Title

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CRYOGENIC DATA BOOK

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Cryogenic Engineering Laboratory
Boulder, Colorado

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PREFACE

Increased activities in Cryogenic Engineering have brought about the need for a compilation of available data. The purpose of the Cryogenic Data Book is to provide a condensed source of reliable data and reference information for those working in the cryogenic field. Specifically the data were compiled with a view toward the design of liquid hydrogen bubble chambers.

The compilation does not constitute a critical survey of the literature. It is hoped that additional information can be added in the future.

For their aid in compiling this book, the authors wish to thank Rod. A. Byrns and Homer S. Hoard, both of the University of California Radiation Laboratory.

This work was done under the auspices of the U. S. Atomic Energy Commission.

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CRYOGENIC DATA BOOK

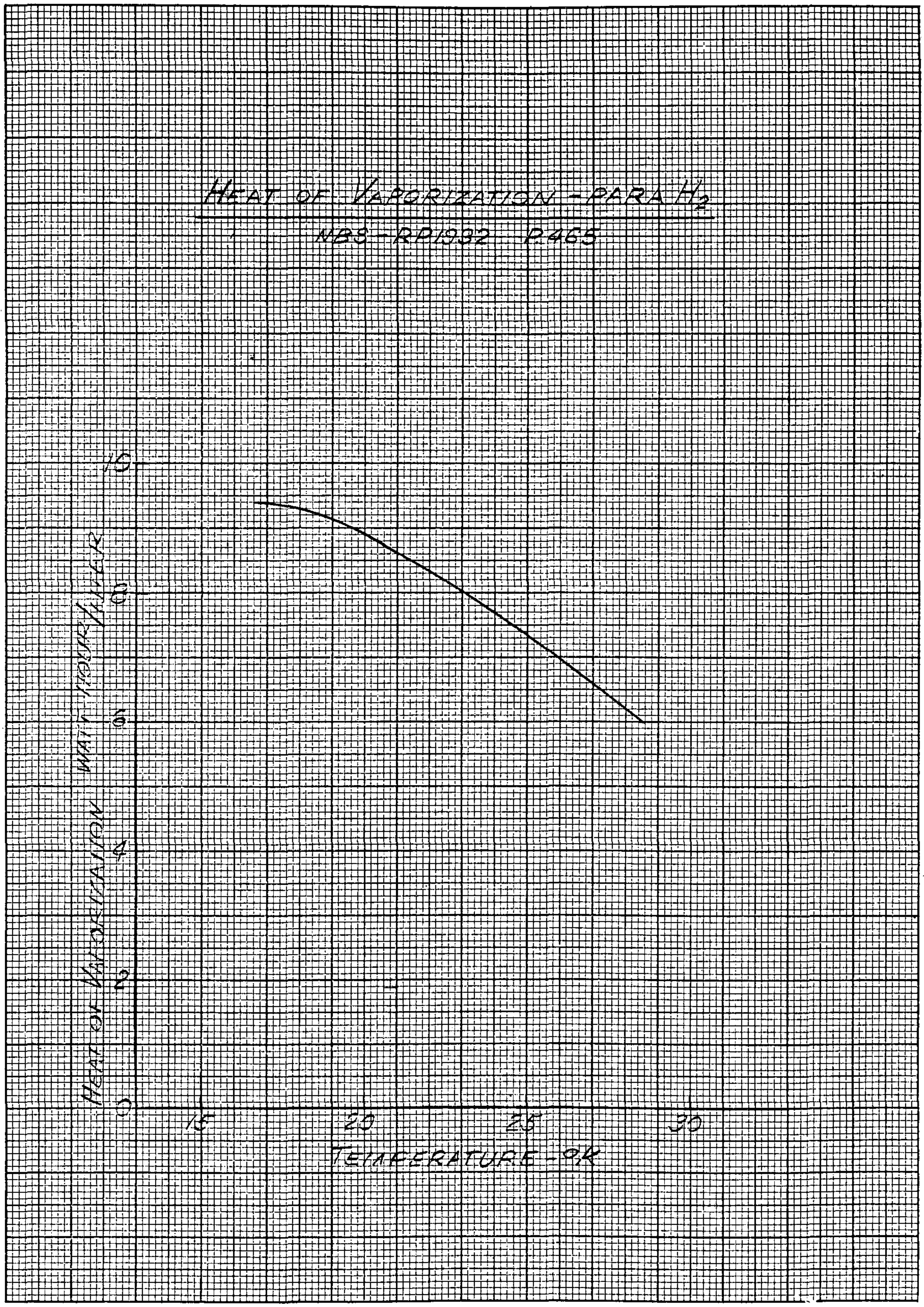
Chelton and Mann

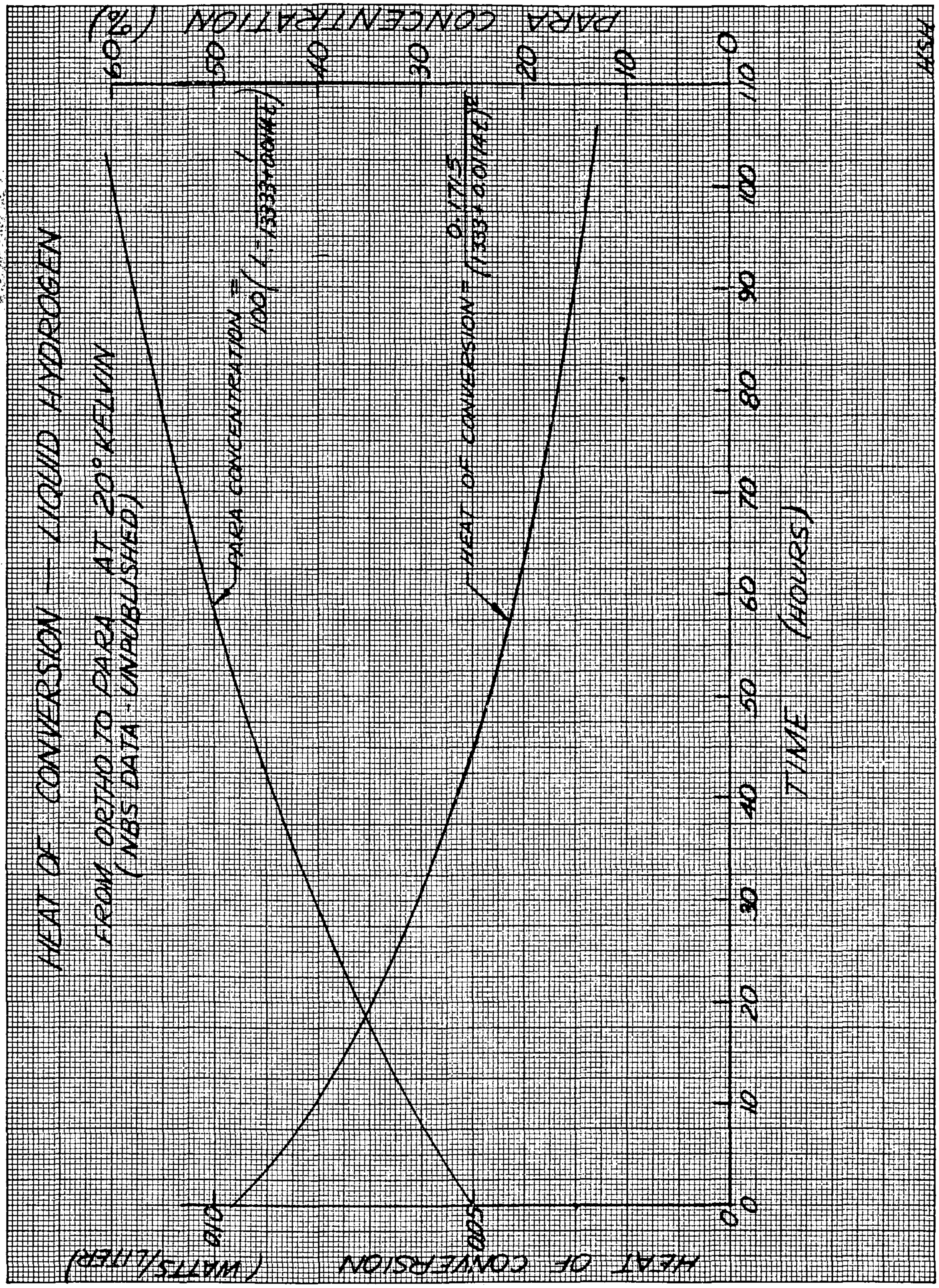
Contents

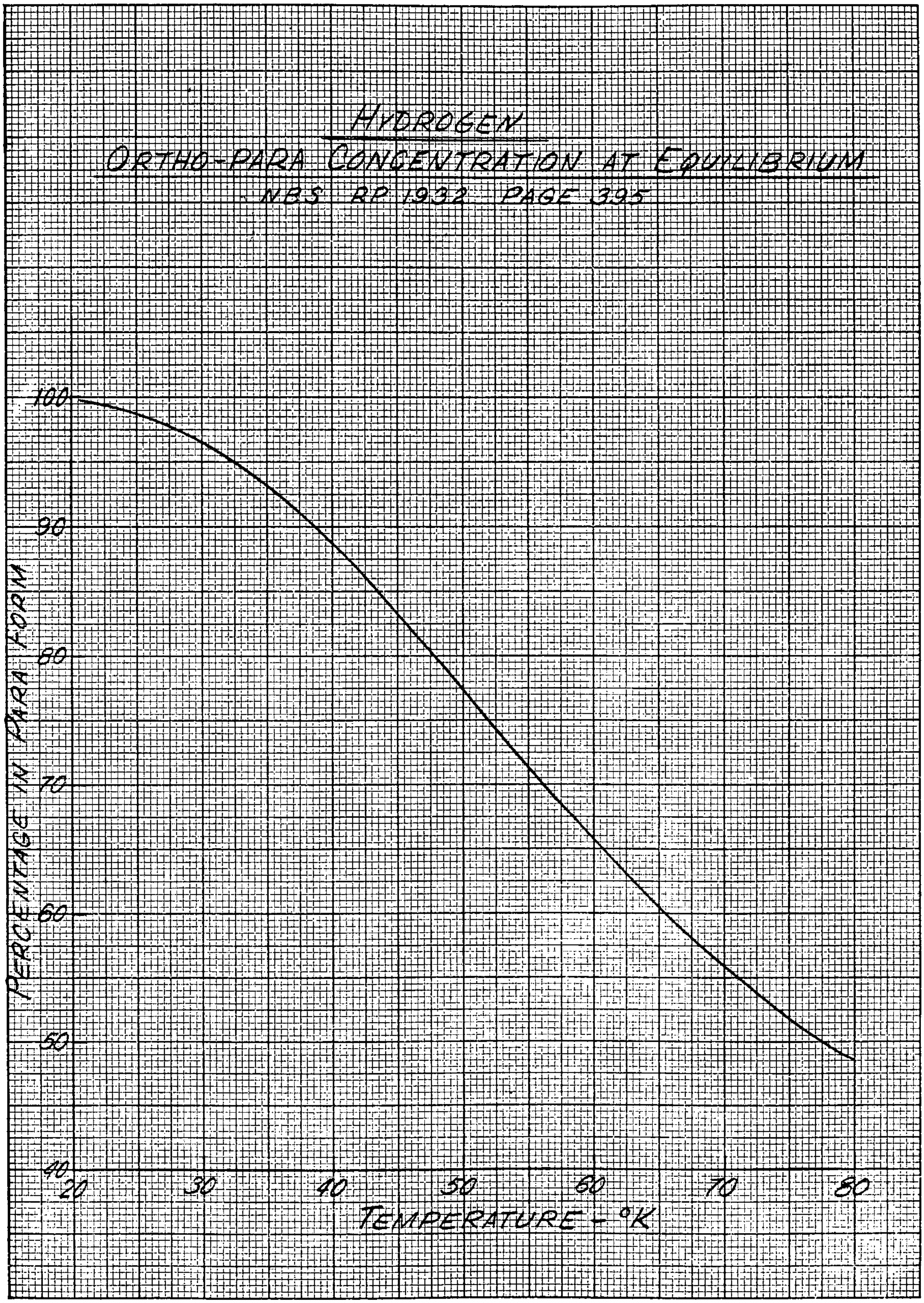
CONVERSION TABLES

Quantity	Multiply quantity expressed in	by	To obtain quantity expressed in
Viscosity	micropoise	1×10^{-6}	$\frac{g}{cm\ sec}$
	micropoise	6.73×10^{-8}	$\frac{lb(m)}{ft\ sec}$
Density	g/liter	6.24×10^{-2}	lb/ft^3
Heat Transfer	$watts/cm^2$	927	$watts/ft^2$
Sound Velocity	meters/sec	3.28	ft/sec
Thermal Conductivity	watts/cm ^oK	2.54	watts/in ^oK
		57.8	$\frac{BTU\ ft}{ft^2\ hr\ ^oF}$
Specific Heat	$\frac{watts - sec}{g\ ^oK}$	454	$\frac{watts - sec}{lb\ ^oK}$
		0.239	$\frac{cal}{g\ ^oK}$
		0.239	$\frac{BTU}{lb\ ^oF}$

0 0 1 0 1 5 0 0 7 3 5




HEAT OF CONVERSION — LIQUID HYDROGEN
FROM ORTHO TO PARA AT 20° KELVIN
(NBS DATA - UNPUBLISHED)
PARA CONCENTRATION (%)
HEAT OF CONVERSION (WATTS/LITER)
TIME (HOURS)
PARA CONCENTRATION =
HEAT OF CONVERSION =



HYDROGEN
ORTHO-PARA CONCENTRATION AT EQUILIBRIUM
NBS RP 1932 PAGE 395
PERCENTAGE IN PARA FORM
100
90
80
70
60
50
40
20
30
40
50
60
70
80
TEMPERATURE - °K

