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FLUID PROPERTY MEASUREMENTS STUDY

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 1.38×10^8 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 x 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	-9.4852106×10^4	-1.6509519×10^5
B	-2.5727266×10^3	-1.0815884×10^3
C	14.262312	1.0265358
D	$-6.3655244 \times 10^{-3}$	4.4064684×10^{-2}
E	6.8276335×10^{-6}	$-6.0960478 \times 10^{-5}$

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

	Pressure, psia		
T, °K	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 x 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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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/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
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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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 K	Temperature °F	Pressure N/m² x E-6	Pressure psia	Density kg/m² x E-3	Density lb/ft³	Coefficient of Thermal Expansion 1E3/°C	Coefficient of Thermal Expansion 1E4/°F	Bulk Modulus N/m² x E-8	Bulk Modulus 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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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/m² x E-6	psia	kg/m² x E-3	lb/ft³	1E3/°C	1E4/°F	N/m² 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	
$N/m^2 \times 10^{-6}$	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
$N/m^2 \times 10^{-6}$	A	$B \times 10^{-1}$	$C \times 10^3$	Of Estimate
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	Coefficients			Standard Error
Range, Kelvin	A	$B \times 10^{-2}$	$C \times 10^3$	Of Estimate
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
K	°F	A X 10^{1}	B X 10^{6}	Of Estimate
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 K	Temperature °F	Pressure $N/m^2 \times 10^{-6}$	Pressure Psia	Viscosity cp	Viscosity $\frac{lbf\text{-}s}{ft^2} \times 10^6$
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					
		4.14×10^6 N/m^2 (600 psia)		6.90×10^6 N/m^2 (1000 psia)		10.34×10^6 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	$kg/m^3 \times 10^{-3}$	lb/ft^3	cp	$\frac{lbf\text{-}s}{ft^2} \times 10^6$
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

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

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

TABLE 13

SMOOTHED THERMAL CONDUCTIVITY OF REFRIGERANT 21

0.344×10^6 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

2.76×10^6 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

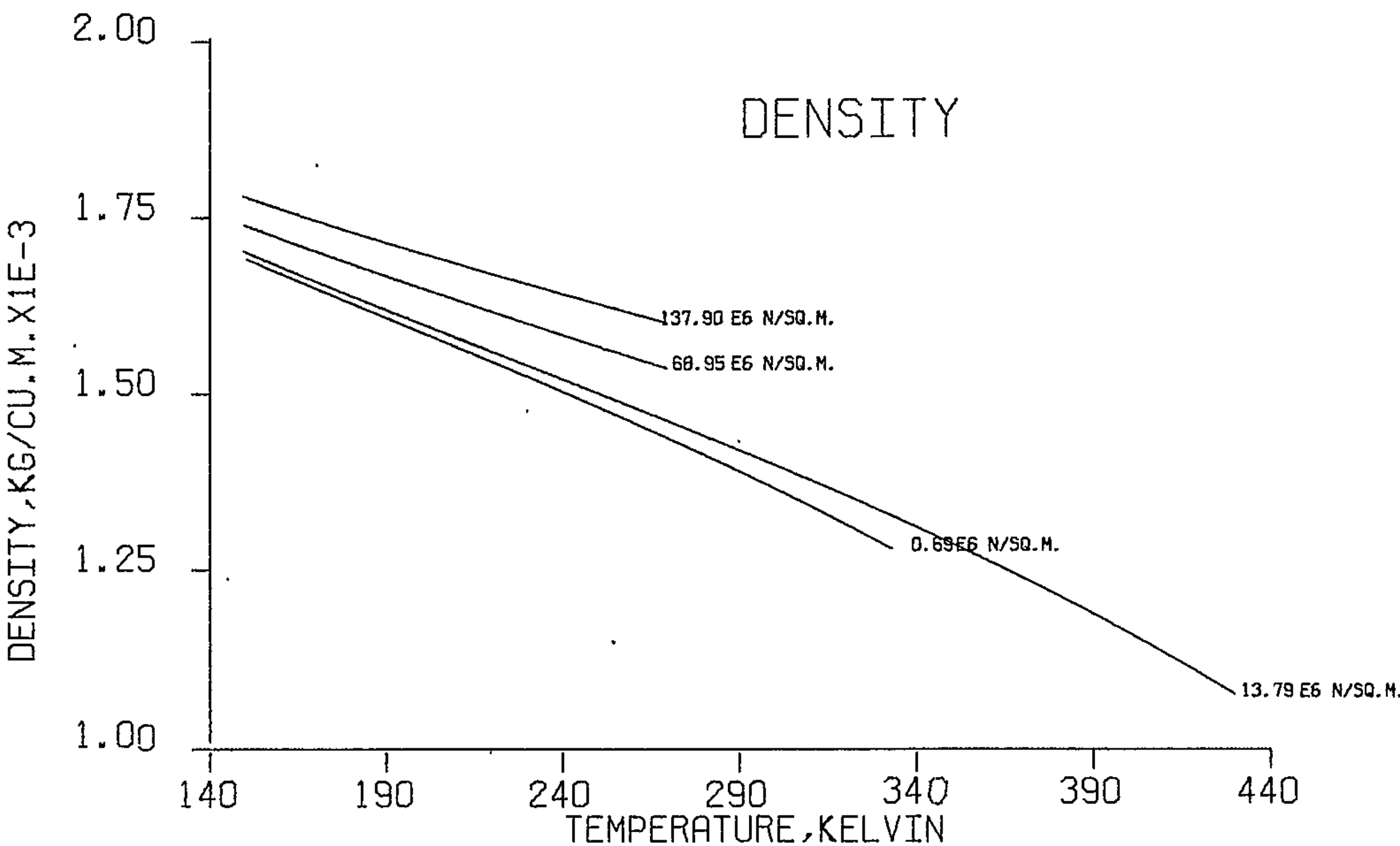


Figure 1 - Effect of Temperature on the Density of Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x 10^6 N/m^2

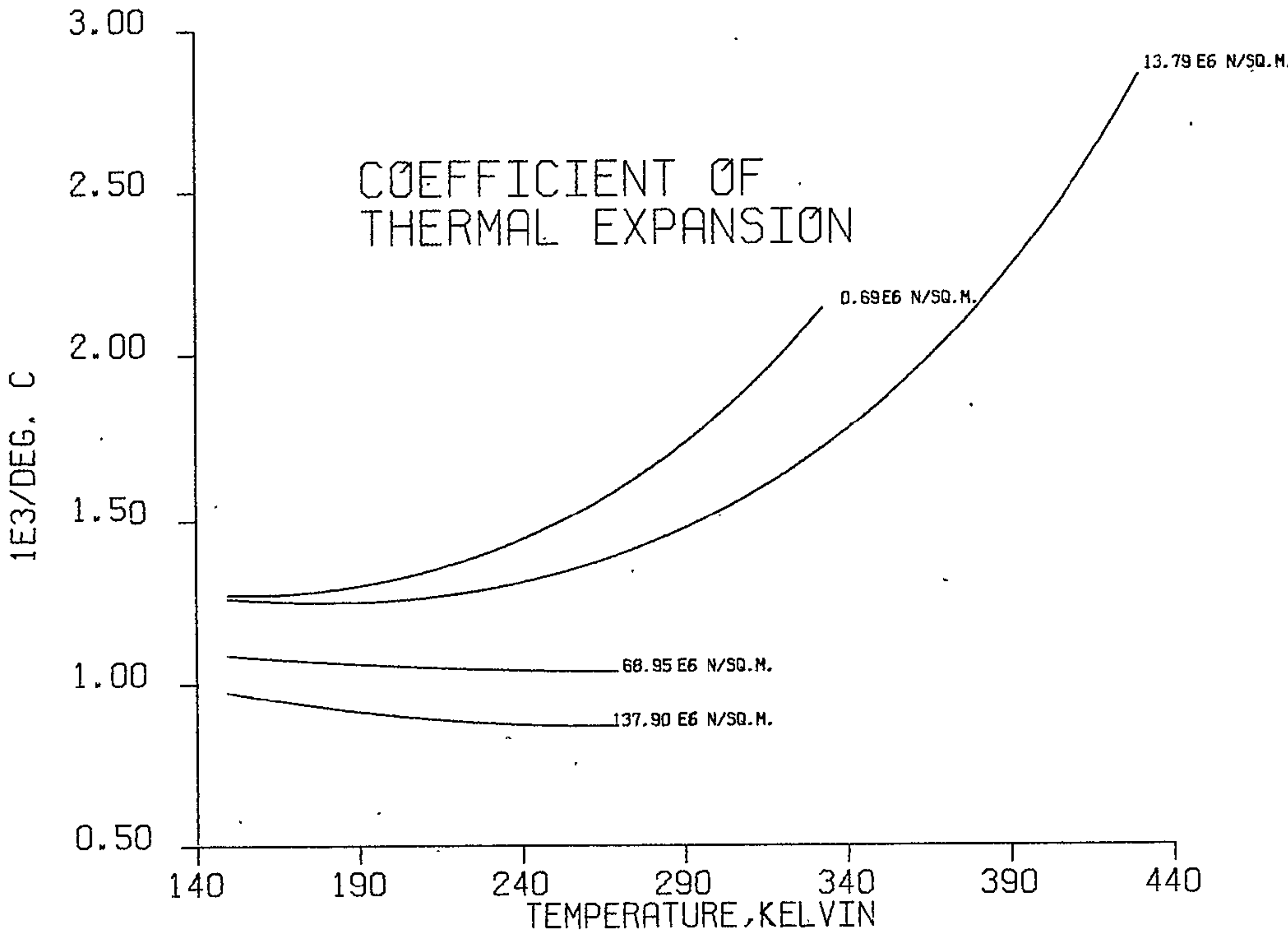


Figure 2 - Coefficient of Thermal Expansion for Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x 10^6 N/m^2

