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The creep of thorium near room temperature

D. T. Peterson
Iowa State University

J. D. Young
Iowa State University

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The creep of thorium near room temperature

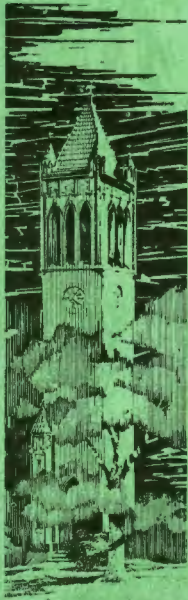
Abstract

The rate of plastic deformation of thorium has been investigated as a function of stress and strain at temperatures from 0 to 60°C. The rate of creep or plastic deformation was found to depend on the instantaneous values of the stress, strain and temperature and thus could be expressed by a mechanical equation of state. The yield point phenomenon was observed even at the lowest plastic strain rates. A critical stress was found below which no plastic deformation was observed.

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IS-986



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NEAR ROOM TEMPERATURE**

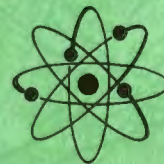
by

D. T. Peterson and J. D. Young

AMES LABORATORY

**RESEARCH AND
DEVELOPMENT
REPORT**

U.S.A.E.C.



PHYSICAL SCIENCES READING ROOM

IS-986

Metals, Ceramics and Materials(UC-25)
TID 4500, September 1, 1964

UNITED STATES ATOMIC ENERGY COMMISSION

Research and Development Report

THE CREEP OF THORIUM
NEAR ROOM TEMPERATURE

by

D. T. Peterson and J. D. Young

September, 1964

Ames Laboratory
at
Iowa State University of Science and Technology
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THE CREEP OF THORIUM NEAR ROOM TEMPERATURE

D. T. Peterson and J. D. Young

ABSTRACT

The rate of plastic deformation of thorium has been investigated as a function of stress and strain at temperatures from 0 to 60°C. The rate of creep or plastic deformation was found to depend on the instantaneous values of the stress, strain and temperature and thus could be expressed by a mechanical equation of state. The yield point phenomenon was observed even at the lowest plastic strain rates. A critical stress was found below which no plastic deformation was observed.

INTRODUCTION

Polycrystalline thorium metal exhibits two interesting and somewhat unusual characteristics when plastically deformed at room temperature. Thorium is one of the few face-centered cubic metals which displays a yield point phenomenon in the fully annealed condition. Thorium is also one of the few metals to exhibit a very pronounced creep behavior at temperatures on the order of 600°C below its recrystallization temperature. The plastic deformation of thorium near room temperature can be described quite simply. Below some critical stress the deformation is entirely elastic or anelastic. At stresses greater than the critical stress, plastic deformation occurs at a strain rate which is a function of strain, stress, and temperature, or, in equation form,

$$\dot{\epsilon} = f(\epsilon, T, \sigma) . \quad (1)$$

The yield point phenomenon, usually observed only in tensile tests, was manifested in the creep tests conducted during this investigation.

EXPERIMENTAL METHODS

The thorium used in this investigation was prepared by the thorium tetrafluoride-calcium process described by Wilhelm¹ and had the analysis given in Table I. A 1.5 in. -thick section of a cast ingot of this thorium was hot rolled at 600°C to a 3/4 in. -thick plate. This plate was sawed into 3/4 by 3/4 in. bars, which were cold swaged in four passes to 3/8 in. -diameter rod. This rod was machined to creep specimens having a 0.252 in. diameter reduced section 1.600 in. long, with 0.4 in. of 3/8-16 NC thread on each end.

The specimens were degreased in trichloroethylene, annealed for one hour at 800°C in a 0.05 micron vacuum, and allowed to furnace cool to room temperature. This procedure completely recrystallized the thorium specimens to an equiaxed, number 8 ASTM grain size of approximately 2500 grains per square millimeter, as well as removing any hydrogen which may have been present.

Table I
Analysis of thorium ingot used in this study

Element	Content, ppm	Element	Content, ppm
O	1300	Cr	20
C	410	Al	40
N	70	Ca	50
Fe	130	Mg	20
Ni	20	Si	55
Mn	20	Be	170

The specimen loading was accomplished with an Arcweld Model JE Creep Rupture Machine, which has a lever type dead weight loading system. A revised load unit, similar to the one used by Rose et al.² was constructed to facilitate immersion of the specimen in a constant temperature bath.

The measurement of the axial elongation of the specimen was made with Budd Metalfilm HE-181 Bonded Resistance Strain Gages used in conjunction with a Baldwin-Lima-Hamilton Type 20 Strain Indicator. A consistent strain range of 6% was obtained by employing Budd GA-5 Epoxy Cement to bond the strain gages to the test specimens.

RESULTS AND DISCUSSION

The rate of deformation of thorium at strains beyond the yield point range was found to be a function of the instantaneous values of the strain, stress, and temperature. Consequently, the plastic deformation behavior could be represented by a mechanical equation of state. One form of this equation was established from the data of this investigation. The strain of a specimen at constant stress and temperature was measured as a function of time. From these data, the strain rate could be evaluated at definite values of the stress, strain, and temperature. A linear relationship was observed between logarithm true strain and logarithm strain rate at constant stress and temperature in the strain range investigated from 0.08 to 0.14 true strain. The equation determined from these tests states that

$$\log \dot{\epsilon} = -p \log \epsilon - K. \quad (2)$$

In this equation, $\dot{\epsilon}$ is the strain rate in reciprocal minutes, ϵ is the true strain, p is $\left. \frac{\partial \log \dot{\epsilon}}{\partial \log \epsilon} \right|_{\sigma, T}$, K is the value of logarithm $\dot{\epsilon}$ at unit true strain, and all logarithms are to the base 10. The tests from which Eq. (2) was determined are shown in Figs. 1, 2 and 3.

