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DENSITY MEASUREMENTS FOR NEON
AT LOW TEMPERATURES

Leon Rouzelle Scott

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ABSTRACT

The density of pure neon was measured at 154 points over the range from 28°K to 70°K for pressures up to 240 atmospheres.

This data was taken in such a way that nineteen isochores comprising fifteen isothermal lines were generated. The data thus fills the gap in previously published data around the vapor dome and near the critical point. This data is the only experimental data available around the vapor dome and in the compressed liquid region for neon.

The data was obtained using a constant volume system which was constructed for this purpose. The test cell in which measurements were made was within an evacuated chamber in a liquid hydrogen bath. The cell was electrically heated for temperature control. The pressures were measured with a dead weight gage. A precision platinum resistance thermometer in conjunction with a Mueller Bridge was used for temperature measurements. Volumes were measured by two different methods: a Burnett type expansion, and a volume measuring device constructed as a part of this project. Mass measurements were made using a second group of temperature, pressure, and volume measurements for a multiple expansion process. This process was developed for this purpose.

The majority of the resultant data from these measurements is within an estimated 0.2 percent of the true values, based on an error analysis of the system and equations used.

The data obtained in this study agrees well with other experimental data where there is overlap in the ranges covered. In general, this data is between the extremes from the other data.

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NOMENCLATURE

Symbols

A	gravitational anomaly
A_{eff}	effective area of dead weight gage piston
B	coefficient in compressibility expansion
g_f	local acceleration of gravity calculated by formula
g_m	measured local acceleration of gravity
m	mass of gas in system
M_i	apparent weight of dead weight gage weight at standard gravity
M_p	apparent weight of dead weight gage piston and weight pan at standard gravity
M_{wt}	weight of small weights used to balance air piston gage
P	pressure
P_{bar}	pressure on weight side of pressure gage (psi)
P_{oil}	pressure due to oil head on dead weight gage (psi)
P_{nom}	uncorrected or nominal gage pressure (psi)
P_{wt}	pressure equivalent of small weights used with dead weight gage
R	gas constant for neon
T	temperature
V	total volume
Z	compressibility

Subscripts

a	expansion tank one
b	expansion tank two

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c	critical conditions
critical	critical conditions
g	pressure gage
i	summation index for various locations
1	original condition
2	condition after one expansion
3	condition after two expansions
o	test cell

Double subscripts: first subscript refers to location, the second to condition.

CHAPTER I

INTRODUCTION

Neon is one of the inert gases found only in the atmosphere. Atmospheric air consists of about 18 parts per million of neon. Because of its low concentration in the air, it has been considered one of the "rare" gases. Until commercial liquefaction of air became a large scale operation, the production of neon was limited to very extensive laboratory separations to obtain a relatively small amount of neon. Now neon is far more widely available and is being used for a number of applications. Among these is the growing use of liquefied neon as a cryogenic fluid to partially fill the temperature gap between liquid hydrogen and liquid oxygen. The temperatures obtainable with liquid neon would be from about 25°K to about 40°K. In the range of overlap with hydrogen, neon has the advantage of a much greater heat of vaporization, and the fact that neon is chemically inert is also an important advantage as a cryogenic fluid. As neon becomes more readily available in large quantities, and as more is determined about its properties, more uses will undoubtedly arise.

Compared to most other gases, very little is known of the properties of neon. This is probably due largely to the general lack of availability of neon in past years.

This work presents measurements of the density of neon in the range from 28 to 70° Kelvin, over a pressure range up to 240 atmospheres.

This region includes the vapor region for this substance. The primary emphasis is the determination of the pressure-specific volume-temperature surface in the region near the critical point where no other data is available for this substance.

CHAPTER II

PUBLISHED THERMODYNAMIC PROPERTIES OF NEON

1. INTRODUCTION

Of the thermodynamic properties of neon, several are of particular interest in this study. These include: measured densities as a function of temperature and pressure; liquid-vapor vapor pressure curve; critical point data; and correlations and equations of state for neon. The interest in the measured density is of primary concern in this work. The interest in the liquid-vapor vapor pressure curve is twofold, serving as a lower limit for each isochore and also providing a check of the accuracy of temperature and pressure measurements.

The data covered herein covers all measurements of the types mentioned above for neon, whether or not they have application in the range of interest of this study.

2. P-V-T MEASUREMENTS OF NEON

The first measurements of the density of neon were made by Ramsey and Travers (33)¹ in 1906. These were the men who were responsible for the discovery and early separation processes for neon. Burt (6) in 1910 measured the density of neon over a somewhat wider pressure range at 0°C. These works were of limited usefulness and poor accuracy, par-

¹Numbers in parenthesis refer to References.

tially because of the small neon samples which they had available.

In 1915 at Leiden, H. Kamerlingh Onnes and C. A. Crommelin (30) made the first major measurements of the density of neon, covering the range from 55°K to 293°K at 22 to 93 atm. pressure. This work was supplemented in 1919 by additional measurements over the same range by Crommelin, Martinez and Onnes (11). Then in 1922 at the same laboratory, Mathias, Crommelin and Onnes (21) measured the density of the saturated liquid and vapor, and determined the critical density by the method of rectilinear diameters.

The only other determination of liquid densities was an earlier determination of two liquid points given in reference 30.

Soon after the work at Leiden, other laboratories began measurements of the density of neon. Holborn and Otto (17) at Berlin published data in 1925 covering the range from 90°K to 673°K from 20 to 100 atm. In 1926 (18), they added a 65°K isotherm over the same range of pressures.

Michels and Gibson (25) presented data in 1928 for five isotherms from 0 to 100°C at 30 to 500 atm.

Also in 1928, Baxter and Starkweather (3) made measurements of the density of neon at low pressures and 0°C. Their main interest was the determination of the molecular weight and normal volume, however. LeDuce (20) had done much the same thing in 1918, attempting to determine the same properties.

Heuse and Otto (15) used P-v-T measurements of neon at low pressures to determine the zero of the thermodynamic temperature scale in 1929. These density measurements were limited to 0°C, however.

No additional P-v-T work was done on neon for the next twenty

years until two low pressure isotherms at 0°C and 20°C were measured by Oiski (28).

In 1955 Nicholson and Schneider (27) at the National Research Council in Canada measured a series of high temperature isotherms using the Burnett method. These tests covered the range from 0°C to 700°C and 10 to 80 atm.

In 1960 Michels, Wassenaar and Louwerse (26) at the Van der Waals Laboratory in Amsterdam, Netherlands, published data covering the range from 0°C to 150°C and pressures up to 2900 atm.

Research on neon at the University of Michigan was begun by Sullivan (37). He published four isotherms from 70°K to 120°K at pressures up to 300 atm. His work also used a Burnett method.

The ranges of the data listed above is summarized in Figure 1. This figure also shows the need for more data to accurately define the P-v-T surface for neon at low temperatures.

The validity of the data mentioned above is primarily a function of the time at which it was taken, the older data in general being the least reliable. Plots of the second virial coefficient by Schneider, Sullivan and others show considerable scatter in the early work. The lack of accuracy in pressure and temperature measurements as well as neon purity are probable reasons for the discrepancies.

3. VAPOR PRESSURES OF NEON

The vapor pressure of liquid neon was first measured by Cath and H. Kamerlingh Onnes (7) in 1918. This measurement was plagued by impurities in the neon. Crommelin and Gibson (10) measured the vapor pressure of both solid and liquid in 1927 using the same equipment used by

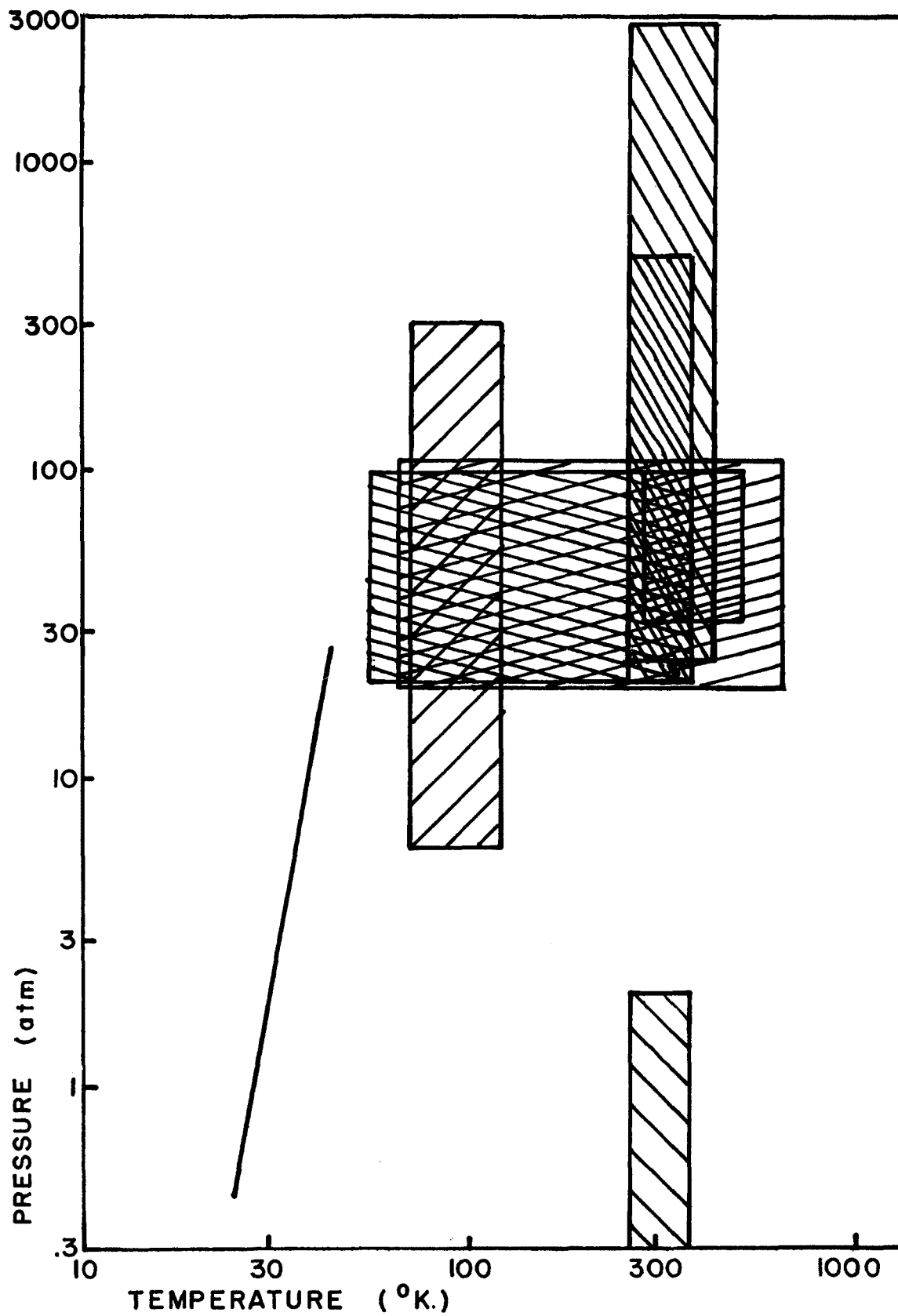


Figure 1. Range of Published Density Measurements for Neon.

Cath. This work was continued at Leiden in 1928 by Verschaffelt (39), who presented data for both liquid and solid neon.

Clusius (8) presented data on the vapor pressure in 1929 for both the liquid and solid as a part of his determination of the specific heats of neon.

Keesom and Haantjes (19) continued the work on vapor pressure at Leiden in 1935.

The effect of isotopic content on the vapor pressure and the triple point was measured in 1960 by Boato, Casanova, and Vallauri (5). The work was extended further by Roth and Bigeleisen (34,35) in 1960 and 1961.

In 1962 Grilly (13) published work on the vapor pressure of liquid and solid neon for the normal isotopic content. He provided the following equation for the liquid:

$$\begin{aligned} \log_{10} P = 7.46116 - 106.090 T^{-1} - 3.56616 \times 10^{-2} T \\ + 4.11092 \times 10^{-4} T^2 \end{aligned} \quad \text{eq. (1)}$$

for P in mmHg and T in degrees Kelvin.

The work of Grilly agrees with the earlier vapor pressure measurements but apparently has much less scatter.

4. CRITICAL POINT

As with the other measurements on neon, the critical point was first determined at Leiden in 1909 by Onnes (29). A more accurate determination was made later by Onnes, et al., (31). This was later modified at Leiden by Crommelin (9).

The most recent and probably the most accurate determination was

that of Grilly (13) in 1962. Table 1 summarizes the measurements of critical temperature and pressure.

These measurements all used the disappearance of the meniscus as the means of determining the critical point.

TABLE 1
PUBLISHED CRITICAL PROPERTIES OF NEON

Investigator	Critical Temperature	Critical Pressure	Critical Density
Onnes (29)	----	26 atm	----
Onnes, et al. (31)	44.74°K	26.86 atm	----
Crommelin (9)	44.38°K	26.86 atm	----
Grilly (13)	44.40 ± 0.02°K	26.193 ± 0.066 atm	----
Mathias (21)	----	----	0.4835 g/cc

5. EQUATIONS OF STATE

A large number of empirical and semi-empirical equations of state have been used to interpolate and extrapolate the existing data on neon. These equations and methods have met with varying degrees of success depending on the ranges of application.

Beattie and Bridgeman (4) were able to fit their equation to give an average deviation of 0.21 percent in density for the 229 points of the Leiden and Berlin data. It should be noted that this is limited to low and moderate densities as are all the data available for neon (except

the saturated liquid data which was not used in this correlation).

Yendall (41) attempted to fit a modified Beattie-Bridgeman equation (having seven constants) but was not able to get as good a fit as when using a modified Benedict-Webb-Rubin equation (with 12 coefficients). With the latter equation he was able to obtain a fit with an average deviation of 0.19 percent for the 102 Leiden points. Yendall used his equation to prepare tables of neon properties.

A number of corresponding states correlations have been attempted with neon. Hamrin and Thodos (14) showed in their work on the rare gases that argon, xenon, and krypton would correlate on the same graph. Neon, helium, and hydrogen would neither correlate well with one another nor with the heavier gases. This is in spite of the fact that neon, helium, and hydrogen have the same critical compressibility. The reason for their not correlating is the fact that with these three gases the quantum effects are still appreciable. DeBoer and Michels (12) "quantum mechanical parameter", which is a measure of the importance of quantum effects, is 2.74 for helium, 1.80 for hydrogen, 0.58 for neon, and 0.18 for argon with the other gases being still lower. Therefore, one would not expect very good results from a corresponding states correlation for neon.

The virial equation of state, which was used at first as only a correlating empirical equation, can be derived from statistical thermodynamics. This equation has been derived and the second virial coefficients, including quantum effects, evaluated for several molecular force potentials. Empirical data is needed in the analysis to provide data on the forces between molecules. The method has been to use empirical second virial coefficient data to evaluate the parameters in a molecular

force potential such as the Lennard-Jones 6-12 potential. These potential parameters have been evaluated by a number of investigators and show comparatively little scatter (see 27, 37).

The problem with the use of the virial equation is that it is valid only for low densities in finite form--as the density of the liquid is approached the virial equation no longer converges. Therefore, it is necessary to utilize an empirical relation to cover the moderate and high density conditions.

McCarty and Stewart (22, 23, 24) at the National Bureau of Standards Cryogenic Engineering Laboratory expanded on the work of Yendall and extended the tables produced well into the liquid region. Their method was to use existing measured data (with some corrections and deletions) and a corresponding states relation based on nitrogen and argon. This data was then fit with an eighteen constant equation which was a modified Strohbridge equation, of the general form of the equation used by Yendall, with an added exponential multiplier. The tables produced by this work cover the range from 25°K to 300°K and pressures to 200 atm, including the compressed liquid range. They are probably the best tabular data available although their accuracy may be questionable. The authors estimate that the density values are within 2 percent over the entire range. This applies only to reference 23, according to the authors.

CHAPTER III

COMPARISON OF METHODS FOR P-V-T MEASUREMENTS

1. INTRODUCTION

There are basically two methods of obtaining specific volume data for gases: (a) direct weighing of a known volume of gas at a known temperature and pressure, and (b) extrapolation of density to zero pressure. The first method was that used by early investigators and resulted in the determination of the numerical value for the normal volume and molecular weight. The latter value is assumed known in all methods which use the second type of specific volume determination. There are several specific ways to utilize the second method of measuring specific volume. These would be: (a) Burnett method, (b) piezometer method, and (c) final expansion method.

2. DIRECT WEIGHING

A volume is mounted on an analytical type, high precision balance. The system is calibrated with oxygen or other known gases to correct for pressure, thermal expansion, etc. The entire system must be in an evacuated chamber to avoid buoyancy effects, and at the desired temperature. A modification of this type of system that has been used is to weigh the gas and then transfer it into the measuring vessel.

3. BURNETT METHOD

The Burnett method consists of a series of isothermal expansions between two tanks, the same one of the two tanks having been evacuated between successive expansions. The initial pressure in the tanks is high, but after a number of expansions the pressure is reduced to where the successive pressures become linear with pressure. Using the method of Sullivan (37), an extrapolation to zero pressure yields all needed information about the system and gas.

This method has several advantages: (a) it is probably the fastest method available, (b) no mass measurements nor precision volume measurements need be made, and (c) temperature expansion corrections are automatically made.

Basically this method has the inherent disadvantage that it is not applicable to a temperature much below the critical temperature of the substance being tested. Further, application to cryogenic temperatures produces problems with locating valves in the cold region of the system, and the large differences in heat load to any temperature control system during the expansion between tanks and during the evacuation of the expansion tank. Not being able to select the pressures desired for testing and having most of the data at low pressures are also limitations of this method.

4. PIEZOMETER METHOD

The piezometer method consists of measuring the mass of a gas sample by a series of compressions by displacing the gas with a liquid (mercury). The gas sample is then forced into the test chamber where

measurements of temperature, pressure, and volume are made. This method is straight forward and has only the disadvantage that the system arrangement is dictated by the filling fluid. The pressure measuring and separating equipment available for the tests discussed herein would not allow such a filling operation without a great deal of noxious volume devoted to mercury traps.

5. FINAL EXPANSION METHOD

The final expansion method is essentially the same as the piezometer method except that the mass is measured after the tests. This allows an evacuation to take the place of a mercury fill.

6. METHOD SELECTION

The advantages and disadvantages listed above are applicable to the range of tests of interest in this test program and to the instrumentation available for these tests. The final expansion method was selected for these tests on the basis of the advantages and disadvantages listed above.

CHAPTER IV

DESCRIPTION OF EQUIPMENT

1. THEORY OF MASS DETERMINATION

The following technique was developed to determine the mass in the system: The test cell of known volume was filled with neon and brought to the desired temperature, at which time the pressure was measured. A relation for the mass of the system could now be written:

$$m = \frac{P_{o1}V_o}{Z_{o1}RT_{o1}} + \sum_i \frac{P_{i1}V_i}{Z_{i1}RT_{i1}} \quad \text{eq. (2)}$$

where m is the mass, P is the pressure, R is the gas constant for neon, V is the volume, T is the temperature, and Z is the compressibility. The pressures are subscripted differently to allow for the possibility of different pressures in the system at various locations due to elevation changes, etc.

The summation represents the small noxious volumes used for system control, etc., which are not at the control temperature.

The gas was then expanded into an evacuated expansion tank and the pressures and temperatures again measured. Again we may write:

$$m = \frac{P_{o2}V_{o2}}{Z_{o2}RT_{o2}} + \frac{P_{a2}V_a}{Z_{a2}RT_{a2}} + \sum_i \frac{P_{i2}V_i}{Z_{i2}RT_{i2}} \quad \text{eq. (3)}$$

After an expansion into a second evacuated expansion tank we may

write:

$$m = \frac{P_{o3}V_{o3}}{Z_{o3}RT_{o3}} + \frac{P_{a3}V_a}{Z_{a3}RT_{a3}} + \frac{P_{b3}V_b}{Z_{b3}RT_{b3}} + \sum_i \frac{P_{i3}V_i}{Z_{i3}RT_{i3}} \quad \text{eq. (4)}$$

In general, in the above relations, m , Z_{o1} , Z_{o2} , Z_{o3} , Z_{a2} , Z_{a3} , Z_{b3} , Z_{i1} , Z_{i2} , and Z_{i3} are unknown. Some of these variables can be eliminated as follows: Z_{i1} , Z_{i2} , and Z_{i3} can be obtained from published data. This is justifiable even if the published values are inaccurate because the total term is very small. If $T_{o2}=T_{o3} \gg T_{\text{critical}}$ and if $P_{o2}/P_{\text{critical}} \gg 1.0$, then we may write:

$$Z_{o2} = (Z_{o3} - 1) \frac{P_{o2}}{P_{o3}} + 1 \quad \text{eq. (5)}$$

A similar relation could be written for the compressibilities in the expansion tanks if their temperatures were the same. This would leave one more equation required to evaluate the unknowns listed above. This could be obtained by another expansion or by knowing the compressibilities at the tank temperature. The latter method was selected in this case.

Equations 3, 4, and 5 may then be solved to give:

$$Z_{o3} = 1 - \frac{P_{o3}}{P_{o2}} + \frac{1}{2S} \left(\frac{V_{o3}}{T_{o3}} - \frac{V_{o2}}{T_{o2}} \right) + \left\{ \left[1 - \frac{P_{o3}}{P_{o2}} + \frac{1}{2S} \left(\frac{V_{o3}}{T_{o3}} - \frac{V_{o2}}{T_{o2}} \right) \right]^2 - \frac{V_{o2}}{ST_{o2}} \left(1 - \frac{P_{o3}}{P_{o2}} \right) \right\}^{\frac{1}{2}} \quad \text{eq. (6)}$$

where:

$$S = \frac{1}{P_{o3}} \left(\sum_i \frac{V_i P_{i2}}{T_{i2} Z_{i2}} + \frac{V_a P_{a2}}{Z_{a2} T_{a2}} \right) - \frac{1}{P_{o3}} \left(\frac{V_a P_{a3}}{Z_{a3} T_{a3}} + \frac{V_b P_{b3}}{Z_{b3} T_{b3}} + \sum_i \frac{V_i P_{i3}}{Z_{i3} T_{i3}} \right) \quad \text{eq. (7)}$$

It should be noted that the solution is independent of equation 2 and can, therefore, be used for several points having constant total mass.

The assumptions given above also provide an additional means of measuring mass. If the expansion tanks are filled with gas, the mass can then be calculated directly from the known properties at the condition of the tanks. This latter method measures only the mass in the tanks while the former method measures the mass in the cell and in the tanks.

2. OVERALL SYSTEM

The methods described above were applied by placing the two expansion tanks in an oil bath at a temperature just above room temperature. The measurement volume is placed in a cryostat at a controlled condition.

The apparatus used to measure the specific volume of neon is shown in block diagram form in Figure 2. The system used a liquid hydrogen cryostat with a liquid nitrogen shield. An evacuated test package was located in the hydrogen bath. Within the test package was an electrically heated test cell in which the neon was placed for the measurements. Pressure (DWG system) and temperature measurement systems were included in the apparatus. A temperature controller was used to control the heat input to the test cell to maintain it at the desired temperature. Means were provided to balance the pressures within the test

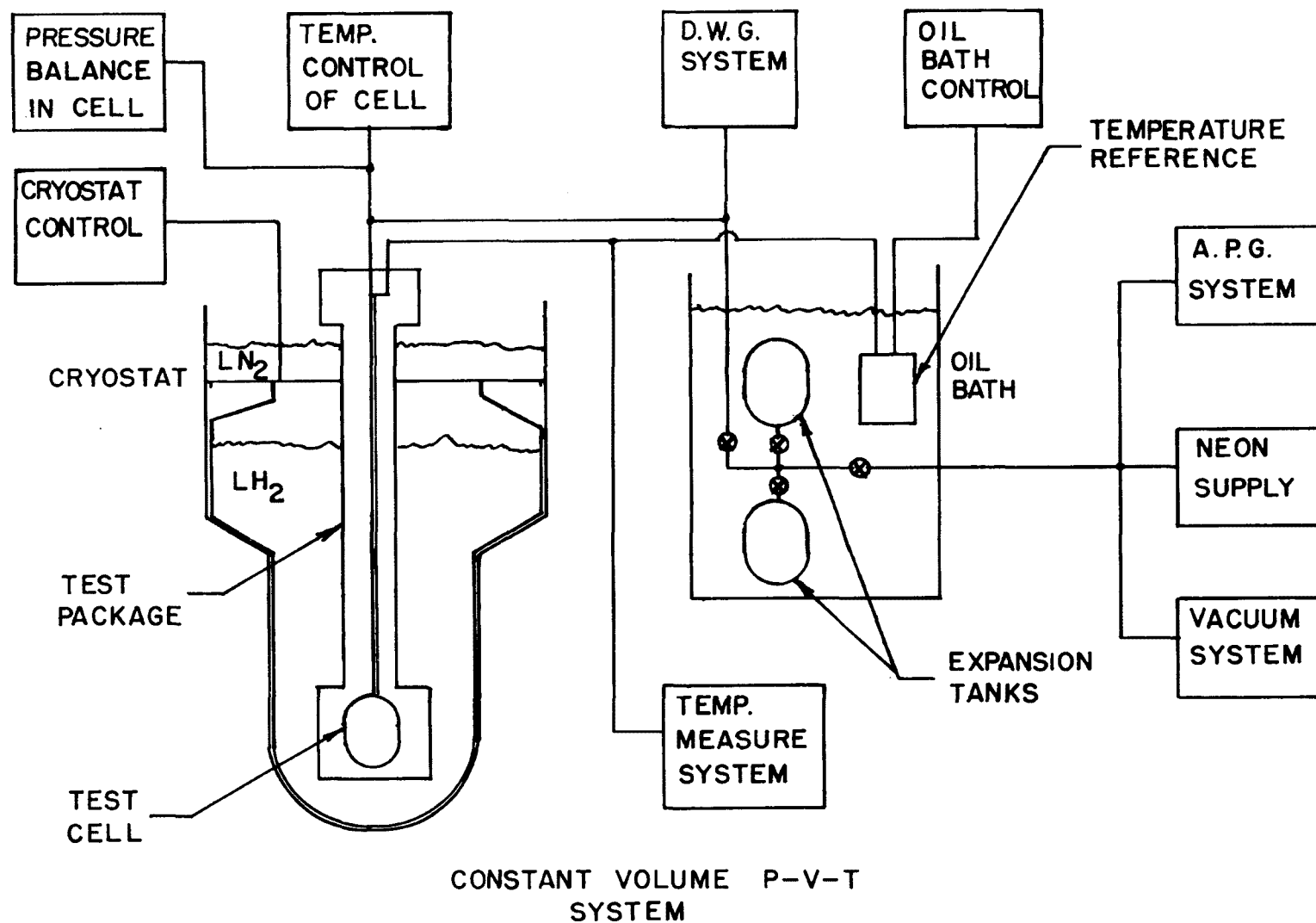


Figure 2. Constant Volume System for Density Measurements.

cell to eliminate changes in the volume of the cell due to pressure.

Two additional tanks of known volume were placed in the temperature controlled oil bath and were used in measuring the mass of gas in the system after a test in accordance with the two methods given above. These tanks used an independent pressure measuring system (APG system) and part of the same temperature measuring system. The oil bath contained a copper reference temperature block which was used as a reference for several systems. A neon supply system and a vacuum system were also attached to the tanks in the oil bath. Figure 3 is an overall view of the main control panel used in conjunction with this system.

Each of these systems will be described in detail in the following sections.

3. CRYOSTAT SYSTEM

The cryostat and cryostat control system is shown schematically in Figure 4. The cryostat was constructed of stainless steel and had the vacuum space filled with multilayer Linde Super Insulation. Being constructed primarily for use with hydrogen which has a low heat of vaporization and density, the cryostat has a large reservoir at the top to provide long operation times without refilling. The narrow region at the bottom permitted maximum utilization of the hydrogen liquid. Operation times in excess of 70 hours per fill could be obtained with this unit with the heat loads imposed by the overall system discussed herein. The total internal volume of the cryostat was about 75 liters.

The top of the cryostat contained a liquid nitrogen guard bath to limit heat conduction down the system to the hydrogen.

The cryostat itself was the one designed and used by Sullivan(37).

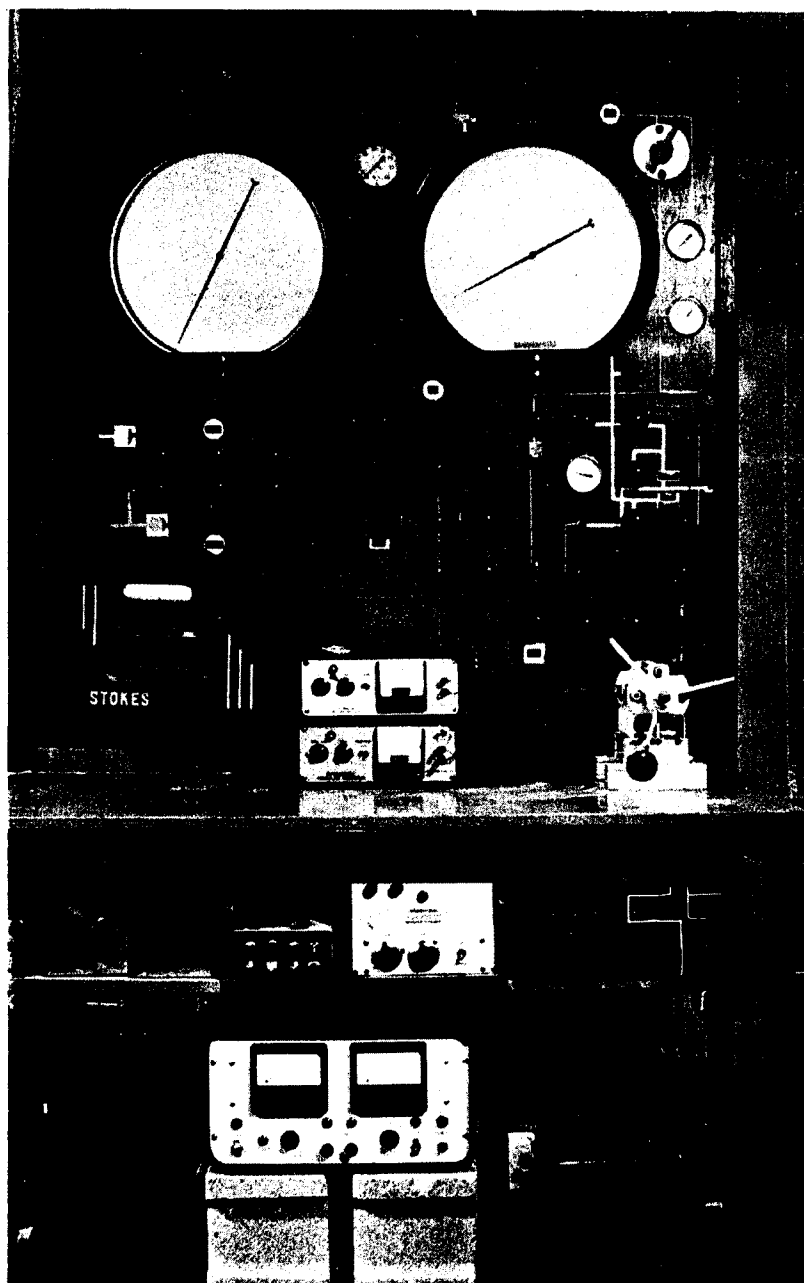


Figure 3. Overall View of the Main Control Panel.

