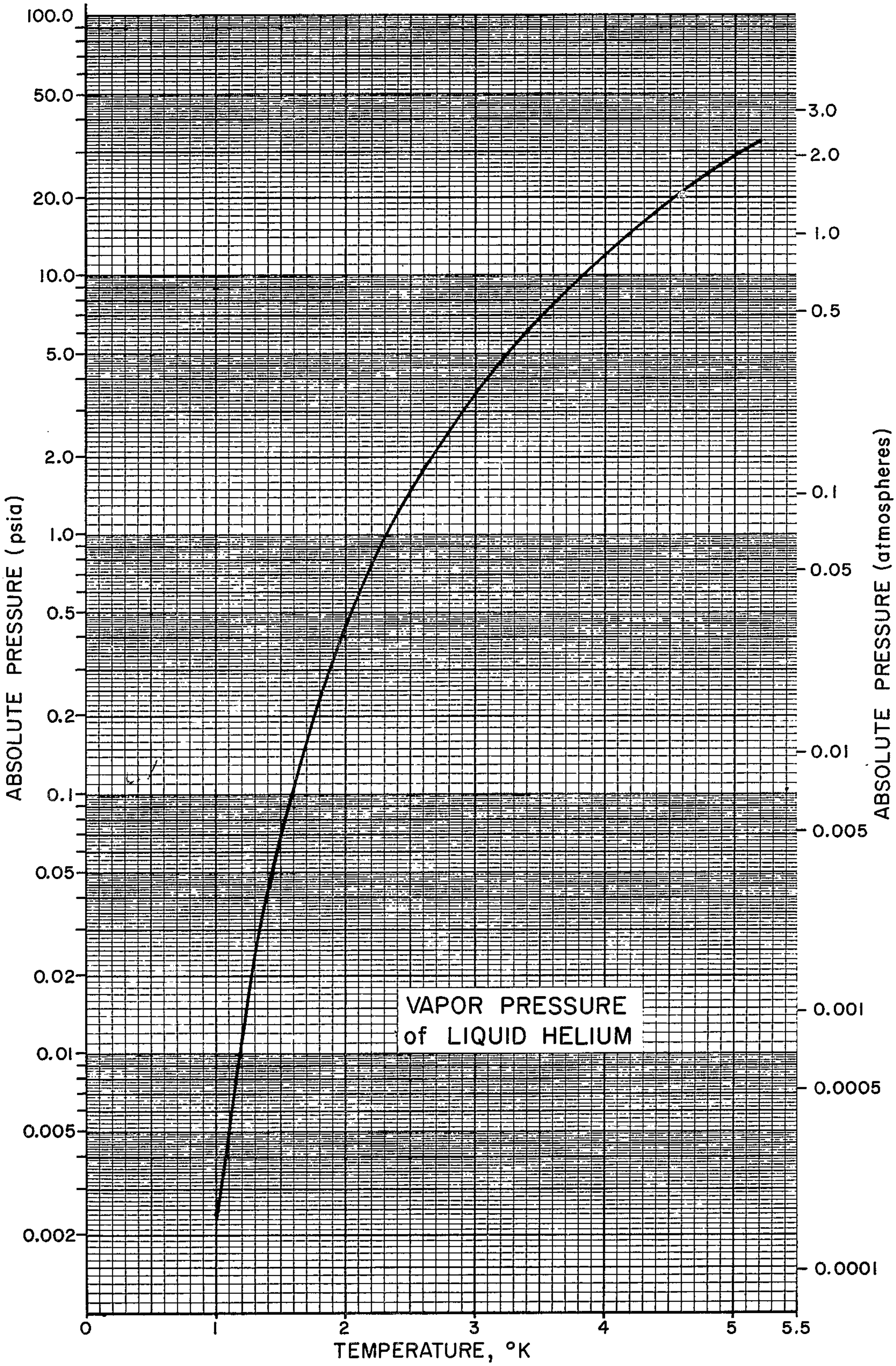
II. PROPERTIES OF HELIUM

CONTENTS


VAPOR PRESSURE
of LIQUID HELIUM
ABSOLUTE PRESSURE (psia)
ABSOLUTE PRESSURE (atmospheres)
TEMPERATURE, °K
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
3.0
2.0
1.0
0.5
0.1
0.05
0.01
0.005
0.001
0.0005
0.0001
0
1
2
3
4
5
5.5

VAPOR PRESSURE of LIQUID HELIUM

Source of Data:

Clement, J. R., et al., Phys. Rev. 100, 743-4 (Oct. 1955)

Other References:

Berman, R. and Swenson, C. A., Phys. Rev. 95, No. 2, 311-14 (July 1954)

Erickson, R. A. and Roberts, L. D., Phys. Rev. 93, 957-62 (Mar. 1954)

Gratch, S., Trans. ASME 70, 631-40 (Aug. 1948)

Van Dijk, H. and Durieux, M., Progress in Low Temperature Physics, Vol. II, North Holland Publishing Co., Amsterdam, The Netherlands, (1957) 480 pp.

Van Dijk, H. and Shoenberg, D., Nature, 164, 151 (July 1949)

Worley, R. D., Zemansky, M. W. and Broose, H. A., Phys. Rev. 93, No. 1, (Jan. 1954)

Comments:

The Absolute temperature scale (0°C = 273.16°K) was used in the table of selected values below.

Temp.		Pressure		Temp.		Pressure	
°K	°R	mm Hg	lb/in^2	°K	°R	mm Hg	lb/in^2
1	1.8	0.12	0.002 31	3.2	5.76	243	4.68
1.2	2.16	0.62	0.011 9	3.4	6.12	316	6.09
1.4	2.52	2.1	0.040 4	3.6	6.48	402	7.74
1.6	2.88	5.7	0.101	3.8	6.74	503	9.68
1.8	3.24	12.5	0.241	4.0	7.2	619	11.9
2.0	3.6	23.8	0.458	4.2	7.56	753	14.5
2.2	3.96	41.	0.790	4.4	7.82	900	17.3
2.4	4.32	64.	1.23	4.6	8.28	1080	20.8
2.6	4.68	94.	1.81	4.8	8.64	1270	24.5
2.8	5.04	134	2.58	5.0	9.00	1490	28.7
3.0	5.40	183	3.53	5.2	9.36	1720	33.1

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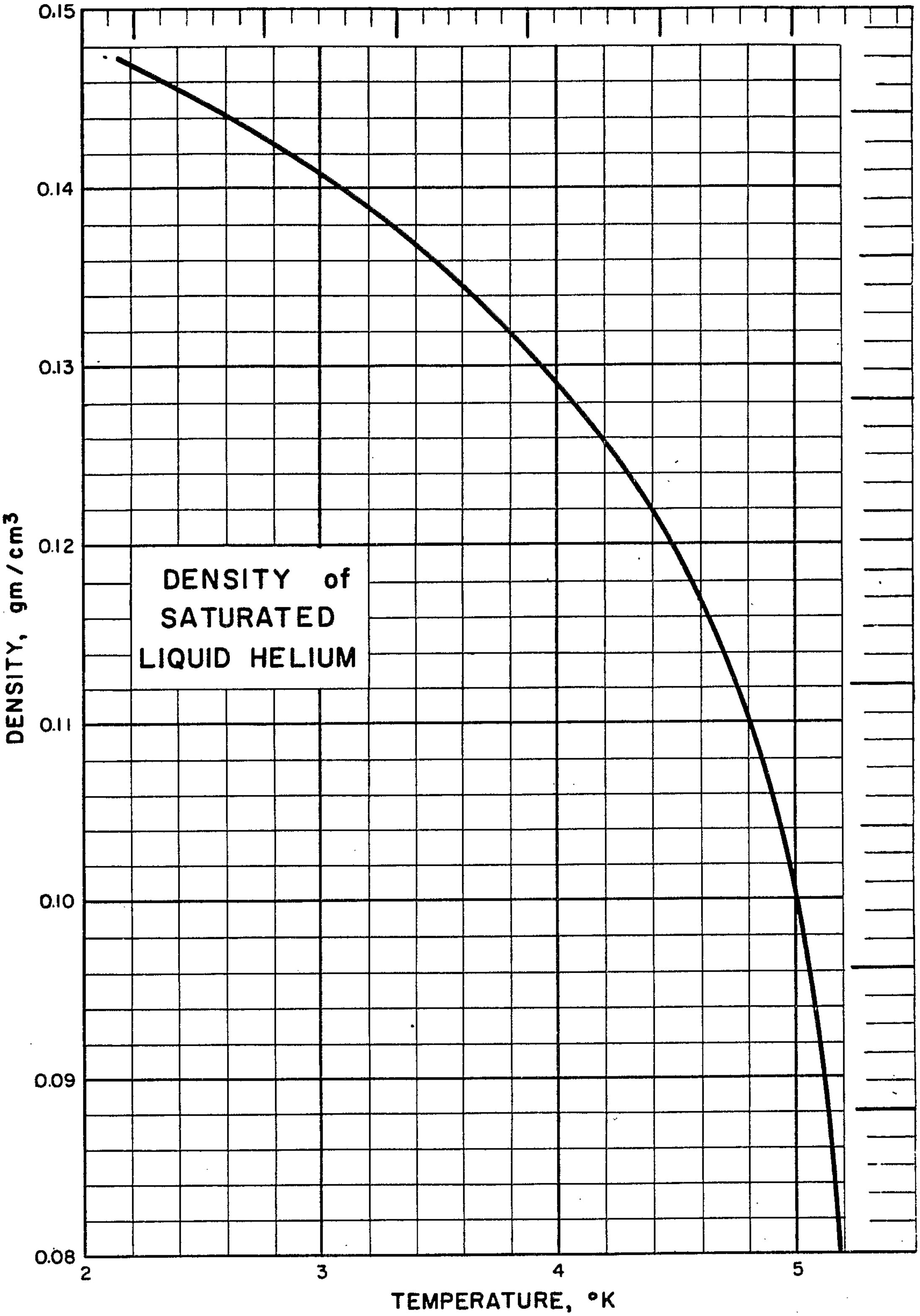

DENSITY of
SATURATED
LIQUID HELIUM
DENSITY, gm/cm3
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
2
3
4
5
TEMPERATURE, °K

DENSITY of LIQUID HELIUM

(At Saturation)

Source of Data:

Berman, R. and Mate, C. F., Phil. Mag. (8) 3, 461-69 (May 1958)

Other References:

Kerr, E. C., J. Chem. Phys. 26, 511-14 (Mar. 1957)

Ham, N. S., Roy. Australian Chem. Inst. J. & Proc. 17, 273-83 (July 1950)

Keller, W. E., Phys. Rev. 97, No. 1, 1-8 (Jan. 1955)

Dash, J. G. and Taylor, R. D., Phys. Rev. 107, No. 5, 1228-1237 (Sept. 1957)

Borelius, G., Arkiv. Fysik, Band 13, No. 29, 369-378 (Jan. 1958)

Keesom, W. H., Helium, Elsevier, Amsterdam, (1942) p. 494

Temp. °K	Density $\frac{gm}{cm^3}$	Temp. °K	Density $\frac{gm}{cm^3}$
2.2	0.147	3.8	0.132
2.3	0.146	4.00	0.129
2.4	0.146	4.2	0.125
2.6	0.144	4.4	0.122
2.8	0.143	4.6	0.117
3.00	0.141	4.8	0.111
3.2	0.139	5.0	0.101
3.4	0.137	5.15	0.087
3.6	0.134	5.18	0.079

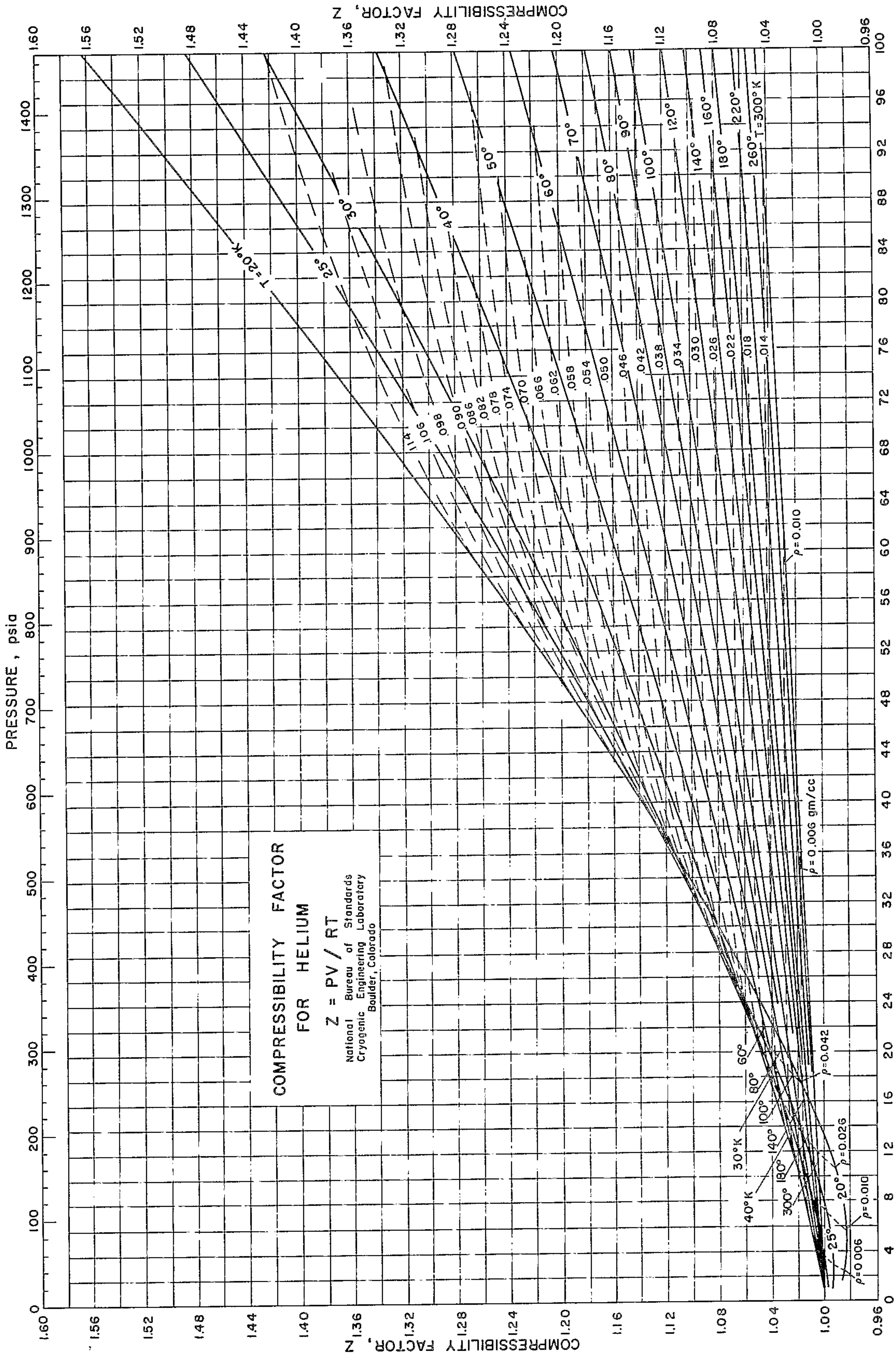
Reprinted from WADD TECH. REPORT 60-56

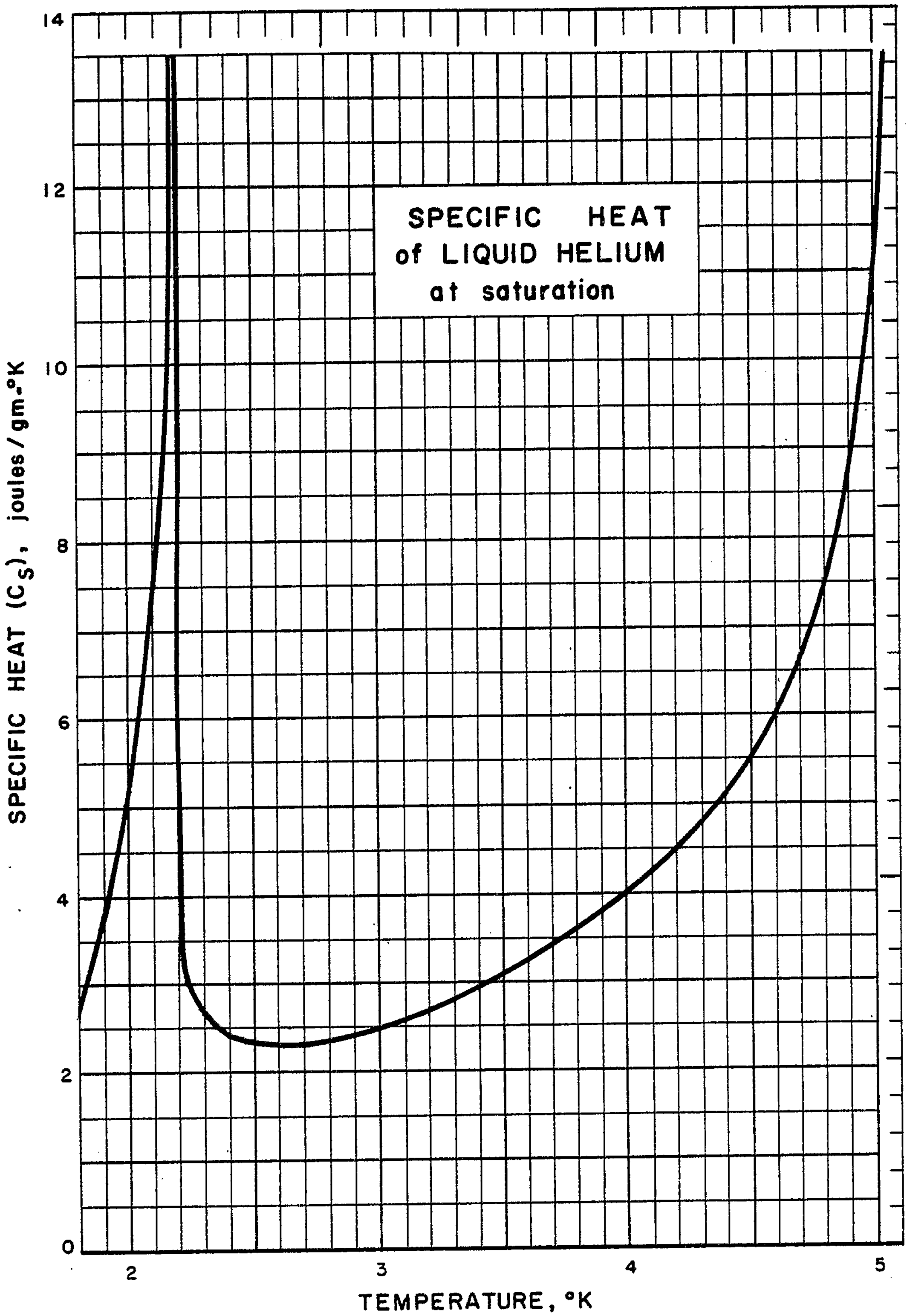
COMPRESSIBILITY FACTOR for HELIUM

[P = Pressure, (atm); Z = Compressibility Factor]

