III. PROPERTIES OF HYDROGEN

CONTENTS

P-ρ-T OF NORMAL AND PARAHYDROGEN AT THE TRIPLE POINT, BOILING POINT, AND CRITICAL POINT

Source of Data: R.B. Stewart and H. M. Roder
Chapter 11. Properties of Normal and Parahydrogen. p. 379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

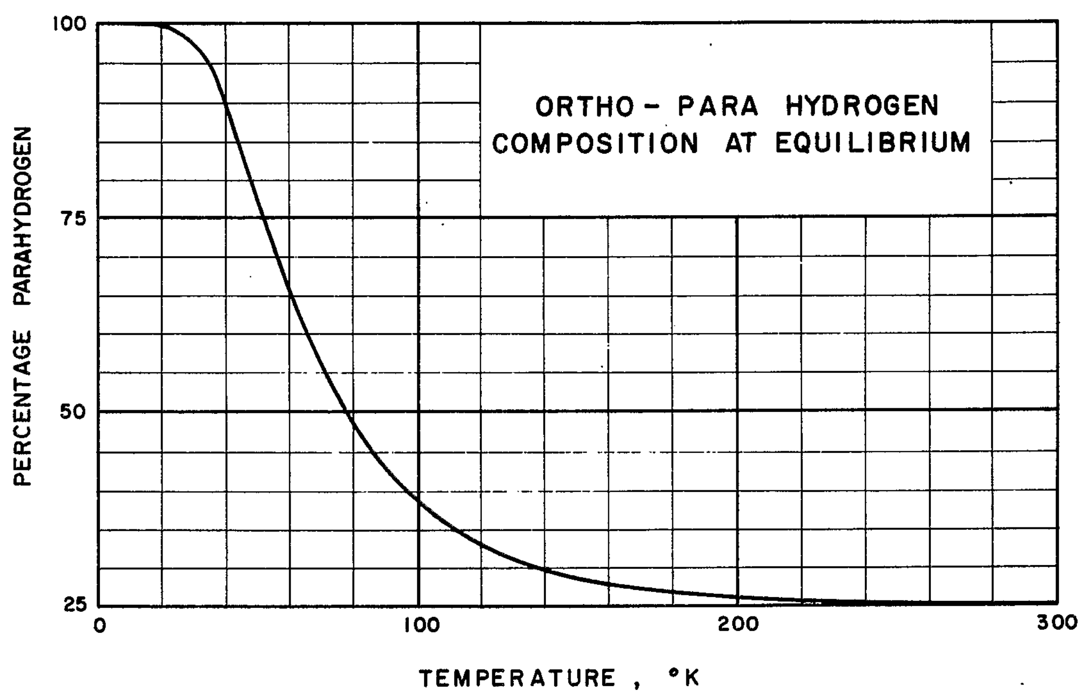
Comments: These values were calculated from data referenced in the Stewart and Roder paper.

	Normal Hydrogen	Parahydrogen
Triple Point		
Pressure, atm	0.071	0.0695
Temperature °K	13.947	13.803
Density (Solid) g mole/cm^3	0.04301	0.04291
Density (Liquid) g mole/cm^3	0.03830	0.03821
Density (Vapor) g mole/cm^3	0.0000631	0.0000624
Boiling Point (1 atm)		
Temperature, °K	20.380	20.268
Density (Liquid) g mole/cm^3	0.0352	0.03511
Density (Vapor) g mole/cm^3	0.0006606	0.0006636
Critical Point		
Pressure, atm	12.98	12.759
Temperature, °K	33.18	32.976
Density, g mole/cm^3	0.01494	0.01559

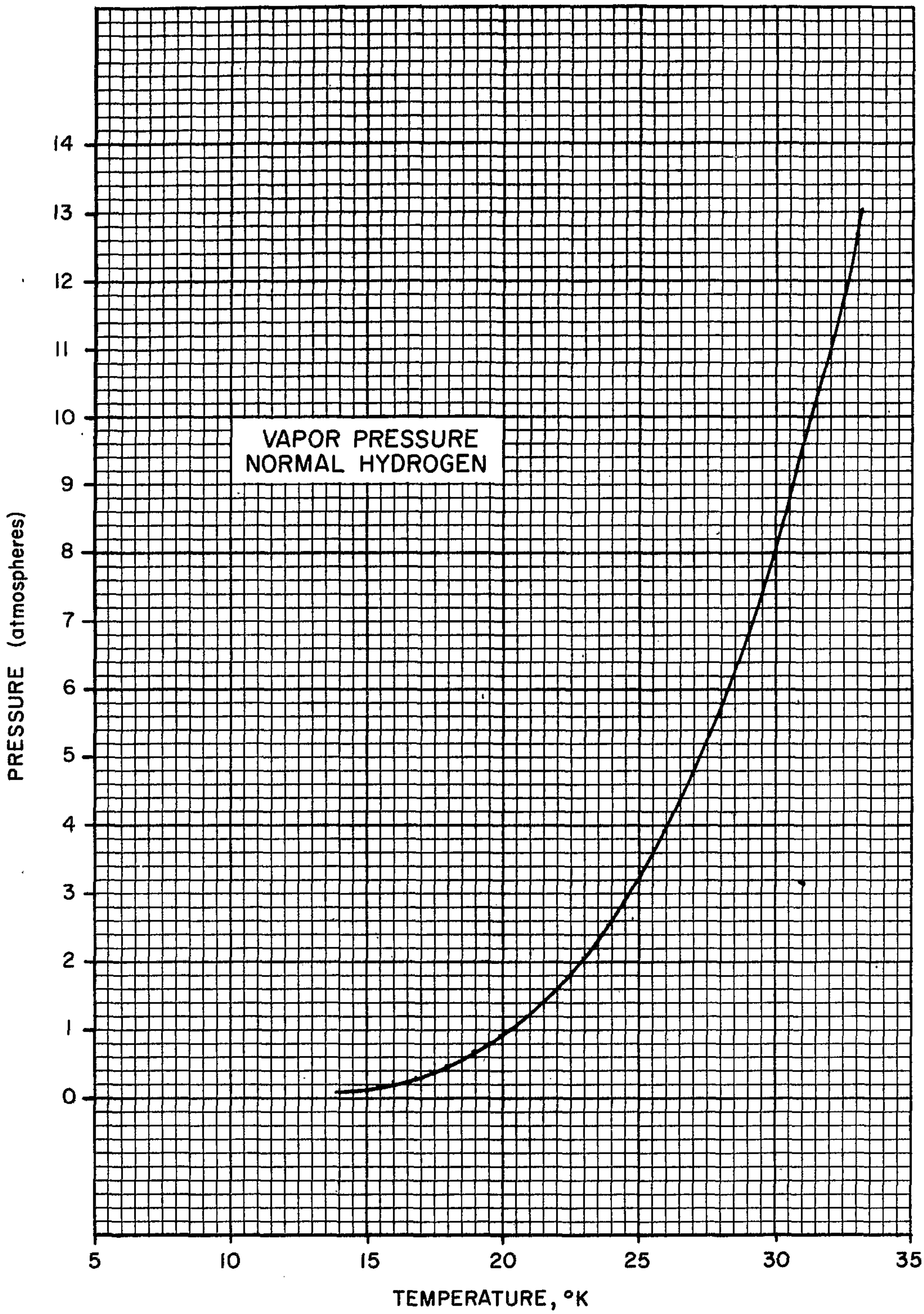
Mol.Wt. = 2.01594 g/g mole, based on the C^{12} = 12.000 scale recently adopted.

The equilibrium concentration of ortho and para hydrogen in the ideal gas state has been calculated by Woolley, Scott, and Brickwedde (1948), J. Res. Natl. Bur. Std. 41, 379-475. The effect of pressure on these equilibrium concentrations is considered to be negligible. These values are tabulated and illustrated graphically below. The NBS-1939 Temperature Scale was used in this table.

Ortho-Para Composition at Equilibrium	
Temp. °K	Percentage in para form for H_2
10	99.9999
20	99.821
30	97.021
40	88.727
50	77.054
60	65.569
70	55.991
80	48.537
90	42.882
100	38.620
120	32.959
150	28.603
200	25.974
250	25.264
300	25.072



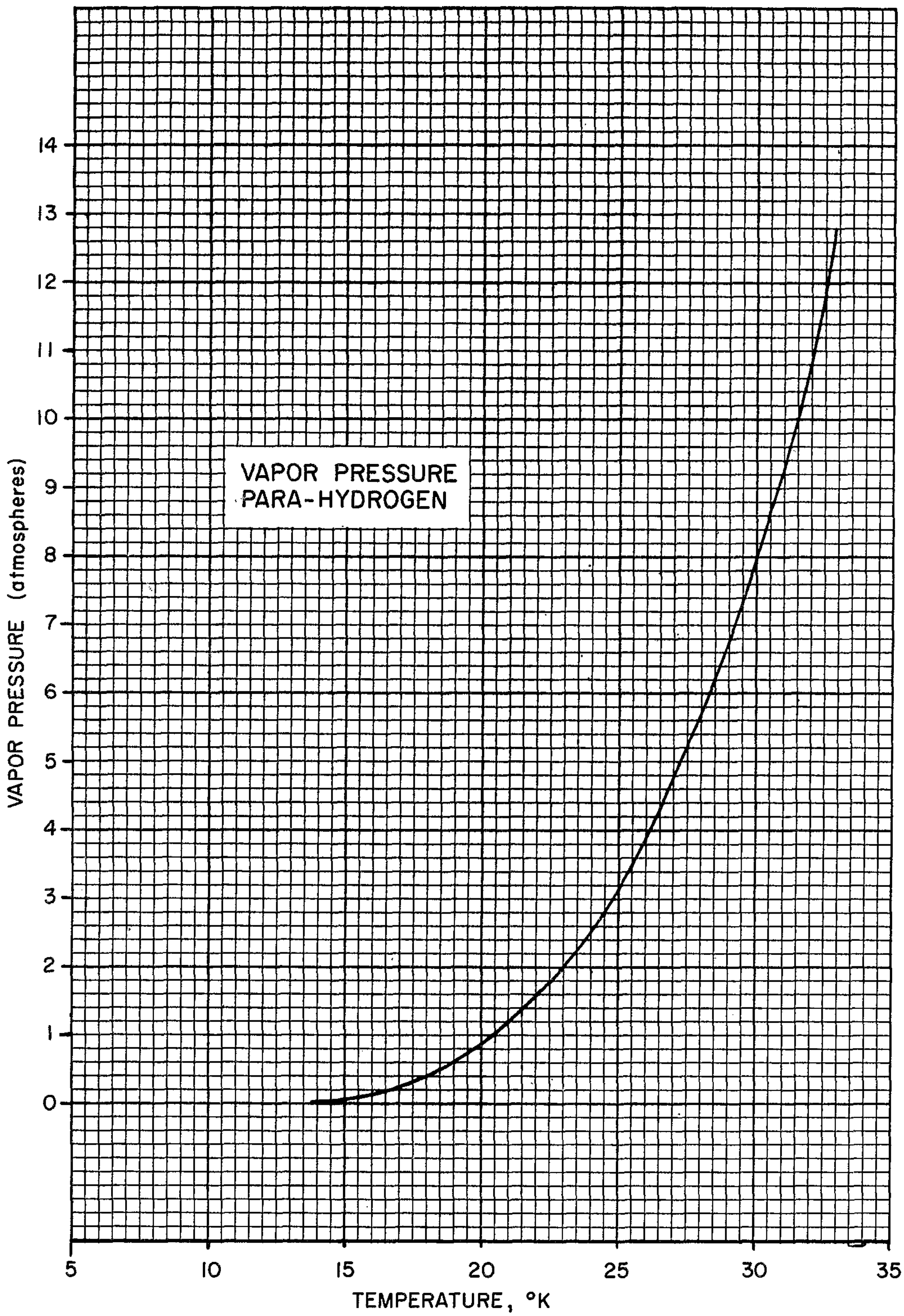
Reprinted from NBS Report 8812


VAPOR PRESSURE
NORMAL HYDROGEN
PRESSURE (atmospheres)
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35
TEMPERATURE, °K

VAPOR PRESSURE NORMAL HYDROGEN

Source of Data: Table II A, Chapter 11 "Technology and Uses of Liquid Hydrogen", 381, Pergamon Press

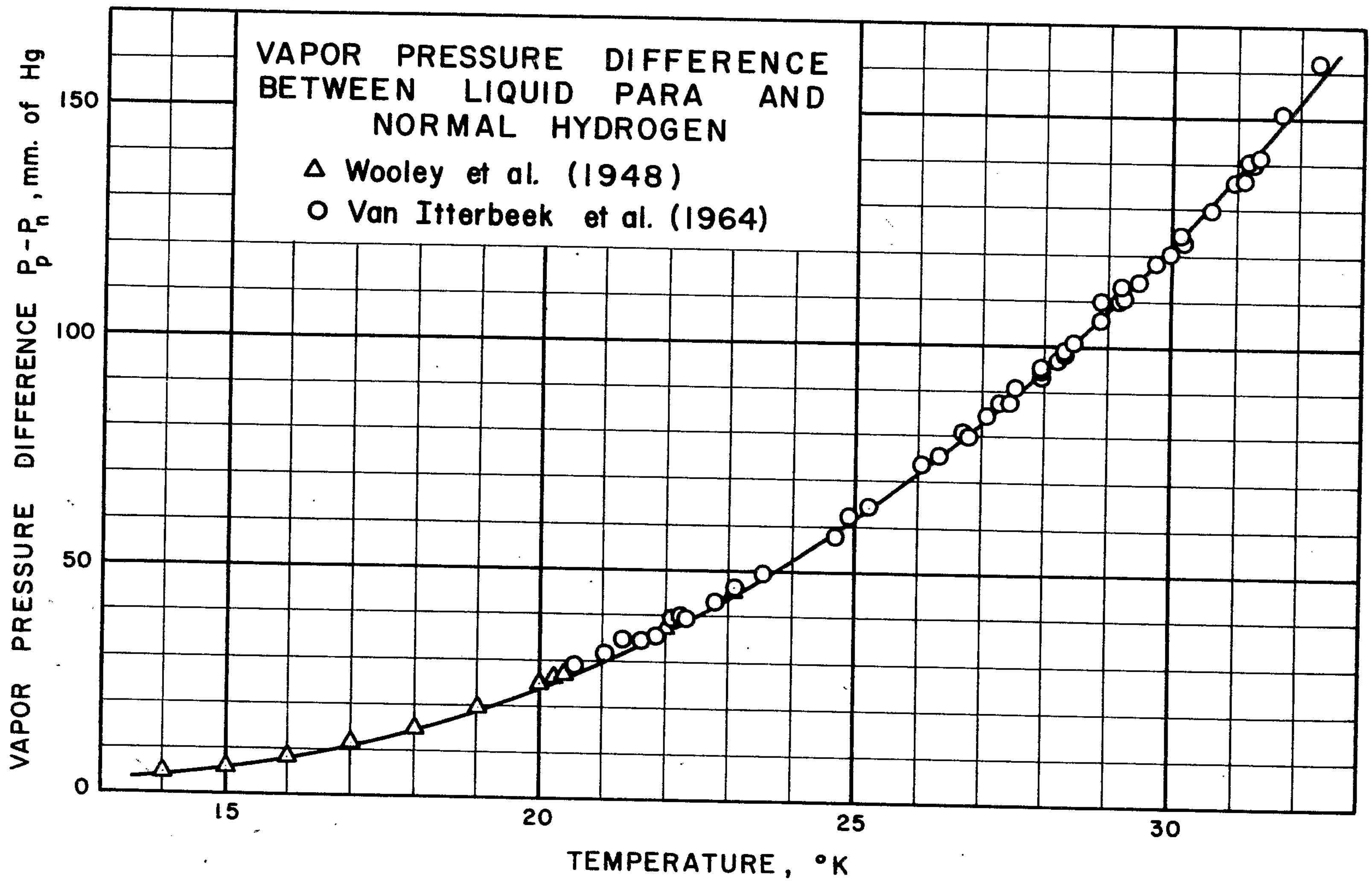
Temperature °K	Pressure atm
13.947	0.071
14	0.073
15	0.125
16	0.202
17	0.310
18	0.456
19	0.648
20	0.891
20.380	1.000
21	1.196
22	1.569
23	2.018
24	2.551
25	3.178
26	3.906
27	4.746
28	5.705
29	6.794
30	8.023
31	9.410
32	10.94
33	12.65
33.18	12.98


VAPOR PRESSURE
PARA-HYDROGEN
VAPOR PRESSURE (atmospheres)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
5
10
15
20
25
30
35
TEMPERATURE, °K

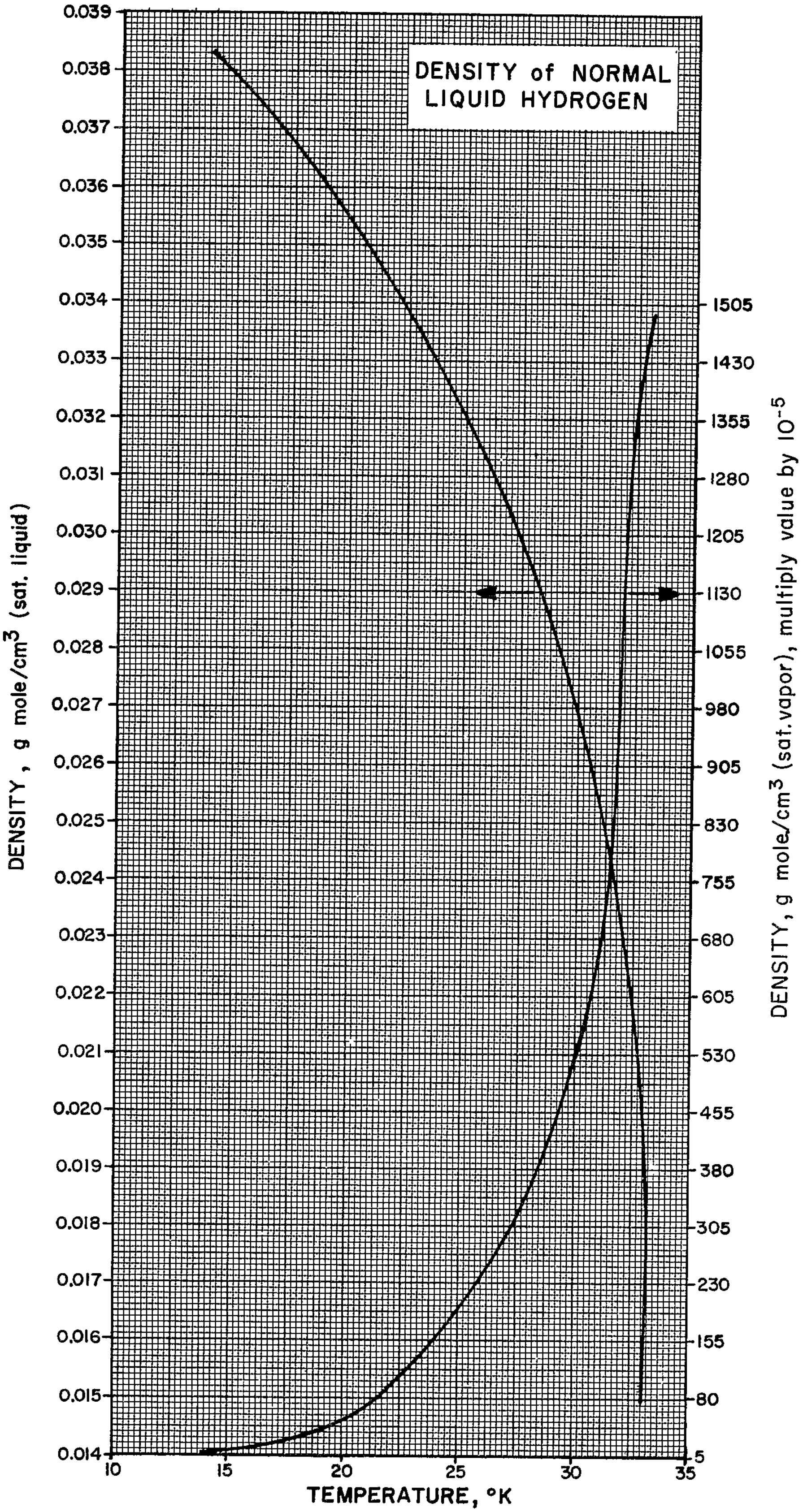
VAPOR PRESSURE PARA-HYDROGEN

Source of Data: Table II A, Chapter 11 "Technology and Uses of Liquid Hydrogen", 381, Pergamon Press

Temperature °K	Pressure, atm
13.803	0.069
14	0.077
15	0.132
16	0.212
17	0.325
18	0.475
19	0.672
20	0.922
20.268	1.000
21	1.233
22	1.612
23	2.069
24	2.610
25	3.245
26	3.981
27	4.828
28	5.793
29	6.886
30	8.117
31	9.500
32	11.051
32.976	12.759



Reprinted from NBS Report 8812



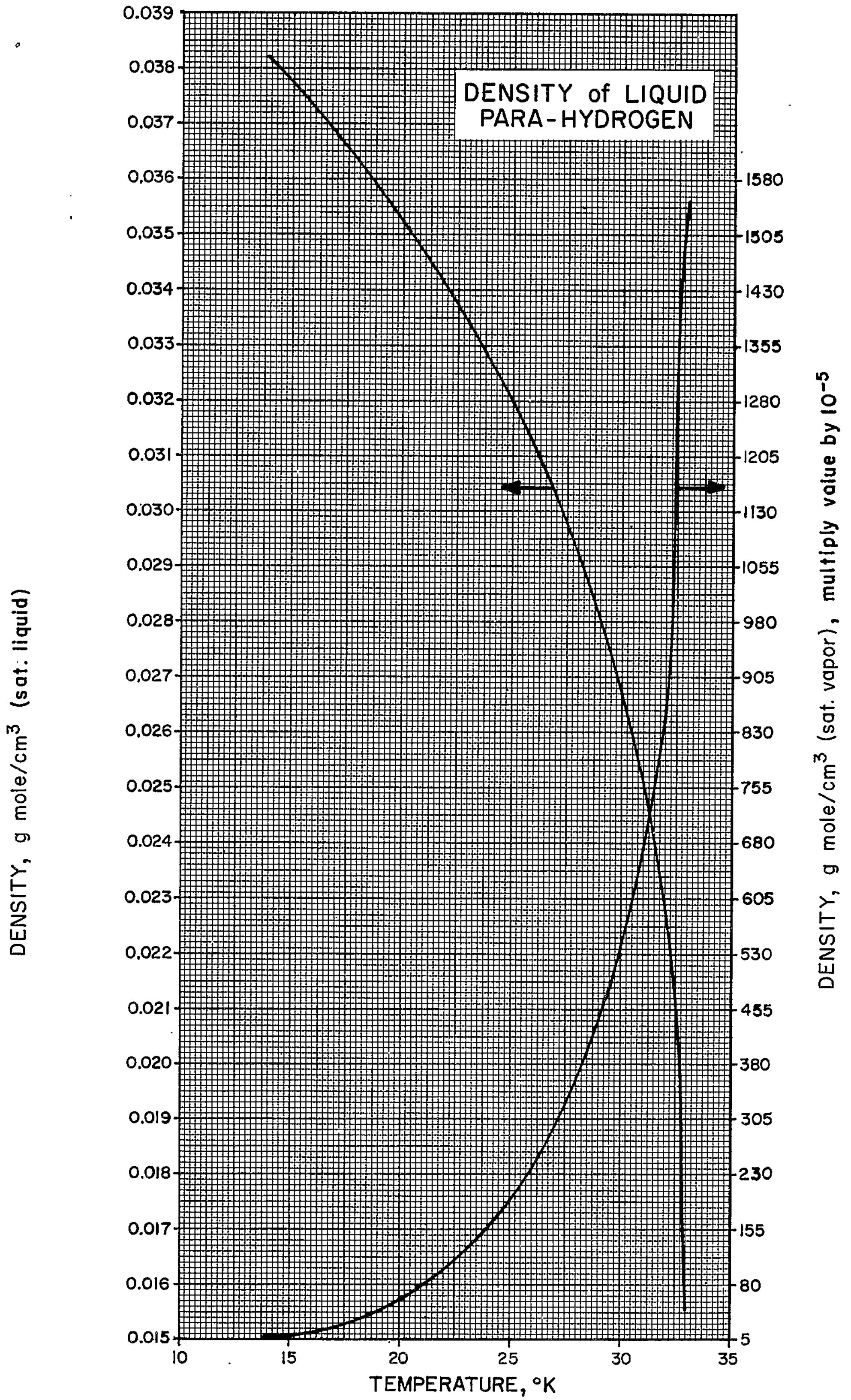
DENSITY of NORMAL LIQUID HYDROGEN
DENSITY, g mole/cm3 (sat. liquid)
DENSITY, g mole/cm3 (sat. vapor), multiply value by 10-5
TEMPERATURE, °K
0.039
0.038
0.037
0.036
0.035
0.034
0.033
0.032
0.031
0.030
0.029
0.028
0.027
0.026
0.025
0.024
0.023
0.022
0.021
0.020
0.019
0.018
0.017
0.016
0.015
0.014
1505
1430
1355
1280
1205
1130
1055
980
905
830
755
680
605
530
455
380
305
230
155
80
5
10
15
20
25
30
35

DENSITY OF NORMAL LIQUID HYDROGEN

Source of Data: R.B. Stewart and H.M. Roder, Chapter 11. Properties of Normal and Parahydrogen. p.379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

Comments: These values were calculated from data referenced in the Stewart and Roder paper.

