Submitted to High Temperature Science

UCRL-16988 Rev.
Preprint

c.2

RECEIVED
LAWRENCE
RADIATION LABORATORY

JUN 5 1970

LIBRARY AND
DOCUMENTS SECTION

THE VISCOSITY OF URANIUM AND TWO URANIUM-CHROMIUM ALLOYS

J. S. Finucane and D. R. Olander

October 1969

AEC Contract No. W-7405-eng-48

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

UCRL-16988 Rev. c.2

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

THE VISCOSITY OF URANIUM AND TWO URANIUM-CHROMIUM ALLOYS

by J. S. Finucane and D. R. Olander

Inorganic Materials Research Division of the Lawrence Radiation Laboratory and the Department of Nuclear Engineering, University of California, Berkeley, California 94720.

ABSTRACT

The viscosity of liquid uranium and the 2.2 and 4.1 wt.% chromium-uranium alloys have been measured with an oscillating crucible viscometer.

INTRODUCTION

The viscosities of uranium metal and uranium chromium alloy systems are of interest for several reasons. Measurements of the transport properties of such a simple system as a liquid metal may yield greater insight into the structure of liquids. The transport properties of liquid uranium have also been used in hazards analyses of meltdown of metal fueled reactors as well as for studies of the feasibility of non-aqueous fuel reprocessing systems(1). The viscosity of uranium chromium alloys were measured since the low melting point of the eutectic (860°C) makes this binary a potential choice for a uranium-based molten metal reactor fuel.

The viscosity of a Newtonian fluid is defined as the proportionality constant between the shear stress and the velocity gradient and can be measured only in a dynamic system. The techniques which have been employed to measure this property of liquid metals, which includes capillary, rotational, and oscillatory methods, have been reviewed by Thresh (2).

Oscillating cylinder viscometers lend themselves well to high temperature systems. Moreover, our design, in which the sample is contained in a ~~completely~~ vacuum sealed cylindrical crucible, permits the use of samples which

have a high vapor pressure or are chemically reactive.

DATA ANALYSIS

The viscometer consists of a torsion pendulum containing the liquid metal in a cylindrical crucible supported by a wire. Upon displacement from the equilibrium position, the pendulum performs torsional oscillations of the simple damped harmonic type about the axis. The angular displacement is given by:

$$\theta(t) = \theta_0 e^{-\beta t}\cos(2\pi t/\tau) \qquad (1)$$

where τ is the period of the oscillation. The decay constant β is related to the logarithmic decrement δ by*

$$\delta = \beta\tau \qquad (2)$$

The period and decay constant are determined by the viscous drag of the liquid on the cylindrical walls and bottom of the crucible (the upper surface of the liquid is assumed to contact a vacuum). The equations of motion for the oscillating cylinder have been solved by Hopkins and Toye(3). Expressed in terms of the dimensionless parameters introduced by Wittenberg, Ofte and Curtiss (4), the solution may be written as (5):

$$4\pi\delta + Q[\delta\,\mathrm{Im}(F) - 2\pi\mathrm{Re}(F)] = 0 \qquad (3)$$

---

*The logarithmic decrement is defined as the natural logarithm of the ratio of the amplitudes on successive swings to the same side of the equilibrium position (i.e., $\delta = \ln[\theta(t)/\theta(t+\tau)]$).

where

$$Q = \frac{\frac{1}{2}ma^2}{I} \tag{4}$$

m is the mass of the liquid contained in the cylinder of radius a and I is the moment of inertia of the empty system.

Re(F) and Im(F) denote the real and imaginary parts of the complex function F, which is

$$F = \frac{4\lambda}{R}[S_1(\lambda) + 2BS_2(\lambda)] \tag{5}$$

The terms $S_1(\lambda)$ and $S_2(\lambda)$ in Eq(5) have been shown by Roscoe(6) to be well approximated by the series:

$$S_1(\lambda) = 1 - \frac{3}{2\lambda} + \frac{3}{8\lambda^2} + \frac{3}{8\lambda^3} + \frac{63}{128\lambda^4} + \cdots \tag{6}$$

$$S_2(\lambda) = \frac{1}{8} - \frac{2}{\pi\lambda} + \frac{9}{8\lambda^2} - \frac{1}{\pi\lambda^3} - \frac{45}{128\lambda^4} + \cdots \tag{7}$$

The dimensionless parameter B is the radius-to-liquid height ratio*

$$B = a/H \tag{8}$$

The parameter λ is a complex quantity dependent upon R and δ:

$$\lambda^2 = R(2\pi i - \delta) \tag{9}$$

---

*The S_1 term accounts for the torque exerted by the fluid on the cylindrical wall of the cylinder; the second term in the brackets of Eq(5) reflects the viscous drag on the cylinder bottom. For the values of the parameter B used in the present experiments (B~0.15), inclusion of the second term in the brackets of Eq(5) affects the computed viscosity by ~5%. This term was neglected in the development of ref 4.

where the dimensionless group R contains the kinematic viscosity of the liquid, ν*:

$$R = \frac{a^2}{\nu\tau} \qquad (10)$$

The geometry of the system and the mass of the sample determine the dimensionless parameters B of Eq(8) and Q of Eq(4). Eqs(3), (5), and (9) then constitute a relation between δ and R, the general shape of which is illustrated by Fig. 1 of ref. 4. The measured decay constant β (from which the inherent decay constant of the empty system has been subtracted) and the measured period τ fix the logarithmic decrement δ by Eq(2). With δ, B and Q specified, R is obtained by trial-and-error solution of Eq.(3) (on a computer).** The kinematic viscosity of the fluid is then obtained from Eq(10), the absolute viscosity can be calculated from the liquid density by:

$$\mu = \rho\nu \qquad (11)$$

The density of the liquid is directly involved in the analysis only as a means of estimating the liquid height (and hence the parameter B) from the sample mass

---

*The definition of R in Eq(10) differs from that of ref. 4, where the period of the empty cylinder was used instead of the period with the liquid inside. The ~~latter~~ former does not enter the present analysis (2).

**There may be two values of R which offer a solution (4,7). Our experiments were all in the "large cup" region, where the decay constant increases with decreasing R.

and crucible radius. Since the contribution of the last term in the brackets of Eq(5) is small, errors in the density do not significantly affect the accuracy of the kinematic viscosity. However, the accuracy of the absolute viscosity is no better than the accuracy of the liquid density. The estimated liquid height may also be in error because of the non-planar shape of the free liquid surface(2).

EXPERIMENTAL APPARATUS

General Description

The apparatus is shown in Fig. 1. The temperature control is accomplished by varying the power supplied to the Brew tungsten mesh resistance furnace (A) which is 3 in. in diameter and 6 in. in height. The heater element is surrounded by a series of tungsten radiation shields (B). The entire system is contained within a vacuum system (C) in order to minimize energy transfer by convection from the hot zone, to eliminate any viscous drag on the cylindrical crucible arising from the surrounding gases, and to prevent attack of the crucible by gaseous impurities.

The torsion pendulum consists of three primary parts: the crucible (D) which contains the sample; a centerless ground refractory metal rod (E) which rigidly connects the crucible with that part of the pendulum external to the heater; and the external portion of the pendulum (F) which has a polished surface to reflect a beam of light by which the motion of the pendulum is monitored. A hole is drilled through the pendulum perpendicular to its axis of rotation into which rods may be inserted and fixed such that moment of inertia of the pendulum may be varied over a wide range. Since these inertia rods

rotate about 4 in. above the heater which carries up to 750 amps DC, it was necessary that they be of a non-magnetic material. Molybdenum rods were used. The small chuck (G) attaches the pendulum to the torsion wire. A picture of the entire pendulum is shown in Fig. 2. The white piece at the top of the vertical rod is an alumina connector used to reduce the heat load on the upper portion of the pendulum.

