(as e.g. I) could produce an effect similar to the one observed.

When a magnetic field is applied, the focus is changed. The change is a particularly simple one if $\beta t=2\pi$ where t is the time necessary to go through the field. In this case, we have $(x, y)=(x_0, y_0)$ and $(\dot{x}, \dot{y})=(\dot{x}_0, \dot{y}_0)$ where x_0, y_0, $\dot{x}_0$, $\dot{y}_0$ are the values of x, y, $\dot{x}$, $\dot{y}$ at the point where the electron enters the field. In this case, the focus is thus displaced along the field by the length through which the field is applied. For other values of βt the change in the focus is more complicated.

We may thus expect marked effects on focussing due to magnetic fields even if the periodicity condition $\beta t=2\pi$ is satisfied. However, if the distance in which $\mathcal{H}$ is applied is relatively short, we will still have the same type of asymmetry for $\beta t=2\pi$ as for $\beta t=0$.

The above remarks are not intended as a proof of the absence of a preferential orientation of the spin, but simply to point out that the more trivial explanation is also possible.

Note added in proof, October 8, 1934. Since this research was completed, both Dymond[25] and Rupp[26] have published results of further experiments in double scattering. Dymond now ascribes the asymmetry previously observed by him to instrumental irregularities and finds no asymmetry greater than 1 percent in the double scattering by thin gold foils of electrons with energies up to 160 kv. Rupp finds with gold foils and electrons accelerated by 250 kv an asymmetry of 10 percent. He has applied magnetic fields between the targets with the same result as before. (See reference 19.) Dymond mentions the possibility that such tests may not preclude the existence of instrumental asymmetries. It is not clear, however, whether a sufficiently complete calculation of the kind indicated in the appendix has been made by him or whether his considerations are qualitative.

[25] Dymond, Proc. Roy. Soc. **A145**, 657 (1934).
[26] Rupp, Zeits. f. Physik **90**, 166 (1934).

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The Joule-Thomson Effect in Argon

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The measurements employed the same apparatus as for helium and air. Slight changes were made in the compressor and the purification system. The argon was of high purity except for 0.5 percent of nitrogen. Clogging of the plug gave trouble in a limited part of the field. The vapor phase from Pyrofax gas makes an excellent low temperature bath liquid. The data for the isenthalpic curves are given in detail and plotted. The values of the Joule-Thomson coefficient, μ, over the field (−150 to 300°C and 1 to 200 atm.) are calculated, tabulated, and plotted as a function of temperature and pressure. The lower branch of the inversion curve ($\mu=0$) falls within the low temperature range of these measurements. The trends of the Joule-Thomson effect in argon over the measured range of temperature and pressure are exceedingly like those in air and nitrogen. Lack of specific heat data prevents the calculation of other important thermodynamic coefficients.

THE measurements on the Joule-Thomson effect in air[1, 2] and in helium[3, 4] are here extended to argon. They cover the same range of pressure (1 to 200 atm.) and of temperature (−150° to 300°C). The apparatus is the same as that used for helium,[3] and reference is made to this and the earlier articles[1, 2] for the details of both apparatus and methods. A few small changes are described below.

ARGON SUPPLY

The argon used for these measurements was presented by the General Electric Company through Mr. B. L. Benbow of the Cleveland Wire Works. It came from a lot which was stated to contain 99.5 percent A, 0.00001 percent O_2, 0.000005 percent H_2, less than 0.000001 percent carbon compounds, with a residue of N_2 of about 0.5 percent.

The nearness of the critical temperature of argon ($T_c=-122.4$°C) to that of nitrogen ($T_c=-147.1$°C) leads one to expect that the presence of a small amount of nitrogen in argon will alter the Joule-Thomson effect in argon but slightly. Work with argon as an impurity in nitrogen showed that the percent change in μ for nitrogen was close to the percent of argon impurity when small. These results suggest that a small percent impurity of nitrogen in argon

[1] Roebuck, Proc. Am. Acad. Sci. **60**, 537 (1925).
[2] Roebuck, Proc. Am. Acad. Sci. **64**, 287 (1930).
[3] Roebuck and Osterberg, Phys. Rev. **43**, 60 (1933).
[4] Roebuck and Osterberg, Phys. Rev. **45**, 332 (1934).