Density gm/cc		Temperature, °K 20	25	30	40	50	60	70	80	90	100	120	140	160	180	220	260	300		Density gm/cc
.0002	P																1.067	1.231	P	.0002
	Z																1.001	1.001	Z	
.0004	P												1.149	1.314	1.478	1.806	2.135	2.463	P	.0004
	Z												1.001	1.001	1.001	1.001	1.001	1.001	Z	
.0010	P					1.026	1.232	1.438	1.644	1.850	2.056	2.467	2.879	3.290	3.701	4.523	5.346	6.168	P	.0010
	Z					1.001	1.002	1.002	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	Z	
.0012	P					1.232	1.480	1.727	1.974	2.221	2.468	2.962	3.456	3.950	4.444	5.431	6.419	7.406	P	.0012
	Z					1.001	1.002	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	Z	
.0014	P				1.149	1.438	1.727	2.016	2.304	2.593	2.881	3.458	4.034	4.611	5.187	6.340	7.493	8.645	P	.0014
	Z				1.000	1.002	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	1.004	Z	
.0016	P				1.313	1.644	1.974	2.305	2.635	2.965	3.295	3.954	4.613	5.273	5.932	7.250	8.568	9.886	P	.0016
	Z				1.001	1.002	1.003	1.004	1.004	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	Z	
.0018	P			1.104	1.477	1.850	2.222	2.594	2.966	3.337	3.709	4.451	5.193	5.935	6.677	8.161	9.644	11.13	P	.0018
	Z			.9975	1.001	1.003	1.004	1.004	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	Z	
.0020	P		1.020	1.227	1.642	2.056	2.470	2.884	3.297	3.710	4.123	4.948	5.773	6.598	7.423	9.073	10.72	12.37	P	.0020
	Z		.9948	.9975	1.001	1.003	1.004	1.005	1.005	1.005	1.006	1.006	1.006	1.006	1.006	1.006	1.006	1.006	Z	
.0040	P	1.619	2.037	2.455	3.292	4.129	4.964	5.798	6.630	7.461	8.292	9.953	11.61	13.27	14.93	18.25	21.57	24.89	P	.0040
	Z	.9872	.9933	.9978	1.004	1.007	1.009	1.010	1.011	1.011	1.011	1.011	1.011	1.011	1.011	1.012	1.012	1.012	Z	
.0060	P	2.423	3.055	3.688	4.956	6.221	7.484	8.743	10.00	11.26	12.51	15.02	17.52	20.02	22.53	27.53	32.54	37.55	P	.0060
	Z	.9848	.9932	.9993	1.007	1.011	1.014	1.015	1.016	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.017	1.018	Z	
.0080	P	3.226	4.075	4.928	6.633	8.335	10.03	11.72	13.41	15.09	16.78	20.14	23.50	26.86	30.21	36.93	43.65	50.37	P	.0080
	Z	.9835	.9939	1.001	1.011	1.016	1.019	1.021	1.022	1.023	1.023	1.023	1.023	1.023	1.023	1.023	1.024	1.024	Z	
.0100	P	4.031	5.101	6.175	8.326	10.47	12.61	14.74	16.86	18.98	21.09	25.32	29.55	33.77	37.99	46.44	54.89	63.34	P	.0100
	Z	.9829	.9952	1.004	1.015	1.021	1.025	1.027	1.028	1.028	1.029	1.029	1.029	1.029	1.029	1.030	1.030	1.030	Z	
.0120	P	4.837	6.132	7.432	10.04	12.63	15.21	17.78	20.35	22.91	25.46	30.57	35.67	40.77	45.87	56.07	66.27	76.48	P	.0120
	Z	.9829	.9969	1.007	1.020	1.027	1.031	1.033	1.034	1.035	1.035	1.035	1.036	1.036	1.036	1.036	1.036	1.036	Z	
.0140	P	5.645	7.169	8.700	11.76	14.81	17.85	20.87	23.88	26.89	29.89	35.88	41.86	47.85	53.84	65.82	77.80	89.79	P	.0140
	Z	.9834	.9991	1.010	1.025	1.032	1.036	1.039	1.040	1.041	1.041	1.042	1.042	1.042	1.042	1.042	1.043	1.043	Z	
.0160	P	6.458	8.214	9.979	13.51	17.02	20.52	23.99	27.46	30.91	34.36	41.25	48.14	55.03	61.91	75.70	89.49		P	.0160
	Z	.9843	1.002	1.014	1.030	1.038	1.042	1.045	1.046	1.047	1.048	1.048	1.048	1.048	1.049	1.049	1.049		Z	
.0180	P	7.274	9.266	11.27	15.27	19.26	23.22	27.15	31.08	34.99	38.89	46.70	54.49	62.29	70.09	85.70			P	.0180
	Z	.9855	1.004	1.018	1.035	1.044	1.049	1.051	1.053	1.053	1.054	1.054	1.055	1.055	1.055	1.056			Z	
.0200	P	8.095	10.33	12.57	17.06	21.52	25.95	30.36	34.74	39.12	43.48	52.21	60.93	69.65	78.38	95.84			P	.020
	Z	.9870	1.007	1.022	1.040	1.050	1.055	1.058	1.059	1.060	1.060	1.061	1.061	1.062	1.062	1.062			Z	
.0240	P	9.751	12.48	15.22	20.69	26.13	31.52	36.88	42.21	47.53	52.84	63.45	74.06	84.67	95.29				P	.0240
	Z	.9909	1.014	1.031	1.051	1.062	1.068	1.071	1.072	1.073	1.074	1.075	1.075	1.075	1.076				Z	
.0280	P	11.43	14.67	17.92	24.41	30.85	37.24	43.57	49.88	56.17	62.45	74.99	87.54						P	.0280
	Z	.9957	1.022	1.040	1.063	1.075	1.081	1.084	1.086	1.087	1.088	1.089	1.089						Z	
.0320	P	13.14	16.90	20.68	28.23	35.70	43.10	50.45	57.75	65.04	72.31	86.85							P	.0320
	Z	1.001	1.030	1.051	1.076	1.088	1.095	1.099	1.100	1.102	1.102	1.103							Z	
.0360	P	14.88	19.18	23.51	32.14	40.68	49.13	57.51	65.84	74.15	82.45	99.05							P	.0360
	Z	1.008	1.039	1.062	1.089	1.102	1.109	1.113	1.115	1.116	1.117	1.118							Z	
.0400	P	16.64	21.51	26.41	36.16	45.80	55.32	64.76	74.15	83.52	92.88								P	.0400
	Z	1.015	1.049	1.073	1.102	1.117	1.124	1.128	1.130	1.132	1.133								Z	
.0440	P	18.45	23.90	29.38	40.29	51.06	61.69	72.22	82.70	93.16									P	.0440
	Z	1.023	1.060	1.086	1.117	1.132	1.140	1.144	1.146	1.148									Z	
.0480	P	20.29	26.34	32.43	44.54	56.47	68.26	79.93	91.54										P	.0480
	Z	1.031	1.071	1.099	1.132	1.148	1.156	1.160	1.163										Z	
.0520	P	22.17	28.85	35.57	48.91	62.06	75.02	87.85											P	.0520
	Z	1.040	1.082	1.112	1.147	1.164	1.173	1.177											Z	
.0600	P	26.07	34.07	42.10	58.07	73.73	89.16												P	.0600
	Z	1.060	1.108	1.141	1.180	1.199	1.208												Z	
.0700	P	31.22	41.01	50.86	70.34	89.40													P	.0700
	Z	1.088	1.143	1.181	1.225	1.246													Z	
.0800	P	36.73	48.51	60.34	83.66														P	.0800
	Z	1.120	1.183	1.226	1.275														Z	
.0900	P	42.66	56.65	70.66	98.21														P	.0900
	Z	1.156	1.228	1.276	1.331														Z	
.1000	P	49.10	65.52	81.96															P	.1000
	Z	1.198	1.278	1.333															Z	
.1100	P	56.12	75.28	94.42															P	.1100
	Z	1.244	1.335	1.396															Z	
.1200	P	63.84	86.08																P	.1200
	Z	1.297	1.400																Z	
.1300	P	72.38	98.13																P	.1300
	Z	1.358	1.473																Z	
.1400	P	81.93																	P	.1400
	Z	1.427																	Z	
.1500	P	92.72																	P	.1500
	Z	1.508																	Z	

Reprinted from: "Compressibility Factor for Helium", Data Sheet 11.001 in A Compendium of the Properties of Materials at Low Temperature (Phase II) by the National Bureau of Standards, Cryogenic Engineering Laboratory, R. B. Stewart and V. J. Johnson, General Editors; Wright Air Development Division, U. S. A. F., WADD Technical Report 60-56


COMPRESSIBILITY FACTOR
FOR HELIUM
Z = PV / RT
National Bureau of Standards
Cryogenic Engineering Laboratory
Boulder, Colorado
PRESSURE , psia
PRESSURE , atmospheres
COMPRESSIBILITY FACTOR, Z


SPECIFIC HEAT
of LIQUID HELIUM
at saturation
SPECIFIC HEAT (C_S), joules / gm-°K
TEMPERATURE, °K
0
2
4
6
8
10
12
14
2
3
4
5

SPECIFIC HEAT of LIQUID HELIUM
(At Saturation)

Source of Data:

Hill, R. W. and Lounasmaa, O. V., Phil. Mag. (8) 2, 143-48 (Feb. 1957)

Other References:

Wiebes, C. G., Niels-Hakkenberg, C. G. and Kramers, H. C., Physica 23, 625-32 (1957)

Markham, A. H., Thesis submitted for Degree of Doctor of Philisophy, Univ. Wisconsin (1958)

Kramers, H. J., Wassches, J. D. and Gorter, C., Physica 18, No. 5, 329-38 (1952)

Keesom, W. H., Helium, Elsevier, Amsterdam (1942)

Comments:

The absolute temperature scale (0°C = 273.16°K = 491.69°R) was used in the Table of Selected Values below.

Temperature		Specific Heat (C_s)		Temperature		Specific Heat (C_s)	
°K	°R	Joules/gm °K	BTU/lb °R	°K	°R	Joules/gm °K	BTU/lb °R
1.8	3.24	2.81	0.672	3.0	5.40	2.49	0.595
1.85	3.33	3.26	0.779	3.2	5.76	2.69	0.643
1.9	3.42	3.79	0.906	3.4	6.12	2.97	0.710
2.0	3.60	5.18	1.24	3.6	6.48	3.26	0.779
2.05	3.69	6.16	1.47	3.8	6.84	3.60	0.860
2.10	3.78	7.51	1.80	4.0	7.2	3.99	0.953
2.15	3.87	9.35	2.23	4.2	7.56	4.48	1.07
2.1735	3.91	12.6	3.01	4.4	7.92	5.11	1.22
2.2	3.96	3.98	0.951	4.6	8.28	5.94	1.42
2.3	4.14	2.64	0.631	4.8	8.64	7.53	1.80
2.4	4.32	2.38	0.569	5.0	9.00	11.5	2.75
2.6	4.68	2.27	0.542	5.05	9.09	13.5	3.23
2.8	5.04	2.34	0.559				

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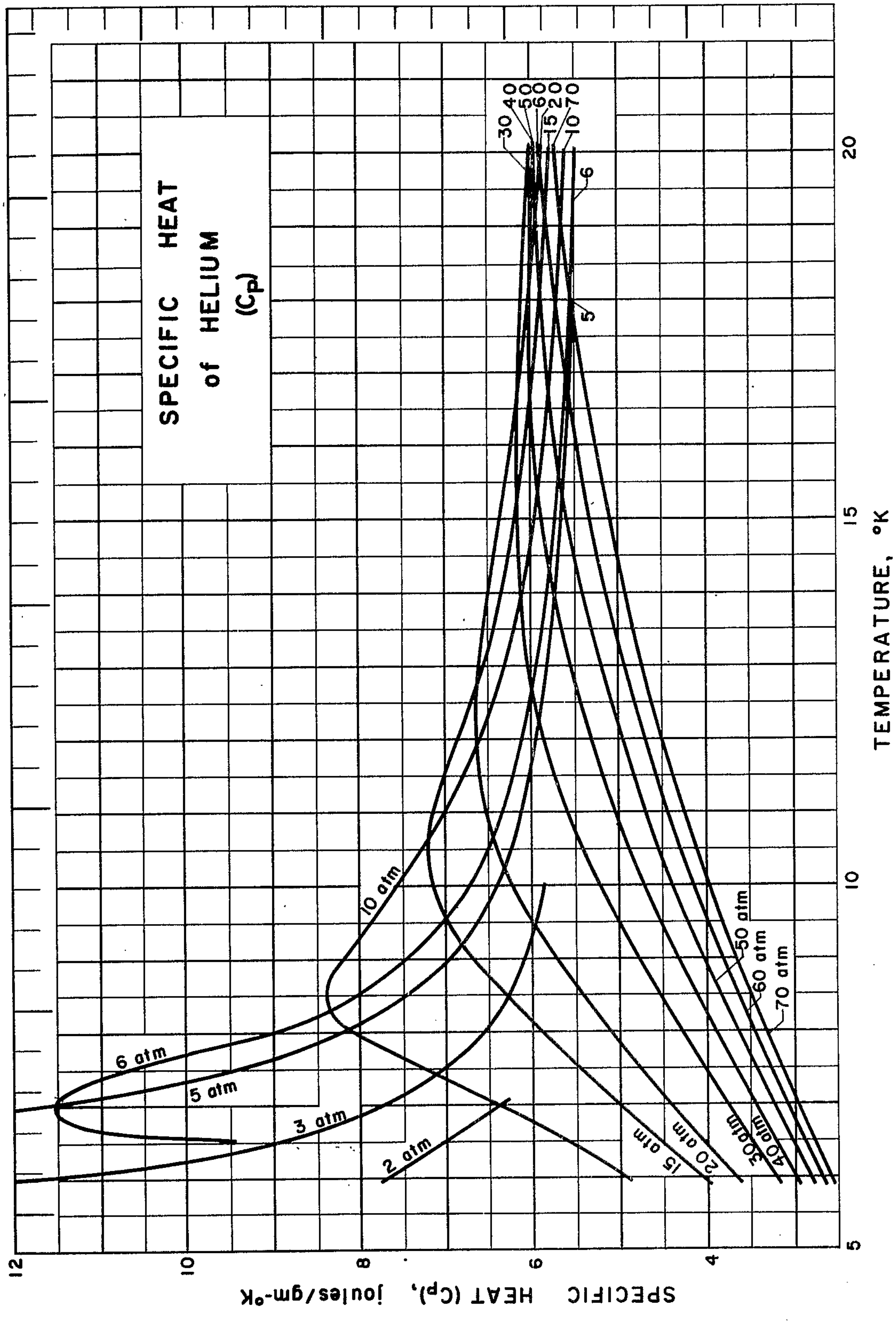

SPECIFIC HEAT
of HELIUM
(C_p)
TEMPERATURE, °K
SPECIFIC HEAT (C_p), joules/gm-°K
2 atm
3 atm
5 atm
6 atm
10 atm
15 atm
20 atm
30 atm
40 atm
50 atm
60 atm
70 atm

SPECIFIC HEAT (C_p) of HELIUM

Source of Data:

Lounasmaa, O. V., Thesis submitted for the Degree of Doctor of Philosopy, University of Oxford 1958.