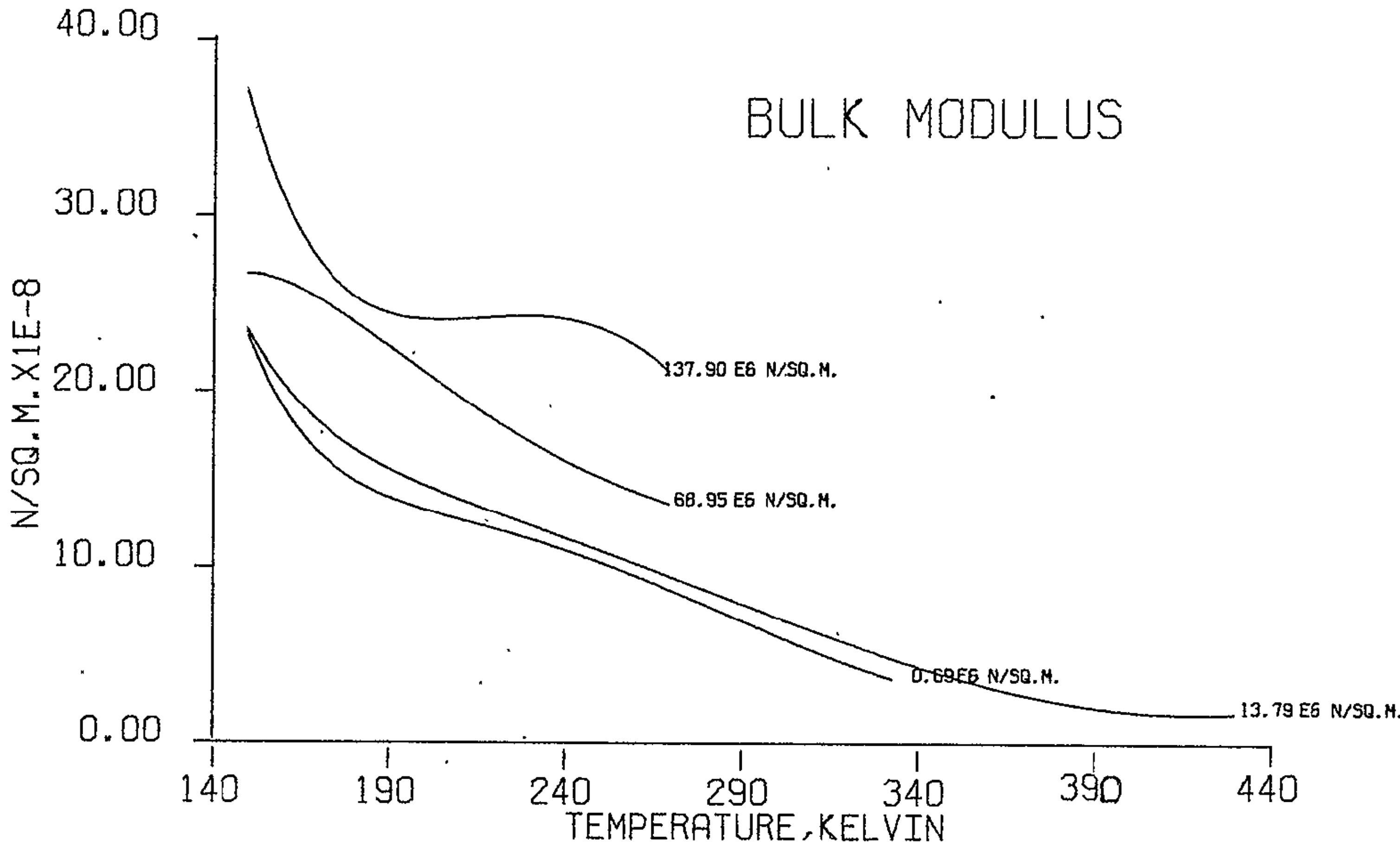


Figure 3 - Bulk Modulus of Elasticity for Refrigerant-21 at 0.69, 13.79, 68.95 and 137.90 x 10^6 N/m^2

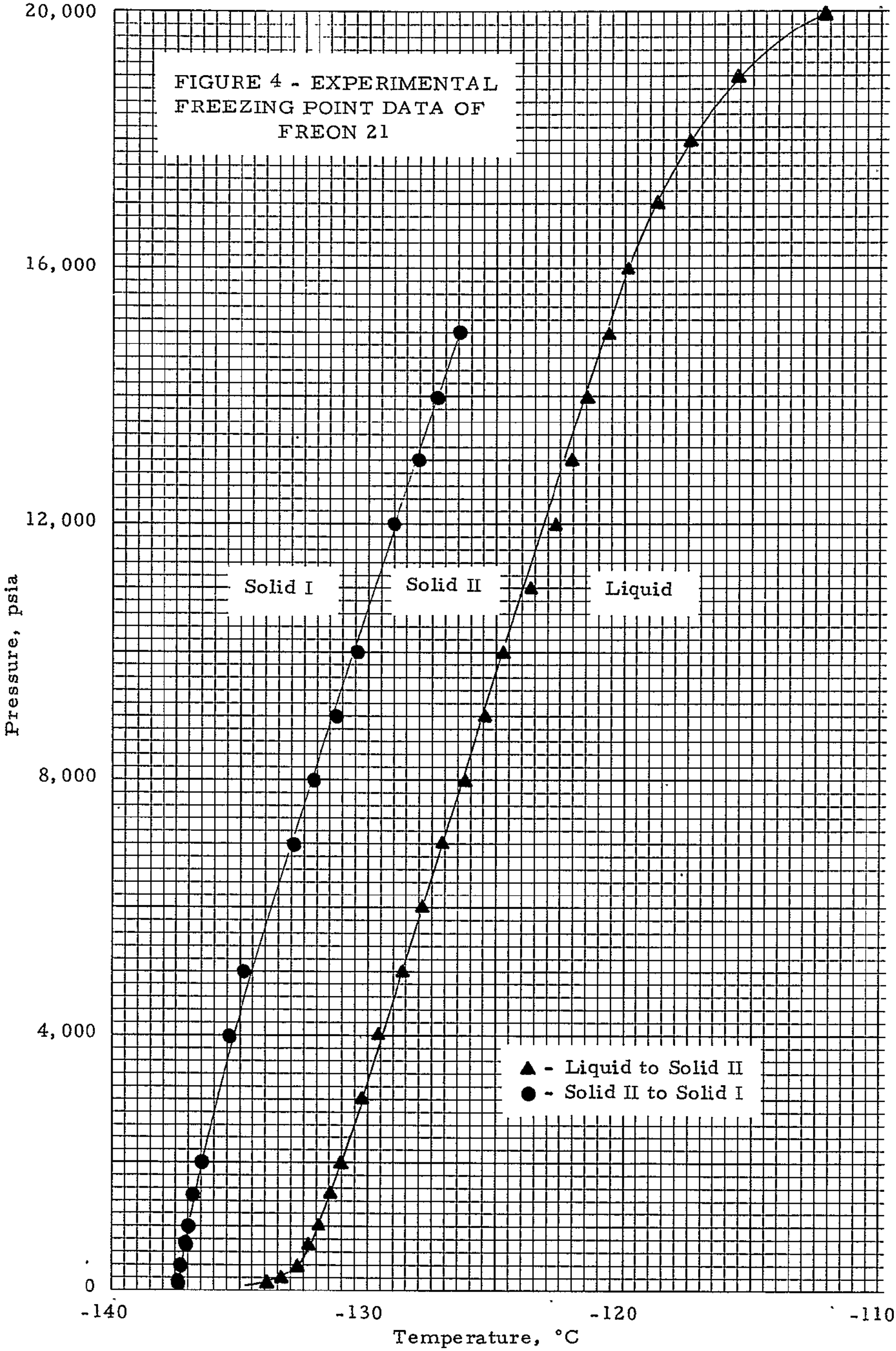


FIGURE 4 - EXPERIMENTAL FREEZING POINT DATA OF FREON 21
20,000
16,000
12,000
8,000
4,000
0
Pressure, psia
Solid I
Solid II
Liquid
▲ - Liquid to Solid II
● - Solid II to Solid I
-140
-130
-120
-110
Temperature, °C

