43 (Cb-9W-1Zr)	1366	5.87×10^{7}	8.3×10^{-6}	2 000	11
	1478	2.94	1.2×10^{-5}	1 800	11
	1256	1.38×10^{8}	6.4	1 200	16
		1.52	1.4×10^{-4}	600	
		1.55	1.8	400	
		1.72	4.9	-----	
		1.90	1.0×10^{-3}	70	
		2.41	7.2	8	
	1366	8.96×10^{7}	8.0×10^{-5}	1 000	
		1.03×10^{8}	1.6×10^{-4}	600	
		1.03	1.8	500	
		1.21	6.3	150	
		1.21	1.2×10^{-3}	130	
		1.55	2.7	25	
		1.55	3.8	20	
		1.72	9.3	10	
	1478	4.48×10^{7}	4.2×10^{-5}	-----	
		5.52	1.1×10^{-4}	1 000	
		6.21	1.9	600	
		6.21	2.5	500	
		6.90	3.1	400	
		8.62	1.2×10^{-3}	100	
		1.03×10^{8}	2.5	40	
		1.21	9.0	12	
Cb-1Zr	1256	1.03×10^{8}	8.2×10^{-3}	15	17
		8.27×10^{7}	2.0	65	
		6.90	1.3	148	
		6.90	1.8	160	
		5.86	1.0	260	
		4.48	1.7×10^{-4}	1 450	
	1473	4.14	2.4×10^{-2}	10	
		3.45	1.2	25	
		2.76	7.9×10^{-4}	320	
		2.76	9.4	150	
		2.76	6.5	230	
		2.07	4.6	960	
		2.07	1.4	960	
		2.07	5.7×10^{-5}	640	
316 Stainless steel (Fe-18Cr-13Ni-Mo)	1005	1.38×10^{8}	6.5×10^{-3}	38	18
		1.21	3.7	64	
		1.03	1.1	139	
		8.62×10^{7}	6.0×10^{-4}	389	