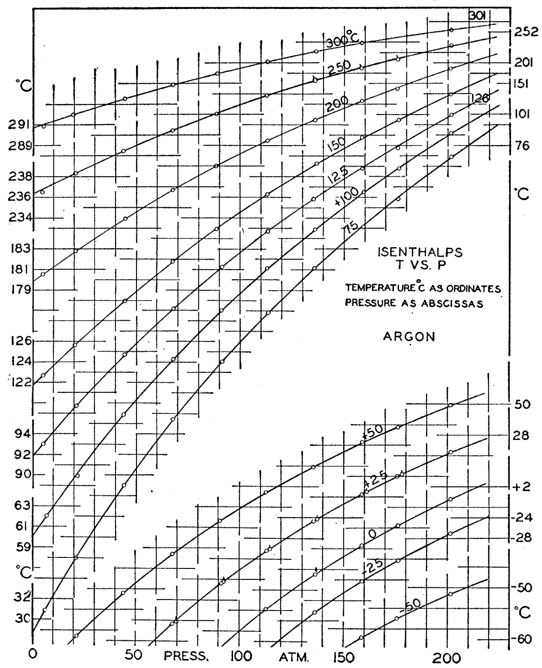

FIG. 1. t as function of p at constant enthalpy.

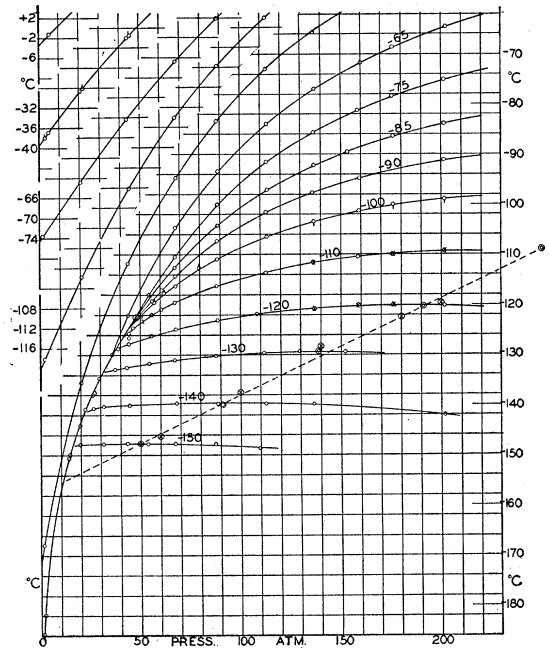

FIG. 2. t as function of p at constant enthalpy.

will alter μ for argon by a percent considerably less than the percent of impurity. It was inexpedient to waste our limited argon supply in direct experimental test of this statement since plans were in mind for a study of the whole range of mixtures. Satisfactory methods for analysis for these small percentages of nitrogen in argon and for their removal promised to be both difficult and time consuming. The argon was therefore used as received and every effort made to protect it from admixture with air. The system remained unexpectedly tight, as shown by the very small loss of argon. Moreover, the measurements were completed in a very much shorter time than with He.

Compressor

In the helium measurements the time required to keep the compressor in satisfactory order was the greatest interference. The replacement of steel by monel metal in both cylinder liners, by excluding rusting, greatly prolonged the life of the fiber packing. The change from monel metal disk valves in steel housings to stainless steel disks in monel metal housings removed entirely the distortion of the disks from pounding. The substitution of a rubber packing on the piston rod for the oily fiber packing removed the last means by which oil can enter the system.

Plug Clogging

As before, extreme measures were taken to remove condensable impurity. The compressed argon passed successively through a water trap, a 1.5 meter column of lump sodium hydrate, a 70 cm column of potassium hydrate and a regenerative cooler in which the argon fell to liquid air temperature and rose to room temperature again. Before each day's low temperature runs, the apparatus was held above 75°C and dry argon passed through it for at least half an hour.