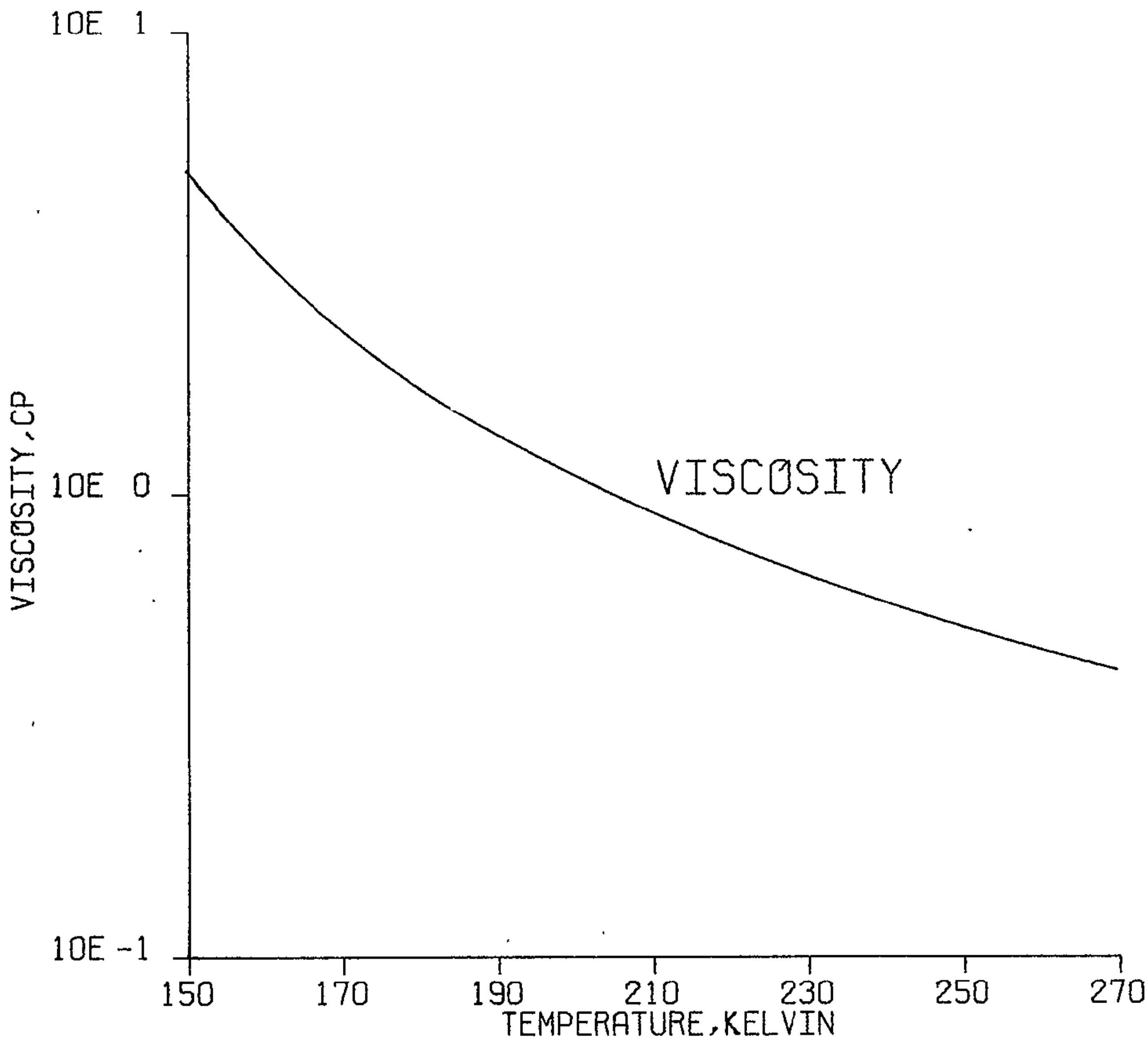


Figure 5 - Viscosity of Refrigerant-21,
143 to 273 Kelvin

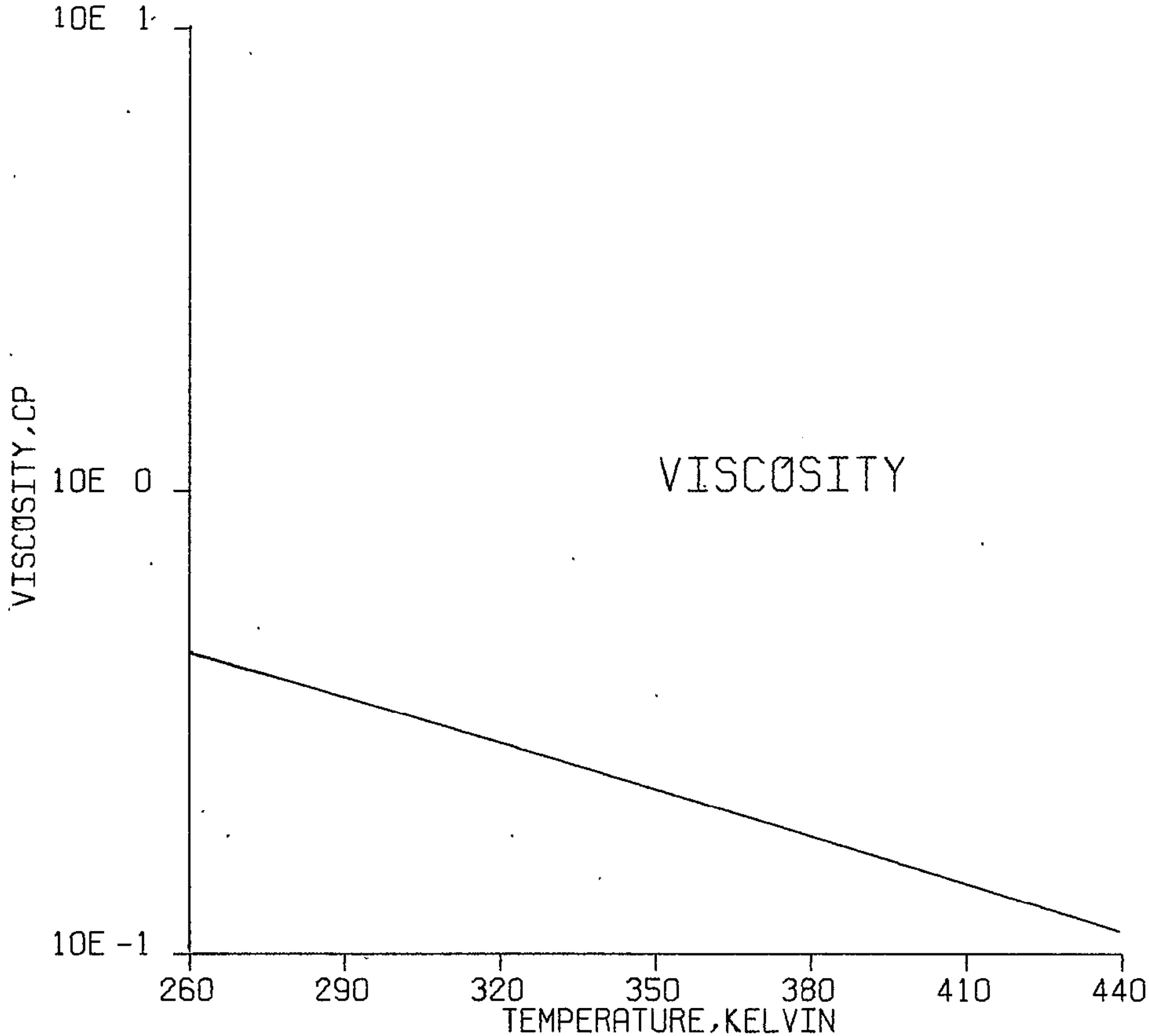


Figure 6 - Viscosity of Refrigerant-21,
273 to 423 Kelvin

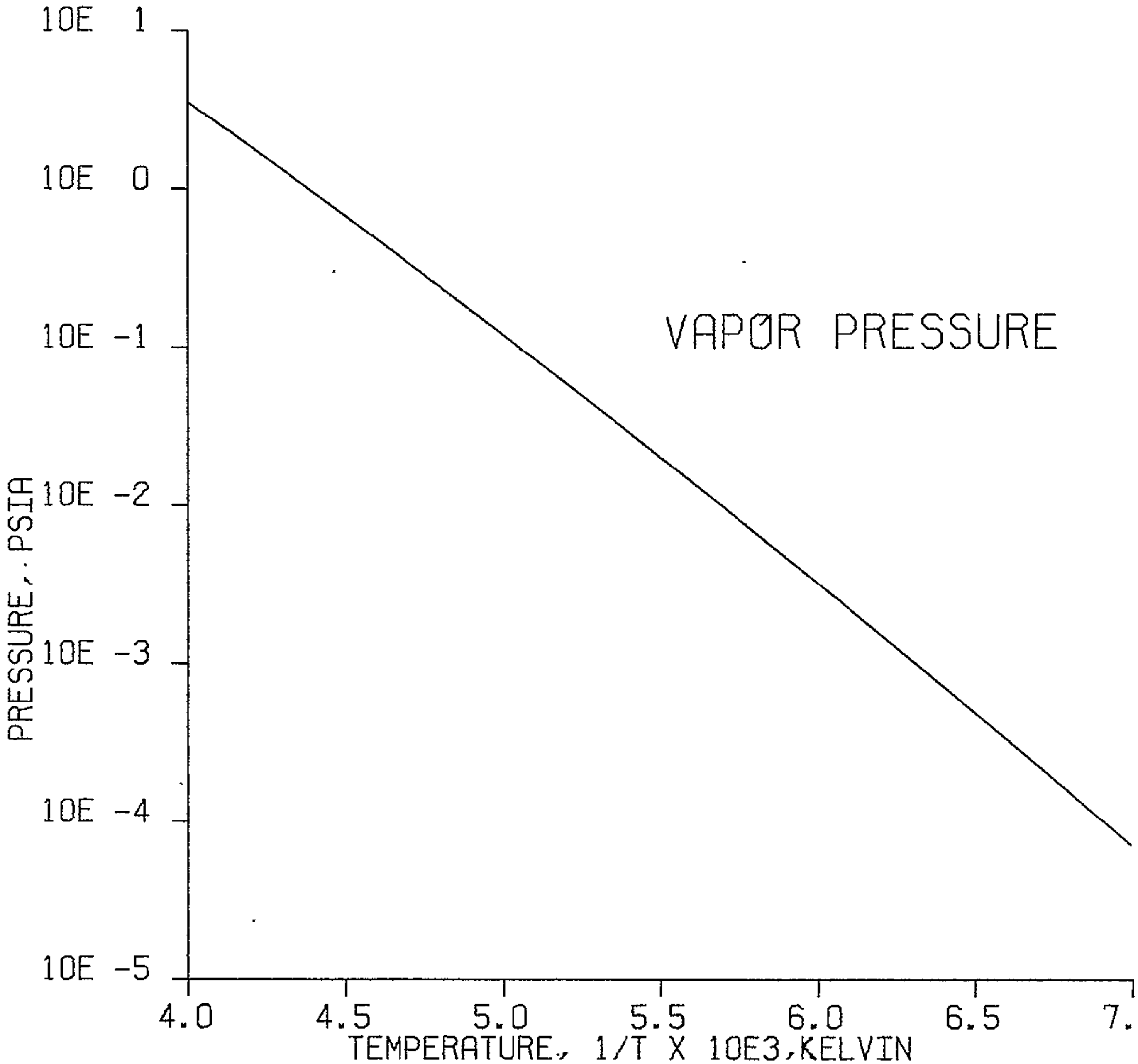


Figure 7 - Vapor Pressure of Refrigerant-21, Low Temperature

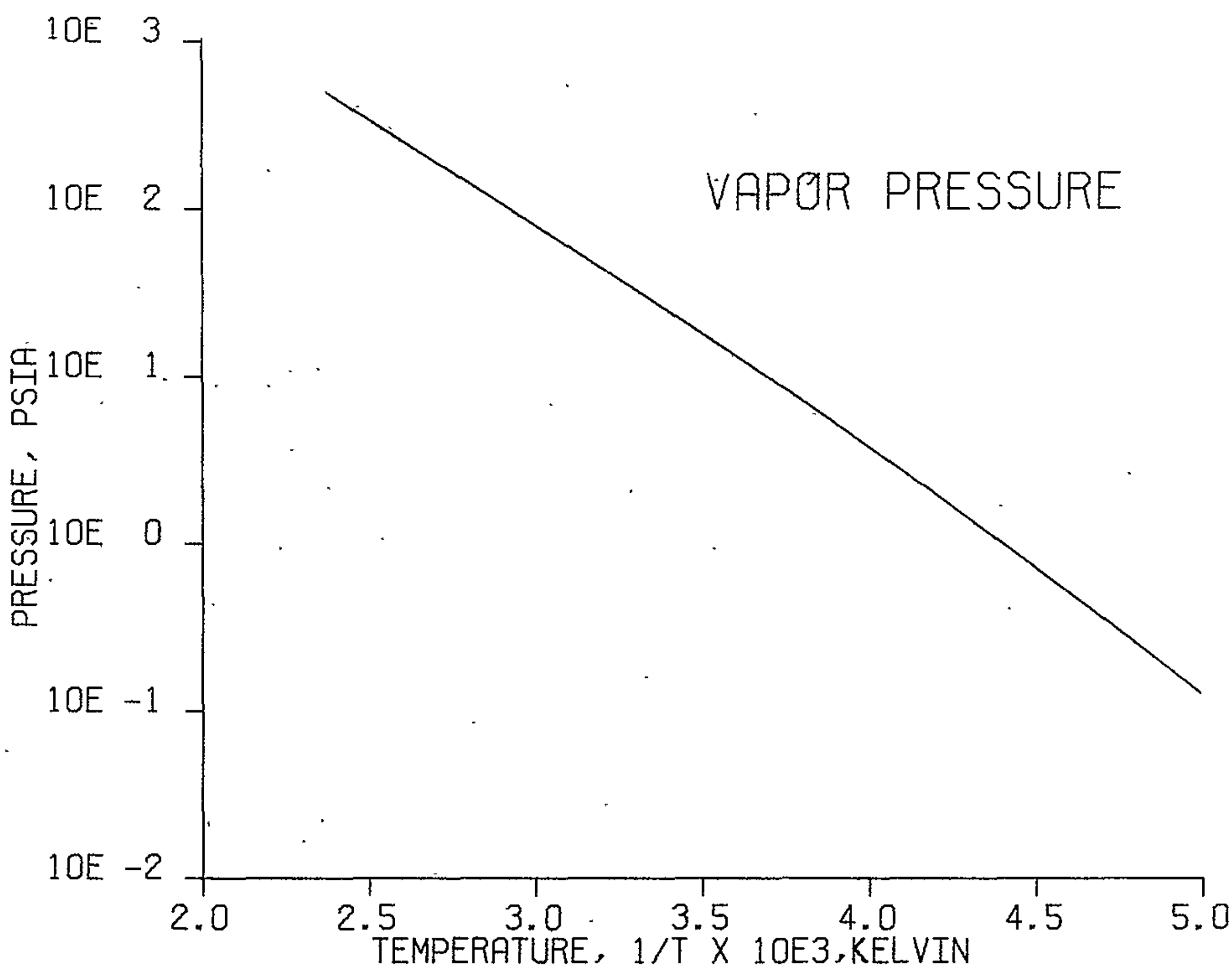


