Contract NAS 9-14685
DRL number: T-1042
Line item number: 4
DRD number: MA-183T
Lab. No. D-75175

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# FLUID PROPERTY MEASUREMENTS STUDY

August 31, 1976

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August 31, 1976

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# ABSTRACT

A thorough investigation of the fluid properties of refrigerant-21 was made at temperatures from the freezing point to 423 Kelvin and at pressures to $1.38 \times 10^8$ N./m$^2$ (20,000 psia).

The fluid properties included in this investigation were: density, vapor pressure, viscosity, specific heat, thermal conductivity, thermal expansion coefficient, freezing point and bulk modulus. The data have been smoothed by various techniques and tables of smooth values are reported.

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## SUMMARY

Fluid properties of refrigerant-21 are of interest in the design of a wide heat load range modular radiator system. In this work the following fluid properties of refrigerant-21 were determined: density, coefficient of expansion, bulk modulus, freezing point, viscosity, vapor pressure, specific heat and thermal conductivity.

Various pieces of laboratory equipment were used for these determinations. A new piece of equipment was designed and constructed to allow the determination of the density, bulk modulus and coefficient of expansion simultaneously. By changing operating procedure, this same piece of equipment was used for the freezing point determinations. Two procedures were used in determining the viscosity. A modified Ostwald-Cannon-Fenske glass viscometer was used for atmospheric pressure measurements. A Ruska rolling-ball viscometer was used to obtain the data above atmospheric pressure.

Vapor pressures were determined using calibrated Heise gages, mercury manometer and helium transpiration procedure for the different pressure ranges of measurements.

A flowing calorimeter was used for the measurements of isobaric heat capacity of the refrigerant from 143 to 423 K. Data were obtained for the compressed liquid at pressures of 0.20, 0.69 and 3.45 x $10^6$ N/$m^2$.

Thermal conductivity of the liquid refrigerant was determined relative to toluene over the temperature range of 143 to 423 K at pressures to 2.76 x $10^6$ N/$m^2$.

The exponents given in column headings in the tables indicate that the numbers in the column have been raised to that power. Operating procedures and the experimental data are reported in the appendices.

## RESULTS

A) Density, bulk modulus and thermal expansion.

The density of refrigerant-21 liquid was measured at 0° C and 2000 psia. Relative volumes were measured from 143.15 to 273.15 K, at pressures of 0.69 to 137.9 x $10^6$ N/$m^2$, and from 273.15 to 423.15 K at 4.14 to 13.79 x $10^6$ N/$m^2$. From this primary field of data, values of the density, coefficient of thermal expansion, and bulk-modulus of elasticity were calculated.

The measured density of liquid R-21, at 273.15 K and 13.79 x $10^6$ N/$m^2$ is 1.4483 ±0.0017 g/cc. This is based on a series of displacements and weighings, and is the basis for converting relative volume measurements to density.

Of the 140 measured points, only 2 were excluded from the final least-squares curve fit. Each of these experimental points deviated by more than 3 times the standard deviation of a least-squares fit which included these points. With these 2 points excluded, the least-squares standard deviation was reduced from ±0.0045 to ±0.0020, a reduction of 55% in the value of the uncertainty. Only 7 of the 138 points differ by more than ±0.3% between the measured and calculated values.

The equation used to represent the density as a function of temperature and pressure is:

$$\text{Density} = \sum_{i=0}^{3} \sum_{j=0}^{3} A_{ij} T^i P^j$$

which results in 16 constants. The final values of these constants are:

| Constant | Value | Exponents of T, i= | Exponents of P, j= |
|---|---|---|---|
| A(0, 0) | 2.213576E-00 | 0 | 0 |
| A(0, 1) | -7.505527E-05 | 0 | 1 |
| A(0, 2) | 9.184581E-09 | 0 | 2 |
| A(0, 3) | -2.912648E-13 | 0 | 3 |
| A(1, 0) | -5.175337E-03 | 1 | 0 |
| A(1, 1) | 1.124595E-06 | 1 | 1 |
| A(1, 2) | -1.326322E-10 | 1 | 2 |
| A(1, 3) | 4.204631E-15 | 1 | 3 |
| A(2, 0) | 1.433549E-05 | 2 | 0 |
| A(2, 1) | -5.136580E-09 | 2 | 1 |
| A(2, 2) | 6.169528E-13 | 2 | 2 |
| A(2, 3) | -1.960998E-17 | 2 | 3 |
| A(3, 0) | -2.173285E-08 | 3 | 0 |
| A(3, 1) | 8.000805E-12 | 3 | 1 |
| A(3, 2) | -9.432766E-16 | 3 | 2 |
| A(3, 3) | 2.984979E-20 | 3 | 3 |

The average error between measured and calculated densities is ±0.098%, and with these constants the density of R-21 can be calculated within ±0.1% on the average.

The equation and the final 16 constants were used to compute the values of density, coefficient of thermal expansion, and bulk modulus of elasticity, for R-21 given in Table 1. The values can all be obtained from the density equation by the following relationships:

$$\text{Volume} = V = 1/\text{Density} = 1/D$$

$$\text{Coeff. of Thermal Expansion} = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p = -\frac{1}{D}\left(\frac{\partial D}{\partial T}\right)_p$$

$$\text{and Bulk Modulus} = -V\left(\frac{\partial P}{\partial V}\right)_T = +\frac{D}{\left(\frac{\partial D}{\partial P}\right)_T}$$

The density equation and its derivatives were substituted into these relationships, and values computed at 10° C intervals over the entire range of pressures.

Figure 1 shows the effect of temperature on the density of R-21 at pressures of 0.69, 13.79, 68.95 and 137.90 x $10^6$ N/$m^2$ (100, 2000, 10,000 and 20,000 psia). Figure 2 is a plot of the coefficient of thermal expansion over the same temperature and pressure range. The bulk modulus of elasticity is plotted as a function of temperature in Figure 3. Experimental procedure and data are given in Appendix A.

## B.) FREEZING POINT

The freezing-point temperature of Refrigerant 21, Dichloromonofluoromethane, has been measured at pressures from 0.69 to 137.90 x $10^6$ N/$m^2$. The experimental results, Table 2, show two distinctly different freezing-point curves, each of which could be reproduced, and which differed by 4 to 6° C.

Our interpretation of these results is that R-21 forms two different crystalline solid phases. There is a very distinct transition temperature between the liquid and first solid phase, and at the transition from Solid II to Solid I. We believe the atmospheric pressure freezing point is 135.8 K and the transition is from Liquid to Solid I. The Solid II curve intersects the Liquid-Solid I curve between atmospheric pressure and 0.69 x $10^6$ N/$m^2$ (100 psia) at an L- S I - S II triple point, as shown in Figure 4.

Solid I is formed by freezing at low pressures and Solid II by increasing the pressure on Solid I. The approximate densities of the solids were found to be 1.857 g/cc at 100 psia and 135.3 K for Solid I; 1.909 g/cc at 2000 psia and 142.4 K for Solid II. The volume change on freezing of supercooled liquid to Solid I gave a 6.4% decrease in volume at 100 psia and 135.3 K. Supercooled liquid to Solid II shows a 9.7% decrease in volume at 2000 psia and 142.4 K.

These freezing-point temperatures show a 21° C rise from 0.69 to 137.90 x $10^6$ N/$m^2$ (100 to 20,000 psia). This is a much smaller rise than is predicted by the method of reference $^{(4)}$. The reported freezing-point temperatures are an average of from 3 to 7 repeat measurements, with an uncertainity of ±0.3° C. Appendix B gives more detailed information on the freezing point measurements.

## C.) VISCOSITY

The viscosity of Refrigerant 21, Dichloromonofluoromethane, has been measured from 143.15 to 423.15 K. Data were obtained on the liquid at 0.10 x $10^6$ N/$m^2$ (15 psia) from 143.15 to 273.15 K, and at 5 pressures from the vapor-pressure 0.345 x $10^6$ N/$m^2$ to 10.34 x $10^6$ N/$m^2$ from 273.15 to 423.15 K.

A modified Ostwald-Cannon-Fenske glass viscometer for atmospheric pressure measurements was calibrated with water and n-pentane. Above atmospheric pressure, data were obtained with a Ruska rolling-ball viscometer. The temperature coefficients for the calibration constants were measured using n-hexane and n-heptane.

The experimental data were represented by an equation of the form:

$$\ln(\text{viscosity, cp}) = A + B/T + CT \quad (T \text{ in Kelvin})$$

The coefficients derived from a least-squares fit of the data at the elevated pressures are given in Table 3. The standard error of estimate is approximately 1%. The coefficients derived from a least-squares fit of the low temperature data are given in Table 4. The standard error of estimate is from 0.2 to 0.4%.

The data were adjusted to even values of temperature and the data at each temperature as a function of pressure were examined by the least-squares technique. The coefficients derived from the least-squares fit for the isotherms and their respective standard errors of estimate are given in Table 5.

Smoothed values of viscosity were calculated using the coefficients given in Tables 3 and 4 and are given in Table 6. These are probably accurate to ±1% or 0.002 cp, whichever is greater. Smoothed values at atmospheric pressure for the low temperature viscosities are given in Table 7 and probably are accurate to ±0.004 cp. These were calculated using the coefficients given in Table 4. Figures 5 and 6 show the viscosity as a function of temperature.

## D.) VAPOR PRESSURE

The vapor pressure of Refrigerant 21, Dichloromonofluoromethane, has been measured from 153.15 to 423.15 K. This represents pressures from 0.0003 to 480 psia, 207 to $3.31 \times 10^6$ N/m$^2$. The data were represented by 2 fifth order polynomials, one for temperatures above 0° C, and the other for temperatures below 0° C.

The experimental data were represented by a series of equations of increasing complexity, but all of the form:

$$\ln \text{v.p. (psia)} = \sum_{i=n}^{m} A_i T^i \quad \text{(T in Kelvin)}$$

The best fit was obtained with a fifth order polynomial, where i = -2 to +2, or:

$$\ln \text{v.p.} = \frac{A}{T^2} + \frac{B}{T} + C + DT + ET^2$$

This polynomial was fit to the data from 273.15 to 423.15 K, and from 273.15 to 153.15 K. The coefficients for each range are:

| | Above 273.15 | Below 273.15 |
|---|---|---|
| A | $-9.4852106 \times 10^{4}$ | $-1.6509519 \times 10^{5}$ |
| B | $-2.5727266 \times 10^{3}$ | $-1.0815884 \times 10^{3}$ |
| C | 14.262312 | 1.0265358 |
| D | $-6.3655244 \times 10^{-3}$ | $4.4064684 \times 10^{-2}$ |
| E | $6.8276335 \times 10^{-6}$ | $-6.0960478 \times 10^{-5}$ |

Two data points were calculated with both sets of constants and the agreement is considered acceptable.

| T, °K | Pressure, psia<br>Measured | By T > 0°C | By T < 0°C |
|---|---|---|---|
| 274.54 | 11.00 | 11.021 | 11.015 |
| 283.30 | 15.60 | 15.546 | 15.527 |

The two sets of constants were used to calculate the vapor pressure of R-21 at even values of temperature, from 143.15 to 423.15 K. These values are given in Table 8, and shown graphically in Figures 7 and 8. The smoothed values represent the data above 243 K to within a standard error of ±0.30 psia. The data below 273 K have a standard error of ±0.045 psi.

## E.) HEAT CAPACITY

The isobaric heat capacity (specific-heat), $C_p$, of Refrigerant 21, Dichloromonofluoromethane, has been measured from 143.15 to 423.15 K. Data were obtained for the compressed liquid, at pressures of 0.21, 0.69 and $3.45 \times 10^6$ N/m$^2$ (30, 100 and 500 psia.)

The experimental data are actually enthalpy changes between inlet and outlet temperatures. The average heat capacity is obtained by dividing the enthalpy change by the temperature interval between inlet and outlet.

The enthalpy change for R-21 was measured at pressures of 0.21, 0.69 and 3.45 x $10^6$ N/$m^2$. Intervals of 20°, 40° and 60° C between inlet and outlet temperatures were utilized, except above 403.15 K at 3.45 x $10^6$ N/$m^2$ where 5° C intervals were measured. Inlet temperatures started at 143.15 K and increased by 40° C steps. The maximum outlet temperatures at 0.21 and 0.69 x $10^6$ N/$m^2$ were limited by approach to the vapor pressure curve.

The experimental data were smoothed by comparison with a set of heat capacity values calculated for R-21 at corresponding conditions with the Mark V(3) computer program. The ratios between measured and calculated heat capacities were then fit as a function of temperature, by a polynomial:

$$\text{ratio (m/c)} = A + BT + CT^2 + DT^3$$

where T is the average of the inlet and outlet temperatures. The coefficients generated in this manner were used to calculate a set of smoothed values at conditions identical to the measured values.

Heat capacities were then calculated at 20° C intervals for the three isobars and are given in Tables 9, 10 and 11 respectively. These smoothed values represent the experimental measurement within ±0.5%. Figure 9 shows the effect of temperature on liquid heat capacity of R-21 at 3.45 x $10^6$ N/$m^2$ (500 psia).

## F.) THERMAL CONDUCTIVITY

Thermal conductivities of refrigerant-21 have been determined relative to toluene over the temperature range of 140 to 425 Kelvin. A modified hot-wire procedure was used for these measurements and was verified by determining the thermal conductivity of methanol at 0° C relative to toluene and carbon tetrachloride. The value so determined for methanol was within 2 percent of the literature value.

Thermal conductivities of toluene and R-21 were measured at the same conditions and the measured toluene values compared to those in the literature. A correction curve was determined from the toluene data and applied to the measured R-21 data.

The thermal conductivities of R-21 were then smoothed by the method of least-squares to an equation of the form $\lambda = A + BT$. The coefficients determined from the curve fit are given in Table 12 and the smoothed thermal conductivities are reported in Tables 13, 14 and 15. The thermal conductivities are shown graphically in Figure 10 and 11. The thermal conductivities of R-21 reported average 9 percent greater than those given by DuPont. The reported data average 6 percent above ASHRAE's data at temperatures below 273 K and 30 percent greater at temperatures above 273 K. The accuracy of the data reported is estimated at 6 percent.

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F. | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 143.15 | -202 | .10 | 15 | 1.7028 | 106.30 | 1.412 | 7.844 | 28.33 | 4.109 |
| | | .69 | 100 | 1.7032 | 106.33 | 1.405 | 7.806 | 28.25 | 4.098 |
| | | 1.38 | 200 | 1.7036 | 106.35 | 1.396 | 7.756 | 28.16 | 4.084 |
| | | 2.76 | 400 | 1.7044 | 106.40 | 1.379 | 7.661 | 27.99 | 4.059 |
| | | 4.14 | 600 | 1.7052 | 106.45 | 1.363 | 7.572 | 27.82 | 4.035 |
| | | 5.52 | 800 | 1.7061 | 106.51 | 1.348 | 7.489 | 27.66 | 4.012 |
| 143.15 | -202 | 6.89 | 1000 | 1.7069 | 106.56 | 1.333 | 7.406 | 27.51 | 3.990 |
| | | 8.62 | 1250 | 1.7080 | 106.63 | 1.315 | 7.306 | 27.33 | 3.964 |
| | | 10.34 | 1500 | 1.7091 | 106.70 | 1.298 | 7.211 | 27.16 | 3.939 |
| | | 12.07 | 1750 | 1.7102 | 106.76 | 1.282 | 7.122 | 27.01 | 3.917 |
| | | 13.79 | 2000 | 1.7113 | 106.83 | 1.267 | 7.039 | 26.86 | 3.895 |
| | | 27.58 | 4000 | 1.7203 | 107.40 | 1.174 | 6.522 | 26.03 | 3.775 |
| | | 41.37 | 6000 | 1.7295 | 107.97 | 1.124 | 6.244 | 25.74 | 3.733 |
| | | 55.16 | 8000 | 1.7387 | 108.54 | 1.103 | 6.128 | 25.94 | 3.763 |
| 153.15 | -184 | .10 | 15 | 1.6792 | 104.83 | 1.377 | 7.650 | 21.30 | 3.089 |
| | | .69 | 100 | 1.6797 | 104.86 | 1.371 | 7.617 | 21.33 | 3.094 |
| | | 1.38 | 200 | 1.6802 | 104.89 | 1.364 | 7.578 | 21.37 | 3.100 |
| | | 2.76 | 400 | 1.6813 | 104.96 | 1.350 | 7.500 | 21.46 | 3.113 |
| | | 4.14 | 600 | 1.6824 | 105.03 | 1.337 | 7.428 | 21.55 | 3.125 |
| | | 5.52 | 800 | 1.6835 | 105.10 | 1.324 | 7.356 | 21.64 | 3.138 |
| 153.15 | -184 | 6.89 | 1000 | 1.6845 | 105.16 | 1.311 | 7.283 | 21.73 | 3.151 |
| | | 8.62 | 1250 | 1.6859 | 105.25 | 1.297 | 7.206 | 21.84 | 3.167 |
| | | 10.34 | 1500 | 1.6872 | 105.33 | 1.282 | 7.122 | 21.95 | 3.183 |
| | | 12.07 | 1750 | 1.6885 | 105.41 | 1.269 | 7.050 | 22.06 | 3.200 |
| | | 13.79 | 2000 | 1.6898 | 105.49 | 1.256 | 6.978 | 22.17 | 3.216 |
| | | 27.58 | 4000 | 1.7002 | 106.14 | 1.175 | 6.528 | 23.13 | 3.354 |
| | | 41.37 | 6000 | 1.7101 | 106.76 | 1.126 | 6.256 | 24.15 | 3.502 |
| | | 55.16 | 8000 | 1.7197 | 107.36 | 1.098 | 6.100 | 25.26 | 3.663 |
| 153.15 | -184 | 68.95 | 10000 | 1.7289 | 107.93 | 1.085 | 6.028 | 26.46 | 3.837 |
| | | 86.18 | 12500 | 1.7399 | 108.62 | 1.075 | 5.972 | 28.10 | 4.076 |
| | | 103.42 | 15000 | 1.7502 | 109.26 | 1.057 | 5.872 | 29.96 | 4.345 |
| | | 120.66 | 17500 | 1.7600 | 109.87 | 1.016 | 5.644 | 32.05 | 4.648 |
| | | 137.90 | 20000 | 1.7692 | 110.45 | .935 | 5.194 | 34.43 | 4.994 |

## TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m² x E-6 | psia | kg/m² x E-3 | lb/ft³ | 1E3/°C | 1E4/°F | N/m² x E-8 | psia XE-5 |
| 163.15 | -166 | .10 | 15 | 1.6565 | 103.41 | 1.347 | 7.483 | 17.74 | 2.573 |
| | | .69 | 100 | 1.6571 | 103.45 | 1.342 | 7.456 | 17.80 | 2.582 |
| | | 1.38 | 200 | 1.6577 | 103.49 | 1.337 | 7.428 | 17.88 | 2.594 |
| | | 2.76 | 400 | 1.6590 | 103.57 | 1.326 | 7.367 | 18.04 | 2.616 |
| | | 4.14 | 600 | 1.6602 | 103.64 | 1.315 | 7.306 | 18.20 | 2.639 |
| | | 5.52 | 800 | 1.6615 | 103.73 | 1.304 | 7.244 | 18.35 | 2.662 |
| 163.15 | -166 | 6.89 | 1000 | 1.6627 | 103.80 | 1.294 | 7.189 | 18.51 | 2.685 |
| | | 8.62 | 1250 | 1.6643 | 103.90 | 1.282 | 7.122 | 18.71 | 2.714 |
| | | 10.34 | 1500 | 1.6658 | 103.99 | 1.270 | 7.056 | 18.91 | 2.743 |
| | | 12.07 | 1750 | 1.6673 | 104.09 | 1.259 | 6.994 | 19.11 | 2.772 |
| | | 13.79 | 2000 | 1.6688 | 104.18 | 1.248 | 6.933 | 19.32 | 2.802 |
| | | 27.58 | 4000 | 1.6803 | 104.90 | 1.177 | 6.539 | 20.96 | 3.040 |
| | | 41.37 | 6000 | 1.6910 | 105.57 | 1.128 | 6.267 | 22.62 | 3.281 |
| | | 55.16 | 8000 | 1.7009 | 106.18 | 1.095 | 6.083 | 24.24 | 3.516 |
| 163.15 | -166 | 68.95 | 10000 | 1.7103 | 106.77 | 1.072 | 5.956 | 25.75 | 3.735 |
| | | 86.18 | 12500 | 1.7215 | 107.47 | 1.051 | 5.839 | 27.37 | 3.970 |
| | | 103.42 | 15000 | 1.7321 | 108.13 | 1.026 | 5.700 | 28.56 | 4.142 |
| | | 120.66 | 17500 | 1.7425 | 108.78 | .989 | 5.494 | 29.19 | 4.233 |
| | | 137.90 | 20000 | 1.7528 | 109.42 | .928 | 5.156 | 29.19 | 4.233 |
| 173.15 | -148 | .10 | 15 | 1.6345 | 102.04 | 1.324 | 7.356 | 15.66 | 2.271 |
| | | .69 | 100 | 1.6352 | 102.08 | 1.320 | 7.333 | 15.73 | 2.282 |
| | | 1.38 | 200 | 1.6359 | 102.13 | 1.316 | 7.311 | 15.82 | 2.294 |
| | | 2.76 | 400 | 1.6373 | 102.21 | 1.307 | 7.261 | 15.99 | 2.319 |
| | | 4.14 | 600 | 1.6387 | 102.30 | 1.298 | 7.211 | 16.16 | 2.344 |
| | | 5.52 | 800 | 1.6401 | 102.39 | 1.290 | 7.167 | 16.34 | 2.370 |
| 173.15 | -148 | 6.89 | 1000 | 1.6415 | 102.48 | 1.282 | 7.122 | 16.51 | 2.395 |
| | | 8.62 | 1250 | 1.6432 | 102.58 | 1.272 | 7.067 | 16.73 | 2.427 |
| | | 10.34 | 1500 | 1.6448 | 102.68 | 1.262 | 7.011 | 16.96 | 2.460 |
| | | 12.07 | 1750 | 1.6465 | 102.79 | 1.253 | 6.961 | 17.19 | 2.493 |
| | | 13.79 | 2000 | 1.6482 | 102.89 | 1.243 | 6.906 | 17.42 | 2.526 |
| | | 27.58 | 4000 | 1.6606 | 103.67 | 1.180 | 6.556 | 19.28 | 2.796 |
| | | 41.37 | 6000 | 1.6720 | 104.38 | 1.130 | 6.278 | 21.17 | 3.070 |
| | | 55.16 | 8000 | 1.6824 | 105.03 | 1.092 | 6.067 | 23.01 | 3.337 |
| 173.15 | -148 | 68.95 | 10000 | 1.6922 | 105.64 | 1.061 | 5.894 | 24.67 | 3.578 |
| | | 86.18 | 12500 | 1.7037 | 106.36 | 1.029 | 5.717 | 26.29 | 3.813 |
| | | 103.42 | 15000 | 1.7147 | 107.05 | .999 | 5.550 | 27.19 | 3.943 |
| | | 120.66 | 17500 | 1.7255 | 107.72 | .964 | 5.356 | 27.22 | 3.948 |
| | | 137.90 | 20000 | 1.7366 | 108.41 | .921 | 5.117 | 26.39 | 3.828 |

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 183.15 | -130 | .10 | 15 | 1.6132 | 100.71 | 1.308 | 7.267 | 14.33 | 2.079 |
| | | .69 | 100 | 1.6138 | 100.75 | 1.305 | 7.250 | 14.40 | 2.089 |
| | | 1.38 | 200 | 1.6146 | 100.80 | 1.302 | 7.233 | 14.49 | 2.101 |
| | | 2.76 | 400 | 1.6161 | 100.89 | 1.295 | 7.194 | 14.66 | 2.126 |
| | | 4.14 | 600 | 1.6177 | 100.99 | 1.288 | 7.156 | 14.82 | 2.150 |
| | | 5.52 | 800 | 1.6191 | 101.08 | 1.281 | 7.117 | 15.00 | 2.175 |
| 183.15 | -130 | 6.89 | 1000 | 1.6206 | 101.17 | 1.274 | 7.078 | 15.17 | 2.200 |
| | | 8.62 | 1250 | 1.6225 | 101.29 | 1.266 | 7.033 | 15.39 | 2.232 |
| | | 10.34 | 1500 | 1.6243 | 101.40 | 1.257 | 6.983 | 15.61 | 2.264 |
| | | 12.07 | 1750 | 1.6260 | 101.51 | 1.249 | 6.939 | 15.83 | 2.296 |
| | | 13.79 | 2000 | 1.6278 | 101.62 | 1.241 | 6.894 | 16.05 | 2.328 |
| | | 27.58 | 4000 | 1.6411 | 102.45 | 1.183 | 6.572 | 17.90 | 2.596 |
| | | 41.37 | 6000 | 1.6532 | 103.21 | 1.133 | 6.294 | 19.79 | 2.871 |
| | | 55.16 | 8000 | 1.6642 | 103.89 | 1.089 | 6.050 | 21.66 | 3.141 |
| 183.15 | -130 | 68.95 | 10000 | 1.6744 | 104.53 | 1.051 | 5.839 | 23.34 | 3.385 |
| | | 86.18 | 12500 | 1.6864 | 105.28 | 1.010 | 5.611 | 24.99 | 3.624 |
| | | 103.42 | 15000 | 1.6978 | 105.99 | .975 | 5.417 | 25.86 | 3.751 |
| | | 120.66 | 17500 | 1.7092 | 106.70 | .943 | 5.239 | 25.82 | 3.745 |
| | | 137.90 | 20000 | 1.7208 | 107.43 | .913 | 5.072 | 24.89 | 3.610 |
| 193.15 | -112 | .10 | 15 | 1.5923 | 99.41 | 1.300 | 7.222 | 13.42 | 1.947 |
| | | .69 | 100 | 1.5930 | 99.45 | 1.297 | 7.206 | 13.49 | 1.957 |
| | | 1.38 | 200 | 1.5938 | 99.50 | 1.294 | 7.189 | 13.57 | 1.968 |
| | | 2.76 | 400 | 1.5954 | 99.60 | 1.288 | 7.156 | 13.73 | 1.991 |
| | | 4.14 | 600 | 1.5970 | 99.70 | 1.283 | 7.128 | 13.89 | 2.014 |
| | | 5.52 | 800 | 1.5986 | 99.80 | 1.277 | 7.094 | 14.04 | 2.037 |
| 193.15 | -112 | 6.89 | 1000 | 1.6001 | 99.89 | 1.271 | 7.061 | 14.20 | 2.060 |
| | | 8.62 | 1250 | 1.6021 | 100.02 | 1.264 | 7.022 | 14.40 | 2.089 |
| | | 10.34 | 1500 | 1.6040 | 100.14 | 1.257 | 6.983 | 14.61 | 2.119 |
| | | 12.07 | 1750 | 1.6059 | 100.25 | 1.250 | 6.944 | 14.81 | 2.148 |
| | | 13.79 | 2000 | 1.6077 | 100.37 | 1.243 | 6.906 | 15.02 | 2.179 |
| | | 27.58 | 4000 | 1.6218 | 101.25 | 1.188 | 6.600 | 16.73 | 2.427 |
| | | 41.37 | 6000 | 1.6345 | 102.04 | 1.136 | 6.311 | 18.51 | 2.685 |
| | | 55.16 | 8000 | 1.6462 | 102.77 | 1.088 | 6.044 | 20.27 | 2.940 |
| 193.15 | -112 | 68.95 | 10000 | 1.6570 | 103.44 | 1.044 | 5.800 | 21.90 | 3.177 |
| | | 86.18 | 12500 | 1.6696 | 104.23 | .995 | 5.528 | 23.57 | 3.419 |
| | | 103.42 | 15000 | 1.6815 | 104.97 | .955 | 5.306 | 24.59 | 3.567 |
| | | 120.66 | 17500 | 1.6933 | 105.71 | .925 | 5.139 | 24.79 | 3.596 |
| | | 137.90 | 20000 | 1.7052 | 106.45 | .905 | 5.028 | 24.15 | 3.503 |

## TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 203.15 | - 94 | .10 | 15 | 1.5718 | 98.13 | 1.299 | 7.217 | 12.76 | 1.851 |
| | | .69 | 100 | 1.5725 | 98.17 | 1.297 | 7.206 | 12.82 | 1.859 |
| | | 1.38 | 200 | 1.5733 | 98.22 | 1.294 | 7.189 | 12.89 | 1.869 |
| | | 2.76 | 400 | 1.5750 | 98.33 | 1.289 | 7.161 | 13.03 | 1.890 |
| | | 4.14 | 600 | 1.5766 | 98.42 | 1.284 | 7.133 | 13.17 | 1.910 |
| | | 5.52 | 800 | 1.5783 | 98.53 | 1.279 | 7.106 | 13.31 | 1.930 |
| 203.15 | - 94 | 6.89 | 1000 | 1.5799 | 98.63 | 1.274 | 7.078 | 13.45 | 1.951 |
| | | 8.62 | 1250 | 1.5819 | 98.76 | 1.267 | 7.039 | 13.63 | 1.977 |
| | | 10.34 | 1500 | 1.5839 | 98.88 | 1.261 | 7.006 | 13.82 | 2.004 |
| | | 12.07 | 1750 | 1.5859 | 99.01 | 1.254 | 6.967 | 14.00 | 2.030 |
| | | 13.79 | 2000 | 1.5878 | 99.12 | 1.247 | 6.928 | 14.18 | 2.057 |
| | | 27.58 | 4000 | 1.6026 | 100.05 | 1.194 | 6.633 | 15.71 | 2.279 |
| | | 41.37 | 6000 | 1.6160 | 100.88 | 1.140 | 6.333 | 17.31 | 2.510 |
| | | 55.16 | 8000 | 1.6284 | 101.66 | 1.087 | 6.039 | 18.91 | 2.743 |
| 203.15 | - 94 | 68.95 | 10000 | 1.6398 | 102.37 | 1.038 | 5.767 | 20.45 | 2.966 |
| | | 86.18 | 12500 | 1.6531 | 103.20 | .983 | 5.461 | 22.14 | 3.211 |
| | | 103.42 | 15000 | 1.6657 | 103.99 | .939 | 5.217 | 23.38 | 3.391 |
| | | 120.66 | 17500 | 1.6778 | 104.74 | .910 | 5.056 | 23.99 | 3.480 |
| | | 137.90 | 20000 | 1.6899 | 105.50 | .897 | 4.983 | 23.90 | 3.488 |
| 213.15 | - 76 | .10 | 15 | 1.5514 | 96.85 | 1.306 | 7.256 | 12.22 | 1.772 |
| | | .69 | 100 | 1.5522 | 96.90 | 1.304 | 7.244 | 12.27 | 1.779 |
| | | 1.38 | 200 | 1.5530 | 96.95 | 1.301 | 7.228 | 12.33 | 1.788 |
| | | 2.76 | 400 | 1.5548 | 97.06 | 1.297 | 7.206 | 12.45 | 1.806 |
| | | 4.14 | 600 | 1.5565 | 97.17 | 1.292 | 7.178 | 12.57 | 1.825 |
| | | 5.52 | 800 | 1.5582 | 97.28 | 1.287 | 7.150 | 12.69 | 1.841 |
| 213.15 | - 76 | 6.89 | 1000 | 1.5599 | 97.38 | 1.282 | 7.122 | 12.82 | 1.859 |
| | | 8.62 | 1250 | 1.5620 | 97.51 | 1.275 | 7.083 | 12.98 | 1.882 |
| | | 10.34 | 1500 | 1.5640 | 97.64 | 1.269 | 7.050 | 13.13 | 1.905 |
| | | 12.07 | 1750 | 1.5661 | 97.77 | 1.262 | 7.011 | 13.29 | 1.928 |
| | | 13.79 | 2000 | 1.5681 | 97.89 | 1.256 | 6.978 | 13.45 | 1.951 |
| | | 27.58 | 4000 | 1.5835 | 98.86 | 1.201 | 6.672 | 14.78 | 2.144 |
| | | 41.37 | 6000 | 1.5977 | 99.74 | 1.144 | 6.356 | 16.18 | 2.347 |
| | | 55.16 | 8000 | 1.6108 | 100.56 | 1.088 | 6.044 | 17.62 | 2.556 |
| 213.15 | - 76 | 68.95 | 10000 | 1.6229 | 101.32 | 1.034 | 5.744 | 19.06 | 2.764 |
| | | 86.18 | 12500 | 1.6370 | 102.20 | .975 | 5.417 | 20.75 | 3.010 |
| | | 103.42 | 15000 | 1.6502 | 103.02 | .928 | 5.156 | 22.22 | 3.223 |
| | | 120.66 | 17500 | 1.6627 | 103.80 | .898 | 4.989 | 23.32 | 3.382 |
| | | 137.90 | 20000 | 1.6749 | 104.56 | .889 | 4.939 | 23.91 | 3.468 |