The torsion wire (H) extends from the pendulum to a second chuck which is attached to a rotatable holder (J) which rests on a support plate (K). Torsion wires made of 302 stainless steel about 6 in. long and varying in diameter from .006 in. to .014 in. were used. The holder is attached mechanically to a rotary feedthrough (L) by which the torsional motion of the pendulum may be initiated from outside the vacuum system.

The temperature within the furnace region is measured by an optical pyrometer (M) which is sighted through a right angle prism (N) into a hole, 1/8 in. in diameter, drilled through the bottom shield pack into the inner furnace region.

The electrical power required by the heater is 750 amps at zero to 25 volts. To reduce changes in magnetic field intensity (which could damp pendulum oscillation) the 480 three-phase AC line voltage was transformed and full wave rectified to give DC. A filter network was

included to reduce the ripple on the DC, but it could not be shown that this improved the performance of the power supply.

The vacuum system consists of a 15 c.f.m. mechanical pump and a 200ℓ/sec ion pump (P). The vacuum system has an ultimate pressure after bake-out of 5×10^{-8} torr, and maintains the pressure at 3×10^{-7} torr during operation with furnace temperatures up to 1500°C.

The ion pump system was chosen in preference to a diffusion pump system to allow the mechanical fore pump to be turned off before viscosity measurements were to be made. This was necessary to prevent pump vibrations from interfering with the pendulum motion. The entire vacuum system was mounted on a platform resting within a box of sand to isolate the system from building vibrations.

Pendulum Motion Recording System

The recording system is illustrated in Fig. 3. The period of oscillation and the decay constant associated with the motion of pendulum are measured by aiming a beam of light (A) at the mirrored surface of the pendulum (B) so that the reflected beam sequentially strikes a series of three photo cells (C). The photo cells are ~5° apart. A small voltage is applied across each photo cell and the output of each cell is fed into a high speed chart recorder. In addition, a series of timing impulses is fed into the

recorder so that the instant at which the light beam passed each photo cell could be determined to the nearest millisecond. The only assumption inherent in this technique is that the pendulum is in identically the same position every time a single photo cell fires. Assuming that the angular displacement is given by Eq(1), the period τ and decay constant β can be determined from the raw data. The period is calculated as the average time between successive firings of the individual photo cells. The decay constant is calculated as illustrated with reference to Fig. 4. The damped harmonic curve (a) represents the angular displacement of the light beam as a function of time. The position (b) represents the location of one of the three photocells. The firing times of the photocell are represented by $t_1 \ldots t_6$. If damping over the intervals t_2-t_1 and t_6-t_5 is neglected, the curves in Fig. 4 can be considered symmetric about the peaks. In this case, the height of the peaks are proportional to $\cos[(t_2-t_1)\pi/\tau]$ and $\cos[(t_6-t_5)\pi/\tau]$ respectively, and the decay constant is given by:

$$\beta = \frac{1}{2\tau} \ln \left\{ \frac{\cos\left[\frac{(t_6-t_5)\pi}{\tau}\right]}{\cos\left[\frac{(t_2-t_1)\pi}{\tau}\right]} \right\} \tag{12}$$

Generally, the decay constant is calculated by comparing the firing time intervals for peaks separated by more than two periods. In this case, the "2" in Eq(12) is replaced by the number of cycles separating t_6-t_5 and t_2-t_1.

If the asymmetry of the peaks caused by damping of the oscillations is taken into account, it can be shown that the exact value of β differs from the value given by Eq(12) by the factor

$$1 + \frac{X_{56} - X_{12}}{4\pi}$$

where $X = y/\tan y$, $y = \pi\Delta t/\tau$, and $\Delta t = t_2 - t_1$ or $t_6 - t_5$. For the case of $\beta\tau \ll 1$, the above factor can be expressed by

$$1 + \left[\frac{\beta\tau}{2\pi}\right] \left\{ \frac{\frac{y}{\tan y} - \cos^2 y}{\sin^2 y} \right\}$$

where here $y = \pi(t_2 - t_1)/\tau$. In the experiments reported here, $(\beta\tau/2\pi) < 0.01$. The bracketed term in the above expression is always less than 2/3. Therefore, the approximate decay constant formula, Eq(12), is valid to within 0.7%.

EXPERIMENTAL PROCEDURE

Preliminary Measurements

The inherent decay constant (β with no viscous damping due to the liquid) was measured while the sample was in the solid state both before and after each run. It was found to be in the range .0002 sec^{-1} to .0016 sec^{-1}. A system decay constant (viscous + inherent) of the order .0060 sec^{-1} to .0160 sec^{-1} could be conveniently and accurately measured while the pendulum performed 10 to 20 complete oscillations. The primary quantity used to determine the decay constant was the time interval between two consecutive firings of a single photocell (i.e., t_2-t_1 ~~or~~ and t_6-t_5 in Fig. 4). Since these times could be measured only to the nearest millisecond, the minimum acceptable ~~interval~~ difference between (t_2-t_1) and (t_6-t_5) was set at 30 milliseconds. These restraints required a period of at least 3 sec. In order to insure that the period and decay constant fell within these ranges, a parametric study to determine the best values for both the moment of inertia and the torsion wire diameter (based upon an approximate value of the viscosity) was made for each sample run.

The moment of inertia was measured as follows. The metal sample was melted at least once to allow it to assume the shape and size of the crucible. With the system

at room temperature and one of the inertia bars inserted symmetrically through the hole perpendicular to the axis of rotation, the period was measured. The inertia bar was then removed and the period was determined again. The change in the moment of inertia may be calculated to better than 0.1% from the dimensions and the mass of the bar. Knowing the exact change in the moment of inertia and using the fact that the period varies inversely with the square root of the moment of inertia, the moment of inertia for the whole system was calculated. Finally, the moment of the solid metal sample was calculated and subtracted from the value for the whole system to obtain the value needed for the empty system.

Sample Preparation

The materials used in this work were obtained from the National Lead Company. They consisted of depleted uranium (0.22% U^{235}) and uranium-chromium pellets weighing about 5 grams each. The oxide coat was removed from the samples by first pickeling in hot concentrated nitric acid and then electrolyzing in a dilute sulphuric acid solution using 12 volts DC (the pellets were the cathode).

After a sufficient number of pellets had been melted in a BeO crucible to form a rod 3/4 in. in diameter and about 3 in. long, the ingot was machined down to the

dimensions of the crucible. The oxygen content of the sample~~s~~ after vacuum melting in BeO crucibles was always less than 25 parts per million. The specimen was then weighed, inserted into a crucible, and put into a container which was then evacuated. It was shipped in this condition to the Lawrence Radiation Laboratory in Livermore where the lid~~s~~ of the crucibles ~~were~~ was electron-beam welded on under vacuum conditions.

Spectrochemical analyses were performed on the samples and the results are given in the Table ~~IV~~ I. All samples except the first one were analyzed after undergoing the viscosity measurements.

