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TITLE THERMODYNAMIC PROPERTIES OF FREON 13

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THERMODYNAMIC PROPERTIES OF FREON 13

by

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To [illegible] Parents

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NOMENCLATURE

A	function of density in the equation of state
B	function of density in the equation of state
C	function of density in the equation of state
c_v	specific heat of gas at constant volume, v, in BTU/lb./°R
Δc_v	change of specific heat of gas at constant volume with change of volume in BTU/lb./°R.
d	density of gas in lbs./cu.ft.
d_c	critical density in lbs./cu.ft.
d_L	density of liquid in lbs./cu.ft.
H	enthalpy in BTU/lb.
ΔH_T	change of enthalpy in BTU/lb. with volume at constant temperature
ΔH_v	change of enthalpy in BTU/lb. with temperature at constant volume
J	0.18506 - factor for converting cu.ft., lb./sq.in., lb. to BTU/lb.
L	latent heat of vaporization in BTU/lb.
p	pressure in psia
p_c	critical pressure in psia
R	gas constant, 0.10271, lbs., cu.ft./sq.in. lbs., °R.
S	entropy in BTU/lb., °R.
ΔS_T	change of entropy in BTU/lb., °R. with volume at constant temperature
ΔS_v	change of entropy in BTU/lb., °R. with temperature at constant volume

NOMENCLATURE (Cont'd)

T	absolute temperature, °R - °R = °F plus 459.69
t	temperature, °F.
t_c	critical temperature, °F
v	gas volume in cu.ft./lb.
v_c	critical volume in cu.ft./lb.
v_L	liquid volume in cu.ft./lb.
Z	compressibility factor, pv/RT

INTRODUCTION

Freon 13, the common name for chlorotrifluoromethane ($CClF_3$), is a member of the group of chloro-fluoro derivatives of methane, ethane, and propane, which are being successfully used as refrigerants. These compounds are frequently known as the freon family, and all of the group are characterized by chemical inertness and non-toxic physiological properties.

Freon 13 within the last few years has been extensively used as a low-temperature refrigerant. Its use has caused a demand for an accurate determination of its physical and thermodynamic properties, which can be used in the design and operation of refrigeration equipment. As a result, the E. I. du Pont de Nemours and Co., a manufacturer of Freon 13, suggested that a thorough investigation be made to determine these properties of Freon 13.

The present investigation was made to determine the above-mentioned physical and thermodynamic properties of Freon 13. The physical properties that have been determined are as follows:

(1) Vapor pressure from -200°F to the critical temperature, about 84°F.

(2) p-v-T relationship of the superheated vapors at densities up to the critical density and at pressures from 0-2000 psi.

(3) Saturated liquid density from -200°F to the critical temperature.

(4) Specific heat of the vapor at infinite volume from -200 to 500°F.

The first three physical properties were measured experimentally, and the fourth was calculated from the fundamental frequencies determined from spectroscopic data, which were reported in the literature. Empirical equations were next developed to represent the four physical properties. The four equations were then used in thermodynamic formulas to calculate the thermodynamic properties of the saturated liquid and vapor from -200°F to the critical temperature, and of the superheated vapors from -200 to 500°F and 1.0 psia to the critical pressure, about 560 psia.

LITERATURE SURVEY

Vapor pressure measurements of Freon 13 have been reported by several investigators. Riedel (11) reported data over the temperature range of -218 to 76°F. at pressures from 0.14 to 514 psia. He determined the following equation to represent his data within 0.3%.

(1) $\log_{10} p = 7.9701 - 1991.41/T - 7.8483 \times 10^{-3} T + 5.812 \times 10^{-6} T^2$

McNabney (8) made vapor pressure measurements over the temperature range of -31 to 83.84°F. Thornton et al (14) reported data between the temperatures of -169 to -114°F. Ruff and Keim (13) made measurements below -103°F.

Whitney (16) found that the vapor pressure data reported by McNabney and by Thornton et al formed a smooth curve. He also found that Riedel's data formed another smooth curve with a different slope from the first. Whitney then made vapor pressure measurements at 32 and -110°F. and found his measurements agreed with Riedel's. By using his own data and the data of Riedel, he developed the following equation:

(2) $\log_{10} p = 38.2602 - 2669.61/T - 12.3876 \log_{10} T + 0.0060403 T$

This equation predicted their experimental results within 0.3%. When the equation was compared with McNabney's results,

the deviations were as high as 3.8%. The deviations between the equation and Thornton et al's results were as high as 2.5%, and between the equation and Ruff and Keim's results 6.5% or higher.

The p-v-T relationship of the superheated vapors was also investigated by Riedel (11) and Whitney (16). Riedel obtained data at densities up to 11.77 lbs./cu.ft. and pressures of about 300 psia for seven isometrics and other scattered points. The temperature range of each of his isometrics was about 110°F. He used his data to determine the following equation, which represents his results within about 0.4%.

$$(3)\quad p = \frac{0.10265\ T}{\theta} - \frac{5.6918 \times 10^{-3}}{\left[\frac{T}{100}\right]^{0.75}\theta^2}\left[1399 - \frac{27.928}{\theta} + \frac{0.2785}{\theta^2} - \frac{1.113 \times 10^{-3}}{\theta^3} + \frac{(\theta + \theta_K)^3}{0.01(\theta + \theta_K)^3 + 1.437 \times 10^{-5}}\right]$$

where

$$\theta = v - 0.0076048$$

$$\theta_K = 0.01995$$

Whitney (16) obtained isometric data at densities of 11.72 and 36.05 lbs./cu.ft. He used his own and Riedel's data to obtain the constants of the following simplified Beattie-Bridgeman equation, which predicts straight lines for the isometrics.

$$(4)\quad p = (0.04671 - 0.00004746\ T)\ d^3 + (0.004022\ T - 4.048)\ d^2 + 0.10273\ T\ d$$

This equation represents the experimental data within 2% up to densities of 11.77 lbs./cu.ft. and within 6% at the density of 36.05.

Saturated liquid density data from -190 to 77°F were reported by Riedel (11). He developed the following equation which represents his data within 0.3%.

$$(5)\quad d_L = 36.27 + 5.444 \times 10^{-2}(t_c - t) + 7.951\ (t_c - t)^{1/3}$$

Whitney (16) used Riedel's saturated liquid density results to obtain the following equation:

$$(6)\quad d_L = 76.933 - 0.17807\ t - 0.1597 \times 10^{-3}\ t^2$$

This equation predicts Riedel's data within 0.5% from -180 to 14°F.

Critical constants for Freon 13 have been reported by several investigators. McNabney (8) measured the critical temperature as 83.84°F and the critical pressure as 561.5 psia. He made these determinations by measuring the temperature and pressure when the meniscus of the liquid disappeared.

Riedel (11) reported the critical temperature as 83.84°F. He extrapolated his vapor pressure curve and used the law of rectilinear diameter respectively to obtain the critical pressure as 559.7 psia and the critical density as

36.27 lbs./cu.ft. Whitney (16) reported the critical temperature as 83.89 ±0.09°F.

Specific heat values of the gas at infinite volume have been calculated from the fundamental frequencies, which were determined from infra-red or Raman spectra. Justi and Langer (5) used the fundamental frequency values reported by Kahovec and Wagner (6) when they made specific heat calculations. Whitney (16) used an approximate average of the fundamental frequency values of Kahovec and Wagner, and of McGovern et al (7) when he made his specific heat calculations. Whitney's specific heat values agreed within 0.2% of those of Justi and Langer. Whitney used his results to determine the following equation:

$$(7) \qquad c_v = 0.0197 + 0.0002707\ T - 0.0000001075\ T^2$$

This equation predicts his calculated specific heat values within 2.5% from -200 to 500°F.

Fundamental frequency values reported by Kahovec and Wagner (6), McGovern et al (7), and Plyler (10) are shown in Table I.

TABLE I
FUNDAMENTAL FREQUENCIES OF FREON 13

Vibrational Band	Kahovec and Wagner	McGovern et al	Plyler
2, 5	1092 cm^{-1}	1107 cm^{-1}	1105 cm^{-1}
1	356		
3	784	783	781
4	478	-	450
6, 8	1203	1216	1212
7, 9	560	-	563

Kahovec and Wagner's values were assigned from the Raman spectrum of the liquid, while the other two investigations used the infra-red spectrum of the gas.

Values for the thermodynamic properties of Freon 13 were calculated by Whitney (16). He used Equations 2, 4, 6, and 7 respectively for the vapor pressure, equation of state, liquid density, and the specific heat of the gas to compute the thermodynamic properties of the saturated liquid and vapor and of the superheated vapors. For the superheated vapors he calculated the enthalpy, entropy, and pressure at constant volumes and temperatures. The volumes were from 0.04 to 20 cu.ft./lb., and the temperatures were from -180 to 500°F. From these results he constructed a pressure-enthalpy diagram with constant temperature, volume, and entropy lines. Riedel (12) used Equations 1, 3, and 5, and Justi and Lenger's specific heat values to calculate the thermodynamic properties of the saturated liquid and vapor from -220°F to the critical temperature. Riedel's results agreed closely with those of Whitney, for essentially the same physical property data were used by both investigators.

The conclusions that are made from the literature survey are as follows:

(1) The vapor pressure, p-v-T, and saturated liquid density data available for calculating the thermodynamic properties of Freon 13 are either incomplete or of questionable accuracy.

(2) The values of the thermodynamic properties that were calculated by Whitney and Riedel with the above-mentioned physical property data are also of questionable accuracy.

(3) The assignments of the values for the fundamental frequencies, shown in Table I, agreed closely for the three independent investigations, and were, as a result, probably relatively accurate. Reliable specific heat values of the gas at infinite volume can then probably be calculated from these values of the frequencies.

EXPERIMENTAL TECHNIQUE

Various sets of equipment were built and operated to obtain vapor pressure, p-v-T, saturated liquid density, and critical temperature data. In order to obtain reliable data with this equipment, accurate temperature, pressure, and weighing standards were required.

The temperature, pressure, and weighing standards, and the vapor pressure, p-v-T, saturated liquid, and critical temperature determinations are now described in detail.

Temperature, Pressure, and Weighing Standards

All temperature measurements of this investigation were made with a Leeds and Northrup platinum resistance thermometer No. 169313. A Leeds and Northrup Mueller Bridge No. 203295 was used to measure the resistances of the thermometer. The thermometer was calibrated by Leeds and Northrup platinum resistance thermometers Nos. 228968 and 247123 both of which had been calibrated by the National Bureau of Standards. The details of this calibration are shown in Appendix F. From the results of this calibration, a modified Callendar equation, Equation 44, was determined for thermometer No. 169313. It was felt that this equation would predict the temperature within 0.01°C. or 0.018°F.

The pressure gauges used in this investigation were calibrated up to 600 psi with a Mansfield and Green Dead Weight Gauge Tester and above 600 psi with the American Dead Weight Gauge Tester, type No. 315, serial No. 6059. The American gauge with its weights had been calibrated by the National Bureau of Standards, and the calibrated readings were reported to be accurate to within 0.05%. This gauge was used to calibrate the Mansfield and Green gauge. The nominal readings of this latter gauge agreed within 0.02% of the calibrated readings of the American gauge up to 600 psi. As a result, up to this pressure the Mansfield and Green gauge can be considered accurate to within 0.07%.

All weights used in this experimental work were calibrated by a set of Seederer-Kohlbusch weights with a National Bureau of Standard Test No. 82232. All such calibrations were made on a Christian Becker Analytical Balance, No. 28347.

Vapor Pressure Determinations

Vapor pressure determinations were made with a Freon 13 of the highest purity obtainable. This material was furnished by the E. I. du Pont de Nemours and Co. The best grade of commercial Freon 13 had been fractionated at a high reflux ratio. The first and last cuts of the fractionations were discarded. The middle three cuts were

saved for these determinations. Du Pont's analysis of these three cuts indicated the material contained only a trace of impurities and was probably better than 99.9% pure.

The vapor pressure measurements were made from -200°F to the critical temperature, about 84°F. These measurements were made in three different sets of equipment, each designed for a different pressure range. The low-pressure equipment was designed for pressures from a few millimeters of mercury absolute to about atmospheric pressure. The medium-pressure equipment was for pressures from atmospheric to 200 psi, and the high-pressure equipment was for pressures from 200 to 600 psi.

Low-Pressure Vapor Pressure Equipment

The low-pressure vapor pressure equipment designed for pressures below atmospheric was built for the most part of glass. A flowsheet of the apparatus is shown in Figure 1 and a picture in Figure 2.

The isoteniscope (3) was a glass bulb of approximately 20 cc. capacity. It was constructed from 20 mm. I.D. glass tubing. One end of the tubing was sealed off, and the other end was welded to one end of a 6" length of 7 mm. O.D. glass tubing, which had a tee connected to its other

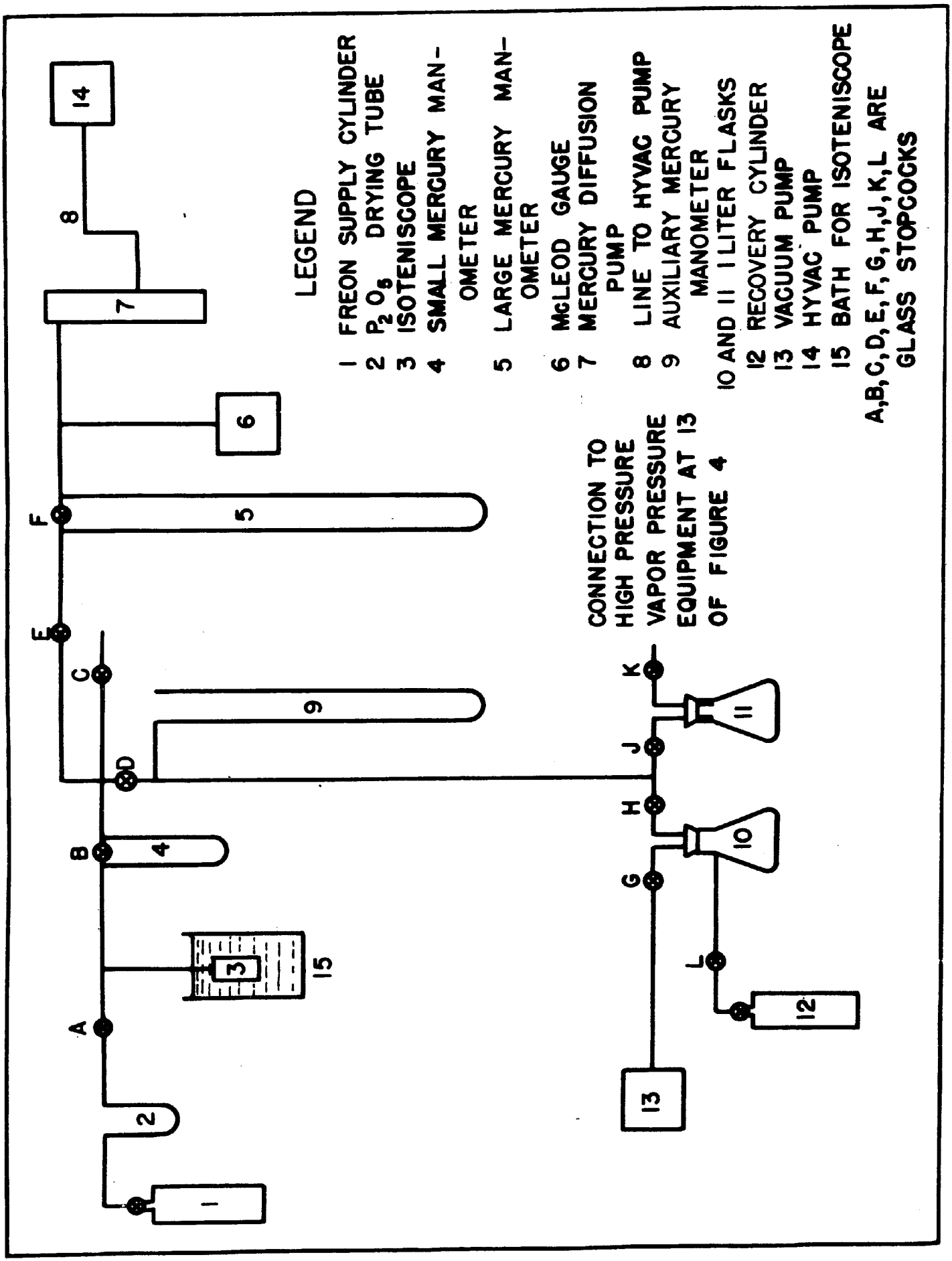


FIGURE 1 LOW PRESSURE VAPOR PRESSURE EQUIPMENT

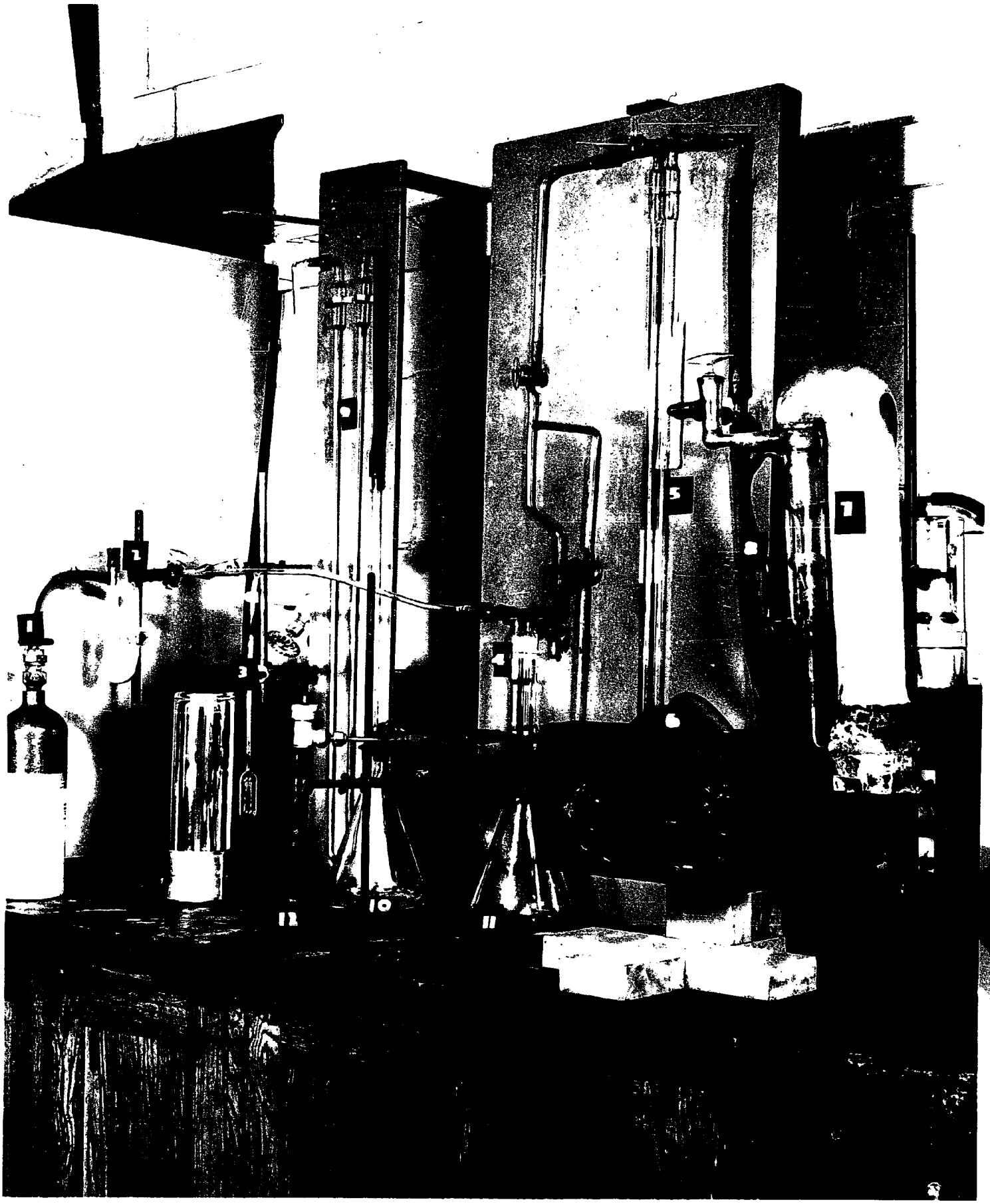


Figure 2 Picture of Low-Pressure Vapor Pressure Equipment

end. One side of the tee was connected by the P_2O_5 drying tube (2) to the Freon 13 supply cylinder (1). The other side of the tee was connected to the mercury manometer (4), which was constructed of 18 mm. I.D. glass tubing. The manometer was about 60 mm. long, and stopcock B connected the upper end of the legs of this manometer. The line from manometer (4) divided, and one line ran to the mercury manometer (5), which was constructed of 12 mm. I.D. glass tubing and was approximately 900 mm. long. The legs of manometer (5) were connected by stopcock F. The line from manometer (5) ran to the mercury diffusion pump (7), which was connected by rubber tubing (8) to the Hyvac pump (14). A McLéod gauge (6) was used to measure pressures from 0-5000 microns of mercury in the line from manometer (5) to the mercury diffusion pump. The other line from manometer (4) was connected to a tee, one side of which was connected to the liter flask (10) and the other side to the liter flask (11). Rubber tubing connections from flask (10) were made to a vacuum pump (13) and to the recovery cylinder (12). The recovery cylinder was a 1" x 6" steel nipple with a cap welded to one end and a Frigidaire packless valve to the other end. A line from flask (11) was later connected through stopcock K to the medium and high-pressure vapor pressure equipment. An open end

mercury manometer (9), 800 mm. long, was connected to the line joining flasks (10) and (11).

A cathetometer with scale divisions of 0.01 mm. was used to read the mercury levels of the manometers. Readings of the cathetometer were reproducible to 0.02 mm.

The mercury diffusion pump and the Hyvac pump were used to obtain an absolute pressure of 4 microns of mercury or less in the isoteniscope system. This system was checked for leaks as follows: The pressure in it was reduced to 4 microns. Stopcock F was closed, and the pressure on the mercury diffusion side of manometer (5) was maintained at 4 microns. After several hours manometer (5) indicated no pressure change of the isoteniscope system when it was read by means of the cathetometer. This indicated that there were no significant leaks in the system.

The temperature of the isoteniscope was controlled by immersing it in a suitable stirred bath (15). A silvered one quart Dewar flask with two clear slits in the silvering was used as the bath container. The slits in the silvering were 90 degrees from each other, and the isoteniscope could be viewed when it was immersed in the bath. The bath temperatures were measured with platinum resistance thermometer No. 169313. The middle of the platinum coil in the thermometer was always placed at the same level as the isoteniscope

and as close to it as possible. The bath operation was different for the temperature of -110°F and for the temperatures from -200 to -110°F.

The bath for -110°F used acetone as the bath fluid, and it was cooled with dry ice. Sufficient dry ice was added to the acetone until a small amount of it remained on the bottom of the flask. A stirrer mounted on a high-speed electric motor provided sufficient agitation to the acetone to keep the temperature gradients of the bath less than 0.02°F. The temperature of the bath rose gradually after dry ice had been added to it at the rate of approximately 0.20°F for 15 minutes. When the dry ice in the bottom of the flask was depleted and more was added to the bath, the temperature of the bath dropped about 0.50°F. To maintain a temperature within 0.04°F, it was necessary to add a small amount of powdered dry ice every few minutes.

The bath for -200 to -110°F is represented in Figure 3. A liquid with a low viscosity at temperatures down to -200°F was needed as the bath fluid. A petroleum ether with a boiling range of 25 to 40°C was found to be suitable for the bath, and it was agitated with a stirrer mounted on a small electric motor. The ether was cooled by means of a glass coil through which liquid air flowed. The liquid air was contained in a pint Dewar flask. The

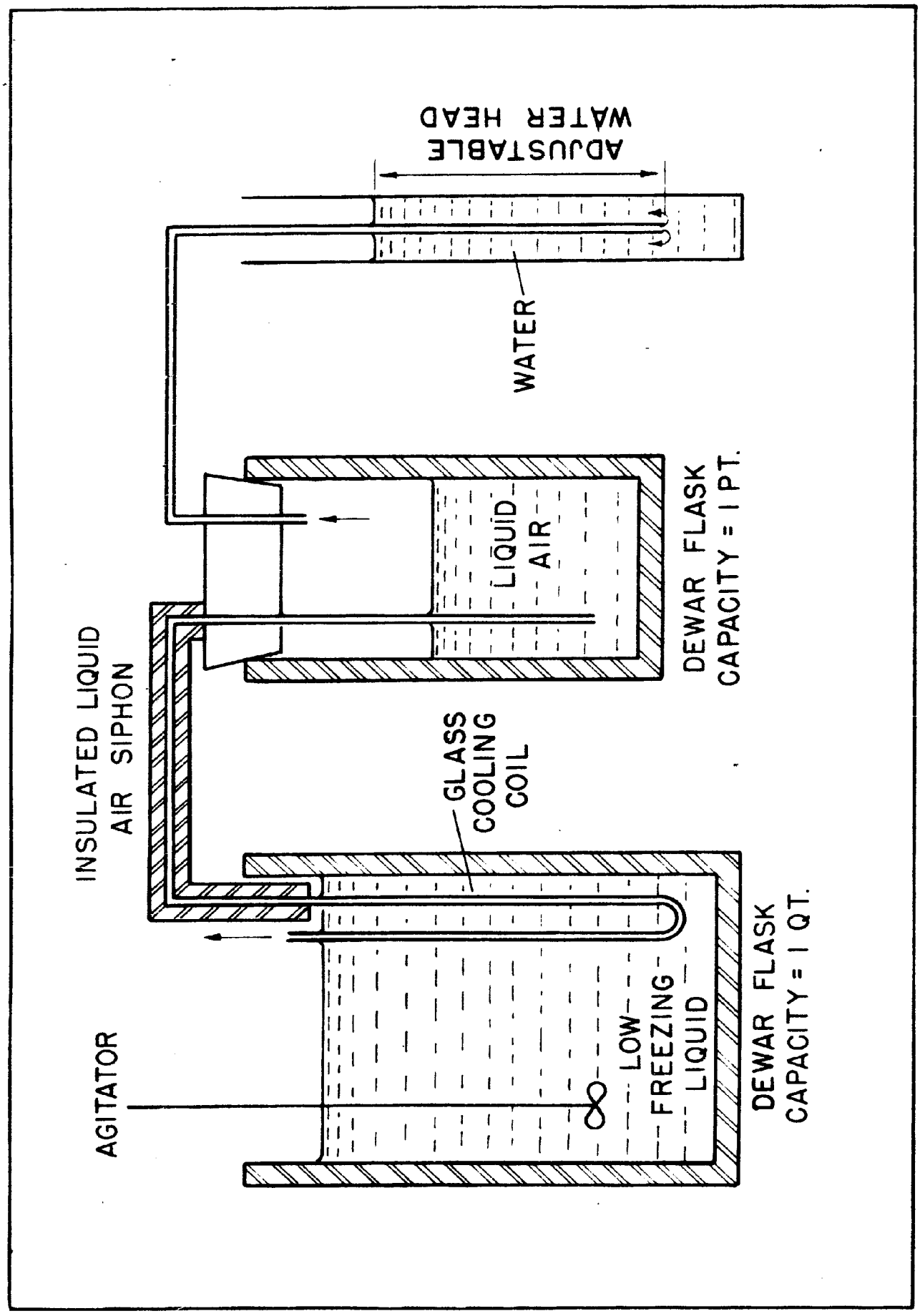


FIGURE 3 LOW TEMPERATURE BATH FOR -200 TO -110 °F

connecting line from the coil to the liquid air flask was insulated with rubber and asbestos in order to minimize the heat conduction from the atmosphere. The liquid air flowed through the coil because of the air pressure in the pint Dewar flask. This pressure was regulated by the adjustable water head. By regulating the air pressure the amount of liquid air that flowed through the coil was varied so that the heat gained from the atmosphere by the bath was just absorbed by the liquid air. As the liquid air level in the pint Dewar flask dropped, it was necessary to increase the length of the water leg in order to maintain a constant flow of liquid air. Bath temperatures were maintained with this equipment within 0.10°F for 10-15 minutes and within 0.04°F for 3-4 minutes. The temperature gradients of the bath at any one time were less than 0.02°F.

Operation of Low Pressure Vapor Pressure Equipment

The first step in the operation of the low-pressure vapor pressure equipment was the evacuation of the isoteniscope (3) and the connecting lines to the supply cylinder (1). Stopcocks A, B, E, and F were opened, and C and D were closed. The system was now evacuated by the mercury diffusion pump (7) to an absolute pressure of less than 5 microns of mercury as indicated by the McLeod gauge (6).

The second step was to load the isoteniscope with liquid Freon 13. The isoteniscope was immersed in the bath (15) whose temperature was approximately equal to that at which the vapor pressure was to be determined. Stopcock F was closed, and the valve of the supply cylinder was cracked. This allowed freon vapors to flow from the supply cylinder to the cold isoteniscope where they condensed. The isoteniscope was nearly filled with liquid, and then the supply cylinder valve and stopcock A were closed.

The next step was to "boil off" part of the liquid in the isoteniscope. The auxiliary vacuum pump (13) was started, stopcocks G, H, and L were opened, and J was closed. The recovery cylinder (12) was now immersed in liquid air. After the recovery cylinder and the connecting lines to stopcock D had been evacuated to less than 1.0 mm. of mercury as indicated by manometer (9), stopcock G was closed. Stopcock D was opened, and approximately one quarter of the liquid in the isoteniscope was allowed to vaporize (boil off) and condense in the recovery cylinder. Stopcock D was now closed. Flasks (10) and (11) were available for use as a temporary storage for the freon gas. This "boil off" procedure was used to remove any air or other impurities from the isoteniscope.

The vapor pressure of the liquid in the isoteniscope was read in mm. of mercury from manometer (5). This reading was essentially mm. of mercury absolute as the right leg of the manometer was being continuously evacuated by the mercury diffusion pump to a pressure of less than 5 microns of mercury. If the mercury level difference of manometer (5) was less than 60 mm., stopcock B was closed and F was opened, and the small manometer (4) was used to measure the pressure. As this manometer was constructed of larger diameter glass tubing than manometer (5), it would cause less error in the height of the mercury levels because of decreased surface effects. After the temperature of the isoteniscope was maintained by bath (15) within 0.10°F. for five minutes, the manometer reading became constant. This indicated that equilibrium was reached, and three readings were now taken at five minute intervals. In addition, the temperature of the cathetometer and the mercury manometer were recorded during these readings.

After the three readings were taken, another "boil off" was made from the isoteniscope. The recovery cylinder was again immersed in liquid air, the proper valves and stopcocks were opened, and about one quarter of the liquid in the isoteniscope was boiled off. The freon liquid left in the isoteniscope was now allowed to come to equilibrium again, and three more readings were taken at five minute

intervals. This "boil off" technique and subsequent vapor pressure readings were repeated three or four times, and they were used to check the purity of the freon. As the vapor pressure of the liquid was independent of the amount of liquid, the pressures should be the same for a constant temperature if the freon was uncontaminated with air or other impurities. It was found in all cases that the readings for "boiloffs" were in agreement within the experimental limits of accuracy.

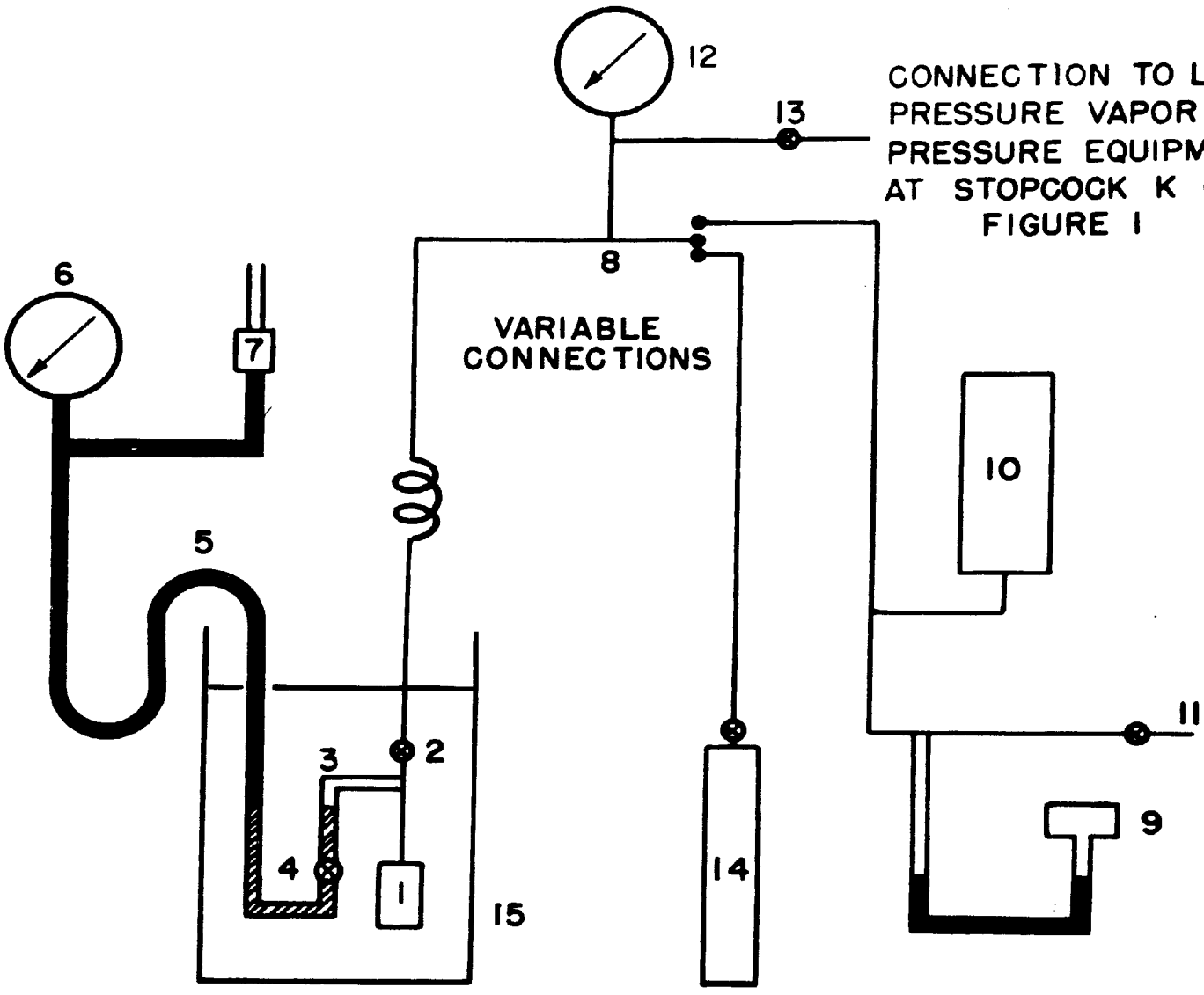
Medium-Pressure and High-Pressure Vapor Pressure Equipment

The medium-pressure and high-pressure vapor pressure equipment was designed for pressures from atmospheric to 200 psi and from 200 to 600 psi respectively.

The isoteniscope for the medium-pressure equipment was of about 20 cc. capacity, and it was constructed of 20 mm. I.D. thick-walled glass tubing. One end of the tubing was sealed off, and the other end was welded to one end of a 4" length of 3 mm. I.D. thick-walled glass tubing. A male ground glass joint was welded to the other end of the 3 mm. tubing. A special steel tee with a steel female joint at one of its openings was sealed to the ground glass joint with Pyroseal wax. The glass isoteniscope and the steel tee when assembled were hydraulically pressure tested to 1200 psi without failure. The vapor

pressure of the liquid Freon 13 to be held in the isoteniscope was measured by suitable pressure gauges. The gauges were connected by an 18" length of 1/4" copper tubing to the side opening of the tee on top of the isoteniscope.