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m² x E-6 | psia | kg/m² x E-3 | lb/ft³ | 1E3/°C | 1E4/°F | N/m² x E-8 | psia XE-5 |
| 223.15 | - 58 | .10 | 15 | 1.5312 | 95.59 | 1.322 | 7.344 | 11.71 | 1.698 |
| | | .69 | 100 | 1.5320 | 95.64 | 1.319 | 7.328 | 11.76 | 1.705 |
| | | 1.38 | 200 | 1.5329 | 95.70 | 1.317 | 7.317 | 11.80 | 1.712 |
| | | 2.76 | 400 | 1.5346 | 95.80 | 1.312 | 7.289 | 11.91 | 1.727 |
| | | 4.14 | 600 | 1.5364 | 95.92 | 1.306 | 7.256 | 12.01 | 1.742 |
| | | 5.52 | 800 | 1.5382 | 96.03 | 1.301 | 7.228 | 12.12 | 1.758 |
| 223.15 | - 58 | 6.89 | 1000 | 1.5399 | 96.13 | 1.296 | 7.200 | 12.22 | 1.773 |
| | | 8.62 | 1250 | 1.5421 | 96.27 | 1.289 | 7.161 | 12.36 | 1.793 |
| | | 10.34 | 1500 | 1.5442 | 96.40 | 1.282 | 7.122 | 12.49 | 1.812 |
| | | 12.07 | 1750 | 1.5463 | 96.53 | 1.275 | 7.083 | 12.63 | 1.832 |
| | | 13.79 | 2000 | 1.5484 | 96.66 | 1.268 | 7.044 | 12.77 | 1.852 |
| | | 27.58 | 4000 | 1.5645 | 97.67 | 1.209 | 6.717 | 13.92 | 2.019 |
| | | 41.37 | 6000 | 1.5795 | 98.61 | 1.149 | 6.383 | 15.14 | 2.196 |
| | | 55.16 | 8000 | 1.5933 | 99.47 | 1.089 | 6.050 | 16.43 | 2.383 |
| 223.15 | - 58 | 68.95 | 10000 | 1.6062 | 100.27 | 1.033 | 5.739 | 17.76 | 2.576 |
| | | 86.18 | 12500 | 1.6212 | 101.21 | .970 | 5.389 | 19.46 | 2.822 |
| | | 103.42 | 15000 | 1.6350 | 102.07 | .921 | 5.117 | 21.13 | 3.065 |
| | | 120.66 | 17500 | 1.6479 | 102.88 | .890 | 4.944 | 22.69 | 3.291 |
| | | 137.90 | 20000 | 1.6601 | 103.64 | .880 | 4.889 | 24.03 | 3.485 |
| 233.15 | - 40 | .10 | 15 | 1.5109 | 94.32 | 1.346 | 7.478 | 11.18 | 1.621 |
| | | .69 | 100 | 1.5117 | 94.37 | 1.344 | 7.467 | 11.21 | 1.626 |
| | | 1.38 | 200 | 1.5126 | 94.43 | 1.341 | 7.450 | 11.26 | 1.633 |
| | | 2.76 | 400 | 1.5145 | 94.55 | 1.334 | 7.411 | 11.35 | 1.646 |
| | | 4.14 | 600 | 1.5163 | 94.66 | 1.328 | 7.378 | 11.44 | 1.659 |
| | | 5.52 | 800 | 1.5181 | 94.77 | 1.322 | 7.344 | 11.53 | 1.672 |
| 233.15 | - 40 | 6.89 | 1000 | 1.5199 | 94.89 | 1.316 | 7.311 | 11.62 | 1.686 |
| | | 8.62 | 1250 | 1.5222 | 95.03 | 1.308 | 7.267 | 11.74 | 1.703 |
| | | 10.34 | 1500 | 1.5244 | 95.17 | 1.300 | 7.222 | 11.86 | 1.720 |
| | | 12.07 | 1750 | 1.5266 | 95.30 | 1.292 | 7.178 | 11.98 | 1.737 |
| | | 13.79 | 2000 | 1.5288 | 95.44 | 1.283 | 7.128 | 12.09 | 1.754 |
| | | 27.58 | 4000 | 1.5457 | 96.50 | 1.218 | 6.767 | 13.09 | 1.899 |
| | | 41.37 | 6000 | 1.5614 | 97.48 | 1.154 | 6.411 | 14.18 | 2.056 |
| | | 55.16 | 8000 | 1.5761 | 98.39 | 1.091 | 6.061 | 15.34 | 2.225 |
| 233.15 | - 40 | 68.95 | 10000 | 1.5897 | 99.24 | 1.033 | 5.739 | 16.59 | 2.406 |
| | | 86.18 | 12500 | 1.6056 | 100.24 | .969 | 5.383 | 18.28 | 2.651 |
| | | 103.42 | 15000 | 1.6201 | 101.14 | .919 | 5.106 | 20.10 | 2.915 |
| | | 120.66 | 17500 | 1.6334 | 101.97 | .885 | 4.917 | 22.04 | 3.197 |
| | | 137.90 | 20000 | 1.6457 | 102.74 | .872 | 4.844 | 24.07 | 3.491 |

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | $N/m^2$ x E-6 | psia | $kg/m^2$ x E-3 | lb/ $ft^3$ | 1E3/°C | 1E4/°F | $N/m^2$ x E-8 | psia XE-5 |
| 243.15 | - 22 | .10 | 15 | 1.4905 | 93.05 | 1.381 | 7.672 | 10.58 | 1.534 |
| | | .69 | 100 | 1.4913 | 93.10 | 1.377 | 7.650 | 10.61 | 1.539 |
| | | 1.38 | 200 | 1.4923 | 93.16 | 1.373 | 7.628 | 10.65 | 1.545 |
| | | 2.76 | 400 | 1.4942 | 93.28 | 1.366 | 7.589 | 10.73 | 1.556 |
| | | 4.14 | 600 | 1.4961 | 93.40 | 1.358 | 7.544 | 10.81 | 1.568 |
| | | 5.52 | 800 | 1.4980 | 93.52 | 1.350 | 7.500 | 10.89 | 1.580 |
| 243.15 | - 22 | 6.89 | 1000 | 1.4999 | 93.64 | 1.342 | 7.456 | 10.97 | 1.591 |
| | | 8.62 | 1250 | 1.5022 | 93.78 | 1.332 | 7.400 | 11.07 | 1.606 |
| | | 10.34 | 1500 | 1.5046 | 93.93 | 1.323 | 7.350 | 11.18 | 1.622 |
| | | 12.07 | 1750 | 1.5069 | 94.07 | 1.313 | 7.294 | 11.29 | 1.637 |
| | | 13.79 | 2000 | 1.5092 | 94.22 | 1.303 | 7.239 | 11.39 | 1.652 |
| | | 27.58 | 4000 | 1.5269 | 95.32 | 1.229 | 6.828 | 12.29 | 1.783 |
| | | 41.37 | 6000 | 1.5434 | 96.35 | 1.159 | 6.439 | 13.28 | 1.926 |
| | | 55.16 | 8000 | 1.5589 | 97.32 | 1.095 | 6.083 | 14.36 | 2.083 |
| 243.15 | - 22 | 68.95 | 10000 | 1.5734 | 98.23 | 1.036 | 5.756 | 15.55 | 2.256 |
| | | 86.18 | 12500 | 1.5901 | 99.27 | .972 | 5.400 | 17.22 | 2.498 |
| | | 103.42 | 15000 | 1.6052 | 100.21 | .921 | 5.117 | 19.13 | 2.775 |
| | | 120.66 | 17500 | 1.6190 | 101.07 | .884 | 4.911 | 21.32 | 3.092 |
| | | 137.90 | 20000 | 1.6314 | 101.85 | .863 | 4.794 | 23.84 | 3.457 |
| 253.15 | - 4 | .10 | 15 | 1.4697 | 91.75 | 1.425 | 7.917 | 9.89 | 1.434 |
| | | .69 | 100 | 1.4706 | 91.81 | 1.421 | 7.894 | 9.91 | 1.438 |
| | | 1.38 | 200 | 1.4716 | 91.87 | 1.416 | 7.866 | 9.96 | 1.444 |
| | | 2.76 | 400 | 1.4736 | 91.99 | 1.405 | 7.806 | 10.03 | 1.455 |
| | | 4.14 | 600 | 1.4757 | 92.13 | 1.395 | 7.750 | 10.11 | 1.466 |
| | | 5.52 | 800 | 1.4777 | 92.25 | 1.385 | 7.694 | 10.18 | 1.477 |
| 253.15 | - 4 | 6.89 | 1000 | 1.4797 | 92.38 | 1.375 | 7.639 | 10.26 | 1.488 |
| | | 8.62 | 1250 | 1.4821 | 92.53 | 1.363 | 7.572 | 10.36 | 1.502 |
| | | 10.34 | 1500 | 1.4846 | 92.68 | 1.351 | 7.506 | 10.45 | 1.516 |
| | | 12.07 | 1750 | 1.4870 | 92.83 | 1.339 | 7.439 | 10.56 | 1.531 |
| | | 13.79 | 2000 | 1.4894 | 92.98 | 1.328 | 7.378 | 10.65 | 1.545 |
| | | 27.58 | 4000 | 1.5081 | 94.15 | 1.241 | 6.894 | 11.51 | 1.669 |
| | | 41.37 | 6000 | 1.5256 | 95.24 | 1.165 | 6.472 | 12.45 | 1.805 |
| | | 55.16 | 8000 | 1.5419 | 96.26 | 1.099 | 6.106 | 13.49 | 1.957 |
| 253.15 | - 4 | 68.95 | 10000 | 1.5571 | 97.21 | 1.041 | 5.783 | 14.65 | 2.125 |
| | | 86.18 | 12500 | 1.5746 | 98.30 | .980 | 5.444 | 16.30 | 2.364 |
| | | 103.42 | 15000 | 1.5905 | 99.29 | .929 | 5.161 | 18.22 | 2.642 |
| | | 120.66 | 17500 | 1.6047 | 100.18 | .887 | 4.928 | 20.48 | 2.970 |
| | | 137.90 | 20000 | 1.6175 | 100.98 | .854 | 4.744 | 23.17 | 3.360 |

TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature |  | Pressure |  | Density |  | Coefficient of Thermal Expansion |  | Bulk Modulus |  |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 263.15 | 14 | .10 | 15 | 1.4485 | 90.43 | 1.480 | 8.222 | 9.10 | 1.320 |
|  |  | .69 | 100 | 1.4495 | 90.49 | 1.474 | 8.189 | 9.14 | 1.325 |
|  |  | 1.38 | 200 | 1.4505 | 90.55 | 1.468 | 8.156 | 9.17 | 1.330 |
|  |  | 2.76 | 400 | 1.4527 | 90.69 | 1.454 | 8.078 | 9.25 | 1.341 |
|  |  | 4.14 | 600 | 1.4549 | 90.83 | 1.441 | 8.006 | 9.32 | 1.352 |
|  |  | 5.52 | 800 | 1.4570 | 90.96 | 1.428 | 7.933 | 9.40 | 1.363 |
| 263.15 | 14 | 6.89 | 1000 | 1.4592 | 91.10 | 1.416 | 7.867 | 9.48 | 1.375 |
|  |  | 8.62 | 1250 | 1.4618 | 91.26 | 1.400 | 7.778 | 9.58 | 1.389 |
|  |  | 10.34 | 1500 | 1.4644 | 91.42 | 1.385 | 7.694 | 9.67 | 1.403 |
|  |  | 12.07 | 1750 | 1.4670 | 91.58 | 1.371 | 7.617 | 9.78 | 1.418 |
|  |  | 13.79 | 2000 | 1.4696 | 91.75 | 1.357 | 7.539 | 9.88 | 1.433 |
|  |  | 27.58 | 4000 | 1.4894 | 92.98 | 1.255 | 6.972 | 10.74 | 1.557 |
|  |  | 41.37 | 6000 | 1.5079 | 94.14 | 1.172 | 6.511 | 11.68 | 1.694 |
|  |  | 55.16 | 8000 | 1.5250 | 95.20 | 1.104 | 6.133 | 12.72 | 1.845 |
| 263.15 | 14 | 68.95 | 10000 | 1.5410 | 96.20 | 1.049 | 5.828 | 13.88 | 2.013 |
|  |  | 86.18 | 12500 | 1.5592 | 97.34 | .991 | 5.506 | 15.50 | 2.248 |
|  |  | 103.42 | 15000 | 1.5757 | 98.37 | .942 | 5.233 | 17.36 | 2.518 |
|  |  | 120.66 | 17500 | 1.5905 | 99.29 | .895 | 4.972 | 19.50 | 2.828 |
|  |  | 137.90 | 20000 | 1.6038 | 100.12 | .845 | 4.694 | 21.96 | 3.185 |
| 273.15 | 32 | .10 | 15 | 1.4268 | 89.07 | 1.547 | 8.594 | 8.25 | 1.196 |
|  |  | .69 | 100 | 1.4278 | 89.14 | 1.539 | 8.550 | 8.28 | 1.201 |
|  |  | 1.38 | 200 | 1.4290 | 89.21 | 1.530 | 8.500 | 8.32 | 1.206 |
|  |  | 2.76 | 400 | 1.4313 | 89.35 | 1.513 | 8.406 | 8.40 | 1.218 |
|  |  | 4.14 | 600 | 1.4337 | 89.50 | 1.496 | 8.311 | 8.48 | 1.230 |
|  |  | 5.52 | 800 | 1.4360 | 89.65 | 1.480 | 8.222 | 8.56 | 1.242 |
| 273.15 | 32 | 6.89 | 1000 | 1.4383 | 89.79 | 1.464 | 8.133 | 8.65 | 1.254 |
|  |  | 8.62 | 1250 | 1.4412 | 89.97 | 1.445 | 8.028 | 8.75 | 1.269 |
|  |  | 10.34 | 1500 | 1.4440 | 90.15 | 1.426 | 7.922 | 8.85 | 1.284 |
|  |  | 12.07 | 1750 | 1.4468 | 90.32 | 1.408 | 7.822 | 8.96 | 1.299 |
|  |  | 13.79 | 2000 | 1.4496 | 90.50 | 1.390 | 7.722 | 9.07 | 1.315 |
|  |  | 27.58 | 4000 | 1.4707 | 91.81 | 1.270 | 7.056 | 9.98 | 1.447 |
|  |  | 41.37 | 6000 | 1.4903 | 93.04 | 1.179 | 6.550 | 10.97 | 1.591 |
|  |  | 55.16 | 8000 | 1.5082 | 94.15 | 1.111 | 6.172 | 12.05 | 1.748 |
| 273.15 | 32 | 68.95 | 10000 | 1.5248 | 95.19 | 1.059 | 5.883 | 13.23 | 1.919 |
|  |  | 86.18 | 12500 | 1.5437 | 96.37 | 1.007 | 5.594 | 14.83 | 2.151 |
|  |  | 103.42 | 15000 | 1.5608 | 97.44 | .960 | 5.333 | 16.55 | 2.401 |
|  |  | 120.66 | 17500 | 1.5763 | 98.41 | .906 | 5.033 | 18.37 | 2.665 |
|  |  | 137.90 | 20000 | 1.5904 | 99.29 | .835 | 4.639 | 20.23 | 2.934 |

## TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 283.15 | 50 | .10 | 15 | 1.4043 | 87.67 | 1.625 | 9.028 | 7.35 | 1.066 |
| | | .69 | 100 | 1.4055 | 87.74 | 1.615 | 8.972 | 7.38 | 1.071 |
| | | 1.38 | 200 | 1.4068 | 87.82 | 1.604 | 8.911 | 7.43 | 1.078 |
| | | 2.76 | 400 | 1.4094 | 87.99 | 1.582 | 8.789 | 7.52 | 1.090 |
| | | 4.14 | 600 | 1.4119 | 88.14 | 1.561 | 8.672 | 7.61 | 1.103 |
| | | 5.52 | 800 | 1.4145 | 88.31 | 1.540 | 8.556 | 7.70 | 1.116 |
| 283.15 | 50 | 6.89 | 1000 | 1.4170 | 88.46 | 1.520 | 8.444 | 7.78 | 1.129 |
| | | 8.62 | 1250 | 1.4201 | 88.65 | 1.496 | 8.311 | 7.89 | 1.145 |
| | | 10.34 | 1500 | 1.4232 | 88.85 | 1.473 | 8.183 | 8.01 | 1.161 |
| | | 12.07 | 1750 | 1.4263 | 89.04 | 1.450 | 8.056 | 8.12 | 1.178 |
| | | 13.79 | 2000 | 1.4293 | 89.23 | 1.429 | 7.939 | 8.24 | 1.195 |
| 293.15 | 68 | .15 | 22 | 1.3812 | 86.23 | 1.716 | 9.533 | 6.46 | .937 |
| | | .69 | 100 | 1.3823 | 86.30 | 1.704 | 9.467 | 6.49 | .942 |
| | | 1.38 | 200 | 1.3838 | 86.39 | 1.690 | 9.389 | 6.54 | .949 |
| | | 2.76 | 400 | 1.3867 | 86.20 | 1.662 | 9.233 | 6.63 | .962 |
| | | 4.14 | 600 | 1.3896 | 86.75 | 1.636 | 9.089 | 6.73 | .976 |
| | | 5.52 | 800 | 1.3924 | 86.93 | 1.610 | 8.944 | 6.83 | .990 |
| 293.15 | 68 | 6.89 | 1000 | 1.3952 | 87.10 | 1.585 | 8.806 | 6.92 | 1.004 |
| | | 8.62 | 1250 | 1.3986 | 87.31 | 1.555 | 8.639 | 7.04 | 1.021 |
| | | 10.34 | 1500 | 1.4020 | 87.52 | 1.526 | 8.478 | 7.16 | 1.039 |
| | | 12.07 | 1750 | 1.4054 | 87.74 | 1.499 | 8.328 | 7.29 | 1.058 |
| | | 13.79 | 2000 | 1.4087 | 87.94 | 1.473 | 8.183 | 7.42 | 1.076 |
| 303.15 | 86 | .21 | 31 | 1.3572 | 84.73 | 1.819 | 10.11 | 5.61 | .814 |
| | | .69 | 100 | 1.3583 | 84.80 | 1.807 | 10.04 | 5.64 | .819 |
| | | 1.38 | 200 | 1.3600 | 84.90 | 1.789 | 9.939 | 5.70 | .826 |
| | | 2.76 | 400 | 1.3632 | 85.10 | 1.755 | 9.750 | 5.79 | .840 |
| | | 4.14 | 600 | 1.3665 | 85.31 | 1.722 | 9.567 | 5.89 | .854 |
| | | 5.52 | 800 | 1.3696 | 85.50 | 1.690 | 9.389 | 5.98 | .868 |
| 303.15 | 86 | 6.89 | 1000 | 1.3728 | 85.70 | 1.659 | 9.217 | 6.09 | .883 |
| | | 8.62 | 1250 | 1.3766 | 85.94 | 1.622 | 9.011 | 6.22 | .902 |
| | | 10.34 | 1500 | 1.3804 | 86.18 | 1.588 | 8.822 | 6.35 | .921 |
| | | 12.07 | 1750 | 1.3841 | 86.41 | 1.554 | 8.633 | 6.49 | .941 |
| | | 13.79 | 2000 | 1.3877 | 86.63 | 1.523 | 8.461 | 6.62 | .960 |

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 313.15 | 104 | .30 | 43 | 1.3321 | 83.16 | 1.936 | 10.76 | 4.83 | .700 |
| | | .69 | 100 | 1.3332 | 83.23 | 1.924 | 10.69 | 4.85 | .704 |
| | | 1.38 | 200 | 1.3351 | 83.35 | 1.902 | 10.57 | 4.90 | .711 |
| | | 2.76 | 400 | 1.3388 | 83.58 | 1.860 | 10.33 | 5.01 | .726 |
| | | 4.14 | 600 | 1.3425 | 83.81 | 1.819 | 10.11 | 5.10 | .740 |
| | | 5.52 | 800 | 1.3461 | 84.04 | 1.780 | 9.889 | 5.21 | .755 |
| 313.15 | 104 | 6.89 | 1000 | 1.3496 | 84.25 | 1.743 | 9.683 | 5.31 | .770 |
| | | 8.62 | 1250 | 1.3540 | 84.53 | 1.698 | 9.433 | 5.45 | .791 |
| | | 10.34 | 1500 | 1.3582 | 84.79 | 1.656 | 9.200 | 5.58 | .810 |
| | | 12.07 | 1750 | 1.3623 | 85.05 | 1.616 | 8.978 | 5.72 | .830 |
| | | 13.79 | 2000 | 1.3664 | 85.30 | 1.579 | 8.772 | 5.87 | .851 |
| 323.15 | 122 | .39 | 57 | 1.3060 | 81.53 | 2.068 | 11.49 | 4.12 | .598 |
| | | .69 | 100 | 1.3070 | 81.59 | 2.057 | 11.43 | 4.14 | .601 |
| | | 1.38 | 200 | 1.3091 | 81.73 | 2.030 | 11.28 | 4.19 | .608 |
| | | 2.76 | 400 | 1.3134 | 81.99 | 1.979 | 10.99 | 4.29 | .622 |
| | | 4.14 | 600 | 1.3176 | 82.26 | 1.930 | 10.72 | 4.39 | .637 |
| | | 5.52 | 800 | 1.3217 | 82.51 | 1.883 | 10.46 | 4.50 | .652 |
| 323.15 | 122 | 6.89 | 1000 | 1.3257 | 82.76 | 1.838 | 10.21 | 4.60 | .667 |
| | | 8.62 | 1250 | 1.3306 | 83.07 | 1.784 | 9.911 | 4.74 | .687 |
| | | 10.34 | 1500 | 1.3354 | 83.37 | 1.734 | 9.633 | 4.87 | .707 |
| | | 12.07 | 1750 | 1.3400 | 83.65 | 1.686 | 9.367 | 5.02 | .728 |
| | | 13.79 | 2000 | 1.3446 | 83.94 | 1.641 | 9.117 | 5.16 | .749 |
| 333.15 | 140 | .52 | 75 | 1.2788 | 79.83 | 2.215 | 12.31 | 3.51 | .509 |
| | | .69 | 100 | 1.2794 | 79.87 | 2.207 | 12.26 | 3.52 | .511 |
| | | 1.38 | 200 | 1.2819 | 80.03 | 2.175 | 12.08 | 3.56 | .517 |
| | | 2.76 | 400 | 1.2868 | 80.33 | 2.113 | 11.74 | 3.66 | .531 |
| | | 4.14 | 600 | 1.2916 | 80.63 | 2.054 | 11.41 | 3.76 | .545 |
| | | 5.52 | 800 | 1.2963 | 80.93 | 1.997 | 11.09 | 3.86 | .560 |
| 333.15 | 140 | 6.89 | 1000 | 1.3009 | 81.21 | 1.944 | 10.80 | 3.96 | .575 |
| | | 8.62 | 1250 | 1.3064 | 81.56 | 1.880 | 10.44 | 4.10 | .594 |
| | | 10.34 | 1500 | 1.3119 | 81.90 | 1.820 | 10.11 | 4.23 | .614 |
| | | 12.07 | 1750 | 1.3171 | 82.22 | 1.763 | 9.794 | 4.38 | .635 |
| | | 13.79 | 2000 | 1.3222 | 82.54 | 1.710 | 9.500 | 4.52 | .656 |

# TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 343.15 | 158 | .67 | 97 | 1.2504 | 78.06 | 2.378 | 13.21 | 2.98 | .432 |
| | | .69 | 100 | 1.2505 | 78.07 | 2.377 | 13.21 | 2.98 | .432 |
| | | 1.38 | 200 | 1.2533 | 78.24 | 2.338 | 12.99 | 3.03 | .439 |
| | | 2.76 | 400 | 1.2590 | 78.60 | 2.264 | 12.58 | 3.12 | .452 |
| | | 4.14 | 600 | 1.2645 | 78.94 | 2.194 | 12.19 | 3.21 | .465 |
| | | 5.52 | 800 | 1.2699 | 79.28 | 2.126 | 11.81 | 3.30 | .479 |
| 343.15 | 158 | 6.89 | 1000 | 1.2751 | 79.60 | 2.062 | 11.46 | 3.40 | .493 |
| | | 8.62 | 1250 | 1.2814 | 80.00 | 1.987 | 11.04 | 3.53 | .512 |
| | | 10.34 | 1500 | 1.2876 | 80.38 | 1.916 | 10.64 | 3.66 | .531 |
| | | 12.07 | 1750 | 1.2936 | 80.76 | 1.849 | 10.27 | 3.81 | .552 |
| | | 13.79 | 2000 | 1.2993 | 81.11 | 1.787 | 9.928 | 3.96 | .573 |
| 353.15 | 176 | .85 | 124 | 1.2207 | 76.21 | 2.557 | 14.21 | 2.52 | .366 |
| | | 1.38 | 200 | 1.2233 | 76.37 | 2.522 | 14.01 | 2.56 | .371 |
| | | 2.76 | 400 | 1.2298 | 76.77 | 2.434 | 13.52 | 2.64 | .383 |
| | | 4.14 | 600 | 1.2361 | 77.17 | 2.350 | 13.06 | 2.74 | .396 |
| | | 5.52 | 800 | 1.2423 | 77.56 | 2.270 | 12.61 | 2.82 | .409 |
| 353.15 | 176 | 6.89 | 1000 | 1.2482 | 77.92 | 2.195 | 12.19 | 2.92 | .423 |
| | | 8.62 | 1250 | 1.2555 | 78.38 | 2.106 | 11.70 | 3.03 | .440 |
| | | 10.34 | 1500 | 1.2625 | 78.82 | 2.022 | 11.23 | 3.16 | .459 |
| | | 12.07 | 1750 | 1.2695 | 79.25 | 1.945 | 10.81 | 3.30 | .478 |
| | | 13.79 | 2000 | 1.2758 | 79.65 | 1.872 | 10.40 | 3.43 | .498 |
| 363.15 | 194 | 1.08 | 156 | 1.1899 | 74.28 | 2.753 | 15.29 | 2.14 | .311 |
| | | 1.38 | 200 | 1.1916 | 74.39 | 2.729 | 15.16 | 2.16 | .314 |
| | | 2.76 | 400 | 1.1991 | 74.86 | 2.625 | 14.58 | 2.24 | .325 |
| | | 4.14 | 600 | 1.2063 | 75.31 | 2.525 | 14.03 | 2.32 | .337 |
| | | 5.52 | 800 | 1.2134 | 75.75 | 2.431 | 13.51 | 2.41 | .349 |
| 363.15 | 194 | 6.89 | 1000 | 1.2203 | 76.18 | 2.342 | 13.01 | 2.49 | .361 |
| | | 8.62 | 1250 | 1.2285 | 76.69 | 2.238 | 12.43 | 2.61 | .378 |
| | | 10.34 | 1500 | 1.2365 | 77.19 | 2.140 | 11.89 | 2.73 | .396 |
| | | 12.07 | 1750 | 1.2442 | 77.67 | 2.050 | 11.39 | 2.85 | .414 |
| | | 13.79 | 2000 | 1.2515 | 78.13 | 1.965 | 10.92 | 2.99 | .433 |

TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 373.15 | 212 | 1.33 | 193 | 1.1579 | 72.29 | 2.967 | 16.48 | 1.83 | .265 |
| | | 1.38 | 200 | 1.1582 | 72.30 | 2.962 | 16.46 | 1.83 | .265 |
| | | 2.76 | 400 | 1.1668 | 72.84 | 2.839 | 15.77 | 1.90 | .275 |
| | | 4.14 | 600 | 1.1751 | 72.36 | 2.722 | 15.12 | 1.97 | .286 |
| | | 5.52 | 800 | 1.1832 | 73.87 | 2.611 | 14.51 | 2.05 | .297 |
| 373.15 | 212 | 6.89 | 1000 | 1.1911 | 74.36 | 2.507 | 13.93 | 2.13 | .309 |
| | | 8.62 | 1250 | 1.2005 | 74.95 | 2.385 | 13.25 | 2.23 | .324 |
| | | 10.34 | 1500 | 1.2096 | 75.51 | 2.271 | 12.62 | 2.35 | .341 |
| | | 12.07 | 1750 | 1.2182 | 76.05 | 2.166 | 12.03 | 2.47 | .358 |
| | | 13.79 | 2000 | 1.2266 | 76.57 | 2.068 | 11.49 | 2.59 | .376 |
| 383.15 | 230 | 1.63 | 236 | 1.1247 | 70.21 | 3.199 | 17.77 | 1.56 | .226 |
| | | 2.76 | 400 | 1.1328 | 70.72 | 3.080 | 17.11 | 1.61 | .233 |
| | | 4.14 | 600 | 1.1423 | 71.31 | 2.942 | 16.34 | 1.68 | .243 |
| | | 5.52 | 800 | 1.1516 | 71.89 | 2.812 | 15.62 | 1.74 | .253 |
| 383.15 | 230 | 6.89 | 1000 | 1.1605 | 72.45 | 2.690 | 14.94 | 1.82 | .264 |
| | | 8.62 | 1250 | 1.1713 | 73.12 | 2.548 | 14.16 | 1.92 | .279 |
| | | 10.34 | 1500 | 1.1815 | 73.76 | 2.416 | 13.42 | 2.03 | .294 |
| | | 12.07 | 1750 | 1.1914 | 74.38 | 2.294 | 12.74 | 2.14 | .310 |
| | | 13.79 | 2000 | 1.2008 | 74.96 | 2.182 | 12.12 | 2.25 | .327 |
| 393.15 | 248 | 1.97 | 286 | 1.0906 | 68.08 | 3.448 | 19.16 | 1.33 | .193 |
| | | 2.76 | 400 | 1.0970 | 68.48 | 3.351 | 18.62 | 1.37 | .198 |
| | | 4.14 | 600 | 1.1079 | 69.16 | 3.189 | 17.72 | 1.43 | .207 |
| | | 5.52 | 800 | 1.1184 | 69.82 | 3.038 | 16.88 | 1.49 | .216 |
| 393.15 | 248 | 6.89 | 1000 | 1.1286 | 70.46 | 2.895 | 16.08 | 1.56 | .226 |
| | | 8.62 | 1250 | 1.1408 | 71.22 | 2.730 | 15.17 | 1.65 | .239 |
| | | 10.34 | 1500 | 1.1524 | 71.94 | 2.577 | 14.32 | 1.74 | .253 |
| | | 12.07 | 1750 | 1.1636 | 72.64 | 2.436 | 13.53 | 1.85 | .268 |
| | | 13.79 | 2000 | 1.1742 | 73.30 | 2.306 | 12.81 | 1.96 | .284 |

TABLE 1 - SMOOTHED VALUES OF DENSITY, COEFFICIENT OF THERMAL EXPANSION, AND BULK MODULUS OF ELASTICITY OF REFRIGERANT-21

| Temperature | | Pressure | | Density | | Coefficient of Thermal Expansion | | Bulk Modulus | |
|---|---|---|---|---|---|---|---|---|---|
| K | °F | N/m$^2$ x E-6 | psia | kg/m$^2$ x E-3 | lb/ft$^3$ | 1E3/°C | 1E4/°F | N/m$^2$ x E-8 | psia XE-5 |
| 403.15 | 266 | 2.37 | 344 | 1.0557 | 65.91 | 3.714 | 20.63 | 1.14 | .166 |
| | | 2.76 | 400 | 1.0592 | 66.12 | 3.658 | 20.32 | 1.16 | .168 |
| | | 4.14 | 600 | 1.0716 | 66.90 | 3.468 | 19.27 | 1.21 | .176 |
| | | 5.52 | 800 | 1.0836 | 67.65 | 3.290 | 18.28 | 1.27 | .184 |
| 403.15 | 266 | 6.89 | 1000 | 1.0951 | 68.37 | 3.124 | 17.36 | 1.33 | .193 |
| | | 8.62 | 1250 | 1.1090 | 69.23 | 2.932 | 16.29 | 1.41 | .205 |
| | | 10.34 | 1500 | 1.1221 | 70.05 | 2.755 | 15.31 | 1.50 | .218 |
| | | 12.07 | 1750 | 1.1347 | 70.84 | 2.593 | 14.41 | 1.60 | .232 |
| | | 13.79 | 2000 | 1.1466 | 71.58 | 2.444 | 13.58 | 1.70 | .247 |
| 413.15 | 284 | 2.83 | 410 | 1.0202 | 63.69 | 3.995 | 22.19 | .099 | .143 |
| | | 4.14 | 600 | 1.0335 | 64.52 | 3.783 | 21.02 | 1.03 | .150 |
| | | 5.52 | 800 | 1.0471 | 65.37 | 3.575 | 19.86 | 1.08 | .157 |
| 413.15 | 284 | 6.89 | 1000 | 1.0601 | 66.18 | 3.381 | 18.78 | 1.14 | .166 |
| | | 8.62 | 1250 | 1.0757 | 67.15 | 3.157 | 17.54 | 1.22 | .177 |
| | | 10.34 | 1500 | 1.0906 | 68.08 | 2.953 | 16.41 | 1.30 | .188 |
| | | 12.07 | 1750 | 1.1047 | 68.96 | 2.766 | 15.37 | 1.39 | .201 |
| | | 13.79 | 2000 | 1.1181 | 69.80 | 2.595 | 14.42 | 1.48 | .214 |
| 423.15 | 302 | 3.34 | 484 | .9843 | 61.45 | 4.292 | 23.84 | .085 | .123 |
| | | 4.14 | 600 | .9934 | 62.02 | 4.141 | 23.00 | .088 | .127 |
| | | 5.52 | 800 | 1.0087 | 62.97 | 3.896 | 21.64 | .092 | .134 |
| 423.15 | 302 | 6.89 | 1000 | 1.0234 | 63.89 | 3.670 | 20.39 | .098 | .142 |
| | | 8.62 | 1250 | 1.0410 | 64.99 | 3.409 | 18.94 | 1.05 | .152 |
| | | 10.34 | 1500 | 1.0577 | 66.03 | 3.173 | 17.63 | 1.12 | .163 |
| | | 12.07 | 1750 | 1.0736 | 67.02 | 2.958 | 16.43 | 1.20 | .174 |
| | | 13.79 | 2000 | 1.0886 | 67.96 | 2.762 | 15.34 | 1.28 | .186 |