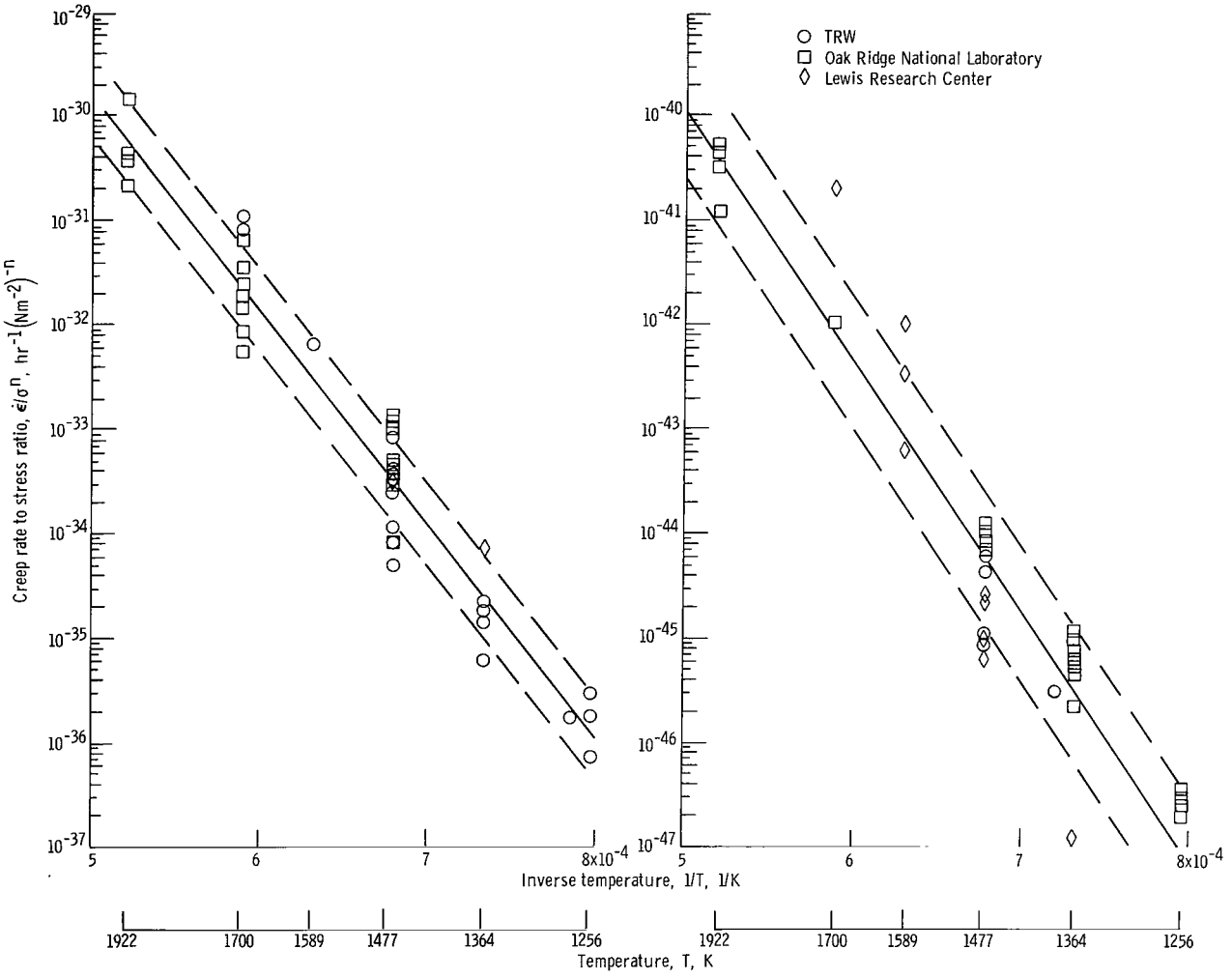
Material	Temperature, K	Stress Nm^{-2}	Steady-state creep rate, hr^{-1}	Test duration, hr	Reference
316 Stainless steel (Fe-18Cr-13Ni-Mo)	1005	6.90×10^{7}	1.2×10^{-4}	2 140	18
		1.38×10^{8}	9.4×10^{-3}	30	
		1.21	4.3	58	
		1.03	1.2	225	
		8.62×10^{7}	5.0×10^{-4}	626	
		6.90	1.3	1 702	
		1.38×10^{8}	1.1×10^{-2}	15	
		1.21	3.3×10^{-3}	67	
		1.03	1.0	164	
		8.62×10^{7}	5.3×10^{-4}	524	
		6.90	1.3	1 006	
	1088	8.62	1.5×10^{-2}	21	
		7.58	5.8×10^{-3}	48	
		6.90	2.0	134	
		6.21	1.5	182	
		5.52	1.1	280	
		4.83	3.2×10^{-4}	784	
		4.48	2.2	933	
		3.79	8.5×10^{-5}	1 075	
		3.45	4.7	1 417	
		3.10	2.2	1 488	
		2.76	4.0×10^{-6}	1 267	
		2.07	2.4	1 393	
		6.90	4.0×10^{-3}	73	
		6.21	2.4	146	
		5.52	1.0	235	
		4.83	4.5×10^{-4}	592	
		3.45	4.2×10^{-5}	2 235	
		2.76	1.9	1 598	
		2.07	2.4×10^{-6}	1 637	
		6.90	4.1×10^{-3}	57	
		6.90	4.2	44	
		6.21	3.0	97	
		5.52	1.0	258	
		4.83	3.4×10^{-4}	548	
		3.45	3.7×10^{-5}	1 290	
		2.07	3.7×10^{-6}	-----	
	1172	4.83	1.6×10^{-2}	25	
		4.48	6.1×10^{-3}	47	
		4.14	4.5	70	
		3.45	2.2	148	
		2.76	4.5×10^{-4}	623	
		4.83	1.3×10^{-2}	21	
		4.14	4.8×10^{-3}	45	
		3.45	2.0	123	
		2.76	4.8×10^{-4}	370	
		4.83	1.2×10^{-2}	24	
		4.14	7.2×10^{-3}	36	
		3.45	2.2	118	
		2.76	8.2×10^{-4}	198	
	1005	2.76	1.8×10^{-7}	8 132	19
		1.86	1.8×10^{-8}	5 900	
		3.45	8.0	5 040	
		2.07	1.0×10^{-7}	10 151	
	1088	3.72	1.4×10^{-4}	1 075	
		4.88	8.3	302	
		5.87	2.6×10^{-3}	104	
		2.07	3.8×10^{-6}	10 196	

