MASTER

EXPERIMENTAL HIGH TEMPERATURE COEFFICIENTS
OF COMPRESSIBILITY AND EXPANSIVITY OF LIQUID
SODIUM AND OTHER RELATED PROPERTIES

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Surajit Das Gupta

(C. F. Bonilla, Supervisor)

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ABSTRACT

The subcooled compressibility of liquid sodium was directly measured upto 200 ata between 900 K and 1867 K, utilising a new multi-property apparatus which was previously tested with water.

The experimental data were correlated by a 6-term equation having the form :

$$(d\rho/dP)_{T,P} = a/(b + c.T + d.T^2) + (e.T + f.T^2).P$$

and a standard deviation of 9.2%. The equation can be used to estimate the subcooled compressibilities and densities of liquid sodium upto 2300 K and 500 ata.

The thermal expansion of liquid sodium was also measured along the isobars 1 ata, 28.9 ata and 69 ata. Densities within 1% of those obtained from the compressibilities, were obtained.

The above compressibility data were used to calculate the thermal pressure coefficient of saturated liquid sodium. Also, Bhise and Bonilla's correlations for the vapor pressure and the saturated liquid density of sodium were improved by including more data in the analysis. The critical temperature and density were thus reestimated as 2508.7 K and 0.2141 g/cc. Furthermore, a new correlation was developed to determine the heat of vaporization of sodium upto the critical point, which was then used to estimate the internal energy and the entropy of vaporization and the saturated vapor density of sodium upto the critical point.

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I. INTRODUCTION

Liquid metals, especially the alkali metals, have been intensely investigated over the last 50 years, due mainly to their good qualities as heat transfer agents and their potential as nuclear coolants. In real and conceptual terms, alkali metals have been used in a variety of ways - starting with the use of NaK in the Experimental Breeder Reactor (EBR) and culminating in the choice of sodium as the coolant for the Liquid Metal Fast Breeder Reactor (LMFBR). The thermophysical properties that make the alkali metals so promising (sodium in particular and lithium even more so) are their low melting points, vapor pressures, densities, viscosities and neutron absorption cross-sections, and their high heat capacities, thermal conductivities, and boiling and critical points.

The alkali metal of greatest interest now is sodium. Its saturation properties have been investigated in some detail (1-6), but experiments on its subcooled state properties are comparatively rare. A property of significance is its isothermal compressibility (β_T), since it is used in theoretical analyses of hypothetical reactor accidents (7,8,9,10). While the operating temperature of sodium in the LMFBR is in the range of 800 K, hypothetical accident temperatures in excess of 2000 K may be attained. Thus there is great interest in the high temperature properties of liquid sodium, including the accurate identification of its critical and of its subcooled PVT properties. The critical point has now been reliably determined (1), but so far as the subcooled properties are concerned there are few data.

It is the purpose of this investigation, therefore, to determine the compressibility and thermal expansion of subcooled sodium to as high temperatures and pressures as possible. It is also hoped that this information, while useful in itself, can be used to refine existing theories of the liquid state and general purpose predictive methods to determine the subcooled thermophysical properties of other alkali metals.

II. SURVEY OF PREVIOUS WORK

The speed of sound measurements of Chasanov, Leibowitz et al (11) and the thermal expansion measurements of Vargaftik et al (12) are the only experiments at high enough temperatures and pressures to be useful in reactor safety calculations.

Leibowitz et al measured the speed of sound in saturated sodium up to 1500°C (Fig. 1b), from which the adiabatic compressibility of sodium, β_S , was determined using the equation

$$\beta_S = \frac{1}{\rho c^2} \quad (2.1)$$

β_S was then used to calculate β_T , the isothermal compressibility, from the exact thermodynamic equation,

$$\beta_T = \frac{\beta_S C_{sat} + T.V. \alpha_{sat} (\alpha_{sat} + \beta_S \gamma_{sat})}{C_{sat} - T.V. \alpha_{sat} (\alpha_{sat} + \beta_S \gamma_{sat})} \quad (2.2)$$

where C_{sat} = heat capacity

α_{sat} = thermal expansibility along the saturation line

γ_{sat} = slope of the vapor pressure curve

Though the vapor pressure of sodium is now known to the critical point (1), C_{sat} and α_{sat} have been experimentally determined only to 1500 K (6) and 1644 K (2), respectively. Thus, the calculation of β_T to higher temperatures would require considerable extrapolations of the unknown quantities and hence is liable to have considerable errors, especially near the critical region.

Padilla (13), however, did necessarily use the above approach to predict β_T up to the critical temperature of sodium, in the absence of experimental data. He used separate equations to predict the values of C_{sat} and α_{sat} beyond their experimental ranges, obtaining the constants of his equations by matching with the known slope and value at the maximum experimental temperature. For example, the saturated density of liquid sodium was approximated between 1644°C (the highest experimental temperature (21) and 2503 C (the critical tem-

FIG 1a. Apparatus of Chasanov, Leibowitz et al.(11)

FIG 1b. Apparatus of Vargaftik et al.(12)

perature (1)) by an equation of the form

$$\frac{\rho_L}{\rho_c} = 1 + a \left(1 - \frac{T}{T_c}\right)^b \quad (2.3)$$

The constants 'a' and 'b' in eq. 2.3 were determined by matching the slope and value at 1644°C. Besides the likelihood of large extrapolation errors, as mentioned above, this method is not as convenient to use as, for example, an explicit equation of state.

Vargaftik et al (12), however, measured the thermal expansion of sodium along several isobars and were able to correlate their data in a pressure-explicit equation of state.

However, the maximum temperature reached was only 1100K. This relatively low temperature is a characteristic of the pictometer design and operation of the experiment (Fig. 1a), in which evidently expansion was only carried out to the top of the capillary. For accurate measurements, the diameter of the capillary has to be relatively small, thus limiting the volume and the temperature range of experiments

A recent technique that overcomes the above disadvantages of thermal expansion experiments is the "Transient Interferometric Technique" (14,15,16). Here the metal sample is electrically self heated in a large chamber filled with inert gas at the desired isobar pressures. By discharging a suitably designed capacitor through the metal sample, heating rates exceeding 10^4 K/sec (referred to as "subsecond" or "submicrosecond" heating) can be achieved. The expansion of the sample is measured by laser interferometry and high speed photography - and the temperature is detected by a sensitive pyrometer.

The method is suitable for metals which remain as solid or can be held in the apparatus at the experimental temperatures. Liquid metals, for example, can be used by means of magnetic 'levitation'. However, the pyrometer begins to respond only above 2000 K, so that experiments with this technique are restricted to higher temperatures.

The complexity, and obviously the cost, of such a scheme ruled out its use for this investigation. Moreover, the range between 1000 K - 2000 K, which is important from the point of view of accident analyses, it is felt could not have been successfully studied.

A concept that showed promise, in so far as it permitted the compression of liquid sodium up to 300 ata in the temperature range of interest, was the "pressure tube" method of measuring vapor-pressure (1,17,18,19). Though this method was used for an entirely different objective, it seemed possible, by modifying the apparatus in several crucial areas, to use it for measuring compressibility.

The actual apparatus used in this investigation is described in the next two sections. The final design retained the simplicity of the picnometer design and also contained the simple arrangement, used in the pressure-tube method, for compressing sodium. With the final design, besides compressibility, it was also possible to measure the isobaric thermal expansivity, the vapor pressure and, in principle at least, the thermal expansivity along the saturation curve.

III. CONCEPTUAL DEVELOPMENT OF THE APPARATUS

As mentioned above, the proposed method is an adaptation of the "pressure tube" concept for determining high temperature vapor pressure of alkali metals. Qualitatively the method is also similar to some of the picnometric methods that have been used in liquid metal research (2,4,5,12).

The proposed apparatus is illustrated in Fig. 2. A high temperature and high pressure capsule of known internal volume, having an enlarged bulb connected to a long capillary neck, is filled with sodium and heated in a furnace such that the bulb is the hottest part of the capsule and is as isothermal as possible. The capillary extends out of the furnace and is connected through a valve B to the external system, which consists of the pressurizer, or injector, for forcing sodium into the capsule, and suitable pressure measuring instruments. Ideally, the external system is also filled with sodium, just above its melting point, at low compressibility. With this arrangement, experiments can be conducted both in the isothermal mode to get compressibility, and in the isobaric mode to determine the thermal expansion. The two modes differ only in the operative procedure, and can be used alternatively to get the P-V-T properties of the liquid sodium in the capsule.

A. Isothermal Compressibility

In this mode, each experiment consists of two successive pressurizations while keeping the bulb temperature constant. First, with valve B open, the whole system is pressurized to some suitable pressure by turning the injector valve stem clockwise inwards, and then depressurized by withdrawing the injector counterclockwise to its exact original position. This depressurization will permit checking for leaks and/or hysteresis in the system by comparing curvature and initial, middle, and final pressures. Valve B is then closed tightly, and the remaining system, ie. the external system, is repressurized at the same temperature and over the same pressure range as in the first step. If the system pressure is plotted as a function of

FIG 2. Proposed apparatus

FIG. 3. Conceptual plot of an isothermal experiment.

the angular or linear displacement of the injector stem, two curves will be obtained, as in Fig. 3. Since the displacement of the injector stem is linearly related to the change in the system volume, the curves actually represent the pressure vs. volume relationship for the cases of B open and B closed.

Consider the two pressures P_1 and P_2 on the curve marked '1' in Fig. 3. From the figure it is obvious that:

ΔV_1 = volume change of the whole system caused by the pressure increase from P_1 to P_2 .

But ΔV_1 actually represents the sum of the volume changes experienced by the sodium in the capsule (ΔV_c), and in the external system (ΔV_E) respectively, i.e.

$$\Delta V_1 = \Delta V_c + \Delta V_E \quad (3.1)$$

The curve marked '2', with valve B closed, is due to the compression of the external system only.

For a closed system we can write that

$$\Delta V = V \cdot \beta_T \cdot \Delta P \quad (3.2)$$

where ΔV = volume change (+ or -)

ΔP = pressure change (- or +)

and β_T = isothermal compressibility

i.e. $\Delta V = \text{a constant} \cdot V$, if P and T are constant, (3.3)

and it is assumed that the capsule is rigid, i.e. V_c is independent of P .

Let V_E be the external volume for curve '1'. On closing B, However, V_E decreases by the volume of the stem of valve B introduced into the system by the closing action. Thus ΔV_2 , the volume change of the external section from curve '2' of Fig. 3, will be different from ΔV_E of eq. 3.1, since V_E is different for the two cases (eq. 3.3). However, the difference between ΔV_E and ΔV_2 can be made negligibly small by choosing for B a valve with a very small internal volume and stem diameter and travel compared to V_E . Also B could be

turned only a 1/4 turn for example, instead of fully opened, for the whole system test. Further, the operating procedure can also be simplified by adjusting the injector stem position (thus reading) to compensate for the decrease in the external volume caused by the closing of B.

With the above precautions, then, we write

$$\begin{aligned} \Delta V_1 &= \Delta V_c + \Delta V_2 \\ \text{or } \Delta V_c &= \Delta V_1 - \Delta V_2 \end{aligned} \quad (3.4)$$

However, ΔV_c , as calculated from eq. 3.4, also includes the contribution from the volume of valve B below the stem,

$$\text{ie. } (\Delta V_c)_{\text{actual}} = \Delta V_1 - \Delta V_2 - \Delta V_B$$

ΔV_B can also be made negligibly small (as before) by choosing for B a valve with very small internal volume, so that $(\Delta V_c)_{\text{actual}}$ can be calculated directly from eq. 3.4.

Now, if the external system volume (V_E) is negligible, then

$$\Delta V_c = \Delta V_1$$

Practically, however, V_E can never be made negligible due to the appreciable volumes always present in tubing, valves and pressure gauges. Therefore, ΔV_2 has to be explicitly determined for each experiment. ΔV_2 can, in fact, be referred to as the correction to ΔV_1 , for the external system compressibility.

Referring to eq. 3.3, both ΔV_1 and ΔV_2 are volume displacements measured at the injector. If the density of the sodium in the injector (ρ_I) is known, then the mass of sodium transferred from the external system to the capsule is given by

$$\Delta m_c = (\Delta V_1 - \Delta V_2) \cdot \rho_I \quad (3.5)$$

Dividing eq. 3.5 by the capsule volume (V_c) gives the change in the density of the sodium in the capsule due to the pressure rise.

$$\text{ie. } \Delta p_c = \Delta m_c / V_c = (\Delta V_1 - \Delta V_2) \rho_I / V_c \quad (3.6)$$

Dividing eq. 3.5 by the pressure rise and taking the limit as $P_2 \rightarrow P_1$, one obtains

$$P_{2 \rightarrow P_1} \text{Lt} \frac{\Delta p_c}{P_2 - P_1} = P_{2 \rightarrow P_1} \text{Lt} \frac{(\Delta V_1 - \Delta V_2) \rho_I}{(P_2 - P_1) V_c} \quad (3.7)$$

$$\text{or } \left(\frac{dp_c}{dP} \right)_{P_1} = \left(\frac{dV_1}{dP} - \frac{dV_2}{dP} \right) \cdot \frac{\rho_I}{V_c} \quad (3.8)$$

If the equations of the P-V curves in Fig. 3 are known, then they can be differentiated and used in eq. 3.8 to calculate $\frac{dp_c}{dP}$ at

various pressures along each experimental isotherm. Also, eq. 3.8 can be integrated from the saturation pressure to any desired pressure, within the range of the experiments, to give sub-cooled densities along the isotherm. The isothermal compressibility β_T at any pressure can then be calculated by dividing the result of the first calculation by that of the second for that pressure.

An important consideration in the final design of the apparatus is the internal volume of the capsule capillary. All calculations pertain only to the sodium in the bulb. However, if the capillary volume is substantial it will also contribute to the total compressibility, and this contribution will have to be subtracted out to get the actual compressibility of the sodium in the bulb. However, if the capillary volume is small in comparison to the bulb volume, then this correction is not necessary.

Another significant factor is the ratio of the external to the capsule volumes. Since the compressibility is measured as the difference of two slopes, the slopes themselves have to be quite accurate for their difference to have statistical significance. A limiting case is obviously when the external section volume is very large compared to the capsule volume. Then the two compression curves of Fig. 3 would merge, and

their difference would be inaccurate. Also, since the volume of the injector travel acts as a reservoir from which sodium is transferred into the capsule during compression, there is an advantage in it being large; lack of adequate volume may restrict the experiments to a narrow pressure range. As a matter of judgement it was decided to make the capsule and external volumes (including the volume displaced by injector) about equal in the actual apparatus.

B. Thermal Expansion Mode

With only a slight modification of the operating procedure, the apparatus can also be used to determine the isobaric thermal expansion of sodium. Contrary to the previous mode, where the volume change is measured as a function of the system pressure at a constant bulb temperature, in this mode the volume change is measured as a function of the bulb temperature at a constant system pressure. Due to operation under constant pressure, it is also not necessary to correct for the external system compressibility.

The operating procedure is illustrated in Fig. 4. Consider the capsule bulb at an initial temperature T_1 and pressure P^* . The temperature of the bulb is now raised to T_2 holding the system volume constant, valve B being always open in this mode. As a consequence of the temperature rise, the pressure will also rise to some value P_1 . After steady state is achieved, the pressure is gradually reduced isothermally to P^* by means of the injector. This heating followed by a depressurization procedure is repeated at successively higher temperatures till the saturation temperature for the pressure P^* is met or exceeded. At this point a different isobar can be chosen and the experiments repeated.

Referring to Fig. 4, it is observed that the volume displacements of the injector, ΔV_I , necessary to reduce the system pressure to the isobar value after each temperature increase, is actually equal to the volume of sodium that has expanded out from the capsule to the external section. Thus the observed expansion of sodium can be written as

FIG 4. Conceptual plot of thermal expansion experiments

$$\frac{\Delta m_c}{\Delta T} = - \frac{\Delta V_I}{\Delta T} \times \rho_I \quad (3.9a)$$

The -ve sign takes into account the fact that the capsule loses sodium due to the expansion. If the temperature steps, ΔT , are small, the eq. 3.9a can be written as

$$d m_c / d T = - (d V_I / d T) \cdot \rho_I \quad (3.9b)$$

and the observed density change as

$$(d \rho_c / d T)_{obs} = -(d V_I / d T) \times \rho_I / V_c \quad (3.9c)$$

The mass of sodium in the capsule, at any time, is given by

$$m_c = \rho_c \cdot V_c \quad (3.10)$$

In eqs. 3.9a - 3.10, the subscript 'c' indicates the capsule.

Eq. 3.10 on differentiation with respect to temperature gives

$$d m_c / d T = \rho_c \cdot d V_c / d T + V_c \cdot d \rho_c / d T \quad (3.11)$$

Substitution of eq. 3.9b into eq. 3.11 and rearrangement gives

$$d \rho_c / d T = - \left(\rho_c \cdot \frac{d V_c / d T}{V_c} + \rho_I \cdot \frac{d V_I / d T}{V_c} \right) \quad (3.12)$$

An analytical equation for $\frac{d V_I}{dT}$ can be obtained by

curve fitting the experimental $\frac{\Delta V_I}{\Delta T}$ data; $\frac{d V_c}{dT}$ can be deter-

mined from the equation for the thermal expansion of the capsule material; ρ_I can be determined from low temperature compressibility data (13,38). Thus eq. 3.12 can be numerically integrated to determine the subcooled densities along the isobar.

C. Determination of the Saturated Vapor Pressures and Liquid Densities

1) Vapor Pressures

The vapor pressures of sodium can be easily determined from the isothermal compressibility runs. If the injector stem is gradually withdrawn till the system pressure(P) is at or below

KE 10 X 10 TO THE CENTIMETER 47 1513
25 X .25 CM. KEUFFEL & ESSER CO.

Pressure (psia)

1100

1000

900

800

700

600

500

400

300

200

100

FIG - 5

8/2/74 Run 1-8

P vs θ for Liquid Na

Avg. Temp of bulb = 2236.9°F

Saturation Pressure

Vapor - Liquid equilibrium

Subcooled sodium

0 60 120 180 240 300 0 60 120 180 240 300

θ (deg. deg.)

the saturation value (P_g), then the liquid in the hot bulb will flash causing a two-phase, vapor-liquid equilibrium situation in the capsule; since the bulb is deliberately made the hottest part of the system, the flashing takes place only in the bulb. Further withdrawal of the injector will only cause more of the liquid in the bulb to vaporize though the pressure will be maintained constant at the saturation value, P_g . Thus a P-V plot for this type of experiment will consist of horizontal lines at different pressures (Fig. 5). The actual slope of these lines depend on the temperature profile on the capsule bulb; horizontal lines will be obtained only if the temperature is uniform over the bulb. However the vapor pressure measurements by this technique cannot be expected to have the same accuracy as the "pressure tube" method due to the larger volume of the bulb (compared to the pressure tube) and the corresponding uncertainty as to the position of the vapor-liquid interface and its temperature. However the vapor pressure measurements can be a useful part of the overall experimental procedure since it provides a convenient means to check the actual temperature profile during experiments.

11) Saturated Liquid Density

The property that is most easily measured by this technique is the difference in the saturation densities at two different temperatures. The concept is illustrated in Fig. 6, where the P-V plots at two temperatures T_1 & T_2 are shown. Each experiment is initiated by having a vapor-liquid equilibrium in the capsule bulb and at the same injector position. If now the injector stem is pushed in, then sodium from the external section will be forced into the bulb, increasing the amount of saturated liquid (and correspondingly decreasing the amount of saturated vapor) in the bulb. Since condensation takes place at a constant pressure the system pressure will remain the same during this operation. At a certain point, however, e.g. V_1 at temperature T_1 and V_2 at temperature T_2 , the bulb will be totally filled with only saturated liquid. Continuous compression beyond this point will sub-cool the liquid and increase the pressure at a rate approximately

FIG. 6 - Conceptual plot for saturation density experiments.

given by the isothermal compressibility of liquid sodium at the temperature of the bulb. Experimentally it may not be possible to determine either V_1 or V_2 exactly; however they can be easily determined from the intersection of the horizontal and the steep portions of the P-V plots.

Referring to Fig. 6, it is observed that the difference, $V_1 - V_2$, is actually proportional to the change in the saturation density between T1 and T2. This is similar to the thermal expansion case (Fig. 4) where ΔV_I represented the isobaric density

change.

Now, the mass of sodium injected into the bulb to achieve exact saturation at temperature T1 is :

$$\Delta m_1 = \Delta V_1 \times \rho_I \quad (3.13)$$

Similarly, at T2 we have :

$$\Delta m_2 = \Delta V_2 \times \rho_I \quad (3.14)$$

The change in the mass of sodium in the bulb is :

$$-\Delta m_c = \Delta m_1 - \Delta m_2 \quad (3.15)$$

Also, from eq. 3.11, we have, for small ΔT 's, :

$$\Delta m_c = \rho_c \cdot \Delta V_c + V_c \cdot \Delta \rho_c \quad (3.16)$$

Therefore, equating eqs. 3.15 & 3.16, and rearranging, we get :

$$\Delta \rho_c = \rho_c \cdot (\Delta V_c / V_c) - (\Delta V_1 - \Delta V_2) \cdot \rho_I \quad (3.17)$$

Eq. 3.17 can be used as a forward difference equation to determine the saturation densities at successively higher temperatures. However at least one value of saturation density has to be known beforehand in order to use eq. 3.17. Since the saturation density of liquid sodium is already known accurately to 1645 K (2), this method therefore can be used to determine the saturation densities at higher temperatures.

IV. EXPERIMENTAL APPARATUS

Introduction

The conceptual model and the actual apparatus are essentially similar except for one major difference. In the actual apparatus a second fluid, highly purified dodecane, $C_{12}H_{26}$, was used as the pressurizing medium. Dodecane has a low vapor pressure at the external system temperatures (above the m.p. of sodium), is non-reactive, and has a fairly high viscosity to cut down small leaks.

Sodium filled only the capsule and the lower part of the external system, while the rest of the apparatus, including the injector and the pressure gauges, was filled with the "oil".

Rationale for Using Two Liquids

The most important consideration in the design of a compressibility measuring apparatus is that it should be free of leaks. Generally speaking, the most difficult part to seal against leak is the stem of the pressure injector. To be able to reach high pressures with little effort, the stem has to have a reasonably large diameter. It should also be capable of large displacements in order to cause adequate changes in system volume, ie. sufficient travel. Thus the packing for the injector stem has to be carefully chosen due to the large perimeter of the stem, that has to be sealed against the wide fluctuations of pressure and the friction generated by the movement of the stem. If sodium were to be pressurized directly, as in the conceptual model, a further problem would arise, that of temperature, since sodium has to be kept molten (above $100^{\circ}C$) everywhere during experiments. No suitable packing exists that could do the job reliably under the above conditions over long periods of time. Yet another consideration was the necessity of being able to change the packing, if leaks did develop, without having to dismantle the entire apparatus, which would require the cleaning out of all the sodium in the apparatus,

and then recharging. Thus it was necessary to pressurize the sodium indirectly. Dodecane was chosen due mainly to its successful use in the vapor pressure measurements on alkali metals (1,17,18,19) made in this Laboratory, and the experience gained thereby. With dodecane, Teflon packing was used with full confidence.

Besides making the selection of the injector packing easier, several other advantages also accrued from the use of dodecane. Firstly, the amount of sodium used in the system was greatly reduced. This also reduced the number of heating tapes required to keep the sodium in the external system molten and thereby made it easier to control its temperature. Secondly, since most of the external section was now open to plain sight, leaks were more easily noticed and corrected. Also, the pressure transducers, being now located in the room temperature, dodecane-filled section, worked more reliably. It was also concluded that there was less risk in the case of equipment failure during a test, the smaller the volume of contained sodium. A prior disadvantage of using dodecane, that if it were to penetrate to the capsule and overheat it could carbonize and plug the neck of the capsule, no longer is a problem, due to keeping the sodium molten between tests, or allowing it to freeze upwards.

Description of Apparatus

The experimental apparatus is illustrated in Fig. 7. Except for the high temperature and high pressure capsule C, all other parts of the system are located outside the furnace. Sodium and dodecane form two legs in the external section which meet above valve V2. In operation, the sodium-dodecane interface stays in the tube T located between V2 and the pressure injector V1. This slightly enlarged section acts as an expansion chamber and prevents any drastic changes in the interface position as sodium is compressed into, or expands from, the capsule during experiments. As a precaution, the interface

FIG 7. EXPERIMENTAL APPARATUS

position was occasionally monitored by measuring the electrical resistance of different sections of T. For this procedure, 3-5 amps of current was passed through T by connecting the current taps CT1 to a constant current source (20). The potential drops across the voltage terminals VT1 were then measured on a sensitive microvoltmeter (21). Sodium-filled 1-inch sections had potential-drops of 0.2 mV compared to 1.5 mV for dodecane-filled sections, so that it was easy to detect the interface.

All parts of the external section in contact with sodium were maintained at approximately 125°C by heating tapes wrapped around the sections. Thermocouples were attached at strategic locations to ensure that the temperatures were always at the proper level. Thermocouple TC3 and the heating tape on T were connected to a temperature controller (22) so that interface temperature remained constant at 125°C ($\pm 0.1^{\circ}$).

Excess sodium and dodecane were stored in their respective reservoirs R1 and R2 and were used to change the relative amounts of the two fluids in the operating system when the situation demanded.

The above general description is now followed by detailed descriptions of the major parts of the apparatus.