Figure 8 - Vapor Pressure of Refrigerant-21, High Temperature

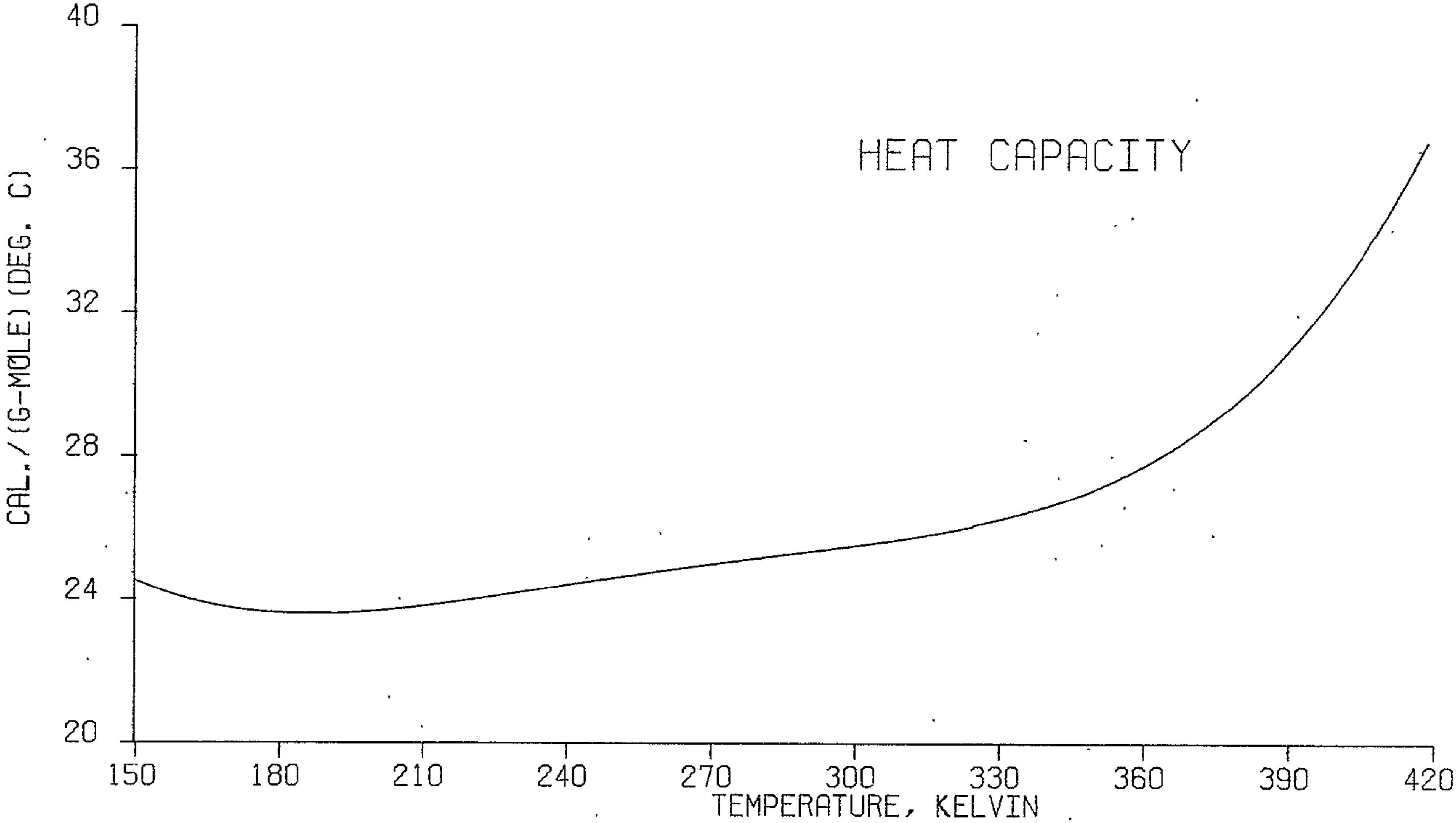


Figure 9 - Heat Capacity of Refrigerant-21 as a Function of Temperature at 3.415×10^6 N/m^2

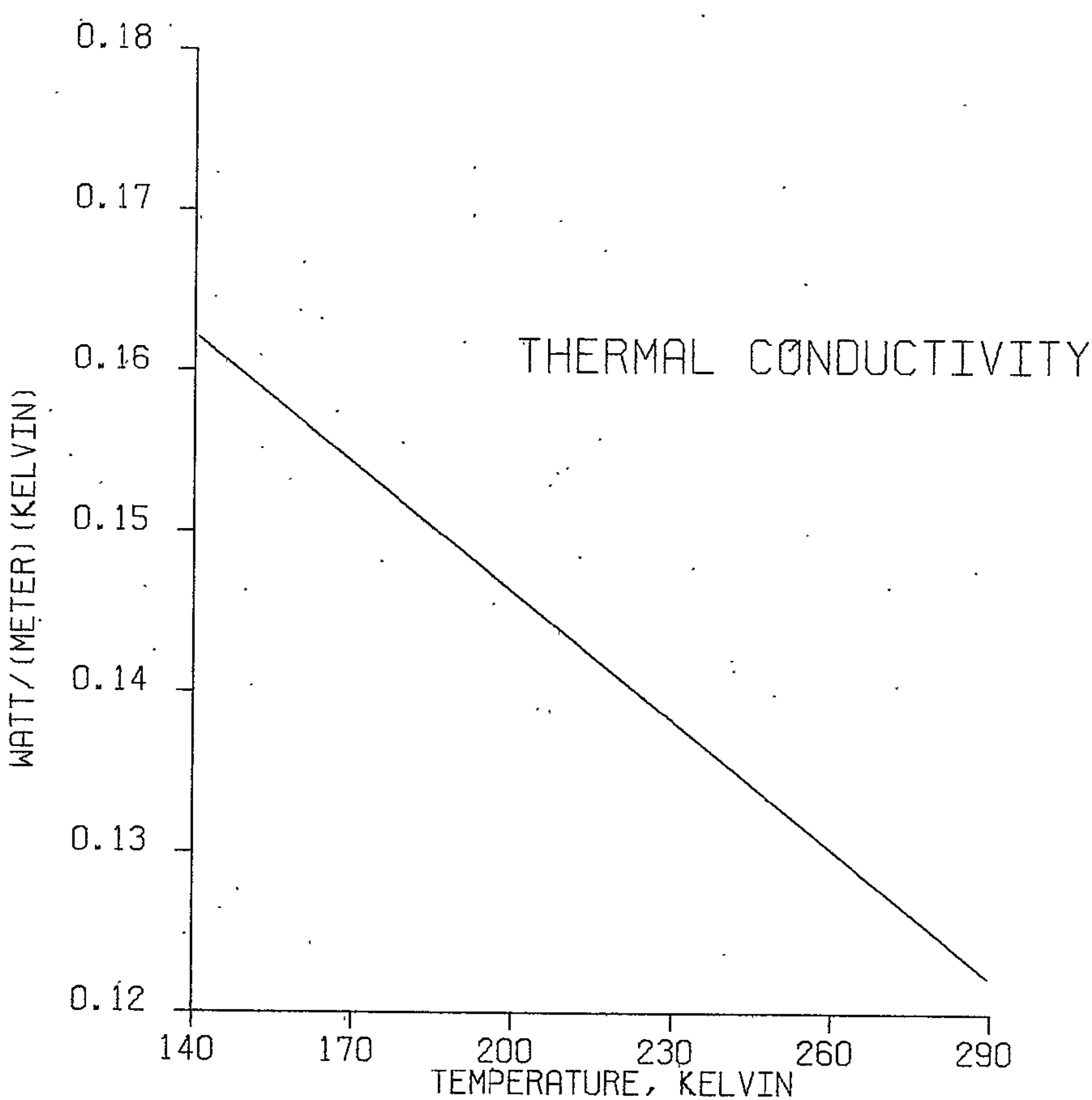


Figure 10 - Thermal Conductivity of Refrigerant-21 143 to 273 K at 0.34×10^6 N/m^2

