# PROPERTIES OF HOT EXPANDED LIQUID ALUMINUM

G. Roger Gathers
Marvin Ross

July 1, 1983

Lawrence
Livermore
National
Laboratory

MASTER

PROPERTIES OF HOT EXPANDED LIQUID ALUMINUM*

G. Roger GATHERS and Marvin Ross

University of California, Lawrence Livermore National Laboratory,
Livermore, California 94550

Measurements of temperature, volume, enthalpy, and electrical resistivity
have been made on aluminum expanded isobarically by 50% in volume to
temperatures of about 4000 K. These measurements are compared with the
predictions of liquid-metal pseudopotential theory.

1. BACKGROUND

In the isobaric expansion experiment (IEX)[1], cylindrical wire samples
approximately 1 mm in diameter are rapidly heated by the discharge of a
capacitor bank through them in a time of 12-50 μs. The sample is subjected
to a predetermined ambient pressure of a few tenths of gigapascals by argon
gas in a pressure cell. The volume of the cell is large enough so that
changes in pressure produced by gas displacement from sample expansion are
negligible. In addition, the rate of expansion is slow enough to allow sound
waves to communicate pressure changes throughout the cell in a time interval
that is short compared with the measurement times of the experiment. As a
result, the pressure in the cell is relatively constant and uniform. The
compressibility of the metal samples is sufficiently small that the results
are not sensitive to the cell pressure. The most important purpose of the
high pressure gas is to allow large expansion of the metal without large dis-
tortions in sample geometry. The density of argon gas increases rapidly with
pressure, and is 1.28 g/cm$^3$ at a pressure of 0.24 GPa. Taylor instability
at the metal surface is thus substantially reduced. In addition the amount of
expansion before the boiling line of the metal is reached is increased. The
inert gas also prevents chemical interaction with the hot surface.

Optical diagnostics are performed through sapphire windows as shown in Fig.
1. In one line of sight (LOS) continuous back lighting is provided by a CW
argon-ion laser. The shadow of the sample is directed to a slit oriented
perpendicular to the wire sample axis, and an electronic streak camera is used
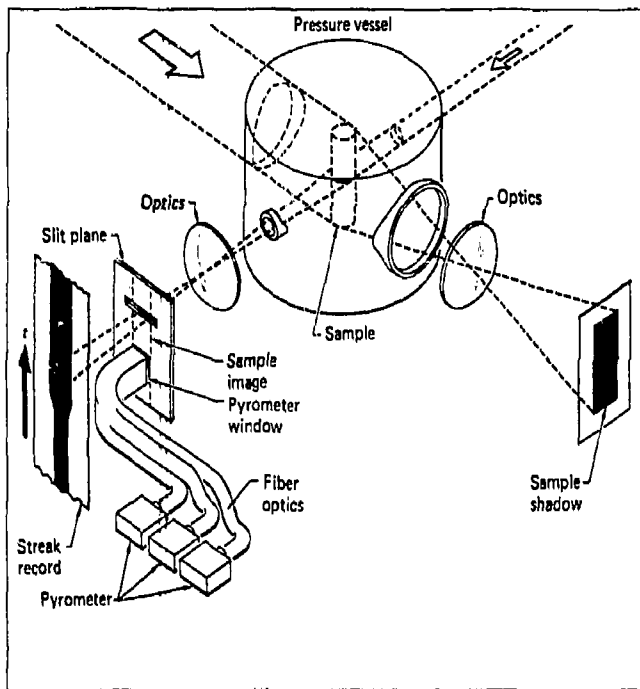to record shadow width at the slit as a function of time. If the sample is

FIGURE 1

Schematic representation of optical diagnostics for the isobaric expansion experiment.

clamped at each end to prevent axial motion then the specific volume of the sample varies as the square of the shadow width. The streak is started short-ly before the sample expansion begins in order to calibrate the magnification of the system.

A second LOS is used to determine the degree of sample distortion in the measurement. A Q-switched ruby laser is used as a back lighting source to take an overall snapshot picture of the sample at a late time. Shots which show significant distortion are discarded. A fast three channel optical pyrometer is used to determine the surface temperature of the sample as a function of time.

The sample heating current is measured using a wide band current trans-former. Voltage probes are arranged to contact the sample surface at a known distance of separation and the voltage difference between probes is recorded. Inductive voltage corrections are determined by differentiating the recorded current pulse and using a sample self inductance that results in a resistive voltage which increases smoothly from zero at the start of the pulse.

The integral of the product of current and resistive voltage gives the enthalpy input to the sample. Since all variables are measured simultaneously, time can be eliminated as a common parameter. The enthalpy is determined

continuously as a function of temperature, giving specific heat data. Since
current, sample diameter and resistive voltage are measured, one can determine
the electrical resistivity, properly corrected for thermal expansion, as a
function of either specific volume, enthalpy or temperature. Since the pres-
sure is known, the volume data can be combined with either the enthalpy or the
temperature to produce an isobar of the equation of state.