A. Pressure Capsule

The high pressure capsule in which sodium is heated and compressed is constructed almost entirely of chemically vapor-deposited tungsten. The constructional details are shown in Fig. 8. The capsule is held at its open end by a male thermocouple connector (23) attached to the top flange of the furnace. However, it is very difficult to attach commercial high pressure tube fittings to tungsten due to its extreme hardness, which cannot be scored by the steel ferrules of Hoke-type fittings. Thus the top 2-1/2" of the capillary is constructed of molybdenum, which is softer but has about the same high

FIG 8. High pressure &
high temperature capsule

temperature strength. A further advantage of molybdenum is its greater ductibility compared to tungsten, which makes it much less prone to breaking off due to bending stresses induced by vibrations or accidental knocks on the apparatus.

The internal volume of the capsule, ie. bulb and capillary, is 8.289 cc. In the as-manufactured condition, the capillary I.D. was .01" so that the capillary volume was approximately 1/1000 of the capsule volume, too small to cause significant errors in the compressibility results due to any uncertainty in temperature distribution along the stem. Unfortunately .01" was too small to be practical and severe difficulties were encountered in trying to charge the capsule with sodium and also in cleaning it out when the need for a fresh charge arose. Eventually it got plugged up with dirt and/or oxide and had to be rebores by electric discharge machining (EDM). This procedure however, enlarged the capillary I.D. to .06", making the capillary volume approximately 5% of the total capsule volume. It was difficult to modify the apparatus or the operating procedure to offset the effect of the increased capillary volume, but a simple calculation procedure was developed that effectively eliminated its contribution to the overall error of the results (Appendix VI).

During experiments the capsule bulb is located approximately in the same axial position as the furnace hot spot. By milling out grooves in the graphite heater tube, the length of the hot spot was increased so that a more uniform temperature profile could be maintained over the length of the bulb.

The capsule was freshly filled (or charged) with sodium three separate times. Prior to each new charge, the external dimensions and the internal volumes were rechecked. There was no noticeable change or drift.

B. Injector (Fig. 9A)

The "pressure injector" was a specially designed needle valve having low internal volume and no seat. The stem and the packing nut were utilized from a Hoke No. 3514F8E high pressure hydraulic valve.

FIG 9a . Injector details

FIG 9b. Linear Variable Differential Transducer (LVDT) (24) and Protractor Assembly.

The 3/8" O.D. stem was screwed in or out by its handle, to decrease or increase the system volume respectively. Teflon was used as the stem packing and worked without leaking throughout the entire period of experiments.

To determine the volume displaced by the injector, ΔV_I , either of two formulae can be used, viz

$$\Delta V_I = \frac{\pi}{4} \cdot D_I^2 \cdot \Delta L \quad (4.1)$$

$$\text{or, } \Delta V_I = V_\theta \cdot \frac{\Delta \theta}{360} \quad (4.2)$$

where ΔL = linear displacement of the stem

and $\Delta \theta$ = angular displacement of the stem

and V_θ = volume displaced per turn by the stem.

Both methods were initially used, but the angular displacement method proved more convenient and accurate, and was thus solely used for the reported experiments. ΔL was measured by means of an LVDT Spring-forced against a conical indentation axially in the end of the stem. The $\Delta \theta$ was measured by visually reading a circular protractor, graduated every 3° . The combined installation is shown in Fig. 9b.

C. Valves

Valves V2 and V8 are the only ones in contact with sodium. V2 (SNOTRIK No. SX-44-6-NR) is a high temperature-high pressure valve with special asbestos-inconel packing to withstand molten sodium above its melting point. Also it has a very small internal volume, 0.311 cc in the fully open position and a stem displacement of 0.035 cc from the open to the closed position (3-1/2 turns). During experiments V2 is kept open only 1/4 turn, so that the operational volume is only 0.3085 cc and the volume change on closing is only $0.035/14 = 0.0025$ cc. If it is assumed that exactly half the operational volume remains on the capsule side, then using the available estimates of β_T (13,38) it is possible to calculate the error involved in calculating V_c directly from eq. 3.4.

Using eq. 3.2, we can write

$$\frac{\Delta V_{V2}}{(\Delta V_c)_{\text{actual}}} = \frac{(.3085/2) \cdot \beta_{400 \text{ K}} \cdot \Delta P}{8.289 \beta_T \text{ capsule} \cdot \Delta P}$$

Table 4.1 lists the expected value of $\Delta V_{V2}/\Delta V_c$ at various temperatures of the capsule, using the estimates of Padilla (13) for β_T .

TABLE 4.1

Expected error due to the internal volume of V2.

<u>Capsule Temperature (K)</u>	<u>$\Delta V_{V2}/(\Delta V_c)_{\text{actual}} \%$</u>
1000	0.99
1500	0.55
2000	0.20
2500	0.6×10^{-4}

Though the error rapidly becomes negligible above 1500°C, it was necessary to take it into account for greater accuracy of the low temperature results. Actually, this correction was combined with the capillary volume correction and treated as a single correction. The procedure used to correct the observed values of $\frac{dQ}{dP}$ is discussed under "Experimental Results and Analysis" (Chapter 6).

D. Pressure Indicators

To reduce system volume, pressure transducers, P1 and P2 (25) were used to measure pressures instead of bourdon tube gauges. The transducers were of the flush diaphragm, unbonded strain gauge type and were guaranteed to less than 0.2% non-linearity. However, the transducers were recalibrated in this laboratory against a 5000 psig test gauge (26) accurate to 0.05% of full scale. Each transducer was found to be actually accurate to better than 0.2%. As an added precaution, a 3000 psia Heise gauge, P3, accurate to 0.1%, was also installed in the system. Occasionally, between runs, the transducers were checked against the Heise gauge, at various pressures. Addition-

ally, the external system would often be opened to atmospheric pressure, by opening valve V3, to check the zero drift of the transducers.

Both transducers were supplied with 6VDC excitation voltage from a constant voltage source (27), and their outputs, usually 0 - 25 mV, were fed to signal amplifiers (28) set at 200 gain. The resulting output (0 - 5V) was read on a precision 4-1/2 digit voltmeter (29). The amplification was necessary to increase the resolution of the transducers.

E. Furnace (Fig. 10)

The high temperature electric resistance furnace (30) in which the pressure capsule was heated had a maximum temperature and power rating of 2500°C and 17 KVA, respectively. The heater was a 15" long graphite tube, 1-3/4" O.D. x 1-1/2" I.D., held between two water-cooled copper flanges, which also served as the current connectors. Both the top and the bottom flanges had access holes drilled in their centers - the test capsule was suspended inside the furnace by a connector to the top hole, while the thermocouples were taken out through connectors in the bottom one. Due to the method of suspension of the capsule, considerable heat loss occurred by conduction along the capsule neck. Uncompensated, this would have caused considerable lowering of the temperature of the top of the bulb compared to its bottom and to the furnace. However, the problem of this heat loss was greatly alleviated by redesigning the heater so that the top half of the heater generated more heat than by its original design. This was accomplished by drilling several rows of holes on the graphite tube, as shown in Fig. 11. This arrangement also increased the length of the hot spot and thus helped to maintain the bulb approximately isothermal up to the highest temperature of the experiments.

The heater power was provided by a 17 KVA SCR controller (31), designed to deliver power in proportion to a signal

FIG 10. Furnace details

FIG 11. Graphite heater

from a temperature controller (32). One of the thermocouples measuring the capsule bulb temperature, was connected to the temperature controller, and the furnace was operated merely by dialing in the desired temperature on the controller. The standard triple-mode control action of this controller was able to bring up the furnace temperature to the set point within five minutes, but usually 15 to 20 minutes elapsed before complete steady state conditions were achieved.

F. Temperature Measurement

The temperature of the capsule bulb was measured by tungsten-rhenium thermocouples (W-26% Re/W-5% Re), placed on the bulb at different positions. The thermocouples were calibrated at the factory (33) from 200 F to 4200 F, roughly every 200°. However, instead of fitting the entire range with a single polynomial, several polynomials were used, valid over smaller, separate ranges. For each measurement location on the capsule bulb, four wires, two positive and two negative, were used, tied down to the bulb surface by 0.010 in. molybdenum wire. The arrangement allowed either positive wire to be measured against either negative wire at the same location, thus doubling the number of readings possible for the same group of four wires.

The thermocouple outputs (0 - 40 mV) were measured on a 4-1/2 digit DVM (34). When it was available, a 40-channel automatic data logger (35) was also used to monitor and record the thermocouple outputs. With this instrument, all the thermocouples were automatically scanned at a constant speed of approximately 2-1/2 channels a second. The data logger could be operated both in the continuous scan and periodic scan modes. During experiments, usually the second mode was used with a scan interval of one minute. The measurements (in mV) were directly available as hard print from a built-in printer, eliminating the error-prone necessity of having to write down readings of all the thermocouples.

G. Maximum Range Experimental Conditions

While the aim of this investigation was to cover as wide a range in temperature and pressure as possible, it was useful to know, beforehand, the accurate and safe limits of operation of the pressure capsule.

The most obvious criterion was the high temperature yield strength of CVD-W. However, a more critical criterion was its high temperature creep properties. The first criterion set the pressure limit, while the second set the temperature limits of the experiments. The available data concerning the above properties (36) of vapor-deposited tungsten are combined on Fig. 10 where the "time to 1% creep" curves are cross-plotted on the yield strength vs. temperature plot. It is obvious from the Figure, that below 1700°C , yield is the limiting factor, but above 1700°C creep becomes increasingly important. Thus it is not possible to have any runs above 1750°C without risking damage to the capsule.

H. Water Test

In order to check the validity of this concept and the operational characteristics of the apparatus, an initial test was deemed desirable. Water was chosen as the test-substance since its thermodynamic properties are accurately known upto the critical point(61). The procedure involved filling a simplified version of the apparatus with demineralised and degassed water and then conducting three series of experiments to determine :

- a) the saturation vapor pressure,
- b) the saturation density,

and c) the subcooled compressibility

at different temperatures and then compare the results with the steam-table value at the same temperatures.

The results are plotted and shown in Appendix 7. The results of the comparisons are summarised below :

STRESS - PSIA

FIG. 12. Yield & creep strength of chemically deposited vapor

TABLE 4.2

<u>Property</u>	<u>Average deviation from steam-table value(61)</u>
Vapor pressure (425 K $\leq$ T $\leq$ 639 K)	2%
Saturated liquid density (450 K $\leq$ T $\leq$ 537 K)	1%
Average compressibility ($\Delta\rho/\Delta P$) ($\begin{matrix} 477 \text{ K} \leq T \leq 537 \text{ K} \\ P < 70 \text{ ata} \end{matrix}$)	2%

In spite of the relatively large deviations, the water-test proved the validity of the experimental concept. For sodium, accuracies of the same order of magnitude as above or less can be expected - less in view of the fact that much higher temperatures are involved, as well as pressure;

V. OPERATING PROCEDURES

The complete operating procedure for any series of runs consists of (a) the charging phase and (b) the experimental phase. The experiments were conducted in 12 batches and the capsule was charged with fresh sodium three times.

A. Charging Procedure

Sodium of 99.979% purity (Table 5.1) was provided in 20 gm glass ampoules from the manufacturer (37). The ampoules were broken under vacuum and the sodium was first melted down into the reservoir R1 (Fig. 7 and 13).

TABLE 5.1

Spectrographic analysis of high purity sodium (37).

<u>Element</u>	<u>%</u>	
Na	99.979	
K	100	ppm
Fe	15	"
Cr, Si, Ni, Zr, Rb	10	" each
B, Co, Al, Sn, Pb, Ti	5	" each
Ca	3	"
Ba	3	"
Cu	1	"
Mn, Mg, Mo, V, Be, Ag, Li	1	" each

The melting of the sodium was conducted in a special apparatus (Fig. 13), separate from the main experimental set-up, consisting only of R1, the sodium reservoir, and a glass holder (H) for the sodium ampoule, connected by a flexible steel bellows. R1 remains vertical, whereas the glass holder can be fixed horizontally or vertically because of the bellows.

To break the ampoule neck, the apparatus is first flushed with argon and evacuated with the ampoule holder in the horizontal position. The steel plunger is then screwed down onto the neck till it snaps and falls into the curved leg below (Fig. 13).

FIG 13. Sodium charging apparatus

The ampoule holder is then rotated upwards to the vertical position and the entire assembly heated by heating tapes. Sodium melts and gradually falls into R1. When all the sodium is in R1, valve V9 is closed off and R1 disconnected and hooked up to the main apparatus, for the final transfer of sodium into the capsule. To control the amount of sodium allowed into the capsule, the level of sodium in R1 is first determined by measuring the voltage drop along R1.

Vacuum is then applied to the main apparatus, and the furnace and rest of the heating tapes turned on. When the temperatures recorded by TC1-5 (Fig. 7) are all above the melting point of sodium, valve V8 (under R1) is opened about 1/4 turn and a small trickle of sodium allowed to enter the main apparatus. A shot of argon is usually necessary to initiate the flow along the constricted passage of the valves and tubing. To avoid the possibility of sodium preferentially filling up the expansion tube T, the level of sodium in T is also monitored by the potential drop technique. If the above adverse condition does develop, the valve V8 is closed off and the sodium in T is forced down into the capsule by argon pressure.

The apparatus is considered adequately charged when sodium totally fills the capsule and the bottom 1-inch of T. This condition is indicated when the level of sodium in T does not decrease with the application of argon pressure. To ensure that no trapped argon remains in the capsule, the sodium is then alternately cooled and heated several times.

As the final step in the charging procedure, valve V3, under the dodecane reservoir R2, is opened and the oil allowed to fill the remaining space above the sodium.

B. Experimental Procedures

The actual experiments were conducted in the first two modes described in Chapter III. However, a majority of the runs were made in the isothermal mode only.

1) Determination of Isothermal Compressibility

The isothermal runs were obtained with an operating system consisting of the pressure capsule, valve V2, the injector, and pressure transducers P1 and P2 (Fig. 5). When system pressures exceeded 2500 psig, or when a tighter (or less compressible) system was desired, valve V4 was also closed off, leaving only P1, the 5000 psig transducer, for measuring system pressures.

Each isothermal experiment consisted of two separate pressurization steps. In the first step the whole system, i.e., the capsule plus the external section, was pressurized. In the second, V2 was closed off and only the external section was pressurized.

Each pressurization step consisted of rotating the injector stem by constant incremental amounts, eg. 180° or $1/2$ turn at a time, and noting the resultant equilibrium pressure of the system, P, and the protractor reading θ , yielding the P- θ plots shown in Appendix I. It was possible also to create a vapor bubble in the capsule simply by reducing the system pressure below the saturation value corresponding to the bulb temperature. Thus the pressurizations could be initiated right from the saturation line (eg. run Nos. 2-7 to 9, Appendix I). However, the creation of a vapor bubble sometimes caused severe fluctuations of the sodium-dodecane interface in T (Fig. 5), which in turn caused small globules of sodium to break off from the interface and lodge inside the injector body and the small bore tubes to the pressure transducers. Since these parts of the apparatus were at room temperature, the dislodged globules of sodium froze and caused plugging. Furthermore, the fluctuations would render the interface undetectable by electrical means, due to intimate mixing of the sodium and the dodecane. So, for a majority of the isotherms, the starting pressure was 50 psia-100 psia greater than the saturation value calculated from the available vapor pressure equations (1,2).

Thus, starting with the initial pressure determined as above, the system was pressurized in two steps as explained. However,

to check for leaks and hysteresis, the pressurization step, or "up" run, was usually followed by depressurization, or a "down" run, to the initial injector position. The difference between the slopes of the "up" and "down" curves was then used to determine the presence of hysteresis, if any. The difference between the initial and final pressures was used to detect leaks.

The maximum pressure attained along any isotherm was 2860 psia. The main reason for not being able to reach higher pressures, was the large amount of time required to complete a single experiment, which was generally about 30 minutes and sometimes as high as 45 minutes. This, coupled with furnace start-up times of about two hours and temperature stabilization times of 15-30 minutes, severely limited the number of experiments that could be performed at a stretch. After each continuous series of 5 to 10 isothermal runs, the furnace was shut down, since it was inadvisable to leave it on unattended. This thermal cycling, accompanied by some amount of graphitization caused the thermocouples to become unusable after 40 to 60 hours.

Thus in order to optimize the amount of data that could be obtained from a given set of thermocouples, 3000 psig was chosen as the practical limit for the isothermal runs.

2) Isobaric Thermal Expansion of Sodium

As a test of the versatility of the apparatus, the thermal expansion of sodium along three isobars, - 1, 28.9 and 69 atmos.abs.- was also measured.

The experimental procedure along each isobar was as follows:

The capsule was first heated to a suitable initial temperature, eg. 659.8 K in the case of 1 atm. (Appendix II). As the temperature increased, the system pressure also increased but was continuously reduced by screwing out the injector. At steady state, the injector position was carefully

FIG 14. Experimental P- θ plot
of thermal expansion

adjusted so that the system pressure exactly equalled the isobar valve. The set screw holding the protractor to the injector stem was then loosened and the protractor initialized to zero.

After this step, the capsule temperature was increased in stops of 25 - 50 K. However, the pressure rise accompanying this ΔT was so large that it was necessary to continuously decrease the pressure even before steady state was achieved. The procedure is illustrated in Fig. 14 where the bold lines indicate the final P- θ curves after steady state, at successive temperatures T_1 and T_2 ; the lines in between represent the sharp increases in pressure due to heating and the pressure control steps. The volumetric expansion of sodium between T_1 and T_2 is proportional to $\Delta\theta = \theta_2 - \theta_1$, where θ_1 and θ_2 are determined by graphically, or numerically, by finding the intersection of the final P- θ curves with the isobar.

The experimental plots for the three isobaric runs are shown in Appendix II. The plots show only the final isothermal P- θ curve at each temperature, since only they are of importance to the calculation of thermal expansion. The curves are numbered in increasing order to represent the actual succession of the experiments. However, due to the finite capacity (approximately 3 cc) of the expansion tube T it was necessary, after 5 to 10 successive temperature increments, to reduce the level of sodium in T. This was done by closing V2 (Fig. 7), opening V8, and pushing out into R1 the requisite amount of sodium. After each such sodium transfer, the injector was again initialized. Table 6.3.1 (Chapter 6) lists the temperatures and the $\Delta\theta$'s for each thermal expansion experiment. The temperatures at which the injectors were initialized are indicated by double asterisks.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

I. Calculation of Bulb Temperature

Thermocouple location

Two methods were used to determine the average capsule temperatures. In the first case, thermocouples were placed at three locations - two pairs at the top, one pair at the middle and two pairs at the bottom of the bulb (Runs 1-2 to 3-3, Table 6.1.2). Thus there were four temperature readings for the top and bottom positions, while only one for the middle position.

In the second case, thermocouples were located at only two locations, 1-1/2" from the top and 1-1/2" from the bottom of the bulb, two pairs at each location (Runs 3-7 to 3-16, Table 6.1.2).

Temperature calculation

The thermocouple outputs were first converted to deg - F by using the equations in Table 6.1.1, derived by fitting the factory supplied calibration points with Least Squares polynomials. The average temperatures were then calculated using the formulae:

$$(a) \quad T_{av} = \frac{\sum T_{top} + 4 \times T_{middle} + \sum T_{bottom}}{12} \quad (6.1)$$

for the first method of thermocouple attachment, and

$$(b) \quad T_{av} = \frac{\sum T_{top} + \sum T_{bottom}}{8} \quad (6.2)$$

for the second method of thermocouple attachment.

Often, either the positive wire or the negative wire at a location would become unserviceable. In such cases, each of the two remaining temperature readings for that location would be weighted double in order to avoid the readings of the other locations from overinfluencing the average temperature.

The individual temperatures and the averages are listed in Table 6.1.2.

TABLE 6.1.1Conversion equations from thermocouple e.m.f's to deg-F

Equation used is :

$$T (F) = a + b.e + c.e^2 + d.e^3, \text{ where } e = \text{thermocouple output, mV}$$

<u>Temperature Range (F)</u>	<u>Coefficients</u>			
	<u>a</u>	<u>b</u>	<u>c</u>	<u>d</u>
200 - 800	35.6989	132.681	- 6.12179	-0.337223
800 - 1400	120.421	96.3708	- 0.386296	0.014118
1400- 2000	217.295	77.7573	0.717219	-0.004917
2000- 2600	166.648	99.6743	- 1.08089	0.036516
2600- 3200	-1.54732×10^4	1.81134×10^3	- 63.2794	0.786591
3200- 3800	-7.32715×10^3	7.72383×10^2	- 21.1237	0.234138

(The thermocouples used were Tungsten-5% Rhenium/Tungsten-26% Rhenium, manufactured by Hoskins Manufacturing Co.(33), Lot no. 5158/26251)

TABLE - 6.1.2

Average capsule bulb temperatures (deg. F)

Run no. 1-2		Individual readings								Average
Expt.		Top		Middle			Bottom			
1	1168.4	1168.4	1164.6	1163.6	1205.6	*	*	1188.8	1188.8	1186.9
2	1592.9	1595.8	1591.9	1588.1	1620.0	1599.7	1600.6	1601.2	1600.6	1604.2
3	1674.4	1676.6	1673.5	1672.5	1709.6	1679.3	1678.3	1682.2	1682.2	1688.3
4	1923.9	1923.9	1917.9	1916.9	1954.8	1912.9	1916.9	*	*	1930.1
5	2050.1	2058.2	2052.6	2044.0	2081.5	2040.0	2036.0	*	*	2056.9
6	2025.9	2033.0	2026.9	2018.9	*	2013.9	2014.9	2018.9	2017.9	-
7	2098.8	2106.0	2099.8	2092.7	2129.5	2084.5	2088.6	2086.6	2083.5	2104.9
8	2122.3	2124.4	2119.3	2117.2	2151.2	2108.0	2112.1	2111.1	2108.0	2127.3
9a	2183.3	2185.4	2179.2	2178.1	2214.7	2167.7	2171.9	2169.8	2165.7	2188.3
9b	2177.1	2178.1	2172.9	2171.9	2208.4	2162.5	2166.7	2164.6	2160.5	2182.3
10a	2189.6	2191.6	2185.4	2184.4	2220.4	2174.0	2178.1	2176.0	2171.9	2194.4
10b	2185.4	2186.4	2181.2	2180.2	2217.3	2169.8	2174.0	2171.9	2167.7	2190.5
11	2208.4	2210.5	2205.2	2200.0	*	2190.6	2195.8	2193.7	2189.6	2210.0**
12	2251.5	2249.4	2237.8	2246.2	2283.4	2231.5	2236.7	2234.6	2229.4	2251.2
13	2300.5	2304.8	2300.5	2296.2	2332.7	2278.1	2283.4	2282.3	2277.0	2304.5
14a	-	-	-	-	-	-	-	-	2319.8	2348.0**
14b	-	-	-	-	-	-	-	-	2320.9	2349.0**
15a	-	-	-	-	-	-	-	-	2351.1	2379.0**
15b	-	-	-	-	-	-	-	-	2349.0	2376.9**
16a	2390.4	2394.7	2393.6	2389.3	2424.4	2363.1	2367.4	2365.2	2360.9	2393.5
16b	-	-	-	-	-	-	-	2378.9	-	2407.4**

* thermocouple malfunction

** average calculated by trend analysis

- thermocouple output not recorded

TABLE - 6.1.2 (contd.)

Run no. 3-1

Expt.	Top				Middle		Bottom			Average
1	716.8	716.8	716.8	716.8	734.0	733.0	733.0	732.1	732.1	727.8
2	774.4	775.3	774.4	773.4	792.7	791.8	790.8	790.8	790.8	786.0
3	799.5	799.5	800.5	799.5	818.1	816.3	816.3	815.3	816.3	811.3
4	850.7	851.6	851.6	851.6	870.2	867.4	866.5	866.5	866.5	862.7
5	847.9	849.7	848.8	849.7	868.3	865.5	865.5	864.6	865.5	860.9
6	877.6	877.6	877.6	877.6	896.2	893.4	892.5	892.5	892.5	888.8
7	918.5	918.5	918.5	918.5	938.0	934.3	933.3	933.3	933.3	930.0
8	973.3	973.7	975.1	974.2	995.5	990.0	989.0	989.0	990.0	986.4
9	1016.0	1016.9	1017.8	1017.8	1039.2	1032.7	1032.7	1032.7	1032.7	1029.7
10	1049.4	1048.5	1049.4	1049.4	1072.6	1064.3	1064.3	1064.3	1064.3	1062.0
11	1090.3	1089.3	1091.2	1092.1	1114.4	1105.1	1105.1	1105.1	1105.1	1103.4
12	1129.3	1127.4	1130.2	1130.2	1153.5	1142.3	1142.3	1142.3	1142.3	1141.7
13	1183.2	1182.3	1182.3	1183.2	1206.5	1193.5	1193.5	1193.5	1193.5	1194.3
14	1219.6	1219.6	1219.6	1219.6	1243.8	1229.8	1229.8	1229.8	1229.8	1231.0
15	1242.8	1243.8	1244.7	1244.7	1267.1	1252.2	1252.2	1252.2	1252.2	1254.4
16	1303.5	1303.5	1303.5	1304.4	1326.8	1310.9	1310.0	1310.0	1310.0	1313.6
17	1328.7	1328.7	1329.6	1330.6	1352.1	1335.2	1334.3	1334.3	1335.2	1338.7
18	1353.0	1353.0	1353.9	1353.9	1375.5	1357.7	1356.7	1357.7	1357.7	1362.1
19	1347.4	1346.5	1349.3	1349.3	1370.8	1353.0	1352.1	1352.1	1353.0	1357.1
20	1347.4	1346.5	1349.3	1349.3	1370.8	1353.0	1352.1	1352.1	1353.0	1357.1
21	1386.7	1386.7	1388.6	1388.6	1410.2	1390.4	1389.5	1390.4	1390.4	1396.0
22	1434.9	1433.9	1435.8	1436.8	1458.7	1436.8	1435.8	1436.8	1436.8	1443.5
23	1474.9	1472.9	1474.9	1474.9	1495.9	1473.9	1472.9	1473.9	1473.9	1481.3
24	1517.9	1517.9	1517.9	1519.8	1540.0	1516.9	1516.0	1516.0	1516.9	1524.9
25	1551.5	1550.5	1550.5	1551.5	1572.7	1549.6	1548.6	1548.6	1549.6	1557.6
26	1590.0	1589.1	1589.1	1591.0	1612.3	1588.1	1587.1	1587.1	1588.1	1596.6
27	1619.1	1617.1	1619.1	1621.0	1643.3	1618.1	1617.1	1617.1	1618.1	1626.7

TABLE - 6.1.2 (contd.)