That most of the persistent clogging was not due to water vapor is shown first by the means taken to remove it, and second by the following phenomenon. The plug clogged rapidly whenever there was a large temperature drop across it. If after considerable clogging, the temperature drop was cut to one-quarter or less by reducing the pressure drop, the flow grew steadily. This could be done repeatedly, though the maximum

TABLE I. *Data for isenthalp of argon which are plotted in Figs. 1 and 2.*

No.	p	t
300° curve, Plug 65		
1	5.0	290.86
2	19.4	292.00
3	44.4	293.53
4	67.7	294.90
5	88.4	295.98
6	113.1	297.12
7	136.4	298.07
8	158.6	298.89
9	201.5	300.22
250° curve, Plug 65		
1	4.3	236.48
2	20.5	238.34
3	43.8	240.46
4	67.4	242.45
5	88.4	244.06
6	112.7	245.84
7	136.0	247.22
8	158.3	248.45
9	201.3	250.70
250° curve, Plug 25		
1	136.0	247.39
2	158.3	248.54
3	175.8	249.30
4	201.3	250.70
200° curve, Plug 65		
1	4.8	180.55
2	20.2	182.78
3	44.4	185.90
4	67.4	188.70
5	88.2	191.00
6	112.9	193.45
7	135.9	195.43
8	158.5	197.29
9	175.7	198.52
10	201.3	200.45
150° curve, Plug 65		
1	4.9	122.67
2	20.3	125.65
3	44.1	129.92
4	67.4	133.77
5	88.4	136.92
6	112.9	140.32
7	136.6	143.22
8	158.5	145.74
9	176.2	147.53
10	201.3	149.95
125° curve, Plug 65		
1	5.0	93.00
2	21.0	96.77
3	44.3	101.72
4	67.7	106.21
5	91.2	110.24
6	113.2	113.69
7	135.1	116.81
8	158.8	119.77
9	175.7	121.74
10	201.5	124.97

No.	p	t
100° curve, Plug 65		
1	6.7	62.06
2	21.6	65.94
3	43.9	71.88
4	67.7	77.31
5	90.9	82.02
6	112.8	86.11
7	135.8	89.92
8	159.1	93.50
9	176.3	95.79
10	201.5	99.15
75° curve, Plug 65		
1	5.8	30.90
2	20.8	35.95
3	44.0	43.02
4	67.7	49.42
5	91.1	55.05
6	113.2	59.81
7	135.6	64.12
8	159.1	68.17
9	175.9	70.83
10	201.5	74.90
50° curve, Plug 65		
1	5.5	−1.22
2	21.3	+4.85
3	44.0	13.24
4	67.7	20.81
5	90.6	27.30
6	112.8	32.92
7	135.4	37.89
8	158.8	42.57
9	176.1	45.57
10	201.5	49.82
25° curve, Plug 65		
1	4.7	−36.80
2	20.5	−28.60
3	44.0	−17.98
4	67.9	− 8.65
5	91.2	− 0.82
6	113.1	+ 5.50
7	135.5	11.30
8	158.7	16.53
9	176.0	20.01
10	201.5	24.71
25° curve, Plug 57		
1	3.1	−37.91
2	22.1	−28.08
3	45.6	−17.69
4	69.8	− 8.25
5	92.5	− 0.58
6	114.7	+ 5.89
7	137.5	11.73
8	161.1	16.92
9	178.2	20.35
10	201.5	24.71

No.	p	−t
0° curve, Plug 57		
1	1.5	73.62
2	20.4	62.82
3	43.6	50.28
4	68.0	38.68
5	88.7	30.17
6	112.8	21.75
7	136.4	14.88
8	158.8	9.34
9	176.1	5.48
10	201.5	0.44
−25° curve, Plug 57		
1	2.0	118.06
2	20.7	101.74
3	43.7	84.13
4	67.5	70.02
5	88.6	59.75
6	112.8	50.05
7	136.2	42.37
8	158.8	36.27
9	176.4	32.25
10	201.5	27.07
−50° curve, Plug 57		
1	1.2	167.93
2	20.2	135.49
3	44.0	111.75
4	67.9	94.60
5	88.3	83.49
6	112.9	72.90
7	136.4	65.66
8	158.8	59.72
9	175.9	56.00
10	201.5	51.21
−65° curve, Plug 57		
1	1.9	181.88
2	14.3	150.49
3	20.8	143.46
4	27.1	137.41
5	33.4	132.59
6	43.9	122.08
7	67.6	104.68
8	89.0	93.50
9	113.2	84.01
10	136.8	77.04
11	160.0	71.83
12	175.9	68.59
13	201.5	64.42
−75° curve, Plug 14		
1	19.8	144.09
2	27.5	137.16
3	33.2	132.20
4	38.8	128.90
5	44.3	125.61
6	54.3	118.05
7	67.5	110.49
8	88.7	99.99
9	112.9	91.60
10	136.4	85.66
11	158.4	81.34
12	175.6	78.44
13	201.5	75.11