Other References:

Itterbeck, A. Van, Bull. Inst. Intern. Froid, Annexe, 1955-2, 99-106 (1955);

Masi, J. F., Trans. ASME 76, No. 7, 1067-74 (Oct. 1954);

Akin, S. W., Trans. ASME 72, 751-57 (Aug. 1950);

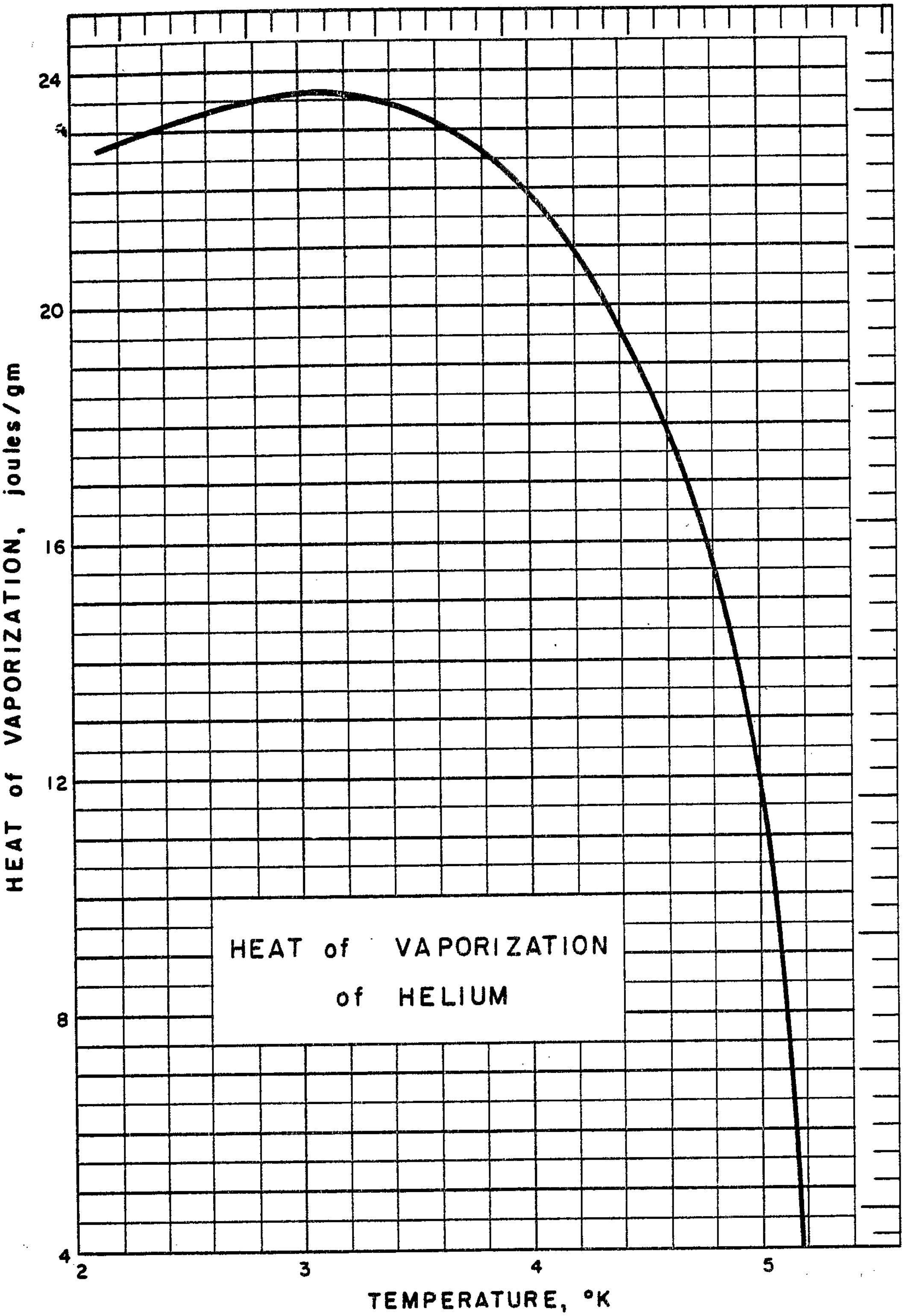
Zelmanov, J., Journal of Phys. (USSR) 3, No. 1, 43-52 (1940);

Zelmanov, J., Journal of Phys. (USSR) 8, No. 3, 129-134 (1944).
Keesom, W. H., Helium, Elsevier, Amsterdam (1942) pp494

Specific Heat at Constant Pressure, cal/gm-°K

Temp. °K	3 atm	5 atm	6 atm	10 atm	15 atm	30 atm	50 atm	70 atm
6	2.91			1.18	0.97	0.77	0.67	0.615
6.5	2.14	3.40	2.25	1.35	1.09			
7	1.84	2.83	2.84	1.53	1.20	0.90	0.74	0.71
8	1.55	1.96	2.17	1.93	1.41	1.02	0.87	0.79
9	1.46	1.67	1.78	1.96	1.60	1.14	0.91	0.87
10	1.40	1.53	1.61	1.81	1.71	1.25	1.05	0.95
12		1.42	1.46	1.59	1.64	1.40	1.18	1.08
14		1.37	1.39	1.47	1.52	1.47	1.28	1.18
16		1.34	1.35	1.40	1.45	1.48	1.37	1.22
18		1.32	1.33	1.36	1.41	1.46	1.41	1.32
20			1.31	1.34	1.38	1.44	1.43	1.37

Reprinted from WADD TECH. REPORT 60-56


HEAT of VAPORIZATION of HELIUM
HEAT of VAPORIZATION, joules/gm
24
20
16
12
8
4
2
3
4
5
TEMPERATURE, °K

HEAT of VAPORIZATION of HELIUM

Source of Data:

Berman, R. and Mate, C. R., Phil. Mag. (8) 3, 461-69 (May 1958)

Other References:

Dranen, J. Van, J. Chem. Phys. 23, 213 (Jan. 1955)

Keesom, W. H., Helium, Elsevier, Amsterdam (1942)

Rosenbaum, B. and Atkins, R., Bull. Am. Phys. Soc. 1, 218 (1956)

Van Dijk, H. and Durieux, M., Progress in Low Temperature Physics, Vol. II, North Holland Publishing Co., Amsterdam, The Netherlands (1957) 480 pp.

Comments:

The Absolute temperature scale (0°C = 273.16°K) was used in the table of selected values below.

Temp. °K	H_V Joules/gm	Temp. °K	H_V Joules/gm
2.20	22.8	4.00	21.9
2.40	23.1	4.20	20.9
2.60	23.3	4.40	19.7
2.80	23.5	4.60	18.0
3.00	23.7	4.80	15.6
3.20	23.6	5.00	12.0
3.40	23.5	5.10	8.99
3.60	23.2	5.15	6.70
3.80	22.7	5.18	4.00

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HELIUM

Properties of Saturated Liquid and Saturated Vapor*

Temp	Pressure	Volume (cm³/g)		Enthalpy (j/g)		Entropy (j/g °K)		Temp	Pressure	Volume (cm³/g)		Enthalpy (j/g)		Entropy (j/g °K)	
°K	atm	Sat Liquid	Sat Vapor	Sat Liquid	Sat Vapor	Sat Liquid	Sat Vapor	°K	atm	Sat Liquid	Sat Vapor	Sat Liquid	Sat Vapor	Sat Liquid	Sat Vapor
3.0	0.241	7.085	224.1	5.30	28.96	2.356	10.247	4.0	0.814	7.779	73.86	8.81	30.72	3.255	8.736
3.2	0.320	7.185	174.8	5.85	29.48	2.527	9.911	4.2	0.990	7.989	60.61	9.85	30.79	3.460	8.443
3.4	0.416	7.303	138.7	6.47	29.93	2.690	9.606	4.4	1.190	8.231	49.80	10.96	30.65	3.674	8.150
3.6	0.529	7.439	111.5	7.18	30.34	2.883	9.322	4.6	1.417	8.547	40.72	12.33	30.32	3.920	7.845
3.8	0.661	7.597	90.50	7.93	30.59	3.059	9.021	4.8	1.672	9.033	32.87	13.88	29.49	4.188	7.473
								5.0	1.959	9.940	25.67	16.00	28.02	4.598	7.000

* From published data in National Bureau of Standards, Technical Note No. 154 (Jan 1962)

Properties of Liquid and Vapor*

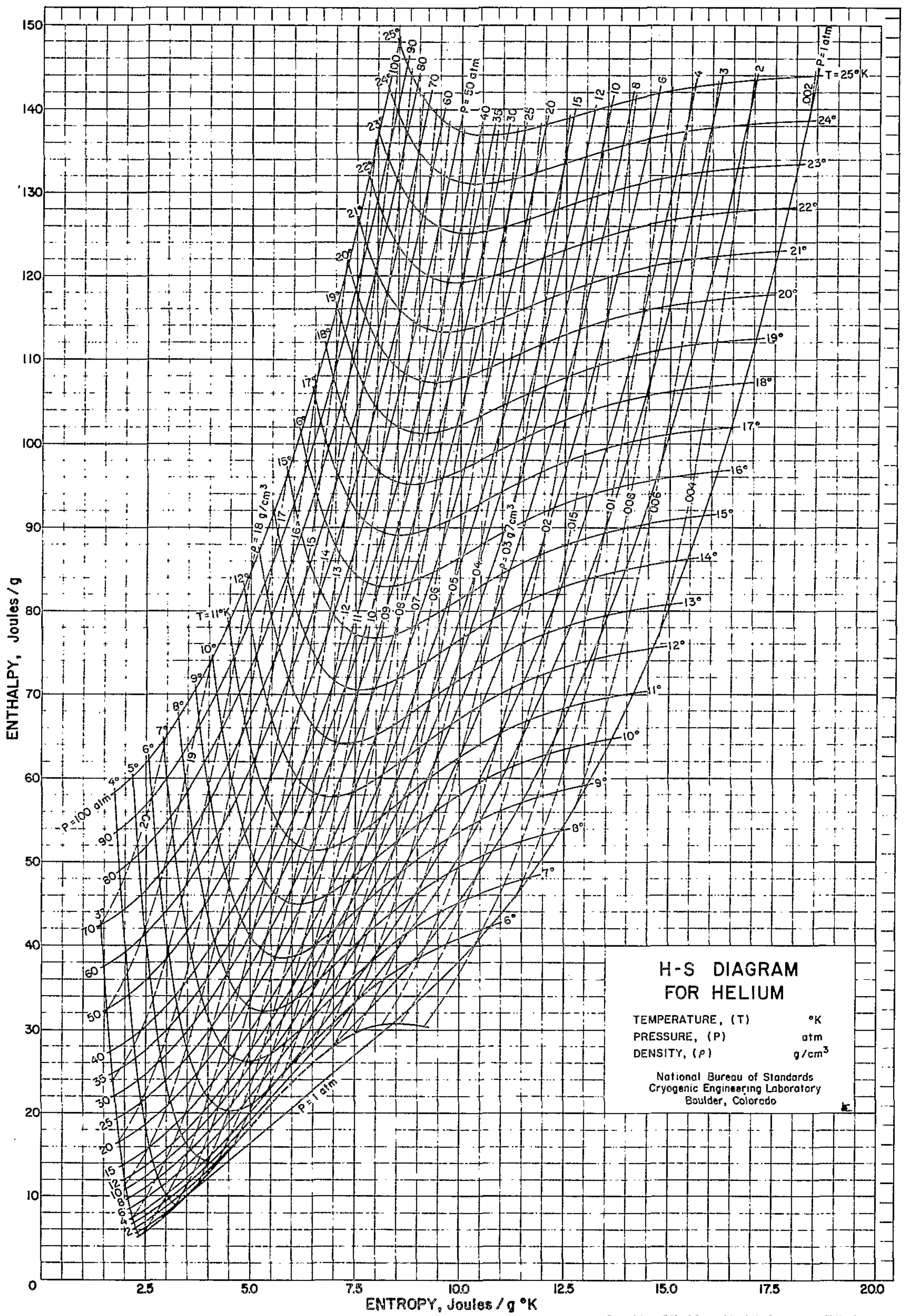
Temp °K	P = 0.5 atm (Sat temp = 3.56°K)			P = 1 atm (Sat temp = 4.21°K)			P = 2 atm (Sat temp = 5.03°K)			P = 5 atm			P = 10 atm		
T	v cm³/g	h j/g	s j/g°K	v cm³/g	h j/g	s j/g°K	v cm³/g	h j/g	s j/g°K	v cm³/g	h j/g	s j/g°K	v cm³/g	h j/g	s j/g°K
(Sat Liq)	7.41	7.0	2.84	8.01	10.0	3.47	10.18	16.5	4.67						
(Sat Vapor)	117.6	30.2	9.38	59.83	30.9	8.43	24.33	27.7	6.90						
3	7.06	5.5	2.34	6.99	5.7	2.32	6.87	6.3	2.28	6.60	8.1	2.17	6.30	10.9	2.05
4	140.1	32.9	10.12	7.70	8.9	3.23	7.45	9.3	3.14	6.99	10.7	2.94	6.56	13.3	2.74
5	186.3	38.6	11.39	82.88	36.2	9.61	9.36	15.9	4.55	7.71	14.5	3.82	6.96	16.5	3.47
6	231.4	44.1	12.38	108.1	42.3	10.76	45.83	38.2	8.90	9.59	21.2	5.02	7.61	20.7	4.24
8	318.3	55.0	13.95	154.3	53.8	12.41	72.35	51.3	10.78	23.74	43.3	8.24	10.64	33.7	6.08
10	304.1	65.7	15.14	198.1	64.8	13.64	95.82	62.9	12.09	35.01	57.6	9.84	16.09	50.1	7.92
15	611.7	92.0	17.27	304.3	91.5	15.81	150.7	90.5	14.32	58.89	87.5	12.28	28.88	83.5	10.64
20	818.5	118.2	18.78	408.6	117.8	17.32	203.7	117.1	15.86	80.39	115.3	13.88	40.44	112.7	12.33
25	1025	144.2	19.94	512.2	144.0	18.49	256.0	143.5	17.04	102.4	142.3	15.08	51.50	140.5	13.57
30	1230	170.3	20.89	615.4	170.1	19.44	307.9	169.8	17.99	123.6	168.9	16.06	62.31	167.7	14.56
40	1641	222.3	22.39	821.3	222.2	20.94	411.3	222.1	19.50	165.4	221.7	17.57	83.54	221.3	16.10
60	2462	326.2	24.49	1232	326.3	23.05	617.2	326.3	21.61	248.3	326.4	19.70	125.3	326.8	18.24
80	3283	430.1	25.99	1643	430.2	24.55	822.7	430.3	23.11	330.7	430.7	21.20	166.7	431.5	19.75
100	4103	534.0	27.15	2053	534.1	25.71	1028	534.3	24.27	413.0	534.9	22.36	208.0	535.8	20.91
120	4923	637.9	28.09	2463	638.0	26.65	1233	638.2	25.21	495.1	638.9	23.31	249.2	640.0	21.86
140	5743	741.7	28.90	2873	741.9	27.46	1438	742.1	26.01	577.3	742.9	24.11	290.3	744.1	22.67
180	7383	949.4	30.20	3693	949.6	28.76	1848	949.9	27.32	741.4	950.7	25.42	372.5	952.2	23.97
220	9024	1157.2	31.24	4514	1157.3	29.80	2259	1157.6	28.36	905.6	1158.5	26.46	454.6	1160.1	25.02
260	10664	1364.9	32.11	5334	1365.0	30.67	2669	1365.3	29.23	1070	1366.3	27.33	536.6	1367.9	25.89
300	12304	1572.6	32.85	6154	1572.7	31.41	3079	1573.1	29.97	1234	1574.1	28.07	618.7	1575.7	26.63

Temp °K	P = 20 atm			P = 40 atm			P = 60 atm			P = 80 atm			P = 100 atm		
3	5.90	16.6	1.88	5.42	27.4	1.66	5.12	37.5	1.50						
4	6.06	18.7	2.49	5.52	29.2	2.20	5.20	39.2	2.01	4.96	48.9	1.86	4.78	58.3	1.74
5	6.28	21.3	3.11	5.65	31.4	2.73	5.28	41.3	2.49	5.03	50.9	2.32	4.84	60.2	2.18
6	6.59	24.6	3.70	5.80	34.1	3.21	5.39	43.7	2.93	5.11	53.1	2.72	4.91	62.3	2.56
8	7.56	33.1	4.91	6.22	40.6	4.15	5.66	49.5	3.75	5.32	58.4	3.48	5.07	67.3	3.28
10	9.13	45.0	6.24	6.79	49.7	5.15	6.01	57.5	4.65	5.57	65.9	4.32	5.27	74.4	4.07
15	14.80	78.3	8.94	8.86	77.5	7.40	7.20	82.4	6.66	6.40	89.2	6.19	5.90	96.6	5.86
20	20.70	109.2	10.72	11.49	107.4	9.12	8.73	110.2	8.25	7.45	115.3	7.69	6.69	121.6	7.29
25	26.39	138.2	12.02	14.28	136.9	10.43	10.47	138.9	9.53	8.66	142.8	8.92	7.61	148.0	8.47
30	31.94	166.2	13.04	17.07	165.7	11.48	12.29	167.5	10.58	9.96	170.9	9.94	8.61	175.4	9.47
40	42.76	220.9	14.61	22.57	221.7	13.10	15.94	223.9	12.20	12.67	227.1	11.56	10.73	231.0	11.07
60	63.92	327.6	16.78	33.31	330.2	15.30	23.16	333.5	14.42	18.10	337.2	13.80	15.07	341.3	13.31
80	84.78	433.0	18.30	43.86	436.7	16.83	30.24	440.7	15.97	23.44	445.1	15.35	19.36	449.6	14.87
100	105.5	537.9	19.47	54.30	542.2	18.01	37.25	546.9	17.15	28.73	551.7	16.54	23.61	556.7	16.06
120	126.2	642.4	20.42	64.69	647.3	18.96	44.21	652.3	18.11	33.97	657.6	17.50	27.82	662.8	17.03
140	146.8	746.7	21.22	75.05	752.0	19.77	51.14	757.4	18.92	39.19	762.9	18.31	32.01	768.5	17.84
180	188.0	955.1	22.53	95.70	960.9	21.08	64.95	966.9	20.24	49.57	972.8	19.63	40.34	978.8	[illegible]
220	229.1	1163.2	23.58	116.3	1169.4	22.13	78.71	1175.7	21.28	59.92	1182.0	20.68	48.63	1188.3	20.22
260	270.1	1371.2	24.44	136.9	1377.7	23.00	92.45	1384.2	22.16	70.24	1390.8	21.55	56.90	1397.3	[illegible]
300	311.2	1579.1	25.19	157.4	1585.8	23.75	106.2	1592.6	22.90	80.54	1599.3	22.30	65.16	1606.0	21.84

* From published data, National Bureau of Standards, Technical Note 154 (Jan 1962)
Bold horizontal line indicates phase change (liquid above, vapor below the line).