Run no. 3-2

Expt.	Top				Middle		Bottom			Average
1	1046.6	1046.6	1046.6	1046.6	1066.1	1059.6	1059.6	1059.6	1055.9	1057.1
2	1090.3	1089.3	1089.3	1091.2	1110.7	1103.3	1103.3	1103.3	1103.3	1101.3
3	1146.0	1144.2	1145.1	1145.1	1165.6	1157.2	1156.3	1157.2	1157.2	1155.9
4	1218.6	1217.2	1217.7	1218.6	1239.1	1227.9	1227.0	1227.0	1227.9	1228.2
5	1240.0	1240.0	1241.0	1241.0	1261.5	1250.3	1249.4	1250.3	1250.3	1250.7
6	1269.9	1269.9	1270.8	1269.9	1292.3	1278.3	1278.3	1278.3	1279.2	1280.3
7	1300.7	1299.7	1300.7	1300.7	1322.2	1307.2	1307.2	1307.2	1308.1	1310.0
8	1336.2	1333.4	1335.2	1336.2	1356.7	1340.8	1339.9	1340.8	1341.8	1344.3
9	1380.1	1378.3	1380.1	1380.6	1400.8	1382.9	1382.9	1383.9	1383.9	1388.0
10	1415.9	1414.0	1414.0	1415.9	1435.8	1416.9	1415.9	1416.9	1417.8	1422.5
11	1447.2	1444.4	1446.3	1447.2	1468.2	1447.2	1447.2	1447.2	1448.2	1454.0
12	1484.4	1483.4	1485.4	1486.3	1506.4	1483.4	1483.4	1484.4	1484.4	1491.7
13	1516.9	1514.1	1516.0	1517.9	1538.0	1515.0	1514.1	1515.0	1516.0	1523.1
14	1552.5	1550.5	1551.5	1553.4	1573.6	1549.6	1548.6	1549.6	1549.6	1558.3

AVG. BULB TEMPERATURES FOR RUN #3-3

1	1261.5	1261.5	1262.0	1262.4	1282.9	1268.9	1268.0	1268.9	1269.9	1271.2
2	1295.1	1296.0	1296.9	1296.9	1315.6	1301.6	1300.7	1301.6	1302.5	1304.5
3	1329.2	1328.2	1329.2	1330.1	1346.9	1332.9	1332.4	1332.9	1333.8	1336.4
4	1375.5	1373.6	1375.5	1375.9	1393.3	1377.3	1376.4	1377.3	1377.3	1381.8
5	1426.3	1424.4	1425.4	1427.3	1446.3	1426.3	1425.4	1426.3	1426.3	1432.7
6	1464.4	1462.5	1463.4	1465.3	1484.4	1462.5	1462.5	1463.4	1463.4	1470.4
7	1499.7	1498.7	1499.7	1500.6	1520.8	1496.8	1496.8	1497.8	1497.8	1505.9

TABLE - 6.1.2 (contd.)

Run no. 3-3

Expt.	Top				Middle		Bottom			Average
8	1535.2	1533.2	1535.2	1536.1	1557.3	1533.2	1532.3	1533.2	1533.2	1541.7
9	1574.6	1572.7	1574.6	1575.6	1595.8	1570.3	1569.8	1570.7	1570.7	1580.2
10	1628.8	1626.3	1628.3	1629.7	1650.1	1622.5	1622.0	1622.9	1622.9	1633.7
11	1679.3	1676.4	1678.8	1681.3	1699.8	1672.5	1671.5	1672.0	1672.5	1683.6
12	1727.2	1724.2	1726.2	1728.2	1748.7	1719.4	1718.4	1718.4	1719.4	1731.4
13	1638.5	1636.5	1637.0	1638.5	1667.6	1638.5	1637.5	1638.0	1638.5	1647.8
14	1756.6	1754.6	1756.6	1757.6	1783.2	1751.7	1749.7	1750.7	1751.7	1763.5
15	1782.2	1780.2	1782.2	1783.2	1808.3	1776.3	1775.3	1775.3	1776.3	1788.7
16	1817.7	1816.7	1818.7	1819.6	1843.4	1810.8	1808.8	1809.8	1810.8	1823.8
17	1866.2	1864.2	1867.2	1868.2	1892.0	1857.2	1856.3	1856.3	1858.2	1871.8
18	1905.9	1903.9	1905.9	1907.9	1930.8	1894.0	1892.5	1894.0	1895.0	1910.2
19	1941.8	1938.8	1941.3	1942.8	1966.8	1927.9	1926.9	1928.8	1928.8	1945.4
20	1982.3	1980.3	1983.3	1984.4	2008.4	1966.3	1965.3	1966.8	1967.3	1985.8
21	2014.4	2012.9	2013.9	2015.9	2040.0	1996.4	1995.9	1996.9	1997.9	2017.0
22	2066.8	2064.7	2065.8	2066.8	2092.2	2045.5	2044.5	2046.6	2046.6	2068.0
23	2051.1	2049.1	2051.1	2052.1	2076.9	2032.0	2030.9	2033.0	2033.0	2053.3
24	2064.2	2062.2	2064.2	2065.3	2089.6	2044.0	2042.5	2044.0	2045.0	2065.8
25	2074.9	2073.4	2074.4	2075.4	2100.8	2054.1	2053.1	2054.1	2055.1	2076.5
26	2093.7	2092.7	2093.7	2095.7	2119.8	2072.3	2070.3	2072.3	2073.4	2095.3
27	2143.9	2141.4	2141.9	2143.9	2169.8	2117.2	2118.2	2119.3	2118.7	2143.6
28	2181.2	2178.1	2179.2	2182.3	2207.3	2153.2	2153.2	2155.3	2154.3	2180.5
29	2242.0	2237.8	2237.8	2242.0	2267.4	2210.5	2210.5	2211.5	2211.5	2239.4
30	2323.6	2319.8	2319.8	2324.1	2349.0	2286.6	2286.6	2288.7	2288.7	2319.5
31	2340.9	2356.6	2356.6	2360.9	2386.0	2323.0	2323.0	2324.1	2324.1	2356.1
32	2428.9	2425.5	2423.3	2426.6	2453.3	2388.2	2387.1	2389.3	2389.3	2422.6
33	2363.1	2358.7	2357.6	2360.9	2387.6	2326.3	2323.0	2325.2	2327.3	2357.7

TABLE - 6.1.2 (contd.)

Run no. 3-7 Expt.	Top				Bottom				Average
1	1047.5	1052.2	1046.6	1042.0	1051.3	1053.1	1052.2	1050.3	1049.4
2	1218.6	1219.6	1218.6	1216.8	1219.6	1221.4	1220.5	1219.6	1219.3
3	1417.8	1417.8	1417.8	1417.8	1416.9	1416.9	1416.9	1415.0	1417.1
4	1312.8	1312.8	1311.9	1311.9	1312.8	1312.8	1311.9	1310.0	1312.1
AVG. BULB TEMPERATURES FOR RUN #3-8									
1	1505.4	1507.3	1506.4	1504.5	1499.7	1500.6	1499.7	1497.8	1502.7
2	1598.7	1600.7	1598.7	1596.8	1590.5	1592.0	1591.0	1589.1	1594.7
3	1706.6	1708.6	1708.6	1706.6	1701.8	1703.7	1701.8	1698.8	1704.6
4	1802.9	1806.8	1807.8	1803.8	1796.9	1798.9	1796.9	1796.0	1801.3
AVG. BULB TEMPERATURES FOR RUN #3-9									
1	2092.7	2096.8	2095.7	2092.7	2080.5	2081.5	2079.5	2078.4	2087.2
2	2212.6	2214.7	2213.6	2212.6	2193.7	2195.8	2193.7	2192.7	2203.7
AVG. BULB TEMPERATURES FOR RUN #3-10									
1	2210.5	2212.6	2210.5	2208.4	2193.2	2194.8	2193.2	2191.6	2201.8
2	2271.7	2273.8	2271.7	2269.6	2252.6	2254.7	2253.6	2250.5	2262.3
3	2331.7	2334.9	2336.0	2334.9	2313.4	2314.4	2313.4	2312.3	2323.9
4	2368.5	2370.7	2371.8	2370.7	2347.9	2350.0	2349.0	2346.8	2359.4
5	2530.8	2535.3	2536.4	2531.9	2507.6	2508.1	2505.9	2502.5	2519.7
6	2568.4	2576.4	2576.4	2570.7	2544.4	2545.5	2543.3	2541.0	2558.3
7	2616.0	2624.3	2624.3	2617.2	2589.6	2591.4	2589.0	2586.7	2604.8
8	2582.1	2590.2	2590.2	2582.1	2555.8	2558.1	2555.8	2552.4	2570.8
9	2648.9	2657.1	2657.1	2650.1	2619.6	2621.9	2619.6	2617.2	2636.4
10	2711.4	2719.5	2720.6	2712.6	2683.8	2684.9	2682.6	2679.1	2699.3
11	2767.6	2775.6	2776.7	2769.9	2741.3	2743.5	2740.1	2736.7	2756.4
12	2768.7	2775.6	2777.9	2771.0	2741.3	2742.4	2739.0	2736.7	2756.6

TABLE - 6.1.2 (contd.)

Run no. 3-10

Expt.	Top				Bottom				Average
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13	2842.2	2851.5	2852.6	2844.5	2814.6	2815.7	2810.0	2808.8	2830.0
14	2902.9	2909.9	2913.5	2906.4	2874.7	2877.1	2870.1	2867.7	2890.3
15	2911.1	2917.0	2920.6	2914.7	2884.1	2885.2	2878.2	2875.9	2898.4
16	3013.1	3016.8	3023.1	3019.3	2978.4	2980.9	2971.1	2968.7	2996.4
17	3035.7	3038.3	3054.9	3052.3	3003.1	3006.8	2998.1	2993.2	3022.8
18	2870.1	2877.1	2885.2	2877.1	2856.1	2859.6	2849.2	2845.7	2865.0
19	2784.8	2790.5	2795.1	2790.5	2773.3	2776.7	2766.4	2761.9	2779.9
20	2693.0	2699.9	2703.4	2696.5	2682.6	2686.1	2676.8	2672.2	2688.8
21	2639.6	2647.8	2648.9	2641.9	2629.0	2633.7	2624.3	2619.6	2635.6
22	2634.9	2643.1	2645.4	2637.2	2625.5	2629.0	2618.4	2614.8	2631.0
23	2570.7	2577.5	2578.7	2570.7	2561.5	2566.1	2554.7	2552.4	2566.5
24	2629.0	2638.4	2641.9	2634.9	2620.8	2623.1	2614.8	2610.1	2626.6
25	2493.5	2500.3	2501.4	2494.6	2487.9	2490.1	2482.3	2478.9	2491.1
26	2338.1	2345.7	2345.7	2339.2	2336.0	2340.3	2331.7	2327.3	2338.0
27	2095.7	2101.9	2100.8	2094.7	2096.8	2101.9	2094.7	2090.6	2097.1
28	2058.2	2064.2	2063.2	2055.1	2060.2	2064.2	2057.2	2053.1	2059.4
29	2069.3	2075.4	2074.4	2067.3	2070.3	2075.4	2068.3	2062.2	2070.3
30	1956.8	1963.8	1962.8	1955.8	1959.8	1965.9	1958.8	1953.8	1959.7
31	1830.5	1838.4	1836.4	1829.5	1836.4	1842.4	1835.5	1829.5	1834.8
32	1749.7	1757.6	1755.6	1747.8	1756.6	1762.5	1758.6	1751.7	1755.0

Run no. 3-11

1	*	*	1776.3	1769.4	1779.2	1781.2	1779.2	1778.2	1776.1
2	*	*	1736.0	1729.1	1739.9	1741.9	1739.9	1738.9	1736.4
3	*	*	1699.9	1692.0	1703.7	1706.6	1704.7	1702.7	1700.2
4	*	*	1665.7	1657.9	1669.6	1671.5	1670.5	1668.6	1665.9
5	*	*	1630.7	1623.9	1635.5	1637.5	1638.5	1635.5	1632.0

TABLE - 6.1.2 (contd.)

Run no. 3-11

Expt.	Top		Bottom						Average
6	*	*	1589.1	1583.3	1593.9	1596.8	1597.8	1594.9	1591.0
7	*	*	1553.4	1544.8	1558.2	1560.2	1562.1	1559.2	1554.5
8	*	*	1515.0	1507.3	1519.8	1523.6	1522.7	1519.8	1516.3
9	*	*	1479.6	1472.0	1483.4	1488.2	1488.2	1483.4	1480.8

AVG. BULB TEMPERATURES FOR RUN #3-13

1	2180.2	2186.4	2174.0	2166.7	2178.1	2185.4	2176.0	2167.7	2176.8
2	2270.6	2279.1	2265.3	2257.9	2267.4	2278.1	2266.4	2257.9	2267.8

AVG. BULB TEMPERATURES FOR RUN #3-14

1	2339.2	2339.2	2338.1	2339.2	2357.6	2360.9	2359.8	2358.7	2349.1
2	2339.2	2339.2	2338.1	2339.2	2357.6	2359.8	2359.8	2357.6	2348.8
3	2426.6	2426.6	2425.5	2427.8	2446.6	2448.8	2447.7	2444.4	2436.8
4	2522.8	2522.8	2522.8	2524.0	2545.5	2549.0	2536.4	2533.0	2532.1
5	2607.7	2606.5	2607.7	2607.7	2634.5	2636.1	2627.8	2626.6	2619.4
6	2694.2	2693.0	2693.0	2693.0	2721.8	2721.8	2714.9	2714.9	2705.8

AVG. BULB TEMPERATURES FOR RUN #3-15

1	*	*	2298.9	2296.7	2284.5	2282.9	2282.9	2283.4	2290.6
2	*	*	2326.3	2324.1	2299.4	2298.3	2297.6	2298.3	2311.8

TABLE - 6.1.2 (contd.)

un no. 3-16

xpt.

Average

Top

Bottom

1	*	*	2651.3	2653.6	2625.5	2626.1	2626.6	2626.6	2639.3
2	*	*	2695.3	2698.8	2669.9	2669.9	2668.1	2667.6	2683.0
3	*	*	2737.8	2742.4	2711.4	2712.6	2712.6	2710.3	2725.9
4	*	*	2788.2	2795.1	2753.9	2755.0	2755.0	2755.0	2773.2
5	*	*	2831.8	2839.9	2800.8	2799.7	2798.5	2799.7	2817.8
6	*	*	2877.6	2880.6	2846.9	2842.2	2841.1	2845.1	2861.5
7	*	*	2912.9	2917.0	2891.1	2880.6	2883.5	2892.3	2900.9
8	*	*	2908.8	2913.5	2889.9	2877.6	2882.9	2894.0	2898.6
9	*	*	2875.9	2874.7	2853.8	2843.4	2846.9	2856.1	2862.7
10	*	*	2844.5	2841.1	2818.0	2811.1	2814.6	2821.5	2829.6
11	*	*	2810.0	2805.4	2780.7	2776.7	2779.0	2782.5	2793.7
12	*	*	2775.6	2771.0	2744.7	2742.4	2745.8	2745.8	2759.0
13	*	*	2742.4	2743.0	2708.0	2708.0	2710.3	2708.6	2725.7
14	*	*	2702.2	2695.3	2673.9	2674.5	2675.7	2674.5	2686.7
15	*	*	2662.9	2657.7	2639.0	2640.7	2640.7	2638.4	2650.0
16	*	*	2626.6	2625.5	2600.6	2603.0	2602.4	2600.0	2613.8
17	*	*	2588.5	2587.9	2562.7	2566.1	2567.2	2563.8	2576.6
18	*	*	2591.4	2598.3	2571.8	2575.3	2577.5	2575.3	2584.9
19	*	*	2585.6	2588.5	2562.1	2564.9	2566.1	2564.4	2575.7

II. Calculation of Isothermal Compressibility

a. Calculation Procedure

For each experimental isotherm, two P- θ curves were obtained, one for the compression of the capsule and the external section and one for the compression of the external section only. For each such curve the first step was to fit the θ 's to second order polynomials in P, ie.

$$\theta(P)_i = A_i + B_i \cdot P + C_i \cdot P^2 \quad (6.3)$$

where, for the capsule plus external section $i = 1$, and for the external section only, $i = 2$. (See, for example, Table 6.2.1). If V_θ is the volume displaced by the injector per stem turn, then

$$\frac{dV_i}{dP} = \frac{d\theta(P)_i}{dP} \times \frac{V_\theta}{360} \quad (6.4a)$$

$$= (B_i + 2C_i P) \times V_\theta / 360 \quad (\text{using eq. 6.3}) \quad (6.4b)$$

The two equations derived from eq. 6.4b can be substituted into the eq. 3.8 derived earlier, to give

$$\frac{d\rho_c}{dP} = \{(B_1 - B_2) + 2(C_1 - C_2)P\} \times \frac{V_\theta}{360} \times \frac{\rho_T}{V_c} \quad (6.5)$$

Eq. 6.5 gives the change of density with pressure, of the sodium in the capsule.

To evaluate eq. 6.5 it is necessary to know the variation of the density of sodium in the expansion tube, ρ_T , with pressure. As a first approximation, ρ_T was assumed to be equal to the saturation density of liquid sodium at 125 C, the temperature of the expansion tube. It was also possible to estimate ρ_T from the compressibility calculations of Padilla (13) and the data of Makarenko et al (38). A computer analysis showed that calculated values of $d\rho_c/dP$ were relatively insensitive to the particular method by which ρ_T was calculated since it varied by less than 0.3% (at 125°C) over the pressure range of the experiments. However, for the sake of accuracy, the pressure dependence of ρ_T was accounted for in the final calculations by using the

equation:

$$(\rho_T)_P \text{ (g/cc)} = 1.2 \times 10^{-6} P(\text{psi}) + (\rho_s)_{398 \text{ K}} \text{ (g/cc)} \quad (6.6)$$

where ρ_s = saturation density of liquid sodium. The constant in eq. 6.6 is the average value of $d\rho/dP$ at 125 C obtained from Padilla (13) and Makarenko (38).

The thermal expansion of the CVD-tungsten capsule was also considered and was estimated from the equation:

$$L_T/L_0 = 1.0 + 3.83 \times 10^{-6} T + 7.92 \times 10^{-10} T^2 \quad (6.7)$$

(with T in deg. C)

The Young's modulus of tungsten was found from literature (36) to be 30×10^6 psi or greater up to 2000 C. The elastic strain of the capsule under the worst condition was thus less than 0.01% and was neglected.

Using the above information, eq. 6.5 was evaluated at various pressures along each experimental isotherm. The chosen points comprised the experimentally observed subcooled equilibrium pressures and also the saturation pressure (ρ_s) of the isotherm.

The subcooled liquid density at each of the above pressures was then calculated from the difference equation:

$$\Delta\rho_c = \rho_{P_{i+1}} - \rho_{P_i} = \Delta\theta \cdot (V_\theta/360) \cdot \rho_T/V_c \quad (6.8)$$

where,

$$\Delta\theta = \left\{ \theta(P_{i+1})_1 - \theta(P_i)_1 \right\} - \left\{ \theta(P_{i+1})_2 - \theta(P_i)_2 \right\} \quad (6.9)$$

In the above equations:

P_i 's are the successive pressure points along each isotherm, $\theta(P)_1$ and $\theta(P)_2$ are calculated from eq. 6.3, and, ρ_T is calculated from eq. 6.6.

The initial value of P (i.e. P_1) in the above numerical procedure is P_s , the saturation pressure. Thus ρ_{P_1} is the saturated liquid density (ρ_s). The values of P_s and ρ_s used in eqs. 6.5 to 6.9 were obtained from the correlations developed in Appendices IV and V respectively.

From the values of $d\rho_c/dP$ and ρ_c calculated above, the isothermal compressibility (β_T) and compressibility factor (z) were also obtained using the equations:

$$\beta_T = (d\rho_c/dP)/\rho_c \quad (6.10)$$

$$\text{and } z = P/(\rho_c \cdot R \cdot T) \quad (6.11)$$

b. Corrections for the Volumes of the Capillary and Valve V2

The compressibility of sodium in the volume between the capsule bulb and valve V2 was not explicitly considered in eqs. 6.5 to 6.9. However the actual calculations were performed in two cycles in order to subtract its contribution to the results. In the first cycle, the apparent or observed values of $d\rho_c/dP$, at different temperatures and pressures, were calculated by using the above equations as written. The maximum possible error by this procedure is only 6%. Thus, as a first approximation, the $d\rho_c/dP$ values were assumed to be accurate and then fitted by Least Squares to various equations involving temperature and pressure. The best-fit equation had the form:

$$(d\rho/dP)_{T,P} = (d\rho/dP)_s + (C4 + C5 \cdot P) \cdot T \cdot P \quad (6.12)$$

where,

$$\begin{aligned} (d\rho/dP)_s &= \text{the saturation value of } d\rho/dP \\ &= (d\rho/dP)_{398 \text{ K}} / (C1 + C2 \cdot T_r + C3 \cdot T_r^2) \end{aligned} \quad (6.13)$$

In the above equation, C1 to C5 are the Least Squares coefficients, $(d\rho/dP)_{398 \text{ K}}$ was determined from Padilla (13) and Makarenko (38) and T_r is the reduced temperature. Eq. 6.12 was then used in a second cycle to calculate the corrected values of $d\rho_c/dP$ by substituting in the eq. A.6.8 derived in Appendix 6. The average temperature of the capillary, for use in eq. A.6.8, was calculated from the equation:

$$T_{\text{cap}} = (T_c + T_{\text{ext}})/2$$

where,

T_c = average temperature of the capsule
and T_{ext} = temperature of the external section.

The subcooled liquid densities were also corrected by using the equation

$$\rho_{\text{correct}} = \rho_{\text{observed}} - \frac{V_{\text{cap}} + V_{V2}}{V_{\text{bulb}}} \cdot \int_{P_1}^{P_1+1} \phi(T,P) \cdot dP \quad (6.14)$$

where, ρ_{observed} was calculated from eq. 6.8 and $\phi(T,P)$ is eq. 6.12. The actual values of β_T and z were calculated using only the above corrected values of $d\rho_c/dP$ and ρ_c . The final results for each isotherm are shown in Appendix III. The pertinent data are also plotted in Figs. 15 & 16.

c. Analysis of Experimental Data

An important aspect of the previous calculations was the preliminary analyses of the P- θ curves obtained for each run. As explained in "Experimental Procedures", each isothermal P- θ curve was composed of one or more 'up' and 'down' runs, where 'up' refers to pressurization and 'down' refers to depressurization. But before using a composite curve for the calculations described in the previous sections, it was necessary to make several tests to ensure accuracy and internal consistency.

Thus, each of the 'up' and 'down' components of a P- θ curve were separately fitted with equations like eq. 6.3. The coefficients of the separate equations were then statistically analysed using the standard z-test. The null-hypothesis tested was that the coefficients were not significantly different at the 5% significance level, or that

$$\left| \frac{x_1 - x_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \right| \leq z_{.025} = 1.96 \quad (50) \quad (6.15)$$

where, x_1 and x_2 are the coefficients being tested, σ_1 and σ_2 are the respective standard deviations, and n_1 and n_2 are the respective sample sizes.

The z-test is illustrated in Table 6.2.1 as performed on Run 3-7-2. The coefficients B and C of both curves satisfy the z-test. However, the coefficient A of the external-section

TABLE 6.2.1

Statistical testing of the isothermal compressibility curves

Run no. : 3-7-2

Temperature of bulb = 1679 R

Date : 11-4-76

= 933 K

P-θ data and curve-fit for the capsule and externals

POINTS FITTED = # 1 TO #17

ORDER OF POLYNOMIAL USED = 2

EXPT	PSIG	-----THEIA-----		
		OBS	CALC	DIFF
1	51.4	180.0	192.1	12.1
2	154.8	270.0	256.0	-14.0
3	310.3	360.0	349.1	-10.9
4	477.8	450.0	445.3	-4.7
5	657.3	540.0	543.7	3.7
6	842.0	630.0	639.7	9.7
7	1005.7	720.0	720.6	0.6
8	1193.5	810.0	808.3	-1.7
9	1388.9	900.0	894.0	-6.0
10	1196.0	810.0	809.5	-0.5
11	1013.9	720.0	724.6	4.6
12	833.1	630.0	635.2	5.2
13	656.7	540.0	543.3	3.3
14	480.9	450.0	447.1	-2.9
15	314.7	360.0	351.7	-8.3
16	166.2	270.0	263.0	-7.0
17	59.0	180.0	196.8	16.8

STANDARD DEVIATION = 0.8862D 01

COEFFS ARE =

SIGMA(COEFF) =

1(A)	1.59697574D 02	5.57622597D 00
2(B)	6.33986297D 00	1.98277474D-01
3(C)	-7.58304221D-03	1.42268361D-03

POINTS FITTED = # 1 TO # 9

STANDARD DEVIATION = 0.1001D 02

COEFFS ARE =

SIGMA(COEFF) =

1(A)	1.63649311D 02	8.65109259D 00
2(B)	6.22847853D 00	2.96108232D-01
3(C)	-6.84227726D-03	2.03145156D-03

TABLE 6.2.1 (contd.)