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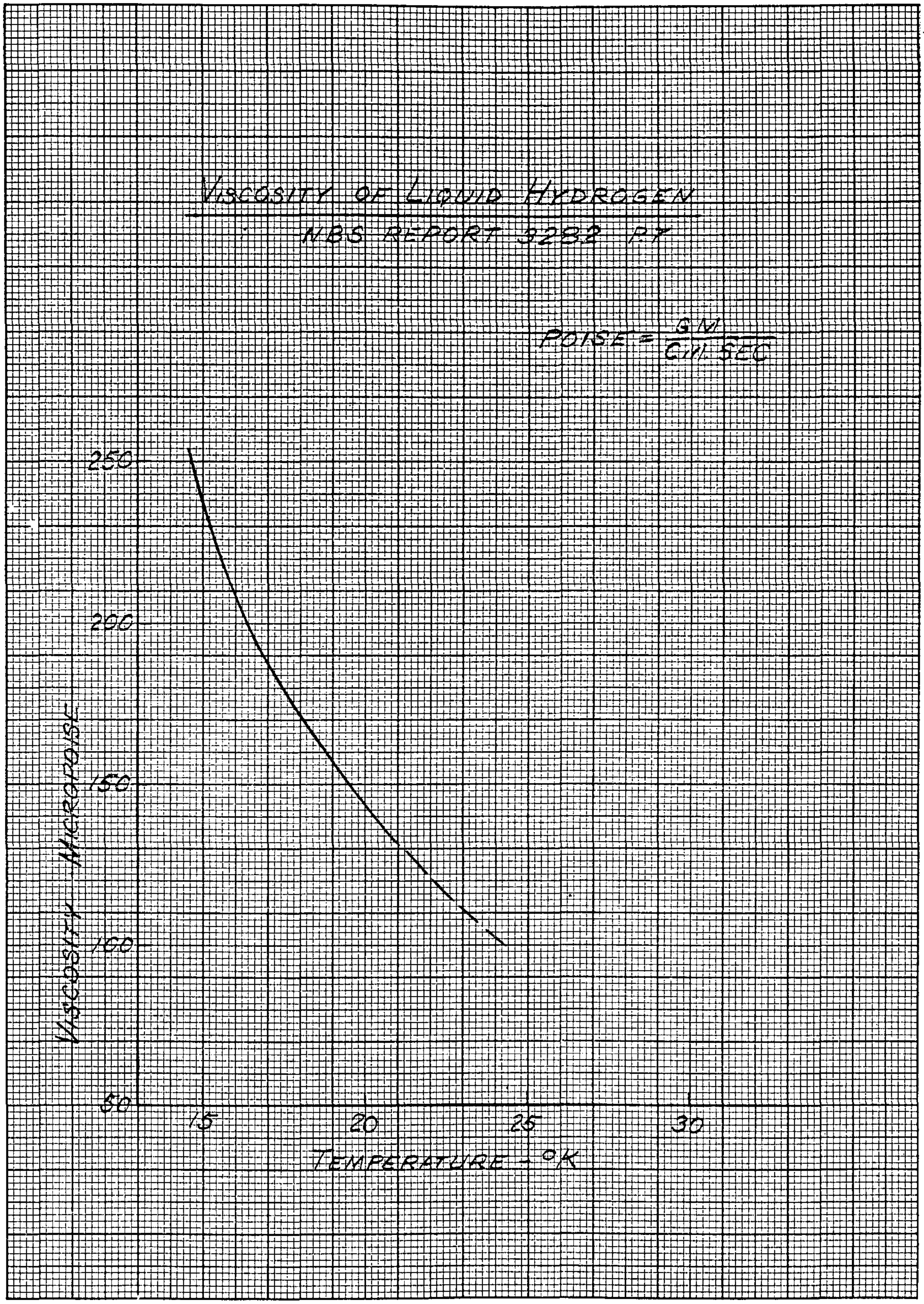