The isoteniscope for the high-pressure equipment was constructed of a 1/2" x 3" extra heavy steel nipple with a cap brazed on one end and a 1/8" x 1/2" reducing coupling on the other. The coupling was connected by a 1/8" x 3" nipple to a 1/8" tee. The flowsheet of the high-pressure equipment, which includes the high-pressure isoteniscope, is shown in Figure 4, and the picture of it in Figure 5. The side opening of the tee on top of the isoteniscope (1) was connected by a 1/8" street elbow (3), U-leg (4), and a 1/4" copper tubing (5) to the pressure gauge (6). The U-leg was constructed of 1/8" pipe and fittings, except for the 5000 psi steel Metric needle valve in the leg. The safety rupture disc (7) set at 900 psi was connected to line (5). The U-leg, including the valve, was filled with mercury to within about one inch of the elbow (3). The other side of the U-leg on top of the mercury, the copper tubing (5), the copper tubing to the safety rupture disc, and the Bourdon tube of the pressure gauge were filled with a light mineral seal oil. The mercury and oil in the U-leg and line (5)



LEGEND

1	METAL ISOTENISCOPE	9	DEAD WEIGHT GAUGE
2	1/8" BRASS HOKE VALVE	10	BUFFER TANK
3	ELBOW	11	NITROGEN VALVE
4	MERCURY LEG WITH VALVE	12	0-1000 PSI GAUGE
5	OIL LEG	13	NEEDLE VALVE
6	PRESSURE GAUGE	14	SUPPLY CYLINDER
7	SAFETY RUPTURE DISC	15	CONSTANT TEMPERATURE BATH
8	1/4" TEE		

OIL LEG

MERCURY LEG

FIGURE 4 HIGH PRESSURE VAPOR PRESSURE EQUIPMENT

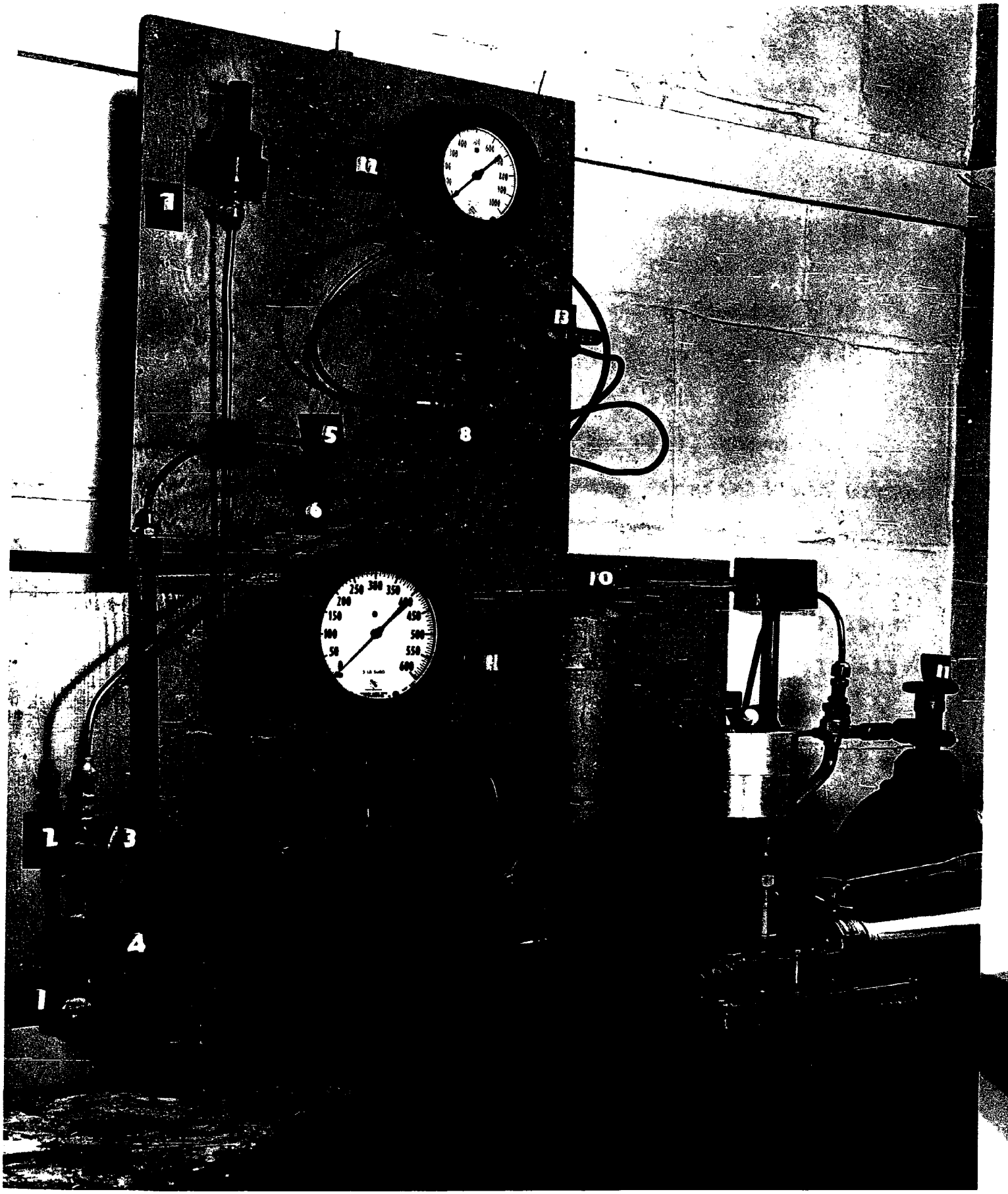


Figure 5 Picture of High-Pressure Vapor Pressure Equipment

transmitted the pressure from the isoteniscope to the pressure gauge and served to reduce the volume of the isoteniscope system to approximately 40 cc.

The medium-pressure or the high-pressure isoteniscope was connected at the upper opening of the tee on top of the isoteniscope to valve (2), shown in Figures 4 and 5. Valve (2) was connected by copper tubing to the tee (8). The right side of the tee was connected with copper tubing either to the Freon 13 supply cylinder (14), shown in Figure 4 but not in Figure 5, or to the Mansfield and Green Dead Weight Gauge (9). Tee connections in the line from tee (8) to the dead weight gauge ran to the nitrogen cylinder (11) and to the buffer tank (10). This tank was a cylinder of approximately 1500 cc. capacity, which was hydraulically pressure tested to 2000 psi.

A line from the upper opening of tee (8) joined it to another tee. The openings of this latter tee were connected to a pressure gauge (12), a 0-1000 psi Ashcroft Duragauge, and to a 1/4" steel Metric needle valve (13). A rubber tubing connection was made from this valve to the flask (11) at stopcock K of Figures 1 and 2. From stopcock K there were lines to the mercury diffusion pump (7), the vacuum pump (14), and the recovery cylinder (12).

The pressure gauges used to measure the pressure in the medium-pressure and high-pressure isoteniscopes were

as follows: The first gauge was a 0-30 psi Star Gauge with 0.5 psi subdivisions. Several 0.25 psi subdivisions were drawn on the gauge and the gauge could then be read within 0.025 psi. The second gauge was a 0-160 psi Ashcroft Duragauge with 1.0 psi subdivisions which could be read within 0.1 psi. The third gauge was a 0-300 Ashcroft Laboratory Test Gauge with 1.0 psi subdivisions which could be read within 0.2 psi. The fourth gauge was a 0-600 psi Ashcroft Duragauge with 5.0 psi subdivisions which could be read within 0.5 psi.

The temperature of the isoteniscope was controlled by immersing it in a bath (15). Three different bath arrangements were used to cover the temperature range from -110 to 80°F.

The first bath arrangement is shown in Figure 6. It could be used to obtain temperatures from -110 to 70°F, but it was only used in the vapor pressure measurements to obtain temperatures at about -72 and -15°F. The insulated container used for this bath was a special Dewar flask of about two quarts capacity that had two slits in the silvering so that the interior of the bath could be viewed. The bath fluid used was n-propyl alcohol, which has a relatively high flash point, and it was agitated vigorously with a stirrer mounted on a high-speed electric motor. A 1.0" I.D. test tube that was filled with dry ice and acetone was

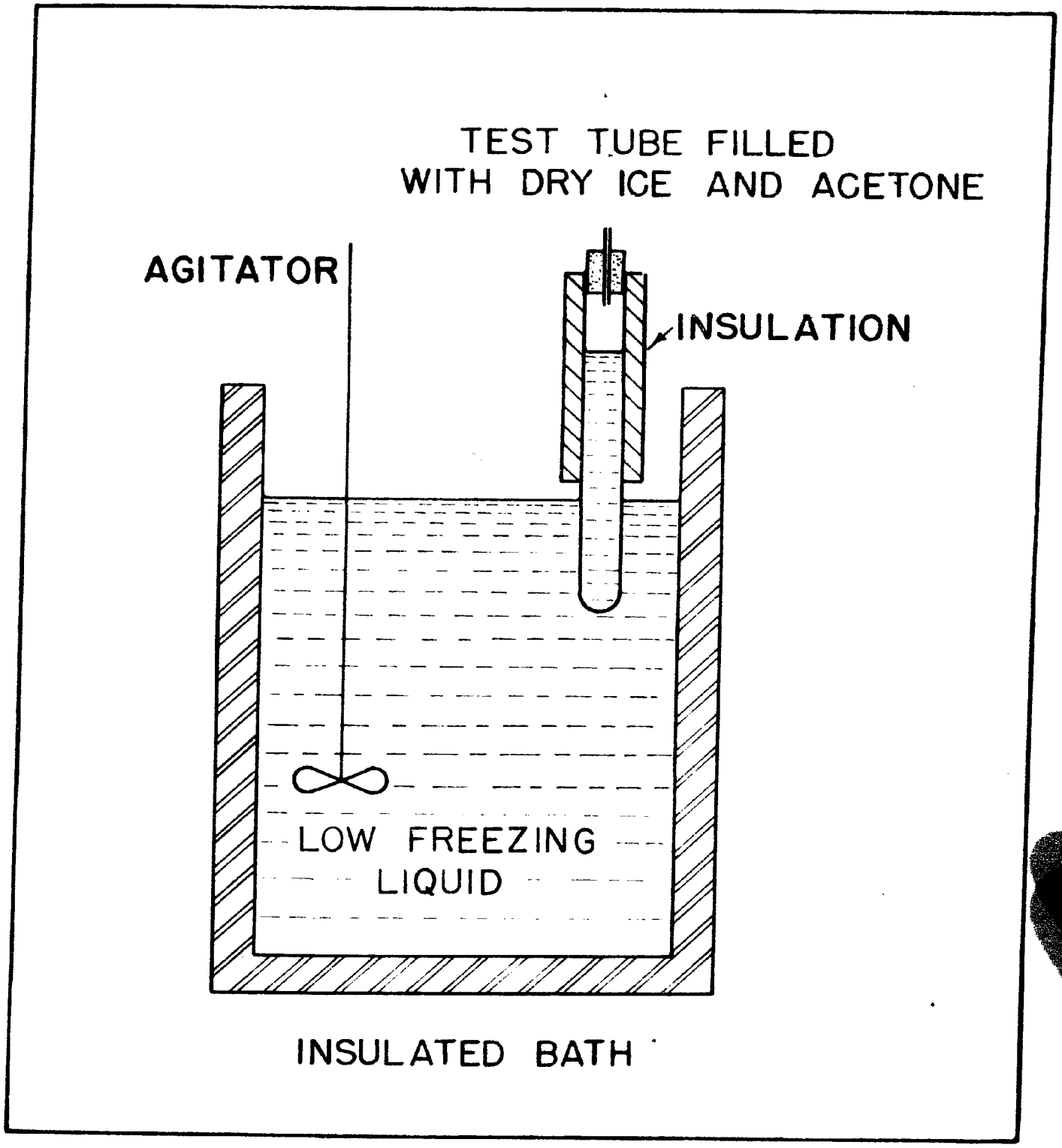


FIGURE 6 BATH FOR -110 TO 70 °F

immersed in the bath in order to cool it. The temperature of the bath was controlled by manually adjusting the depth of immersion of the test tube. The temperatures of this bath were controlled within 0.05°F and the temperature gradients throughout the bath were less than 0.02°F.

The second bath, which was used to obtain a temperature of 32°F, was a crushed ice mixture. It was contained in a 6" I.D. x 12" deep battery jar. The jar was insulated by wrapping several layers of asbestos around it. No temperature gradients were measured by the platinum resistance thermometer No. 169313 within several inches of the isoteniscope, which was placed at the center of the bath.

The third bath was operated at a temperature of about 80°F. The bath container was a 6" I.D. x 12" deep battery jar. A light mineral seal oil was used as the bath fluid, and it was vigorously agitated with a high-speed stirrer. The 80°F temperature was just slightly above that of the room, and a 25 watt electric heater was immersed in the bath. The heater was hooked in series with a variable resistance, which was controlled manually to regulate the heat added to the bath. By this arrangement the bath temperature was maintained within 0.05°F, and temperature gradients throughout the bath were less than 0.02°F.

Operation of Medium-Pressure and High-Pressure Vapor Pressure Equipment

The operation of the medium-pressure and the high-pressure vapor pressure equipment was almost identical. The first step in the operation of the equipment was to calibrate the pressure gauge (6) with the dead weight gauge (9). The pressure gauge for the medium-pressure equipment was calibrated while it was connected by the copper tubing to the isoteniscope. The gauge for the high-pressure equipment was calibrated while it was connected to the oil-filled line (5), and while the U-leg was immersed in the bath (15). For both the medium-pressure and the high-pressure equipment, the dead weight gauge was connected to the tee (8). Valve (13) was closed, and valve (2) was opened. The valve to the U-leg, in the case of the high-pressure equipment, was also opened. Nitrogen gas was bled into the isoteniscope system through valve (11) until the dead weights just floated. The pressure gauge (6) was now read. The calibration was made of this gauge in the approximate range of pressure desired from the low to the high end of the range, and then from the high to the low end. The true pressure gauge reading was taken as the average of those for the rising and falling pressures. In no case did the rising and falling readings vary by more than 0.025, 0.1, 0.2, and 0.5 psi for the 0-30 psi, 0-160 psi, 0-300 psi, and 0-600 psi pressure gauges respectively. After the calibration was completed, the nitrogen was exhausted through valve (13).

The next step was to evacuate the isoteniscope. The copper tubing line from the dead weight gauge was disconnected from tee (8), and the freon supply cylinder (14) was connected to tee (8). The valve in the U-leg, in the case of the high-pressure equipment, was closed. Valve (13) was opened, and the isoteniscope was evacuated by the mercury diffusion pump to a pressure of 10 microns of mercury or less.

The isoteniscope was now filled with Freon 13. The medium-pressure isotensicope was loaded as follows: After the isoteniscope was evacuated, valve (13) was closed. The isoteniscope was immersed in a bath at the approximate temperature required for the vapor pressure determination. The supply cylinder valve was now cracked, and Freon 13 gas condensed in the isoteniscope. When the isoteniscope was filled with liquid, valve (2) and valve on the supply cylinder were closed.

The metal isoteniscope for the high-pressure equipment was loaded as follows: After the isoteniscope was evacuated, valve (13) was closed, and the supply cylinder valve was cracked until gauge (12) read 10-15 psi. Now the valve in the U-leg was opened. As it was impossible to see the liquid level in the metal isoteniscope, the following method was used to determine when the isoteniscope was filled with liquid. The bulb of the isoteniscope was immersed in an ice bath. As long as the liquid level in the

isoteniscope remained below the ice bath level, the temperature of the liquid level would be about 32°F , and the vapor pressure as measured by gauge (6) would be less than 300 psi. When the liquid level rose above the ice bath, the surface temperature of the liquid would be between 32°F and room temperature. The vapor pressure for such a temperature was between 300 and 500 psi. As a result when the pressure gauge read above 300 psi, it indicated that the liquid level was above the ice bath level, and that the isoteniscope was filled with liquid. At this time valve (2) and the freon supply cylinder valve were closed.

A "boil off" was now made of about one fifth of the liquid in the isoteniscope. The "boil off" was made through valve (13) and the liter flasks (10) and (11) of Figures 1 and 2 to the recovery cylinder (12). The following procedure was used for the glass isoteniscope. Stopcock D was closed, and stopcocks G, H, J, K, and L, and valve (13) were opened. Flasks (10) and (11) and the connecting line to valve (2) were evacuated by the vacuum pump (13) to a pressure of less than 5 mm. of mercury a s read by manometer (9). Stopcock G was now closed, and the recovery cylinder was immersed in liquid air. Valve (2) on top of the isoteniscope was cracked, and about one fifth of liquid in the isoteniscope was allowed to vaporize (boil off) and condense in the recovery cylinder. Valve (2) and the recovery cylinder valve were now closed.

As it was impossible to see the liquid level in the metal isoteniscope, the following method was used to boil off a definite quantity of Freon 13 from it. After flasks (10) and (11) were evacuated to a pressure of less than 5 mm. of mercury, stopcocks G and L were closed, and the recovery cylinder was immersed in liquid air. Valve (2) above the isoteniscope was cracked which allowed Freon 13 gas to flow to the flasks. This caused the pressure in the flasks to increase. In each case the amount of freon bled to the flasks was controlled to give a definite pressure increase, which was about one and three inches of mercury for temperatures of the bath of 80 and 32°F respectively. After the "boil off" was completed, valve (2) was closed, stopcock L was opened, and the freon condensed in the recovery cylinder.

Vapor pressure readings were now made of the liquid Freon 13 in the isoteniscope. The isoteniscope was immersed in the bath (15) at the required temperature. The U-leg, in the case of the high-pressure equipment, was also immersed in the bath. A constant reading of gauge (6), which indicated that equilibrium was reached, was obtained in less than five minutes. The temperature of the bath was held constant, and three readings were obtained at five minute intervals. The barometric pressure was also read during this time.

Another "boil off" was now made from the isoteniscope. Then the Freon 13 liquid left in the isoteniscope was again allowed to come to equilibrium, and more readings were taken. After several "boil offs" and subsequent readings were made, no more liquid remained in the isoteniscope. The supply cylinder was then disconnected from the tee (8). The dead weight gauge was now connected to the tee (8) again, and the pressure gauge (6) was recalibrated. In all cases it was found that the calibration of the gauge before and after the run was the same within the limits of accuracy in reading the pressure gauges.

P-V-T Determinations

Equipment was built to obtain p-v-T data of the superheated vapor. The Freon 13 used to obtain these data was purified by E. I. du Pont de Nemours and Co. A commercial Freon 13 had been fractionated at high reflux ratio, and the end cuts had been discarded. Du Pont's analysis of the middle cuts indicated that the material contained only a trace of impurities, which was mainly air, and the Freon 13 was about 99.7% pure. Since that time about half of the material was removed in the vapor phase from the storage cylinder. This procedure probably removed most of the air, so the remaining Freon 13 used in this investigation was probably better than 99.7% pure.

P-V-T Equipment

A flowsheet of the equipment for the p-v-T measurements from 300 - 2000 psi is shown in Figure 7. A picture of the assembled equipment is shown in Figure 8.

The vapor density bulb (15) was a 3" O.D. cylinder, which was about 8" long and had about 1/4" thick walls. It was sand-polished on the inside and outside in a ball mill. The cylinder was then nickel-plated on the inside in order to decrease the amount of freon gas that would be adsorbed on the walls. The outside of the cylinder was chromium-plated. A special high-pressure cross was machined and screwed in the top of the bulb. The first opening of the cross was connected to the charging valve (16), a 3000 psi steel Lunkenheimer needle valve, so that the packing side was away from the vapor density bulb. The second opening from the cross was connected to a safety rupture disc (4) set at 2800 psi. The third opening was connected to the right hand leg of the U-leg (18) by an 8" length of 5000 psi 1/16" I.D. steel tubing. The left hand leg of the U-leg was connected to the pressure gauge (1). The U-leg was built of 10,000 psi 3/32" I.D. steel tubing except for a 3000 psi Lunkenheimer needle valve (17) connected in the leg. The U-leg including the valve was filled with mercury to the top of the right hand leg. The left hand leg on top of the mercury and the Bourdon tube

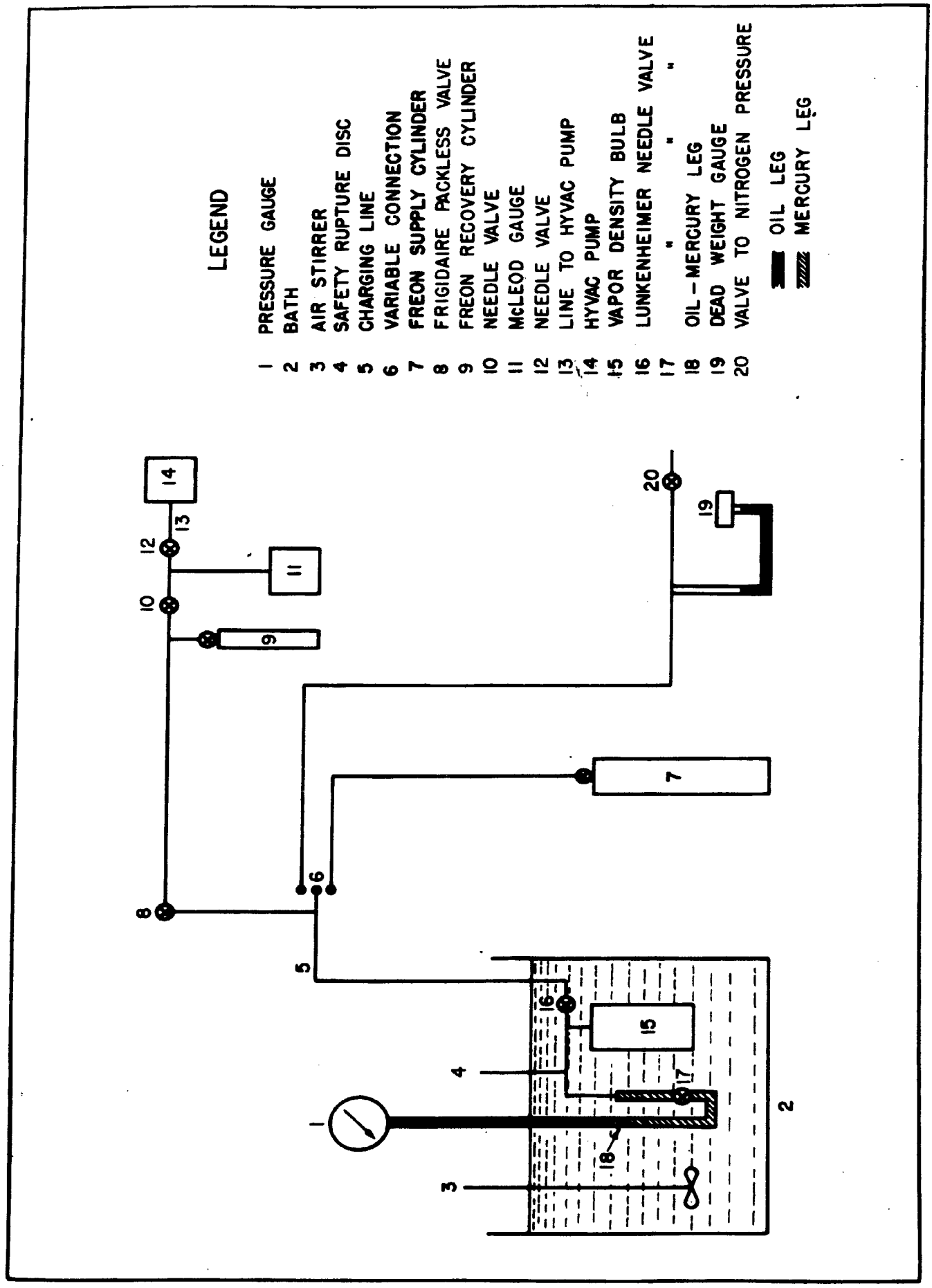


FIGURE 7 PRESSURE-VOLUME-TEMPERATURE EQUIPMENT



Figure 8 Picture of Pressure-Volume-Temperature Equipment

of the pressure gauge were filled with a mineral seal oil. The pressure gauges used were a 0-600 psi Ashcroft Duragauge with 5 psi subdivisions which could be estimated within 0.5 psi, and a 0-2000 Ashcroft Laboratory Test Gauge with 10 psi subdivisions which could be estimated within 1.0 psi.

The total volume of the vapor density bulb and the connecting lines to valve (16) and to the top of the mercury in the U-leg was found to be 620.8 cc. at 77°F. This was determined from their weights empty and filled with distilled water.

For pressures below 300 psi a larger vapor density bulb (15) was used. This bulb consisted of two hemispherical steel sections, 8" I.D. of 1/8" thickness, which had been copper welded together and chromium-plated on the outside. Another change for this equipment was the mounting of the oil- and mercury-filled U-leg (18) with valve (17) outside of the bath. This change was necessary as the bath temperature at the lower pressures was sometimes below -40°F. The mercury in the U-leg would freeze at temperatures as low as this if it remained in the bath. The connection from the U-leg to the cross above the vapor density bulb was a 2 foot length of 5000 psi 1/16" I.D. steel tubing. The volume of the sphere and its

connections was determined from their weights empty and filled with distilled water. The total gas volume was found to be 4075 cc. at 77°F of which approximately 2.0 cc. were outside the bath.

Two pressure gauges were used below 300 psi. The first was a 0-100 Ashcroft Gauge with 1.0 psi subdivisions which could be estimated within 0.1 psi. The second was a 0-300 psi Ashcroft Laboratory Test Gauge with 1.0 psi subdivisions which could be estimated to 0.2 psi or less.

The charging valve (16) was used for both the high-pressure and low-pressure vapor density bulbs, and it was connected by the copper tubing charging line (5) to a tee (6), the right side of which was a variable connection. This side connected either to the freon supply cylinder (7), which had a capacity of about 600 cc., or to a Mansfield and Green dead weight gauge (19), which is shown in Figure 7 but not Figure 8. Valve (20) was used to bleed nitrogen into the connecting line between connection (8) and the dead weight gauge.

The top of tee (6) was connected to a Frigidaire packless valve (8). This valve was connected by copper tubing to a tee, one outlet of which connected to the recovery cylinder (9), which had a capacity of about 20 cc., and the other outlet to a 125 psi Lunkenheimer needle valve (10). Valve (10) was connected to another tee. The first

outlet from this tee went to a McLeod gauge (11) for measuring pressures from 0-1000 microns of mercury, and the second outlet went to another 125 psi Lunkenheimer needle valve (12). The copper tubing line (13) from valve (12) was connected to a Hyvac Pump (14).

A large analytical balance was used to weigh the supply cylinder (7) and the recovery cylinder (9). This balance could be estimated to 0.001 grams at 2000 grams, and its results were reproducible to within 0.005 grams.

The bath (2) for the p-v-T measurements was a steel container 20" I.D. and 24" deep. It was insulated on the sides and bottom with three to four inches of rock cork. Perchlorethylene was used as the bath fluid for temperatures from -70 to 100°F , and a light mineral seal oil from 100 to 260°F. Platinum resistance thermometer No. 169313 was used for all temperature measurements.

The bath temperature from -70 to 70°F was controlled by the arrangement shown in Figure 6. A glass test tube, 2" I.D. and 18" long, was filled with dry ice and acetone and was immersed in the bath fluid. The temperature of the bath was controlled within 0.10°F by manually varying the depth of immersion of the test tube. The air stirrer (3) provided sufficient agitation to keep temperature gradients in the bath below 0.02°F. Four heaters with power rating of 125, 250, 750, and 1250 watts respectively were used for increasing the temperature rapidly from one point to another.

The bath temperature from 70 to 250°F was manually controlled within 0.15°F by using various combinations of the four heaters. The air stirrer provided sufficient agitation to keep the temperature gradients in the bath less than 0.02°F.

Operation of P-V-T Equipment

The first step in the operation of the p-v-T equipment was to calibrate the pressure gauge (1). Below 600 psi pressure, the gauge was calibrated by the dead weight gauge (19). This latter gauge was connected to the variable connection (6). Valves (16) and (17) were opened and valve (8) closed. Nitrogen gas was bled into the system by valve (20) until the dead weights floated, and the gauges were calibrated in the same manner as that described for the high-pressure vapor pressure equipment. For pressures from 600-2000 psi, the gauge (1) was disconnected from the U-leg (18) and was calibrated directly on the standard American Dead Weight Gauge Tester.

The evacuation and loading of the vapor density bulb were as follows: The freon supply cylinder (7), which had been previously weighed to within 0.001 gram, was connected to tee (6). Valve (17) was closed, valves (16), (8), (10), and (12) were opened, and the system was evacuated by the Hyvac pump (14) to an absolute pressure of 10 microns

of mercury or less as indicated by the McLeod Gauge (11). Meanwhile the bath was brought to the approximate temperature desired. Valve (8) was closed and the valve on the supply cylinder was cracked allowing some freon to enter the vapor density bulb (15). Now valve (17) was opened and more freon was admitted to the system until a pressure, one to two pounds less than the vapor pressure, was obtained in the vapor density bulb. When this pressure was reached, the freon supply cylinder valve and valve (16) were closed.

The freon in the line between the supply cylinder and valve (16) was recovered quantitatively in the recovery cylinder (9), whose tare weight was known. This recovery was made by closing valve (10), immersing the recovery cylinder in liquid air, and opening valve (8) and the valve on the recovery cylinder. After most of the freon had condensed in the recovery cylinder, valve (12) was closed, and valve (10) was opened. The pressure of the freon remaining in the line was measured by the McLeod gauge, and the recovery cylinder was left in the liquid air until the freon pressure was less than 200 microns of mercury. The recovery cylinder valve was now closed, and the recovery and supply cylinders were disconnected from the apparatus and weighed. The loss in weight of

the supply cylinder minus the gain in weight of the recovery cylinder was the quantity of freon added to the vapor density bulb.

Experimental isometric data were now obtained as follows: The temperature of the bath (2) was first leveled off. The pressure gauge (1) was read at five minute intervals until three consecutive readings were identical within the limits of accuracy of the pressure gauge readings. This indicated that equilibrium was reached. As soon as three such readings were obtained, the temperature of the bath was increased by means of the heaters. The first temperature increase was generally 3-4°F. in order to insure that the temperature was sufficiently high to have only a vapor phase present and not a vapor-liquid equilibrium. The increase of the pressure along the vapor pressure curve was larger for the same temperature rise than that along an isometric in the vapor phase for all vapor densities below the critical density. After it was apparent that there was only a vapor phase present, the temperature increases were about 25-35°F between readings, and each isometric covered a temperature range of 130-190°F. The barometric pressure was read at frequent intervals while the isometric readings were being taken.

After the highest temperature of the isometric was reached, the freon was removed quantitatively from the vapor density bulb. The supply and recovery cylinders were reconnected to the system. Valves (8), (10), and (12) were opened, and the pressure in the connecting lines was reduced to 10 microns of mercury or less by the vacuum pump. The supply cylinder was immersed in a dry ice-acetone bath, and valve (8) was closed. Valve (16) and the valve on the supply cylinder were opened. Most of the freon condensed in the supply cylinder, and the pressure in the bulb was reduced to approximately atmospheric. The supply cylinder valve and valve (17) in the U-leg were closed. The remainder of the freon was recovered in the recovery cylinder as follows: The cylinder was immersed in liquid air, valve (10) was closed, and valve (8) and the recovery cylinder valve were opened. After most of the freon gas had condensed in the recovery cylinder, valve (12) was closed, and valve (10) was opened. The recovery cylinder was left in the liquid air until the freon pressure in the vapor density bulb and the connecting lines was reduced to less than 200 microns of mercury as indicated by the McLeod gauge. The recovery cylinder was now closed, and the recovery and supply cylinders were disconnected from the apparatus and weighed. The sum of

the gains of weights of the two cylinders was the amount of freon removed from the vapor density bulb. For each isometric reported the amount of freon loaded and that removed agreed within 0.1% and generally within 0.04%.

After the removal of the freon from the vapor density bulb, the pressure gauge was again calibrated. In no case did this recalibration very from the calibration before the run beyond the limits of accuracy in reading the pressure gauge.

Saturated Liquid Density Determinations

The saturated liquid density measurements were made with a Freon 13 of the highest purity obtainable. The Freon 13 had been analyzed by the E. I. de Pont de Nemours and Co. as being 99.9% pure or better.

The saturated liquid densities were measured by using eleven hollow Pyrex glass floats, which had a length of about 25 mm. and a diameter of 6 mm. Each float was weighed with shot before being sealed in order to give it the approximate desired density. The exact densities of the floats were determined from their weights in air and in distilled water, and the densities ranged from about 0.82 to 1.74 g./cc. at approximately 0.1 g./cc. intervals. Each float was placed in a glass tube, which was constructed of 18 mm. O.D. glass tubing with 2 mm. walls. The tubes used were about 150 mm.

long, and they were sealed off at one end. After the floats were placed in the tubes, the tubes were necked down to about 3 mm. I.D. at about 50 mm. from the open ends.

The following technique was used to load a tube with Freon 13. The tube was connected by a one-hole rubber stopper to a glass stopcock, as is shown in Figure 9. A piece of vacuum rubber tubing connected this stopcock to stopcock C of the low-pressure vapor pressure equipment, shown in Figure 1. Stopcocks A, B, C, E, and F were opened, and D was closed. The tube was now evacuated by the mercury diffusion pump (7) to a pressure of 4 microns of mercury or less, and it was now immersed in a dry ice-acetone bath. Then stopcock F was closed, and the valve of the supply cylinder (1) was cracked. This allowed freon gas to flow to the tube where it condensed. After the tube was half full of liquid, the supply cylinder valve was closed.

Part of the liquid freon was now boiled off from the tube in order to remove any air present in the tube. This boil off procedure was as follows: Stopcock C, J, and L were closed, and stopcocks, D, G, and H were opened. The absolute pressure in the line at stopcock C was reduced to 5 mm. of mercury or less by the vacuum pump (13) as

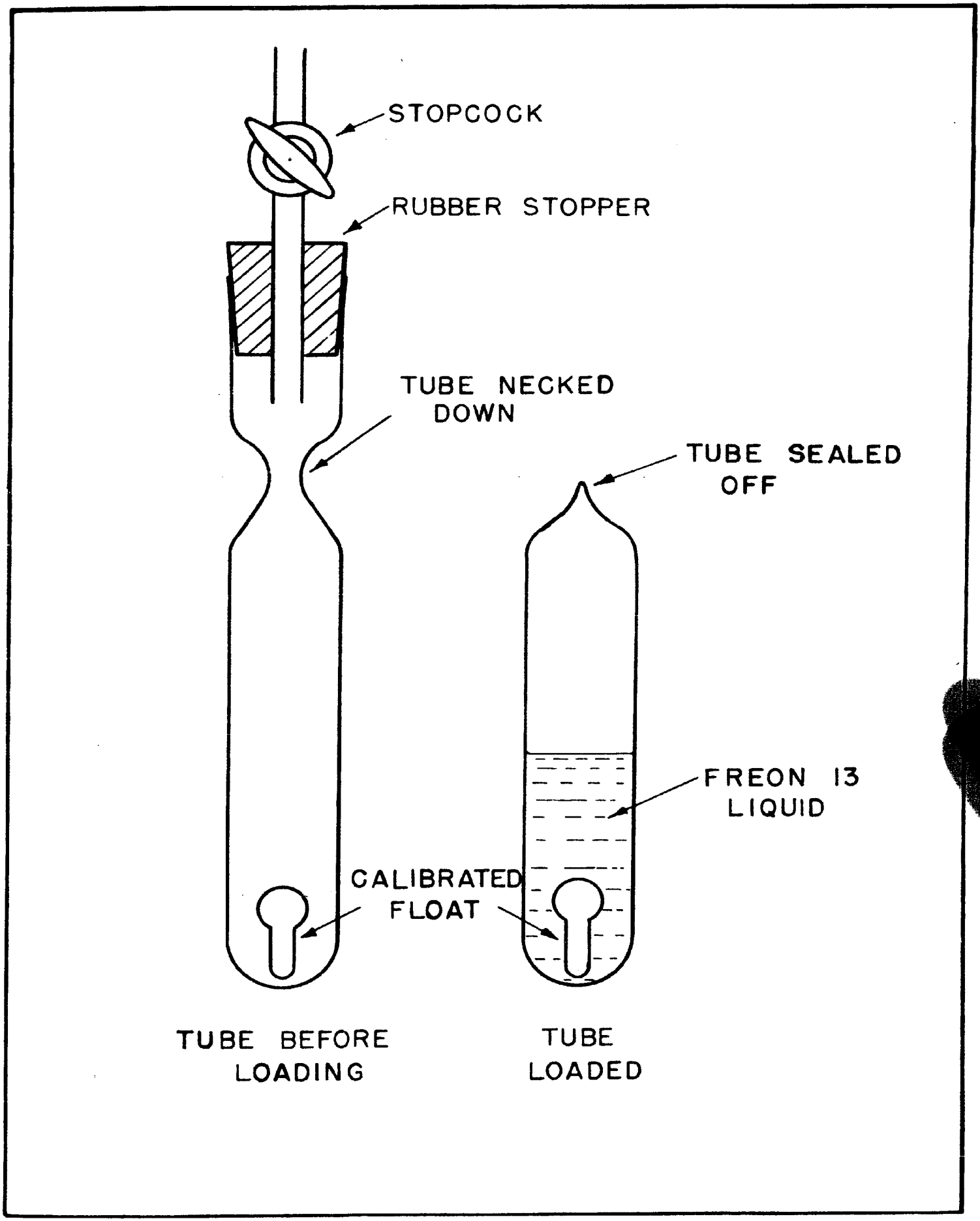


FIGURE 9 LIQUID DENSITY TUBE

indicated by manometer (9). Now stopcock C was opened, and freon was boiled out of the tube until it was about one-third full of liquid. The stopcock on top of the tube was now closed, and it was disconnected from the rubber tubing. The tube was now sealed off by a gas flame. The diagram of the loaded tube is shown in Figure 9.