POINTS FITTED = # 9 TO #17

STANDARD DEVIATION = 0.89920 01

	COEFFS ARE =	SIGMA(COEFF) =
1(A)	1.566443280 02	7.985930770 00
2(B)	6.385568030 00	2.714556640-01
3(C)	-7.678661970-03	1.849078560-03

z - testCoefficient A

$$\frac{A_1 - A_2}{\sqrt{\sigma_{A_1}^2/n_1 + \sigma_{A_2}^2/n_2}} = \frac{(1.6365 - 1.5664) \times 10^2}{\sqrt{8.6511^2/9 + 7.986^2/9}}$$

$$= 1.8 < z_{0.025}$$

Coefficient B

$$\frac{B_1 - B_2}{\sqrt{\sigma_{B_1}^2/n_1 + \sigma_{B_2}^2/n_2}} = \frac{6.2285 - 6.3856}{\sqrt{0.2961^2/9 + 0.2715^2/9}}$$

$$= 1.17 < z_{0.025}$$

Coefficient C

$$\frac{C_1 - C_2}{\sqrt{\sigma_{C_1}^2/n_1 + \sigma_{C_2}^2/n_2}} = \frac{-(6.842 - 7.679) \times 10^{-3}}{\sqrt{0.00203^2/9 + 0.00185^2/9}}$$

$$= 0.914 < z_{0.025}$$

TABLE 6.2.1 (contd.)

P-θ data and curve-fit for the external system only

POINTS FITTED = # 1 TO #25

ORDER_OF_POLYNOMIAL_USED = 2

EXPT	PSIG	THEIA		
		URS	CALC	DIFF
1	73.0	180.0	188.0	8.0
2	133.2	225.0	220.4	-4.6
3	211.3	270.0	261.5	-8.5
4	301.4	315.0	307.7	-7.3
5	396.6	360.0	355.3	-4.7
6	496.8	405.0	403.9	-1.1
7	595.8	450.0	450.4	0.4
8	698.6	495.0	497.1	2.1
9	800.1	540.0	541.7	1.7
10	906.1	585.0	586.5	1.5
11	1019.0	630.0	632.4	2.4
12	1128.1	675.0	674.9	-0.1
13	1234.7	720.0	714.7	-5.3
14	1123.0	675.0	672.9	-2.1
15	1014.5	630.0	630.6	0.6
16	907.3	585.0	587.0	2.0
17	805.8	540.0	544.1	4.1
18	701.7	495.0	498.5	3.5
19	600.9	450.0	452.7	2.7
20	498.7	405.0	404.8	-0.2
21	403.5	360.0	358.7	-1.3
22	310.3	315.0	312.2	-2.8
23	221.4	270.0	266.7	-3.3
24	142.1	225.0	225.1	0.1
25	80.6	180.0	192.1	12.1

STANDARD DEVIATION = 0.4718D 01

COEFFS ARE =		SIGMA(COEFF) =
1(A)	1.48061868D 02	2.88279287D 00
2(B)	5.52764972D 00	1.09900941D-01
3(C)	-7.60344632D-03	8.59820321D-04

POINTS FITTED = # 1 TO #13

STANDARD DEVIATION = 0.5010D 01

COEFFS ARE =		SIGMA(COEFF) =
1(A)	1.51274843D 02	4.18689426D 00
2(B)	5.46783331D 00	1.55511558D-01
3(C)	-7.27929406D-03	1.17827199D-03

TABLE 6.2.1 (contd.)

POINTS FITTED = #13 TO #25

STANDARD DEVIATION = 0.4537D 01

COEFFS ARE =

SIGMA(COEFF) =

1 (A)	1.45704221D 02	3.91371691D 00
2 (B)	5.52949405D 00	1.44074243D-01
3 (C)	-7.32330070D-03	1.08671195D-03

z - testCoefficientz

A

3.5

B

1.04

C

0.09

curve fails the test at the 5% level. But in the calculation of compressibility, only B and C are used (eq. 6.5) and thus 3-7-2 can be accepted for this purpose.

A further check on the validity of a particular run is the sign of the differences $(B_1 - B_2)$ and $(C_1 - C_2)$ used in eq. 6.5. Since $d\rho/dP$ of a subcooled liquid is always positive and decreases (or remains constant) with pressure, we should have

$$B_1 - B_2 > 0 \quad (6.16)$$

$$\text{and } C_1 - C_2 \leq 0 \quad (6.17)$$

Examining the coefficients of the composite curves of 3-7-2 (Table 6.2.1), it is seen that $C_1 - C_2 > 0$. Therefore the pressure variation of $d\rho/dP$ as obtained in Run 3-7-2 was in error. Thus the run was not used in the final least squares analysis of the compressibility data. In fact, in this investigation, the condition that $B_1 - B_2 > 0$ was always satisfied, whereas the other condition was not. Some examples of this case are Runs 1-2-8A, 1-2-9B, 1-2-13C, 1-2-16A & B and 3-7-2-E (Appendix III). In all these runs, it is observed that $d\rho/dP$ increases (rather than decreases) with pressure; thus none of these runs were used in the subsequent Least Squares analysis of the data.

d. Analysis of Results

The experimental $d\rho/dP$, β_T and z data were finally analysed by Least Squares to obtain a suitable equation of state for liquid sodium. Since only pressure and temperature were the directly observed thermodynamic variables, the $d\rho/dP$, β_T and z data were fitted to different forms of equations involving only T and P . It was also evident from the plots of the above data (Figs. 15 & 16) that within the experimental range, each of the quantities $d\rho/dP$, β_T and z varied linearly with pressure at a constant temperature. Thus the form:

$$x = A(T) + B(T)P$$

where $x \equiv d\rho/dP$, β_T or z

and $A(T)$ & $B(T)$ are temperature dependent constants, was ini-

0.0001

K. S. L. X 1.0 TO 1.5 CENTIM
KEUFFEL & ESSER CO. MA

$(de/dP)_T$ (g/cc/ata)

$(de/dP)_T$ vs. P

Fig. 15

Pressure, psia

tially chosen to represent the data.

The Least Squares analysis was performed in two steps:

- a) the coefficients were determined simultaneously using the standard linear least squares formulation,
- b) the coefficients were determined individually, in order of significance, using the step-wise regression procedure.

Though the standard deviations of the fits were similar in both cases, the second method was chosen because it was observed that slightly better fit was obtained if 'A(T)', the intercept in eq. 6.18, was first determined by fitting only the saturation values of the property investigated. For example in the case of dp/dP , A(T) was first determined by fitting only the saturation dp/dP data. B(T) was then obtained by fitting the remaining subcooled data. Initially all the data were used in the Least Squares Analysis. But it was observed that the runs above 1700 K were not fitted well when all the data were used (see Fig. 15). It was therefore decided to use only those runs which satisfied the conditions in eq. 6.16 & 6.17.

The best fit, using the above step-wise procedure, was obtained when dp/dP was the fitted property. The resulting equation was

$$dp/dP = a/(b + c \cdot T + d \cdot T^2) + e \cdot T \cdot P/1000 + f \cdot T^2 \cdot P/10^6 \quad (6.19)$$

where, $a = 1.7994 \times 10^{-5}$

$b = 1.2773035$

$c = -7.281814 \times 10^{-4}$

$d = 8.730754 \times 10^{-8}$

$e = -2.212105 \times 10^{-8}$

$f = -1.912547 \times 10^{-8}$

$T = ^\circ K$

$T_r = T/T_c$ (the critical temperature)

$P = \text{ata}$

$\sigma = 9.2 \%$

With both β_T and z , σ 's greater than 10% were obtained, though equations having up to 6 terms were investigated.

Comparing eqs. 6.18 and 6.19, it is obvious that

$$A(T) = a/(b + c \cdot T + d \cdot T^2) \quad (6.20)$$

$$\text{and } B(T) = e(T/1000) + f(T/1000)^2 \quad (6.21)$$

With only the above two temperature dependent constants, the standard deviation (σ) was 9.2%. A seventh coefficient was also used in eq. 6.19, having the form 'g.(T/1000).P' - but no significant reduction in the value of σ was observed. Also, instead of representing $A(T)$ by a simple polynomial in temperature, fitting only the present saturation data, ie.

$$A(T) = a + b \cdot T + c \cdot T^2, \quad (6.22)$$

it was deemed more desirable to have an equation which, if possible, merged with the available low temperature ($T < 1000$ K) data (13,38) and also predicted as infinity the value $(d\rho/dP)_{\text{sat}}$ at the critical point. An equation that was immediately suggestive and could satisfy both of the above criteria was:

$$\frac{(d\rho/dP)_{400 \text{ K}}}{(d\rho/dP)_T} = b + c \cdot T + d \cdot T^2 \quad (6.23a)$$

$$\text{or, } A(T) = (d\rho/dP)_T = \frac{(d\rho/dP)_{400 \text{ K}}}{b + c \cdot T + d \cdot T^2} \quad (6.23b)$$

The saturation value of $(d\rho/dP)$ at 400 K was assumed to be 1.7994×10^{-5} , the average of the values given by Padilla (13) and Makarenko (38). Surprisingly, equation 6.23b was able to fit the data with a slightly better σ compared to the polynomial form of eq. 6.22 though both have, effectively, the same number of coefficients, ie. three; thus eq. 6.23b was chosen to represent the function $A(T)$.

The particular step-wise procedure adopted here, implies that the saturation values of $d\rho/dP$ have to be calculated from eq. 6.23b whereas for subcooled values of $d\rho/dP$,

eq. 6.19 has to be used. However, it was found that the final equation (eq. 6.19) fitted the present saturation data with even lower σ than eq. 6.23; also, the values of $(d\rho/dP)_{\text{sat}}$ below 1000 K differed by less than 1% when calculated from either equation. Thus eq. 6.19 can be considered as the equation of state of liquid sodium derived from this investigation.

A property of interest from the point of view of comparison with available data is the isothermal compressibility of saturated liquid sodium, $(\beta_T)_{\text{sat}}$, since it has been calculated up to 1770 K (13) from the adiabatic compressibility (β_S) data of Chasanov and Leibowitz (11). Fig. 17 is a plot of $(\beta_T)_{\text{sat}}$ calculated from eq. 6.19 by substituting the values of P_{sat} , the saturated vapor pressure and dividing by ρ_{sat} , the saturated liquid density, as determined from eqs. A.4.1 and A.5.1-2, respectively. Also plotted are the representative values from Padilla (13), and the experimental data of this investigation. Representative values of $(\beta_T)_{\text{sat}}$, as calculated from eq. 6.19 are also shown in Table 6.2.2.

It is of interest, also, to know the pressure-temperature limits of eq. 6.19. The temperature limit is illustrated in Fig. 18 which is a plot of the subcooled isotherms of liquid sodium, as obtained by integrating eq. 6.19, i.e.

$$\rho_{T,P} = \int_{P_{\text{sat}}}^P (d\rho/dP) \cdot dP + \rho_{\text{sat}} \quad (6.24)$$

where P_{sat} and ρ_{sat} are at temperature T .

It is observed from the above plot that above 2300 K, erroneous values of density are obtained. Thus the equation is not recommended above 2300 K.

Subcooled values of β_T and the compressibility factor, z or PV/RT , of liquid sodium are also calculable from eqs. 6.19 and 6.24 since,

$$\beta_T = (d\rho/dP)_{T,P} / \rho_{T,P} \quad (6.25)$$

$$z = P / (\rho_{T,P} \cdot R \cdot T) \quad (6.26)$$

TABLE - 6.2.2

The Isothermal Compressibility of
Saturated Sodium

<u>T (K)</u>	<u>β_T (ata⁻¹) x 10⁵</u>
400	1.954
500	2.145
600	2.362
700	2.612
800	2.900
900	3.235
1000	3.626
1100	4.087
1200	4.632
1300	5.281
1400	6.060
1500	7.005
1600	8.166
1700	9.625
1800	11.51
1900	14.07
2000	17.74
2100	23.60
2200	34.24
2300	57.75
2400	135.9
2500	2698.
2508.7 (critical temp.)	∞

FIG. 17
ISOTHERMAL COMPRESSIBILITY
OF SATURATED LIQUID SODIUM

FIG. 18 : PRESSURE - DENSITY - TEMPERATURE OF LIQUID SODIUM

Calculated values along several isotherms are given in Table A.8.1. It is observed that for the isobars 450 ata and 500 ata, β_T decreases, rather than increases, with temperature for all $T < 1200$ K. But above 1200 K, β_T increases with temperature for all isobars. Thermodynamically, β_T should be constant or increase with temperature at constant pressure. Therefore eq. 6.19 is valid only to 400 ata at temperatures less than 1200 K. Above 1200 K, eq. 6.19 can be used to 500 ata. Further extrapolations will yield thermodynamically valid results but may entail significant errors due to the relatively large extrapolation beyond the experimental range. In any case, as mentioned earlier, eq. 6.19 is not recommended above 2300 K.

III) Calculation of Thermal Expansivity

a) α_p of the Saturated Liquid:

The saturation value of α_p is obtained from the exact thermodynamic expression

$$(\alpha_p)_{\text{sat}} = - \frac{1}{\rho} \cdot \left(\frac{d\rho}{dT} \right)_p = \alpha_{\text{sat}} + (\beta_T)_{\text{sat}} \cdot \gamma_{\text{sat}} \quad (6.27)$$

where $\alpha_{\text{sat}} = - \frac{1}{\rho} \cdot \frac{d\rho_{\text{sat}}}{dT}$ = expansivity along the saturation

line

$(\beta_T)_{\text{sat}}$ = isothermal compressibility at saturation

and γ_{sat} = temperature derivative of the vapor pressure equation.

α_{sat} is obtained from the density equation derived in Appendix V, γ_{sat} , from the vapor pressure equation derived in Appendix IV, and $(\beta_T)_{\text{sat}}$ is obtained directly from the compressibility experiments. Fig. 19 is a plot of $(\alpha_p)_{\text{sat}}$ vs. temperature calculated using eq. 6.27. The three experimental points obtained from the isobaric experiments (described below), and the estimates of Padilla (13) are also plotted on the same figure for comparison. Representative values of $(\alpha_p)_{\text{sat}}$ are tabulated in Table 6.3.1.

TABLE - 6.3.1The Thermal Expasivity of Saturated Sodium

<u>T (K)</u>	<u>$\alpha_P (K^{-1}) \times 10^4$</u>
400	2.559
500	2.626
600	2.697
700	2.772
800	2.851
900	2.935
1000	3.024
1100	3.120
1200	3.224
1300	3.337
1400	3.462
1500	3.602
1600	3.760
1700	3.943
1800	4.157
1900	4.414
2000	5.048
2100	6.470
2200	8.764
2300	13.11
2400	24.69
2500	233.5
2508.7 (critical temp.)	∞

46 5810

K² SEMI-LOG PLOT OF CYCLES PER DECADE
REPLIES & PSEUDOS $(\alpha_p)_{SAT}, K^{-1}$

b) Subcooled densities from thermal expansion experiments

The data from the thermal expansion experiments consists of a series of P- θ curves for each isobar (Appendix 2). The curves were individually fitted by Least Squares to parabolic equations for the 1 atm runs and to straight lines for the runs at 28.9 and 69 atm. The intersections of the P- θ curves with the isobar, were then determined from these best fit equations.

If θ_1 and θ_2 (eg Fig. 14) are two such intersections, then the volume expansion of sodium is given by

$$\frac{\Delta V}{\Delta T} = \frac{\Delta \theta}{\Delta T} \cdot \frac{V_\theta}{360} \quad (6.28)$$

where V_θ = volume displaced by the injector per turn

and $\Delta \theta = \theta_2 - \theta_1$

Thus the observed change in density of the sodium in the capsule is

$$\Delta \rho / \Delta T = -(\Delta V / \Delta T) \times \rho_T / V_c \quad (6.29)$$

$$= -(\Delta \theta / \Delta T) \cdot V_\theta \cdot \rho_T / (360 \cdot V_c) \quad (6.30)$$

Since the temperature steps are small, eq. 6.30 can be written as:

$$\left(\frac{d\rho}{dT}\right)_{T_m} = \frac{\Delta \theta}{\Delta T} \cdot \frac{V_\theta}{360} \cdot \frac{\rho_T}{V_c} \quad (6.31)$$

where T_m = mean temperature = $(T_1 + T_2)/2$

The actual subcooled density of liquid sodium is then calculated by substituting eq. 6.31 into eq. 3.11.

Table 6.3.2 lists the $\Delta \theta$'s for all the isobaric runs. To facilitate the use of eq. 3.11, the observed $\frac{d\rho}{dT}$ data for for each isobar (ie. calculated from eq. 6.31) were fitted to polynomials in temperature. The polynomials are:

at 1 atm

$$\left(\frac{d\rho}{dT}\right)_{\text{obs}} = .1134 \times 10^{-3} \quad (6.32)$$

$$\sigma = 4\%$$

28.9 atm

$$\left(\frac{d\rho}{dT}\right)_{\text{obs}} = 9.18205 \times 10^{-5} + 1.07749 \times 10^{-8}T + 1.70215 \times 10^{-12}T^2 \quad (6.33)$$

$$\sigma = 3.52\%$$

69 atm

$$\left(\frac{d\rho}{dT}\right)_{\text{obs}} = 6.37028 \times 10^{-5} + 1.62697 \times 10^{-8}T + 3.12823 \times 10^{-12}T^2 \quad (6.34)$$

$$\sigma = 4.7\%$$

with $\left(\frac{d\rho}{dT}\right) = \text{gm/cc}/^{\circ}\text{R}$

$(T) = ^{\circ}\text{R}$

The above analytical forms are then used in eq. 3.11 to calculate subcooled densities of sodium along the experimental isobars. The results are plotted in Fig. 18, the P- ρ -T diagram of sodium calculated from the best-fit compressibility equation. It is observed that similar subcooled densities, compared to the isothermal compressibility experiments, are obtained. However, due to the limited range of these experiments only the compressibility runs were utilised in order to determine the appropriate equation of state of liquid sodium. This two-way check attests to the validity of the technique used in this investigation to determine the subcooled properties of liquid sodium.

TABLE 6.3.2I. Isobar = 1 atm (Run 3-1)

<u>No.</u>	<u>Temperature (F)</u>	<u>$\Delta\theta$ (deg)*</u>
1	727.8	**
2	786.0	245.4
3	811.3	96.6
4	862.7	242.4
5	860.9	- 15.0
6	888.8	120.0
7	930.0	159.0
8	986.4	208.5
9	1029.7	183.0
10	1062.0	123.0
11	1103.4	180.0
12	1141.7	171.0
13	1194.3	210.0
14	1231.0	123.0
15	1254.4	90.0
16	1313.6	246.0
17	1338.7	108.0
18	1362.1	87.0
19	1357.1	**
20	1396.0	156.0
21	1443.5	204.0
22	1481.3	171.0
23	1524.9	177.0
24	1577.6	147.0
25	1596.6	168.0
26	1626.7	132.0

II. Isobar = 425.3 (Run 3-2, 3-3)

<u>No.</u>	<u>Temperature (F)</u>	<u>$\Delta\theta$ (deg)*</u>
1	1057.1	**
2	1101.3	138.0
3	1155.9	190.5
4	1228.2	277.5
5	1250.7	99.0
6	1280.3	135.0
7	1310.0	132.0
8	1344.3	162.0
9	1388.0	192.0
10	1422.5	154.5
11	1454.0	135.0
12	1491.7	168.0
13	1523.1	150.0
14	1558.3	96.0
15	1271.2	**
16	1304.5	120.0
17	1336.4	153.0
18	1381.8	198.0
19	1432.7	204.0
20	1470.4	165.0
21	1505.9	156.0
22	1541.7	141.0
23	1580.2	150.0
24	1633.7	240.0
25	1683.6	156.0
26	1731.4	204.0
27	1647.8	**
28	1763.5	405.0
29	1788.7	117.0
30	1823.8	154.5
31	1871.8	193.5
32	1910.2	168.0
33	1945.4	166.5

<u>No.</u>	<u>Temperature (F)</u>	<u>$\Delta\theta$ (deg)*</u>
34	1985.8	171.0
35	2017.0	150.0
36	2068.0	240.0
37	2053.3	- 60.0
38	2065.8	36.0
39	2076.5	**
40	2095.3	94.5
41	2143.6	212.4
42	2180.5	172.5
43	2239.4	281.4
44	2319.5	387.0
45	2356.1	184.8

III. Isobar = 1014.7 psia (Run 3-10, 3-11)

<u>No.</u>	<u>Temperature (F)</u>	<u>$\Delta\theta$ (deg)*</u>
1	2201.8	**
2	2263.3	405.6
3	2323.9	247.9
4	2359.4	123.7
5	2519.7	788.3
6	2559.3	201.3
7	2604.8	270.1
8	2570.8	**
9	2636.4	324.0
10	2699.3	342.1
11	2756.4	373.1
12	2756.6	0.0
13	2830.0	431.5
14	2890.3	338.5
15	2898.4	81.6
16	2996.4	554.5
17	3022.8	162.3
18	2865.0	-858.1
19	2779.9	-472.5
20	2688.8	-488.6
21	2635.6	-289.4
22	2631.0	- 1.0
23	2566.5	-320.1
24	2626.6	**
25	2491.1	-668.8
26	2338.0	-732.6
27	2097.1	-1115.3
28	2059.4	-179.9
29	2070.3	**
30	1959.7	-517.0
31	1834.8	-593.3
32	1755.0	-334.0

<u>No.</u>	<u>Temperature (F)</u>	<u>$\Delta\theta$ (deg)*</u>
33	1776.1	**
34	1736.4	-350.8
35	1700.2	-144.9
36	1665.9	- 88.0
37	1632.0	- 63.5
38	1591.0	-169.9
39	1554.5	-140.3
40	1516.3	-149.7
41	1480.8	-191.1

* $\Delta\theta = \theta_2 - \theta_1$, Fig. 11.

** The protractor was initialised at these temperatures.

VII. OTHER THERMODYNAMIC PROPERTIES PERTINENT TO THE FAST BREEDER REACTOR (LMFBR) SAFETY CALCULATIONS.

Besides the vapor pressures and the saturated and sub-cooled densities of liquid sodium, the following properties have also been used in the calculations of hypothetical reactor accidents (13,60) :

- a) the thermal pressure coefficient, γ_V ,
- b) the heat, internal energy and entropy of vaporisation, ΔH_V , ΔS_V , ΔU_V , and
- c) the saturated vapor density, $\rho_{V,sat}$.

γ_V is generally calculated from the thermodynamic equation :

$$\gamma_V = \left(\frac{dP}{dT} \right)_V = - \frac{\alpha_P}{\beta_T} = - \frac{d\rho/dT}{d\rho/dP} \quad (7.1)$$

However for a one-phase system, e.g. liquid sodium, it has been observed that γ_V is almost independent of pressure (51, 57), and can therefore be estimated from its value at saturation conditions. Due to its pressure independence, γ_V has been used in the following equation to describe the sub-cooled behaviour of liquid sodium (13) :

$$P - P_{sat} = \int_{T_{sat}}^T \gamma_V dT \quad (7.2)$$

where, γ_V is its value at P_{sat} & T_{sat} . Though the equation of state experimentally obtained in this investigation (eq. 6.19) is more convenient to use than the above equation, it is limited to below 2300 K and 500 ata. Thus γ_V values can be used for calculating the subcooled properties of liquid sodium beyond the experimental range.

γ_V of liquid sodium, as mentioned above, is pressure independent and is estimated from its value at saturation. The calculation involves the determination of $(\alpha_P)_{sat}$, as from eq. 6.27 and $(\beta_T)_{sat}$, as from eq. 6.19, and then substituting into eq. 7.1 above. Representative values, using eqs. 6.19 & 6.27, are shown in Table 7.1, calculated every 100 K and are also plotted in

Fig. 20. It is observed that the slope of the γ_V vs. T curve is similar to many such curves in Rowlinson's book (57).

TABLE 7.1

<u>γ_V of liquid sodium</u>	
<u>T (K)</u>	<u>γ_V (ata/K)</u>
400	13.097
500	12.247
600	11.419
700	10.614
800	9.832
900	9.073
1000	8.340
1100	7.635
1200	6.960
1300	6.318
1400	5.712
1500	5.142
1600	4.605
1700	4.096
1800	3.610
1900	3.138
2000	2.846
2100	2.741
2200	2.560
2300	2.269
2400	1.816
2500	0.862

The heat of vaporization :

ΔH_V is at present determined using either the method of Padilla (13) or Bhise (1b,41). Padilla (13) utilised the quasi-chemical approach of Golden and Tokar (58) upto 1675 K and an empirical equation (eq. 7.3) suggested by Miller et. al. (59), between 1675 K and the critical temperature.

$$\Delta H_V = b.(1 - T_r)^c \quad (7.3)$$

FIG. 20 : Thermal Pressure Coefficient of Sodium

However, Padilla's method is inconvenient to use below 1675 K and also has the defect that in calculating $p_{V,sat}$ from eq. 7.3, via the Clapeyron Equation, i.e.

$$p_{V,sat} = \left[\frac{\Delta H_V}{T \cdot (dp_{sat}/dT)} + \frac{1}{p_{L,sat}} \right]^{-1} \quad (7.4)$$

where, ΔH_V is calculated from eq. 7.3, a slight inflection is produced in the $p_{V,sat}$ vs. T curve near 2150 K (62). A further disadvantage as pointed out by Bhise (41) is that the vapor densities calculated from eq. 7.4 are severely underestimated in the critical region.