# TABLE 2 - EXPERIMENTAL FREEZING POINTS OF REFRIGERANT-21

| Pressure | | Temperature | | | |
|---|---|---|---|---|---|
| | | Solid I | | Solid II | |
| N/m$^2$ X 10$^{-6}$ | Psia | K | °F | K | °F |
| 0.69 | 100 | 135.8 | -215.3 | 139.3 | -209.0 |
| 1.38 | 200 | 135.8 | -215.3 | 139.9 | -207.9 |
| 2.76 | 400 | 135.9 | -215.2 | 140.5 | -206.9 |
| 4.83 | 700 | 136.1 | -214.8 | 140.9 | -206.1 |
| 6.89 | 1000 | 136.0 | -214.6 | 141.3 | -205.4 |
| 10.34 | 1500 | 136.4 | -214.2 | 141.8 | -204.5 |
| 13.79 | 2000 | 136.7 | -213.7 | 142.2 | -203.8 |
| 20.69 | 3000 | - | - | 143.0 | -202.4 |
| 27.58 | 4000 | 137.8 | -211.7 | 143.6 | -201.3 |
| 34.48 | 5000 | 138.4 | -210.6 | 144.6 | -199.5 |
| 41.37 | 6000 | - | - | 145.4 | -198.0 |
| 48.27 | 7000 | 140.4 | -207.0 | 146.1 | -196.8 |
| 55.16 | 8000 | 141.1 | -205.8 | 147.0 | -195.2 |
| 62.06 | 9000 | 142.0 | -204.2 | 147.8 | -193.7 |
| 68.95 | 10000 | 142.8 | -202.7 | 148.5 | -192.5 |
| 75.85 | 11000 | - | - | 149.6 | -190.5 |
| 82.74 | 12000 | 144.2 | -200.2 | 150.6 | -188.7 |
| 89.64 | 13000 | 145.6 | -198.4 | 151.2 | -187.6 |
| 96.53 | 14000 | 145.9 | -197.1 | 151.8 | -186.5 |
| 103.42 | 15000 | 146.8 | 195.5 | 152.6 | -185.1 |
| 110.32 | 16000 | - | - | 153.4 | -183.6 |
| 117.22 | 17000 | - | - | 154.5 | -181.7 |
| 124.11 | 18000 | - | - | 155.8 | -179.3 |
| 131.00 | 19000 | - | - | 157.6 | -176.1 |
| 137.90 | 20000 | - | - | 161.1 | -169.8 |

### TABLE 3 - COEFFICIENTS FROM LEAST-SQUARES FIT OF VISCOSITY OF REFRIGERANT-21 AS A FUNCTION OF TEMPERATURE

ln Viscosity (cp) = A + B/T + CT (T in K)
273 to 423 Kelvin

| Pressure | Coefficients | | | Standard Error Of Estimate |
|---|---|---|---|---|
| $N/m^2 \times 10^{-6}$ | A | $B \times 10^{-1}$ | $C \times 10^3$ | |
| 4.14 | 1.822 | -10.25 | -8.654 | 0.0033 |
| 6.89 | 1.764 | - 9.095 | -8.545 | 0.0023 |
| 10.34 | 1.755 | - 9.666 | -8.416 | 0.0029 |

### TABLE 4 - COEFFICIENTS FROM LEAST-SQUARES FIT OF VISCOSITY OF REFRIGERANT-21 AS A FUNCTION OF TEMPERATURE

ln Viscosity (cp) = A + B/T + CT (T in K)
143 to 273 Kelvin

| Temperature Range, Kelvin | Coefficients | | | Standard Error Of Estimate |
|---|---|---|---|---|
| | A | $B \times 10^{-2}$ | $C \times 10^3$ | |
| 193 to 273 | - 4.472 | 8.403 | 1.768 | 0.0029 |
| 143 to 193 | -13.40 | 16.68 | 25.83 | 0.0037 |

# TABLE 5 - COEFFICIENTS FROM LEAST-SQUARES FIT OF VISCOSITY OF REFRIGERANT-21 AS A FUNCTION OF PRESSURE

Viscosity, cp = A + BP, (P in psia)
(Vapor Pressure +50) psia to 1500 psia

| Temperature | | Coefficients | | Standard Error Of Estimate |
|---|---|---|---|---|
| K | °F | $A \times 10^1$ | $B \times 10^6$ | |
| 273.15 | 32 | 3.99 | 5.24 | 0.0021 |
| 293.15 | 68 | 3.37 | 11.24 | 0.0012 |
| 313.15 | 104 | 2.92 | 8.60 | 0.0015 |
| 333.15 | 140 | 2.53 | 5.46 | 0.0022 |
| 353.15 | 176 | 2.16 | 5.11 | 0.0015 |
| 373.15 | 212 | 1.85 | 4.26 | 0.0017 |
| 393.15 | 248 | 1.57 | 4.66 | 0.0014 |
| 413.15 | 284 | 1.30 | 7.15 | 0.0003 |
| 423.15 | 302 | 1.20 | 6.05 | 0.0020 |

## TABLE 6 - CALCULATED VISCOSITY OF REFRIGERANT-21
273 to 423 Kelvin

| Temperature | | Pressure | | Viscosity | |
|---|---|---|---|---|---|
| K | °F | $N/m^2 \times 10^{-6}$ | Psia | cp | $\frac{lbf\text{-}s}{ft^2} \times 10^6$ |
| 273.15 | 32 | 0.072 | 10.4 | 0.399 | 8.33 |
| 293.15 | 68 | 0.154 | 22.3 | 0.337 | 7.04 |
| 313.15 | 104 | 0.295 | 42.8 | 0.292 | 6.10 |
| 333.15 | 140 | 0.520 | 75.4 | 0.253 | 5.28 |
| 353.15 | 176 | 0.855 | 124 | 0.217 | 4.53 |
| 373.15 | 212 | 1.33 | 193 | 0.186 | 3.88 |
| 393.15 | 248 | 1.97 | 286 | 0.159 | 3.32 |
| 413.15 | 284 | 2.83 | 410 | 0.133 | 2.78 |
| 423.15 | 302 | 3.34 | 484 | 0.123 | 2.57 |

| Temperature | | Viscosity | | | | | |
|---|---|---|---|---|---|---|---|
| | | $4.14 \times 10^6$ N/m$^2$ (600 psia) | | $6.90 \times 10^6$ N/m$^2$ (1000 psia) | | $10.34 \times 10^6$ N/m$^2$ (1500 psia) | |
| K | °F | cp | $\frac{lbf\text{-}s}{ft^2} \times 10^6$ | cp | $\frac{lbf\text{-}s}{ft^2} \times 10^6$ | cp | $\frac{lbf\text{-}s}{ft^2} \times 10^6$ |
| 273.15 | 32 | 0.401 | 8.38 | 0.404 | 8.44 | 0.407 | 8.50 |
| 293.15 | 68 | 0.345 | 7.21 | 0.350 | 7.31 | 0.353 | 7.37 |
| 313.15 | 104 | 0.297 | 6.20 | 0.301 | 6.29 | 0.304 | 6.35 |
| 333.15 | 140 | 0.254 | 5.30 | 0.258 | 5.39 | 0.262 | 5.47 |
| 353.15 | 176 | 0.218 | 4.55 | 0.221 | 4.62 | 0.225 | 4.70 |
| 373.15 | 212 | 0.186 | 3.88 | 0.189 | 3.95 | 0.193 | 4.03 |
| 393.15 | 248 | 0.159 | 3.32 | 0.161 | 3.36 | 0.165 | 3.45 |
| 413.15 | 284 | 0.135 | 2.82 | 0.137 | 2.86 | 0.141 | 2.94 |
| 423.15 | 302 | 0.125 | 2.61 | 0.127 | 2.65 | 0.131 | 2.74 |

## TABLE 7 - CALCULATED DENSITY AND VISCOSITY OF REFRIGERANT 21

143.15 to 273.15 K, Atmospheric Pressure

| Temperature | | Density | | Viscosity | |
|---|---|---|---|---|---|
| K | °F | kg/m$^3$ x 10$^{-3}$ | lb/ft$^3$ | cp | $\frac{\text{lbf-s}}{\text{ft}^2}$ x 10$^6$ |
| 273.15 | 32 | 1.4223 | 88.792 | 0.401 | 8.38 |
| 263.15 | 14 | 1.4436 | 90.122 | 0.443 | 9.25 |
| 253.15 | - 4 | 1.4648 | 91.445 | 0.494 | 10.32 |
| 243.15 | - 22 | 1.4860 | 92.769 | 0.556 | 11.6 |
| 233.15 | - 40 | 1.5074 | 94.105 | 0.634 | 13.2 |
| 223.15 | - 58 | 1.5290 | 95.453 | 0.732 | 15.3 |
| 213.15 | - 76 | 1.5509 | 96.821 | 0.858 | 17.9 |
| 203.15 | - 94 | 1.5733 | 98.219 | 1.02 | 21.3 |
| 193.15 | -112 | 1.5962 | 99.649 | 1.25 | 26.1 |
| 183.15 | -130 | 1.6197 | 101.12 | 1.54 | 32.2 |
| 173.15 | -148 | 1.6440 | 102.63 | 2.01 | 42.0 |
| 163.15 | -166 | 1.6691 | 104.20 | 2.81 | 58.7 |
| 153.15 | -184 | 1.6951 | 105.82 | 4.23 | 88.3 |
| 143.15 | -202 | 1.7222 | 107.51 | 6.99 | 146 |

TABLE 8 - SMOOTHED VALUES OF THE VAPOR PRESSURE FOR REFRIGERANT 21 FROM 143.15 to 423.15 KELVIN

| Temperature | | Pressure | |
|---|---|---|---|
| K | °F | $\frac{N}{m^2} \times 10^{-6}$ | Psia |
| 143.15 | -202 | 0.0000005 | 0.00007 |
| 153.15 | -184 | 0.00000296 | 0.00043 |
| 163.15 | -166 | 0.0000134 | 0.00195 |
| 173.15 | -148 | 0.0000501 | 0.00727 |
| 183.15 | -130 | 0.000158 | 0.0229 |
| 193.15 | -112 | 0.000436 | 0.0632 |
| 203.15 | - 94 | 0.001071 | 0.1554 |
| 213.15 | - 76 | 0.00239 | 0.347 |
| 223.15 | - 58 | 0.00492 | 0.713 |
| 233.15 | - 40 | 0.00940 | 1.364 |
| 243.15 | - 22 | 0.0169 | 2.45 |
| 253.15 | - 4 | 0.0287 | 4.16 |
| 263.15 | 14 | 0.0464 | 6.73 |
| 273.15 | 32 | 0.0717 | 10.40 |
| 283.15 | 50 | 0.1065 | 15.44 |
| 293.15 | 68 | 0.1535 | 22.27 |
| 303.15 | 86 | 0.2153 | 31.23 |
| 313.15 | 104 | 0.2948 | 42.76 |
| 323.15 | 122 | 0.395 | 57.3 |
| 333.15 | 140 | 0.520 | 75.4 |
| 343.15 | 158 | 0.672 | 97.4 |
| 353.15 | 176 | 0.855 | 124.0 |
| 363.15 | 194 | 1.073 | 155.6 |
| 373.15 | 212 | 1.329 | 192.8 |
| 383.15 | 230 | 1.630 | 236.4 |
| 393.15 | 248 | 1.975 | 286.4 |
| 403.15 | 266 | 2.372 | 344.0 |
| 413.15 | 284 | 2.823 | 409.5 |
| 423.15 | 302 | 3.336 | 483.8 |

## TABLE 9 - SMOOTHED HEAT CAPACITIES FOR REFRIGERANT-21 AT 0.207 X $10^6$ N/m$^2$ (30 psia)

| Temperature | | Heat Capacity, $C_p$ | |
|---|---|---|---|
| K | °F | Cal. / (g-mole) (°C) | Btu/(lb) (°F) |
| 153.15 | -184 | 23.82 | 0.231 |
| 173.15 | -148 | 23.93 | 0.232 |
| 193.15 | -112 | 24.00 | 0.233 |
| 213.15 | - 76 | 24.07 | 0.234 |
| 233.15 | - 40 | 24.19 | 0.235 |
| 253.15 | - 4 | 24.50 | 0.238 |

## TABLE 10 - SMOOTHED HEAT CAPACITIES FOR REFRIGERANT-21 AT 0.69 X $10^6$ N/m$^2$ (100 psia)

| Temperature | | Heat Capacity, $C_p$ | |
|---|---|---|---|
| K | °F | Cal. / (g-mole) (°C) | Btu/(lb) (°F) |
| 153.15 | -184 | 23.98 | 0.233 |
| 173.15 | -148 | 23.97 | 0.233 |
| 193.15 | -112 | 23.98 | 0.233 |
| 213.15 | - 76 | 24.06 | 0.234 |
| 233.15 | - 40 | 24.28 | 0.236 |
| 253.15 | - 4 | 24.78 | 0.241 |
| 273.15 | 32 | 25.78 | 0.250 |

## TABLE 11 - SMOOTHED HEAT CAPACITIES FOR REFRIGERANT-21 AT 3.45 X $10^6$ N/$m^2$ (500 psia)

| Temperature | | Heat Capacity, $C_p$ | |
|---|---|---|---|
| K | °F | Cal. /(g-mole) (°C) | Btu/(lb) (°F) |
| 153.15 | -184 | 24.17 | 0.235 |
| 173.15 | -148 | 23.77 | 0.231 |
| 193.15 | -112 | 23.76 | 0.231 |
| 213.15 | - 76 | 23.95 | 0.233 |
| 233.15 | - 40 | 24.24 | 0.235 |
| 253.15 | - 4 | 24.55 | 0.239 |
| 273.15 | 32 | 24.91 | 0.242 |
| 243.15 | 68 | 25.34 | 0.246 |
| 313.15 | 104 | 25.87 | 0.251 |
| 333.15 | 140 | 26.54 | 0.258 |
| 353.15 | 176 | 27.41 | 0.266 |
| 373.15 | 212 | 28.67 | 0.279 |
| 393.15 | 248 | 30.78 | 0.299 |
| 413.15 | 284 | 35.83 | 0.348 |

## TABLE 12 - COEFFICIENTS FROM LEAST-SQUARES FIT OF THERMAL CONDUCTIVITY DATA FOR REFRIGERANT-21

$$\lambda\ (W/(m)(k)) = A + BT\ (T \text{ in K})$$

| | Coefficients | |
|---|---|---|
| Temperature Range | A | $B \times 10^4$ |
| 143 to 273 K<br>(50 psia) | 0.1997 | -2.674 |
| 273 to 423 K<br>(Vapor pressure +50) psia | 0.2059 | -2.882 |
| 273 to 403 K<br>(400 psia) | 0.2044 | -2.881 |

## TABLE 13

## SMOOTHED THERMAL CONDUCTIVITY OF REFRIGERANT 21

0.344 X $10^6$ N/$m^2$, 143.15 to 273.15 Kelvin
(50 psia)

| Temperature | | Thermal Conductivity | |
|---|---|---|---|
| K | °F | W/(m) (C deg.) | Btu/(hr)(ft)(F deg.) |
| 273.15 | 32 | 0.1267 | 0.0733 |
| 263.15 | 14 | 0.1294 | 0.0748 |
| 253.15 | 4 | 0.1320 | 0.0763 |
| 243.15 | - 22 | 0.1347 | 0.0779 |
| 233.15 | - 40 | 0.1374 | 0.0794 |
| 223.15 | - 58 | 0.1401 | 0.0810 |
| 213.15 | - 76 | 0.1427 | 0.0825 |
| 203.15 | - 94 | 0.1454 | 0.0841 |
| 193.15 | -112 | 0.1481 | 0.0856 |
| 183.15 | -130 | 0.1508 | 0.0872 |
| 173.15 | -148 | 0.1534 | 0.0887 |
| 163.15 | -166 | 0.1561 | 0.0903 |
| 153.15 | -184 | 0.1588 | 0.0918 |
| 143.15 | -202 | 0.1614 | 0.0933 |

## TABLE 14

## SMOOTHED THERMAL CONDUCTIVITY OF REFRIGERANT 21

(Vapor Pressure + 0.344 X $10^6$) N/$m^2$, 273.15 to 423.15 Kelvin
(Vapor Pressure +50) psia

| Temperature | | Thermal Conductivity | |
|---|---|---|---|
| K | °F | W/(m) (C deg.) | Btu/(hr)(ft)(F deg.) |
| 423.15 | 302 | 0.0839 | 0.0485 |
| 413.15 | 284 | 0.0868 | 0.0502 |
| 403.15 | 266 | 0.0897 | 0.0519 |
| 393.15 | 248 | 0.0926 | 0.0535 |
| 383.15 | 230 | 0.0955 | 0.0552 |
| 373.15 | 212 | 0.0984 | 0.0569 |
| 363.15 | 194 | 0.1012 | 0.0585 |
| 353.15 | 176 | 0.1041 | 0.0602 |
| 343.15 | 158 | 0.1070 | 0.0619 |
| 333.15 | 140 | 0.1099 | 0.0635 |
| 323.15 | 122 | 0.1128 | 0.0652 |
| 313.15 | 104 | 0.1156 | 0.0668 |
| 303.15 | 86 | 0.1185 | 0.0685 |
| 293.15 | 68 | 0.1214 | 0.0702 |
| 283.15 | 50 | 0.1243 | 0.0719 |
| 273.15 | 32 | 0.1271 | 0.0735 |

# TABLE 15

## SMOOTHED THERMAL CONDUCTIVITY OF REFRIGERANT 21

2.76 X $10^6$ N/$m^2$, 273.15 to 403.15 Kelvin
(400 psia)

| Temperature | | Thermal Conductivity | |
|---|---|---|---|
| K | °F | W/(m) (C deg.) | Btu/(hr)(ft)(F deg.) |
| 403.15 | 266 | 0.0883 | 0.0511 |
| 393.15 | 248 | 0.0912 | 0.0527 |
| 383.15 | 230 | 0.0940 | 0.0543 |
| 373.15 | 212 | 0.0969 | 0.0560 |
| 363.15 | 194 | 0.0998 | 0.0577 |
| 353.15 | 176 | 0.1027 | 0.0594 |
| 343.15 | 158 | 0.1056 | 0.0611 |
| 333.15 | 140 | 0.1084 | 0.0627 |
| 323.15 | 122 | 0.1113 | 0.0644 |
| 313.15 | 104 | 0.1142 | 0.0660 |
| 303.15 | 86 | 0.1171 | 0.0677 |
| 293.15 | 68 | 0.1200 | 0.0694 |
| 283.15 | 50 | 0.1229 | 0.0711 |
| 273.15 | 32 | 0.1257 | 0.0727 |

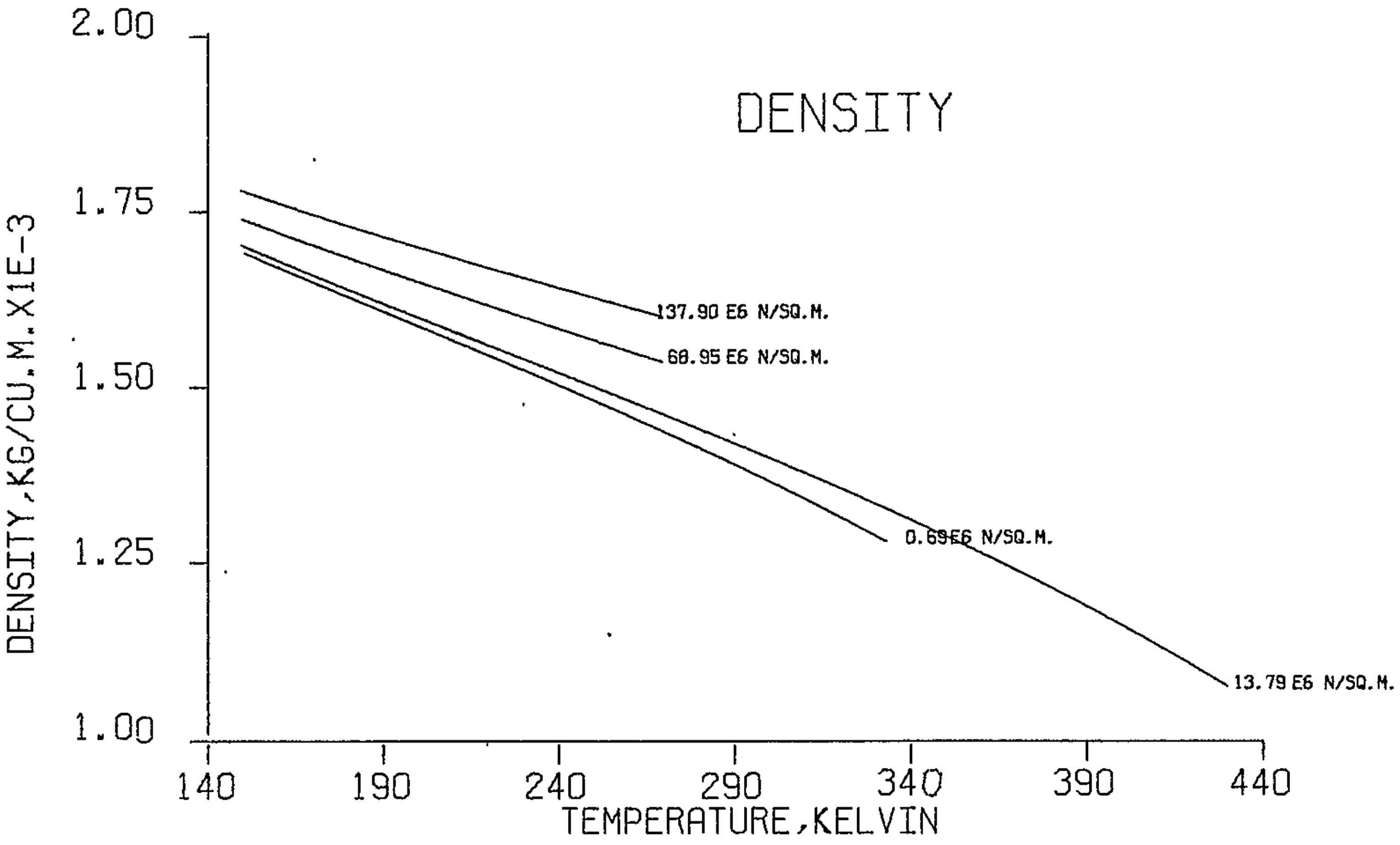

Figure 1 - Effect of Temperature on the Density of Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x $10^6$ N/$m^2$

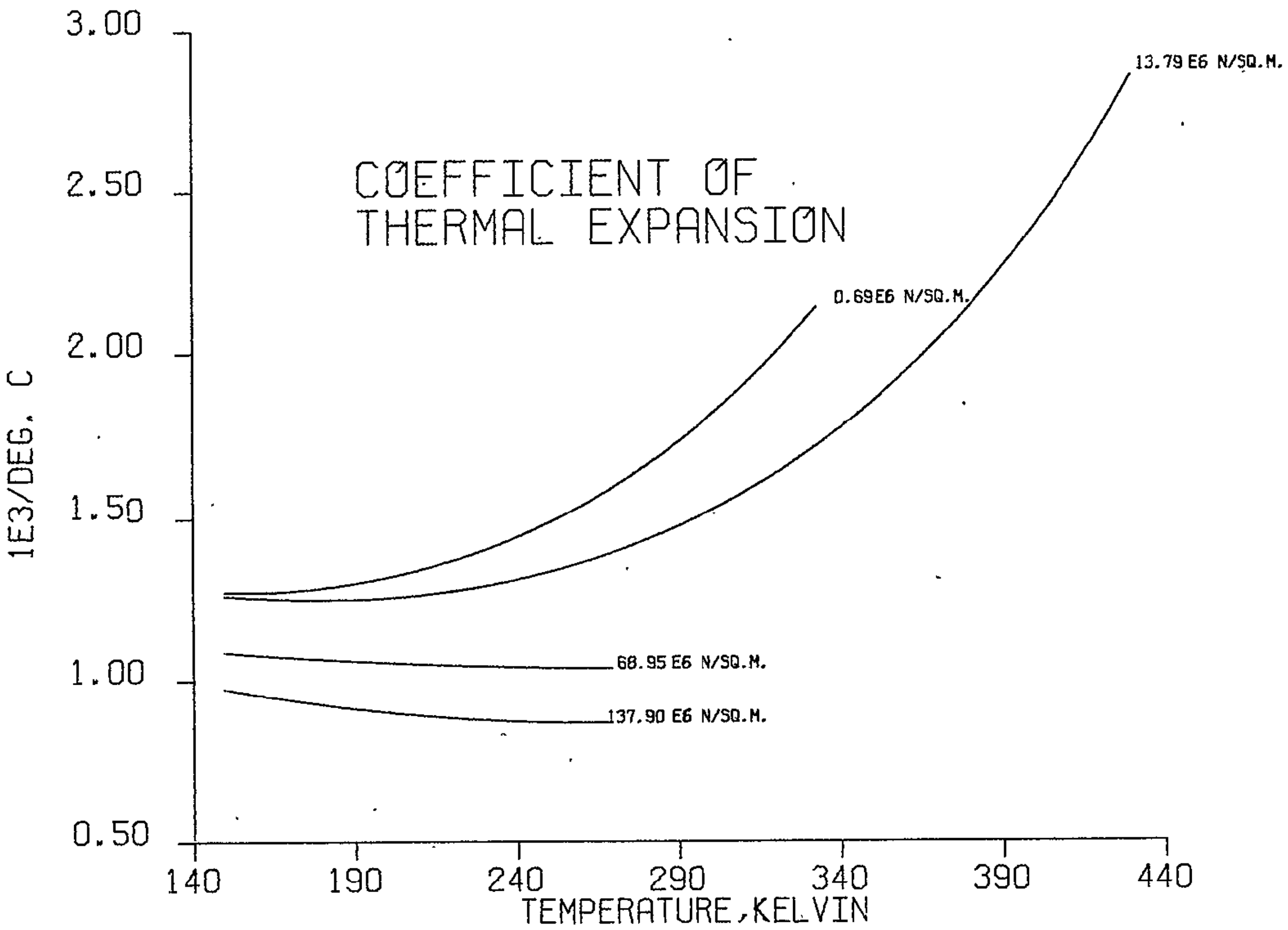

Figure 2 - Coefficient of Thermal Expansion for Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x $10^6$ N/$m^2$

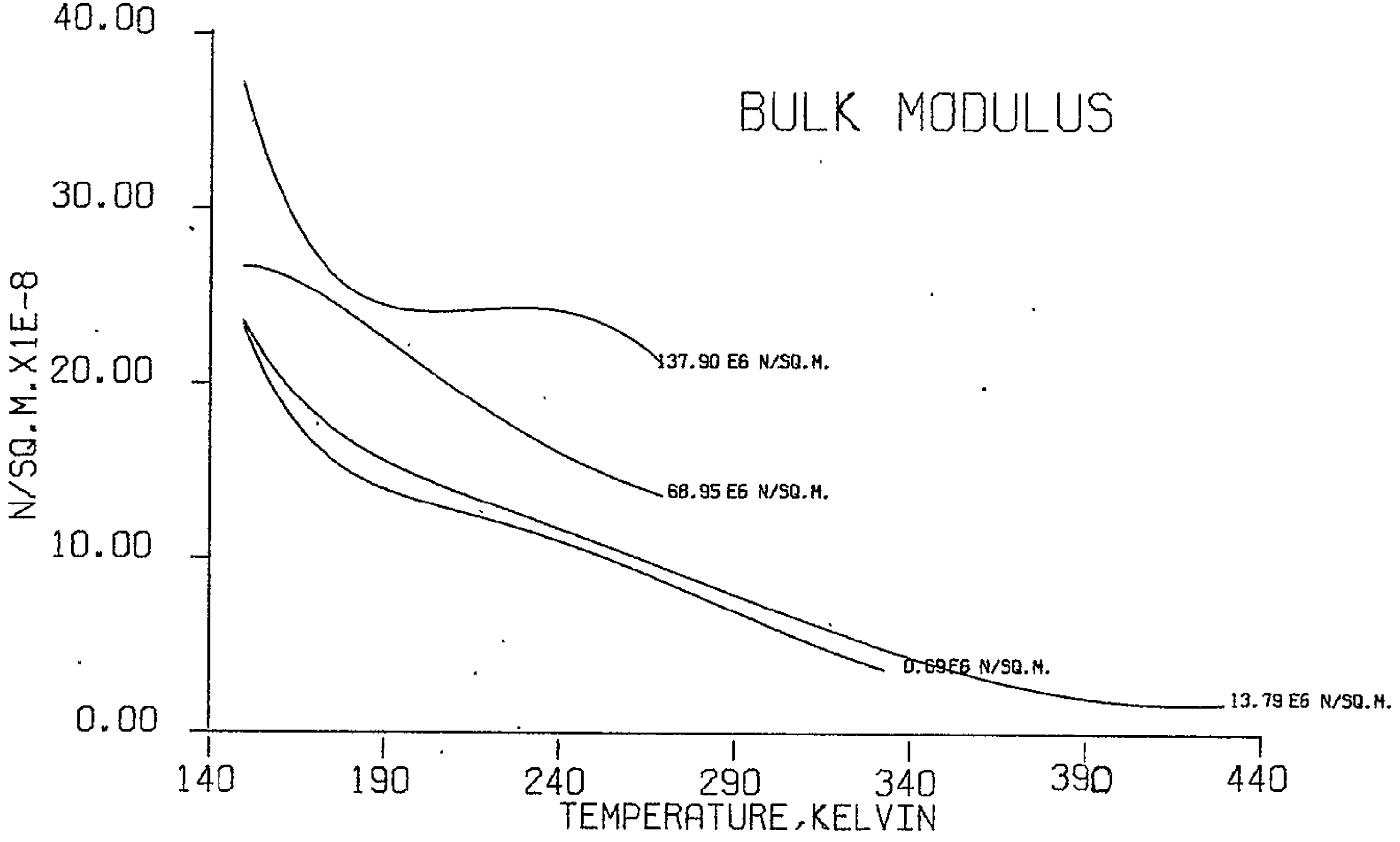

Figure 3 - Bulk Modulus of Elasticity for Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x $10^6$ N/$m^2$