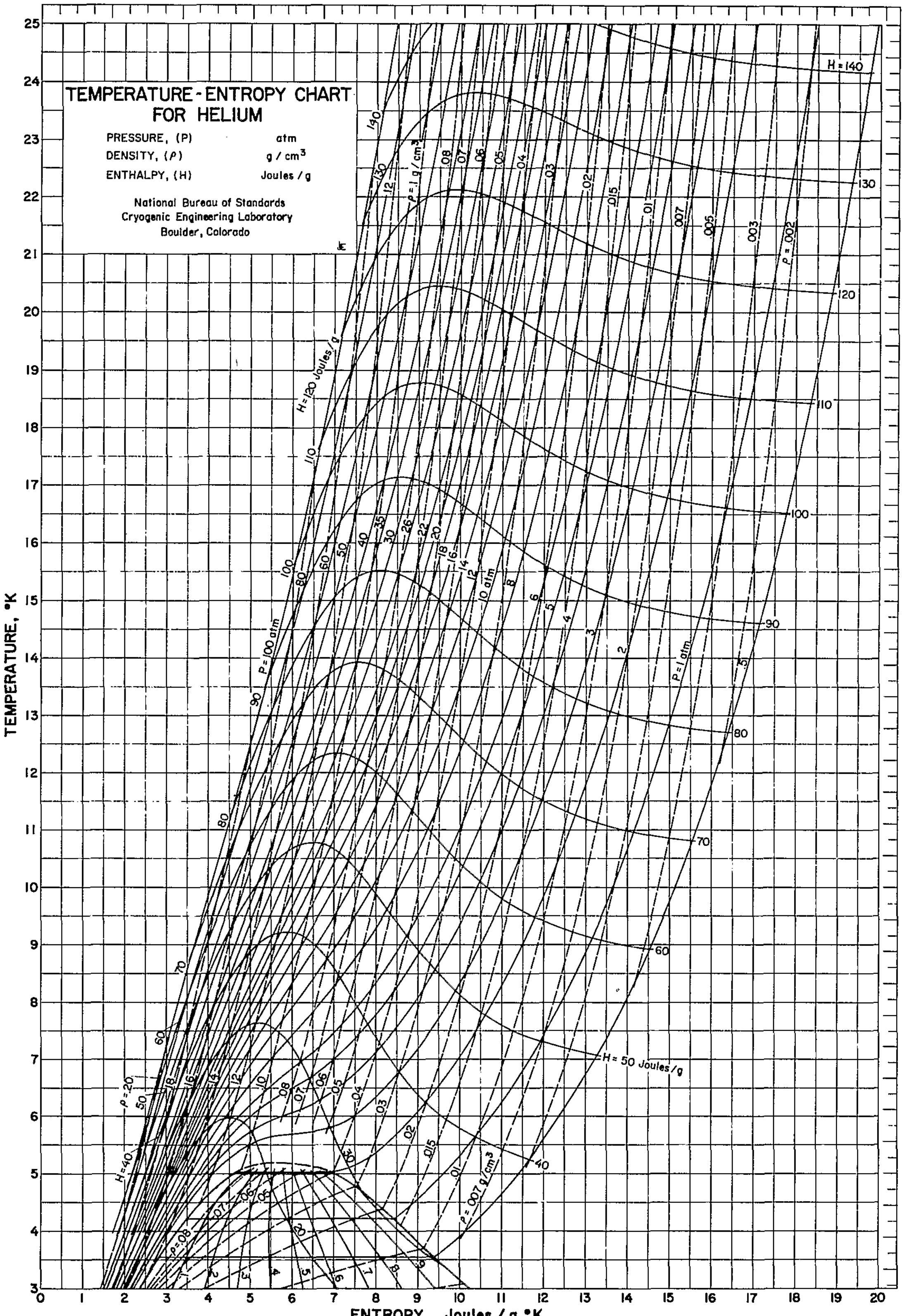
Conversions for Units, to Equivalent in British System of Units:

To convert temperature in degrees Kelvin (°K) to degrees Rankine (°R), multiply (°K) by 1.8
To convert pressure in atmospheres (atm) to (psia), multiply (atm) by 14.696
To convert volume (v) in cubic centimeters per gram (cm³/g) to (cu ft/lb), multiply (cm³/g) by .016018
To convert enthalpy (h) in joules per gram (j/g) to (Btu/lb), multiply (j/g) by .42993
To convert entropy (s) in joules per gram °K (j/g°K) to (Btu/lb°R), multiply (j/g°K) by .23885



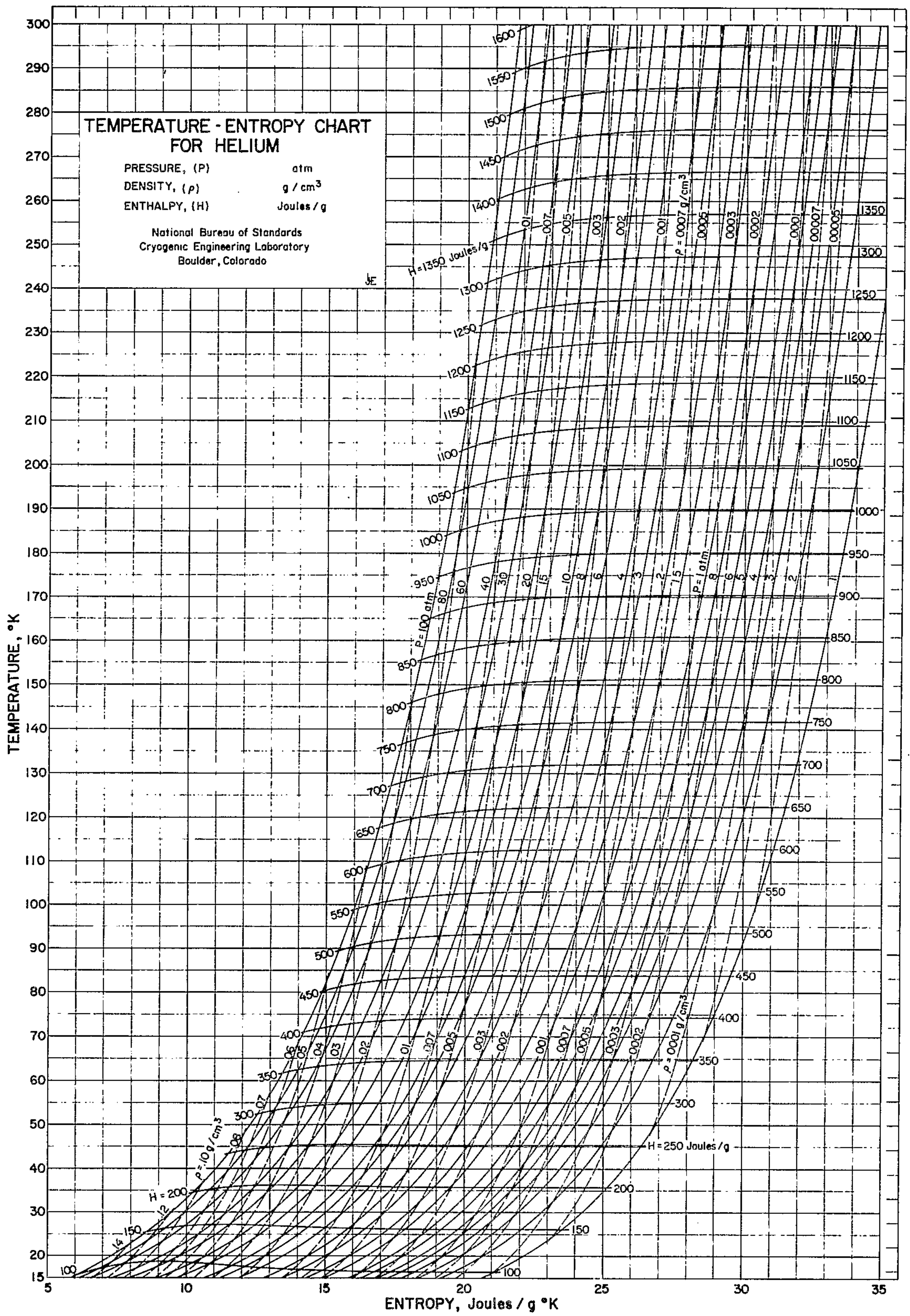
Prepared from: National Bureau of Standards, Technical Note, TN 154, January 19[illegible], "The Thermodynamic Properties of Helium from [illegible] to [illegible] between [illegible] and [illegible] Atmospheres", Douglas B. Mann, [illegible] Data Center, National Bureau of Standards, Boulder, [illegible]

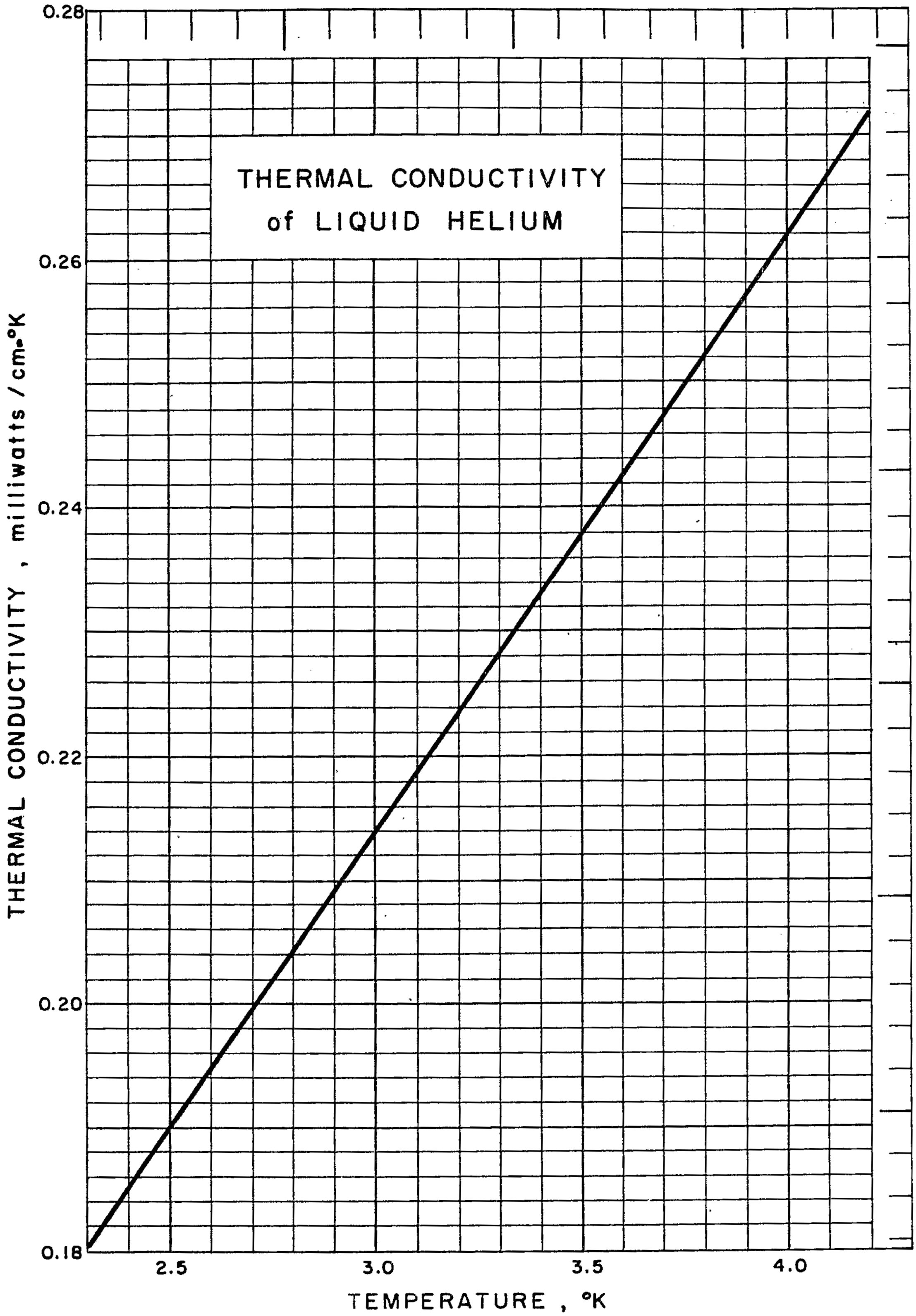
[illegible] D. McCarty, [illegible] (January [illegible])



Prepared from: National Bureau of Standards, Technical Note, TN [illegible] January [illegible], "The Thermodynamic Properties of Helium from [illegible] to [illegible]°K between [illegible] and [illegible] Atmospheres", Douglas B. Mann: by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado.

D. D. McCarty, L. J. Ericks (January [illegible])


TEMPERATURE - ENTROPY CHART
FOR HELIUM
PRESSURE, (P) atm
DENSITY, (ρ) g / cm3
ENTHALPY, (H) Joules / g
National Bureau of Standards
Cryogenic Engineering Laboratory
Boulder, Colorado
TEMPERATURE, °K
ENTROPY, Joules / g °K
H = 1350 Joules / g
P = 100 atm
P = 1 atm
P = 0007 g/cm3
P = 0001 g/cm3
P = .10 g/cm3
H = 250 Joules / g
H = 200


THERMAL CONDUCTIVITY
of LIQUID HELIUM
THERMAL CONDUCTIVITY , milliwatts / cm-°K
0.28
0.26
0.24
0.22
0.20
0.18
2.5
3.0
3.5
4.0
TEMPERATURE , °K

THERMAL CONDUCTIVITY of LIQUID HELIUM
(at Saturation)

Source of Data:

Grenier, C., Phys. Rev. 83, No. 3, 589-603 (1951)

Other References:

Bowers, I. R., Proc. Phys. Soc. (London) A65, 511-18 (1952)

Brewer, D. F. and Edwards, D. O., Proc. Phys. Soc. (London) 71, 117-125 (1958)

Fairbank, H. A. and Wilks, J., Phys. Rev. 95, 277-8 (July 1954)

Comments:

The thermal conductivity is a linear function of temperature between 2.5° and 4.5°K.

The Absolute Temperature Scale (0°C = 273.16°K = 491.56°R) was used in the table of selected values below.