The sealed off glass tubes were mounted in suitable baths. The temperature of the bath was increased slowly until the float sank. Then the temperature was lowered slowly until the float rose. This process was repeated until the temperature of the rising and sinking agreed within approximately 0.20°F or less. The average of the two temperatures was taken as the temperature at which the float and the liquid freon had the same density.

The baths needed for the saturated liquid density measurements were for temperatures from -225 to 85°F. The baths for -200 to -100°F and for -110 to 70°F were shown in Figures 3 and 6 respectively, and they were both described in the operation of the vapor pressure equipment. The bath for -225 to -200°F operated on the same principle as the -200 to -100°F bath shown in Figure 3. The only change in the two baths was that Freon 12, dichlorodifluoromethane, was used as the bath fluid instead of a petroleum ether.

The bath for 70 to 85°F used water as the bath fluid, and it was vigorously agitated with a high-speed stirrer. This bath was heated by a 25 watt electric heater that was hooked in series with a large variable resistance. This resistance was manually controlled so that the temperature was maintained within 0.05°F. The temperature gradients in the bath were less than 0.02°F.

Critical Temperature Determination

The critical temperature was determined with Freon 13 sealed in glass tubes similar to those used to measure the saturated liquid densities. The liquid density floats were not required in the critical temperature tubes although they did not interfere with the determination. The freon was loaded in the tubes in the same manner as that used for the liquid density measurements until the tubes were about a third full of liquid at the dry ice temperature. Freon 13 that was 99.9% pure or better was used for this measurement.

The method that was used to measure the critical temperature is as follows: A loaded tube was mounted vertically in a water bath, and the temperature was raised about 0.02°F per minute until the meniscus of the liquid disappeared. The disappearance of the meniscus was gradual as the temperature increased, and the meniscus was replaced

with a wide band, which showed density gradients. As the temperature was further increased, the density gradients gradually disappeared, and the tube appeared to be filled with a homogeneous gas. The point where the meniscus disappeared was approximately at the half-way point of the tube.

The temperature was now decreased at about 0.02°F per minute. First, a faint white haze appeared throughout the tube. This changed to a more intense white haze and then to a tannish haze as the temperature was further decreased. Then, the meniscus of the liquid appeared as a sharp line near the half-way point of the tube, and the tannish color still prevailed throughout the tube. The point where the meniscus appeared in the tube was sometimes slightly different than the point where it had disappeared.

When the tube was shaken, the meniscus and density gradients disappeared at temperatures about 0.09°F lower than when it was rigidly mounted. The shaking, however, did not change the temperature at which the meniscus appeared or the location of the meniscus.

Critical temperature measurements were made with four tubes. Each tube was estimated to have a slightly different loading of Freon 13. The points where the

meniscus disappeared and appeared in the four tubes were slightly different. These points were just above the middle of the two tubes estimated to be the heaviest loaded. The points were at the middle of the tube with the average loading, and the points were slightly below the middle of the tube with the lightest loading. In all four tubes the temperatures of the disappearance and appearance of the meniscus were the same within the limits of the experimental accuracy. These two temperatures were found to agree within 0.20°F for the rigidly mounted tubes, and the average of these temperatures was considered to be the critical temperature.

RESULTS

The following empirical equations have been developed to represent the experimental data of this investigation.

The Vapor Pressure Equations

(9) $\log_{10} p = 36.76130 - 2623.988/T - 11.80586 \log_{10} T + 5.71495 \times 10^{-3} T$

This equation represents the experimental vapor pressure data within 0.08% from -200 to -15°F, and within 0.14% from -15°F to the critical temperature, 83.93°F.

(10) $\log_{10} p = 56.34405 - 3351.281/T - 19.16910 \log_{10} T + 9.20366 \times 10^{-3} T$

This equation predicts the vapor pressure data within 0.07% from -15 to 83.93°F, but it is relatively inaccurate when extrapolated beyond this range.

The Equation of State for the Superheated Vapors

(25) $p = A + B T + C/T^4$

where

$A = -2.837 d^2 + 0.01594 d^3 - 0.0003964 d^4$

$B = 0.1027 d + 2.328 \times 10^{-3} d^2 + 4.944 \times 10^{-7} d^4$

$C = (-23.55 d^2 + 0.0287 d^4 - 5.816 \times 10^{-6} d^6) \times 10^9$

This equation predicts the experimental isometric data within an average of 0.2% at densities up to the critical density, 36.07 lbs./cu.ft.

The Saturated Liquid Density Equation

(28) $d_L = 36.07 + 0.01566 (t_c - t) + 1.110 (t_c - t)^{1/2} + 6.665 (t_c - t)^{1/3} + 3.245 \times 10^{-5} (t_c - t)^2$

This equation represents the experimental liquid density data within 0.10% from -225°F to the critical temperature, 83.93°F.

The Equation for the Specific Heat of the Gas at Infinite Volume

(29) $c_v = 0.01602 + 0.0002823\ T - 1.159 \times 10^{-7}\ T^2$

This equation predicts the specific heat values of the gas that were calculated from the fundamental frequencies within 1.0%. The fundamental frequencies were determined from spectroscopic data reported in the literature.

$c_v + R = c_p$ at zero pressure

c_p at zero pressure = c_p at 1 atm. within limits of accuracy in calculating c_p at zero pressure

$c_p = 0.03504 + 0.0002823\ T - 1.159 \times 10^{-7} T^2$

Results for the Critical Constants

$t_c = 83.93°F.$

$p_c = 561.3$ psia

$d_c = 36.07$ lbs/cu.ft.

$v_c = 0.02772$ cu.ft./lb.

The critical temperature was considered to be the average of the temperatures for the disappearance and appearance of the liquid meniscus in a tube filled with Freon 13. These temperatures were measured experimentally as 84.01°F and 83.86°F respectively. The critical pressure was calculated by substituting the critical temperature in the vapor pressure equation, Equation 10.

The critical density (and the critical volume) were obtained by using the law of rectilinear diameters.

Results for the Thermodynamic Properties of Freon 13

Values of the thermodynamic properties of Freon 13 for the saturated liquid and vapor and for the superheated vapor are presented in Tables II and III respectively. A pressure-enthalpy diagram with constant temperature, volume, and entropy lines is shown in Figure 10.

TABLE II. THERMODYNAMIC PROPERTIES OF SATURATED FREON 13 ($CClF_3$)

Temp. °F.	Abs. Pres. psia	Volume, cu.ft./lb. Liquid	Volume, cu.ft./lb. Vapor	Enthalpy above -40°F.(Btu/lb.) Liquid	Enthalpy above -40°F.(Btu/lb.) Latent	Enthalpy above -40°F.(Btu/lb.) Vapor	Entropy above -40°F.(Btu/lb)°R. Liquid	Entropy above -40°F.(Btu/lb)°R. Vaporization	Entropy above -40°F.(Btu/lb)°R. Vapor
-200	.4329	.009466	61.33	-34.551	73.096	38.545	-.10081	.28147	.18066
-190	.7490	.009574	36.74	-32.429	72.029	39.600	-.09313	.26708	.17395
-180	1.238	.009685	22.99	-30.298	70.970	40.672	-.08575	.25375	.16800
-170	1.967	.009801	14.942	-28.208	69.904	41.696	-.07858	.24131	.16273
-160	3.104	.009920	9.750	-26.083	68.808	42.725	-.07213	.22960	.15747
-150	4.464	.01004	6.976	-24.010	67.783	43.773	-.06491	.21887	.15396
-140	6.455	.01017	4.950	-21.902	66.696	44.794	-.05844	.20863	.15019
-130	9.080	.01031	3.605	-19.792	65.596	45.804	-.05209	.19896	.14687
-120	12.48	.01045	2.681	-17.671	64.473	46.802	-.04590	.18980	.14390
-110	16.81	.01060	2.031	-15.527	63.316	47.789	-.03977	.18106	.14129
-100	22.23	.01075	1.5642	-13.387	62.138	48.751	-.03286	.17275	.13889
- 90	28.89	.01091	1.2232	-11.241	60.941	49.700	-.02806	.16484	.13678
- 80	36.98	.01109	.9689	- 9.052	59.672	50.620	-.02230	.15716	.13486
- 70	46.68	.01127	.7766	- 6.843	58.362	51.519	-.01665	.14977	.13312
- 60	58.19	.01146	.6289	- 4.604	56.993	52.389	-.01106	.14259	.13153
- 50	71.71	.01167	.5139	- 2.320	55.546	53.226	-.00548	.13558	.13009
- 40	87.43	.01189	.4234	0.000	54.023	54.023	.00000	.12872	.12872
- 30	105.6	.01213	.3512	2.363	52.416	54.779	+.00545	.12199	.12744
- 20	126.4	.01239	.2930	4.809	50.668	55.477	.01096	.11524	.12620
- 10	150.1	.01268	.2454	7.484	48.630	56.114	.01686	.10814	.12500
0	176.8	.01299	.2066	10.052	46.638	56.690	.02234	.10146	.12380
10	206.8	.01335	.17443	12.696	44.479	57.175	.02789	.09470	.12259
20	240.4	.01375	.14732	15.443	42.100	57.543	.03351	.08777	.12128
30	277.9	.01422	.12437	18.247	39.472	57.719	.03921	.08061	.11982
40	319.6	.01477	.10455	21.370	36.450	57.820	.04516	.07295	.11811
45	342.2	.01509	.09565	22.979	34.769	57.748	.04826	.06889	.11715
50	365.9	.01546	.08734	24.651	32.958	57.609	.05143	.06466	.11609
55	390.8	.01588	.07945	26.418	30.946	57.364	.05473	.06013	.11486
60	417.0	.01637	.07189	28.310	28.677	56.987	.05824	.05518	.11342
65	444.5	.01696	.06468	30.322	26.137	56.459	.06193	.04981	.11174
70	473.4	.01771	.05767	32.515	23.193	55.708	.06591	.04379	.10970
75	503.7	.01874	.05027	35.110	19.382	54.492	.07059	.03625	.10684
80	535.5	.02047	.04131	38.527	13.565	52.092	.07672	.02513	.10185
83.93	561.3	.02772	.02772	45.271	-	45.271	.08898	-	.08898

TABLE III

THERMODYNAMIC PROPERTIES OF SUPERHEATED FREON 13 ($CClF_3$) VAPOR

| Abs. Press. | | Temperature °F. | | |

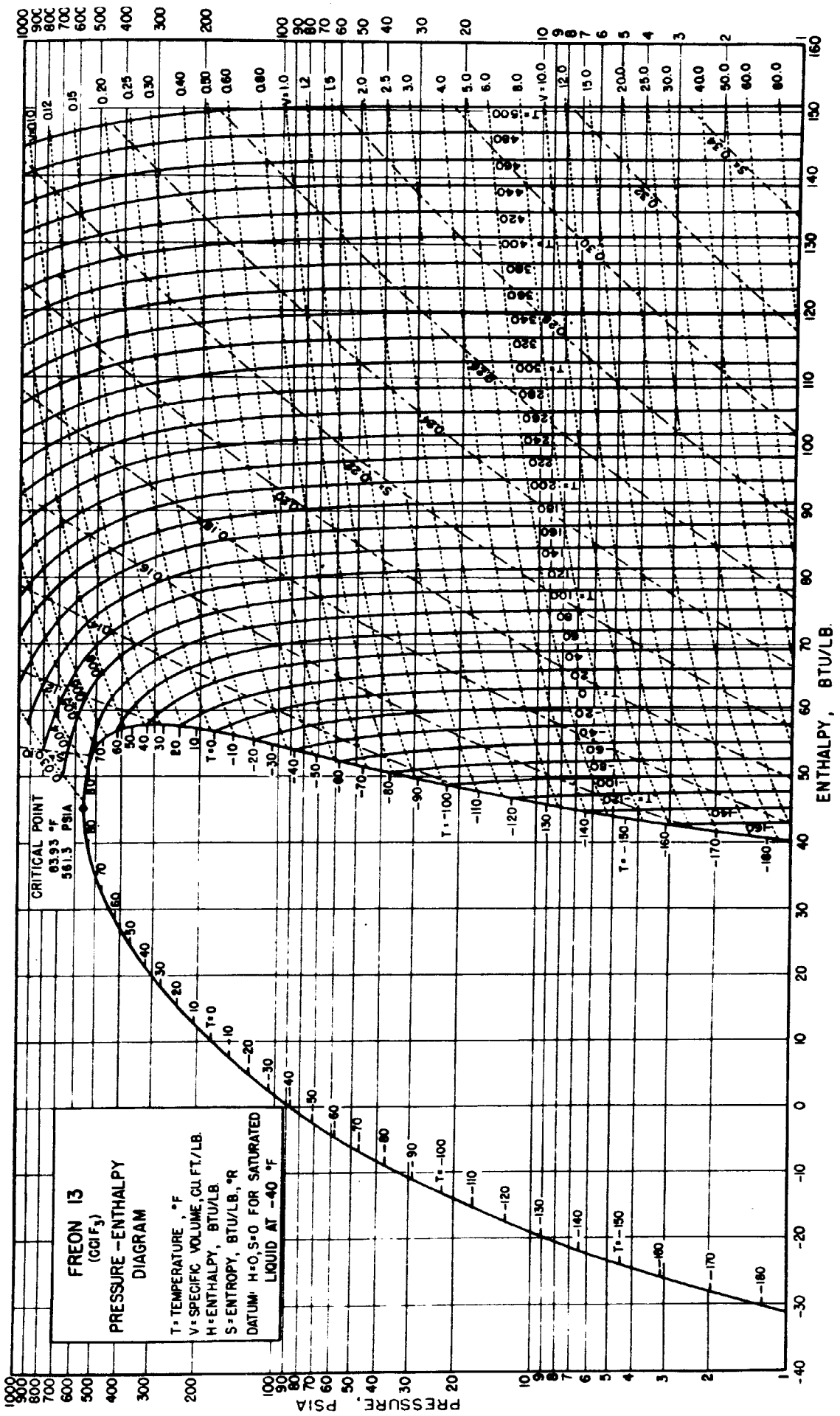


FIGURE 10 PRESSURE-ENTHALPY DIAGRAM FOR FREON 13 ($CClF_3$)

CALCULATION PROCEDURE

Empirical equations were developed to represent the experimental vapor pressure, p-v-T, and saturated liquid density data. In addition, an equation was derived to predict the specific heat values of the gas at infinite volume, which were calculated from the fundamental frequencies that had been determined from spectroscopic data. The above-mentioned equations were then used to calculate values of the thermodynamic properties of Freon 13.

The calculation procedures used to develop empirical equations for the vapor pressure, p-v-T relationship of the gas, saturated liquid density, and specific heat of the gas are now described. Then the method used to calculate the thermodynamic properties of Freon 13 is explained.

Calculation Procedure - Vapor Pressure Data

Empirical equations were derived to predict the vapor pressure data that had been obtained experimentally. These equations were then used to predict the vapor pressure from -200°F to the critical temperature, 83.93°F, in the calculations of the thermodynamic properties of Freon 13. The procedure used to calculate the vapor pressure equations from the experimental data is outlined below.

Vapor pressure data were obtained at seven approximate temperatures. At each approximate temperature the isoteniscope was loaded three or four times with a fresh charge of Freon 13. A sample data sheet for one of these loadings is shown in Appendix B. Three to six vapor pressure points were determined for each separate loading of the isoteniscope. At each approximate temperature there were then a total of about 10 to 20 vapor pressure points. A sample summary sheet of the vapor pressure data at one approximate temperature is shown in Appendix B. The vapor pressure data at each approximate temperature were arithmetically averaged to give a composite vapor pressure point. This was permissible as the temperature range covered by the data was 0.90°F or less, and over such a narrow range the vapor pressure curve could be considered a straight line.

The averaged results of the seven vapor pressure measurements are shown in Table VI in Appendix B. These experimental points were plotted as the logarithm of the pressure versus 1/T°R, and this plot is shown in Figure 11. The plot indicates a definite curvature downward at the lower pressures, but as the critical pressure is approached, the curve becomes almost straight. On a larger graph, it could be seen that there was a slight upward curvature in this pressure range.

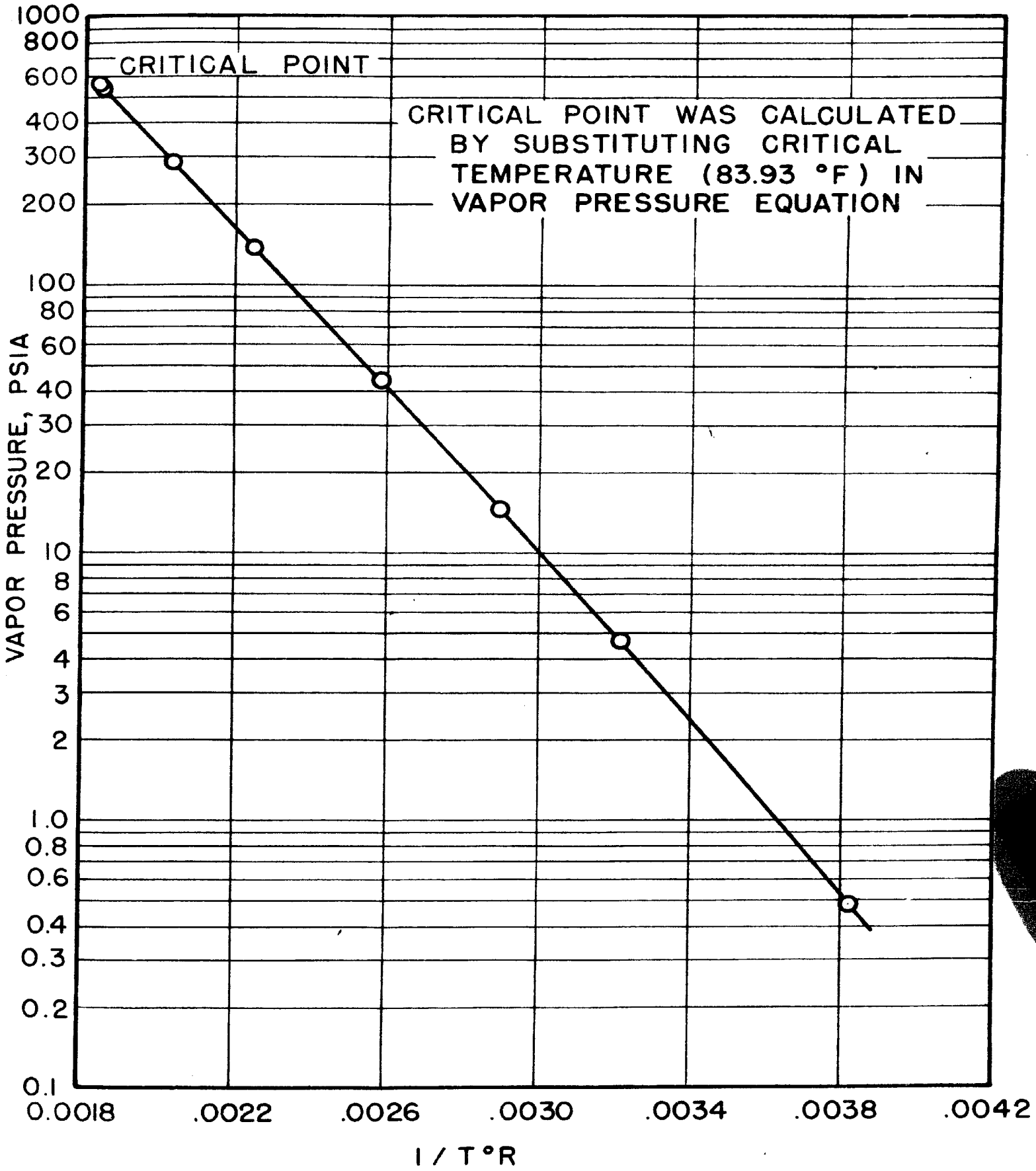


FIGURE 11 EXPERIMENTAL VAPOR PRESSURE DATA FOR FREON 13

The vapor pressure equations reported by Dodge (3) and the following equations were tested to determine how well they represented the experimental data.

$$\log_{10} p = a + \frac{b}{c + t}$$

Of the equations tested the following form of equation was found to represent the data best:

(8) $\log_{10} p = a + b/T + c \log_{10} T + d T$

where a, b, c, and d are constants.

The detailed calculations for obtaining the constants of this equation are shown in Appendix B. The final equation from these calculations was as follows:

(9) $\log_{10} p = 36.76130 - 2623.988/T - 11.80586 \log_{10} T + 5.71495 \times 10^{-3} T$

The above equation predicts the experimental data within 0.08% from -200 to -15°F and within 0.1% from -15 to 80°F, as shown in Table VI.

An auxiliary equation was developed to represent the vapor pressure data from -15 to 80°F with higher accuracies than Equation 9. The calculations made in determining this equation are shown in Appendix B, and the equation is as follows:

(10) $\log_{10} p = 56.34405 - 3351.281/T - 19.16910 \log_{10} T + 9.20366 \times 10^{-3} T$

The maximum deviation of the predicted values of this equation and the experimental results from -15 to 80°F was found to be less than 0.07%.

The critical pressure was determined from Equation 10 as follows: The critical temperature, 83.93°F , was substituted in the equation, and the equation was solved for the pressure, which was found to be 561.3 psia.

Calculation Procedure - P-V-T Data:

An empirical equation of state was derived to represent the experimental p-v-T data. This equation was the one used to predict the p-v-T relationship of the vapor in the thermodynamic calculations of Freon 13. The procedure used in calculating this equation from the experimental data is described below.

Experimental data were obtained for thirteen isometrics, eight with the high-pressure vapor density bulb and five with the low-pressure one. These isometrics were at densities from about 1.15 to 44.45 lbs./cu. ft. A sample data sheet for an isometric and the calculations made with these data are shown in Appendix C. The calculations consisted of the following steps:

The temperature was calculated from the resistance of the platinum resistance thermometer #169313 by Equation 44, shown in Appendix F. The pressure gauge readings were converted to absolute pressures by adding the gauge calibration and the barometric pressure to them. The gas density was calculated by dividing the weight of Freon 13 used by the vapor volume. The amount of freon used was considered to be the average of that loaded to the system and that recovered from it. In all cases these two amounts agreed within 0.10% and generally within 0.04%. The volume of the vapor density bulb was corrected for temperature by using 34×10^{-6} $cm^3/cm^3/°C$ for the cubical

coefficient of expansion, which was reported by Perry (9). The results of the above calculations on the various isometric data are shown in Table VII in Appendix C under the headings of temperature, experimental density, and experimental pressure.

The densities for each experimental isometric changed about 0.3% because of the expansion of the steel vapor density bulb due to temperature changes. In order to facilitate fitting an equation to the experimental isometric data, the data of each approximate density were corrected to a single density. The density selected was approximately the average of the experimental densities, and the maximum density correction was then about 0.15%. The methods used to correct the experimental data to constant densities are outlined below:

The correction of the data from one density to another can be computed from the following equation:

$$p = Z\ R\ T\ d$$

For conditions 1 and 2 when the temperature is constant,

$$p_1 = Z_1\ R\ T\ d_1 \quad \text{and} \quad p_2 = Z_2\ R\ T\ d_2$$

When the two equations are divided by each other,

$$p_2 = d_2/d_1 \times Z_2/Z_1 \times p_1$$

If the compressibility factor is considered to be constant over the density change, then Z_2/Z_1 is equal to 1.0000, and

(11) $$p_2 = d_2/d_1 \times p_1$$

Equation 11 was used to correct the experimental data to constant densities up to densities of 12.77 lbs./cu. ft.

The actual ratio of Z_2/Z_1 can be estimated from a plot of the compressibility factor of a gas versus reduced temperature with reduced pressures as parameters. Such a plot was presented by Hougen and Watson (4). The ratio of the compressibility factors for density changes of 0.15% was found to differ from 1.0000 as high as 0.006%, 0.05%, and 0.15% for densities of 1.15, 12.77, and 35.9 lbs./cu. ft. respectively. The errors of the corrected pressures that were caused by using Equation 11 were as high as 0.006% to 0.05% respectively as the density increased from 1.15 to 12.77 lbs./cu. ft.

At densities above 12.77 lbs./cu. ft. the experimental p-v-T data were corrected to constant densities by using Equation 4, the equation of state of Whitney (16). Changes of the pressure resulting from density changes were evaluated by using the following form of Equation 4.

$$(12) \quad \Delta p = (0.04671 - 0.00004746\ T)(d_2^3 - d_1^3) + (0.004022\ T - 4.058)(d_2^2 - d_1^2) + 0.10273\ T\ (d_2 - d_1)$$

The pressure at the corrected density was equal to the experimental pressure plus the pressure change. Equation 4 was found to predict the experimental data of this investigation within 2-6%. Equation 12 should then be accurate within 6% for calculating pressure changes. As the pressure changes were small, approximately 0.15% of

the total pressure, for density changes of 0.15%, the errors of the corrected pressure that were caused by using Equation 12 were probably less than 0.01%.

The results of correcting the experimental isometric data to constant densities are shown in Table VII in Appendix C under the headings of temperature, corrected density, and corrected pressure. The corrected pressures were plotted against the temperatures at constant densities. Vapor pressures from -80°F to the critical temperature, 83.93°F, were also plotted against the temperature. The complete plot, including the isometrics and the vapor pressure curve, is shown in Figure 12.

Figure 12 shows that a smooth curve can be drawn through all of the corrected experimental points of each isometric. A definite curvature is found in all of the isometrics with most of the curvature at the low-temperature end, and the isometrics tending to approach straight lines at the high-temperature end. The isometrics up to and including the density of 28.0 lbs./cu. ft. are concave downward, and the isometrics at densities of 35.9 and 44.45 lbs./cu. ft. are concave upwards.

The curvature of the isometrics indicated that the isometrics could not be accurately represented by equations for a straight line, such as Whitney (16) used in Equation 4. Equations of the following form were now tested in

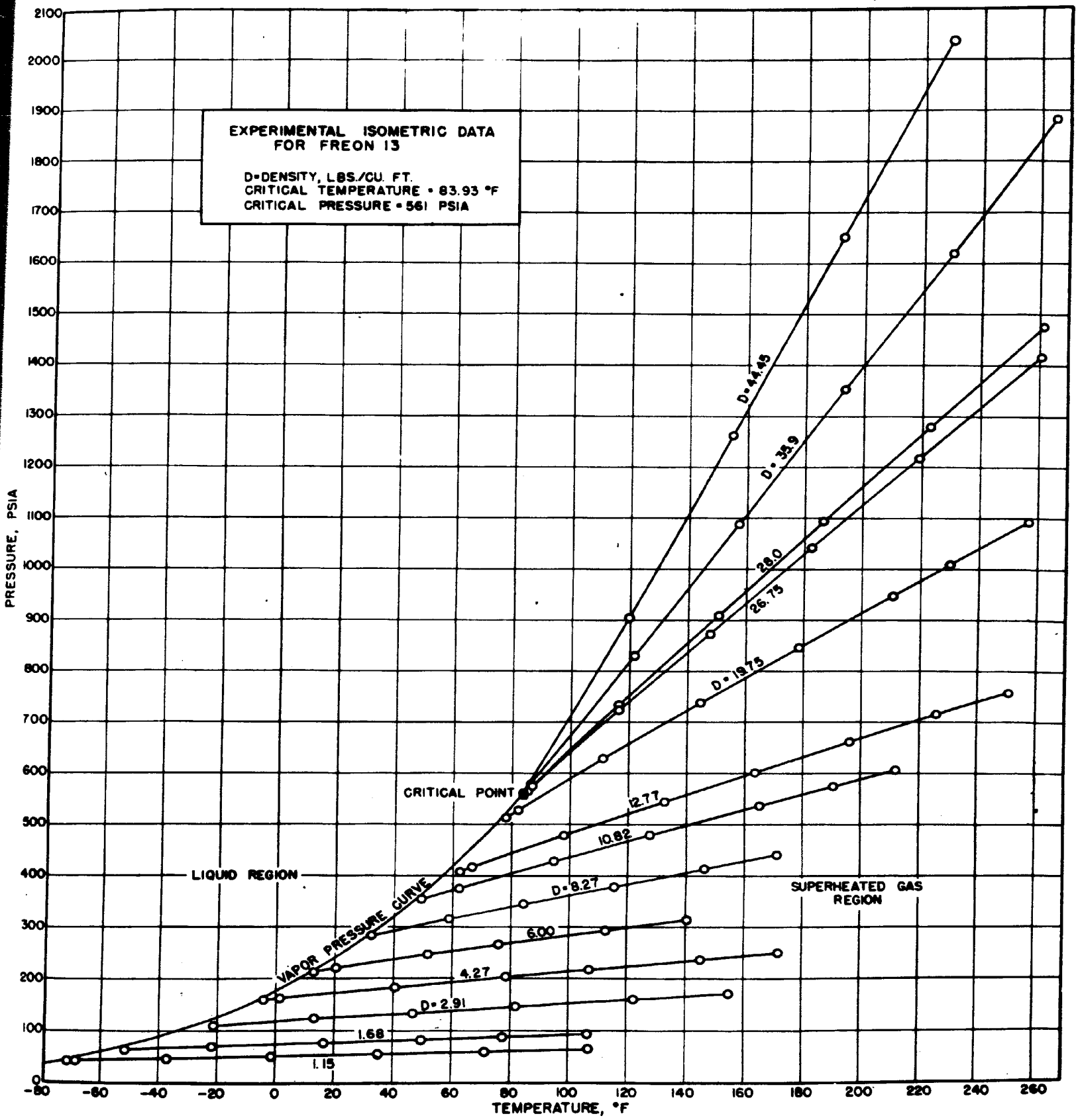


FIGURE 12 EXPERIMENTAL ISOMETRIC DATA FOR FREON 13

order to determine how well they would represent the isometrics.

(13) $$p = A + B\,T + C / T^2$$

(14) $$p = A + B\,T + C / T^4$$

where A, B, and C are constants for a definite density. Equation 13 is the form of equation that was used by various investigators, including Beattie and Bridgeman (1) and Benedict, Webb, and Rubin (2), to represent an isometric.

The following procedure was used to determine whether Equation 13 or 14 was a suitable form of an equation for the isometrics. The constants for Equation 13 and 14 were calculated by a similar algebraic method for several isometrics of widely different densities. A sample calculation of this determination for Equation 14 is shown in Appendix C. The resulting equations were then compared with the experimental isometrics. Equation 13 was found to predict insufficient curvature at the low-temperature end of each isometric. The deviations of the predicted values of this equation and the isometric data were as high as 0.25%. Equation 14 fitted the isometric data better, especially at the low-temperature end of the isometrics. The deviations of the predicted values of this equation and the isometric data were less than 0.20%. Equation 14 probably represents the isometric data within the experimental accuracy, and this form of the equation was used to represent the isometrics.

A graphical procedure which shows how well Equation 14 represents the isometric data and which shows how the constants A, B, and C can vary for a single isometric is as follows: Any point, (p_o, T_o) is selected on an isometric curve. When this point is substituted in Equation 14,

(15) $$p_o = A + B T_o + C / T_o^4$$

Subtracting Equation 15 from Equation 14,

$$p - p_o = B (T - T_o) + C (1/T^4 - 1/T_o^4)$$

Dividing by $(T - T_o)$

(16) $$\left[\frac{p - p_o}{T - T_o}\right] = B + C \left[\frac{T_o^4 - T^4}{T^4 T_o^4 (T - T_o)}\right]$$

If Equation 14 is the proper form of the equation to be used for an isometric, when

$$\left[\frac{p - p_o}{T - T_o}\right] \quad \text{is plotted versus} \quad \left[\frac{T_o^4 - T^4}{T^4 T_o^4 (T - T_o)}\right],$$

a straight line can be drawn through the points. The intercept of the line will be B and the slope of the line C. A can be solved from Equation 15. These plots were constructed for several isometrics of widely varying densities. A representative plot is that of the isometric at a density of 8.27 lbs./cu. ft., which is shown in Figure 13.