Temperature °K	Density, g mole/cm^3	
	Sat. Liquid	Sat. Vapor
13.947	0.03830	6.3 x 10^{-5}
14	0.03828	6.4 "
15	0.03786	10.4 "
16	0.03742	15.9 "
17	0.03695	23.2 "
18	0.03647	32.7 "
19	0.03595	44.7 "
20	0.03540	59.5 "
20.380	0.03519	66.0 "
21	0.03483	77.6 "
22	0.03421	99.5 "
23	0.03355	125.7 "
24	0.03285	156.9 "
25	0.03209	193.8 "
26	0.03127	237.7 "
27	0.03036	290.0 "
28	0.02935	352.7 "
29	0.02821	429.0 "
30	0.02689	524.1 "
31	0.02528	648.2 "
32	0.02312	
33	0.01903	
33.18	0.01494	1494.0 "



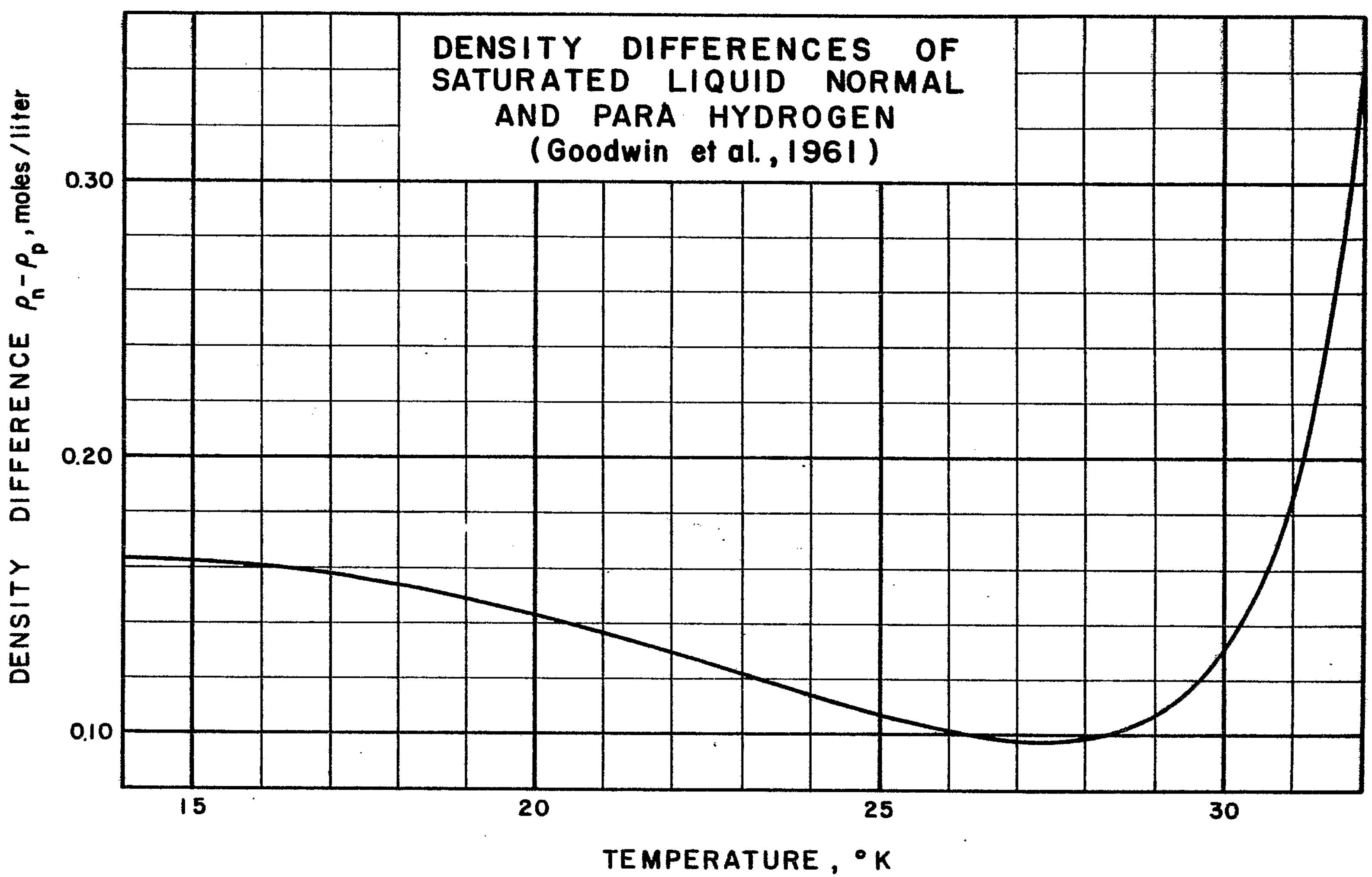
DENSITY of LIQUID
PARA-HYDROGEN
DENSITY, g mole/cm3 (sat. liquid)
DENSITY, g mole/cm3 (sat. vapor), multiply value by 10-5
TEMPERATURE, °K
0.039
0.038
0.037
0.036
0.035
0.034
0.033
0.032
0.031
0.030
0.029
0.028
0.027
0.026
0.025
0.024
0.023
0.022
0.021
0.020
0.019
0.018
0.017
0.016
0.015
1580
1505
1430
1355
1280
1205
1130
1055
980
905
830
755
680
605
530
455
380
305
230
155
80
5
10
15
20
25
30
35

DENSITY OF LIQUID PARA-HYDROGEN

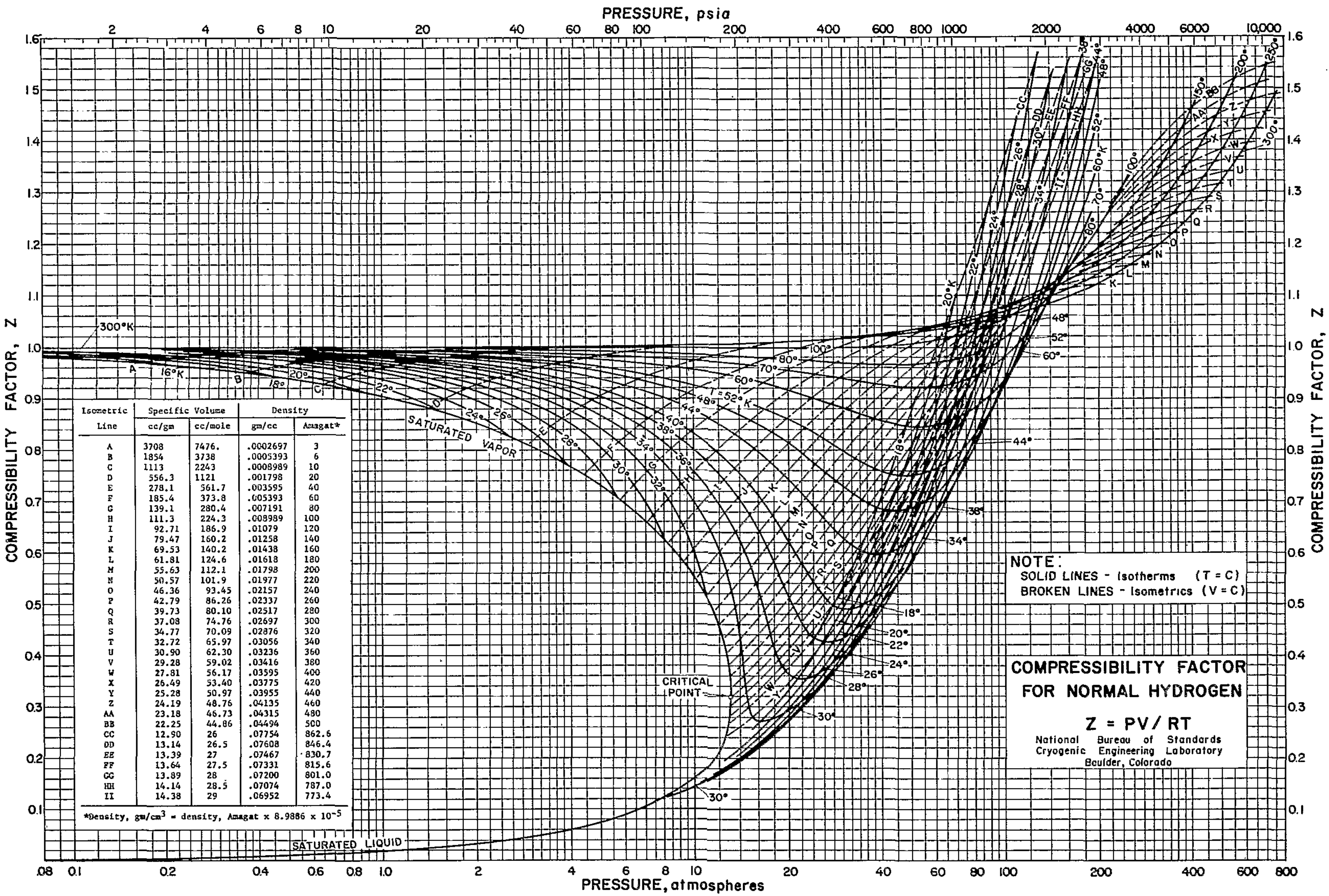
Source of Data: R.B. Stewart and H.M. Roder Chapter 11. Properties of Normal and Parahydrogen. p. 379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

Comments: These values were calculated from data referenced in the Stewart and Roder paper.

Temperature °K	Density, g mole/cm^3	
	Sat. Liquid	Sat. Vapor
13.803	0.03821	6.24 x 10^{-5}
14	0.03812	6.90 "
15	0.03770	11.04 "
16	0.03726	16.78 "
17	0.03679	24.40 "
18	0.03631	34.20 "
19	0.03580	46.53 "
20	0.03526	61.76 "
20.268	0.03511	66.36 "
21	0.03469	80.30 "
22	0.03409	102.7 "
23	0.03344	129.6 "
24	0.03274	161.5 "
25	0.03199	199.3 "
26	0.03117	244.1 "
27	0.03026	297.6 "
28	0.02925	362.0 "
29	0.02810	440.8 "
30	0.02675	540.1 "
31	0.02509	671.7 "
32	0.02281	868.0 "
32.976	0.01559	1559.0 "

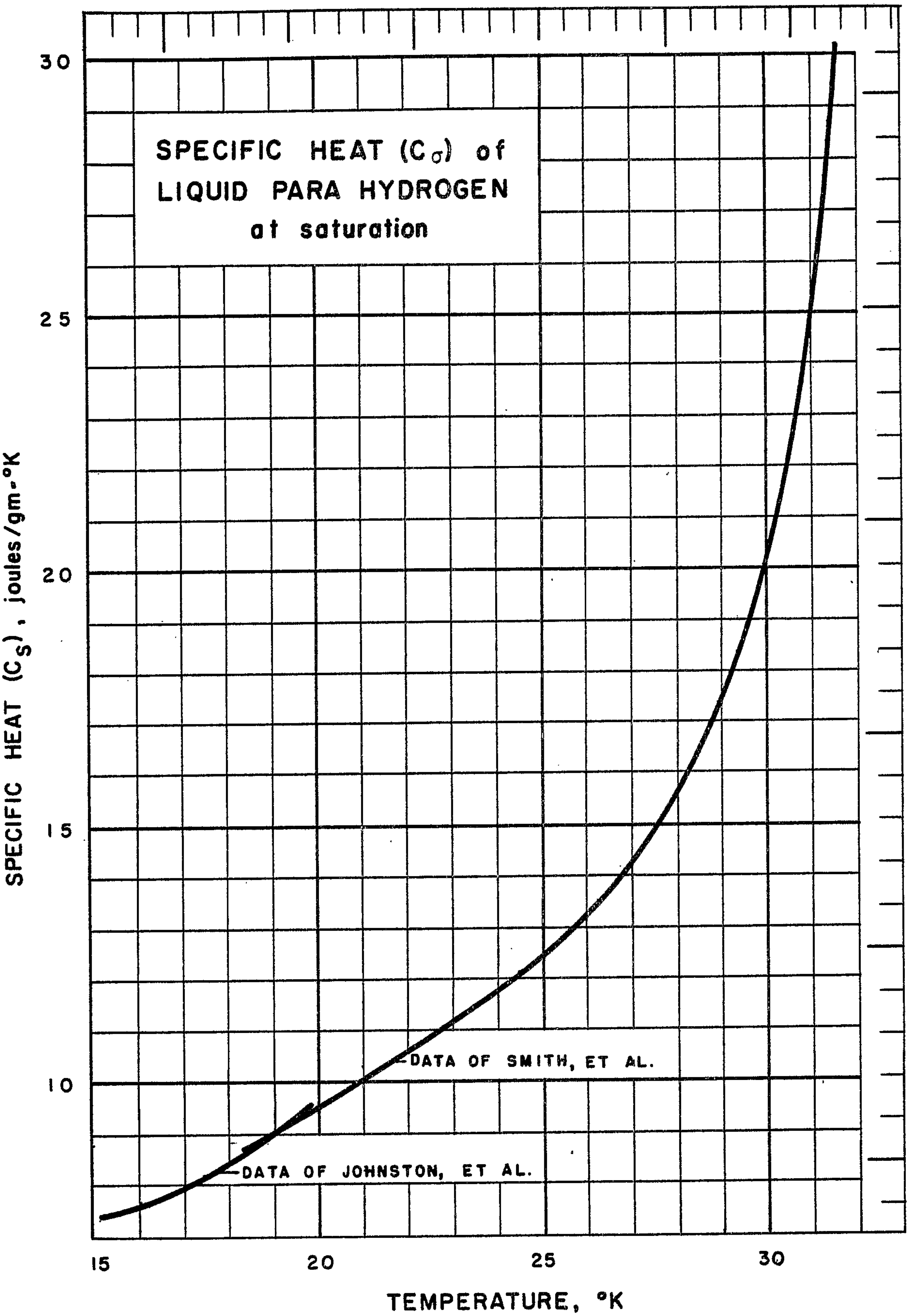


Reprinted from NBS Report 8812



Isometric Line	Specific Volume cc/gm	Specific Volume cc/mole	Density gm/cc	Density Amagat*
A	3708	7476.	.0002697	3
B	1854	3738	.0005393	6
C	1113	2243	.0008989	10
D	556.3	1121	.001798	20
E	278.1	561.7	.003595	40
F	185.4	373.8	.005393	60
G	139.1	280.4	.007191	80
H	111.3	224.3	.008989	100
I	92.71	186.9	.01079	120
J	79.47	160.2	.01258	140
K	69.53	140.2	.01438	160
L	61.81	124.6	.01618	180
M	55.63	112.1	.01798	200
N	50.57	101.9	.01977	220
O	46.36	93.45	.02157	240
P	42.79	86.26	.02337	260
Q	39.73	80.10	.02517	280
R	37.08	74.76	.02697	300
S	34.77	70.09	.02876	320
T	32.72	65.97	.03056	340
U	30.90	62.30	.03236	360
V	29.28	59.02	.03416	380
W	27.81	56.17	.03595	400
X	26.49	53.40	.03775	420
Y	25.28	50.97	.03955	440
Z	24.19	48.76	.04135	460
AA	23.18	46.73	.04315	480
BB	22.25	44.86	.04494	500
CC	12.90	26	.07754	862.6
DD	13.14	26.5	.07608	846.4
EE	13.39	27	.07467	830.7
FF	13.64	27.5	.07331	815.6
GG	13.89	28	.07200	801.0
HH	14.14	28.5	.07074	787.0
II	14.38	29	.06952	773.4

*Density, gm/cm^3 = density, Amagat x 8.9886 x 10^{-5}



SPECIFIC HEAT (C_σ) of
LIQUID PARA HYDROGEN
at saturation
SPECIFIC HEAT (C_S), joules/gm-°K
30
25
20
15
10
DATA OF SMITH, ET AL.
DATA OF JOHNSTON, ET AL.
15
20
25
30
TEMPERATURE, °K

SPECIFIC HEAT (C_σ) of LIQUID PARA HYDROGEN
(At Saturation)

Sources of Data:

Johnston, H. L., Clarke, J. T., Rifkin, E. B. and Kerr, E. C., J. Am. Chem. Soc. 72, 3933 (1950)

Smith, A. L., Hallett, N. C. and Johnston, H. L., J. Am. Chem. Soc. 76, 1486 (1954)

Other References:

Bonnhoefer, K. F. and Harteck, P., Naturwiss. 17, 182 (1929)

Clusius, K. and Hiller, K., Z. physik. Chem. B4, 158 (1929)

Dewar, J., Proc. Roy. Soc. (London) A76, 325 (1905)

Eucken, A., Verhandl. deut. physik. Ges. 18, 4-17 (1916)

Keesom, W. H., Comm. Phys. Lab. Univ. Leiden 137e (1911)

Simon, F. and Lange, R., Z. Physik. 15, 312 (1923)

Comments:

Heisenberg, Z. Physik. 38, 411 (1926); Hund, Z. Physik. 42, 93 (1927); and Dennison, Proc. Roy. Soc. (London) A115, 483 (1927) predicted the existence of two forms of molecular hydrogen on the basis of quantum theory. Shortly thereafter methods were developed for catalyzing the conversion. Since then heat capacity measurements have been carried out on known concentrations of the two varieties. Prior to 1929 all work was based on normal hydrogen (75% ortho and 25% para). Data for the curves were derived under conditions of saturation vapor pressure (C_s).

Data of Johnston, Clarke Rifkin and Kerr. J. Am. Chem. Soc. 72, 3933 (1950).

Temp. °K	C_σ cal/mole °K	C_σ cal/gm °K
15.15	3.52	1.746
15.30	3.54	1.756
16.05	3.67	1.820
16.26	3.66	1.815
17.03	3.81	1.890
17.31	3.85	1.910
17.98	4.03	1.999
18.27	4.10	2.034
18.89	4.24	2.103
18.99	4.32	2.143

Data of Smith, Hallett and Johnston. J. Am. Chem. Soc. 76, 1486 (1954).

Temp. °K	C_σ cal/mole °K	C_σ cal/gm °K
18.28	4.18	2.073
20.45	4.71	2.336
22.71	5.33	2.644
25.00	6.03	2.991
26.04	6.46	3.204
28.20	7.85	3.894
30.10	9.94	4.931
31.49	14.56	7.222

Reprinted from WADD TECH. REPORT 60-56

SPECIFIC HEAT (C_p) of NORMAL HYDROGEN GAS

Sources of Data:

Eucken, A., Sitzber. kgl. preuss. Akad. Wiss. 141 (1912)

Hilsenrath, J., et al., Nat. Bur. Standards Cir. 564, 282 (1955)

Scheel, K. and Heuse, W., Ann. Physik. (4) 40, 473 (1913)

Workman, E. J., Phys. Rev. (2) 37, 1345 (1931)

Comments:

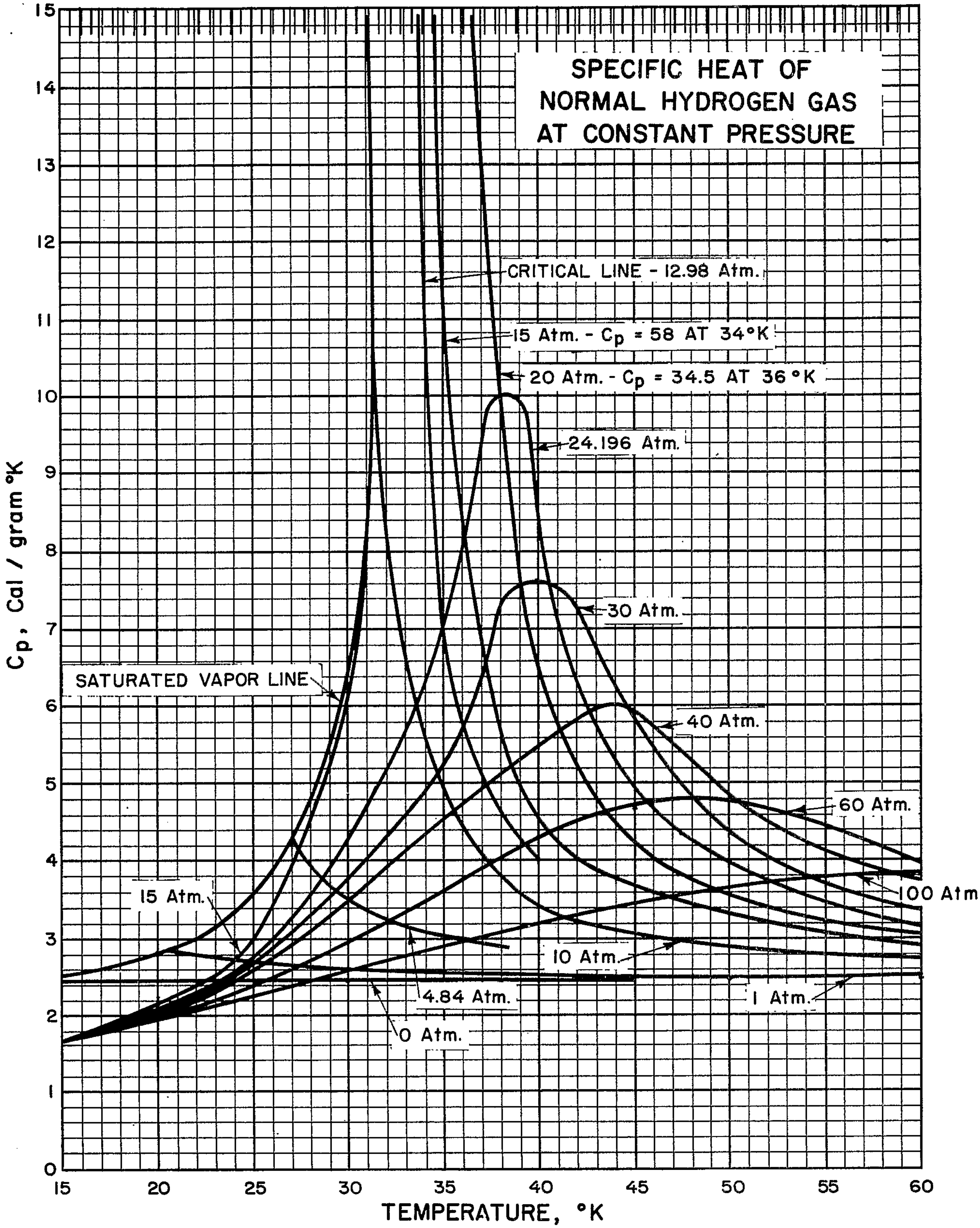
The above articles were all used by the NBS staff in compiling the data for Circular 564. Accordingly the present curves have been constructed using these same data. We have been unable to discover anything more recent. When more does appear, it should take into account the existence of ortho and para-hydrogen.