Table ~~IV~~ I

Spectrochemical Analyses

Contaminant	U Vacuum Melted in BeO (ppm)	U from Ta ~~Container~~ Crucible (ppm)	U from BeO ~~Container~~ Crucible (ppm)	U-2.2 w/o Cr from BeO ~~Container~~ Crucible (ppm)
Si	50	10	50	50
Cu	< 10*	< 10*	< 10*	< 10*
Mn	< 10*	< 10*	< 10*	< 10*
Mg	< 10*	< 10*	< 10*	< 10*
B	< 10*	< 10*	< 10*	< 10*
Ni	< 10*	~ 100	200	< 10*
Fe	< 100	< 100	< 100	100
Cr	< 10	< 10*	< 10	2.2%[a]
Be	< 10	< 10	1000[c]	10
Na	< 100	< 100	< 100	< 100
Zn	< 10	< 10	< 10	< 10
Sn	< 10	< 10	< 10	< 10
Ti	< 10	< 10	< 10	< 10
Ta	~~<~~ b	~~<~~ b	~~<~~ b	~~<~~ b

* The spectral lines of these elements were observed but the intensity was less than the standard value, which is listed.

[a] The 2.2 weight percent chromium was determined by weighing the separated chromium as Cr_2O_3.

[b] Ta was determined using the solution copper spark method. The low limit of the sensitivity of this method is 0.5%. No Ta was detected in any sample.

[c] The high content of Be in this sample resulted from allowing the sample to remain several hours at about 1600°C.

Viscosity Measurements

The heater was turned on and the temperature within the hot zone was monitored until a steady temperature was reached. The initial setting of the heater power supply was adjusted to yield a temperature just below the melting point of the sample. The mechanical starter was then engaged and the pendulum was given an initial angular displacement. (The initial displacement was nominally limited by the yield point of the torsion wire; however, displacements of up to 90° from the equilibrium position caused no difficulty.) The recorder was then started and the inherent decay constant of the pendulum system without the effect of viscous damping was measured. The inherent damping constant was measured with a solid tungsten crucible at temperatures up to 1950°C and was found to be temperature independent.

The temperature was then increased in steps, each time allowing thermal equilibrium to be reached before the decay constant and period of the liquid sample were measured. The temperature was increased in such a manner that one half of the desired number of data points were obtained while approaching the highest temperature and the rest were measured while the system was cooling back down. This procedure was adopted to insure that a reaction between the sample and the container had not occurred and that the viscosity data in the low temperature range were reproducible.

RESULTS

Testing

The torsion pendulum system is an absolute method of viscosity determination. The testing of the system was accomplished by measuring the viscosity of a material for which accepted literature values of the viscosity were available. For this purpose tin was chosen. Tin is available in a very pure state and does not react with the BeO crucible. The density of tin was taken from Kirshenbaum and Cahill.[8] The temperature was measured over the entire temperature range of the viscosity measurements (230°C to 1100°C) with a calibrated chromel alumel thermocouple. As an additional check on the temperature measurements, a calibrated optical pyrometer was used to confirm the values of the temperature above 850°C. The results of the measurement of the viscosity of tin are given in Fig. 5. The solid line represents a least squares curve fit to the viscosity data for tin from reference 9. The data points shown as open circles were measured during initial testing of the system. The data points shown as closed circles were obtained when the system was recalibrated after the completion of the uranium metal and uranium chromium alloy measurements. The activation energy calculated from our data was 1.44 kcal/gram atom, which compares quite favorably with the value of 1.52 kcal/gram atom calculated from the data

given in ref. 9 as well as the value of 1.4 kcal/gram atom reported for pure tin by Kanda and Colburn.[10]

Pure Uranium

The uranium viscosity measurements were carried out on two separate runs. The first sample was held in a molybdenum crucible with a beryllium oxide liner and its viscosity was measured from the melting point at 1132°C to a temperature of 1532°C. In order to isolate any possible effect of a reaction between the sample material and its container, a second sample of pure uranium was measured in a tantalum crucible. The density of pure liquid uranium was taken as that recently reported by the Mound Laboratory.[11] The viscosity results are shown in Fig. 6 and in Table II. Figure 6 also contains a line representing the Mound Laboratory data for the viscosity of pure uranium.[12] The activation energy calculated from our data was 6.5 kcal/gram which is comparable with the value of 7.3 kcal/gram reported in ref. 12; however, the absolute value of the viscosity measured by the Mound Laboratory averaged ~35% lower than the values reported here. The cause of this discrepancy is unknown.

Chromium Uranium Alloys

The viscosity of two different chromium uranium alloy systems was measured. The densities of these liquids have not been measured but were estimated by a method reported

Table II Uranium metal

Container: BeO
Moment of inertia: 825.1 gr cm^2
Radius: .809 cm
Mass: 222.5 gr
Height of liquid at 1128°C: 6.26 cm
11 mil torsion wire

Temp °C	Decay Constant ($\times 10^4$ sec^{-1})	Period (sec)	Density (g/cc)	Viscosity cP
1128	135.3	3.510	17.28	10.09
1158	132.3	3.517	17.23	9.54
1245	124.5	3.520	17.09	8.17
1347	119.0	3.521	16.92	7.26
1361	118.9	3.526	16.90	7.25
1532	111.0	3.533	16.63	6.09

Container: Ta
Moment of inertia: 723.7 gr cm^2
Radius: .794 cm
Mass: 206.1 gr
Height of liquid at 1131°C: 6.03 cm
9 mil torsion wire

Temp °C	Decay Constant ($\times 10^4$ sec^{-1})	Period (sec)	Density (g/cc)	Viscosity cP
1131	116.6	4.693	17.27	10.00
1136	115.8	4.696	17.26	9.83
1150	115.0	4.696	17.24	9.64
1179	114.7	4.695	17.19	9.55
1202	112.8	4.694	17.16	9.12
1228	110.2	4.693	17.12	8.57

by Pasternak.[13] The density of uranium is represented by the equation[9]

$$\rho = 19.083 - 16.01 \times 10^{-4} T$$

where the density is in g/cc and the temperature in °C. This equation indicates that the density of the subcooled liquid uranium at 1000°C is 91.7% of the room temperature density of the solid (19.06 g/cc). The room temperature density of the U-Cr eutectic was determined to be 17.5 g/cc,[13] which is within a percent of the value calculated for an ideal mixture. Assuming the ratio $\rho_{liq}(1000°C)/\rho_s(25°C)$ of the eutectic is the same as that for pure uranium, the density of the molten eutectic at 1000°C is estimated to be 16.05 g/cc. The temperature dependence of the liquid density was assumed to be that predicted by Strauss.[14] The density of the intermediate composition alloy was estimated by assuming that density varied linearly with percent Cr composition from zero percent, represented by the density for pure uranium, to 5 wt.% chromium, represented by the estimated density for the eutectic.

The 2.2 wt.% chromium alloy was prepared by adding a 110.4 gram ingot of uranium metal to a 94.9 gram ingot of eutectic (4.46 wt.% chromium) and co-melting the mixture in the crucible. The results are shown in Fig. 7 and Table III. The measured viscosities ranged from 11.9 cP at 1018°C to 7.5 cP at a temperature of 1285°C. The value of 11.02 cP for this alloy at 1007°C is due to a

Table III Uranium - 2.2 weight percent chromium

Container: BeO
Moment of inertia: 826.3 gr cm^2
Radius: .810 cm
Mass: 205.3 gr
Height of liquid at 1018°C: 5.91 cm
11 mil torsion wire

Temp. °C	Decay Constant ($\times 10^4$ sec^{-1})	Period (sec)	Density gr/cc	Viscosity cP
1007	130.6	3.522	16.85	11.02
1018	134.6	3.516	16.84	11.87
1026	134.1	3.514	16.82	11.73
1063	130.1	3.516	16.78	10.85
1090	128.1	3.509	16.75	10.38
1141	121.8	3.513	16.67	9.13
1168	120.6	3.515	16.64	8.91
1175	122.6	3.514	16.63	9.38
1180	119.3	3.514	16.62	8.66
1236	115.5	3.514	16.55	7.97
1285	112.4	3.516	16.49	7.44

partial solidification of the sample. A least squares fit, as shown by the solid line through the data points gave an activation energy for viscous flow of 6.7 kcal/gram atom.