No.	p	−t
−85° curve, Plug 57		
1	43.6	126.06
2	67.3	112.63
3	88.7	104.17
4	113.2	97.21
5	136.7	92.33
6	153.1	89.57
7	176.1	86.47
8	201.5	83.93
−90° curve, Plug 14		
1	38.3	129.10
2	44.4	125.47
3	50.6	122.19
4	55.9	119.25
5	60.8	117.24
6	67.5	114.28
7	88.3	107.29
8	112.8	101.65
9	135.8	97.74
10	159.4	94.77
11	201.5	91.09
−100° curve, Plug 57		
1	67.6	116.33
2	88.4	110.87
3	113.1	106.50
4	136.5	103.41
5	159.0	101.36
6	175.9	99.96
7	201.5	98.82
−100° curve, Plug 14		
1	46.2	124.53
2	50.4	122.29
3	57.0	119.64
4	61.8	117.72
5	79.4	112.75
6	201.5	98.82
−100° curve, Plug 65		
1	136.4	103.46
2	158.8	101.40
3	176.0	100.12
4	201.5	98.82
−110° curve, Plug 14		
1	38.8	128.68
2	44.4	125.77
3	50.6	123.17
4	55.8	121.96
5	60.6	120.84
6	67.3	119.46
7	88.3	116.27
8	112.8	113.61
9	136.2	111.63
10	158.5	110.46
11	176.6	110.04
12	201.5	109.27

No.	p	−t
−110° curve, Plug 65		
1	136.1	111.86
2	158.4	110.60
3	175.9	109.83
4	201.5	109.27
−120° curve, Plug 14		
1	15.1	150.80
2	20.1	143.54
3	26.8	138.21
4	33.4	132.91
5	44.1	127.77
6	55.7	126.16
7	67.7	124.83
8	88.6	123.13
9	108.1	121.90
10	136.7	120.91
11	158.8	120.06
12	176.1	119.93
13	201.5	120.10
−120° curve, Plug 65		
1	136.4	120.93
2	158.5	120.38
3	175.9	120.07
4	201.5	120.10
−130° curve, Plug 65		
1	37.3	132.94
2	43.0	132.42
3	54.2	131.67
4	67.0	131.00
5	87.6	130.21
6	111.6	129.62
7	129.5	129.28
8	152.1	129.38
−140° curve, Plug 14		
1	14.9	150.87
2	20.4	144.12
3	26.4	141.40
4	31.3	140.92
5	44.1	140.63
6	67.9	140.27
7	88.4	140.30
8	112.6	140.33
9	136.4	140.39
10	201.5	141.97
−150° curve, Plug 65		
1	19.7	147.93
2	31.1	147.79
3	43.3	147.74
4	53.6	147.83
5	67.2	147.81
6	87.3	147.89
7	109.3	148.71

flow decreased. This can be interpreted as the deposition in and the subsequent sublimation from the pores of the plug of some substance solid at these temperatures. Since it occurred with the plug at −100°C, it could hardly be water.

Once, after a considerable time of flow with nitrogen at these low temperatures, the regenerative liquid air purifier was disconnected as soon as possible after the pressure was dropped, and was left open. As the regenerator warmed up, the nitrogen left therein and any other volatile material escaped. Clogging troubles were much less evident in succeeding runs.