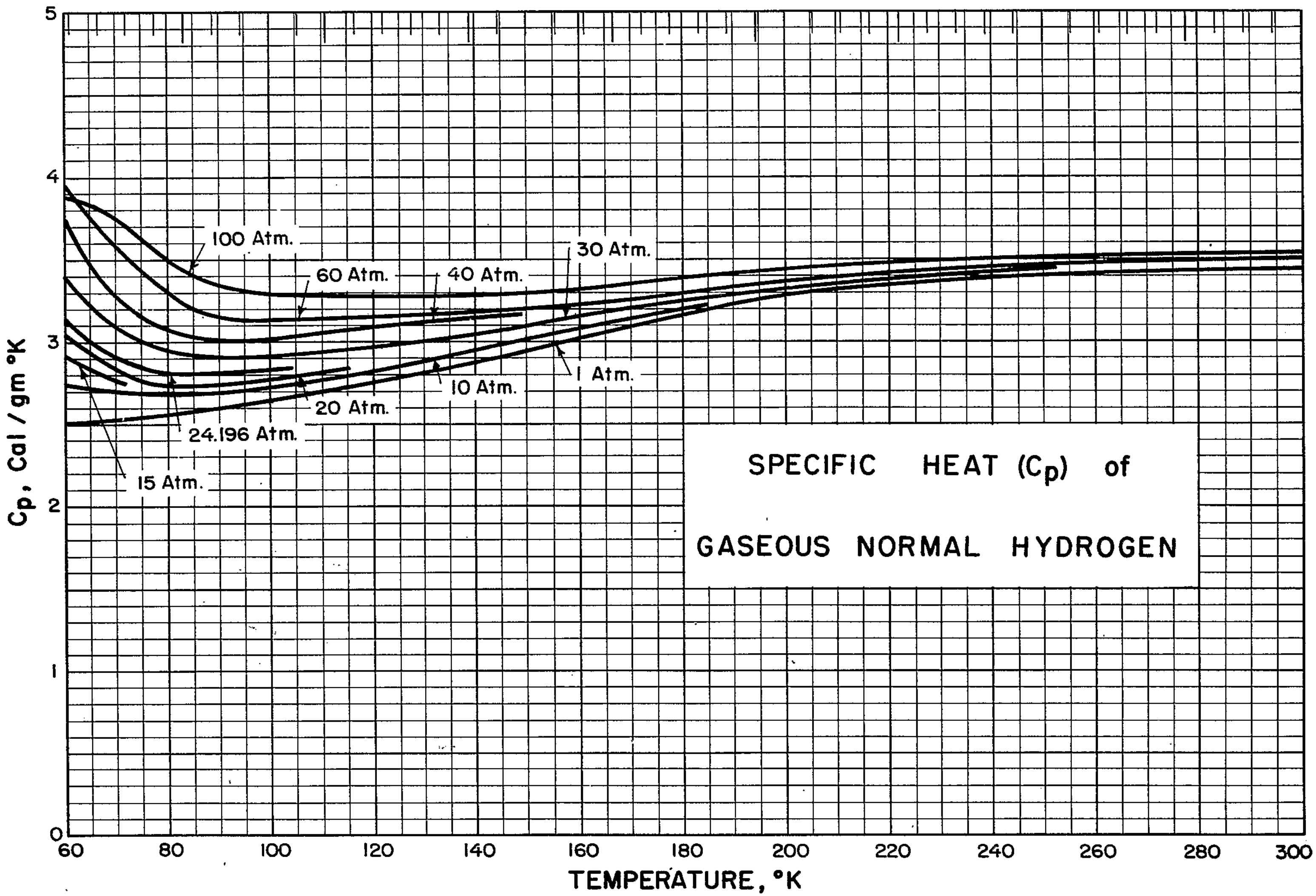
Table of Selected Values

Temp. °K	$\frac{C_p}{R}$	C_p $\frac{cal}{gm °K}$	$\frac{C_p}{R}$	C_p $\frac{cal}{gm °K}$	$\frac{C_p}{R}$	C_p $\frac{cal}{gm °K}$	$\frac{C_p}{R}$	C_p $\frac{cal}{gm °K}$
	0 Atm		1 Atm		10 Atm		100 Atm	
20	2.50	2.4643						
30	2.50	2.4643	2.628	2.5904				
40	2.501	2.4653	2.564	2.5274	3.463	3.4135		
50	2.505	2.4692	2.543	2.5067	2.947	2.9049		
60	2.519	2.4830	2.544	2.5076	2.780	2.7403	3.957	3.9005
70	2.547	2.5106	2.565	2.5283	2.732	2.6930	3.786	3.7319
80	2.591	2.5540	2.605	2.5678	2.723	2.6841	3.564	3.5131
90	2.648	2.610	2.658	2.6200	2.747	2.7077	3.366	3.3179
100	2.714	2.6752	2.722	2.6831	2.790	2.7501	3.295	3.2479
120	2.857	2.8162	2.862	2.8211	2.905	2.8635	3.242	3.1957
140	2.993	2.9502	2.996	2.9532	3.026	2.9828	3.264	3.2174
160	3.108	3.0636	3.111	3.0665	3.135	3.0902	3.326	3.2785
180	3.204	3.1582	3.206	3.1602	3.226	3.1800	3.377	3.3287
200	3.280	3.2331	3.282	3.2351	3.296	3.2489	3.413	3.3642
220	3.340	3.2923	3.341	3.2933	3.355	3.3071	3.454	3.4046
240	3.387	3.3386	3.388	3.3396	3.399	3.3504	3.486	3.4362
260	3.424	3.3751	3.425	3.3761	3.433	3.3839	3.504	3.4539
270	3.438	3.3889	3.439	3.3899	3.446	3.3968	3.510	3.4598
280	3.450	3.4007	3.451	3.4017	3.458	3.4086	3.516	3.4658
300	3.469	3.4194	3.470	3.4204	3.476	3.4263	3.526	3.3756

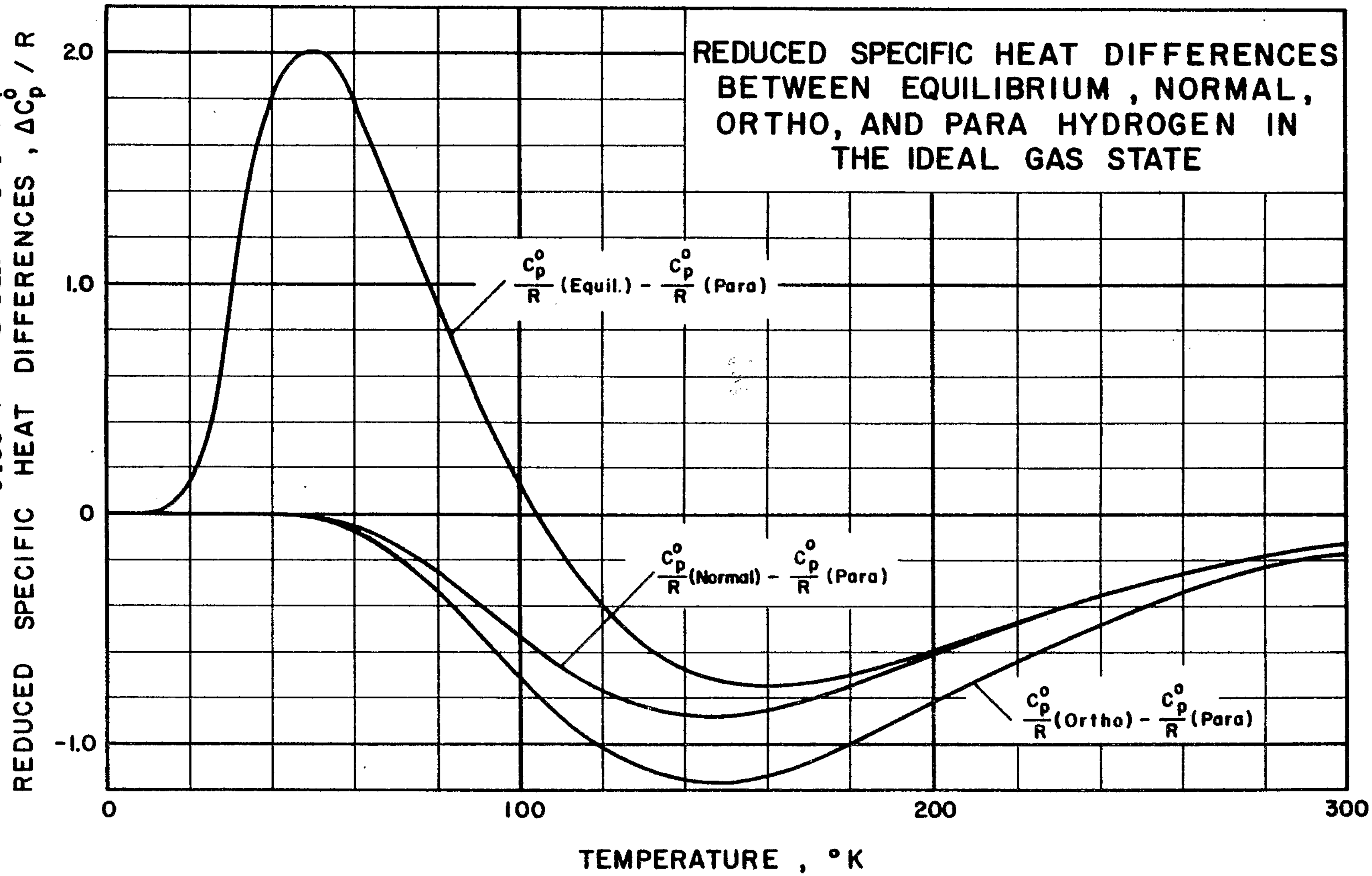
See next two pages for graphical presentation of the data.

Reprinted from WADD TECH.REPORT 60-56

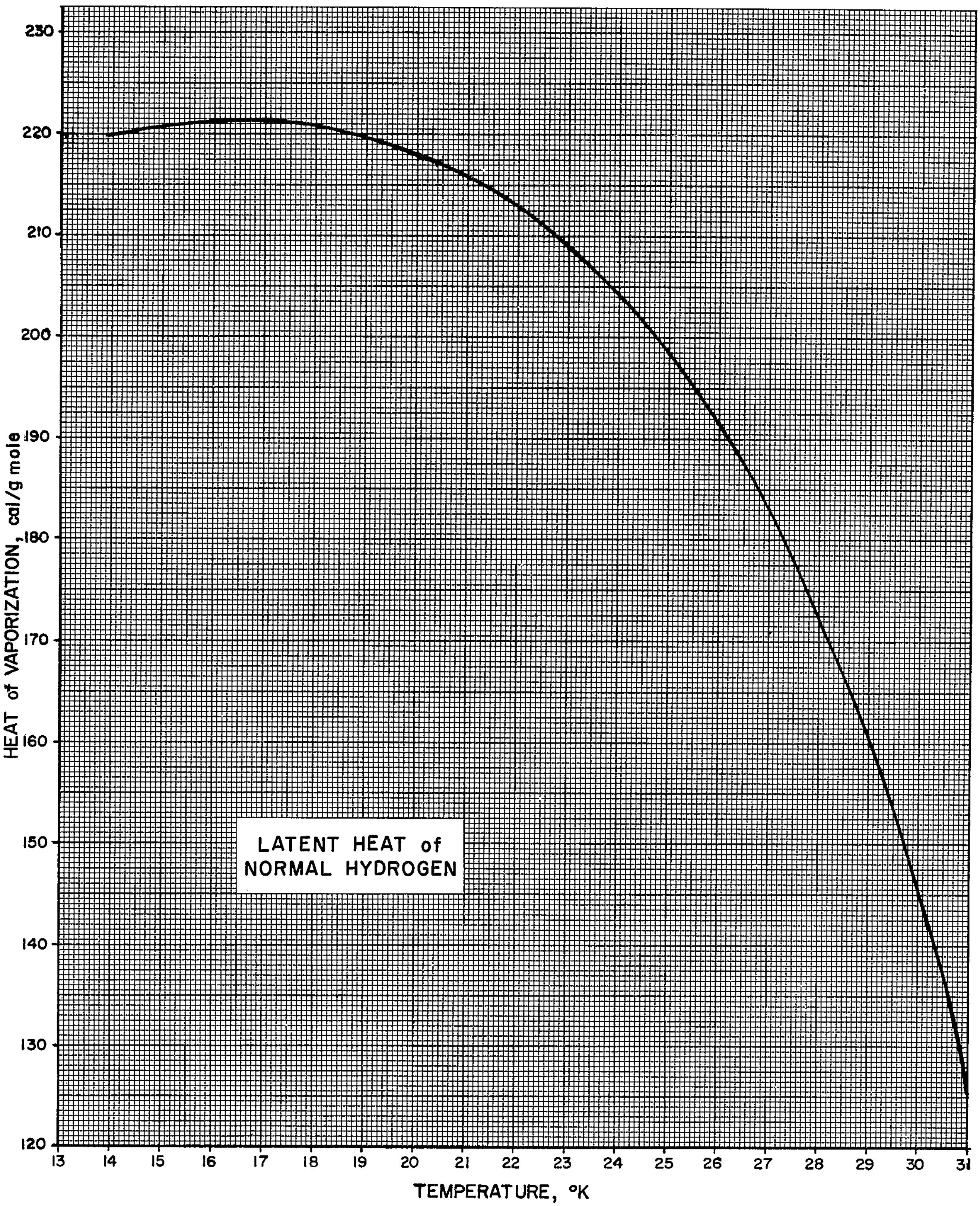

SPECIFIC HEAT OF
NORMAL HYDROGEN GAS
AT CONSTANT PRESSURE
CRITICAL LINE - 12.98 Atm.
15 Atm. - Cp = 58 AT 34°K
20 Atm. - Cp = 34.5 AT 36°K
24.196 Atm.
30 Atm.
40 Atm.
60 Atm.
100 Atm.
SATURATED VAPOR LINE
15 Atm.
10 Atm.
4.84 Atm.
1 Atm.
0 Atm.
Cp, Cal / gram °K
TEMPERATURE, °K
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
15
20
25
30
35
40
45
50
55
60



SPECIFIC HEAT (Cp) of GASEOUS NORMAL HYDROGEN
Cp, Cal / gm °K
TEMPERATURE, °K
0
1
2
3
4
5
60
80
100
120
140
160
180
200
220
240
260
280
300
100 Atm.
60 Atm.
40 Atm.
30 Atm.
1 Atm.
10 Atm.
20 Atm.
24.196 Atm.
15 Atm.



Reprinted from NBS Report 8812


LATENT HEAT of
NORMAL HYDROGEN
HEAT of VAPORIZATION, cal/g mole
TEMPERATURE, °K
230
220
210
200
190
180
170
160
150
140
130
120
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

NORMAL HYDROGEN - HEAT OF VAPORIZATION

Source of Data:

R. B. Stewart and H. M. Roder
Chapter 11. Properties of Normal and Parahydrogen.
p. 379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

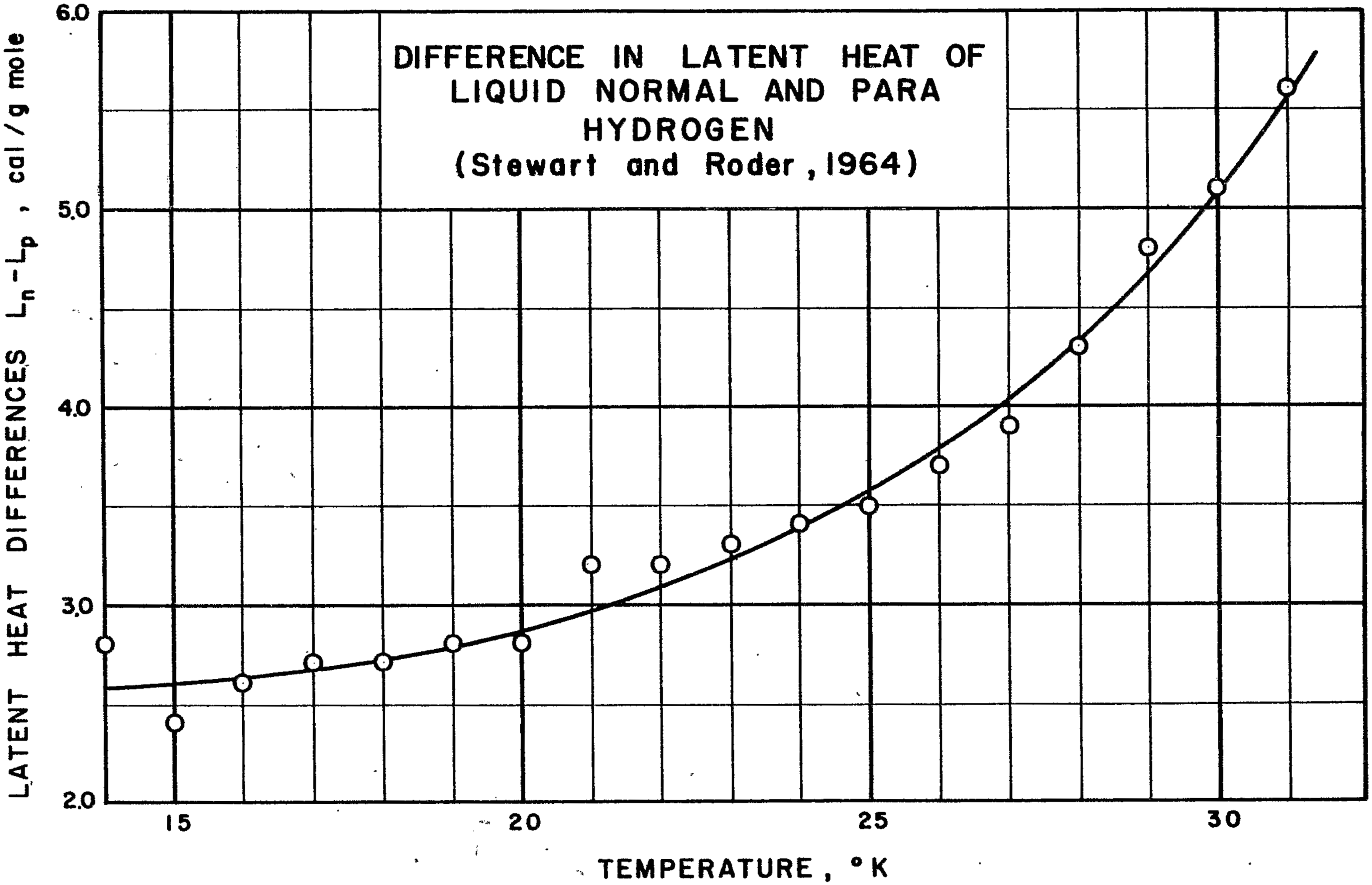
Comments:

These values were calculated from data referenced in the Stewart and Roder paper.

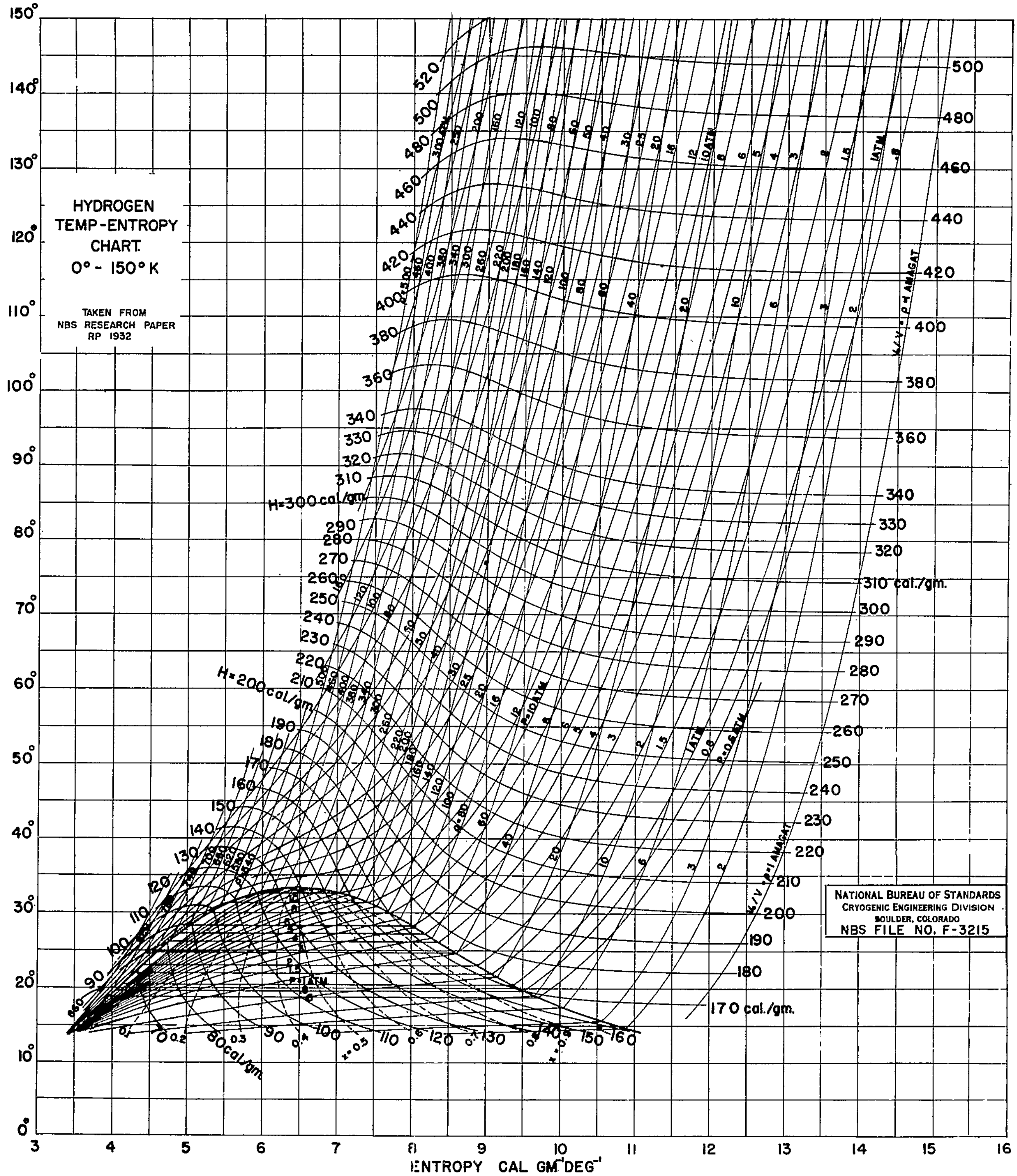
Latent Heat of Normal Hydrogen

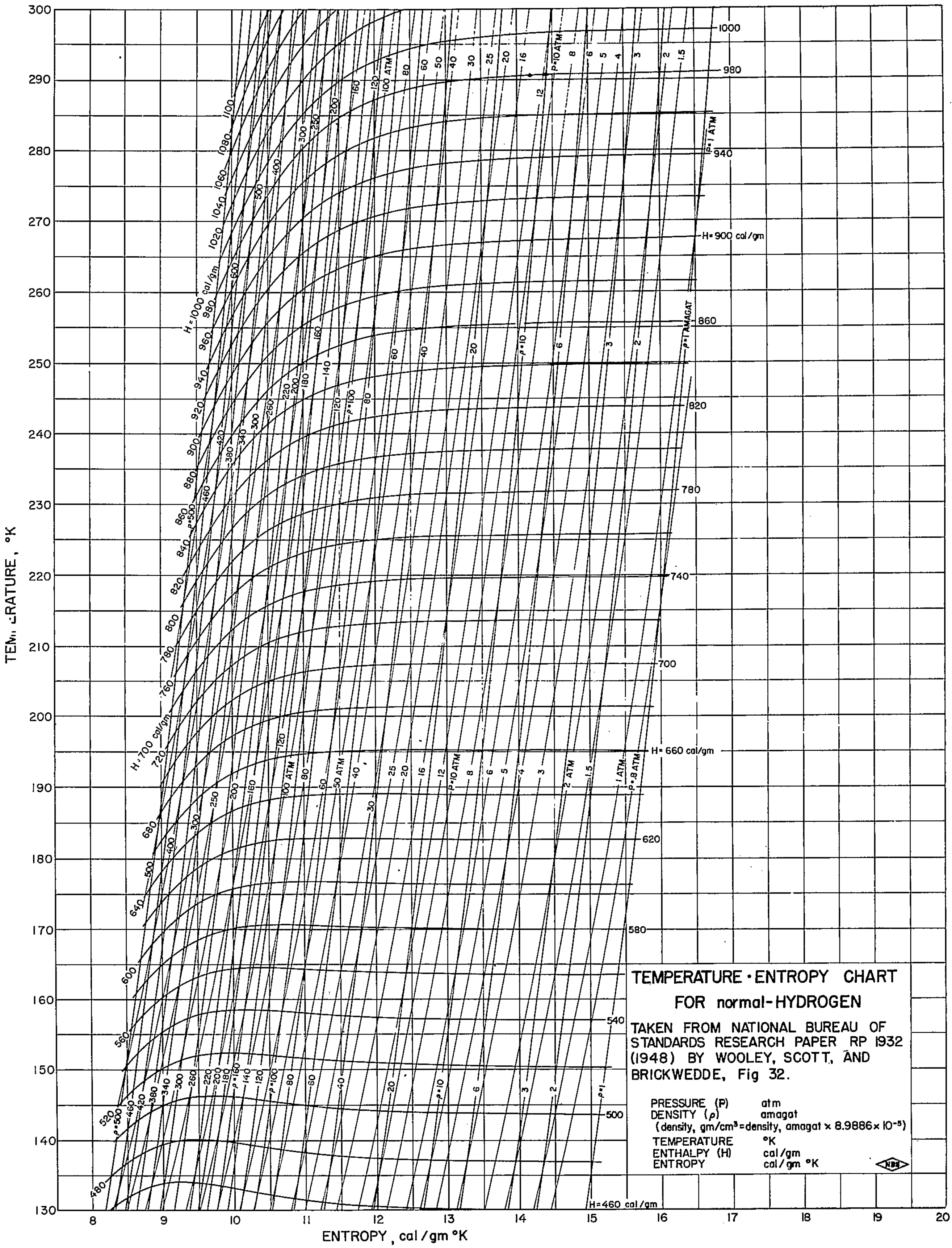
Temperature* °K	Heat of Vaporization cal/g mole
13.947	219.84
14	219.89
15	220.68
16	221.10
17	221.09
18	220.60
19	219.58
20	217.97
20.380	217.19
21	215.71
22	212.72
23	208.92
24	204.21
25	198.46
26	191.51
27	183.11
28	172.97
29	160.60
30	145.25
31	125.42

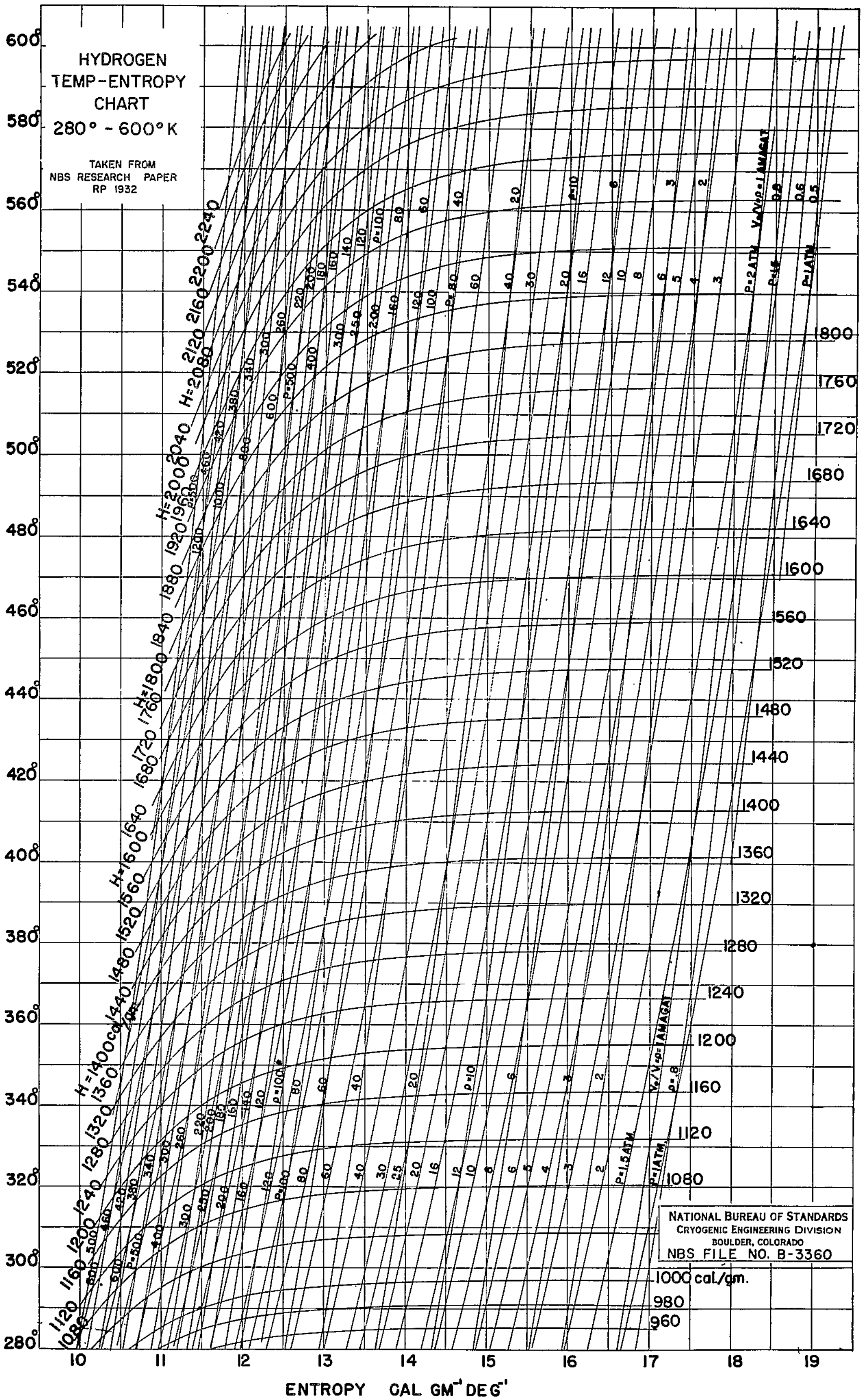
* Temperatures adjusted to NBS-1955 Temperature Scale.