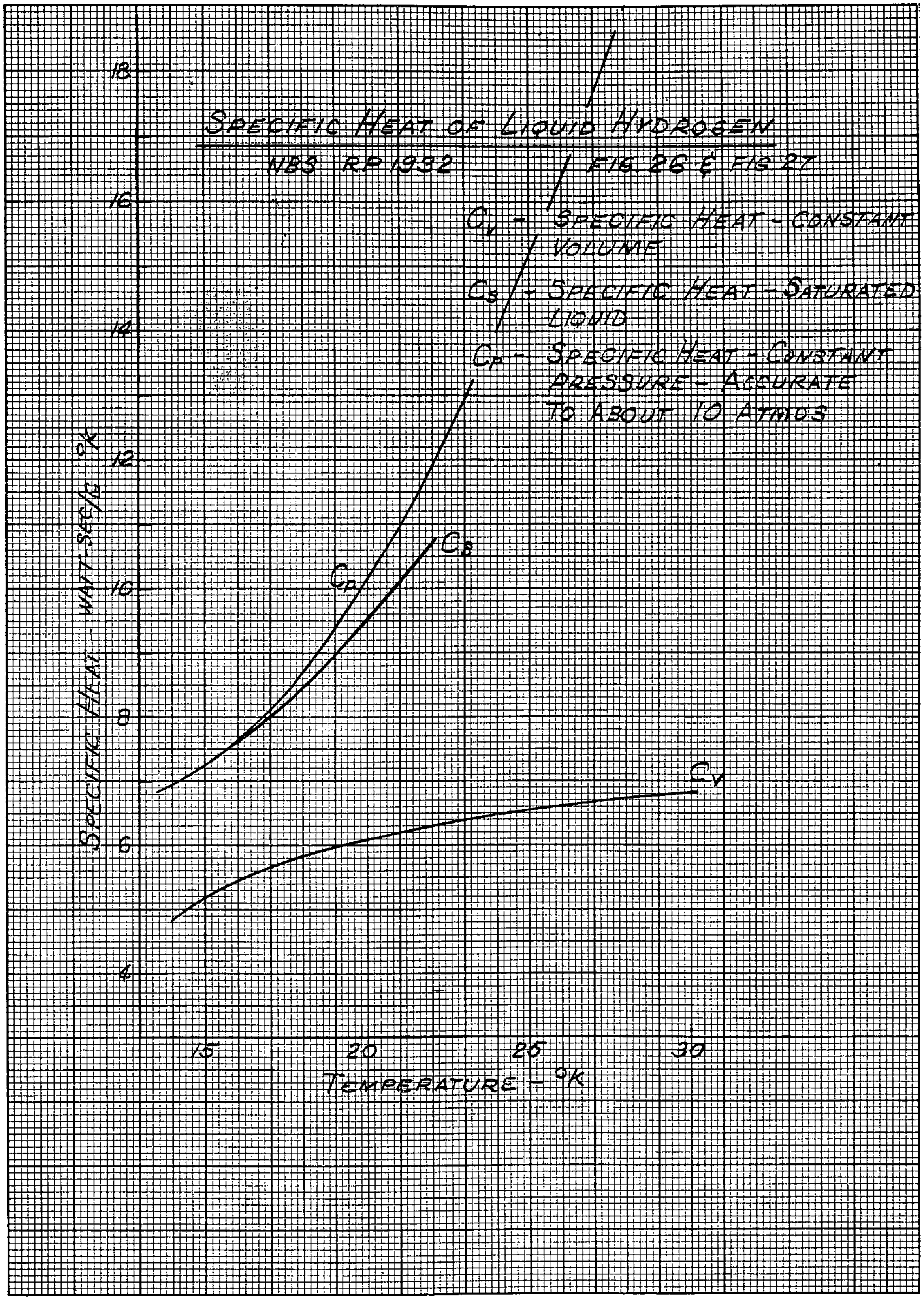
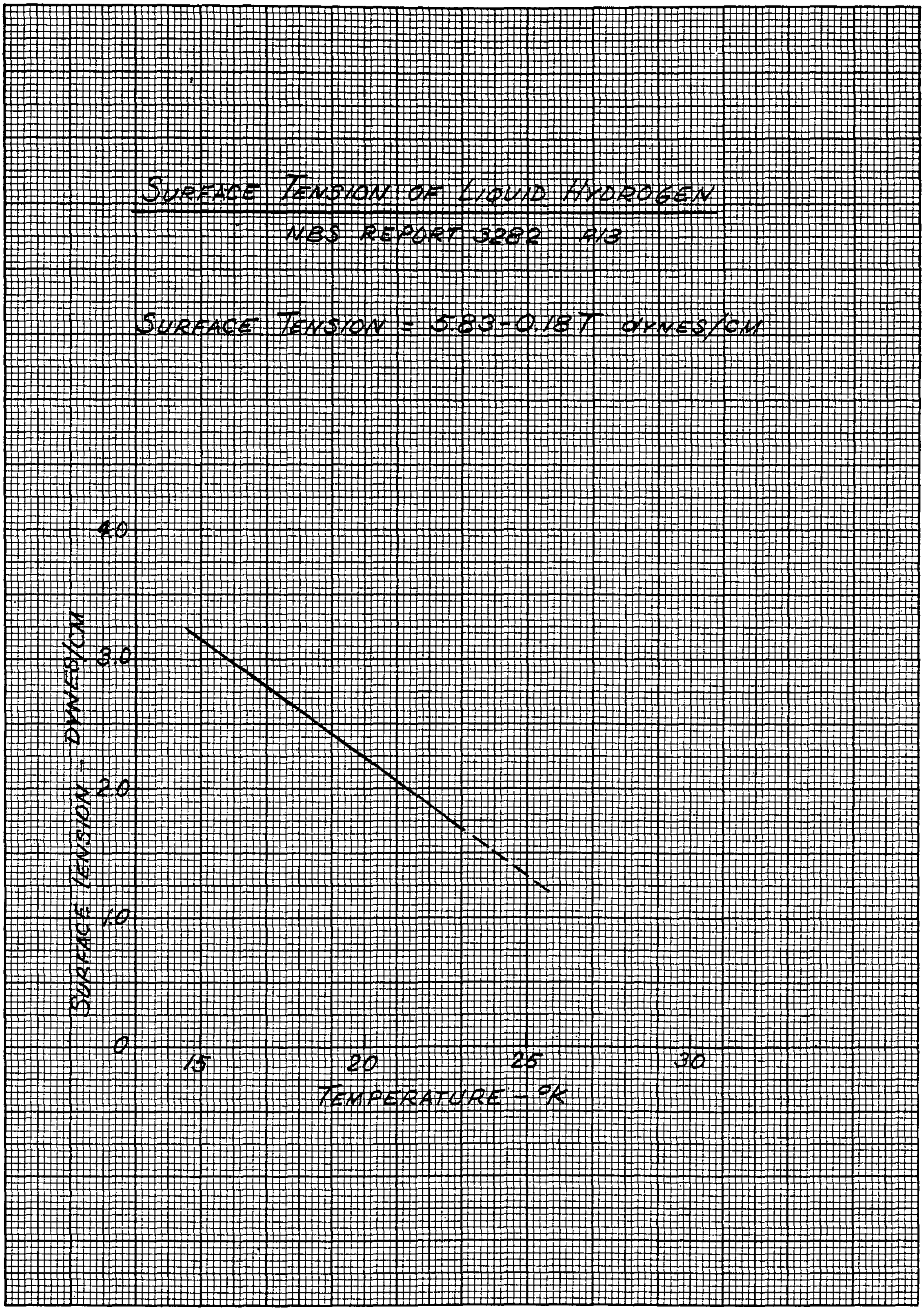