Bhise (1b,41), therefore, used an alternate approach to estimate the high temperature ΔH_V 's of sodium. He used an empirical equation for the high temperature $p_{V,sat}$ of sodium, having the form :

$$(1 - p_{Vr}) = a \cdot (1 - T_r) + b \cdot (1 - T_r)^{0.53} \quad (7.5)$$

and substituted that equation into the Clapeyron Equation (eq. 7.4) to back-calculate ΔH_V . The constants 'a' & 'b' in eq. 7.5 were determined by matching the slope and the value of the equation with the low temperature data (1b,41). Below 1952.5 K, the lower limit of eq. 7.5, Bhise used the equation of Achener and Jouthas (4a) to calculate ΔH_V .

However, Bhise's approach also has a major drawback. The data of Achener and Jouthas (4a) extend only to 1200 K and analysis has shown that extrapolation of their straight-line equation leads to greater than 3% overestimation in the calculated values of ΔH_V beyond 1600 K. Moreover, there is a sharp change in slope of the ΔH_V vs. T curve, near 2000 K, which seems unreasonable. (see Fig. 21).

While both methods of calculating ΔH_V (i.e. Padilla's and Bhise's) can be easily implemented into computer codes for safety analysis, neither are suitable for quick hand-calculations. Their complexities therefore seem unreasonable specially due to the large differences in the calculated values ΔH_V above 1900 K and the peculiarities of the ΔH_V and $p_{V,sat}$ curves (as des-

cribed above) in the critical region.

Thus, as a part of this investigation, it was decided to determine a single equation for ΔH_V that could fit the low temperature data and also give satisfactory estimates of $\rho_{V,sat}$ in the critical region. After a little trial and error it was observed that both the above criteria were adequately satisfied simply by adding a linear term to eq. 7.3, e.g.

$$\Delta H_V = a.(1 - T_r) + b.(1 - T_r)^c \quad (7.6)$$

To determine the best values of a , b and c , the experimental data to 1200 K of Achener and Jouthas (4a) were used with the ΔH_V data to 1675 K of Stone, Ewing et.al. (2), derived by substituting their experimental $\rho_{V,sat}$ data into the Clapeyron Equation. Actually, the exponent c was varied between 0.1 and 0.9 and the coefficients a and b were then determined by Least Squares for each value of c . It was observed that the minimum standard deviation (σ) was obtained at $c = 0.16$ but that the differences in σ were statistically insignificant for $0.1 \leq c \leq 0.4$. On the other hand, when eq. 7.6 was used in the Clapeyron Equation, satisfactory estimates of $\rho_{V,sat}$ in the critical region were obtained only when c was equal to or greater than 0.4. Thus $c=0.4$ was chosen as the optimum exponent. The best-fit equation for the above value of c is :

$$\Delta H_V = - 5.557012 (1 - T_r) + 31.25992 (1 - T_r)^{0.4} \quad (7.7)$$

(kcal/g-mole)

The critical temperature used with eq. 7.7, since $T_r = T/T_c$, is 2508.7 K, the value consistent with vapor pressure equation A.4.1.

The internal energy and the entropy of vaporization :

ΔU_V & ΔS_V of sodium was then calculated from H_V by using the thermodynamic equations :

$$\Delta U_V = \Delta H_V - P_{sat} \cdot \Delta V \quad (7.8)$$

and

$$\Delta S_V = \Delta H_V / T \quad (7.9)$$

where P_{sat} = saturation pressure (calculated from eqs. A.4.1 & 2)

TABLE 7.2The Heat of Vaporization of Sodium

<u>TEMPERATURE</u>	<u>PROPERTY</u>
<u>T(K)</u>	<u>Heat of Vaporization</u> <u>ΔH_V (Kcal/mol)</u>
400	24.491
500	24.151
600	23.794
700	23.419
800	23.024
900	22.606
1000	22.164
1100	21.696
1200	21.197
1300	20.664
1400	20.933
1500	19.478
1600	18.812
1700	18.084
1800	17.284
1900	16.392
2000	15.385
2100	14.222
2200	12.837
2300	11.099
2400	8.665
2500	3.220
2508.7 (critical point)	0

FIG. 21 - Heat of Vaporization of Sodium

and ΔV = difference in specific volumes between the saturated vapor and the saturated liquid of sodium as calculated from the Clapeyron Equation :

$$\Delta V = \Delta H_V / (T (dP_{\text{sat}} / dT)) \quad (7.10)$$

Representative values of ΔH_V , ΔU_V & ΔS_V are shown in Tables 7.2 & 7.3, calculated every 100 K, from 400 K to 2500 K, using eqs. 7.7 to 7.9. The variation of the above three properties with temperature are also shown in Figs. 21 & 22.

The saturated vapor density :

The $\rho_{V,\text{sat}}$ of sodium was calculated by substituting the equation for ΔH_V (eq. 7.7) and the saturated liquid density equations A.5.1 & 2 into the Clapeyron Equation, eq. 7.4. Calculated values of both $\rho_{V,\text{sat}}$ and $\rho_{L,\text{sat}}$ are tabulated in Table 7.4 and plotted in Fig. 23.

The present data on $\rho_{V,\text{sat}}$ can be compared to the one obtained by Bhise (1) utilising a slightly different approach. It is observed that above 2200 K, his values are substantially higher than are presented here. Also his curve of $\rho_{V,\text{sat}}$ (1) is more symmetric in shape (compared to the $\rho_{L,\text{sat}}$ curve) around the critical point. However his ΔH_V curve has an unreasonable discontinuity in slope near 2000 K, as explained earlier in the section on ' heat of vaporization '(also see Fig. 21). Instead of attaching a greater significance or validity to one or the other of the above approaches, the author proposes the present approach as an alternative to the one proposed by Bhise (1) in order to highlight the lack of, and the need for, accurate ΔH_V and/or $\rho_{V,\text{sat}}$ data in the range 2000 K to 2200 K, if not higher.

TABLE 7.3

<u>Temperature</u>	<u>Property</u>	
T(K)	Internal Energy of Vaporization (Δu_v) (Kcal/gm.atom)	Entropy of Vaporization (ΔS_v) (Kcal/gm.atom K)
400	23.714	0.061227
500	23.190	0.048302
600	22.654	0.039657
700	22.104	0.033456
800	21.540	0.028780
900	20.961	0.025118
1000	20.365	0.022164
1100	19.751	0.019723
1200	19.068	0.017664
1300	18.412	0.015896
1400	17.729	0.014352
1500	17.018	0.012985
1600	16.272	0.011757
1700	15.485	0.010638
1800	14.648	0.9602 E-02
1900	13.748	0.86274 E-02
2000	12.767	0.76923 E-02
2100	11.676	0.67724 E-02
2200	10.425	0.58351 E-02
2300	8.914	0.4826 E-02
2400	6.881	0.3610 E-02
2500	2.528	0.1288 E-02
(critical point) 2508.7	0	0

TABLE 7.4

<u>TEMPERATURE</u>	<u>PROPERTY</u>	
	Saturation Density	
T(K)	ρ_{liquid} (g/cm ³)	ρ_{vapor} (g/cm ³)
400	0.9209	0.9800E-12
500	0.8973	0.4302E-09
600	0.8738	0.2373E-07
700	0.8502	0.4032E-06
800	0.8266	0.3299E-05
900	0.8031	0.1663E-04
1000	0.7795	0.5994E-04
1100	0.7559	0.1695E-03
1200	0.7324	0.3867E-03
1300	0.7088	0.7850E-03
1400	0.6852	0.1438E-02
1500	0.6617	0.2430E-02
1600	0.6381	0.385 E-02
1700	0.6145	0.5794E-02
1800	0.5909	0.8366E-02
1900	0.5674	0.1170E-01
2000	0.5435	0.1596E-01
2100	0.5159	0.2143E-01
2200	0.4826	0.2860E-01
2300	0.4404	0.3859E-01
2400	0.3818	0.5482E-01
2500	0.2618	0.1135
2508.7 (critical temperature)	0.2141	0.2141

FIG. 22 - INTERNAL ENERGY AND ENTROPY
OF VAPORIZATION OF SODIUM

VIII. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

A new and versatile variable-volume picnometer apparatus was developed, tested with water and used with liquid sodium to determine its subcooled compressibility from 900 K to 1867 K and upto 200 ata, the range where no previous data existed. It was determined that for liquid sodium, the compressibility, $d\rho/dP$, the coefficient of compressibility, β_T , and the compressibility factor, $P/\rho RT$, along any isotherm, are all linear with pressure over the experimental range (Figs. 15 & 16). Also, the saturation values of compressibility and expansivity were found to agree well with Padilla's estimates (13) based on the speed of sound measurements of Leibowitz, Chasanov et al. (11) (Figs. 17 & 19).

The compressibility data were correlated by a 6-term equation (eq. 6.19) which can be used to predict the subcooled densities of liquid sodium upto 500 ata and 2300 K (eq. 6.24). The equation requires accurate correlations for the vapor pressure and saturated liquid density, which are also derived in Appendix IV & V respectively.

Wide range correlations are also derived for the heat (eq. 7.7), internal energy (eq. 7.8) and entropy (eq. 7.9) of vaporization and the saturated vapor density (eq. 7.4) of sodium, which are required for the LMFBR safety calculations (61). The thermal pressure coefficient, which was previously used to predict PVT properties of sodium (13), has also been determined from the experimental data.

The experimental results confirm the validity of the present concept for determining liquid phase compressibilities at high temperatures and pressures. The temperature range can be increased by operating in a pressurised furnace and using a smaller capsule (6 cm^3 to 7 cm^3 internal volume and .04 in. capillary).

Further experimental work is necessary on the heat of vaporization and liquid and vapor densities in the range 1800 K to 2200 K (atleast) which is well within the scope of simple, yet accurate, experiments. The present apparatus itself can be used, without modification, to measure thermal expansivity along the saturation line atleast to 1900 K (see Ch. III).

APPENDIX I - P - θ plots of the isothermal compressibility experiments.

P - θ plots for isothermal compressibility runs 1-2-1 to 1-2-5.

Appendix I - P - θ plots for isothermal compressibility
runs 1-2-6 to 1-2-13.

K-E 10 x 10 TO THE CENTIMETER 10 x 10 CM
 46 1513

46 1513

PSIA
10 X 10 TO THE CENTIMETER 10 X 20 CM
REPROD. BY BUREAU OF STANDARDS

APPENDIX II

P - θ plots of the isobaric thermal expansion experiments.

Appendix II - P - θ plots for the thermal expansion experiments at 1014.7 psia.

Appendix II - P - θ plots for the thermal expansion
experiments at 1014.7 psia.

Appendix II - P - θ plots for the thermal expansion
experiments at 425.3 psia.

Appendix II - P - θ plots for the thermal expansion experiments at 425.3 psia.

Appendix II - P - θ plots for the thermal expansion
experiments at 425.3 psia.

Appendix II - P - θ plots of the thermal expansion experiments at 1 ata.

APPENDIX III

Computer outputs of the calculations to determine
the subcooled compressibility of liquid sodium.

RUN NO. = 1-2-1A

AVG. BULB TEMPERATURE = 1646.6 DEG-R
914.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.79233D 00	5.3279D-05	6.7244D-05	3.8655D-04
2	179.0	0.79291D 00	5.0158D-05	6.3258D-05	4.7048D-03
3	554.7	0.79410D 00	4.3017D-05	5.4171D-05	1.4558D-02
4	915.2	0.79507D 00	3.6160D-05	4.5480D-05	2.3990D-02
5	1331.3	0.79598D 00	2.8239D-05	3.5476D-05	3.4857D-02
5	1735.4	0.79665D 00	2.0539D-05	2.5782D-05	4.5399D-02

RUN NO. = 1-2-1B

AVG. BULB TEMPERATURE = 1646.6 DEG-R
914.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.79233D 00	4.3422D-05	5.4803D-05	3.8655D-04
2	211.8	0.79290D 00	4.0983D-05	5.1687D-05	5.5670D-03
3	591.9	0.79390D 00	3.6277D-05	4.5694D-05	1.5538D-02
4	986.1	0.79480D 00	3.1392D-05	3.9497D-05	2.5857D-02
5	1388.1	0.79559D 00	2.6408D-05	3.3193D-05	3.6362D-02

RUN NO. = 1-2-4A

AVG. BULB TEMPERATURE = 2389.8 DEG-R
1327.7 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	56.6	0.702260 00	4.28430-05	6.10080-05	1.15660-03
2	114.6	0.702430 00	4.20870-05	5.99160-05	2.34270-03
3	299.2	0.702940 00	3.96810-05	5.64500-05	6.11190-03
4	496.8	0.703460 00	3.71060-05	5.27470-05	1.01410-02
5	712.0	0.703980 00	3.43000-05	4.87220-05	1.45230-02
6	933.7	0.704480 00	3.14080-05	4.45840-05	1.90320-02
7	1160.9	0.704940 00	2.84440-05	4.03490-05	2.36470-02

RUN NO. = 1-2-5A

AVG. BULB TEMPERATURE = 2516.6 DEG-R
1398.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	88.9	0.685660 00	5.02600-05	7.33010-05	1.76770-03
2	219.4	0.686100 00	4.84090-05	7.05570-05	4.36050-03
3	422.6	0.686750 00	4.55270-05	6.62940-05	8.39100-03
4	632.3	0.687380 00	4.25520-05	6.19050-05	1.25430-02
5	852.9	0.687990 00	3.94220-05	5.73000-05	1.69040-02
6	1080.1	0.688580 00	3.61970-05	5.25670-05	2.13890-02

RUN NO. = 1-2-7A

AVG. BULB TEMPERATURE = 2564.6 DEG-R
1424.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	104.2	0.67938D 00	4.3842D-05	6.4533D-05	2.0530D-03
2	127.7	0.67945D 00	4.3748D-05	6.4387D-05	2.5149D-03
3	283.9	0.67991D 00	4.3117D-05	6.3416D-05	5.5872D-03
4	453.2	0.68040D 00	4.2434D-05	6.2366D-05	8.9126D-03
5	621.4	0.68088D 00	4.1756D-05	6.1326D-05	1.2212D-02
6	799.4	0.68138D 00	4.1038D-05	6.0228D-05	1.5698D-02
7	973.0	0.68187D 00	4.0338D-05	5.9159D-05	1.9094D-02
8	1135.8	0.68231D 00	3.9682D-05	5.8159D-05	2.2274D-02
9	1323.6	0.68281D 00	3.8926D-05	5.7008D-05	2.5938D-02
10	1514.8	0.68331D 00	3.8156D-05	5.5840D-05	2.9663D-02

RUN NO. = 1-2-7B

AVG. BULB TEMPERATURE = 2564.6 DEG-R
1424.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	104.2	0.67938D 00	4.7364D-05	6.9716D-05	2.0530D-03
2	133.2	0.67947D 00	4.7107D-05	6.9329D-05	2.6231D-03
3	275.1	0.67992D 00	4.5850D-05	6.7435D-05	5.4139D-03
4	447.7	0.68045D 00	4.4322D-05	6.5136D-05	8.8038D-03
5	613.7	0.68094D 00	4.2851D-05	6.2929D-05	1.2059D-02
6	789.6	0.68144D 00	4.1293D-05	6.0596D-05	1.5504D-02
7	964.3	0.68193D 00	3.9745D-05	5.8283D-05	1.8921D-02
8	1141.2	0.68239D 00	3.8177D-05	5.5946D-05	2.2377D-02
9	1322.5	0.68286D 00	3.6570D-05	5.3555D-05	2.5915D-02
10	1507.1	0.68330D 00	3.4934D-05	5.1125D-05	2.9512D-02

RUN NO. = 1-2-8A

AVG. BULB TEMPERATURE = 2587.0 DEG-R
1437.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	112.0	0.676440 00	3.57620-05	5.28670-05	2.19720-03
2	177.9	0.676610 00	3.61130-05	5.33740-05	3.48770-03
3	345.0	0.677020 00	3.70050-05	5.46580-05	6.75960-03
4	513.2	0.677450 00	3.79040-05	5.59510-05	1.00490-02
5	685.8	0.677900 00	3.88270-05	5.72750-05	1.34190-02
6	849.6	0.678340 00	3.97040-05	5.85310-05	1.66140-02
7	1024.4	0.678820 00	4.06410-05	5.98700-05	2.00180-02
8	1193.7	0.679290 00	4.15490-05	6.11660-05	2.33100-02
9	1368.4	0.679790 00	4.24880-05	6.25010-05	2.67020-02
10	1543.2	0.680300 00	4.34270-05	6.38360-05	3.00900-02
11	1707.0	0.680790 00	4.43090-05	6.50850-05	3.32600-02
12	1890.5	0.681350 00	4.52980-05	6.64820-05	3.68050-02

RUN NO. = 1-2-8B

AVG. BULB TEMPERATURE = 2587.0 DEG-R
1437.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	112.0	0.676440 00	4.91280-05	7.26260-05	2.19720-03
2	164.8	0.676620 00	4.85280-05	7.17210-05	3.23080-03
3	480.5	0.677620 00	4.49380-05	6.63180-05	9.40600-03
4	812.5	0.678600 00	4.11620-05	6.06580-05	1.58820-02
5	1165.3	0.679540 00	3.71480-05	5.46670-05	2.27470-02
6	1514.8	0.680370 00	3.31700-05	4.87530-05	2.95330-02
7	1887.2	0.681160 00	2.89300-05	4.24720-05	3.67510-02

RUN NO. = 1-2-9A

AVG. BULB TEMPERATURE = 2648.0 DEG-R
1471.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	135.6	0.66846D 00	4.5306D-05	6.7777D-05	2.6282D-03
2	212.9	0.66869D 00	4.4768D-05	6.6949D-05	4.1260D-03
3	377.8	0.66919D 00	4.3622D-05	6.5186D-05	7.3163D-03
4	540.5	0.66967D 00	4.2490D-05	6.3450D-05	1.0460D-02
5	705.5	0.67014D 00	4.1343D-05	6.1693D-05	1.3643D-02
6	871.5	0.67060D 00	4.0189D-05	5.9930D-05	1.6842D-02
7	1045.1	0.67107D 00	3.8982D-05	5.8089D-05	2.0182D-02
8	1219.9	0.67152D 00	3.7766D-05	5.6240D-05	2.3542D-02
9	1392.4	0.67196D 00	3.6567D-05	5.4418D-05	2.6854D-02
10	1559.5	0.67237D 00	3.5405D-05	5.2657D-05	3.0058D-02

RUN NO. = 1-2-9B

AVG. BULB TEMPERATURE = 2642.0 DEG-R
1467.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	133.1	0.66924D 00	3.1917D-05	4.7691D-05	2.5832D-03
2	337.4	0.66970D 00	3.3151D-05	4.9502D-05	6.5438D-03
3	677.1	0.67049D 00	3.5208D-05	5.2511D-05	1.3117D-02
4	1026.6	0.67135D 00	3.7328D-05	5.5602D-05	1.9862D-02
5	1366.2	0.67223D 00	3.9392D-05	5.8599D-05	2.6397D-02
6	1709.2	0.67318D 00	4.1481D-05	6.1619D-05	3.2978D-02

RUN NO. = 1-2-13B

AVG. BULB TEMPERATURE = 2767.4 DEG-R
1537.5 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	192.0	0.65282D 00	4.8399D-05	7.4138D-05	3.6478D-03
2	356.0	0.65336D 00	4.7977D-05	7.3432D-05	6.7565D-03
3	1198.0	0.65605D 00	4.5817D-05	6.9837D-05	2.2644D-02
4	2069.6	0.65870D 00	4.3589D-05	6.6175D-05	3.8960D-02

RUN NO. = 1-2-13C

AVG. BULB TEMPERATURE = 2768.4 DEG-R
1538.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	192.6	0.65269D 00	4.3821D-05	6.7139D-05	3.6574D-03
2	380.0	0.65326D 00	4.4322D-05	6.7848D-05	7.2106D-03
3	1229.7	0.65588D 00	4.6605D-05	7.1056D-05	2.3240D-02
4	2086.0	0.65867D 00	4.8924D-05	7.4277D-05	3.9257D-02

RUN NO. = 1-2-14A

AVG. BULB TEMPERATURE = 2807.7 DEG-R
1559.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	214.5	0.64755D 00	4.8658D-05	7.5142D-05	4.0493D-03
2	393.1	0.64814D 00	4.8321D-05	7.4554D-05	7.4128D-03
3	1240.6	0.65088D 00	4.6730D-05	7.1795D-05	2.3296D-02
4	2104.5	0.65358D 00	4.5118D-05	6.9032D-05	3.9355D-02

RUN NO. = 1-2-14B

AVG. BULB TEMPERATURE = 2807.7 DEG-R
1559.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	214.5	0.64755D 00	4.7059D-05	7.2673D-05	4.0493D-03
2	414.9	0.64819D 00	4.7285D-05	7.2950D-05	7.8233D-03
3	1261.4	0.65094D 00	4.8250D-05	7.4123D-05	2.3684D-02
4	2111.1	0.65376D 00	4.9234D-05	7.5309D-05	3.9467D-02

RUN NO. = 1-2-15A

AVG. BULB TEMPERATURE = 2838.7 DEG-R
1577.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	233.1	0.64349D 00	5.2744D-05	8.1966D-05	4.3793D-03
2	417.1	0.64415D 00	5.2303D-05	8.1198D-05	7.8277D-03
3	1256.1	0.64708D 00	5.0297D-05	7.7730D-05	2.3466D-02
4	2113.3	0.64995D 00	4.8257D-05	7.4248D-05	3.9306D-02

RUN NO. = 1-2-15B

AVG. BULB TEMPERATURE = 2836.6 DEG-R
1575.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	231.8	0.64376D 00	5.2594D-05	8.1697D-05	4.3563D-03
2	414.9	0.64442D 00	5.2370D-05	8.1267D-05	7.7889D-03
3	1252.6	0.64737D 00	5.1353D-05	7.9325D-05	2.3408D-02
4	2101.3	0.65031D 00	5.0335D-05	7.7401D-05	3.9090D-02

RUN NO. = 1-2-16A

AVG. BULB TEMPERATURE = 2853.2 DEG-R
1585.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	242.2	0.64159D 00	4.9603D-05	7.7313D-05	4.5401D-03
2	428.0	0.64222D 00	4.9970D-05	7.7808D-05	8.0154D-03
3	1267.9	0.64512D 00	5.1638D-05	8.0043D-05	2.3638D-02
4	2119.8	0.64817D 00	5.3348D-05	8.2306D-05	3.9335D-02

RUN NO. = 1-2-16B

AVG. BULB TEMPERATURE = 2867.1 DEG-R
1592.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	251.1	0.63977D 00	5.0270D-05	7.8576D-05	4.6983D-03
2	333.0	0.64005D 00	5.0426D-05	7.8785D-05	6.2271D-03
3	1168.5	0.64296D 00	5.2027D-05	8.0917D-05	2.1752D-02
4	2016.1	0.64601D 00	5.3669D-05	8.3077D-05	3.7353D-02

RUN NO. = 3-7-2-E

AVG. BULB TEMPERATURE = 1679.0 DEG-R

932.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.78863D 00	1.9629D-05	2.4890D-05	3.8087D-04
2	169.5	0.78885D 00	2.1616D-05	2.7402D-05	4.3916D-03
3	180.9	0.78887D 00	2.1762D-05	2.7587D-05	4.6869D-03
4	325.0	0.78909D 00	2.3613D-05	2.9924D-05	8.4180D-03
5	329.4	0.78910D 00	2.3669D-05	2.9996D-05	8.5319D-03
5	492.5	0.78937D 00	2.5765D-05	3.2640D-05	1.2752D-02
7	495.6	0.78938D 00	2.5805D-05	3.2690D-05	1.2832D-02
8	671.4	0.78970D 00	2.8065D-05	3.5539D-05	1.7377D-02
9	672.0	0.78970D 00	2.8073D-05	3.5549D-05	1.7392D-02
10	847.8	0.79005D 00	3.0335D-05	3.8396D-05	2.1933D-02
11	856.7	0.79007D 00	3.0449D-05	3.8540D-05	2.2162D-02
12	1020.4	0.79042D 00	3.2557D-05	4.1189D-05	2.6385D-02
13	1028.6	0.79044D 00	3.2662D-05	4.1322D-05	2.6597D-02
14	1208.2	0.79085D 00	3.4976D-05	4.4225D-05	3.1224D-02
15	1210.7	0.79086D 00	3.5008D-05	4.4266D-05	3.1289D-02
15	1403.6	0.79133D 00	3.7494D-05	4.7381D-05	3.6252D-02

RUN NO. = 3-7-3E

AVG. BULB TEMPERATURE = 1876.7 DEG-R

1042.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.76606D 00	3.5631D-05	4.6512D-05	3.5078D-04
2	137.8	0.76636D 00	3.4852D-05	4.5478D-05	3.2879D-03
3	147.3	0.76638D 00	3.4792D-05	4.5398D-05	3.5145D-03
4	449.3	0.76708D 00	3.2881D-05	4.2866D-05	1.0710D-02
5	450.0	0.76708D 00	3.2877D-05	4.2860D-05	1.0727D-02
6	799.6	0.76783D 00	3.0664D-05	3.9936D-05	1.9042D-02
7	800.2	0.76783D 00	3.0661D-05	3.9931D-05	1.9056D-02
8	1161.2	0.76856D 00	2.8376D-05	3.6921D-05	2.7627D-02
9	1173.9	0.76858D 00	2.8295D-05	3.6815D-05	2.7928D-02
10	1541.3	0.76926D 00	2.5969D-05	3.3759D-05	3.6637D-02