Scattered observations seemed to connect the clogging with oil in the compressor. Our tentative hypothesis is that the persistent clogging is due to some decomposition product of the oil resulting from the high compression temperatures (300°C), this product solidifying in the plug over the temperature range in which we were bothered. It is probably not an oxidation product since the same phenomenon has been observed with air, He, A and N.

Low Temperature Bath Liquid

A very low temperature bath liquid was obtained by drawing off the vapor phase from a

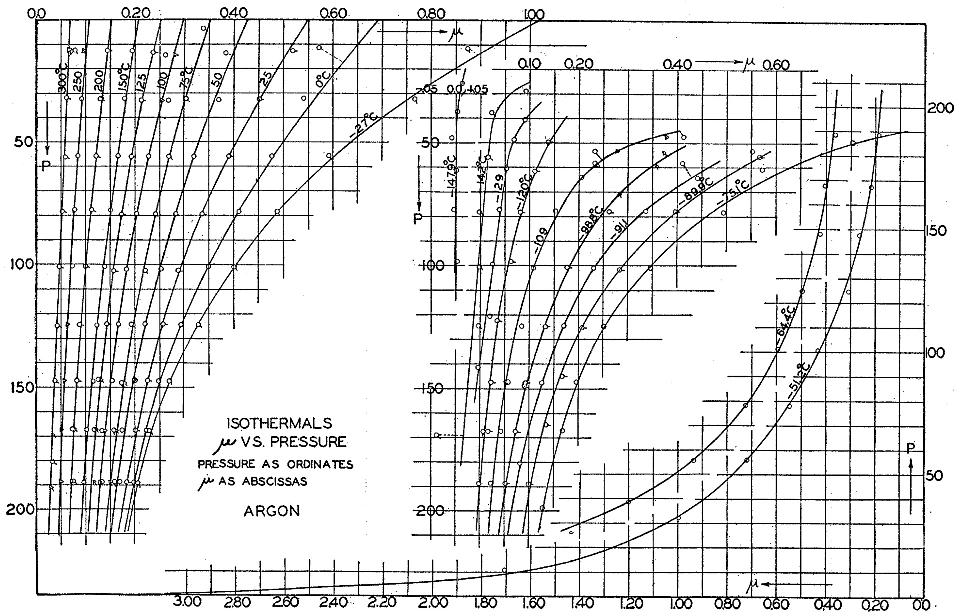

FIG. 3. μ as function of p at constant enthalpy.

100 lb. drum of Pyrofax gas and condensing it in the cooled apparatus. The liquid so obtained, probably largely butane, gave no sign of any freezing with the bath at $-150°$C, where the thermostat tank walls lay somewhere between $-150°$ and $-190°$C. It is both cheap and readily available, and solves the previous difficulty.

Experimental Results

The data are given in Table I, and are plotted in Figs. 1 and 2. The individual curves are referred to by their approximate bath temperature. The last temperature and pressure readings in a table are, respectively, the bath temperature and the inlet high pressure. The temperatures are all in the hydrogen centigrade scale, and the pressures in atmospheres absolute.

Where it seemed advisable, the data were taken in duplicate and are distinguished by the plotting symbols. When a plug had been shown to be reliable by the test of duplication, a group of runs were made without further duplication; and if the points fell well on a smooth curve and the curves made an accordant family, the data were considered satisfactory.

In Fig. 1, the isenthalpic curves above 75°C are plotted to twice the temperature scale used for those below 75°C. The original large plot was cut across the middle to form Figs. 1 and 2. The pressure scale is alike for all the curves but the temperature scale is broken so as to crowd the curves together. The data for the vapor pressure curve are taken from the *International Critical Tables.* The vapor pressure points are not shown in Fig. 2. Many of the runs were followed down the vapor pressure curve and a few of the readings are plotted. The points belonging to the isenthalps entering from the vapor side coincide with the vapor pressure curve within the expected error of experiment. The points belonging to the isenthalps entering from the liquid side fall within a narrow band below the vapor pressure curve, their variations exceeding the expected error. This may be simply the lowering of the boiling point due to volatile impurity in the argon, probably the known impurity nitrogen.