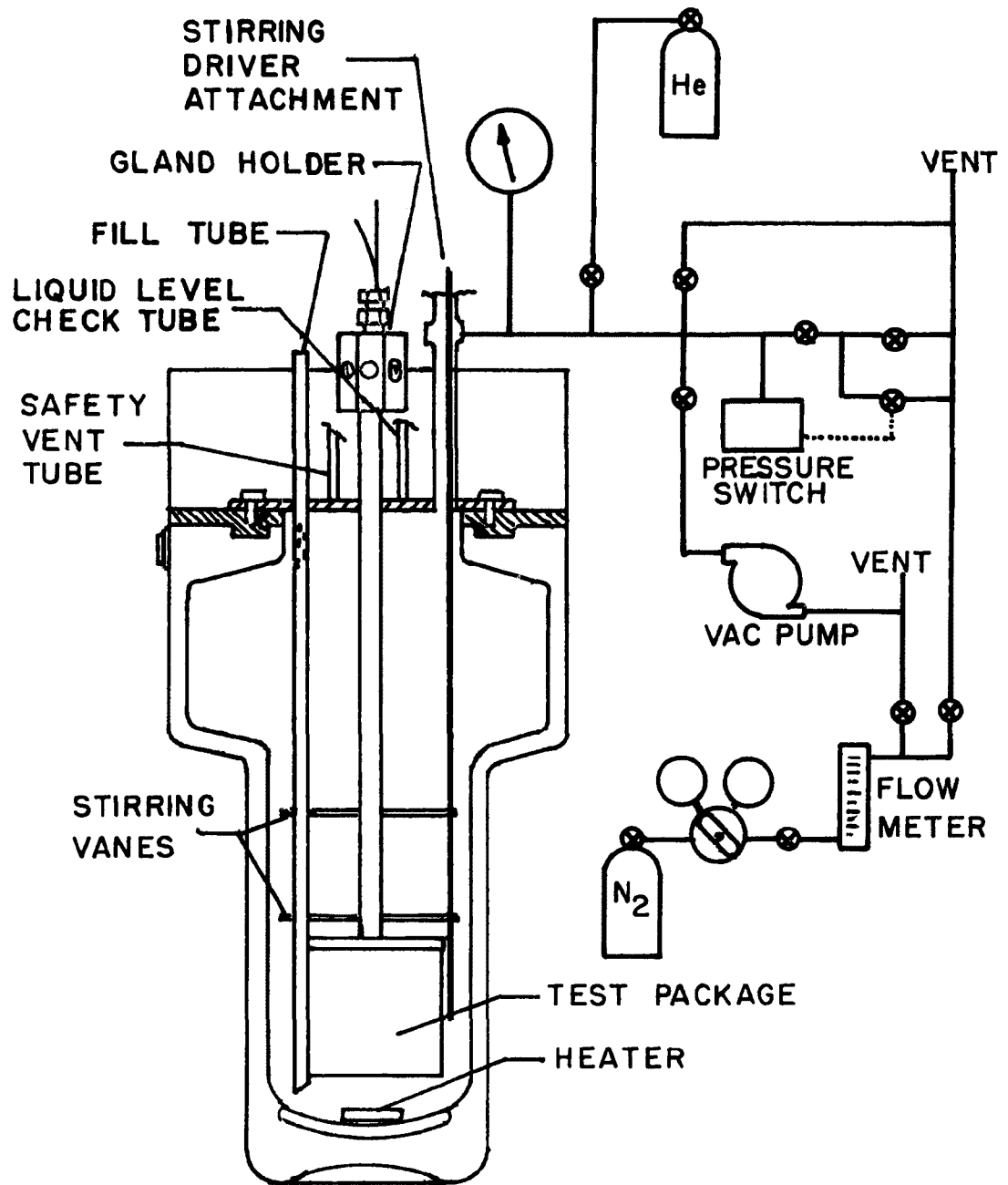


Figure 4. Cryostat and Cryostat Control System.

The cover plate was modified, however, to accomodate the new test package. All other parts of the working system were new.

Also shown in Figure 4 is the control system schematic used to purge, fill, and control pressures in the cryostat. The automatic pressure control regulated the pressure to within ± 0.05 psi. The valve in parallel with the solenoid valve, as well as the valve in series with both, was used to adjust the effect of the solenoid to obtain good stability of the control system. The vacuum pump and the helium supply were used for purging the system before filling with hydrogen. Nitrogen was used to purge the vent lines after the initial transfer of hydrogen. Helium was used when the lines were cold during cool down.

The cryostat was arranged so that the cryostat top could be unbolted and the cryostat lowered away from the top and test package to allow work on the test package without disturbing the connections to it.

An overall view of the cryostat from above is shown in Figure 5. Figure 6 shows the cryostat in the lowered position. A stirring assembly to stir the fluid in the cryostat was also available and is visible in Figure 6. A heater was also provided at the bottom of the cryostat to assist in removing any excess liquid nitrogen after pre-cooling.

4. TEST PACKAGE ASSEMBLY

A cross section of the test package constructed for this research is shown in Figure 7. It consisted of a brass lower vessel supported by a $1\frac{3}{4}$ inch inside diameter thin wall 304 stainless steel tube. The tube was welded to the cryostat top. The upper end of the tube contained a gland holder through which all connections to the test package were made. The gland holder contained: (a) two Conax 16 wire glands for thermo-

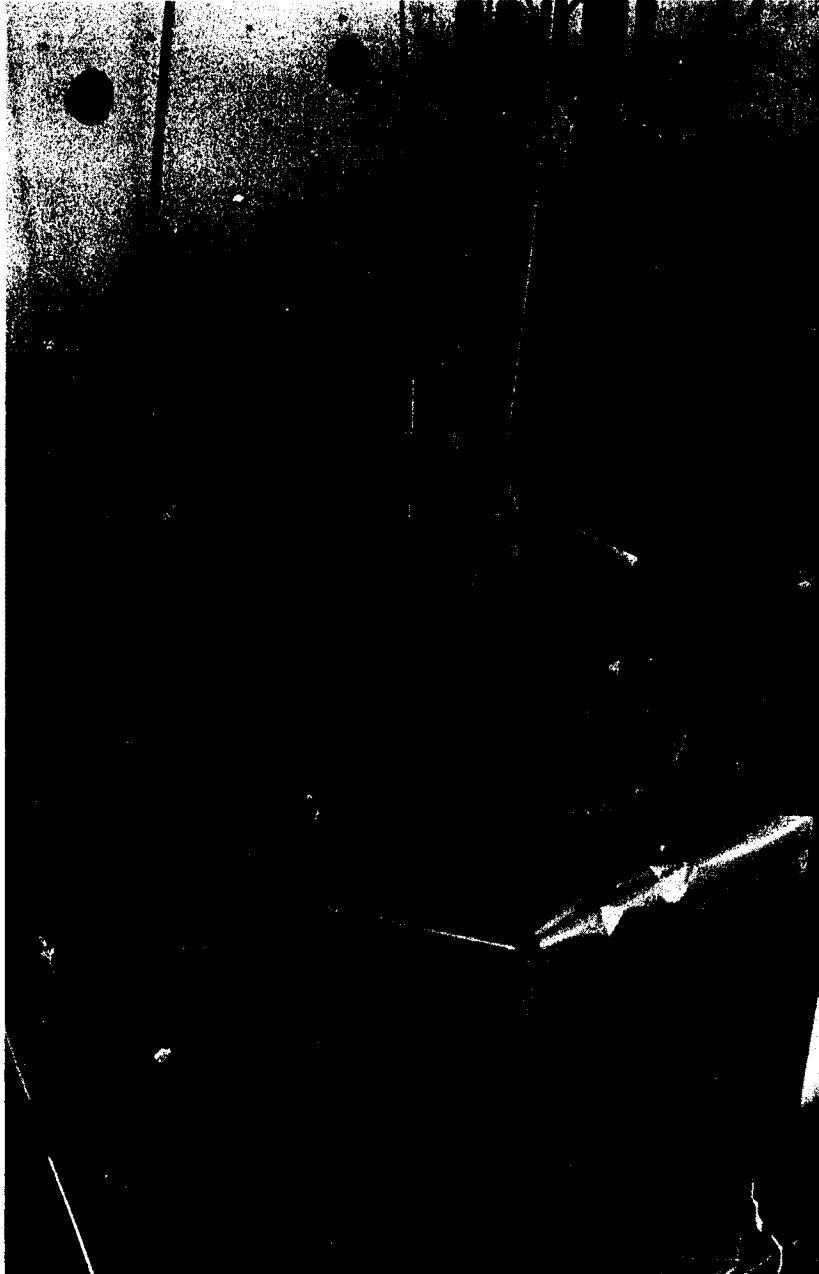


Figure 5. View of Cryostat Assembly From Above.

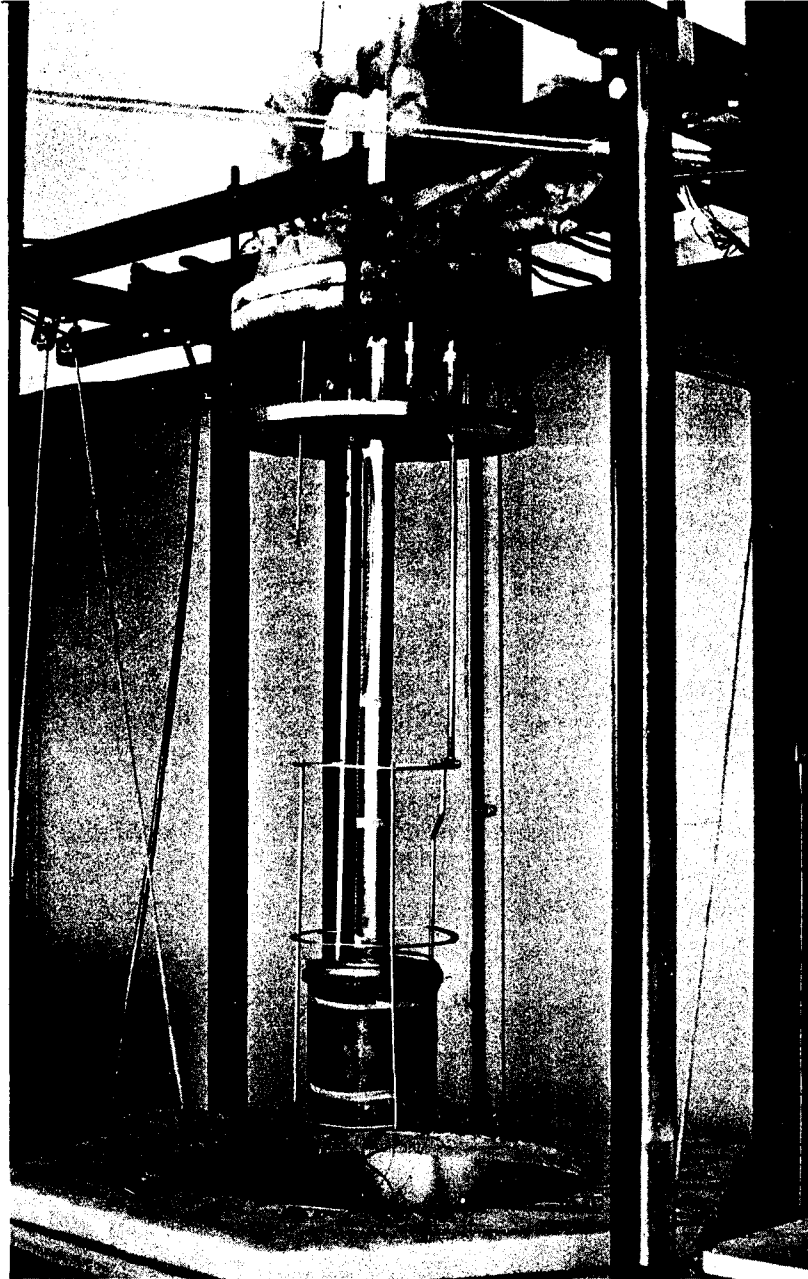
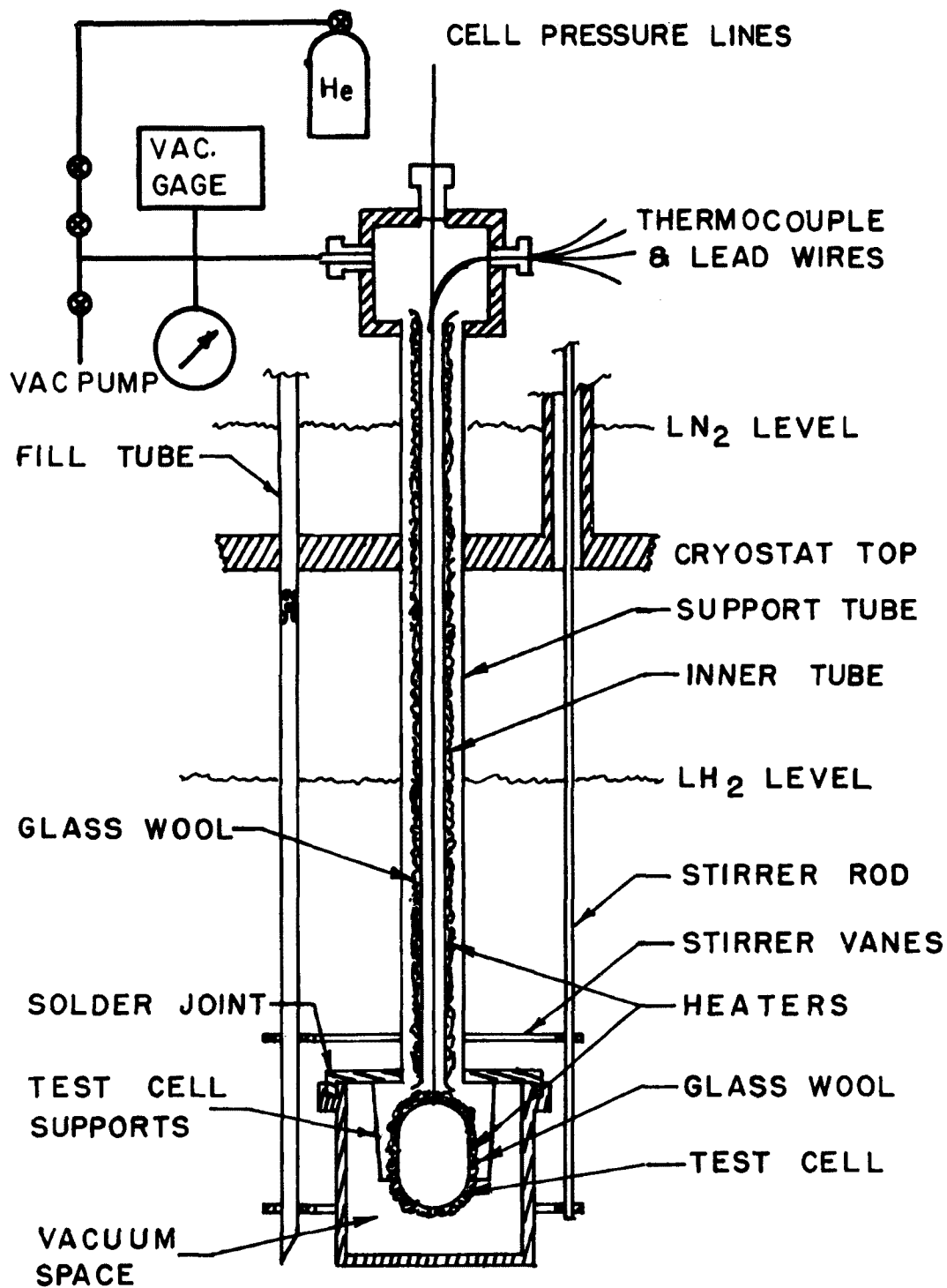


Figure 6. Cryostat Assembly with Cryostat in Lowered Position



TEST PACKAGE CROSS SECTION

Figure 7. Test Package Cross-section.

couples, thermometer, and temperature control wires, (b) one 8 wire Conax gland for heater power leads, (c) a Conax gland through which the two cell pressure lines passed, (d) a rupture disc to prevent inadvertant overpressure of the test package, and (e) pressure and vacuum connections to the main control panel.

Within the support tube a 0.5 inch thin wall, 304 stainless tube was placed through which the tubes to the cell and instrumentation lines passed. The outside of the 0.5 inch tube was heated by two sets of heaters. The heater elements were $\frac{1}{2}$ watt carbon resistors connected in parallel. The purpose of these heaters was to prevent freezing of the neon in the cell pressure line. Outside of the heaters was wrapped with pyrex glass wool for insulation.

The lower vessel was constructed of brass and made in two pieces, the upper section of which was brazed to the support rod. The lower section or can was soldered to the upper section using low melting temperature (160°F) solder. The can could then be removed easily without damage to electrical or other insulators.

The test cell was mounted within the lower vessel of the test package. It was suspended from the upper section of the vessel by three 0.031 inch diameter wires which attached to the mounting studs on the cell. The wires were 304 stainless steel and were about six inches long, including several kinks to increase the length.

The test cell was heated by four sets of heaters. Outside of these heaters was also wrapped with glass wool. The heater wires for both the cell and the inner tube went up the outside of the small inner tube to avoid interference with the instrumentation.

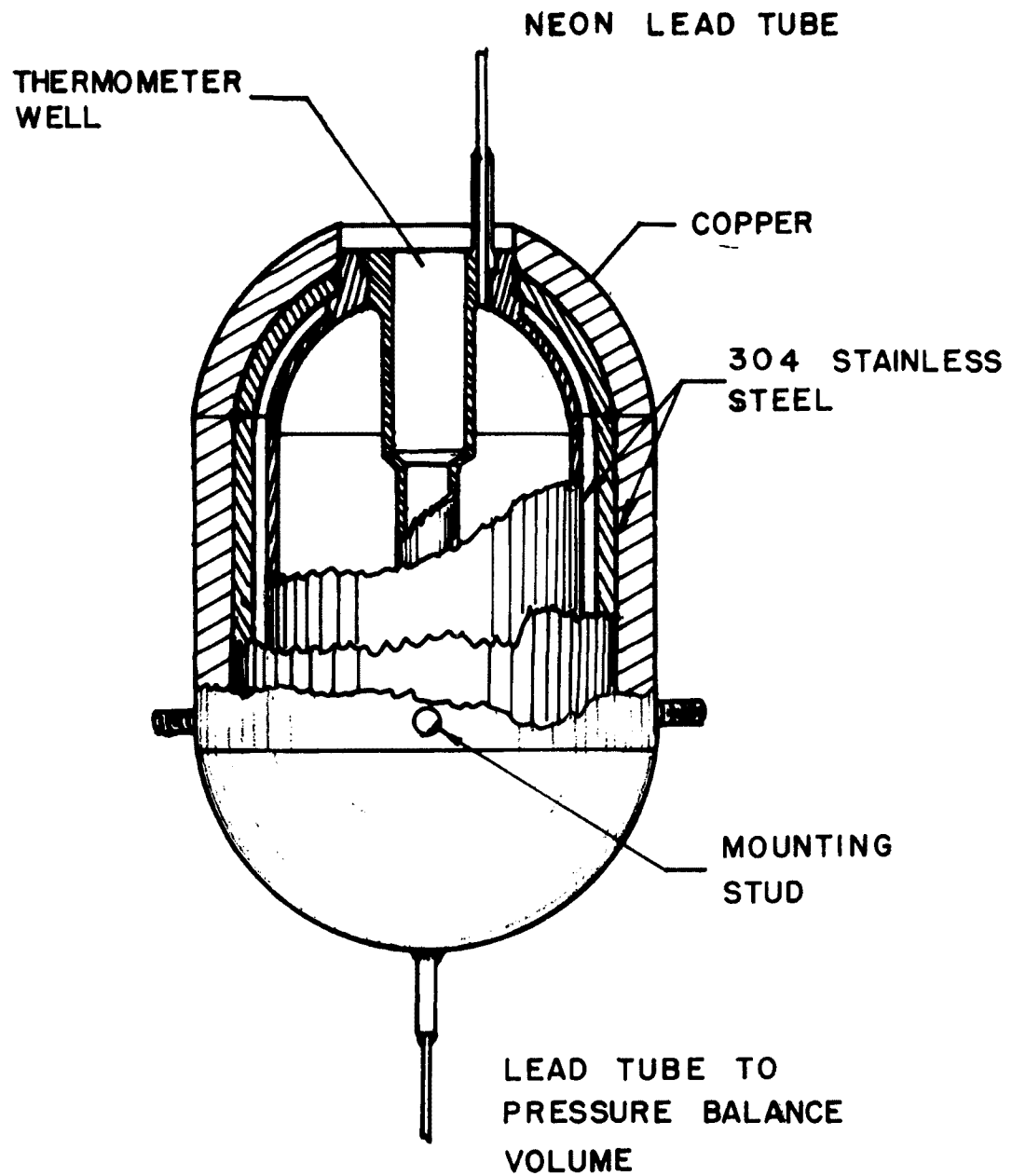
The entire test package was evacuated to reduce the heat loss to the hydrogen bath. The pressure was measured with a McLeod gage in the

vacuum system, and/or a thermocouple gage.

In order to provide fairly rapid cooling transients for temperature changes, the chamber was filled with helium which could be removed again as the desired temperature was reached. The system used to do this is also shown in Figure 7.

5. TEST CELL

Figure 8 is a cross section of the test cell assembly. The inside parts of the test cell, including the thermometer well, were machined from a single piece of 304 stainless steel stock and heliarc welded together. The inside vessel was then leak tested with a Consolidated Electrodynamics Corporation helium leak detector, model 24-120B, and the leakage was found to be less than 5×10^{-9} atmospheric cc/sec, for the cell and all plumbing up to the valve, with one atmosphere pressure differential. The walls on this vessel were nominally 0.070 inches thick and the ends were hemispheres with a cylindrical section in the center. The outside of the inner vessel was a 0.100 inch thick 304 stainless steel shell of the same shape separated from the inner shell by a space of nominally 0.070 inches. The parts were machined to size after welding to prevent the tolerance accumulation from closing this clearance at the bottom of the cell. The only attachment between the two vessels is at the top around the thermometer well. The purpose of the space between the vessels was to provide a very low pressure differential across the test cell walls to prevent changes in the test volume due to pressure. By making the inner vessel so that it was free to expand thermally, the thermal expansion of the volume could be easily calculated.



TEST CELL CROSS SECTION

Figure 8. Test Cell Cross-section.

Although not shown in Figure 8, the thermometer well ended just above the lower tangent line. Some expansion due to pressure would, of course, occur at the thermometer well. This is essentially free expansion also and, while very small, was included in the analysis.

Another shell of the same basic shape as the inner pieces was silver soldered to the outside of the outer stainless steel shell. This one was made of tellurium copper (free machining) and was approximately $\frac{1}{4}$ inch thick. The tellurium copper still has a reasonably high thermal conductivity at the test temperatures of interest in this work.

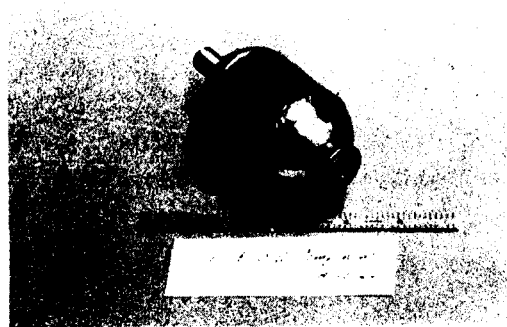
Figure 9 is a composite showing the various parts and phases of the test cell fabrication, including a rebuilding necessitated by not being able to get a leak tight weld on the two lead in tubes. The thermometer well was redesigned at the same time to provide better contact to the gases inside the cell. Figure 8 is the final configuration.

A 0.020 inch inside diameter, 1/16 inch outside diameter, 304 stainless steel tube was connected to each chamber of the cell. These connected at the bottom of the cell for the outer chamber and at the side of the thermometer well for the test volume. The outer chamber could thus be pressurized with helium to the same pressure as the test volume with the system shown in Figure 10. The compensating pressure system consisted of a series of valves, check valves, and a hand pump to allow pressurization of the outer volume of the test cell to the same pressure as the test volume. This minimized changes in the test volume due to pressure. The pressure in the outer volume was read on a Heise gage with a 0 to 5000 psi range. This allowed the pressures to be balanced within ± 3.0 psi.

This entire test cell assembly was pressure tested with nitrogen to 6000 psi at room temperature to assure its structural integrity.



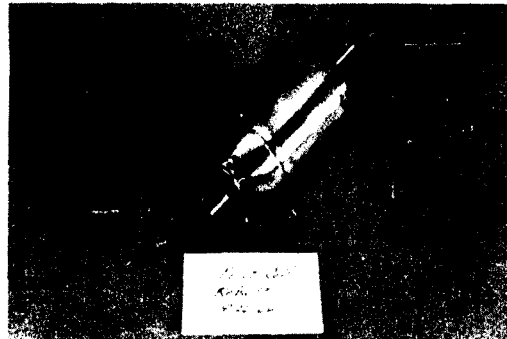
INNER SHELLS AND THERMOMETER WELL



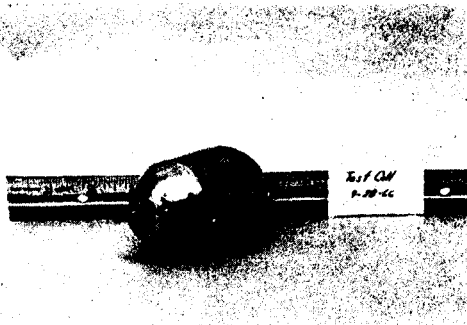
INNER SHELLS ASSEMBLED



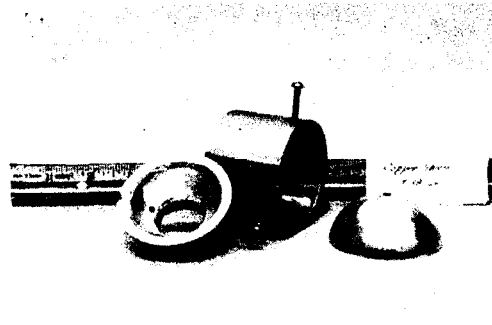
WELDED THEN MODIFIED FOR TUBE ATTACHMENT



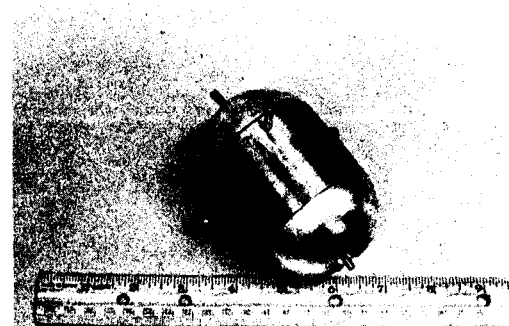
MODIFICATION ASSEMBLED



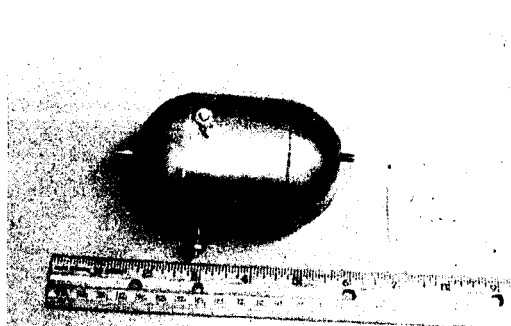
STAINLESS STEEL SHELLS COMPLETE



COPPER SHELL



COPPER ASSEMBLED



SILVER SOLDERED

Figure 9. Test Cell Components and Fabrication.

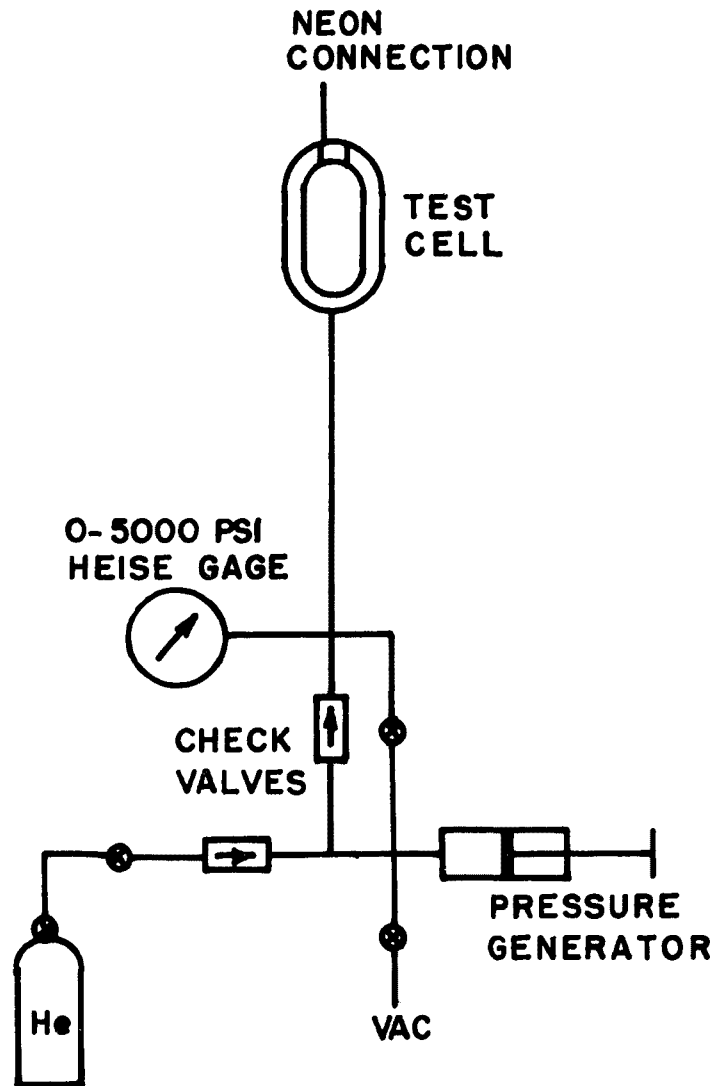


Figure 10. Pressure Compensation Pressurization System.

Carbon resistors were placed on the outside of the copper to heat the entire assembly as mentioned above. These resistors were flattened on one side to increase the contact area with the copper. Each resistor was held in contact with the copper by multiple layers of glass tape around the entire assembly. The resistors on the test cell assembly were connected in four sets, all resistors in each set being in parallel. One set of resistors was located on the lower hemisphere of the copper, the second on the cylindrical center section, and the third on the top hemisphere. The fourth set of resistors was spread fairly uniformly over the entire cell surface and was used for intermittent control heating of the cell. The three sets of heaters operated continuously. Figure 11 shows the heaters being assembled on the test cell assembly.

Two other heaters were located on the $\frac{1}{2}$ inch tube above the cell as mentioned above. These heaters were all controlled by the same control system. Figure 12 is a schematic of the electrical heater system.

During operation the heat input required to maintain the cell at any given temperature was primarily a function of pressure. At pressures of about twenty microns, the total steady heat input for a fifty degree temperature difference was about one-half watt. At lower pressures the heat conduction down the tubes, wires, etc., would be sufficient to maintain the temperature. Therefore, in this condition no temperature control was possible.

The temperature of the copper was sensed by two 100 ohm platinum thermometer elements which were set into grooves in the copper at the upper tangent line. The two elements were located about 180° apart. These elements were G-19 elements built by Electric Thermometers, Incorporated and were about 0.10 inches in diameter and 0.6 inches long.