Temperature		Thermal Conductivity	
°K	°R	milliwatts / cm-°K	BTU / ft hr°R
2.3	4.14	0.181	0.010 45
2.4	4.32	.185	.010 65
2.6	4.68	.195	.011 25
2.8	5.04	.205	.011 81
3.0	5.4	.214	.012 35
3.5	6.3	.238	.013 71
4.0	7.2	.262	.015 1
4.2	7.56	.271	.015 65

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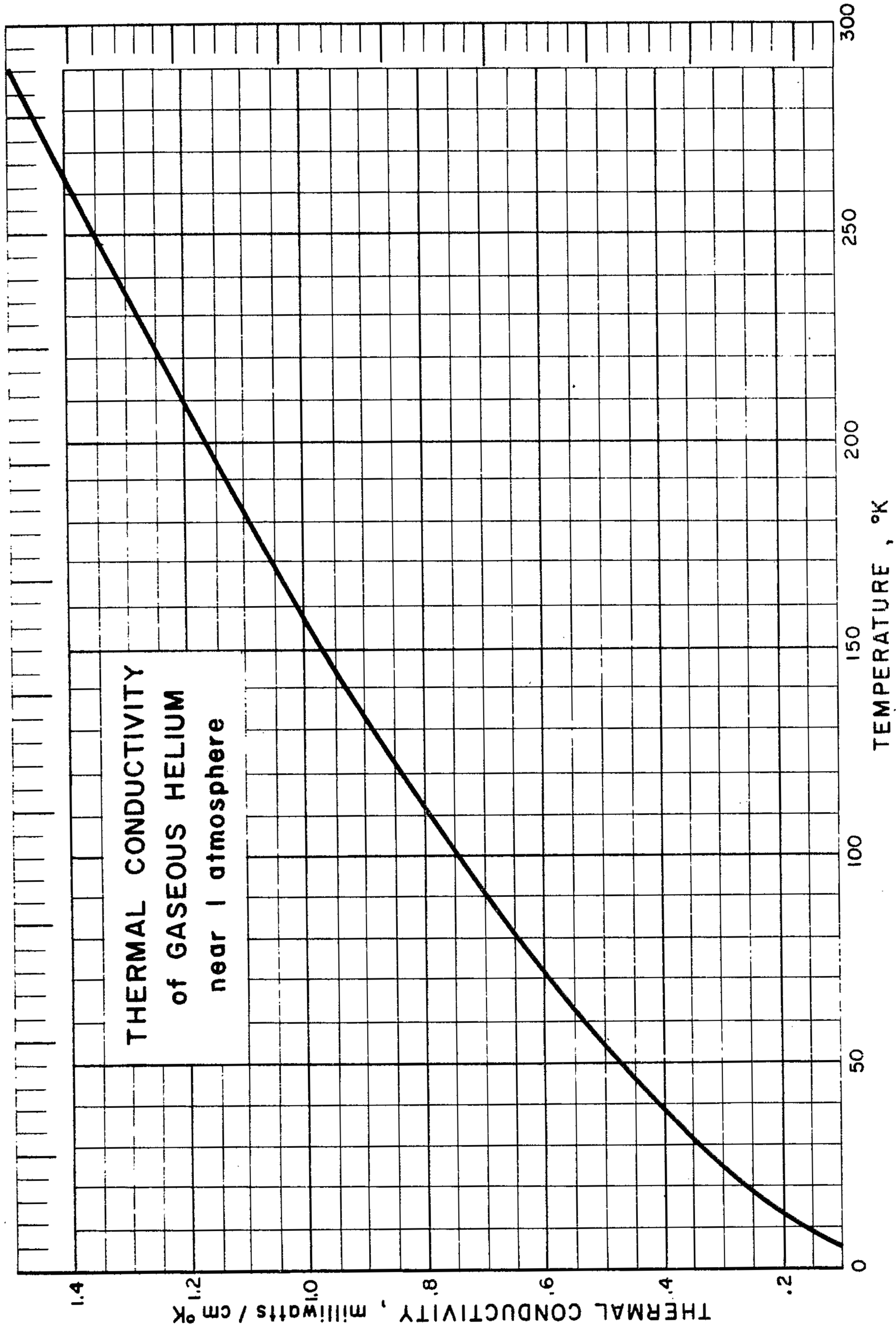
THERMAL CONDUCTIVITY
of GASEOUS HELIUM
near 1 atmosphere
TEMPERATURE , °K
0
50
100
150
200
250
300
THERMAL CONDUCTIVITY , milliwatts / cm °K
.2
.4
.6
.8
1.0
1.2
1.4

THERMAL CONDUCTIVITY of GASEOUS HELIUM

(Near One Atmosphere)

Source of Data:

Akin, S. W., Trans. ASME 72, 751-57 (Aug. 1950)

Other References:

Amdur, I., J. Chem. Phys. 15, No. 7, 482-85 (July 1947)

Hawkins, G. A., Trans. ASME 70, 655 (1948)

Hilsenrath, J. and Touloukian, Y. S., Trans. ASME 76, No. 6 (Aug. 1954)

Kannuluik, W. G. and Carman, E. H., Proc. Phys. Soc. (London) B65, No. 393, 701-9 (Sept. 1952)

Keyes, F. G., Trans. ASME 73, 589 (July 1951)

Keyes, F. G., Trans. ASME 76, No. 5, 809-16 (July 1954)

Waelbrock, P. Zuckerbrodt, J. Chem. Phys. 28, 523 (1958)

Comments:

The Absolute temperature scale (0°C = 273.16°K = 491.56°R) was used in the table below.

Temperature			Thermal Conductivity	
°K	°R	°F	milliwatts / cm °K	BTU / ft hr °R
5.38	9.69	-450	0.109	0.0063
10.94	19.69	-440	0.183	0.0106
16.49	29.69	-430	0.230	0.0133
22.05	39.69	-420	0.277	0.0160
27.61	49.69	-410	0.322	0.0186
33.16	59.69	-400	0.363	0.0210
88.72	159.69	-300	0.692	0.0400
144.27	259.69	-200	0.95	0.0550
199.83	359.69	-100	1.16	0.0673
255.38	459.69	0	1.37	0.0792
366.49	659.69	200	1.73	0.1000

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DIELECTRIC CONSTANT OF LIQUID HELIUM

Sources of Data:

Wolfke, M.,and Onnes, H. K. (1924), Further Experiments with Liquid Helium. Wolfke on the Dielectric Constant of Liquid Helium., Verslag Gewone Vergader. Afdeel. Natuurk. Ned. Akad. Wetenschap. 33,696-700; Communs. Phys. Lab. Univ. Leiden No. 171b (1924); Proc. Acad. Sci. Amsterdam 27, 621 (1924); C.A. 19, 758 (1925).

Wolfke, M.,and Keesom, W. H. (1927), On the Change of the Dielectric Constant of Liquid Helium with the Temperature. Provisional Measurements., Verslag Gewone Vergader. Afdeel. Natuurk. Ned. Akad. Wetenschap. 36, 1209-17; Communs. Phys. Lab. Univ. Leiden No. 190a (1927); Proc. Acad. Sci. Amsterdam 31, 81-89 (1928); C.A. 22, 1896 (1928).

Wolkfe, M.,and Keesom, W. H. (1928), New Measurements About the Way in which the Dielectric Constant of Liquid Helium Depends on the Temperature., Verslag Gewone Vergader. Afdeel. Natuurk. Ned. Akad. Wetenschap. 37, 533-39; Proc. Acad. Sci. Amsterdam 31, 800-06 (1928); Communs. Phys. Lab. Univ. Leiden No. 192a (1928); C.A. 22, 4348 (1928).

Keesom, W. H. (1942), Helium, Elsevier Publishing Company, Amsterdam, page 322.

Benedicks, C. (1948), On the Nature of "Suprafluid" Helium II., Arkiv. Mat. Astron. Fysik 35A, No. 10, 1-21; C.A. 43, 455 (1949).

Grebenkemper, C. J.,and Hagen, J. P. (1950), The Dielectric Constant of Liquid Helium., Phys. Rev. 80, 89; C.A. 45, 406 (1951).

Maryott, A. A.,and Smith, E. R. (1951), Table of Dielectric Constants of Pure Liquids., Natl. Bur. Standards Circ. No. 514; C.A. 46, 2357 (1952).

Lynch, E. J. (1956), On the Lambda Point in Liquid Helium., Duke University, Master's Thesis.

Chase, C. E., Maxwell, E.,and Millett, W. E. (1961), The Dielectric Constant of Liquid Helium., Physica 27, 1129-45; Maxwell, E., Chase, C. E. and Millett, W. E., (1958), Dielectric Constant of Liquid Helium., Low Temperature Physics and Chemistry, 53-56, Proc. 5th Intern. Conf. held at Madison, Wisc., Aug. 1957; University of Wisconsin Press, Madison, 1958.

Comments:

Wolfke and Onnes determined the dielectric constant of liquid helium at 765 mm and 4.2°K by means of high-frequency oscillations by a method elaborated by Wolfke at the Physical Institute of the Technical High School at Warsaw. They found a value of 1.048 ± 0.001 at 765 mm and 4.2°K.

DIELECTRIC CONSTANT OF LIQUID HELIUM

(cont.)

Wolfke and Keesom report two sets of data on the variation of the dielectric constant with temperature between 1.8 and 4.2°K at pressures between 10 and 760 mm of Hg in what they refer to as provisional measurements. They regarded the second set of measurements as less reliable than the first, but both sets showed a discontinuity at the λ point. In a second paper Wolfke and Keesom report additonal values between 2.0 and 4.2°K at pressures from 20 to 757 mm of Hg.

Wolfke and Keesom made their determinations employing a radio frequency of 500 kc and quote an accuracy of ± 0.001. From optical data they calculate the value of the dielectric constant of liquid helium at the normal boiling point to be 1.0495, differing by only 0.14% from the value of 1.0480 of Wolfke and Onnes.

Keesom in his book Helium, page 323, calculated the value from optical data to be 1.0491, differing by only 0.11% from the value of Wolfke and Onnes. In addition, Keesom states: "As a matter of fact we are now convinced that a jump in the dielectric constant does not exist, but that a discontinuity in the course of the dielectric constant is in fact a discontinuity in the derivative to temperature, just as is the case in the curve of the density."

Commenting on the dielectric constant, Benedicks states: "Due to the ionization admitted, it is natural to expect considerable change of this constant to occur near the lambda point. As a matter of fact, the curve dielectric constant versus temperature is the only one where an actual discontinuity has been supposed to occur in the lambda range - it was actually drawn as if it corresponded to a phase transition. Even if, as Keesom says, a jump in the dielectric constant is now considered not to exist, the change at the lambda point appears to be still more obvious for the dielectric constant than for any other property known."

Grebenkemper and Hagen made measurements of the dielectric constant of liquid helium at a series of temperatures and obtained values between 1.62 and 4.21°K. Their data are consistently higher by 0.1% than those of Wolfke and Keesom.

Maryott and Smith have compiled six values at 1 atmosphere and temperatures from 2.06 to 4.19°K.

Lynch presents dieletric constant data in graphical form for the range 1.75 to 3.25°K. These values are indicated to be in agreement with Wolfke and Keesom's results.

Chase, Maxwell,and Millett quote no numerical data, but a graph of their results illustrates agreement with the curve of Grebenkemper and Hagen down to about 2.6°K but is somewhat higher near and below the lambda point. The difference reaches a maximum of about 0.03% at 1.6°K.

DIELECTRIC CONSTANT OF LIQUID HELIUM

(cont.)

Wolfke and Keesom

1st Set (1927)

Temp. °K	Pressure mm Hg	Dielectric Constant
4.21	766.5	1.0480
2.64	82.9	1.0566
2.55	69.6	1.0576
2.48	60.1	1.0579
2.39	49.8	1.0582
2.28	38.1	1.0590
2.12	25.8	1.0577
1.90	13.8	1.0580

2nd Set (1927)

Temp. °K	Pressure mm Hg	Dielectric Constant
4.19	753.0	1.0480
2.39	748.8	1.0577
2.30	740.1	1.0581
2.26	736.2	1.0582
2.24	734.1	1.0581
2.20	731.1	1.0581
2.19	730.2	1.0579
2.11	724.9	1.0577
2.03	719.9	1.0579
1.80	710.1	1.0576
1.75	708.8	1.0575

(1928)

Temp. °K	Pressure mm Hg	Dielectric Constant
4.19	751.0	1.048
3.57	377.2	1.05179
3.59	387.2	1.05174
3.09	189.6	1.05377
3.58	385.8	1.05165
2.64	83.6	1.05535
3.09	188.9	1.05394
2.311	40.1	1.05579
2.630	82.3	1.05525
2.296	38.8	1.05594
2.288	38.0	1.05583
2.311	40.4	1.05586
2.335	42.5	1.05573
2.282	37.5	1.05580
2.295	38.65	1.05593
2.295	38.66	1.05586
2.279	37.2	1.05585
2.286	37.9	1.05581
2.055	20.7	1.05549
2.276	37.0	1.05584
2.04	20.0	1.05575

Maryott and Smith (1951)

(atmospheric pressure)

Temp. °K	Dielectric Constant
2.06	1.0555
2.30	1.0559
2.63	1.0553
3.09	1.0539
3.58	1.0518
4.19	1.0480

Grebenkemper and Hagen (1950)

(atmospheric pressure)

Temp. °K	Dielectric Constant
4.21	1.0492
3.04	1.0554
2.64	1.0568
2.25	1.0574
2.19	1.0574
1.97	1.0571
1.62	1.0569

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DIELECTRIC CONSTANT OF GASEOUS HELIUM

Sources of Data:

Hochheim, E. (1908), Bestimmung der Dielektrizitatskonstante von Helium. (Determination of the Dielectric Constant of Helium.), Verhandl. deut. physik. Ges. 10, 446; C.A. 2, 3175 (1908).

*Koch, J. (1913), The Dispersion of Gaseous Substances in the Ultraviolet Spectrum., Arkiv Mat. Astron. Fysik 8, No. 20; C.A. 7, 2711 (1913).

*Koch, J. (1913), The Dispersion of Light in Gases in the Ultraviolet Region., Arkiv Mat. Astron. Fysik 9, No. 6; P.A. 17, 233 (1914).

Watson, H. E., Rao, G. G., and Ramaswamy, H. L. (1931), The Dielectric Coefficients of Gases. Part I. The Rare Gases and Hydrogen., Proc. Roy. Soc. (London) 132A, 569-85; C.A. 25, 5320 (1931).

Cuthbertson, C., and Cuthbertson, M. (1932), The Refraction and Dispersion of Neon and Helium., Proc. Roy. Soc. (London) 135A, 40; C.A. 26, 2093 (1932).

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Hector, L. G., and Woernley, D. L. (1946), The Dielectric Constants of Eight Gases., Phys. Rev. 69, 101-5; C.A. 40, 2366 (1946).

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Clay, J., and Van der Maesen, F. (1949), The Absolute Dielectric Constant of Gases at Pressures of 0-80 Atm. at 25°C., Physica 15, 467-80; C.A. 44, 3318 (1950).

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Khaikin, M. S., and Prozorova, L. A. (1952), The Measurement of the Dielectric Constant of Gaseous Helium. (In Russian), Zhur. Eksptl. i Teoret. Fiz. 23, 733-4; C.A. 47, 5196 (1953).

Essen, L. (1953), The Refractive Indices of Water Vapour, Air, Oxygen, Nitrogen, Hydrogen, Deuterium and Helium., Proc. Phys. Soc. (London) 66B, 189-93; C.A. 47, 9083f (1953).

Maryott, A. A., and Buckley, F. (1953), Table of Dielectric Constants and Electric Dipole Moments of Substances in the Gaseous State., Natl. Bur. Standards. Circ. 537; C.A. 47, 10928 (1953).

Oudemans, G. J., and Cole, R. H. (1959), Dielectric Constant and Pair Interactions in Gaseous Helium and Argon., J. Chem. Phys. 31, 843-4; C.A. 54, 5194 (1960).

Johnston, D. R., Oudemans, G. J., and Cole, R. H. (1960), Dielectric Constants of Imperfect Gases. I. Helium, Argon, Nitrogen, and Methane., J. Chem. Phys. 33, 1310-17; C.A. 55, 15032 (1961).

Comments:

Using the electrostatic method, Hochheim in 1908 reported a value of the dielectric constant of gaseous helium of 1.000074 ± 0.000004, very much in line with the best of recent determinations. He stated that the value agreed well with the value calculated from the data of Rayleigh (1.0000842), Ramsay (1.0000724), and Scheel (1.0000662) on the index of refraction (n), using Maxwell's relation $D = n^2$.

Watson et al. measured the dielectric constant by the heterodyne beat method at 25 and -191°C. They report values of 1.0000667 and 1.0000654 for 25°C and 760 mm, determined from measurements at 25 and -191°C respectively. They also report values of 1.0000728 and 1.0000713 for 0°C and 760 mm, determined from measurements at 25 and -191°C respectively. These values are compared with those given by optical methods where the square of the index of refraction at 0°C as measured at infinite wavelength is given as 1.0000696. This value is apparently an average of values as determined by C. and M. Cuthbertson, Scheel, and Siertsema. Van Itterbeek and Spaepen give values at 20.38, 90.22 and 292.3°K.

Hector and Woernley report an average of eleven determinations of 1.0000684±0.0000005 using the heterodyne beat method. This value is reported as at NTP which probably means 0°C and 1 atmosphere.