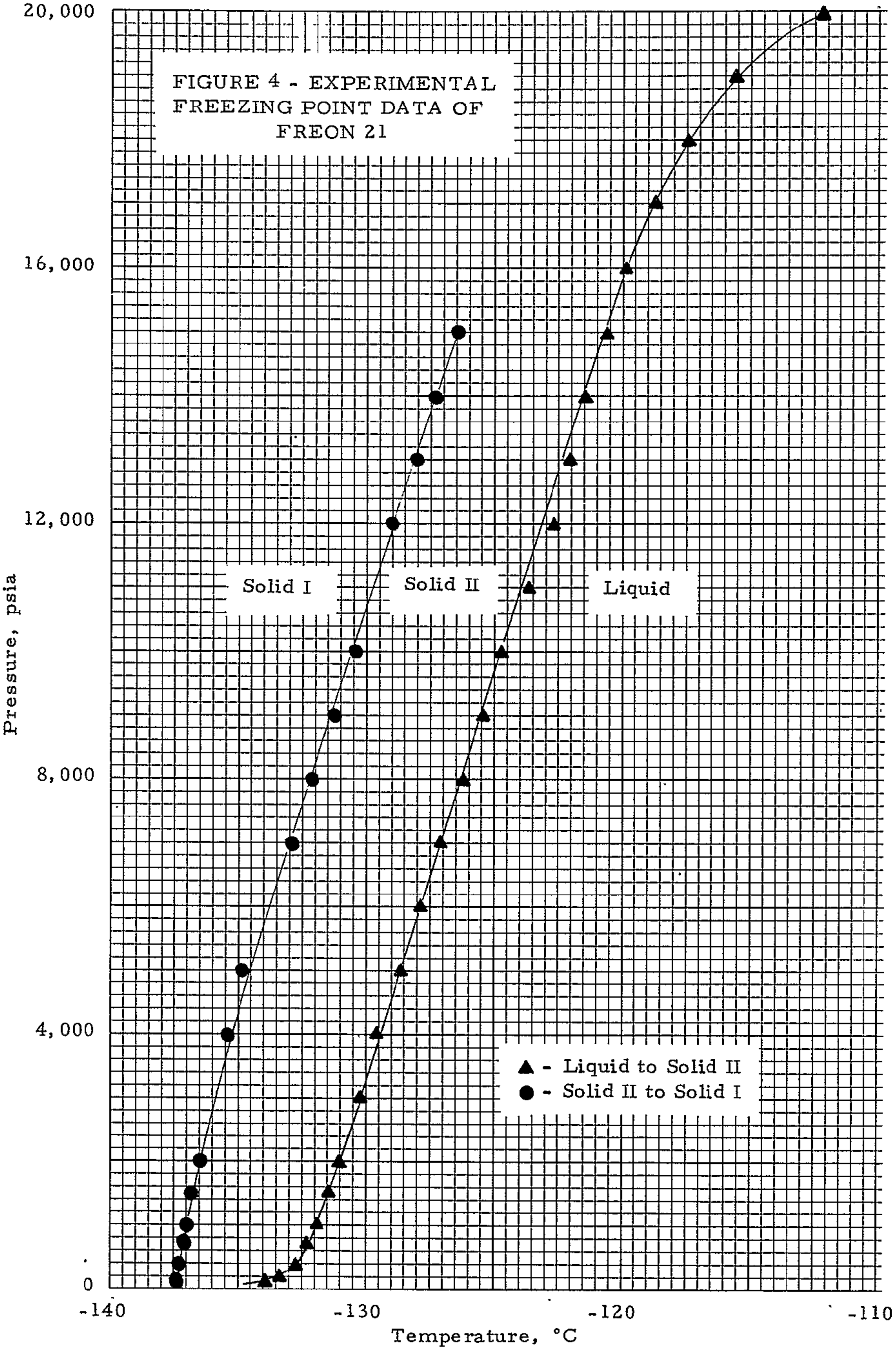

FIGURE 4 - EXPERIMENTAL FREEZING POINT DATA OF FREON 21

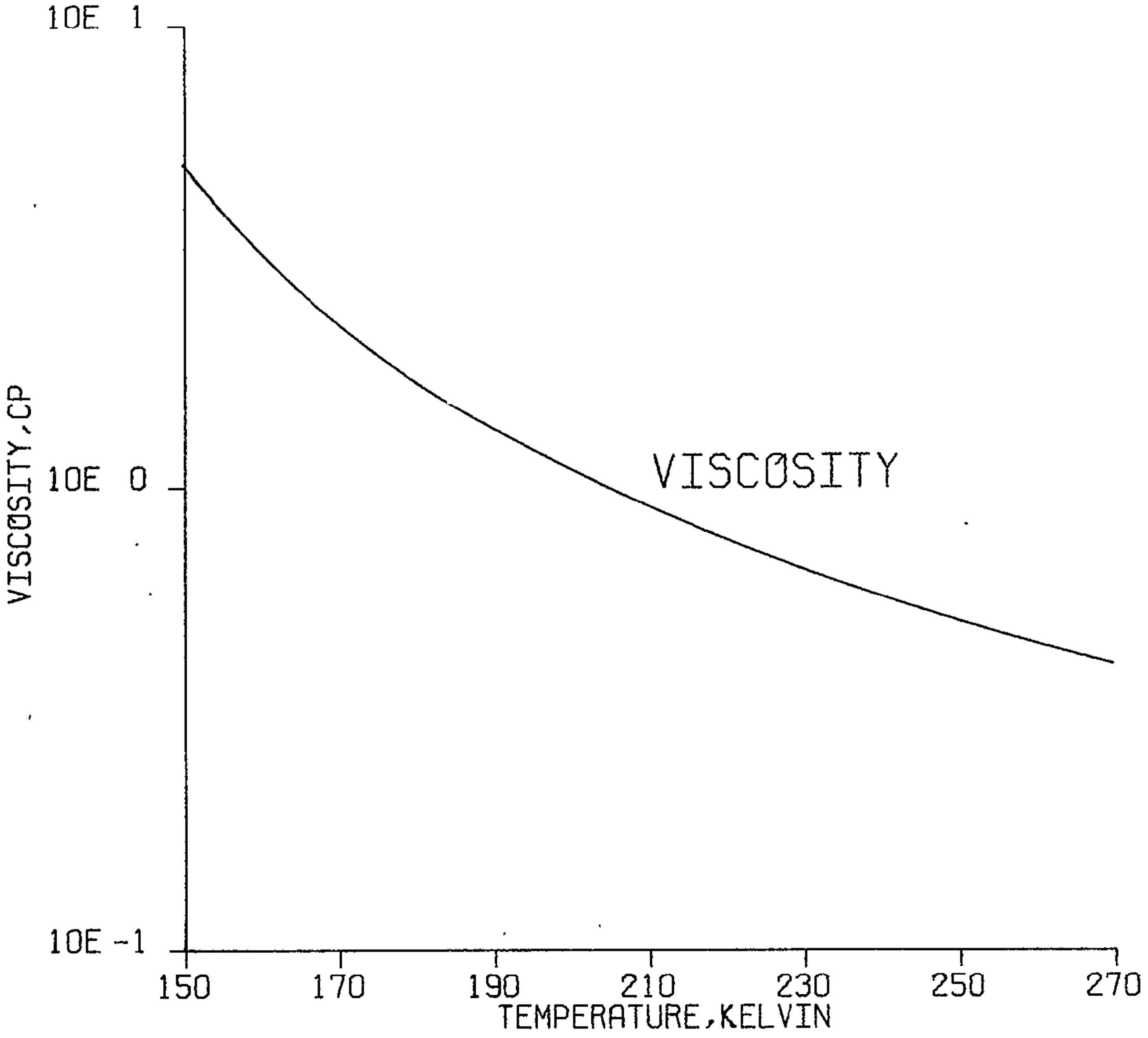

Figure 5 - Viscosity of Refrigerant-21,
143 to 273 Kelvin

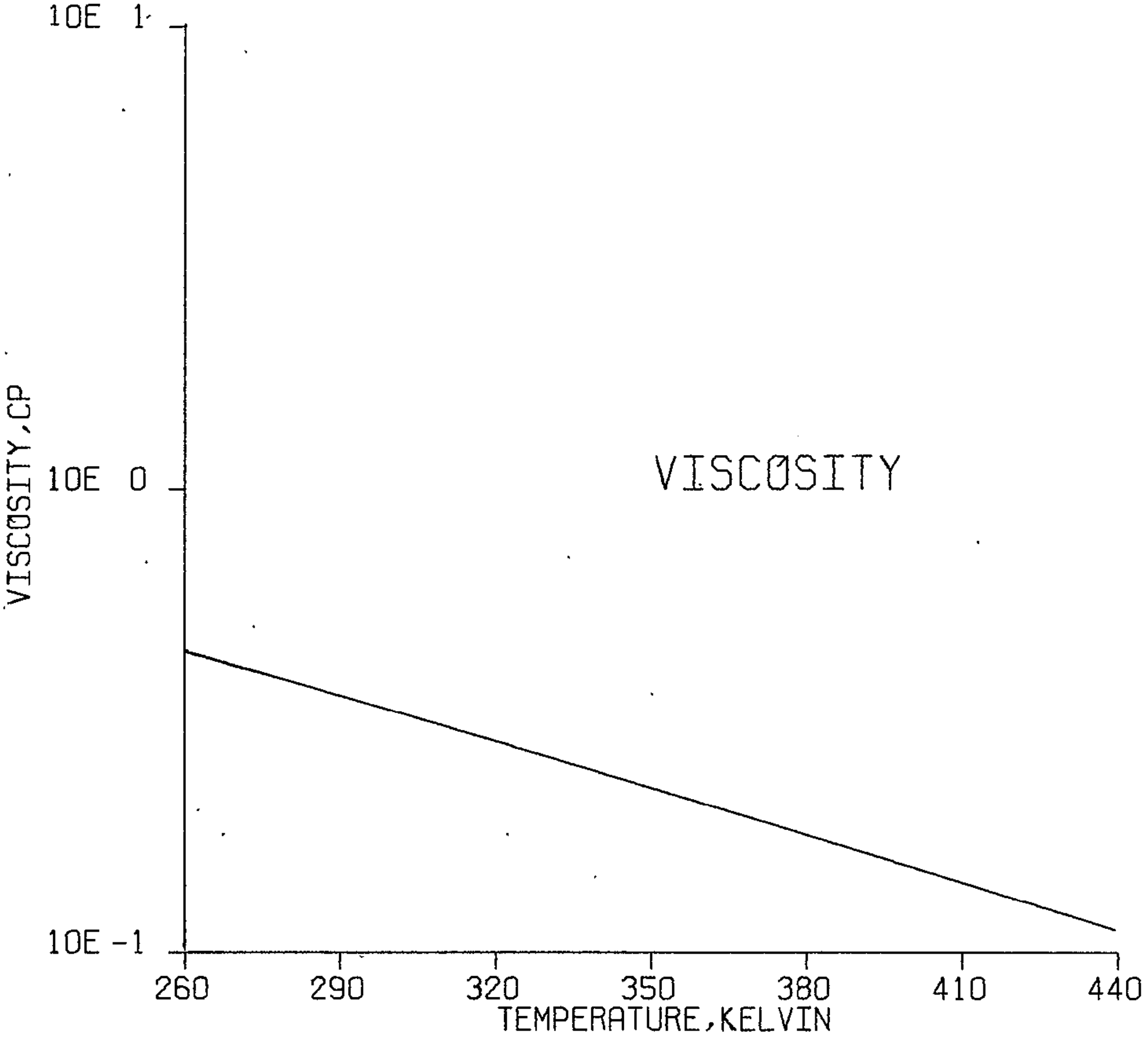

Figure 6 - Viscosity of Refrigerant-21,
273 to 423 Kelvin

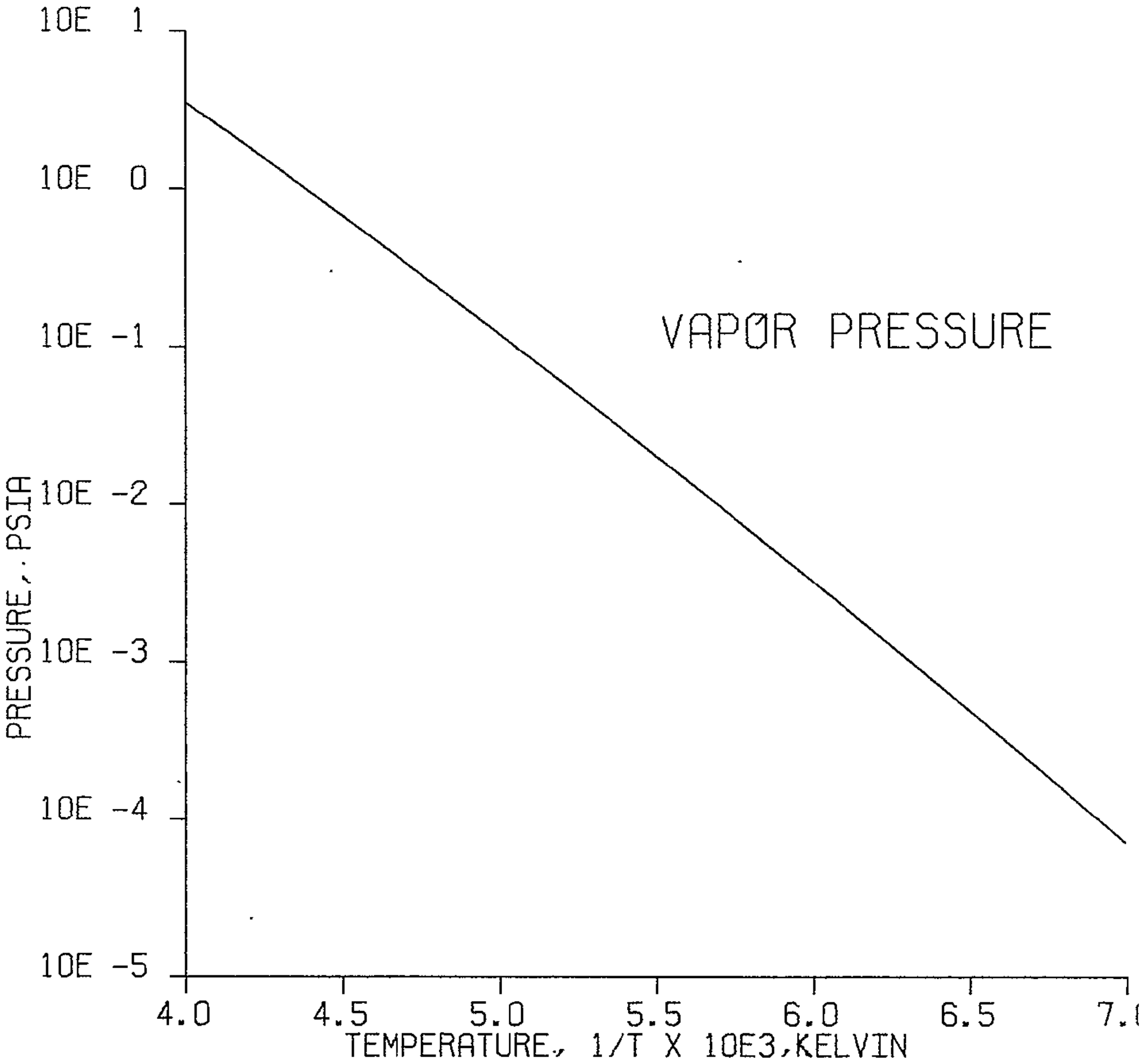

Figure 7 - Vapor Pressure of Refrigerant-21,
Low Temperature

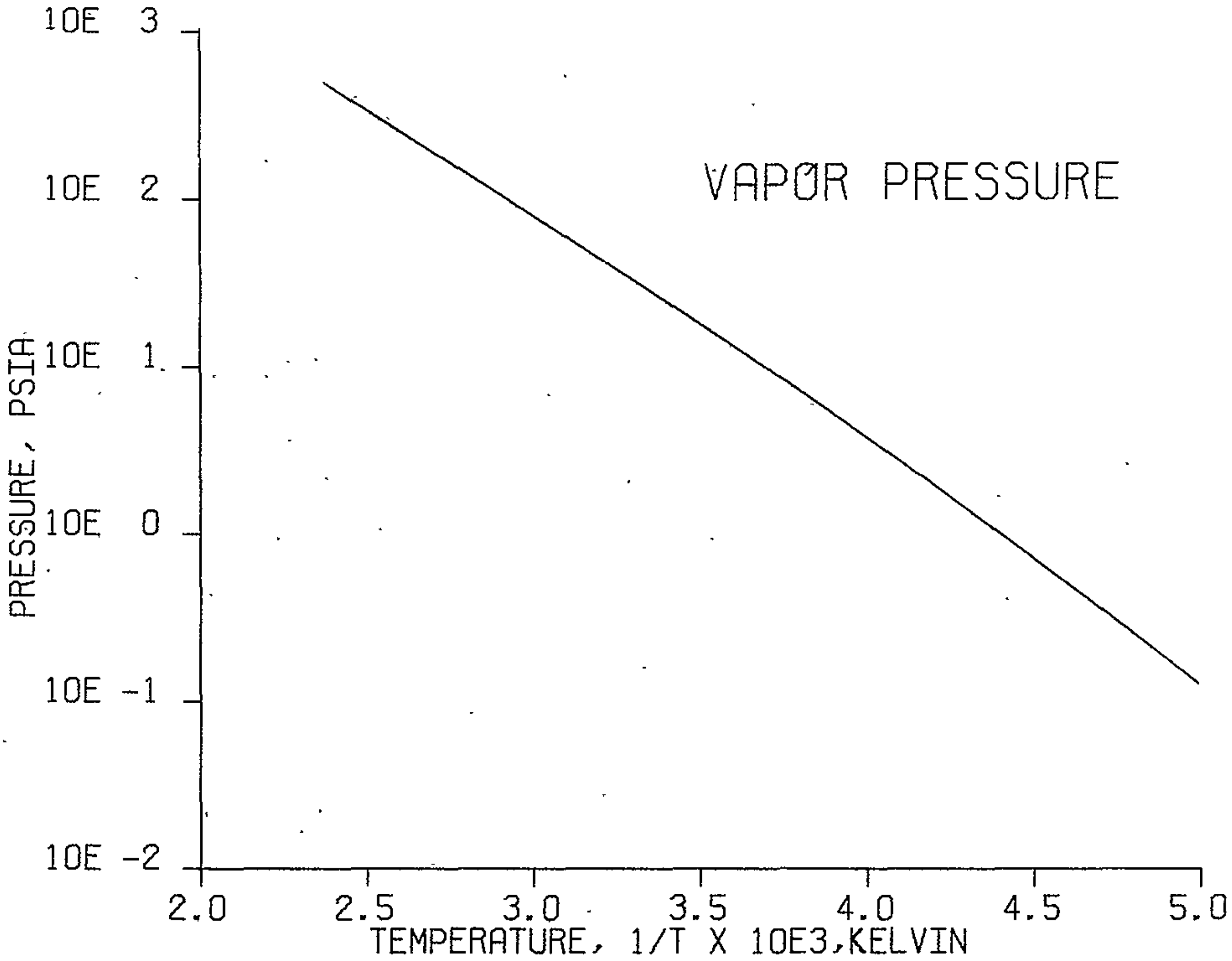

Figure 8 - Vapor Pressure of Refrigerant-21, High Temperature

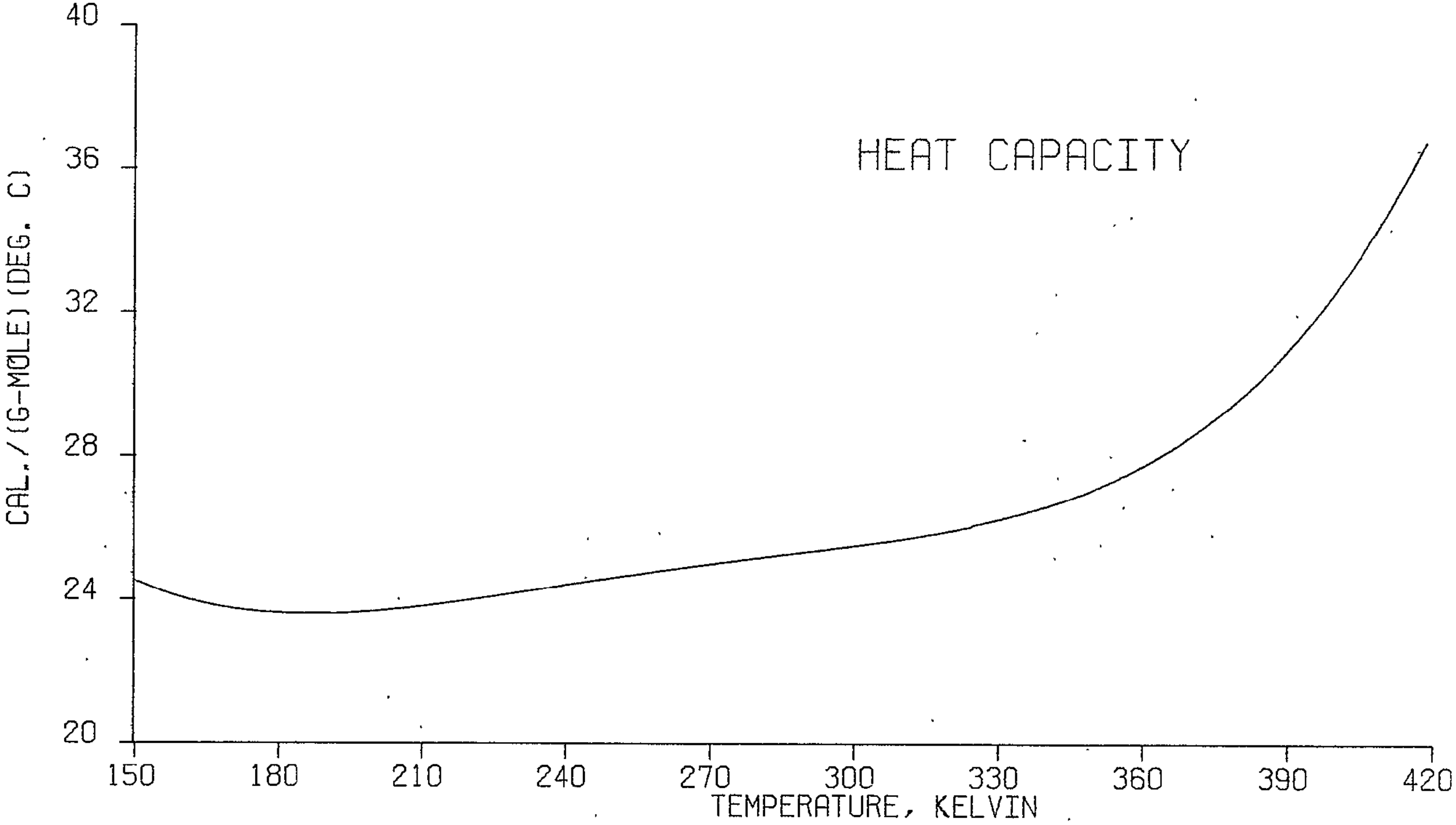

Figure 9 - Heat Capacity of Refrigerant-21 as a Function of Temperature at $3.415 \times 10^6$ N/m$^2$

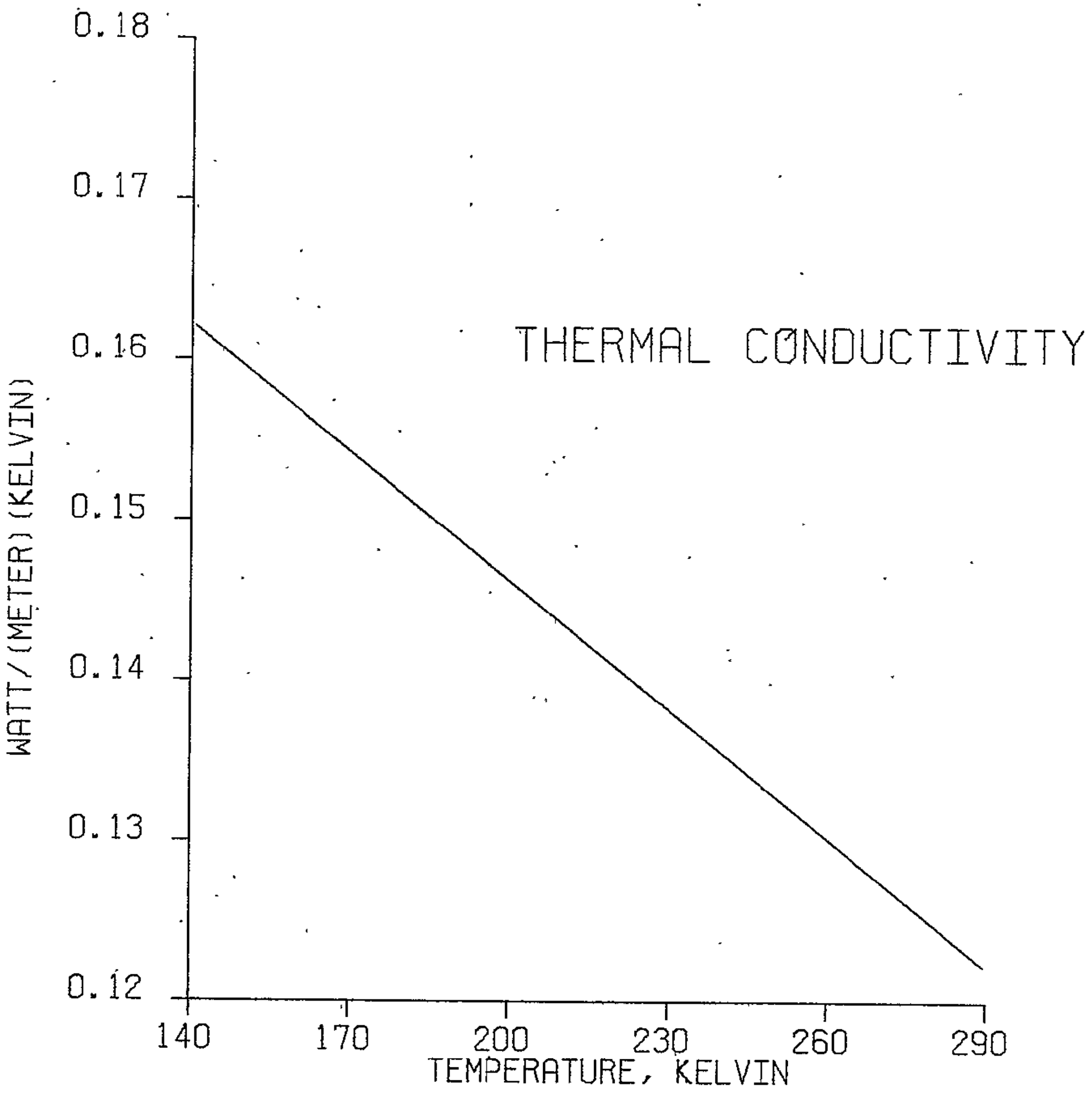

Figure 10 - Thermal Conductivity of Refrigerant-21 143 to 273 K at 0.34 x $10^6$ N/$m^2$

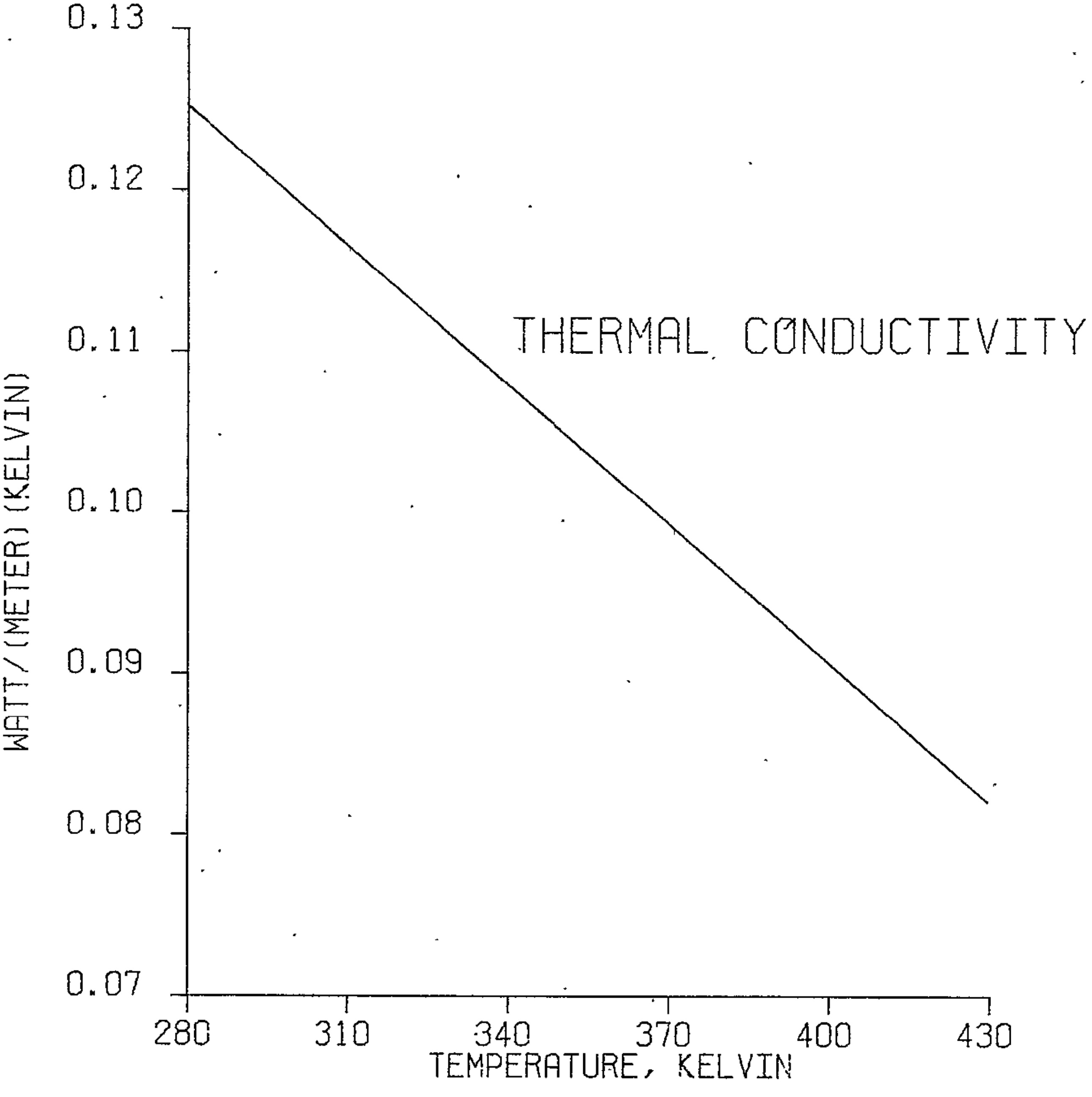

Figure 11 - Thermal Conductivity of Refrigerant-21 273 to 423 K (Vapor Pressure +0.34 x $10^6$ N/$m^2$)

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(1) "Handbook of Chemistry and Physics," 56th ed., p E-11, Chemical Rubber Company Press, Cleveland Ohio, 1975.

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(3) Wilson, G.M., DeVaney, W.E., "MARK V Computer Program," available from the Gas Processors Association, Tulsa, Ok.

(4) Gambill, W.R., "Find Heat of Fusion and Sublimation, "Chemical Engineering, 10 March 1958.

# APPENDIX A

## Density, Bulk Modulus, Coefficient of Thermal Expansion

The apparatus used for density determinations is shown in Figure 1-A. This piece of equipment consists of a calibrated mercury displacement pump, a 300 ml, 1800 psi cylinder, a 10 ml, 20,000 psi cylinder, an ice bath, the necessary pressure gages and valves, a high pressure density cell, a copper-constantan thermocouple and a constant temperature bath.

The constant temperature bath is set at a given temperature and the sample and isolation cells and the manifolds are evacuated. The volume of R-21 necessary to charge the isolator cell and manifold up to the cell isolation valve (V-1) is measured by mercury displacemant of R-21 from the system charging cell.

With the manifold and isolator cell charged with R-21, the sample cell is now ready to charge. The cell isolation valve is opened slightly, and the volume of mercury necessary to displace sufficient R-21 to fill the sample cell is measured. This is the reference volume, measured at $13.79 \times 10^6$ N/m$^2$ (2000 psia) and 0° C. All pump readings are made with the manifold, isolation cell and pump at 2000 psia, with the cell isolation valve closed.

While the temperature is maintained constant around the sample cell, the volume change of the R-21 liquid inside the cell is measured over the complete range of increasing pressures, and at two repeat pressures as liquid is withdrawn.

The bath temperature around the sample cell is lowered to the next test temperature, and the series of P-V points repeated at the new temperature. The final run for any given series is a repeat of the initial reference temperature P-V points. This provides an excellent check on the integrity of the system, as well as the reproducibility of measurements within a given series of runs and between successive series of runs.

These relative volume data provide the basic information for calculating density, coefficient of thermal expansion and bulk modulus of elasticity for R-21 as a function of pressure and temperature. One additional data point is needed: an absolute value of the density of R-21 at 0° C and 2000 psia. This value is obtained by displacing a series of approximately 10 ml volumes from the charging cell into a pycnometer, and obtaining the difference between the evacuated and filled weights of the pycnometer for each displacement. The absolute density at the reference charging pressure and temperature is then known.

The temperature in the sample cell is obtained from a sheathed thermocouple located inside this cell. The emf is referenced to an ice point TC, and is read on a K-3 potentiometer. Temperature variations of ±0.20° F can be detected, and temperatures are read to ±0.1° F.

Pressures are read on calibrated Heise gages. Both a 0 - 2000 and a 0 - 20,000 psia gage are connected to the isolator cell manifold.

The Ruska volumetric mercury pump is calibrated for linearity of displacement, and for actual volume displaced versus pump reading. All pump displacement readings are made with the manifold, pump, and isolator at 2000 psia. This minimizes the corrections required in the calculations. The pump is read directly to ±0.01 cc, and estimated to 0.002 cc.

The sample cell is calibrated for effect of temperature and pressure on volume at two temperatures, using a completely mercury filled system. The thermal and strain properties of 304 stainless steel are used to extrapolate these volume effects to low temperatures. This procedure introduces a small uncertainty at the lowest temperatures. The volume of the sample cell was determined to be 53.799 ml at 0° C and 2000 psia.

Bulk modulus is calculated directly from the relative volume measurements at each temperature. The modulus is calculated between each pair of pressure points, or over any desired range.

The thermal expansion is calculated from data at succeeding temperatures, at each pressure level. The fact that you have many pairs of measurements provides a check on data accuracy. You can work with successive temperatures, or over a wide temperature range.

The experimental relative volume measurements on R-21 are given in Table 1-A. These values have been corrected for changes in the test cell volume due to temperature and pressure, and for variations in room temperature where the actual mercury pump readings were made. They are all relative to a volume of 1.0000 at 0° C and 2000 psia, the reference condition.