TABLE II. - CREEP-RATE CORRELATION CONDITIONS AND DEVIATIONS

Alloy material	Temperature range, K	Stress range, Nm^{-2}	Sample size, N	Variation for ±1 standard deviation, $\dot{\epsilon}_{max}/\dot{\epsilon}_{min}$	One standard deviation, log hr^{-1}
T-111	1256 to 1922	3.45×10^{6} to 2.41×10^{8}	40	6.7	0.41226
T-222	1256 to 1922	1.72×10^{7} to 4.83×10^{8}	39	20.8	.65881
TZM	1256 to 1922	2.41×10^{7} to 5.86×10^{8}	27	163.7	1.10699
TZC	1256 to 1589	9.65×10^{7} to 5.17×10^{8}	17	30.4	.74124
D-43	1256 to 1478	2.76×10^{7} to 2.41×10^{8}	24	2.9	.23065
Cb-1Zr	1256 to 1473	2.07×10^{7} to 1.03×10^{8}	14	4.4	.32048
316 SS	1006 to 1172	1.86×10^{7} to 1.38×10^{8}	62	2.0	.14673

TABLE III. - COMPARISON OF ACTIVATION ENERGY

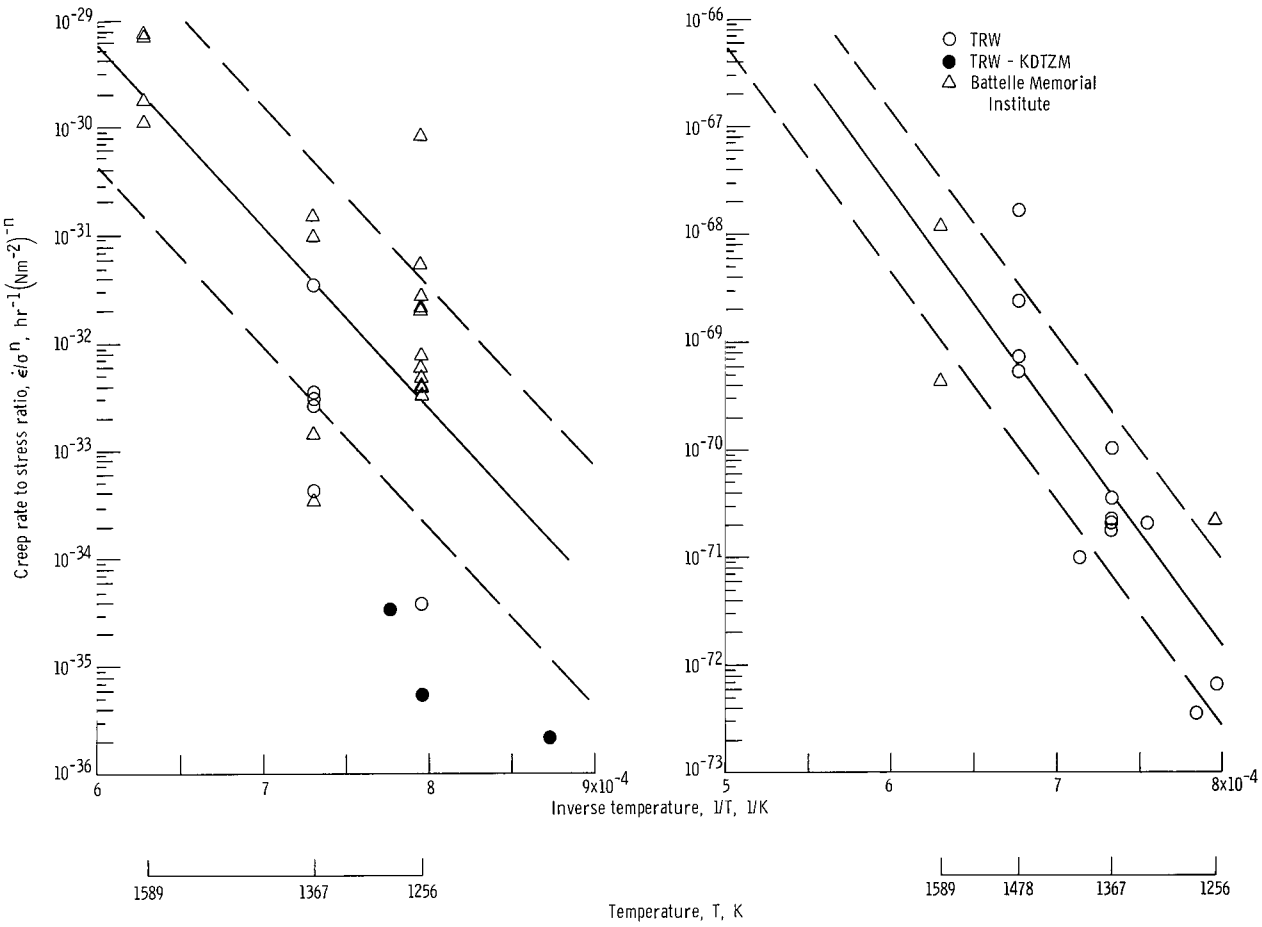
Present work		Other investigations			
Alloy material	Activation energy for creep, ΔH, kJ/g-mole	Base material	Activation energy for creep, ΔH, kJ/g-mole	Activation energy for self-diffusion, ΔH_d, kJ/g-mole	Reference for base material
T-111	397.1	Tantalum	---	460	3
T-222	458.9	Tantalum	---	460	3
TZM	321.5	Molybdenum	502	---	4
TZC	402.6	Molybdenum	502	---	4
D-43	353.9	Columbium	477	439	3
Cb-1Zr	370.9	Columbium	477	439	3
316 SS	418.2	Austenitic SS	314	---	3