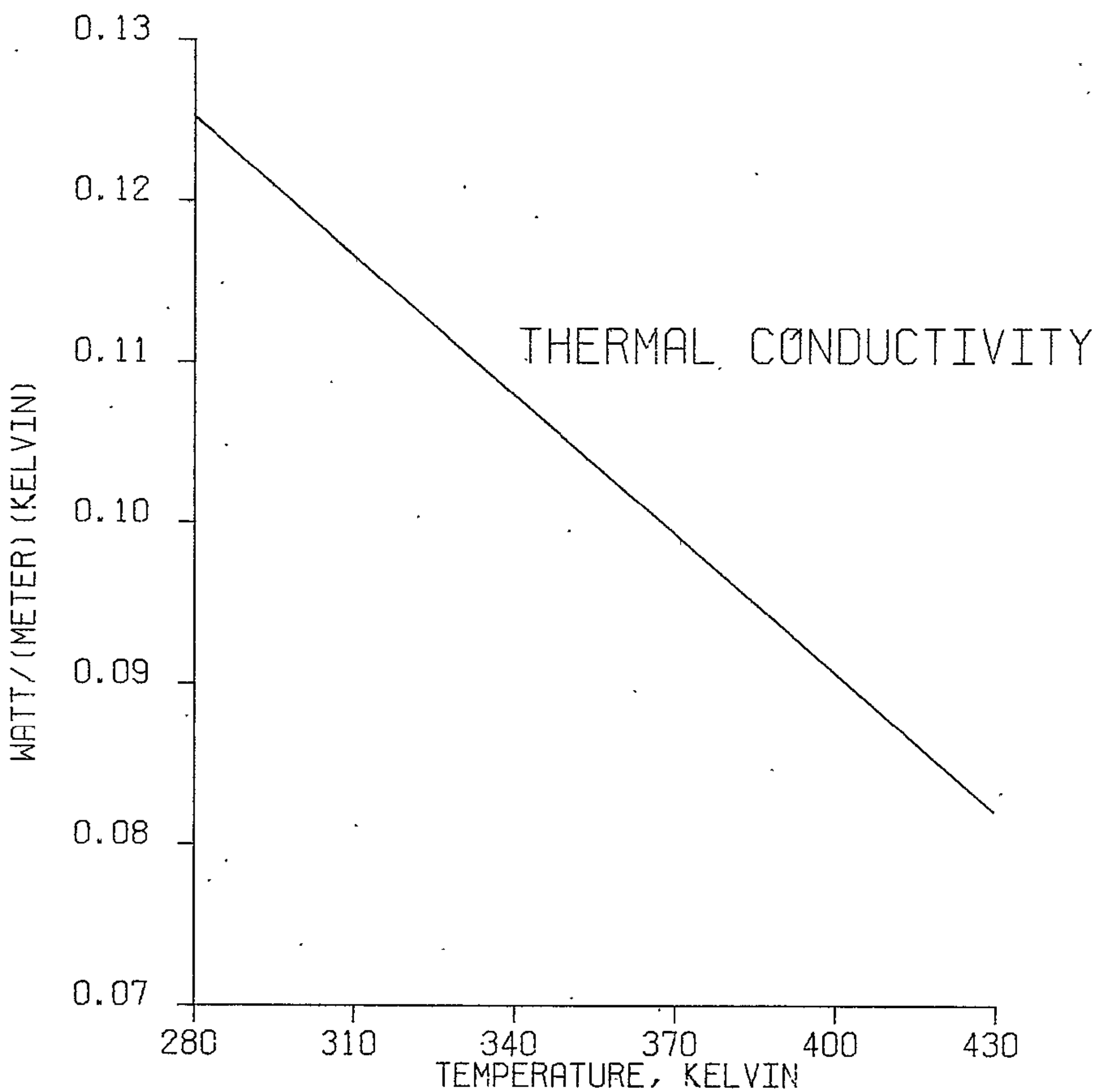


Figure 11 - Thermal Conductivity of Refrigerant-21 273 to 423 K (Vapor Pressure +0.34 x 10^6 N/m^2)

Literature Cited

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

(2) Reid, R.C., Sherwood, T.K., "The Properties of Gases and Liquids," 2nd ed., p 502, McGraw-Hill, New York, N.Y., 1966.

(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 13.79×10^6 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, DEG. C.	KELVIN	PRESSURE, PSIA	RELATIVE VOLUME *	DENSITY, 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.	TEMPERATURE, 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, DEG. C.	KELVIN	PRESSURE, PSIA	RELATIVE VOLUME *	DENSITY, 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	352.67	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	1.08920

* 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
212.62	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

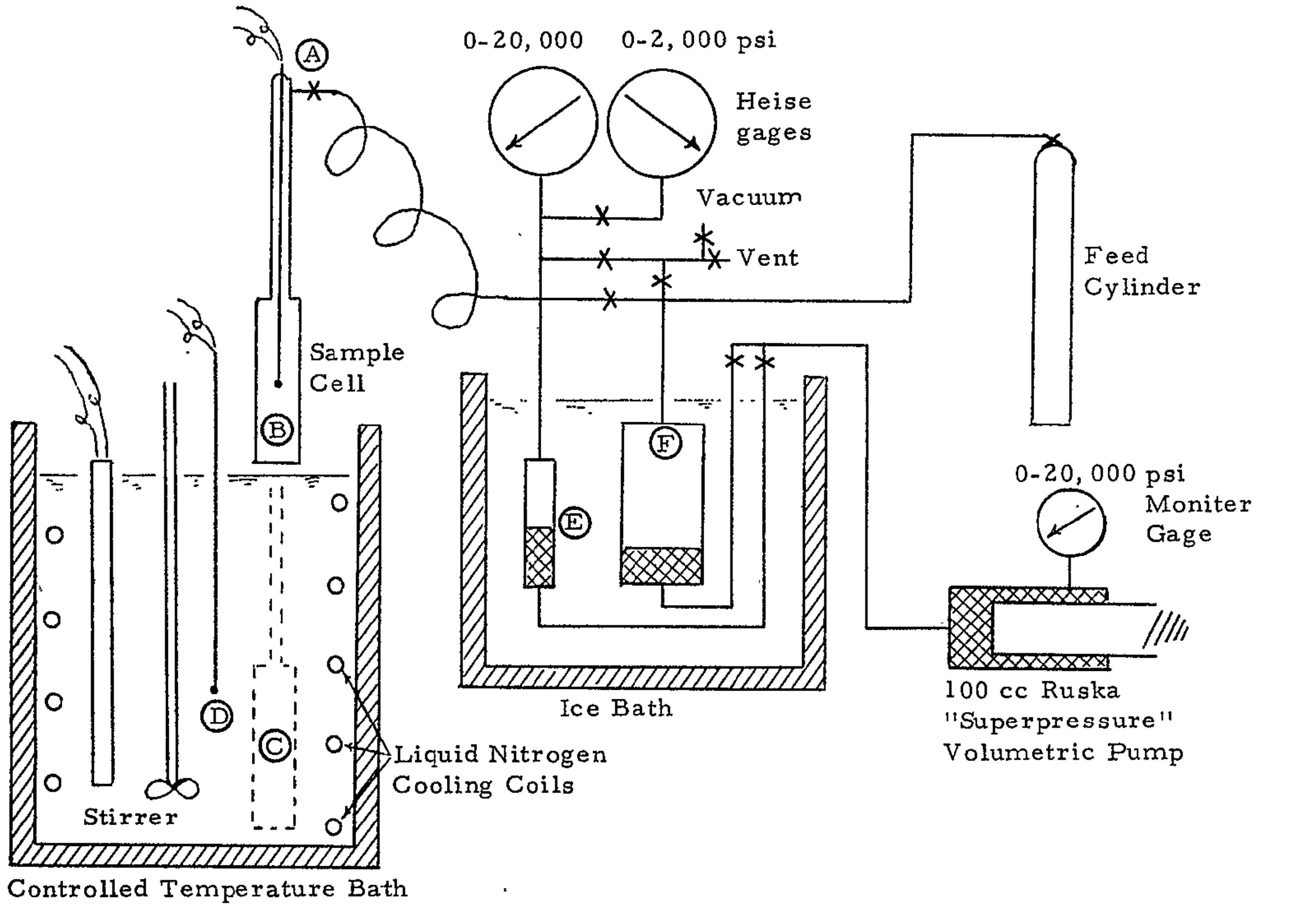
TABLE 2-A - LEAST SQUARES FIT OF REFRIGERANT-21
EXPERIMENTAL DENSITY DATA

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

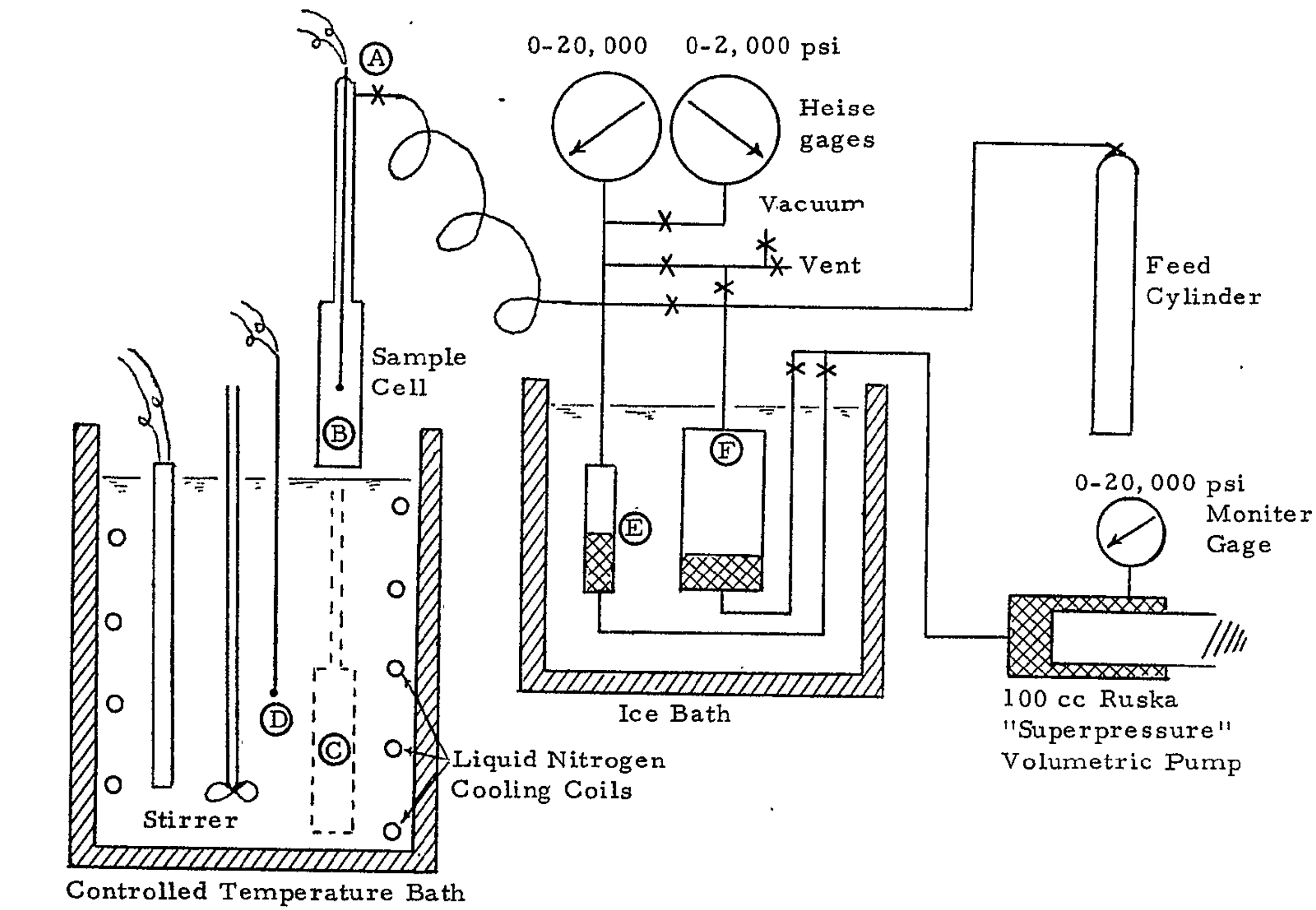
FIGURE 1-A - Schematic of Freezing Point and Relative Volume Apparatus

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

Nominal Temp., °C	600 psia Temp., °C	600 psia Density, g/cc	600 psia Viscosity, cp	1000 psia Temp., °C	1000 psia Density, g/cc	1000 psia Viscosity, cp	1500 psia Temp., °C	1500 psia Density, g/cc	1500 psia 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.