The experimental density data were fitted by a least-squares procedure as a function of temperature and pressure to an equation of the form:

$$\text{Density (g/cc)} = \sum_{i=0}^{3} \sum_{j=0}^{3} A_{ij} \, T^{i} \, P^{i}$$

T in Kelvin
P in Psia

The results of which are given in Table 2-A.

All of the data for a given pressure were fit by a least-squares procedure to an equation of the form:

$$\text{Density, g/cc} = \sum_{i=0}^{N} A_{i} \, T^{i} \quad \text{(T in Kelvin)}$$

It was found that using values of i from 0 to 3 gave a very good fit of the data. The coefficients derived for each pressure, and the standard deviation of their fit, are given in Table 3-A.

## TABLE 1-A - EXPERIMENTAL RELATIVE VOLUME MEASUREMENTS ON REFRIGERANT-21

| TEMPERATURE, |  | PRESSURE, | RELATIVE | DENSITY, |
|---|---|---|---|---|
| DEG. C. | KELVIN | PSIA | VOLUME * | G/CC ** |
| -130.32 | 142.83 | 100 | .85142 | 1.70104 |
| -130.26 | 142.89 | 200 | .85114 | 1.70160 |
| -130.13 | 143.02 | 400 | .85071 | 1.70246 |
| -130.21 | 142.94 | 700 | .84988 | 1.70413 |
| -130.21 | 142.94 | 700 | .84987 | 1.70414 |
| -130.17 | 142.98 | 1000 | .84909 | 1.70570 |
| -130.22 | 142.93 | 1500 | .84789 | 1.70812 |
| -130.31 | 142.84 | 2000 | .84651 | 1.71091 |
| -130.35 | 142.80 | 4000 | .84161 | 1.72087 |
| -130.35 | 142.80 | 4000 | .84164 | 1.72082 |
| -130.24 | 142.91 | 7000 | .83501 | 1.73448 |
| -119.87 | 153.28 | 100 | .86231 | 1.67955 |
| -119.96 | 153.19 | 200 | .86195 | 1.68027 |
| -119.94 | 153.21 | 400 | .86139 | 1.68135 |
| -119.94 | 153.21 | 700 | .86050 | 1.68309 |
| -119.95 | 153.20 | 1000 | .85963 | 1.68480 |
| -120.04 | 153.11 | 1500 | .85827 | 1.68746 |
| -120.02 | 153.13 | 2000 | .85714 | 1.68968 |
| -119.98 | 153.17 | 2000 | .85667 | 1.69062 |
| -119.89 | 153.26 | 4000 | .85182 | 1.70024 |
| -120.06 | 153.09 | 7000 | .84430 | 1.71539 |
| -120.01 | 153.14 | 10000 | .83769 | 1.72892 |
| -119.88 | 153.27 | 15000 | .82766 | 1.74987 |
| -119.78 | 153.37 | 20000 | .81873 | 1.76896 |
| -100.15 | 173.00 | 100 | .88454 | 1.63735 |
| -100.11 | 173.04 | 200 | .88414 | 1.63809 |
| -100.06 | 173.09 | 400 | .88339 | 1.63948 |
| -100.02 | 173.13 | 700 | .88238 | 1.64135 |
| -100.06 | 173.09 | 1000 | .88141 | 1.64316 |
| -100.09 | 173.06 | 1500 | .87984 | 1.64609 |
| -100.04 | 173.11 | 2000 | .87838 | 1.64883 |
| -99.36 | 173.79 | 4000 | .87294 | 1.65911 |
| -100.14 | 173.01 | 7000 | .86371 | 1.67683 |
| -100.07 | 173.08 | 10000 | .85607 | 1.69179 |
| -100.03 | 173.12 | 15000 | .84446 | 1.71507 |
| -100.00 | 173.15 | 20000 | .83409 | 1.73637 |

* RELATIVE VOLUME = V(T,P)/V(0 C, 2000 PSIA)

** DENSITY BASED ON 1.4483 G/CC AT 0 C, 2000 PSIA

## TABLE 1-A - EXPERIMENTAL RELATIVE VOLUME MEASUREMENTS ON REFRIGERANT-21

| TEMPERATURE, DEG. C. | KELVIN | PRESSURE, PSIA | RELATIVE VOLUME * | DENSITY, G/CC ** |
|---|---|---|---|---|
| -79.84 | 193.31 | 100 | .90801 | 1.59503 |
| -80.01 | 193.14 | 200 | .90739 | 1.59612 |
| -80.00 | 193.15 | 400 | .90666 | 1.59740 |
| -79.94 | 193.21 | 700 | .90538 | 1.59965 |
| -79.90 | 193.25 | 1000 | .90422 | 1.60172 |
| -80.13 | 193.02 | 1500 | .90269 | 1.60443 |
| -80.26 | 192.89 | 2000 | .90044 | 1.60844 |
| -79.86 | 193.29 | 2000 | .90044 | 1.60841 |
| -79.61 | 193.54 | 2000 | .90047 | 1.60838 |
| -79.96 | 193.19 | 4000 | .89326 | 1.62136 |
| -79.63 | 193.52 | 7000 | .88349 | 1.63929 |
| -79.85 | 193.30 | 10000 | .87424 | 1.65663 |
| -79.85 | 193.30 | 15000 | .86091 | 1.68230 |
| -79.91 | 193.24 | 20000 | .84969 | 1.70450 |
| | | | | |
| -60.26 | 212.89 | 100 | .93153 | 1.55476 |
| -60.20 | 212.95 | 200 | .93108 | 1.55551 |
| -60.18 | 212.97 | 400 | .93020 | 1.55698 |
| -60.23 | 212.92 | 700 | .92881 | 1.55930 |
| -60.13 | 213.02 | 1000 | .92732 | 1.56182 |
| -60.19 | 212.96 | 1500 | .92493 | 1.56585 |
| -60.23 | 212.92 | 2000 | .92255 | 1.56989 |
| -60.33 | 212.82 | 4000 | .91383 | 1.58486 |
| -60.25 | 212.90 | 7000 | .90232 | 1.60508 |
| -60.29 | 212.86 | 10000 | .89206 | 1.62354 |
| -60.25 | 212.90 | 15000 | .87715 | 1.65115 |
| -60.26 | 212.89 | 20000 | .86436 | 1.67558 |
| | | | | |
| -40.59 | 232.56 | 100 | .95728 | 1.51294 |
| -40.55 | 232.60 | 200 | .95669 | 1.51386 |
| -40.59 | 232.56 | 400 | .95552 | 1.51573 |
| -40.58 | 232.57 | 700 | .95374 | 1.51854 |
| -40.50 | 232.65 | 1000 | .95203 | 1.52128 |
| -40.58 | 232.57 | 1500 | .94919 | 1.52583 |
| -40.79 | 232.36 | 2000 | .94616 | 1.53072 |
| -40.37 | 232.78 | 4000 | .93630 | 1.54683 |
| -40.27 | 232.88 | 7000 | .92292 | 1.56926 |
| -40.07 | 233.08 | 10000 | .91120 | 1.58944 |
| -40.14 | 233.01 | 15000 | .89416 | 1.61974 |
| -40.26 | 232.89 | 20000 | .87978 | 1.64621 |

* RELATIVE VOLUME = V(T,P)/V(0 C, 2000 PSIA)

** DENSITY BASED ON 1.4483 G/CC AT 0 C, 2000 PSIA

## TABLE 1-A - EXPERIMENTAL RELATIVE VOLUME MEASUREMENTS ON REFRIGERANT-21

| TEMPERATURE, DEG. C. | KELVIN | PRESSURE, PSIA | RELATIVE VOLUME * | DENSITY, G/CC ** |
|---|---|---|---|---|
| -20.23 | 252.92 | 100 | .98575 | 1.46923 |
| -20.20 | 252.95 | 200 | .98506 | 1.47026 |
| -20.22 | 252.93 | 400 | .98354 | 1.47254 |
| -20.18 | 252.97 | 700 | .98136 | 1.47581 |
| -20.22 | 252.93 | 1000 | .97914 | 1.47916 |
| -20.17 | 252.98 | 1500 | .97569 | 1.48438 |
| -20.21 | 252.94 | 2000 | .97233 | 1.48951 |
| -20.75 | 252.40 | 4000 | .95934 | 1.50968 |
| -20.76 | 252.39 | 7000 | .94345 | 1.53510 |
| -20.69 | 252.46 | 10000 | .92984 | 1.55759 |
| -20.87 | 252.28 | 15000 | .91054 | 1.59060 |
| -20.82 | 252.33 | 20000 | .89466 | 1.61883 |
| 0. | 273.15 | 100 | 1.01733 | 1.42363 |
| 0. | 273.15 | 200 | 1.01577 | 1.42581 |
| 0. | 273.15 | 400 | 1.01391 | 1.42842 |
| 0. | 273.15 | 700 | 1.01111 | 1.43239 |
| 0. | 273.15 | 1000 | 1.00843 | 1.43619 |
| 0. | 273.15 | 1500 | 1.00413 | 1.44234 |
| 0. | 273.15 | 2000 | 1.00000 | 1.44830 |
| 0. | 273.15 | 4000 | .98488 | 1.47054 |
| 0. | 273.15 | 7000 | .96540 | 1.50020 |
| 0. | 273.15 | 10000 | .94941 | 1.52548 |
| 0. | 273.15 | 10000 | .94959 | 1.52519 |
| 0. | 273.15 | 15000 | .92770 | 1.56118 |
| 0. | 273.15 | 20000 | .91073 | 1.59026 |
| 7.85 | 281.00 | 2000 | 1.01283 | 1.42995 |
| 20.05 | 293.20 | 72 | 1.05107 | 1.37793 |
| 19.55 | 292.70 | 600 | 1.04399 | 1.38728 |
| 19.97 | 293.12 | 1000 | 1.03990 | 1.39273 |
| 20.10 | 293.25 | 1500 | 1.03454 | 1.39995 |
| 20.53 | 293.68 | 2000 | 1.03028 | 1.40573 |
| 39.71 | 312.86 | 94 | 1.08647 | 1.33304 |
| 39.72 | 312.87 | 600 | 1.07870 | 1.34263 |
| 39.78 | 312.93 | 1000 | 1.07277 | 1.35006 |
| 39.74 | 312.89 | 1500 | 1.03299 | 1.40205 *** |
| 39.58 | 312.73 | 2000 | 1.05942 | 1.36707 |

* RELATIVE VOLUME = V(T,P)/V(0 C, 2000 PSIA)

** DENSITY BASED ON 1.4483 G/CC AT 0 C, 2000 PSIA

*** OMITTED FROM FINAL FIT

## TABLE 1-A - EXPERIMENTAL RELATIVE VOLUME MEASUREMENTS ON REFRIGERANT-21

| TEMPERATURE, | | PRESSURE, | RELATIVE | DENSITY, |
|---|---|---|---|---|
| DEG. C. | KELVIN | PSIA | VOLUME * | G/CC ** |
| 59.77 | 332.92 | 130 | 1.12983 | 1.28188 |
| 59.85 | 333.00 | 600 | 1.11992 | 1.29322 |
| 59.85 | 333.00 | 1000 | 1.11216 | 1.30224 |
| 59.72 | 332.87 | 1500 | 1.10301 | 1.31304 |
| 59.02 | 332.17 | 2000 | 1.09383 | 1.32406 |
| | | | | |
| 80.44 | 353.59 | 175 | 1.18275 | 1.22451 |
| 80.51 | 353.66 | 600 | 1.16998 | 1.23789 |
| 80.46 | 353.61 | 1000 | 1.15905 | 1.24956 |
| 80.49 | 353.64 | 1500 | 1.14741 | 1.26223 |
| 79.72 | 352.87 | 2000 | 1.13491 | 1.27613 |
| | | | | |
| 99.99 | 373.14 | 242 | 1.24413 | 1.16411 |
| 99.95 | 373.10 | 600 | 1.22798 | 1.17942 |
| 99.98 | 373.13 | 1000 | 1.21287 | 1.19411 |
| 99.95 | 373.10 | 1500 | 1.19631 | 1.21064 |
| 99.97 | 373.12 | 2000 | 1.18086 | 1.22648 |
| | | | | |
| 119.82 | 392.97 | 332 | 1.32177 | 1.09573 |
| 119.78 | 392.93 | 600 | 1.30142 | 1.11286 |
| 119.75 | 392.90 | 1000 | 1.27718 | 1.13398 |
| 119.76 | 392.91 | 1500 | 1.25266 | 1.15618 |
| 119.78 | 392.93 | 2000 | 1.23322 | 1.17441 |
| | | | | |
| 139.94 | 413.09 | 510 | 1.42198 | 1.01851 |
| 139.88 | 413.03 | 600 | 1.40788 | 1.02871 |
| 139.82 | 412.97 | 1000 | 1.36326 | 1.06238 |
| 139.85 | 413.00 | 1500 | 1.32491 | 1.09313 |
| 139.84 | 412.99 | 2000 | 1.29582 | 1.11768 |
| 139.90 | 413.05 | 2000 | 1.29580 | 1.11769 |
| | | | | |
| 149.67 | 422.82 | 600 | 1.48341 | .97633 *** |
| 149.65 | 422.80 | 1000 | 1.42066 | 1.01946 |
| 149.69 | 422.84 | 1500 | 1.36684 | 1.05960 |
| 149.32 | 422.47 | 2000 | 1.32969 | 1.08926 |

* RELATIVE VOLUME = V(T,P)/V(0 C, 2000 PSIA)
** DENSITY BASED ON 1.4483 G/CC AT 0 C, 2000 PSIA
*** OMITTED FROM FINAL FIT

## TABLE 2-A - LEAST SQUARES FIT OF REFRIGERANT-21 EXPERIMENTAL DENSITY DATA

| TEMPERATURE, KELVIN | PRESSURE, PSIA | DENSITY, G/CC MEASURED | DENSITY, G/CC CALCULATED | PERCENT ERROR |
|---|---|---|---|---|
| 142.83 | 100 | 1.7010 | 1.7039 | -.169 |
| 142.89 | 200 | 1.7016 | 1.7042 | -.152 |
| 143.02 | 400 | 1.7025 | 1.7047 | -.132 |
| 142.94 | 700 | 1.7041 | 1.7062 | -.119 |
| 142.94 | 700 | 1.7041 | 1.7062 | -.118 |
| 142.98 | 1000 | 1.7057 | 1.7073 | -.096 |
| 142.93 | 1500 | 1.7081 | 1.7096 | -.086 |
| 142.84 | 2000 | 1.7109 | 1.7120 | -.061 |
| 142.80 | 4000 | 1.7209 | 1.7210 | -.005 |
| 142.80 | 4000 | 1.7208 | 1.7210 | -.008 |
| 142.91 | 7000 | 1.7345 | 1.7346 | -.004 |
| | | | | |
| 153.28 | 100 | 1.6795 | 1.6794 | .010 |
| 153.19 | 200 | 1.6803 | 1.6801 | .008 |
| 153.21 | 400 | 1.6814 | 1.6812 | .010 |
| 153.21 | 700 | 1.6831 | 1.6828 | .018 |
| 153.20 | 1000 | 1.6848 | 1.6844 | .022 |
| 153.11 | 1500 | 1.6875 | 1.6873 | .010 |
| 153.13 | 2000 | 1.6897 | 1.6899 | -.012 |
| 153.17 | 2000 | 1.6906 | 1.6898 | .049 |
| 153.26 | 4000 | 1.7002 | 1.6999 | .018 |
| 153.09 | 7000 | 1.7154 | 1.7151 | .019 |
| 153.14 | 10000 | 1.7289 | 1.7289 | .001 |
| 153.27 | 15000 | 1.7499 | 1.7500 | -.008 |
| 153.37 | 20000 | 1.7690 | 1.7688 | .009 |
| | | | | |
| 173.00 | 100 | 1.6373 | 1.6355 | .114 |
| 173.04 | 200 | 1.6381 | 1.6361 | .121 |
| 173.09 | 400 | 1.6395 | 1.6374 | .126 |
| 173.13 | 700 | 1.6414 | 1.6394 | .117 |
| 173.09 | 1000 | 1.6432 | 1.6416 | .096 |
| 173.06 | 1500 | 1.6461 | 1.6450 | .064 |
| 173.11 | 2000 | 1.6488 | 1.6482 | .036 |
| 173.79 | 4000 | 1.6591 | 1.6593 | -.014 |
| 173.01 | 7000 | 1.6768 | 1.6776 | -.044 |
| 173.08 | 10000 | 1.6918 | 1.6923 | -.032 |
| 173.12 | 15000 | 1.7151 | 1.7147 | .021 |
| 173.15 | 20000 | 1.7364 | 1.7366 | -.015 |

# TABLE 2-A - LEAST SQUARES FIT OF REFRIGERANT-21 EXPERIMENTAL DENSITY DATA

| TEMPERATURE, KELVIN | PRESSURE, PSIA | DENSITY, G/CC MEASURED | DENSITY, G/CC CALCULATED | PERCENT ERROR |
|---|---|---|---|---|
| 193.31 | 100 | 1.5950 | 1.5927 | .149 |
| 193.14 | 200 | 1.5961 | 1.5938 | .144 |
| 193.15 | 400 | 1.5974 | 1.5954 | .125 |
| 193.21 | 700 | 1.5996 | 1.5977 | .124 |
| 193.25 | 1000 | 1.6017 | 1.5999 | .111 |
| 193.02 | 1500 | 1.6044 | 1.6042 | .012 |
| 192.89 | 2000 | 1.6084 | 1.6082 | .013 |
| 193.29 | 2000 | 1.6084 | 1.6074 | .061 |
| 193.54 | 2000 | 1.6084 | 1.6069 | .090 |
| 193.19 | 4000 | 1.6214 | 1.6217 | -.020 |
| 193.52 | 7000 | 1.6393 | 1.6398 | -.031 |
| 193.30 | 10000 | 1.6566 | 1.6567 | -.006 |
| 193.30 | 15000 | 1.6823 | 1.6813 | .060 |
| 193.24 | 20000 | 1.7045 | 1.7051 | -.034 |
| | | | | |
| 212.89 | 100 | 1.5548 | 1.5527 | .133 |
| 212.95 | 200 | 1.5555 | 1.5534 | .133 |
| 212.97 | 400 | 1.5570 | 1.5551 | .119 |
| 212.92 | 700 | 1.5593 | 1.5578 | .096 |
| 213.02 | 1000 | 1.5618 | 1.5601 | .108 |
| 212.96 | 1500 | 1.5658 | 1.5644 | .093 |
| 212.92 | 2000 | 1.5699 | 1.5685 | .086 |
| 212.82 | 4000 | 1.5849 | 1.5841 | .047 |
| 212.90 | 7000 | 1.6051 | 1.6048 | .018 |
| 212.86 | 10000 | 1.6235 | 1.6234 | .008 |
| 212.90 | 15000 | 1.6512 | 1.6506 | .034 |
| 212.89 | 20000 | 1.6756 | 1.6753 | .018 |
| | | | | |
| 232.56 | 100 | 1.5129 | 1.5129 | .003 |
| 232.60 | 200 | 1.5139 | 1.5137 | .008 |
| 232.56 | 400 | 1.5157 | 1.5157 | .004 |
| 232.57 | 700 | 1.5185 | 1.5184 | .010 |
| 232.65 | 1000 | 1.5213 | 1.5209 | .022 |
| 232.57 | 1500 | 1.5258 | 1.5256 | .018 |
| 232.36 | 2000 | 1.5307 | 1.5304 | .024 |
| 232.78 | 4000 | 1.5468 | 1.5464 | .031 |
| 232.88 | 7000 | 1.5693 | 1.5693 | -.004 |
| 233.08 | 10000 | 1.5894 | 1.5899 | -.026 |
| 233.01 | 15000 | 1.6197 | 1.6203 | -.033 |
| 232.89 | 20000 | 1.6462 | 1.6460 | .011 |

## TABLE 2-A - LEAST SQUARES FIT OF REFRIGERANT-21 EXPERIMENTAL DENSITY DATA

| TEMPERATURE, KELVIN | PRESSURE, PSIA | DENSITY, G/CC MEASURED | DENSITY, G/CC CALCULATED | PERCENT ERROR |
|---|---|---|---|---|
| 252.92 | 100 | 1.4692 | 1.4711 | -.124 |
| 252.95 | 200 | 1.4703 | 1.4720 | -.119 |
| 252.93 | 400 | 1.4725 | 1.4741 | -.105 |
| 252.97 | 700 | 1.4758 | 1.4770 | -.082 |
| 252.93 | 1000 | 1.4792 | 1.4801 | -.064 |
| 252.98 | 1500 | 1.4844 | 1.4849 | -.037 |
| 252.94 | 2000 | 1.4895 | 1.4899 | -.024 |
| 252.40 | 4000 | 1.5097 | 1.5095 | .011 |
| 252.39 | 7000 | 1.5351 | 1.5352 | -.008 |
| 252.46 | 10000 | 1.5576 | 1.5583 | -.043 |
| 252.28 | 15000 | 1.5906 | 1.5917 | -.072 |
| 252.33 | 20000 | 1.6188 | 1.6186 | .012 |
| | | | | |
| 273.15 | 100 | 1.4236 | 1.4278 | -.292 |
| 273.15 | 200 | 1.4258 | 1.4290 | -.222 |
| 273.15 | 400 | 1.4284 | 1.4313 | -.204 |
| 273.15 | 700 | 1.4324 | 1.4348 | -.171 |
| 273.15 | 1000 | 1.4362 | 1.4383 | -.147 |
| 273.15 | 1500 | 1.4423 | 1.4440 | -.114 |
| 273.15 | 2000 | 1.4483 | 1.4496 | -.087 |
| 273.15 | 4000 | 1.4705 | 1.4707 | -.013 |
| 273.15 | 7000 | 1.5002 | 1.4994 | .051 |
| 273.15 | 10000 | 1.5255 | 1.5248 | .045 |
| 273.15 | 10000 | 1.5252 | 1.5248 | .026 |
| 273.15 | 15000 | 1.5612 | 1.5608 | .027 |
| 273.15 | 20000 | 1.5903 | 1.5904 | -.009 |
| | | | | |
| 281.00 | 2000 | 1.4299 | 1.4337 | -.259 |
| 293.20 | 72 | 1.3779 | 1.3818 | -.282 |
| 292.70 | 600 | 1.3873 | 1.3906 | -.239 |
| 293.12 | 1000 | 1.3927 | 1.3953 | -.182 |
| 293.25 | 1500 | 1.3999 | 1.4018 | -.134 |
| 293.68 | 2000 | 1.4057 | 1.4076 | -.132 |
| | | | | |
| 312.86 | 94 | 1.3330 | 1.3338 | -.061 |
| 312.87 | 600 | 1.3426 | 1.3432 | -.040 |
| 312.93 | 1000 | 1.3501 | 1.3501 | -.006 |
| 312.73 | 2000 | 1.3671 | 1.3673 | -.017 |

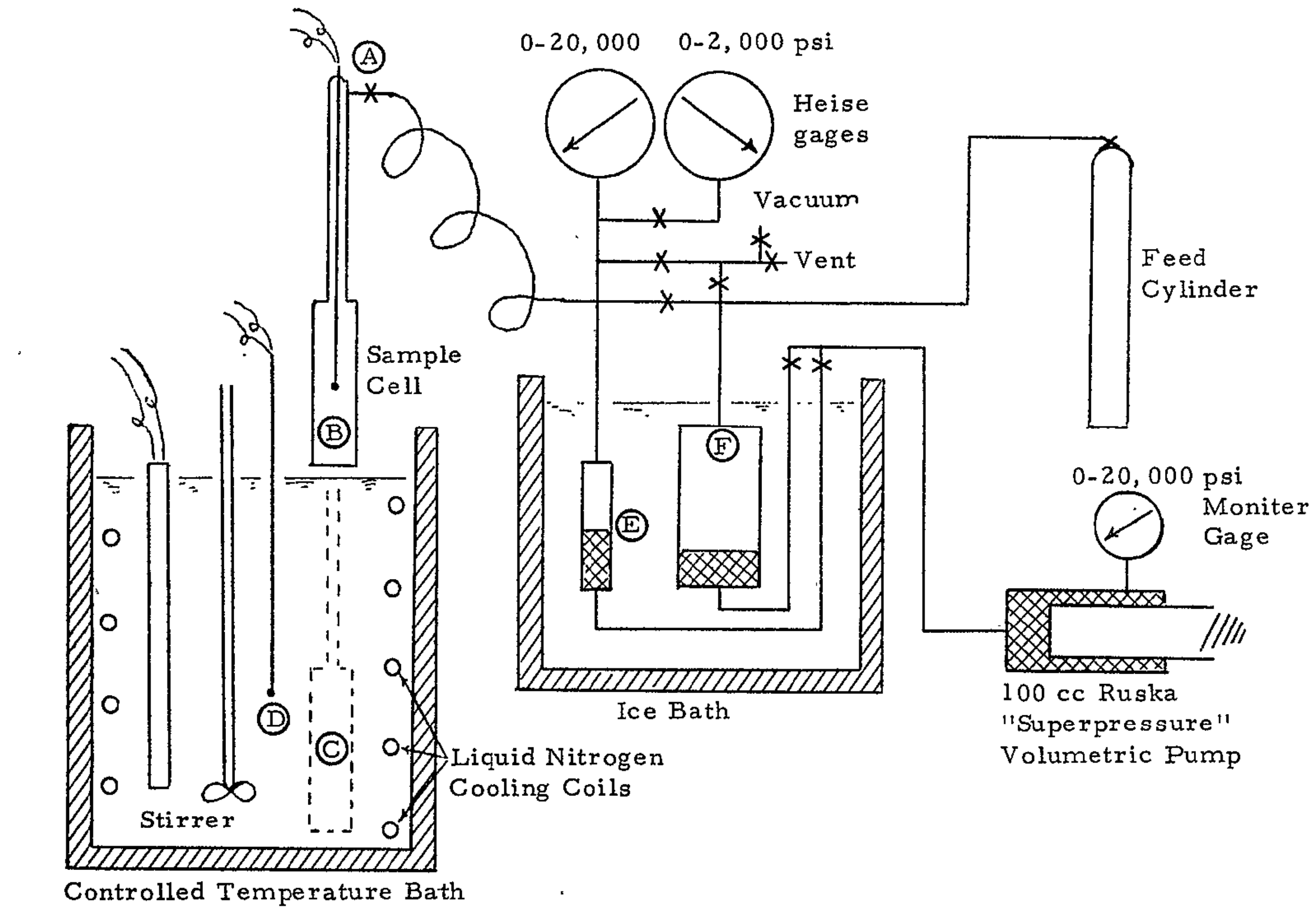
## TABLE 2-A - LEAST SQUARES FIT OF REFRIGERANT-21 EXPERIMENTAL DENSITY DATA

| TEMPERATURE, KELVIN | PRESSURE, PSIA | DENSITY, G/CC MEASURED | DENSITY, G/CC CALCULATED | PERCENT ERROR |
|---|---|---|---|---|
| 332.92 | 130 | 1.2819 | 1.2808 | .083 |
| 333.00 | 600 | 1.2932 | 1.2920 | .094 |
| 333.00 | 1000 | 1.3022 | 1.3012 | .076 |
| 332.87 | 1500 | 1.3130 | 1.3125 | .038 |
| 332.17 | 2000 | 1.3241 | 1.3245 | -.030 |
| | | | | |
| 353.59 | 175 | 1.2245 | 1.2211 | .281 |
| 353.66 | 600 | 1.2379 | 1.2346 | .265 |
| 353.61 | 1000 | 1.2496 | 1.2470 | .206 |
| 353.64 | 1500 | 1.2622 | 1.2613 | .077 |
| 352.87 | 2000 | 1.2761 | 1.2765 | -.025 |
| | | | | |
| 373.14 | 242 | 1.1641 | 1.1600 | .350 |
| 373.10 | 600 | 1.1794 | 1.1753 | .350 |
| 373.13 | 1000 | 1.1941 | 1.1911 | .251 |
| 373.10 | 1500 | 1.2106 | 1.2097 | .078 |
| 373.12 | 2000 | 1.2265 | 1.2266 | -.014 |
| | | | | |
| 392.97 | 332 | 1.0957 | 1.0939 | .171 |
| 392.93 | 600 | 1.1129 | 1.1087 | .378 |
| 392.90 | 1000 | 1.1340 | 1.1294 | .405 |
| 392.91 | 1500 | 1.1562 | 1.1531 | .263 |
| 392.93 | 2000 | 1.1744 | 1.1747 | -.029 |
| | | | | |
| 413.09 | 510 | 1.0185 | 1.0275 | -.881 |
| 413.03 | 600 | 1.0287 | 1.0340 | -.513 |
| 412.97 | 1000 | 1.0624 | 1.0608 | .152 |
| 413.00 | 1500 | 1.0931 | 1.0911 | .189 |
| 412.99 | 2000 | 1.1177 | 1.1186 | -.079 |
| 413.05 | 2000 | 1.1177 | 1.1184 | -.062 |
| | | | | |
| 422.80 | 1000 | 1.0195 | 1.0247 | -.518 |
| 422.84 | 1500 | 1.0596 | 1.0587 | .080 |
| 422.47 | 2000 | 1.0892 | 1.0906 | -.129 |

## TABLE 3-A - RESULTS OF LEAST - SQUARES FIT OF REFRIGERANT -21 DENSITY AS F(T) AT CONSTANT PRESSURE

$$\text{Density (g/cc)} = A_0 + A_1T + A_2T^2 + A_3T^3, \text{ (T in K)}$$

| Pressure, psia | Temp. Range, °C | Coefficients | | | | Standard Error of Estimate |
|---|---|---|---|---|---|---|
| | | $A_0$ | $A_1 \times 10^3$ | $A_2 \times 10^6$ | $A_3 \times 10^9$ | |
| 100 | -130° to 0° | 2.07477 | -3.29817 | 6.36516 | -11.04465 | 0.00038 |
| 200 | -130° to 0° | 2.05840 | -3.02520 | 4.92446 | -8.52268 | 0.00031 |
| 400 | -130° to 0° | 2.05486 | -2.95067 | 4.51822 | -7.73084 | 0.00030 |
| 600 | 0° to 150° | 3.32902 | -15.31144 | 44.39610 | -50.03732 | 0.00133 |
| 700 | -130° to 0° | 2.04154 | -2.73204 | 3.44790 | -5.89183 | 0.00022 |
| 1000 | -130° to +150° | 2.16243 | -4.30782 | 10.09863 | -14.78292 | 0.00165 |
| 1500 | -130° to +150° | 2.11564 | -3.70331 | 7.64401 | -11.31366 | 0.00123 |
| 2000 | -130° to +150° | 2.09074 | -3.32174 | 5.94549 | -8.73176 | 0.00111 |
| 4000 | -130° to 0° | 2.06496 | -2.90525 | 4.35961 | -6.19128 | 0.00035 |
| 7000 | -130° to 0° | 2.04769 | -2.48026 | 2.34169 | -2.20158 | 0.00047 |
| 10,000 | -130° to 0° | 2.06111 | -2.53970 | 2.78667 | -2.45663 | 0.00043 |
| 15,000 | -130° to 0° | 2.05472 | -2.24849 | 1.77292 | -0.57994 | 0.00047 |
| 20,000 | -130° to 0° | 2.10398 | -2.80369 | 4.88206 | -5.50481 | 0.00026 |



A. Cell Isolation Valve
B. Sample Cell, Charging Position
C. Sample Cell, Test Position
D. Bath Thermocouple
E. Mercury - Test Fluid Isolator
F. Test Fluid Charging Cell

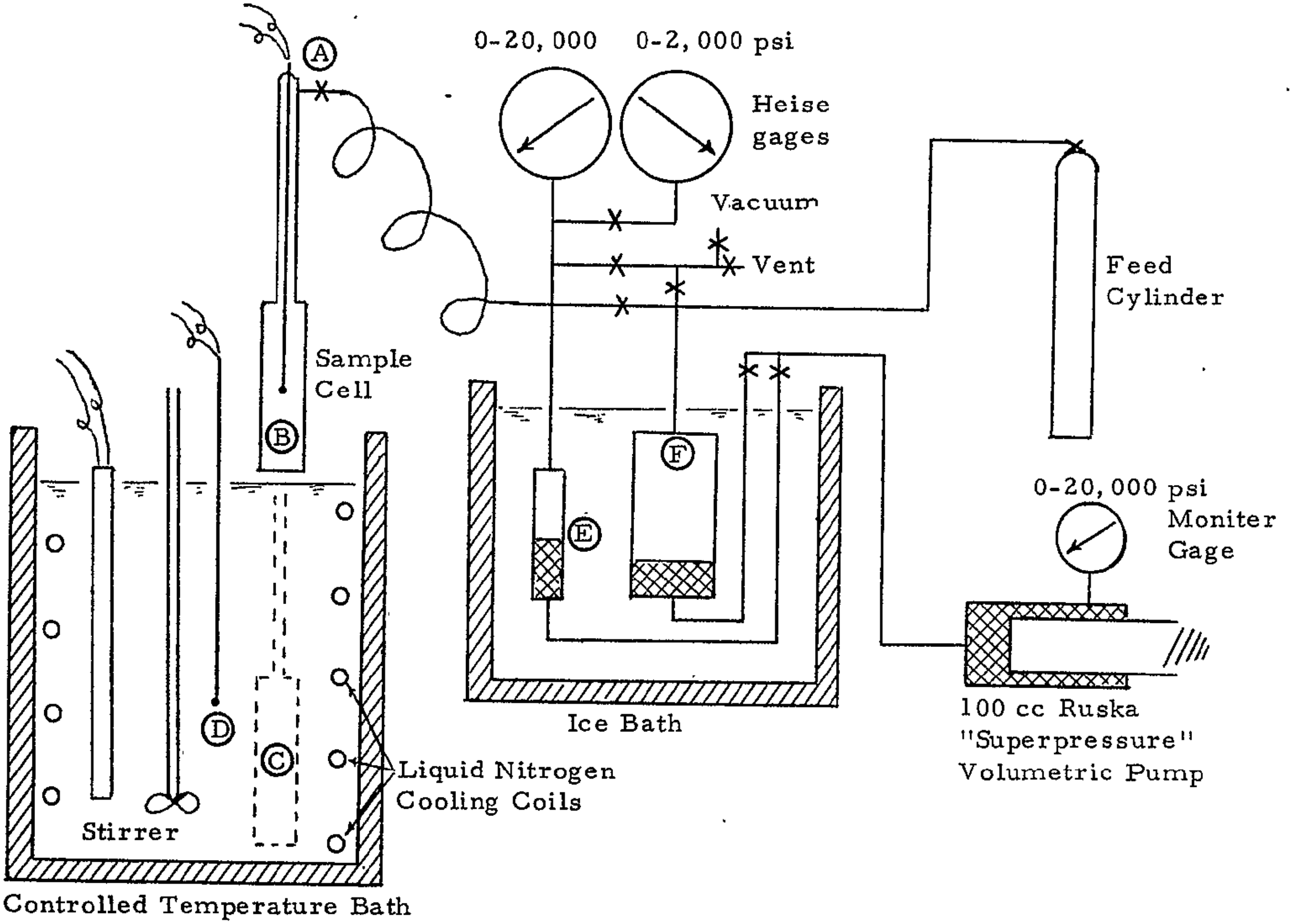
FIGURE 1-A - Schematic of Freezing Point and Relative Volume Apparatus

# APPENDIX B

## Freezing Point

The freezing point apparatus is essentially a stainless steel tube containing a thermocouple and the R-21 to be frozen, a bath for rapidly cooling the tube, and a mercury pump to maintain the R-21 in the tube at a pre-selected pressure as it is cooled. The apparatus is shown schematically in Figure 1-B.