The second sample shown in Fig. 8 and in Table ~~III~~ IV had a composition of 4.1 wt.% chromium, which is somewhat lower than the composition of the chromium-uranium eutectic alloy (5.0 wt.%[15]). The calculated activation energy for this sample was 8.6 kcal/gram atom.

Table ~~III~~ IV. Uranium - 4.1 weight percent chromium*

Container: BeO
Moment of Inertia: 814.0 gr cm^2
Radius: .812 cm
Mass: 202.4 gr
Height of liquid at 933°C: 6.07 cm

Temp °C	Decay Constant ($\times 10^4$ sec^{-1})	Period (sec)	Density (gr/cc)	Viscosity cP
11 mil torsion wire				
933	158.8	3.490	16.12	17.27
1005	147.6	3.486	16.05	14.08
1070	137.2	3.489	15.98	11.61
1105	134.0	3.488	15.95	10.90
1108	133.7	3.484	15.95	10.82
1147	128.8	3.491	15.91	9.85
1211	122.0	3.490	15.85	8.58
1243	120.5	3.493	15.81	8.31
1283	117.1	3.493	15.78	7.74
9 mil torsion wire				
942	122.1	4.996	16.11	15.87
1006	117.9	4.986	16.05	14.22
1095	107.5	4.986	15.96	10.93
1204	99.0	4.986	15.85	8.72
6 mil torsion wire				
942	67.3	11.560	16.11	16.18
974	66.3	11.551	16.08	15.14
982	65.7	11.551	16.07	14.55
1016	64.4	11.539	16.03	13.31
1046	62.4	11.533	16.00	12.11
1071	61.4	11.542	15.98	11.08
1131	59.0	11.526	15.92	9.58

* Chromium content was determined by colorimetry using the diphenylcarbazide method.

DISCUSSION OF RESULTS

Uranium Metal

The experimental value of the activation energy for viscous flow was found to be in good agreement with the empirical correlations of Chapman[16] and of Grosse[17] as shown in Table ~~IV~~ V. The absolute value of the viscosity, however, was not predicted nearly ~~so~~ as well. The only reported experimental viscosity measurement on another actinide element is the determination of the viscosity of plutonium by Jones, et al.[18] The measured viscosities of uranium and plutonium are both higher than the predicted values. ~~and it may be necessary to develop a different correlation to adequately describe the behavior of the actinide elements.~~

Table ~~IV~~ V

	η_{mp} (cP)	E_{vis} (kcal/mole)
Grosse-Andrade	5.9	7.5
Chapman	3.9	6.2
Mound Laboratory (12)	6.5	7.3
Present work	10.0	6.5

Uranium-Chromium Alloys

~~The temperatures at which each chromium uranium alloy began solidification (as indicated by an abrupt decrease in~~

~~the decay constant) agreed quite well with those predicted from the phase diagram 15 shown in Fig. 9~~. The viscosity of the alloys was not greatly different from the viscosity of uranium metal at the same temperature, but the addition of small amounts of chromium ~~did~~ permitted lower temperatures and hence higher viscosities to be attained. The viscosity isotherms shown in Fig. ~~10~~ 9 exhibit minima at low temperatures. The minima occur at compositions less than the eutectic composition. Since the estimated densities are probably accurate to within 1%, the >4% minimum in the 1132°C curve of Fig 9 is believed to be real.

Wittenberg et al(4) observed abnormal behavior in viscosity measurements of two plutonium alloys for large periods and high viscosities. From the dimensionless grouping of Eq(10), this combination of parameters is equivalent to a small value of R. The abnormal effect, which was attributed to non-Newtonian characteristics of the liquid metal, was observed for R<~ 7. To investigate whether the U-Cr system exhibited similar abnormalities, a set of measurements was performed on the 4.1% sample with a 6 mil diameter torsion wire (Table ~~III~~ IV). Although R values as low as 5.7 were attained in this experiment, the ~~computed~~ measured viscosities were indistinguishable from those with much shorter periods and R values considerably greater than 7.

REFERENCES

1. D. R. Olander and A. D. Pasternak, "Mass Transfer and Transport Properties in Fused Salt and Liquid Metal Systems", Nuclear Fuel Reprocessing Symposium, Ames Laboratory, August 1969.