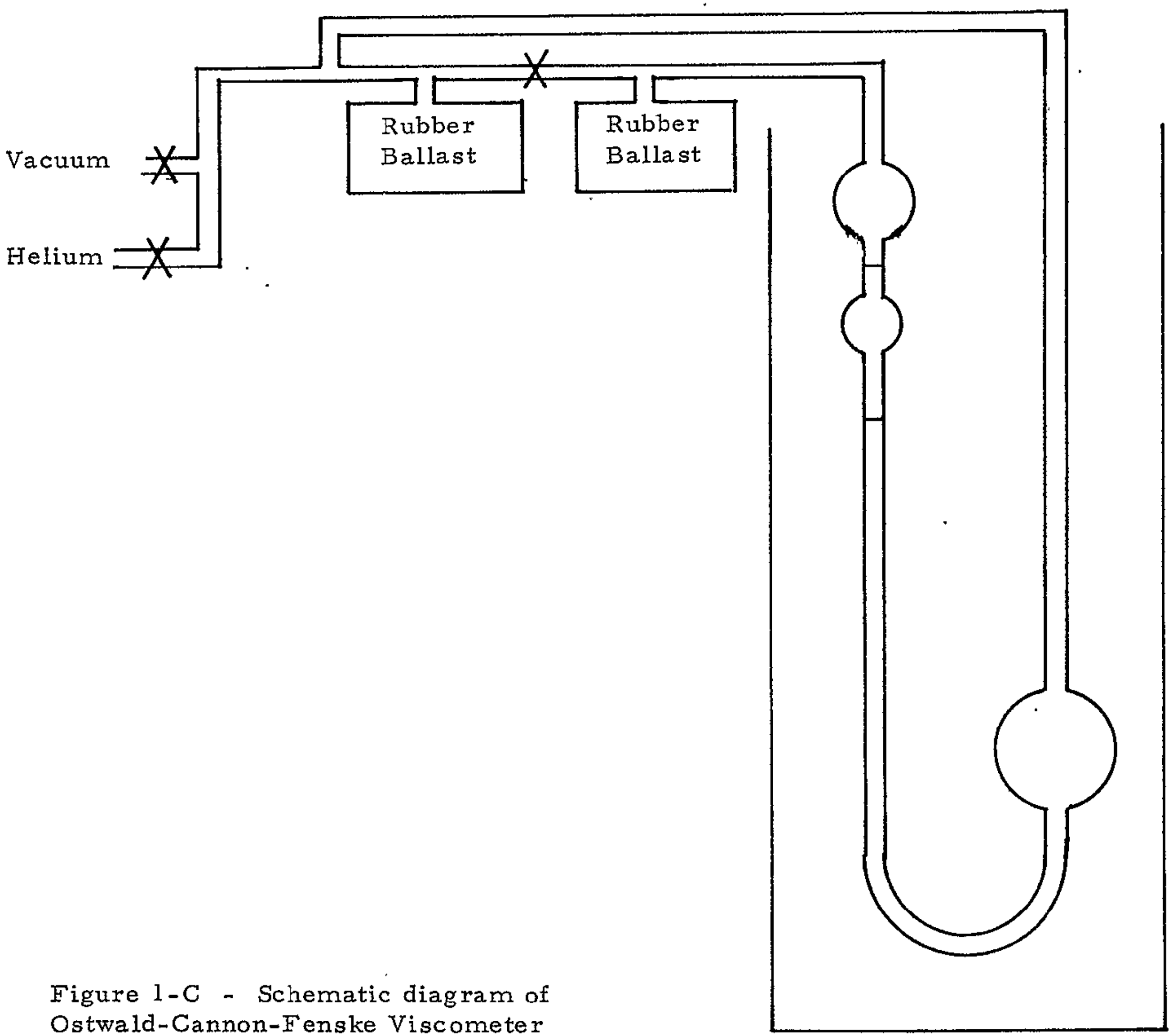


Figure 1-C - Schematic diagram of
Ostwald-Cannon-Fenske Viscometer

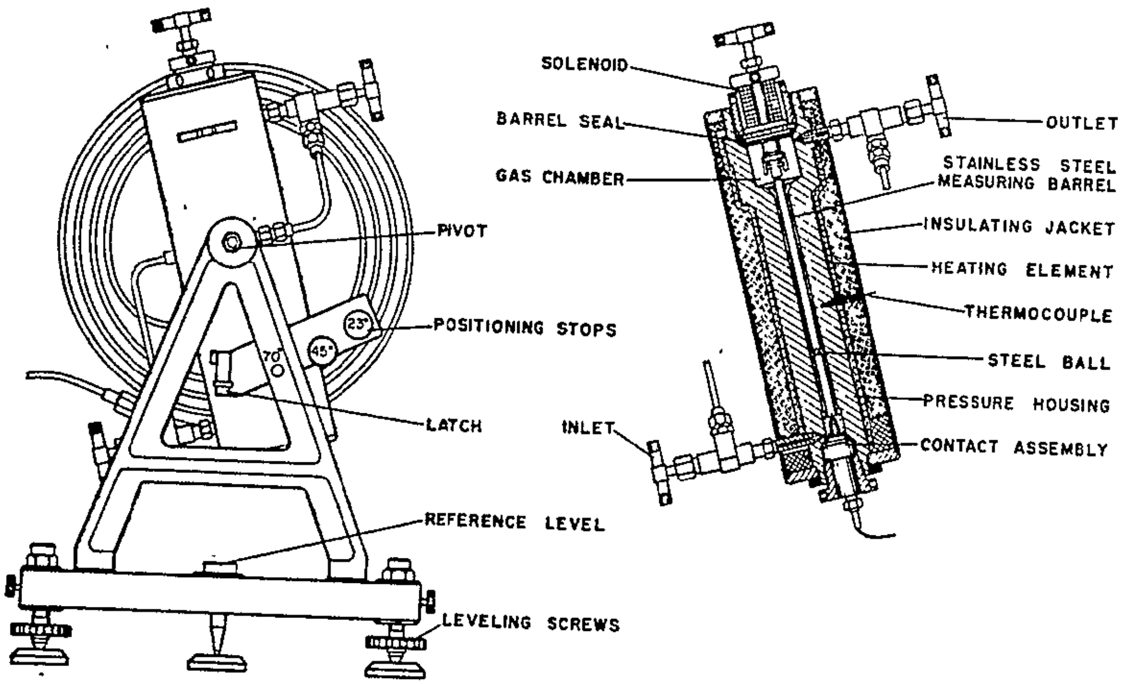


FIGURE 2-C - Details of Ruska Viscometer

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	$N/m^2 \times 10^{-3}$
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 °K	Temperature °C	Vapor Pressure psia	Vapor Pressure $N/m^2 \times 10^{-3}$
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 °K	Vapor Pressure, Psia Measured	Calculated	Error (Meas. - Calc.) 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 °K	Vapor Pressure, Psia Measured	Vapor Pressure, Psia Calculated	Error (Meas. - Calc.) Psia	Error (Meas. - Calc.) %
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

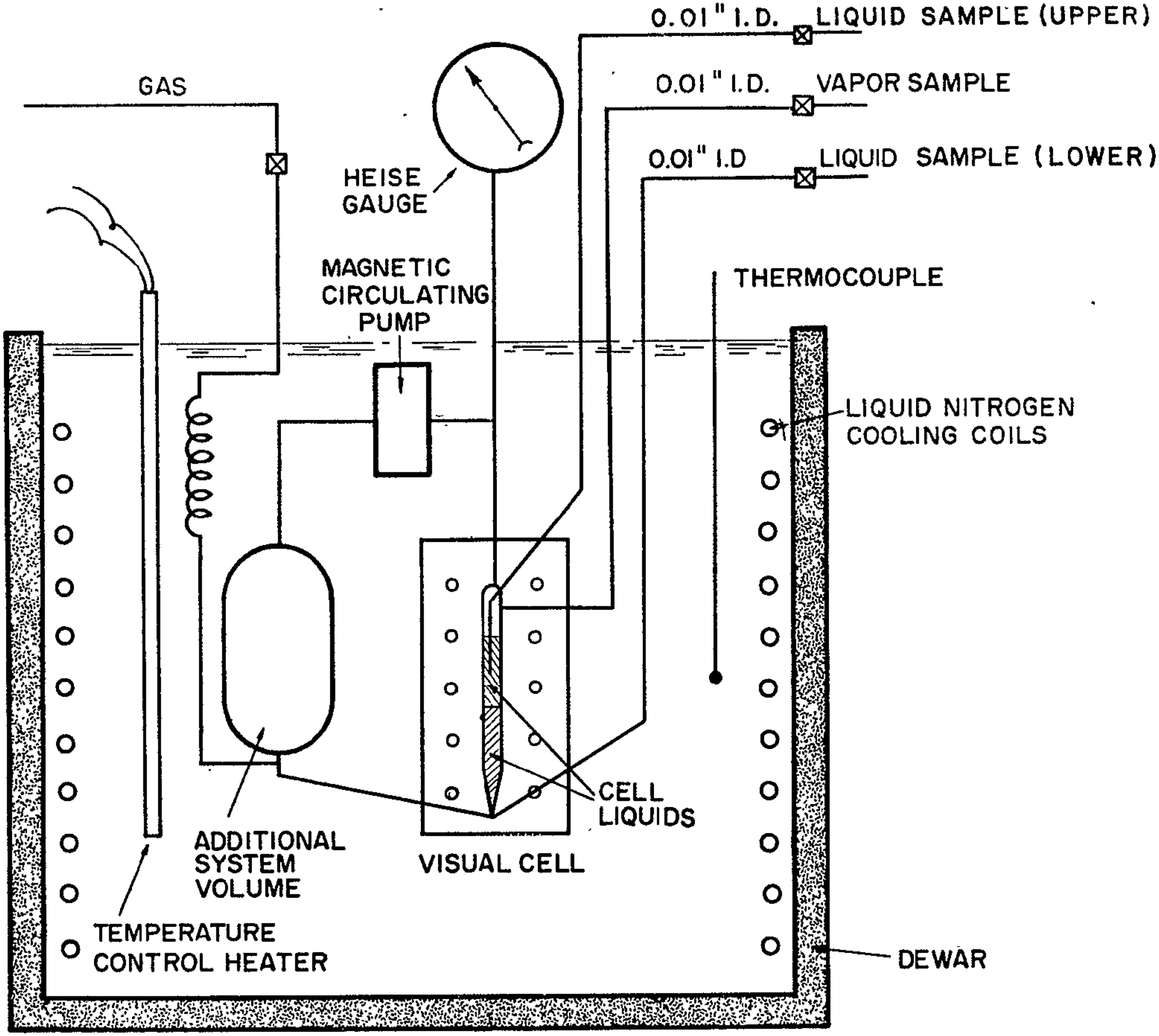


FIGURE 1-D - SCHEMATIC OF CELL ASSEMBLY

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}, ΔT, 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 $\dfrac{1447.3 - 959.5}{(204.80-144.67) - (184.07-144.21)}$

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	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 No.	Fluid	Pressure, PSIA	Temperature, K In	Temperature, K Out	Heat Capacity, Cp Meas.	Heat Capacity, Cp Lit. *	Ratio 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 In	Temperature, K Out	Heat Capacity, C_p Meas.	Heat Capacity, C_p Lit.	Ratio 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 No.	Temperature, K In	Temperature, K Out	Enthalpy Change cal./g-mole	Heat Capacity 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.