Figure 13 indicates that the straight line Y represents the experimental points fairly well. The points

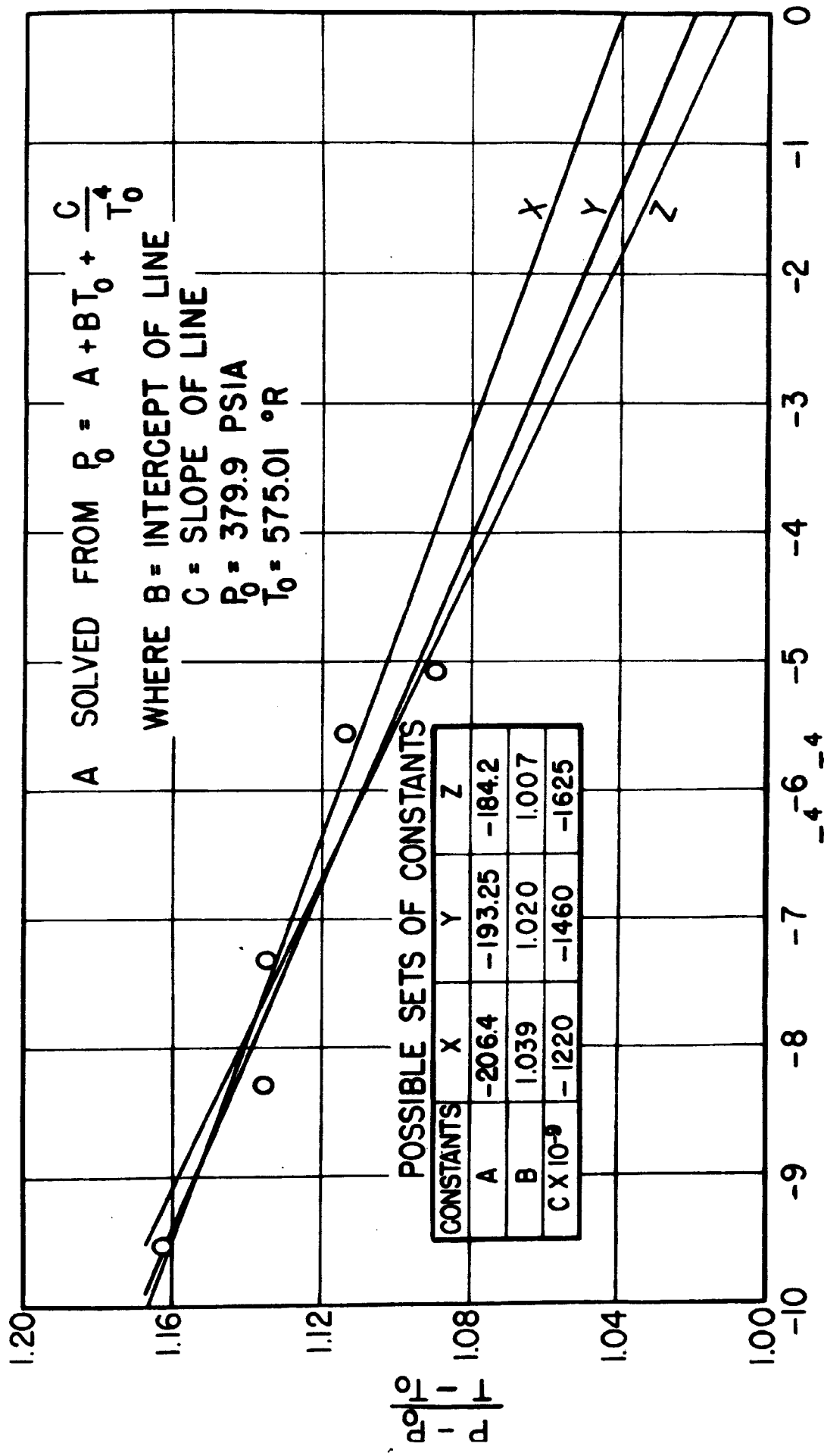
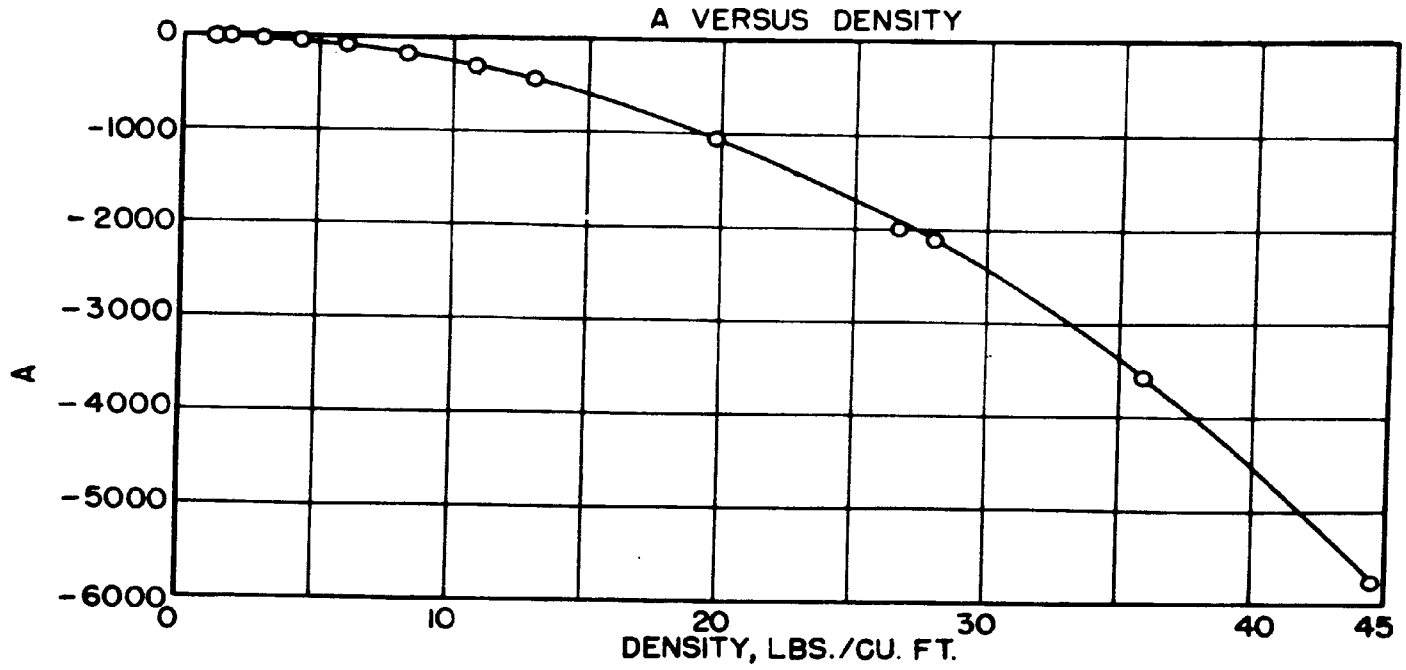
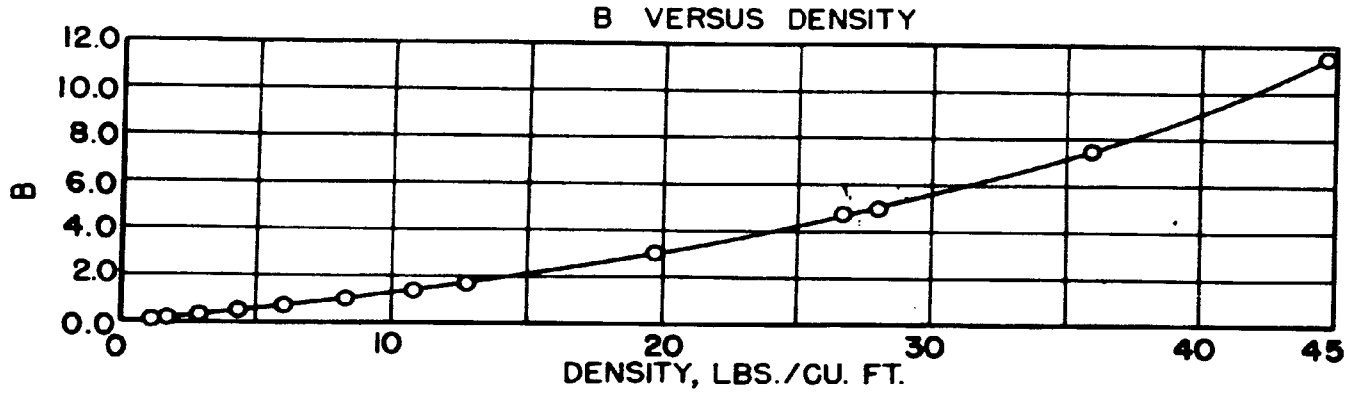


FIGURE 13 DETERMINATION OF CONSTANTS IN ISOMETRIC EQUATION AT 8.27 LBS. PER CU. FT.

can also be represented almost as well by straight lines X and Z as by line Y. The values for A, B, and C, which were determined from these three lines, are considerably different from each other, and they are shown on Figure 13. The three sets of constants were substituted in Equation 14, and the resulting equations were solved to determine how well they predicted the corrected isometric data. The equation resulting from line Y gave a maximum deviation of 0.10%, that from line Z 0.12%, and that from line X 0.20%. This indicated that the values of the constants for Equation 14 could vary considerably, and the equation would still predict the isometric data with approximately the same accuracy.

The most probable values of A, B, and C were calculated algebraically for each experimental isometric. The values obtained for the constants are shown in Table VIII in Appendix C. These values for the constants gave equations which predicted all of the smoothed isometrics within 0.2% and most of them within 0.10%. Plots of A, B, and C versus density are shown in Figure 14. All three constants are zero at zero density. The curves of A and B are somewhat parabolic in shape. The curve of C changes sign at approximately 32 lbs./cu. ft. This indicates a change of curvature of the isometrics from concave downward to concave upward with increasing density.





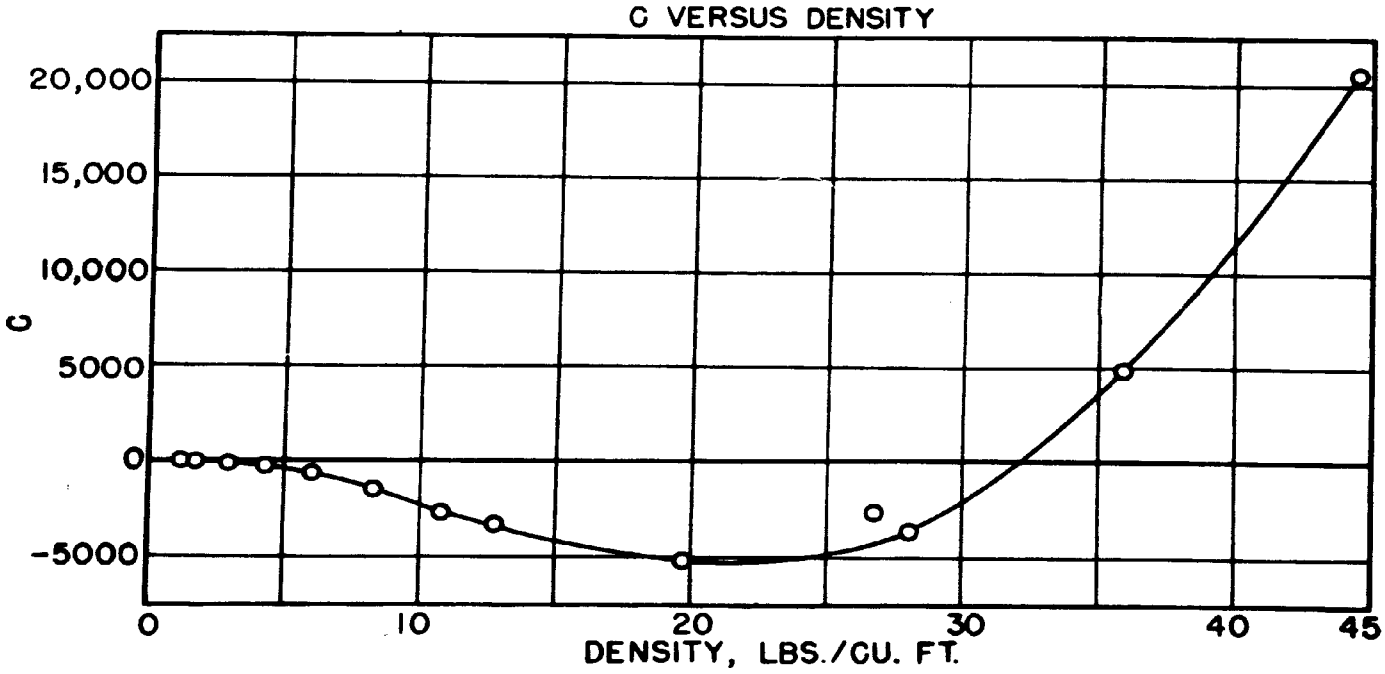


FIGURE 14 VARIATION OF A,B, AND C WITH DENSITY

Equations were now developed to represent the constants A, B, and C as functions of the density. The following graphical technique was used to facilitate finding the proper form of the equation for each constant. To determine the equation for A, any point, (A_o, d_o), on the curve of A versus the density, which is shown in Figure 14, was selected. The equation with the following form was tested.

(17) $$A = e\, d^2 + f\, d^3 + g\, d^4$$

where e, f, and g are constants.

Substituting the point, (A_o, d_o) in Equation 17,

(18) $$A = e\, d_o^2 + f\, d_o^3 + g\, d_o^4$$

Equations 17 and 18 were divided by d^2 and d_o^2 respectively.

$$\frac{A}{d^2} = e + f\, d + g\, d^2$$

and

$$\frac{A_o}{d_o^2} = e + f\, d_o + g\, d_o^2$$

Subtracting these two equations from each other,

$$\frac{A}{d^2} - \frac{A_o}{d_o^2} = f\,(d - d_o) + g\,(d^2 - d_o^2)$$

Dividing both sides by $(d - d_o)$,

(19) $$\left[\frac{\frac{A}{d^2} - \frac{A_o}{d_o^2}}{d - d_o}\right] = f + g\,(d + d_o)$$

If $\left[\frac{\frac{A}{d^2} - \frac{A_o}{d_o^2}}{d - d_o}\right]$ was plotted against $(d + d_o)$, a straight line could be drawn through the points if Equation 17 was the proper form of the equation. The intercept of the straight line would be equal to f and the slope of the line would be g. e would be solved by substituting f and g in Equation 18. The plot to test Equation 17 is shown in Figure 15. Although the points scatter badly at low densities, a straight line represents the points fairly well. This indicates that Equation 17 can be used to represent A.

A slight change of the value of A, especially at lower densities, would considerably change the position of the points on Figure 15. For instance, the points 8.27 X, 8.27 Y, and 8.27 Z, were calculated from the values of A, which had been determined from the lines X, Y, and Z respectively of Figure 13 for the isometric with a density of 8.27 lbs./cu. ft.

The following equations for B and C were tested in a manner similar to that used for Equation 17.

(20) $$B = R\,d + h\,d^2 + j\,d^3 + kd^4$$

(21) $$C = l\,d^2 + m\,d^4 + n\,d^6$$

where h, j, k, l, m, and n are constants.
These equations were converted to the following forms:

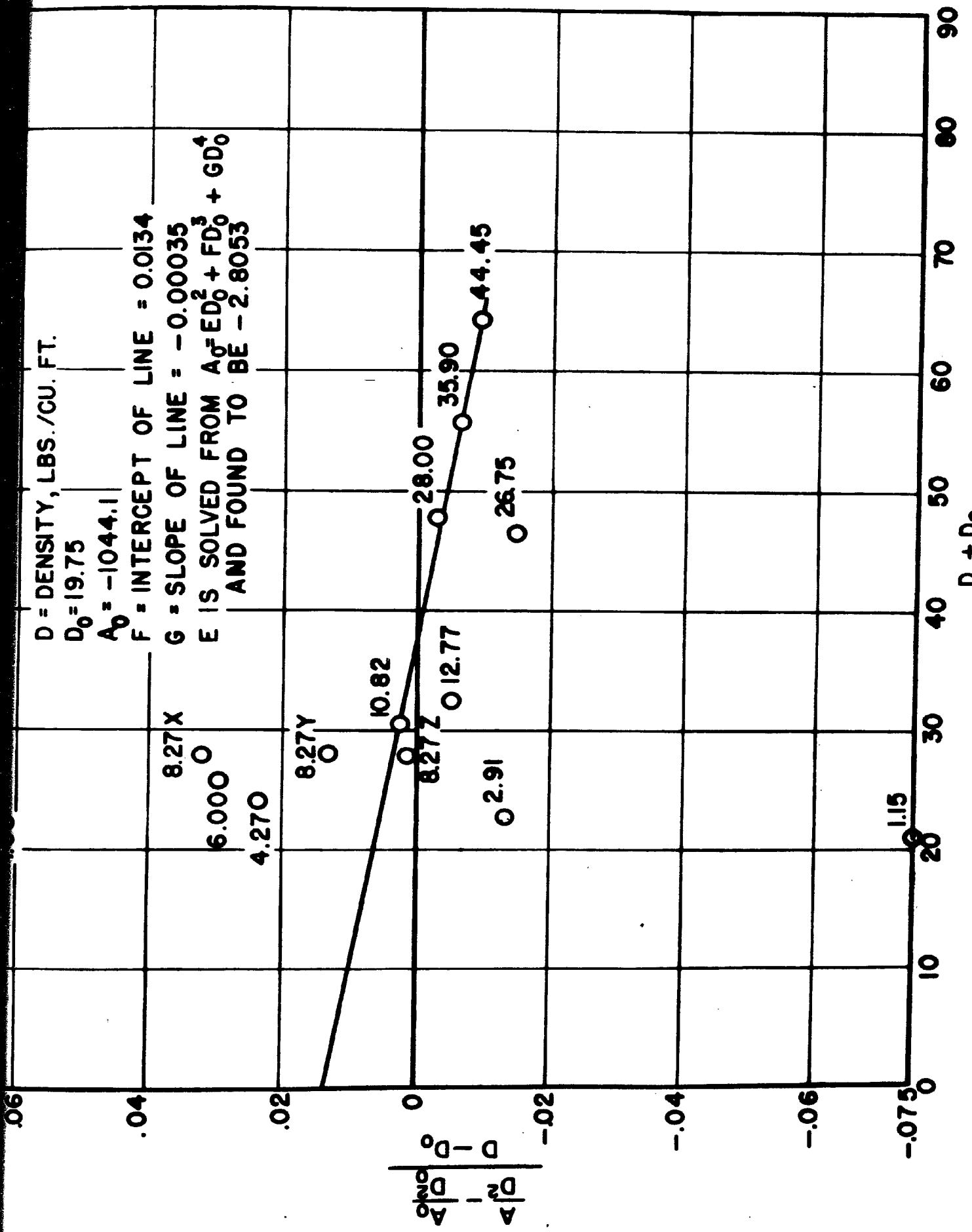


FIGURE 15 DETERMINATION OF CONSTANTS IN EQUATION $A = ED^2 + FD^3 + GD^4$

$$(22) \qquad \left[\frac{\frac{B - Rd}{d^2} - \frac{B_o - Rd_o}{d_o^2}}{d - d_o} \right] = j + k\,(d + d_o)$$

$$(23) \qquad \left[\frac{\frac{C}{d^2} - \frac{C_o}{d_o^2}}{d^2 - d_o^2} \right] = m + n\,(d^2 + d_o^2)$$

The plots of Equation 22 and 23 are shown in Figures 16 and 17 respectively. The points in these plots are represented fairly well by straight lines, which indicate that Equation 20 and 21 can be used to represent B and C respectively. B and C values for the isometric density of 8.27 lbs./cu. ft., which had been determined from Figure 13, are shown in both Figures 16 and 17.

The constants of the equations for A, B, and C that were determined from Figures 15, 16, and 17 are shown on these figures. These values when substituted in Equations 14, 17, 20, and 21 gave an equation of state for the superheated vapor that predicts the experimental data within 2% over the entire density range.

A trial and error procedure was used to find an equation of state, which would represent the experimental data better than 2%. The following equation was finally determined:

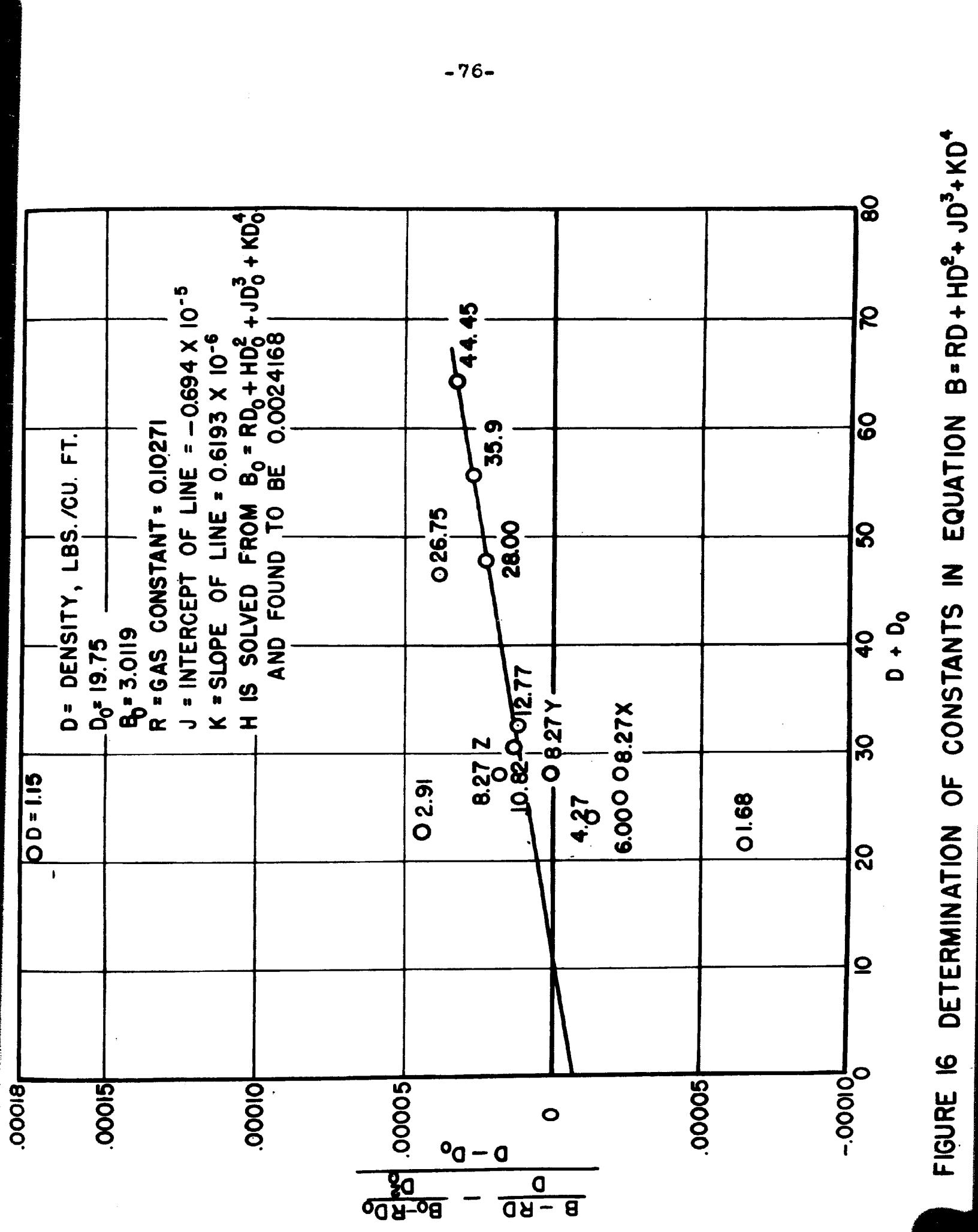


FIGURE 16 DETERMINATION OF CONSTANTS IN EQUATION $B = RD + HD^2 + JD^3 + KD^4$

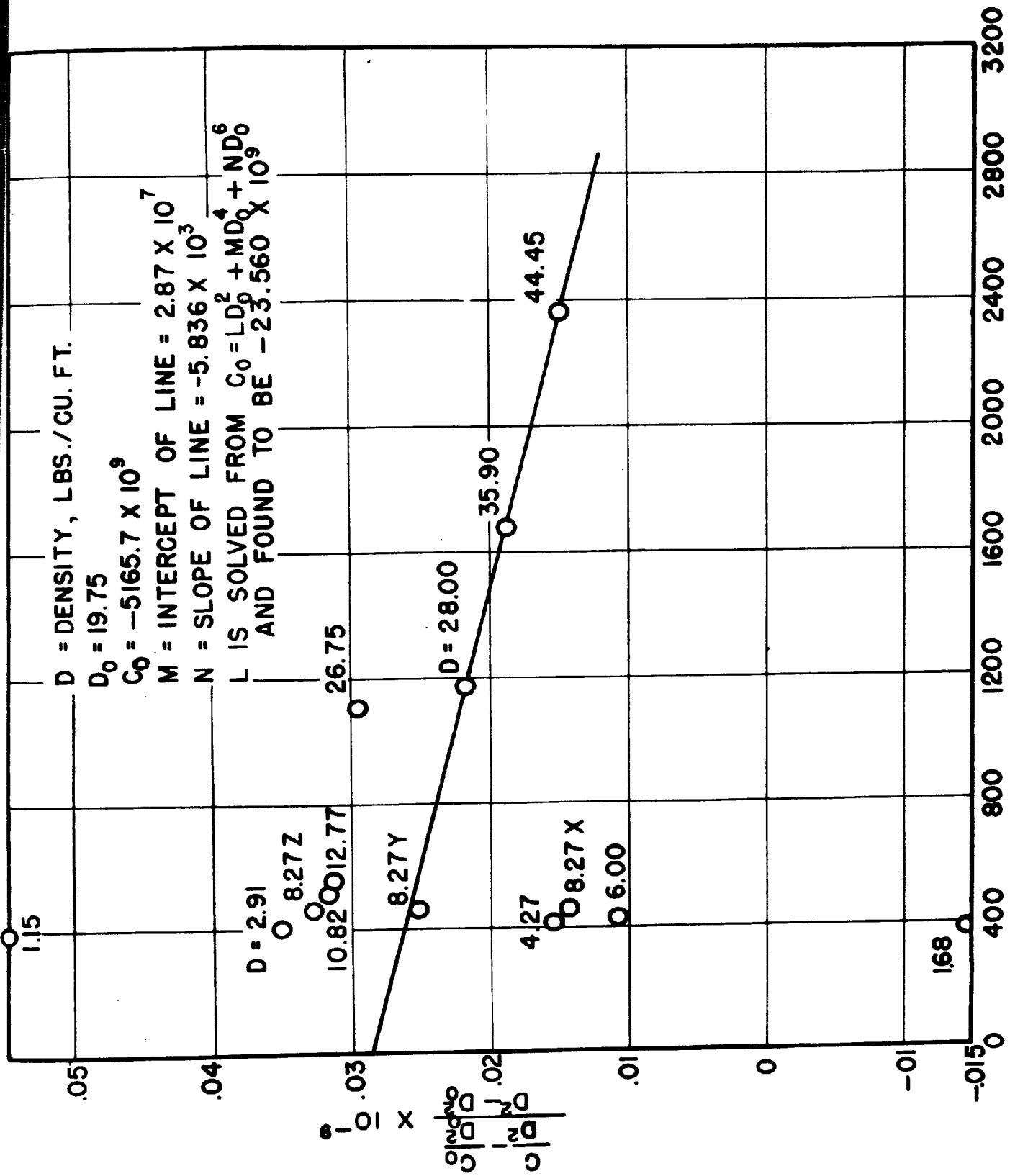


FIGURE 17 DETERMINATION OF CONSTANTS IN EQUATION

$C = LD^2 + MD^4 + ND^6$

(24) $$p = A + BT + C/T^4$$

where

$$A = -2.5450\ d^2 + 0.0003502\ d^3 - 0.0001887\ d^4$$

$$B = 0.10271\ d + 0.0020840\ d^2 + 9.7728 \times 10^{-6} d^3 + 4.1169 \times 10^{-7}\ d^4$$

$$C = (-26.551\ d^2 + 0.032562\ d^4 - 7.0092 \times 10^{-6}\ d^6) \times 10^9$$

This equation predicts the experimental data from 1.15 to 44.45 lbs./cu. ft. within about 1.0%.

An equation of state that would represent the experimental data up to densities of 35.9 lbs./cu. ft. to within 0.5% was determined largely by trial and error. The equation is as follows:

(25) $$p = A + B\,T + C\,/\,T^4$$

where

$$A = -2.837\ d^2 + 0.01594\ d^3 - 0.0003964\ d^4$$

$$B = 0.1027\ d + 2.328 \times 10^{-3}\ d^2 + 4.944 \times 10^{-7}\ d^4$$

$$C = (-23.55\ d^2 + 0.0287\ d^4 - 5.816 \times 10^{-6} d^6) \times 10^9$$

The comparison of this equation with the corrected isometric data is shown in Table VII. This table shows that the deviations of the pressures predicted by the equation and the corrected pressures are less than 0.2% at densities up to and including 35.9 lbs./cu. ft., except for the isometrics with densities of 1.15, 1.68, and 8.27 at which the deviations are as high as 0.5%. At densities above 35.9 lbs./cu. ft. the equation becomes relatively inaccurate, and at a density of 44.45 the deviations are from 3 to 9%.

Calculation Procedure - Saturated Liquid Density Data:

An equation was derived to predict the experimental saturated liquid density data. This equation was later used to predict the liquid densities from -200°F to the critical temperature, 83.93°F, in the thermodynamic calculations of Freon 13. The calculations procedure used to determine this equation from the experimental data is outlined below.

Eleven saturated liquid density measurements were made from -224 to 78°F. A sample data sheet of one of these measurements is shown in Appendix D. The calculations made on these data are shown on the data sheet and consisted of the following steps: The temperature was calculated from the resistance of the platinum resistance thermometer #169313 by Equation 44, shown in Appendix F. The density of the glass float at the experimental temperature was calculated from the density at room temperature by using 9.8×10^{-6} $cm.^3/cm.^3/°C$ as the cubical coefficient of expansion. This coefficient had been reported by the Corning Glass Works. The results of these calculations for all the experimental data are shown in Table IX of Appendix D. A plot of the experimental values of the saturated liquid density versus the temperature is presented in Figure 18.

The critical density had to be determined in order to complete the liquid density curve to the critical temperature. The critical density was obtained by using

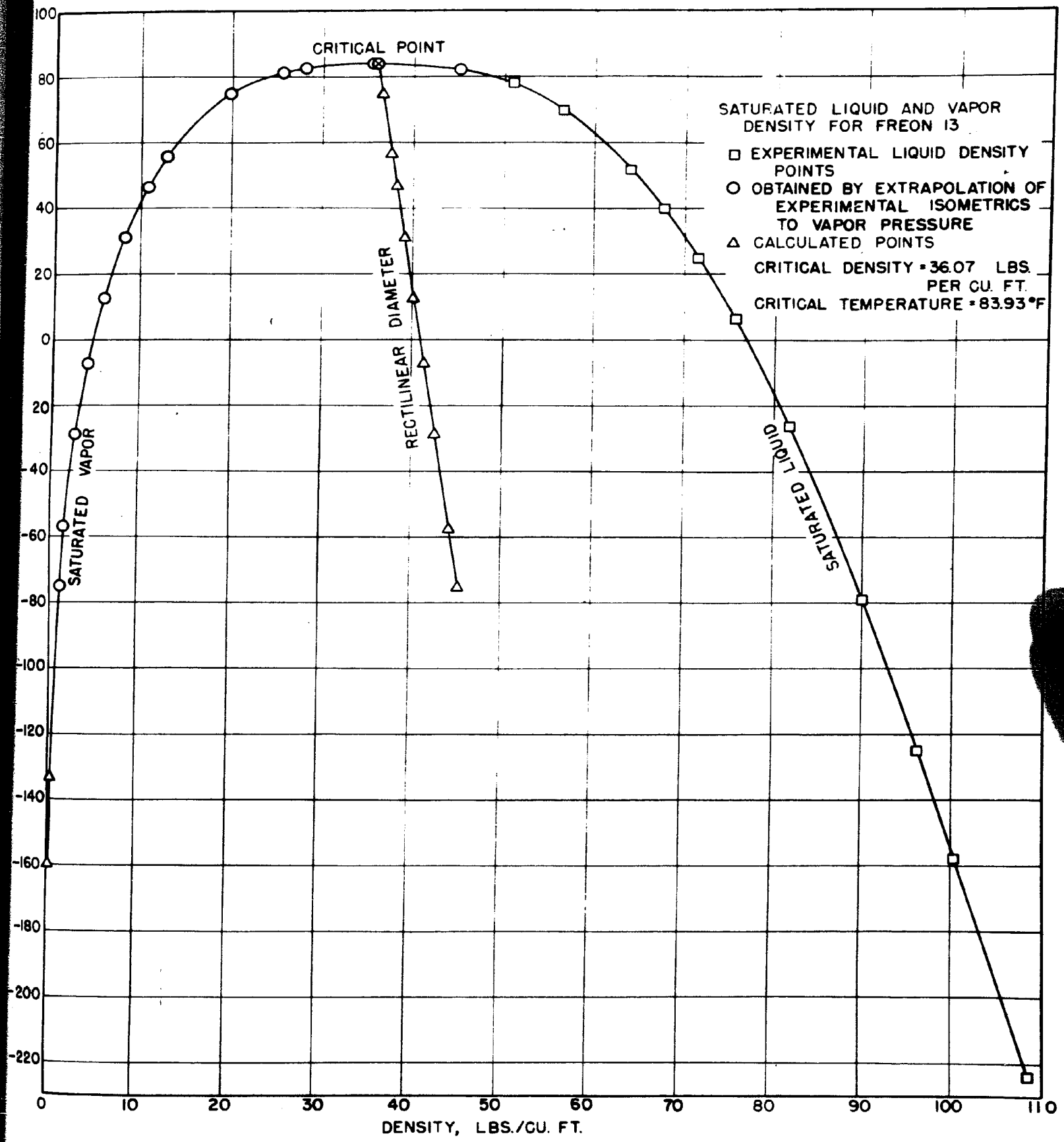


FIGURE 18 SATURATED LIQUID AND VAPOR DENSITY FOR FREON 13

the Law of Cailletet and Mathias, also known as the law of rectilinear diameters. This law states that the average of the saturated liquid and saturated vapor densities form a straight line when plotted against the temperature. As the vapor and liquid densities are equal at the critical point, an extrapolation of this straight line to the critical temperature will predict the critical density.

The saturated vapor densities to be used in this measurement of the critical density were obtained by extrapolating the experimental isometrics to the vapor pressure curve on large scale graphs to determine the saturation temperature at the various densities. Several additional saturated vapor density points were found by extrapolating isometrics calculated from the equation of state, Equation 25, to the vapor pressure curve. These saturated vapor density points were plotted on Figure 18. This graph indicates that the change of the saturated vapor density with respect to temperature becomes large near the critical temperature.

Rectilinear diameter points are the average of the saturated vapor and liquid densities. The rectilinear diameter points that were obtained and the liquid and vapor densities used to calculate them are shown in Table X. The rectilinear diameter points were then plotted on Figure 18, and it was found that a straight line could be drawn through them.

The calculations necessary to develop an equation that represents the rectilinear diameter points are shown in Appendix D. The final equation of these calculations is as follows:

$$(26) \qquad (d_L + d)/2 = 40.95 - 0.05812\ t$$

The deviations of the values predicted by this equation from the rectilinear diameter points were 0.1% or less, as shown by Table X. When the critical temperature, 83.93°F., was substituted into Equation 26, the critical density was found to be 36.07 lbs./cu.ft.

The critical density completed the saturated liquid density curve to the critical temperature. The following form of equation was found largely by trial and error to represent the experimental saturated liquid density.

$$(27) \qquad d_L = d_c + a(t_c - t) + b(t_c - t)^{1/2} + c(t_c - t)^{1/3} + d(t_c - t)^2$$

where

a, b, c, and d are constants.

The calculations for the determination of the constants of this equation are shown in Appendix D. The final equation determined from these calculations was as follows:

$$(28) \quad d_L = 36.07 + 0.01566\ (t_c - t) + 1.110\ (t_c - t)^{1/2} + 6.665\ (t_c - t)^{1/3} + 3.245 \times 10^{-5}\ (t_c - t)^2$$

This equation predicts liquid density values within 0.1% of those that were measured experimentally, as shown in Table IX.

Calculation Procedure - Specific Heat of the Gas at Infinite Volume

The specific heat values of the gas at infinite volume were calculated from the fundamental frequencies obtained from spectroscopic data. The method of calculating was based on statistical mechanics, and it is outlined in detail by Penner (15). The Maxwell-Boltzmann distribution law was used in this method to evaluate the vibrational contribution due to each fundamental frequency at any temperature. The heat capacity at constant volume was computed by adding the vibrational contributions to the equipartition values for translation and rotation.

The values used for the fundamental frequencies were as follows:

$$\nu_1 = 1105; \quad \nu_2 = \nu_5 = 356; \quad \nu_3 = 781; \quad \nu_4 = 450$$

$$\nu_6 = \nu_8 = 1212; \quad \text{and} \quad \nu_7 = \nu_9 = 563 \text{ cm}^{-1}$$

These values were the ones reported by Plyler (17) with the exception of the one for ν_2 and ν_5, which he did not measure. The value used for these frequencies was the one reported by Kahovec and Wagner (6).

Values of the specific heat of the gas at infinite volume were calculated from -200 to 500°F at 100°F intervals from the above values for the fundamental frequencies.

These specific heat values are presented in Table XI of Appendix E under the heading of statistical specific heat. A sample calculation of the determination of a statistical specific heat value is shown in Appendix E.

An equation to represent the statistical specific heat values shown in Table XI was calculated as is shown in Appendix E. The equation obtained was as follows:

(29) $c_{v_{\bullet}} = 0.01602 + 0.0002823\ T - 1.159 \times 10^{-7}\ T^2$

A comparison of the specific heat values predicted by this equation and the statistical specific heat values is shown in Table XI. The maximum deviation of the two values is less than 0.5%.

Calculation Procedure - Thermodynamic Properties of Freon 13:

Values of the thermodynamic properties of Freon 13 are to be calculated for the saturated liquid and vapor and for the superheated vapor. The thermodynamic tables to be obtained are to report values of the enthalpy, entropy, pressure, volume and temperature.

Before the calculations of the thermodynamic tables were started, the datum point of zero enthalpy and entropy was selected as the saturated liquid at -40°F. This was the same point that had been selected in thermodynamic calculations of other freons. The calculations of the thermodynamic properties of Freon 13 were divided into two parts, the first of the saturated vapor and saturated liquid and the second of the superheated vapor.

Saturated Vapor and Liquid

The thermodynamic properties of the saturated vapor and liquid were calculated at temperature intervals of 10°F from -200 to 40°F and of 5°F from 40 to 80°F. The following properties were determined at these temperatures: Vapor pressure, saturated vapor and saturated liquid volumes, latent heat of vaporization, entropy of vaporization, and the enthalpies and entropies of both the saturated vapor and saturated liquid. The final results of these calculations are shown in Table II.

The vapor pressures were calculated directly from the vapor pressure equations. Equation 9 was used from -200 to -15°F, and Equation 10 from -15 to 80°F. The vapor pressures were reported to within 0.1%.