2. H. R. Thresh, Trans. ASM 55, 790 (1962).

3. M. R. Hopkins and T. C. Toye, Proc. Phys. Soc. (London) B63, 773 (1950).

4. L. J. Wittenberg, D. Ofte, and C. F. Curtiss, J. Chem. Phys. 48, 3253 (1968).

5. J. Finucane, (Ph.D. Thesis), U.C.R.L.-16988 (1969)

6. R. Roscoe, Proc. Phys. Soc. London, 72, 576 (1958).

7. J. Kestin and G. F. Newell, Z. Angew, Math. U. Physik, 8, 433 (1957)

8. A. D. Kirshenbaum and J. A. Cahill, Trans. ASM, 55, 844 (1962).

9. C. J. Smithells, Metals Reference Book, (Plenum Press, New York, 1967), 4th ed., Vol. III, p. 689.

10. F. A. Kanda and R. P. Colburn, Physics and Chemistry of Liquids, 1968, Vol. I, pg. 147-157.

11. Mound Laboratory Report, MLM-1445, May 13, 1968, pp. 12-13.

12. D. Ofte, J. Nuclear Materials, 22, 28-32 (1967).

13. A. D. Pasternak, (Ph.D. Thesis), UCRL-16108, January 1966.

14. S. W. Strauss, Nuclear Sci. Eng., 18, 280 (1964).

15. M. Hansen, Constitution of Binary Alloys, (McGraw-Hill Book Company, Inc., New York, 1958), pp. 569-570.

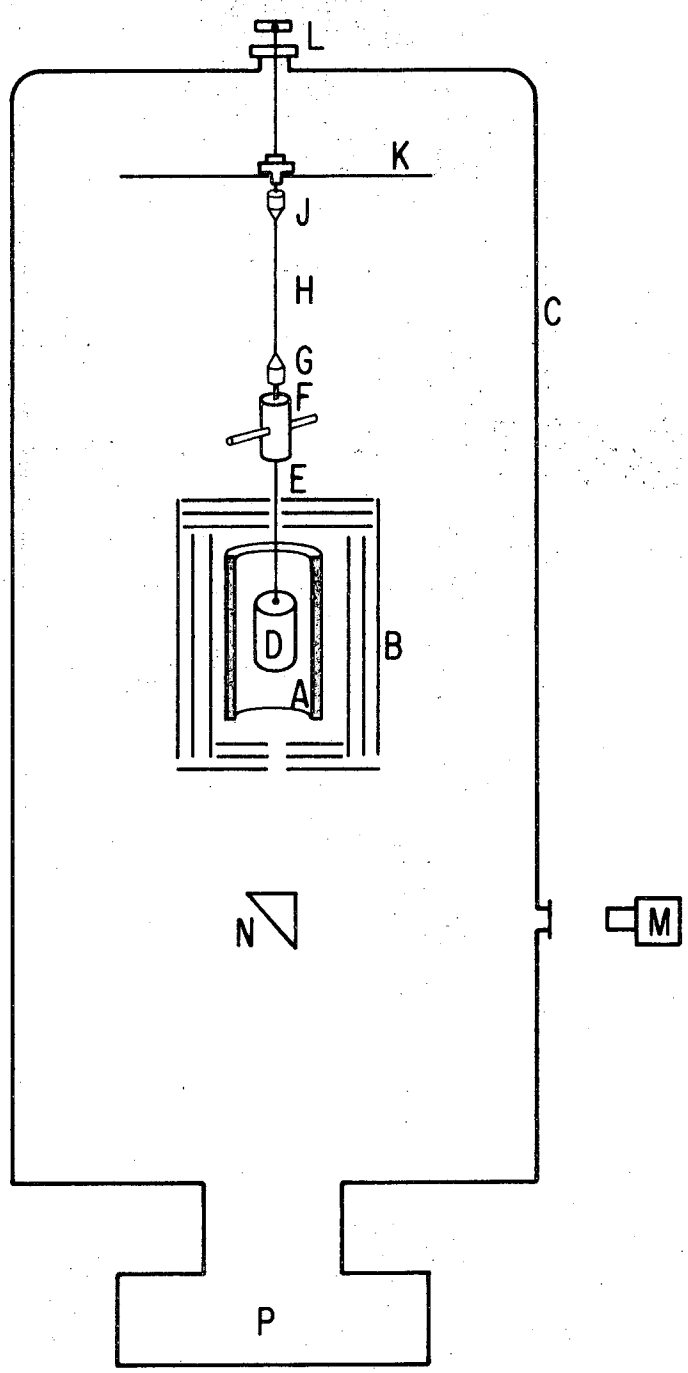
16. T. W. Chapman, A.I.Ch.E. Journal, 12, 395 (1966).

17. A. V. Grosse, J. Inorg. and Nuc. Chem., 25, 317 (1963).

18. L. V. Jones, D. Ofte, W. G. Rohr, and L. J. Wittenberg, Trans. ASM, 55, 819 (1962).

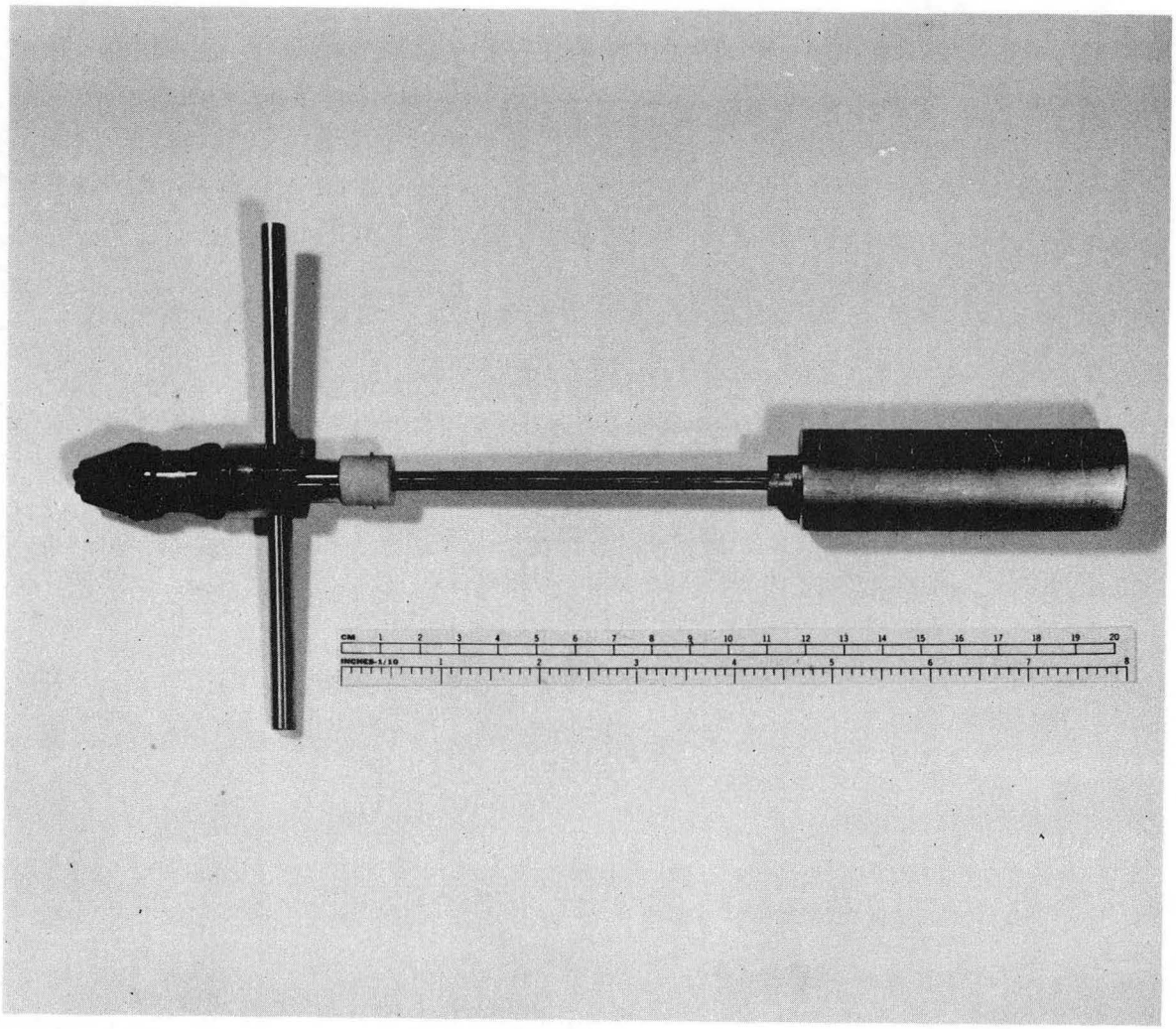
Figure Captions

Fig. No.	Caption
1	Diagram of the Experimental arrangement
2	Torsion pendulum
3	Diagram of oscillation recording system
4	Decay constant calculation method
5	Viscosity of Tin
6	Viscosity of uranium
7	Viscosity of the 2.2 wt.% chromium-uranium alloy
8	Viscosity of the 4.1 wt.% chromium-uranium alloy
~~9~~	~~Uranium-chromium phase diagram~~
~~10~~ 9	Viscosity isotherms in the uranium-chromium system