Reprinted from NBS Report 8812


HYDROGEN
TEMP-ENTROPY
CHART
0° - 150° K
TAKEN FROM
NBS RESEARCH PAPER
RP 1932
NATIONAL BUREAU OF STANDARDS
CRYOGENIC ENGINEERING DIVISION
BOULDER, COLORADO
NBS FILE NO. F-3215
ENTROPY CAL GM⁻¹DEG⁻¹
H=300 cal/gm
H=200 cal/gm
310 cal./gm.
170 cal./gm.
80 cal/gm
10 ATM
1 ATM
P=10 ATM
P=0.6 ATM
K/V, ρ=1 AMAGAT


TEMPERATURE · ENTROPY CHART
FOR normal-HYDROGEN
TAKEN FROM NATIONAL BUREAU OF STANDARDS RESEARCH PAPER RP 1932 (1948) BY WOOLEY, SCOTT, AND BRICKWEDDE, Fig 32.
PRESSURE (P) atm
DENSITY (ρ) amagat
(density, gm/cm³=density, amagat × 8.9886×10⁻⁵)
TEMPERATURE °K
ENTHALPY (H) cal/gm
ENTROPY cal/gm °K
TEMPERATURE, °K
ENTROPY, cal/gm °K
H=460 cal/gm
H=660 cal/gm
H=700 cal/gm
H=900 cal/gm
H=1000 cal/gm
ρ=1 AMAGAT
P=1 ATM
P=10 ATM


HYDROGEN
TEMP-ENTROPY
CHART
280° - 600°K
TAKEN FROM
NBS RESEARCH PAPER
RP 1932
NATIONAL BUREAU OF STANDARDS
CRYOGENIC ENGINEERING DIVISION
BOULDER, COLORADO
NBS FILE NO. B-3360
ENTROPY CAL GM⁻¹ DEG⁻¹

NORMAL HYDROGEN

Properties of Vapor*

Temp °K	P = 1 atm (Sat temp = 20.39°K)			P = 2 atm (Sat temp = 22.97°K)			P = 5 atm (Sat temp = 27.29°K)			P = 10 atm (Sat temp = 31.41°K)			P = 15 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 Vapor)	751.1	718	39.16	398.7	729	37.16	162.7	730	34.21	70.89	691	31.02			
22	827.2	737	39.94												
24	917.6	760	41.00	425.0	742	37.71									
26	1006	782	41.93	474.4	767	38.72									
28	1094	804	42.75	522.0	791	39.60	172.4	742	34.64						
30	1180	826	43.50	568.2	814	40.40	197.2	774	35.72						
35	1393	880	45.16	680.1	871	42.13	251.0	842	37.81	104.7	782	33.75	37.29	636	28.51
40	1603	933	46.58	788.7	926	43.60	297.5	903	39.45	135.2	860	35.86	81.24	812	33.34
45	1812	985	47.82	895.5	979	44.87	345.8	961	40.82	162.3	928	37.46	100.2	891	35.22
50	2019	1038	48.92	1001	1032	46.00	390.5	1017	42.01	187.0	990	38.78	119.2	962	36.71
60	2431	1143	50.84	1210	1139	47.93	477.6	1127	44.02	233.6	1108	40.92	152.4	1088	39.02
70	2842	1248	52.46	1418	1245	49.57	562.8	1236	45.69	278.1	1221	42.67	183.4	1207	40.84
80	3252	1354	53.88	1624	1352	51.00	646.9	1345	47.15	321.5	1334	44.17	213.1	1323	42.39
90	3661	1463	55.16	1829	1461	52.28	730.3	1456	48.45	364.2	1446	45.50	242.2	1438	43.74
100	4070	1574	56.32	2034	1572	53.45	813.3	1568	49.63	406.5	1561	46.70	271.0	1554	44.97
120	4886	1804	58.42	2444	1803	55.55	978.3	1800	51.74	490.1	1796	48.84	327.5	1791	47.12
140	5702	2046	60.28	2852	2045	57.41	1143	2043	53.61	572.8	2040	50.72	382.9	2037	49.02
160	6517	2298	61.97	3260	2297	59.10	1307	2296	55.31	655.4	2295	52.43	438.4	2293	50.73
180	7332	2559	63.50	3668	2558	60.64	1470	2558	56.85	737.6	2557	53.97	493.4	2556	52.28
200	8147	2826	64.91	4076	2826	62.05	1634	2826	58.26	819.7	2826	55.39	548.3	2826	53.70
220	8961	3100	66.21	4484	3100	63.35	1797	3100	59.57	901.6	3100	56.70	603.1	3101	55.01
240	9776	3377	67.42	4891	3378	64.56	1960	3378	60.78	983.4	3379	57.91	657.8	3380	56.23
260	10589	3658	68.55	5298	3658	65.69	2123	3659	61.90	1065	3661	59.04	712.3	3663	57.36
280	11401	3941	69.60	5704	3942	66.74	2286	3943	62.95	1147	3945	60.09	766.7	3947	58.41
300	12219	4227	70.58	6113	4228	67.72	2450	4229	63.94	1228	4231	61.07	821.3	4233	59.40

Temp °K	P = 20 atm			P = 40 atm			P = 60 atm			P = 80 atm			P = 100 atm		
30							14.27	423	19.74	13.76	436	19.41	13.25	450	19.12
35							15.57	488	21.75	14.67	492	21.13	14.14	502	20.68
40	50.27	747	30.89				17.87	568	23.91	16.19	563	22.99	15.20	567	22.38
45	70.07	853	33.42	28.50	707	28.25	20.26	665	26.09	18.26	643	24.86	16.55	640	24.10
50	85.36	933	35.10	35.95	819	30.61	25.11	754	28.08	20.82	729	26.67	18.27	719	25.76
60	112.0	1069	37.59	52.49	994	33.80	34.56	935	31.41	26.95	900	29.79	22.95	881	28.64
70	136.1	1193	39.50	66.12	1139	36.04	43.91	1094	33.85	33.65	1061	32.28	28.01	1040	31.09
80	159.1	1312	41.09	78.66	1271	37.80	52.63	1236	35.76	40.20	1210	34.27	33.13	1192	33.12
90	181.4	1429	42.47	90.56	1397	39.29	60.87	1370	37.33	46.46	1349	35.91	38.12	1334	34.79
100	203.2	1547	43.71	102.1	1522	40.60	68.82	1501	38.70	52.53	1484	37.33	42.99	1471	36.24
120	246.0	1787	45.89	124.3	1771	42.87	84.08	1758	41.05	64.20	1748	39.73	52.40	1740	38.69
140	288.0	2035	47.80	146.0	2025	44.82	98.81	2017	43.04	75.40	2011	41.76	61.47	2008	40.75
160	329.9	2291	49.52	167.3	2286	46.58	113.3	2282	44.82	86.39	2281	43.56	70.32	2280	42.57
180	371.4	2556	51.08	188.4	2554	48.15	127.5	2554	46.42	97.17	2555	45.18	79.03	2557	44.20
200	412.7	2826	52.50	209.3	2827	49.59	141.6	2831	47.87	107.8	2832	46.64	87.60	2837	45.68
220	453.9	3102	53.82	230.1	3105	50.92	155.6	3110	49.20	118.4	3114	47.98	96.09	3120	47.03
240	495.0	3381	55.03	250.8	3387	52.14	169.5	3392	50.44	128.9	3399	49.22	104.5	3407	48.27
260	535.9	3664	56.16	271.4	3671	53.28	183.3	3679	51.58	139.3	3686	50.37	112.9	3695	49.42
280	576.8	3949	57.22	292.0	3957	54.34	197.1	3966	52.65	149.7	3975	51.44	121.2	3984	50.50
300	617.8	4236	58.21	312.6	4245	55.33	210.9	4254	53.64	160.0	4264	52.44	129.5	4275	51.50

* From published data, National Bureau of Standards, Technical Note 120 (Nov 1961)

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 density (ρ) in Amagat to density (lb/cu ft), multiply Amagat by .005611
- To convert enthalpy (h) in joules per gram (j/g) to (Btu/lb), multiply (j/g) by .42993
- To convert enthalpy (h) in calories per gram (cal/gm) to (Btu/lb), multiply (cal/gm) by 1.8
- To convert entropy (s) in joules per gram °K (j/g°K) to (Btu/lb°R), multiply (j/g°K) by .23885
- Entropy (s) in calories per gram °K (cal/gm°K) is equal to (Btu/lb°R)

PARAHYDROGEN

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
13.803[a]	0.0695	12.98	7966	-308.92	140.30	4.961	37.520	23	2.069	14.83	[illegible]	-226.37	200.52	9.287	27.856
14	0.0778	13.01	7203	-307.63	142.13	5.055	37.188	24	2.611	15.15	307.3	-213.92	202.66	9.783	27.152
15	0.133	13.16	4489	-300.74	151.11	5.527	35.650	25	3.245	15.51	249.0	-200.52	203.60	10.289	26.462
16	0.213	13.32	2955	-293.39	159.60	5.993	34.305	26	3.982	15.91	203.2	-185.99	203.10	10.810	25.787
17	0.325	13.48	2032	-285.60	167.58	6.454	33.115	27	4.829	16.39	166.7	-170.21	200.87	11.356	25.108
18	0.476	13.66	1449	-277.27	174.97	6.921	32.048	28	5.794	16.96	137.0	-152.90	196.51	11.926	24.413
19	0.673	13.86	1065	-268.39	181.67	7.382	31.076	29	6.887	17.66	112.5	-133.60	189.51	12.536	23.684
20	0.923	14.07	801.7	-258.91	187.67	7.853	30.188	30	8.118	18.54	91.86	-111.67	178.79	13.201	22.890
20.268[b]	1.000	14.13	747.6	-256.29	189.36	7.977	29.969	31	9.501	19.77	73.86	- 85.78	162.57	13.965	21.977
21	1.233	14.30	617.8	-248.79	193.03	8.325	29.374	32	11.051	21.74	57.16	- 52.24	136.08	14.923	20.811
22	1.613	14.56	482.9	-237.98	197.25	8.801	28.595	32.976[c]	12.759	31.82	31.82	38.27	38.27	17.567	17.567

* From published data, National Bureau of Standards Monograph 94 (Aug 1965).
† See Table 28 on page 59 for properties of liquid and vapor parahydrogen.
[a] Triple point.
[b] Normal boiling point.
[c] Critical point.

B- 62363

PARAHYDROGEN

Properties of Liquid and Vapor*†

Temp °K	P = 1 atm (Sat temp = 20.27°K)			P = 2 atm (Sat temp = 22.86°K)			P = 5 atm (Sat temp = 27.19°K)			P = 10 atm (Sat temp = 31.34°K)			P = 15 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)	14.24	-258	8.04	14.91	-230	9.29	16.62	-168	11.55	20.47	-76	14.37			
(Sat Vapor)	753.4	191	30.21	398.3	202	28.18	162.0	202	25.18	68.75	156	21.80			
15	13.25	-302	5.55	13.23	-301	5.54	13.19	-298	5.50	13.11	-292	5.43	13.04	-287	5.16
20	14.18	-261	7.91	14.15	-260	7.89	14.07	-257	7.82	13.95	-252	7.72	13.83	-247	7.62
25	970.0	234	32.18	453.7	229	29.35	15.53	-201	10.30	15.27	-198	10.11	15.05	-195	9.94
30	1190	301	34.66	572.9	290	31.54	198.7	249	26.82	18.21	-116	13.07	17.38	-121	12.62
35	1404	355	36.33	685.5	346	33.29	253.0	317	28.94	105.1	256	24.63	47.28	144	20.57
40	1616	409	37.76	795.0	402	34.76	301.9	379	30.58	136.5	336	26.98	80.18	286	24.39
50	2035	515	40.13	1009	510	37.18	393.5	494	33.16	188.3	467	29.91	120.1	439	27.83
60	2451	623	42.08	1220	618	39.16	481.2	607	35.21	235.3	587	32.10	153.5	568	30.18
70	2865	732	43.78	1429	729	40.86	567.1	720	36.96	280.1	705	33.92	184.6	690	32.07
80	3278	847	45.31	1636	845	42.41	651.8	838	38.53	323.8	826	35.53	214.6	815	33.78
100	4102	1101	48.14	2050	1099	45.24	819.6	1094	41.39	409.4	1087	38.44	272.9	1080	36.68
120	4887	1378	50.41	2444	1377	47.54	978.3	1373	43.73	489.9	1368	40.82	327.2	1363	39.10
140	5703	1688	52.80	2853	1687	49.93	1143	1685	46.13	572.6	1681	43.23	382.6	1678	41.52
160	6518	2012	54.96	3261	2011	52.09	1307	2010	48.30	655.2	2008	45.41	438.1	2006	43.71
180	7333	2339	56.89	3669	2339	54.02	1470	2338	50.23	737.4	2337	47.34	493.2	2335	45.65
200	8148	2663	58.60	4077	2663	55.73	1634	2663	51.94	819.5	2662	49.06	548.0	2662	47.37
220	8962	2982	60.11	4484	2982	57.25	1797	2982	53.46	901.4	2982	50.59	602.8	2982	48.90
240	9777	3294	61.47	4892	3294	58.61	1960	3295	54.82	983.2	3295	51.95	657.5	3296	50.26
260	10590	3600	62.70	5298	3601	59.84	2123	3601	56.05	1065	3602	53.18	712.0	3604	51.50
280	11403	3902	63.82	5705	3902	60.95	2286	3903	57.17	1146	3905	54.30	766.5	3906	52.62
300	12220	4201	64.85	6114	4201	61.98	2450	4202	58.20	1228	4204	55.33	821.1	4206	53.65

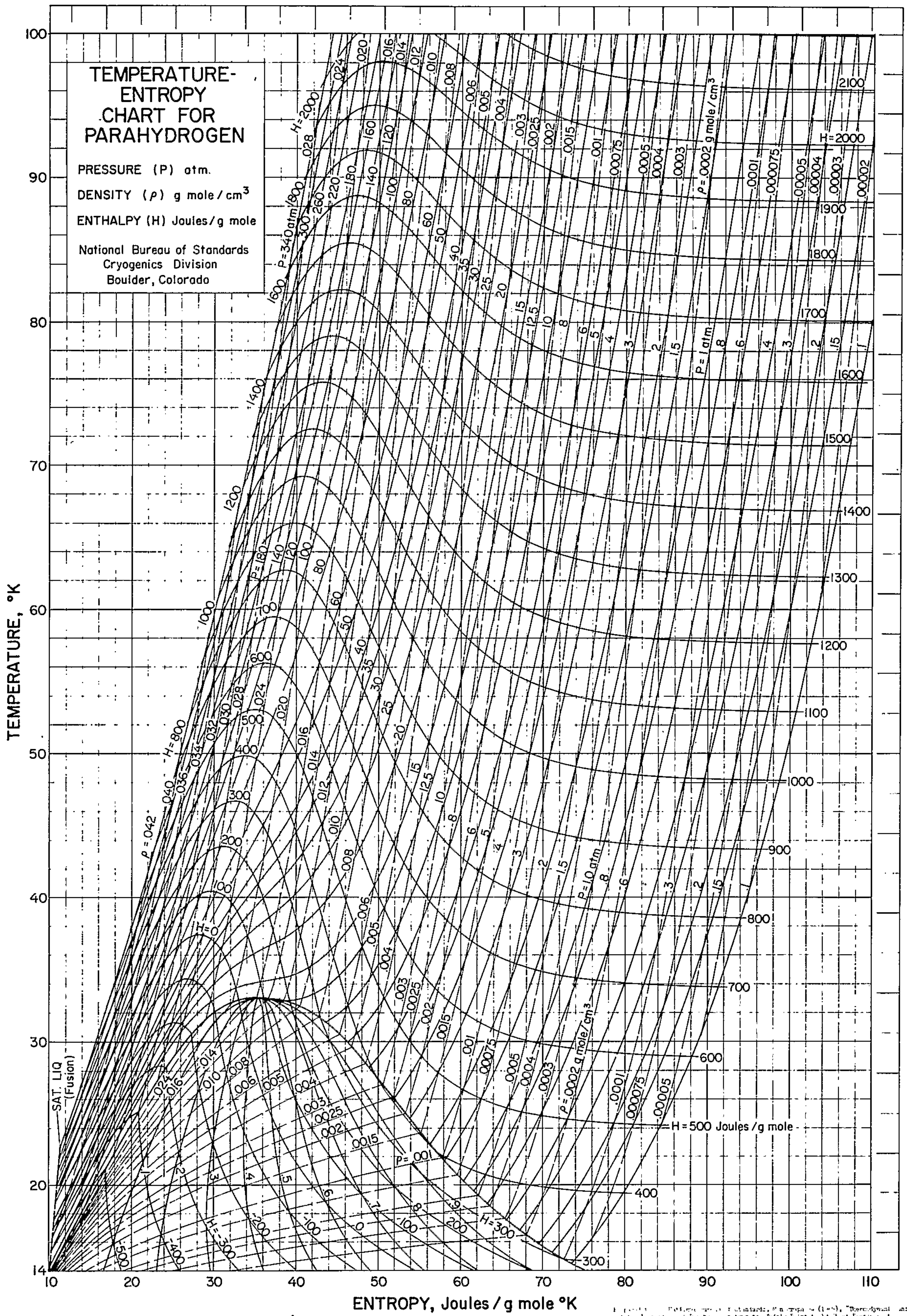
Temp °K	P = 20 atm			P = 40 atm			P = 60 atm			P = 80 atm			P = 100 atm		
15	12.97	-281	5.29												
20	13.73	-242	7.52	13.36	-221	7.19	13.07	-200	6.91	12.82	-179	6.67	12.60	-157	6.45
25	14.85	-191	9.79	14.25	-174	9.30	13.62	-155	8.92	13.46	-135	8.60	13.17	-115	8.33
30	16.82	-122	12.30	15.55	-114	11.46	14.81	-100	10.91	14.29	-83	10.48	13.88	-65	10.13
35	22.96	0	16.01	17.66	-39	13.78	16.22	-35	12.92	15.37	-23	12.34	14.77	-8.4	11.88
40	51.30	223	22.01	21.63	61	16.45	18.28	43	14.99	16.81	46	14.18	15.90	56	13.59
50	85.98	410	26.22	37.31	296	21.70	25.37	231	19.16	21.15	212	17.76	19.03	202	16.86
60	[illegible]	548	28.74	52.90	473	24.94	34.89	416	22.54	27.25	381	20.93	23.32	364	19.80
70	[illegible]	676	30.42	66.58	622	27.24	44.22	577	25.04	33.91	545	23.47	28.27	525	22.29
80	160.2	813	32.42	79.22	762	29.11	53.00	728	27.05	40.47	701	25.55	33.36	682	24.39
100	204.6	1072	35.42	102.8	1047	32.28	69.38	1025	30.37	52.91	1008	28.98	43.29	996	27.89
120	245.9	1359	37.87	124.3	1342	34.84	84.09	1329	33.01	64.25	1319	31.69	52.46	1311	30.65
140	287.9	1675	40.30	145.9	1664	37.32	98.83	1656	35.53	75.44	1651	34.25	61.53	1648	33.24
160	329.7	2004	42.50	167.3	1997	39.54	113.3	1993	37.78	86.43	1992	36.52	70.38	1991	35.54
180	371.2	2334	44.44	188.3	2331	41.51	127.5	2331	39.77	97.22	2332	38.53	79.08	2334	37.56
200	412.5	2662	46.17	209.3	2662	43.25	141.6	2665	41.53	107.9	2667	40.29	87.65	2671	39.33
220	453.7	2983	47.70	230.1	2985	44.79	155.6	2989	43.08	118.4	2994	41.85	96.15	3000	40.90
240	494.8	3297	49.07	250.8	3301	46.16	169.5	3306	44.46	128.9	3313	43.24	104.6	3321	42.29
260	535.8	3605	50.30	271.4	3611	47.40	183.3	3618	45.70	139.3	3626	44.49	112.9	3634	43.55
280	576.7	3908	51.42	292.0	3915	48.53	197.1	3923	46.84	149.7	3932	45.63	121.3	3942	44.69
300	617.7	4208	52.46	312.5	4216	49.57	210.9	4225	47.88	160.1	4235	46.67	129.6	4245	45.74

Temp °K	P = 140 atm			P = 200 atm			P = 240 atm			P = 300 atm			P = 340 atm		
20	12.24	-114	6.08	11.81	-50	5.62									
25	12.70	-74	7.87	12.18	-12	7.32	11.91	29	7.01	11.56	90	6.62	11.36	131	6.39
30	13.27	-27	9.57	12.62	32	8.92	12.28	72	8.57	11.88	132	8.12	11.65	171	7.86
35	13.94	26	11.19	13.12	81	10.44	12.71	119	10.04	12.23	178	9.23	11.87	216	9.25
40	14.74	84	17.75	13.69	135	11.88	13.20	171	11.43	12.63	228	10.87	12.32	265	10.55
50	16.77	215	15.67	15.05	254	14.53	14.33	286	13.98	13.53	337	13.32	13.12	373	12.94
60	19.40	360	18.31	16.71	386	16.93	15.67	413	16.28	14.58	458	15.52	14.04	491	15.20
70	22.50	511	20.65	18.63	526	19.09	17.19	548	18.36	15.75	588	17.51	15.06	618	17.05
80	25.84	666	22.70	20.74	673	21.06	18.87	690	20.27	17.03	726	19.35	16.16	753	18.86
100	32.71	983	26.24	25.25	986	24.54	22.48	998	23.70	19.79	1027	22.71	18.54	1051	22.17

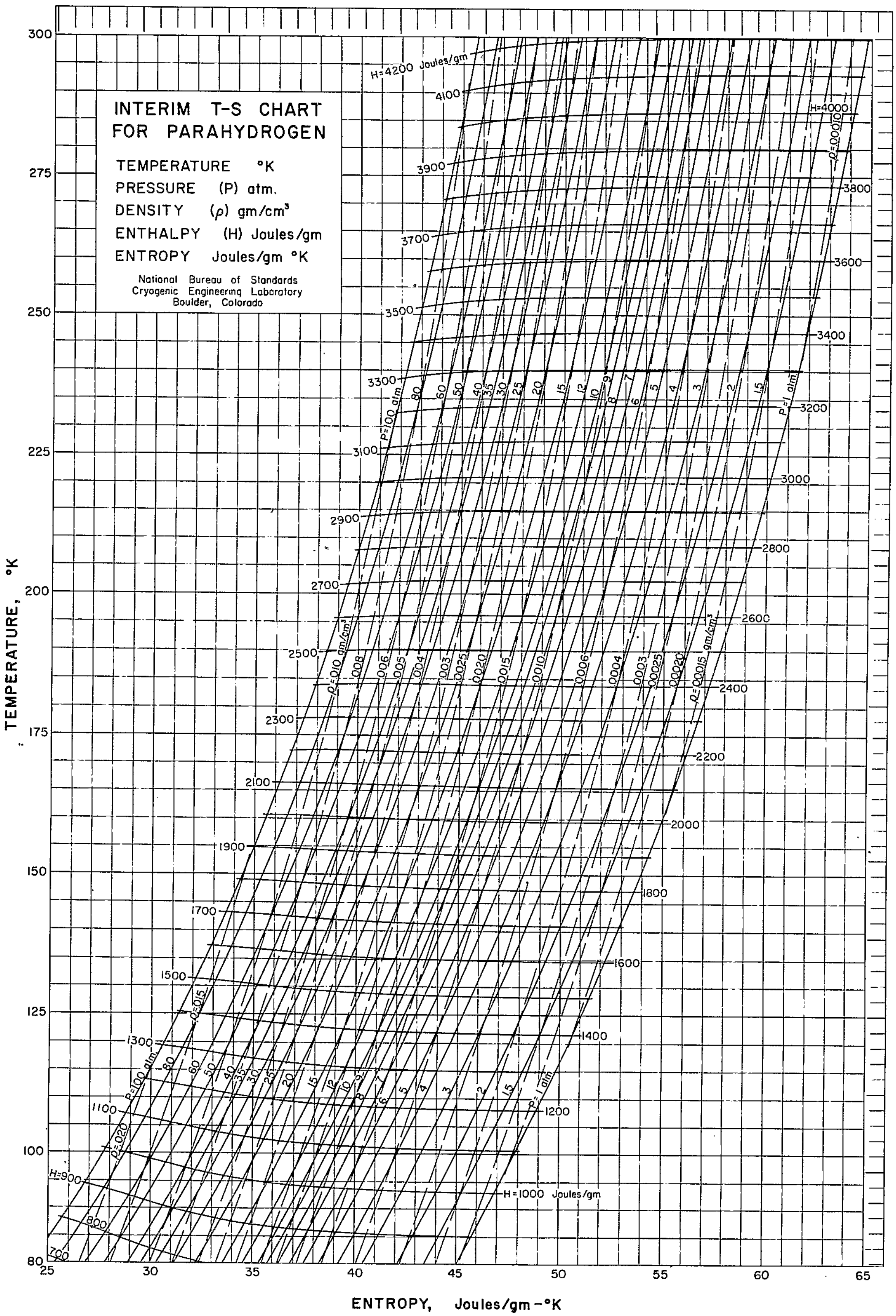
* Data from 15 to 100°K, from published data, National Bureau of Standards Monograph 94 (Aug 1965).
Data from 120 to 300°K, published data from National Bureau of Standards, Technical Note 130 (Dec 1961).
† See Table 27 on page 55 for properties of saturated liquid and saturated vapor parahydrogen.
Bold 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