Whenever the stress or temperature was changed, there was a transient period before the strain rate reached the value associated with the second condition of stress and temperature. This transient effect was observed for both increases and decreases in the value of the stress and temperature and is the deviation from linearity at the beginning of the tests shown in Figs. 1, 2 and 3.

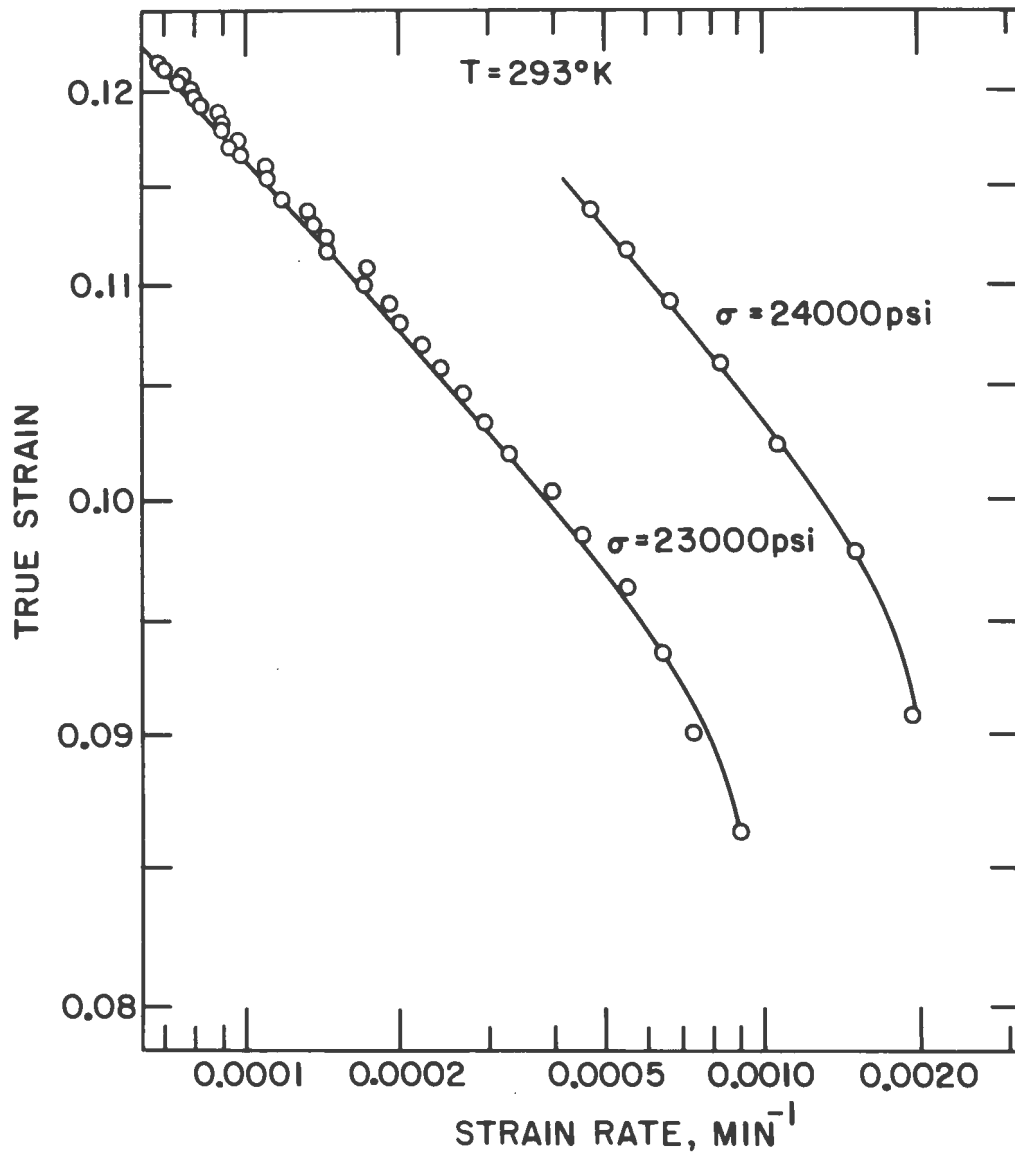


Fig. 1. Logarithm true strain - logarithm strain rate diagram of Ames thorium at 298°K.