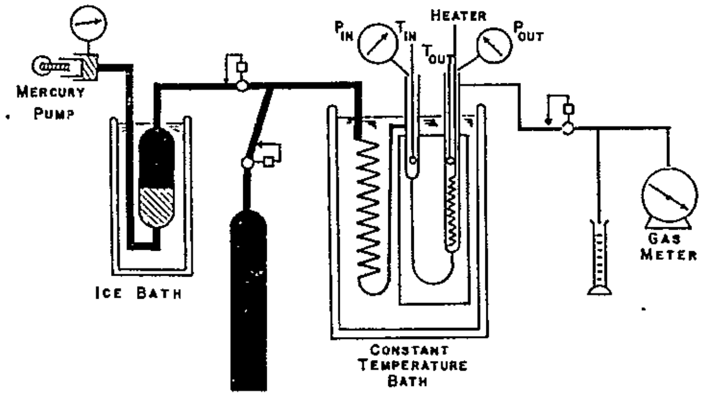


FIGURE 1-E - CALORIMETER AND ASSOCIATED EQUIPMENT

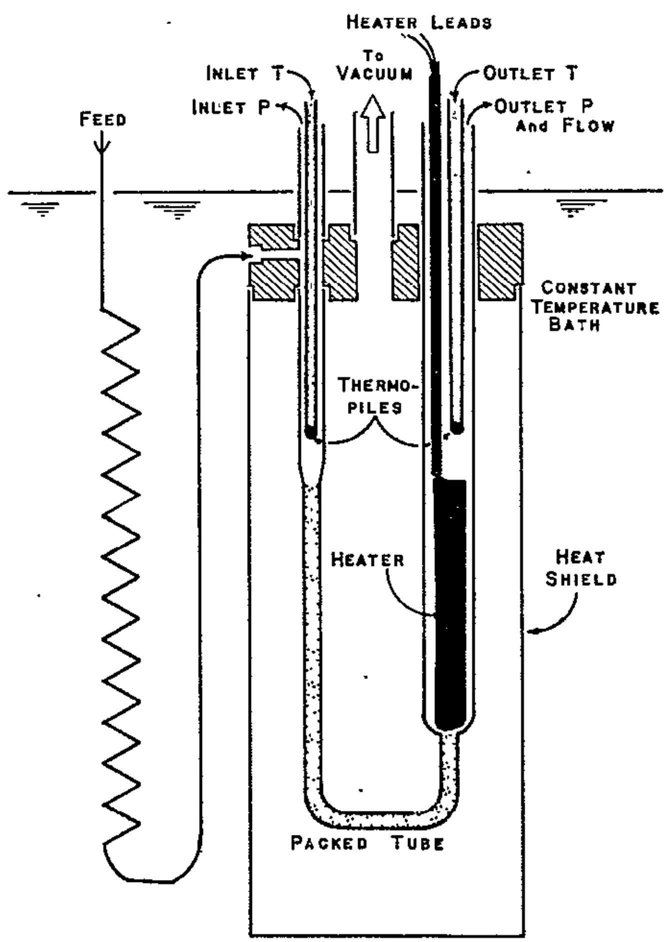


FIGURE 2-E - SCHEMATIC OF NEW P-V-T, INC. CALORIMETER

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, λ'_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 λ_o is the thermal conductivity at 0° C. A value of λ_o = 0.1408 W/m/C deg. was used.

At each temperature the calculated apparent thermal conductivity, λ'_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 λ_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	$N/m^2 \times 10^{-5}$	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

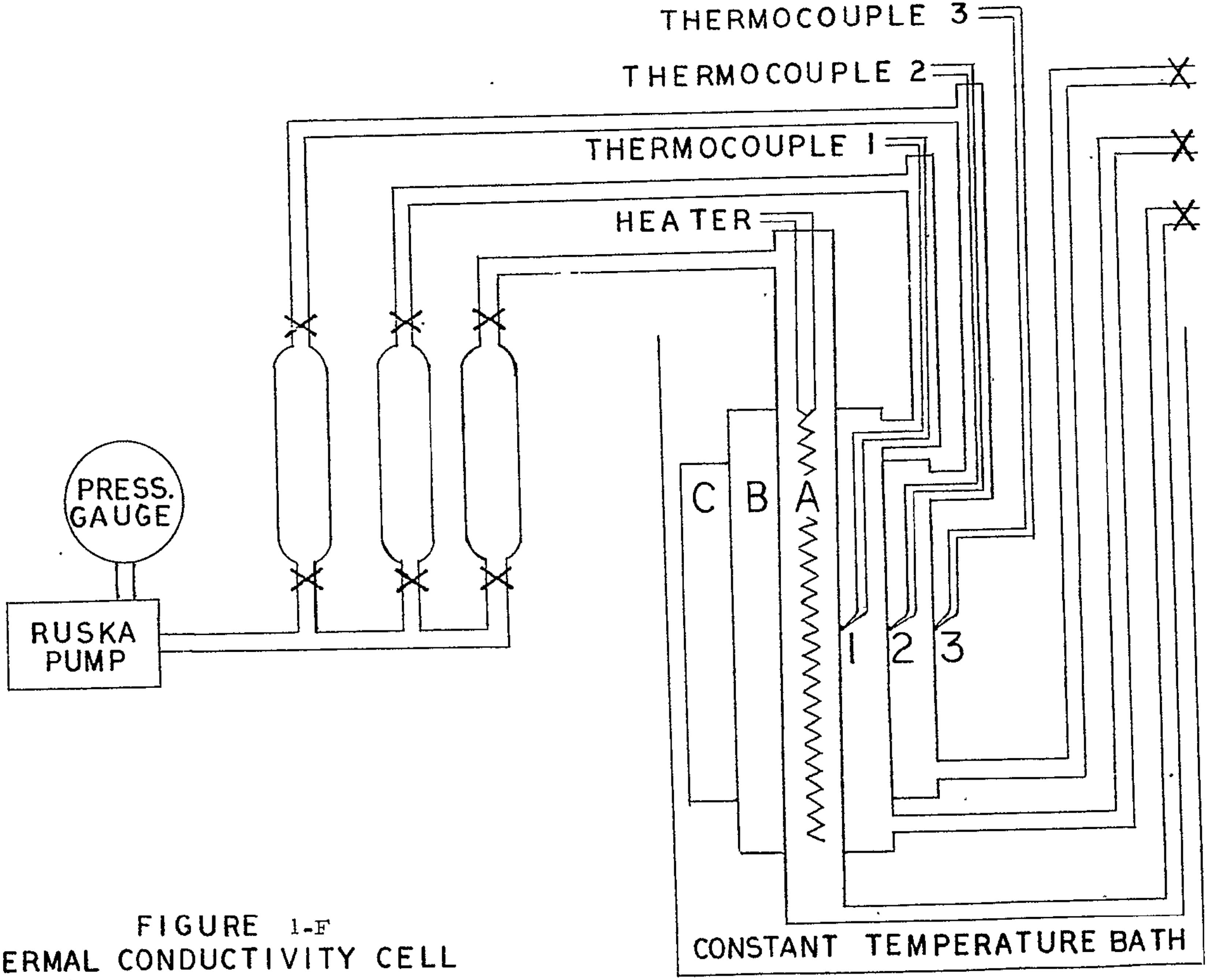


FIGURE 1-F
THERMAL CONDUCTIVITY CELL

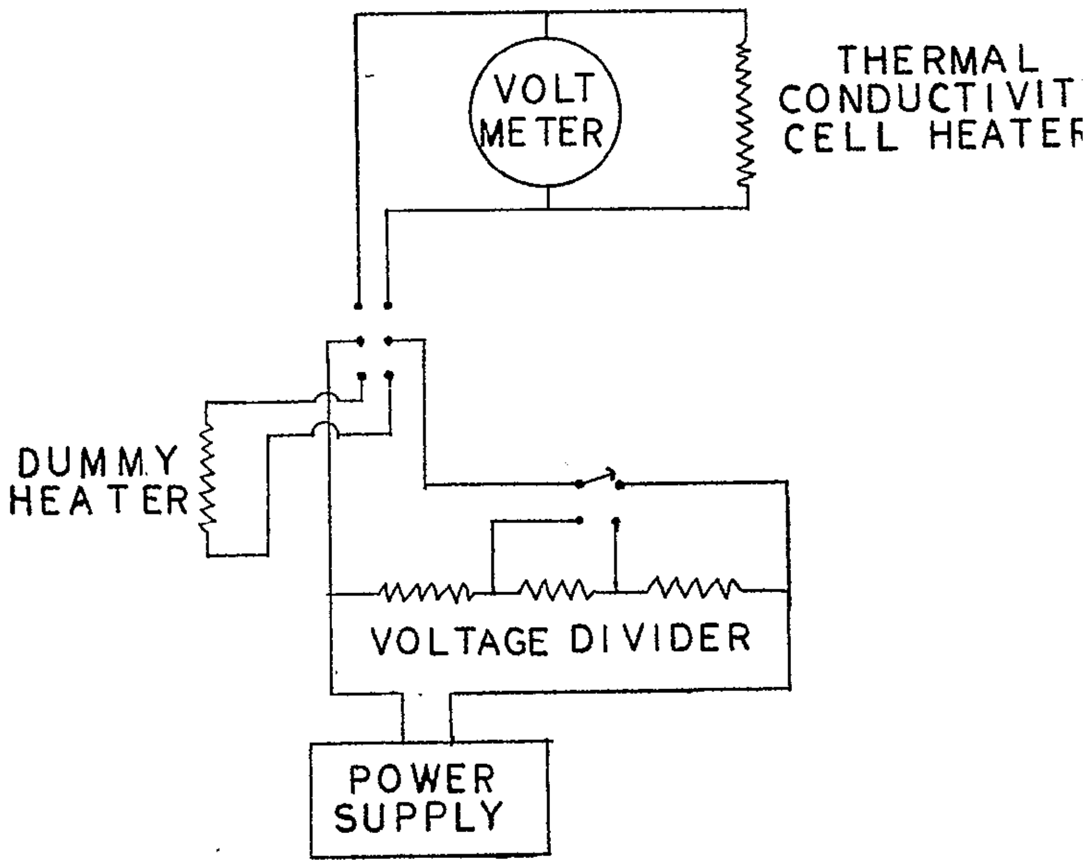


FIGURE 2-F. POWER SUPPLY SECTION

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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.