The saturated vapor volumes were determined by substituting the vapor pressure and temperature into the equation of state, Equation 25, and solving for the saturated vapor density. The inverse of the density was the volume, which was reported to within 0.05%.

The saturated liquid volumes were determined from the liquid density equation, Equation 28. The liquid densities were calculated directly from this equation, and the inverse of the density was the volume, which was reported to within 0.1%.

The latent heats of vaporization were calculated to within 0.0001 BTU/lb. by using the Clausius-Clapeyron equation

$$\frac{dp}{dT} = \frac{L}{T(v-v_L)} \times \frac{1}{J} \tag{30}$$

The slope of the vapor pressure curve, dp/dT, was found by differentiating the vapor pressure equation with respect to temperature. The slope determined from Equation 9 was as follows:

$$\frac{dp}{dT} = 2.302590p\left[\frac{2623.9882}{T^2} - \frac{5.127207}{T} + 5.71495 \times 10^{-3}\right] \tag{31}$$

The slope determined from Equation 10 was as follows:

$$(32)\quad \frac{dp}{dT} = 2.30259p\left[\frac{3351.2814}{T^2} - \frac{8.325014}{T} + 9.20366 \times 10^{-3}\right]$$

When Equation 31 was substituted into Equation 30, the following latent heat equation, which was used from -200 to -15°F, was obtained.

$$(33)\quad L = 2.30259\ pJ(v-v_L)\left[\frac{2623.9882}{T} - 5.127207 + 5.71495 \times 10^{-3}T\right]$$

When Equation 32 was substituted into Equation 30, the following latent heat equation, which was used from -15 to 80°F, was obtained.

$$(34)\quad L = 2.30259\ pJ(v-v_L)\left[\frac{3351.2814}{T} - 8.325014 + 9.20366 \times 10^{-3}T\right]$$

The entropy of vaporization was determined by dividing the latent heat by the absolute temperature, °R. The entropy values were reported to within 0.00002 BTU/lb., °R.

The enthalpy and entropy of the saturated vapor at -40°F were equal to the latent heat and entropy of vaporization at -40°F as the enthalpy and entropy of the saturated liquid at this temperature had been set at zero. The enthalpies of the other point on the saturated vapor curve were determined by adding the changes of enthalpy along constant volume lines and then along constant temperature lines to the enthalpy of the saturated vapor at -40°F. Any point on the saturated vapor line could be determined by selecting the proper constant temperature

and volume lines. The entropy of the saturated vapor line was similarly calculated by adding the entropy changes along constant volume and temperature lines to the entropy of the saturated vapor at -40°F. These various enthalpy and entropy changes were evaluated from thermodynamic equations presented by Dodge (3).

The change of enthalpy with temperature at constant volume was calculated from the following equation:

$$(35) \qquad \Delta H_v = \int_{T_1}^{T_2} c_v \, dT + J \, v \Delta p$$

where $c_v = c_{v\infty} + \Delta c_v$

Equation 29 was used to evaluate $c_{v\infty}$ and Δc_v, the correction of the specific heat from one volume to another, was determined from the following equation presented by Dodge (3) as Equation VI.3.

$$(36) \qquad \Delta c_v = J \, T \int_{v_1}^{v_2} \left[\frac{\partial^2 p}{\partial T^2} \right] dv$$

Equation 36 was evaluated by differentiating the equation of state, Equation 25. The following equation was obtained when $c_{v\infty}$ and Δc_v were substituted into Equation 35 and integrated.

$$(37) \qquad \Delta H_v = 0.01602(T_2 - T_1) + 0.0001412(T_2^2 - T_1^2)$$
$$- 3.862 \times 10^{-8} (T_2^3 - T_1^3)$$
$$+ \left[- \frac{21.794}{v} + \frac{0.008852}{v^3} - \frac{1.0764 \times 10^{-6}}{v^5} \right] \times 10^9 \left[\frac{1}{T_2^4} - \frac{1}{T_1^4} \right]$$
$$+ Jv \, \Delta p$$

The term, $v\Delta p$, was calculated from the equation of state.

The change of entropy with temperature at constant volume was determined from the following equation:

$$(38) \qquad \Delta S_v = \int_{T_1}^{T_2} \frac{c_v}{T}\, dT$$

Upon substituting the value for c_v in this equation and integrating, the following was obtained:

$$(39)\ \Delta S_v = 0.036887(\log_{10}T_2 - \log_{10}T_1) + 0.0002823(T_2 - T_1) - 5.793 \times 10^{-8}\,(T_1^2 - T_2^2) + \left[-\frac{17.435}{v} + \frac{0.0070816}{v^3} - \frac{8.6112 \times 10^{-7}}{v^5}\right]\left[\frac{1}{T_2^5} - \frac{1}{T_1^5}\right] 10^9$$

The change of enthalpy with volume at constant temperature was evaluated from the following equation:

$$(40)\ \Delta H_T = J \int_{v_1}^{v_2} \left[v\left[\frac{\partial p}{\partial v}\right]_T + T\left[\frac{\partial p}{\partial T}\right]_v \right] dv$$

$\left[\partial p/\partial v\right]_T$ and $\left[\partial p/\partial T\right]_v$ were determined by differentiating the equation of state. Upon substituting them in the above equation, the following was determined.

$$(41)\ \Delta H_T = \left[-1.0500 + 0.00043089T - \frac{26.154 \times 10^9}{T^4}\right]\left[\frac{1}{v_2} - \frac{1}{v_1}\right] + 0.0044241\left[\frac{1}{v_2^2} - \frac{1}{v_1^2}\right] + \left[-0.000097817 + 9.150 \times 10^{-8}T + \frac{1.4164 \times 10^7}{T^4}\right]\left[\frac{1}{v_2^3} - \frac{1}{v_1^3}\right] - \frac{2.1528 \times 10^3}{T^4}\left[\frac{1}{v_2^5} - \frac{1}{v_1^5}\right]$$

The change of entropy with volume at constant temperature was calculated from the following:

$$(42) \qquad \Delta S_T = J\int_{v_1}^{v_2} \left[\frac{\partial p}{\partial T}\right]_v dv$$

Upon the substitution of $\left[\partial p/\partial T\right]_v$ and integrating, it became

$$(43) \quad \Delta S_T = 0.043768 \,(\log_{10} v_2 - \log_{10} v_1) - \left[0.0004309 + \frac{17.435 \times 10^9}{T^5}\right]\left[\frac{1}{v_2} - \frac{1}{v_1}\right] - \left[3.0499 \times 10^{-8} - \frac{17.435 \times 10^6}{T^5}\right]\left[\frac{1}{v_2^3} - \frac{1}{v_1^3}\right] - \frac{861.1}{T^5}\left[\frac{1}{v_2^5} - \frac{1}{v_1^5}\right]$$

Equation 37, 39, 41, and 43 were now used to calculate the enthalpies and entropies of the saturated vapors. The enthalpies of the saturated liquid were then obtained by subtracting the latent heats of vaporization from the enthalpies of the saturated vapors. The entropies of the saturated liquids were found similarly by subtracting the entropies of vaporization from the entropies of the saturated vapors.

Superheated Vapors

The thermodynamic table for the superheated vapors, Table III, presented values of the enthalpy, entropy, and volume at tabular temperatures and pressures. These values were determined from an auxiliary table, Table IV

shown in Appendix A, that presents values for the enthalpy, entropy, and pressure at tabular temperatures and volumes. The tabular temperatures of this table were from -180 to 500°F at 20°F intervals, and the volumes were from 0.03 to 60 cu. ft./lb. at 20-35% intervals. The method used in calculating the values shown in Table IV is as follows:

The pressures for the tabular temperatures and volumes were calculated directly from the equation of state, Equation 25, and they were reported to within 0.1%.

The enthalpy and entropy values of Table IV were calculated by adding the enthalpy and entropy changes along suitable temperature and volume lines to the values of the enthalpy and entropy of the saturated vapor, which were reported in Table II. Any point in the superheated vapor region could be determined from any point on the saturated vapor curve by selecting the proper constant temperature and volume lines. The enthalpy and entropy changes were evaluated by using Equation 37, 39, 41, and 43. The enthalpy values in the superheated vapor region were reported to 0.0001 BTU/lb., and the entropy values values to 0.00002 BTU/lb., °R.

Table IV was now used to prepare Table III, which presented values for the volume, enthalpy, and entropy at tabular temperatures and pressures. The temperatures selected for Table III were at 20°F intervals from -180

to 500°F. The pressures were at 20-50% intervals from 1.0 psia to the critical pressure, 561.3 psi. The methods used to calculate the values of the volume, enthalpy, and entropy of Table III are outlined below:

As a large number of laborious calculations would be necessary to calculate the volume directly from the equation of state, which was explicit in pressure, the following method was used to determine the volumes of Table III at tabular temperatures and pressures. A chart of the compressibility factor versus pressure with temperature as a parameter was prepared from the computed values of pressure, shown in Table IV, at constant volumes and temperatures. The final chart was large enough so that the compressibility factors could be read to within 0.0005 along the constant temperature lines. A reduction of this chart with a decreased number of isotherms is shown in Figure 19. The gas volumes of Table III at the tabular temperatures and pressures were calculated by multiplying the compressibility factors by the volumes calculated from the ideal gas law. These volumes are probably accurate to within 0.1% of those predicted by Equation 25.

The enthalpy values of Table III at constant temperature and pressure were determined from plots of the enthalpy values of Table IV against the pressures at constant temperature. Such a plot was made at each 20°F

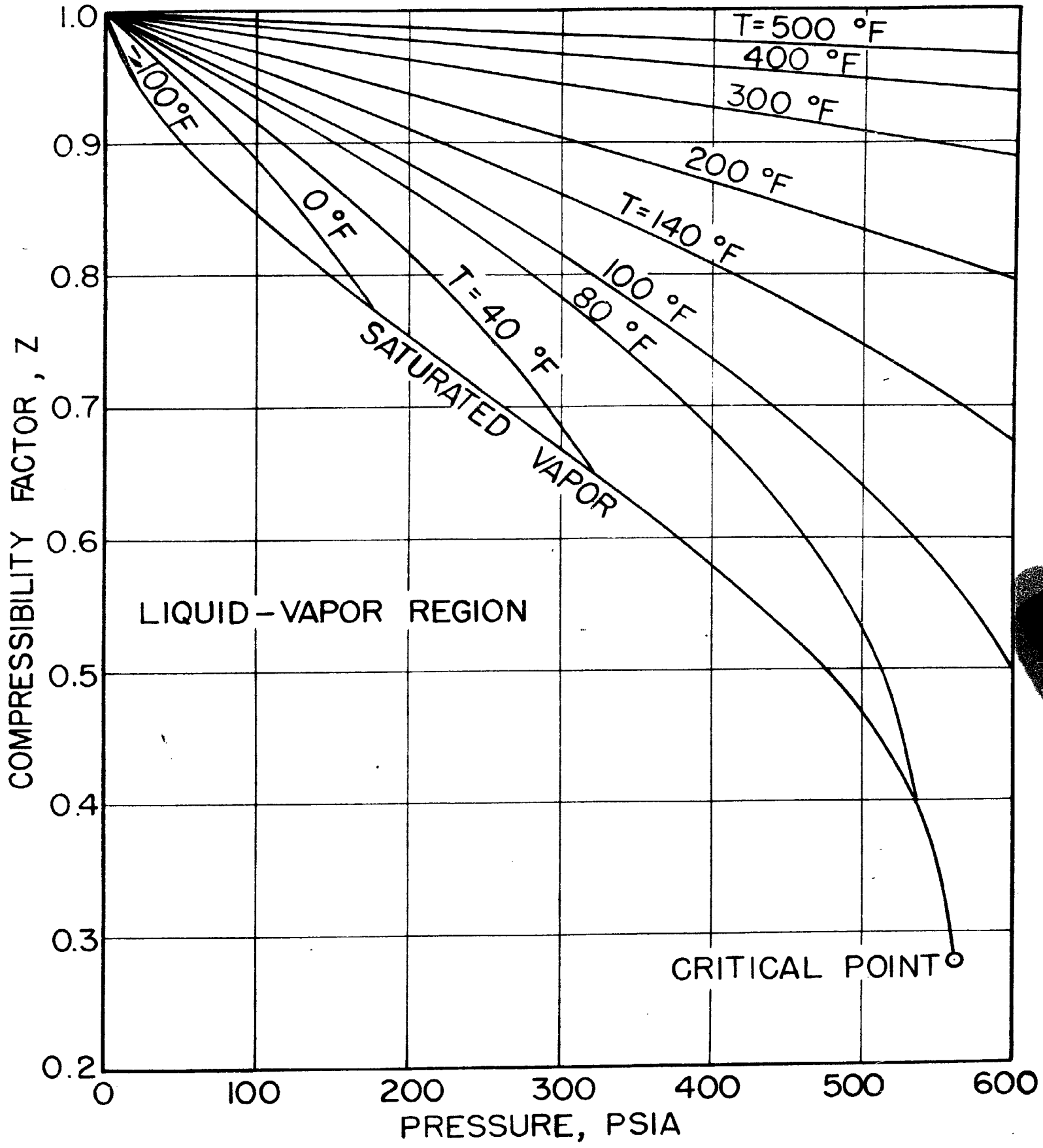


FIGURE 19 COMPRESSIBILITY FACTOR FOR FREON 13

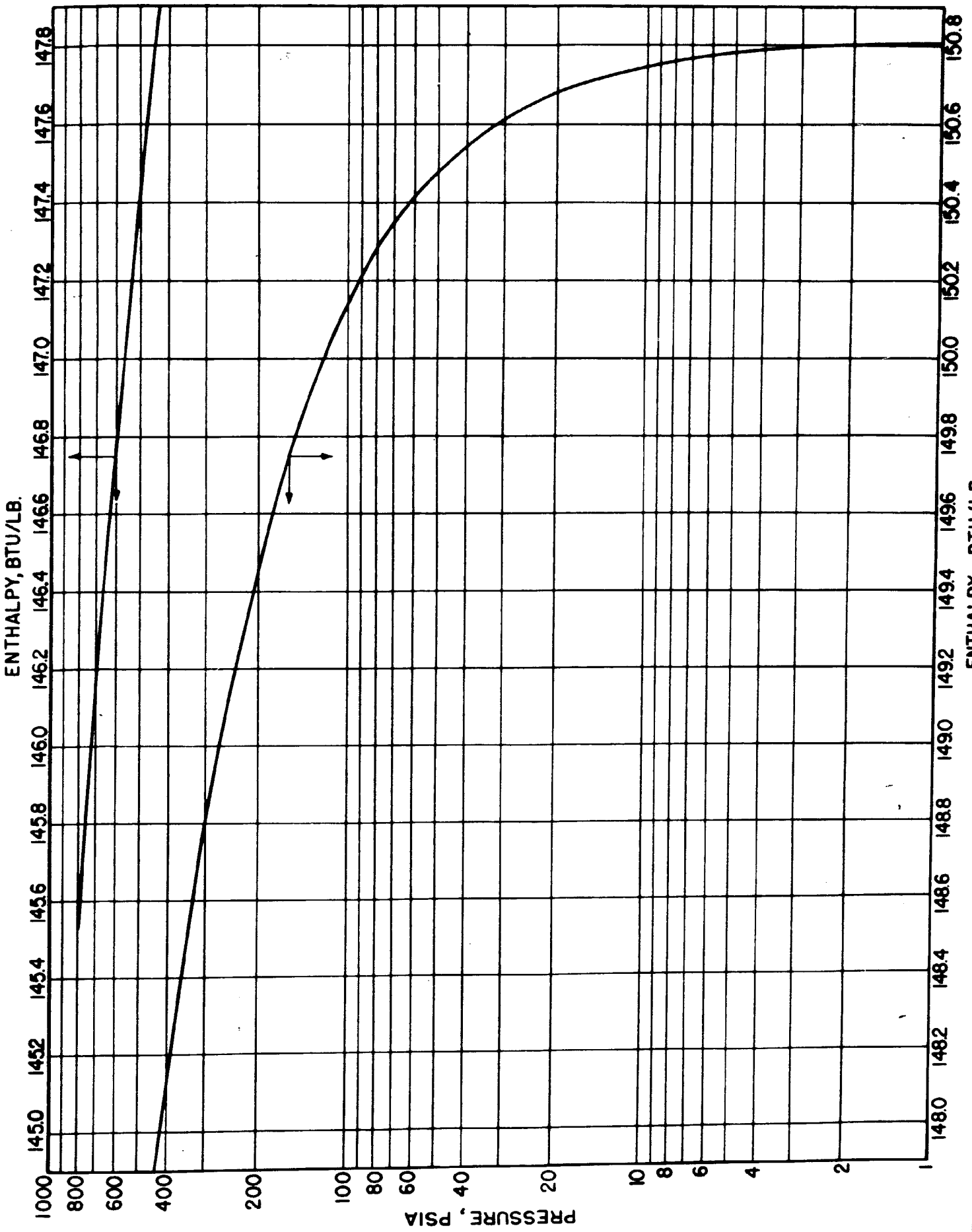


FIGURE 20- PRESSURE-ENTHALPY RELATIONSHIP FOR FREON 13 AT 500 °F

temperature intervals from -180 to 500°F. A typical plot in the one at 500°F, which is shown in Figure 20. The plot indicates that the change of enthalpy with pressure is small especially at low pressures. The original enthalpy-pressure plots were sufficiently large to read the enthalpy within 0.0005 BTU/lb. for all pressures below 300 psia and within 0.001 BTU/lb. at higher pressures.

The entropy values of Table III at constant pressures and temperatures were determined from plots of the entropy values of Table IV against pressure at constant temperature intervals of 20°F. The following three charts were constructed to cover the entire pressure range: 0-10 psia, 10-110 psia, and 100-1000 psia. These charts were plotted on roll graph paper, which was 20" wide with 10 divisions to the inch. The pressure was plotted as the abscissa, and the entropy as the ordinate. The smallest division on the ordinate represented 0.0001 BTU/lb., °R, and each of the finished graphs was from ten to fifteen feet long. Smooth curves were obtained at all tabular temperatures. The entropies were read at tabular pressures and temperatures and were probably correct within 0.0001 BTU/lb., °R. A reduction of the 10-110 psi graph with a decreased number of isotherms is shown in Figure 21.

The large entropy-pressure charts were also used to determine constant entropy lines. The entropy values selected were from 0.10 to 0.35 BTU/lb.,°R at 0.01 BTU/lb.,°R

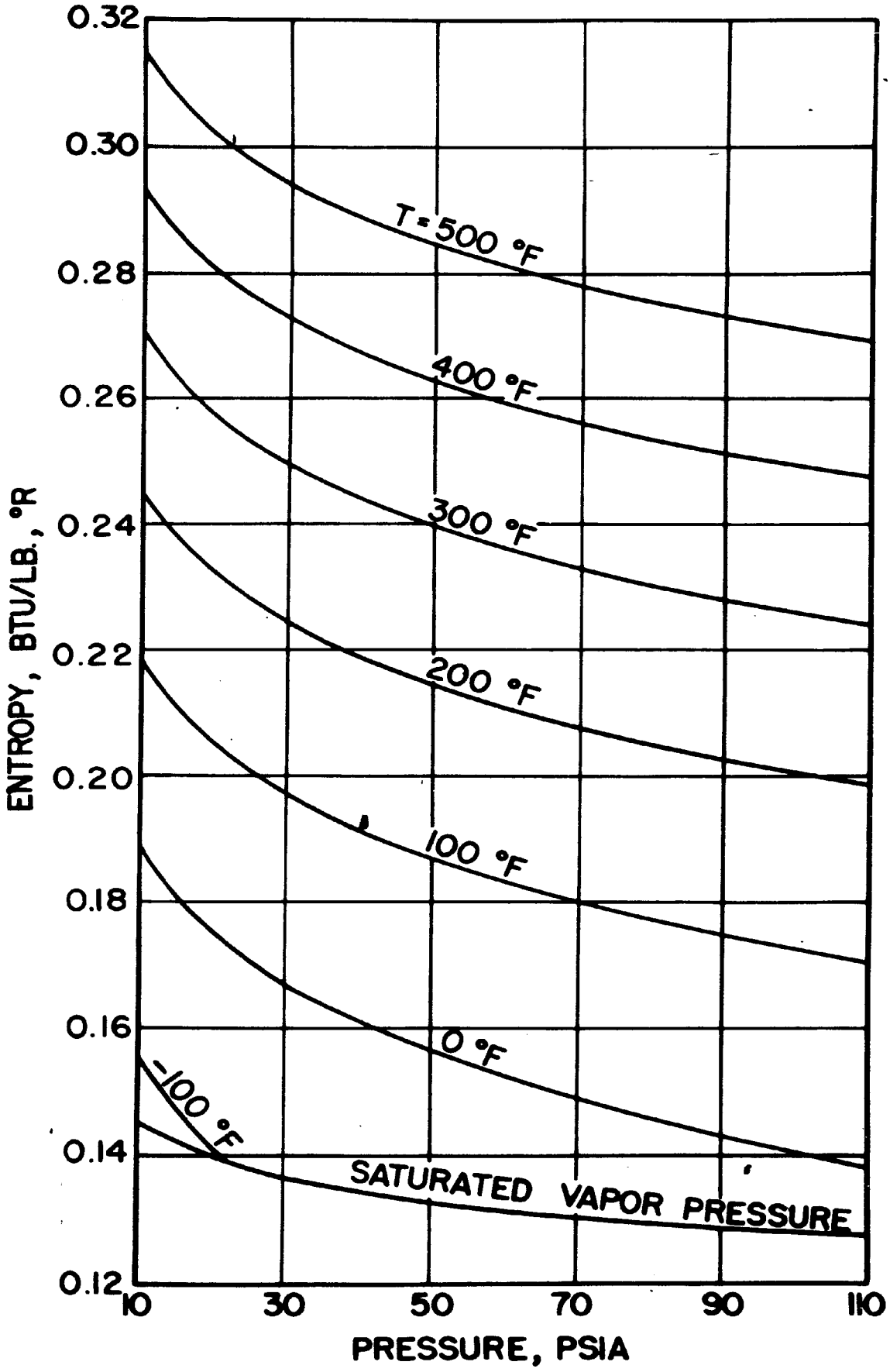


FIGURE 21 - ENTROPY-PRESSURE ISOTHERMS FOR FREON 13

intervals. The pressures were read to within 0.2% at the intersection of each constant temperature and entropy line. These constant entropy results are presented in Table V in Appendix A.

The pressure-enthalpy diagram for the saturated vapor and liquid and for the superheated vapor was constructed from the values of the thermodynamic and physical properties presented in Tables II, IV, and V. Constant temperature, volume, and entropy lines were drawn in the superheated vapor region. This diagram is shown in Figure 10.

DISCUSSION OF RESULTS

Discussion of Vapor Pressure Results:

Vapor pressure equations, Equation 9 and 10, were compared over the temperature ranges from -200 to -15°F and -15 to 80°F respectively with vapor pressure data reported in the literature. The smoothed data of Riedel (11) and Whitney (16) agree within 0.3% of the vapor pressure values calculated from the equations. The deviations between the data of McNabney (8), Thornton et al (14), and Ruff and Keim (13) and the values calculated from the equations are less than 1.5%, 2.5%, and 6.0-70.0% respectively.

Equation 9 represents the experimental data within a maximum of 0.08% and 0.14% for the temperature ranges of -200 to -15°F and 15 to 80°F respectively, as shown in Table VI. Equation 10 predicts the experimental data from -15 to 80°F within a maximum of 0.07%. Equation 9 and 10 were used in the thermodynamic calculations from -200 to -15°F and from -15 to 80°F respectively, and as a result the vapor pressure curve and the slope of the curve were obtained with higher accuracy over the entire temperature range than would be possible if only Equation 9 was used.

Each experimental vapor pressure point of Table VI was the average of 10-20 points in a narrow temperature range. Equation 9 was used from -200 to -15°F and

Equation 10 from -15 to 80°F to determine how well these 10-20 points agreed with each other. The proper equation was solved for pressure at the exact temperature of each point, and the deviations between the calculated and the experimental pressures were determined. It was found that at each approximate temperature the differences in the deviations of each point from any of the other points were less than 0.1%. This indicated that the experimental errors in reading the pressure gauges or manometers and the thermometer were less than 0.1%, and the average was probably less than 0.05%. It also indicated that a pure Freon 13 had been used for the vapor pressure measurements.

The errors in the calibration of the platinum resistance thermometer #169313 and the Mansfield and Green dead weight gauge were considered to be less than 0.02°F and 0.07% respectively. Calculations made with the vapor pressure equations indicated that an error of 0.02°F would cause a maximum error of the vapor pressure of 0.05%. This maximum error would be at the low-temperature end of the vapor pressure curve. The total errors of the experimental vapor pressure points of Table VI were then estimated to be less than 0.15%. As Equations 9 and 10 over their designated temperature ranges predict the experimental data within 0.08% and 0.07% respectively, the vapor pressures calculated from these equations are probably correct within 0.20%.

The slope of the vapor pressure curve was obtained from the derivative, dp/dT, determined from the vapor pressure equations. The derivatives of Equations 9 and 10 are Equations 31 and 32 respectively. The accuracy with which Equation 31 predicts the slope of the experimental vapor pressure curve was determined in the following manner.

The deviations, shown in Table VII, between the vapor pressure values calculated from Equation 9 and the experimental data were plotted against the temperature, and this plot is shown in Figure 22 in Appendix B. Calculations made with the aid of Figure 22 indicated the difference of the slope predicted by Equation 31 and the slope of the curve through the experimental data would be 0.3% or less from -200 to -15°F and would be as high as 1.0% from -15 to 80°F. These calculations are shown in Appendix G. Similar calculations made with Equation 10 indicated that the difference of the slope calculated from Equation 32 and the slope of the experimental vapor pressure curve was less than 0.3% from -15 to 80°F. The slopes at -15°F that were obtained from Equations 31 and 32 agree within 0.3%. Equation 31 was used in the thermodynamic calculations to predict the slope of the vapor pressure curve from -200 to -15°F, and Equation 32 from -15 to 80°F. As a result, the slope of the vapor pressure curve agrees for the thermodynamic calculations within 0.3% of that of the experimentally determined vapor pressure curve.

Discussion of the P-V-T Results

The equation of state, Equation 25, was compared with the p-v-T data reported by Riedel (11) and Whitney (16). Riedel's data agree within about 0.5% of the values calculated from Equation 25, and Whitney's results agree within about 1.0%. The largest deviations of Whitney's results are at each end of the isometrics. His isometrics have less slope than those calculated from Equation 25.

Equation 25, which was used in the thermodynamic calculations, was found to represent most of the experimental data of this investigation within 0.2% and the remainder within 0.5%, as was shown in Table VII. This table indicated that the deviations between the calculated and the corrected experimental data would give relatively smooth deviation curves for any one isometric.

As was indicated in the calculation procedure for the p-v-T data, straight line equations and equations of the following form were considered for representing the experimental isometric data.

$$(13) \quad p = A + B T + C / T^2$$

$$(14) \quad p = A + B T + C / T^4$$

The experimental isometrics have a slight but definite curvature, especially in the vicinity of the vapor pressure curve as shown in Figure 12. As a result, all equations of state that yield straight line equations for the isometrics are relatively inaccurate for representing the p-v-T data.

Whitney's equation of state, Equation 4, is an equation of this type.

Equation 14 was found to represent the isometric data slightly better than Equation 13, which did not predict sufficient curvature at the low-temperature end of the curve. This would indicate for an isometric equation of the form,

$$p = A + B T + C / T^{x} ,$$

where x = power of T

that x should be larger than 2. As a result, all equations of state that yield isometric equations with x values of 2 or less are probably relatively inaccurate for representing the p-v-T data. Equations of state of this type include the Beattie-Bridgeman equation, the Benedict-Webb-Rubin equation, and Equation 3, Riedel's equation of state. Equation 14 with an x value of 4, however, probably represents the isometric data within the limits of the experimental accuracy.

In Equation 25 the values of the variables, A, B, and C, of Equation 14 are represented by power series of the density. The function developed for each variable probably represents the variable within the experimental accuracy up to the critical density. In order to extend the range of the equation above the critical density, however, more terms would probably need to be added to the function of each variable.

The experimental errors in the measurements of the temperature, amount of Freon 13 used, volume, and pressure were evaluated for the p-v-T determinations and are presented below:

The errors in measuring the temperature with the platinum resistance thermometer No. 169313 were probably less than 0.02°F. The temperature gradients throughout the bath for the vapor density bulb were less than 0.02°F, so the total errors in the temperature were probably within 0.04°F. Calculations made with Equation 25 indicated that a temperature change of 0.04°F would change the pressure 0.01 to 0.04 % for densities of the gas of 1.15 to 35.9 lbs./cu. ft. respectively.

The amount of Freon 13 used in the p-v-T measurements was considered to be the average of the amount loaded to the vapor density bulb and that recovered from it. These two amounts agreed for all experimental isometrics within 0.10% and generally within 0.04%. The amount of Freon 13 used was always greater than 75 grams. Two weighings were required of both the supply and recovery cylinder to determine this weight. As the balance used for the weighings gave reproducible results within 0.005 grams, the maximum error in weighing would be about 0.03%. The amount of freon reported for each isometric was then estimated to be accurate within 0.04% to 0.07%.

The volume of the high-pressure vapor density bulb was found to be about 620 cc. at room temperature and atmospheric pressure. It had been calibrated from its weight empty and filled with distilled water. The balance used for these weighings gave reproducible results within 0.1 grams,

so the volume of the bulb was probably accurate to within 0.03%. The volume of the low-pressure bulb was found to be about 4075 cc. It had been weighed on a balance accurate to within 0.5 grams, so its volume was estimated to be correct within 0.025%.

The volumes of the vapor density bulbs were corrected for temperature changes. The cubical coefficient of expansion of the steel was taken as 34×10^{-6} $cm^3/cm^3/°C$, which was reported by Perry (9). As the change of the volume due to temperature was small, approximately 0.3%, any error of this coefficient would probably cause an error of the volume of less than 0.01%.

Several factors that changed the effective volume of the vapor in the p-v-T measurements, and for which no corrections were made are as follows:

(1) The increase of the volume of the vapor density bulbs as a result of pressure increases.

(2) The increase of the vapor volume due to the decrease of the oil and mercury volume in the U-leg as a result of pressure increases.

(3) The decrease of the vapor volume due to the increase of the volume of the oil and mercury in the U-leg as a result of temperature increases.

(4) About 0.05% of the vapor volume of the low-pressure vapor density bulb was actually at room temperature, but was assumed to be at the bath temperature in the vapor density calculations.

The first volume change was calculated to be about 0.05% for a pressure of 2000 psi in the high-pressure vapor density bulb, and about 0.05% for a pressure of 300 psi in the low-pressure bulb. The detailed calculations for this volume change are shown in Appendix G.

The second volume change was experimentally determined as follows: Nitrogen gas was added to the vapor density bulb until a pressure of 600 psi was obtained. The valve (17), shown in Figure 7, in the U-leg (18) was now closed. The pressure was released from the vapor density bulb, and the connection from the vapor density bulb (15) to the U-leg was broken. The amount of mercury necessary to raise the mercury level to the height where it had been at atmospheric pressure was found to be less than 0.1 cc., which was a change of the vapor volume of less than 0.015% at 600 psi. This volume change was approximately proportional to the pressure, so that the volume change at 2000 psi was less than 0.05%.

The third volume change was calculated to be less than 0.03% for a temperature increase from 70 to 250°F. The detailed calculations for this change are shown in Appendix G. Volume changes two and three tended to cancel each other for the most part as higher pressures generally went with higher temperatures.

The fourth volume change was due to the fact that about 2.0 cc. of the total gas volume of about 4070 cc. were outside the bath for experimental isometrics run in the low-pressure vapor density bulb. The 2.0 cc. volume was at room temperature, and the remainder of the volume was at the bath temperature. There were, as a result,

temperature and density gradients in the Freon 13 throughout the vapor volume. When the vapor density was calculated, the assumption was made that the entire volume of the gas was at the bath temperature. The maximum error caused by using the entire volume, instead of a corrected volume, was 0.015%. This maximum error occurred when the difference of the bath and room temperatures was greatest. The calculations of this error are shown in Appendix G.

The total maximum error of the gas volume at experimental temperatures and pressures was estimated to be between 0.05 and 0.10%. The higher error was for the high-pressure end of the isometric, and the lower error for low-pressure end of the isometric.

The pressure gauges for pressures below 600 psi were calibrated in place by the Mansfield and Green dead weight gauge, which was probably accurate to within 0.07%. The pressure gauge for pressures above 600 psi was calibrated directly on the American dead weight gauge, which was considered accurate to within 0.05%. The change in the calibration of this pressure gauge when it was connected to the oil and mercury leg was calculated to be less than 0.06% over the pressure range of 600-2000 psi. The calculations of this error are shown in Appendix G. The pressure gauges for every experimental isometric with the exception of those at densities of 1.05 and 1.68 lbs./cu. ft. could be read to

within 0.1 to 0.2%. The gauge for the isometrics at these other two densities could be read within 0.2 to 0.35%. The maximum error of the experimental pressure measurements was now estimated to be 0.2 to 0.4% with the maximum error at the lower pressures.

A summary of the probable maximum errors of the p-v-T results is as follows:

(1)	Temperature error	0.01 - 0.04%
(2)	Error in the amount of Freon 13 used	0.04 - 0.07
(3)	Volume error	0.05 - 0.10
(4)	Pressure error	0.20 - 0.40

The pressure error was probably at a minimum when the volume error was a maximum and vice versa. The probable maximum total error of the experimental isometric data was estimated to be 0.30 to 0.45%.

The equation of state, Equation 25, represents most of the experimental data within 0.2% and the remainder within 0.5%. As a result, the p-v-T relationships obtained from the equation in the thermodynamic calculations are probably accurate to within 0.5-0.7% over the following range covered by the experimental data:

(1) Vapor densities from 0.00 to 35.9 lbs./cu. ft.

(2) Temperatures from the saturation temperature to 180°F above it.

(3) Pressures from 0-2025 psia.

Equation 25 represents the experimental data at the density of 35.9 lbs./cu.ft. within 0.10%, and an extrapolation of the equation to the critical density of 36.07 lbs./cu. ft. would probably be about as accurate. The experimental data indicates that the high temperature ends of the isometrics are approaching straight lines. Equation 25 gives isometrics that approach straight lines at their high temperature ends. As a result, Equation 25 probably predicted p-v-T relationships up to 500°F in the thermodynamic calculations with reasonable accuracy.

Discussion of the Saturated Liquid Density Results:

The saturated liquid density equation, Equation 28, was compared with the liquid density data presented by Riedel (10). His data agree within 0.1% of the values calculated from the equation except at about -180 and 77°F, where the disagreements are as high as 0.8%.

The comparison of the calculated results of Equation 28 with the experimental data of this investigation is shown in Table XI. The two values in each case agree within 0.1%.

The temperature errors of the experimental data due to the calibration of the platinum resistance thermometer No. 169313 were considered less than 0.02°F. The temperatures at which the float sank and rose agreed within the following limits:

(1) 0.09°F from densities of 50.899 to 75.615 lbs./cu. ft.

(2) 0.11°F from densities of 81.815 to 96.305 lbs./cu. ft.

(3) 0.16 - 0.36°F from densities of 100.51 to 108.48 lbs./cu. ft.

The temperature at which the densities of the float and the liquid Freon 13 were equal was considered to be the average of the temperatures for the rising and sinking float. So the maximum error of this temperature was probably less than 0.05 to 0.19°F as the density increased. Calculations made with Equation 28 indicated that such a temperature error would change the liquid density about 0.02 to 0.05% as the density decreased.

The densities of the floats were calibrated by weighing the floats in air and immersed in water. The weights of the floats in air were considered accurate to within 0.0001 grams out of approximately 1.0 to 1.7 grams. The weights of the floats immersed in water were reproducible to 0.0002 grams. The possible errors of the volumes of the floats were than about 0.0002 cc. out of total volumes of about 1.0 cc. The maximum errors of the float densities at room temperature were then probably less than 0.03%.

The densities of the floats were corrected for temperature changes. The cubical coefficient of expansion of glass was taken as 9.8×10^{-6} $cm^3/cm^3/°C$, as recommended by the Corning Glass Works. The float densities were not corrected for pressure changes. Calculations, shown in Appendix G, indicated that the densities of the floats changed

about 0.04% due to a pressure of 500 psi. The total density errors of the floats at the experimental temperatures and pressures were estimated to be less than 0.07%.