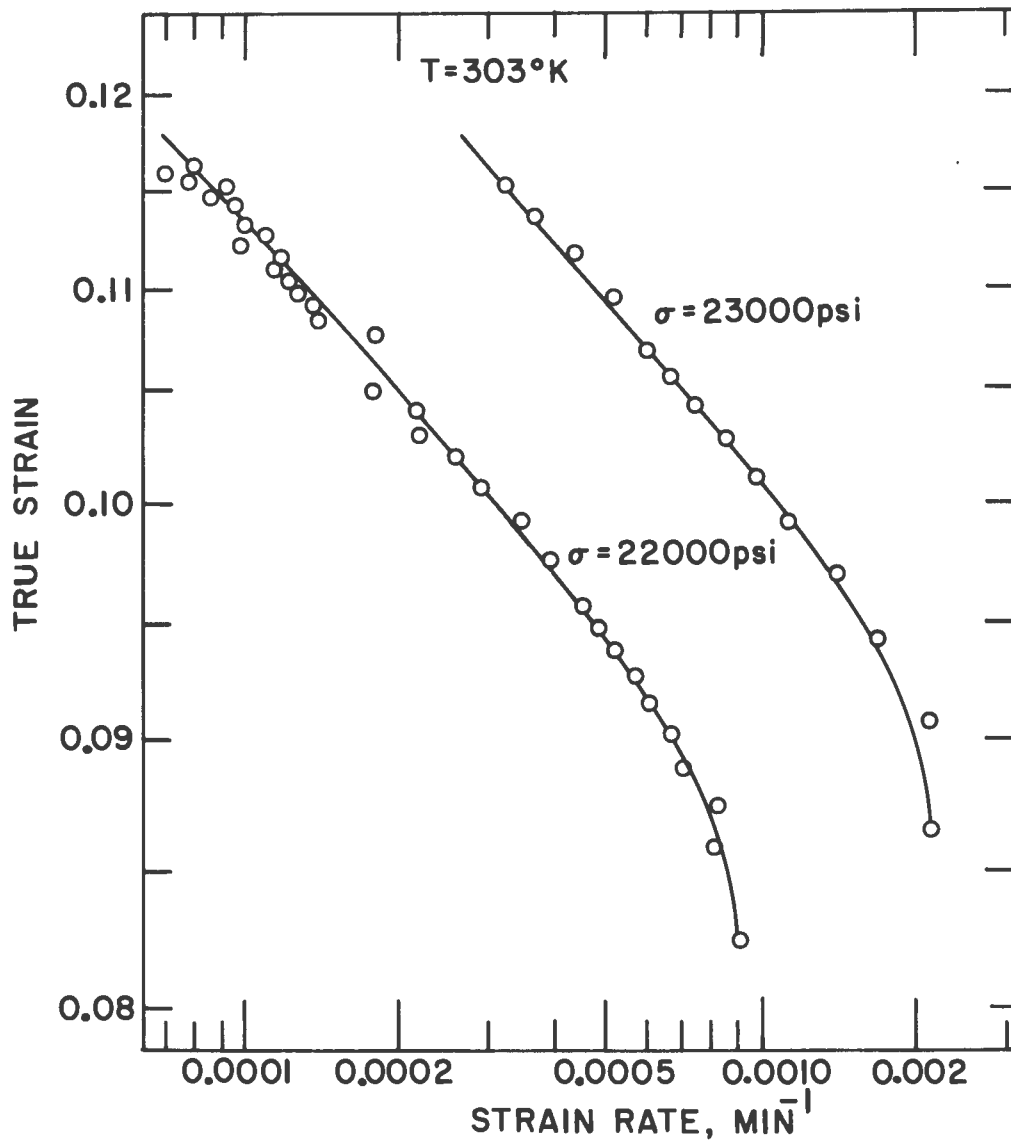


Fig. 2. Logarithm true strain - logarithm strain rate diagram of Ames thorium at 303°K.

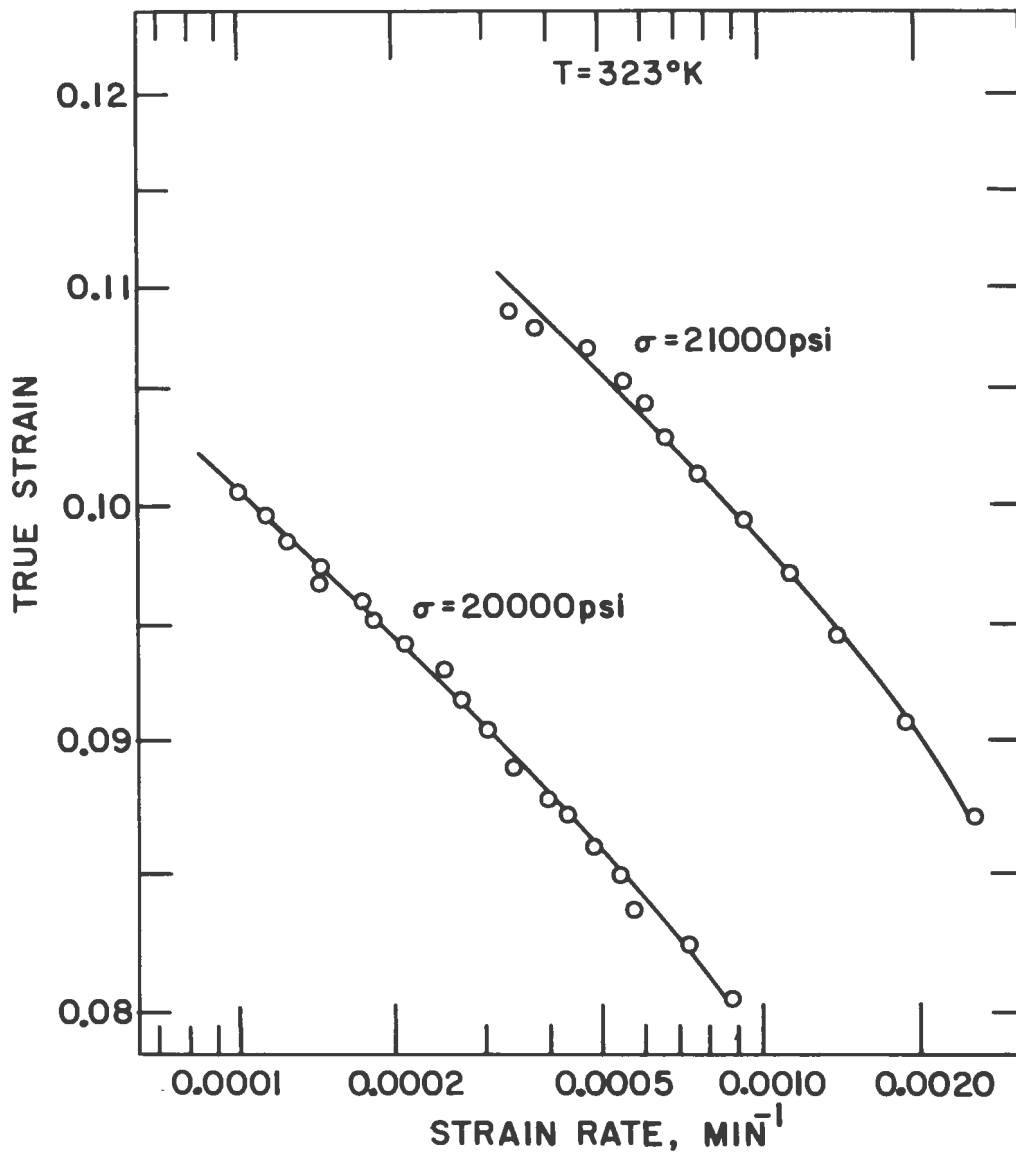


Fig. 3. Logarithm true strain - logarithm strain rate diagram of Ames thorium at 323°K.