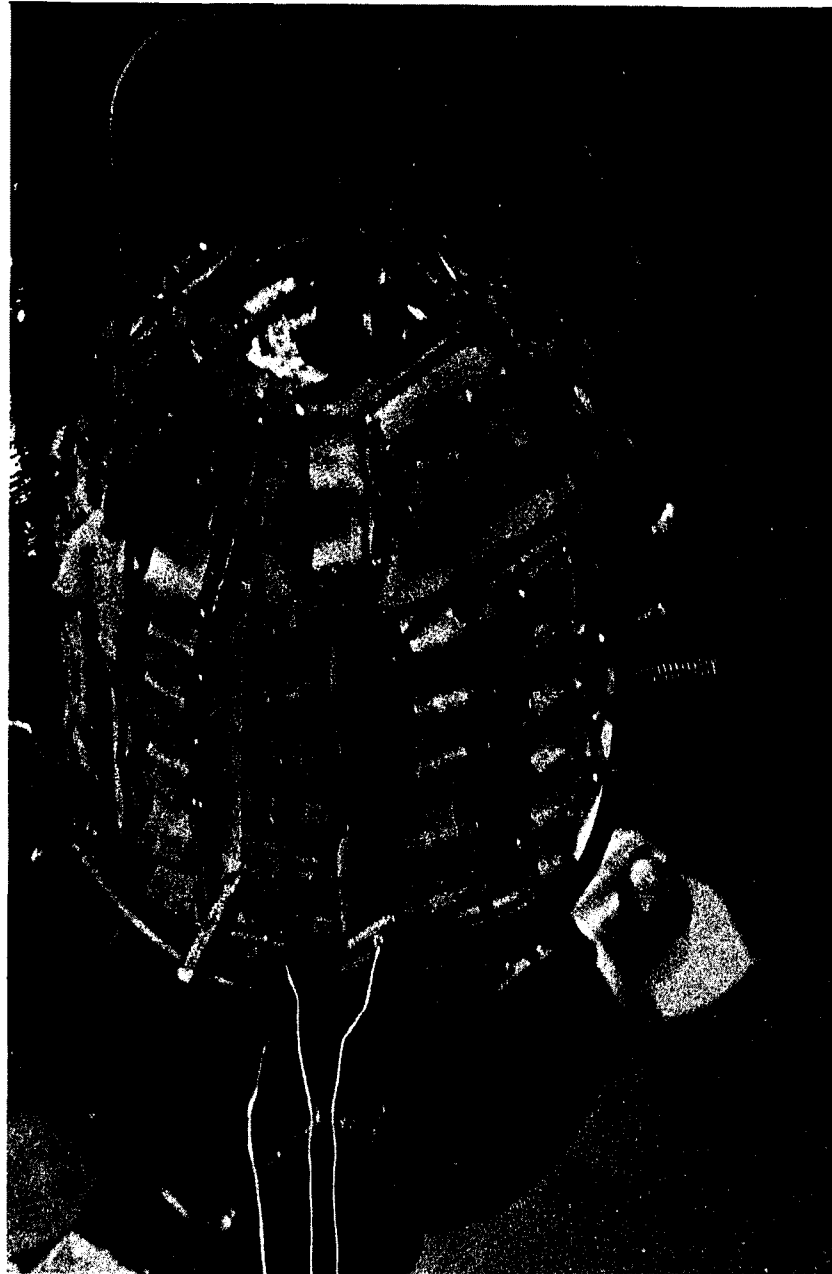


Figure 11. Assembly of Heaters on Test Cell.

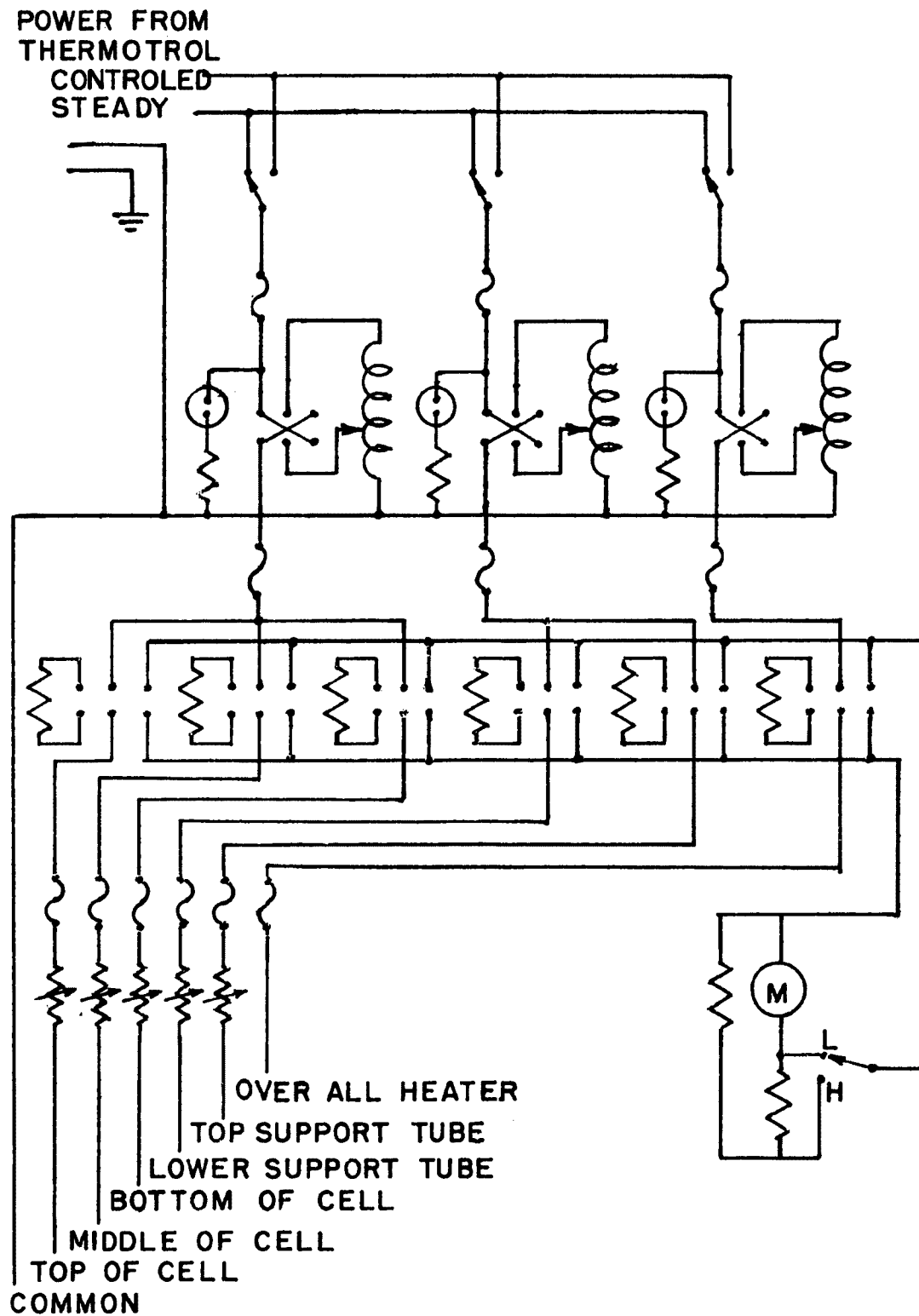


Figure 12. Electrical Heater System Schematic.

The thermometer elements were connected to a model 1053A Thermotrol built by Hallikainen Instruments, which was used in a proportional with reset mode to provide power to the heaters.

The thermotrol unit was modified slightly to allow operation at widely differing conditions. The gain and mode selection switches were moved to a location where they could be changed without removing the thermotrol from its box. The reset time constant values available were changed by adding more resistors to allow for longer reset times. The thermal lags in the cell required longer times than were available on the standard unit. This affected the proportional with reset mode of operation only.

By turning the controller gain to "off" the heaters could be operated manually since voltage would be applied only to the steady line.

Since this controller used a bridge circuit for sensing the temperature, the forth or reference leg of the bridge had to be at controlled conditions also. It was placed in the oil bath described below. The lead wire temperature compensation was set up as shown in Figure 13.

The temperature of the cell was measured with a platinum resistance thermometer located in the thermometer well shown in Figure 8 and 9. In order to provide a good thermal connection to the well, a silver solder spring was constructed to hold the thermometer in place and to provide heat conduction paths during use, as the thermometer area was evacuated during operation. The thermometer well was of two different diameters to allow clearance for the glass bulb on top of the thermometer and to minimize the material between the sensitive portion of the thermometer and the test volume. The spring contacted the thermometer only on the sensitive portion, but contacted the well on both diameters.

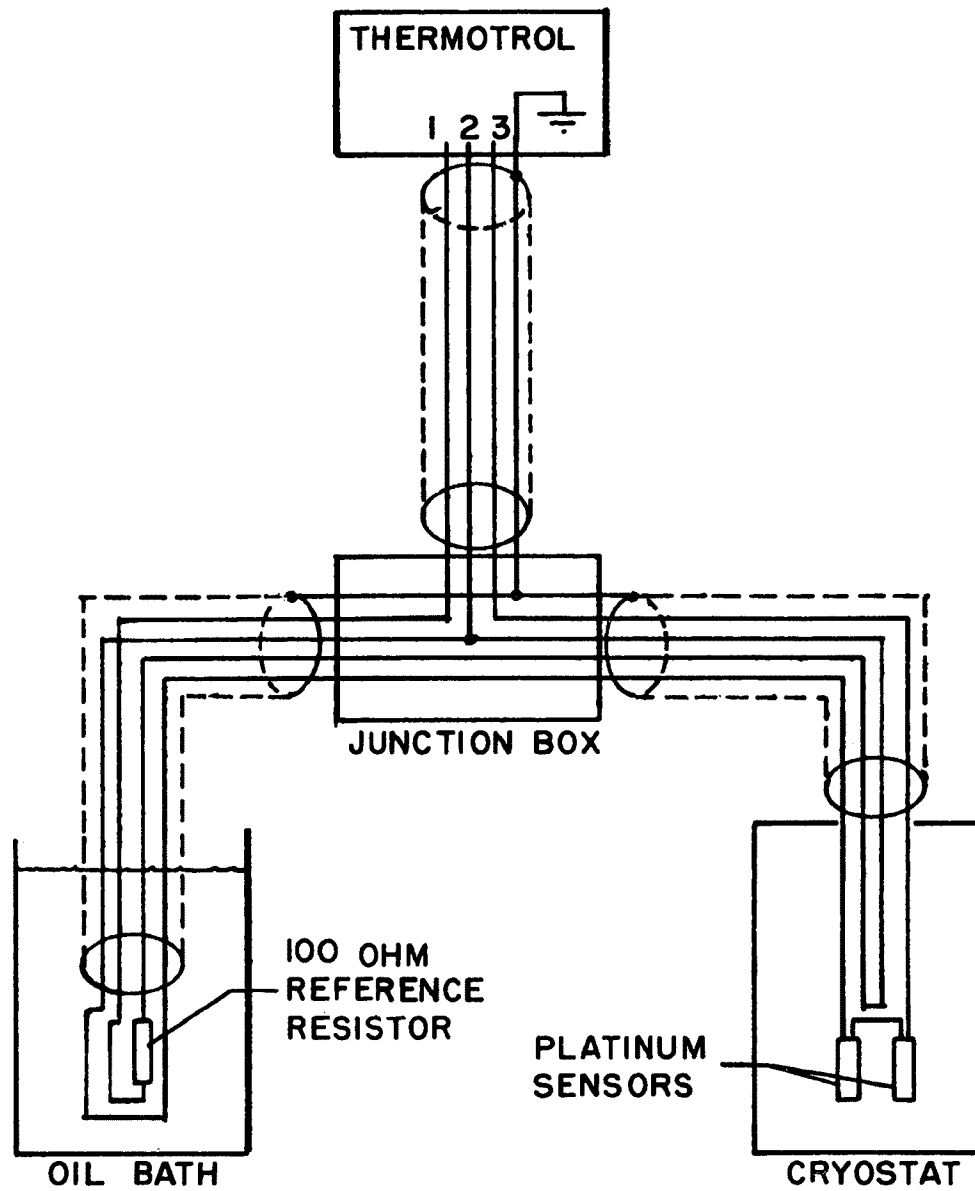


Figure 13. Temperature Controller Lead Wire Resistance Compensation Hookup

The platinum thermometer leads were joined to another section of platinum wire. Junctions to copper lead wires were made and imbedded in four holes in the copper heat shield around the cell. The holes were located as close together as possible to avoid thermal gradients. Such gradients could produce troublesome EMF's which would cause zero shifts on the thermometer bridge.

Several gold, 2.11 atomic percent cobalt-copper thermocouples were used to measure gradients on the test cell and lead out tubes. These thermocouple junctions were placed in holes in the copper shield and packed with aluminum foil. All thermocouples on the cell were referenced to a point near the top of the cell.

6. CONSTANT TEMPERATURE BATH

The remainder of the system used directly for the determination of the mass in the test cell was located in a constant temperature oil bath. Figure 14 shows an overall view and Figure 15 is a schematic of the plumbing, etc., of the constant temperature bath. The system consisted of two 1000 ml stainless steel tanks and five valves for control. All the valves used in this portion of the system were located in the bath with an extension of the stem going through the bath wall.

The two differential pressure cells used with the pressure measuring systems were located within the oil bath inside a second box. The inner box had only a chimney for the lead wires and kept the oil away from the differential pressure cells. It was found that the oil attacked the electrical insulation of the cells and made them unstable.

The bath was approximately a two foot cube with an open top and insulated sides and bottom. The oil used in the bath was a Wemco C

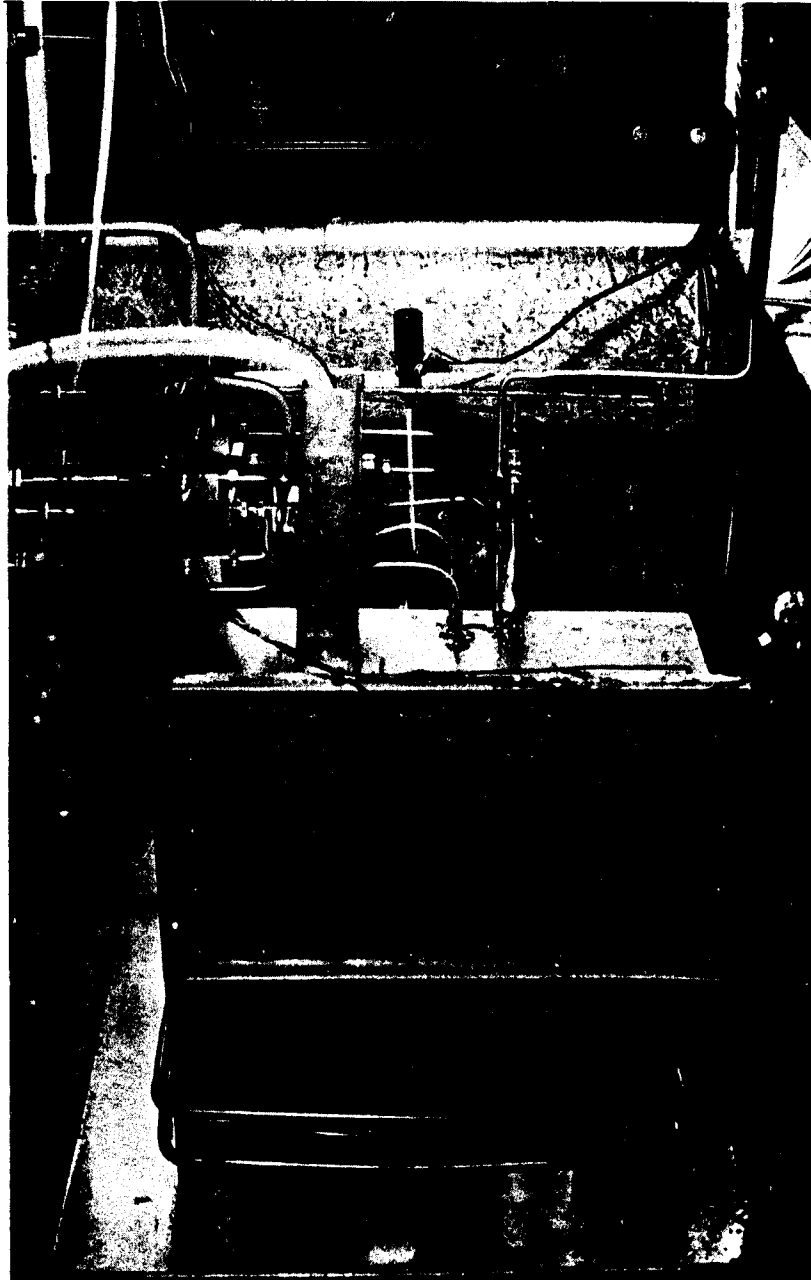
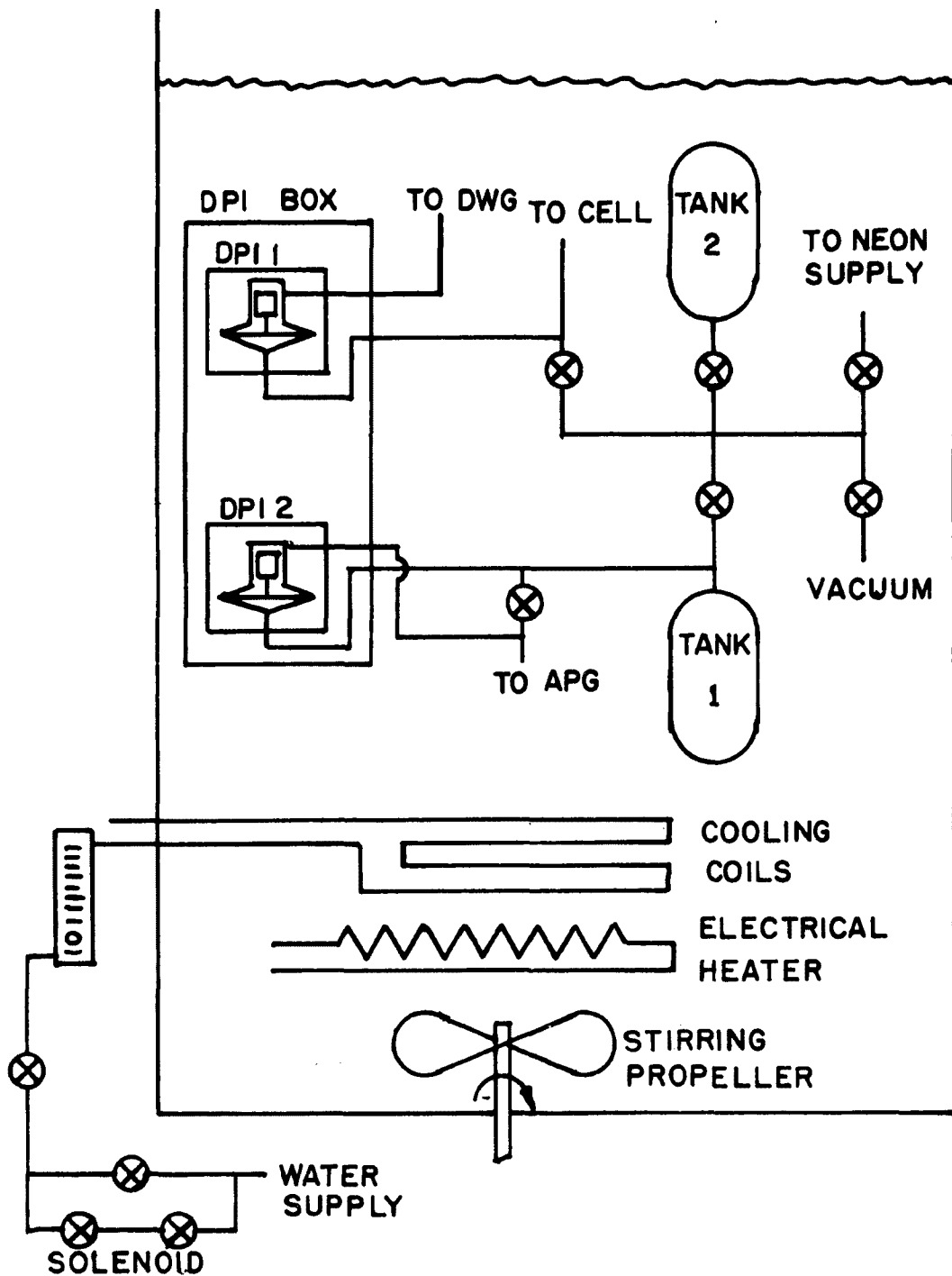


Figure 14. Overall View of Constant Temperature Oil Bath
with Side Removed



OIL BATH SCHEMATIC

Figure 15. Schematic of Constant Temperature Bath.

transformer oil. The bath contained about 38 gallons of oil.

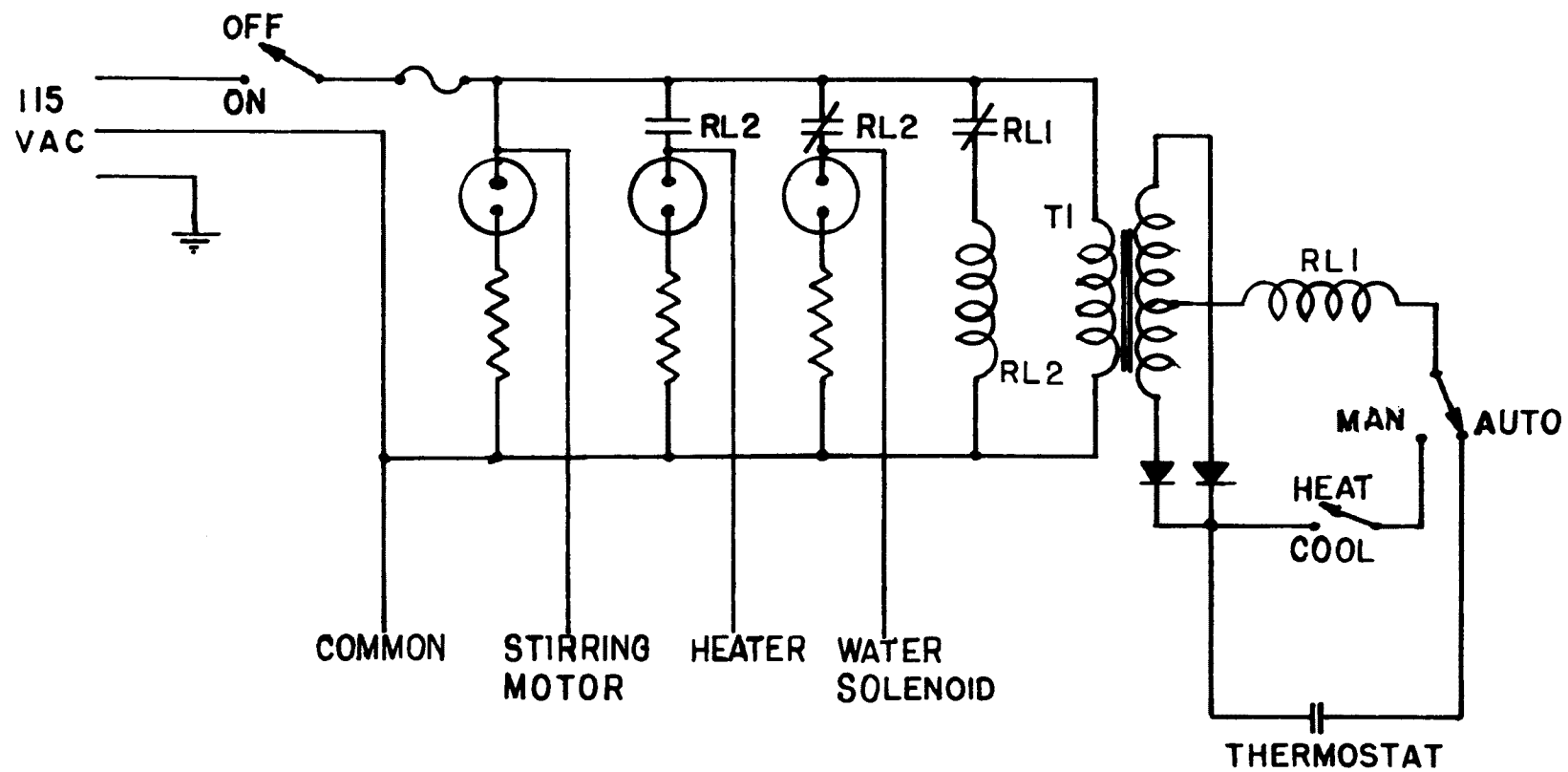
The temperature of the bath was measured by a platinum resistance thermometer and 12 copper-constantan thermocouples located throughout the bath. The thermometer and the reference point on all thermocouples were located in a three inch diameter, three and one-half inch long copper block.

The temperature of the bath was controlled at $300.17 \pm 0.01^{\circ}\text{K}$ by a precision mercury thermostat built by American Instrument Company. The thermostat actuated the control system shown in Figure 16 to turn on the heater and reduce the cooling water flow to maintain the bath temperature.

The oil in the bath was stirred continuously by a large propeller located at the bottom of the bath. The speed of rotation of the propeller was set well above the speed at which cold spots in the corners, etc., could be detected by the differential thermocouples.

7. SIZING OF COMPONENTS

The selection of the test cell size was based on an extensive error analysis of the entire system. After the system had been conceptually designed, it was obvious that it was desirable to minimize the volume in the test cell in order to minimize the mass of which it was necessary to control the temperature. On the other hand, certain noxious volumes were of fixed sizes. Further, the expansion tanks had to be large enough to produce the low pressures required by the assumptions made regarding linearity of the compressibility and yet small enough that the mass entering the tanks from the test cell during the second expansion would be significant.



OIL BATH TEMPERATURE
CONTROLLER

Figure 16. Oil Bath Temperature Control System

A computer program was written to calculate the maximum possible error in calculating a compressibility in the cell from equation 2 based on a mass calculated from equation 6 with additional mass measured independently in the expansion tanks. This program used basic estimates of the accuracy of each measurement of temperature, pressure, and volume, and considered any number of expansions required for the complete mass measurement. Compressibilities were estimated from references 22 and 24. A series of 8 points were selected to serve as worst case points; these included high and low densities, low compressibilities, and high and low temperatures. The maximum error of measurement was calculated for a series of cell volumes with several expansion tank sizes for each one. The errors indicated that the best size and size relationship was different for each operational condition. The condition near the critical point was selected as the criteria for sizing since the errors at the other conditions were smaller than for any other system used at off optimum conditions. The analysis thus indicated that the best overall accuracy could be obtained by use of a test cell of about 75 cc and expansion tanks of 1000 cc each.

8. PRESSURE MEASURING SYSTEM

As shown on the schematic of the oil bath system, two pressure-measuring instruments and control systems were used. There were two reasons for the use of two instruments: the range of pressures to be covered (250 atmospheres to 0.1 atmospheres) was not obtainable in a single high accuracy instrument; and, the noxious volume could be reduced considerably by removing the valving required to use a single instrument. The instruments used were an air piston dead weight gage

(APG) and an oil type dead weight gage (DWG).

a. Air Piston Gage

A Ruska Instrument Corporation air piston gage, model 2460, s/n 13821, was used to measure the pressures in the expansion tanks. This instrument has a range of 0.2 psia to 15.0 psig with the low range piston and 2.0 psi to 600 psi with the high range piston. A vacuum weight loader was generally used with the low range piston and a manual weight set with the high range piston. The smallest weight used in balancing with the vacuum loader was equivalent to 0.0012 psi. With the manual weight set, an analytical class S-1 weight set was used for the small increments. The 5 milligram weight, the smallest used, would correspond to about 0.0008 psi on the high range. Figure 17 shows the system with the vacuum weight loader installed. The controls for the APG are shown in the background. Figure 18 shows the manual set on the gage. The cover was used over the weights for the manual weight set during final balance because the room ventilation system produced a draft near the unit.

Figure 19 shows a schematic of the control and balance system used with the APG. This system consisted of a nitrogen gas supply with high and low range regulators. The main portion of the system was slowly pressurized by using the needle valve to allow flow into the system until the differential pressure indicator (DPI) indicated the pressure to be measured had been passed, then both inlet valves were closed. A similar arrangement was available for slowly decreasing the pressure, even when operating below atmospheric pressure. Since the unit was designed without positive seals around the piston in order to

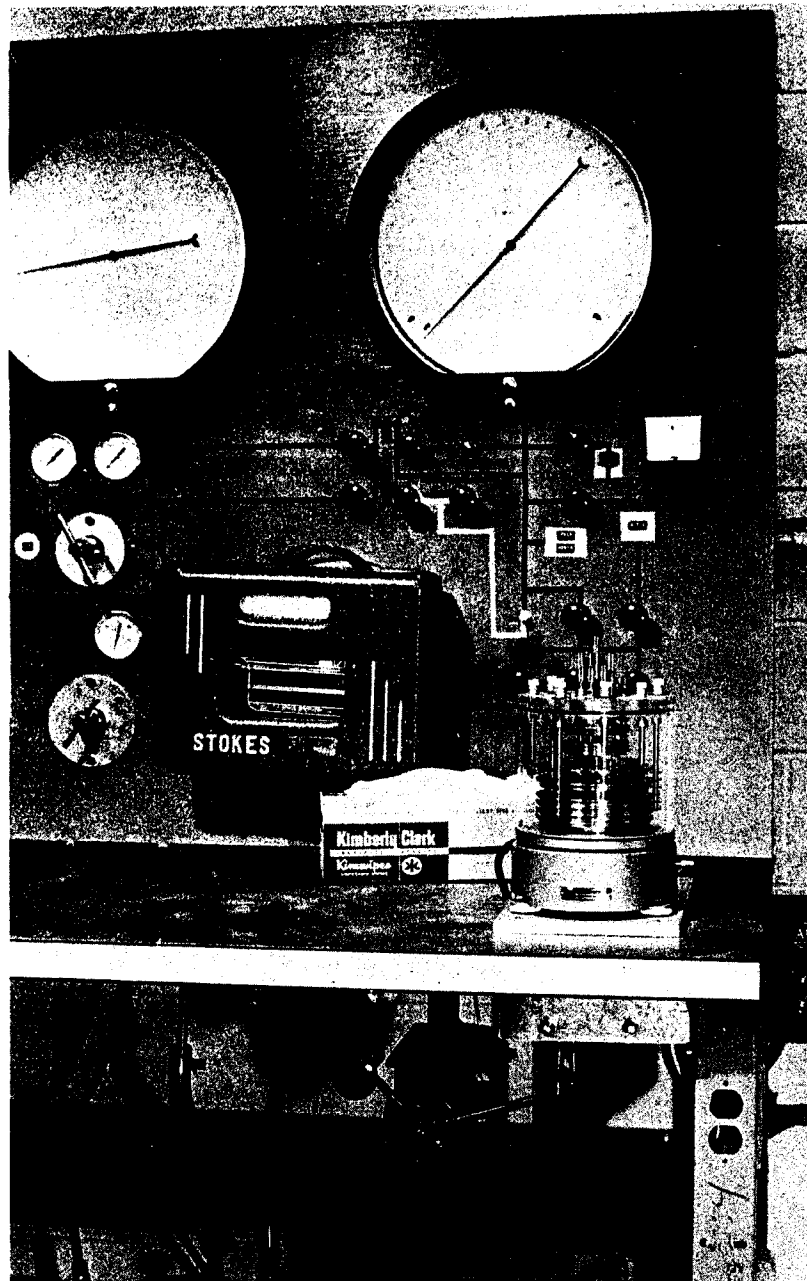


Figure 17. Air Piston Gage and Control System with Vacuum Weight Loader Installed.