(a) T-111. Creep rate, $3.776x10^{-20}\sigma^{3.692}$ exp(-397 075/RT).

(b) T-222. Creep rate, $1.094x10^{-28}\sigma^{4.995}$ exp(-458 902/RT).

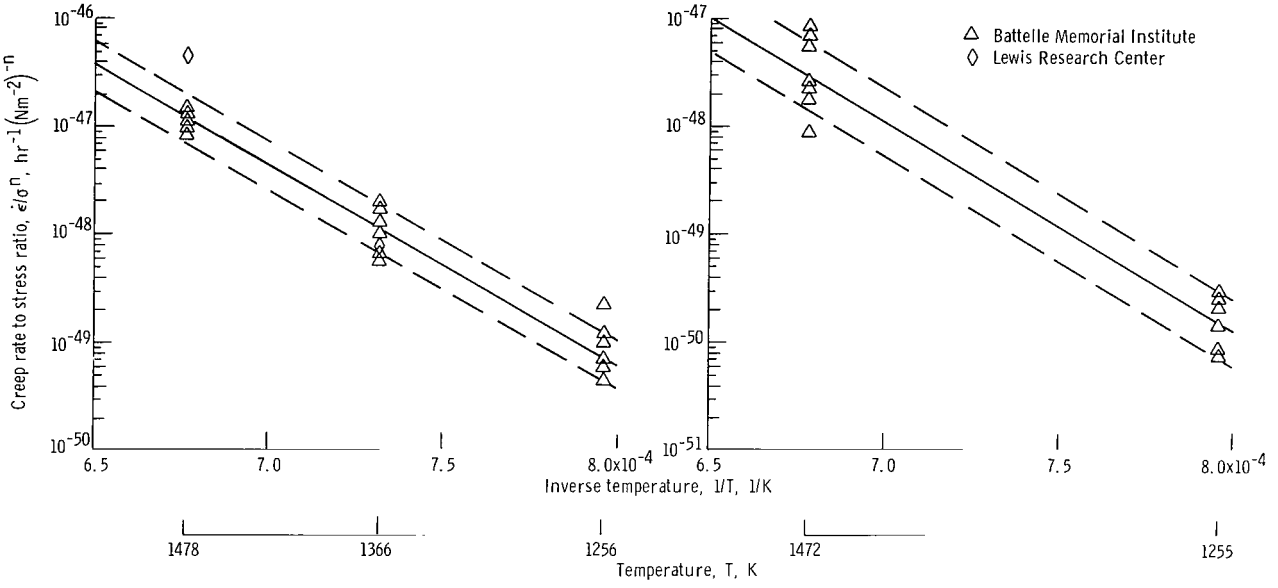
Figure 1. - Cree- rate correlations.