The isenthalpic curves entering on the liquid side were followed as close to the vapor pressure curve as feasible, in order to determine whether the isenthalp bends more markedly just before it enters. The curves in Fig. 2 show very little evidence of any such change of curvature on either side of the vapor pressure curve. (Compare

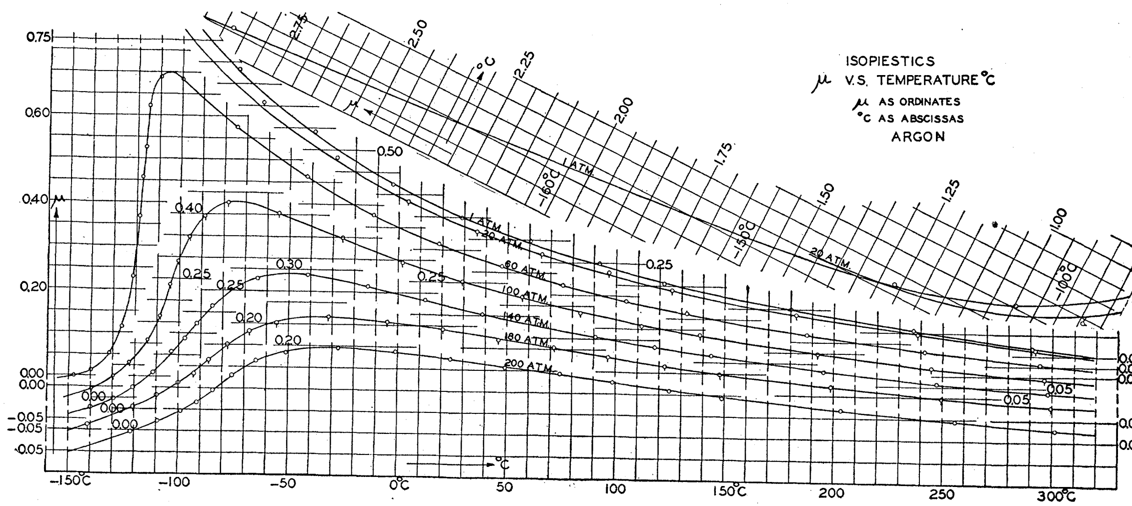

FIG. 4. μ as function of t at constant pressure.

air[2] and carbon dioxide.[5]) This means, for example, that the specific heats of liquid and vapor show no unusual feature on approaching the vapor pressure curve.

The general picture presented by these isenthalpic curves and the curves of Figs. 3 and 4 is exceedingly like that for air[1, 2] and increases one's confidence in the applicability of the theorem of corresponding states to the Joule-Thomson effect. Systematic differences have already appeared, but these are surprisingly small.

Inversion Curve, $\mu=0$

The lower branch of the inversion curve falls within the range of our lowest temperature in Fig. 2. The data for it are collected in Table II.

TABLE II. *Data for the inversion curve.* $\mu=0$.

From Fig. 3		From Fig. 4	
p	$-t$	p	$-t$
250	109	200	119.6
191	119.8	180	122.6
139	129.5	140	128.3
91	139.6	100	137.6
50	148.0	60	146.2

The points in Fig. 2 marked by two concentric circles were read from the curves of Fig. 3. The points marked by a cross inscribed in a circle were read from the curves of Fig. 4. The best curve through these points is a straight line cutting the vapor pressure curve with a marked positive slope. There is no evidence of any sudden bending. The general trend of the curve for air is very similar. The differences of slope and curvature may easily fall within the experimental error.

It is unfortunate that the apparatus would not permit temperatures sufficiently high (estimated 375° to 450°C) to measure the upper branch of the inversion curve. In Fig. 4 the curves approach the axis at the high pressure end, but their slight slope and remaining curvature make extrapolation impracticable.

Joule-Thomson Coefficient, $\mu=(dt/dp)_h$

As in the previous papers,[1, 2] the numerical values of μ are obtained by taking the ratio of successive differences of temperature and of pressure for each run. These values of μ are plotted against the average value of the pressures to give the set of isenthalpic curves of Fig. 3. To avoid crossing and confusion these curves are plotted in three groups. Each curve was obtained from the original isenthalp designated by the same approximate bath temperature.