Cuthbertson and Cuthbertson report an index of refraction which through the Cauchy relation yields a dielectric constant of 1.0000692 at 0°C and 1 atmosphere. The work of Jelatis was concerned mainly with removing the small errors inherent in previous methods of measuring dielectric constants. The helium they used was carefully purified by keeping it in contact with activated charcoal immersed in a bath of liquid nitrogen. He reports a value of 1.0000692 as the average of eight determinations when the charcoal had been freshly activated, 1.0000695 as the average in the case of five determinations using charcoal which had been left standing for several weeks, and finally 1.0000691 as the average of eight determinations using freshly activated charcoal. All the above values are at 0°C and 1 atm. (STP), using the heterodyne beat method.

Miller presents a review of dielectric constant and refractivity data. He includes a compilation of dielectric constant values for 0°C and 1 atmosphere. Because index of refraction data extrapolated to infinite wavelenth are regarded as a more accurate source of dielectric constant values, Miller gives for comparison values of n_∞^2.

Clay and Van der Maesen determined values of the dielectric constants by a heterodyne beat method at 298.15°K and from 0 to 80 atmospheres and report a value for helium of 1.000063 ± 0.000002 at NTP (Probably 25°C and 1 atm).

Birnbaum, Kryder, and Lyons made measurements of the dielectric constant of helium at 9280 Mc by a resonant cavity method and report a value of 1.0000705 ± 0.0000011 for 0°C and 760 mm of Hg.

Khaikin and Prozorova made measurements on gaseous helium at 2.138, 3.454, and 4.120°K by determining the change in resonance frequency at 9500 Mc and report a value of 1.0000690 ± 0.0000003 for 0°C and 1 atmosphere.

Essen reports the index of refraction of gaseous helium at 0°C and 760 mm of Hg as 1.000035. Using the relation $\epsilon = n^2$, we obtain $\epsilon = 1.000070$.

Maryott and Buckley made a critical review of dielectric constants obtained by radio frequency, microwave and optical methods and recalculated by one of two systematic procedures in order to place the work of various experimentors on a more comparable basis than exists in the literature. They recommend a value of 1.0000650 ± 0.0000004 at 20°C and 1 atmosphere.

Johnston et al. indicate graphically the behavior of the Clausius-Mossotti function at 296°K up to a density of 3 moles/liter; but no dielectric constant values are given.

Oudemans and Cole discuss the dielectric constant and pair interactions in gaseous helium and argon as related to the Clausius-Mossotti function. Their results, presented graphically, indicate that the Clausius-Mossotti expression $(\epsilon - 1)/\rho(\epsilon + 2)$ varies linearly from 522 x 10^{-6} liters/mole at zero density and 23.1°C to 520 x 10^{-6} liters/mole at a density of 3.6 moles /liter (100 atmospheres pressure) and 23.1°C.

DIELECTRIC CONSTANT OF GASEOUS HELIUM

(cont.)

Van Itterbeek and Spaepen (1943)		
Temp. °K	Pressure mm Hg	Dielectric Constant
292.3	756	1.000065
292.3	758	1.000076
292.3	762	1.000065
90.22	762	1.000229
90.22	759	1.000240
20.38	763	1.000969
20.38	758	1.000969

Clay and Van der Maesen (1949) (at 298.15°K)	
Pressure atm	Dielectric Constant
5.70	1.000429
16.91	1.001019
24.86	1.001369
33.03	1.001779
39.57	1.002168
49.50	1.002753
60.19	1.003438
64.10	1.003481
65.08	1.003772

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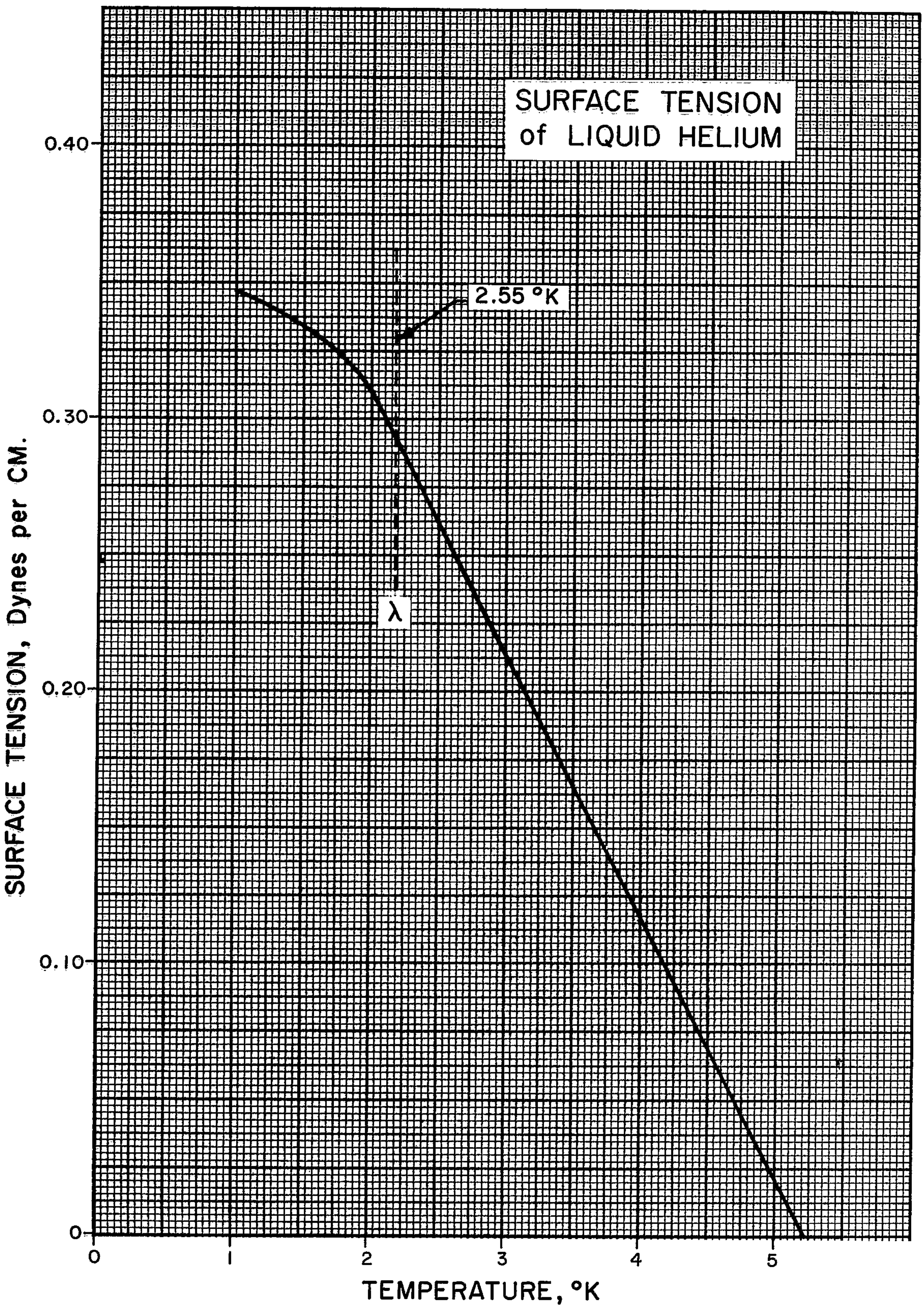

SURFACE TENSION
of LIQUID HELIUM
2.55 °K
λ
0.40
0.30
0.20
0.10
0
SURFACE TENSION, Dynes per CM.
0
1
2
3
4
5
TEMPERATURE, °K

SURFACE TENSION OF LIQUID HELIUM

Source of Data: Van Urk, T.A., Keesom, W.H. and Onnes, H.K., Commun. Phys. Lab. Univ. Leiden No. 179a (1925)

Allen, J.F. and Misener, A.D., Proceedings of the Cambridge Philosophical Society 34, 299 (1938)

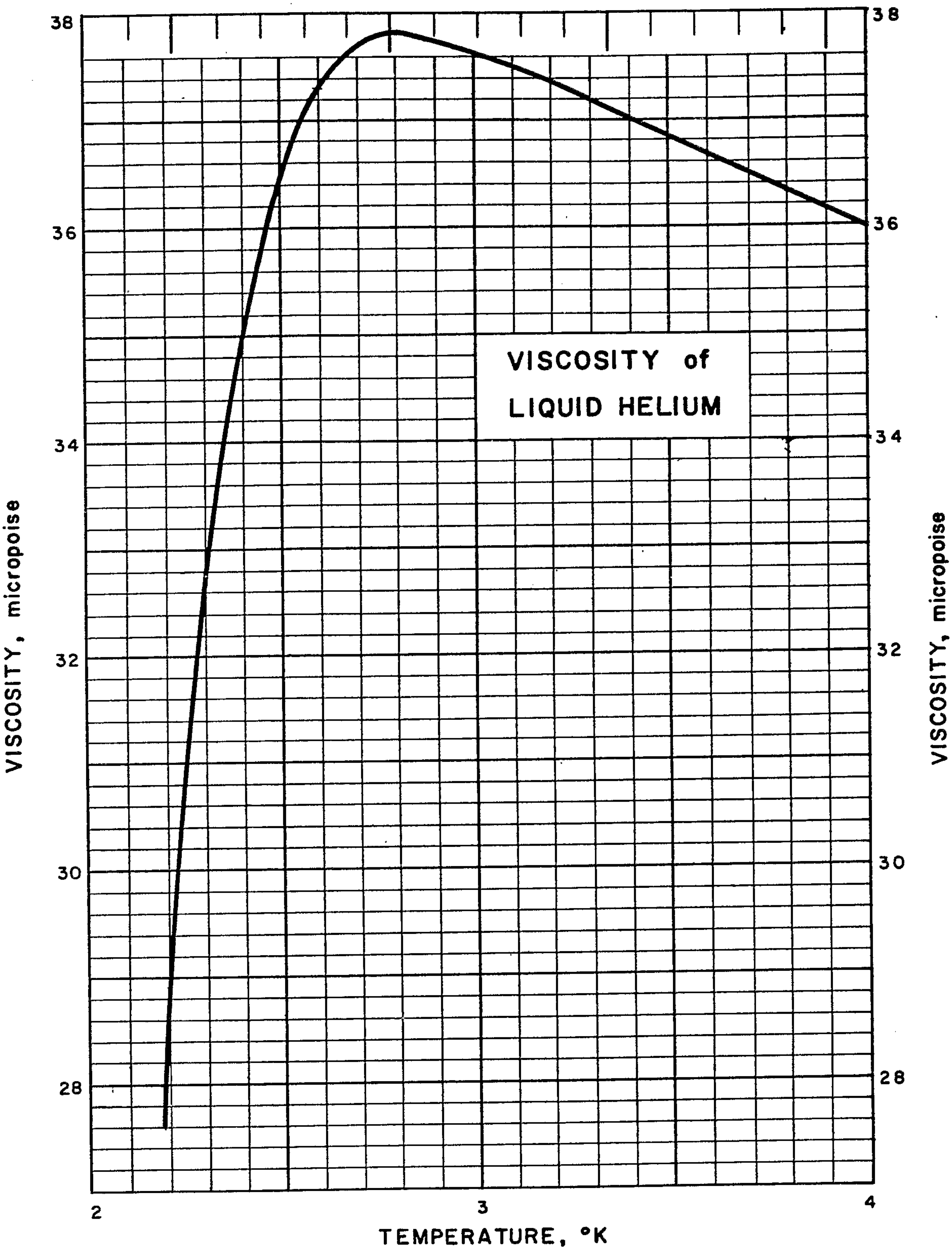
Other References: Keesom, W.H., Helium, Elsevier, Amsterdam (1942) 494 pp.

Atkins, K.R., Can. J. Phys. 31, 1165-69 (1953)

Comments: The absolute temperature scale ($0^{\circ}C = 273.15^{\circ}K$) was used in the table of selected values below. The values in this table are from a smoothed curve down through the data points of the sources.

Temp. $^{\circ}K$	Surface Tension Dynes/cm
1.0	0.347
1.5	0.334
2.0	0.310
2.5	0.264
3.0	0.213
3.5	0.166
4.0	0.116
4.2	0.098
4.5	0.068*
5.0	0.020*
5.2	0.00*

*Extrapolated values


VISCOSITY of
LIQUID HELIUM
VISCOSITY, micropoise
38
36
34
32
30
28
2
3
4
TEMPERATURE, °K

VISCOSITY of LIQUID HELIUM

Source of Data:

Taylor, R. D. and Dash, J. G., Phys. Rev. 106, No. 3, 398-403 (May 1957).

Other References:

Giauque, W. R., et. al., J. Am. Chem. Soc. 61, 654-60 (March 1939)

Woods, A. D. B. and Hollis Hallett, A. C., Can. J. Phys. 36, 253-1125 (1958)

Dash, J. G. and Taylor, R. D., Phys. Rev. 107, No. 5, 1228-1237 (Sept. 1957)

Comments:

The absolute temperature (0°C = 273.16°K) was used in the table of selected values below.

Temp. °K	Viscosity micropoise
2.186 *	27.8
2.2	28.9
2.3	32.6
2.4	35.0
2.6	37.3
2.8	37.8
3.0	37.6
3.2	37.4
3.4	37.0
3.6	36.7
3.8	36.3
4.0	36.0

* λ-Point Transition Temperature

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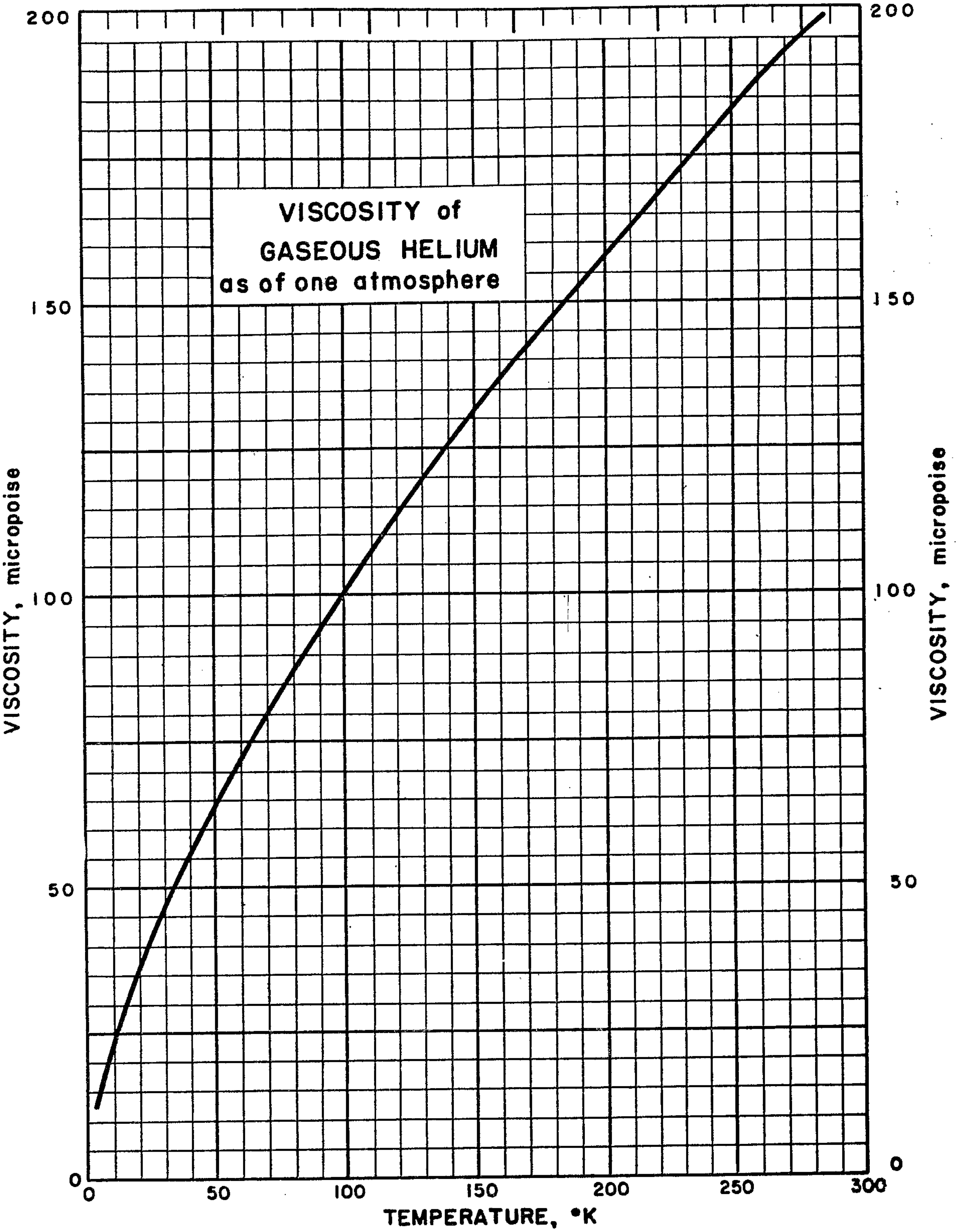
VISCOSITY of
GASEOUS HELIUM
as of one atmosphere
VISCOSITY, micropoise
TEMPERATURE, °K
0
50
100
150
200
250
300

VISCOSITY of GASEOUS HELIUM
(as of 1 atmosphere)

Source of Data:

Akin, S. W., Trans. ASME 72, 751-57 (Aug. 1950)

Other References:

Hawkins, G. A., Trans. ASME 70, 655 (1948)

Hilsenrath, J. and Touloukian, Y. S., Trans. ASME 76, No. 6 (Aug. 1954)

Keller, W. E., Phys. Rev. 105, 41-5 (Jan. 1957)

Keyes, F. G., Trans. ASME 73, 589 (July 1951)

Kestin, J. and Pelarczyk, K., Trans. ASME 76, 987-999 (1954)

Kestin, J. and Wang, H. E., Trans. ASME 80, 11 (1958)

Amdur, I., J. Chem. Phys. 15, No. 7 (July 1947)

Van Itterbeek, F. W., Schapink, G. J., Van den Berg, G. J. and Van Beek, H. J. M., Physica XIX, 1158-1162 (1953)

Comments:

Values for viscosity are given for moderate pressures in the neighborhood of one atmosphere. In this region the viscosity is practically independent of pressure.