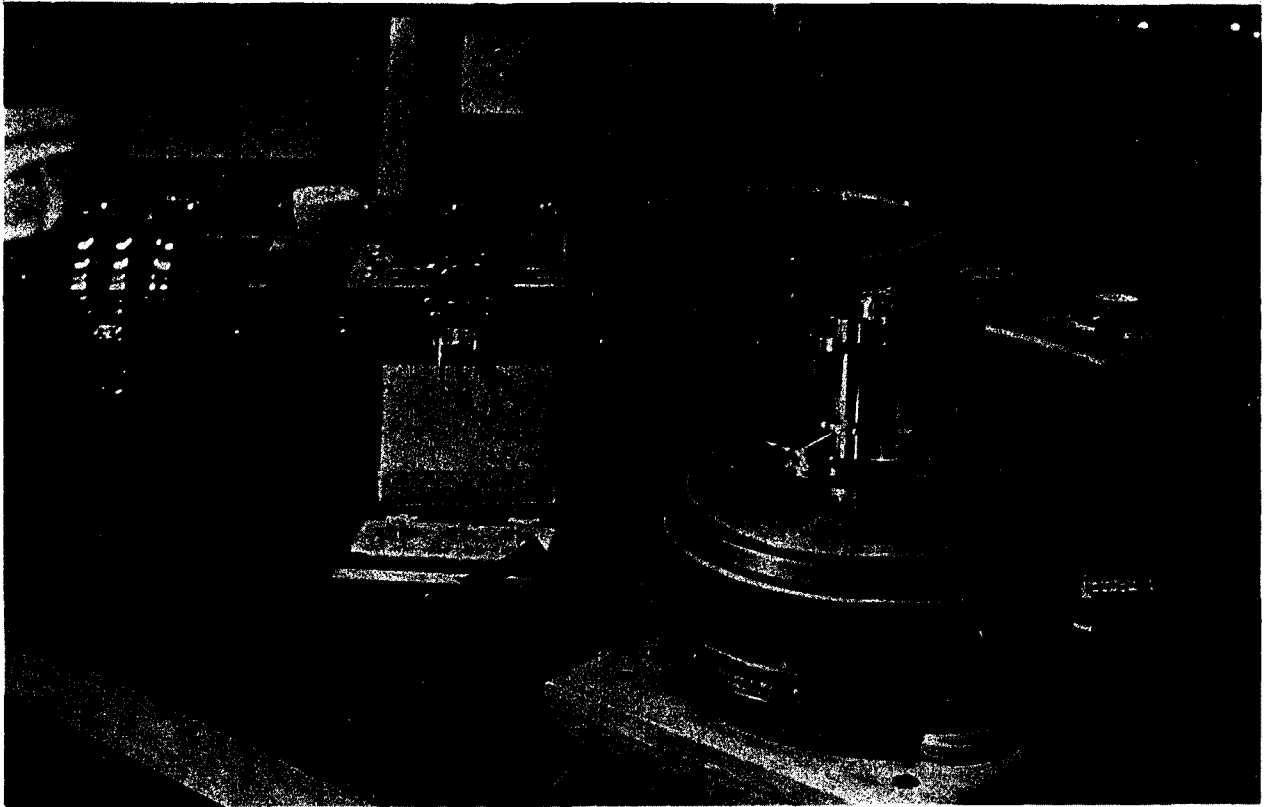


Figure 18. Air Piston Gage with Manual Weight Set.

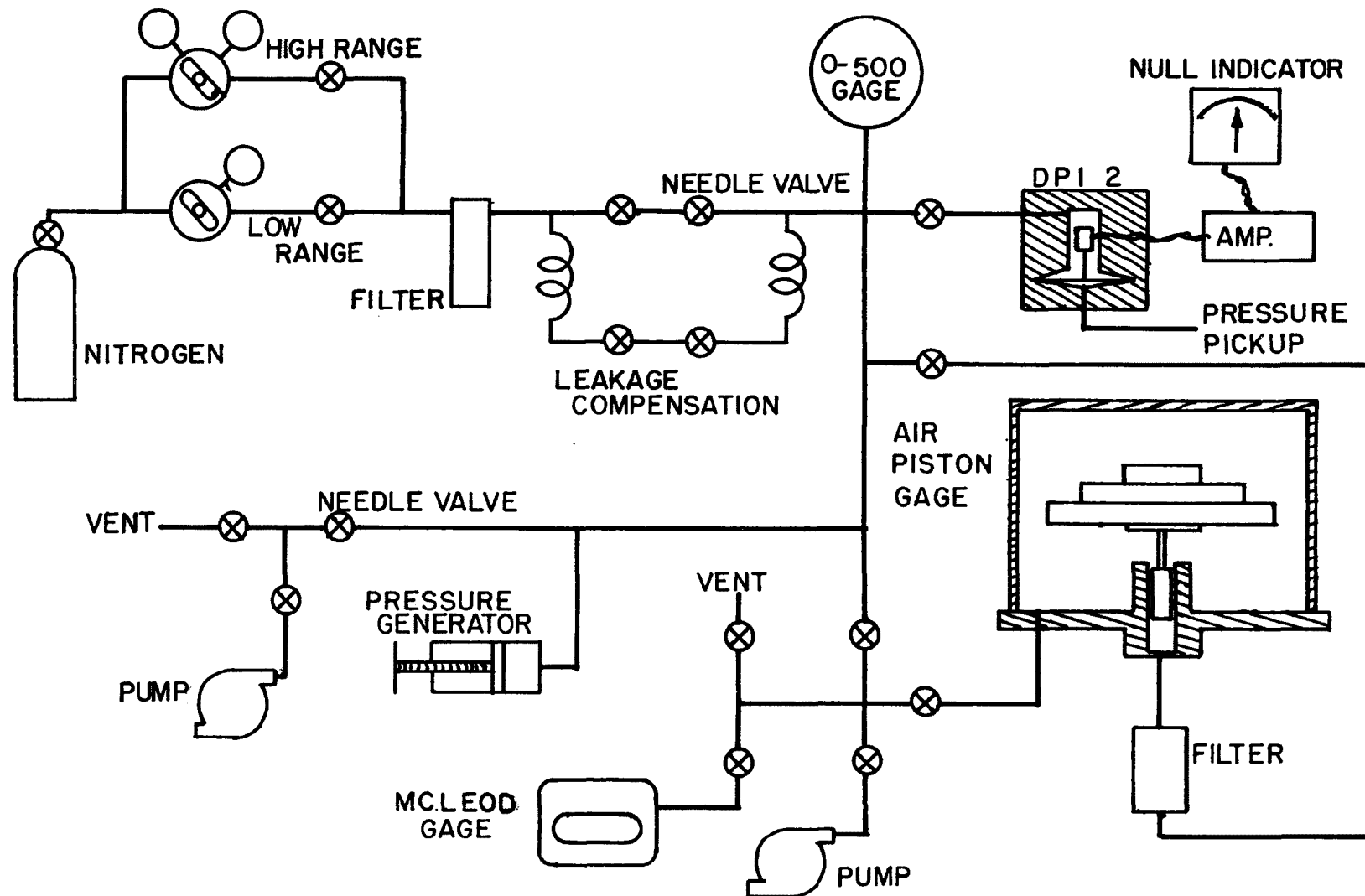


Figure 19. Air Piston Gage Control and Balance System Schematic.

get the maximum accuracy, some leakage of gas always occurred around the piston, particularly on the low range piston. To compensate for this, an extremely fine leakage path was provided. This consisted of fifteen feet of 0.020 capillary tubing in series with two very fine needle valves. The apparent leakage could be completely removed using this system. The pressure generator was used to produce small changes in pressure or volume to float the piston after small weight changes. The second vacuum pump and the McLeod gage were used to evacuate the weight cover when applicable and measure its pressure. The shut off valve on the DPI was provided to assist in zeroing the DPI without filling the expansion tanks with nitrogen (see Figure 15).

b. Dead Weight Gage

The dead weight gage used in these tests to measure the pressure in the cell is shown in Figure 20 with its control system. The gage was a Ruska Instrument Company, model 2400, s/n 10517. Figure 21 shows a schematic of this system. Pressure was applied to the system by a piston oil pump which was valved from the gage, reservoir, DPI, and auxiliary connections. This allowed filling of the pressure generator without loss of pressure on the DPI or damage to the gage. Two valves were provided in the DPI line. The purpose of this is to allow the DPI to be held at zero by adjusting the second valve after closing the first. This operation was required during measurements of mass in the expansion tanks. The manometer was provided in the DPI line to balance the oil head in order to set the DPI amplifier at zero.

The oil head on the DWG was measured with a cathetometer by measuring from the reference line on the DPI to the reference line on the

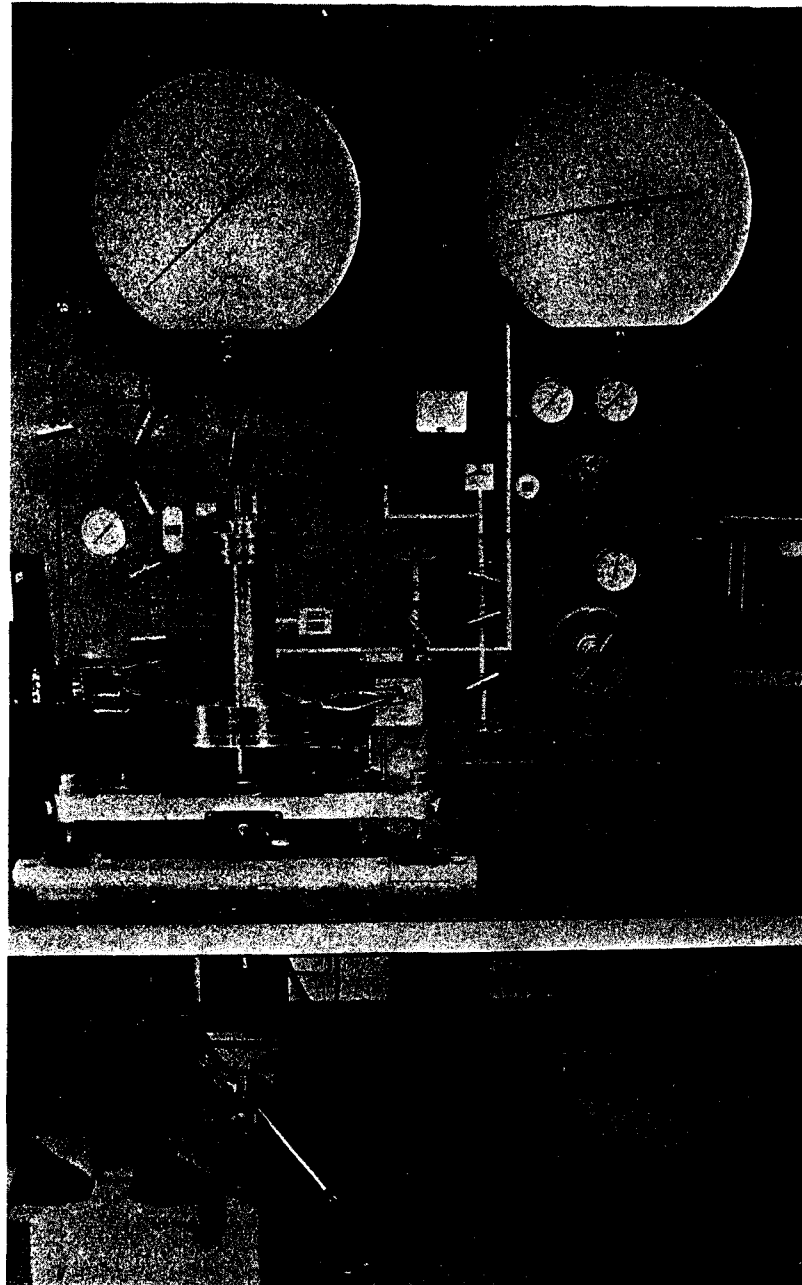


Figure 20. Dead Weight Gage and Control System.

post of the DWG. This distance was 0.681cm. Additional oil head dimensions are provided by the manufacturer for each piston. The oil used in the gage has a specific gravity of 0.850 as given by the manufacturer.

It should be noted relative to this oil head measurement that one side of the oil bath and the same side of the DPI box could be removed to allow easy access for this measurement. The manometer mentioned above was leveled at the same time so that its zero point was at the same height as the reference mark on the DPI.

c. Differential Pressure Indicators

The differential pressure indicators used with these two systems were Ruska Instrument Company, model 2416.1 units. The unit used on the DWG, cell s/n 10565, control box s/n 10591, had an apparent sensitivity of about 0.0008 psi per meter division on full gain, which is less than that specified for these units by the manufacturer. It was, however, compatible with the increments obtainable on that gage.

The unit used on the APG, cell s/n 12884, control box s/n 12902, had a far better sensitivity than the other unit, $< 5 \times 10^{-5}$ psi per meter division. However, the zero drift on this unit was excessive, being often as much as 0.005 psi in a few hours. Therefore, zeroing provisions were made on this unit (see Figure 15).

Both amplifier units were located near the DPI cells and it was necessary to use an auxiliary galvanometer near the pressure gage controls. The galvanometer on the amplifier was disconnected on the unit on the DWG because of the sensitivity problem.

9. TEMPERATURE MEASURING SYSTEM

The overall temperature measuring system is shown schematically in Figure 22. Figure 23 is a photograph of the temperature measuring test bench.

The thermometer in the cell was a Leeds and Northrup platinum resistance thermometer, model 8164, s/n 1653433. The thermometer in the copper block in the oil bath was also a Leeds and Northrup, model 8164, s/n 1606773. Both were calibrated at the National Bureau of Standards. The two thermometers were connected to a Mueller Bridge through a mercury wetted switch built especially for this purpose. Figure 24 is a schematic of this four pole, four throw switch. This switch was equipped for lead equalization in all four sets of incoming leads. The switch output then connected to the fixed leads on the Mueller Bridge.

The resistance of the thermometers was read on a Leeds and Northrup G-2 Mueller Bridge, model 8069, s/n 1605421. This bridge has thermostatically controlled measuring resistors. The galvanometer used in conjunction with this bridge was a Leeds and Northrup, model 2284, mounted in a Julius suspension. The galvanometer was equipped with a prism and mounted above the light source and scale as shown in Figure 25 of the test bench with the cover removed. The area where the galvanometers were mounted was completely enclosed except for a small hole for the light path. The purpose of this was to eliminate spurious effects of air currents.

Also connected to the thermometer switch was a Leeds and Northrup standard resistor, model 8070B, s/n 1613813, used to check the calibration of the Mueller Bridge. This resistor was enclosed in a styrofoam

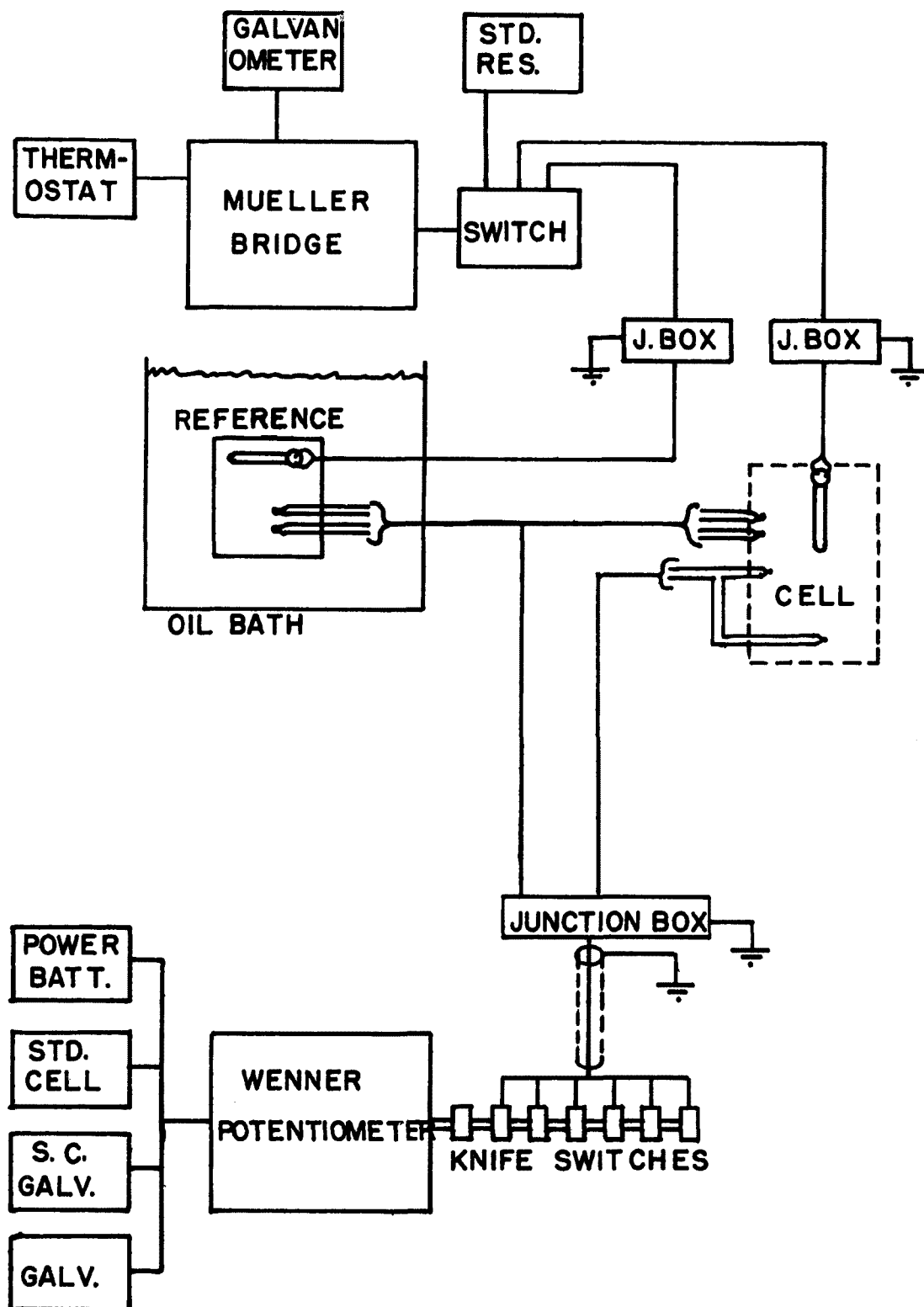


Figure 22. Block Diagram of Temperature Measuring System.

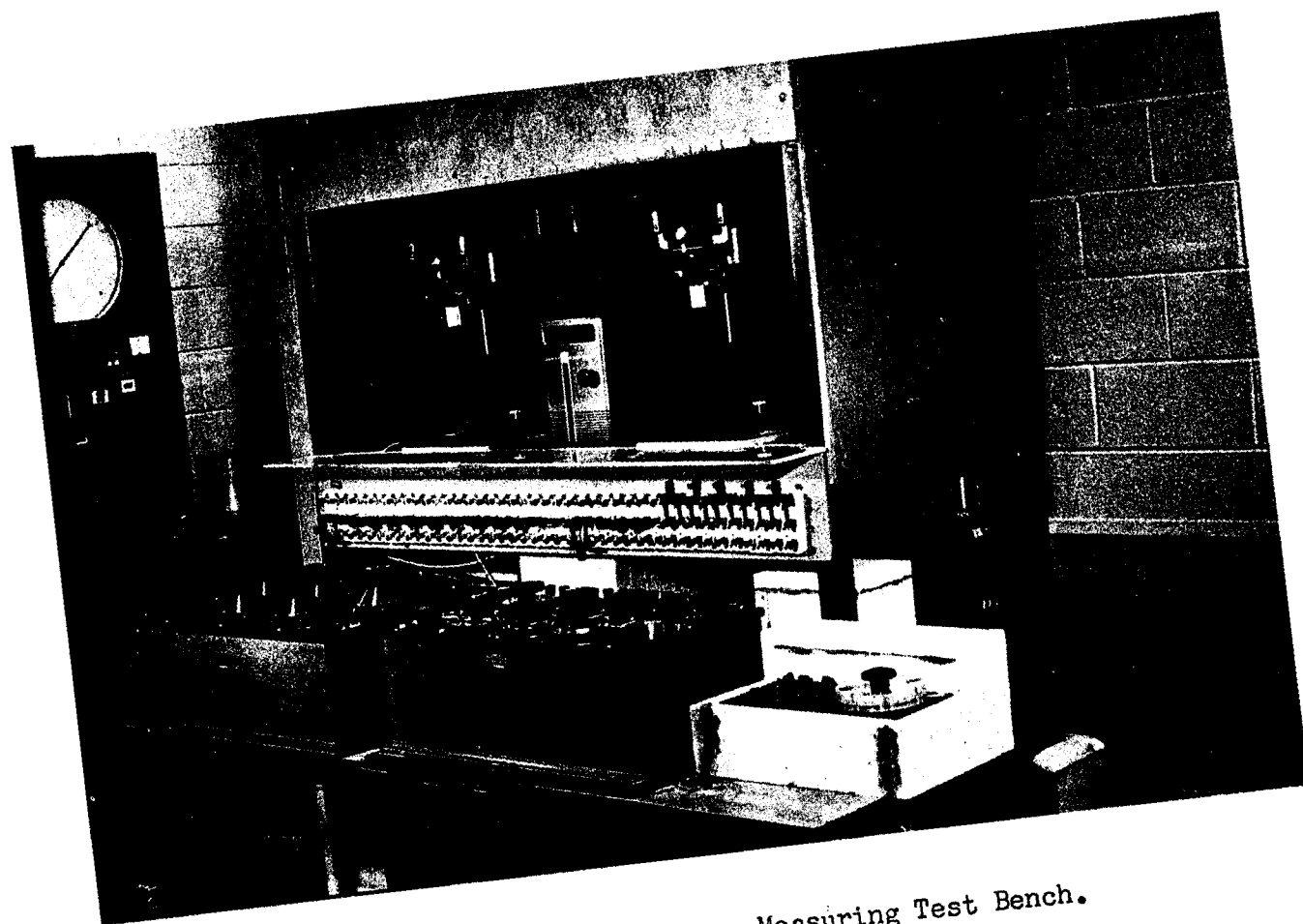


Figure 23. Temperature Measuring Test Bench.

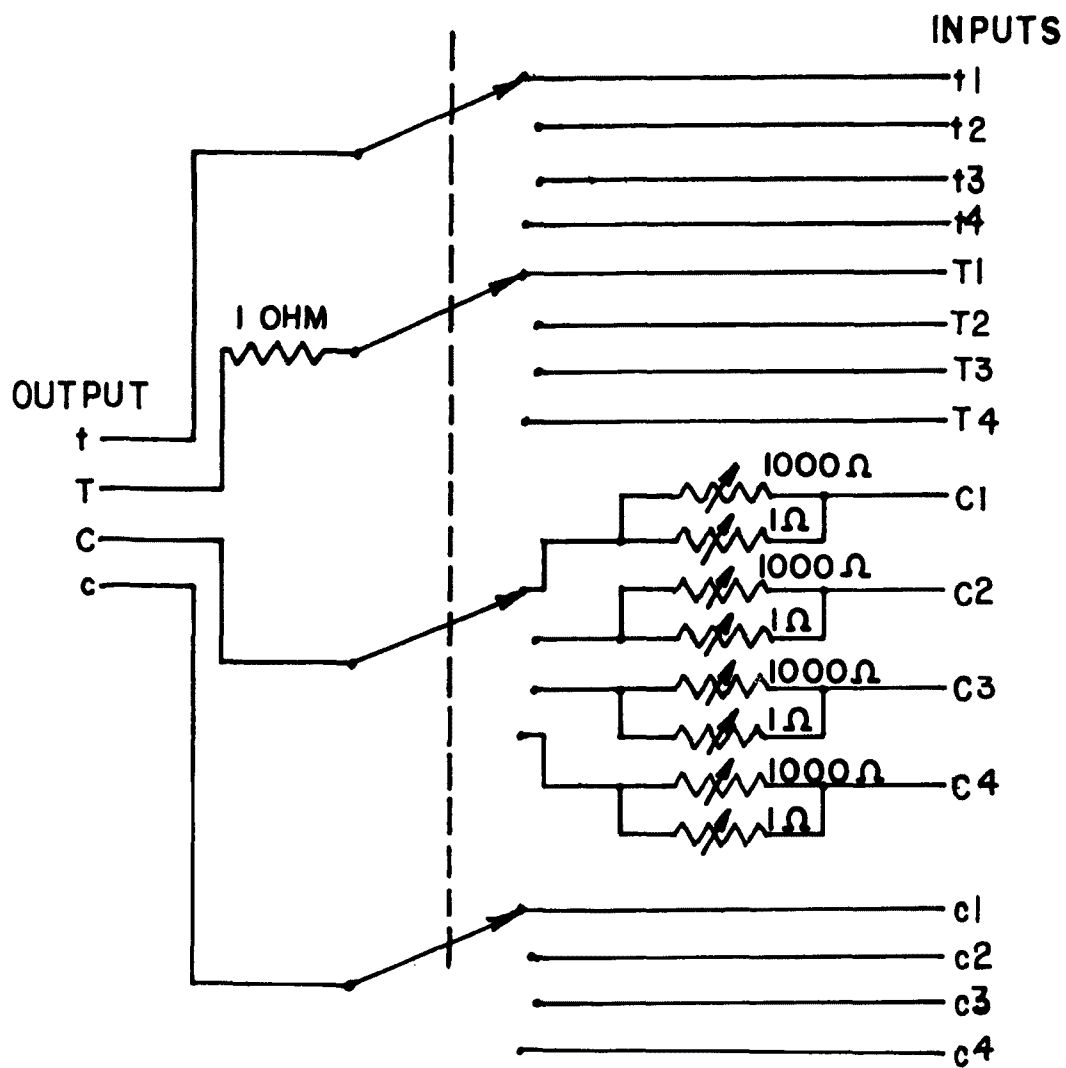


Figure 24. Resistance Thermometer Switch Schematic.

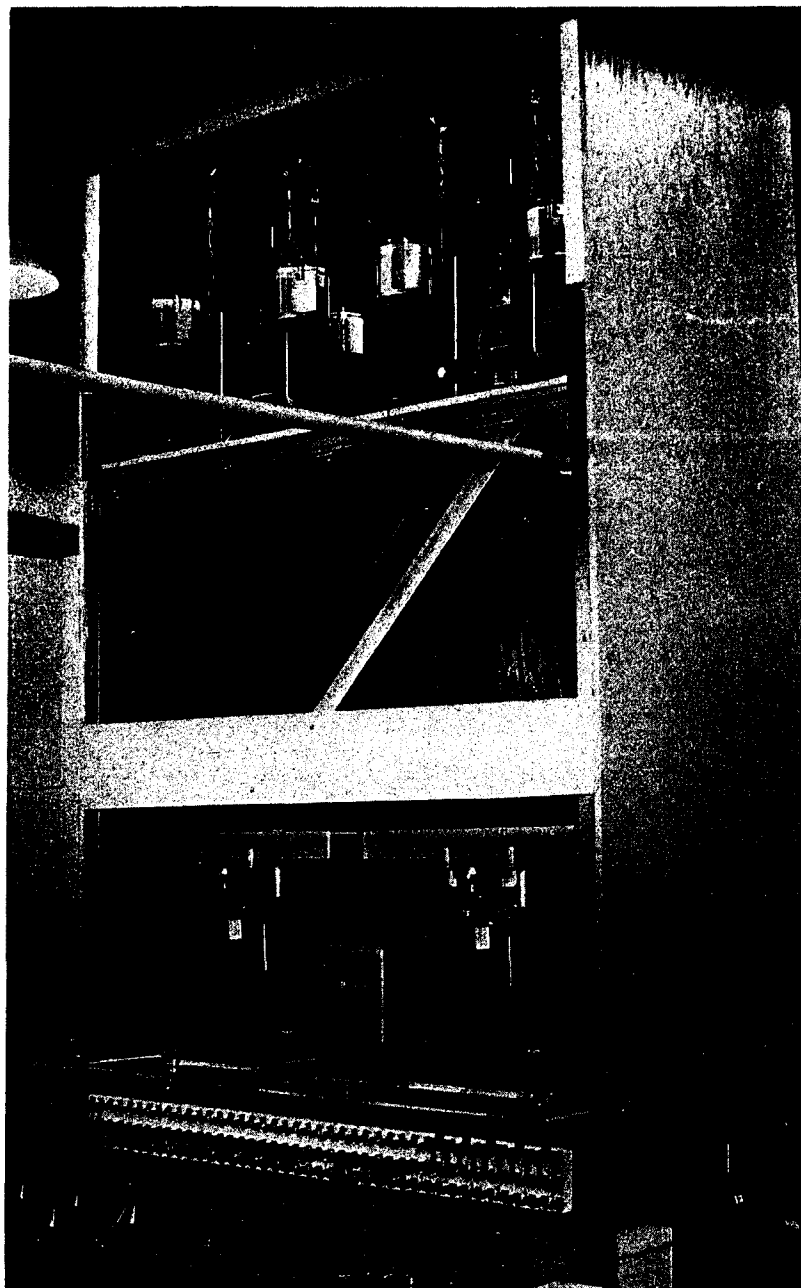


Figure 25. Temperature Measuring Test Bench with Cover Removed Showing Galvanometers and Galvanometer Suspension.

block with only an opening to allow insertion of a thermometer.

Twenty-nine thermocouples were located at various positions throughout the cryostat, test package, and oil bath. Most of these thermocouples were referenced to the copper block in the oil bath or to the copper jacket on the test cell. Those not referenced to one of these locations were differential thermocouples set up to measure the liquid levels of the hydrogen and nitrogen. The locations of these thermocouples are shown in Figure 26. These thermocouples were fed to a bank of 16 double-pole, double-throw knife switches on which the desired thermocouple was selected. All thermocouples were independent; that is, there were none with common reference junctions, or grounds. The location and type of thermocouples used in each location is given in Table 2.

The thermocouple junctions were made in all cases by soft soldering the wires together and then covering the junction with polyvinylchloride spaghetti.

The potential on the thermocouples was read on a Leeds and Northrup Wenner potentiometer, model 7559, s/n 1628187. This unit used a galvanometer identical to that described above for the measuring function and a Leeds and Northrup galvanometer, 2430 series, type E, for balancing the standard cell. The standard cell was an Epply, s/n 771283, enclosed in a styrofoam block. This cell was calibrated just prior to these tests. The low drift battery used for potentiometer power was also enclosed in a styrofoam box.