A linear relationship was observed between logarithm stress, temperature, and logarithm p such that

$$\log p = K_1 \log \sigma + K_2 T + K_3 . \quad (3)$$

In this equation, σ is the true stress, T is the temperature in degrees Kelvin, K_1 is $\left| \frac{\partial \log p}{\partial \log \sigma} \right|_T$, K_2 is $\left| \frac{\partial \log p}{\partial T} \right|_{\log \sigma}$, and K_3 is a constant.

Similarly, the effect of stress and temperature on K of Eq. (2) is such that

$$\log K = K_4 \log \sigma + K_5 T + K_6 . \quad (4)$$

In this equation, σ is the true stress, T is the temperature in degrees Kelvin, K_4 is $\left| \frac{\partial \log K}{\partial \log \sigma} \right|_T$, K_5 is $\left| \frac{\partial \log K}{\partial T} \right|_{\log \sigma}$, and K_6 is a constant.

The values of the constants in Eqs. (3) and (4), respectively, are listed in Table II.

Table II
Values of the constants in Eqs. (3) and (4)

Eq. (3)	Eq. (4)
K_1 -1.7820	K_4 -2.5252
K_2 -0.0023167	K_5 -0.0035333
K_3 +0.4286	K_6 +13.245

By solving Eqs. (3) and (4) for p and k at selected values of σ and T , and substituting these values into Eq. (2), the original creep curves can be calculated to within less than 2% error.

The effect of stress and temperature on the strain rate of Ames

thorium during constant load creep tests can be compared to constant strain rate tensile tests by utilizing an equation determined by Klievoneit.³ This equation is of the same form as Eq. (2) and states that

$$\sigma = C_1 + C_2 \log \dot{\epsilon} + C_3 \log \epsilon . \quad (5)$$

In this equation, C_1 is a constant, C_2 is $\left| \frac{\partial \sigma}{\partial \log \dot{\epsilon}} \right|_{\epsilon, T}$ and C_3 is $\left| \frac{\partial \sigma}{\partial \log \epsilon} \right|_{\dot{\epsilon}, T}$. The values of the constants determined from creep tests at different temperatures are listed in Table III. Values obtained from tensile tests on Ames thorium are included for comparison.

Table III
Values of the constants in Eq. (5)

Temp. (°K)	C_1	C_2	C_3
195	83,800 ^a	2,280 ^a	26,200 ^a
293	56,675	2,150	23,984
298	55,900 ^a	3,100 ^a	16,800 ^a
303	53,960	2,039	22,534
323	42,961	1,253	15,928
373	44,000 ^a	2,760 ^a	15,300 ^a

^aValues from tensile data by Klievoneit.³

The agreement of the constants from Eq. (5) in Table III is quite good when consideration is given to the fact that the data cover a strain rate range of nearly seven orders of magnitude. The fact that reasonable agreement of the data from a constant strain rate tensile test and a constant load creep test was observed serves to strengthen the

mechanical equation of state concept that a general relationship between stress, strain, strain rate and temperature should be independent of the testing technique.

The thermal and mechanical history independence of the deformation of thorium was established by the test results shown in Figs. 4 and 5. At 298°K, creep tests at 23,000 and 24,000 psi were conducted to establish the relationship between the strain rate and the strain. In a third test, the specimen was initially strained at 23,000 psi and the strain rate found to nearly coincide with the previous test at this stress. The stress was then increased to 24,000 psi and, after a short transient period, the strain rate followed the 24,000 psi curve. The stress was reduced to 23,000 psi and again the strain rate approached the 23,000 psi curve quite closely and followed a parallel path.

In order to validate the thermal history independence of the deformation of thorium, the following test was conducted. At 23,000 psi, creep tests at 293 and 303°K were conducted to establish the relationship between the strain rate and the strain. In a third test, the specimen was initially strained at 293°K and the strain rate found to nearly coincide with the previous test at this temperature. The temperature was then increased to 303°K and, after a short transient period, the strain rate followed the 303°K curve. The temperature was reduced to 293°K and again the strain rate approached the 293°K curve quite closely and followed a parallel path; these tests established that the rate of deformation of thorium was primarily a function of the stress, strain and temperature and not of their past history.