Data were obtained by filling the sample cell with R-21 at the desired pressure, with the cell bath at -100° C. The bath was cooled rapidly, with pressure maintained constant, until a sudden rise in temperature indicated formation of the solid. The bath temperature was then raised to the indicated freezing temperature, and by varying pressure at constant bath temperature, the freezing point was measured while both freezing and thawing. The difference ranges from 0.2 to 1.1° C, and the average temperature was recorded as the freezing point.



A. Cell Isolation Valve
B. Sample Cell, Charging Position
C. Sample Cell,Test Position
D. Bath Thermocouple
E. Mercury - Test Fluid Isolator
F. Test Fluid Charging Cell

FIGURE 1-B - Schematic of Freezing Point and Relative Volume Apparatus

# APPENDIX C

## Viscosity

Viscosities are determined using two different procedures. A modified Ostwald-Cannon-Fenske glass viscometer is used for atmospheric pressure measurements and the Ruska rolling ball viscometer for those above atmospheric pressure.

Figure 1-C is a schematic diagram of the apparatus using the modified Ostwald-Cannon-Fenske glass viscometer. The viscometer is calibrated using water and n-pentane. The instrument is evacuated, inserted into a constant temperature bath, and filled with R-21 to a specified weight. Helium is used to pressurize the instrument to 15 psia. This instrument is essentially a capillary tube connected by inlet and outlet reservoirs. The head of fluid is the driving force, and the time for a given volume of fluid in the upper reservoirs to flow through the capillary tube to the bottom chamber is directly related to the viscosity. The data reported in Table 1-C are the average of 2 to 5 flow times.

Above atmospheric data are obtained using a Ruska rolling-ball viscometer and is shown in detail in Figure 2-C. The instrument is calibrated at two temperatures using n-hexane and n-heptane to obtain the temperature coefficients. The instrument is reproducible in flow time to ±1% and accurate to ±2%.

The instrument used is equipped with a fluid circulation jacket, and a constant temperature bath, instead of the insulated heating jacket shown in Figure 1-C. The absolute coefficient in the rolling ball equation was obtained by forcing the 0° C R-21 data from the Ruska instrument to agree with that from the glass viscometer.

Flow times were measured at two different barrel angles, with generally consistent results. The data at vapor pressure and 50 psia, and vapor pressure and 100 psia are given in Table 2-C. Viscosity data at 600, 1000 and 1500 psia are given in Table 3-C.

## TABLE 1-C - EXPERIMENTAL VISCOSITY OF REFRIGERANT-21
15 psia, 0° to -130° C

| Nominal Temp., °C | Temp., °C | Density, g/cc | Viscosity, cp |
|---|---|---|---|
| 0 | 0.17 | 1.4264 | 0.400 |
| - 20 | -17.54 | 1.4645 | 0.483 |
| | -20.26 | 1.4703 | 0.495 |
| - 40 | -40.15 | 1.5112 | 0.632 |
| - 60 | -59.83 | 1.5511 | 0.858 |
| - 80 | -79.93 | 1.5921 | 1.243 |
| | -80.15 | 1.5926 | 1.246 |
| | -80.16 | 1.5926 | 1.254 |
| -100 | -100.06 | 1.6347 | 2.018 |
| -120 | -120.00 | 1.6792 | 4.069(a) |
| -130 | -130.16 | 1.7032 | 7.048 |

(a) Omitted from final least-squares fit.

## TABLE 2-C - EXPERIMENTAL VISCOSITY OF REFRIGERANT-21
Vapor Pressure +50 and +100 psia, 0° to +150° C

| Nominal Temp., °C | (Vapor Pressure +50) psia | | | | (Vapor Pressure +100) psia | | | |
|---|---|---|---|---|---|---|---|---|
| | Temp., °C | Pressure, psia | Density, g/cc | Viscosity, cp | Temp., °C | Pressure, psia | Density, g/cc | Viscosity, cp |
| 0 | -0.67 | 61 | 1.4288 | 0.402 | | | | |
| | -0.50 | 61 | 1.4284 | 0.403 | -0.56 | 111 | 1.4291 | 0.402 |
| 20 | 20.28 | 72 | 1.3813 | 0.337 | | | | |
| | 20.78 | 72 | 1.3801 | 0.335 | 20.78 | 122 | 1.3808 | 0.336 |
| 40 | 40.33 | 93 | 1.3322 | 0.291 | | | | |
| | 40.56 | 93 | 1.3317 | 0.291 | 40.83 | 143 | 1.3319 | 0.289 |
| | 40.83 | 93 | 1.3309 | 0.289 | 44.72 | 148 | 1.3219 | 0.286 |
| | 45.00 | 98 | 1.3202 | 0.282 | | | | |
| 60 | 61.00 | 130 | 1.2774 | 0.250 | 60.83 | 180 | 1.2791 | 0.250 |
| | 61.94 | 130 | 1.2747 | 0.252 | 63.61 | 180 | 1.2712 | 0.249 |
| 80 | 76.39 | 175 | 1.2335 | 0.223 | | | | |
| | 77.78 | 175 | 1.2293 | 0.221 | 79.44 | 225 | 1.2258 | 0.221 |
| 100 | 100.00 | 242 | 1.1600 | 0.187 | 100.00 | 292 | 1.1622 | 0.188 |
| 120 | 119.61 | 332 | 1.0946 | 0.160 | 119.44 | 382 | 1.0980 | 0.161 |
| 140 | 139.28 | 457 | 1.0264 | 0.135 | 139.17 | 507 | 1.0304 | 0.135 |
| 150 | 149.17 | 540 | 0.9922 | 0.123 | 149.28 | 600 | 0.9964 | 0.123 |

# TABLE 3-C - EXPERIMENTAL VISCOSITY OF REFRIGERANT-21

600 to 1500 psia, 0° to +150° C

| | Pressure | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 600 psia | | | 1000 psia | | | 1500 psia | | |
| Nominal Temp., °C | Temp., °C | Density, g/cc | Viscosity, cp | Temp., °C | Density, g/cc | Viscosity, cp | Temp., °C | Density, g/cc | Viscosity, cp |
| 0 | -0.50 | 1.4348 | 0.403 | | | | | | |
| | -0.39 | 1.4345 | 0.407 | -0.39 | 1.4391 | 0.408 | -0.39 | 1.4448 | 0.411 |
| 20 | 20.83 | 1.3877 | 0.339 | 20.83 | 1.3934 | 0.340(a) | 20.83 | 1.4003 | 0.346 |
| | 24.17 | 1.3800 | 0.334 | 24.06 | 1.3862 | 0.336 | 24.06 | 1.3933 | 0.340 |
| 40 | 40.83 | 1.3404 | 0.292 | | | | | | |
| | 43.33 | 1.3343 | 0.293(a) | 44.44 | 1.3391 | 0.292 | 44.72 | 1.3475 | 0.293 |
| 60 | 60.33 | 1.2907 | 0.254 | 60.28 | 1.3002 | 0.257 | | | |
| | | | | 60.56 | 1.2995 | 0.255 | 64.17 | 1.3019 | 0.256 |
| 80 | 76.67 | 1.2457 | 0.226 | | | | | | |
| | 79.44 | 1.2377 | 0.218 | 76.39 | 1.2581 | 0.229 | 78.33 | 1.2668 | 0.224(a) |
| 100 | 100.00 | 1.1751 | 0.190 | 100.00 | 1.1911 | 0.184(a) | 100.00 | 1.2096 | 0.195 |
| 120 | 119.61 | 1.1093 | 0.162 | 119.50 | 1.1302 | 0.153(a) | 119.61 | 1.1536 | 0.168 |
| 140 | 139.28 | 1.0363 | 0.136 | 139.28 | 1.0627 | 0.139 | 139.28 | 1.0929 | 0.142 |
| 150 | 149.28 | 0.9964 | 0.123 | 149.17 | 1.0265 | 0.127 | 149.17 | 1.0605 | 0.130 |

(a) Omitted from final least-squares fit.

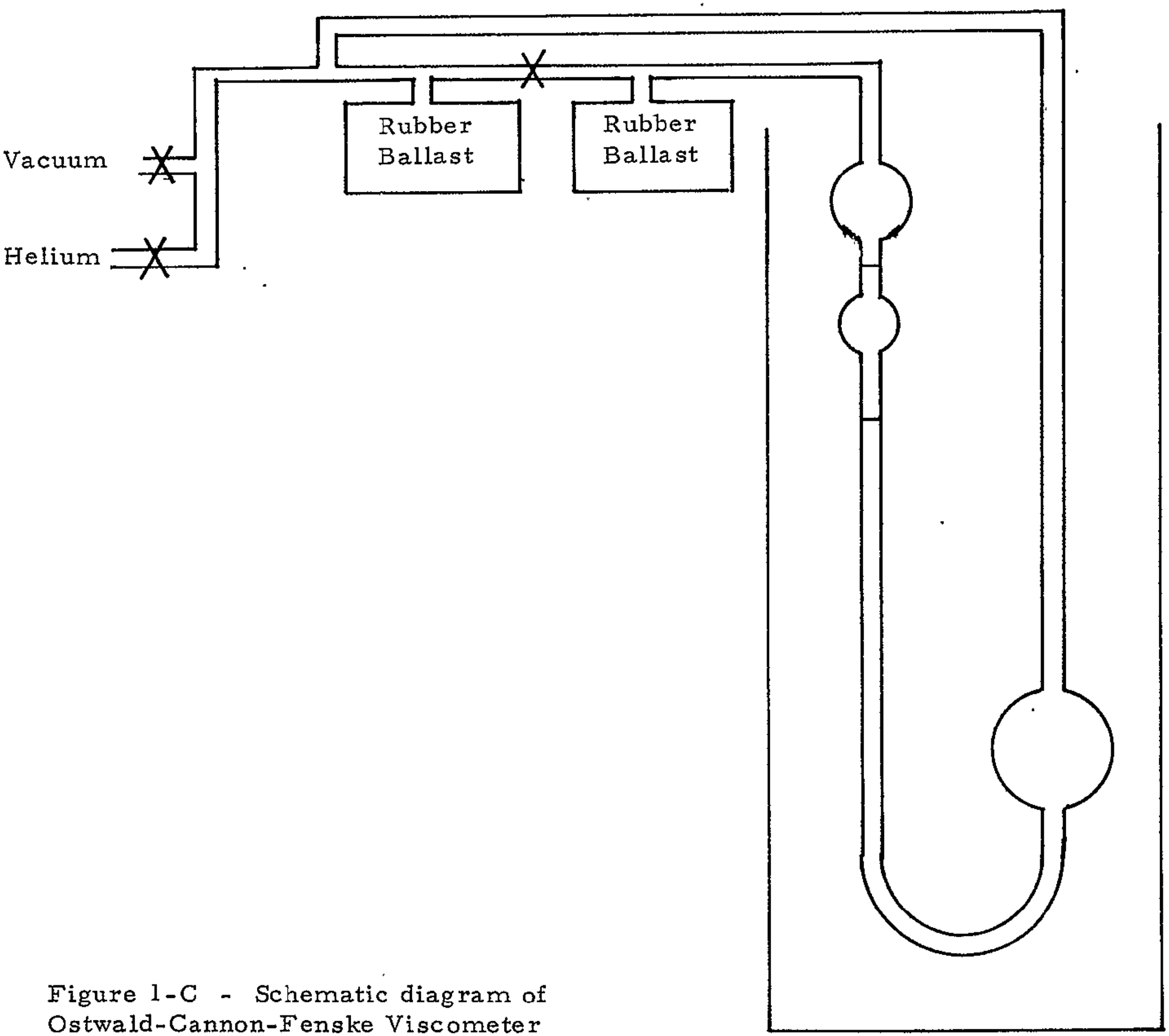


Figure 1-C - Schematic diagram of Ostwald-Cannon-Fenske Viscometer

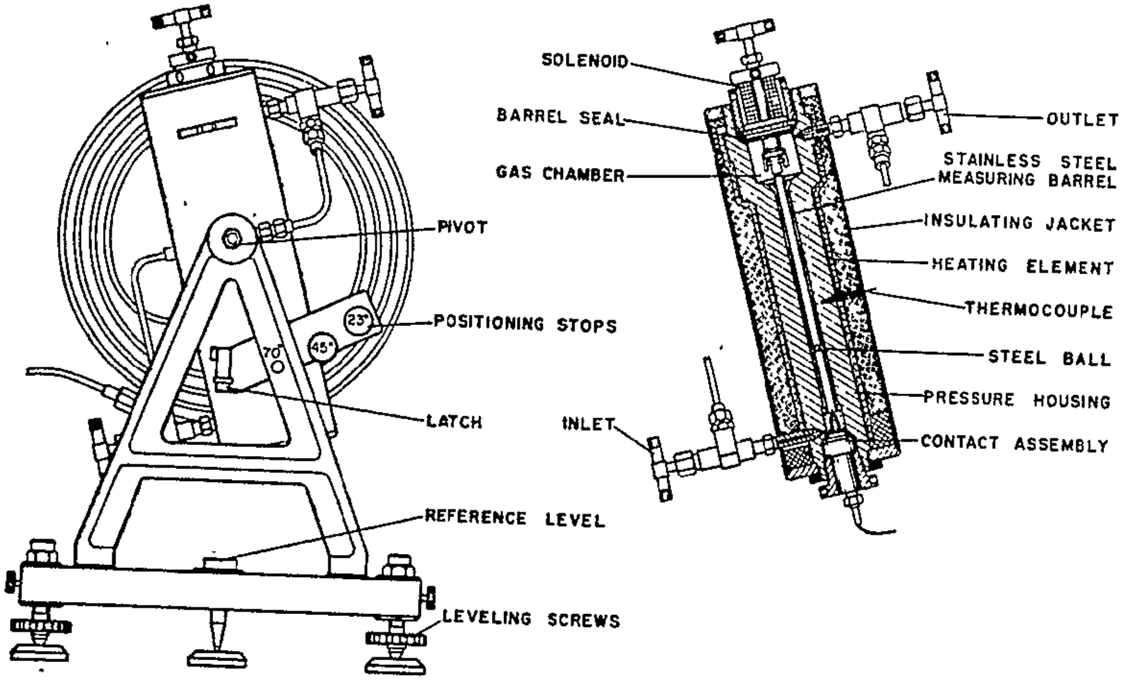


FIGURE 2-C - Details of Ruska Viscometer

# APPENDIX D

## Vapor Pressure

The vapor pressure measurements are broken into four sections:

a) Pressure from 15 to 200 psia.
b) Pressure above 200 psia.
c) Pressure from 100 to 780 mmHg.
d) Pressure below 100 mmHg

The same apparatus is used for all four sections. This apparatus, which is normally used for vapor-liquid equilibria measurements, is shown schematically in Figure 1-D. The first three sections differ only in the means of pressure measurements:

a) A calibrated 0 to 200 psi Heise gage.
b) A calibrated 0 to 500 psi Heise gage.
c) Mercury manometer.
d) Transpiration.

The visual cell and magnetic vapor - recirculating pump are submerged in a bath liquid. Bath liquid is triethylene glycol from 0° to 150° C, and iso-pentane for temperatures below 0° C. This liquid is maintained at a constant temperature by flowing liquid nitrogen through cooling coils near the bath walls. The liquid nitrogen flow rate is controlled by valves in the outlet vaporized nitrogen stream, to provide slight excess cooling for the desired temperature. An electrical heating element in the bath, controlled by a Hollikainen Resistotrol Unit, offsets the excess cooling to maintain bath temperature within ±0.1° F of the set-point. Temperatures are measured to ±0.1° F with a calibrated copper-constantan thermocouple and a ±0.1 microvolt Leeds and Northrup K-3 potentiometer with an electronic null-point detector.

The system is evacuated by a mechanical pump and charged with the R-21 until the cell is approximately 3/4 filled. The closed system is circulated to equilibrium, and vapor then bled from the cell. This is repeated until the cell liquid level has fallen to about $\frac{1}{2}$. This procedure removes any air or light gases either present in the cell or in the R-21.

The Heise gages are checked for linearity at the factory, and re-checked by P-V-T, Inc. using a Ruska Dead Weight Gage. The absolute calibration is made with the gage mounted in the apparatus. A check run is also made with propane (for the 0 to 200 psi gage) and ethane (for the 0 to 500 psi gage) as a final calibration. The reproducibility of the Heise gage is ±0.1% of full scale, or ±0.2 psi for the 200 psi gage, and ±0.5 psi for the 500 psi gage. The vapor pressure curves for these hydrocarbons are very well known.

For pressures below atmospheric, the Heise gages are replaced by a mercury manometer. The manometer legs are read with a cathatometer to ±0.1 mm. A mercury barometer is also read, and the difference between these two gives the cell pressure. This system starts to lose accuracy below 100 mm absolute vapor pressure.

For low pressures, the cell is used as a vapor-liquid equilibrium apparatus, with a very slowly flowing stream of helium bubbling through the liquid. The helium is at near atmospheric pressure, as measured by the manometer. The vapor sample line is open, and helium saturated with R-21 is withdrawn to a gas chromatograph. Samples of the flowing helium stream are injected into the G.C. The response of a thermal conductivity detector, previously calibrated with known helium R-21 mixtures, gives the concentration of R-21 in the sample. By proper selection of the column, operating temperature, and sample size, it is possible to measure vapor-pressures to ±1% at pressure levels of 1.0 mm of mercury. At pressures of 0.01 mm of mercury, the accuracy is reduced to ±5%.

The experimental data measured with calibrated Heise gages are given in Table 1-D. These represent 16 temperatures from 0° to +150° C at approximately 10° C intervals. There are 8 repeat points: 5 represent repeating the last measurements of the previous day before continuing to new temperatures, and 3 are check points where major deviations were observed in the data fit.

The experimental data measured with the mercury manometer, and with the helium-flow-gas-chromatograph transpiration procedure, are given in Table 2-D. Experimental difficulties with volatile contaminants (principally air) limited the accuracy of the manometer measurements at low pressure. Only 5 values, at temperatures from +10° to -10° C are included in the final tabulation. All other values are by transpiration with helium. At the lowest temperature, -120° C, the measured pressure has a very high uncertainty. The GC gave counts from 13 to 17 for the R-21 peak on an attenuation of X1. For comparison, 100% R-21 gave 1125 counts at an attenuation of X256.

The experimental and calculated values are shown in Table 3-D for temperatures above 0° C, and in Table 4-D for temperatures below 0° C. The average percent difference in Table 3-D is 0.16%, when three data points indicated by * are omitted from the fit. The standard error of estimate is ±0.30 psia.

The low temperature data show more variation. (Table 4-D) The average percent difference for all these points is 1.27%. The standard error of estimate is 0.045 psia.

## TABLE 1-D - EXPERIMENTAL VAPOR PRESSURE MEASUREMENTS FOR REFRIGERANT-21

Pressures measured by Heise gage

| Temperature | | Vapor Pressure | |
|---|---|---|---|
| °K | °C | psia | N/m$^2$ X 10$^{-3}$ |
| 274.54 | 1.39 | 11.00 | 75.84 |
| 283.30 | 10.15 | 15.60 | 107.56 |
| 293.03 | 19.88 | 22.20 | 153.06 |
| 303.45 | 30.30 | 31.4 | 216.50 |
| 303.49 | 30.34 | 31.6 | 217.87 |
| 313.19 | 40.04 | 42.8 | 295.10 |
| 322.97 | 49.82 | 57.0 | 393.00 |
| 333.36 | 60.21 | 75.7 | 521.93 |
| 343.40 | 70.25 | 97.8 | 674.31 |
| 353.11 | 79.96 | 124.4 | 857.71 |
| 363.30 | 90.15 | 156.1 | 1076.27 |
| 343.94 | 70.79 | 99.8 | 688.10 |
| 363.52 | 90.37 | 157.0 | 1082.48 |
| 373.07 | 99.92 | 192.4 | 1326.55 |
| **** | | | |
| 363.56 | 90.41 | 156.5 | 1079.03 |
| 373.02 | 99.87 | 192.1 | 1324.48 |
| 383.04 | 109.89 | 237.4 | 1636.82 |
| 393.53 | 120.38 | 289.9 | 1998.79 |
| 403.05 | 129.90 | 344.0 | 2371.80 |
| 413.48 | 140.33 | 411.6 | 2837.88 |
| 423.91 | 150.76 | 489.8 | 3377.05 |
| 383.34 | 110.19 | 237.2 | 1635.44 |
| 394.18 | 121.03 | 291.7 | 2011.20 |
| 403.54 | 130.39 | 345.7 | 2383.52 |

**** Switched from 200 to 500 psia Heise gage

## TABLE 2-D - EXPERIMENTAL VAPOR PRESSURE MEASUREMENTS FOR REFRIGERANT-21

m - Pressures Measured by Mercury Manometer

t - Pressures measured by Helium transpiration

| Meas. by | Temperature | | Vapor Pressure | |
|---|---|---|---|---|
| | °K | °C | psia | N/m$^2$ X $10^{-3}$ |
| m | 283.09 | 9.94 | 15.37 | 105.97 |
| m | 273.12 | -0.03 | 10.23 | 70.53 |
| t | 273.12 | -0.03 | 10.27 | 70.81 |
| m | 273.05 | -0.10 | 10.44 | 71.98 |
| m | 263.77 | -9.38 | 6.85 | 47.23 |
| t | 263.77 | -9.38 | 6.86 | 47.30 |
| m | 263.10 | -10.05 | 6.67 | 45.99 |
| t | 253.37 | -19.78 | 4.26 | 29.37 |
| t | 243.06 | -30.09 | 2.46 | 16.96 |
| t | 233.31 | -39.84 | 1.42 | 9.79 |
| t | 232.91 | -40.24 | 1.30 | 8.96 |
| t | 222.83 | -50.32 | 0.691 | 4.76 |
| t | 212.98 | -60.17 | 0.334 | 2.30 |
| t | 202.96 | -70.19 | 0.156 | 1.08 |
| t | 193.56 | -79.59 | 0.0654 | 0.451 |
| t | 193.25 | -79.90 | 0.0651 | 0.449 |
| t | 193.20 | -79.95 | 0.0633 | 0.436 |
| t | 193.13 | -80.02 | 0.0633 | 0.437 |
| t | 183.14 | -90.01 | 0.0229 | 0.158 |
| t | 183.11 | -90.04 | 0.0228 | 0.157 |
| t | 173.19 | -99.96 | 0.00714 | 0.0492 |
| t | 173.11 | -100.04 | 0.00722 | 0.0498 |
| t | 163.61 | -109.54 | 0.00216 | 0.0149 |
| t | 162.30 | -110.85 | 0.00169 | 0.0116 |
| t | 153.14 | -120.01 | 0.00033 | 0.0023 |

# TABLE 3-D - POLYNOMIAL FIT TO EXPERIMENTAL VAPOR PRESSURE DATA

Date above 0° C

Fifth order polynomial

| Temperature | Vapor Pressure, Psia | | Error (Meas. - Calc.) | |
|---|---|---|---|---|
| °K | Measured | Calculated | Psia | % |
| 274.54 | 11.00 | 11.021 | -0.021 | -0.19 |
| 283.30 | 15.60 | 15.546 | 0.054 | 0.34 |
| 293.03 | 22.20 | 22.173 | 0.027 | 0.12 |
| 303.45 | 31.4 | 31.533 | -0.133 | -0.42 |
| 303.49 | 31.6 | 31.574 | 0.026 | 0.08 |
| 313.19 | 42.8 | 42.811 | -0.011 | -0.03 |
| 322.97 | 57.0 | 57.022 | -0.022 | -0.04 |
| 333.36 | 75.7 | 75.788 | -0.088 | -0.12 |
| 343.40 | 97.8 | 98.027 | -0.227 | -0.23 |
| 353.11 | 124.4 | 123.87 | 0.53 | 0.42 |
| 363.30 | 156.1 | 156.13 | -0.03 | -0.02 |
| 343.94 | 99.8 | 99.348 | 0.452 | 0.45 |
| 363.52 | 157.0 | 156.88 | 0.12 | 0.07 |
| 373.07 | 192.4 | 192.52 | -0.12 | -0.06 |
| 363.56 | 156.5 | 157.02 | -0.52 | -0.33 |
| 373.02 | 192.1 | 192.32 | -0.22 | -0.11 |
| 383.04 | 237.4 | 235.74 | 1.66 | 0.70 |
| 393.53 | 289.9 | 288.47 | 1.43 | 0.49 |
| 403.05 | 344.0 | 343.36 | 0.64 | 0.19 |
| 413.48 | 411.6 | 411.84 | -0.24 | -0.06 |
| 423.91 | 489.8 | 489.77 | 0.03 | 0.01 |
| 383.34 | 237.2 | 237.14 | 0.06 | 0.03 |
| 394.18 | 291.7 | 292.00 | -0.30 | -0.10 |
| * 403.54 | 345.7 | 346.38 | -0.68 | -0.20 |

* Omitted from final fit, and from computed error.

Average percent error = 0.16%

Standard error of estimate = ±0.30 psia

## TABLE 4-D - POLYNOMIAL FIT TO EXPERIMENTAL VAPOR PRESSURE DATA

Data below 0° C

Fifth order polynomial

| Temperature | Vapor Pressure, Psia | | Error (Meas. - Calc.) | |
|---|---|---|---|---|
| °K | Measured | Calculated | Psia | % |
| 274.54 | 11.00 | 11.015 | -0.015 | -0.14 |
| 283.30 | 15.60 | 15.527 | 0.073 | 0.47 |
| 283.09 | 15.37 | 15.405 | -0.035 | -0.23 |
| 273.05 | 10.44 | 10.360 | 0.080 | 0.77 |
| 273.12 | 10.27 | 10.390 | -0.120 | -1.16 |
| 263.10 | 6.67 | 6.714 | -0.044 | -0.66 |
| 253.37 | 4.26 | 4.209 | 0.051 | 1.20 |
| 243.06 | 2.46 | 2.438 | 0.022 | -0.91 |
| 233.31 | 1.420 | 1.3774 | 0.0426 | 3.00 |
| 222.83 | 0.691 | 0.6975 | -0.0065 | -0.94 |
| 212.98 | 0.334 | 0.3424 | -0.0084 | -2.52 |
| 202.96 | 0.1560 | 0.1529 | 0.0031 | 2.00 |
| 193.56 | 0.0654 | 0.06570 | -0.00030 | -0.46 |
| 232.91 | 1.300 | 1.3438 | -0.0438 | -3.37 |
| 193.20 | 0.0633 | 0.06349 | -0.00019 | -0.30 |
| 183.11 | 0.0228 | 0.02284 | -0.00004 | -0.16 |
| 173.11 | 0.00722 | 0.00723 | -0.00001 | -0.15 |
| 163.61 | 0.00216 | 0.00208 | 0.00008 | 3.59 |
| 193.25 | 0.0652 | 0.06379 | 0.00141 | 2.16 |
| 193.13 | 0.0633 | 0.06307 | 0.00023 | 0.37 |
| 183.14 | 0.0229 | 0.02291 | -0.00001 | -0.04 |
| 173.19 | 0.00714 | 0.00730 | -0.00016 | -2.27 |
| 162.30 | 0.00169 | 0.00173 | -0.00004 | -2.41 |
| * 153.14 | 0.00033 | 0.00043 | -0.0001 | -30.30 |

* Omitted from final fit and from computed error.

Average percent error = 1.27%

Standard error of estimate = 0.045 psia

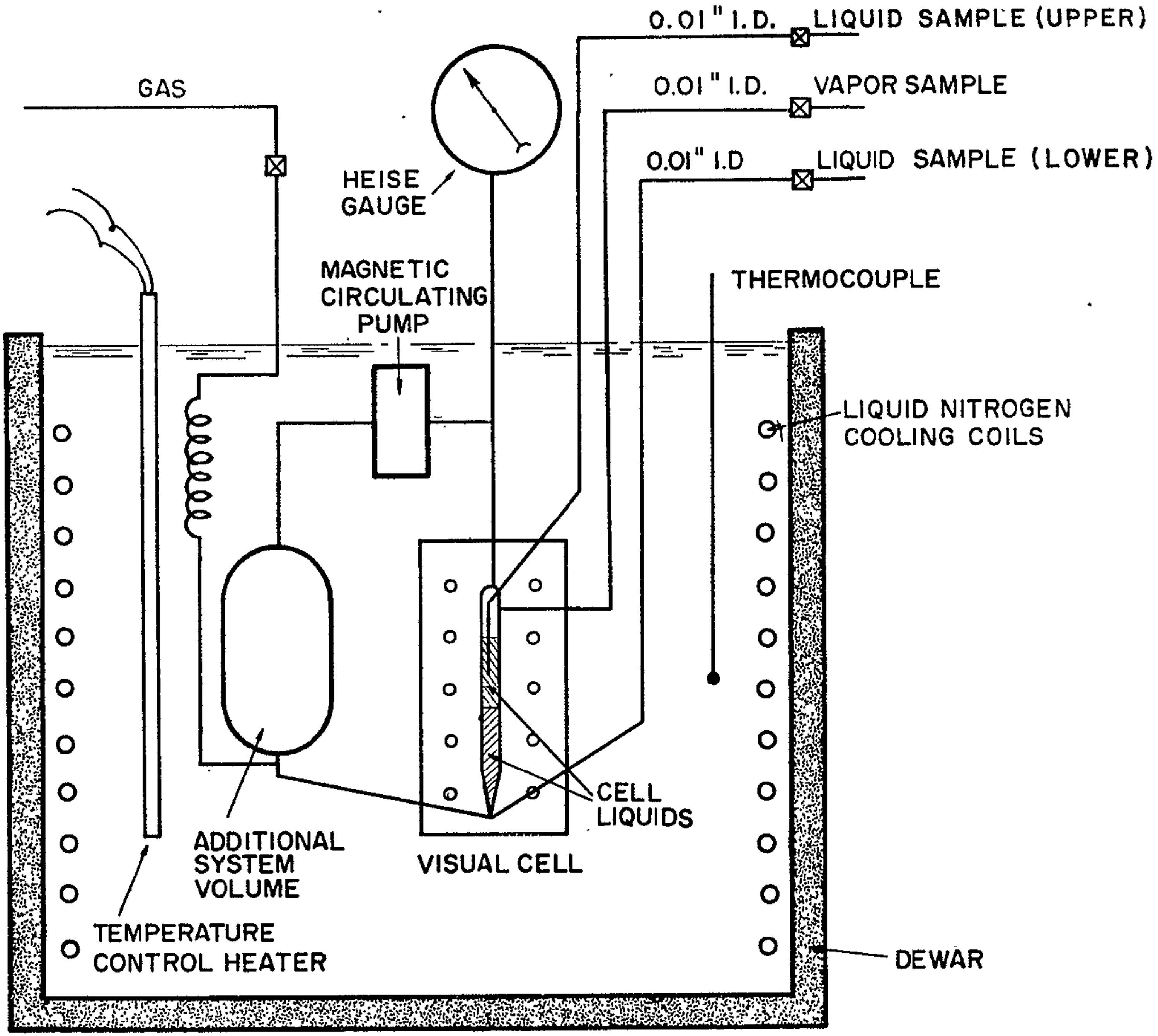


FIGURE 1-D - SCHEMATIC OF CELL ASSEMBLY

## APPENDIX E

### Heat Capacity

The calorimeter used for heat capacity measurements was designed and constructed at P-V-T, Inc. A schematic diagram of the apparatus is given in Figure 1-E. Figure 2-E is a schematic of the calorimeter only.