B-62364


TEMPERATURE-ENTROPY CHART FOR PARAHYDROGEN
PRESSURE (P) atm.
DENSITY (ρ) g mole/cm3
ENTHALPY (H) Joules/g mole
National Bureau of Standards
Cryogenics Division
Boulder, Colorado
TEMPERATURE, °K
ENTROPY, Joules/g mole °K
SAT. LIQ (Fusion)
P=340 atm
P=1 atm
P=10 atm
P=.0002 g mole/cm3
H=2000
H=500 Joules/g mole
H=800
P=.042
P=.001
H=300

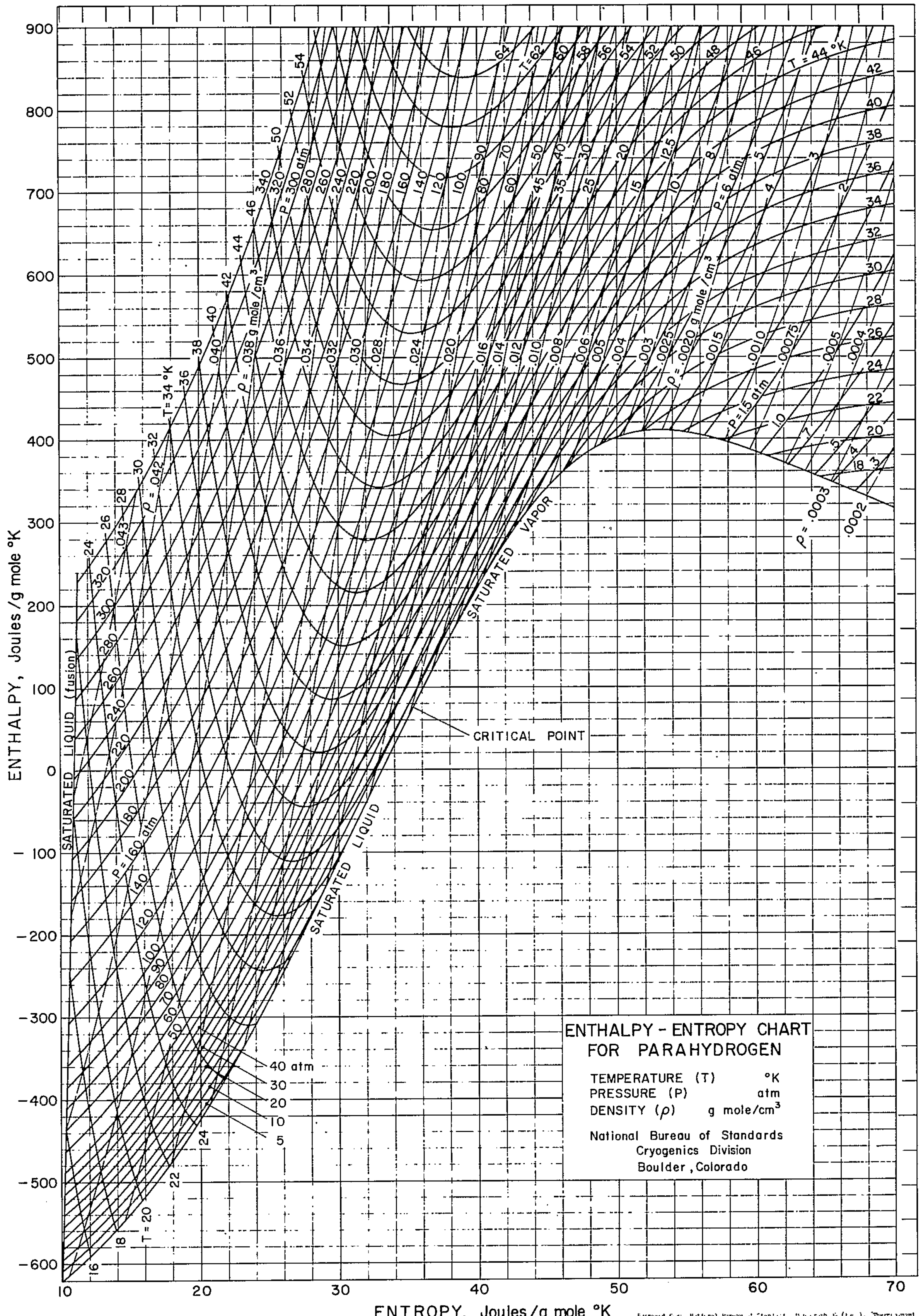
[illegible]



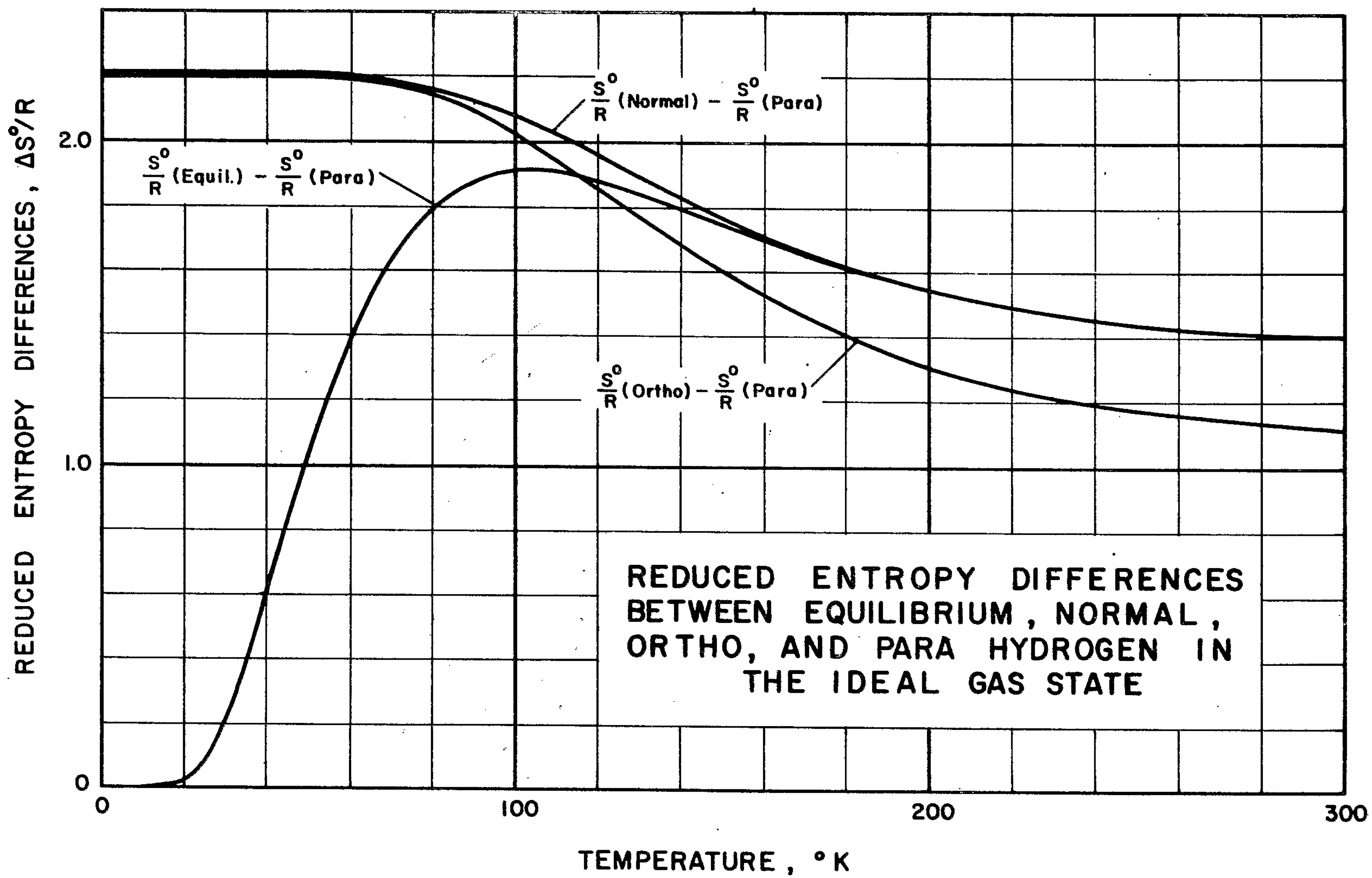
III-H-4.2

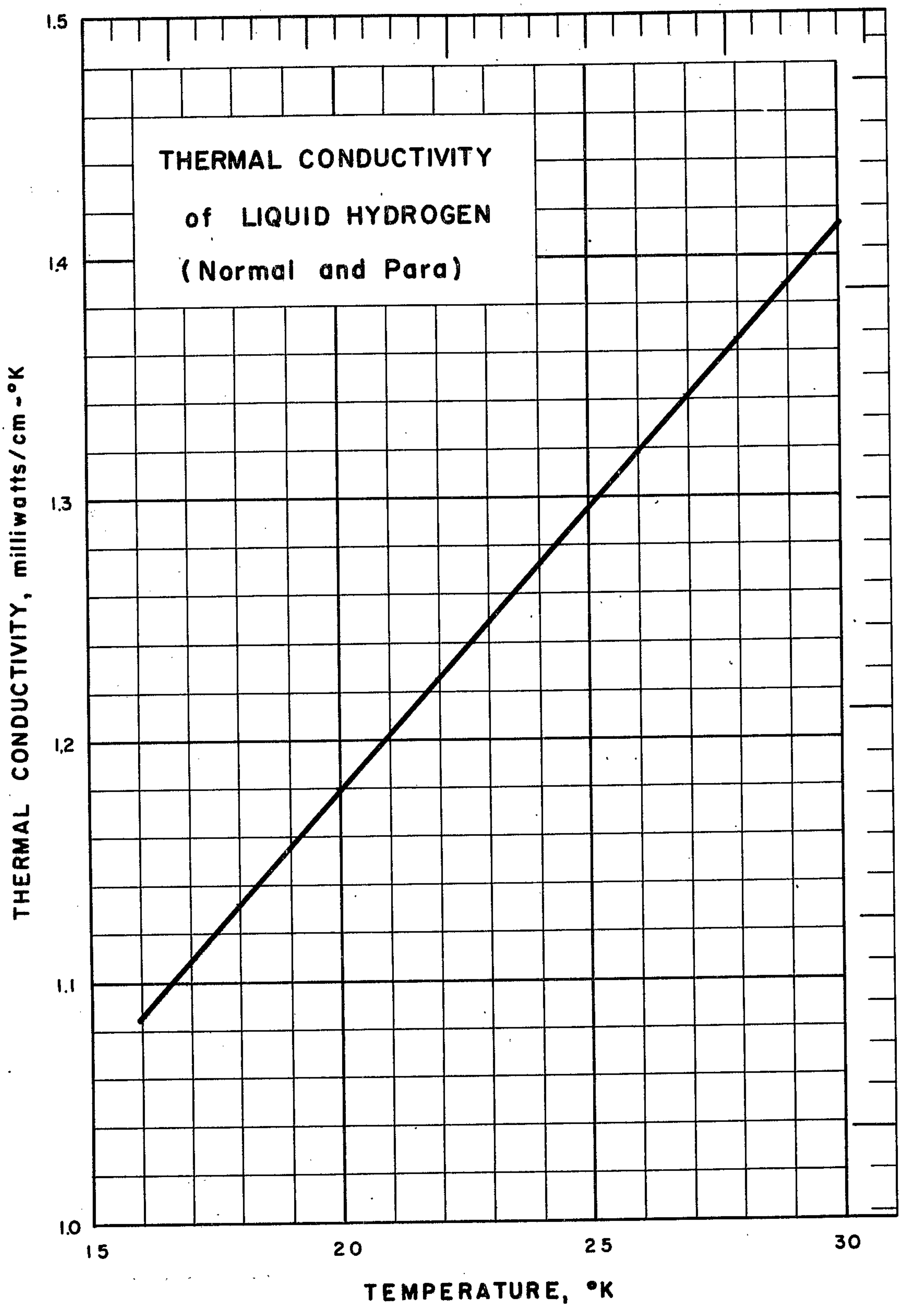
Prepared for: National Bureau of Standards, Technical Note, TN 130 (PB161631) December 1961, "Provisional Thermodynamic Functions for Parahydrogen", H. M. Roder and R. D. Goodwin; by the Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado, from property functions reported in NBS TN 130. These functions were used to calculate temperature and entropy for all intersections of isobars and isenthalps and for intersections of isobars and isometric lines. Additional points were also calculated as necessary to complete the precise definition of the property lines.

P. D. Stewart, R. D. McCarty, T. W. Griffith (December 1961)


ENTHALPY - ENTROPY CHART
FOR PARAHYDROGEN
TEMPERATURE (T) °K
PRESSURE (P) atm
DENSITY (ρ) g mole/cm³
National Bureau of Standards
Cryogenics Division
Boulder, Colorado
ENTHALPY, Joules/g mole °K
ENTROPY, Joules/g mole °K
SATURATED LIQUID (fusion)
SATURATED LIQUID
SATURATED VAPOR
CRITICAL POINT
T = 44 °K
T = 34 °K
T = 62
T = 20
P = 300 atm
P = 160 atm
P = 6 atm
P = 1.5 atm
ρ = .038 g mole/cm³
ρ = .0020 g mole/cm³
ρ = .042
ρ = .0003
40 atm
30
20
10
5

Reprinted from NBS Report 8812




THERMAL CONDUCTIVITY
of LIQUID HYDROGEN
(Normal and Para)
1.5
1.4
1.3
1.2
1.1
1.0
THERMAL CONDUCTIVITY, milliwatts/cm-°K
15
20
25
30
TEMPERATURE, °K

THERMAL CONDUCTIVITY of LIQUID NORMAL and PARA HYDROGEN

Source of Data: Powers, R. W., Mattox, R. W., and Johnston, H. L., J. Am. Chem. Soc. 76, 5968 and 5972 (1954).

Other References: Borovik, E., Matveev, A. and Panina, E., J. Tech. Phys. (U.S.S.R.) 10, 998 (1940); Schaefer, C. A., and Thodos, G., Ind. Eng. Chem. 50, 1585 (1958).

Comments: The only available information on the thermal conductivity of liquid hydrogen is that of Powers, Mattox and Johnston, who find that there is no significant difference between the conductivity of normal and of para hydrogen. They reduced their data to a straight line curve having the equation

$$k = (1.702 + 0.05573\ T) \times 10^{-4}\ \text{cal cm}^{-1}\ \text{sec}^{-1}\ \text{deg}^{-1}.$$

Data for both normal and para hydrogen are shown on this curve of experimental points, and the probable error of 2% is greater than the differences in the conductivities of the normal and para forms. In the measurements, corrections were made in the case of normal hydrogen, for the heat liberated in the spontaneous conversion of the normal to the para form. The curve has a positive slope showing that the thermal conductivity increases with temperature. This contrasts with the change of thermal conductivities of other low boiling liquids N_2, CO, CH_4 and and C_2H_4 previously investigated, which show a decreasing conductivity with rising temperature as shown by the work of Powers, Mattox and Johnston, and by Borovik, Matveev and Panina.

Schaefer and Thodos have developed curves showing a Reduced Thermal Conductivity Correlation for gaseous and liquid hydrogen, using data of other investigators.

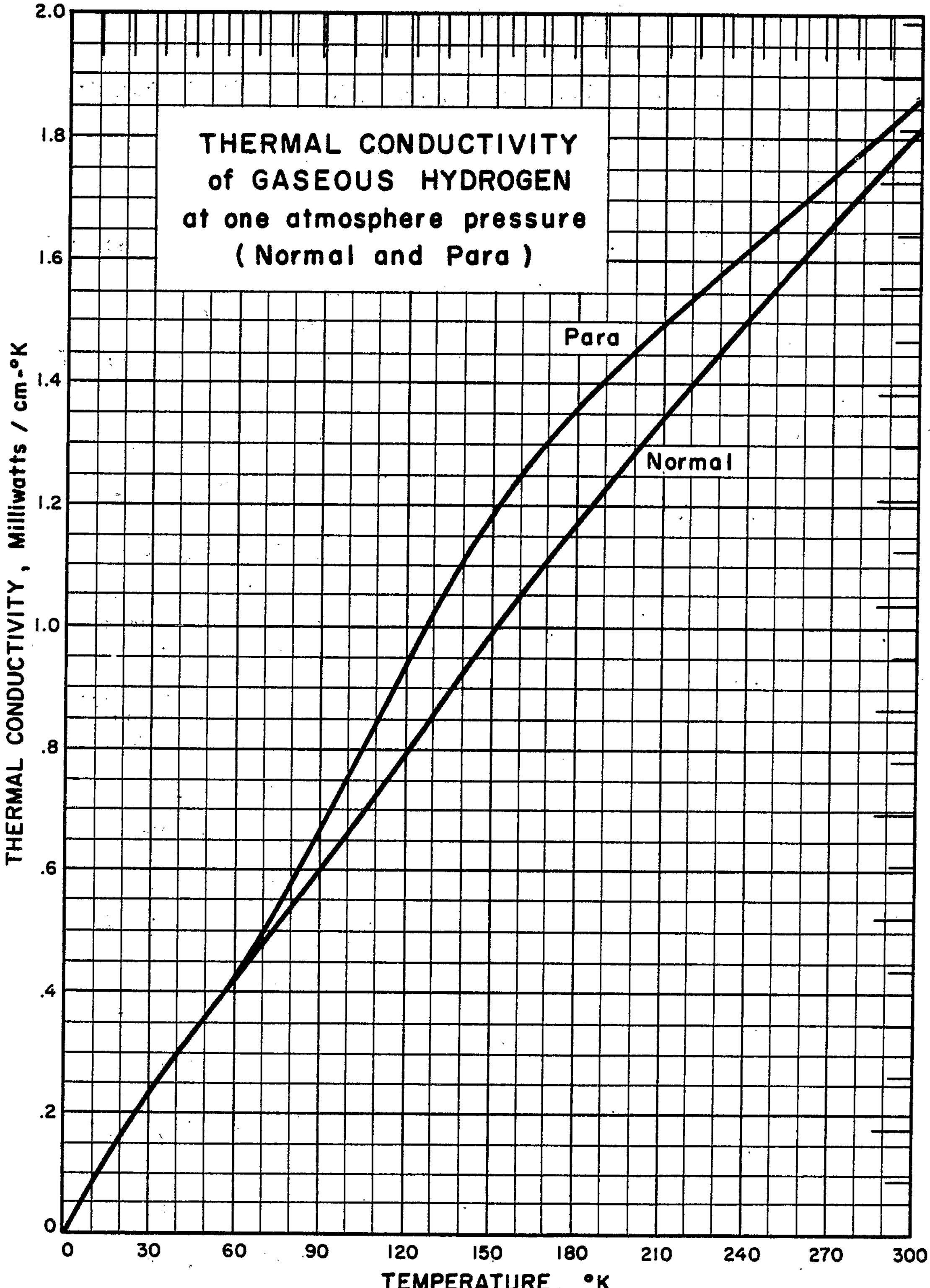
No data on thermal conductivity of solid hydrogen has been found.

Thermal conductivity values computed from the equation:

$$k = (1.702 + .05573\ T)\ 10^{-4}\ \text{cal/cm sec °K}$$

Temp. °K	K watts/cm °K	k cal/cm sec °K	Temp. °K	K watts/cm °K	k cal/cm sec °K
16	10.85×10^{-4}	2.593×10^{-4}	24	12.72×10^{-4}	3.040×10^{-4}
17	11.08 "	2.649 "	25	12.95 "	3.095 "
18	11.32 "	2.705 "	26	13.18 "	3.151 "
19	11.55 "	2.761 "	27	13.42 "	3.207 "
20	11.79 "	2.817 "	28	13.65 "	3.262 "
21	12.02 "	2.872 "	29	13.88 "	3.318 "
22	12.25 "	2.928 "	30	14.12 "	3.374 "
23	12.48 "	2.984 "			

Reprinted from WADD TECH. REPORT 60-56


THERMAL CONDUCTIVITY
of GASEOUS HYDROGEN
at one atmosphere pressure
(Normal and Para)
Para
Normal
THERMAL CONDUCTIVITY, Milliwatts / cm-°K
TEMPERATURE, °K
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
30
60
90
120
150
180
210
240
270
300

THERMAL CONDUCTIVITY of GASEOUS HYDROGEN

(Normal and Para)

Sources of Data:

Farkas, A., Ortho-Para Hydrogen and Heavy Hydrogen, Cambridge University Press (1935)

Hilsenrath, J., et al., Nat. Bur. Standards Cir. 564, 285 (1955)

Other References:

Andrussow, L., J. Chim. Phys. 52, 295 (1955)

Godridge, A. M., Bull. Brit. Coal Utilisation Research Assoc. 18, 1 (1954)

Johnston, H. L. and Grilly, E. R., J. Chem. Phys. 14, 233 (1946)

Schaefer, C. A. and Thodos, G., Ind. Eng. Chem. 50, 1585 (1958)

Weitzel, D. H. and Hershey, R. L., Cryogenic Eng. Conf. Proc., Paper 2.02 (1954)

Comments:

The lower curve, being that for normal hydrogen, represents the data given in the Nat. Bur. Standards Cir. 564.

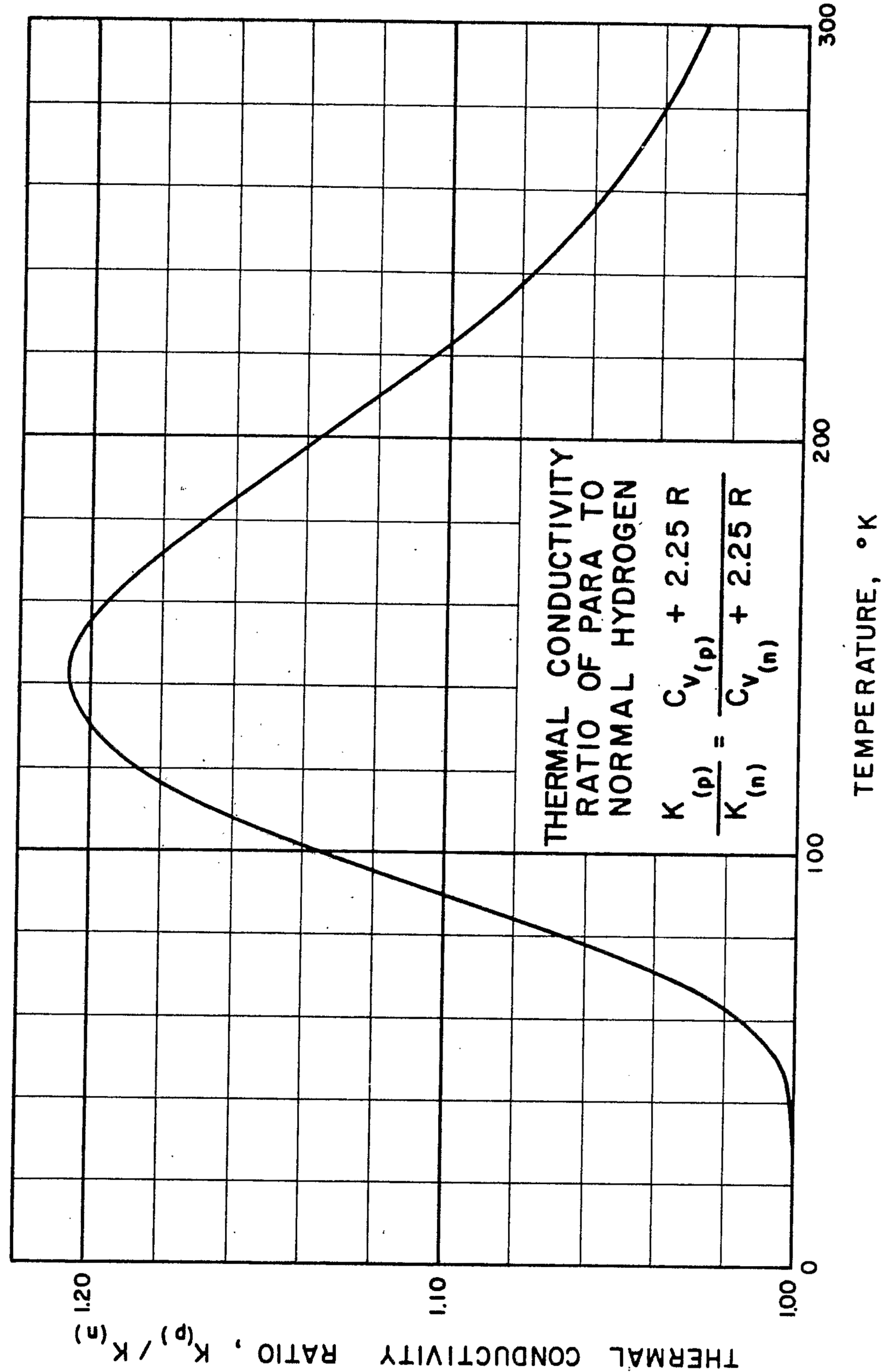
Table 1. Selected Values of Thermal Conductivity from Circular 564 for **Gaseous Normal** Hydrogen and Corresponding Values Computed for **Gaseous Para** Hydrogen

Temp. °K	k_n milliwatt / cm °K	k_p/k_n	k_p milliwatt / cm °K
10	0.074	1.000	0.074
20	0.155	1.000	0.155
30	0.229	1.000	0.229
40	0.298	1.001	0.298
50	0.362	1.004	0.363
60	0.422	1.017	0.429
80	0.542	1.066	0.578
100	0.664	1.136	0.754
120	0.790_5	1.190	0.941
140	0.918	1.204	1.105
160	1.043	1.195	1.246
180	1.166	1.167	1.361
200	1.282	1.135	1.455
220	1.398	1.103	1.542
240	1.507	1.076	1.621_5
260	1.613	1.055	1.702
270	1.665	1.046	1.741_5
280	1.717	1.039	1.784
300	1.816_5	1.027	1.865_5

Reprinted from WADD TECH. REPORT 60-56

Table 2. k_p/k_n Values computed **by Farkas**

Temp. °K	k_p/k_n
30	1.000
40	1.001
50	1.004
75	1.051
100	1.136
125	1.196
150	1.203
175	1.175
200	1.135
225	1.096
250	1.065
273	1.044
298	1.028



Reprinted from NBS Report 8812

DIELECTRIC CONSTANT OF LIQUID HYDROGEN

Source of Data:

Stewart, J. W. (1964), The Dielectric Polarizability of Fluid Parahydrogen., J. Chem. Phys. (in press).