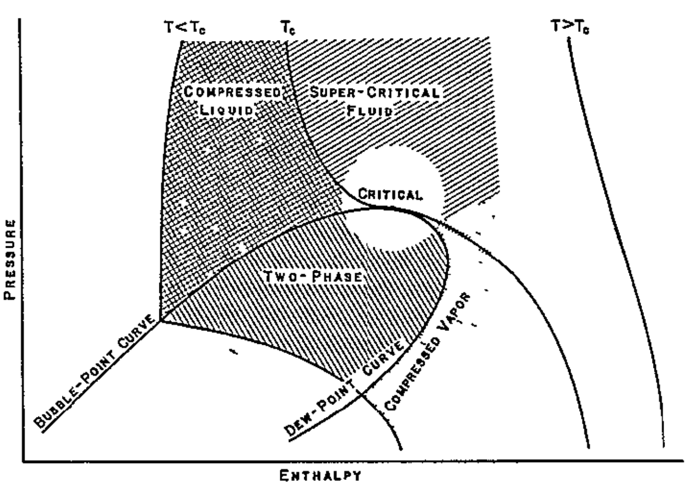


Figure 1
Regions Where New Experimental Data Should be Obtained

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 ΔP 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 ΔP 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 ΔP 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 ΔP 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.

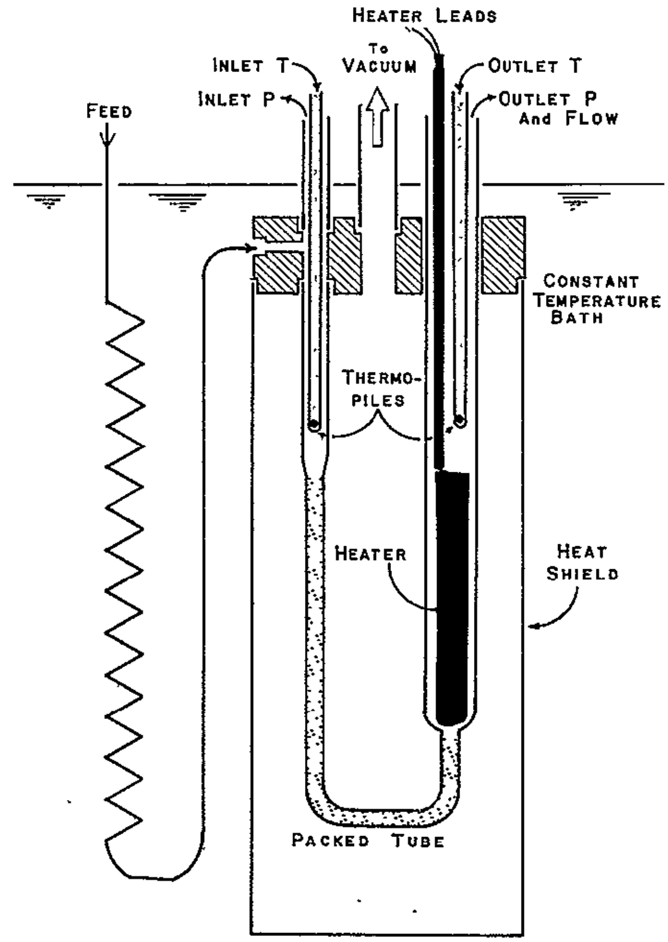


Figure 2
Schematic °F New P-V-T, Inc. Calorimeter

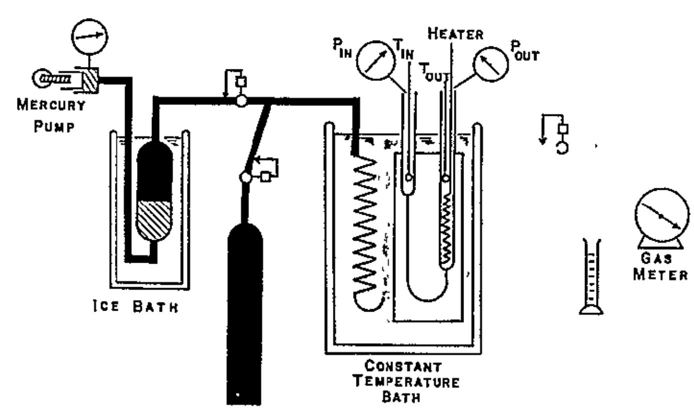


Figure 3
Calorimeter and Associated Equipment

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 ΔH 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, $V_{heater} = V_{meas} \times 0.9989$. 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 ΔT was −6.82°F, corresponding to an isothermal enthalpy change of −60.6 Btu/lb-mole.

Variable	Uncertainty	Variation in ΔH
ΔP (pressure)	±0.5 psi	±0.23 Btu/lb-mole
ΔT (temperature)	±0.02°F	±0.18 Btu/lb-mole
ΔV (flow rate)	±0.2%	±0.12 Btu/lb-mole
ΔQ (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-TΔT of +0.45°F.

Variable	Uncertainty	Variation in ΔH
ΔP	±1.0 psi	±0.016 Btu/lb-mole
ΔT	±0.01°F	±0.18 Btu/lb-mole
ΔV	±0.2%	±0.016 Btu/lb-mole
ΔQ	±0.1%	±0.008 Btu/lb-mole

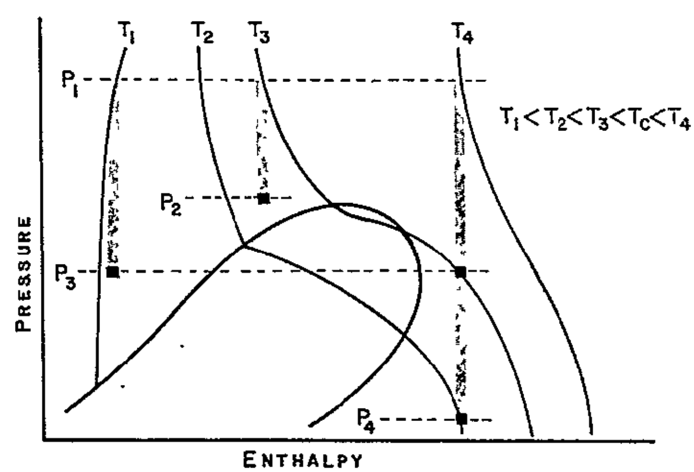
3. Based on the data of Jones[5] at University of Michigan for methane liquid at 400 psia, from −260° to −160°F, the reported smoothed isobaric enthalpy change is 1458 Btu/lb-mole.

Variable	Uncertainty	Variation in ΔH
ΔP	±0.5 psi	±0.05 Btu/lb-mole
ΔT	±0.02°F	±0.29 Btu/lb-mole
ΔV	±0.2%	±2.92 Btu/lb-mole
ΔQ	±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:

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

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:

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

If the expansion is to a low outlet pressure where the fluid exists as a gas, it is possible to estimate quite accurately $\overline{C}_p$(the average heat capacity over the temperature interval). Therefore, a measure of the J-T ΔT 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 ΔP and ΔT from the examples are included:

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

Isothermal Measurements

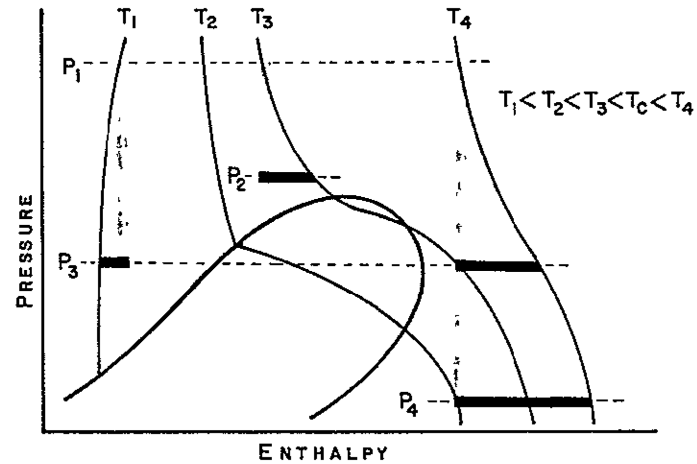
Isothermal enthalpy changes are obtained by throttling the fluid from T_{in}, P_{in} to P_{out}, in the J-T expansion tube, and then adding heat electrically to make $T_{out} = T_{in}$, as shown in Figure 5. If a gas enters at T_4 and P_1, and is throttled to P_4, the temperature will drop to T_2. The 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:

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

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.

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



B. ISOTHERMAL EXPANSION.

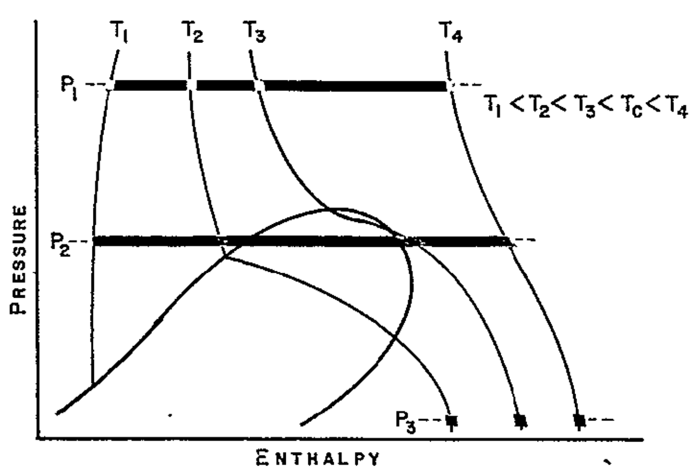
Figure 5
Operation as an Isothermal Calorimeter

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 ΔTs, 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:

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

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 ΔP and ΔT, the results are generally accurate to better than ±1%.

Isothermal data can be checked by making overall ΔP measurements, then two or more incremental ΔP measurements which total the original ΔP. It is also possible to make repeat ΔP 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 ΔP 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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