All thermocouple and thermometer lead junctions were enclosed in styrofoam blocks within an aluminum box to minimize spurious EMF's. These junctions were exclusively copper to copper. For the same reason all knife switches were located in a protected area (minimum drafts) and had a lucite sheet above them to protect them from the operator breath-

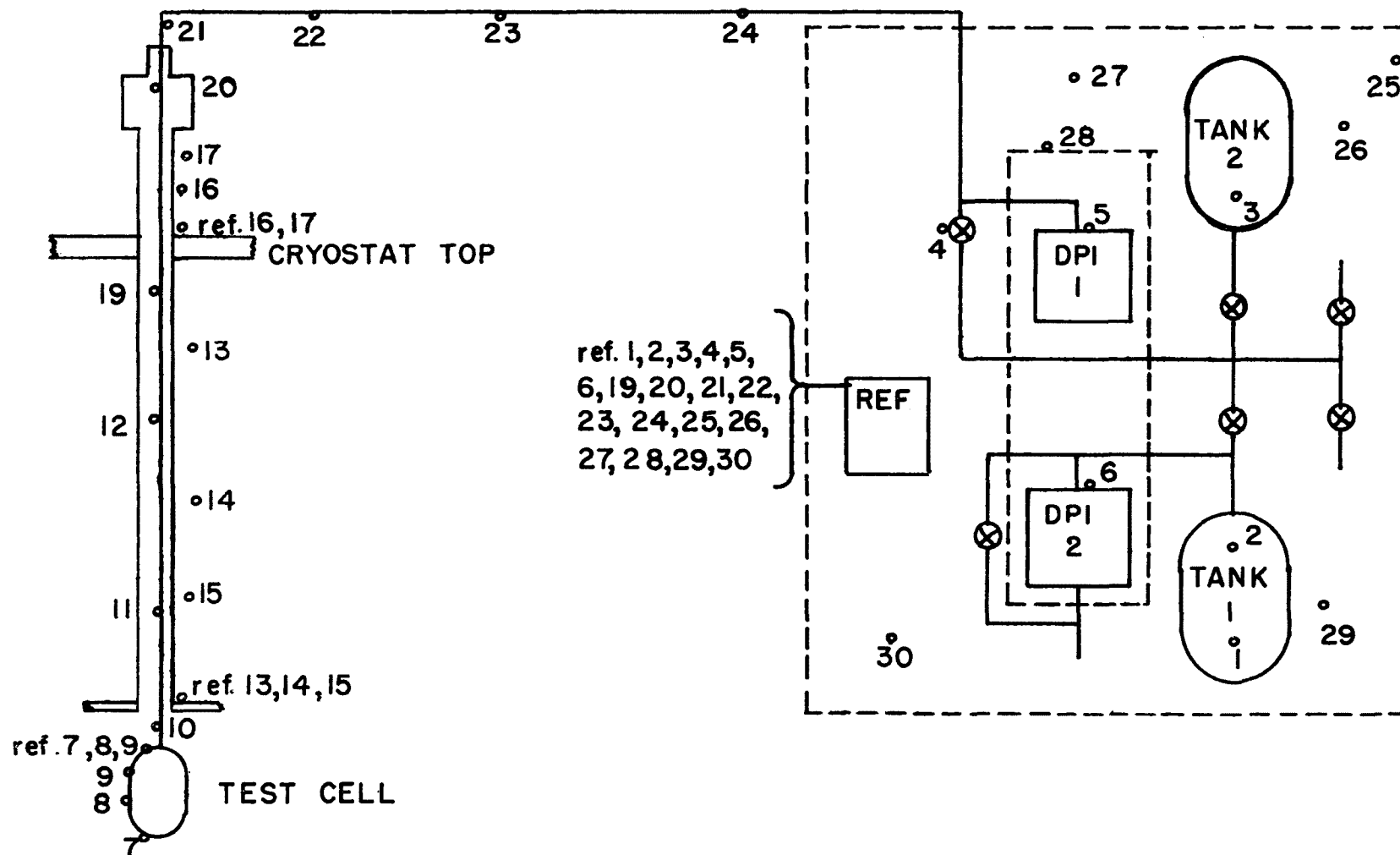


Figure 26. Location of Thermocouples within the System.

TABLE 2

THERMOCOUPLE LOCATIONS

Thermocouple Number	Type	Insulation	Location
#1	Cu-Con	a	Bottom Tank #1
#2	Cu-Con	a	Top Tank #1
#3	Cu-Con	a	Top Tank #2
#4	Cu-Con	a	Valve #1
#5	Cu-Con	a	DPI #1 top
#6	Cu-Con	a	DPI #2 top
#7	Cu-AuCo	b	Bottom Test Cell $\frac{1}{4}$ " from compensation pressure inlet
#8	Cu-AuCo	b	Test Cell Tangent Line $\frac{1}{4}$ " from support
#9	Cu-AuCo	b	Top Test Cell $\frac{3}{4}$ " down from Cu jacket edge
#10	Cu-AuCo	b	Lead Line 1" above cell top
#11	Cu-AuCo	b	Lead Line 6" above cell top
#12	Cu-AuCo	b	Lead Line $13\frac{1}{2}$ " above cell top
#13	Cu-Con	b	LH ₂ Level 15" above can
#14	Cu-Con	b	LH ₂ Level 10" above can
#15	Cu-Con	b	LH ₂ Level 5" above can
#16	Cu-Con	c	LN ₂ Level 2" above cryostat top
#17	Cu-Con	c	LN ₂ Level 3" above cryostat top
#18	Spare		
#19	Cu-Con	b	Lead Line $21\frac{1}{2}$ " above cell top
#20	Cu-Con	b	Lead Line 33" above cell top
#21	Cu-Con	b	Lead Line 96 $\frac{3}{8}$ " from end
#22	Cu-Con	b	Lead Line 67 $\frac{3}{8}$ " from end
#23	Cu-Con	b	Lead Line 56 $\frac{5}{8}$ " from end
#24	Cu-Con	b	Lead Line 19 $\frac{5}{8}$ " from end
#25	Cu-Con	a	Bath Wall (front right, high)
#26	Cu-Con	a	Fluid (front right, high)
#27	Cu-Con	a	Fluid (between box and wall, center front)
#28	Cu-Con	a	Box (top center)
#29	Cu-Con	a	Fluid (rear right, low)
#30	Cu-Con	a	Fluid (rear left, low)

^aWoven glass

^bExtruded teflon

^cTeflon enamel

ing on them.

10. VOLUME MEASURING SYSTEM

Figure 27 shows the volume measuring apparatus constructed for these tests and Figure 28 is a schematic diagram of this device. The system consisted of six precision bore glass tubes, an evacuation and gas filling system, and a mercury filling reservoir. The six precision bore tubes were of three sizes, with a diametrical tolerance of ± 0.0002 inches on each. There were three 1 inch diameter, two $3/8$ inch diameter, and one $1/8$ inch diameter tubes.

A mercury manometer with a high gain near zero was used to measure the system pressure and balance to atmospheric pressure.

The change of height of the mercury in the measuring tubes was determined with a Gaertner model 911 cathetometer which sat on the bench in front of the tubes. The close up lens for the cathetometer was required because of the short distance between the instrument and the tubes. This gave higher magnification and allowed better accuracy in reading the location.

A thumbtack was floated point up in tube number 4 to facilitate measurements. This was required because of the difficulty in locating the actual meniscus on the large tubes. Otherwise the reflections off the meniscus surface could not be separated from the background to locate a consistent point on the meniscus to the accuracy required in these measurements.

It should be pointed out that the volume above the mercury was minimized during construction of the unit to minimize the errors due to pressure differences before and after filling of the volume to be

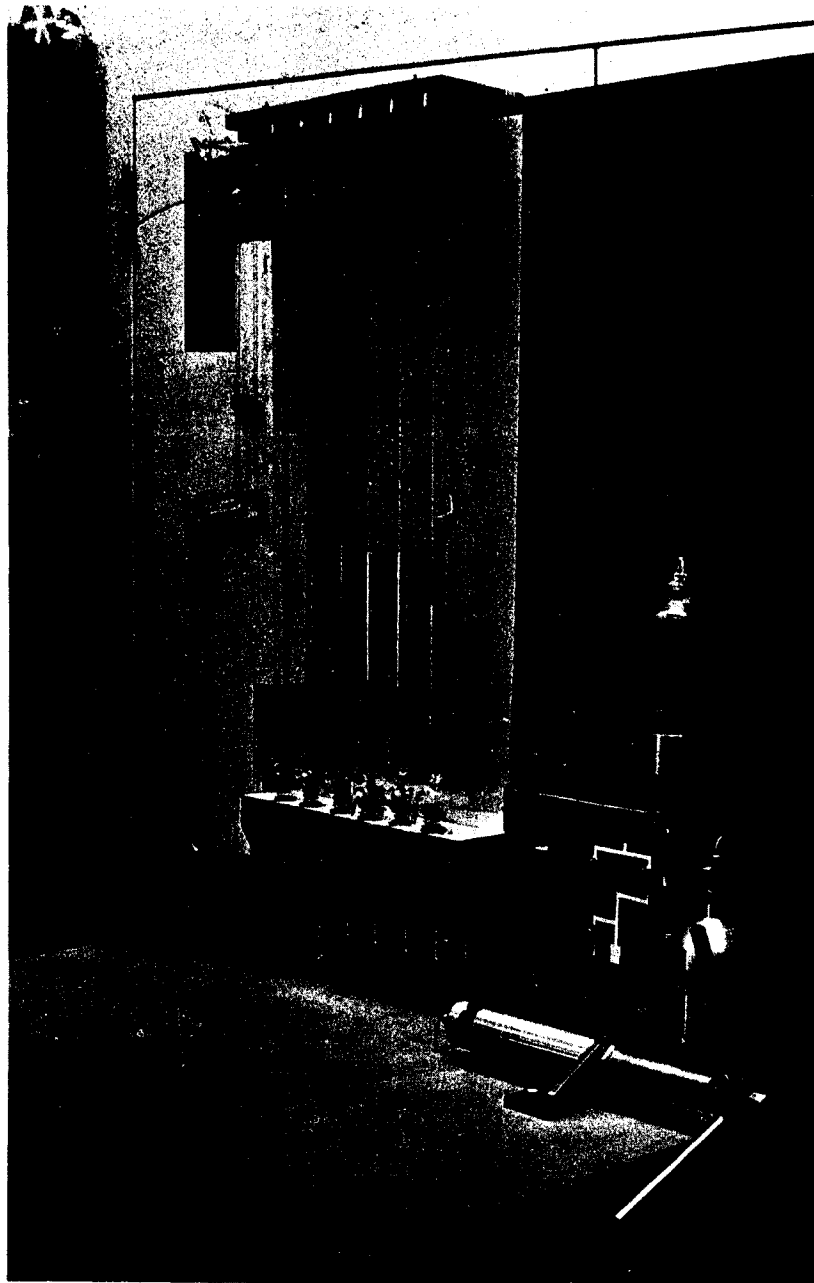


Figure 27. Volume Measuring Device.

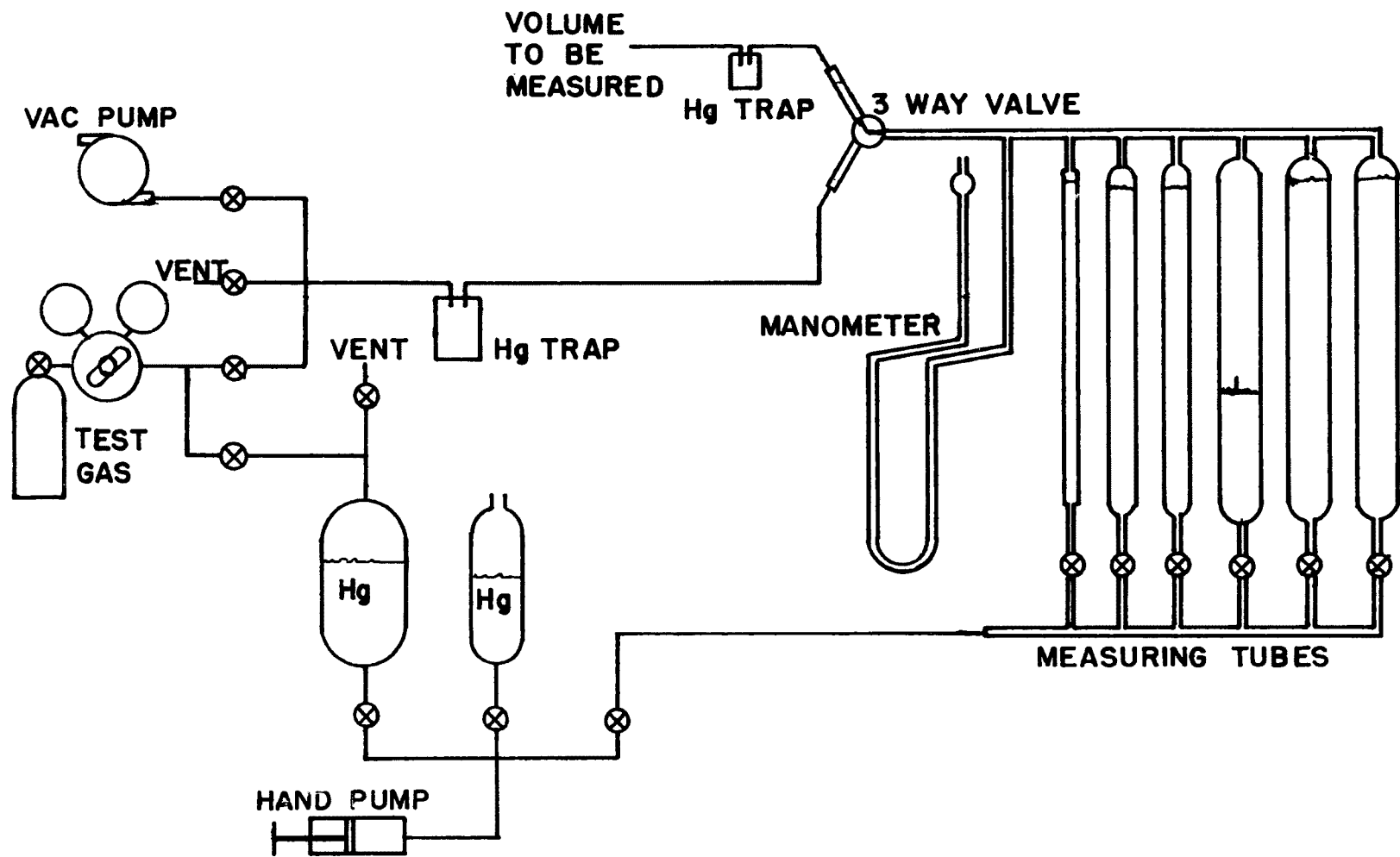


Figure 28. Volume Measuring Device Schematic.

measured. The black area at the top of the tubes in Figure 27 was a wax used to fill the excess volume and to seal the ground glass joints.

11. NEON SUPPLY

The neon supply system shown in Figure 29 consists only of a supply tank and a Ruska, model 2440, pressure intensifier. The intensifier was put into the system anticipating a much shorter run time due to loss of liquid hydrogen from the cryostat. The longer run time made it unnecessary to use the intensifier.

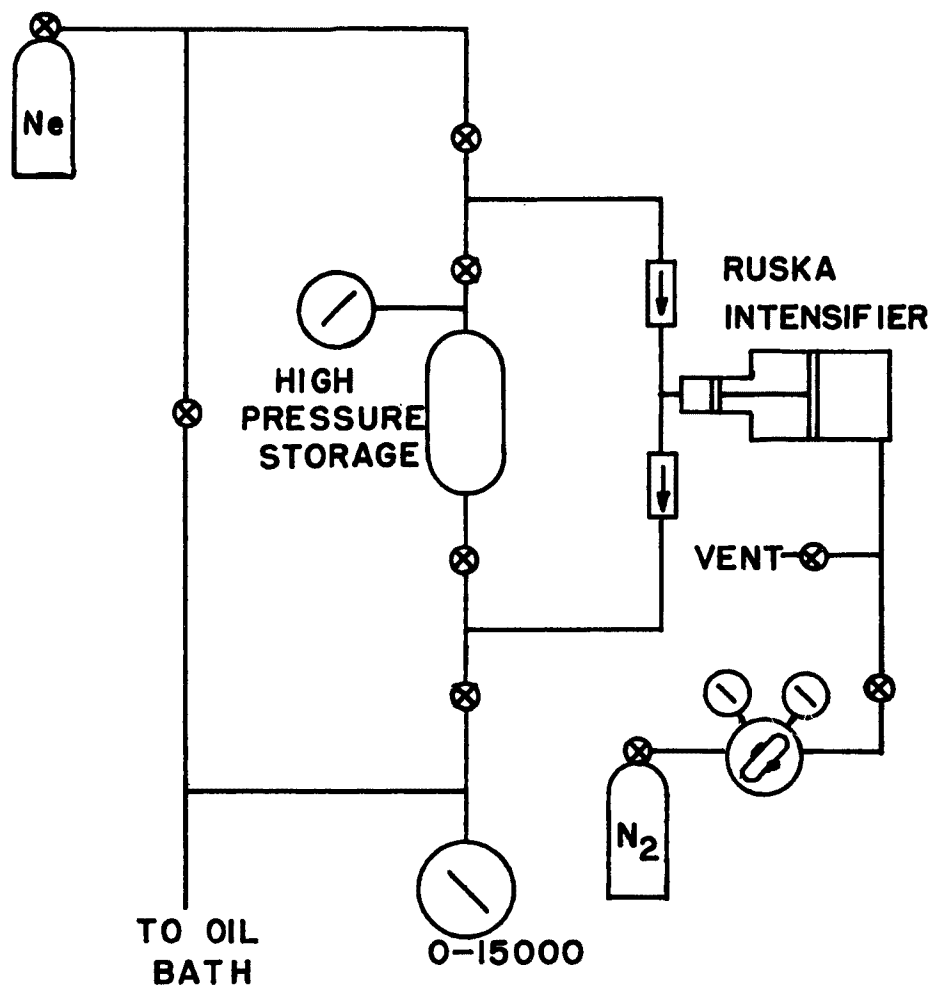


Figure 29. Neon Supply System Schematic.

CHAPTER V

PRELIMINARY TESTS

A number of tests were required before any density measurements of neon could be made. These tests were checks on the system operation and component calibration. The equipment, methods used, and results are discussed in this section.

1. LEAK TESTING

The entire system which was used with neon was tested under pressure and vacuum for leaks.

The pressure leak tests were done on the cell and associated plumbing at 5000 psi and at 500 psi for the expansion tanks and their associated plumbing. With the pressure in the system a liquid leak detection fluid was sprayed on all joints of the system one at a time. The joint was re-worked if there was any indication of leakage.

Vacuum leak detection was done with a Consolidated Electrodynamics leak detector. At the time of system testing, the leak detector had a sensitivity of 2×10^{-10} atm cc/sec per meter division. The system was not considered leak free as long as any increase in reading was detectable due to spraying any or all joints with helium. This does not mean that total leakage was less than the meter sensitivity since the entire system could not be submerged continuously in helium as would be required to get a leakage rate measurement.

When leak testing of the neon system was completed, no leakage was detectable by either method.

The vacuum system and insulation space around the cell was also leak tested to no indication on the leak tester.

2. VOLUME MEASUREMENTS

The method of operation of the volume measuring device shown in Figures 26 and 27 was as follows: The lead tube was attached to the volume to be measured. The mercury was raised in the tubes until the meniscus in the tube or tubes to be used was in the uniform section of the tube. The tube was then shut off. The three way valve was set to connect the system to be measured to the vacuum system. After the system was evacuated, the valve was rotated to connect the volume above the mercury in the tubes to the vacuum line. This portion was then filled with the test gas to atmospheric pressure. Next, the valve was rotated to connect the system to be measured to the volume above the mercury causing the gas to expand to fill the volume being measured. The pressure above the mercury was then brought back to atmospheric by filling the tube with mercury. The displacement of the mercury as read on a cathetometer then represented the volume of the system being measured.

Since this system measured all volume past the three way valve, at least two measurements were required to determine the volume of any given component. The volume of the connection line and mercury trap had to be subtracted from the measured system volume.

All measurements of volume of system components were made with the volume measuring device connection attached to the cell valve, either on the cell side for expansion tank volume measurements, or on

the expansion tank side for cell and DPI volume measurements.

In several cases it was necessary to know the volume change due to a valve closure. To do this, several readings were taken at different valve openings and then extrapolated to zero opening. For most of these measurements, part of the system was plugged off to minimize the total volume being measured at the time.

To reduce the possible error in measured volumes due to inaccuracies in setting the pressure at atmospheric, DPI one was used for pressure zeroing on all tests where possible in preference to the mercury manometer on the volume device.

A consistency of measurement check was made comparing the readings of the various tubes with one another. This check indicated a consistent difference in the measured volumes with different tubes. As a consequence, tube #4 was assumed as the standard and all volumes were adjusted to tube #4. These corrections amounted to 0.02 percent or less. This type of correction does not introduce more error even if tube #4 were the most inaccurate, since volume ratios only are of importance for the final results.

All readings were corrected to account for the difference in temperature between the measuring tube and the system being measured using a perfect gas relation. These corrections never exceeded 2.0°C at approximately 299°K. All volume measurements were made close to room temperature. The reason for this in preference to using the bath control was to avoid the probability of getting oil in the line when changes were made.

Measurements made with this system were repeatable to within 0.010 percent for the values averaged to obtain the final volume for the three largest volumes (that is, the cell and two expansion tanks).

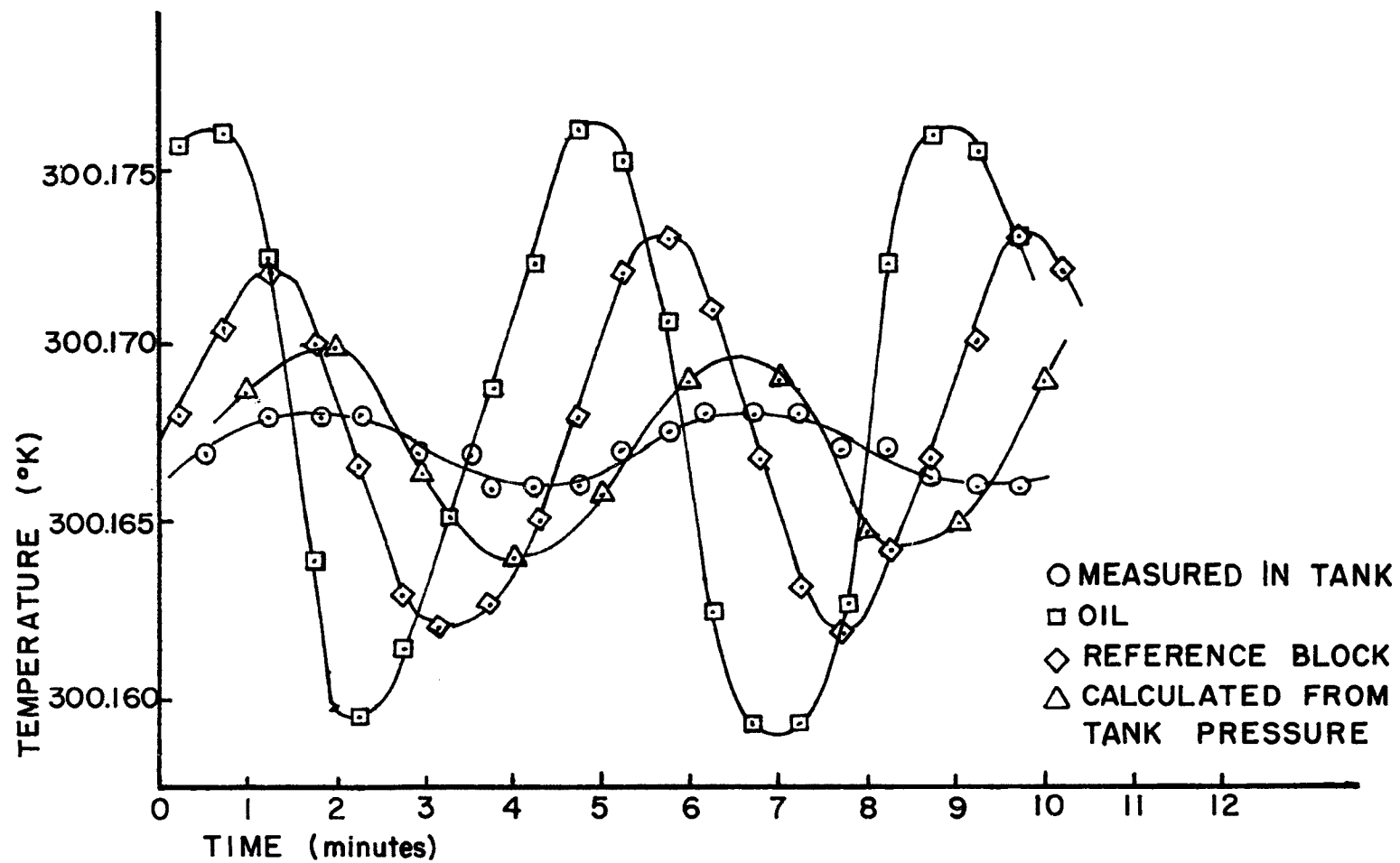


Figure 30. Temperatures in Oil Bath as a Function of Time.

4. THERMAL EXPANSION TESTS

The thermal strain of a specimen of the piece of stock from which the inner pieces of the test cell was constructed was measured. This was done by placing the specimen shown in Figure 31 in a cylindrical glass cryostat. The length of the specimen was then measured with a cathetometer in air and in water at room temperature to check the effect of the index of refraction on the measurement. No difference was noted when the specimen, cryostat, and cathetometer were aligned properly. Using this alignment, the length of the specimen was measured with the cathetometer with the specimen submerged in acetone containing solid carbon dioxide, in acetone at its freezing point (cooled with liquid nitrogen), or in liquid nitrogen.

Figure 32 shows the measured thermal strain of the material of which the test cell was constructed as compared with published values. The scatter in the measured data is about what would be expected from the accuracy of the cathetometer measurements. From this data it was assumed that the published data represents this specimen sufficiently accurately. The dashed line is the line which was actually used in calculation of the cell volumes as a function of temperature.

5. PRESSURE EXPANSION OF TANKS

The dilatation of the expansion tanks as a function of pressure was measured using the setup shown schematically in Figure 33. The tank to be measured was placed in a larger container filled with water and the container was sealed except for two holes. The two holes were used to remove any air bubbles in the water. After all the air was removed

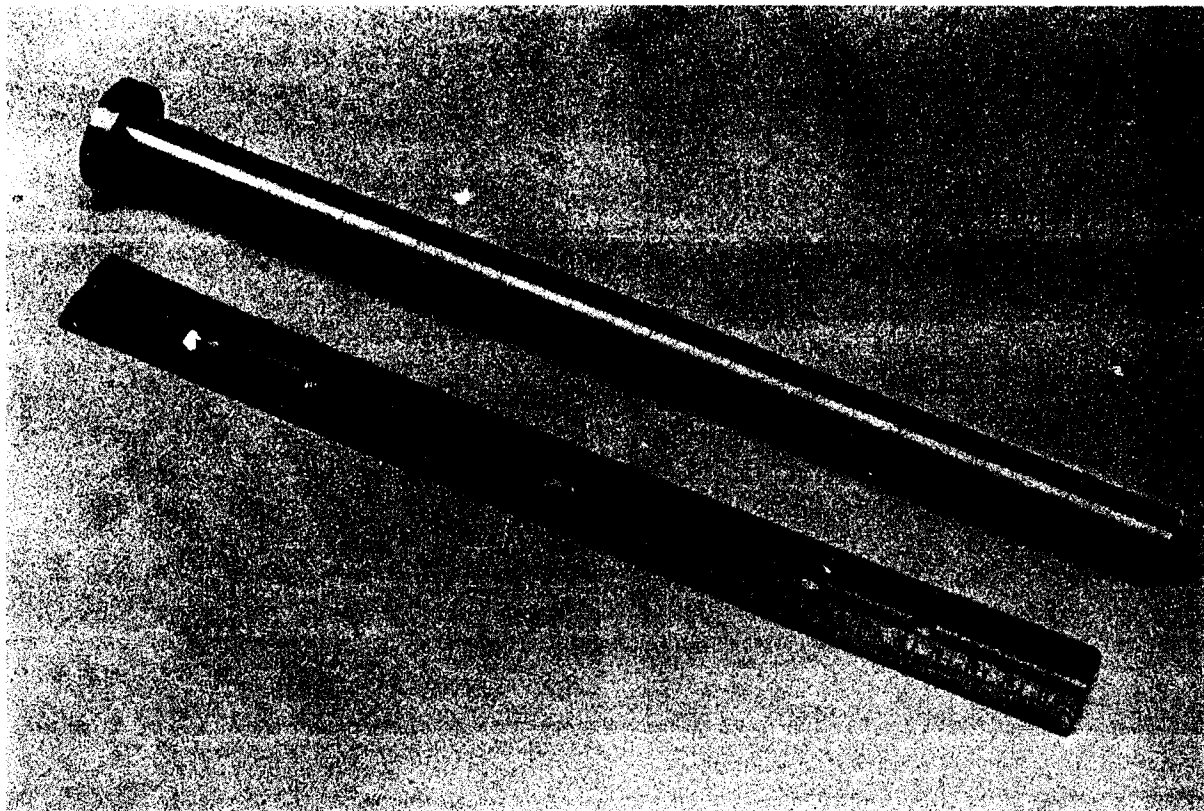


Figure 31. Thermal Expansion Test Specimen.

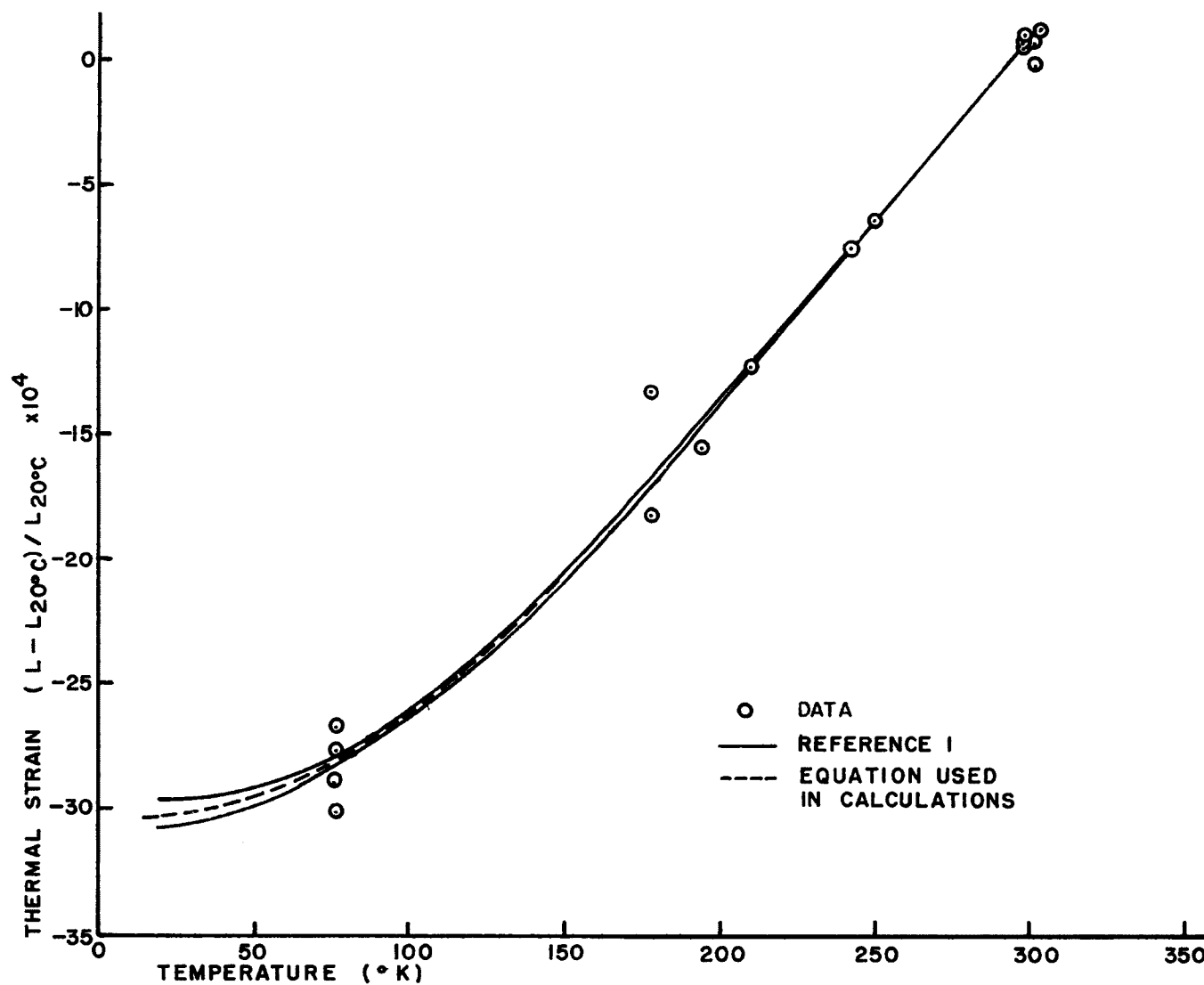


Figure 32. Measured Thermal Strain of Test Cell Material.