Other References:

Breit, G., and Onnes, H. K. (1924), Preliminary Measurements Concerning the Dielectric Constant of Liquid Hydrogen and Liquid Oxygen and Its Dependence on Temperature as Regards the Latter Substance., Kon. Akad. Wetenschap. Amsterdam 33, 705-8; Proc. Acad. Sci. Amsterdam 27, 617-20 (1924); Communs. Phys. Lab. Univ. Leiden No. 171a (1924); C.A. 19, 758 (1925).

Wolfke, M., and Onnes, H. K. (1924), On the Dielectric Constant of Liquid and Solid Hydrogen., Kon. Acad. Sci. Amsterdam 33, 701-4; Proc. Acad. Sci. Amsterdam 27, 627-30 (1924); Communs. Phys. Lab. Univ. Leiden 171c (1924); C.A. 19, 758 (1925).

Werner, W., and Keesom, W. H. (1925), The Variation of the Dielectric Constant of Liquid and Solid Hydrogen with Temperature., Kon. Acad. Wetenschap. Amsterdam 34, 745-54; Communs. Phys. Lab. Univ. Leiden No. 178a (1926); C.A. 20, 1168 (1926).

Guillien, R. (1939), The Dielectric Constants of Hydrogen., Rev. Sci. 77, 575; Chem. Zentr. 1940, II, 1839; C.A. 36, 6851 (1942).

Guillien, R. (1940), La Constante diélectrique au Voisinage du Point de Fusion. (The Dielectric Constant in the Vicinity of the Fusion Point.), J. Phys. radium (8) 1, 29-33; C.A. 34, 3145 (1940).

Van Itterbeek, A., and Spaepen, J. (1942), Détermination de la Constante Diélectrique du Deuterium Liquide. (Determination of the Dielectric Constant of Liquid Deuterium.), Physica 9, 339-44; C.A. 37, 5292 (1943).

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

Comments:

Stewart reports the dielectric constant of parahydrogen for the range 24 to 100°K at densities up to 0.08 g/cm^3. The experiment shows that the dielectric constant depends only on density. Tabular values are presented as calculated from the following equation: $(\epsilon + 2)\rho/(\epsilon - 1) = 0.99575 - 0.09069\rho + 1.1227\rho^2$ with ρ in g/cm^3. Since the values are tabulated as a function of density the usual distinction between gas and liquid could not be accomplished and so all of the values are tabulated as liquid hydrogen data.

The earliest measurements on the dielectric constants of saturated liquid hydrogen were made by Breit and Onnes. They report values for 7 to 76 cm Hg and 14.42 to 20.38°K.

Wolfke and Onnes continued the above work and obtained additional values over the same range.

From a series of experiments at various dates, Werner and Keesom concluded that the best value of the dielectric constant of hydrogen at 20.36°K (the boiling point) was 1.2311 to an accuracy of 0.02%. They also report 14 values between 14.10 and 20.49°K.

Guillien used a wave length of 2.250 m and reported values from 14.00 to 20.60°K.

Van Itterbeek and Spaepen report a value of 1.226 at 755 mm of Hg and 20.35°K.

Maryott and Smith have selected the value of 1.228 at 20.4°K and 1 atmosphere.

DIELECTRIC CONSTANT OF LIQUID HYDROGEN
(cont.)

Stewart (1964)	
Density (g/cm^3)	Dielectric Constant
0.005	1.01515
0.010	1.03046
0.015	1.04594
0.020	1.06158
0.025	1.07739
0.030	1.09336
0.035	1.10950
0.040	1.12580
0.045	1.14226
0.050	1.15889
0.055	1.17569
0.060	1.19265
0.065	1.20977
0.070	1.22705
0.075	1.24449
0.080	1.26210

Taken from NBS Report 8252

Dielectric constant and Clausius–Mossotti function for fluid *para*-hydrogen.

Density (10^{-7}g/cm^3)	Temp. °K	Dielectric constant	$\Delta\rho/\rho$ %	Corr. CM cm^3/g
0016765	28	1.00505	+0.036	1.00228
0025715	28	1.00776	+0.039	1.00304
0026519	40	1.00801	+0.030	1.00359
0034449	28	1.01041	+0.035	1.00339
0037412	32	1.01132	+0.024	1.00449
0050222	50	1.01521	+0.004	1.00421
0056184	38	1.01702	+0.029	1.00374
0056650	80	1.01717	−0.007	1.00481
0057170	33	1.01733	+0.035	1.00455
0059522	80	1.01805	−0.027	1.00495
0060153	32	1.01825	+0.036	1.00505
0060244	55	1.01826	+0.003	1.00413
0067220	65	1.02040	−0.036	1.00506
0075221	40	1.02284	+0.038	1.00390
0077718	100	1.02362	−0.029	1.00546
0079296	90	1.02410	−0.041	1.00527
0081568	42	1.02478	0	1.00441
0088321	32	1.02692	+0.042	1.00669
0089202	60	1.02712	−0.005	1.00449
0090032	46	1.02739	0	1.00491
0092193	55	1.02807	−0.004	1.00537
0094574	48	1.02879	+0.011	1.00499
0098575	70	1.03002	−0.014	1.00515
0104944	34	1.03204	+0.061	1.00639
0115753	32	1.03545	+0.068	1.00837
0115854	50	1.03534	+0.003	1.00498
0123237	80	1.03764	−0.010	1.00466
0125571	37	1.03839	+0.074	1.00544
0126507	55	1.03865	+0.003	1.00533
0136309	80	1.04169	−0.030	1.00578
0141772	40	1.04337	+0.051	1.00456
0148742	65	1.04557	−0.033	1.00634
0149419	32	1.04601	+0.119	1.00888
0151000	44	1.04624	+0.035	1.00490
0160449	100	1.04918	−0.034	1.00561
0163584	90	1.05017	−0.043	1.00592
0173114	80	1.05316	−0.013	1.00584
0173229	33	1.05325	+0.219	1.00459
0180477	38	1.05551	+0.132	1.00530
0186593	46	1.05743	0	1.00667
0195968	55	1.06033	−0.013	1.00607
0196746	42	1.06064	0	1.00698
0205823	80	1.06341	−0.033	1.00608
0206474	50	1.06362	+0.009	1.00560
0210203	34	1.06496	+0.286	1.00536
0218806	70	1.06748	−0.017	1.00555
0220768	90	1.06812	−0.047	1.00621
0221520	60	1.06833	−0.005	1.00530
0221767	48	1.06850	+0.015	1.00646
0223416	34	1.06941	+0.518	1.00689
0224424	65	1.06926	−0.032	1.00585
0225738	100	1.06968	−0.037	1.00590
0238542	80	1.07374	−0.016	1.00587
0249848	55	1.07734	−0.014	1.00609
0253596	40	1.07861	+0.091	1.00596
0264823	46	1.08216	0	1.00656
0281923	80	1.08753	−0.030	1.00592
0283158	37	1.08817	+0.224	1.00607
0286633	90	1.08904	−0.047	1.00611
0293817	50	1.09133	+0.009	1.00546
0296176	55	1.09213	−0.007	1.00605
0300691	42	1.09362	0	1.00644
0301108	80	1.09367	−0.018	1.00576
0309977	65	1.09653	−0.031	1.00601
0315579	60	1.09831	−0.005	1.00549
0316387	44	1.09863	+0.048	1.00556
0326522	100	1.10184	−0.048	1.00598
0328298	48	1.10248	+0.019	1.00598
0336164	70	1.10495	−0.017	1.00562
0346550	55	1.10838	−0.006	1.00616
0347869	80	1.10875	−0.030	1.00586
0348913	90	1.10908	−0.045	1.00596
0349320	55	1.10922	+0.006	1.00553
0358512	80	1.11219	−0.024	1.00576
0360054	50	1.11269	+0.008	1.00541
0398586	65	1.12530	−0.026	1.00611
0400016	42	1.12579	0	1.00600
0400223	70	1.12579	−0.015	1.00567
0401574	40	1.12634	+0.061	1.00569
0404005	55	1.12710	−0.005	1.00613
0405146	50	1.12741	+0.009	1.00548
0407482	60	1.12817	−0.004	1.00556
0409102	100	1.12870	−0.070	1.00617
0409185	46	1.12880	0	1.00608
0418687	55	1.13187	+0.002	1.00566
0421467	38	1.13300	+0.087	1.00635
0422553	48	1.13321	+0.014	1.00602
0423174	34	1.13359	+0.167	1.00578
0423378	80	1.13340	−0.031	1.00589
0423652	80	1.13350	−0.026	1.00588
0430425	90	1.13572	−0.041	1.00600
0435756	33	1.13761	+0.110	1.00537
0449143	70	1.14189	−0.013	1.00564
0450937	55	1.14527	−0.002	1.00606
0465613	55	1.14736	+0.004	1.00554
0466349	60	1.14758	−0.003	1.00546
0474182	32	1.15050	+0.090	1.00653
0478433	90	1.15162	−0.040	1.00594
0482057	44	1.15290	+0.021	1.00578
0483569	80	1.15333	−0.025	1.00577
0485595	80	1.15399	−0.020	1.00566
0489245	100	1.15517	−0.098	1.00620
0491168	40	1.15598	+0.034	1.00592
0505522	55	1.16073	−0.002	1.00593
0506885	90	1.16110	−0.039	1.00580
0508042	60	1.16147	−0.003	1.00536
0508572	55	1.16168	+0.004	1.00547
0511043	46	1.16260	−0.002	1.00608
0511195	33	1.16276	+0.044	1.00627
0511906	42	1.16289	−0.003	1.00606
0513428	34	1.16371	+0.062	1.00726
0516423	65	1.16433	−0.021	1.00580
0516663	70	1.16435	−0.012	1.00540
0520167	37	1.16575	+0.043	1.00612
0527490	40	1.16813	+0.023	1.00586
0529592	38	1.16888	+0.033	1.00595
0535897	55	1.17085	+0.002	1.00541
0536103	100	1.17082	−0.100	1.00591
0540023	33	1.17240	+0.037	1.00597
0541247	34	1.17283	+0.032	1.00607
0541535	80	1.17271	−0.022	1.00546
0545577	80	1.17406	−0.017	1.00534
0546103	48	1.17438	+0.006	1.00589
0547645	30	1.17521	+0.078	1.00679
0555256	40	1.17748	+0.019	1.00575
0556653	55	1.17790	−0.001	1.00568
0567377	44	1.18155	+0.010	1.00563
0567641	70	1.18151	−0.010	1.00517
0574922	33	1.18415	+0.025	1.00570
0576415	32	1.18479	+0.023	1.00637
0577663	40	1.18507	+0.016	1.00570
0580169	30	1.18614	+0.054	1.00645
0587536	34	1.18860	+0.029	1.00641
0597621	40	1.19185	+0.014	1.00561
0597998	33	1.19200	+0.020	1.00564
0599697	80	1.19238	−0.009	1.00496
0601563	70	1.19302	−0.010	1.00497
0606167	38	1.19478	+0.016	1.00565
0606252	65	1.19467	−0.019	1.00533
0606256	55	1.19473	−0.001	1.00542
0613601	28	1.19744	+0.029	1.00604
0614400	42	1.19758	−0.002	1.00559
0615782	46	1.19803	−0.001	1.00559
0622470	34	1.20050	+0.022	1.00620
0625155	34	1.20128	+0.013	1.00563
0626175	70	1.20141	−0.010	1.00483

Density (10^{-7}g/cm^3)	Temp. °K	Dielectric constant	$\Delta\rho/\rho$ %	Corr. CM cm^3/g
0627171	48	1.20192	+0.003	1.00548
0628268	26	1.20247	+0.036	1.00596
0629227	32	1.20277	+0.012	1.00606
0637022	26	1.20547	+0.034	1.00589
0637244	30	1.20556	+0.033	1.00597
0639961	38	1.20635	+0.013	1.00552
0647953	34	1.20924	+0.018	1.00604
0648389	28	1.20933	+0.019	1.00577
0649919	44	1.20972	+0.005	1.00527
0651773	26	1.21052	+0.028	1.00579
0660868	32	1.21365	+0.011	1.00586
0662632	55	1.21407	−0.003	1.00515
0670511	38	1.21689	+0.010	1.00542
0671388	48	1.21713	+0.001	1.00527
0677296	34	1.21936	+0.014	1.00588
0677346	37	1.21926	+0.011	1.00543
0679330	26	1.22000	+0.026	1.00548
0680691	33	1.22038	+0.010	1.00525
0683305	28	1.22137	+0.014	1.00550
0684323	65	1.22147	−0.022	1.00482
0691192	44	1.22397	+0.005	1.00504
0691725	38	1.22422	+0.008	1.00528
0695061	30	1.22549	+0.020	1.00561
0696403	24	1.22598	+0.018	1.00570
0698405	48	1.22649	+0.001	1.00512
0702519	34	1.22809	+0.012	1.00566
0703164	32	1.22827	+0.006	1.00554
0709360	38	1.23034	+0.008	1.00513
0713561	42	1.23176	−0.001	1.00501
0713744	55	1.23174	−0.006	1.00474
0714887	46	1.23222	−0.001	1.00499
0717522	34	1.23318	+0.006	1.00506
0719501	28	1.23391	+0.015	1.00513
0720832	24	1.23443	+0.015	1.00536
0721993	26	1.23477	+0.015	1.00507
0722890	38	1.23506	+0.004	1.00508
0725677	34	1.23615	+0.009	1.00547
0731547	48	1.23801	0	1.00478
0732545	30	1.23852	+0.017	1.00523
0732894	44	1.23847	+0.002	1.00471
0748211	48	1.24381	0	1.00455
0749259	24	1.24433	+0.012	1.00501
0750821	33	1.24477	+0.004	1.00466
0752291	32	1.24538	+0.005	1.00501
0756042	44	1.24654	+0.002	1.00442
0756764	26	1.24687	+0.012	1.00460
0757538	37	1.24716	+0.005	1.00472
0763224	28	1.24916	+0.007	1.00467
0764242	30	1.24958	+0.008	1.00490
0765562	48	1.24986	−0.004	1.00430
0770045	44	1.25143	−0.001	1.00422
0774111	37	1.25297	−0.001	1.00459
0777903	46	1.25418	−0.001	1.00409
0779868	24	1.25504	+0.010	1.00460
0781763	34	1.25562	+0.002	1.00435
0789785	26	1.25847	+0.006	1.00429
0790084	28	1.25859	+0.004	1.00435
0792892	32	1.25962	0	1.00453
0796441	42	1.26071	−0.001	1.00391

Taken from R.B. Stewart and H.M. Roder, Chapter 11. Properties of Normal and Parahydrogen. p.379-404 in Technoloby and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

DIELECTRIC CONSTANT OF GASEOUS HYDROGEN

Source of Data:

Stewart, J. W. (1964), The Dielectric Polarizability of Fluid Parahydrogen., J. Chem. Phys. (in press).

Other References:

Boltzmann, L. (1875), Pogg. Ann. Physik 155, 403-22 .

Clemencic, J. (1885), Exuers Rep. 21, 571-611; Akad. Wiss. Wien. 91 II, 712 .

Scheel, K. (1907), Bestimmung der Brechungsexponenten von Gasen bei Zimmertemperatur und bei der temperatur der Flussigen Luft. (Determination of the Index of Refraction of Gases at Room Temperature and at the Temperature of Liquid Air.), Verhandl. deut. Physik. Ges. 9, 24-36; C.A. 1, 1823 (1907).

Tangl, K. (1908), Über Die Dielektrizitätskonstante einiger Gase bei hohem Druck. (Regarding the Dielectric Constants of Several Gases at High Pressure.), Ann. Physik 26, 59-78; C.A. 2, 2492 (1908).

*Cuthbertson, C., and Cuthbertson, M. (1910), On the Refraction and Dispersion of Air, Oxygen, Nitrogen and Hydrogen and their Relations., Proc. Roy. Soc. (London) 83A, 151; P.A. 13, 362 (1910).

*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)

Occhialini, A. (1914), The Dielectric Constant of Hydrogen at High Pressures., Atti Accad. Lincei 22 II, 482-84; C.A. 8, 1370 (1914).

Occhialini, A. (1914), The Dielectric Constant of Some Strongly Compressed Gases and the Mossotti-Clausius Relation., Nuovo cimento 7, 108-26; C.A. 8, 2518 (1914).

Riegger, H. (1919), Über die Temperaturabhängigkeit der Dielektrizitätskonstanten von Gasen. (Concerning the Temperature Dependence of the Dielectric Constant of Gases.), Ann. Physik 59, 753-60; C.A. 14, 877 (1920).

*Kirn, M. (1921), The Dispersion of Hydrogen in the Ultraviolet., Ann. Physik 64, 566; C.A. 15, 2247 (1921).

Fritts, E. C. (1923), The Measurement of the Dielectric Constant and Magnetic Susceptibility of Gases by High Frequency Methods., Phys. Rev. 21, 198.

Fritts, E. C. (1924), A Determination of the Dielectric Constants of Five Gases by a High Frequency Method., Phys. Rev. 23, 345-56; C.A. 18, 1423 (1924).

Zahn, C. T. (1924), The Electric Moment of Gaseous Molecules of Halogen Hydrides., Phys. Rev. 24, 400-17; C.A. 19, 426 (1925).

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).

Uhlig, H. H., Kirkwood, J. G., and Keyes, F. G. (1933), The Dependence of Dielectric Constants of Gases on Temperature and Density., J. Chem. Phys. 1, 155-59; C.A. 27, 1790 (1933).

Michels, A., Sanders, P., and Schipper, A. (1935), The Dielectric Constant of Hydrogen at Pressures up to 1425 Atm and at Temperatures of 25°C and 100°C., Physica 2, 753-6; C.A. 30, 919 (1936).

Van Itterbeek, A., and Spaepen, J. (1943), Mesures sur la Constante Diélectrique de Quelques Gaz non Polaires (H^2, D^2, He, O^2 et l'Air) et CO Entre la Température Ordinaire et 20°Abs. (Measurements of the Dielectric Constants of Several Non-polar Gases (H_2, D_2, He, O_2 and Air) and CO Between Ordinary Temperature and 20°Abs.), Physica 10, 173-84; C.A. 38, 5442 (1944).

Hector, L. G., and Woernley, D. L. (1946), The Dielectric Constants of Eight Gases., Phys. Rev. 69, 101-05; C.A. 40, 2266 (1946).

Van Itterbeek, A., and de Clippeleir, K. (1946), Mésures Sur la Constante Diélectrique de l'Anhydride Carbonique, de l'Ammoniaque Ainsi que de Mélanges. (Measurement of the Dielectric Constants of Carbonic Anhydride, of Ammonia as Well as of Mixtures.), Physica 12, 97-104; C.A. 40, 5613 (1946).

Van Itterbeek, A., and de Clippeleir, K. (1948), Measurements on the Dielectric Constant of Gaseous NH_3, CO, and H_2 as a Function of Pressure and Temperature., Physica 14, 349-56; C.A. 42, 8036 (1948).

Miller, J. G. (1948), VI - Dielectric-Constant and Refractivity Data., Trans. A.S.M.E. 70, 645-49; C.A. 42, 7117 (1948).

Zieman, C. M. (1951), Dielectric Constants of Various Gases at 9470 Mc., Phys. Rev. 83, 243; C.A. 46, 6449 (1952).

Ishiguro, E., Arai, T., Kotani, M., and Mizushima, M. (1952), Polarizability of the Hydrogen Molecule., Proc. Phys. Soc. (London) 65A, 178-87; C.A. 46, 1829 (1952).

Zieman, C. M. (1952), Dielectric Constants of Various Gases at 9470 Mc., J. Appl. Phys. 23, 154; C. A. 46, 6449 (1952).

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).

Comments:

Both Boltzmann and Clemencic found the value of the dielectric constant of hydrogen at 0°C and 1 atm pressure to be 1.000264. Scheel reports a dielectric constant of 1.00027166 at 0°C and 1 atm.

Tangl made experimental determinations at pressures from 20 to 100 atmospheres and by extrapolation found the value at 20°C and 1 atm. to be 1.000273. To substantiate their value they show the complete agreement of their measurement with the Cauchy relation, by which the square of the index of refraction at 20°C and 1 atm. and infinite wave length is equal to the dielectric constant.

$$n_\infty = 1.000136 \text{ and } n_\infty^2 = 1.000273.$$

Occhialini found that the value of the relation $(D - 1)/\rho(D + 2)$ of Clausius-Mossotti (D is dielectric constant and ρ is density) is more nearly constant than $(D - 1)\rho$. They call the former relation by the name of Lorenz-Lorentz. In Occhialini's second article previous observations are confirmed and he gives a value of 1.0002705 for hydrogen at 0°C and 76 cm Hg.

Riegger made measurements at -191°C at pressures of 400, 600, and 760 mm Hg. His final result calculated for 16.5°C and 760 mm Hg is 1.000253.

Fritts reported a value of 1.000221 at 0°C and 1 atm. in 1923 and a value of 1.000263 ± 0.0000015 in 1924. He used a beat frequency method operating at 0.8 Mc.

DIELECTRIC CONSTANT OF GASEOUS HYDROGEN

(cont.)

Zahn found 1.000265 as the average of 19 readings at 0°C and 1 atmosphere.

Watson et al. measured the dielectric constant by the heterodyne beat method at 25 and -191°C. They report values of 1.0002518 and 1.0002515 for 25°C and 760 mm, determined from measurements at 25 and -191°C respectively. They also report values of 1.0002749 and 1.0002746 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 1.0002716.

Uhlig et al. report values determined by a heterodyne beat method at 0 and 100°C for pressures from 30 to 150 atmospheres.

Van Itterbeek and Spaepen report values at temperatures from 20.3 to 293.3°K.

Michels et al. report values of dielectric constant for pressures up to 1425 atm and temperatures from 25 to 100°C. Only the 25°C isotherm is given here.

Hector and Woernley report a value of 1.00002724 ± 0.00000010 at 0°C and 1 atmosphere obtained by a 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 wavelength are regarded as a more accurate source of dielectric constant values, Miller gives for comparison values of n_∞^2.

Preliminary values of Van Itterbeek and de Clippeleir published in 1946 at 0.8 Mc are reported for a pressure of 1 atm. and temperatures between 0 and 90°C.

In 1948 the above authors published data at pressures from 760 to 11000 mm Hg in three temperature ranges, namely 0, 20, and 100°C.

Ishiguro et al. applied the variation method to calculate the polarizability α using a modification of the wave function of James-Coolidge. Matrix elements of α were calculated by the use of the Morse function and its characteristic functions. On this basis they calculated the dielectric constant of hydrogen to be 1.0002666. They quote earlier experimental values of 1.000273, 1.000263, 1.000259, and 1.000265.

Zieman made use of a cavity comparator and a microwave refractometer in his measurements at 9470 Mc and reported a value of 1.000355 ± 0.000005 at STP (0°C and 1 atm.). As this value is well above all earlier measurements, and does not agree with the square of the index of refraction at infinite wave length, its accuracy should be questioned.

Essen reports the index of refraction of gaseous hydrogen at 0°C and 760 mm of Hg as 1.0001360. Using the relation $\epsilon = n^2$, we obtain $\epsilon = 1.0002720$.

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 1.0002538 ± 0.0000003 at 20°C and 1 atmosphere.

Stewart reports the dielectric constant of parahydrogen for the range 24 to 100°K at densities up to 0.08 g/cm³. The experiment shows that the dielectric constant depends only on density. Tabular values are presented as calculated from the following equation: $(\epsilon + 2)\rho/(\epsilon - 1) = 0.99575 - 0.09069\rho + 1.1227\rho^2$ with ρ in g/cm³. Since the values are tabulated as a function of density the usual distinction between gas and liquid could not be accomplished and so all of the values are tabulated as liquid hydrogen data.