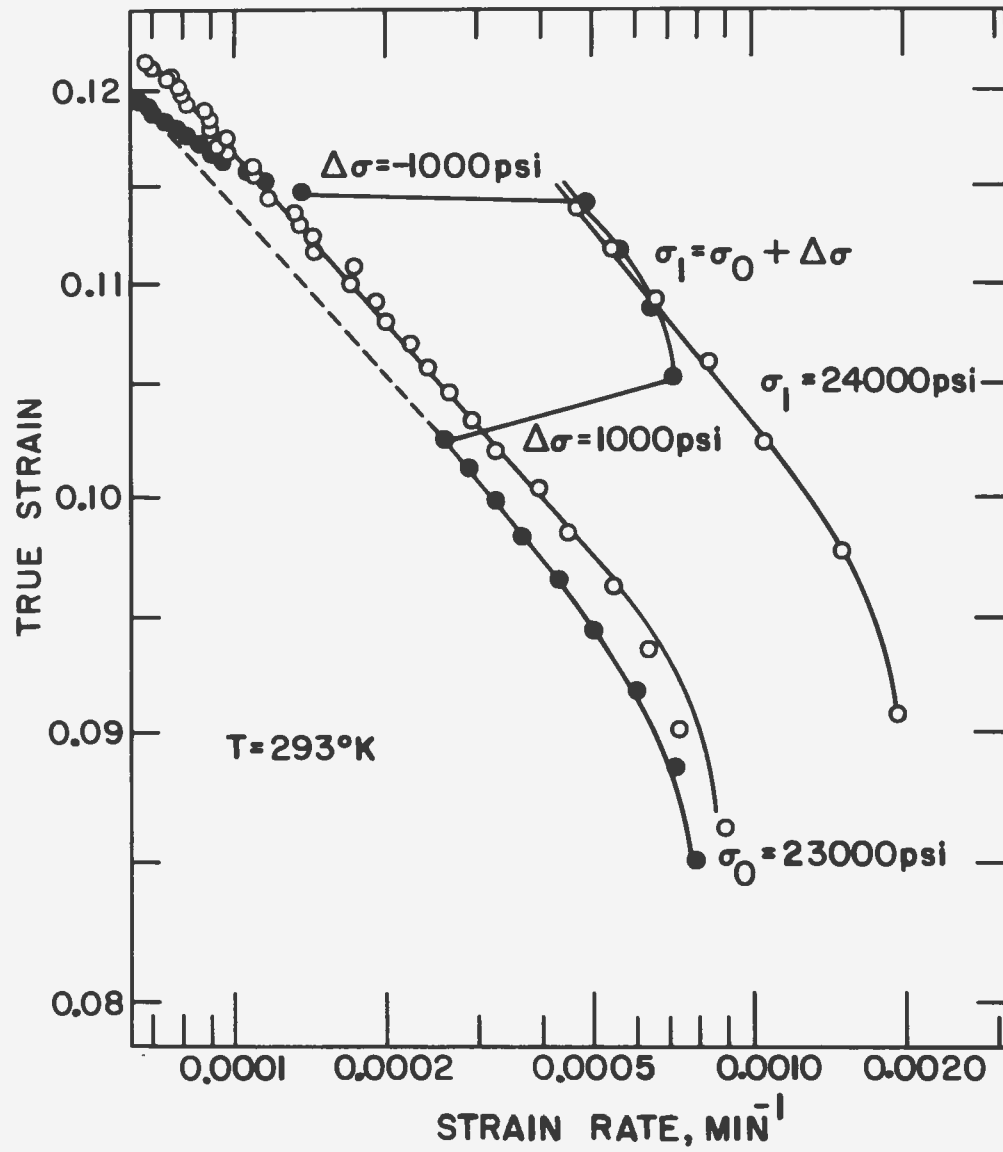


Fig. 4. Stress increment cycle diagram of Ames thorium.