RUN NO. = 3-7-4-C

AVG. BULB TEMPERATURE = 1771.9 DEG-R

984.4 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.77803D 00	4.1919D-05	5.3879D-05	3.6582D-04
2	172.7	0.77846D 00	3.9126D-05	5.0261D-05	4.2965D-03
3	176.5	0.77847D 00	3.9059D-05	5.0174D-05	4.3910D-03
4	490.6	0.77925D 00	3.3505D-05	4.2996D-05	1.2193D-02
5	494.4	0.77926D 00	3.3437D-05	4.2909D-05	1.2287D-02
6	841.4	0.77997D 00	2.7297D-05	3.4997D-05	2.0892D-02
7	859.8	0.78001D 00	2.6971D-05	3.4578D-05	2.1348D-02
8	1219.6	0.78059D 00	2.0599D-05	2.6390D-05	3.0259D-02
9	1222.8	0.78059D 00	2.0543D-05	2.6317D-05	3.0338D-02
10	1602.8	0.78104D 00	1.3809D-05	1.7630D-05	3.9744D-02

RUN NO. = 3-8-1-E

AVG. BULB TEMPERATURE = 1861.6 DEG-R
1034.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.76779D 00	3.4914D-05	4.5474D-05	3.5284D-04
2	128.9	0.76805D 00	3.3826D-05	4.4041D-05	3.0937D-03
3	132.7	0.76806D 00	3.3790D-05	4.3993D-05	3.1848D-03
4	433.5	0.76872D 00	3.0922D-05	4.0225D-05	1.0395D-02
5	437.9	0.76873D 00	3.0880D-05	4.0170D-05	1.0501D-02
6	788.1	0.76943D 00	2.7541D-05	3.5794D-05	1.8881D-02
7	794.5	0.76944D 00	2.7480D-05	3.5714D-05	1.9034D-02
8	1159.3	0.77008D 00	2.3999D-05	3.1164D-05	2.7751D-02
9	1162.5	0.77009D 00	2.3968D-05	3.1124D-05	2.7827D-02
10	1537.5	0.77065D 00	2.0389D-05	2.6457D-05	3.6776D-02

RUN NO. = 3-8-2-C

AVG. BULB TEMPERATURE = 1962.4 DEG-R
1090.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.75628D 00	1.7498D-05	2.3137D-05	3.3980D-04
2	382.1	0.75677D 00	2.1865D-05	2.8892D-05	8.8293D-03
3	388.4	0.75678D 00	2.1940D-05	2.8991D-05	8.9747D-03
4	776.7	0.75742D 00	2.6562D-05	3.5069D-05	1.7932D-02
5	782.4	0.75743D 00	2.6630D-05	3.5158D-05	1.8063D-02
6	1189.8	0.75824D 00	3.1486D-05	4.1525D-05	2.7440D-02
7	1193.6	0.75825D 00	3.1531D-05	4.1585D-05	2.7527D-02
8	1597.1	0.75918D 00	3.6349D-05	4.7879D-05	3.6788D-02
9	1629.5	0.75926D 00	3.6736D-05	4.8384D-05	3.7530D-02

RUN NO. = 3-8-3-C

AVG. BULB TEMPERATURE = 2054.4 DEG-R
1141.4 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	14.7	0.745780 00	3.80710-05	5.10490-05	3.29160-04
2	123.8	0.746060 00	3.75310-05	5.03060-05	2.77180-03
3	262.2	0.746410 00	3.68470-05	4.93650-05	5.86770-03
4	594.0	0.747220 00	3.52050-05	4.71150-05	1.32790-02
5	951.8	0.748060 00	3.34350-05	4.46960-05	2.12530-02
6	1330.6	0.748890 00	3.15620-05	4.21450-05	2.96780-02
7	1720.2	0.749710 00	2.96350-05	3.95290-05	3.83270-02

RUN NO. = 3-8-4

AVG. BULB TEMPERATURE = 2164.3 DEG-R
1202.4 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	22.2	0.731790 00	4.04110-05	5.52220-05	4.80440-04
2	155.6	0.732150 00	3.99630-05	5.45830-05	3.36970-03
3	157.5	0.732160 00	3.99570-05	5.45740-05	3.41080-03
4	467.1	0.732990 00	3.89200-05	5.30980-05	1.01040-02
5	469.0	0.732990 00	3.89140-05	5.30890-05	1.01450-02
6	476.0	0.733010 00	3.88900-05	5.30550-05	1.02960-02
7	825.6	0.733920 00	3.77200-05	5.13950-05	1.78360-02
8	826.2	0.733930 00	3.77180-05	5.13920-05	1.78490-02
9	835.1	0.733950 00	3.76880-05	5.13500-05	1.80410-02
10	1184.7	0.734830 00	3.65190-05	4.96970-05	2.55620-02
11	1187.9	0.734840 00	3.65080-05	4.96820-05	2.56310-02
12	1198.7	0.734870 00	3.64720-05	4.96310-05	2.58630-02
13	1558.4	0.735740 00	3.52700-05	4.79380-05	3.35840-02
14	1569.8	0.735770 00	3.52320-05	4.78840-05	3.38290-02

RUN NO. = 3-8-5

AVG. BULB TEMPERATURE = 2261.0 DEG-R

1256.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	33.9	0.71913D 00	3.2812D-05	4.5628D-05	7.1566D-04
2	175.9	0.71944D 00	3.2360D-05	4.4979D-05	3.7108D-03
3	177.1	0.71944D 00	3.2356D-05	4.4974D-05	3.7361D-03
4	498.2	0.72014D 00	3.1333D-05	4.3510D-05	1.0500D-02
5	498.8	0.72014D 00	3.1331D-05	4.3507D-05	1.0513D-02
6	859.2	0.72090D 00	3.0184D-05	4.1870D-05	1.8089D-02
7	859.8	0.72090D 00	3.0182D-05	4.1867D-05	1.8102D-02
8	1232.9	0.72165D 00	2.8995D-05	4.0179D-05	2.5930D-02
9	1234.2	0.72165D 00	2.8991D-05	4.0173D-05	2.5957D-02
10	1619.3	0.72239D 00	2.7767D-05	3.8438D-05	3.4021D-02

RUN NO. = 3-9-1

AVG. BULB TEMPERATURE = 2352.5 DEG-R

1307.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	49.1	0.70715D 00	2.0774D-05	2.9377D-05	1.0120D-03
2	160.0	0.70731D 00	2.2168D-05	3.1341D-05	3.2997D-03
3	168.9	0.70732D 00	2.2280D-05	3.1499D-05	3.4832D-03
4	349.1	0.70761D 00	2.4546D-05	3.4638D-05	7.1966D-03
5	352.2	0.70761D 00	2.4585D-05	3.4743D-05	7.2604D-03
6	736.1	0.70832D 00	2.9417D-05	4.1531D-05	1.5159D-02
7	750.1	0.70835D 00	2.9594D-05	4.1779D-05	1.5447D-02
8	1156.8	0.70924D 00	3.4722D-05	4.8956D-05	2.3792D-02
9	1170.7	0.70927D 00	3.4897D-05	4.9201D-05	2.4077D-02
10	1590.1	0.71034D 00	4.0194D-05	5.6584D-05	3.2653D-02

RUN NO. = 3-9-2

AVG. BULB TEMPERATURE = 2447.2 DEG-R
1359.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	69.8	0.69475D 00	4.4341D-05	6.3823D-05	1.4092D-03
2	106.1	0.69486D 00	4.3842D-05	6.3095D-05	2.1412D-03
3	131.4	0.69493D 00	4.3494D-05	6.2588D-05	2.6514D-03
4	466.5	0.69587D 00	3.8887D-05	5.5883D-05	9.4005D-03
5	466.5	0.69587D 00	3.8887D-05	5.5883D-05	9.4005D-03
6	863.0	0.69685D 00	3.3433D-05	4.7977D-05	1.7366D-02
7	868.1	0.69686D 00	3.3363D-05	4.7876D-05	1.7468D-02
8	1284.9	0.69772D 00	2.7626D-05	3.9595D-05	2.5823D-02
9	1288.1	0.69773D 00	2.7582D-05	3.9531D-05	2.5888D-02
10	1504.5	0.69811D 00	2.4602D-05	3.5241D-05	3.0220D-02

RUN NO. = 3-9 3

AVG. BULB TEMPERATURE = 2546.9 DEG-R
1415.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	98.4	0.68169D 00	4.6549D-05	6.8285D-05	1.9441D-03
2	142.2	0.68183D 00	4.6465D-05	6.8148D-05	2.8100D-03
3	209.5	0.68205D 00	4.6336D-05	6.7937D-05	4.1386D-03
4	285.0	0.68228D 00	4.6192D-05	6.7702D-05	5.6282D-03
5	640.9	0.68339D 00	4.5511D-05	6.6596D-05	1.2636D-02
6	1033.7	0.68460D 00	4.4762D-05	6.5384D-05	2.0344D-02
7	1441.7	0.68583D 00	4.3986D-05	6.4135D-05	2.8323D-02
8	1859.2	0.68707D 00	4.3194D-05	6.2867D-05	3.6460D-02

RUN NO. = 3-9-4

AVG. BULB TEMPERATURE = 2663.4 DEG-R
1479.7 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	142.0	0.66644D 00	4.9355D-05	7.4057D-05	2.7462D-03
2	161.9	0.66651D 00	4.9279D-05	7.3937D-05	3.1297D-03
3	331.3	0.66707D 00	4.8637D-05	7.2911D-05	6.3990D-03
4	706.9	0.66830D 00	4.7212D-05	7.0645D-05	1.3629D-02
5	1092.7	0.66952D 00	4.5750D-05	6.8333D-05	2.1028D-02
6	1503.2	0.67077D 00	4.4196D-05	6.5888D-05	2.8874D-02

RUN NO. = 3-9-5

AVG. BULB TEMPERATURE = 2756.2 DEG-R
1531.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	186.1	0.65429D 00	3.5656D-05	5.4496D-05	3.5416D-03
2	435.4	0.65491D 00	3.7450D-05	5.7184D-05	8.2774D-03
3	796.4	0.65586D 00	4.0052D-05	6.1068D-05	1.5118D-02
4	1170.7	0.65692D 00	4.2755D-05	6.5085D-05	2.2188D-02
5	1567.3	0.65811D 00	4.5625D-05	6.9328D-05	2.9651D-02

RUN NO. = 3-12-1

AVG. BULB TEMPERATURE = 2269.6 DEG-R

1260.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	35.2	0.71800D 00	5.1783D-05	7.2121D-05	7.4025D-04
2	198.7	0.71855D 00	4.7505D-05	6.6111D-05	4.1811D-03
3	270.1	0.71878D 00	4.5636D-05	6.3491D-05	5.6817D-03
4	342.6	0.71900D 00	4.3739D-05	6.0833D-05	7.2046D-03
5	356.7	0.71904D 00	4.3370D-05	6.0316D-05	7.5006D-03
6	416.2	0.71921D 00	4.1812D-05	5.8136D-05	8.7497D-03
7	489.8	0.71942D 00	3.9885D-05	5.5441D-05	1.0294D-02
8	511.4	0.71948D 00	3.9320D-05	5.4651D-05	1.0747D-02
9	639.1	0.71980D 00	3.5976D-05	4.9980D-05	1.3425D-02
10	662.9	0.71986D 00	3.5353D-05	4.9110D-05	1.3923D-02
11	817.7	0.72021D 00	3.1298D-05	4.3456D-05	1.7167D-02
12	958.4	0.72050D 00	2.7611D-05	3.8323D-05	2.0112D-02
13	1119.6	0.72078D 00	2.3386D-05	3.2446D-05	2.3486D-02
14	1131.5	0.72079D 00	2.3074D-05	3.2012D-05	2.3735D-02
15	1197.7	0.72089D 00	2.1339D-05	2.9601D-05	2.5120D-02
16	1284.1	0.72101D 00	1.9073D-05	2.6454D-05	2.6928D-02
17	1396.8	0.72115D 00	1.6118D-05	2.2350D-05	2.9286D-02
18	1451.8	0.72121D 00	1.4675D-05	2.0348D-05	3.0437D-02
19	1452.9	0.72121D 00	1.4646D-05	2.0308D-05	3.0460D-02
20	1548.7	0.72129D 00	1.2133D-05	1.6821D-05	3.2464D-02

RUN NO. = 3-12-2

AVG. BULB TEMPERATURE = 2288.1 DEG-R

1271.2 DEG-K

	PSIA	RHO (GM/CC)	DRHO DP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	37.9	0.71558D 00	1.0520D-05	1.4702D-05	7.9533D-04
2	221.4	0.71573D 00	1.3089D-05	1.8287D-05	4.6393D-03
3	232.2	0.71574D 00	1.3240D-05	1.8499D-05	4.8656D-03
4	358.8	0.71586D 00	1.5014D-05	2.0973D-05	7.5171D-03
5	522.2	0.71604D 00	1.7304D-05	2.4166D-05	1.0938D-02
6	713.8	0.71628D 00	1.9991D-05	2.7910D-05	1.4946D-02
7	906.4	0.71656D 00	2.2695D-05	3.1671D-05	1.8971D-02
8	1110.9	0.71690D 00	2.5567D-05	3.5663D-05	2.3240D-02
9	1306.8	0.71726D 00	2.8321D-05	3.9485D-05	2.7325D-02
10	1513.5	0.71767D 00	3.1228D-05	4.3513D-05	3.1629D-02
11	1727.8	0.71815D 00	3.4245D-05	4.7685D-05	3.6083D-02
12	1922.6	0.71862D 00	3.6990D-05	5.1473D-05	4.0125D-02
13	2144.4	0.71921D 00	4.0117D-05	5.5780D-05	4.4717D-02
14	2350.0	0.71979D 00	4.3018D-05	5.9766D-05	4.8965D-02
15	2575.1	0.72047D 00	4.6197D-05	6.4121D-05	5.3605D-02

RUN NO. = 3-12-5

AVG. BULB TEMPERATURE = 2454.3 DEG-R
1363.5 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	71.6	0.69382D 00	3.7414D-05	5.3925D-05	1.4431D-03
2	160.8	0.69405D 00	3.7357D-05	5.3826D-05	3.2394D-03
3	169.4	0.69407D 00	3.7352D-05	5.3816D-05	3.4126D-03
4	221.4	0.69420D 00	3.7319D-05	5.3758D-05	4.4593D-03
5	421.6	0.69471D 00	3.7193D-05	5.3537D-05	8.4853D-03
6	585.0	0.69512D 00	3.7090D-05	5.3357D-05	1.1767D-02
7	796.0	0.69565D 00	3.6958D-05	5.3127D-05	1.5999D-02
8	973.5	0.69610D 00	3.6847D-05	5.2934D-05	1.9554D-02
9	1184.5	0.69663D 00	3.6716D-05	5.2706D-05	2.3774D-02
10	1373.9	0.69710D 00	3.6599D-05	5.2502D-05	2.7557D-02
11	1591.4	0.69764D 00	3.6466D-05	5.2270D-05	3.1895D-02
12	1785.1	0.69812D 00	3.6347D-05	5.2065D-05	3.5752D-02
13	2014.6	0.69868D 00	3.6208D-05	5.1823D-05	4.0316D-02
14	2211.5	0.69917D 00	3.6089D-05	5.1617D-05	4.4226D-02
15	2434.5	0.69972D 00	3.5955D-05	5.1385D-05	4.8647D-02
16	2643.3	0.70023D 00	3.5830D-05	5.1169D-05	5.2781D-02
17	2881.4	0.70080D 00	3.5689D-05	5.0925D-05	5.7488D-02

RUN NO. = 3-13-1

AVG. BULB TEMPERATURE = 2636.5 DEG-R

1464.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	130.9	0.66996D 00	4.6134D-05	6.8860D-05	2.5425D-03
2	165.1	0.67007D 00	4.6030D-05	6.8695D-05	3.2070D-03
3	199.7	0.67018D 00	4.5926D-05	6.8528D-05	3.8784D-03
4	336.1	0.67060D 00	4.5514D-05	6.7870D-05	6.5234D-03
5	524.4	0.67118D 00	4.4946D-05	6.6965D-05	1.0169D-02
6	704.0	0.67173D 00	4.4404D-05	6.6104D-05	1.3641D-02
7	884.8	0.67227D 00	4.3859D-05	6.5240D-05	1.7131D-02
8	1083.9	0.67286D 00	4.3259D-05	6.4291D-05	2.0967D-02
9	1287.3	0.67346D 00	4.2647D-05	6.3326D-05	2.4879D-02
10	1477.8	0.67401D 00	4.2074D-05	6.2424D-05	2.8538D-02
11	1689.9	0.67461D 00	4.1436D-05	6.1423D-05	3.2605D-02
12	1877.1	0.67513D 00	4.0874D-05	6.0542D-05	3.6188D-02
13	2115.2	0.67579D 00	4.0159D-05	5.9426D-05	4.0739D-02
14	2310.0	0.67632D 00	3.9575D-05	5.8516D-05	4.4456D-02
15	2536.2	0.67692D 00	3.8897D-05	5.7462D-05	4.8766D-02
16	2760.2	0.67751D 00	3.8227D-05	5.6422D-05	5.3027D-02

RUN NO. = 3-13-2A

AVG. BULB TEMPERATURE = 2727.5 DEG-R
1515.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	171.5	0.658050 00	4.38980-05	6.67090-05	3.27970-03
2	286.3	0.658390 00	4.37050-05	6.63810-05	5.47110-03
3	289.6	0.658400 00	4.36990-05	6.63720-05	5.53400-03
4	461.6	0.658910 00	4.34100-05	6.58820-05	8.81400-03
5	658.6	0.659490 00	4.30800-05	6.53230-05	1.25650-02
6	845.8	0.660040 00	4.27660-05	6.47940-05	1.61230-02
7	1033.0	0.660580 00	4.24530-05	6.42670-05	1.96750-02
8	1248.4	0.661200 00	4.20940-05	6.36630-05	2.37550-02
9	1437.8	0.661740 00	4.17790-05	6.31340-05	2.73370-02
10	1645.5	0.662330 00	4.14330-05	6.25570-05	3.12580-02
11	1849.0	0.662900 00	4.10950-05	6.19940-05	3.50930-02
12	2053.5	0.663470 00	4.07570-05	6.14300-05	3.89410-02
13	2268.9	0.664060 00	4.04010-05	6.08380-05	4.29870-02
14	2476.7	0.664630 00	4.00580-05	6.02700-05	4.68840-02
15	2708.2	0.665260 00	3.96760-05	5.96400-05	5.12180-02

RUN NO. = 3-13-2B

AVG. BULB TEMPERATURE = 2727.5 DEG-R
1515.3 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	171.5	0.65805D 00	4.4013D-05	6.6884D-05	3.2797D-03
2	286.3	0.65839D 00	4.3994D-05	6.6820D-05	5.4710D-03
3	289.6	0.65840D 00	4.3993D-05	6.6818D-05	5.5340D-03
4	461.6	0.65892D 00	4.3966D-05	6.6724D-05	8.8139D-03
5	658.6	0.65951D 00	4.3934D-05	6.6617D-05	1.2564D-02
6	845.8	0.66007D 00	4.3905D-05	6.6517D-05	1.6122D-02
7	1033.0	0.66062D 00	4.3877D-05	6.6417D-05	1.9673D-02
8	1248.4	0.66127D 00	4.3845D-05	6.6305D-05	2.3753D-02
9	1437.8	0.66183D 00	4.3818D-05	6.6207D-05	2.7333D-02
10	1645.5	0.66245D 00	4.3789D-05	6.6101D-05	3.1252D-02
11	1849.0	0.66306D 00	4.3761D-05	6.5999D-05	3.5085D-02
12	2053.5	0.66367D 00	4.3734D-05	6.5897D-05	3.8929D-02
13	2268.9	0.66431D 00	4.3706D-05	6.5792D-05	4.2971D-02
14	2476.7	0.66492D 00	4.3680D-05	6.5692D-05	4.6863D-02
15	2708.2	0.66561D 00	4.3652D-05	6.5582D-05	5.1191D-02

RUN NO. = 3-14-5

AVG. BULB TEMPERATURE = 3079.1 DEG-R
1710.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	419.0	0.61201D 00	4.6069D-05	7.5275D-05	7.6292D-03
2	476.8	0.61220D 00	4.6555D-05	7.6045D-05	8.6800D-03
3	476.8	0.61220D 00	4.6555D-05	7.6045D-05	8.6800D-03
4	868.5	0.61348D 00	4.9846D-05	8.1252D-05	1.5778D-02
5	875.0	0.61350D 00	4.9901D-05	8.1338D-05	1.5895D-02
6	1268.9	0.61488D 00	5.3218D-05	8.6550D-05	2.2999D-02

RUN NO. = 3-14-6

AVG. BULB TEMPERATURE = 3165.5 DEG-R
1758.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	504.9	0.600700 00	6.22560-05	1.03640-04	9.11180-03
2	505.9	0.600710 00	6.22510-05	1.03630-04	9.12980-03
3	507.1	0.600710 00	6.22450-05	1.03620-04	9.15130-03
4	528.7	0.600800 00	6.21370-05	1.03420-04	9.53970-03
5	693.2	0.601490 00	6.13150-05	1.01940-04	1.24930-02
6	711.6	0.601570 00	6.12230-05	1.01770-04	1.28230-02
7	733.3	0.601660 00	6.11150-05	1.01580-04	1.32130-02
8	891.3	0.602310 00	6.03260-05	1.00160-04	1.60420-02
9	895.6	0.602330 00	6.03040-05	1.00120-04	1.61190-02
10	918.3	0.602420 00	6.01910-05	9.99150-05	1.65250-02
11	1066.6	0.603030 00	5.94510-05	9.85870-05	1.91740-02
12	1079.6	0.603080 00	5.93860-05	9.84710-05	1.94060-02
13	1120.7	0.603250 00	5.91810-05	9.81040-05	2.01400-02
14	1262.4	0.603810 00	5.84740-05	9.68410-05	2.26650-02
15	1264.6	0.603820 00	5.84630-05	9.68210-05	2.27040-02
16	1315.5	0.604020 00	5.82090-05	9.63690-05	2.36100-02
17	1450.7	0.604560 00	5.75340-05	9.51680-05	2.60130-02
18	1456.2	0.604580 00	5.75070-05	9.51190-05	2.61110-02
19	1514.6	0.604800 00	5.72160-05	9.46020-05	2.71480-02
20	1516.8	0.604810 00	5.72050-05	9.45830-05	2.71870-02

RUN NO. = 3-15-1B

AVG. BULB TEMPERATURE = 2750.3 DEG-R
1528.0 DEG-K

	PSIA	RHO (GM/CC)	DRHO DP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	183.0	0.65506D 00	4.5618D-05	6.9639D-05	3.4865D-03
2	339.4	0.65555D 00	4.4982D-05	6.8618D-05	6.4599D-03
3	530.9	0.65613D 00	4.4203D-05	6.7370D-05	1.0096D-02
4	732.2	0.65673D 00	4.3386D-05	6.6063D-05	1.3911D-02
5	930.2	0.65731D 00	4.2581D-05	6.4782D-05	1.7657D-02
5	1131.5	0.65788D 00	4.1764D-05	6.3483D-05	2.1460D-02
7	1340.4	0.65847D 00	4.0917D-05	6.2139D-05	2.5399D-02

RUN NO. = 3-15-1A

AVG. BULB TEMPERATURE = 2750.3 DEG-R
1528.0 DEG-K

	PSIA	RHO (GM/CC)	DRHO DP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	183.0	0.65506D 00	4.0743D-05	6.2197D-05	3.4865D-03
2	352.3	0.65554D 00	4.1801D-05	6.3766D-05	6.7055D-03
3	553.6	0.65612D 00	4.3060D-05	6.5629D-05	1.0528D-02
4	744.1	0.65669D 00	4.4254D-05	6.7389D-05	1.4138D-02
5	945.4	0.65730D 00	4.5516D-05	6.9247D-05	1.7946D-02
5	1145.6	0.65793D 00	4.6773D-05	7.1091D-05	2.1726D-02
7	1343.6	0.65857D 00	4.8017D-05	7.2912D-05	2.5456D-02

RUN NO. = 3-15-1C

AVG. BULB TEMPERATURE = 2750.3 DEG-R
1528.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	183.0	0.65506D 00	3.3115D-05	5.0552D-05	3.4865D-03
2	345.8	0.65544D 00	3.5126D-05	5.3591D-05	6.5828D-03
3	542.8	0.65593D 00	3.7561D-05	5.7265D-05	1.0325D-02
4	750.6	0.65648D 00	4.0133D-05	6.1134D-05	1.4266D-02
5	955.1	0.65705D 00	4.2666D-05	6.4935D-05	1.8137D-02
6	1151.0	0.65764D 00	4.5094D-05	6.8570D-05	2.1838D-02
7	1354.4	0.65828D 00	4.7617D-05	7.2336D-05	2.5672D-02