From these curves the values of μ for a series of selected values of pressure were picked off, and the temperatures corresponding to each

[5] Burnett, Phys. Rev. **22**, 590 (1923) (short article); also Bull. Univ. Wis., Vol. 9, No. 6 (extended article).

TABLE III. *Final values of μ from Fig. 4.*

t \ p	1	20	60	100	140	180	200
300°C	0.0620	0.0580	0.0522	0.0445	0.0375	0.0319	0.0280
250	0.0948	0.0884	0.0770	0.0649	0.0552	0.0477	0.0475
200	0.1330	0.1235	0.1080	0.0935	0.0802	0.0714	0.0680
150	0.1777	0.1655	0.1458	0.1275	0.1115	0.0975	0.0965
125	0.2035	0.1905	0.1677	0.1478	0.1290	0.1126	0.1100
100	0.2340	0.2180	0.1927	0.1715	0.1480	0.1312	0.1260
75	0.2690	0.2530	0.2235	0.1975	0.1678	0.1515	0.1417
50	0.3115	0.2935	0.2597	0.2265	0.1920	0.1704	0.1575
25	0.3590	0.3392	0.3000	0.2585	0.2177	0.1886	0.1728
0	0.4170	0.3440	0.3498	0.2995	0.2475	0.2048	0.1871
− 25	0.4890	0.4630	0.4120	0.3460	0.2750	0.2155	0.1967
− 50	0.5765	0.5450	0.4878	0.3934	0.2900	0.2110	0.1877
− 75	0.6847	0.6450	0.5767	0.4285	0.2528	0.1577	0.1312
− 87.5	0.7525	0.7060	0.6275	0.4020	0.1970	0.1085	0.0818
−100	0.8335	0.7780	0.6840	0.2970	0.1227	0.0592	0.0425
−112.5	0.9345	0.8765	0.6675	0.1225	0.0544	0.0230	0.0130
−125	1.0765	1.0155	0.1277	0.0430	0.0077	−0.0058	−0.0110
−137.5	1.2930	1.2875	0.0185	0.0000	−0.0195	−0.0315	−0.0330
−150	1.7503		−0.0040	−0.0238	−0.0390	−0.0540	−0.0550
−160	2.315						
−170°C	3.015						

pressure obtained from the isenthalpic curves of Figs. 1 and 2. These values of μ and t are plotted in Fig. 4 as isopiestics. Since the value of μ in part of the field changes very slowly, it is necessary to shift these curves apart. The scale for each curve is indicated. μ goes up so rapidly for the 1 and 20 atm. isopiestics that the part of the diagram below −50°C has been cut off and shifted into the space above the main family of curves. The largest value of μ is here almost 3°C per atm., and the observed maximum drop of temperature across the plug approached 120°C. The greatest uncertainty in these values of μ occurs in this unsaturated vapor region both on account of the rapid variation of μ and the difficulty arising from the clogging. Clogging was troublesome only over the low pressure part of the isenthalps 0, −25, −50, and −65°C of Fig. 2. In the rest of the field the points fall with excellent precision upon the curves in both Figs. 3 and 4.

Table III was obtained by reading from the curves of Fig. 4, before the fine penciled lines were inked, the values of μ for a set of selected temperatures and pressures.

SPECIFIC HEAT, C_p

The data on the specific heat of argon are very limited. Heuse[6] measured it over the range 90–300°K. Over this range C_p falls linearly by 5 percent. There appear to be no measurements above room temperature. This prevents the calculation of the group of thermodynamic coefficients such as given in the air and helium papers. It is hoped that someone will find occasion to measure the temperature variation of the specific heat of argon and other gases in the near future.

It is a pleasure to acknowledge our indebtedness to the Wisconsin Alumni Research Foundation for financial assistance providing for relief from teaching and for adequate assistance.

It is a pleasure also to record our thanks to the General Electric Company who through Mr. B. L. Benbow of the Cleveland Wire Works supplied the argon necessary for these measurements.

[6] Heuse, Ann. d. Physik **59**, 86 (1919).