Michels et al. (1935)		
Temp. °C	P(atm)	Dielectric Constant
24.92	1.15	1.00028
"	7.96	1.00192
"	13.47	1.00324
"	18.95	1.00466
"	24.53	1.00601
"	30.03	1.00730
"	34.68	1.00843
"	35.52	1.00864
"	41.00	1.00995
"	46.42	1.01125
"	51.89	1.01252
"	57.36	1.01379
"	61.53	1.01475
"	88.13	1.02083
"	114.67	1.02668
"	141.36	1.03244
"	168.07	1.03810
"	194.87	1.04370
"	221.41	1.04885
"	248.15	1.05398
"	274.88	1.05900
"	255.04	1.05540
"	367.15	1.07535
"	478.78	1.09310
"	590.53	1.10925
"	702.20	1.12433
"	814.62	1.13766
"	926.05	1.15014
"	1037.86	1.16157
24.86	1032.74	1.16077
"	1229.25	1.17920
"	1425.36	1.19500

Original and Corrected Data from Two Older Sources

As originally reported						As corrected by Van Urk et al.		As corrected in this Note				
T °K	h cm	H cm	ρ_ℓ g/cm^3	ρ_v g/cm^3	γ dynes/cm	H cm	γ dynes/cm	T °K (NBS 1955)	H cm	ρ_ℓ g/cm^3	ρ_v g/cm^3	γ dynes/cm
Kamerlingh Onnes and Kuypers [1914]												
16.16	2.064	2.231	0.0751	0.0003	2.91_9	2.169	2.631	16.198	Values of VanUrk et al. adopted	0.07524	0.00035	2.634
17.99	1.869	2.021	$.0733_5$	.0005	2.57_5	1.962	2.319_5	18.050		.07345	.00067	2.317
18.70	1.794	1.941	.0726	.0008	2.43_8	1.883	2.194_5	18.764		.07271	.00085	2.196_5
20.40	1.616	1.749	.0708	.0013	2.12_6	1.694	1.910	20.453		.07084	.00136	1.910
Van Itterbeek [1940]												
17.72	1.540_5	1.65_8	.0740	[a].0061	2.66			17.747	1.697	.07375	.00061	2.393
20.32	1.323_8	1.44_7	.0708	.0013	2.19			20.354	1.457	.07096	.00132	1.956

[a]In error. Should be 0.00061

Reprinted from NBS TECH.NOTE 322

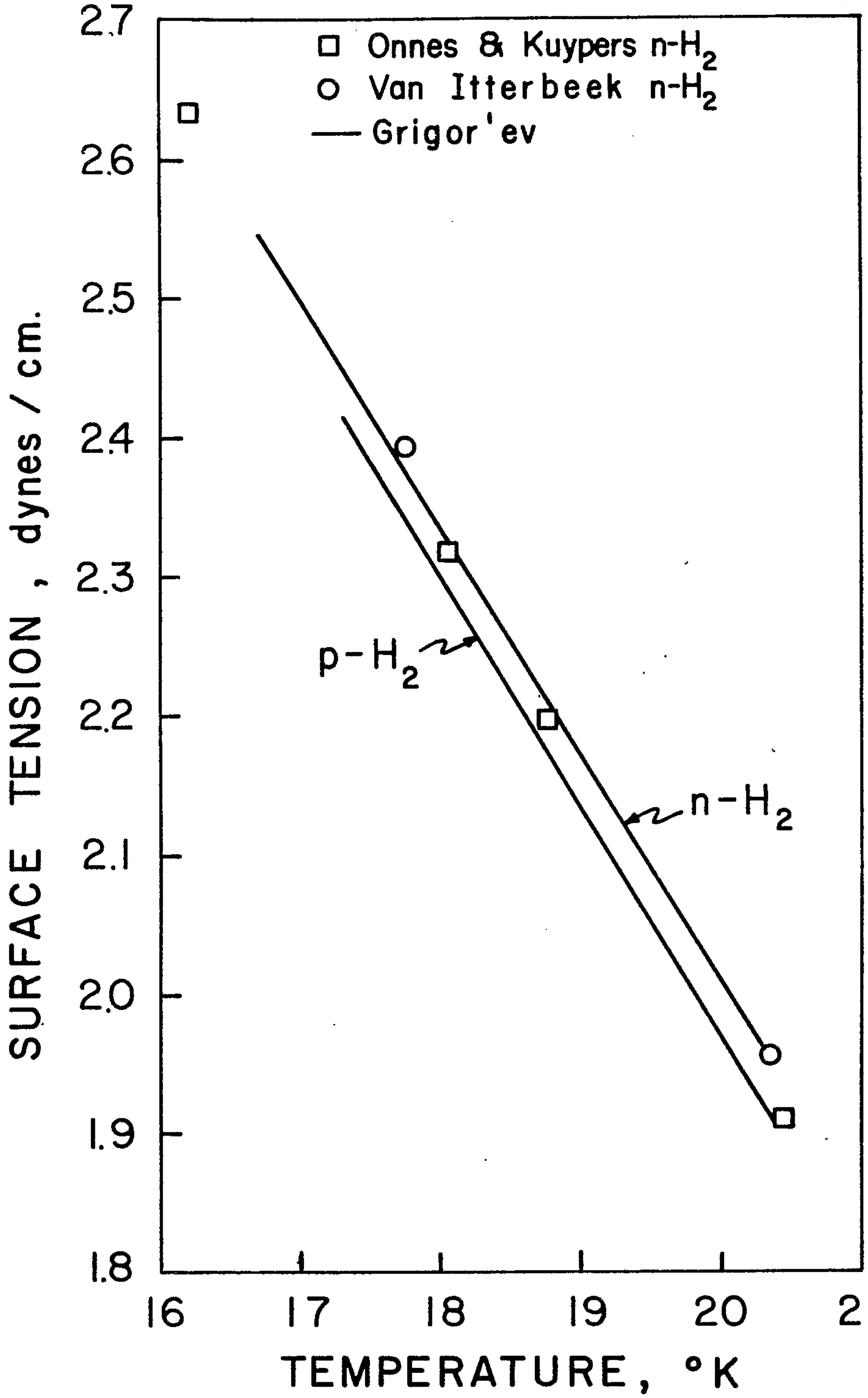
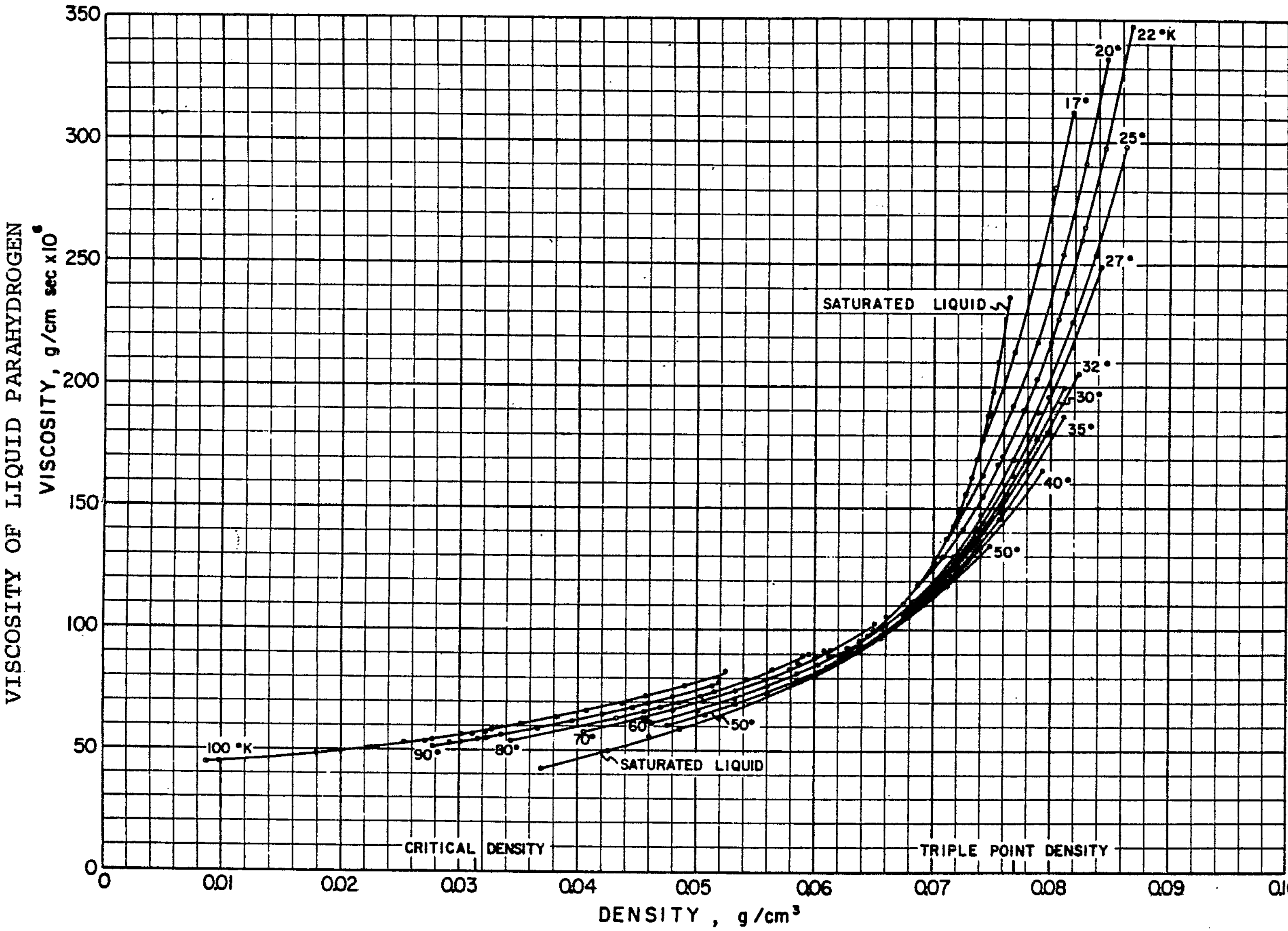


Figure 2.
Corrected experimental surface tension points of Kamerlingh Onnes and Kuypers and of Van Itterbeek and straight lines representing the experimental points of Grigor'ev.

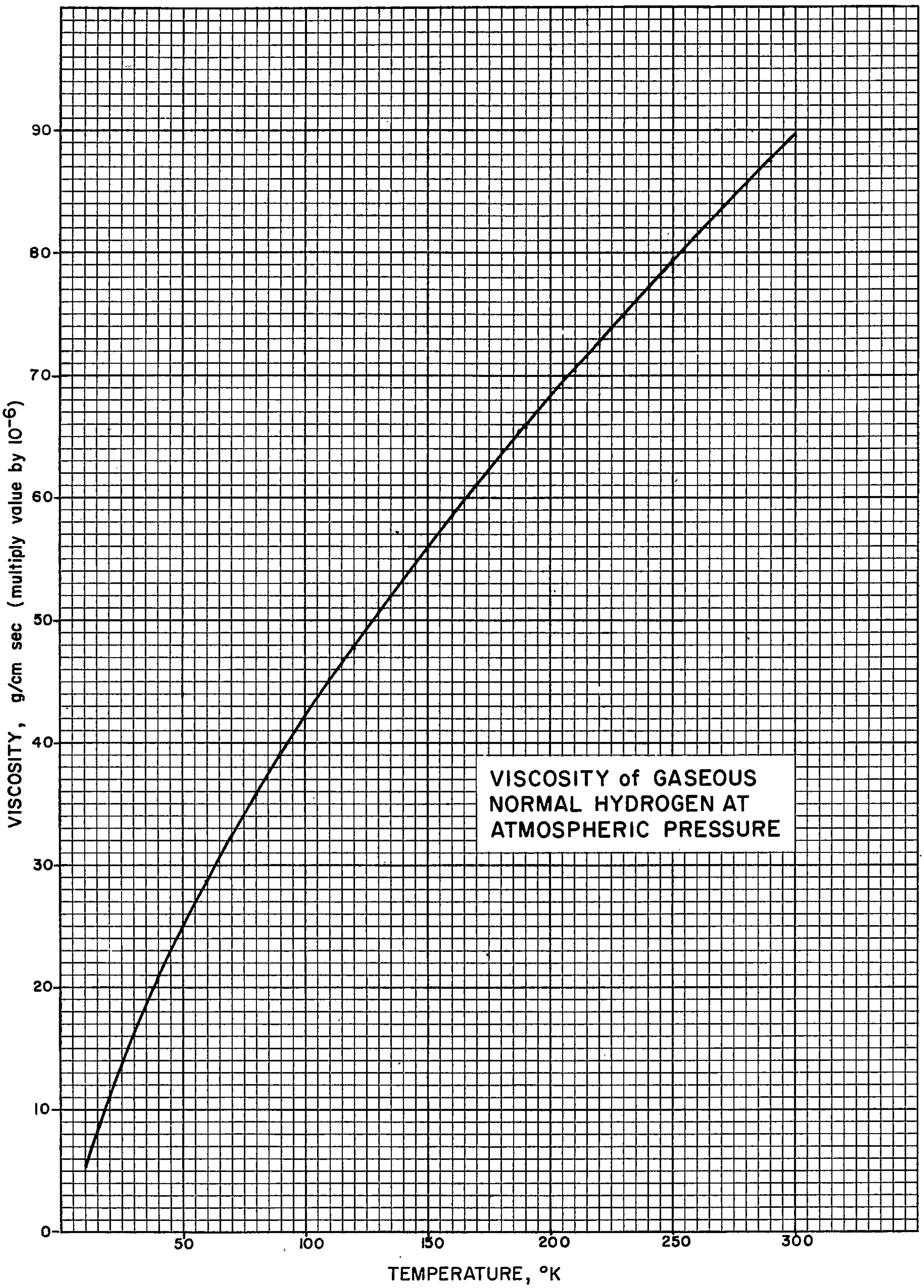
Reprinted from NBS TECH.NOTE 322

GPO 852-191



Preliminary values of the viscosity of para-hydrogen, from Diller

Reprinted from R.B. Stewart and H.M. Roder, Chapter 11. Properties of Normal and Parahydrogen. p.379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)


VISCOSITY of GASEOUS
NORMAL HYDROGEN AT
ATMOSPHERIC PRESSURE
VISCOSITY, g/cm sec (multiply value by 10^-6)
TEMPERATURE, °K
0
10
20
30
40
50
60
70
80
90
50
100
150
200
250
300

VISCOSITY OF GASEOUS NORMAL HYDROGEN

AT ATMOSHPERIC PRESSURE

Source of Data: R.B. Stewart and H.M. Roder Chapter 11. Properties of Normal and Parahydrogen. p.379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

Comments: These values were calculated from data referenced in the Stewart and Roder paper.

Temperature °K	Viscosity g/cm sec	Temperature °K	Viscosity g/cm sec
10	5.10×10^{-6}	160	58.52×10^{-6}
20	10.93	170	61.00
30	16.07	180	63.43
40	20.67	190	65.80
50	24.89	200	68.13
60	28.76	210	70.43
70	32.37	220	72.68
80	35.79	230	74.90
90	39.03	240	77.08
100	42.11	250	79.23
110	45.07	260	81.35
120	47.93	270	83.45
130	50.70	280	85.52
140	53.38	290	87.57
150	55.98	300	89.59

VISCOSITY DIFFERENCES

Data Sources:

Becker, E. W., and Stehl, O. (1952), Ein Zähigkeitsuntershied von Ortho- und Para-Wasserstoff bei Tiefen Temperaturen. (Viscosity Difference between Ortho and Para Hydrogen at Low Temperatures), Z. Physik 133, 615-28.

Webeler, R., and Bedard, F. (1961), Viscosity Difference Measurements for Normal and Para Liquid Hydrogen Mixtures, Phys. Fluids 4, 159-60.

Diller, D. E. (1965), Measurements of the Viscosity of Parahydrogen, J. Chem. Phys. 42, 2089-2100.

Comments:

The viscosity differences of gaseous ortho and para hydrogen determined by Becker and Stehl (1952) are small, approaching 1% near the triple point. Liquid values, however, differ by larger amounts with differences of about 5% at saturation near the triple point. Diller (1965) points out that the liquid differences are nearly zero when compared at the same densities rather than the same temperature. The results of Becker and Stehl (1952) indicate the viscosity of gaseous para hydrogen to be larger than gaseous normal hydrogen; while the results of Diller show the normal hydrogen values to be larger than the para hydrogen values in the liquid region.

Becker and Stehl (1952) measured the difference in viscosity between various mixtures of ortho and para hydrogen with a capillary bridge arrangement.

Webeler and Bedard (1961) measured a quantity equal to the product of viscosity and density of liquid para and ortho hydrogen with a piezoelectric alpha quartz torsional oscillator. They found that the value of $\eta\rho$ for 69% orthohydrogen at temperatures from 13.8 to 14.5 °K is about 4% larger than the corresponding values for 28% ortho hydrogen. The precision of the values of $\eta\rho$ is given as 0.2%.

Diller (1965) also used a torsional crystal method to make extensive measurements on para hydrogen. He included a few points for normal hydrogen along the saturated liquid line. All of the data are analytically represented with a mean deviation of 0.7%. An accuracy of 0.5% is claimed. The tables that follow include Diller's saturation data only.

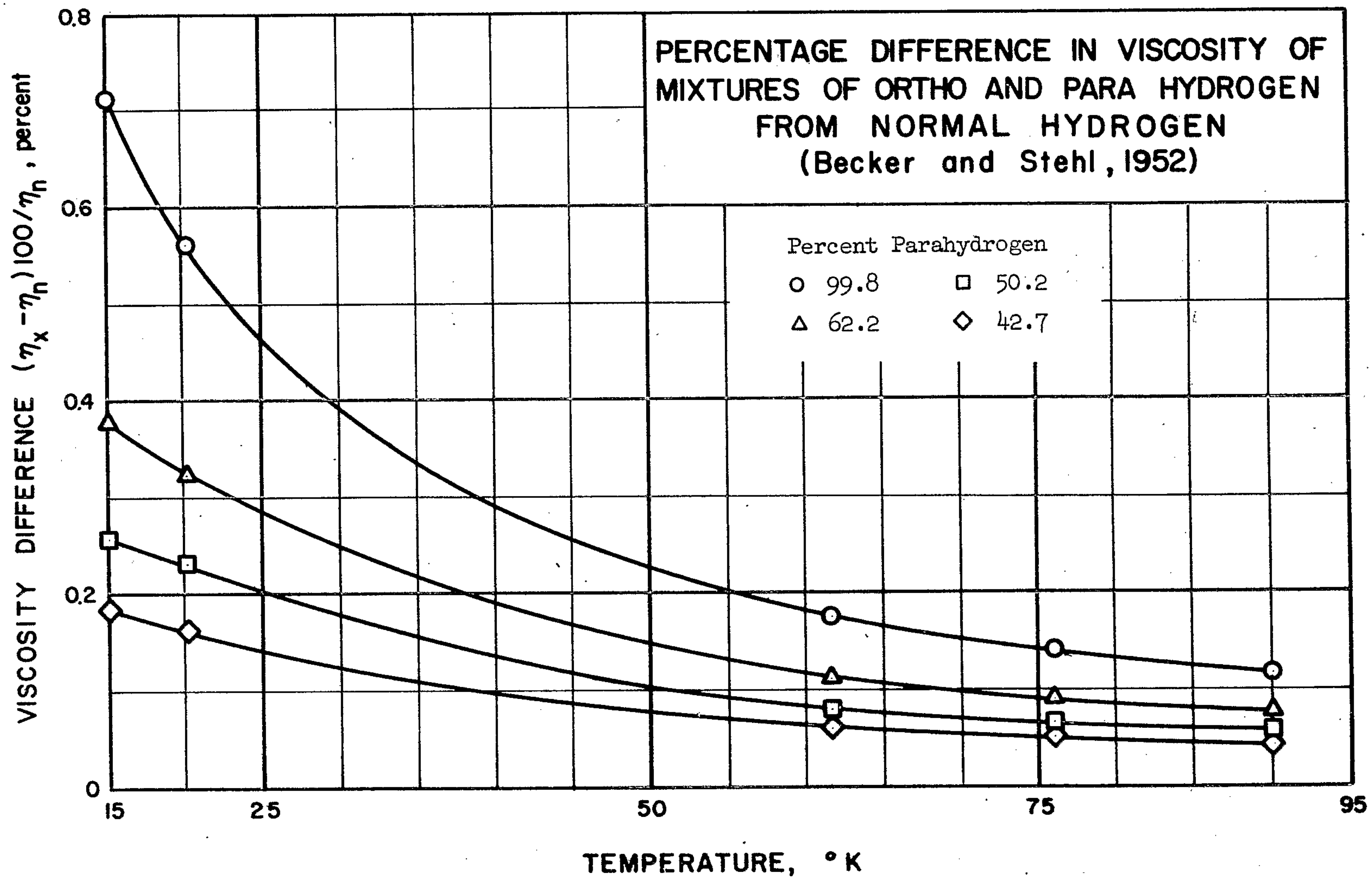
Reprinted from NBS REPORT 8812

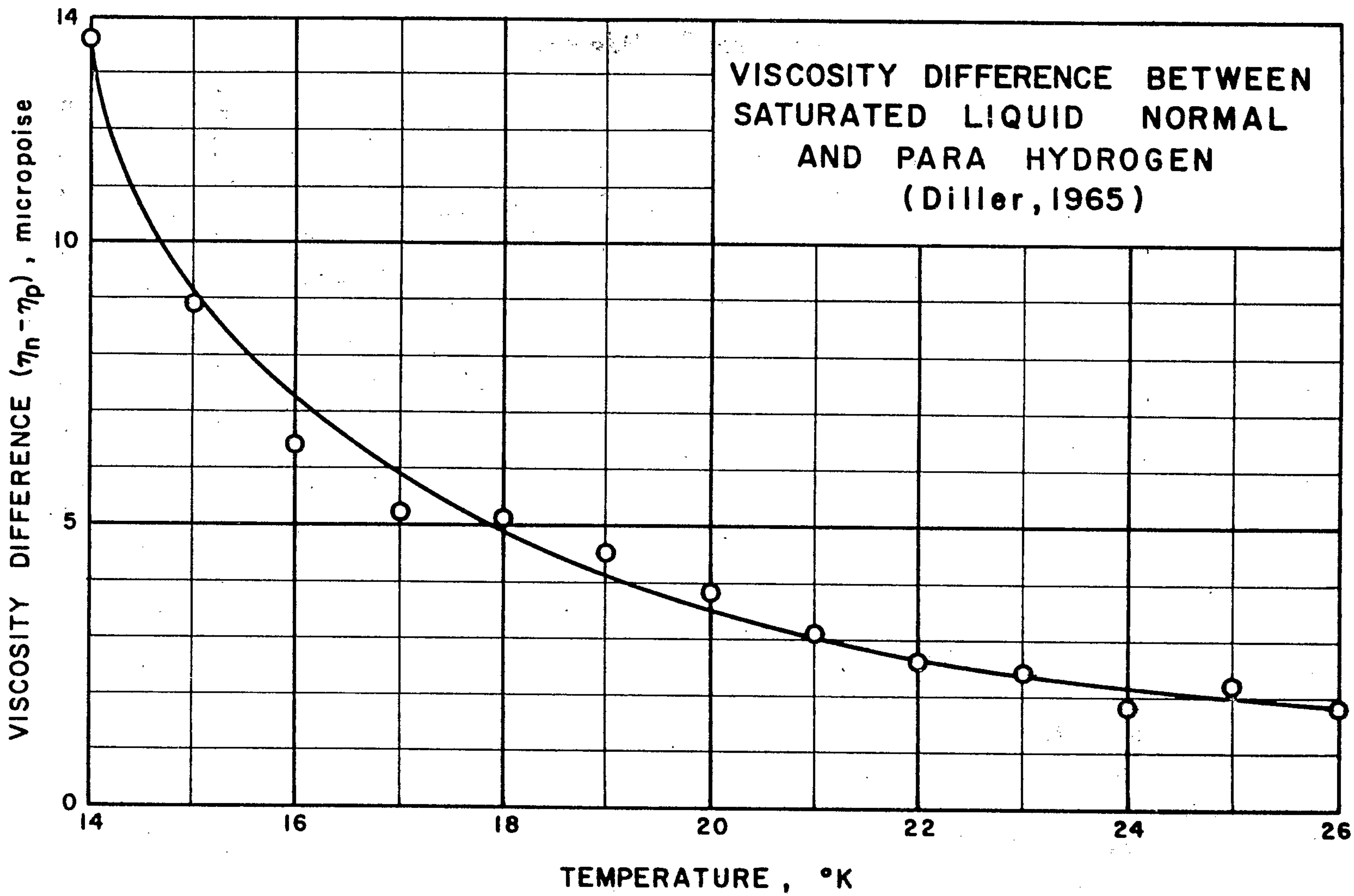
Becker and Stehl (1952)				
Gaseous Hydrogen $(\eta_x - \eta_n)\ 100/\eta_n$				
T, °K	Percent Para Hydrogen			
	99.8	62.2	50.2	42.7
90.1	0.116	0.075	0.055	0.039
77.3	0.139	0.089	0.065	0.049
63.2	0.175	0.110	0.079	0.058
20.3	0.561	0.323	0.231	0.162
15.0	0.712	0.376	0.258	0.182

η_x = Viscosity of ortho-para hydrogen mixture
η_n = Viscosity of normal hydrogen

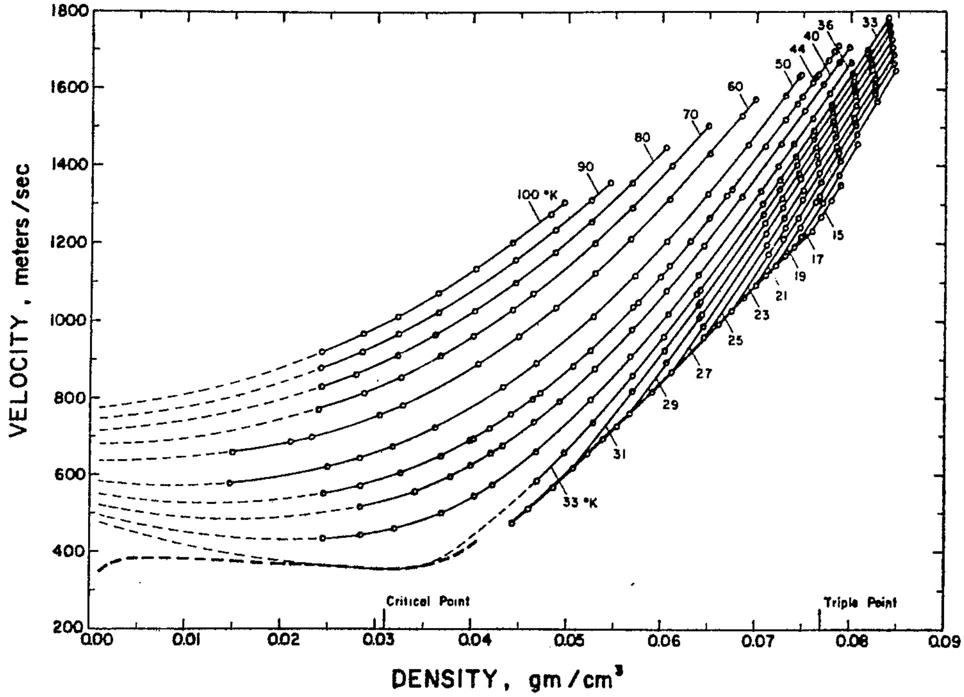
Diller (1965)			
Viscosity of saturated liquid (Micropoise)			
T, °K	Normal	Para	Difference
14	264.3*	250.7	13.6
15	230.2	221.3	8.9
16	203.9	197.5	6.4
17	182.9	177.7	5.2
18	165.6	160.5	5.1
19	151.5	147.0	4.5
20	139.2	135.4	3.8
21	128.4	125.3	3.1
22	118.7	116.1	2.6
23	110.5	108.1	2.4
24	102.6	100.8	1.8
25	95.7	93.5	2.2
26	89.0	87.2	1.8

* This value has been corrected for a typographical error.