RUN NO. = 3-15-1D

AVG. BULB TEMPERATURE = 2750.3 DEG-R
1528.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	183.0	0.65506D 00	4.5787D-05	6.9897D-05	3.4865D-03
2	343.7	0.65556D 00	4.4811D-05	6.8355D-05	6.5416D-03
3	540.6	0.65615D 00	4.3615D-05	6.6471D-05	1.0280D-02
4	739.8	0.65673D 00	4.2405D-05	6.4570D-05	1.4055D-02
5	936.7	0.65729D 00	4.1210D-05	6.2696D-05	1.7781D-02
6	1142.3	0.65786D 00	3.9962D-05	6.0745D-05	2.1665D-02
7	1354.4	0.65843D 00	3.8674D-05	5.8737D-05	2.5666D-02

RUN NO. = 3-15-2

AVG. BULB TEMPERATURE = 2771.5 DEG-R
1539.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	194.3	0.65229D 00	4.5196D-05	6.9288D-05	3.6873D-03
2	355.6	0.65279D 00	4.5563D-05	6.9797D-05	6.7449D-03
3	547.1	0.65338D 00	4.5999D-05	7.0402D-05	1.0368D-02
4	735.4	0.65397D 00	4.6430D-05	7.0996D-05	1.3923D-02
5	932.4	0.65460D 00	4.6881D-05	7.1618D-05	1.7636D-02
6	1131.5	0.65524D 00	4.7338D-05	7.2245D-05	2.1382D-02
7	1339.3	0.65591D 00	4.7816D-05	7.2900D-05	2.5282D-02
8	1534.1	0.65655D 00	4.8265D-05	7.3513D-05	2.8931D-02

RUN NO. = 3-16-1

AVG. BULB TEMPERATURE = 3099.0 DEG-R
1721.7 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	421.1	0.60941D 00	6.8460D-05	1.1234D-04	7.6516D-03
2	438.0	0.60949D 00	6.8159D-05	1.1183D-04	7.9571D-03
3	548.8	0.60999D 00	6.6179D-05	1.0849D-04	9.9624D-03
4	677.5	0.61056D 00	6.3881D-05	1.0463D-04	1.2287D-02
5	807.4	0.61112D 00	6.1560D-05	1.0073D-04	1.4630D-02
6	936.2	0.61165D 00	5.9259D-05	9.6884D-05	1.6949D-02
7	1074.7	0.61219D 00	5.6783D-05	9.2754D-05	1.9439D-02
8	1204.6	0.61268D 00	5.4462D-05	8.8890D-05	2.1771D-02

RUN NO. = 3-16-2

AVG. BULB TEMPERATURE = 3142.7 DEG-R
1746.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	471.4	0.60369D 00	8.1360D-05	1.3477D-04	8.5265D-03
2	481.8	0.60374D 00	8.1112D-05	1.3435D-04	8.7145D-03
3	605.6	0.60441D 00	7.8167D-05	1.2933D-04	1.0941D-02
4	730.0	0.60506D 00	7.5207D-05	1.2430D-04	1.3174D-02
5	850.1	0.60567D 00	7.2349D-05	1.1945D-04	1.5326D-02
6	986.5	0.60632D 00	6.9102D-05	1.1397D-04	1.7766D-02
7	1109.9	0.60689D 00	6.6164D-05	1.0902D-04	1.9970D-02
8	1237.6	0.60745D 00	6.3123D-05	1.0391D-04	2.2247D-02
9	1369.6	0.60801D 00	5.9979D-05	9.8648D-05	2.4597D-02
10	1494.0	0.60850D 00	5.7015D-05	9.3697D-05	2.6809D-02
11	1634.7	0.60903D 00	5.3662D-05	8.8111D-05	2.9308D-02

RUN NO. = 3-16-3

AVG. BULB TEMPERATURE = 3185.6 DEG-R
1769.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	527.8	0.59807D 00	5.8243D-05	9.7384D-05	9.5067D-03
2	547.1	0.59815D 00	5.8319D-05	9.7499D-05	9.8529D-03
3	747.3	0.59895D 00	5.9108D-05	9.8686D-05	1.3440D-02
4	949.7	0.59977D 00	5.9907D-05	9.9884D-05	1.7057D-02
5	1145.6	0.60057D 00	6.0682D-05	1.0104D-04	2.0548D-02
6	1343.6	0.60139D 00	6.1466D-05	1.0221D-04	2.4067D-02
7	1535.2	0.60220D 00	6.2227D-05	1.0333D-04	2.7462D-02
8	1634.7	0.60262D 00	6.2622D-05	1.0392D-04	2.9221D-02

RUN NO. = 3-16-4

AVG. BULB TEMPERATURE = 3232.9 DEG-R
1796.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	581.9	0.59188D 00	5.5166D-05	9.3205D-05	1.0436D-02
2	640.2	0.59210D 00	5.6728D-05	9.5809D-05	1.1477D-02
3	824.2	0.59284D 00	6.1665D-05	1.0402D-04	1.4757D-02
4	1022.2	0.59371D 00	6.6980D-05	1.1282D-04	1.8276D-02
5	1211.6	0.59460D 00	7.2068D-05	1.2120D-04	2.1629D-02
6	1385.8	0.59548D 00	7.6750D-05	1.2889D-04	2.4702D-02
7	1575.2	0.59651D 00	8.1844D-05	1.3721D-04	2.8030D-02
8	1770.0	0.59763D 00	8.7087D-05	1.4572D-04	3.1438D-02

RUN NO. = 3-16-5

AVG. BULB TEMPERATURE = 3277.5 DEG-R
1820.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	636.4	0.58604D 00	7.8753D-05	1.3438D-04	1.1369D-02
2	639.1	0.58605D 00	7.8704D-05	1.3430D-04	1.1418D-02
3	828.5	0.58704D 00	7.5346D-05	1.2835D-04	1.4777D-02
4	1015.7	0.58798D 00	7.2026D-05	1.2250D-04	1.8087D-02
5	1191.0	0.58882D 00	6.8916D-05	1.1704D-04	2.1178D-02
6	1385.8	0.58971D 00	6.5459D-05	1.1100D-04	2.4604D-02
7	1580.6	0.59056D 00	6.2001D-05	1.0499D-04	2.8023D-02
8	1775.4	0.59136D 00	5.8543D-05	9.8998D-05	3.1434D-02

RUN NO. = 3-16-6A

AVG. BULB TEMPERATURE = 3321.2 DEG-R
1845.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	693.0	0.580310 00	6.52970-05	1.12520-04	1.23380-02
2	772.7	0.580670 00	6.51650-05	1.12220-04	1.37490-02
3	952.9	0.581470 00	6.48680-05	1.11560-04	1.69330-02
4	1145.6	0.582310 00	6.45510-05	1.10850-04	2.03270-02
5	1329.5	0.583120 00	6.42480-05	1.10180-04	2.35580-02
6	1515.7	0.583930 00	6.39430-05	1.09500-04	2.68200-02
7	1709.4	0.584770 00	6.36260-05	1.08800-04	3.02040-02

RUN NO. = 3-16-6B

AVG. BULB TEMPERATURE = 3321.2 DEG-R
1845.1 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	693.0	0.580310 00	8.40410-05	1.44820-04	1.23380-02
2	772.2	0.580760 00	8.20320-05	1.41250-04	1.37380-02
3	952.9	0.581740 00	7.74470-05	1.33130-04	1.69250-02
4	1145.6	0.582730 00	7.25570-05	1.24510-04	2.03130-02
5	1329.5	0.583610 00	6.78890-05	1.16330-04	2.35380-02
6	1515.7	0.584440 00	6.31610-05	1.08070-04	2.67970-02
7	1709.4	0.585240 00	5.82400-05	9.95160-05	3.01800-02

RUN NO. = 3-16-7A

AVG. BULB TEMPERATURE = 3360.6 DEG-R
1867.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	746.9	0.57516D 00	7.3611D-05	1.2798D-04	1.3260D-02
2	804.7	0.57544D 00	7.3098D-05	1.2703D-04	1.4279D-02
3	985.4	0.57633D 00	7.1498D-05	1.2406D-04	1.7459D-02
4	1167.2	0.57721D 00	6.9887D-05	1.2108D-04	2.0649D-02
5	1345.8	0.57805D 00	6.8305D-05	1.1817D-04	2.3774D-02
6	1529.7	0.57889D 00	6.6676D-05	1.1518D-04	2.6983D-02
7	1719.1	0.57974D 00	6.4999D-05	1.1212D-04	3.0279D-02

RUN NO. = 3-16-7B

AVG. BULB TEMPERATURE = 3360.6 DEG-R
1867.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	746.9	0.57516D 00	8.2630D-05	1.4367D-04	1.3260D-02
2	804.7	0.57548D 00	8.1776D-05	1.4210D-04	1.4279D-02
3	985.4	0.57647D 00	7.9105D-05	1.3722D-04	1.7455D-02
4	1167.2	0.57743D 00	7.6418D-05	1.3234D-04	2.0641D-02
5	1345.8	0.57834D 00	7.3778D-05	1.2757D-04	2.3762D-02
6	1529.7	0.57925D 00	7.1059D-05	1.2267D-04	2.6966D-02
7	1719.1	0.58015D 00	6.8258D-05	1.1766D-04	3.0258D-02

RUN NO. = 3-16-8A

AVG. BULB TEMPERATURE = 3358.3 DEG-R
1865.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	743.7	0.57546D 00	6.6219D-05	1.1507D-04	1.3205D-02
2	794.9	0.57569D 00	6.7085D-05	1.1653D-04	1.4109D-02
3	982.2	0.57657D 00	7.0252D-05	1.2185D-04	1.7407D-02
4	1170.5	0.57749D 00	7.3438D-05	1.2717D-04	2.0711D-02
5	1346.9	0.57839D 00	7.6425D-05	1.3214D-04	2.3796D-02
6	1526.5	0.57934D 00	7.9469D-05	1.3717D-04	2.6924D-02
7	1710.5	0.58035D 00	8.2589D-05	1.4231D-04	3.0117D-02

RUN NO. = 3-16-8B

AVG. BULB TEMPERATURE = 3358.3 DEG-R
1865.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	743.7	0.57546D 00	7.4171D-05	1.2889D-04	1.3205D-02
2	794.9	0.57572D 00	7.4198D-05	1.2888D-04	1.4109D-02
3	975.7	0.57663D 00	7.4293D-05	1.2884D-04	1.7290D-02
4	1161.8	0.57757D 00	7.4392D-05	1.2880D-04	2.0554D-02
5	1338.2	0.57846D 00	7.4486D-05	1.2877D-04	2.3639D-02
6	1524.3	0.57941D 00	7.4587D-05	1.2873D-04	2.6882D-02
7	1710.5	0.58035D 00	7.4688D-05	1.2869D-04	3.0117D-02

RUN NO. = 3-16-9

AVG. BULB TEMPERATURE = 3322.4 DEG-R
1845.8 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	694.6	0.58016D 00	7.5997D-05	1.3099D-04	1.2366D-02
2	748.4	0.58043D 00	7.5173D-05	1.2951D-04	1.3318D-02
3	925.9	0.58133D 00	7.2452D-05	1.2463D-04	1.6451D-02
4	1108.8	0.58221D 00	6.9649D-05	1.1963D-04	1.9671D-02
5	1287.3	0.58304D 00	6.6912D-05	1.1476D-04	2.2805D-02
5	1476.7	0.58388D 00	6.4008D-05	1.0962D-04	2.6122D-02
7	1661.1	0.58467D 00	6.1180D-05	1.0464D-04	2.9345D-02
3	1862.0	0.58548D 00	5.8098D-05	9.9231D-05	3.2848D-02

RUN NO. = 3-16-10

AVG. BULB TEMPERATURE = 3289.3 DEG-R
1827.4 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	651.3	0.58449D 00	5.9265D-05	1.0140D-04	1.1625D-02
2	669.4	0.58456D 00	5.9534D-05	1.0184D-04	1.1947D-02
3	858.8	0.58535D 00	6.2350D-05	1.0652D-04	1.5306D-02
4	1036.3	0.58612D 00	6.4991D-05	1.1088D-04	1.8446D-02
5	1224.6	0.58697D 00	6.7795D-05	1.1550D-04	2.1766D-02
5	1409.6	0.58784D 00	7.0551D-05	1.2002D-04	2.5017D-02
7	1584.9	0.58870D 00	7.3166D-05	1.2428D-04	2.8087D-02
8	1768.9	0.58963D 00	7.5912D-05	1.2874D-04	3.1298D-02

RUN NO. = 3-16-11

AVG. BULB TEMPERATURE = 3253.4 DEG-R
1807.5 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	606.5	0.589190 00	5.36050-05	9.09800-05	1.08580-02
2	661.8	0.589400 00	5.44990-05	9.24660-05	1.18430-02
3	853.4	0.590130 00	5.76000-05	9.76070-05	1.52530-02
4	1042.8	0.590890 00	6.06680-05	1.02670-04	1.86150-02
5	1239.7	0.591720 00	6.38600-05	1.07920-04	2.20980-02
6	1423.7	0.592540 00	6.68460-05	1.12810-04	2.53430-02
7	1600.1	0.593360 00	6.97100-05	1.17480-04	2.84440-02
8	1731.0	0.593990 00	7.18360-05	1.20940-04	3.07380-02

RUN NO. = 3-16-12

AVG. BULB TEMPERATURE = 3218.7 DEG-R
1788.2 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	565.3	0.593740 00	5.83810-05	9.83290-05	1.01510-02
2	668.3	0.594150 00	5.87110-05	9.88160-05	1.19920-02
3	853.4	0.594890 00	5.93040-05	9.96890-05	1.52940-02
4	1038.4	0.595640 00	5.98980-05	1.00560-04	1.85870-02
5	1227.8	0.596420 00	6.05070-05	1.01450-04	2.19480-02
6	1416.1	0.597190 00	6.11130-05	1.02330-04	2.52810-02
7	1608.7	0.598000 00	6.17350-05	1.03240-04	2.86810-02
8	1739.7	0.598550 00	6.21590-05	1.03850-04	3.09880-02

RUN NO. = 3-16-13A

AVG. BULB TEMPERATURE = 3185.4 DEG-R

1769.7 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	527.6	0.59810D 00	5.8988D-05	9.8627D-05	9.5029D-03
2	588.3	0.59834D 00	6.0565D-05	1.0122D-04	1.0592D-02
3	770.1	0.59912D 00	6.5290D-05	1.0898D-04	1.3847D-02
4	946.5	0.59993D 00	6.9877D-05	1.1647D-04	1.6996D-02
5	1141.2	0.60089D 00	7.4943D-05	1.2472D-04	2.0460D-02
6	1330.6	0.60189D 00	7.9874D-05	1.3271D-04	2.3816D-02
7	1524.3	0.60297D 00	8.4921D-05	1.4084D-04	2.7234D-02
8	1654.2	0.60374D 00	8.8307D-05	1.4627D-04	2.9517D-02

RUN NO. = 3-16-13B

AVG. BULB TEMPERATURE = 3185.4 DEG-R

1769.7 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	527.6	0.59810D 00	7.0887D-05	1.1852D-04	9.5029D-03
2	569.9	0.59830D 00	7.0689D-05	1.1815D-04	1.0262D-02
3	762.5	0.59922D 00	6.9789D-05	1.1647D-04	1.3708D-02
4	946.5	0.60009D 00	6.8930D-05	1.1487D-04	1.6992D-02
5	1131.5	0.60095D 00	6.8066D-05	1.1326D-04	2.0284D-02
6	1316.6	0.60180D 00	6.7202D-05	1.1167D-04	2.3569D-02
7	1512.4	0.60269D 00	6.6288D-05	1.0999D-04	2.7034D-02
8	1644.5	0.60328D 00	6.5672D-05	1.0886D-04	2.9366D-02

RUN NO. = 3-16-14

AVG. BULB TEMPERATURE = 3146.4 DEG-R

1748.0 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	485.7	0.603200 00	6.74460-05	1.11810-04	8.78170-03
2	506.0	0.603290 00	6.72270-05	1.11430-04	9.14750-03
3	703.0	0.604180 00	6.51040-05	1.07760-04	1.26900-02
4	873.9	0.604930 00	6.32620-05	1.04580-04	1.57560-02
5	1061.2	0.605720 00	6.12430-05	1.01110-04	1.91080-02
5	1259.2	0.606530 00	5.91090-05	9.74540-05	2.26420-02
7	1455.1	0.607310 00	5.69970-05	9.38520-05	2.61320-02
9	1658.5	0.608080 00	5.48030-05	9.01250-05	2.97470-02
9	1859.8	0.608820 00	5.26330-05	8.64510-05	3.33170-02

RUN NO. = 3-16-15A

AVG. BULB TEMPERATURE = 3109.7 DEG-R

1727.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	448.4	0.608010 00	5.13810-05	8.45080-05	8.13910-03
2	511.4	0.608230 00	5.13910-05	8.44930-05	9.27840-03
3	709.5	0.608920 00	5.14210-05	8.44460-05	1.28580-02
4	899.9	0.609590 00	5.14510-05	8.44030-05	1.62910-02
5	1095.8	0.610270 00	5.14820-05	8.43600-05	1.98150-02
5	1290.6	0.610950 00	5.15150-05	8.43180-05	2.33110-02
7	1496.2	0.611680 00	5.15490-05	8.42760-05	2.69930-02
9	1696.4	0.612380 00	5.15840-05	8.42360-05	3.05690-02
9	1899.9	0.613090 00	5.16210-05	8.41970-05	3.41970-02

RUN NO. = 3-16-15B

AVG. BULB TEMPERATURE = 3109.7 DEG-R
1727.6 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	448.4	0.60801D 00	5.4391D-05	8.9458D-05	8.1391D-03
2	557.9	0.60841D 00	5.4397D-05	8.9408D-05	1.0119D-02
3	752.7	0.60913D 00	5.4408D-05	8.9321D-05	1.3636D-02
4	946.5	0.60985D 00	5.4421D-05	8.9236D-05	1.7127D-02
5	1138.0	0.61056D 00	5.4433D-05	8.9153D-05	2.0568D-02
6	1331.7	0.61128D 00	5.4447D-05	8.9071D-05	2.4041D-02
7	1518.9	0.61197D 00	5.4461D-05	8.8994D-05	2.7389D-02
8	1725.6	0.61274D 00	5.4478D-05	8.8909D-05	3.1077D-02
9	1932.3	0.61350D 00	5.4496D-05	8.8827D-05	3.4757D-02

RUN NO. = 3-16-16

AVG. BULB TEMPERATURE = 3073.5 DEG-R
1707.5 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	413.7	0.61275D 00	6.6635D-05	1.0875D-04	7.5384D-03
2	455.1	0.61293D 00	6.6016D-05	1.0771D-04	8.2901D-03
3	634.8	0.61372D 00	6.3330D-05	1.0319D-04	1.1549D-02
4	807.9	0.61445D 00	6.0743D-05	9.8856D-05	1.4680D-02
5	985.4	0.61517D 00	5.8089D-05	9.4427D-05	1.7885D-02
6	1171.5	0.61589D 00	5.5306D-05	8.9798D-05	2.1237D-02
7	1360.9	0.61658D 00	5.2473D-05	8.5102D-05	2.4643D-02
8	1556.8	0.61726D 00	4.9542D-05	8.0260D-05	2.8160D-02
9	1750.5	0.61790D 00	4.6643D-05	7.5487D-05	3.1631D-02
10	1944.2	0.61849D 00	4.3744D-05	7.0726D-05	3.5097D-02

RUN NO. = 3-16-17

AVG. BULB TEMPERATURE = 3036.3 DEG-R
1686.9 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	380.0	0.61762D 00	7.5906D-05	1.2290D-04	6.9546D-03
2	401.6	0.61773D 00	7.5538D-05	1.2228D-04	7.3477D-03
3	583.4	0.61864D 00	7.2438D-05	1.1709D-04	1.0658D-02
4	924.3	0.62026D 00	6.6622D-05	1.0741D-04	1.6842D-02
5	1289.0	0.62183D 00	6.0397D-05	9.7127D-05	2.3428D-02
6	1677.5	0.62334D 00	5.3762D-05	8.6248D-05	3.0415D-02
7	1875.5	0.62404D 00	5.0379D-05	8.0730D-05	3.3967D-02

RUN NO. = 3-16-18

AVG. BULB TEMPERATURE = 3044.6 DEG-R
1691.5 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	387.4	0.61653D 00	5.2437D-05	8.5052D-05	7.0820D-03
2	491.4	0.61690D 00	5.2403D-05	8.4945D-05	8.9781D-03
3	675.4	0.61756D 00	5.2342D-05	8.4757D-05	1.2327D-02
4	1060.6	0.61893D 00	5.2218D-05	8.4369D-05	1.9314D-02
5	1453.5	0.62032D 00	5.2095D-05	8.3981D-05	2.6410D-02
6	1853.9	0.62174D 00	5.1973D-05	8.3592D-05	3.3608D-02
7	2112.5	0.62265D 00	5.1895D-05	8.3345D-05	3.8240D-02

RUN NO. = 3-16-19

AVG. BULB TEMPERATURE = 3035.4 DEG-R
1686.4 DEG-K

	PSIA	RHO (GM/CC)	DRHODP (GM/CC/ATM)	BETAT (ATM-1)	PV/RT
1	379.3	0.617730 00	5.84050-05	9.45470-05	6.94090-03
2	467.6	0.618080 00	5.77260-05	9.33960-05	8.55280-03
3	652.6	0.618800 00	5.63060-05	9.09920-05	1.19230-02
4	1037.9	0.620240 00	5.33470-05	8.60110-05	1.89180-02
5	1416.7	0.621580 00	5.04390-05	8.11470-05	2.57670-02
6	1819.2	0.622920 00	4.73490-05	7.60110-05	3.30170-02
7	2024.8	0.623570 00	4.57700-05	7.34010-05	3.67100-02

APPENDIX IV

Wide Range Equation For The Saturated Vapor Pressure Of Sodium

In order to utilise the equation-of-state determined from this dissertation, i.e. eq. 6.19, it is necessary, as explained in the section " Analysis of Results ", to have accurate correlations for the saturated vapor pressure and the saturated liquid density of sodium. The correlation for the vapor pressure is discussed in this Appendix while that for the liquid density is discussed in Appendix V.

At present the high temperature (i.e. $T > 1155$ K) vapor pressures are calculable from the equation of Bhise & Bonilla (1), while the Ditchburn & Gilmour equation (62) is used below 1155 K. But Bhise's data below 1645 K show significantly larger deviations, averaging 2.5%, from their best fit curve than do those above 1645 K, which average 0.7% (Fig. 24). Also his Least Squares best-fit equation differs by almost 2% from the equation of Stone, Ewing et. al. (2) in the common range. In order to resolve the above discrepancies, the Bhise and Bonilla data (1) were re-analysed as a part of this investigation. For the analysis only the vapor pressure points above 1645 K were utilised. A further screening was also conducted by eliminating also those points which were greater than three standard deviations' different from the resulting best-fit curve. The remaining points were then combined with the vapor pressure points of Stone, Ewing et. al. (2) and again analysed by Least Squares.

The analysis was conducted in several phases :

- a) the combined data were fitted to both the Young's and the Kirchoff's forms of the vapor pressure equation without any constraints,
- b) the Kirchoff's form was used with three types of constraints :
 - i) the equation to satisfy exactly the boiling point of sodium which was selected as 1154.6 K,
 - ii) the equation to satisfy the critical point estimates of Bhise and Bonilla(1), i.e. 253 ata and 2503.3 K,

Fig.24 . Deviation Plot, Sodium Vapor Pressure Data

and iii) the equation to satisfy constraints i) & ii) above.
c) step b) was repeated using the Young's form of the vapor pressure equation.

The standard deviations obtained with the different fits are summarised in Table A.1 below :

TABLE A.1

The standard deviations of different vapor pressure equations

Constraints	$\sigma, \%$	
	Young's equation	Kirchoff's equation
No constraints	0.70	0.65
Boiling point only	0.75	0.70
Critical point only	0.95	0.85
Both points	1.15	1.0

Young's eq. : $\ln P = A + B/T$

Kirchoff's eq. : $\ln P = A + B/T + C \ln T$

It is observed from the above table that for all cases the Kirchoff's form was better, though marginally so. Also, the standard deviations increased when both constraints were used compared to either the boiling point or the critical point constraint only. Furthermore the boiling point constraint gave a better fit than the critical point constraint. On the basis of the above analysis it was felt that the Kirchoff's form should be used to represent the combined vapor pressure data. It was also felt that the best-fit equation should satisfy at least one of the constraints. Thus the boiling point constraint was chosen since it is bound to be more reliable. Thus the final recommended equation is :

$$\ln P(\text{ata}) = 12.4494904 - 22029.9768/T(R)$$

$$- 0.242089052 \ln T(R), \quad \sigma = 0.7\%$$

A.4.1

Eq. A.4.1 has a lower σ than the equation of Bhise (1) and is comparable to Stone et.al.'s equation ($\sigma = 0.67\%$). Also the critical temperature predicted by eq A.4.1 is 2508.7 K which is only 1 K higher than the critical temperature obtained by extrapolating the highest temperature points, i.e. Runs 4 & 5, of Bhise (1).

Eq. A.4.1 is valid from the boiling point to the critical point of sodium. Below the boiling point, i.e. 1155 K, the equation of Ditchburn and Gilmour (63) can be used :

$$\begin{aligned} \ln P(\text{ata}) &= 14.631003 - 12818.491/T(\text{K}) \\ &\quad - 0.5 \ln T(\text{K}) \end{aligned} \tag{A.4.2}$$

Representative values of the vapor pressure of sodium are tabulated in Table A.2.