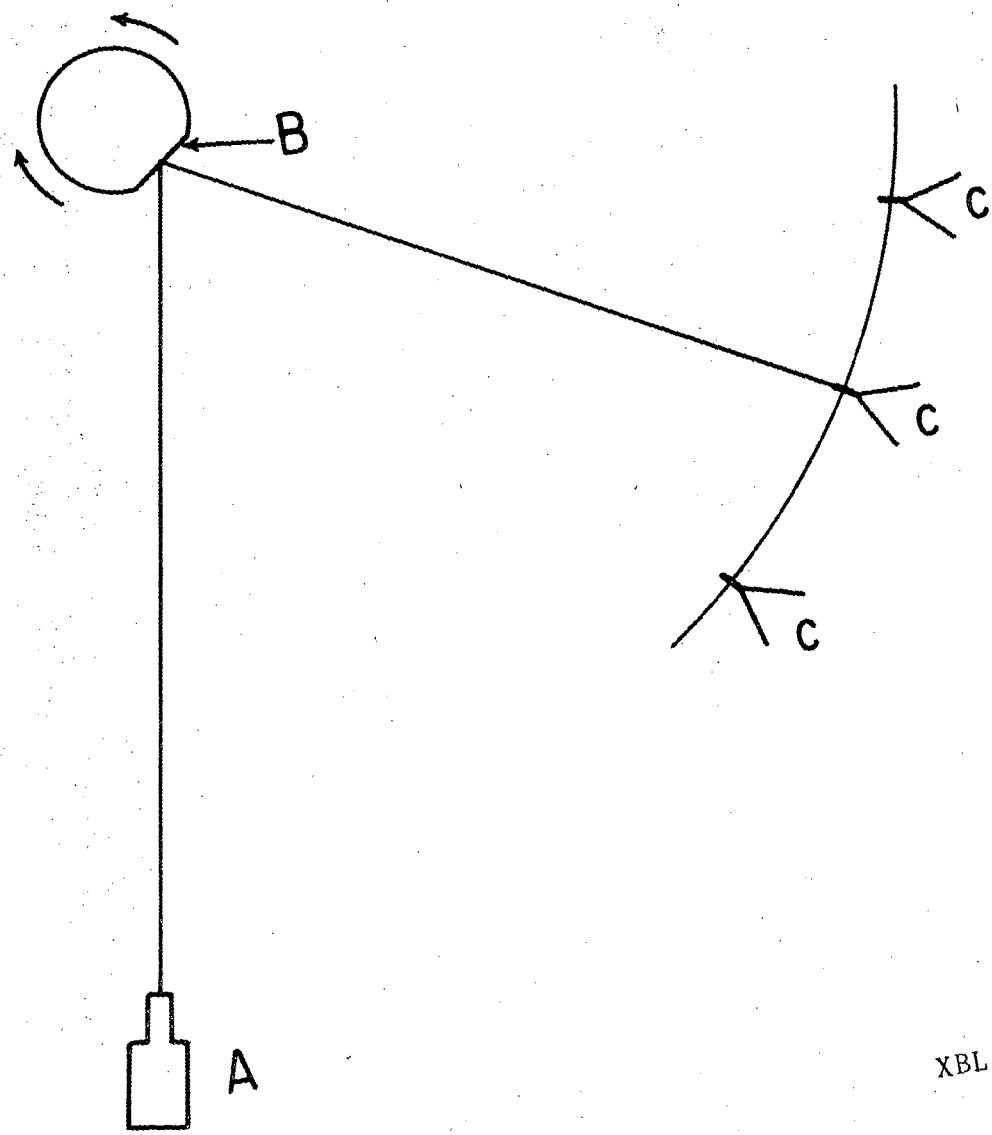
XBL 694-426

Fig. 1



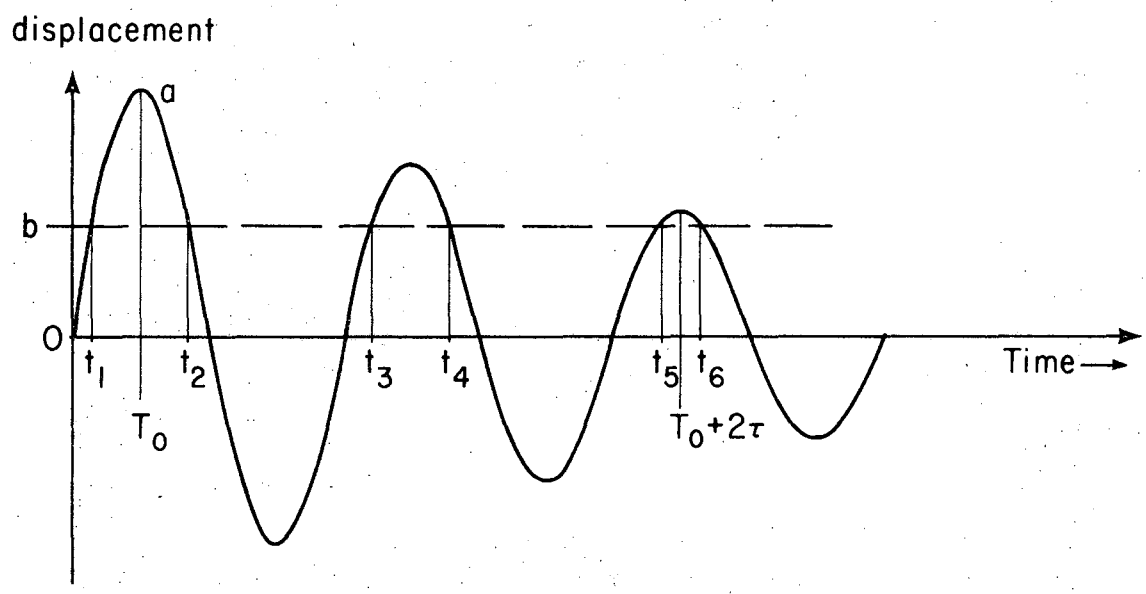
XBB 6811-6906

Fig. 2



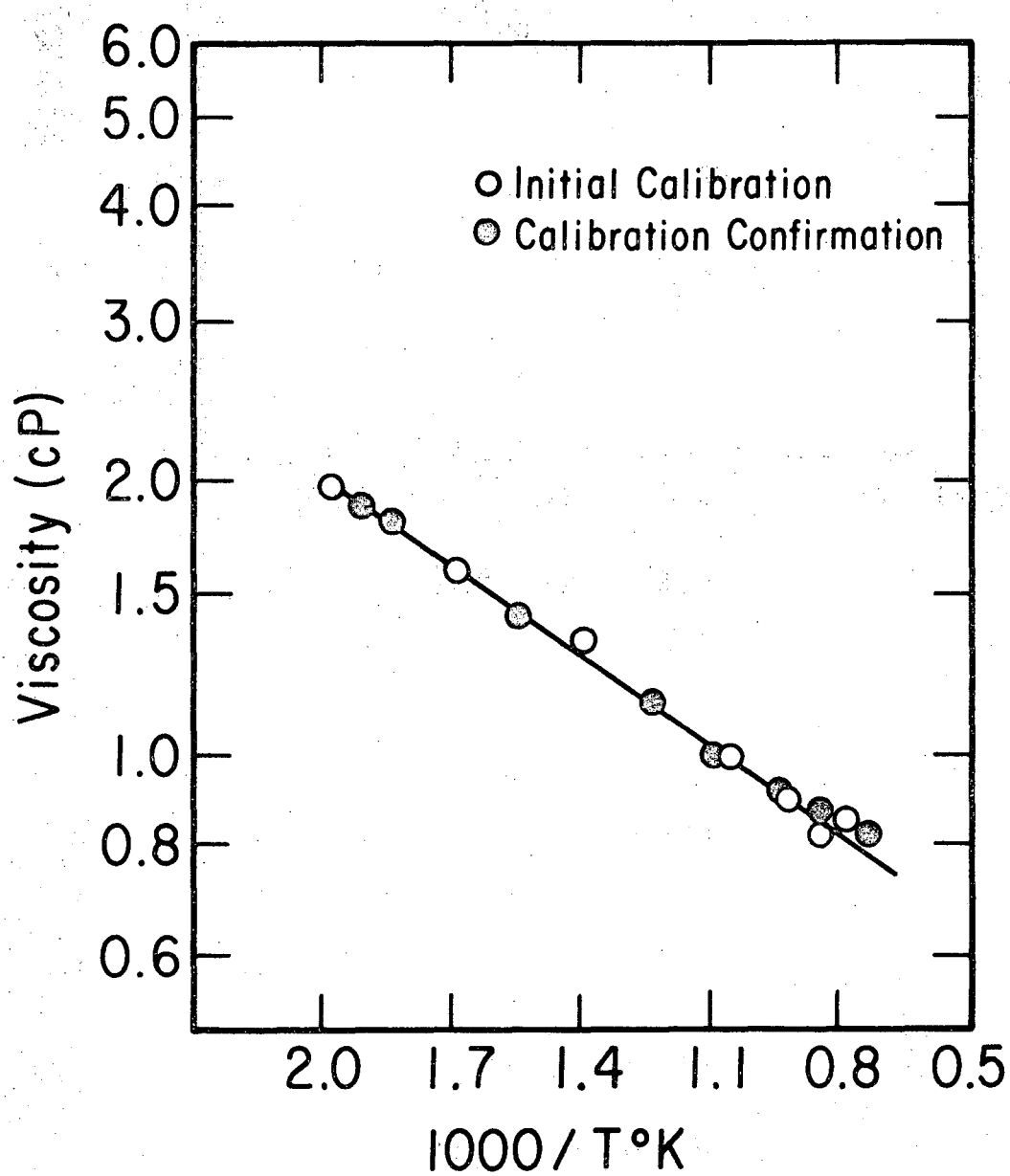
XBL 694-428