When the possible errors of the density of the float and the temperature were added, the total maximum error of the experimental liquid density points was estimated to be less than 0.12%. As the liquid density equation represents the experimental points within 0.10%, the densities calculated from the equation can be considered accurate to within 0.22% and probably to within 0.15%.

Discussion of Results for Critical Constants:

The critical constant results are as follows:

t_c = 83.93 F ; p_c = 561.3 psia ; d_c = 36.07 lbs./cu. ft.

These values agree well with those reported in the literature by the following investigators:

Riedel (11):

t_c = 83.84°F ; p_c = 559.7 psia ; d_c = 36.27 lbs./cu. ft.

McNabney (8):

t_c = 83.84°F ; p_c = 561.5 psia

Whitney (16):

$t_c = 83.89 \pm 0.09$°F

The critical temperature was determined experimentally by measuring the temperature of the appearance and disappearance

of the liquid meniscus in a tube filled with Freon 13. Theoretically, if the tube was filled with more freon than that of the critical density, the liquid level (liquid meniscus) would rise as the temperature increased. Finally, a temperature, lower than the critical temperature, would be reached at which the meniscus would disappear at the top of tube, i. e., the tube would be liquid full. Conversely, If the tube was filled with too little freon, a gas phase would fill the tube before the critical temperature was reached, and the meniscus would have disappeared at the bottom of the tube. Only in case the tube had been loaded to the critical density would the meniscus disappear in the middle of the tube.

In practice, however, it was found that the meniscus disappeared near the middle of the tube even if the tube was not loaded with exactly the critical density. Four tubes loaded with freon were used to measure the critical temperature. Each tube was estimated to be loaded with a slightly different amount of Freon 13. In the two tubes, which appeared to be the heaviest loaded, the menisci disappeared just above the middle of the tubes, which indicated that these tubes were probably filled to a density greater than the critical density. In the third tube, which appeared to be filled with less freon, the meniscus disappeared near the middle, and this tube was probably filled to about the critical density. In the fourth tube the meniscus disappeared just below the middle. This tube appeared to be filled with the

least freon, and it was probably filled to a density lower than the critical density. The location where the meniscus appeared in any particular tube was approximately the same as where it disappeared. A possible explanation of why the meniscus disappeared near the middle of the tube regardless of the density in the tube is as follows: As the critical temperature is approached, the driving forces from the liquid to the vapor become smaller, and the time to reach equilibrium probably becomes longer. In the immediate vicinity of the critical temperature, the time to reach equilibrium becomes so long that equilibrium is never reached while the temperature of the bath is increased or decreased at the rate of 0.02°F, as was done in the experimental investigation.

The temperatures at which the menisci appeared or disappeared were the same for all tubes within the limits of experimental accuracy. The following description of the phenomena observed is typical for all tubes, and it indicates some of the problems encountered in accurately measuring the temperatures of the appearance and disappearance of the meniscus: As the temperature of the bath was raised from 83.50°F at approximately 0.02°F per minute, the meniscus in the tube became increasingly indistinct. At 84.01°F, the meniscus was very fuzzy and was no longer a line but a wide region. At 84.09°F, it was still possible to see density gradients in the tube around the spot where the meniscus had been. Density gradients were still apparent until a temperature of 84.22°F was reached when the entire tube appeared to

be filled with a homogeneous gas. The temperature was now decreased at about 0.02°F per minute. At 84.07°F, a white haze began to appear throughout the entire tube. As the temperature dropped, the white haze became more intense and gradually changed to a tannish haze. At 83.86°F, a thin line of meniscus appeared near the center of the tube, and the tannish color still prevailed throughout the entire tube. The temperatures were increased and decreased several more times with similar results.

The effect of shaking the liquid density tubes was tried. The sharp line meniscus disappeared in this case with increasing temperature at 83.95°F, and the density gradients at approximately 84.13°F. The meniscus appeared with decreasing temperature at 83.86°F, which was the same temperature that had been found in the rigidly mounted tubes.

The temperature at which the meniscus disappeared was selected, largely as a matter of judgment, as the temperature in the rigidly mounted tubes at which the sharp line meniscus disappeared and a broad band appeared to replace it. This temperature was 84.01°F. The temperature of the appearance of the meniscus was 83.86°F. The critical temperature was taken as the average of these two temperatures and was found to be 83.93°F. This temperature is probably correct to within 0.10°F.

The critical pressure was calculated by substituting the critical temperature in the vapor pressure equation, Equation 10, and solving for the pressure, which was found to be 561.3 psia. An error in the critical temperature of 0.10°F would cause an error in the pressure of about 0.15%. Equation 10 was considered accurate to within 0.20% at 80°F. Figure 11 indicated that the plot of the logarithm of vapor pressure against 1/T°R became almost a straight line in the neighborhood of the critical point. As a result, the extrapolation of Equation 10 to the critical temperature should be relatively accurate, and the critical pressure determined as 561.3 psia is probably correct to within 0.5%.

The critical density was measured indirectly by using the Law of Rectilinear Diameters. The rectilinear diameters were calculated from the saturated liquid and vapor densities. As a result, the accuracy of the critical density depends largely on the accuracy of these two densities, especially those which are closest to the critical temperature. In this range of densities the saturated liquid densities are probably accurate to within 0.10%. The saturated vapor densities were determined from the experimental isometric data and the vapor pressure equations, and they are probably correct to within 0.50%. The rectilinear diameter points are then probably accurate to within 0.60%.

The rectilinear diameter equation, Equation 26, represents the rectilinear diameter points within 0.10%. The extrapolation of Equation 26 to the critical temperature is probably relatively accurate, as the temperature interval of the extrapolation is small, less than 10°F, as shown in Figure 18. An error in the critical temperature of 0.10°F would cause an error in the critical density of about 0.02%, as indicated by Equation 26. The critical density was found by extrapolating Equation 26 to the critical pressure to be 36.07 lbs./cu. ft., which is probably accurate to within 1.0%.

Discussion of the Specific Heat Results:

The specific heat values of the gas at infinite volume were to be calculated from the fundamental frequencies, which were determined from spectroscopic data. Three sets of investigators assigned all or part of the values for these frequencies as was shown in Table I. These frequency assignments were appraised to determine which would probably be best for the specific heat calculations.

Kahovec and Wagner (6) assigned the only complete set of values for the frequencies which they obtained from the Raman spectrum of the liquid. Although the values of the frequencies determined from the liquid or from the gas are generally nearly identical, those determined from the gas would probably give more accurate values for calculating the specific heats of the gas. As a result, Kahovec and Wagner's results were not used in this investigation.

McGovern et al's results were obtained from the infra-red spectrum of the gas. They, however, only assigned three of the six values of the frequencies, and their results were too incomplete to be used to calculate the specific heats of the gas.

Plyler (10) assigned five of the six values of the fundamental frequencies from the infra-red spectrum of the gas. His investigation was made at the National Bureau of Standards with the best equipment available. In addition to

his investigation of Freon 13, he has assigned values to the frequencies for several other chloro-fluoro derivatives of methane. Therefore, he has been able to appraise the frequency assignments for any one of these compounds by comparing it with the assignments of similar compounds. Although he did not measure the value of the frequencies γ_2 and γ_5 directly, he found that the value, 356 cm.$^{-1}$, reported by Kahovec and Wagner correlated well with his other data. It was thought that the values for the fundamental frequencies measured or recommended by Plyler would probably give accurate specific heat values of the gas, and these values of the frequencies were used in this investigation to calculate the specific heat values of the gas.

The specific heat values calculated from the fundamental frequencies reported by Plyler are shown in Table XI and were designated as statistical specific heats. These values agree within 1.0% of those calculated by Whitney (16) and Justi and Langer (5). Equation 29 was derived to predict the specific heat values of this investigation. The deviations of the specific heats calculated from Equation 29 and the statistical values were found to be less than 0.5% for temperatures from -200 to 500°F, as shown in Table XI.

Discussion of Results for Thermodynamic Properties:

Table II presents values for the thermodynamic properties of the saturated liquid and vapor, which were compared whenever possible with those reported by Whitney (16) and Riedel (12). The enthalpy and entropy values reported by these two investigators agree within about 1.0 BTU/lb. and 0.003 BTU/lb.,°R respectively with the values shown in Table II.

Table III presents values for the thermodynamic properties of the superheated vapor, and these values were plotted on the pressure-enthalpy diagram, Figure 10. Figure 10 was compared to a similar but less detailed diagram presented by Whitney (16). The enthalpy values in the superheated gas region agree within about 2.0 BTU/lb. for the constant temperature, entropy, and volume lines. The entropy values of the two diagrams agree within about 0.003 BTU/lb.,°R for the same pressure and enthalpy. The major difference in the two diagrams is the location of the constant volume lines with regards to the ordinate, which is pressure, and the constant temperature lines. This is due to the fact that the equation of state, Equation 4, used by Whitney in his calculation disagrees as high as 6.0% with Equation 25 used in this investigation.

The results of Tables II and III are thermodynamically consistent as only exact thermodynamic formulas were used in the calculations of the enthalpy and entropy values. The only

exceptions are when slightly inaccurate interpolation methods were used to determine the values of Table III from auxiliary Table IV. The thermodynamic formulas used to calculate values for Tables II and IV were evaluated by only the following equations:

(1) Equations 9 and 10 for the vapor pressure

(2) Equation 25 for the equation of state of the vapors

(3) Equation 28 for the saturated liquid density

(4) Equation 29 for the specific heat of the gas at infinite volume.

The enthalpy values in Table II are reported to within 0.0001 BTU/lb., and those of entropy to 0.00001 BTU/lb., °R. In Table III these values are reported to 0.001 BTU/lb. and 0.0001 BTU/lb., °R respectively. The values for the volume are reported in each table to 0.05 to 0.10% respectively. All the values for pressure are reported in both tables to 0.1%. All multiplication and division calculations necessary to obtain these results were made with the aid of a ten-place electric calculating machine. Whenever accurate logarithms were needed, a six-place table was used. Numerous checks were made of the mathematical accuracy of the enthalpy and entropy values by the following procedure.

As the equations used to calculate the enthalpy and entropy values are thermodynamically correct, it is immaterial what path is traveled to reach any particular point. Representative points along the saturated vapor line and throughout the

superheated vapor region were tested for accuracy by traveling to them by alternate routes. It was found in each case that the results obtained by traveling the different routes agreed within the required accuracy.

The enthalpy and entropy values of Table II were checked for mathematical accuracy by plotting them against pressure on large scale plots. Smooth and consistent curves were obtained for both values.

The enthalpy and entropy values of the superheated vapors were tested for mathematical accuracy by plotting them against the pressure at constant temperatures. These plots yielded smooth and consistent curves, as is shown in the representative graphs, Figures 20 and 21. The original plots were large enough to indicate any significant mathematical errors. All errors found were corrected. It is regarded as practically certain that Tables II and III accurately reproduce all of the empirical relations put into them. How closely they represent the facts is another matter, which depends on the accuracy of the empirical equations for the vapor pressure, p-v-T relationship of the gas, saturated liquid density, and the specific heat of the gas at infinite volume.

The thermodynamic properties reported in Table II, Table III, and Figure 10, cover the range of conditions that Freon 13 normally encounters when used as a refrigerant. These properties are presented in a form, which is convenient for designing and operating refrigeration equipment that uses Freon 13 as a refrigerant.

SUMMARY COMPARING THIS WORK WITH PREVIOUS WORK

The physical properties determined in this investigation are compared to those found in the literature as follows:

(1) The vapor pressure was measured at temperatures from -200 to 80°F, which is approximately the same range as reported in the literature. Some, although not serious, differences were found.

(2) The p-v-T relationship of the gas was measured for thirteen isometrics at densities ranging from 1.15 to 44.45 lbs./cu.ft. Seven isometrics are reported in the literature at densities from 0.45 to 11.77 lbs./cu.ft., and one isometric is reported at 36.05. No data are available in the literature at densities between 11.77 and 36.05. The temperature ranges of the isometrics reported in the literature are about 1/2 to 2/3 of those of this investigation.

(3) The saturated liquid density was measured at temperatures from -225 to 78°F. The data reported in the literature cover the range from -180 to 77°F. Good agreement was found between the two sets of data except at temperatures around -180 and 77°F.

(4) Specific heat values of the gas were calculated from -200 to 500°F from values of the fundamental frequencies, which have recently been determined. Similar specific heat values were calculated previously over the same temperature range with older values of the fundamental frequencies, which are probably less accurate than the values used in this investigation.

The thermodynamic properties of this investigation are reported at temperatures from -200 to 500°F and at pressures from 1.0 to 1000 psia, which is the same range covered by Whitney (16). The new thermodynamic values determined in this investigation are probably more accurate than those reported by Whitney, as the empirical equations for the physical properties that were used to calculate the thermodynamic properties are considered to be more accurate for this investigation.

APPENDIX

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APPENDIX A

AUXILIARY THERMODYNAMIC TABLES

TABLE IV

ENTHALPY, ENTROPY, AND PRESSURE OF SUPERHEATED FREON 13 VAPORS AT CONSTANT VOLUME AND TEMPERATURE

1. Volume 60 cu.ft./lb.

T°F.	P	H	S
-180	.4770	40.793	.18653
-160	.5116	43.086	.19266
-140	.5459	45.429	.19866
-120	.5802	47.826	.20452
-100	.6146	50.281	.21029
- 80	.6489	52.794	.21598
- 60	.6832	55.369	.22154
- 40	.7175	58.011	.22703
- 20	.7517	60.715	.23243
- 0	.7861	63.489	.23775
20	.8203	66.331	.24300
40	.8546	69.242	.24815
60	.8889	72.219	.25325
80	.9230	75.261	.25828
100	.9573	78.366	.26323
120	.9915	81.530	.26813
140	1.026	84.755	.27295
160	1.060	88.038	.27770
180	1.094	91.373	.28240
200	1.129	94.771	.28704
220	1.163	98.212	.29162
240	1.197	101.701	.29612
260	1.231	105.240	.30058
280	1.265	108.824	.30496
300	1.300	112.463	.30931
320	1.334	116.134	.31358
340	1.368	119.845	.31780
360	1.402	123.597	.32198
380	1.437	127.394	.32607
400	1.471	131.217	.33014
420	1.505	135.073	.33414
440	1.539	138.958	.33808
460	1.574	142.888	.34197
480	1.608	146.831	.34580
500	1.642	150.803	.34959

TABLE IV (Cont'd)

2. Volume 50 cu.ft./lb.

T°F.	P	H	S
-180	.5718	40.779	.18303
-160	.6133	43.071	.18917
-140	.6546	45.424	.19517
-120	.6959	47.821	.20104
-100	.7371	50.273	.20682
- 80	.7783	52.787	.21250
- 60	.8195	55.363	.21807
- 40	.8606	58.004	.22356
- 20	.9017	60.714	.22896
0	.9429	63.486	.23428
20	.9840	66.329	.23953
40	1.0251	69.239	.24469
60	1.066	72.216	.24979
80	1.107	75.257	.25481
100	1.148	78.360	.25975
120	1.190	81.527	.26465
140	1.231	84.752	.26947
160	1.272	88.034	.27422
180	1.313	91.372	.27892
200	1.354	94.763	.28357
220	1.395	98.205	.28815
240	1.436	101.699	.29265
260	1.477	105.240	.29712
280	1.518	108.826	.30150
300	1.559	112.456	.30585
320	1.600	116.131	.31012
340	1.642	119.845	.31434
360	1.683	123.599	.31852
380	1.724	127.389	.32261
400	1.765	131.214	.32668
420	1.806	135.073	.33068
440	1.847	138.963	.33462
460	1.888	142.884	.33851
480	1.929	146.829	.34234
500	1.970	150.801	.34613

TABLE IV (Cont'd)

3. Volume 40 cu.ft./lb.

T°F.	P	H	S
-180	.7140	40.750	.17874
-160	.7660	43.051	.18489
-140	.8178	45.401	.19090
-120	.8694	47.803	.19678
-100	.9210	50.260	.20256
- 80	.9725	52.777	.20825
- 60	1.024	55.354	.21382
- 40	1.076	57.998	.21931
- 20	1.127	60.703	.22471
0	1.178	63.477	.23003
20	1.230	66.319	.23529
40	1.281	69.232	.24044
60	1.333	72.210	.24555
80	1.384	75.252	.25056
100	1.436	78.356	.25551
120	1.487	81.523	.26042
140	1.538	84.747	.26524
160	1.590	88.030	.26998
180	1.641	91.368	.27469
200	1.693	94.759	.27933
220	1.744	98.201	.28391
240	1.786	101.693	.28841
260	1.847	105.235	.29287
280	1.898	108.822	.29725
300	1.950	112.453	.30160
320	2.001	116.127	.30587
340	2.053	119.841	.31009
360	2.104	123.595	.31427
380	2.156	127.385	.31836
400	2.207	131.210	.32243
420	2.258	135.069	.32643
440	2.310	138.957	.33036
460	2.361	142.879	.33426
480	2.412	146.825	.33809
500	2.464	150.801	.34188

TABLE IV (Cont'd)

4. Volume 30 cu.ft./lb.

T°F.	P	H	S
-180	.9507	40.708	.17318
-160	1.020	43.018	.17935
-140	1.089	45.375	.18538
-120	1.159	47.780	.19127
-100	1.228	50.241	.19706
- 80	1.296	52.761	.20275
- 60	1.365	55.340	.20833
- 40	1.434	57.984	.21382
- 20	1.503	60.692	.21922
0	1.571	63.466	.22455
20	1.639	66.311	.22980
40	1.708	69.222	.23496
60	1.776	72.201	.24006
80	1.845	75.243	.24509
100	1.913	78.347	.25003
120	1.982	81.514	.25494
140	2.050	84.736	.25976
160	2.119	88.022	.26451
180	2.187	91.357	.26921
200	2.257	94.756	.27395
220	2.326	98.198	.27843
240	2.394	101.692	.28293
260	2.463	105.234	.28739
280	2.531	108.820	.29177
300	2.600	112.451	.29612
320	2.669	116.126	.30039
340	2.737	119.840	.30461
360	2.805	123.594	.30879
380	2.874	127.386	.31288
400	2.942	131.210	.31695
420	3.011	135.068	.32095
440	3.079	138.956	.32489
460	3.148	142.879	.32878
480	3.216	146.824	.33261
500	3.285	150.798	.33638

TABLE IV (Cont'd)

5. Volume 25 cu.ft./lb.

T°F.	P	H	S
-180	1.139	40.667	.16964
-160	1.222	42.981	.17583
-140	1.307	45.352	.18187
-120	1.389	47.757	.18777
-100	1.472	50.221	.19357
- 80	1.554	52.740	.19927
- 60	1.637	55.322	.20485
- 40	1.720	57.971	.21034
- 20	1.802	60.677	.21574
0	1.884	63.451	.22107
20	1.967	66.300	.22633
40	2.050	69.213	.23148
60	2.132	72.191	.23659
80	2.214	75.235	.24161
100	2.296	78.340	.24656
120	2.379	81.507	.25146
140	2.461	84.732	.25629
160	2.543	88.015	.26104
180	2.625	91.354	.26574
200	2.708	94.745	.27038
220	2.790	98.188	.27496
240	2.872	101.681	.27946
260	2.954	105.223	.28392
280	3.037	108.809	.28830
300	3.119	112.442	.29265
320	3.201	116.115	.29692
340	3.283	119.830	.30114
360	3.366	123.584	.30532
380	3.448	127.374	.30941
400	3.530	131.200	.31348
420	3.612	135.059	.31748
440	3.694	138.947	.32142
460	3.777	142.869	.32531
480	3.859	146.815	.32914
500	3.941	150.787	.33293

TABLE IV (Cont'd)

6. Volume 20 cu.ft./lb.

T°F.	P	H	S
-160	1.527	42.946	.17152
-140	1.631	45.315	.17758
-120	1.736	47.733	.18349
-100	1.839	50.198	.18930
- 80	1.942	52.721	.19500
- 60	2.045	55.304	.20058
- 40	2.149	57.954	.20608
- 20	2.252	60.663	.21148
0	2.356	63.439	.21681
20	2.459	66.285	.22207
40	2.561	69.201	.22723
60	2.664	72.180	.23233
80	2.767	75.224	.23736
100	2.870	78.330	.24231
120	2.973	81.497	.24721
140	3.076	84.724	.25204
160	3.179	88.008	.25679
180	3.282	91.347	.26149
200	3.385	94.739	.26613
220	3.488	98.184	.27071
240	3.591	101.677	.27521
260	3.694	105.220	.27967
280	3.796	108.804	.28405
300	3.899	112.436	.28840
320	4.002	116.112	.29267
340	4.105	119.826	.29689
360	4.208	123.582	.30107
380	4.310	127.368	.30516
400	4.414	131.199	.30924
420	4.516	135.055	.31324
440	4.619	138.944	.31718
460	4.722	142.866	.32107
480	4.825	146.813	.32490
500	4.928	150.784	.32869

TABLE IV (Cont'd)

7. Volume 15 cu.ft./lb.

T°F.	P	H	S
-160	2.028	42.872	.16593
-140	2.169	45.255	.17202
-120	2.308	47.679	.17795
-100	2.447	50.154	.18378
- 80	2.586	52.687	.18949
- 60	2.724	55.274	.19509
- 40	2.862	57.925	.20059
- 20	2.999	60.634	.20600
0	3.137	63.414	.21133
20	3.274	66.262	.21659
40	3.411	69.176	.22175
60	3.550	72.162	.22686
80	3.687	75.205	.23188
100	3.824	78.310	.23684
120	3.961	81.478	.24174
140	4.098	84.704	.24656
160	4.236	87.990	.25132
180	4.373	91.328	.25602
200	4.510	94.719	.26066
220	4.648	98.165	.26524
240	4.785	101.658	.26974
260	4.922	105.200	.27420
280	5.059	108.788	.27858
300	5.196	112.420	.28293
320	5.333	116.093	.28721
340	5.470	119.809	.29143
360	5.608	123.566	.29561
380	5.745	127.355	.29970
400	5.882	131.180	.30377
420	6.019	135.040	.30777
440	6.156	138.928	.31171
460	6.293	142.849	.31560
480	6.430	146.796	.31943
500	6.568	150.768	.32322

TABLE IV (Cont'd)

8. Volume 12 cu.ft./lb.

T°F.	P	H	S
-160	2.530	42.807	.16155
-140	2.705	45.199	.16769
-120	2.881	47.635	.17364
-100	3.054	50.113	.17948
- 80	3.228	52.651	.18521
- 60	3.400	55.240	.19081
- 40	3.574	57.897	.19632
- 20	3.746	60.610	.20173
0	3.918	63.391	.20707
20	4.090	66.239	.21233
40	4.262	69.157	.21749
60	4.434	72.139	.22260
80	4.606	75.186	.22763
100	4.777	78.294	.23258
120	4.950	81.463	.23749
140	5.121	84.689	.24231
160	5.293	87.975	.24707
180	5.464	91.312	.25177
200	5.636	94.706	.25641
220	5.807	98.149	.26099
240	5.979	101.644	.26549
260	6.150	105.186	.26995
280	6.322	108.774	.27434
300	6.493	112.406	.27869
320	6.666	116.084	.28296
340	6.837	119.798	.28718
360	7.009	123.554	.29136
380	7.180	127.343	.29545
400	7.352	131.170	.29952
420	7.523	135.028	.30352
440	7.695	138.919	.30746
460	7.866	142.840	.31135
480	8.038	146.788	.31518
500	8.209	150.760	.31897

TABLE IV (Cont'd)

9. Volume 10 cu.ft./lb.

T°F.	P	H	S
-160	3.028	42.736	.15796
-140	3.241	45.143	.16412
-120	3.451	47.585	.17010
-100	3.661	50.073	.17595
- 80	3.869	52.614	.18169
- 60	4.077	55.208	.18730
- 40	4.285	57.867	.19282
- 20	4.491	60.581	.19824
0	4.699	63.367	.20358
20	4.906	66.219	.20884
40	5.112	69.137	.21401
60	5.319	72.121	.21912
80	5.525	75.167	.22415
100	5.731	78.254	.22910
120	5.937	81.443	.23401
140	6.143	84.672	.23883
160	6.350	87.959	.24358
180	6.556	91.298	.24829
200	6.762	94.691	.25293
220	6.968	98.136	.25751
240	7.174	101.630	.26201
260	7.379	105.171	.26647
280	7.585	108.759	.27086
300	7.791	112.393	.27521
320	7.997	116.068	.27948
340	8.203	119.783	.28370
360	8.409	123.539	.28788
380	8.615	127.330	.29198
400	8.822	131.159	.29604
420	9.028	135.018	.30004
440	9.233	138.905	.30398
460	9.439	142.828	.30787
480	9.645	146.776	.31170
500	9.851	150.749	.31549

TABLE IV (Cont'd)

10. Volume 8 cu.ft./lb.

T°F.	P	H	S
-140	4.037	45.056	.15974
-120	4.302	47.513	.16582
-100	4.565	50.010	.17164
- 80	4.827	52.559	.17739
- 60	5.088	55.162	.18301
- 40	5.348	57.824	.18854
- 20	5.607	60.543	.19396
0	5.867	63.331	.19931
20	6.125	66.184	.20458
40	6.384	69.106	.20975
60	6.642	72.090	.21486
80	6.901	75.139	.21989
100	7.158	78.246	.22485
120	7.417	81.409	.22975
140	7.674	84.616	.23458
160	7.933	87.935	.23923
180	8.190	91.274	.24404
200	8.447	94.667	.24868
220	8.705	98.112	.25326
240	8.964	101.609	.25776
260	9.221	105.152	.26223
280	9.479	108.741	.26661
300	9.736	112.373	.27096
320	9.994	116.048	.27523
340	10.25	119.764	.27945
360	10.51	123.521	.28363
380	10.77	127.310	.28772
400	11.02	131.137	.29179
420	11.28	134.999	.29579
440	11.54	138.889	.29973
460	11.80	142.811	.30362
480	12.05	146.759	.30745
500	12.31	150.732	.31124

TABLE IV (Cont'd)

11. Volume 6 cu.ft./lb.

T°F.	P	H	S
-140	5.352	44.916	.15403
-120	5.709	47.395	.16010
-100	6.063	49.911	.16602
- 80	6.414	52.472	.17181
- 60	6.763	55.083	.17745
- 40	7.112	57.754	.18299
- 20	7.459	60.481	.18843
0	7.806	63.274	.19378
20	8.152	66.131	.19906
40	8.497	69.055	.20423
60	8.842	72.043	.20935
80	9.186	75.092	.21438
100	9.531	78.202	.21934
120	9.876	81.376	.22425
140	10.22	84.607	.22908
160	10.56	87.894	.23383
180	10.91	91.237	.23854
200	11.25	94.632	.24318
220	11.60	98.078	.24776
240	11.94	101.573	.25226
260	12.29	105.118	.25673
280	12.63	108.708	.26111
300	12.97	112.342	.26546
320	13.32	116.017	.26973
340	13.66	119.734	.27395
360	14.01	123.492	.27814
380	14.35	127.283	.28223
400	14.69	131.110	.28630
420	15.04	134.971	.29030
440	15.38	138.860	.29424
460	15.72	142.784	.29813
480	16.07	146.732	.30196
500	16.41	150.705	.30575

TABLE IV (Cont'd)

12. Volume 5 cu.ft./lb.

T°F.	P	H	S
-140	6.392	44.803	.15039
-120	6.824	47.300	.15650
-100	7.250	49.828	.16243
- 80	7.675	52.401	.16826
- 60	8.096	55.021	.17392
- 40	8.515	57.696	.17947
- 20	8.933	60.429	.18492
0	9.349	63.224	.19028
20	9.765	66.085	.19556
40	10.18	69.012	.20074
60	10.60	72.002	.20586
80	11.01	75.055	.21089
100	11.42	78.168	.21585
120	11.84	81.342	.22076
140	12.25	84.574	.22559
160	12.67	87.863	.23035
180	13.08	91.205	.23506
200	13.49	94.600	.23970
220	13.90	98.047	.24428
240	14.32	101.544	.24879
260	14.73	105.088	.25325
280	15.14	108.679	.25763
300	15.55	112.311	.26198
320	15.97	115.991	.26625
340	16.38	119.708	.27048
360	16.80	123.464	.27466
380	17.21	128.256	.27875
400	17.62	131.083	.28282
420	18.03	134.945	.28682
440	18.45	138.836	.29076
460	18.86	142.758	.29465
480	19.27	146.707	.29848
500	19.68	150.680	.30227

TABLE IV (Cont'd)

13. Volume 4 cu.ft./lb.

T°F.	P	H	S
-120	8.487	47.156	.15204
-100	9.026	49.705	.15804
- 80	9.559	52.292	.16388
- 60	10.09	54.925	.16957
- 40	10.62	57.611	.17514
- 20	11.14	60.350	.18060
0	11.67	63.153	.18597
20	12.19	66.017	.19126
40	12.71	68.949	.19644
60	13.23	71.944	.20157
80	13.75	74.999	.20661
100	14.27	78.115	.21158
120	14.78	81.291	.21649
140	15.30	84.525	.22132
160	15.82	87.815	.22608
180	16.34	91.160	.23078
200	16.86	94.557	.23543
220	17.37	98.005	.24001
240	17.89	101.503	.24452
260	18.41	105.050	.24898
280	18.92	108.640	.25336
300	19.44	112.277	.25772
320	19.96	115.953	.26199
340	20.48	119.672	.26621
360	20.99	123.430	.27039
380	21.51	127.222	.27448
400	22.03	131.050	.27856
420	22.54	134.912	.28256
440	23.06	138.804	.28650
460	23.58	142.729	.29039
480	24.09	146.677	.29422
500	24.61	150.653	.29801

TABLE IV (Cont'd)

14. Volume 3 cu.ft./lb.

T°F.	P	H	S
-120	11.20	46.919	.14621
-100	11.94	49.509	.15229
- 80	12.66	52.122	.15819
- 60	13.37	54.772	.16392
- 40	14.08	57.475	.16952
- 20	14.77	60.219	.17500
0	15.48	63.037	.18039
20	16.17	65.907	.18570
40	16.88	68.851	.19089
60	17.57	71.847	.19602
80	18.26	74.905	.20107
100	18.96	78.028	.20604
120	19.65	81.206	.21096
140	20.35	84.447	.21579
160	21.04	87.738	.22055
180	21.73	91.085	.22526
200	22.42	94.483	.22991
220	23.11	97.933	.23450
240	23.81	101.436	.23900
260	24.50	104.984	.24347
280	25.19	108.576	.24785
300	25.88	112.213	.25220
320	26.57	115.891	.25648
340	27.26	119.610	.26070
360	27.95	123.369	.26488
380	28.64	127.162	.26897
400	29.33	130.991	.27304
420	30.02	134.853	.27704
440	30.71	138.745	.28099
460	31.40	142.670	.28488
480	32.09	146.620	.28871
500	32.78	150.596	.29250

TABLE IV (Cont'd)

15. Volume 2.5 cu.ft./lb.

T°F.	P	H	S
-100	14.23	49.339	.14861
- 80	15.11	51.977	.15455
- 60	15.97	54.644	.16031
- 40	16.83	57.360	.16594
- 20	17.68	60.122	.17144
0	18.52	62.940	.17685
20	19.36	65.820	.18216
40	20.20	68.760	.18726
60	21.04	71.764	.19250
80	21.87	74.831	.19755
100	22.71	77.957	.20253
120	23.55	81.142	.20745
140	24.38	84.380	.21229
160	25.21	87.674	.21705
180	26.05	91.027	.22176
200	26.87	94.422	.22641
220	27.70	97.873	.23100
240	28.53	101.373	.23550
260	29.37	104.927	.23997
280	30.20	108.521	.24435
300	31.03	112.159	.24871
320	31.86	115.838	.25298
340	32.69	119.558	.25720
360	33.52	123.318	.26139
380	34.35	127.113	.26548
400	35.17	130.939	.26955
420	36.00	134.802	.27355
440	36.83	138.695	.27749
460	37.66	142.621	.28138
480	38.49	146.572	.28522
500	39.32	150.550	.28901

TABLE IV (Cont'd)

16. Volume 2.0 cu.ft./lb.

T°F.	P	H	S
-100	17.62	49.093	.14403
- 80	18.73	51.758	.15005
- 60	19.82	54.451	.15585
- 40	20.90	57.184	.16152
- 20	21.97	59.962	.16705
0	23.04	62.796	.17247
20	24.10	65.688	.17781
40	25.15	68.638	.18302
60	26.20	71.647	.18817
80	27.25	74.718	.19323
100	28.30	77.847	.19821
120	29.35	81.035	.20314
140	30.39	84.276	.20798
160	31.44	87.578	.21274
180	32.48	90.928	.21746
200	33.52	94.331	.22211
220	34.56	97.784	.22670
240	35.61	101.290	.23121
260	36.65	104.841	.23567
280	37.69	108.436	.24006
300	38.73	112.076	.24441
320	39.77	115.757	.24869
340	40.82	119.479	.25291
360	41.85	123.240	.25710
380	42.89	127.037	.26119
400	43.93	130.869	.26526
420	44.97	134.733	.26926
440	46.01	138.628	.27320
460	47.05	142.555	.27709
480	48.09	146.507	.28093
500	49.13	150.484	.28472

TABLE IV (Cont'd)

17. Volume 1.5 cu.ft./lb.

T°F.	P	H	S
-80	24.62	51.401	.14404
-60	26.11	54.135	.15003
-40	27.57	56.900	.15576
-20	29.02	59.704	.16134
0	30.46	62.557	.16680
20	31.88	65.464	.17216
40	33.30	68.429	.17739
60	34.71	71.451	.18256
80	36.12	74.531	.18763
100	37.54	77.668	.19262
120	38.94	80.865	.19755
140	40.34	84.113	.20240
160	41.74	87.418	.20718
180	43.14	90.775	.21189
200	44.54	94.183	.21655
220	45.93	97.640	.22114
240	47.33	101.149	.22565
260	48.72	104.702	.23012
280	50.12	108.302	.23451
300	51.51	111.944	.23887
320	52.90	115.627	.24314
340	54.29	119.351	.24737
360	55.69	123.117	.25155
380	57.08	126.914	.25564
400	58.47	130.748	.25972
420	59.86	134.614	.26372
440	61.25	138.510	.26766
460	62.65	142.442	.27155
480	64.04	146.396	.27539
500	65.43	150.377	.27918

TABLE IV (Cont'd)

18. Volume 1.2 cu.ft./lb.

T°F.	P	H	S
-80	30.37	51.046	.13946
-60	32.26	53.820	.14543
-40	34.12	56.617	.15122
-20	35.95	59.444	.15684
0	37.77	62.318	.16234
20	39.56	65.241	.16772
40	41.36	68.223	.17298
60	43.13	71.254	.17816
80	44.91	74.345	.18325
100	46.69	77.493	.18825
120	48.45	80.692	.19319
140	50.22	83.950	.19805
160	51.97	87.258	.20283
180	53.73	90.621	.20755
200	55.48	94.031	.21221
220	57.24	97.495	.21681
240	58.99	101.005	.22132
260	60.74	104.563	.22579
280	62.50	108.166	.23018
300	64.24	111.811	.23454
320	66.00	115.500	.23881
340	67.74	119.224	.24304
360	69.49	122.992	.24722
380	71.24	126.793	.25132
400	72.98	130.628	.25539
420	74.73	134.497	.25940
440	76.48	138.396	.26334
460	78.23	142.329	.26723
480	79.97	146.283	.27106
500	81.71	150.264	.27486

TABLE IV (Cont'd)

19. Volume 1.0 cu.ft./lb.

T°F.	P	H	S
-80	35.93	50.689	.13555
-60	38.24	53.501	.14161
-40	40.51	56.331	.14746
-20	42.73	59.183	.15313
0	44.94	62.077	.15866
20	47.12	65.020	.16407
40	49.29	68.012	.16935
60	51.45	71.059	.17455
80	53.59	74.158	.17965
100	55.73	77.312	.18466
120	57.86	80.519	.18961
140	59.99	83.782	.19447
160	62.11	87.098	.19926
180	64.23	90.465	.20399
200	66.35	93.882	.20865
220	68.46	97.347	.21325
240	70.58	100.862	.21776
260	72.69	104.424	.22224
280	74.80	108.029	.22663
300	76.91	111.677	.23099
320	79.01	115.367	.23527
340	81.12	119.096	.23949
360	83.23	122.865	.24368
380	85.33	126.668	.24778
400	87.44	130.507	.25185
420	89.54	134.377	.25585
440	91.65	138.279	.25980
460	93.75	142.211	.26369
480	95.85	146.169	.26752
500	97.96	150.153	.27132