The absolute temperature scale (0°C = 273.16°K) was used in the table of selected values below.

Temp. °K	Viscosity micropoise	Temp. °K	Viscosity micropoise
5.5	10.4	125.0	114
10.0	22.3	150.0	128
20.0	35.0	175.0	142
30.0	45.4	200.0	155
40.0	54.8	225.0	166
50.0	63.3	250.0	178
75.0	81.9	275.0	191
100.0	99.0	300.0	201

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VELOCITY of SOUND in LIQUID HELIUM

Sources of Data:

Atkins, K. R. and Stasior, R. A.; Can. J. Phys. 31, 1156 (1953)

Chase, C. E.; Phys. Fluids 1, 193 (1958)

Findlay, J. C., Pitt, A., Smith, H. G. and Wilhelm, J. O.; Phys. Rev. 54, 506 (1938)

Findlay, J. C., Pitt, A., Smith, H. G. and Wilhelm, J. O.; Phys. Rev. 56, 122 (1939)

Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 63 (1957)

Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 905 (1957)

Other References:

Atkins, K. R. and Osborne, D. V.; Phil. Mag. 41, 1078 (1950)

Atkins, K. R. and Chase, C. E.; Proc. Phys. Soc. (London) A64, 826 (1951)

Burton, E. F.; Nature, 141, 970 (1938)

Chase, C. E.; Proc. Roy. Soc. (London) A220, 116 (1953)

Pellam, J. R. and Squire, C. F.; Phys. Rev. 72, 1245 (1947)

Pippard, A. B.; Phil. Mag. 42, 1209 (1951)

Van Itterbeek, A. and Forrez, G.; Physica 20, 133 (1954)

Van den Berg, G. J., Van Itterbeek, A., Van Aardenne, G. M. V. and Herfkens, J. H. J.; Physica 21, 860 (1955)

Comments:

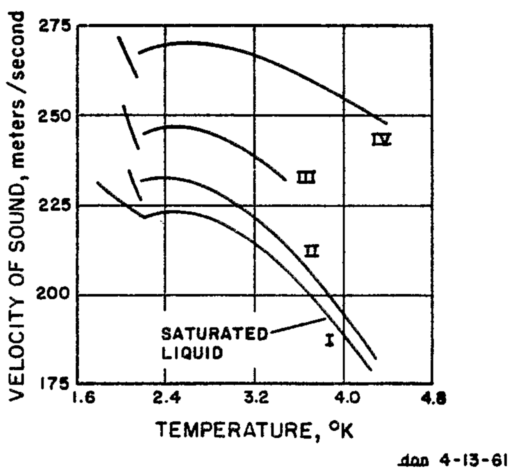
The values of velocity of sound reported here are for ordinary sound in He^4 and do not include the velocities of second sound also associated with liquid helium. The data for the velocity of sound tabulated below and illustrated on the graph are from the references listed above as sources of data. The data for the Saturated Liquid (liquid at the boiling point) listed in Table I, are from the paper by Findlay, et al. with additional data for Helium II listed in Table II from the paper by Chase. The values for pressures from 2.5 to 70 atm. tabulated in Table III are from the paper by Atkins and Stasior. Additional data in Tables IV, V, VI, VII illustrate the variation of the velocity of sound as a function of frequency. These data are from the two papers by Van Itterbeek, Forrez and Teirlinck.

It will be noted that the graph indicates a discontinuity at the λ point (phase boundary between Helium I and Helium II). The work of Findlay, Pitt, Smith and Wilhelm showed a drop in the velocity of sound in liquid Helium I as the λ point (2.19°K) was approached, and below the λ point the velocity rose again, as illustrated on the graph, however, no discontinuous decrease in velocity was noted. However, Ehrenfest's thermodynamic relations for a phase change of the second order (one involving no latent heat) require that there be a discontinuity in the velocity of sound at this point. The authors concluded that this failure to show

(Continued on following page)

Comments: (cont.)

a decrease was due to the formation of bubbles. In order to check this theory they repeated the experiment using pressures up to five atmospheres in order to prevent the formation of bubbles. Under these conditions the predicted discontinuity was observed, as illustrated below.



The Velocity of Sound in Liquid Helium under Various Pressures

I - Vapor Pressure
II - 1 Atmosphere
III - 2.47 Atmospheres
IV - 5.5 Atmospheres

Pellam and Squire, working at normal evaporation pressures found no discontinuity, and concluded that their results were due to the lack of higher pressures as used in the experiments of Findlay et al. On strictly theoretical grounds, using numerous assumptions, Pippard concluded that the anomalous behavior at the λ point was due to inclusions of He II in He I immediately above the λ point, and inclusions of He I in He II immediately below the λ point. Pippard also stated that these inclusions should have a mean radius of 2.1×10^{-7} cm, each consisting of about 850 atoms, in order to explain the curves. In this way the absence of the discontinuity required by Ehrenfest could be accounted for. Atkins and Osborne determined the velocities below the λ point. Atkins and Chase determined the velocity curve both above and below the λ point and found no discontinuity. Their velocities were slightly lower than those of Findlay et al. near the λ point. Atkins and Stasior observed no discontinuities for the series of velocity-temperature curves at constant pressure reported here. The work of Chase published in 1953 and in 1958 is in close agreement with that of Findlay et al.

Van Itterbeek, Forrez and Teirlinck made measurements on the velocity of sound in liquid helium in the neighborhood of 1°K with frequencies of 200, 500, 600, 800, and 1500 kilocycles per second. A small minimum was observed at 800 kilocycles per second for the velocity as a function

(Continued on following page)

Comments: (cont.)

of frequency which does not appear at the boiling point. These values are tabulated in Tables IV and V. Van Itterbeek, Forrez and Teirlinck in a second article made the observations listed in Table VI, and stated that the velocity as a function of frequency is constant to within one part in 2400, and that the velocity seems to be constant as a function of temperature. At the boiling point they found no difference in the velocity using two frequencies, as shown in Table VII.

Table I. The Velocity of Sound for Saturated Liquid*

Temperature °K	Velocity m/sec
He I	
4.22	179.8
4.0	189.2
3.6	206.5
2.5	223.3
2.20	221.2
He II	
2.18	221.7
2.0	225.3
1.76	231.4

* Findlay, Pitt, Smith and Wilhelm

Table II. Velocity of Sound in Helium II*

Temp. °K	Velocity (m/sec)	Temp. °K	Velocity (m/sec)
1.3	236.73	1.9	229.47
1.4	236.35	2.0	226.68
1.5	235.66	2.05	224.90
1.6	234.61	2.10	222.72
1.7	233.28	2.15	220.20
1.8	231.70	2.179	218.00

* Chase

(Continued on following page)

Comments: (cont.)

Table III. The Velocity of First Sound in Liquid Helium*
Velocity of Sound, m/sec

Temp. °K	Pressure, atm. Vapor Press.	2.5	5	10	15	20	25	30	40	50	60	70
1.25	237	257	273	300	326	346	365					
1.50	235	256	272	299	325	345	362					
1.75	233	252	270	298	323	342	355					
1.80	232	251	269	297	321	339	352					
1.90	229	249	267	295	318	333	348	372				
2.00	227	247	265	292	312	336	358	379				
2.10	222	240	259	288	317	340	361	382				
2.20	219	240	259	293	322	344	366	385	419			
2.25	220	242	261	295	323	345	367	386	420			
2.50	222	244	265	298	326	348	369	388	422	451		
3.00	218	242	264	298	327	349	370	389	423	452	481	510
3.50	206	230	256	296	325	349	370	389	423	452	481	510
4.00	190	216	246	290	321	347	369	388	423	452	481	510
4.20	180	206	241	285	318	345	368	387	422	452	481	510

Values above the line in the table are for Helium II, and below the line for Helium I.

* Atkins and Stasior

Table IV. Variation of Velocity of Sound with Frequency*

Temp. °K	Press. mm Hg	Vel. m/sec	Frequency Kc/sec	Temp. °K	Press. mm Hg	Vel. m/sec	Frequency Kc/sec
1.076	.241	238.05	218.59	1.116	.336	237.75	218.63
1.108	.315	238.05	218.56	1.123	.357	238.05	218.56
1.081	.250	237.75	513.12	1.116	.336	237.40	813.76
1.081	.250	237.75	512.76	1.146	.420	237.22	813.44
1.081	.250	237.57	624.01	1.123	.357	237.78	1449.28
1.090	.273	237.48	800.33	1.123	.357	237.69	1476.05
1.076	.241	237.81	1484.92	1.116	.336	237.64	1476.05
1.099	.294	237.68	1476.05				

* Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 63 (1957)

(Continued on following page)

Comments: (cont.)

Table V. Variation of Velocity of Sound with Frequency, for Saturated Liquid*

Temp. °K	Pressure mm Hg	Velocity m/sec	Velocity** m/sec	Frequency Kc/sec
4.221	763.3	180.38	180.32	1469.92
4.216	761.2	180.39	180.18	1484.78
4.222	764.3	180.08	180.05	814.45
4.223	765.1	179.91	179.91	799.83
4.222	764.3	180.68	180.65	623.60
4.218	761.5	180.37	180.22	512.70
4.214	758.50	180.51	180.24	218.33
4.226	767.41	180.01	180.10	218.21

* Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 63 (1957)

** Corrected to 4.223°K

Table VI. Variation of Velocity of Sound with Frequency**

Temp. °K	Press. mm Hg	Velocity m/sec	Frequency Kc/sec	Temp. °K	Press. mm Hg	Velocity m/sec	Frequency Kc/sec
0.985	.105	238.51	218.24	0.985	.105	237.63	226.212
0.985	.105	238.35	218.012	0.985	.105	237.63	523.03
0.985	.105	238.27	211.257	0.985	.105	237.53	800.374
0.985	.105	237.81	226.385	0.997	.146	237.73	1455.76
0.985	.105	237.65	226.241				

Table VII. Velocity of Sound at 4.223°K**

Frequency Kc/sec	Velocity m/sec
217.97	180.69
226.706	180.49
226.485	180.75
226.706	180.59

** Van Itterbeek, A., Forrez, G. and Teirlinck, M.; Physica 23, 905 (1957)

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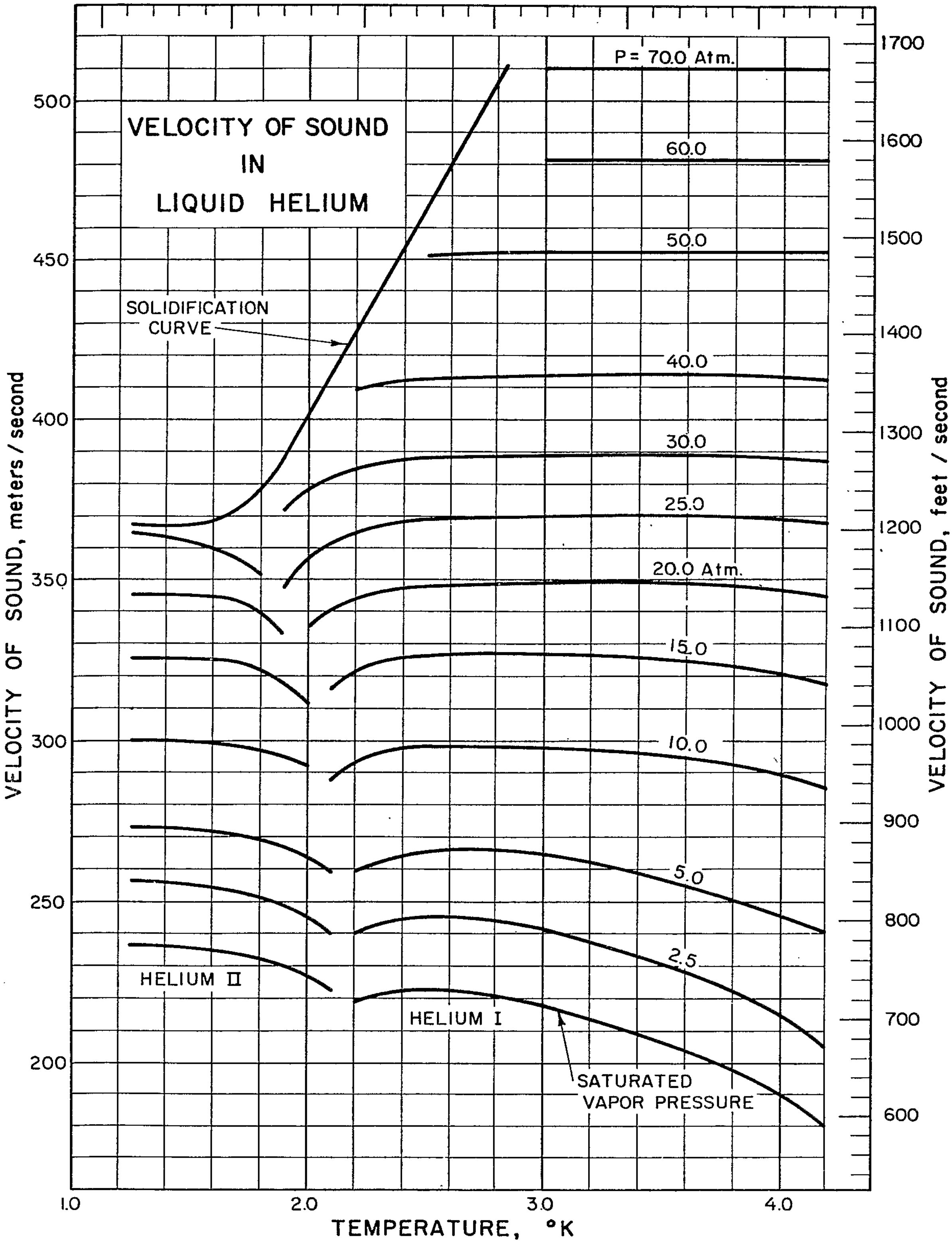
VELOCITY OF SOUND
IN
LIQUID HELIUM
SOLIDIFICATION
CURVE
P = 70.0 Atm.
60.0
50.0
40.0
30.0
25.0
20.0 Atm.
15.0
10.0
5.0
2.5
HELIUM II
HELIUM I
SATURATED
VAPOR PRESSURE
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
TEMPERATURE, °K
1.0
2.0
3.0
4.0
200
250
300
350
400
450
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700

VELOCITY of SOUND in GASEOUS HELIUM

Sources of Data:

Van Itterbeek, A. and Keesom, W. H., Communs. Phys. Lab. Univ. Leiden Commun. No. 209c (1930); Wis-en Natuurk. Tijdschr. 5, 69 (1930)

Keesom, W. H. and Van Itterbeek, A., Koninkl. Ned. Akad 34, 204 (1931); Communs. Phys. Lab. Univ. Leiden Commun. No. 213b (1931)

Van Itterbeek, A. and Thys, L., Physica 5, 889 (1938)

Van Itterbeek, A. and Van Doninck, W., Proc. Phys. Soc. (London) 58, 615 (1946)

Van Itterbeek, A. and Van Doninck, W., Proc. Phys. Soc. (London) 62B, 62 (1949)

Schneider, W. G. and Thiessen, G. J., Can. J. Research 28A, 509 (1950)

Van Itterbeek, A. and Forrez, G., Physica 20, 767 (1954)

Van Itterbeek, A. and De Laet, W., Physica 24, 59 (1958)

Other References:

Keesom, W. H. and Van Itterbeek, A., Koninkl. Ned Akad. Wetenschapen, Proc. 33, 440 (1930); Communs. Phys. Lab. Univ. Leiden Commun. No. 209a (1930)

Comments:

The values of the velocity of sound in gaseous helium are presented here as functions of temperature and pressure, from temperatures of 2.078°K to 290°K, and pressures from 0 to 1 atmosphere. The velocity of sound at the vapor pressure at various temperatures is also given. The data tabulated below and illustrated on the graphs are from the references listed above under "Sources of Data".