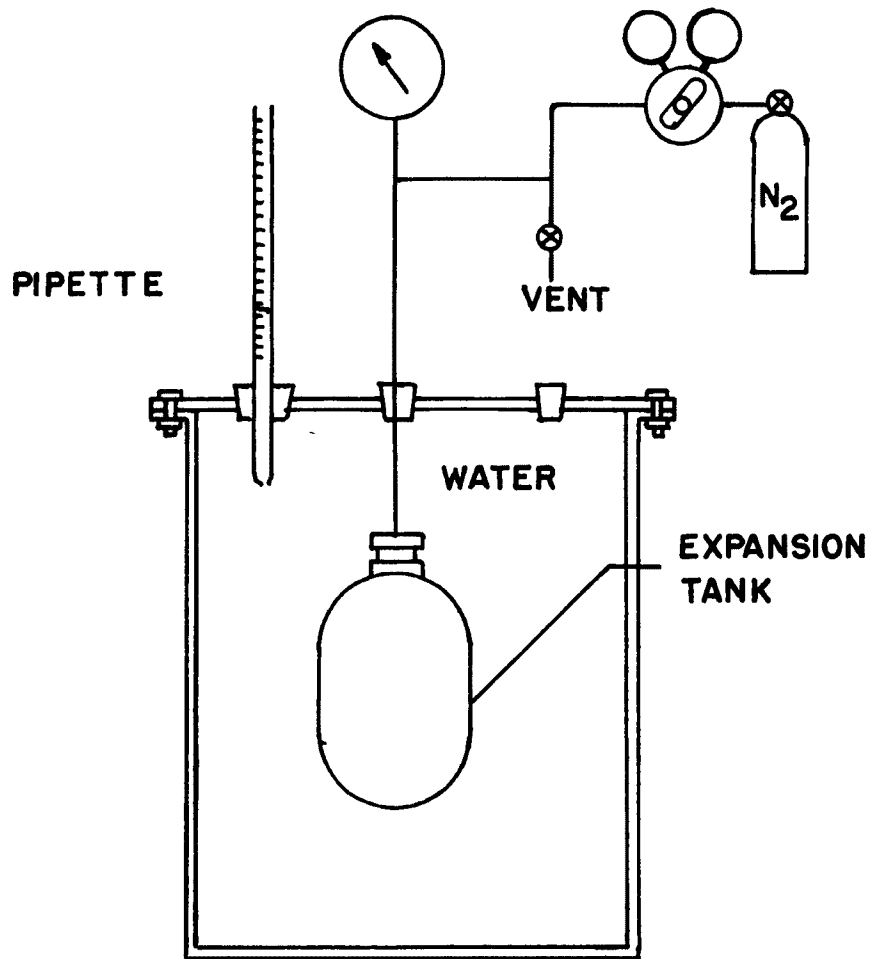


Figure 33. Method of Measuring Pressure Dilatation of Expansion Tanks.

one of the holes was sealed. A small measuring pipette was placed in the other hole and the water level adjusted to a measureable value. The expansion tank was then pressurized to a known pressure and the change in volume measured on the pipette.

The results of these tests are shown in Figure 34, and are linear with pressure within the accuracy of the measurement. The calculated value shown on Figure 34 is based on a uniform wall thickness calculated from the weight of the tank. Inspection of the tanks shows this to be a poor assumption.

These tests were made at 27°C which is very close to the temperature in the oil bath.

During these tests, the tanks contained the thermocouple wells, but only a short length of tubing was included. Because of the small tubing diameter (0.125 inch O. D. 0.035 well) the change in volume due to the plumbing should be completely negligible.

Even the effect of the thermocouple wells seems to have been negligible in spite of their thin walls, as one tank contained two wells while there was only one in the other. Still, the measured dilatation was the same for both tanks.

6. COMPRESSIBILITY OF NEON AT 300°K

The oil bath was placed in operation at the temperature to be used in the later tests. Expansion tank one was filled with neon to the desired pressure. Tank two was evacuated for several hours. The pressure in tank one was measured using the APG. The gas was then expanded into tank two, and the pressure was again measured. This process was repeated a number of times at several pressure levels up to 25 atm.

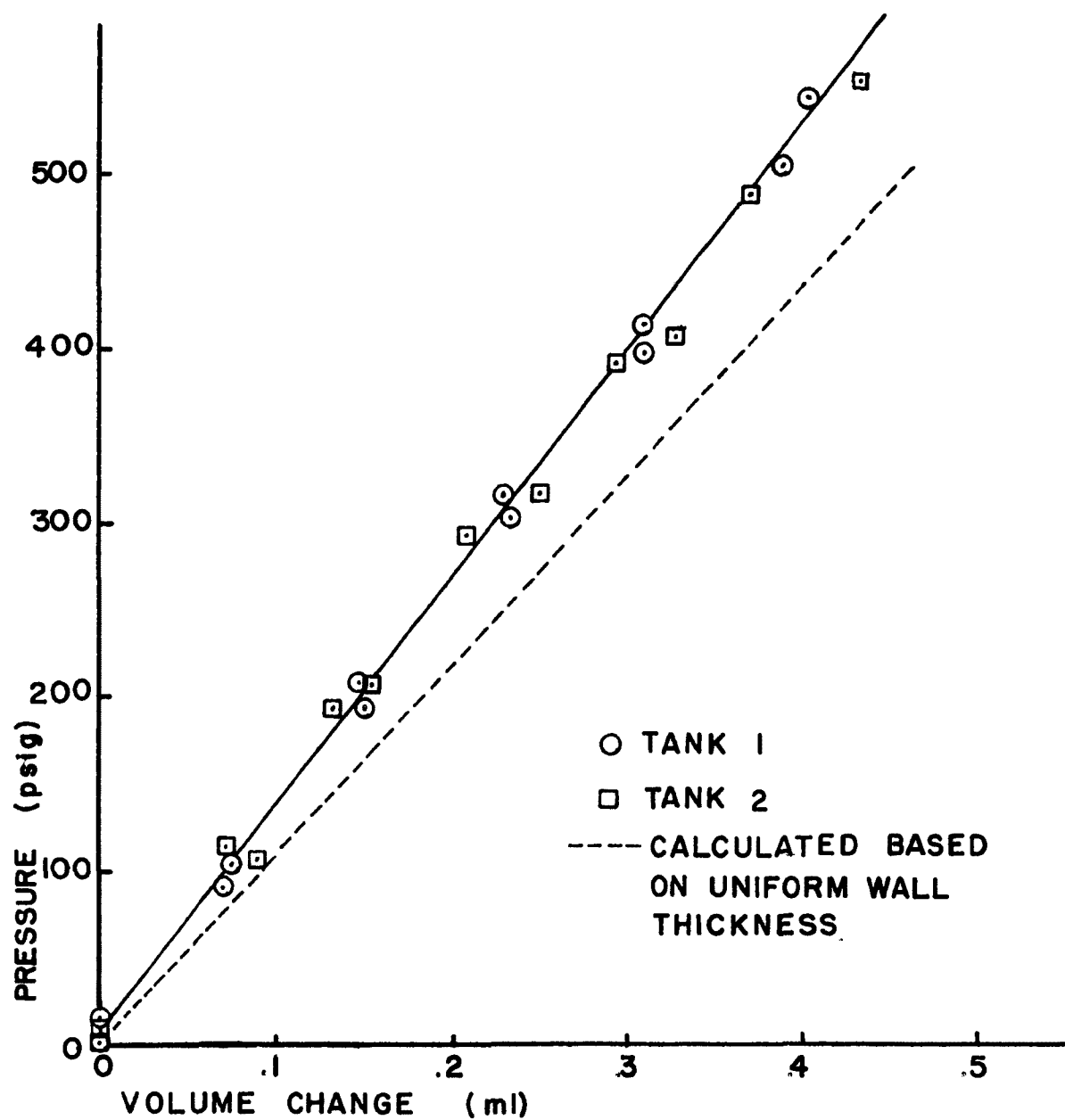


Figure 34. Volume Change of Expansion Tanks as a Function of Pressure.

The results of these tests were then plotted as a pressure ratio versus the final pressure. This plot is shown in Figure 35. This data contains the correction to the barometer reading discussed in a subsequent section. If a relation of the form

$$Z = 1 + BP \quad \text{eq. (8)}$$

is assumed where Z is the compressibility, P the pressure, and B is some coefficient, a relation for B can be written from the conservation of mass as:

$$B = \frac{K-1}{P_1 - KP_2} \quad \text{eq. (9)}$$

where

$$K = \frac{P_1 V_1 T_2}{P_2 V_2 T_1} \quad \text{eq. (10)}$$

and the subscripts 1 and 2 refer to conditions before and after an expansion, respectively.

The values of B obtained from these tests are shown in Figure 36 as a function of pressure as compared to published values interpolated to the same temperature. The value of B was assumed constant since no slope is indicated in Figure 36. The value of B that was used was 4.543×10^{-4} per atmosphere.

7. THERMOCOUPLE CALIBRATION

In the system were two types of thermocouples which were read during the actual testing whose values entered into the calculation of

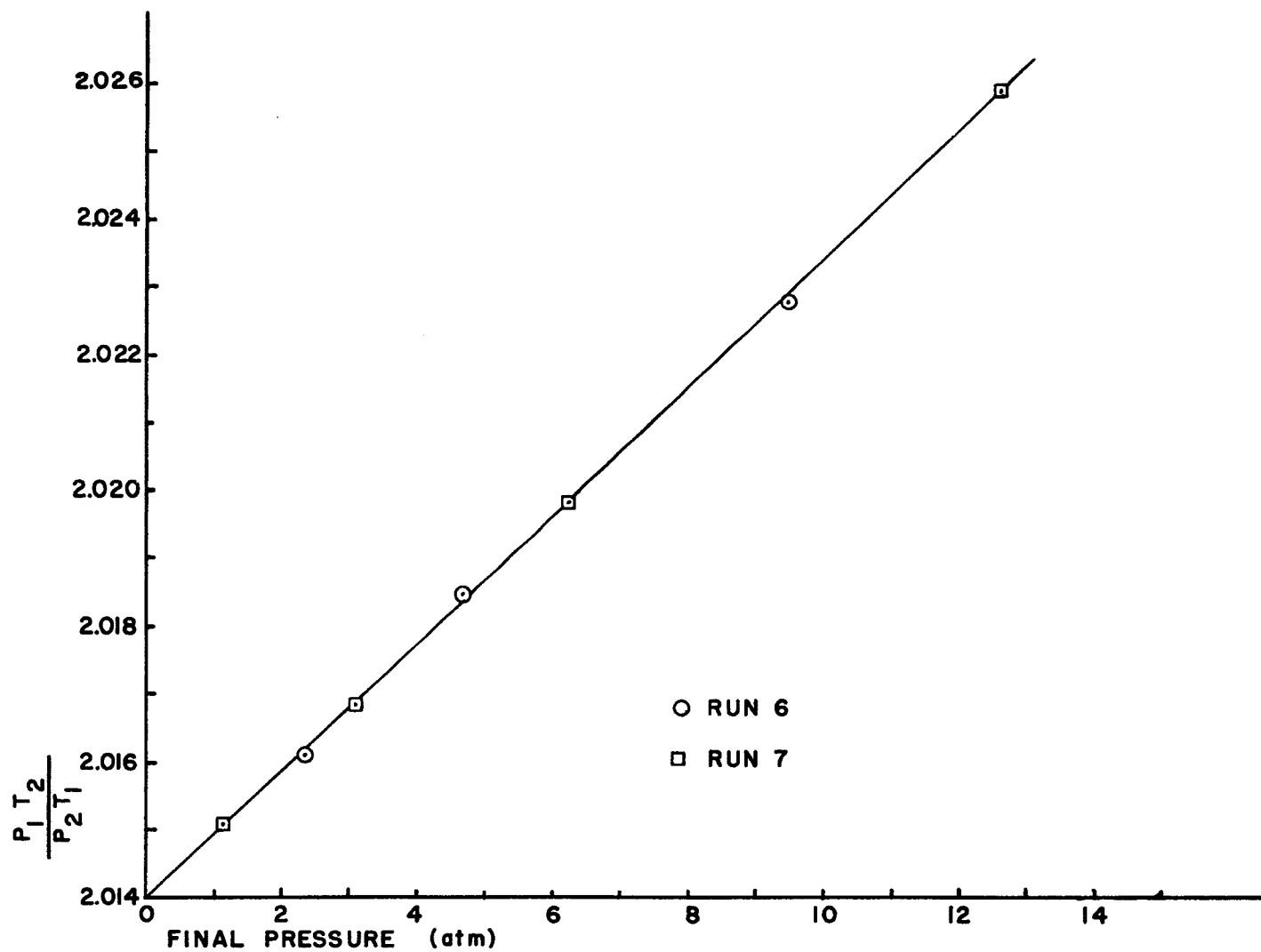


Figure 35. Compressibility Computation for Neon at 300°K.

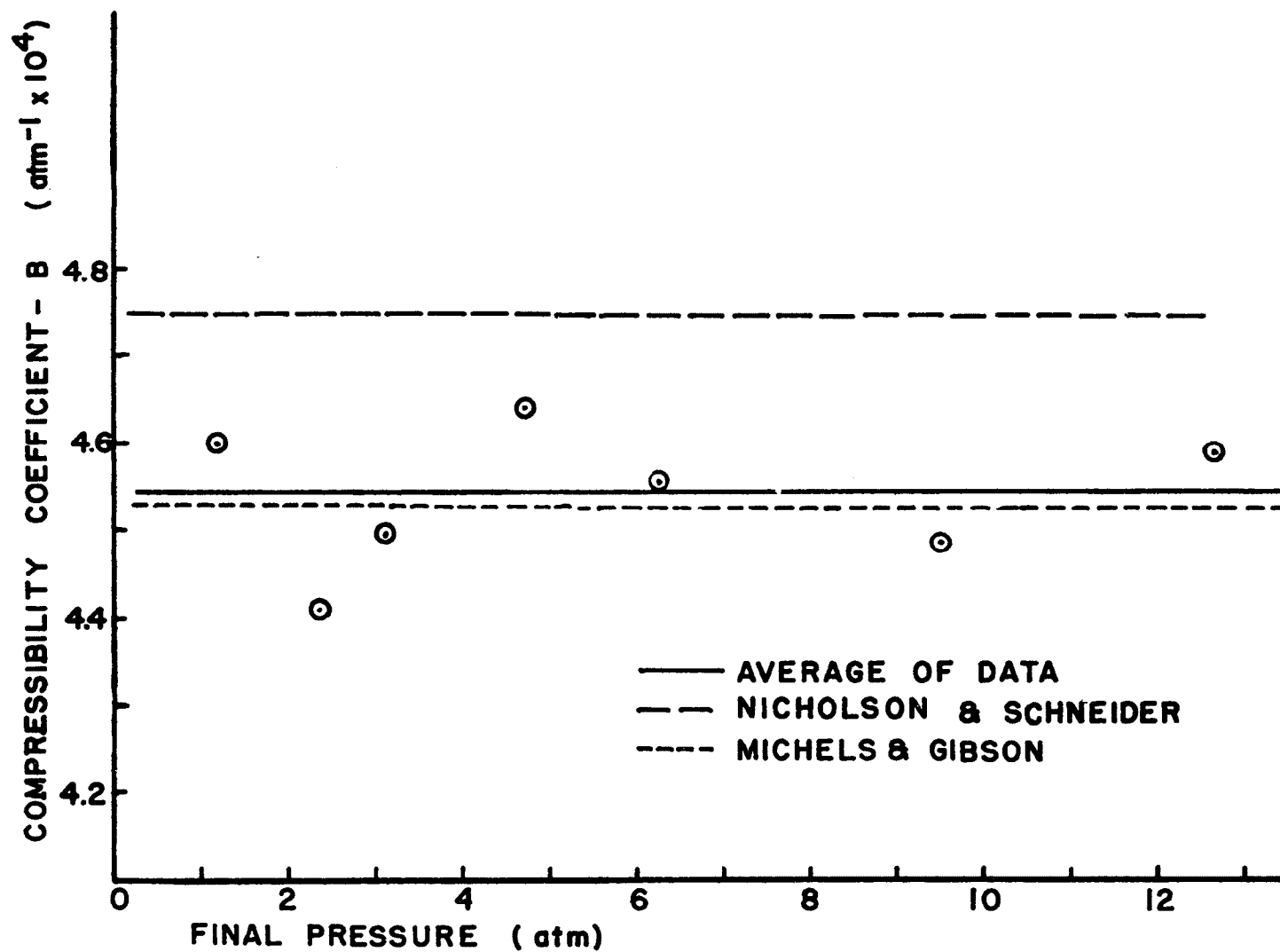


Figure 36. Compressibility Coefficients.

density. These were the copper-constantan and the gold cobalt-copper thermocouples on the tube connected to the test volume. As shown in Figure 26, and Table 2, thermocouples #19 and #20 are referenced to the oil bath and measure temperatures inside the cryostat.

The output of these thermocouples was checked at liquid nitrogen temperature by comparison with the two thermometers in the system. The cryostat and its guard bath were filled with liquid nitrogen. The transfer space was filled with helium to about 30 psig and the heaters were all turned off. When the system reached equilibrium, the thermocouples and thermometers were read. At this condition, the thermometers should read the same temperatures as felt by the junctions on the thermocouples.

The EMF obtained on both thermocouples agreed very closely with the value in reference 32. Therefore, the values from this reference were used as the thermocouple calibration. In Table 2 this calibration applied to thermocouples labeled extruded teflon.

The gold-cobalt-copper thermocouples were not calibrated. The calibration from reference 32 was assumed.

8. BAROMETER CALIBRATION

The barometer was checked by three independent means to check its accuracy. These means were (a) comparison with the air piston gage measurements of atmospheric pressure, (b) consistency of low pressure compressibility data, and (c) comparison with a "standard" barometer. Method b requires some explanation. When the pressure ratio of successive expansions from a Burnett type test is plotted versus pressure, the result should approach a straight line at low pressures. Tests were made using Sullivan's apparatus at low pressures at the ice point and also in

the mass measuring tanks of this apparatus. The dead weight gage was used on Sullivan's apparatus and the air piston gage, on the latter. Both sets of results showed less linearity at low pressures than at moderate pressures. To correct this condition it was necessary to make a constant additive correction to barometer readings to keep the ratio from dropping off rapidly at low pressures.

A correction of -0.54 mmHg was obtained by each of the first two methods. The correction as measured by the third method above was about -0.1 mmHg. The "standard" barometer had not been calibrated for several years and the reading accuracy was not sufficient to give a consistent correction value.

Therefore, a correction of -0.54 mmHg was added to all barometer readings used in the data reported herein.

9. LOCAL ACCELERATION OF GRAVITY

Several different values for the local acceleration of gravity have been used in this laboratory. From the usual accuracy standpoint the differences in these values are negligibly small. However, when the dead weight gage and air piston gage data are reduced it would be desirable to have any error introduced by the acceleration value used smaller than the gage inaccuracies. Therefore, a study was begun to obtain a value of the local acceleration of gravity such that the error would be negligibly small.

As near as can be found, no precision measurements of the local acceleration of gravity have been made at this location. Small differences in elevation and latitude would have to be accounted for even if a local measurement were available. The closest measurement to our

location was made at Willow Run Airport near Detroit, Michigan, as given in reference 40. This same reference also gives an anomaly chart for Michigan. It does not, however, give the equation used to determine the anomalies and the various equations given in references 36, 16, 2, and 38, differ by as much as $0.020 \text{ cm-sec}^{-2}$ in the calculated value for local acceleration. The local acceleration of gravity cannot then be calculated directly to the desired accuracy, and some other means of obtaining it must be found.

An anomaly is defined by the equation

$$A = g_f - g_m \quad \text{eq. (11)}$$

where A is the anomaly, g_f the calculated gravitational acceleration based on a particular gravity formula, and g_m the local measured value. "A" is then a function of the gravity formula used. However, if we write equation 11 for two locations, subtract the equations, and rearrange the terms, we get:

$$g_{m1} = g_{f1} + (g_{m2} - g_{f2}) + (A_2 - A_1) \quad \text{eq. (12)}$$

The last term in this relation is not a function of the gravity formula used in the other terms (within the accuracy desired here). This may be shown by considering the value of this for two known locations as in Table 4 for Willow Run, Michigan and Lansing, Michigan.

From reference 40, the difference in anomalies between Willow Run and Ann Arbor ($A_2 - A_1$) is $-0.006 \text{ cm-sec}^{-2}$. This, when applied to equation 12 using Willow Run data and any of the five equations, gives a value of $980.302 \text{ cm-sec}^{-2}$.

TABLE 4

ANOMALY COMPARISON

Gravity Equation Reference	Anomaly at Willow Run	Anomaly at Lansing	Awr - A1
36	-0.0065	-0.0042	-0.0023
16	-0.0199	-0.0177	-0.0022
2 (1)	-0.0001	0.0023	-0.0024
2 (2)	-0.0002	0.0021	-0.0023
38	-0.0059	-0.0038	-0.0021

Another method would be to find which equation gives anomalies the same as shown on the anomaly chart for Michigan from reference 40. As near as the chart can be read, the anomalies from the equation of reference 16 match those given in the chart for known points close to Ann Arbor. This equation gives a value of $980.302 \text{ cm-sec}^{-2}$ directly when applied with equation 11.

10. CALIBRATION OF THERMOTROL

It was necessary to calibrate the coarse setting on the Thermotrol to know the temperature which corresponded to a given setting. This calibration was limited to the coarse dial since maximum repeatability of settings on the coarse dial corresponded to about one-quarter of the range of the fine adjustment.

The Thermotrol unit was placed in operation with the reference resistor connected, but with two decade resistance boxes in parallel in place of the sensing element. The decade boxes did not have sufficiently

small resistance increments to obtain the needed steps for low temperatures. The larger increments of the decade boxes were sufficient by using the boxes in parallel.

With the Thermotrol set for on-off operation with maximum gain, the Thermotrol coarse settings corresponding to a given resistance setting were found. Since there was some hysteresis in this, the average of the on and off settings was used. These measurements were made with the fine adjustment set on 500.

The platinum resistance thermometers used as cell temperature sensors for the Thermotrol were checked at Liquid nitrogen temperature to see if their resistance agreed with the values published by the manufacturer. Since the value agreed with the published value, the resistance parameter between the setting and the temperature was eliminated and a calibration obtained. This calibration included everything but the lead wire resistance, which was significant compared to the sensor resistance at low temperatures.

The calibration curve was then checked at nitrogen temperatures with the sensors installed on the cell. From this data a shift from the curve obtained above was evident, presumably due to lead wire resistance. This shift was then added to the data to obtain the calibration curve given in Figure 37. By virtue of the lead wire arrangement shown in Figure 13, this shift was constant at all temperatures.

The slope of the calibration curve is such that on the coarse adjustment, one division corresponds to about 0.2°K . The fine adjustment has a gain which is lower by about a thousand, giving about 0.0002°K per adjustment division.

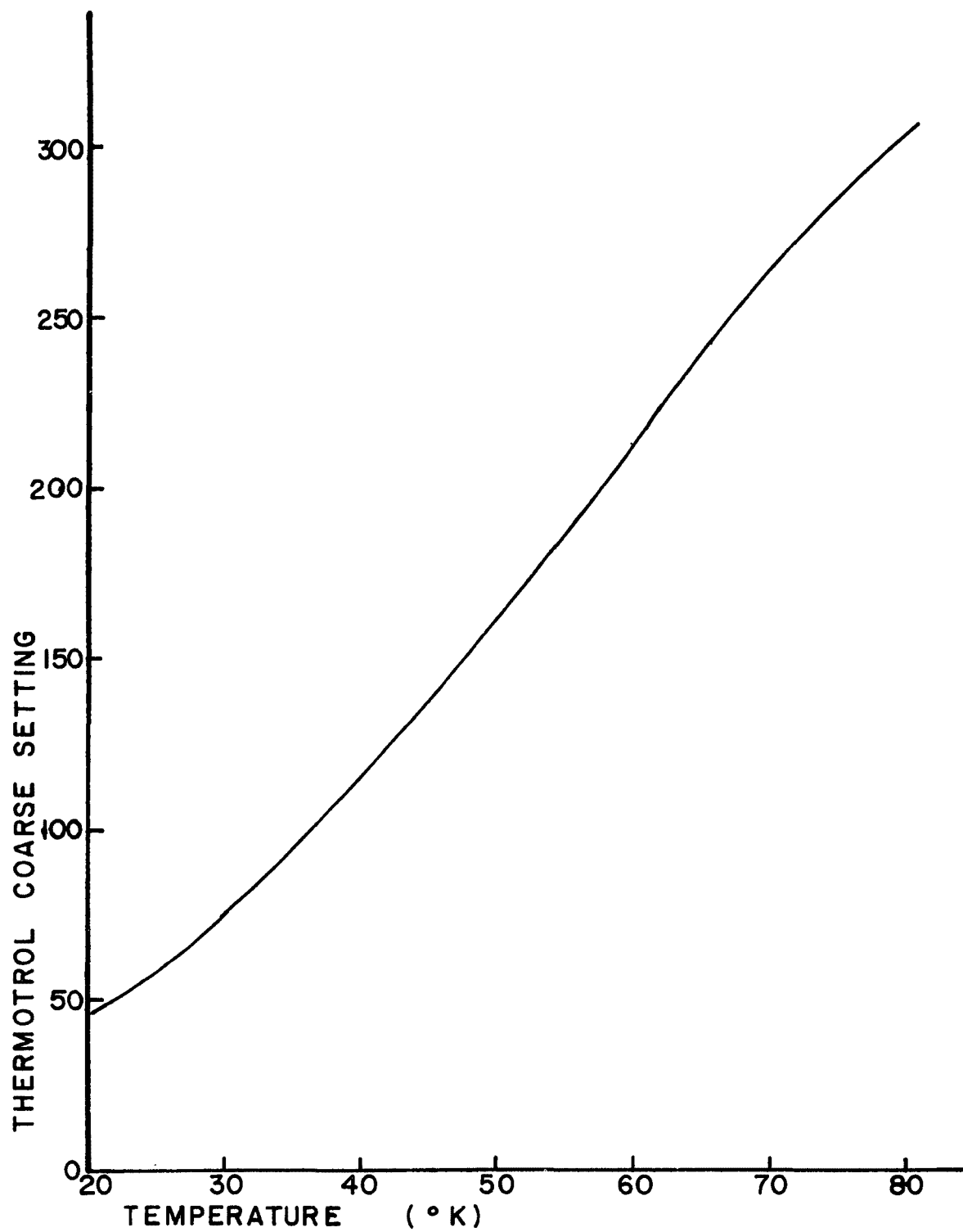


Figure 37. Thermotrol Calibration for Coarse Adjustment.

11. NEON ANALYSIS

The neon that was tested was research grade neon purchased from the Linde Division of Union Carbide. No detailed analysis was made on this container of neon. However, a cylinder filled at the same time was analyzed. This analysis should be the same except for the water content. Since the water comes primarily from the container, there is no way of knowing exactly what the water content would be; Linde guarantees this to be less than 3 ppm, however. Table 5 presents the analysis of the cylinder filled at the same time as that used in these tests. This analysis should represent the gas actually used fairly well.

TABLE 5

ANALYSIS OF NEON

Helium	5 ppm
Nitrogen	2 ppm
Water	1 ppm
All other impurity	< 1 ppm

CHAPTER VI

DENSITY MEASUREMENT TEST METHODS

1. SYSTEM FINAL PREPARATION

The DPI controls were turned on and allowed to warm up for approximately a day. The valve across DPI two was opened and the instrument zero set. The valve was closed and the APG side of the DPI cell was pressurized to 500 psi. After opening the valve again, the zero was checked and readjusted as required to bring it to zero. The pressurization was repeated until no shift occurred.

DPI one was zeroed by opening the valves into the vacuum header and the atmospheric vent. The manometer valve was also opened and the liquid level adjusted to zero. After about ten minutes in this condition the instrument was set at zero. The liquid side was then closed up and pressurized to remove the zero shift as explained above. From this point on a positive pressure was maintained on the liquid side of this DPI. The DPI amplifiers were left turned on until after completion of the tests.

A cylinder of good quality neon was attached to the system. The system, including the pressure intensifier, was evacuated for several hours to about 100 micron and filled with neon. This process was repeated four times. The system sat in this condition for about 30 days awaiting arrival of the neon actually tested. At that time, the new cylinder was attached to the system. The pressure intensifier system

was closed off and was not used in these tests. The system was then purged three more times.

The oil bath was turned on and the cooling water flow rate adjusted. A small water flow was maintained through the cooling coils at all times. The second flow rate was set at about five times the lower value.

The complete check out of the Mueller bridge was done, including ratio setting, zero, and the comparison with the standard resistor. The comparison with the standard resistor and the instrument zero check were then made at least once a day thereafter. The thermostat on the bridge was then left turned on at all times.

The transfer space around the cell and the pressure compensation system were purged and filled with helium to remove anything which might condense and give trouble during operation.

2. GENERAL TEST PROCEDURE

The system was prepared according to the method given above. A single point was selected which would give the density desired for the highest density isochore to be run. This did not have to be at a test temperature, but could be. The system was then filled with neon until the point was reached. A series of points at different temperatures along the isochore were then measured. The density in the test cell was changed by expanding some of the gas from the cell into the expansion tanks. This mass in the tanks was then measured. The second series of points was then measured using, wherever possible, the same temperatures as used the first time. This procedure was repeated for several isochores, following which the mass of neon remaining in the

system was measured.

Each set of data taken was given a point number. The first two digits of the number were the run number. The second two digits were assigned in consecutive order for each pressure measurement made. Any series of points using the same gas were considered a single run. That is, the system was filled with neon once for each run.

For each run the densities were spaced so that the points for other runs would fall between them to give some check on the consistency between runs.

The following paragraphs describe the method in more detail.

3. FILLING PROCEDURE

The transfer space was filled with helium to about 30 psig and the pressure compensation volume was filled to about 2500 psi. This was to provide good heat transfer to the cell for rapid cooling.

The cryostat was filled with liquid nitrogen and allowed to sit for several hours to get the cell to as low a temperature as possible. The nitrogen was removed from the cryostat after the pre-cooling by inserting a tube to the bottom of the cryostat and pressurizing the cryostat. The cryostat was then evacuated. The nitrogen remaining after use of the tube was removed by evacuation and the heater in the bottom of the cryostat. After purging the cryostat, fill, vent, and control lines, the cryostat was filled with liquid hydrogen. The liquid nitrogen bath on top of the cryostat was kept filled after the initial pre-cooling of the cryostat.

A filling temperature and pressure point on the lower portion of the liquid-vapor line was selected to give the desired maximum den-

sity for the run. Before the cell reached this temperature, mass was added to the cell, which tended to prevent further lowering of the temperature. The supply pressure was kept just above the filling pressure so that the flow in would balance the condensation of the neon. As the rate of change of pressure indicated that the cell was getting full of liquid, the transfer space was evacuated. The heaters were turned on and adjusted to hold the desired temperature. More neon was added until the desired temperature and pressure were reached. Using this method, a pressure above the saturation pressure had to be used.

The evacuation of the transfer space continued until a pressure of between 15 and 30 microns was reached. This space was then closed off for the running of a complete isochore.

At this point the valve to the cell was tightly closed.

4. METHOD OF TEST FOR DATA POINTS

The procedure used on data points amounted to bringing the cell to the desired temperature and holding it long enough for the cell to reach equilibrium and the data to be read. Two methods were used to do this. The first method was using the automatic temperature control, and the second slightly different method was manual.

The automatic temperature controller was set to the desired temperature using the coarse adjustment. As the desired temperature was approached as read on the cell thermometer, the fine adjustment was set by a trial and error method to bring the cell temperature to the desired value. In order to keep the unit stable, the heater gain was held low by keeping the three heaters on steady at a heating rate that would not quite hold the desired temperature. The Thermotrol output voltage was

then set low, and the Thermotrol made up the difference in heating rate on the other heater.