TABLE IV (Cont'd)

20. Volume 0.8 cu.ft./lb.

T°F.	P	H	S
-60	46.93	53.028	.13684
-40	49.83	55.905	.14278
-20	52.67	58.795	.14852
0	55.47	61.719	.15410
20	58.24	64.690	.15955
40	60.98	67.700	.16486
60	63.71	70.763	.17009
80	66.43	73.880	.17511
100	69.13	77.046	.18024
120	71.82	80.266	.18520
140	74.50	83.537	.19007
160	77.17	86.860	.19487
180	79.84	90.234	.19960
200	82.51	96.659	.20417
220	85.17	97.131	.20887
240	87.83	100.665	.21339
260	90.48	104.216	.21787
280	93.14	107.826	.22226
300	95.79	111.479	.22663
320	98.44	115.172	.23091
340	101.09	118.906	.23514
360	103.74	122.679	.23932
380	106.39	126.485	.24342
400	109.03	130.326	.24749
420	111.69	134.202	.25150
440	114.33	138.105	.25544
460	116.97	142.041	.25934
480	119.62	146.002	.26317
500	122.27	149.989	.26697

TABLE IV (Cont'd)

21. Volume 0.6 cu.ft./lb.

T°F.	P	H	S
-40	64.65	55.198	.13657
-20	68.57	58.154	.14242
0	72.40	61.128	.14809
20	76.18	64.136	.15362
40	79.92	67.186	.15898
60	83.63	70.277	.16424
80	87.30	73.416	.16940
100	90.95	76.602	.17445
120	94.61	79.842	.17944
140	98.23	83.129	.18432
160	101.8	86.467	.18913
180	105.5	89.853	.19388
200	109.1	93.288	.19856
220	112.6	96.771	.20317
240	116.2	100.299	.20770
260	119.8	103.874	.21218
280	123.4	107.490	.21658
300	127.0	111.152	.22094
320	130.5	114.852	.22523
340	134.1	118.592	.22946
360	137.7	122.371	.23365
380	141.2	126.183	.23775
400	144.8	130.030	.24183
420	148.4	133.910	.24583
440	151.9	137.818	.24978
460	155.5	141.760	.25367
480	159.1	145.726	.25751
500	162.6	149.716	.26130

TABLE IV (Cont'd)

22. Volume 0.5 cu.ft./lb.

T°F.	P	H	S
-40	75.87	54.635	.13252
-20	80.68	57.640	.13847
0	85.38	60.654	.14420
20	90.00	63.696	.14978
40	94.57	66.773	.15519
60	99.08	69.887	.16048
80	103.6	73.047	.16566
100	108.0	76.250	.17074
120	112.4	79.502	.17574
140	116.8	82.803	.18064
160	121.2	86.151	.18546
180	125.6	89.548	.19022
200	129.9	92.991	.19491
220	134.3	96.482	.19952
240	138.6	100.018	.20405
260	143.0	103.601	.20854
280	147.3	107.224	.21295
300	151.6	110.889	.21731
320	155.9	114.595	.22160
340	160.3	118.341	.22584
360	164.6	122.124	.23003
380	168.9	125.940	.23413
400	173.2	129.791	.23821
420	177.5	133.676	.24222
440	181.8	137.590	.24616
460	186.1	141.534	.25006
480	190.4	145.503	.25389
500	194.7	149.499	.25769

TABLE IV (Cont'd)

23. Volume 0.4 cu.ft./lb.

T°F.	P	H	S
-20	97.90	56.871	.13359
0	103.9	59.945	.13933
20	109.9	63.038	.14499
40	115.7	66.156	.15045
60	121.5	69.306	.15580
80	127.2	72.493	.16102
100	132.9	75.715	.16613
120	138.5	78.996	.17115
140	144.1	82.314	.17608
160	149.6	85.673	.18092
180	155.2	89.092	.18568
200	160.7	92.549	.19038
220	166.2	96.051	.19501
240	171.7	99.598	.19955
260	177.2	103.190	.20404
280	182.7	106.822	.20845
300	188.2	110.499	.21283
320	193.7	114.216	.21712
340	199.1	117.962	.22135
360	204.6	121.757	.22555
380	210.0	125.576	.22965
400	215.5	129.439	.23374
420	221.0	133.333	.23775
440	226.4	137.248	.24170
460	231.8	141.196	.24559
480	237.3	145.175	.24943
500	242.7	149.173	.25323

TABLE IV (Cont'd)

24. Volume 0.3 cu.ft./lb.

T°F.	P	H	S
-20	124.0	55.594	.12678
0	132.5	58.770	.13279
20	140.8	61.948	.13858
40	148.9	65.133	.14416
60	156.9	68.341	.14959
80	164.8	71.580	.15487
100	172.5	74.846	.16003
120	180.2	78.166	.16510
140	187.9	81.508	.17006
160	195.5	84.900	.17492
180	203.1	88.338	.17971
200	210.6	91.815	.18443
220	218.1	95.336	.18907
240	225.6	98.902	.19363
260	233.1	102.511	.19813
280	240.5	106.156	.20255
300	248.0	109.847	.20693
320	255.5	113.579	.21123
340	262.9	117.341	.21547
360	270.3	121.143	.21967
380	277.8	124.984	.22378
400	285.1	128.847	.22787
420	292.6	132.753	.23188
440	300.0	136.682	.23583
460	307.3	140.638	.23973
480	314.8	144.629	.24357
500	322.2	148.639	.24737

TABLE IV (Cont'd)

25. Volume 0.25 cu.ft./lb.

T°F.	P	H	S
0	153.2	57.840	.12848
20	163.5	61.084	.13438
40	173.6	64.328	.14004
60	183.3	67.575	.14553
80	193.0	70.855	.15087
100	202.6	74.156	.15607
120	212.0	77.491	.16117
140	221.5	80.872	.16615
160	230.7	84.283	.17105
180	240.0	87.740	.17587
200	249.2	91.236	.18059
220	258.4	94.774	.18524
240	267.6	98.357	.18981
260	276.7	101.977	.19432
280	285.8	105.638	.19875
300	294.9	109.339	.20313
320	304.0	113.079	.20744
340	313.0	116.850	.21169
360	322.1	120.666	.21589
380	331.1	124.510	.22000
400	340.1	128.386	.22409
420	349.2	132.299	.22811
440	358.1	136.232	.23206
460	367.2	140.205	.23597
480	376.2	144.198	.23981
500	385.2	148.215	.24361

TABLE IV (Cont'd)

26. Volume 0.20 cu.ft./lb.

T°F.	P	H	S
20	194.5	59.804	.12904
40	207.6	63.126	.13482
60	220.3	66.443	.14041
80	232.9	69.777	.14583
100	245.2	73.118	.15109
120	257.3	76.504	.15624
140	269.5	79.922	.16126
160	281.4	83.366	.16618
180	293.4	86.854	.17102
200	305.2	90.376	.17578
220	317.0	93.939	.18045
240	328.7	97.540	.18503
260	340.4	101.181	.18956
280	352.1	104.862	.19400
300	363.7	108.578	.19840
320	375.4	112.337	.20271
340	386.9	116.124	.20696
360	398.4	119.950	.21117
380	410.1	123.814	.21529
400	421.6	127.703	.21938
420	433.1	131.624	.22340
440	444.6	135.574	.22736
460	456.2	139.558	.23127
480	467.7	143.562	.23511
500	479.1	147.587	.23891

TABLE IV (Cont'd)

27. Volume 0.15 cu.ft./lb.

T°F.	P	H	S
20	237.8	57.709	.12175
40	256.4	61.153	.12773
60	274.4	64.580	.13349
80	292.1	68.007	.13902
100	309.5	71.441	.14439
120	326.6	74.891	.14962
140	343.5	78.365	.15471
160	360.3	81.868	.15969
180	376.8	85.399	.16457
200	393.3	88.966	.16936
220	409.7	92.568	.17407
240	426.0	96.206	.17868
260	442.2	99.880	.18323
280	458.4	103.590	.18768
300	474.4	107.335	.19209
320	490.5	111.117	.19642
340	506.6	114.933	.20069
360	522.6	118.786	.20491
380	538.6	122.668	.20903
400	554.6	126.583	.21313
420	570.6	130.528	.21716
440	586.4	134.495	.22112
460	602.4	138.499	.22503
480	618.3	142.522	.22888
500	634.1	146.567	.23269

TABLE IV (Cont'd)

28. Volume 0.12 cu.ft./lb.

T°F.	P	H	S
40	295.9	59.218	.12189
60	319.8	62.756	.12780
80	343.1	66.273	.13346
100	365.9	69.784	.13892
120	388.3	73.303	.14424
140	410.4	76.836	.14939
160	432.2	80.390	.15442
180	453.8	83.969	.15935
200	475.3	87.579	.16418
220	496.6	91.219	.16891
240	517.7	94.891	.17354
260	538.8	98.598	.17811
280	559.8	102.338	.18259
300	580.7	106.114	.18702
320	601.5	109.921	.19135
340	622.3	113.761	.19563
360	643.1	117.639	.19986
380	663.8	121.544	.20400
400	684.5	125.481	.20811
420	705.1	129.444	.21214
440	725.7	133.436	.21611
460	746.3	137.456	.22002
480	766.9	141.501	.22387
500	787.4	145.566	.22768

TABLE IV(Cont'd)

29. Volume 0.10 cu.ft./lb.

T°F.	P	H	S
60	357.2	60.976	.12292
80	386.4	64.579	.12870
100	415.1	68.167	.13425
120	443.1	71.740	.13965
140	470.8	75.342	.14486
160	498.0	78.946	.14994
180	525.0	82.572	.15491
200	551.7	86.220	.15977
220	578.3	89.899	.16454
240	604.7	93.607	.16919
260	630.9	97.346	.17379
280	657.3	101.121	.17828
300	683.0	104.919	.18272
320	708.9	108.753	.18707
340	734.6	112.615	.19136
360	760.4	116.517	.19560
380	786.2	120.446	.19974
400	811.9	124.405	.20386
420	837.4	128.388	.20789
440	863.0	132.400	.21187
460	888.6	136.432	.21579
480	914.1	140.504	.21964
500	939.7	144.591	.22346

TABLE IV (Cont'd)

30. Volume .08 cu.ft./lb.

T°F.	P	H	S
60	399.6	58.395	.11659
80	438.5	62.122	.12254
100	476.5	65.815	.12823
120	513.7	69.492	.13373
140	550.3	73.165	.13904
160	586.4	76.845	.14419
180	622.0	80.536	.14922
200	657.3	84.245	.15413
220	692.2	87.976	.15894
240	727.0	91.734	.16363
260	761.5	95.519	.16825
280	795.9	99.333	.17276
300	830.1	103.169	.17723
320	864.2	107.051	.18160
340	898.2	110.952	.18590
360	932.0	114.888	.19015
380	965.9	118.850	.19430
400	999.6	122.841	.19843
420	1033.3	126.859	.20248
440	1066.9	130.902	.20646
460	1100.5	134.972	.21038
480	1134.1	139.066	.21425
500	1167.6	143.180	.21806

TABLE IV (Cont'd)

31. Volume 0.06 cu.ft./lb.

T°F.	P	H	S
80	496.1	58.262	.11401
100	551.2	62.114	.11990
120	605.0	65.928	.12556
140	658.0	69.725	.13100
160	710.1	73.512	.13625
180	761.7	77.304	.14139
200	812.7	81.105	.14635
220	863.2	84.920	.15122
240	913.5	88.757	.15596
260	963.4	92.616	.16062
280	1013.0	96.498	.16517
300	1062.5	100.408	.16967
320	1111.7	104.343	.17406
340	1160.8	108.304	.17839
360	1209.8	112.299	.18266
380	1258.6	116.316	.18683
400	1307.4	120.362	.19097
420	1356.1	124.432	.19503
440	1404.6	128.525	.19902
460	1453.1	132.646	.20296
480	1501.6	136.788	.20683
500	1549.9	140.950	.21056

TABLE IV (Cont'd)

32. Volume .05 cu.ft./lb.

T°F.	P	H	S
80	521.9	55.401	.10822
100	591.5	59.356	.11424
120	659.8	63.265	.12001
140	726.9	67.145	.12553
160	793.1	71.009	.13085
180	858.6	74.872	.13603
200	923.5	78.736	.14106
220	987.9	82.613	.14597
240	1051.9	86.506	.15074
260	1115.5	90.419	.15543
280	1178.8	94.354	.16001
300	1241.9	98.313	.16452
320	1304.7	102.297	.16894
340	1367.3	106.303	.17328
360	1429.8	110.344	.17756
380	1492.2	114.404	.18174
400	1554.4	118.492	.18589
420	1616.5	122.604	.18996
440	1678.6	126.739	.19396
460	1740.5	130.901	.19790
480	1802.4	135.082	.20178
500	1864.2	139.284	.20561

TABLE IV (Cont'd)

33. Volume 0.04 cu.ft./lb.

T°F.	P	H	S
100	630.9	55.547	.10691
120	721.6	59.591	.11279
140	811.4	63.569	.11840
160	900.4	67.526	.12380
180	988.8	71.475	.12904
200	1076.5	75.422	.13412
220	1163.7	79.378	.13907
240	1250.5	83.346	.14388
260	1337.1	87.333	.14864
280	1423.3	91.340	.15321
300	1509.3	95.368	.15774
320	1595.1	99.420	.16217
340	1680.8	103.493	.16653
360	1766.2	107.599	.17083
380	1851.5	111.724	.17502
400	1936.8	115.877	.17918
420	2021.7	120.050	.18326
440	2107.0	124.250	.18727
460	2191.8	128.472	.19121
480	2276.7	132.714	.19510
500	2361.5	136.978	.19893

TABLE IV (Cont'd)

34. Volume 0.03 cu.ft./lb.

T°F.	P	H	S
100	667.6	50.168	.09682
120	798.4	54.272	.10276
140	929.3	58.339	.10842
160	1060.5	62.392	.11386
180	1191.9	66.436	.11913
200	1323.4	70.482	.12424
220	1455.0	74.539	.12922
240	1586.8	78.610	.13405
260	1718.6	82.700	.13879
280	1850.6	86.809	.14340
300	1982.6	90.943	.14795
320	2114.6	95.101	.15239
340	2246.7	99.280	.15676
360	2378.7	103.492	.16106
380	2510.9	107.725	.16526
400	2643.0	111.984	.16943
420	2775.4	116.268	.17351
440	2907.5	120.573	.17752
460	3039.8	124.906	.18147
480	3172.0	129.257	.18536
500	3304.3	133.629	.18920

TABLE V

VALUES OF TEMPERATURE AND PRESSURE AT CONSTANT ENTROPY OF FREON 13 VAPORS

(Entropy in BTU/lb., °R.)

S = 0.10

T°F.	P
100	653.5
80.8	542.0

S = 0.11

T°F.	P
140	910.5
120	746.0
100	616.0
80	514.5

S = 0.12

T°F.	P
160	962.5
140	793.0
120	660.5
100	550.0
80	458.0
60	378.0
40	308.5

S = 0.13

T°F.	P
180	972.0
160	806.0
140	670.5
120	556.5
100	459.5
80	376.0
60	304.0
40	239.5
20	187.5
0	146.0
-20	110.5
-40	83.45

S = 0.14

T°F.	P
200	947.0
180	786.5
160	651.5
140	536.5
120	438.5
100	355.5
80	283.0
60	223.0
40	174.5
20	134.5
0	101.4
-20	75.85
-40	56.20
-60	41.00
-80	29.65
-100	21.25

S = 0.15

T°F.	P
240	1072.0
220	892.0
200	738.0
180	608.0
160	496.5
140	402.0
120	322.0
100	254.5
80	199.5
60	154.5
40	117.0
20	89.25
0	66.70
-20	49.35
-40	36.05
-60	26.25
-80	18.90
-100	13.30
-120	9.35

TABLE V (Cont'd)

S = 0.16	
T°F.	P
260	981.0
240	814.0
220	669.5
200	546.5
180	443.5
160	356.0
140	283.0
120	222.5
100	173.0
80	133.5
60	101.3
40	76.35
20	57.10
0	42.25
-20	31.10
-40	22.70
-60	16.25
-80	11.55
-100	8.200
-120	5.740
-140	3.990
-160	2.725

S = 0.17	
T°F.	P
300	1051
280	869.0
260	718.5
240	587.5
220	477.5
200	384.5
180	305.5
160	241.5
140	188.5
120	146.0
100	112.0
80	84.95
60	63.95
40	47.85
20	35.55
0	26.20
-20	19.15
-40	13.80
-60	9.775
-80	7.030
-100	4.985
-120	3.480
-140	2.410
-160	1.655
-180	1.115

TABLE V (Cont'd)

S = 0.18		S = 0.19	
T°F.	P	T°F.	P
320	912.5	360	936.0
300	754.0	340	774.5
280	616.5	320	634.5
260	501.5	300	516.0
240	403.5	280	417.5
220	321.5	260	333.0
200	256.0	240	266.0
180	200.5	220	209.5
160	156.0	200	163.0
140	121.0	180	127.5
120	92.25	160	97.65
100	70.0	140	74.65
80	52.70	120	56.70
60	39.40	100	42.70
40	29.30	80	32.05
20	21.70	60	23.95
0	15.80	40	17.65
-20	11.20	20	13.10
-40	8.280	0	9.470
-60	5.960	-20	6.890
-80	4.210	-40	4.970
-100	2.980	-60	3.545
-120	2.075	-80	2.525
-140	1.445	-100	1.775
-160	0.985	-120	1.235
-180	0.670	-140	0.855

TABLE V (Cont'd)

S = 0.20		S = 0.21	
T°F.	P	T°F.	P
400	943.0	440	928.5
380	778.5	420	769.0
360	639.5	400	633.0
340	520.5	380	518.0
320	422.0	360	418.5
300	338.5	340	337.0
280	269.5	320	271.0
260	213.5	300	215.5
240	167.5	280	169.5
220	131.5	260	133.0
200	101.2	240	104.2
180	78.1	220	80.55
160	59.9	200	62.10
140	45.35	180	47.45
120	34.30	160	36.05
100	25.90	140	27.50
80	19.30	120	20.60
60	14.40	100	15.40
40	10.45	80	11.45
20	7.765	60	8.550
0	5.655	40	6.295
-20	4.100	20	4.615
-40	2.945	0	3.380
-60	2.110	-20	2.430
-80	1.500	-40	1.760
-100	1.060	-60	1.250
-120	0.730	-80	0.890

TABLE V (Cont'd)

S = 0.22		S = 0.23	
T°F.	P	T°F.	P
480	902.0	500	713.5
460	746.0	480	586.5
440	615.0	460	482.5
420	502.0	440	394.0
400	408.0	420	319.5
380	331.5	400	258.0
360	266.0	380	207.0
340	213.5	360	165.0
320	168.0	340	130.5
300	133.0	320	103.55
280	104.4	300	80.60
260	81.4	280	63.15
240	63.1	260	49.00
220	48.65	240	38.05
200	37.55	220	29.20
180	28.50	200	22.30
160	21.65	180	17.00
140	16.30	160	12.90
120	12.35	140	9.73
100	9.205	120	7.330
80	6.850	100	5.465
60	5.090	80	4.065
40	3.745	60	3.040
20	2.720	40	2.220
0	2.005	20	1.620
-20	1.440	0	1.180
-40	1.040	-20	0.86
-60	0.750		

TABLE V (Cont'd)

S = 0.24		S = 0.25	
T°F.	P	T°F.	P
500	455.5	500	284.0
480	373.0	480	231.5
460	304.0	460	188.0
440	241.5	440	150.5
420	198.5	420	120.5
400	158.0	400	96.0
380	125.5	380	76.25
360	100.3	360	60.30
340	79.1	340	47.55
320	62.2	320	37.20
300	48.65	300	29.05
280	37.80	280	22.60
260	29.30	260	17.35
240	22.70	240	13.40
220	17.40	220	10.30
200	13.30	200	7.880
180	10.05	180	6.010
160	7.64	160	4.540
140	5.80	140	3.425
120	4.355	120	2.555
100	3.230	100	1.920
80	2.405	80	1.430
60	1.785	60	1.060
40	1.315	40	0.760
20	0.970		

TABLE V (Cont'd)

S = 0.26		S = 0.27	
T°F.	P	T°F.	P
500	173.5	500	104.65
480	140.5	480	84.40
460	113.0	460	68.05
440	90.80	440	54.40
420	72.50	420	43.45
400	57.50	400	34.30
380	45.60	380	27.15
360	36.10	360	21.40
340	28.30	340	16.80
320	22.10	320	13.20
300	17.25	300	10.20
280	13.55	280	7.905
260	10.40	260	6.130
240	7.945	240	4.730
220	6.110	220	3.635
200	4.680	200	2.775
180	3.570	180	2.105
160	2.680	160	1.580
140	2.025	140	1.204
120	1.520	120	0.885
100	1.135		
80	0.830		

TABLE V (Cont'd)

S = 0.28		S = 0.29	
T°F.	P	T°F.	P
500	62.80	500	37.50
480	50.60	480	30.15
460	40.60	460	24.10
440	32.25	440	19.15
420	25.95	420	15.30
400	20.45	400	12.10
380	16.20	380	9.565
360	12.70	360	7.540
340	9.940	340	5.900
320	7.780	320	4.630
300	6.080	300	3.590
280	4.685	280	2.780
260	3.630	260	2.130
240	2.780	240	1.655
220	2.150	220	1.270
200	1.640	200	0.970
180	1.235		
160	0.940		

TABLE V (Cont'd)

S = 0.30		S = 0.31	
T°F.	P	T°F.	P
500	22.20	500	13.25
480	17.85	480	10.65
460	14.30	460	8.015
440	11.35	440	6.750
420	9.030	420	5.370
400	7.165	400	4.230
380	5.665	380	3.345
360	4.455	360	2.645
340	3.485	340	2.070
320	2.720	320	1.610
300	2.125	300	1.250
280	1.630	280	0.930
260	1.275		
240	0.965		

TABLE V (Cont'd)

S = 0.32

T°F.	P
500	7.790
480	6.250
460	5.005
440	3.990
420	3.160
400	2.520
380	1.965
360	1.560
340	1.210
320	0.910

S = 0.34

T°F.	P
500	2.720
480	2.180
460	1.745
440	1.375
420	1.025
400	0.745

S = 0.33

T°F.	P
500	4.580
480	3.685
460	2.955
440	2.360
420	1.865
400	1.480
380	1.130
360	0.835

S = 0.35

T°F.	P
500	1.595
480	1.215
460	0.890

APPENDIX B

VAPOR PRESSURE

SAMPLE DATA SHEET

VAPOR PRESSURE

Run No. 3 of Vapor Pressure at -198°F. Fresh Freon 13 added to isoteniscope

Time	Manometer (4) Right Leg	Left Leg	Diff. in mm.	Platinum Resistance Thermometer No. 169313 in ohms NZ	RZ	Aver.	T°C.
			First Boil Off				
2:50	455.13	430.21	24.92	1.2132	1.2120	1.2126	
3:00	455.11	430.21	24.90	1.2130	1.2120	1.2125	
3:05	455.13	430.21	24.93	1.2130	1.2121	1.2126	
		Average	24.92			1.2126	-127.88
			Second Boil Off				
3:15	455.09	430.23	24.86	1.2128	1.2120	1.2124	
3:25	455.08	430.24	24.84	1.2127	1.2119	1.2123	
3:35	455.08	430.27	24.81	1.2128	1.2117	1.2122	
		Average	24.84			1.2123	-127.91
			Third Boil Off				
3:45	455.08	430.27	24.81	1.2128	1.2117	1.2122	
3:50	455.08	430.28	24.80	1.2128	1.2117	1.2122	
3:55	455.08	430.27	24.81	1.2128	1.2117	1.2122	
		Average	24.81			1.2122	-127.92
			Fourth Boil Off				
4:10	455.09	430.28	24.81	1.2128	1.2117	1.2122	
4:15	455.08	430.26	24.82	1.2128	1.2117	1.2122	
4:20	455.08	430.27	24.81	1.2128	1.2117	1.2122	
		Average	24.81			1.2122	-127.92

Fifth Boil Off - Liquid Gone

Temperature of Cathetometer 77°F. (25°C.)

Temperature of Manometer (4) 77°F. (25°C.)

McLeod Gauge (6) read less than 5 microns throughout all readings.

CALCULATION OF DATA

Boil Off Number	T°C.	t°F.	Uncorrected pressure mm. Hg at 25°C.	Corrected pressure mm. Hg at 0°C.	psia
1	-127.88	-198.18	24.92	24.82	0.4800
2	-127.91	-198.24	24.84	24.74	0.4784
3	-127.92	-198.26	24.81	24.71	0.4779
4	-127.92	-198.26	24.81	24.71	0.4779

COMMENTS

Resistance of platinum resistance thermometer No. 169313 converted to t°C by Equation 44, Appendix F.

Table I, page 783 of Perry (9) used to correct mm. Hg. at 25°C. to mm. Hg. at 0°C.

psia = mm. Hg. at 0°C/51.71

SAMPLE SUMMARY OF VAPOR PRESSURE DATA AT APPROXIMATE TEMPERATURE

Temperature -198°F.

Run	Boil Off	T°F.	PSIA
1	1	-198.08	0.4825
	2	-198.12	0.4817
	3	-198.10	0.4822
2	1	-198.23	0.4785
	2	-198.21	0.4794
	3	-198.18	0.4802
	4	-198.22	0.4783
3	1	-198.18	0.4800
	2	-198.24	0.4784
	3	-198.26	0.4779
	4	-198.26	0.4779
	Average	-198.19°F.	0.4797 psia

TABLE VI

EXPERIMENTAL VAPOR PRESSURE DATA
COMPARED TO VAPOR PRESSURE EQUATIONS

Point	Experimental Data t	T	Exp. psia	Intermediate Equation Calc. psia	% Dev. (calc.-exp./calc) × 100	Equation 9 Calc. psia	% Dev. (calc.-exp./calc.) × 100
1	80.37	540.06	537.9	537.9	0.00	537.2	-0.125
2	32.00	491.69	285.9	286.7	+0.26	286.3	+0.14
3	-15.22	444.47	137.44	137.44	0.00	137.33	-0.08
4	-72.19	387.50	44.38	44.42	+0.10	44.415	+0.08
5	-114.77	344.92	14.623	14.623	0.00	14.623	0.00
6	-148.85	310.84	4.674	4.672	-0.03	4.673	-0.02
7	-198.19	261.50	0.4797	0.4797	0.00	0.4797	0.00

Equation 9

$$\log_{10} p = 36.76130 - 2623.988/T - 11.80586 \log_{10} T + 5.71495 \times 10^{-3} T$$

Intermediate Equation

$$\log_{10} p = 36.590640 - \frac{2618.4337}{T} - 11.740525 \log_{10} T + 5.682365 \times 10^{-3} T$$



CALCULATION OF VAPOR PRESSURE EQUATIONS

Equation 9 Calculations:

The experimental vapor pressure data of Table VI was fitted by the equation of the following form

$$\log_{10} p = a + \frac{b}{T} + c \log_{10} T + dT$$

Points 1, 3, 5, and 7 were used to set up the following equations

$$\log_{10} 537.9 = a + \frac{b}{540.06} + c \log_{10} 540.06 + 540.06\, d$$

$$\log_{10} 137.44 = a + \frac{b}{444.47} + c \log_{10} 444.47 + 444.47\, d$$

$$\log_{10} 14.623 = a + \frac{b}{344.92} + c \log_{10} 344.92 + 344.92\, d$$

$$\log_{10} 0.4797 = a + \frac{b}{261.50} + c \log_{10} 261.50 + 261.50\, d$$

These four equations were solved simultaneously to determine the constants of the following equation:

$$\log_{10} p = 36.590640 - \frac{2618.4337}{T} - 11.740525 \log_{10} T + 5.682365 \times 10^{-3} T$$

(Intermediate Equation)

This intermediate equation was compared to the vapor pressure data in Table VI.

Points 1 and 3 were adjusted to 537.2 and 137.33 psia respectively. Adjusted points 1 and 3 and data points 5 and 7 were used to re-determine the constants for the equation. The resulting equation was as follows:

$$\log_{10} p = 36.76130 - 2623.988/T - 11.80586 \log_{10} T + 5.71495 \times 10^{-3} T$$

(Equation 9)

Equation 9 was compared to the vapor pressure data shown in Table VI. The plot of the percent deviations of the vapor pressure values versus temperature is shown in Figure 22.

Equation 10 calculations:

Experimental points 1, 2, 3, and 4 of Table VI were used to determine the constants for the equation. The resulting equation was as follows:

$$\log_{10} p = 56.34405 - 3351.281/T - 19.16910 \log_{10} T + 9.20366 \times 10^{-}$$

(Equation 10)

Equation 10 predicted points 1, 2, 3, and 4 with zero deviation from the experimental data. To calculate the deviations between these points, the following technique was used:

Approximate midpoint between points 1 and 2, 55.31°F.
Approximate midpoint between points 2 and 3, 8.31°F.
Approximate midpoint between points 3 and 4, -44.69°F.

Equation 9 was solved at these temperatures. The percent deviation of calculated results from predicted experimental results was read from Figure 22. The calculated results were corrected to predicted experimental results. These steps are shown below:

T°F.	Calc.Press. Equation 9	% Deviation	"Corrected" psia
55.13	392.80	+0.04	392.65
8.31	201.63	+0.04	201.55
-44.69	79.77	+0.00	79.77

The comparisons between Equation 10 and the "corrected" pressures

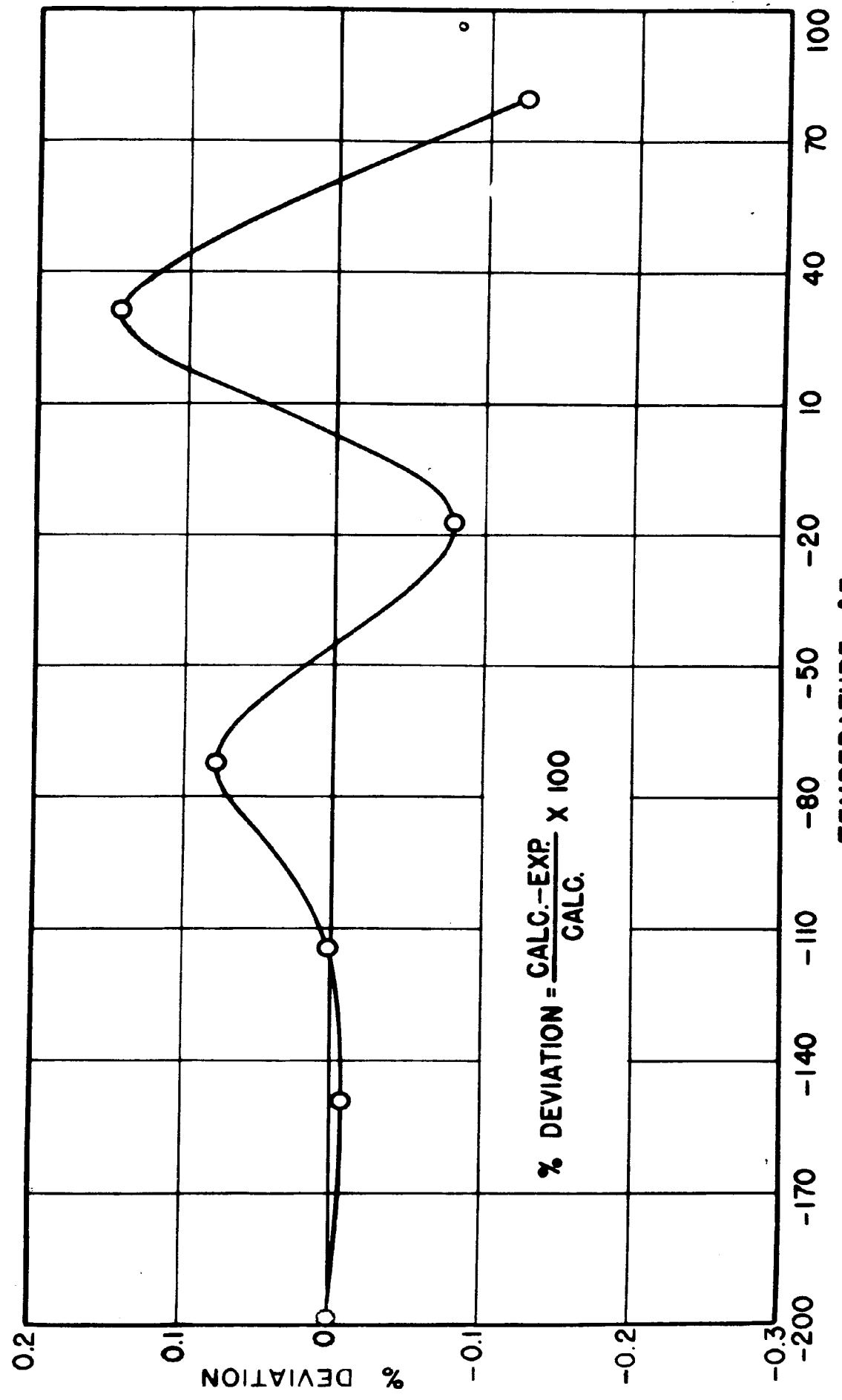


FIGURE 22 DEVIATION CURVE OF VAPOR PRESSURE EQUATION, EQUATION 9

are shown below:

T°F.	Calc.Press. Equation 10	Corrected psia	$\frac{\text{Calc.}-\text{Corr.}}{\text{Calc.}} 100$ % Dev.
55.13	392.38	392.65	-0.07
8.31	201.51	201.55	-0.04
-44.69	77.91	79.77	+0.17

There is zero deviation of Equation 10 and experimental points at 80.37, 32.00, -15.22, and -72.19°F.

Therefore maximum deviation of Equation is 0.07% from -15 to 80°F.

APPENDIX C

P-V-T RELATIONSHIP OF VAPORS

Sample Data Sheet: Isometric Data

Isometric density 8.27 lbs./cu.ft.

Material Balance

A. Freon 13 loaded to vapor density bulb.

Supply Cylinder	Recovery Cylinder
522.902 g before loading	710.639 g after loading
436.520 g after loading	706.508 g before loading
86.382 g net	4.131 g net

86.382 - 4.131 = 82.251 g F-13 loaded

B. Freon 13 recovered from vapor density bulb

Supply Cylinder	Recovery Cylinder
515.390 g after recovery	709.872 g after recovery
436.506 g before recovery	706.508 g before recovery
78.884 g net	3.364 g net

78.884 + 3.364 = 82.248 g F-13 recovered

Calibration of 0-600 psi Ashcroft Durogauge

Dead Weight Gauge	Before Run Pressure Gauge Reading	After Run Pressure Gauge Reading	Average Pressure Gauge Reading	Gauge Calibration
250	254.00	254.00	254.00	-4.00
275	279.25	279.25	279.25	-4.25
300	304.25	304.25	304.25	-4.25
325	329.50	329.25	329.25	-4.25
350	354.25	354.25	354.25	-4.25
375	379.25	379.25	379.25	-4.25
400	404.25	404.00	404.25	-4.25
425	429.25	429.25	429.25	-4.25
450	454.50	454.00	454.25	-4.25

Time	Pressure Gauge Reading	Platinum resistance thermometer No. 169313 in ohms NZ	RZ	Aver.	T°C.	Barometer in mm Hg at 21°C.
		First Temperature				
5:50	273.5	2.4996	2.4976	2.4986		
5:55	273.5	2.4995	2.4975	2.4985		
6:00	273.5	2.4996	2.4976	2.4986		739.5
Aver.	273.5			2.4986	+0.15	
		Second Temperature				
7:45	305.5	2.6437	2.6416	2.6427		
7:50	305.75	2.6443	2.6423	2.6433		
7:55	305.75	2.6445	2.6425	2.6435		
Aver.	305.75			2.6432	14.89	
		Third Temperature				
9:45	334.5	2.7819	2.7800	2.7810		740.0
9:50	334.5	2.7817	2.7798	2.7808		
9:55	334.5	2.7815	2.7796	2.7806		
Aver.	334.5			2.7808	28.98	
		Fourth Temperature				
10:35	369.75	2.9501	2.9481	2.9491		
10:40	369.75	2.9497	2.9479	2.9487		
10:45	369.75	2.9497	2.9479	2.9487		
Aver.	369.75			2.9488	46.29	
		Fifth Temperature				
11:45	404.0	3.1166	3.1146	3.1156		
11:50	404.0	3.1156	3.1136	3.1146		741.5
11:55	404.0	3.1158	3.1137	3.1147		
Aver.	404.0			3.1150	63.49	
		Sixth Temperature				
12:55	430.5	3.2490	3.2472	3.2481		
1:00	430.5	3.2498	3.2480	3.2489		
1:05	430.5	3.2498	3.2478	3.2488		
Aver.	430.5			3.2481	77.39	

SAMPLE CALCULATIONS OF ISOMETRIC DATA

Isometric density 8.27 lbs./cu.ft.
Freon 13 used 82.250 grams

Barometer readings during run = 739.5 - 741.5 mm. Hg at 21°C.