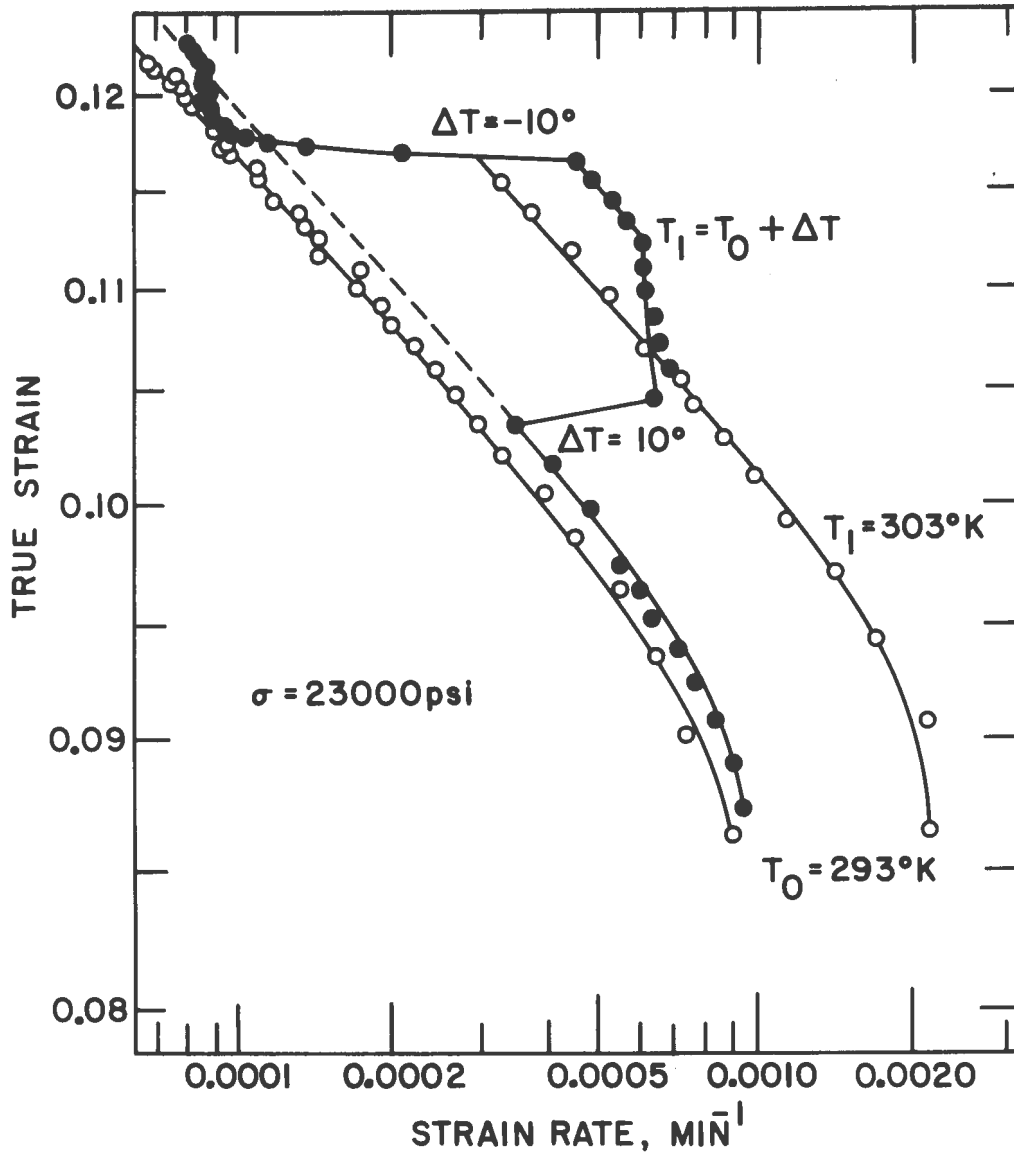


Fig. 5. Temperature increment cycle diagram of Ames thorium.

The slight mismatch of increment curves and the uninterrupted curves was probably due to a small error in measurement of the plastic prestrain. This would shift the assumed true strain value at the beginning of the test. It was noted, however, as can be seen in Figs. 4 and 5, that the plastic state of the system did not instantaneously follow a stress or temperature increment, but that a transient period preceded the achievement of the value of the strain rate associated with a given value of the stress, temperature, and strain in an uninterrupted test. This is not unexpected, however, when consideration is given to the fact that the structure at a particular plastic state is a function of all atomic and imperfection arrangements, both in kind and quantity, and that these are neither produced, annihilated or rearranged instantaneously.

It was found that although the strain-rate decreased with decreasing stress, there was a lower limiting stress below which additional plastic strain could not be observed. This critical stress was determined for annealed specimens and for specimens with various amounts of plastic prestrain. A stress was applied to the specimen and, if no additional strain was observed after the initial elastic and anelastic strain, the specimen was unloaded to verify that the strain was entirely recovered. A larger stress was then applied and the specimen observed for evidence of plastic strain. This was continued until a stress was found which caused observable plastic deformation. The minimum observable strain rate was 1×10^{-7} per min.

The critical stress was found to increase as a function of plastic

strain as shown in Fig. 6. An empirical equation was determined that relates the critical stress to the plastic prestrain. The equation states that

$$\sigma_c = 30,440 + 9,220 \log \epsilon_p . \quad (6)$$

In this equation, σ_c is the critical stress, and $\log \epsilon_p$ is the logarithm to the base 10 of the true plastic strain. This equation was established in the strain range of 0.01 to 0.2. Below a plastic strain of 0.01, the yield point behavior made the critical stress a more complicated function of the strain as the critical stress must pass through a minimum at the lower yield point strain.

To determine the effect of temperature on the critical stress, the critical stress was determined at 0, 25, 35, 45, and 60°C. At all temperatures, the critical stress for a given specimen was the same. Possible mechanisms that could explain this athermal nature of the critical stress are the critical stress required to activate the production of dislocations by a Frank-Read generator, the long range interaction of parallel dislocations and other obstacles which involve a large number of atoms. The average distance between the pinning sites of a Frank-Read generator is several hundred atomic spacings, which has been shown by Schoeck⁴ to form too large a dislocation loop to be affected by random thermal fluctuations. The fact that Eqs. (3) and (4) indicate that the flow stress is temperature dependent can be resolved by considering that part of the stress retarding dislocations sweeping along the glide plane can be thermally activated. The frictional stress is a function of dislocations threading the glide plane, interstitial atoms,