During the run, if the Thermotrol stopped functioning manual control of the heaters was used. This was faster, but less consistent; nevertheless, it was possible to manually set the heating rates sufficiently accurately for most of the data. The heaters were set to bring the cell to about 0.1°K below the desired temperature. The heating rate to the cell was adjusted to where it would just allow a perceivable cooling. The other set of cell heaters was set at a low voltage and used intermittently to increase the temperature slightly.

When a temperature about 0.03°K below the desired temperature was reached, the cell pressure was measured and the compensation pressure was set. The DWG was balanced and kept in approximate balance until the point was measured.

While trying to hold the temperature constant, the bridge was adjusted to where both the normal and reverse readings were approximately equal. This was done by taking the average of the two readings, setting the average on the instrument, and adjusting the lead resistance fine adjustment for zero galvanometer deflection.

The temperature of the cell was then increased in small, timed increments to where the cell temperature was within $\pm 0.01^{\circ}\text{K}$ of the desired temperature. The DWG was carefully balanced to where it would stay on scale while the temperature fluctuated slightly while efforts were made to hold the temperature within tolerance for about ten minutes. The temperature was held for a longer period of time if there was any evidence of a continual change in pressure in one direction. At the end of this time, readings of the thermometer, thermocouples, barometer, DWG temperature, compensation pressure, heater settings, and weights

used were taken in rapid succession in the order mentioned.

The temperature of the oil bath was not read each time, but an average value was used which was taken every several hours. It was felt that using the average value would induce less error than allowing the other values to change with time while this temperature was read.

No attempt was made to hold the temperature constant after the beginning of the reading of the data when manual control was used. Consequently the temperature or pressure was sometimes out of tolerance before the readings were completed.

The entire process of making a measurement generally required about 30 minutes after the temperature was stabilized within a tenth of a degree. Some points, notably those at low density and high temperatures, required considerably longer. The points very near the critical point often required several hours and still it was not always possible to maintain the tolerance indicated above.

The above process was repeated for each desired temperature on a given isochore.

5. CHANGING ISOCHORES

The valve to DPI two in the APG system was closed; the expansion tank valves and the zeroing valve on DPI two were opened and the system was evacuated to about twenty microns or below. In this condition DPI two was checked for zero setting. Most of the time no change in zero setting was required, but occasionally the galvanometer would be off scale and would require adjustment.

The vacuum system valve and DPI two zeroing valve were closed tightly, and the DPI valve in the APG control system and the expansion

tank valves were opened completely.

The APG system was pressurized to a pressure just below the pressure desired in the expansion tanks when filled with neon from the cell. This pressure was calculated based on the estimated change in density desired in the test cell. The valve to the test cell was opened until DPI two indicated the set pressure had been reached. The APG system pressure was then increased and more mass allowed to come into the expansion tanks until the desired pressure was reached.

The valve to the cell was again closed tightly.

After time had been allowed for the temperature in the expansion tanks to reach the bath temperature, the APG was balanced using the procedure outlined below. The balance was made such that as the bath temperature changed the pressure would only go below that set on the gage (see Figure 30).

The temperature of the bath was read when DPI two returned to the zero position. The barometric pressure, gage, and temperature conditions were then read immediately.

6. CELL MASS DETERMINATION

When the density in the cell was 0.1 gms/cc or less, the total mass remaining in the system could be measured using the method developed in Chapter 4.

The mass measuring system was evacuated and DPI two zeroed as given above. Expansion tank two valve, the vacuum system valve, and DPI two zeroing valve were closed. The valve to the test cell was opened completely.

The cell temperature was brought to $70.00 \pm 0.01^{\circ}\text{K}$ using the

methods given above for the data points. As the temperature was approached, the compensation pressure was set, and DPI one was set on zero using the two valves in the supply line. As the temperature closely approached the desired value, the APG was balanced.

With the cell temperature and the oil bath temperature varying slightly, a real juggling act was required to bring the APG into balance at the same time the cell temperature was within tolerance. As the cell temperature was the least critical, it was allowed lowest priority. Consequently, some of the temperatures during mass measurements vary from $70.00 \pm 0.01^\circ\text{K}$. Whenever possible, the automatic temperature control system was used for these measurements.

After the data was recorded for this condition, the valve to tank two was opened and the above process was repeated. The second time it was essential that the cell temperature be the same as the first time.

7. PRESSURE MEASUREMENT WITH THE AIR PISTON GAGE

Before the system in which the pressure was to be measured was pressurized, the pressure in the air piston gage system (APG) was set at a value as high or higher than the pressure in the measured system would go. The purpose of this was to prevent zero shifts of the DPI due to pressure reversal. As the pressure in the measured system became steady, the pressure in the APG system was decreased slowly using the needle valve on the vent. As the DPI indicated that the pressure was reached, the needle valve was closed. Using the hand pressure generator, the DPI galvanometer was brought to zero. If it did not stay in that position, the four needle valves (inlet, vent, and two leakage compensation) were adjusted until the galvanometer would hold at any posi-

tion to which it was set using the hand pump. DPI two exhibited a false null condition on both sides of the true null so that when the pressure was far too high or low the needle would indicate an on-scale reading. Fortunately, the false null would never give a zero value. The false null was also detectable because of its low gain. Zero was used as the point to which the galvanometer was balanced while adjusting the needle valves to balance the leakage.

With the galvanometer at zero, the pressure in the APG system was read from the Heise gage and recorded on the data sheet. The proper piston and weight set was then selected to get the most accurate reading. This may have necessitated a change of piston or back pressure. If this were the case, the APG system would require some shutdown. If the low range piston was to be installed, the APG gage valve was then closed and installation of the piston was made in accordance with the manufacturers instructions. If the high range piston was to be installed, the DPI valve was closed, the APG system pressure was reduced, and the piston was installed. The piston was then tested for proper function by the period of oscillation test suggested by the manufacturer. If the period was too low the piston was washed in accordance with the manufacturers cleaning instructions. This test was essential for every installation of the high range piston because of the extreme sensitivity of the piston to dirt and lint.

After any changes in the setup, the APG system pressure was re-adjusted using the method given above.

Once the pressure was again balanced with the galvanometer on zero, the weights indicated by the Heise gage were placed on the APG gage. The drive motor was turned on. If the piston was still at the top, more weights were added in decreasing increments. The weight was

left on as long as the piston remained at the top with the galvanometer on zero. At increments equivalent to 0.01 psi or less, the piston was floated using the hand pump. The pressure being too high or low was then used as the criterion for using a given weight.

This method prevents zero shifts of the DPI because the addition of the largest weight would not cause pressure changes of large enough magnitude to cause a zero shift. If, however, a significant pressure reversal occurred, the APG system was pressurized to 500 psi and then the pressure rebalanced. If the low range piston was in use, the gage had to be shut off to prevent overpressurizing the piston while taking out any zero shift of the DPI.

CHAPTER VII

DATA REDUCTION METHODS

1. PRESSURE REDUCTION--APG

The pressure was calculated from the data taken on the air piston gage using a computer program following the method given by the gage manufacturer.

The apparent mass of each weight used was added to the apparent mass of the piston and weight table (if applicable). This sum was then divided by the nominal piston area and the barometric pressure added to get the nominal pressure. The true pressure was obtained by multiplying the nominal pressure by a correction term which corrected for gage temperature, local acceleration of gravity, weight buoyancy, and true piston effective area. The net equations for this for the low range piston were:

$$P_{\text{nom}} = \left(M_p + M_{\text{wt}} + \sum_i M_i \right) / 0.520296 + P_{\text{bar}} \quad \text{eq. (13)}$$

$$P = P_{\text{nom}} \left(\frac{980.302}{980.665} \cdot \frac{0.520296}{0.520266} - 10^{-5} P_{\text{bar}} + (20 - T_g) 2 \times 10^{-5} \right) \quad \text{eq. (14)}$$

The corresponding equations for the high range piston were:

$$P_{\text{nom}} = \frac{M_p + M_{\text{wt}} + \sum_i M_i}{0.0130074} + P_{\text{bar}} \quad \text{eq. (15)}$$

$$P = P_{\text{nom}} \left(\frac{980.302}{980.665} \cdot \frac{0.0130074}{0.0130045} + 10^{-5} (20 - T_g) - 10^{-5} P_{\text{bar}} \right) \quad \text{eq. (16)}$$

Where:

- P_{nom} is the nominal pressure value,
- M_p is the apparent weight of piston and weight pan,
- M_{wt} is the apparent weight of small weights,
- M_i is the apparent weight of weights used,
- P_{bar} is the pressure surrounding weights,
- T_g is the gage temperature.

It should be noted that the barometric pressure above could be the pressure measured on the McLeod gage if the vacuum weight loader were used while evacuated.

In the case of the small gram weights used for small increments with the manual weight set, the nominal weight value was used. Tolerances on these weights were such that such corrections would be insignificant.

2. PRESSURE REDUCTION--DWG

The pressures from the DWG were also calculated on the computer using methods outlined by the gage manufacturer. The corrections used included the local acceleration of gravity, pressure and temperature effects on the effective piston area, change in DPI zero with pressure, and head of oil between the DPI and the DWG. A summation of the apparent masses of each weight used was made, including the piston and weight pan,

but not including the small increment weight set. This summation was then used to get the nominal pressure.

The resultant equations for the calculation of the pressure for the low range piston were:

$$P_{nom} = \frac{980.302}{980.665} \cdot \frac{M_p + \sum M_i}{0.13022} + P_{bar} + P_{wt} \quad \text{eq. (17)}$$

$$A_{eff} = 0.13022 \left[1 + 1.6 \times 10^{-5} (T_g - 25) \right] \cdot$$

$$\left[1 - 3.6 \times 10^{-8} P_{nom} \right] \quad \text{eq. (18)}$$

$$P_{oil} = 0.00946 \quad \text{eq. (19)}$$

For the high range piston, the corresponding equations were:

$$P_{nom} = \frac{980.302}{980.665} \cdot \frac{M_p + \sum M_i}{0.0260417} + P_{bar} + P_{wt} \quad \text{eq. (20)}$$

$$A_{eff} = 0.0260417 \left[1 + 1.6 \times 10^{-5} (T_g - 25) \right] \cdot$$

$$\left[1 - 3.6 \times 10^{-8} P_{nom} \right] \quad \text{eq. (21)}$$

$$P_{oil} = 0.00823 \quad \text{eq. (22)}$$

Where:

P_{nom} is the nominal pressure--psia

A_{eff} is the effective piston area

M_p is the apparent weight of weight pan

M_i is the apparent weight of weights used

P_{bar} is the barometric pressure

P_{wt} is the small weights used--psi

P_{oil} is the pressure due to oil head on gage

T_g is the gage temperature

The final pressure was then calculated by

$$P = \frac{980.302}{980.665} \cdot \frac{M_p + \sum M_i}{A_{eff}} + P_{wt} + P_{oil} + P_{bar} + 3.56 \times 10^{-6} P_{nom} \quad \text{eq. (23)}$$

The first term in this equation corrects for the local acceleration of gravity and uses the true effective piston area accounting for thermal and pressure expansion of the piston. The small weights used with the system are then added in with the second term. The oil head and barometric pressure are accounted for with the third and fourth terms. The last term accounts for the change in the DPI zero with pressure.

3. P-V-T REDUCTION METHODS

A computer program was written to do the complete data reduction to obtain all needed information in final form directly from the raw data. The method began with the final mass measurement for a test run. Equation 6 was solved for the final compressibility in the cell. From this the total mass in the system was calculated.

For the summation terms, the dead space volumes were divided into eleven segments, each with a measured temperature that was assumed to represent the temperature of that segment. Figure 38 shows the breakdown of these segments, the volumes, and lengths of each segment.

The compressibilities at each location for the dead space volumes

After the mass in the cell was calculated, each of the following points was labeled to indicate if it was a data point or if it was additional mass being removed from the cell. Thus all points were calculated in reverse order from which they were taken.

Calculations for the data points consisted only of finding pressures and temperatures, correcting the total mass to account for mass in the dead space volumes, and calculation of the cell volume as a function of temperature and pressure. Thus this calculation used nothing not used above.

The additional mass was calculated using calculated expansion tank volumes and the compressibilities measured in the oil bath. This also used nothing which was not inherent in the total mass calculation. The calculated additional mass was then added to the mass the machine had been using to get the mass for the points that followed.

CHAPTER VIII

EXPERIMENTAL RESULTS

Five test runs were made to determine the density of neon over the range from 28 to 70°K and up to 240 atm. From these runs a total of 154 points were determined. The measured densities and compressibilities are shown in Table 6 along with the point number, temperature, and pressure for each of these points. All points marked "sat" in the table are points which are, or should be, on the saturation line.

Figure 39 presents the data obtained in pressure-temperature coordinates. The lines shown are the approximate constant density lines generated by the basic method employed in these tests. Many of these lines show a curvature near the saturation line, particularly around the critical point when plotted to a larger scale. The curvature is always away from the critical density.

The same data is shown in Figure 40 on pressure-specific volume coordinates. The lines of constant temperature and the estimated saturation curve are also shown. The saturation density values were obtained from the pressure-temperature plot where the extrapolation of the density lines intersect the vapor pressure curve or by the intersection of the constant temperature-constant pressure line in the saturated region with the extrapolated isotherm.

The compressibilities of neon are plotted in Figure 41 with lines of constant temperature and density shown. The constant density lines are again the data lines rather than even values of density. The high

TABLE 6

EXPERIMENTAL DATA

Point	Temperature °K	Pressure Atm.	Density g/cc	Compressibility
1260	69.225	0.8471	0.00302	0.99792
1106	70.029	1.1579	0.00412	0.98731
1259	69.998	1.5051	0.00531	0.99631
1105	70.047	2.0483	0.00736	0.97756
960	70.060	3.8925	0.01383	0.98839
959	70.072	6.8915	0.02470	0.97944
958	70.005	27.2883	0.10349	0.92644
1257	70.013	32.1047	0.12326	0.91507
956	70.004	57.3344	0.23461	0.85864
1248	70.000	75.8069	0.31893	0.83519
943	69.992	98.5165	0.41973	0.82482
1102	69.991	100.3202	0.42602	0.82753
1237	70.004	125.9350	0.52015	0.85069
925	69.983	143.6276	0.57605	0.87632
1226	70.000	204.1185	0.70977	1.01050
946	65.002	50.9500	0.23478	0.82116
1247	65.003	66.2615	0.31919	0.78551
944	64.994	84.6024	0.42018	0.76199
1236	64.995	106.3962	0.52071	0.77325
926	64.971	120.5221	0.57654	0.79138
1225	64.993	169.9257	0.71053	0.90506
923	64.981	227.9538	0.80940	1.06602
1360	60.234	3.1284	0.01299	0.98367
1359	60.314	5.4409	0.02284	0.97160
1358	59.998	18.8328	0.08517	0.90649
1256	59.997	26.1809	0.12337	0.87000
955	59.991	44.4791	0.23481	0.77665
1246	59.997	56.6121	0.31940	0.72663
942	60.005	70.5892	0.42050	0.68810
1235	60.006	87.0443	0.52082	0.68505
927	59.984	97.4216	0.57678	0.69260
1224	59.999	135.8200	0.71099	0.78313
922	59.987	183.2097	0.81020	0.92719
1350	54.994	32.0950	0.18678	0.76853
954	55.001	37.9761	0.23490	0.72299
1245	54.993	46.9047	0.31962	0.65638
941	55.005	56.4699	0.42033	0.60074
1234	55.002	67.3852	0.52122	0.57814

TABLE 6--continued

Point	Temperature	Pressure	Density	Compressibility
928	54.981	74.2784	0.57712	0.57578
1310	54.994	88.2367	0.65262	0.60471
1223	54.997	101.8043	0.71132	0.64008
921	55.008	138.3505	0.81089	0.76290
1214	55.010	206.0996	0.90882	1.01398
1357	49.999	14.8869	0.08525	0.85907
1255	50.012	20.1533	0.12349	0.80261
1349	49.991	27.1046	0.18687	0.71363
953	50.003	31.3503	0.23517	0.65574
1244	50.002	37.0491	0.31984	0.56982
940	50.006	42.2858	0.42100	0.49403
1101	49.993	42.6066	0.42659	0.49139
1233	49.998	47.7962	0.52168	0.45071
929	50.006	51.3707	0.57775	0.43735
1309	50.005	59.0528	0.65331	0.44461
1222	50.003	67.2605	0.71220	0.46455
920	50.007	92.7406	0.81149	0.56211
1213	49.996	145.4310	0.90994	0.78629
913	50.002	214.3497	0.99468	1.06004
1348	48.002	25.0460	0.18694	0.68650
952	47.995	28.6319	0.23509	0.62415
1243	48.003	33.0616	0.31991	0.52954
939	47.991	36.5627	0.42085	0.44527
1232	48.003	39.9872	0.52188	0.39261
930	48.012	42.2785	0.57813	0.37464
1308	48.002	47.4659	0.65369	0.37207
1221	47.997	53.5398	0.71254	0.38505
919	48.017	74.6909	0.81192	0.47122
1212	48.008	121.0117	0.91036	0.68103
1356	45.992	13.2569	0.08529	0.83123
1254	45.995	17.6570	0.12355	0.76427
1347	46.005	23.0128	0.18697	0.65807
951	46.001	25.8988	0.23529	0.58856
1242	46.006	29.0375	0.31996	0.48520
1339	46.000	30.3089	0.38619	0.41964
938	45.997	30.8521	0.42121	0.39168
1331	46.000	31.3698	0.47566	0.35263
1324	46.009	31.9430	0.50346	0.33919
1231	46.001	32.2896	0.52215	0.33065
1317	45.997	32.9718	0.56362	0.31282

TABLE 6--continued

Point	Temperature	Pressure	Density	Compressibility
931	46.022	33.4016	0.57823	0.30872
1307	46.004	36.2087	0.65385	0.29608
1220	46.004	40.1146	0.71286	0.30086
918	46.014	56.2613	0.81221	0.37027
1211	46.000	96.2299	0.91068	0.56501
912	46.012	153.5848	0.99567	0.82458
1346	45.001	21.9583	0.18698	0.64186
950	45.013	24.5122	0.23454	0.57108
1241	44.994	26.9028	0.32003	0.45954
1338	45.005	27.6142	0.38626	0.39072
937	44.998	27.9098	0.42130	0.36211
1330	45.000	28.0262	0.47573	0.32200
1323	44.997	28.2802	0.50354	0.30700
1230	44.995	28.4782	0.52226	0.29807
1316	45.008	28.9261	0.56360	0.28047
932	45.023	29.0537	0.57833	0.27445
1306	44.994	30.5518	0.65411	0.25533
1219	44.995	33.4164	0.71301	0.25620
917	45.024	47.4052	0.81276	0.31863
1345	44.406	21.3304	0.18701	0.63179
1240	44.395	25.3870	0.32007	0.43944
1337	44.401	25.8626	0.38632	0.37086
935	44.412	25.8110	0.42144	0.33918
1329	44.394	26.0616	0.47576	0.30350
1322	44.401	26.2056	0.50358	0.28827
1229	44.395	26.2901	0.52233	0.27886
1315	44.404	26.4843	0.56359	0.26030
933	44.415	26.4362	0.57867	0.25300
1305	44.407	27.3432	0.65420	0.23151
1218	44.405	29.5409	0.71309	0.22947
1355	44.002	12.4393	0.08531	0.81504
1253	44.014	16.4070	0.12357	0.74196
1344	44.007	20.9081	0.18702	0.62486
949	44.002	23.0847	0.23526	0.54850
1239	43.990	24.3112	0.32009	0.42467
1334	44.001 (sat)	24.4369	0.38633	0.35359
936	44.010 (sat)	24.9140	0.42114	0.33062
1326	44.001 (sat)	24.8332	0.47577	0.29177
1319	43.999 (sat)	24.8557	0.50360	0.27591
1228	43.993 (sat)	24.8616	0.52238	0.26609

TABLE 6--continued

Point	Temperature	Pressure	Density	Compressibility
1312	43.993 (sat)	25.0250	0.56375	0.24818
1302	43.992 (sat)	25.0178	0.65429	0.21379
1217	43.988	26.7839	0.71318	0.21000
916	44.018	38.2699	0.81254	0.26318
1210	43.990	71.4441	0.91121	0.43839
911	44.001	123.1632	0.99626	0.69106
1343	43.000	19.8412	0.18703	0.60683
948	43.100	21.7801	0.23544	0.52793
1333	42.999 (sat)	21.6616	0.38638	0.32069
1301	43.002 (sat)	21.7661	0.65437	0.19025
1216	43.001 (sat)	21.8371	0.71330	0.17511
1354	42.004	11.6229	0.08533	0.79766
1252	41.999	15.1039	0.12361	0.71559
1351	41.989	18.7138	0.18706	0.58601
947	41.988 (sat)	18.9860	0.23496	0.47335
915	42.008	20.5361	0.81320	0.14786
1209	42.002	46.8569	0.91192	0.30090
910	42.011	92.4501	0.99673	0.54305
1206	42.031	215.6964	1.09972	1.14779
1353	40.000	10.7774	0.08535	0.77649
1251	40.008	13.7661	0.12364	0.68446
1341	40.008	14.2170	0.18716	0.46699
1208	39.998	22.0576	0.91258	0.14863
909	40.002	61.2816	0.99735	0.37781
1205	39.994	173.8722	1.10031	0.97182
1250	37.994	10.3662	0.12369	0.54257
908	38.073	31.0220	0.99779	0.20086
1204	37.936	131.5395	1.10062	0.77488
907	36.138 (sat)	7.8350	0.99893	0.05338
905	36.081	219.5982	1.18651	1.26169
1203	35.898	87.2019	1.10135	0.54249
904	33.663	158.1862	1.18740	0.97339
903	33.757	159.7419	1.18740	0.98022
1202	32.391	13.1512	1.10351	0.09050
902	30.616	77.6587	1.18860	0.52491
901	28.067	8.6011	1.19000	0.06334

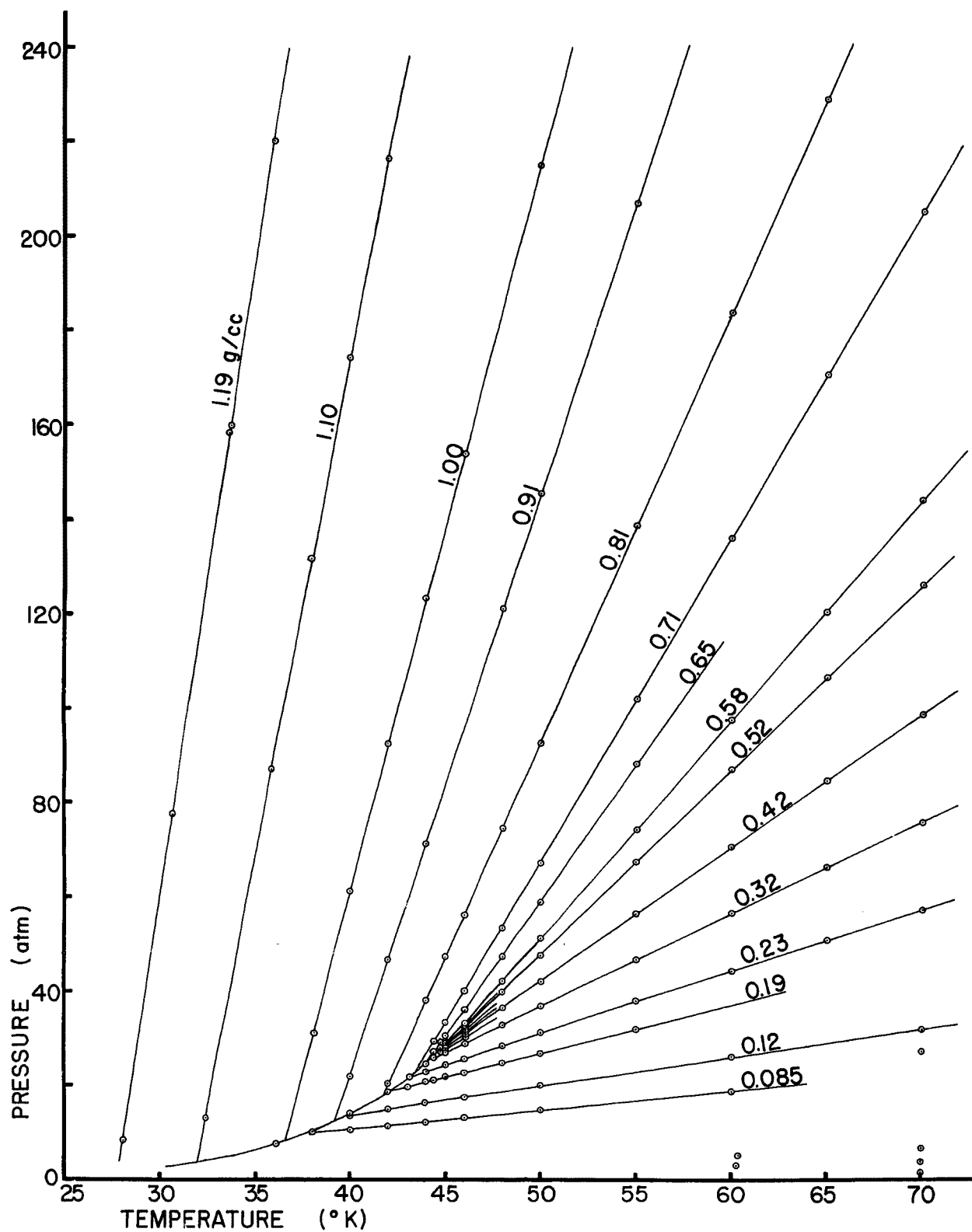


Figure 39. Pressure-Temperature Plot of Experimental Data.

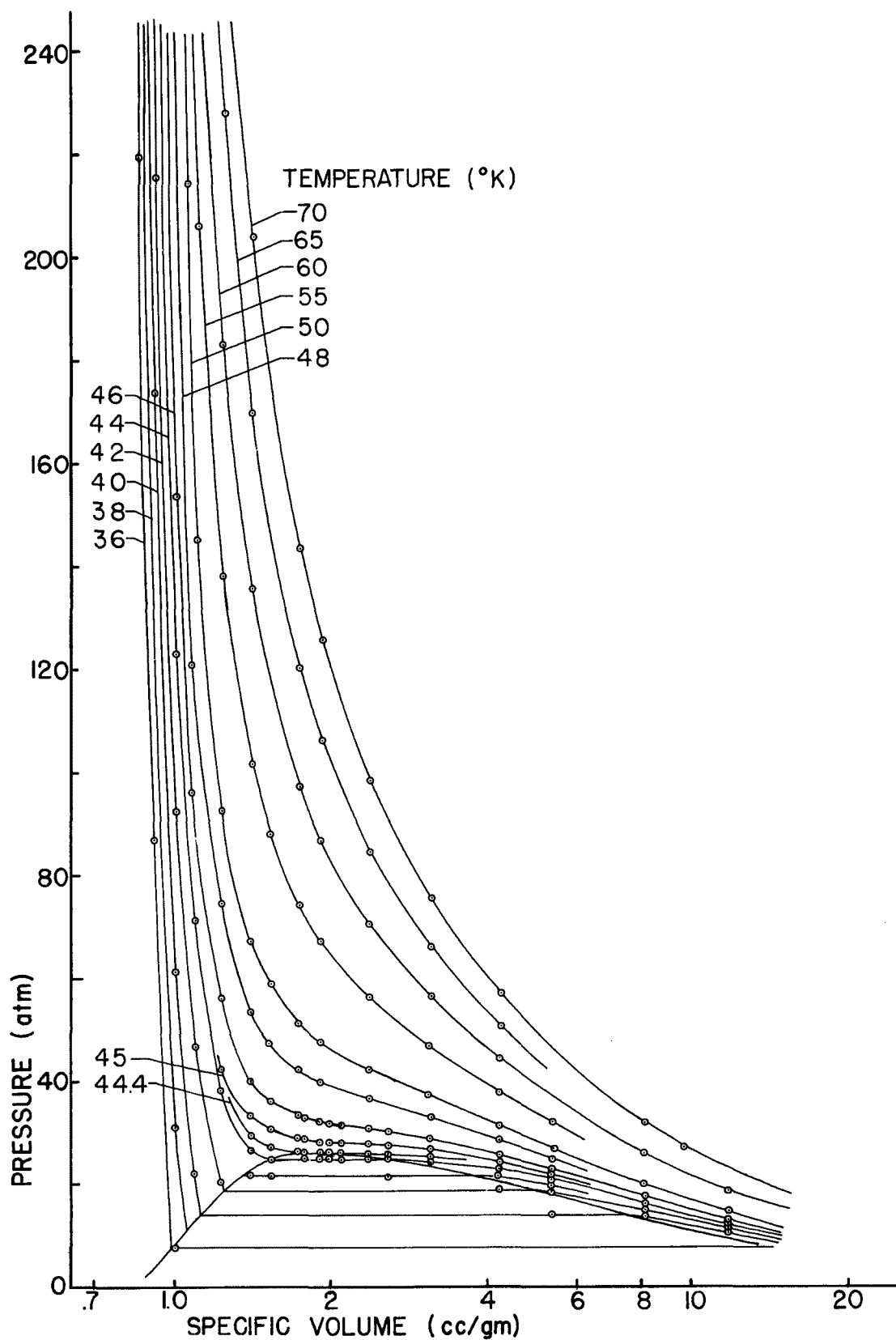


Figure 40. Pressure-Specific Volume Plot of Experimental Data.

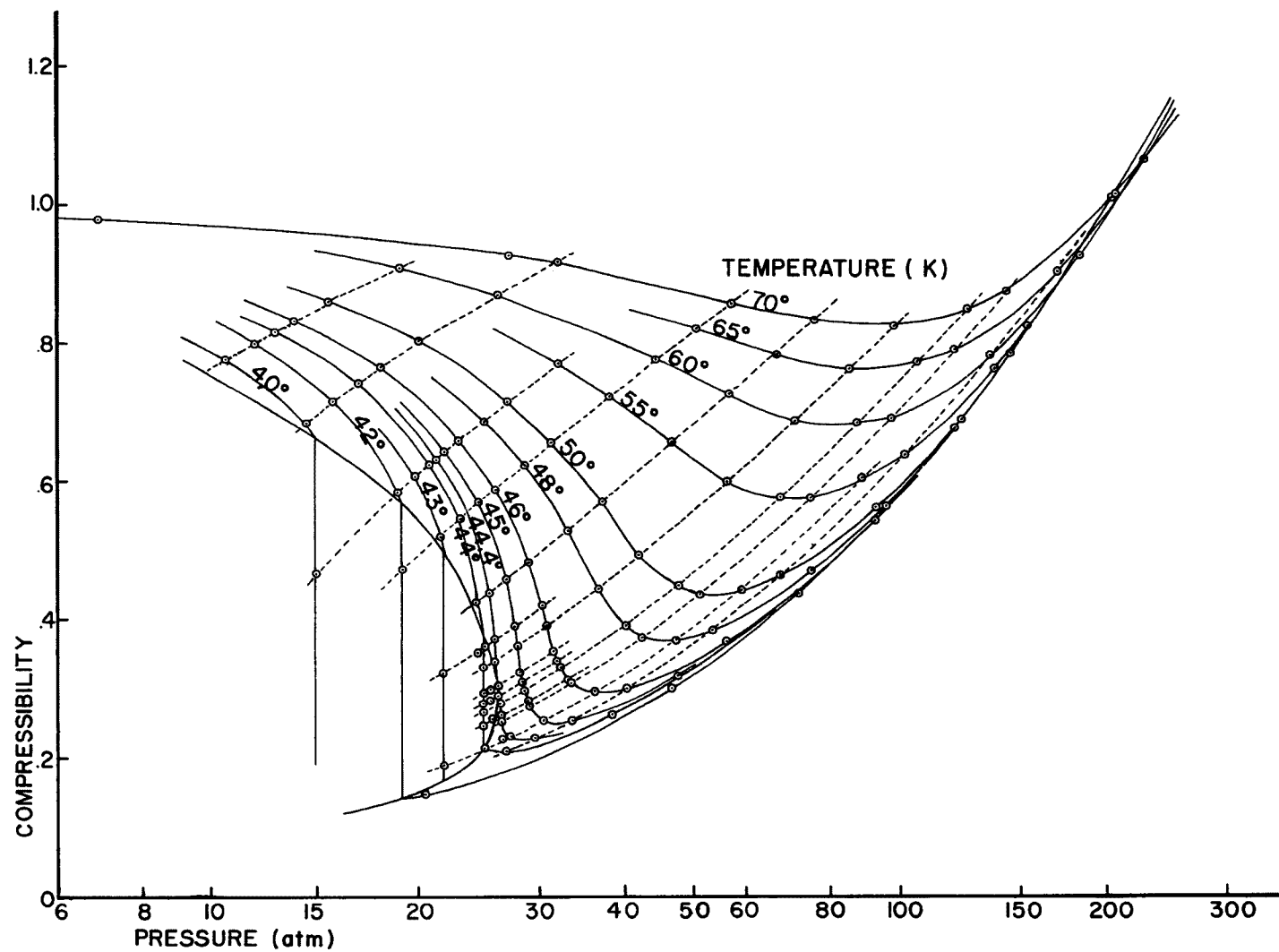


Figure 41. Compressibility-Pressure Plot of Experimental Data.

density points are not shown in Figure 41 because they overlap onto the curves shown.