Fig. 3



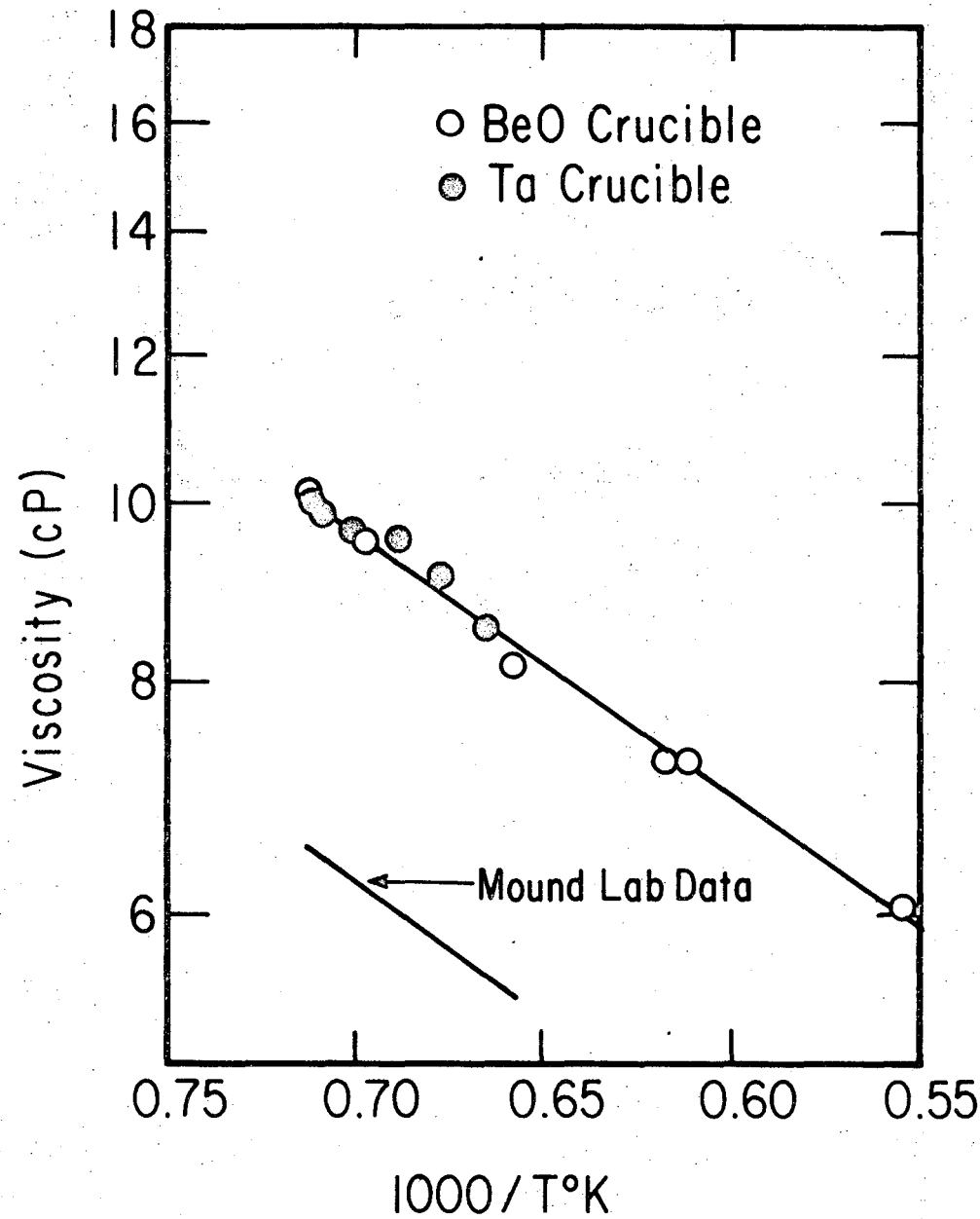
XBL 695-483

Fig. 4



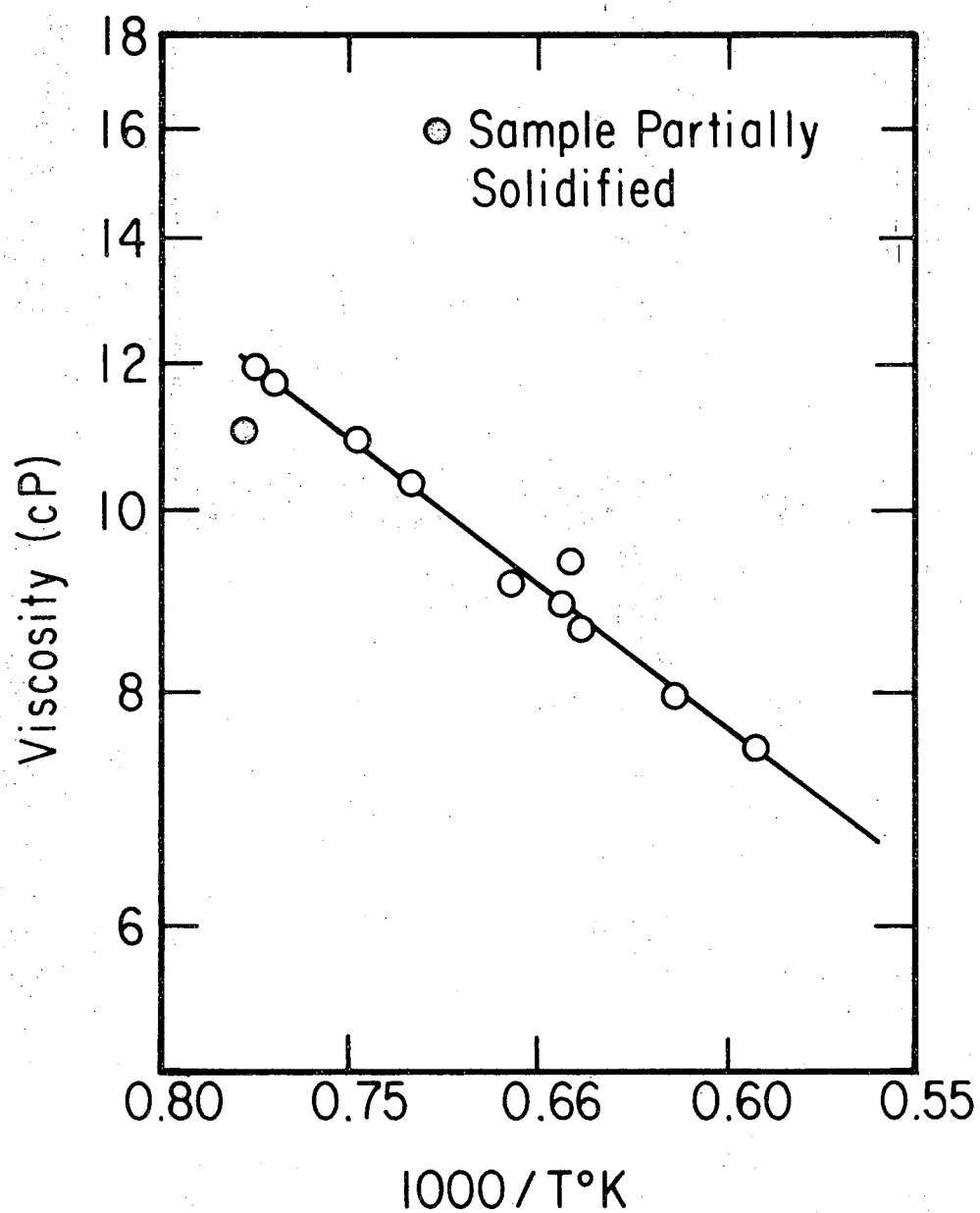
XBL 694-425

Fig. 5



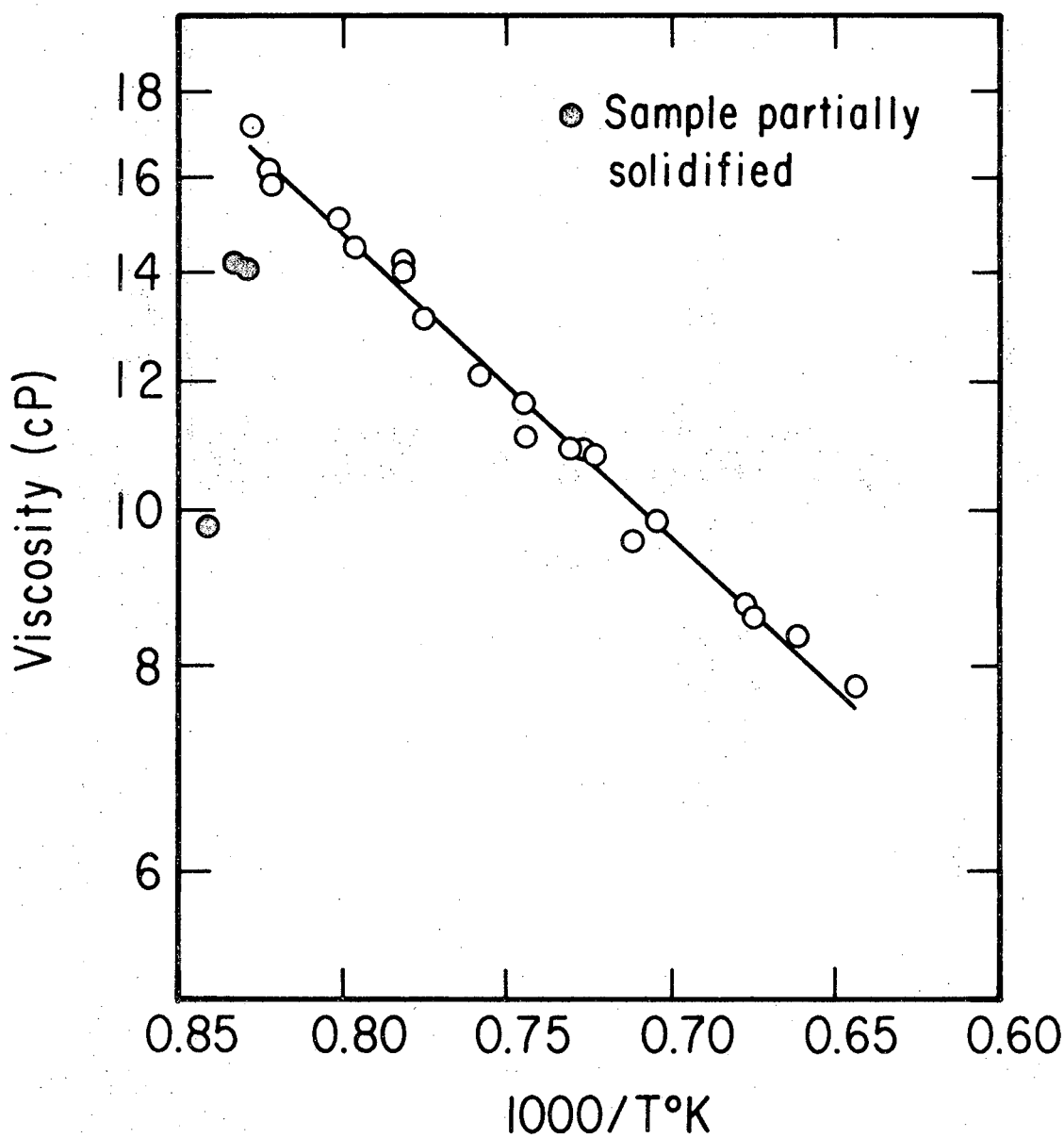