(c) TZM. Creep rate, $7.083x10^{-20}\sigma^{3.333}\exp(-321\,475/RT)$.

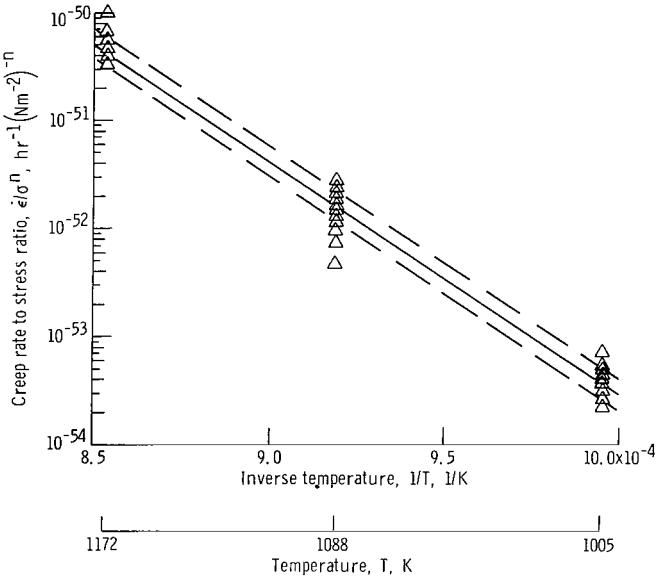
(d) TZC. Creep rate, $1.036x10^{-55}\sigma^{7.880}\exp(-402\,628/RT)$.

Figure 1. - Continued.



(e) D-43. Creep rate, $3.863x10^{-35}\sigma^{5.549}\exp(-353\,944/RT)$.

(f) Cb-1Zr. Creep rate, $4.333x10^{-35}\sigma^{5.988}\exp(-370\,856/RT)$.



(g) 316 Stainless steel. Creep rate, $1.944x10^{-32}\sigma^{6.307}\exp(-418\,218/RT)$.

Figure 1. - Concluded.

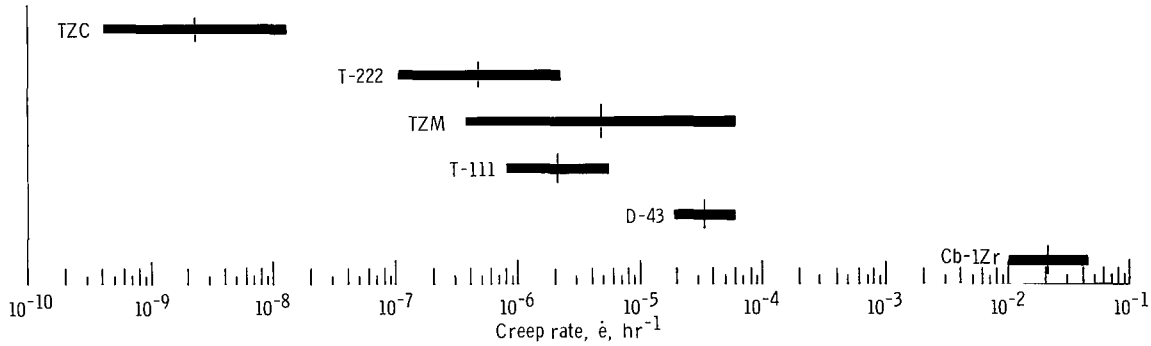


Figure 2. - Comparison of creep properties at 1366 K and 6.9×10^7 newtons per square meter.

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