## 2. MEASUREMENTS

IEX measurements have been made on aluminum. Since it is such a good
conductor a sample diameter of 0.69 mm was chosen in order to reach melting in
the desired time with the available capacitor bank. Sudden rapid acceleration
in sample growth rate with a corresponding rapid rise in apparent electrical
resistivity was observed, and determined the upper bounds of the data. Figure
2 shows the pressure-volume plane with the track of these measurements, made
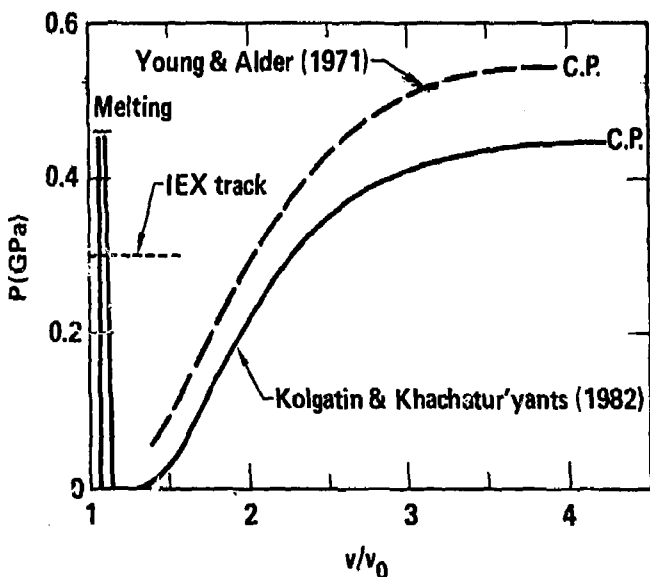at a pressure of 0.3 GPa. The dotted curve ends at the onset of the sudden



FIGURE 2
Pressure vs volume plane for aluminum. The critical points and boiling curves
of Young and Alder and of Kolgatin and Khachatur'yants are shown along with
the melting transition. The IEX track ends at the onset of sudden rapid
growth in sample diameter and resistivity.

rapid growth. Young and Alder[2] used a hard sphere van der Waals model to predict a critical pressure of 0.546 GPa and a critical volume of 3.91 x $10^{-5}$ $m^3$ $mol^{-1}$ corresponding to $v_c/v_0 = 3.93$ where $v_0$ is the specific volume at room temperature and atmospheric pressure. Their boiling line is shown in the figure. Kolgatin and Khachatur'yants[3] made a fit to the critical data in the review by Fortov, et al[4] and other standard thermophysical data to give an interpolation equation of state. Their boiling line is also shown. It appears unlikely that the instability is caused by the onset of boiling. The behavior is rather like that described by Lebedev[5] and the current densities of these measurements are in the range he discusses.

The relatively low mass density of the metal also contributed noticeably to hydromagnetic instability. The magnetic pressure evidently caused axial movement of metal producing a bulge at the tip of one sample clamping jaw. As a result the full radial expansion was not achieved and the volumes are quite substantially less than those expected from the literature. The electrical resistivities near the beginning of the liquid range where this problem was not significant are in good agreement with the literature. The pyrometer measurements gave results in excellent agreement with extrapolation of the 1973 Hultgren[6] tables, and extend the data to 4000 K. The full details of the measurements will appear in Int. J. of Thermophysics, along with data for copper.

## 3. DISCUSSION

Aluminum is considered to be a simple, nearly free electron metal which provides a useful test for theory. The thermophysical properties of liquid aluminum near normal density have been calculated using liquid metal pseudo-potential theory.[7] In the present calculations we used a Harrison pseudo-potential[8] with a modified Geldart-Vosko dielectric constant,[9,10] and a set of parameters fitted to reproduce the solid isotherm and the Grüneisen parameter. The thermodynamic properties were calculated by minimizing the Helmholtz free energy with respect to the hard sphere packing fraction and taking the appropriate derivatives of the free energy to obtain pressure and energy. In these calculations we used a soft sphere rather than a hard sphere reference entropy.[11]