XBL 694-429

Fig. 6



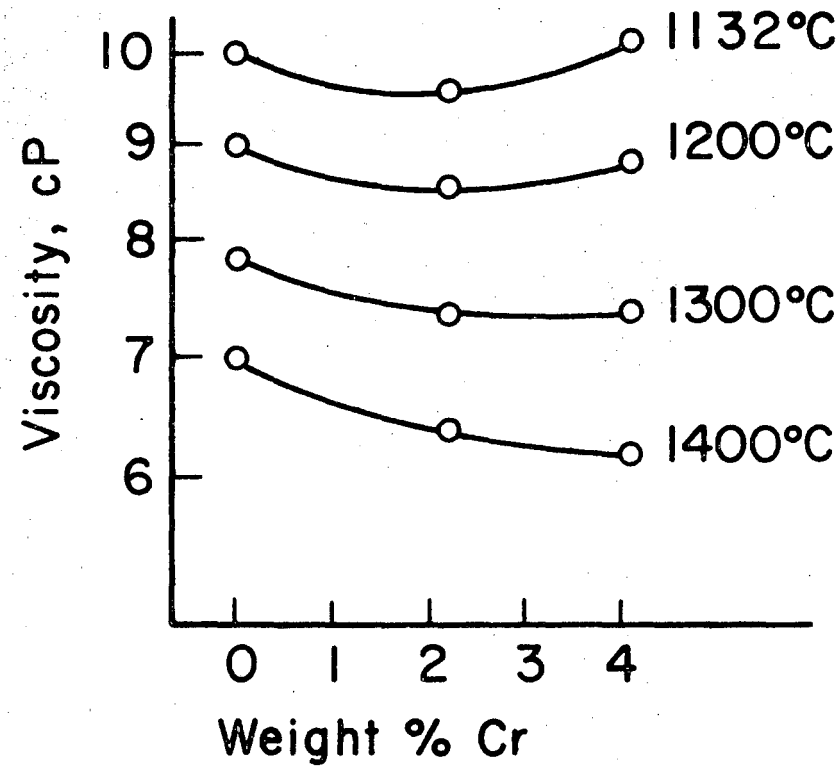
XBL 694-427

Fig. 7



XBL 695-485

Fig. 8



XBL 704-810

Fig. 9

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.