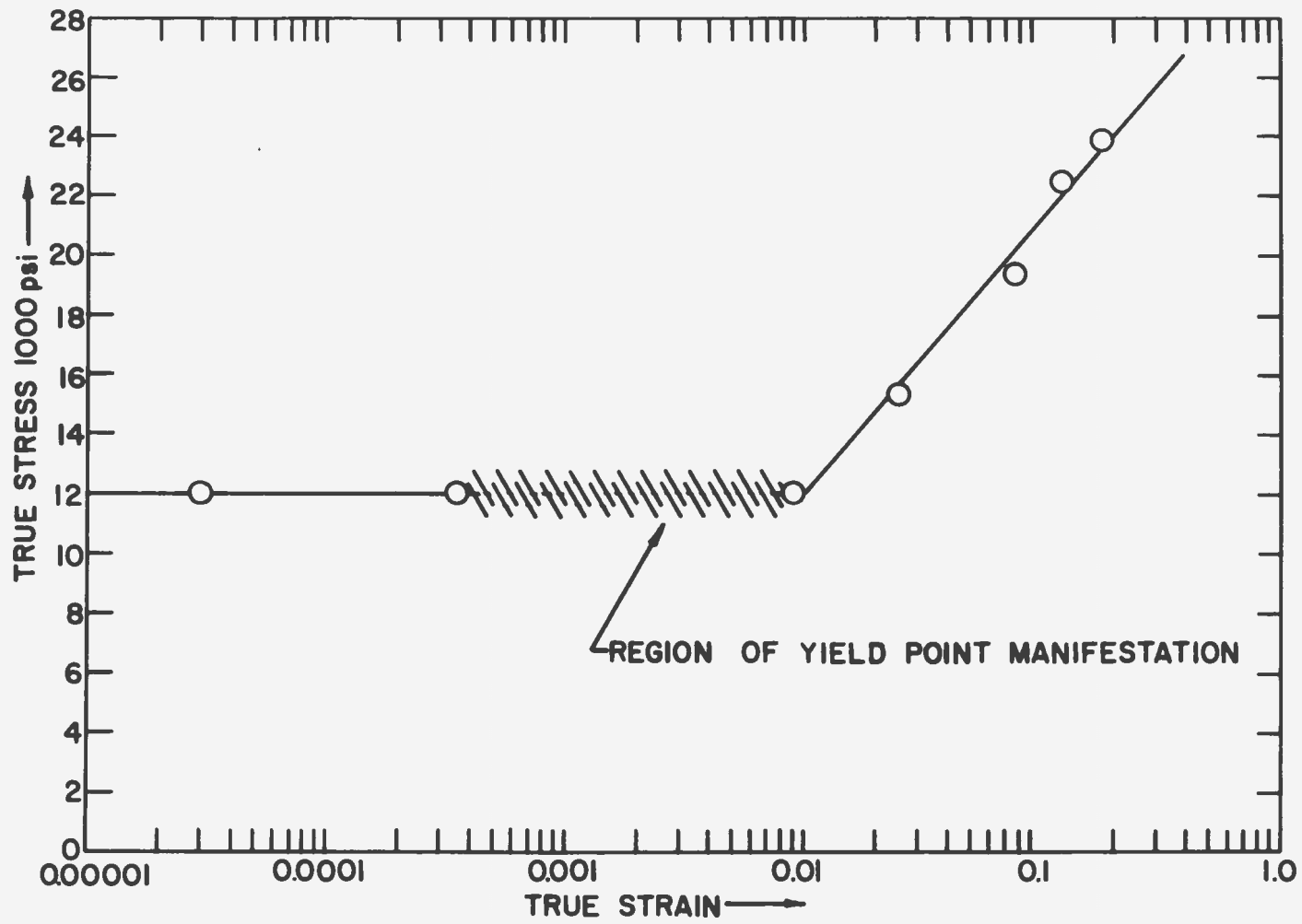


Fig. 6. Critical stress - true strain diagram of Ames thorium.

Pierls stress hills, jogs on edge dislocations or other obstacles small enough for dislocations to surmount with the aid of random thermal fluctuations. Thus, there is apparently an athermal component, σ_c , and a thermally activated component, $\sigma_f - \sigma_c$, of the flow stress, where σ_f is the flow stress. In equation form,

$$\sigma_f = \sigma_c + \sigma_T = 30,440 + 9,220 \log \epsilon_p + \sigma_T \quad (7)$$

where σ_T is the thermally affected component of the stress. A graphical representation of Eq. (7) is shown in Fig. 7, plotted from tensile and creep data for Ames thorium at 25°C.

The yield point phenomenon manifested as a decrease in load with increasing plastic strain at the beginning of plastic deformation in tensile tests on annealed Ames thorium was also observed in the creep tests of this investigation. A typical creep curve for annealed Ames thorium is shown in Fig. 8. Following the instantaneous strain upon application of the load, a small period of decreasing strain rate with increasing strain is observed. This corresponds to the small plastic strain observed in a tensile test prior to the upper yield point. Starting at the upper yield point, the strain rate increases with increasing plastic strain to a maximum value. This maximum value of the strain rate corresponds to the lower yield point. With increasing plastic strain beyond the lower yield point, the strain rate continues to decrease, which is typical of low temperature creep behavior.

A determination of the modulus of elasticity for annealed Ames thorium at 25°C was obtained from measurements of the elastic strain