TABLE A.2

The Saturated Vapor Pressure of Sodium

T(K)	P(ATA)	T(K)	P(ATA)
650	0.242E-03	1600	17.67
700	0.952E-03	1650	22.11
750	0.312E-02	1700	27.31
800	0.878E-02	1750	33.31
850	0.219E-01	1800	40.17
900	0.491E-01	1850	47.96
950	0.101	1900	56.71
1000	0.194	1950	66.48
1050	0.348	2000	77.30
1100	0.592	2050	89.21
1150	0.961	2100	102.23
1200	1.479	2150	116.4
1250	2.203	2200	131.7
1300	3.180	2250	148.3
1350	4.466	2300	166.0
1400	6.119	2350	184.9
1450	8.202	2400	205.1
1500	10.778	2450	226.4
1550	13.912	2500	249.0
		2508.7	253.0 (critical point)

APPENDIX V

Saturated Liquid Density Of Sodium

The saturated liquid density of sodium is a necessary property in order to use eq. 6.19, the experimental equation-of-state, to calculate the density of subcooled sodium. However, experimental data are available only to 1355 K, so that reasonable methods of extrapolation are necessary to utilise the above equation to 2300 K, the temperature limit of the equation.

Recently, Bhise and Bonilla (1b,41) were able to apply the principle of "Corresponding States" to predict the saturation densities upto the critical point. The procedure used was as follows :

a) they first used the experimental reduced densities of liquid rubidium (42) to obtain the "best" reduced density correlation for liquid alkali metals. The "best" fit, in the Least Squares sense, was obtained when separate equations were used for the rubidium data below and above $T_r = 0.78$ respectively,

b) the sodium density data of Stone et. al (2), which were all below $T_r = 0.78$, were then substituted into the pertinent equation to obtain the critical density of sodium,

c) utilising the experimentally determined value of the critical temperature (1) and above estimate of the critical density, Bhise and Bonilla (1b,41) were able to predict the saturated liquid densities of sodium between 1355 K and the critical temperature.

The above procedure was also adopted for this investigation. However, the analysis had to be repeated in order to consider the rubidium density data of Tepper et. al. (43) and Achener et. al. (44), and the sodium density data of Hagen (45), Jackson et. al. (46), Ewing et. al. (47) and Rinck (48), which were not used in the analysis of Bhise and Bonilla (1b,41). The best-fit equations obtained thereby are :

$$\rho_L/\rho_c - 1 = 0.9799513 + 2.761335 (1 - T/T_c) \quad (\text{A.5.1})$$

$$\text{for } T/T_c \leq 0.78$$

and,

$$\rho_L/\rho_c - 1 = -2.261627 (1 - T/T_c) + 4.651817 (1 - T/T_c)^{0.53} \quad (\text{A.5.2})$$

for $T/T_c \gg 0.78$

The critical density of sodium, calculated using the new sodium data, is :

$$\rho_c = 0.2141 \text{ g/cc ,}$$

which differs only slightly from the estimate of Bhise and Bonilla (1b,41) but is more reliable since more data are used. As a test of the " goodness " of the above estimate of ρ_c , the standard deviation of eq. A.5.1, when fitting the available sodium data, was determined and found to be only 0.4%, which is better than the reported standard deviation of 0.67% of the three term equation used by Stone, Ewing et. al. (2). In fact, a three term equation does not seem to be justified from the plot of the available sodium density data below 1355 K (Fig. 25).

Equations A.5.1 and A.5.2 are plotted in Fig. 23, together with the plot of the vapor density data obtained earlier. For consistency, the critical temperature estimate of 2508.7 K, derived in Appendix IV, should be used, though only minor differences will be noted if the estimate of Bhise and Bonilla (1b,41) is used.

FIG. 25

Temperature (R)

APPENDIX VI

Correction-Equation To Correct The Observed $\Delta\theta/\Delta P$ Data

As explained in the chapter "Experimental Results and Analysis" (Chapter VI), it was necessary to consider the compressibility of the sodium in the capsule capillary and the capsule side of the valve V2 (Fig. 7) in order to correctly evaluate the experimental $d\theta/dP$ and ρ data. The correction-equation was derived as follows :

Let $\Delta\theta_{\text{obs}}$ be the net compression of the capsule, corresponding to a pressure rise of ΔP . Actually $\Delta\theta_{\text{obs}}$ is the difference between $\Delta\theta$ required to pressurise the whole system and the $\Delta\theta$ required to pressurise the external system only, for the same ΔP (see eq. 3.4).

Since the $\Delta\theta_{\text{obs}}$ consists of the compressions of the bulb, capillary and the capsule side of valve V2 (Fig. 7), we can write :

$$\Delta\theta_{\text{obs}} = \Delta\theta_{\text{bulb}} + \Delta\theta_{\text{cap}} + \Delta\theta_{\text{V2}} \quad (\text{A.6.1})$$

Rearranging, we get :

$$\Delta\theta_{\text{bulb}} = \Delta\theta_{\text{obs}} - \Delta\theta_{\text{cap}} - \Delta\theta_{\text{V2}} \quad (\text{A.6.2})$$

From eqs. 3.8 & 6.4a we get :

$$\Delta\rho_{\text{bulb}} = \Delta\theta_{\text{bulb}} \cdot K/V_{\text{bulb}} \quad (\text{A.6.3})$$

$$\Delta\rho_{\text{obs}} = \Delta\theta_{\text{obs}} \cdot K/V_c \quad (\text{A.6.4})$$

$$\Delta\rho_{\text{cap}} = \Delta\theta_{\text{cap}} \cdot K/V_{\text{cap}} \quad (\text{A.6.5})$$

$$\Delta\rho_{\text{V2}} = \Delta\theta_{\text{V2}} \cdot K/V_{\text{V2}} \quad (\text{A.6.6})$$

where, $K = V_\theta \cdot \rho_T / 360$

Substitution of eqs. A.6.3 - 6 into eq. A.6.2 gives :

$$\Delta\rho_{\text{bulb}} \cdot V_{\text{bulb}} / K = \Delta\rho_{\text{obs}} \cdot V_c / K - \Delta\rho_{\text{cap}} \cdot V_{\text{cap}} / K - \Delta\rho_{\text{V2}} \cdot V_{\text{V2}} / K \quad (\text{A.6.7})$$

Division of eq. A.6.7 by ΔP and rearranging gives :

$$\frac{\Delta\rho_{\text{bulb}}}{\Delta P} = \frac{\Delta\rho_{\text{obs}}}{\Delta P} \cdot \frac{V_c}{V_{\text{bulb}}} - \frac{\Delta\rho_{\text{cap}}}{\Delta P} \cdot \frac{V_{\text{cap}}}{V_{\text{bulb}}} - \frac{\Delta\rho_{\text{V2}}}{\Delta P} \cdot \frac{V_{\text{V2}}}{V_{\text{bulb}}} \quad (\text{A.6.8})$$

For small P 's, eq. A.6.8 can be written in the differential form, i.e. :

$$\begin{aligned} d\rho_{\text{bulb}}/dP = & (d\rho_{\text{obs}}/dP) 1.0526 - (d\rho_{\text{cap}}/dP) 0.0526 \\ & - (d\rho_{V2}/dP) 0.0196 \end{aligned} \quad (\text{A.6.9})$$

where, the volume ratios V_c/V_{bulb} , $V_{\text{cap}}/V_{\text{bulb}}$ and V_{V2}/V_{bulb} have been replaced by their actual numerical values. The correct compressibility is therefore given by $d\rho_{\text{bulb}}/dP$ as calculated from eq. A.6.9.

In the actual calculations, the corrections due to the capillary volume and the volume of $V2$ were combined. The average temperature of sodium in the capillary and $V2$ was assumed as the arithmetic mean of the average capsule and external system temperatures. The $d\rho/dP$ of the sodium in the capillary and $V2$ was then calculated from a best-fit equation correlating the observed $d\rho/dP$ data to observed temperatures and pressures.

APPENDIX VII

Experimental PVT and Vapor Pressure plots
of the preliminary water-test runs.

Appendix VII - P- ρ -T plot for the water test

Appendix VII - Vapor pressure plot from the water test.

APPENDIX VIII

Subcooled Density, β_T , and PV/RT of
Liquid Sodium

TABLE A.8.1

ISOTHERM = 400. K			
ATA	RHD	BETA-T	PV/RT
500.0	C. 9284	C. 1297E-04	0.3772E 00
450.0	C. 9278	C. 1362E-04	0.3397E 00
400.0	C. 9271	C. 1427E-04	0.3022E 00
350.0	C. 9265	C. 1492E-04	0.2646E 00
300.0	C. 9258	C. 1558E-04	0.2270E 00
250.0	C. 9250	C. 1623E-04	0.1893E 00
200.0	C. 9242	C. 1689E-04	0.1516E 00
150.0	C. 9235	C. 1755E-04	0.1138E 00
100.0	C. 9226	C. 1821E-04	0.7592E-01
50.0	C. 9218	C. 1888E-04	0.3799E-01
0.0	C. 9209	C. 1954E-04	0.1039E-11
ISOTHERM = 500. K			
ATA	RHD	BETA-T	PV/RT
500.0	0.9050	0.1251E-04	0.3096E 00
450.0	C. 5044	C. 1340E-04	0.2788E 00
400.0	C. 9038	C. 1428E-04	0.2480E 00
350.0	C. 9031	C. 1517E-04	0.2172E 00
300.0	C. 9024	C. 1606E-04	0.1863E 00
250.0	C. 9016	C. 1695E-04	0.1554E 00
200.0	C. 9009	C. 1784E-04	0.1244E 00
150.0	C. 9000	C. 1874E-04	0.9339E-01
100.0	C. 8992	C. 1964E-04	0.6232E-01
50.0	C. 8983	C. 2054E-04	0.3119E-01
0.0	0.8973	0.2145E-04	0.4636E-09
ISOTHERM = 600. K			
ATA	RHC	BETA-T	PV/RT
500.0	C. 8816	0.1198E-04	0.2648E 00
450.0	C. 8810	C. 1313E-04	0.2385E 00
400.0	C. 8804	C. 1428E-04	0.2122E 00
350.0	C. 8797	C. 1544E-04	0.1858E 00
300.0	C. 8790	C. 1660E-04	0.1594E 00
250.0	C. 8783	C. 1776E-04	0.1329E 00
200.0	C. 8775	C. 1893E-04	0.1064E 00
150.0	C. 8766	C. 2009E-04	0.7990E-01
100.0	C. 8757	C. 2127E-04	0.5332E-01
50.0	C. 8748	C. 2244E-04	0.2669E-01
0.0	0.8738	0.2362E-04	0.2598E-07
ISOTHERM = 700. K			
ATA	RHO	BETA-T	PV/RT
500.0	C. 8816	0.1198E-04	0.2648E 00
450.0	C. 8810	C. 1313E-04	0.2385E 00
400.0	C. 8804	C. 1428E-04	0.2122E 00
350.0	C. 8797	C. 1544E-04	0.1858E 00
300.0	C. 8790	C. 1660E-04	0.1594E 00
250.0	C. 8783	C. 1776E-04	0.1329E 00
200.0	C. 8775	C. 1893E-04	0.1064E 00
150.0	C. 8766	C. 2009E-04	0.7990E-01
100.0	C. 8757	C. 2127E-04	0.5332E-01
50.0	C. 8748	C. 2244E-04	0.2669E-01
0.0	0.8738	0.2362E-04	0.2598E-07

500.0	C.8582	C.1139E-04	0.2332E 00
450.0	0.8577	0.1285E-04	0.2100E 00
400.0	0.8571	C.1431E-04	0.1868E 00
350.0	0.8564	0.1577E-04	0.1636E 00
300.0	C.8557	0.1723E-04	0.1403E 00
250.0	0.8550	C.1870E-04	0.1170E 00
200.0	0.8541	0.2018E-04	0.9372E-01
150.0	0.8532	0.2165E-04	0.7036E-01
100.0	0.8523	0.2314E-04	0.4696E-01
50.0	0.8513	0.2462E-04	0.2351E-01
0.0	C.8502	0.2612E-04	0.4483E-06

ISOTHERM = 800. K

ATA	RHO	BETA-T	PV/RT
500.0	0.8349	C.1078E-04	0.2097E 00
450.0	0.8344	C.1258E-04	0.1889E 00
400.0	0.8338	0.1439E-04	0.1680E 00
350.0	C.8332	C.1620E-04	0.1471E 00
300.0	0.8325	C.1801E-04	0.1262E 00
250.0	0.8317	C.1982E-04	0.1053E 00
200.0	C.8308	C.2165E-04	0.8431E-01
150.0	0.8299	C.2347E-04	0.6330E-01
100.0	0.8289	C.2531E-04	0.4225E-01
50.0	0.8278	C.2715E-04	0.2115E-01
0.0	0.8266	C.2900E-04	0.3723E-05

ISOTHERM = 900. K

ATA	RHO	BETA-T	PV/RT
500.0	C.8116	0.1020E-04	0.1918E 00
450.0	0.8112	0.1239E-04	0.1727E 00
400.0	C.8106	C.1458E-04	0.1536E 00
350.0	C.8100	C.1678E-04	0.1345E 00
300.0	0.8093	C.1898E-04	0.1154E 00
250.0	C.8084	C.2119E-04	0.9627E-01
200.0	0.8075	C.2340E-04	0.7710E-01
150.0	0.8065	0.2562E-04	0.5789E-01
100.0	0.8055	C.2786E-04	0.3865E-01
50.0	C.8043	C.3010E-04	0.1935E-01
0.0	C.8031	C.3235E-04	0.1905E-04

ISOTHERM = 1000. K

ATA	RHO	BETA-T	PV/RT
500.0	0.7885	C.9702E-05	0.1777E 00
450.0	C.7880	0.1232E-04	0.1600E 00
400.0	0.7875	C.1495E-04	0.1423E 00
350.0	0.7868	C.1759E-04	0.1246E 00
300.0	C.7861	0.2023E-04	0.1069E 00
250.0	C.7853	C.2287E-04	0.8920E-01

200.0	0.7843	0.2553E-04	0.7144E-01
150.0	C.7833	0.2820E-04	0.5365E-01
100.0	C.7821	0.3088E-04	0.3582E-01
50.0	0.7808	0.3357E-04	0.1794E-01
0.2	C.7795	C.3626E-04	0.6963E-04

ISOTHERM = 1100. K

ATA	RHO	BETA-T	PV/RT
500.0	0.7654	C.9384E-05	0.1664E 00
450.0	C.7650	0.1249E-04	0.1498E 00
400.0	C.7645	C.1561E-04	0.1333E 00
350.0	C.7638	0.1873E-04	0.1167E 00
300.0	0.7630	0.2186E-04	0.1001E 00
250.0	C.7621	C.2500E-04	0.8355E-01
200.0	0.7611	0.2815E-04	0.6693E-01
150.0	C.7600	0.3131E-04	0.5027E-01
100.0	C.7588	0.3449E-04	0.3357E-01
50.0	0.7574	0.3769E-04	0.1681E-01
0.6	0.7559	0.4087E-04	0.1996E-03

ISOTHERM = 1200. K

ATA	RHO	BETA-T	PV/RT
500.0	0.7425	0.9371E-05	0.1572E 00
450.0	0.7421	C.1302E-04	0.1416E 00
400.0	C.7416	0.1668E-04	0.1259E 00
350.0	0.7409	C.2034E-04	0.1103E 00
300.0	C.7401	0.2402E-04	0.9464E-01
250.0	C.7391	C.2771E-04	0.7897E-01
200.0	0.7380	C.3141E-04	0.6327E-01
150.0	C.7368	C.3514E-04	0.4753E-01
100.0	0.7354	0.3888E-04	0.3175E-01
50.0	0.7339	C.4264E-04	0.1591E-01
1.5	C.7324	C.4632E-04	0.4717E-03

ISOTHERM = 1300. K

ATA	RHO	BETA-T	PV/RT
500.0	0.7198	0.9845E-05	0.1497E 00
450.0	0.7194	0.1410E-04	0.1348E 00
400.0	C.7188	C.1836E-04	0.1199E 00
350.0	0.7181	C.2263E-04	0.1050E 00
300.0	C.7172	C.2691E-04	0.9015E-01
250.0	C.7162	C.3122E-04	0.7523E-01
200.0	C.7150	0.3554E-04	0.6029E-01
150.0	C.7136	C.3989E-04	0.4530E-01
100.0	C.7121	0.4426E-04	0.3026E-01
50.0	0.7105	C.4866E-04	0.1517E-01
3.2	C.7088	C.5281E-04	0.9669E-03

ISOTHERM = 1400. K

ATA	RHO	BETA-T	PV/RT
500.0	0.6974	0.1107E-04	0.1435E 00
450.0	0.6969	0.1599E-04	0.1292E 00
400.0	0.6963	0.2092E-04	0.1150E 00
350.0	0.6954	0.2586E-04	0.1007E 00
300.0	0.6945	0.3083E-04	0.8645E-01
250.0	0.6933	0.3582E-04	0.7216E-01
200.0	0.6920	0.4083E-04	0.5784E-01
150.0	0.6905	0.4588E-04	0.4347E-01
100.0	0.6888	0.5096E-04	0.2905E-01
50.0	0.6870	0.5608E-04	0.1457E-01
6.1	0.6852	0.6060E-04	0.1787E-02

ISOTHERM = 1500. K

ATA	RHO	BETA-T	PV/RT
500.0	0.6752	0.1342E-04	0.1383E 00
450.0	0.6747	0.1908E-04	0.1246E 00
400.0	0.6739	0.2476E-04	0.1109E 00
350.0	0.6730	0.3045E-04	0.9714E-01
300.0	0.6719	0.3617E-04	0.8340E-01
250.0	0.6706	0.4192E-04	0.6964E-01
200.0	0.6691	0.4772E-04	0.5583E-01
150.0	0.6674	0.5355E-04	0.4198E-01
100.0	0.6655	0.5943E-04	0.2807E-01
50.0	0.6634	0.6536E-04	0.1408E-01
10.8	0.6616	0.7005E-04	0.3043E-02

ISOTHERM = 1600. K

ATA	RHO	BETA-T	PV/RT
500.0	0.6534	0.1748E-04	0.1340E 00
450.0	0.6527	0.2396E-04	0.1207E 00
400.0	0.6518	0.3046E-04	0.1075E 00
350.0	0.6507	0.3699E-04	0.9418E-01
300.0	0.6494	0.4356E-04	0.8089E-01
250.0	0.6479	0.5017E-04	0.6757E-01
200.0	0.6462	0.5684E-04	0.5420E-01
150.0	0.6442	0.6355E-04	0.4077E-01
100.0	0.6421	0.7034E-04	0.2727E-01
50.0	0.6397	0.7719E-04	0.1369E-01
17.7	0.6381	0.8166E-04	0.4849E-02

ISOTHERM = 1700. K

ATA	RHO	BETA-T	PV/RT
500.0	0.6321	0.2411E-04	0.1304E 00
450.0	0.6312	0.3151E-04	0.1175E 00
400.0	0.6301	0.3893E-04	0.1046E 00

350.0	C.6288	C.4640E-04	0.9174E-01
300.0	0.6272	C.5392E-04	0.7883E-01
250.0	C.6254	C.6150E-04	0.6588E-01
200.0	0.6233	C.6915E-04	0.5288E-01
150.0	C.6211	C.7688E-04	0.3980E-01
100.0	0.6186	C.8470E-04	0.2664E-01
50.0	C.6158	C.9262E-04	0.1338E-01
27.3	C.6145	0.9625E-04	0.7323E-02

ISOTHERM = 1800. K

ATA	RHC	BETA-T	PV/RT
500.0	0.6115	C.3473E-04	0.1273E 00
450.0	0.6103	0.4314E-04	0.1148E 00
400.0	C.6088	0.5160E-04	0.1023E 00
350.0	0.6071	C.6013E-04	0.8973E-01
300.0	0.6052	C.6873E-04	0.7716E-01
250.0	0.6030	C.7742E-04	0.6453E-01
200.0	C.6005	C.8622E-04	0.5184E-01
150.0	C.5978	C.9512E-04	0.3906E-01
100.0	0.5948	0.1042E-03	0.2617E-01
50.0	0.5916	0.1133E-03	0.1315E-01
40.2	C.5909	C.1151E-03	0.1058E-01

ISOTHERM = 1900. K

ATA	RHO	BETA-T	PV/RT
500.0	C.5918	C.5167E-04	0.1246E 00
450.0	0.5902	C.6123E-04	0.1124E 00
400.0	C.5882	C.7087E-04	0.1003E 00
350.0	C.5860	C.8062E-04	0.8807E-01
300.0	C.5835	C.9048E-04	0.7581E-01
250.0	C.5807	C.1005E-03	0.6348E-01
200.0	0.5777	C.1106E-03	0.5105E-01
150.0	C.5743	C.1209E-03	0.3851E-01
100.0	C.5707	C.1314E-03	0.2584E-01
56.7	0.5674	C.1407E-03	0.1474E-01

ISOTHERM = 2000. K

ATA	RHO	BETA-T	PV/RT
500.0	0.5734	C.7911E-04	0.1221E 00
450.0	C.5710	C.9002E-04	0.1104E 00
400.0	0.5683	C.1011E-03	0.9860E-01
350.0	C.5653	C.1123E-03	0.8674E-01
300.0	C.5619	C.1237E-03	0.7479E-01
250.0	C.5583	C.1353E-03	0.6273E-01
200.0	0.5544	C.1472E-03	0.5054E-01
150.0	C.5501	C.1593E-03	0.3819E-01
100.0	C.5456	C.1717E-03	0.2567E-01
77.3	C.5435	C.1774E-03	0.1992E-01

ISCTHERM = 2100. K

ATA	RHO	BETA-T	PV/RT
500.0	0.5540	0.1259E-03	0.1204E 00
450.0	0.5504	0.1386E-03	0.1091E 00
400.0	0.5464	0.1516E-03	0.9767E-01
350.0	0.5421	0.1648E-03	0.8614E-01
300.0	0.5375	0.1784E-03	0.7447E-01
250.0	0.5325	0.1924E-03	0.6264E-01
200.0	0.5272	0.2067E-03	0.5061E-01
150.0	0.5216	0.2215E-03	0.3837E-01
102.2	0.5159	0.2360E-03	0.2644E-01

ISOTHERM = 2200. K

ATA	RHO	BETA-T	PV/RT
500.0	0.5339	0.2121E-03	0.1193E 00
450.0	0.5281	0.2278E-03	0.1085E 00
400.0	0.5219	0.2440E-03	0.9761E-01
350.0	0.5153	0.2608E-03	0.8649E-01
300.0	0.5084	0.2782E-03	0.7514E-01
250.0	0.5012	0.2964E-03	0.6353E-01
200.0	0.4936	0.3152E-03	0.5160E-01
150.0	0.4856	0.3349E-03	0.3934E-01
131.7	0.4826	0.3424E-03	0.3476E-01

ISOTHERM = 2300. K

ATA	RHO	BETA-T	PV/RT
500.0	0.5169	0.3938E-03	0.1178E 00
450.0	0.5066	0.4169E-03	0.1082E 00
400.0	0.4958	0.4413E-03	0.9827E-01
350.0	0.4847	0.4671E-03	0.8796E-01
300.0	0.4732	0.4945E-03	0.7723E-01
250.0	0.4613	0.5238E-03	0.6602E-01
200.0	0.4490	0.5550E-03	0.5426E-01
166.0	0.4404	0.5775E-03	0.4591E-01

ISCTHERM = 2400. K

ATA	RHO	BETA-T	PV/RT
500.0	0.5278	0.8922E-03	0.1106E 00
450.0	0.5040	0.9504E-03	0.1042E 00
400.0	0.4799	0.1015E-02	0.9730E-01
350.0	0.4553	0.1088E-02	0.8973E-01
300.0	0.4303	0.1170E-02	0.8138E-01
250.0	0.4050	0.1264E-02	0.7207E-01
205.1	0.3818	0.1359E-02	0.6270E-01

ISOTHERM = 2500. K

ATA	R+Q	BETA-T	PV/RT
500.0	2.0300	0.3459E-02	0.2760E-01
450.0	1.6787	0.4189E-02	0.3004E-01
400.0	1.3269	0.5306E-02	0.3378E-01
350.0	0.9746	0.7233E-02	0.4024E-01
300.0	0.6220	0.1135E-01	0.5406E-01
250.0	0.2689	0.2628E-01	0.1042E 00
249.0	0.2619	0.2698E-01	0.1065E 00

APPENDIX IX NOMENCLATURE

α_s, α_{sat}	=	Thermal expansion coefficient at saturation (K^{-1})
α_p	=	Isobaric thermal expansion coefficient (K^{-1})
β_s	=	Adiabatic compressibility (ata^{-1})
β_T	=	Isothermal compressibility (ata^{-1})
$(\beta_T)_{sat}$	=	Isothermal compressibility at saturation (ata^{-1})
γ_{sat}	=	Temperature derivative of the vapor pressure equation (ata/K)
γ_V	=	Isochoric thermal pressure coefficient (ata/K)
ρ_L	=	Liquid density (g/cc)
$\rho_s, \rho_{L,sat}$	=	Saturated liquid density (g/cc)
$\rho_v, \rho_{v,sat}$	=	Saturated vapor density (g/cc)
P	=	Pressure (ata)
P_s, P_{sat}	=	Saturated vapor pressure (ata)
T	=	Temperature
P_c, T_c, ρ_c	=	Critical pressure, temperature and density
V_c	=	Capsule volume
T_r	=	Reduced temperature, T/T_c
ΔT	=	Small change in temperature
	=	" " " density
ΔP	=	" " " pressure
ΔV	=	" " " volume
$\Delta \theta$	=	" " " position of the injector stem as measured by the attached protractor

(The subscript 'c' has been alternately used to denote either the 'capsule' or the 'critical point'. The particular usage is made clear in the appropriate context)

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