The resistivity was calculated by the method of Ashcroft and Lekner.[12] The predicted expansions (Fig. 3) and electrical resistivities (Fig. 4) are in reasonably good agreement with the measurements. These results suggest that liquid metal pseudopotentials may be useful for metals expanded to 50% of their solid density.
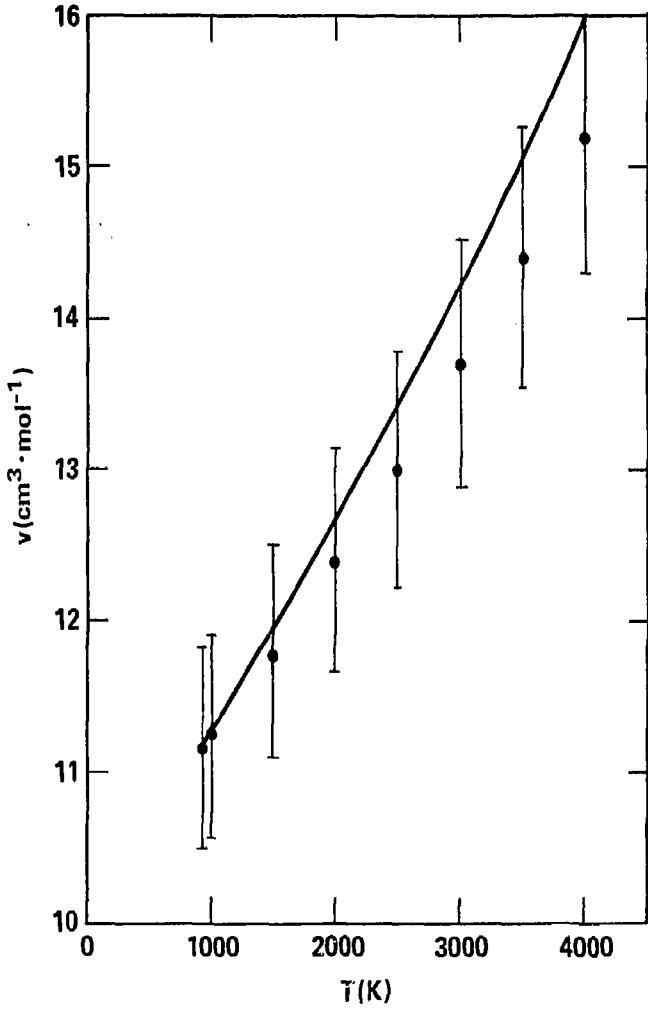
FIGURE 3
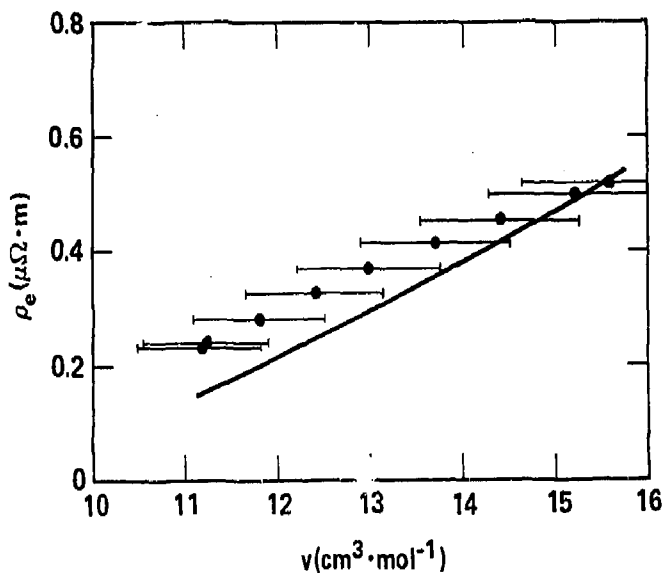Thermal expansion of aluminum. The error bars correspond to $\pm$ 6%.

FIGURE 4
Electrical resistivity of aluminum. The error bars correspond to ± 6%.

REFERENCES
1) G. R. Gathers, J. W. Shaner, R. L. Brier, Rev. Sci. Instrum. 47 (1976) 471.

2) D. A. Young, B. J. Alder, Phys. Rev. A3 (1971) 364.

3) S. N. Kolgatin, A. V. Khachatur'yants, High Temp. (USSR) 20 (1982) 380.

4) V. E. Fortov, A. N. Dremin, A. A. Leont'ev, High Temp. (USSR) 13 (1975) 984.

5) S. V. Lebedev, High Temp. (USSR) 17 (1980) 222.

6) R. Hultgren, P. D. Desai, D. T. Hawkins, M. Gleiser, K. K. Kelley, D. D. Wagman, Selected Values of the Thermodynamic Properties of the Elements (American Society for Metals, Metals Park, Ohio, 1973).

7) H. D. Jones, Phys. Rev. A8 (1973) 3215.

8) W. A. Harrison, Pseudopotentials in the Theory of Metals (Benjamin, New York, 1966).

9) D. J. W. Geldart and S. H. Vosko, Can. J. Phys. 44 (1966) 2137.

10) D. J. W. Geldart and S. H. Vosko, Can. J. Phys. 45 (1967) 2229(E).

11) M. Ross, H. E. DeWitt, and W. B. Hubbard, Phys. Rev. A24 (1981) 1016.

12) N. W. Ashcroft and J. Lekner, Phys. Rev. 145 (1966) 83.

## DISCLAIMER