The data illustrated in the graph of velocity of sound versus temperature and tabulated below are from Keesom and Van Itterbeek; Van Itterbeek and Keesom; Van Itterbeek and Van Doninck; Van Itterbeek and Thys; and Schneider and Thiessen. All of the above investigators report that all values were obtained at nearly atmospheric pressures. No mention is made by any of the above authors of the purity of the experimental samples used. The data reported by Keesom and Van Itterbeek are estimated by the authors to have a maximum error of 0.1%. The frequency of the sound used is not given. Van Itterbeek and Keesom report a maximum error in their observations of 0.15%, and again no mention is made of the frequency of the sound used. Van Itterbeek and Van Doninck report a frequency of 523.78 kilocycles per second used in their determinations of velocity of sound, but they make no specific claims on the accuracy of their data. Schneider and Thiessen; and Van Itterbeek and Thys used ultrasonics of unreported frequency in their experiments and did not estimate the accuracy of their observations.

Van Itterbeek and Forrez; and Van Itterbeek and De Laet report velocities of sound at various constant temperatures below 5°K as a function of

(Continued on following page)

Comments: (cont.)

pressure. These data are tablulated below and illustrated in the graph of velocity of sound versus pressure, together with the velocity of sound at the vapor pressure as reported by Van Itterbeek and De Laet. Van Itterbeek and Forrez report using a quartz crystal with a frequency of 510 kilocycles per second to propagate the sound waves through their experimental sample. Using audible sound, Van Itterbeek and De Laet measured the velocity of sound in helium gas at very low temperatures and pressures. Using these data they extrapolated the velocity of sound to the vapor pressure at various temperatures. A graphical comparison was made between Keesom and Van Itterbeek's observations at 4.247°K and Van Itterbeek's values at 4.228°K. The agreement between these two sets of data is very good. No information is given by any of the investigators mentioned above as to the purity of their experimental samples.

The units of the velocity of sound in helium gas used in the tabulations below and on the graphs are: temperature in degrees Kelvin (0°C = 273.16°K), pressure in atmospheres (g = 980.665) and the velocity of sound in meters per second.

Velocity of Sound in Gaseous Helium

as a Function of Temperature

near One Atmosphere Pressure

Temperature °K	Velocity m/sec
Van Itterbeek & Keesom	
15.181	229.1
17.186	244.2
18.424	253.1
20.429	266.2
20.519	266.2
Van Itterbeek & Thys	
290.6	997.0
Keesom & Van Itterbeek	
4.247	103.94

Temperature °K	Velocity m/sec
Van Itterbeek & Van Doninck	
20.3	265.9
75	509.9
80	526.9
85	542.9
90	559.5
90.2	559.5
Schneider & Thiessen	
194.99	822.5
273.1	973.9

(Continued on following page)

<u>Comments</u>: (cont.)

Velocity of Sound in Gaseous Helium as a Function of Pressure

Van Itterbeek and De Laet

Pressure atm.	Velocity m/sec
4.228°K	
0	121.00
.0195	120.87
.0346	120.69
.0528	120.47
.0837	120.01
.1285	119.34
.1804	118.54
.2305	117.75
.2991	116.63
.3700	115.46
.4459	113.94
.5513	112.16
.6330	110.55
.7538	107.95
.8828	104.78
3.760°K	
0	114.12
.0153	114.11
.0255	113.92
.0378	113.70
.0873	112.80
.1227	112.10
.1724	111.12
.2923	108.63
.3534	107.21
.3944	106.25
.4291	105.41
.5048	103.34
.5563	101.86
3.184°K	
0	105.01
.0350	104.28
.0708	103.33
.1098	102.29
.1514	101.10
.1913	99.88
.2487	98.04
2.824°K	
0	98.89
.0231	98.24
.0341	98.03
.0437	97.74
.0683	96.94
.1074	95.58
.1482	94.06
2.642°K	
0	95.65
.0169	95.55
.0207	95.46
.0285	95.19
.0390	94.76
.0508	94.27
.0669	93.63
.0813	93.15
.0923	92.66
.1156	91.72
2.259°K	
0	88.44
.0226	87.92
.0269	87.80
.0335	87.56
.0391	87.28
.0455	87.00
.0506	86.76
2.218°K	
0	87.64
.0256	87.11
.0314	86.70
.0382	86.24
.0446	85.70
2.078°K	
0	84.85
.0182	84.25
.0245	83.93
.0298	83.59

Van Itterbeek and Forrez

Pressure atm.	Velocity m/sec
3.582°K	
0	111.3
.1275	109.1
.1653	108.8
.2143	108.2
.2517	106.5
.3206	105.6
.3876	104.1
.4318	102.5
.5204	100.0

(Continued on following page)

Comments: (cont.)

Velocity of Sound in Helium Gas
at the Vapour Pressure

Van Itterbeek and De Laet		
Temperature °K	Pressure atm.	Velocity m/sec
4.228	1.0116	101.96
3.760	0.6288	99.62
3.184	0.3118	95.37
2.824	0.1823	92.62
2.642	0.1336	90.08
2.259	0.0615	86.12
2.218	0.0558	84.83
2.078	0.0392	82.71

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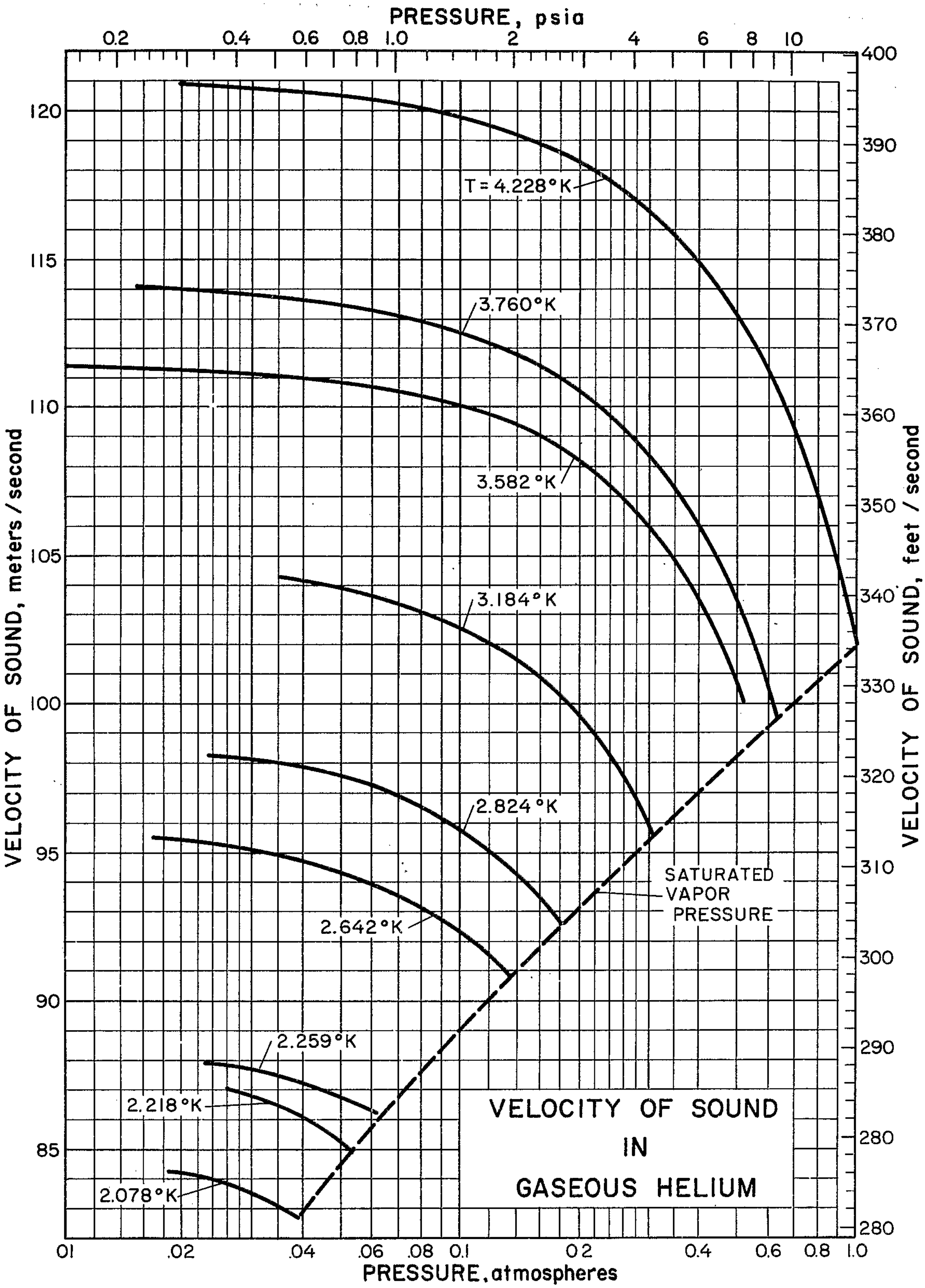
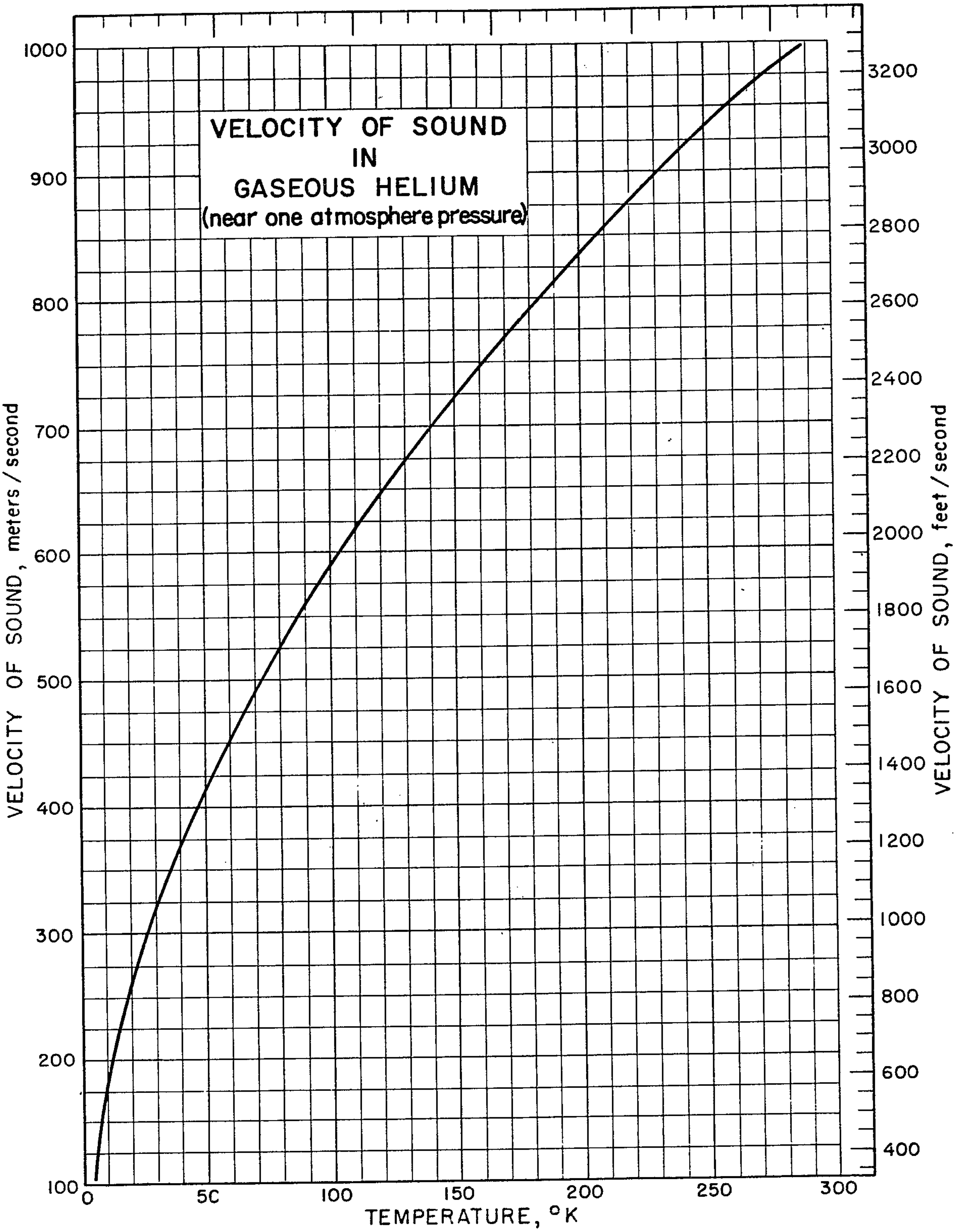
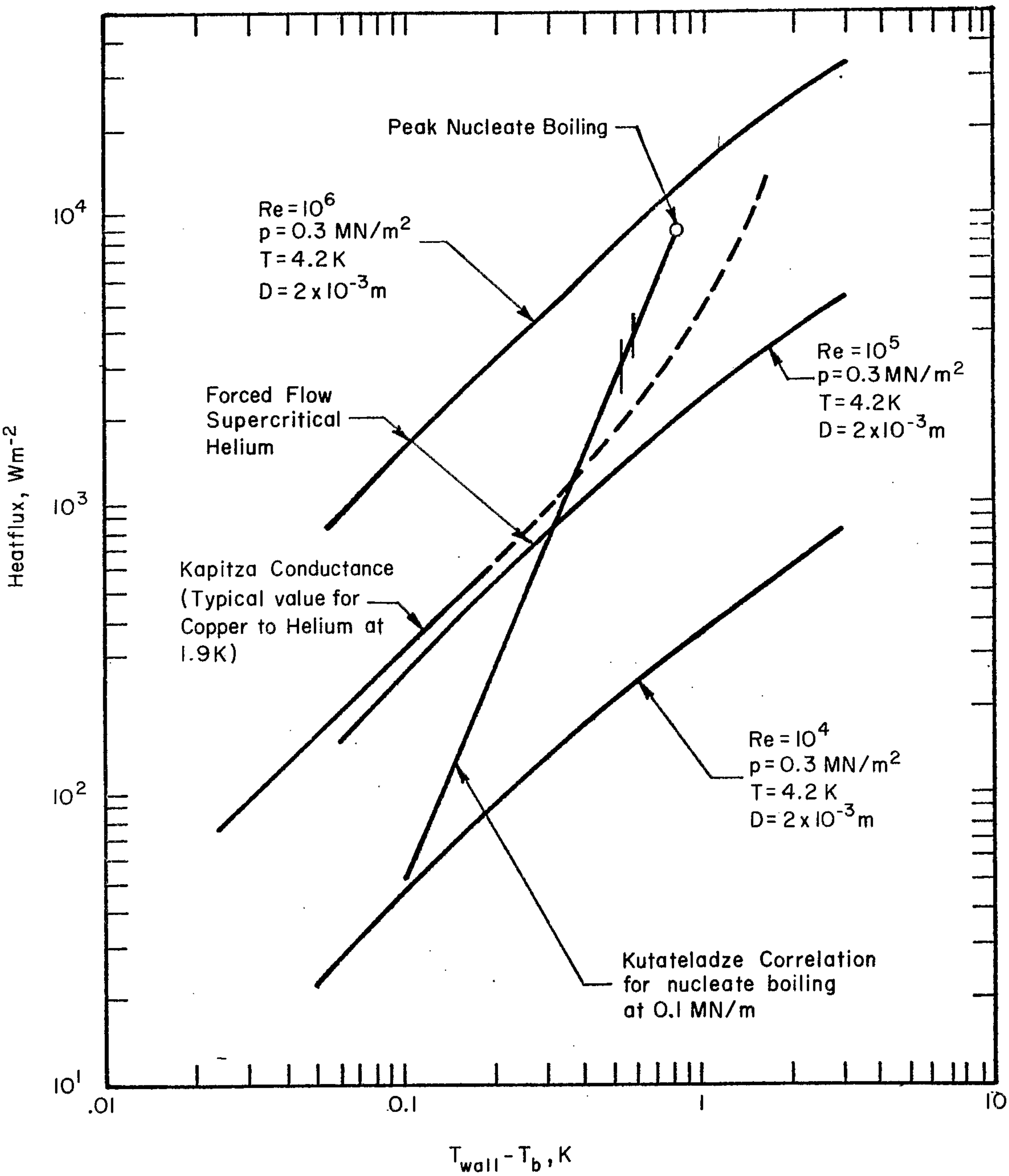

PRESSURE, psia
0.2
0.4
0.6
0.8
1.0
2
4
6
8
10
400
390
380
370
360
350
340
330
320
310
300
290
280
280
120
115
110
105
100
95
90
85
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
T = 4.228 °K
3.760 °K
3.582 °K
3.184 °K
2.824 °K
2.642 °K
2.259 °K
2.218 °K
2.078 °K
SATURATED
VAPOR
PRESSURE
VELOCITY OF SOUND
IN
GASEOUS HELIUM
01
.02
.04
.06
.08
0.1
0.2
0.4
0.6
0.8
1.0
PRESSURE, atmospheres


VELOCITY OF SOUND
IN
GASEOUS HELIUM
(near one atmosphere pressure)
VELOCITY OF SOUND, meters / second
VELOCITY OF SOUND, feet / second
TEMPERATURE, °K
100
200
300
400
500
600
700
800
900
1000
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
0
5C
100
150
200
250
300



COMPARISON OF VARIOUS MODES OF HELIUM HEAT TRANSFER