Temp. No.	Pressure Gauge Reading	psi gauge	barometer psi	experimental psia	t°C.	t°F.	T°R.
1	273.5	269.25	14.3	283.5	0.15	32.27	491.96
2	305.75	301.50	14.3	315.8	14.89	58.80	518.49
3	334.5	330.25	14.3	344.5	28.98	84.16	543.85
4	369.75	365.50	14.3	379.8	46.29	115.32	575.01
5	404.0	399.75	14.3	414.0	63.49	146.28	605.97
6	430.5	426.25	14.3	440.5	77.39	171.30	630.99

Temp. No.	Volume gas cc	Density g/cc.	Density lbs/cu.ft.	Corrected Density lbs/cu.ft.	Corrected Pressure psia
1	620.40	0.13258	8.277	8.27	283.4
2	620.65	.13252	8.273	8.27	315.7
3	620.95	.13246	8.269	8.27	344.5
4	621.30	.13238	8.265	8.27	379.9
5	621.60	.13232	8.261	8.27	414.4
6	621.80	.13228	8.258	8.27	440.9

(a) Resistance of platinum resistance thermometer No. 169313 converted to t°C by Equation 44 (Appendix F).

(b) $T°R = t°F + 459.69$

(c) Pressure gauge reading plus gauge calibration equals psi ga.

(d) Barometer readings corrected to mm. Hg. at 0°C by Table 1, page 783 of Perry (9).

(e) Barometer psi equals mm. Hg. at 0°C. divided by 51.71.

(f) psi ga. plus barometer psi equals experimental psia.

(g) Volume of vapor at 25°C. (77°F.) is 620.80 cc.

(h) Volume of sphere at t°C. equals $620.80 \left[1 + 34 \times 10^{-6}(t°C - 25)\right]$

(i) Density, grams/cc. equals 82.250 grams divided by volume in cc.

(j) Density, grams/cc. times 62.43 equals density, lbs./cu.ft.

(k) Corrected density is an approximate average density. Taken as 8.27.

(l) Corrected pressurs equals 8.27 divided by the density in lbs./cu.ft. times the experimental psia.

TABLE VII

EXPERIMENTAL ISOMETRIC DATA
COMPARED TO EQUATION OF STATE

Equation of State (Equation 25)

$$p = A + BT + C/T^4$$

where

$$A = -2.837\ d^2 + 0.01594\ d^3 - 0.0003964\ d^4$$

$$B = 0.1027\ d + 2.328 \times 10^{-3}\ d^2 + 4.944 \times 10^{-7}\ d^4$$

$$C = (-23.55\ d^2 + 0.0287\ d^4 - 5.816 \times 10^{-6} d^6) \times 10^9$$

Isometric Density 1.15 lbs./cu.ft.

T°F.	Experimental Data density lbs/cu.ft.	Exp. press psia	Corr. Density lbs/cu.ft.	Corr. Press. psia	Calc. Press. psia	%Dev. calc.-corr. / calc × 100
-71.46	1.1526	41.85	1.15	41.76	41.94	+0.43
-68.35	1.1526	42.35	1.15	42.25	42.36	+0.21
-37.07	1.1518	46.50	1.15	46.43	46.50	+0.15
- 1.64	1.1512	50.95	1.15	50.95	51.06	+0.21
34.92	1.1506	55.50	1.15	55.47	55.68	+0.38
71.56	1.1498	59.95	1.15	59.96	60.25	+0.48
107.10	1.1493	64.25	1.15	64.29	64.65	+0.56
		Isometric Density 1.68 lbs./cu.ft.				
-51.77	1.6816	63.05	1.68	62.99	62.74	-0.40
-21.82	1.6803	68.80	1.68	68.79	68.70	-0.13
16.54	1.6795	75.90	1.68	75.92	76.08	+0.21
49.86	1.6787	81.90	1.68	81.96	82.35	+0.47
77.45	1.6779	87.10	1.68	87.21	87.48	+0.31
106.57	1.6770	92.45	1.68	92.62	92.86	+0.26
		Isometric Density 2.91 lbs./cu.ft.				
-21.12	2.9115	110.8	2.91	110.7	110.8	+0.05
13.08	2.9101	123.2	2.91	123.2	123.1	+0.08
46.90	2.9087	134.8	2.91	134.8	134.8	0.00
82.11	2.9066	146.5	2.91	146.6	146.7	+0.07
122.25	2.9044	159.5	2.91	159.8	160.1	+0.12
154.96	2.9030	170.3	2.91	170.7	170.8	+0.06

TABLE VII (Cont'd)

T°F.	Experimental Exp. density lbs/cu.ft.	Exp. press psia	Corr. Density lbs/cu.ft.	Corr. Press. psia	Calc. Press. psia	% Dev. calc.-corr. / calc × 100
Isometric Density 4.27 lbs./cu.ft.						
-4.22	4.277	159.3	4.27	159.0	158.8	-0.13
1.13	4.277	162.1	4.27	161.8	161.8	+0.00
40.32	4.275	183.2	4.27	183.0	183.2	+0.11
78.19	4.272	203.1	4.27	203.0	203.2	+0.10
107.02	4.270	218.0	4.27	218.0	218.0	+0.00
145.18	4.267	237.2	4.27	237.4	237.3	-0.04
171.79	4.265	250.4	4.27	250.7	250.6	-0.04
Isometric Density 6.00 lbs./cu.ft.						
12.63	6.003	214.4	6.000	214.4	215.5	+0.51
20.17	6.001	220.4	6.000	220.4	220.3	-0.05
51.75	5.997	247.0	6.000	247.1	247.3	+0.08
75.88	5.995	265.7	6.000	266.0	266.2	+0.08
112.62	5.991	293.8	6.000	294.2	294.3	+0.04
140.29	5.988	314.3	6.000	314.9	315.0	+0.03
Isometric Density 8.27 lbs./cu.ft.						
32.27	8.277	283.5	8.27	283.4	285.3	+0.67
58.80	8.273	315.8	8.27	315.7	316.8	+0.41
84.16	8.269	344.5	8.27	344.5	346.0	+0.43
115.32	8.265	379.8	8.27	379.9	380.9	+0.26
146.28	8.261	414.0	8.27	414.4	414.8	+0.10
171.30	8.258	440.5	8.27	440.9	441.7	+0.18
Isometric Density 10.82 lbs./cu.ft.						
49.30	10.831	354.6	10.82	354.4	355.1	+0.20
62.33	10.829	375.3	10.82	375.2	376.6	+0.37
94.55	10.823	428.5	10.82	428.5	428.3	-0.05
127.71	10.817	479.8	10.82	479.9	479.6	-0.06
165.16	10.810	536.0	10.82	536.4	536.0	-0.07
190.71	10.805	574.3	10.82	574.9	573.9	-0.17
212.05	10.801	605.8	10.82	606.5	605.2	-0.21
Isometric Density 12.77 lbs./cu.ft.						
62.51	12.783	408.3	12.77	408.0	408.4	+0.10
66.78	12.782	417.8	12.77	417.6	417.0	-0.14
97.79	12.776	478.3	12.77	478.2	478.2	+0.00
132.44	12.769	544.3	12.77	544.3	544.1	-0.04
163.49	12.761	601.3	12.77	601.6	601.7	+0.02
196.18	12.754	661.3	12.77	662.1	661.2	+0.02
225.88	12.747	714.8	12.77	715.7	714.6	-0.01
250.57	12.742	754.6	12.77	758.0	758.5	+0.07

TABLE VII (Cont'd)

Isometric Density 19.75 lbs./cu.ft.

T°F.	Experimental Exp. density lbs/cu.ft.	Exp. press. psia	Corr. Density lbs/cu.ft.	Corr. Press. psia	Calc. Press. psia	% Dev. calc.-corr. / calc × 100
77.94	19.76	513.8	19.75	513.7	513.3	-0.08
82.00	19.76	527.3	19.75	527.2	527.4	+0.04
111.15	19.75	628.3	19.75	628.3	626.6	-0.27
144.46	19.74	738.3	19.75	737.6	736.9	-0.09
178.32	19.73	846.1	19.75	846.9	846.4	-0.06
210.51	19.72	947.3	19.75	948.7	949.9	+0.12
229.82	19.71	1008.8	19.75	1010.3	1009.9	-0.04
256.95	19.70	1092.3	19.75	1094.3	1094.8	+0.05
		Isometric Density 26.75 lbs./cu.ft.				
83.86	26.78	558.3	26.75	558.3	559.8	+0.27
85.59	26.78	568.3	26.75	568.3	568.5	+0.04
116.56	26.76	724.0	26.75	723.9	722.6	-0.18
147.51	26.75	873.8	26.75	873.9	874.3	+0.05
182.44	26.73	1041.6	26.75	1042.1	1043.7	+0.04
219.06	26.71	1217.5	26.75	1218.7	1219.5	+0.07
260.35	26.69	1415.3	26.75	1417.4	1416.4	-0.07
		Isometric Density 28.0 lbs./cu.ft.				
83.91	28.05	559.3	28.0	559.3	561.3	+0.35
86.82	28.05	571.3	28.0	571.3	572.4	+0.19
116.31	28.03	734.3	28.0	734.1	732.0	-0.29
150.42	28.02	910.3	28.0	910.0	909.5	-0.06
186.21	28.00	1093.8	28.0	1093.8	1094.0	+0.02
222.51	27.98	1278.3	28.0	1278.9	1279.7	+0.06
261.19	27.97	1475.3	28.0	1476.6	1476.7	+0.01
		Isometric Density 35.9 lbs./cu.ft.				
84.00	35.94	561.3	35.9	561.3	561.2	+0.02
86.52	35.94	578.0	35.9	578.0	579.0	+0.17
121.64	35.92	830.8	35.9	830.6	830.8	+0.02
157.21	35.90	1088.8	35.9	1088.8	1088.8	+0.00
193.26	35.88	1352.3	35.9	1352.9	1352.8	-0.01
229.59	35.86	1618.8	35.9	1620.3	1620.3	+0.00
264.87	35.84	1879.0	35.9	1881.5	1881.4	-0.01
		Isometric Density 44.45 lbs./cu.ft.				
83.93	44.53	562.3	44.45	562.2	515.3	-9.12
119.46	44.50	904.1	44.45	904.0	856.7	-5.52
154.92	44.47	1262.5	44.45	1262.2	1211.4	-4.19
192.31	44.44	1651.5	44.45	1651.7	1595.7	-3.51
229.35	44.41	2036.0	44.45	2037.3	1984.1	-2.68

SAMPLE ALGEBRAIC CALCULATIONS FOR ISOMETRIC EQUATION CONSTANTS

Isometric density 8.27 lbs./cu.ft.

Temp. No.	Exp. Data		Equation a		Equation b	
	T°R.	Corr. psia	Calc. psia	% Dev. $\frac{\text{calc-corr}}{\text{calc}}$ 100	Calc. psia	% Dev. $\frac{\text{calc-corr}}{\text{calc}}$ 100
1	491.96	283.4	283.4	0.00	283.6	+0.07
2	518.49	315.7	315.3	-0.13	315.4	-0.10
3	543.85	344.5	344.8	+0.09	344.7	+0.06
4	575.01	379.9	379.9	0.00	379.9	0.00
5	605.97	414.4	413.9	-0.12	414.0	-0.10
6	630.99	440.9	440.9	0.00	441.1	+0.05

Solve for constants in equation:

$$p = A + BT + \frac{C}{T^4}$$

Use points at temperatures numbered 1, 4, and 6 to set up following equations:

$$283.4 = A + 491.96\ B + \frac{C}{(491.96)^4}$$

$$379.9 = A + 575.01\ B + \frac{C}{(575.01)^4}$$

$$440.9 = A + 630.99\ B + \frac{C}{(630.99)^4}$$

These equations were solved simultaneously to give constants of the following equation:

$$p = -184.3 + 1.0071\ T - \frac{1626.6 \times 10^9}{T^4} \quad \text{(Equation a)}$$

Adjust points 1 and 6 to 283.6 and 441.1 psia respectively.

Solve for constants of following equation:

$$p = -193.4 + 1.0202\ T - \frac{1459.3 \times 10^9}{T^4} \quad \text{(Equation b)}$$

The comparison of Equations a and b to the experimental data is shown above.

TABLE VIII

ISOMETRIC EQUATION CONSTANTS AT VARIOUS DENSITIES

d lbs./cu.ft.	A	B	C × 10^{-9}
1.15	-1.69	0.11718	-45.82
1.68	-10.88	0.18311	-21.61
2.91	-20.78	0.31394	-225.70
4.27	-55.47	0.48828	-345.79
6.00	-111.15	0.71806	-613.58
8.27	-193.4	1.0202	-1459.3
10.82	-316.15	1.3919	-2564.0
12.77	-430.7	1.6928	-3319.9
19.75	-1044.1	3.0119	-5165.7
26.75	-1989.8	4.7454	-2607.9
28.0	-2117.5	5.0040	-3680.0
35.9	-3577.25	7.5093	+4864.2
44.45	-5734.23	11.4866	+20596.3

where isometric equation is

$$p = A + BT + c/T^4$$

APPENDIX D

SATURATED LIQUID DENSITY

SAMPLE DATA SHEET: SATURATED LIQUID DENSITY

Float density 1.2108 g./cc. at 22°C.

Platinum Resistance

Thermometer No. 169313

NZ	RZ	Aver.	t°C.	Comments
2.3601	2.3585	2.3593	-14.05	Float rises to top of liquid
2.3603	2.3587	2.3595	-14.03	Float sinks to bottom of liquid
2.3602	2.3586	2.3594	-14.04	Float remains in center of liquid for one minute.

Liquid density equals float density at -14.04°C.

$$-14.04°C. = 6.73°F.$$

Resistance of Platinum Resistance thermometer No. 169313 converted to t°C. by Equation 44 in Appendix F.

Cubical coefficient of expansion = 9.8×10^{-6} cu.cm./cu.cm./°C.

Density of float at -14.04°C. =

$$= 1.2108 \left[1 + 9.8 \times 10^{-6} (22 - (-14.04)) \right] \text{ g./cc.}$$

$$= 1.2112 \text{ g./cc.}$$

$$= 1.2112 \times 62.43 = 75.615 \text{ lbs./cu.ft.}$$

Saturated Freon 13 liquid at 6.73°F. has density 75.615 lbs./cu.ft.

TABLE IX

EXPERIMENTAL SATURATED LIQUID DENSITIES
COMPARED TO LIQUID DENSITY EQUATIONS

	Experimental Data			Intermediate Equation		Equation 28	
Points	temp. °F. t	$t_c - t$	Exp. d_L	Calc. d_L	%Dev. Calc-Exp./calc × 100	Calc. d_L	% Dev. Calc-Exp./calc × 100
1	78.08	5.85	50.90	50.90	0.00	50.86	-0.08
2	69.82	14.11	56.55	56.62	+0.12	56.57	+0.04
3	52.12	31.81	63.95	64.03	+0.12	63.98	+0.05
4	40.14	43.79	67.64	67.70	+0.09	67.66	+0.03
5	25.18	58.75	71.55	71.55	0.00	71.52	-0.04
6	6.73	77.20	75.62	75.61	-0.01	75.60	-0.03
7	-26.14	110.07	81.81	81.74	-0.09	81.77	-0.05
8	-78.84	162.77	90.11	89.96	-0.17	90.03	-0.09
9	-125.25	209.18	96.30	96.30	0.00	96.38	+0.08
10	-158.03	241.96	100.51	101.49	-0.02	100.56	+0.05
11	-224.05	307.98	108.48	108.48	0.00	108.46	-0.02

Equation 28:

$$d_L = 36.07 + 0.01566\ (t_c - t) + 1.110\ (t_c - t)^{1/2} + 6.665\ (t_c - t)^{1/3} + 3.245 \times 10^{-5}\ (t_c - t)^2$$

Intermediate Equation:

$$d_L = 36.07 + 0.010204\ (t_c - t) + 1.1742 \sqrt[2]{t_c - t} + 8.0509 \sqrt[3]{t_c - t} + 4.1802 \times 10^{-5}\ (t_c - t)^2$$

TABLE X

RECTILINEAR DIAMETERS COMPARED TO RECTILINEAR DIAMETER EQUATIONS

Points	Experimental Rectilinear Diameters				Intermediate Equation		Equation 26	
	T°F	d_L	d	Exp. $\frac{d_L + d}{2}$	Calc. $\frac{d_L + d}{2}$	%Dev. calc-exp / calc. X 100	Calc. $\frac{d_L + d}{2}$	%Dev. calc-exp / calc. X 100
1	-75.37	89.60	1.15	45.375	45.375	0.00	45.33	-0.10
2	-56.97	86.84	1.68	44.26	44.29	+0.07	44.26	0.00
3	-28.75	82.26	2.91	42.585	42.64	+0.13	42.62	+0.08
4	- 7.24	78.38	4.27	41.33	41.37	+0.10	41.37	+0.10
5	12.70	74.38	6.00	40.18	40.20	+0.05	40.21	+0.08
6	31.03	70.08	8.27	39.18	39.13	-0.13	39.15	-0.08
7	46.62	65.74	10.82	38.28	38.21	-0.18	38.24	-0.10
8	55.85	62.51	12.77	37.64	37.64	0.00	37.68	+0.10
9	74.77	53.55	19.75	36.65	36.56	-0.25	36.61	-0.12

Equation 26

$$\frac{d_L + d}{2} = 40.95 - 0.05812\ t$$

Intermediate Equation

$$\frac{d_L + d}{2} = 40.95 - 0.05874\ t$$



CALCULATION OF RECTILINEAR DIAMETER EQUATION

The rectilinear diameters of Table X were fitted by the following form of a straight line equation:

$$\frac{d_L + d}{2} = a + bt$$

Points 1 and 8 were used to set up the following equations:

$$45.375 = a - 75.37b$$

$$37.64 = a + 55.85b$$

Above two equations were solved simultaneously for the constants of following equation:

$$\frac{d_L + d}{2} = 40.95 - 0.05874t \quad \text{(Intermediate Equation)}$$

The intermediate equation was compared to the rectilinear diameter points in Table X.

Points 1 and 8 were adjusted to 45.33 and 37.68 respectively. These points were used to redetermine the constants of the equation. This gave the following equation:

$$\frac{d_L + d}{2} = 40.95 - 0.05812\ t \qquad \text{Equation 26}$$

which is compared to the rectilinear diameters points in Table X.

At the critical temperature the rectilinear diameter equation predicts the critical density. Equation 26 predicts it as 36.07 lbs./cu.ft.

CALCULATIONS OF LIQUID DENSITY EQUATION

The experimental liquid density data of Table IX were fitted by an equation of the following form:

$$d_L = d_c + a(t_c - t) + b\sqrt[2]{t_c - t} + c\sqrt[3]{t_c - t} + d(t_c - t)^2$$

Where $d_c = 36.07$ lbs./cu.ft.

$t_c = 83.93$ °F

Points 1, 5, 9, and 11 were used to set-up the following equations:

$$50.90 = 36.07 + 5.85a + \sqrt[2]{5.85}\, b + \sqrt[3]{5.85}\, c + (5.85)^2 d$$
$$71.55 = 36.07 + 58.75a + \sqrt[2]{58.75}\, b + \sqrt[3]{58.75}\, c + (58.75)^2 d$$
$$96.30 = 36.07 + 209.18a + \sqrt[2]{209.18}\, b + \sqrt[3]{209.18}\, c + (209.18)^2 d$$
$$108.48 = 36.07 + 307.98a + \sqrt[2]{307.98}\, b + \sqrt[3]{307.98}\, c + (307.98)^2 d$$

These equations were solved simultaneously to determine the constants of the following equation:

$$d_L = 36.07 + 0.010204(t_c - t) + 1.1742\sqrt[2]{t_c - t} + 8.0509\sqrt[3]{t_c - t} + 4.1802 \times 10^{-5}(t_c - t)^2$$

Intermediate Equation

This intermediate equation was compared to the liquid density data in Table IX

Points 1, 5, 9, and 11 were adjusted to 50.86, 71.52, 96.38, and 108.46 lbs./cu. ft. respectively. These adjusted points were used to redetermine the constants of the equation. The resulting equation was as follows:

$$d_L = 36.07 + 0.01566(t_c - t) + 1.110(t_c - t)^{1/2} + 6.665(t_c - t)^{1/3} + 3.245 \times 10^{-5}(t_c - t)^2$$

(Equation 28)

Equation 28 was compared to the experimental liquid density data in Table IX.

APPENDIX E

SPECIFIC HEAT OF VAPORS

SAMPLE SPECIFIC HEAT CALCULATIONS FROM FUNDAMENTAL FREQUENCIES DETERMINED FROM SPECTROSCOPIC DATA

Calculations for specific heat at 0°F. (255.38°K)

Fundamental Frequencies cm^{-1}	W	X	C_1
356	509.6	1.996	1.440
356	509.6	1.996	1.440
450	644.2	2.522	1.200
563	805.9	3.156	.920
563	805.9	3.156	.920
781	1118.0	4.378	.491
1105	1581.8	6.194	.156
1212	1735.0	6.794	.103
1212	1735.0	6.794	.103
			$C_1 = 6.773$

$W = (1.432)\ X$ (Fundamental Frequency Value)

$$X = \frac{W}{T°K} = \frac{W}{255.38}$$

$$C_1 = RX^2 \frac{e^X}{(e^X-1)^2} \qquad \text{where } R = 1.987$$

Freon 13 has 6 degrees of freedom

$$C_{v\infty} = 6\left[\frac{R}{2}\right] + C_1 = \text{BTU/lb. mole}$$

$$= 5.961 + 6.773 = 12.734$$

Molecular Weight Freon 13 = 104.467

$$C_{v\infty} = \frac{12.734}{104.467} = 0.12189 \text{ BTU/lb.}$$

This is statistical value of specific heat gas at infinite volume.

TABLE XI

STATISTICAL SPECIFIC HEAT VALUES
COMPARED TO SPECIFIC HEAT EQUATIONS

	Statistical Specific heat		Intermediate Equation		Equation 29	
Temp. Number	T°F	$C_{v\infty}$ BTU/lb.	calc. $C_{v\infty}$ BTU/lb.	%Dev. Calc-Stat. / Calc X 100	calc. $C_{v\infty}$ BTU/lb.	%Dev. Calc-Stat. / Calc. X 100
1	-200	0.08131	0.08131	0.00	0.08152	+0.26
2	-100	0.10284	0.10240	-0.43	0.10257	-0.27
3	0	0.12189	0.12118	-0.58	0.12131	-0.48
4	100	0.13815	0.13766	-0.36	0.13773	-0.30
5	200	0.15183	0.15183	0.00	0.15184	0.00
6	300	0.16326	0.16376	+0.30	0.16362	+0.22
7	400	0.17272	0.17328	+0.32	0.17309	+0.21
8	500	0.18054	0.18054	0.00	0.18025	-0.16

Equation 29

$$C_{v\infty} = 0.01602 + 0.0002823\ T - 1.159 \times 10^{-7}\ T^2$$

Intermediate Equation:

$$C_{v\infty} = 0.12118 + 0.0001763\ t - 1.1514 \times 10^{-7}\ t^2$$

CALCULATIONS OF SPECIFIC HEAT EQUATIONS

Statistical heat values of Table XI were fitted by equation of following form:

$$C_{v\infty} = a + bt + ct^2$$

Temperature points 1, 5, and 8 used to set up following three equations:

$$0.08131 = a + (-200)b + (-200)^2 c$$

$$0.15183 = a + 200\ b + (200)^2 c$$

$$0.18054 = a + 500\ b + (500)^2 c$$

These 3 equations were solved simultaneously to give constants of following equation:

$$C_{v\infty} = 0.12118 + 0.0001763t - 1.1514 \times 10^{-7}\ t^2$$

(Intermediate Equation)

The comparison of this intermediate equation to the statistical values was shown in Table XI.

Points 1, 5, and 8 were adjusted to 0.08152, 0.15184, and 0.18025 BTU/lb. respectively. Using these points new constants for the equation were determined. The equation was as follows:

$$C_{v\infty} = 0.12131 + 0.0001758t - 1.1586 \times 10^{-7}\ t^2$$

This was converted to absolute temperature units by substituting $T - 459.69$ for t.

$$C_{v\infty} = 0.01602 + 0.0002823T - 1.159 \times 10^{-7}\ T^2$$

(Equation 29)

The comparison of Equation 29 to the statistical values was shown in Table XI.

APPENDIX F

CALIBRATION OF PLATINUM RESISTANCE THERMOMETER NO. 169313

CALIBRATION OF PLATINUM RESISTANCE THERMOMETER NO. 169313

1929 Calibration of Pt. Resistance thermometer No. 169313 by the National Bureau of Standards was as follows:

$R_{0°C}$ = 2.4960 ohms

$R_{100°C}$ = 3.4631 ohms

δ in Callendar equation = 1.501

$\frac{R_{100°C}}{R_{0°C}}$ = 1.3875

Thermometer No. 169313 was calibrated by platinum resistance thermometers No. 247123 and No. 228968. These thermometers had been calibrated by the National Bureau of Standards who had determined the following constants for their modified Callendar equations:

	Thermometer No. 247123	Thermometer No. 228968
$R_{0°C}$	2.5063 ohms	2.5200 ohms
$R_{100°C}$	3.4898 ohms	3.5078 ohms
δ	1.493	1.493
β	0.1089	0.111

Constants for the modified Callendar equation will be determined for thermometer No. 169313. This equation is as follows:

$$t°C = 100\left[\frac{R - R_{0°C}}{R_{100°C} - R_{0°C}}\right] + \delta\left[\frac{t}{100} - 1\right]\frac{t}{100} + \beta\left[\frac{t}{100} - 1\right]\frac{t}{100}^3$$

The β term is used only for temperatures below 0°C.

EXPERIMENTAL CALIBRATION DATA:

	Pt. Resist. Thermometer Number	Resistances in ohms of Platinum Resistance Thermometers NZ	RZ	Aver.	T°C
Ice	228968	2.5205	2.5194	2.5200	0.00
"	247123	2.5091	2.5036	2.5063	0.00
"	169313	2.4984	2.4963	2.4973	---
				Aver.	0.00
Boiling water	228968	3.5052	3.5034	3.5043	99.64
" "	247123	3.4909	3.4817	3.4863	99.64
" "	169313	3.4627	3.4601	3.4614	----
				Aver.	99.64
Liquid Air	228968	0.4800	0.4810	0.4807	-195.41
" "	247123	0.4749	0.4766	0.4758	-195.44
" "	169313	0.4996	0.4992	0.4994	----
				Aver.	-195.42

For Thermometer No. 169313

$R_{0°C}$ = 2.4973 ohms

$R_{99.64°C}$ = 3.4614 "

$R_{-195.42°C}$ = 0.4994 "

As resistance between 0–100°C is almost a straight line

$$(3.4614 - 2.4973)\ \frac{100}{99.64} = 0.9676 \text{ ohms resistance change between } 0° \text{ and } 100°C$$

$R_{100°C} = 2.4973 + 0.9676 = 3.4649$ ohms

$$\frac{R_{100°C}}{R_{0°C}} = \frac{3.4649}{2.4973} = 1.3875$$

This is additional check on the value for $R_{100°C}$ which was just determined.

As the change of the resistances at 0°C and 100°C was small, the δ value was probably the same as in the 1929 calibration, which was 1.501.

β was calculated from the modified Callendar equation by substituting the resistance at -195.42°C in the equation. β was found to be 0.1089.

The final equation for platinum resistance thermometer No. 169313 was as follows:

$$t°C = 100 \left[\frac{R_t - 2.4973}{0.9676}\right] + 1.501\left[\frac{t}{100} - 1\right]\frac{t}{100} + 0.1089\left[\frac{t}{100} - 1\right]\frac{t}{100}^{3}$$

(Equation 44)

APPENDIX G

CALCULATIONS OF ERRORS OF EXPERIMENTAL DATA

EFFECT OF PRESSURE ON VOLUMES OF VAPOR DENSITY BULBS

High-Pressure Vapor Density Bulb:

3.0" O. D. X 6" long

Approximately 1/4" wall thickness 2 1/2" I.D.

Cross-sectional area of cylinder on inside

$$\frac{\pi d^2}{4} = \frac{\pi (2.5)^2}{4} = 4.9 \text{ sq. in.}$$

At 2000 psi internal pressure

4.9 X 2000 = 9,800 lbs. pressing on bottom of cylinder

Cross-sectional area of metal

π X 3 X 1/4 = 2.36 sq. in. metal

$\frac{9,800}{2.36}$ = 4,340 psi tension on metal for internal pressure of 2000 psi

Modulus of Elasticity from Perry (9) p. 2136 = 30×10^6

$$\frac{4,340}{30 \times 10^6} \times 3 = 4.35 \times 10^{-4} \text{ cm}^3/\text{cm}^3/2000 \text{ psi}$$

or

0.0435% Volume expansion with 2000 psi

Low-Pressure Vapor Density Bulb:

8" O. D. sphere

1/8" wall thickness

7.75" I. D.

Cross-sectional area of sphere:

$$\frac{\pi (7.75)^2}{4} = 47.2 \text{ sq. in.}$$

EFFECT OF PRESSURE ON VOLUMES OF VAPOR DENSITY BULBS (CONT.)

Low-Pressure Vapor Density Bulb: (cont.)

Cross-sectional area of metal in sphere

π (8) (1/8) = 3.14 sq. in.

At 300 psi

47.2 X 300 = 14,150 lbs. exerted on hemisphere

$\frac{14,150}{3.14}$ = 4,500 psi tension on metal

$\frac{4,500}{30 \times 10^6} \times 3 = 450 \times 10^{-6}$ cm^3/cm^3/300 psi

or

0.045% volume change with 300 psi

EFFECT OF TEMPERATURE ON MERCURY AND OIL VOLUME IN U-LEG OF P-V-T EQUIPMENT

Approximately 6.0 cc. mercury

Approximately 0.5 cc. oil changes temperature

Cubical coefficients of expansion from Perry(9) p. 485:

Mercury 0.18186×10^{-3} $cm^3/cm^3/°C$

Oil 0.955×10^{-3} $cm^3/cm^3/°C$

For temperature change from 70 to 250°F

$\Delta T = 180°F = 100°C$

Volume Change for Mercury:

$6 \times 0.18186 \times 10^{-3} \times 100 = 0.110$ cc.

Volume Change for Oil:

$0.5 \times 0.955 \times 10^{-3} \times 100 = 0.05$ cc.

Total Volume Change = 0.11 + 0.05 = 0.16 cc.

$\frac{0.16}{620}$ = 0.03% Volume Change for vapor volume from 70 to 250°F.

CHANGE OF CALIBRATION OF PRESSURE GAUGE ATTACHED TO OIL AND MERCURY LEG OF P-V-T EQUIPMENT

Oil and mercury volume increased about 0.16 cc. as temperature increased from 70 to 250°F as shown on page 206.

Oil and mercury volume decreased about 0.1 cc. with pressure increase of 600 psi as described on page 105.

These volume changes tend to cancel each other as higher pressures generally go with higher temperatures.

Assume maximum volume change 0.05 cc.

U-leg built of 3/32" I.D. tubing

$3/32 \times 2.54 = 0.238$ cm.

Cross-sectional area,

$\pi (0.238)^2 \times 1/4 = 0.0563$ sq. cm.

$\frac{.05}{.0563} = 0.893$ cm. Mercury displacement in one leg

$0.893 \times 2 = 1.786$ cm. displacement in both legs.

$\frac{1.786}{2.54} = 0.7$" Hg = 0.35 psi Calibration change from 600 to 2000 psi

$\frac{0.35}{600} = 0.06\%$ Calibration Change of gauge at 600 psi.

CORRECTION OF P-V-T VOLUME TO CONSTANT TEMPERATURE

At densities up to 6.00 lbs./cu.ft., 2.0 cc. of gas volume was outside bath. If entire volume was considered to be at bath temperature, the maximum error in computing the gas density would be when the difference of bath and room temperatures was largest. This was for isometric density of 1.15 lbs./cu. ft.

Bath temperature	-71.46°F
Room "	70.0°F
Pressure in system	42 psia
Total Volume for Vapor	4066 cc.
Volume at 70°F	2.0 cc.
Volume at -71.43°F	4064 cc.

Let subscript 1 refer to conditions at -71.46°F and subscript 2 to those at 70°F.

From Compressibility Factor chart, Figure 19

$Z_1 = 0.915$

$Z_2 = 0.945$

$$p = Z_1 RT_1 d_1 = Z_2 RT_2 d_2$$

$$\frac{d_1}{d_2} = \frac{Z_2 T_2}{Z_1 T_1} = \frac{0.945 \quad (459.69 + 70)}{0.915 \quad (459.69 - 71)}$$

$d_2 = 0.702\ d_1$

2.0 cc. Volume for material at d_2

2.0 X 0.702 = 1.404 cc. This volume at bath temperature contains as much material as 2.0cc. at room temperature.

CORRECTION OF P-V-T VOLUME TO CONSTANT TEMPERATURE (cont.)

4064 + 1.404 = 4065.4 cc. Corrected Volume

0.015% Volume error by assuming 4066 cc. at bath temperature.

DENSITY CHANGES OF GLASS FLOATS WITH PRESSURE

Floats have about 3/8" sphere attached on one end. Glass thickness about 1/32" or more.

Cross-sectional area of sphere

$$\pi (3/8)^2 \quad (1/4) = 0.11 \text{ sq. in.}$$

Cross sectional area of glass of sphere

$$\pi (3/8) (1/32) = 0.0367 \text{ sq. in. glass}$$

For pressure of 500 psi on sphere

$$500 \times 0.11 = 55 \text{ lbs. on sphere}$$

$$\frac{55}{0.0367} = 1500 \text{ psi compression on glass}$$

Modulus of Elasticity from Perry (9) p. 2151 = 10.0×10^6

$$\frac{1500}{10 \times 10^6} \times 3 = 450 \times 10^{-6} \text{ cm}^3/\text{cm}^3/500 \text{ psi}$$

0.045% Volume change or
0.045% Density change with
500 psi.

ERROR IN SLOPE OF VAPOR PRESSURE CURVE PREDICTED BY EQUATION 31

The vapor pressure curve was considered a straight line over narrow temperature ranges for both the calculated (Equation 9) and experimental curves. This assumption will cause approximately the same error in the slope of both curves. Equation 31 evaluates the slope of curve predicted by Equation 9.

T°F	Predicted psia from Eq.9	Calc. Slope Eq.31 psia/°F	% Dev. Fig.22	"Experimental" psia	Exp. Slope psia/°F	% Dev. Slope Calc-exp. / calc X 100
80	535.5		-0.125	536.2		
75	503.7		-0.085	504.1		
5	31.8	6.360		32.1	6.420	-1.0
10	206.8		+0.05	206.7		
0	176.8		-0.015	176.8		
10	30.0	3.000		29.9	2.990	+0.3
-40	87.43		-0.02	87.45		
-50	71.71		+0.02	71.69		
10	15.72	1.572		15.76	1.576	-0.3
-130	9.080		-0.005	9.0804		
-140	6.455		-0.008	6.4555		
10	2.625	0.2625		2.6249	0.2625	0.0

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