R-21 is displaced at a constant rate through the calorimeter by means of a constant rate mercury displacement pump. Pressures are maintained by a back pressure regulator on the calorimeter exit. After passing through the regulator, the R-21 totally vaporizes and the volume is measured on a calibrated wet test meter.

The calorimeter is surrounded by a constant temperature bath and the sample passes through a pre-cooler coil prior to entering the calorimeter. The inlet temperature is measured with a four-junction copper-constantan thermocouple. The fluid passes over a heater and the outlet temperature is measured as a differential from the inlet temperature. After a steady state condition has been reached, measurements are taken in 5 minute intervals of the flow, $T_{in}$, $\Delta T$, $P_{in}$, $P_{out}$, voltage and current applied to the heater, wet test meter temperature and wet test meter reading. Flows are also determined by knowing the density and displacement rate of the mercury pump. These series of measurements are then entered as inputs to a computer program which calculates the inlet temperature, outlet temperature, molar flow rate, quantity of heat added, and the necessary correction values for heat leaks due to radiation and conduction. The heat capacity is then determined by:

$$C_p = \frac{Q}{(\text{flow})\,(T_{out} - T_{in})}$$

Where $Q$ = heat input, cal/hr.
$F$ = flow, g-mole/hr.
$T$ = $T_{out} - T_{in}$, in Kelvin
$Cp$ = Heat capacity, cal/g-mole
Additional information on the calorimeter is given in Appendix G.

The experimental data are actually enthalpy changes between inlet and outlet temperatures. The average heat capacity is obtained by dividing the enthalpy change by the temperature interval between inlet and outlet. An initial series of 13 test runs were made with helium and propane, from -130° to 10° C. The results are given in Table 1-E, with literature values for comparison. The average ratio between measured and literature value is 1.0006 ± 0.0045, or an average deviation of ±0.5% for both gaseous and liquid measurements.

Additional check runs were made during the course of the R-21 measurements and are summarized in Table 2-E. In the vicinity of 0° F, an unexpected convection problem was encountered in the calorimeter. This was solved by reversing the direction of flow, and runs 551 through 571 were made with the modified instrument. The last two runs were made as checks after completion of the R-21 measurements.

The enthalpy change for R-21 was measured at pressures of 30, 100 and 500 psia. Intervals of 20°, 40° and 60° C between inlet and outlet temperatures were utilized, except above 130° C at 500 psia, where 5° C intervals were measured. Inlet temperatures started at -130° C and increased by 40° C steps. Experimental results at 30 psia are given in Table 3-E, at 100 psia in Table 4-E and at 500 psia in Table 5-E the maximum outlet temperature at 30 and 100 psia were limited by approach to the vapor pressure curve.

The overlap of the temperature intervals permits direct comparison of the measured heat capacities. For example, at 500 psia the following comparisons can be made:

Run 508 183.49° to 203.48° K $C_p = 23.88$

Run 507 - Run 506 $$\frac{1447.3 - 959.5}{(204.80-144.67) - (184.07-144.21)}$$

or 184.07° to 204.80° K $C_p = 24.07$

The ratio of the directly measured $C_p$ to that backed out by difference between these two measurements is: 23.88/24.07 = 0.9923, which we consider acceptable. Some other comparisons are given below:

| Interval, °K | Heat Capacity, $C_p$ Direct | Heat Capacity, $C_p$ by Difference | Ratio |
|---|---|---|---|
| 224 to 244 | 24.18 | 24.20 | 1.0007 |
| 243 to 263 | 24.38 | 24.59 | 0.9916 |
| 263 to 283 | 24.78 | 25.52 | 0.9710 |
| 303 to 323 | 25.79 | 25.79 | 1.0000 |
| 343 to 363 | 27.44 | 27.55 | 0.9958 |
| 383 to 403 | 31.00 | 31.20 | 0.9937 |

Only the values over the interval 263° to 283° K differ by more than 1%.

The experimental data were smoothed by comparison with a set of heat capacity values calculated for R-21 at corresponding conditions with the Mark V computer program. The corresponding values at 500 psia are given in Table 6-E.

## TABLE 1-E - INITIAL CALORIMETER CALIBRATION RUNS

| Run | | Pressure, | Temperature, K | | Heat Capacity, Cp | | Ratio |
|---|---|---|---|---|---|---|---|
| No. | Fluid | PSIA | In | Out | Meas. | Lit. * | Meas. /Lit. |
| 483 | Helium | 100 | 143.19 | 172.31 | 4.995 | 4.968 | 1.0055 |
| 484 | Helium | 100 | 143.65 | 199.94 | 5.035 | 4.968 | 1.0134 |
| 485 | Propane | 400 | 143.78 | 170.21 | 21.002 | 21.080 | 0.9963 |
| 486 | Propane | 400 | 144.13 | 199.63 | 21.425 | 21.606 | 0.9916 |
| 487 | Propane | 401 | 144.06 | 171.59 | 21.090 | 21.080 | 1.0005 |
| 488 | Propane | 400 | 144.38 | 200.19 | 21.505 | 21.606 | 0.9953 |
| 489 | Propane | 399 | 200.09 | 228.42 | 22.630 | 22.567 | 1.0028 |
| 490 | Propane | 399 | 220.17 | 256.40 | 23.427 | 23.353 | 1.0032 |
| 491 | Propane | 400 | 200.23 | 228.38 | 22.557 | 22.567 | 0.9995 |
| 492 | Propane | 399 | 200.40 | 256.07 | 23.343 | 23.353 | 0.9996 |
| 493 | Helium | 100 | 233.40 | 262.26 | 4.945 | 4.968 | 0.9954 |
| 494 | Helium | 100 | 233.72 | 289.37 | 4.957 | 4.968 | 0.9978 |
| 495 | Helium | 100 | 233.42 | 261.90 | 5.004 | 4.968 | 1.0072 |
| | | | | | Average | | 1.0006 |
| | | | | | | | ±0.0045 |

* The heat capacity of helium at all conditions studied in this project is 4.968. The literature values for propane were interpolated from the data of V. F. Yesavage, "The Measurement and Prediction of the Enthalpy of Fluid Mixtures Under Pressure." Ph.D. Thesis, Department of Chemical and Metallurgical Engineering, University of Michigan (Nov. 1968).

# TABLE 2-E - OTHER CALORIMETER CALIBRATION RUNS

| Run No. | Fluid | Pressure, PSIA | Temperature, K | | Heat Capacity, $C_p$ | | Ratio Meas./Lit. |
|---|---|---|---|---|---|---|---|
| | | | In | Out | Meas. | Lit. | |
| 525 | Helium | 148 | 263.35 | 288.36 | 4.875 | 4.968 | 0.9813 |
| 526 | Helium | 148 | 263.66 | 313.65 | 4.916 | 4.968 | 0.9815 |
| 527 | Helium | 149 | 264.11 | 338.60 | 4.946 | 4.968 | 0.9956 |
| 528 | Helium | 148 | 264.00 | 313.37 | 4.919 | 4.968 | 0.9901 |
| 529 | Helium | 150 | 263.67 | 313.34 | 5.007 | 4.968 | 1.0079 |
| 530 | Helium | 150 | 263.68 | 338.42 | 5.021 | 4.968 | 1.0107 |
| 551 | Helium | 100 | 263.41 | 337.94 | 4.991 | 4.968 | 1.0046 |
| 552 | Helium | 102 | 263.48 | 338.46 | 5.018 | 4.968 | 1.0101 |
| 553 | Helium | 101 | 263.55 | 338.65 | 5.004 | 4.968 | 1.0072 |
| 554 | Helium | 104 | 144.44 | 218.60 | 4.984 | 4.968 | 1.0032 |
| 555 | Helium | 105 | 144.18 | 218.53 | 5.036 | 4.968 | 1.0137 |
| 556 | Helium | 104 | 144.51 | 264.44 | 4.996 | 4.968 | 1.0056 |
| 557 | Helium | 104 | 143.23 | 220.11 | 5.003 | 4.968 | 1.0070 |
| 558 | Helium | 104 | 143.53 | 263.93 | 5.001 | 4.968 | 1.0066 |
| 559 | Helium | 103 | 143.41 | 218.35 | 4.967 | 4.968 | 0.9998 |
| 560 | Propane | 398 | 263.13 | 282.99 | 25.870 | 25.604 | 1.0104 |
| 561 | Propane | 400 | 263.33 | 303.28 | 27.055 | 26.722 | 1.0125 |
| 562 | Propane | 398 | 263.48 | 323.37 | 29.070 | 28.009 | 1.0379 |
| 563 | Propane | 400 | 263.38 | 283.24 | 25.675 | 25.636 | 1.0015 |
| 564 | Propane | 400 | 263.45 | 303.33 | 26.541 | 26.731 | 0.9929 |
| 565 | Propane | 399 | 263.66 | 323.54 | 27.623 | 28.035 | 0.9853 |
| 566 | Propane | 401 | 263.44 | 303.31 | 26.580 | 26.731 | 0.9944 |
| 567 | Propane | 400 | 263.69 | 323.24 | 27.592 | 28.015 | 0.9849 |
| 568 | Helium | 99 | 263.32 | 313.07 | 4.934 | 4.968 | 0.9932 |
| 569 | Helium | 99 | 264.00 | 413.80 | 5.000 | 4.968 | 1.0064 |
| 570 | Helium | 99 | 263.72 | 363.91 | 4.954 | 4.968 | 0.9972 |
| 571 | Helium | 99 | 264.05 | 314.28 | 4.924 | 4.968 | 0.9911 |
| 589 | Helium | 100 | 403.41 | 428.13 | 4.953 | 4.968 | 0.9970 |
| 590 | Helium | 100 | 403.56 | 453.56 | 4.999 | 4.968 | 1.0062 |

## TABLE 3-E - EXPERIMENTAL HEAT CAPACITIES FOR REFRIGERANT-21 AT 30 PSIA

| Run No. | Temperature, K In | Temperature, K Out | Enthalpy Change cal. /g-mole | Heat Capacity cal. /(g-mole) (°C) |
|---|---|---|---|---|
| 496 | 143.90 | 163.77 | 476.5 ± 5.3 | 23.98 |
| 499 | 142.12 | 161.54 | 460.4 ± 3.5 | 23.71 |
| 500 | 142.51 | 182.68 | 961.4 ± 8.0 | 23.93 |
| 501 | 142.77 | 202.99 | 1442.6 ± 5.4 | 23.96 |
| 514 | 183.37 | 203.20 | 478.9 ± 7.5 | 24.15 |
| 515 | 183.71 | 223.89 | 963.3 ± 3.2 | 23.98 |
| 516 | 183.99 | 244.13 | 1450.5 ± 4.1 | 24.12 |
| 517 | 223.29 | 243.32 | 483.9 ± 2.6 | 24.16 |
| 518 | 223.54 | 263.80 | 980.3 ± 3.6 | 24.35 |

## TABLE 4-E - EXPERIMENTAL HEAT CAPACITIES FOR REFRIGERANT-21 AT 100 PSIA

| Run No. | Temperature, K In | Temperature, K Out | Enthalpy Change cal. /g-mole | Heat Capacity cal. /(g-mole) (°C) |
|---|---|---|---|---|
| 498 | 143.94 | 164.13 | 483.9 ± 4.2 | 23.97 |
| 502 | 142.41 | 162.50 | 481.9 ± 3.3 | 23.99 |
| 503 | 142.72 | 182.92 | 969.3 ± 3.5 | 24.11 |
| 504 | 144.43 | 204.02 | 1431.6 ± 3.2 | 24.03 |
| 511 | 183.58 | 203.11 | 466.8 ± 1.7 | 23.90 |
| 512 | 183.95 | 223.90 | 964.8 ± 2.9 | 24.15 |
| 513 | 184.15 | 244.26 | 1452.5 ± 2.2 | 24.17 |
| 519 | 223.48 | 243.51 | 485.1 ± 3.0 | 24.22 |
| 520 | 223.58 | 263.53 | 977.4 ± 4.0 | 24.47 |
| 521 | 223.79 | 283.46 | 1484.9 ± 7.2 | 24.89 |

## TABLE 5-E - EXPERIMENTAL HEAT CAPACITIES FOR REFRIGERANT-21 AT 500 PSIA

| Run | Temperature, K | | Enthalpy Change | Heat Capacity |
|---|---|---|---|---|
| No. | In | Out | cal. /g-mole | cal. /(g-mole) (°C) |
| 505 | 143.61 | 163.37 | 472.3 ± 1.5 | 23.90 |
| 506 | 144.21 | 184.07 | 959.5 ± 2.0 | 24.07 |
| 507 | 144.67 | 204.80 | 1447.3 ± 5.7 | 24.07 |
| 508 | 183.49 | 203.48 | 477.5 ± 2.5 | 23.88 |
| 509 | 183.85 | 223.67 | 955.3 ± 1.8 | 23.99 |
| 510 | 184.01 | 243.53 | 1432.0 ± 3.7 | 24.06 |
| 522 | 223.76 | 243.79 | 484.3 ± 3.9 | 24.18 |
| 523 | 224.00 | 263.91 | 973.1 ± 2.1 | 24.38 |
| 524 | 224.22 | 284.26 | 1486.8 ± 3.3 | 24.76 |
| 572 | 243.15 | 263.06 | 485.4 ± 2.8 | 24.38 |
| 573 | 262.99 | 282.94 | 494.3 ± 1.6 | 24.78 |
| 574 | 263.16 | 303.17 | 1002.9 ± 3.9 | 25.07 |
| 575 | 263.31 | 323.31 | 1518.4 ± 7.3 | 25.31 |
| 576 | 303.39 | 323.33 | 514.2 ± 0.6 | 25.79 |
| 577 | 303.58 | 343.41 | 1045.1 ± 4.8 | 26.24 |
| 578 | 303.78 | 363.77 | 1600.6 ±13.8 | 26.68 |
| 579 | 343.29 | 363.28 | 548.6 ± 1.2 | 27.44 |
| 580 | 343.39 | 383.48 | 1128.9 ± 1.2 | 28.16 |
| 581 | 343.63 | 403.34 | 1741.0 ± 4.1 | 29.16 |
| 582 | 383.75 | 403.68 | 617.8 ± 2.1 | 31.00 |
| 584 | 403.33 | 408.45 | 170.5 ± 0.4 | 33.30 |
| 585 | 403.26 | 412.59 | 314.6 ± 2.7 | 33.72 |
| 586 | 403.26 | 416.94 | 470.4 ± 3.4 | 34.38 |
| 587 | 403.30 | 423.40 | 717.4 ± 2.0 | 35.69 |
| 588 | 403.27 | 423.17 | 707.4 ± 2.9 | 35.55 |

## TABLE 6-E - MEASURED AND CALCULATED HEAT CAPACITIES FOR REFRIGERANT-21 AT 500 PSIA

| Temperature, K | | Heat Capacity, Cal/g-mole °C | | Ratio |
|---|---|---|---|---|
| Inlet | Outlet | Measured | Calculated* | Meas/Calc |
| 143.61 | 163.37 | 23.90 | 24.16 | 0.9892 |
| 144.21 | 184.07 | 24.07 | 23.83 | 1.0101 |
| 144.67 | 204.80 | 24.07 | 23.63 | 1.0186 |
| 183.49 | 203.48 | 23.88 | 23.22 | 1.0284 |
| 183.85 | 223.67 | 23.99 | 23.21 | 1.0336 |
| 184.01 | 243.53 | 24.06 | 23.23 | 1.0357 |
| 223.76 | 243.79 | 24.18 | 23.28 | 1.0387 |
| 224.00 | 263.91 | 24.38 | 23.37 | 1.0432 |
| 224.22 | 284.26 | 24.76 | 23.50 | 1.0536 |
| 243.15 | 263.06 | 24.38 | 23.46 | 1.0392 |
| 262.99 | 282.94 | 24.78 | 23.76 | 1.0429 |
| 263.16 | 303.17 | 25.07 | 23.98 | 1.0455 |
| 263.31 | 323.31 | 25.31 | 24.27 | 1.0429 |
| 303.39 | 323.33 | 25.79 | 24.84 | 1.0382 |
| 303.58 | 343.41 | 26.24 | 25.31 | 1.0367 |
| 303.78 | 363.77 | 26.68 | 25.89 | 1.0305 |
| 343.29 | 363.28 | 27.44 | 27.06 | 1.0140 |
| 343.39 | 383.48 | 28.16 | 28.01 | 1.0054 |
| 343.63 | 403.34 | 29.16 | 29.37 | 0.9928 |
| 383.75 | 403.68 | 31.00 | 32.09 | 0.9660 |
| 403.33 | 408.45 | 33.30 | 35.32 | 0.9428 |
| 403.86 | 412.59 | 33.72 | 36.21 | 0.9312 |
| 403.26 | 416.94 | 34.38 | 37.09 | 0.9269 |
| 403.30 | 423.40 | 35.69 | 39.02 | 0.9147 |
| 403.27 | 423.27 | 35.55 | 38.97 | 0.9122 |

* Calculated from the Mark V computer program.

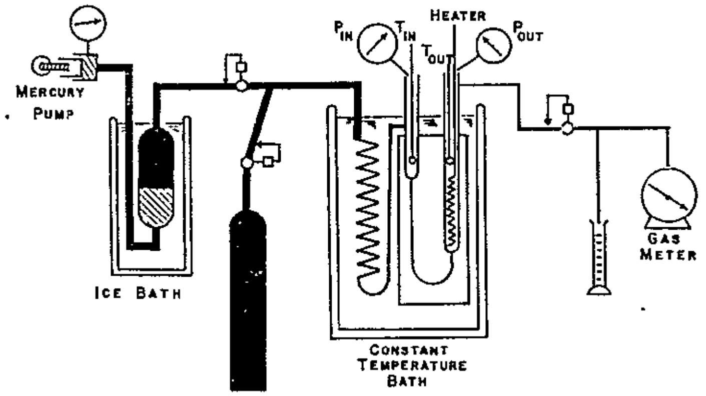


FIGURE 1-E - CALORIMETER AND ASSOCIATED EQUIPMENT

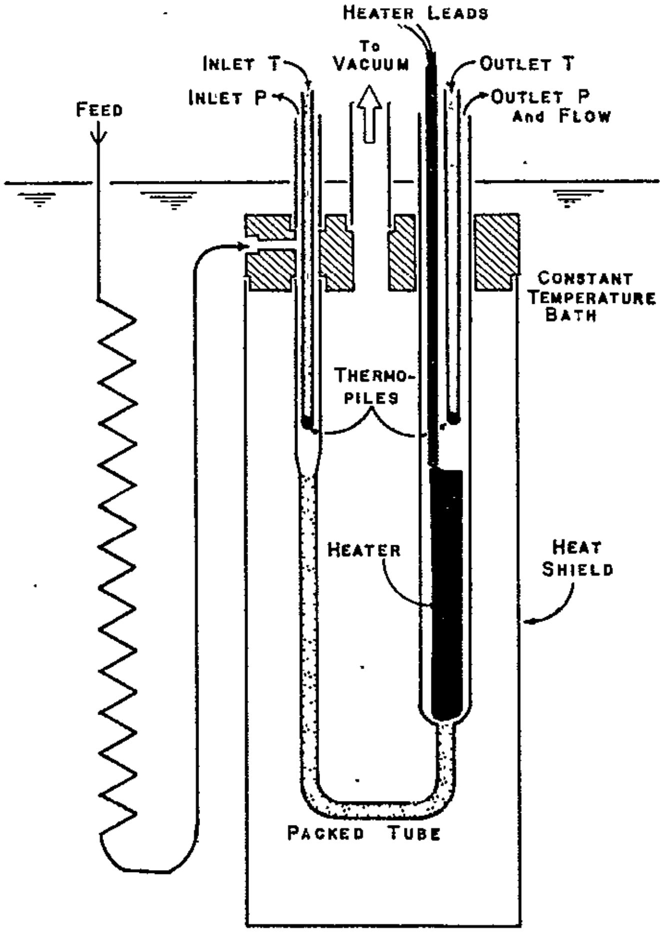


FIGURE 2-E - SCHEMATIC OF NEW P-V-T, INC. CALORIMETER

# APPENDIX F

## Thermal Conductivity

The thermal conductivity cell, shown in Figure 1-F consists of three concentric cylinders. The innermost cylinder, A, is a 0.125 in. O.D. thin wall stainless steel tube with an I.D. of 0.113 in. A sheathed copper-constantan thermocouple, 1, is soldered to the outside of this tube. This cylinder contains a 26 inch, 100 ohm resistance heater enclosed in a metal sheath and folded to a total length of approximately 6 inches. The middle cylinder, B, is a 0.375 in. O.D. stainless steel tube approximately 6 in. long connected to tube A directly over the portion containing the heater. The wall thickness of this tube is 0.020 in. leaving a gap of 0.105 in. between the walls of the two cylinders. A 0.125 in. O.D. stainless steel tubing is connected to the ends of this cylinder at the top and bottom, for admitting sample, evacuation and flow through cleaning. A sheathed copper-constantan thermocouple, 2, is soldered to the outside of this tube at the center. The 3rd cylinder, C, is a 0.625 in. O.D. stainless tube approximately 5 in. in length. It is centered on and attached to tube B. The wall thickness of this tube is 0.028 in. leaving a gap of 0.097 in. between the walls of B and C. A 0.125 in. tubing is also attached to the top and bottom of this cylinder, and a copper-constantan thermocouple, 3, soldered to the outside at the center of the tube. A Ruska Positive Displacment Pump is used for charging the thermal conductivity cell and maintaining pressure.

The apparatus is placed in a constant temperature bath and kept covered with fluid at a level approximately 2 inches above the top of tube B. The bath is controlled to ±0.1 degree C. by a proportional temperature controller.

The electrical portion of the apparatus consists of two parts: (1) A power supply section and (2) a temperature measuring section. Figure 2-F shows the power supply section. It is composed of a System Research Corporation power supply, voltage divider, dummy heater, volt meter, and the thermal conductivity cell heater.

The temperature measuring section consists of the copper-constantan thermocouples, L & N K-3 potentiometer, and a Fluke High Impedence Voltmeter-Null Detector. Thermocouples 1 and 2, Figure 1-F are operated as a difference couple for measuring the temperature gradient across the fluid in cylinder B. Thermocouple 3 serves a dual purpose. Combined with thermocouple 2 it forms a difference couple for measuring the temperature gradient across the fluid contained in cylinder C. Connected to a reference junction it is used to measure the temperature of the cell and bath.

## Procedure Development

Several procedures were tried with the cell before determining an acceptable method of operation. The original procedure for which the cell was designed consisted of: (1) Placing a fluid in A for uniform heat transfer from the heater; (2) Placing the fluid whose thermal conductivity is to be determined in the middle cylinder, B; (3) Placing a reference fluid of known thermal conductivity in the outer tube, C. Power was applied to the heater until constant temperature differences between thermocouples 1 and 2 and between thermocouples 2 and 3 were obtained. The fluids in B and C were reversed and the procedure repeated.

The thermal conductivity of the unknown fluid was calculated for each configuration via:

$$\frac{\lambda_B}{\lambda_C} = \frac{(T_1 - T_2)}{(T_2 - T_3)}$$

and an average of the two values claculated.

The intent of this method was to cancel out errors caused by convection, end effects, radiation, etc., by combining the thermal conductivity calculated with the two configurations.

When this procedure was tried with a test fluid of know thermal conductivity, very large differences were observed between the values of the thermal conductivity calculated from the two configurations, and the average value failed to agree with the know value. After trying several voltage levels and liquids with no success, this procedure was abandoned.

The next attempt was to operatre the cell in a manner similar to a hot wire cell. Power was applied to the heater from an adjustable constant voltage power supply and the time, t, required to establish a set temperature difference, $(T_1 - T_2)$, between thermocouples 1 and 2 and a set temperature difference, $(T_2 - T_3)$, between thermocouples 2 and 3 measured. An extremely small temperature difference between 2 and 3 was observed before convection began. Therefore, the temperature difference $(T_2 - T_3)$ could not be used with this method.

Next a single fluid, methanol, was placed in both cylinders A and C and several fluids of known thermal conductivity were tried in cylinder B. For each fluid, the time required to establish a set temperature gradient, $(T_1 - T_2)$, between thermocouples 1 and 2 was determined. This was repeated for at least 4 different $(T_1 - T_2)$ intervals. A plot was made of $(T_1 - T_2)$ versus time. This plot was linear for a very short time, approximately 10-12 sec., then began to curve downward due to the onset of convection. Only those measurements read before convection was detected were used in the calculations. This procedure was tried at several different power supply voltage levels from 3.75 to 10 volts and the slope of the $(T_1 - T_2)$ versus t plot determined at each voltage level. Different liquids of known thermal conductivity were placed in cylinder B and the process repeated.

The $(T_1 - T_2)$ versus t slopes for these liquids were compared at each voltage level. Results at the different voltage levels showed some disagreement and none could be related directly to the thermal conductivity of the liquids. It was observed that the slopes were very dependent on the voltage supplied. Since the voltage of the power supply was adjusted manually using a volt-ohm meter, it appeared nonreproducible voltages could account for the disagreement among the values obtained at different voltage levels and possibly the calculated thermal conductivities.

A voltage divider consisting of two 100 ohm and one 150 ohm resistor was constructed. The voltage applied to this divider was then set at 7.5 volts and not changed. A dummy heater was also placed in the circuit to minimize voltage surges caused by the sharp change in the load on the power supply when the heater was switched into the circuit. These changes improved the agreement between the thermal conductivities obtained at the different voltage levels but it still was not possible to directly relate the $(T_1 - T_2)$ versus t slopes to the thermal conductivities.

The next procedure tried was to apply heat until a constant temperature gradient was obtained across the liquid in cylinder B. This procedure differed from the original procedure in that the fluids in cylinders B and C were not reversed. This method produced good agreement at 0° C between carbon tetrachloride - hexane and toluene - methanol. However, fairly large differences, up to 15%, were observed when toluene-hexane, toluene-carbon tetrachloride, and methanol-carbon tetrachloride were compared. The value of Refrigerant-21 versus toluene was 0.1552 W/m/C deg. at 0° C using this procedure. Refrigerant-21 and toluene were then run at 12.5°, 0°, -20°, and -40° C. The temperature gradient across the fluid did not change with cell temperature for either toluene or R-21. This procedure was discared.

The final method was a return to the hot wire type operating procedure involving a comparison of the $(T_1 - T_2)$ versus time slopes with thermal conductivities. This procedure was dropped earlier because it was not possible to obtain an exact relation between slope and thermal conductivity, i.e. a 10% difference in thermal conductivity of two liquids did not produce a 10% difference in slopes. Instead of trying to obtain an exact relation between slope and thermal conductivity, a proportionate relation was sought. For example, a 10% change in thermal conductivity might produce only a 1% change in slope. This method was applied to the calculation of the thermal conductivity of methanol based on a comparison of the slopes obtained using methanol, toluene, and carbon tetrachloride with good results. It is described in detail in the operation section.

## Operation

The method of operation used was a modified hot wire procedure. Methanol was placed in cylinders A and C and a test fluid, toluene, in cylinder B. Heat was applied and the time required to establish a set temperature gradient, $T_1 - T_2$, across the test fluid measured. This was repeated for several temperature gradients. A plot was made of $(T_1 - T_2)$ versus time and slope $d(\Delta T)/dt$ determined.

This process was repeated with carbon tetrachloride and with methanol in cylinder B. The ratio of the difference in slope to difference in thermal conductivity between toluene and carbon tetrachloride was calculated. This ratio, approximately 1 to 3, was used to calculate the thermal conductivity of methanol from the difference in slopes between methanol and toluene. Using a thermal conductivity of 0.1408 W/m/C deg. for toluene and 0.1087 W/m/C deg. for carbon tetrachloride (1) the thermal conductivity of methanol determined was 0.2209 W/m/deg. at 0° C. This compares favorably with a literature value of 0.2257 W/m/C deg.(2)

Toluene was placed in cylinder B and R-21 in cylinders A and C each at a pressure of 50 psia. The time, measured on a stop watch readable to 0.1 sec, to produce a given temperature gradient, $(T_1 - T_2)$, across the toluene, was determined. At least four temperature gradients from 0.1 to 0.25 C degrees were used and approximately five time measurements were made for each gradient. The voltage supplied to the heater was 3.75 volts and the time intervals were less than 10.5 seconds. It had been shown from earlier measurements that convection became detectable at approximately 12 seconds. A plot of $(T_1 - T_2)$ versus time was made and the slope, $d(\Delta T)/dt$, calculated.

Measurements were made at 12.5°, 0° and -20° C with the toluene in cylinder B at a pressure of 50 psia. The procedure was repeated at the same three temperatures using carbon tetrachloride and Refrigerant-21 in cylinder B. The thermal conductivity of Refrigerant-21 was then calculated in the same way as methanol. At 0° C the value obtained was 0.1262 W/m/C deg.

Toluene was again placed in the test cylinder, B, and this procedure repeated at approximately 20 deg. C intervals from 12.5° C to -90° C, the pressure in all three cylinders always at 50 psia. The apparent thermal conductivity, $\lambda'_T$, of toluene was calculated at each temperature via:

$$\lambda'_T = \frac{[d(\Delta T)/dt]_o \lambda_o}{[d(\Delta T)/dt]_T} \qquad (1)$$

where $[d(\Delta T)/dt]_o$ and $[d(\Delta T)/dt]_T$ are the slopes of the $(T_1 - T_2)$ versus time curve at 0° C and at the temperature of the measurement respectively, and $\lambda_o$ is the thermal conductivity at 0° C. A value of $\lambda_o = 0.1408$ W/m/C deg. was used.

At each temperature the calculated apparent thermal conductivity, $\lambda'_T$, was compared to the literature value $^{(1)}$ by calculating a percent difference. The percent difference was smoothed by a least square fit to a linear function of temperature from 12.5° C to -90° C. This function was then extrapolated to -130° C. The extrapolation was necessary because the freezing point of toluene is -93° C.

Refrigerant - 21 was placed in cylinders A, B, and C each at 50 psia pressure. Measurements of $d(\Delta T)/dt$ were made from 12.5° C to -130° C in 20 deg. C intervals, the pressure in all three cylinders maintained at 50 psia for each measurement. The apparent thermal conductivity of R-21 was calculated from equation (1) in the same manner as toluene. A $\lambda_o$ of 0.1262 W/m/C deg., determined as previously described by reference to toluene and carbon tetrachloride, was used. The apparent thermal conductivities thus obtained were corrected by the percent difference observed between calculated and literature values for toluene at each temperature. These values are the final thermal conductivities of R-21 and are given in Table 1-F.

The same procedure was followed for the high temperature measurements. The pressure of toluene was 150 psia at each temperature and the pressure of the R-21 in cylinders A and C 600 psia for the toluene runs. For the R-21 runs the pressure of refrigerant in cylinders A and C was again maintained at 600 psia. Measurements were made at each temperature with the R-21 in cylinder B at a pressure of 400 psia and at a pressure equal to the vapor pressure +50 psia.

The thermal conductivities of R-21 were calculated in the same manner as the low temperature thermal conductivities with one exception. The reference thermal conductivity used was 0.1236 W/m/C deg. at 10° C rather than the 0° C value. The thermal conductivity at 10° C was calculated from the smoothed low temperature R-21 data. The alteration was necessary because the original heater developed an electrical short and was replaced. The new heater which had a slightly different resistance was used for all the high temperature measurements. The high temperature thermal conductivities are also given in Table 1-F.