Table 7 presents the virial coefficients obtained from the low pressure data for the only two isotherms which were extended to sufficiently low pressure to allow the virial coefficients to be determined.

TABLE 7

VIRIAL COEFFICIENTS FOR NEON

Temperature °K	Second cc/gm	Third (cc/gm) ²
70.0	-0.863	1.40
60.0	-1.288	2.20

CHAPTER IX

DISCUSSION OF RESULTS

1. COMPARISONS WITH PUBLISHED VALUES

a. Vapor Pressure

Figure 42 shows a comparison of the vapor pressure data obtained as a part of this work with the equation given by Grilly (13). Some of the points are obviously below the line. This is a consequence of the procedure and test equipment. With only a little liquid in the cell the liquid would not touch the thermometer well. Therefore, the temperature measured would represent the gas temperature. The lower portion of the cell was fairly well insulated from the top because of the low conductivity of the 304 stainless steel. This would require then a fairly long time to reach equilibrium because of the energy required to boil away the liquid to reach the saturation conditions. More time should have been allowed on these points as was done on later runs. Around the critical point, the same condition occurred on a number of points. For these points more time would not solve the problem as shown by the fact that the time on condition bears no apparent relation to the apparent error in pressure at the point for the data points in question. Also, the thermometer well should have been in contact with any "liquid" phase at the densities near critical. One must conclude that this system lacked several features needed for reliable measurements of conditions

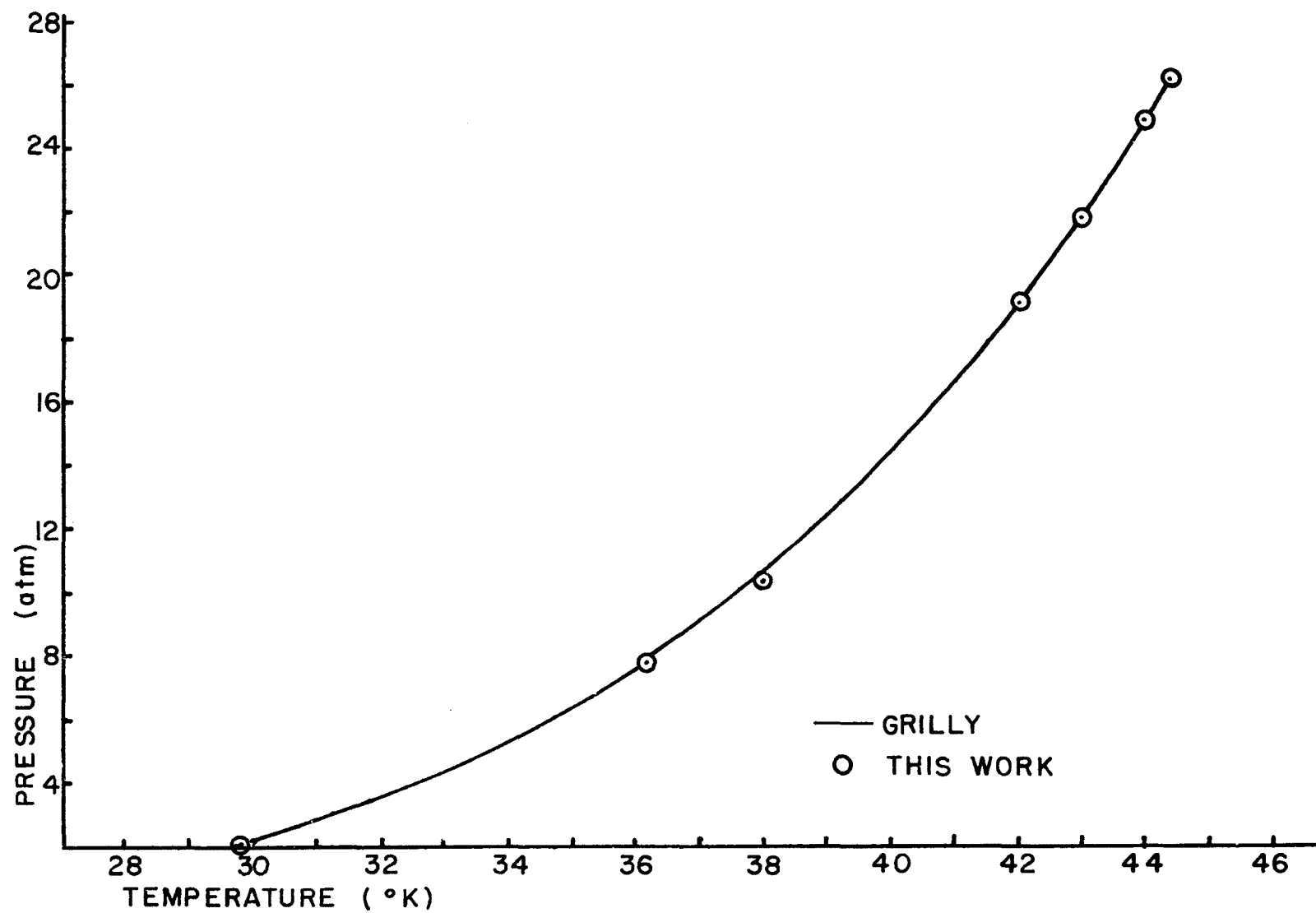


Figure 42. Comparison of Measured Vapor Pressures with Published Values.

near critical. These would include (a) better temperature control, (b) stirring within the test cell, and (c) removal of the static pressure head due to the lead out tube.

Where the neon in the cell is a single phase, the time required to reach equilibrium would be much shorter than on the vapor pressure curve. Therefore, the problem of not being at equilibrium should not be present in points not on the saturation line.

b. Compressibility

Figure 43 compares the previously published measurements of neon density with the results of this work on compressibility-pressure coordinates. The lines on Figure 43 are the nominal lines through the data presented herein as given in Figure 41.

The comparison with the data of Sullivan in Figure 43 shows good agreement for the 70°K common isotherm. The deviation between the two data sets seems to be a function of pressure, leading to 0.5 percent deviation in density at 100 atmospheres and decreasing approximately linearly with pressure. The densities given by this work are higher.

It should be noted that the work by Sullivan was done in the same laboratory as the work presented here and the same basic pressure instrument was common to both sets of data as was the temperature measuring instruments. The thermometers and all other parts of the neon system were entirely different, however, as was the method employed.

The Leiden data (11) shows fairly good agreement for all but six points. These points have been previously recognized as being inconsistent. At low densities the Leiden values exhibit a different trend tending to flatten out at higher pressures. There is a systematic

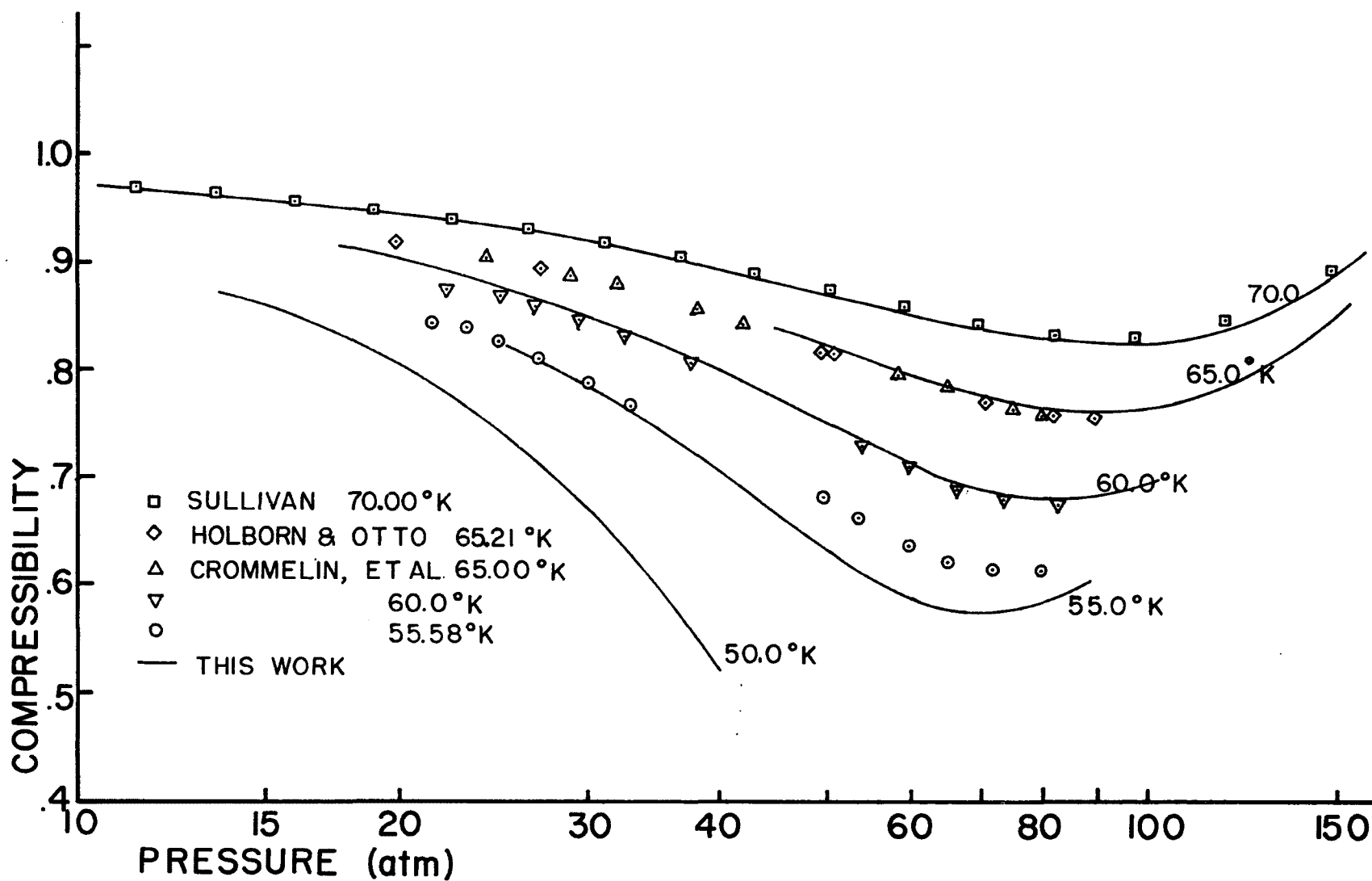


Figure 43. Comparison of Measured Compressibilities with Published Data.

difference in all regions between the Leiden data and this work of about 0.4 percent in density. The Leiden densities are always higher.

The Berlin data (18) shows much the same trend and deviation from the data presented herein as the Leiden data. The difference is of the order of 0.6 percent with the Berlin data giving higher densities. It should be noted relative to Figure 43 that there is a temperature difference between the two sets of data so that the actual difference is larger than is shown on the plot.

c. Saturation Conditions

The temperature-density plot for the saturated conditions from reference 21 is shown in Figure 44 compared to the saturated conditions obtained from the extrapolations to the vapor pressure curve from Figures 39, 40, and 41. This agreement is very good.

d. Virial Coefficients

The second virial coefficients from Table 7 are shown in Figure 45 as compared to those of Sullivan (37), Holborn and Otto (18), and Crommelin, et al (11). Again, the agreement is good.

e. Critical Point

Because of the inherent difficulties of measurement of the critical point, much of the data obtained for the immediate vicinity of the critical point cannot be considered valid and is not shown in Table 6. The equipment was not designed to handle the specialized problems associated with getting valid equilibrium conditions at the critical

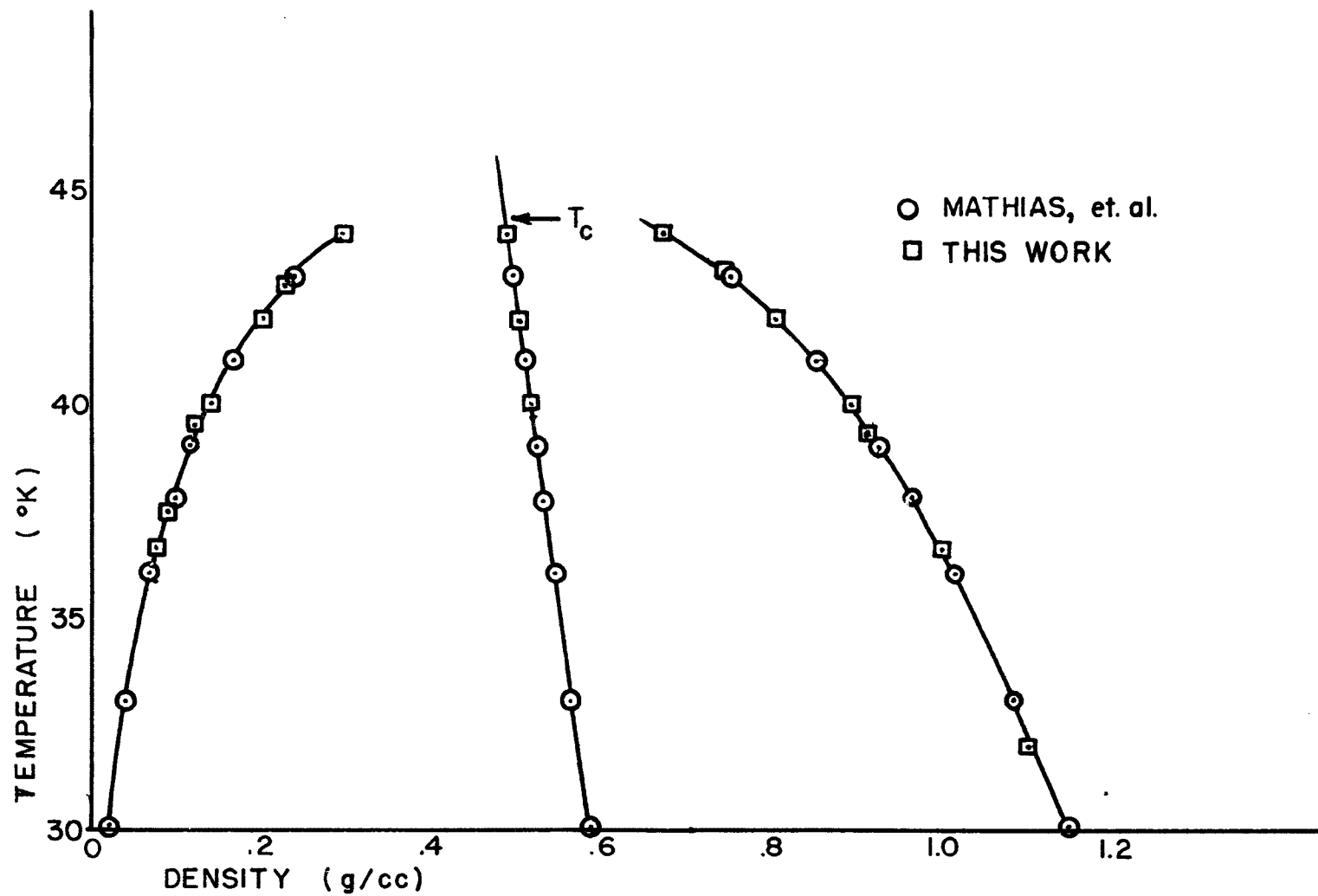


Figure 44. Comparison of Saturation Densities with Published Values.

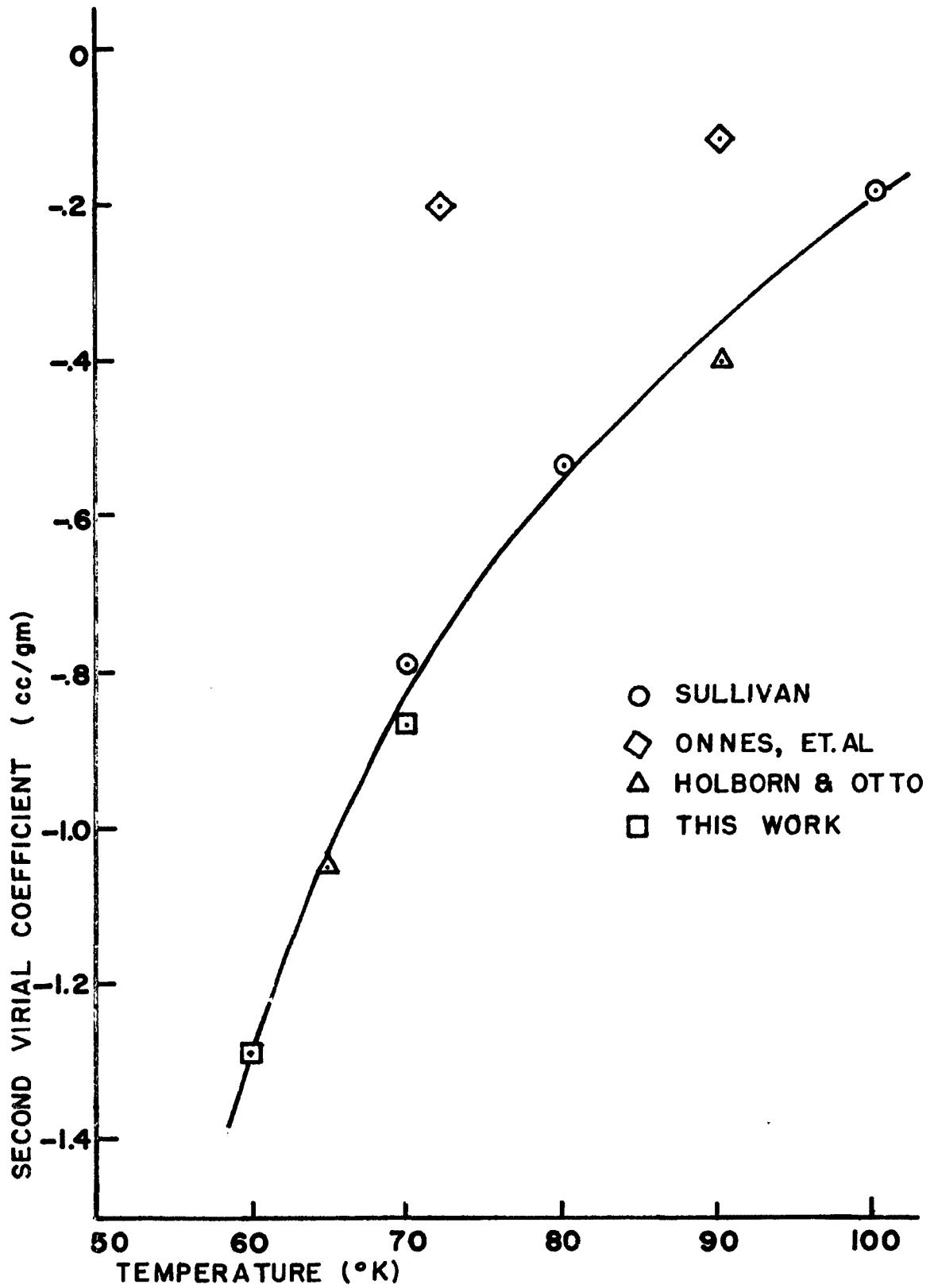


Figure 45. Comparison of Virial Coefficients with Published Values.

range used. With the frequent comparison of the bridge with the standard resistor, the temperature of the thermometer was read to within $\pm 0.001^{\circ}\text{K}$. The question of how well the thermometer temperature matched the neon temperature would be one of comparative thermal lags of the two regions of the cell. The apparent time constant for recording gas temperatures by the thermometer was between five and ten seconds when a change in gas temperature was induced by removing some of the gas. The response to heating by the electrical heaters was slower, having a fifteen second dead time. When the measurements of cell temperature were made, the rate of change of cell temperature would have been 0.002°K per minute or less; thus, the thermal lag and reading time could contribute about $\pm 0.002^{\circ}\text{K}$ uncertainty in the temperature measurement.

The degree to which temperature equilibrium was established in the cell represents the largest uncertainty in temperature measurements. No measurements of gradients inside the cell were made. The only criteria available for this would be the stability of the pressure, and the tendency for it to follow the cell temperature as measured on the cell thermometer.

The total cell temperature uncertainty was presumably $\pm 0.003^{\circ}\text{K}$ from the N.B.S. calibration of the thermometer.

(2) Bath Temperature--The comments made above relative to the cell thermometer also apply to the bath temperature when actual measurements were made. The effect of the higher excursion rate in temperature was cancelled by the faster time response of the unit. Thus, direct readings should have an uncertainty of $\pm 0.003^{\circ}\text{K}$.

For most cases, when a data point was taken, the bath temperature was not read at that time. In this case an additional uncertainty of

$\pm 0.003^{\circ}\text{K}$, which is the apparent change in tank temperature with time, must be added.

(3) Thermocouple Measurements--The temperatures measured with the thermocouples contain the uncertainties of measurement given above in addition to the uncertainties inherent in the thermocouple measuring system. This was because each thermocouple was referenced to either the cell or the oil bath reference block.

The potentiometer was balanced to the nearest microvolt for all readings of the temperature of the tube attaching the cell to the plumbing in the oil bath. This would give a temperature uncertainty of $\pm 0.009^{\circ}\text{K}$. The temperatures as measured on the tube also contain an uncertainty due to conduction down the lead wires. This uncertainty is generally negative since the conduction would raise the measured temperature. This error depends on the length of the copper lead wires and is estimated at -0.25°K in the worst case (thermocouple #19).

The lack of calibration for the gold cobalt-copper thermocouples would contribute an uncertainty of ± 2 percent in the readings of temperature differences from these thermocouples. These differences were generally small, less than 40 degrees in all cases.

The largest uncertainty of the temperature measurements of the tube was how well the measured value represented the average over the segment used in calculation of the dead space mass. This value is dependent on the change along the tube and is assumed to be $\pm 25^{\circ}\text{K}$ in the worst case of the tube length just inside the cryostat. For other lengths, for example, at room temperature, this would be closer to $\pm 0.1^{\circ}\text{K}$. Because of the extremely small volumes associated with the segments of the tube, this error is not really as significant as it may sound.

b. Pressure Measurements

(1) DWG--The resolution of the dead weight gage and differential pressure indicator combination used in these tests (that is, the smallest increment of weight which would produce a change in the output of the indicator) was about 5 ppm or 0.002 psi, whichever was greater. However, this is not meaningful relative to the uncertainty of measurement; because of the variation in cell temperature, the smallest weights available were never used. The reason for this was that the rate of change in pressure caused by the temperature change was about the same as the rate of change of indicator output caused by an unbalance in the DWG. The smallest increments used in balancing the DWG were 0.01 psi for pressures under 500 psi, 0.02 psi up to 2000 psi, and 0.05 psi above 2000 psi for low and moderate densities. At densities over about 0.8 g/cc the rate of change of pressure with temperature was high enough that it was not possible to balance closer than 0.05 psi for all pressure levels. The uncertainty of any measurement due to the balance would then be about one half the smallest increment used.

The error due to pressure balancing masks all other errors inherent in this system; however, the other sources of error should be mentioned.

The oil leg connecting the DPI and the DWG could have introduced small errors in several ways. The height of the net oil head was measured to an estimated ± 0.01 cm. The specific gravity of the oil was known to ± 0.003 . The changes in temperature of the oil in the four foot vertical excursion of the oil tube could also contribute to the uncertainty of pressure measurements. The alignment of the weights with the reference mark on the DWG was only within about ± 0.04 cm; this also con-

tributed to the uncertainty in the oil head pressure. The total uncertainty in pressure due to the oil leg was ± 0.002 psi.

The local acceleration of gravity value used was uncertain by about ± 0.002 cm/sec². This would contribute $\pm 2 \times 10^{-4}$ percent error in the pressure measured on the DWG.

The effective piston area is the largest uncertainty relating to the gage itself. The uncertainty in pressure measurement from the piston area, when the effects of temperature and pressure on the piston size are considered is ± 0.01 percent.

The barometer, after calibration as discussed in Chapter 5, had an uncertainty of ± 0.002 psi in its reading.

The total uncertainty in pressure measurements for any point would then be the sum of each of the items given above.

(2) APG Measurements--The uncertainty of measurement of the pressure with the air piston gage was much smaller than for the DWG. The balance of the gage was done to the nearest 0.001 psi in all cases. The uncertainty of the piston area as a function of temperature and pressure contributes a possible error of ± 0.005 percent. The effect of the local acceleration of gravity and barometer would be the same as given above, $\pm 2 \times 10^{-4}$ percent and ± 0.002 psi, respectively.

No correction was made for the DPI used with the APG to account for changes in zero with pressure. The manufacturer's calibration indicated no change for this unit over the range of use.

c. Volume Measurements

The accuracy of volume measurements with the volume measuring device is estimated to be ± 0.03 percent plus ± 0.04 cc per tube used in

the measurement or ± 0.07 cc for the test cell and ± 0.4 cc for the two expansion tanks. This estimate is based on consideration of the accuracy of the tube bore, the accuracy of height measurements with the cathetometer, possible leakage, and incomplete evacuation effects as well as the inaccuracies of knowing the temperatures in the system during measurement.

A slight decrease occurs in the maximum possible error when the ratio of volumes is used. The volume ratios are, as can be shown from equation 6, the important value in the data reduction of these tests.

The accuracy of the ratio method of measuring the volumes would be about ± 0.03 per cent based on the resolution obtainable in the tests. To get from this measurement to the actual volumes used, certain measured correction volumes were added. These were measured to about ± 0.04 cc with the volume measuring device.

Thus, since two independent means were used, the volumes should be accurate to ± 0.02 percent ± 0.04 cc, or ± 0.06 cc on the test cell and ± 0.25 cc on the tanks.

d. Operational Problems

(1) Cell Overpressurization--During the data taking procedure, the cell was inadvertantly overpressurized by several thousand psi. There is the possibility that this overpressurization caused yielding of the test cell inner vessel. Measurements of the volume after the tests gave a larger volume than when measured before the tests. However, the density data before and after the overpressurization falls on the same constant volume line and there is no evidence that any change occurred from the data. The difference in measured volume may have been due to

incomplete evacuation when the volume measuring device was used before the overpressurization. The volume was measured by both the volume measuring device and the expansion method after the overpressurization. These values agreed as shown in Table 3.

In any event, whether the cell yielded or not would produce no problems since the volume for the points would be known anyway. The elastic contraction would have opened some space between the two vessels which would not close due to thermal strain since the overpressure occurred at low temperature. Therefore, even if the cell did yield, which is unlikely, it would not cause problems.

(2) Data Not Recorded--When the data for point 945 was recorded, the weights used on the APG were not recorded, only the pressure as read on the Heise gage. As this point was a mass measurement it would affect all points in run nine with lower numbers. By comparison of the APG and gage measurements at other points, it is estimated that the Heise gage reading was within ± 0.25 psi out of 119 psi. Further, since only about one-third of the mass in the cell was removed, this amounts to about ± 0.1 percent additional error possible for these points. The effect of this would be further decreased for other isochores of the same run. Run number eleven was made to repeat the isochore which had the highest possible error. This run gave results very close to the value obtained from run number nine.

e. Overall Accuracy

The maximum uncertainty associated with an individual point is a function of temperature, pressure, and the process by which the mass associated with the point was measured. This uncertainty was calculated

for several sample points from run number twelve. The equation was obtained from equations 2 and 6 by taking the total differential, considering all variables for which there is any uncertainty. This equation is rather long and tedious and will not be given here. The results of the calculations for several points are given in Table 8. Based on the apparent scatter in the data shown in the various figures, the probable error per point is smaller than the maximum. However, much of the uncertainty is systematic and would not show up as scatter. There is a systematic difference between the data presented here and the Leiden and Berlin data as shown above as well as a systematic difference in the other direction with Sullivan's.

TABLE 8

ESTIMATED MAXIMUM UNCERTAINTIES IN COMPRESSIBILITY

Point	Temperature °K	Pressure atm	Density g/cc	Uncertainty	
				Random percent	Systematic percent
1205	40	174	1.10	0.08	0.25
1221	48	53	0.71	0.06	0.19
1231	46	32	0.52	0.06	0.18
1237	70	126	0.52	0.06	0.18
1245	55	47	0.32	0.05	0.16
1251	40	14	0.12	0.04	0.13

It should be noted that the uncertainties shown in Table 8 differ from the earlier error calculations mentioned in the section on Sizing of Components. There are two reasons for this. First, the original

analysis was based on an uncertainty in compressibility, not a percentage. Secondly, the assumed elemental accuracies were not the same in all cases as what was finally obtained. The major differences were in volume and pressure measurements. The net accuracy is about the same, however.

The overall accuracy of points measured as a part of run number nine is poorer than for the other runs as indicated by the larger scatter of these points as compared to the other data. Two possible causes exist for this situation: (a) an error during mass measurement which was explained above, and (b) a smooth operating procedure for measurements had not been fully developed; particularly with manual temperature control. The data became more consistent as the procedure for obtaining it became better and smoother.

CHAPTER X

CONCLUSIONS

Additional measurements of the density of neon have been made covering the range of temperatures from 28 to 70°K and pressures up to 240 atmospheres. Included in this data are both liquid and vapor densities.

The accuracy of this data is better than 0.4 percent in the worst case, with an average uncertainty of about two tenths of a percent.

This data is in substantial agreement with previously published measured values where common ranges exist. This agreement includes not only measured densities but saturated liquid and vapor pressures and densities, and virial coefficients.

Agreement with the published tables of McCarty and Stewart is not as good as with the published data. The agreement is generally within one percent on density except in the low temperature vapor region where the actual surface has a considerably different shape than that given by their equations.

Measurement of the compressibility of neon at 300.17°K were also made for low pressures. This data also agrees well with previously published values.

APPENDIX A

PHYSICAL CONSTANTS

Local acceleration of gravity	980.302 cm/sec ²
Standard acceleration of gravity	980.665 cm/sec ²
Gas constant for neon	4.06565 atm cc/gm ^o K
Molecular weight of neon	20.183 gm/gm mole
Standard atmosphere	14.6959 lbf/in ²
Standard atmosphere	760 mmHg
Absolute zero of temperature	273.15°C

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