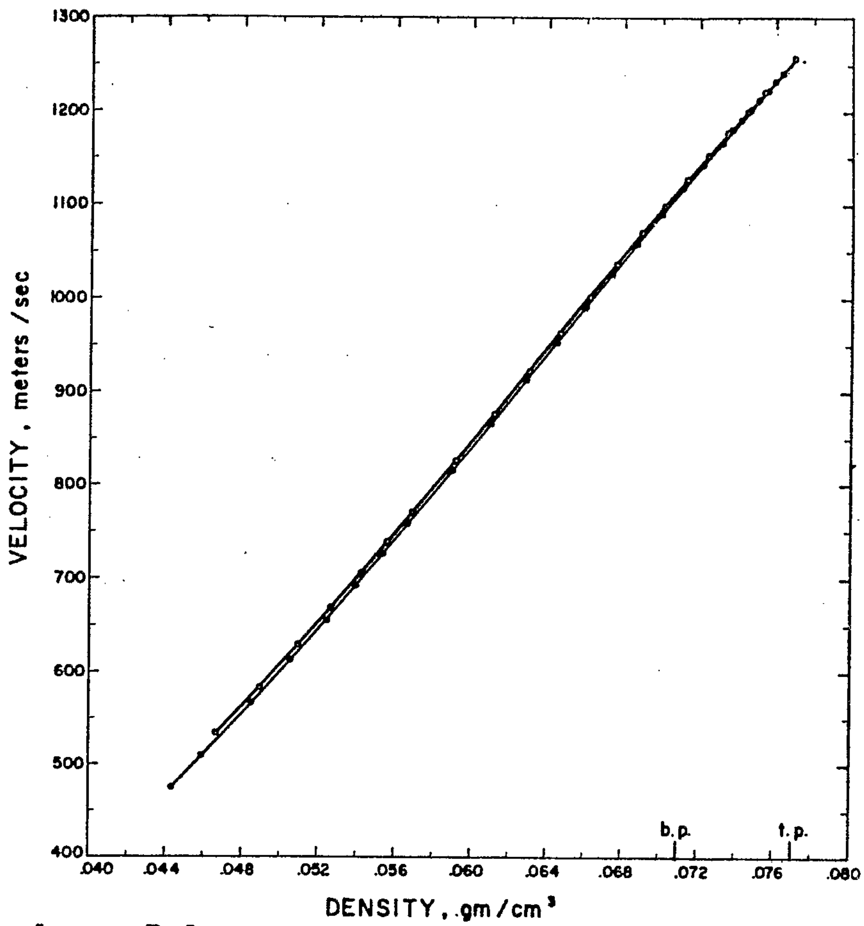

PERCENTAGE DIFFERENCE IN VISCOSITY OF MIXTURES OF ORTHO AND PARA HYDROGEN FROM NORMAL HYDROGEN
(Becker and Stehl, 1952)
Percent Parahydrogen
O 99.8
□ 50.2
Δ 62.2
◇ 42.7
VISCOSITY DIFFERENCE $(\eta_x - \eta_n)100/\eta_n$, percent
TEMPERATURE, °K
0
0.2
0.4
0.6
0.8
15
25
50
75
95


VISCOSITY DIFFERENCE BETWEEN SATURATED LIQUID NORMAL AND PARA HYDROGEN
(Diller, 1965)
VISCOSITY DIFFERENCE $(\eta_n - \eta_p)$, micropoise
TEMPERATURE, °K
14
10
5
0
14
16
18
20
22
24
26

VELOCITY OF SOUND IN LIQUID PARAHYDROGEN

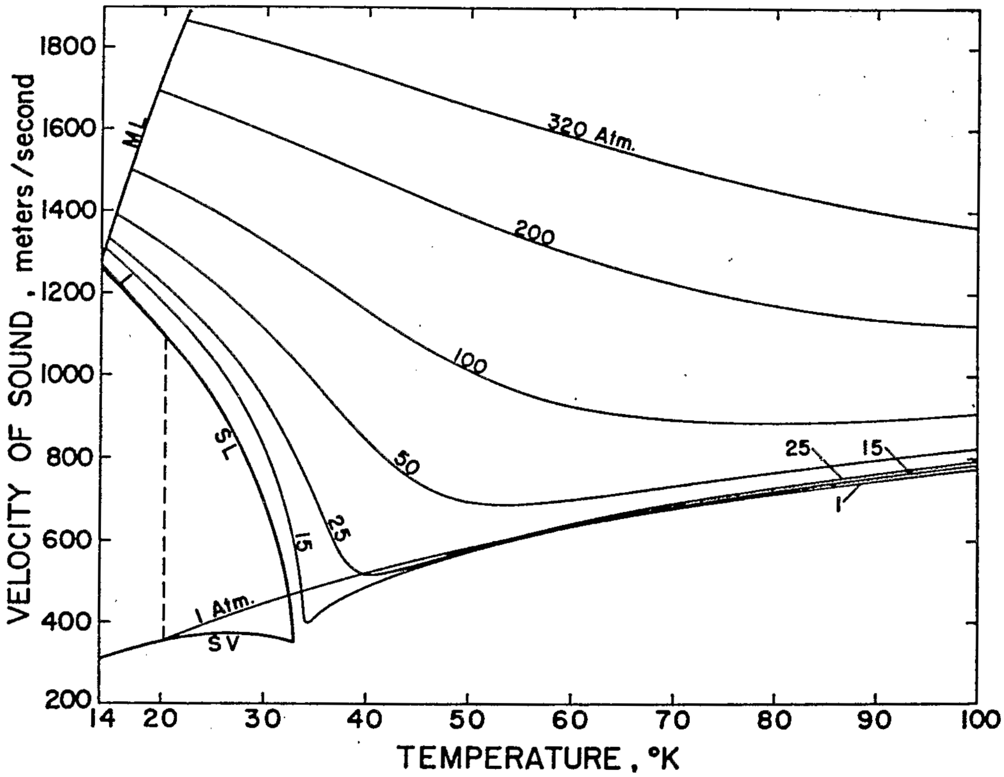


Speed of sound as a function of density showing isotherms. The dashed lines are calculated values.[1] The heavy lines indicate phase boundaries. The open circles indicate location of the measurements. For reference, the densities of the critical point and triple point are indicated on the abcissa.



Speed of sound in saturated liquid normal hydrogen and parahydrogen. The open circles are for normal hydrogen. For reference, the locations of the boiling point and triple point are indicated on the abcissa.

Reprinted from Younglove, B.A.



The velocity of sound in para-hydrogen, from Goodwin, *et al.* [9]. (ML, SL, and SV refer to melting line, saturated liquid and saturated vapor, respectively.)

Reprinted from R.B. Stewart and H.M. Roder Chapter 11. Properties of Normal and Parahydrogen p. 379-404 in Technology and Uses of Liquid Hydrogen, Pergamon Press, New York (1964)

VELOCITY OF SOUND IN HYDROGEN

Data Sources:

Van Itterbeek, A., Van Dael, W., and Cops, A. (1961), Velocity of Ultrasonic Waves in Liquid Normal and Para Hydrogen (14-20°K), Physica 27, 111-16.

Van Itterbeek, A., Van Dael, W., and Cops, A. (1963), The Velocity of Sound in Liquid Normal and Para Hydrogen as a Function of Pressure, Physica 29, 965-73.

Younglove, B. A. (1965), Ultrasonic Velocity in Fluid Parahydrogen, Manuscript submitted for publication.

Comments:

The velocity of sound of liquid normal and para hydrogen has been accurately determined by both Van Itterbeek, et al. (1961, 1963) and Younglove (1965) below 20°K. The agreement of these differences from these sources is excellent. The differences in the gaseous states are not, however, well known. One may estimate these differences from the thermodynamic relationship, $C^2 = \gamma(\partial P/\partial \rho)_T$ where C = velocity of sound, $\gamma = C_p/C_v$, and P, T, and ρ are pressure, temperature and density, respectively. It is known from P-V-T measurements that the values of $(\partial P/\partial \rho)_T$ of normal and para cannot be much different. Thus in regions where the differences in C_p/C_v are large such as around 150°K one can estimate the percentage difference in velocity of sound as one half the percentage difference in the specific heat ratio of normal and para hydrogen.

Van Itterbeek, et al. (1961) measured the velocity of sound in saturated liquid normal and para hydrogen at temperatures from 14 to 20.5°K using a variable length interferometer. Their data indicate the velocity of sound in normal hydrogen to be 8 m/sec greater than in para hydrogen at frequencies of 1, 2, and 5 mc/sec. They estimate the uncertainty at 0.2%.

Van Itterbeek, et al. (1963) extended the above work to pressures of 240 kg/cm². The difference between normal and para hydrogen at low pressures is less than in the previous article by the same authors.

Younglove (1965) made velocity of sound measurements on fluid para hydrogen with a pulsed sound technique. Measurements were made from 15 to 100°K and up to 350 atmospheres, and are claimed to be accurate to 0.05%.

Reprinted from NBS REPORT 8812

Van Itterbeek, et al. (1961)

Velocity of Sound in Saturated Liquid Normal Hydrogen

0.996 mc/sec		1.945 mc/sec		4.904 mc/sec	
Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec
20.37	1120.7	20.42	1119.2	20.44	1119.4
19.97	1131.7	20.10	1128.6	19.08	1156.8
19.67	1140.3	19.85	1136.0	18.42	1171.6
19.37	1149.9	19.58	1142.6	18.04	1182.3
18.93	1159.7	19.32	1150.4	17.45	1194.5
18.61	1166.7	19.02	1157.4	17.04	1203.1
18.18	1176.9	18.70	1165.8	16.57	1214.7
17.72	1187.9	18.35	1173.9	15.98	1227.6
17.15	1200.3	17.95	1183.5	15.32	1240.2
16.61	1211.5	17.52	1193.2	15.23	1241.2
16.04	1224.3	17.50	1203.9	14.59	1254.3
15.15	1242.8	16.49	1214.9	14.13	1262.3
14.59	1254.4	15.92	1227.3		
14.13	1263.6	15.44	1237.4		
		14.89	1247.8		
		14.52	1255.0		
		14.11	1262.6		

Velocity of Sound in Saturated Liquid Para-Hydrogen

0.987 mc/sec		1.937 mc/sec		4.869 mc/sec	
Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec	Temp. °K	Velocity of Sound m/sec
20.36	1114.3	20.41	1110.9	20.40	1115.3
20.08	1122.5	19.91	1125.3	19.46	1137.9
19.77	1130.8	19.53	1134.8	18.92	1151.1
19.55	1136.9	19.06	1146.2	18.24	1168.1
19.29	1144.4	18.62	1157.9	17.66	1182.1
18.87	1154.6	18.13	1168.5	16.99	1196.9
18.48	1164.1	17.53	1183.1	16.52	1204.3
18.02	1175.4	16.91	1196.5	15.88	1220.5
17.52	1186.3	16.38	1208.7	15.33	1230.1
16.91	1200.1	15.76	1221.7	14.83	1240.7
16.20	1214.9	15.08	1234.3	14.38	1249.2
15.29	1232.5	14.63	1243.2		
14.06	1255.9	14.17	1250.8		
		20.40	1111.8		
		19.76	1128.2		
		19.43	1138.7		
		19.00	1149.0		
		18.55	1159.0		
		17.96	1174.3		
		17.43	1188.5		
		16.93	1199.6		
		16.32	1208.5		
		15.59	1225.4		
		14.85	1240.4		
		14.06	1253.6		

Van Itterbeek, et al. (1963)

Velocity of Sound in Liquid Hydrogen

T = 20.50°K				T = 19.17°K			
n-H_2		e-H_2		n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
236.0	1742.1	240.0	1748.6	177.5	1647.4	188.5	1667.6
230.0	1732.7	229.0	1729.3	170.3	1633.3	183.5	1658.4
220.3	1715.4	221.0	1714.9	160.9	1615.6	175.0	1642.4
210.4	1697.3	211.5	1698.7	150.5	1594.0	170.0	1631.8
200.9	1679.9	202.3	1680.5	139.7	1571.4	161.0	1614.4
190.6	1660.7	192.5	1663.1	130.0	1549.6	151.0	1593.7
180.5	1641.6	181.5	1641.3	120.3	1528.0	140.5	1571.4
170.6	1622.0	171.5	1622.5	110.0	1500.0	130.2	1549.6
160.2	1601.0	161.2	1601.1	100.3	1480.6	120.0	1526.1
150.6	1580.9	150.5	1578.6	90.8	1456.4	109.5	1502.3
141.2	1560.4	141.0	1558.4	80.5	1429.7	100.5	1479.5
130.8	1537.1	131.5	1537.6	70.00	1400.6	90.7	1455.3
120.7	1513.0	121.5	1513.6	60.50	1327.5	80.5	1428.4
110.6	1489.4	109.7	1485.2	50.50	1341.3	71.50	1403.2
100.7	1465.3	100.7	1463.1	40.50	1309.5	61.00	1372.6
90.5	1438.5	91.0	1437.1	29.20	1270.2	51.25	1342.4
80.7	1411.6	79.0	1404.7	21.60	1241.1	42.90	1314.6
70.50	1382.1	68.75	1374.5	12.95	1206.3	34.20	1285.0
61.05	1353.6	60.00	1347.6	6.25	1177.3	26.10	1254.9
50.85	1320.7	50.40	1315.7	1.70	1155.5	18.10	1224.1
41.15	1287.2	40.50	1281.6			10.30	1192.6
31.10	1250.0	30.75	1245.5			6.20	1173.2
23.00	1218.1	20.85	1205.4			2.05	1153.9
17.25	1193.4	12.05	1166.4			1.50	1151.3
11.80	1169.4	7.10	1142.3				
8.40	1152.6	2.75	1119.6				
4.95	1135.4	1.20	1111.5				
1.40	1117.5						

T = 18.25°K				T = 16.74°K			
n-H_2		e-H_2		n-H_2		e-H_2	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
127.0	1575.3	146.4	1592.0	90.4	1486.6	85.0	1468.2
135.5	1571.9	137.0	1571.9	88.7	1481.2	78.0	1450.9
128.5	1556.7	129.0	1553.9	84.0	1469.4	68.90	1426.7
118.5	1535.1	118.5	1531.1	74.80	1446.0	60.25	1403.2
108.0	1510.9	108.5	1507.7	65.40	1420.9	50.75	1375.8
97.3	1485.3	99.5	1486.8	55.40	1393.2	41.40	1347.6
87.2	1459.3	90.0	1462.8	45.90	1365.4	31.50	1316.3
87.0	1459.3	79.5	1436.5	37.00	1338.0	21.35	1282.3
78.7	1437.7	70.40	1410.7	26.85	1305.6	13.10	1252.6
69.30	1411.2	60.50	1382.6	19.60	1280.5	8.30	1234.4
60.55	1387.4	50.50	1352.7	13.50	1259.1	2.60	1211.7
50.55	1357.3	40.70	1321.0	6.80	1233.8	1.40	1207.0
40.40	1325.1	30.60	1287.4	1.60	1212.9		
31.00	1294.4	20.45	1250.6				
22.20	1263.6	12.75	1221.2				
15.00	1235.9	6.60	1195.3				
8.30	1208.5	2.40	1177.4				
2.30	1183.3	1.50	1173.1				

Van Itterbeek, et al. (1963) (cont.)

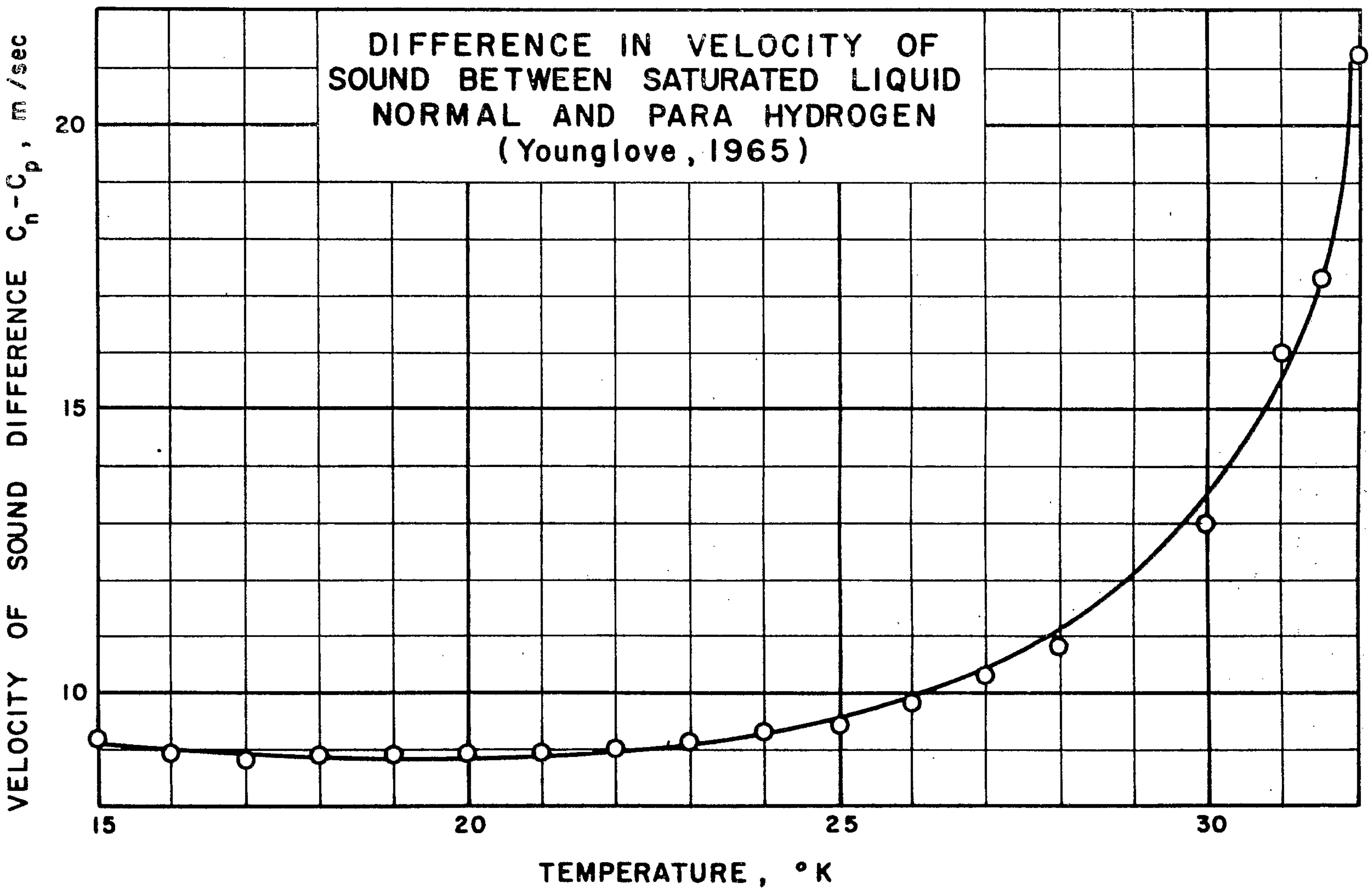
Velocity of Sound in Liquid Hydrogen

T = 16.09°K				T = 15.35°K			
$n-H_2$		$e-H_2$		$n-H_2$		$e-H_2$	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
60.50	1416.5	65.40	1426.8	20.55	1308.9	38.50	1360.7
55.00	1402.4	60.50	1413.6	17.50	1298.6	36.20	1353.9
49.90	1387.7	55.45	1400.1	14.90	1290.0	32.15	1341.5
45.10	1373.7	50.30	1385.0	12.50	1282.2	28.05	1329.1
35.30	1344.5	40.60	1356.6	7.40	1263.0	21.40	1308.2
30.15	1328.4	35.60	1341.6	5.45	1256.8	17.30	1293.9
25.10	1312.6	30.60	1326.0	3.95	1251.1	15.05	1286.4
20.35	1296.2	25.35	1309.1	2.10	1244.6	12.00	1276.1
15.10	1278.4	20.70	1292.8	1.40	1241.5	9.85	1268.7
10.20	1261.6	15.60	1275.4			6.55	1256.7
5.95	1245.3	10.60	1257.2			4.10	1247.3
2.05	1230.4	5.50	1238.3			1.70	1238.2
		2.05	1224.8				

T = 15.14°K			
$n-H_2$		$e-H_2$	
P kg/cm^2	Velocity of Sound m/sec	P kg/cm^2	Velocity of Sound m/sec
28.70	1338.9	29.70	1336.5
26.70	1332.3	26.90	1327.7
23.40	1322.7	23.10	1315.6
20.15	1313.0	20.10	1305.6
17.20	1302.2	17.00	1295.8
14.00	1291.7	14.05	1285.0
11.10	1281.3	11.25	1275.7
8.50	1272.3	8.90	1267.2
5.90	1263.2	6.15	1257.2
3.80	1255.1	3.00	1246.0
1.50	1247.1	0.25	1235.2

Younglove (1965)				
Velocity of Sound in Saturated Liquid Hydrogen				
T,°K	Density, g/cm³		Velocity of Sound, m/sec	
	Para	Normal	Para	Normal
14.5	0.07641		1241.9	
15	0.07599	0.07632	1232.6	1241.8
16	0.07510	0.07543	1212.8	1221.8
17	0.07417	0.07449	1191.7	1200.6
18	0.07319	0.07350	1169.0	1177.9
19	0.07216	0.07246	1144.6	1153.5
20	0.07108	0.07137	1118.5	1127.0
21	0.06992	0.07020	1090.3	1099.3
22	0.06870	0.06896	1060.0	1069.1
23	0.06739	0.06764	1027.3	1036.5
24	0.06599	0.06622	992.0	1001.3
25	0.06447	0.06469	953.6	963.1
26	0.06282	0.06302	911.8	921.7
27	0.06100	0.06120	866.0	876.3
28	0.05897	0.05917	815.2	826.1
29	0.05665	0.05687	758.2	770.0
29.5	0.05536	0.05559	726.6	739.0
30	0.05394	0.05420	692.6	705.6
30.5	0.05236		655.3	
31	0.05058	0.05095	613.2	629.2
31.5	0.04849	0.04898	566.5	583.8
32	0.04592	0.04661	509.2	530.4
32.25	0.04433		470.5	
32.5		0.04353		490.2

Velocity of Sound in Liquid Parahydrogen							
T = 15.000°K		T = 17.000°K		T = 19.000°K		T = 20.500°K	
P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec	P atm	Velocity of Sound m/sec
34.52	1351.6	81.36	1458.3	174.39	1648.3	229.88	1739.8
22.01	1311.4	51.68	1375.3	135.67	1567.2	195.49	1676.7
8.81	1265.3	30.15	1306.3	99.56	1481.6	150.62	1585.5
		6.04	1215.8	73.99	1413.0	124.12	1525.3
				44.23	1321.1	91.73	1442.8
				40.72	1309.7	63.51	1360.2
				22.94	1243.4		


DIFFERENCE IN VELOCITY OF
SOUND BETWEEN SATURATED LIQUID
NORMAL AND PARA HYDROGEN
(Younglove, 1965)
VELOCITY OF SOUND DIFFERENCE $C_n - C_p$, m/sec
20
15
10
15
20
25
30
TEMPERATURE, °K