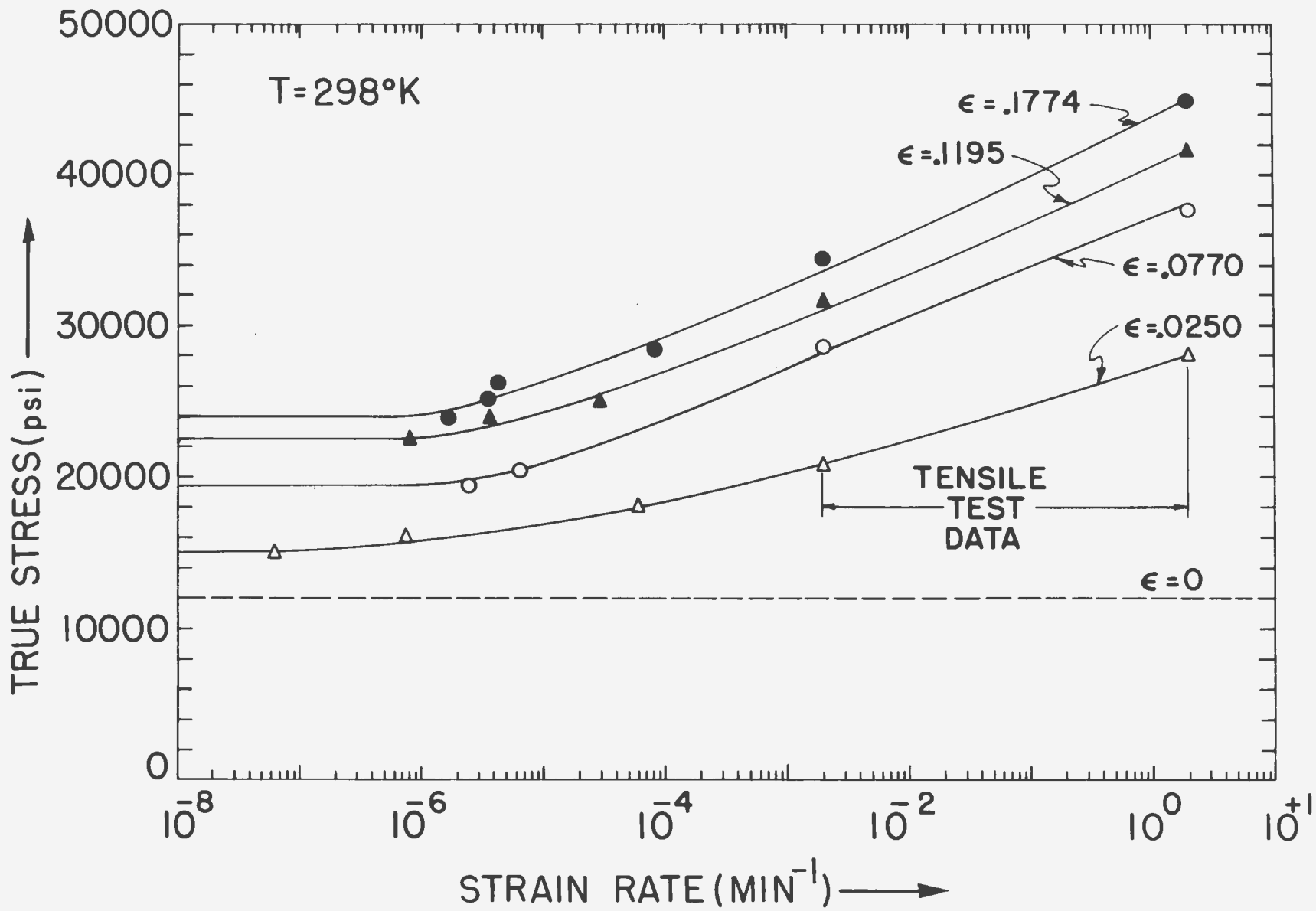


Fig. 7. True stress - strain rate diagram of Ames thorium.

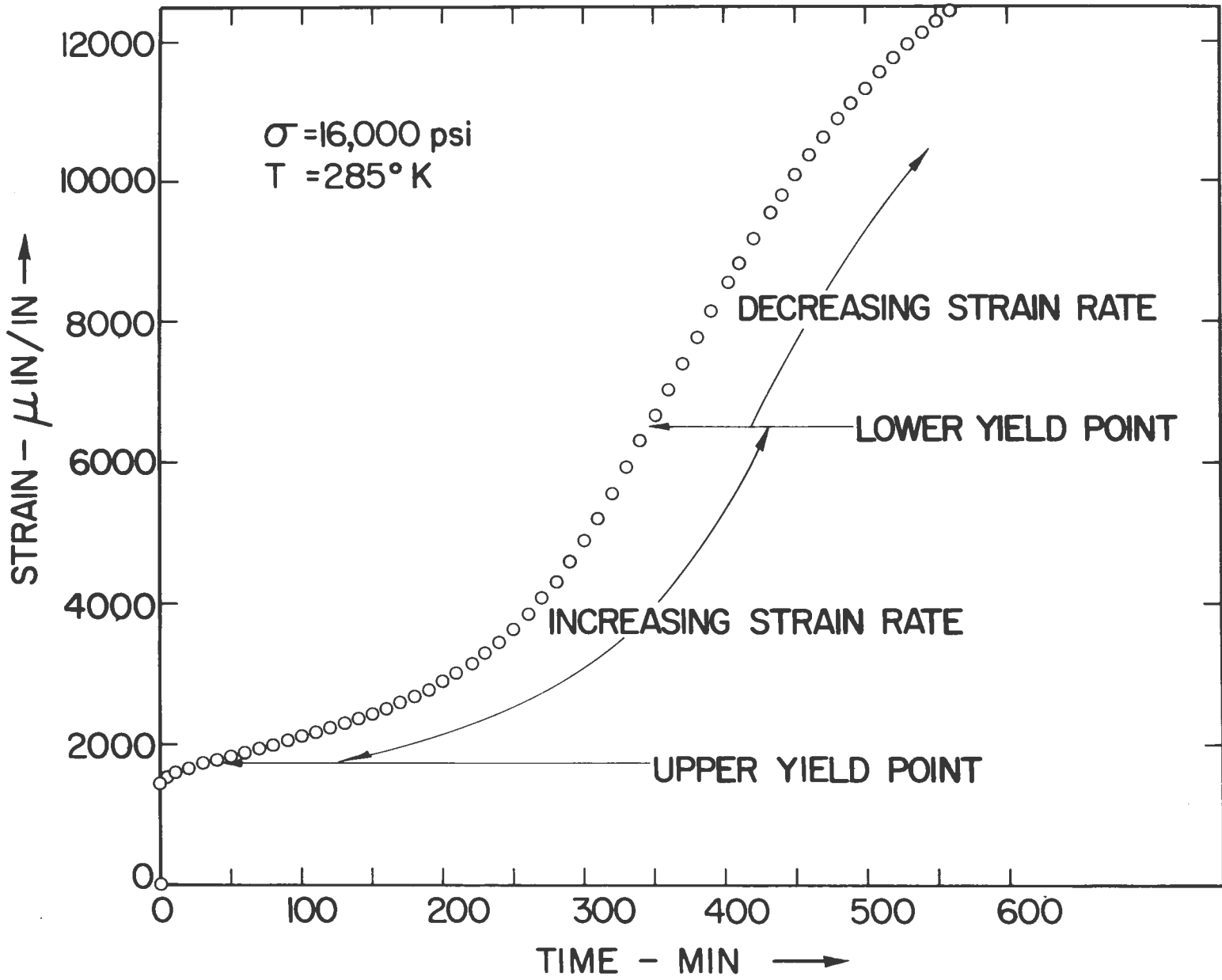


Fig. 8. Strain-time diagram of Ames thorium at 16,000 psi and 285°K.

at stresses below the critical stress. A least squares best fit of the data gave a value of 12.0×10^6 psi for the modulus of elasticity. By including only the completely elastic strain measurements, errors due to small anelastic and plastic strains observed at higher stresses below the conventional tensile yield point were eliminated. This would explain the reason that the above value of the modulus of elasticity is about 10% higher than most published values, which were undoubtedly obtained from tensile tests and would include the small anelastic and plastic strain error mentioned above.

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