## TABLE 1-F

## EXPERIMENTAL THERMAL CONDUCTIVITY OF REFRIGERANT-21

| Temperature | | Pressure | | Thermal Conductivity |
|---|---|---|---|---|
| deg. C | K | psia | $N/m^2$ X $10^{-5}$ | W/m/C deg. |
| 149.91 | 423.06 | 540 | 37.2 | 0.0877 |
| 129.71 | 402.86 | 400 | 27.6 | 0.0905 |
| 110.03 | 383.18 | 400 | 27.6 | 0.0948 |
| 109.91 | 383.06 | 290 | 20.0 | 0.0947 |
| 90.38 | 363.53 | 205 | 14.1 | 0.0970 |
| 90.20 | 363.35 | 400 | 27.6 | 0.0974 |
| 69.84 | 342.99 | 400 | 27.6 | 0.1023 |
| 69.73 | 342.88 | 150 | 10.3 | 0.1020 |
| 50.14 | 323.29 | 400 | 27.6 | 0.1116 |
| 49.96 | 323.11 | 110 | 7.58 | 0.1130 |
| 29.49 | 302.64 | 400 | 27.6 | 0.1194 |
| 29.38 | 302.53 | 80 | 5.52 | 0.1209 |
| 29.23 | 302.38 | 80 | 5.52 | 0.1184 |
| 28.37 | 301.52 | 80 | 5.52 | 0.1215 |
| 12.62 | 285.77 | 50 | 3.45 | 0.1263 |
| 10.13 | 283.28 | 400 | 27.6 | 0.1231 |
| 10.03 | 283.18 | 50 | 3.45 | 0.1236 |
| -0.04 | 273.11 | 50 | 3.45 | 0.1261 |
| -20.44 | 252.71 | 50 | 3.45 | 0.1319 |
| -41.65 | 231.50 | 50 | 3.45 | 0.1386 |
| -60.39 | 212.76 | 50 | 3.45 | 0.1414 |
| -78.97 | 194.18 | 50 | 3.45 | 0.1449 |
| -88.27 | 184.88 | 50 | 3.45 | 0.1494 |
| -109.69 | 163.46 | 50 | 3.45 | 0.1540 |
| -131.60 | 141.55 | 50 | 3.45 | 0.1666 |

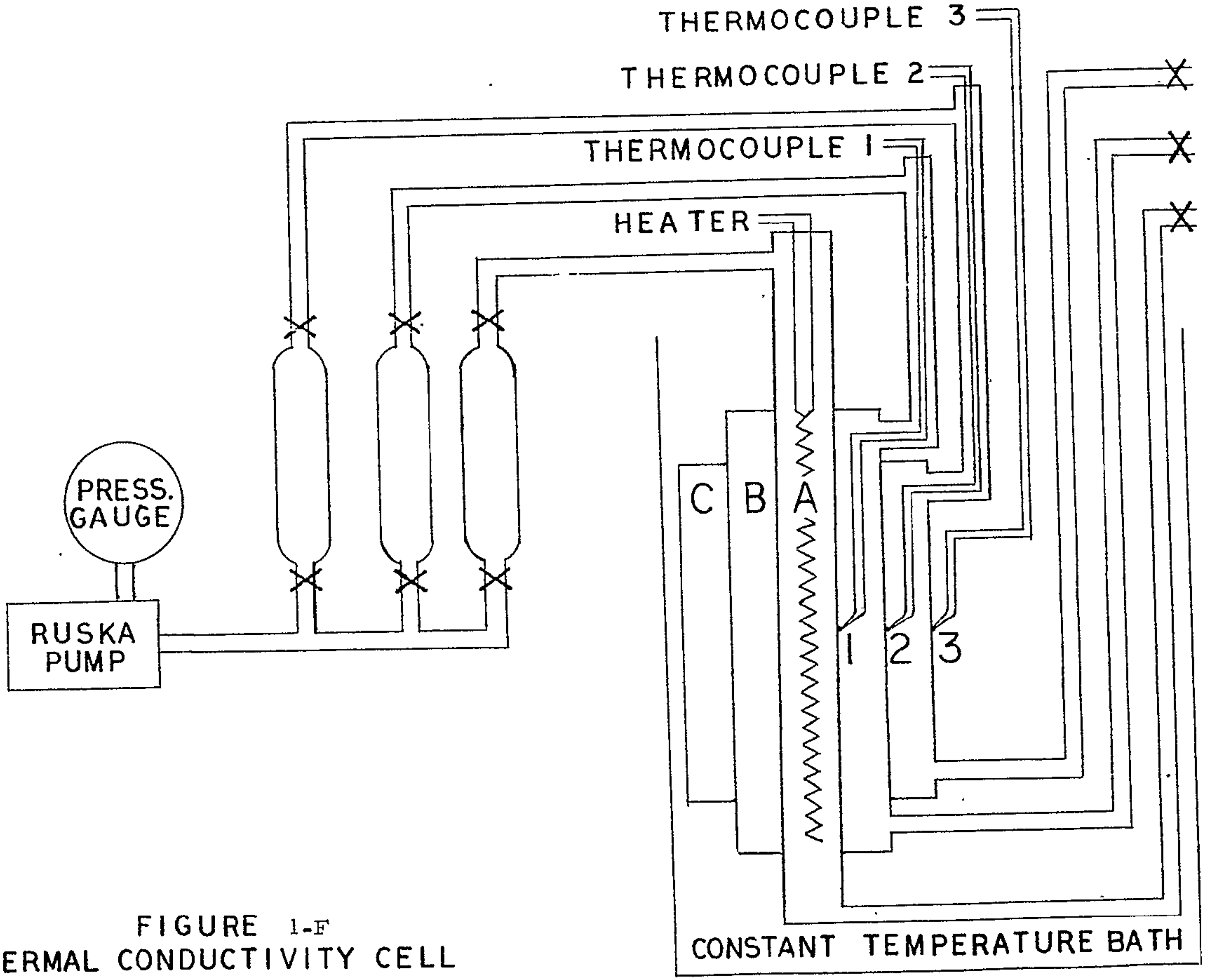


FIGURE 1-F
THERMAL CONDUCTIVITY CELL

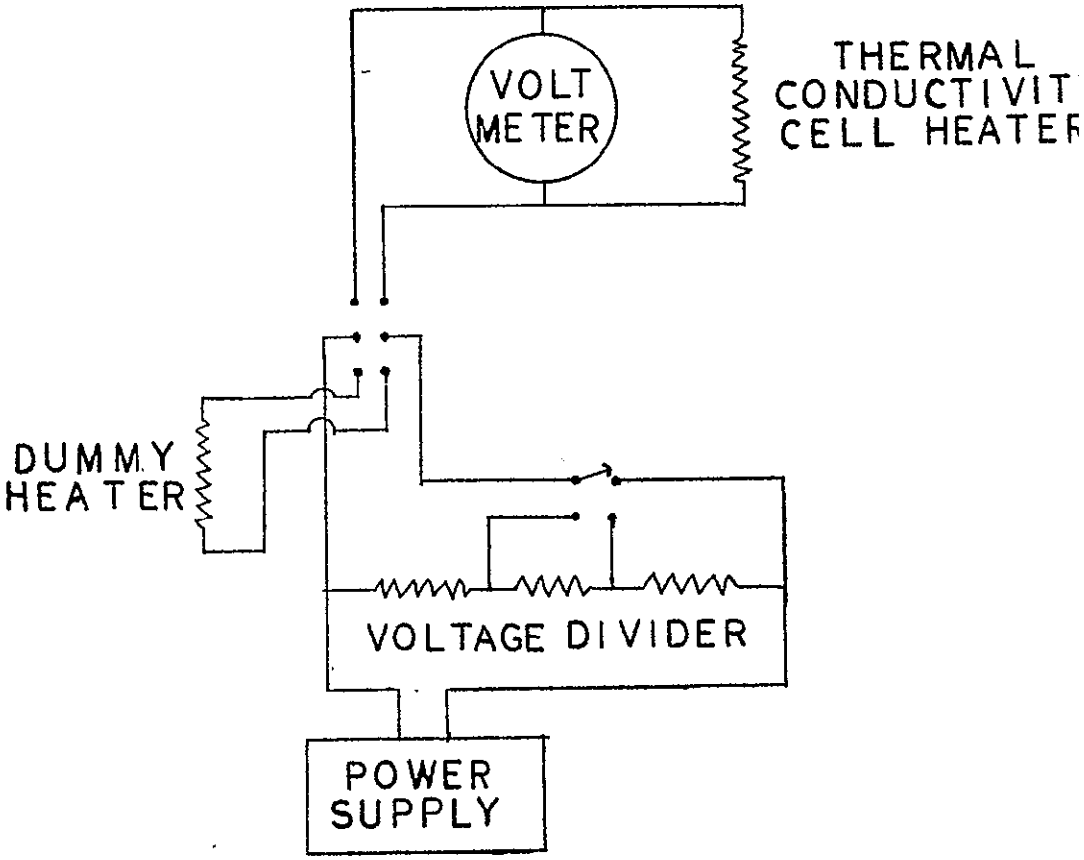


FIGURE 2-F. POWER SUPPLY SECTION

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## APPENDIX G

# Design of the New P-V-T, Inc. Calorimeter

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### ABSTRACT

This new calorimeter design permits measurement of the Joule-Thomson coefficient $(\Delta T/\Delta P)_H$, the isothermal enthalpy change on throttling $(\Delta H/\Delta P)_T$, and the isobaric enthalpy change or heat capacity $C_p = (\Delta H/\Delta T)_p$ with a single instrument. Operating conditions are from −300° to +600°F, at 15 to 2500 psia, in the all liquid or all vapor regions. The integral isothermal and integral isobaric heats of vaporization across the phase envelope can also be measured. Accuracy has been greatly improved.

### DESIGN CONCEPT

The regions where new data are needed include the vapor phase at conditions near the dew point, the liquid phase at conditions near the bubble-point and at higher pressure, the critical region, and heats of vaporization at elevated pressures. These are illustrated in Figure 1. There will soon be a need for accurate data on systems encountered in SNG production, i.e. those containing methane with hydrogen, carbon monoxide, carbon dioxide and water vapor at both ends of the temperature range.

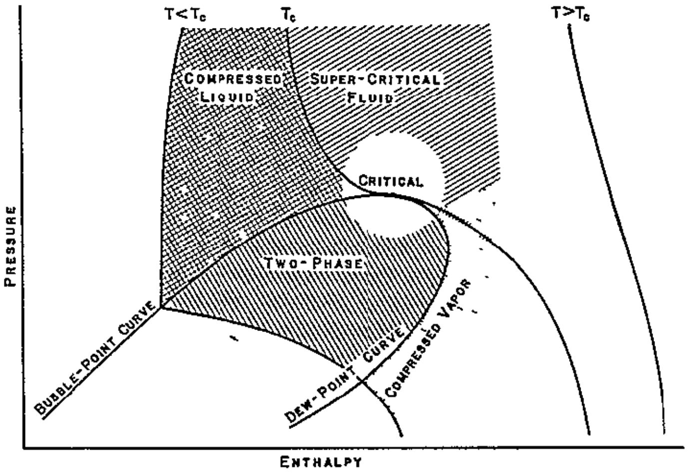


Figure 1
Regions Where New Experimental Data Should be Obtained

The ideal instrument would be one which could:

1. measure liquid phase throttling, or enthalpy change of −100 to 0 to +100 Btu/lb-mole depending on the region.
2. measure vapor phase throttling or enthalpy changes of −20 to −1200 Btu/lb-mole.
3. measure isothermal and isobaric heats of vaporization, of −800 to −12,000 Btu/lb-mole.
4. rapidly achieve and maintain steady-state operation.
5. provide means for internal checks on the accuracy of the experimental results.
6. be capable of operation from −260°F (the LNG region) to +600°F or higher (the SGN region).

Our new calorimeter was designed with these requirements in mind. The new calorimeter retained the best features of earlier P-V-T, Inc. instruments, as described in NGPA RR-6 by Eakin, Wilson, and DeVaney[4]:

- low heat capacity
- fast response time.
- rapid attainment of steady-state conditions.
- low consumption of test fluid.
- operation over any desired $(P,T)_{in}$ to $(P,T)_{out}$.
- operation in all-liquid, all vapor or across the two-phase region.

The new instrument will reduce or eliminate the operational problems and heat-leak corrections inherent in the old design.

### MECHANICAL DESIGN

In addition to our experience with calorimeters at P-V-T, Inc., we reviewed our previous experience and the recent literature. Several features of our new instrument evolved from the various isobaric and isothermal calorimeters at I.G.T., described by Macriss and Eakin[6], and by Dolan, Eakin, and Bukacek[3]. Items which could improve the accuracy or ease of operation were included from the Joule-Thomson calorimeter at University of Leeds, described by Dawe and Snowden[1,2], the instrument at the University of Michigan described by Jones et. al.[5], and the NBS calorimeter at Boulder, described by Younglove[7].

The first consideration was the heat-leak correction. Since the calorimeter is enclosed in an evacuated shell, heat transfer is by conduction and radiation. In the old calorimeter the shell was immersed in liquid nitrogen, and both the calorimeter assembly and the inlet tube looked at a −320°F surface. This did permit measurement of both positive and negative enthalpy changes, but introduced large gradients in parts of the apparatus.

The quickest way to reduce radiation and conduction is to make both surfaces the same temperature. Therefore, the evacuated shell around the new calorimeter is enclosed in a constant-temperature liquid bath, which can be varied from −300° to +200°F. At temperatures above +200°F, a fluidized solids bath is used. The feed flows through a conditioning coil immersed in this constant temperature bath before entering the calorimeter inlet tube. Thus the gradient along the tube housing the inlet thermocouple has been reduced from several hundred degrees per foot, to the order of one degree per foot. This has made the calorimeter accuracy almost independent of thermocouple position, and greatly improved the stability of the inlet temperature. Both the inlet and outlet tubes are made from thin-wall stainless steel to reduce conduction.

The second major problem area involved the throttling valve assembly. The use of a valve permitted setting both the $\Delta P$ and flow rate independently, but this flexibility required frequent and delicate adjustments of the valve to maintain $P_{in}$ at a constant value. Also, whenever you approached the phase boundary at inlet conditions, the flow tended to become unstable.

The I.G.T. calorimeter[3] utilized a 3 foot length of 0.200 inch I.D. tubing filled with an 0.195 inch O.D. wire. This annular design was used to eliminate the plugging problem associated with small-diameter steel capillaries, and has been operated successfully for 7 years. Two principal difficulties with this system are how to get sufficient $\Delta P$ over a short length at low flow rates, and that only one flow rate is possible for a given $P_{in}$ to $P_{out}$.

The short-length problem was successfully solved by the Leeds calorimeter[1]. They utilized short sections of small diameter tubing packed with fine granular solids. By changing the mesh of the packing material, they were able to obtain a set of three identical steel tubes, covering the entire $\Delta P$ range, within the flow rates described.

Therefore, the new throttling calorimeter design utilizes a 1 foot length of 1/16 inch diameter thin-wall steel tubing packed with fine mesh carborumdum powder. Several tubes are included, ranging from an open tube for isobaric measurements, to one allowing 2500 psi $\Delta P$ with methane flowing at 2 cubic feet per hour.

The feed system to the calorimeter is either:

a. displacement by a 1000 cc Ruska volumetric pump at a constant rate, or
b. flow from a high presure cylinder at a constant inlet pressure.

Based on our experience with packed chromatograph columns, the calorimeter should rapidly achieve steady-state operation under either of these feed conditions. The system is provided with a back-pressure regulator on the exit, to permit $P_{out}$ to be set and maintained at any desired pressure level.

The old calorimeter used a single junction thermocouple to measure $T_{in}$, and a second thermocouple for $T_{out}$, with each referenced to an ice-point junction. The temperature sometimes varied considerably during a run on the old calorimeter. These fluctuations have been effectively eliminated with the new design.

With the steady temperatures achieved with this new design, multi-junction thermocouples are used. The inlet temperature is measured with an ice-point reference. The difference between $T_{in}$ and $T_{out}$ is measured by switching the inlet thermocouple into a differential mode with the outlet thermocouple. With this system it is possible to measure $T_{in}$ to $\pm 0.1°F$, and temperature differences between inlet and outlet to $\pm 0.02°F$.

The heater is the same sheathed chromel-alumel element utilized in the earlier P-V-T, Inc. calorimeters[4]. However, the previous instrument had 4 small diameter copper leads coming through the outlet tube. These have been replaced by 2 larger diameter copper leads which introduce a correction of only 0.11% to calculate the heater voltage. Assembly and operation are greatly simplified.

The features of the final design are shown schematically in Figure 2. Details of the seals and special fittings required are not shown. The calorimeter and associated equipment required for operation and measurements are shown schematically in Figure 3.

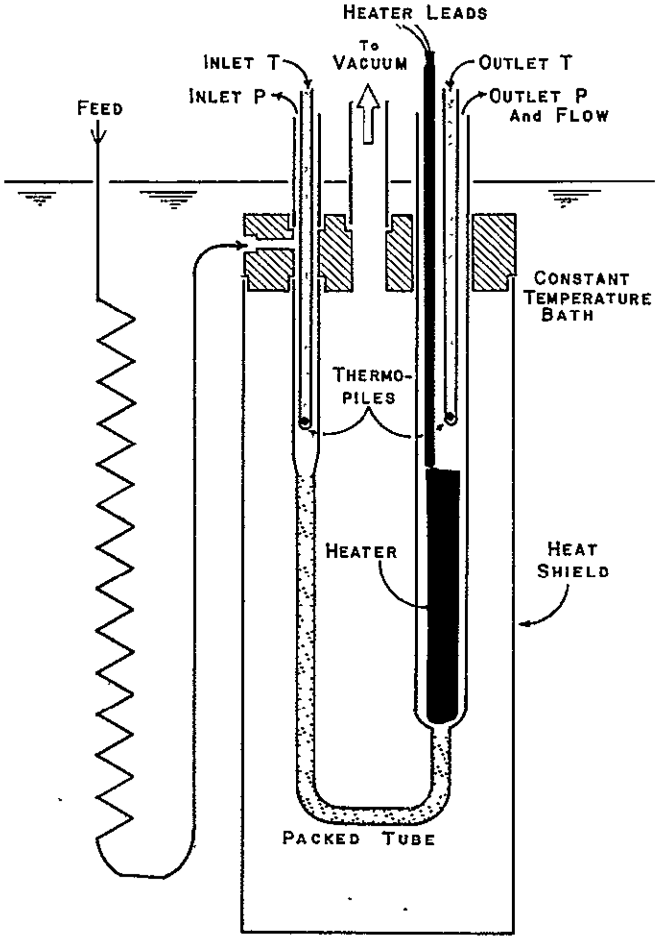


Figure 2
Schematic °F New P-V-T, Inc. Calorimeter

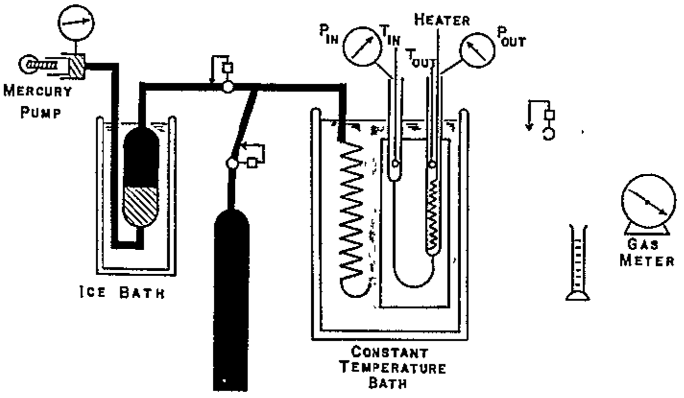


Figure 3
Calorimeter and Associated Equipment

## OPERATION

This new instrument is extremely flexible and permits several modes of operation:

a. As a Joule-Thomson instrument, with measurement of $(\Delta T/\Delta P)_H$.

b. As an Isothermal instrument, with measurement of $(\Delta H/\Delta P)_T$.

c. As an Isobaric instrument, with measurement of $\overline{C}_p = (\Delta H/\Delta T)_p$.

d. As a Combination instrument, with measurement of $\Delta H$ from $T_1$, $P_1$ to $T_2$,$P_2$, where $T_2 > T_1$, and $P_2 < P_1$.

The effect of uncertainties in the measurement of individual quantities on the accuracy of the enthalpy difference will be discussed separately for each mode of operation.

Our instrument utilizes multijunction thermocouples and a K-3 potentiometer for both actual and differential temperature measurements. The sensitivity of this system is ±0.3 microvolts, or ±0.005°F. The thermocouples are calibrated over the entire temperature range, referenced to the ice-point. The inlet temperature is accurate to ±0.1°F from +200° to −100°F and ±0.2°F outside this range. The temperature difference between inlet and outlet is recorded to ±0.005°F, and is probably accurate to ±0.01°F for temperature differences less than 2°F, and ±0.02°F for larger differences.

Pressures are measured with calibrated Heise gauges. These are accurate to ±0.1% of full scale. We use 500 and 2500 psi gauges, adjusted to read absolute pressure.

We use two methods for fluid feed. When the feed rate is set by displacement with the 1000 cc Ruska volumetric pump, the accuracy with which we know the fluid density at displacement conditions determines our error. We determine this density on each feed mixture, to about ±0.2%. When the fluid feed is from a cylinder, to a set inlet pressure, we measure the flow rate at the outlet with a calibrated wet-test meter. The reproducibility of our meter calibration at any one time is ±0.2%.

The heat input to the calorimeter is by an electrical resistance heater. Power is supplied by a regulated and filtered variable D.C. power source. Current is calculated by measuring the voltage drop across an NBS standard resistor. The voltage applied to the heater is measured at the exit of the outlet tube and corrected for the resistance of the copper leads from the heater through the outlet tube, $V_{\text{heater}} = V_{\text{meas}} \times 0.9989$. Both voltages are measured on either a K-3 potentiometer, or an electronic digital voltmeter, to ± 0.03%. Including the resistor, the uncertainty in power input measurements is not over ± 0.1%, at the worst condition.

The following illustrates the effect of these measurement uncertainties on the accuracy of the experimental data. Three sets of data are given: (1) methane throttled in the vapor phase, (2) hydrogen sulfide throttled in the liquid phase, and (3) methane isobarically in the liquid phase.

1. Based on the data of Snowden[2] at Leeds, for methane vapor at 78°F expanded from 147 psia to 14.7 psia, the measured J-T $\Delta T$ was −6.82°F, corresponding to an isothermal enthalpy change of −60.6 Btu/lb-mole.

| Variable | Uncertainty | Variation in $\Delta H$ |
|---|---|---|
| $\Delta P$ (pressure) | ±0.5 psi | ±0.23 Btu/lb-mole |
| $\Delta T$ (temperature) | ±0.02°F | ±0.18 Btu/lb-mole |
| $\Delta V$ (flow rate) | ±0.2% | ±0.12 Btu/lb-mole |
| $\Delta Q$ (heat) | ±0.1% | ±0.06 Btu/lb-mole |

2. Based on the data of Eakin[4] at P-V-T, Inc. for hydrogen sulfide liquid at 100°F expanded from 1000 psia to 500 psia, the measured isothermal enthalpy change was +8.2 Btu/lb-mole, corresponding to a J-T$\Delta T$ of +0.45°F.

| Variable | Uncertainty | Variation in $\Delta H$ |
|---|---|---|
| $\Delta P$ | ±1.0 psi | ±0.016 Btu/lb-mole |
| $\Delta T$ | ±0.01°F | ±0.18 Btu/lb-mole |
| $\Delta V$ | ±0.2% | ±0.016 Btu/lb-mole |
| $\Delta Q$ | ±0.1% | ±0.008 Btu/lb-mole |

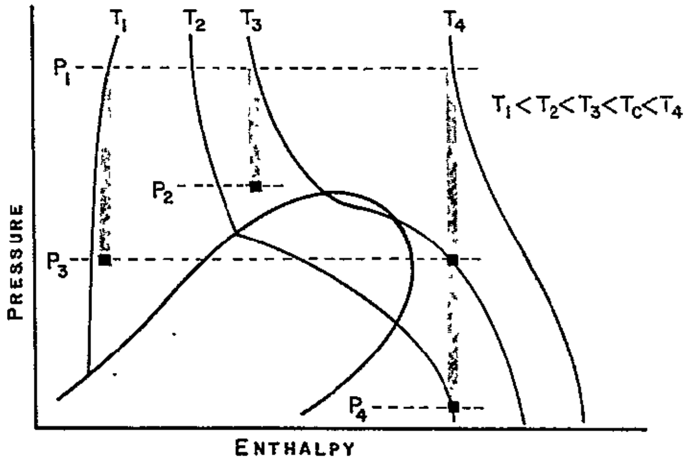
3. Based on the data of Jones[5] at University of Michigan for methane liquid at 400 psia, from −260° to −160°F, the reported smoothed isobaric enthalpy change is 1458 Btu/lb-mole.

| Variable | Uncertainty | Variation in $\Delta H$ |
|---|---|---|
| $\Delta P$ | ±0.5 psi | ±0.05 Btu/lb-mole |
| $\Delta T$ | ±0.02°F | ±0.29 Btu/lb-mole |
| $\Delta V$ | ±0.2% | ±2.92 Btu/lb-mole |
| $\Delta Q$ | ±0.1% | ±1.46 Btu/lb-mole |

These illustration are used below to show the attainable accuracy of measurements in each mode of operation.

**Joule-Thomson Measurements**

When a fluid is expanded from a high pressure to a lower pressure there is a change in the deviation of the real fluid from ideal behavior, which results in a change in temperature, as shown in Figure 4. For example, if the gas enters at a high pressure, $P_1$ at $T_4$, and expands to low pressure $P_4$, the exit will be at a lower temperature $T_2$. If the expansion were from $P_1$, $T_4$ to $P_3$, the outlet temperature would be $T_3$. For a liquid at $T_1$, expansion from $P_1$ to $P_3$ would result in higher exit temperature than $T_1$.



A. JOULE-THOMSON EXPANSION.

Figure 4
Operation as an Isenthalpic Calorimeter

If the expansion is made with no addition or removal of energy from the system, i.e., by throttling through a valve, porous plug or packed tube, it is termed an isenthalpic, or Joule-Thomson, expansion. The thermodynamic equation relating the enthalpy change to the fluid properties is:

$$dH = C_p dT + \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP \qquad (1)$$

where the enthalpy change per mole, dH, is equal to the molal heat capacity $C_p$ times the temperature change dT, plus a difference term involving the molal volume V and the absolute temperature times the rate of change of volume with temperature at constant pressure, $T\left(\frac{\partial V}{\partial T}\right)_P$ times the change between inlet and outlet pressure, dP.

For an isenthalpic J-T expansion, dH = O and the equation becomes:

$$-C_p dT = \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP$$

$$\text{or } \bar{C}_p\,(T_{in} - T_{out}) = \int_{P_{in}}^{P_{out}} \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP \qquad (2)$$

If the expansion is to a low outlet pressure where the fluid exists as a gas, it is possible to estimate quite accurately $\bar{C}_p$(the average heat capacity over the temperature interval). Therefore, a measure of the J-T Δ T can provide a good value of the integral in Equation 2.

The J-T measurement involves pressure and temperature difference only. It is independent of flow rate, and involves no heat input. Therefore, only variation in Δ P and Δ T from the examples are included:

1. −60.6 ±0.41 Btu/lb-mole
2. +8.2 ±0.20 Btu/lb-mole

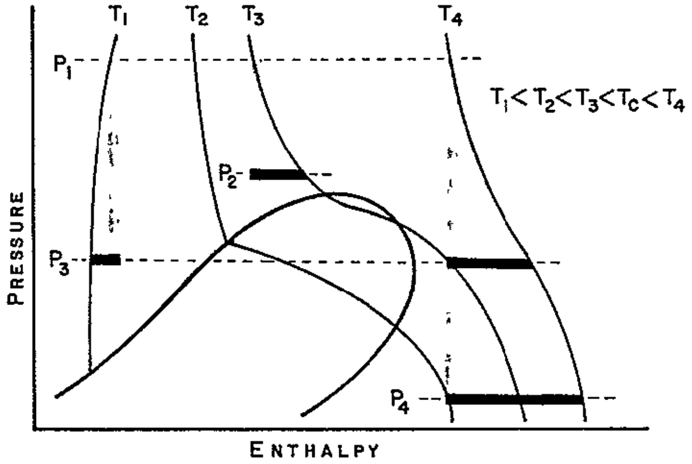
**Isothermal Measurements**

Isothermal enthalpy changes are obtained by throttling the fluid from $T_{in}$, $P_{in}$ to $P_{out}$, in the J-T expansion tube, and then adding heat electrically to make $T_{out} = T_{in}$, as shown in Figure 5. If a gas enters at $T_4$ and $P_1$, and is throttled to $P_4$, the temperature will drop to $T_2$. The heat added at $P_4$ to raise the temperature from $T_2$ to $T_4$ is the isothermal enthalpy change on throttling. For a liquid at $T_1$, and $P_1$, throttled to $P_3$, heat must be removed to get back to $T_1$.

For isothermal expansion, dT = 0 and Equation 1 becomes:

$$\Delta H = \int_{P_{in}}^{P_{out}} \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP \qquad (3)$$

Here the quantity of energy which must be added to each mole of fluid to maintain the outlet and inlet temperature equal is measured, and provides a direct measure of the value of the integral. The accuracy to which the difference between $T_{out}$ and $T_{in}$ can be measured is directly proportional to the error in $(\Delta H/\Delta P)_T$ values. These data are the most useful for development of correlations for predicting enthalpy changes.



B. ISOTHERMAL EXPANSION.

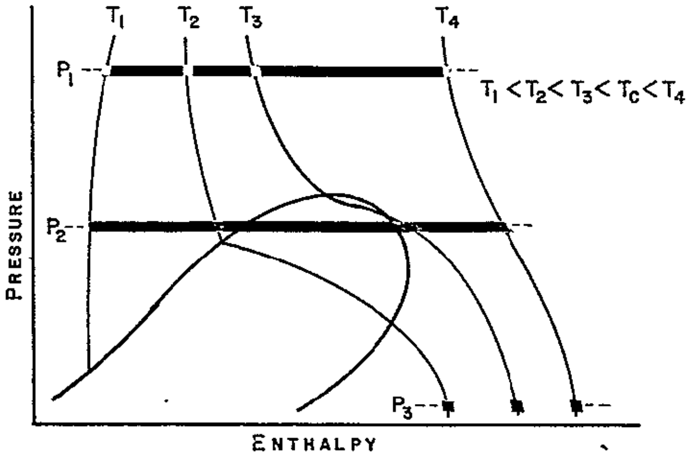
Figure 5
Operation as an Isothermal Calorimeter

The isothermal measurement involves pressure and temperature differences, feed flow rate and electrical power input. The differential temperature will be accurate to ± 0.01°F for isothermal measurements, which reduces its uncertainty in example 1 to ± 0.09 Btu/lb:

1. −60.6 ± 0.50 Btu/lb-mole
2. When operating in the liquid region, where the temperature increases with throttling, this instrument cannot be used in the isothermal mode. It is necessary to obtain J-T Δ Ts, then measure $C_p$ at the outlet P over a temperature range which includes $T_{in}$ and $T_{out}$ to obtain the isothermal values. This has very little effect on the accuracy of the results.

**Isobaric Measurements**

Isobaric data are obtained at constant pressure, over temperature differences of 10° to 100°F, as shown in Figure 6. This illustrates the variation in $C_p$ with temperature and pressure. At a high pressure, above the critical, the heat required to go from $T_2$ to $T_3$ is much less than from $T_3$ to $T_4$. At a pressure of $P_3$, below the critical, but still all liquid at $T_2$, a much larger quantity of heat is required to go from $T_2$ to $T_3$ (which involves



C. ISOBARIC HEATING.

Figure 6
Operation as an Isobaric Calorimeter

a phase change), than to warm the gas from $T_3$ to $T_4$. At a low pressure $P_3$, near ideal behavior occurs, and almost the same heat is required from $T_2$ to $T_3$ or $T_3$ to $T_4$.

For an isobaric expansion, dP = 0, and Equation 1 becomes:

$$\Delta H = C_p\,(T_{out} - T_{in}) \tag{4}$$

This measurement is the easiest to obtain, and provides a means for checking the accuracy and consistency of isothermal data. Any error in the pressure appears at both inlet and outlet, and has negligible effect on the measured quantity.

The flow rate, temperature difference, and electrical energy inputs are measured, and their uncertainties all appear in the enthalpy change:

1. −60.6 ± 0.36 Btu/lb-mole
2. 1458 ± 4.67 Btu/lb-mole

**Combination Measurement**

These data are used to provide an internal loop check on the measurements. They measure the enthalpy change from $P_1$, $T_1$ to $P_2$, $T_2$, where $P_2 < P_1$ and $T_2 > T_1$. These data have the combined uncertainty of both the J-T and isobaric measurements. However, since they are generally over sizeable values of Δ P and Δ T, the results are generally accurate to better than ±1%.

Isothermal data can be checked by making overall Δ P measurements, then two or more incremental Δ P measurements which total the original Δ P. It is also possible to make repeat Δ P interval measurements at different flow rates by changing the packed tube.

Joule-Thomson data can be checked for independence of flow rate by repeating a given Δ P measurement at a second flow, through a different packed tube. The final limit of our J-T instrument becomes the stability of the inlet temperature and pressure.

## SUMMARY

This new calorimeter has the inherent flexibility and accuracy to provide significant new data for industry. It has been tailored to provide accurate enthalpy difference measurements in regions of special interest to the GPA. The ability to measure Joule-Thomson data, as well as isothermal and isobaric enthalpy changes, provides an immediate internal consistency check as new data are obtained. This instrument can be used to measure the very small enthalpy changes accompanying pressure reduction on a liquid, the very large changes accompanying vaporization (either isothermal or isobaric), and the medium sized changes produced by throttling a gas from near the dew-point to atmospheric pressure.

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