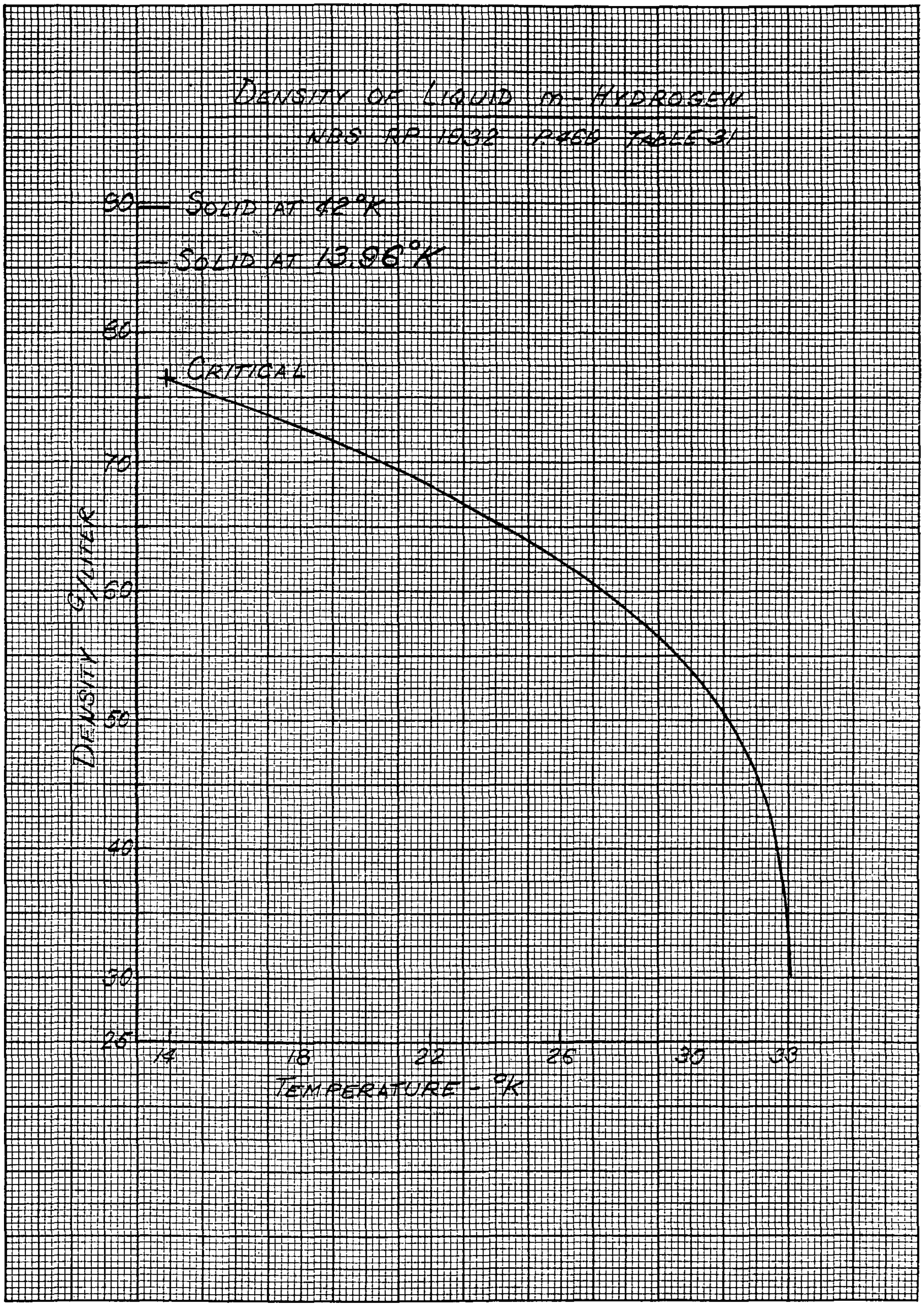
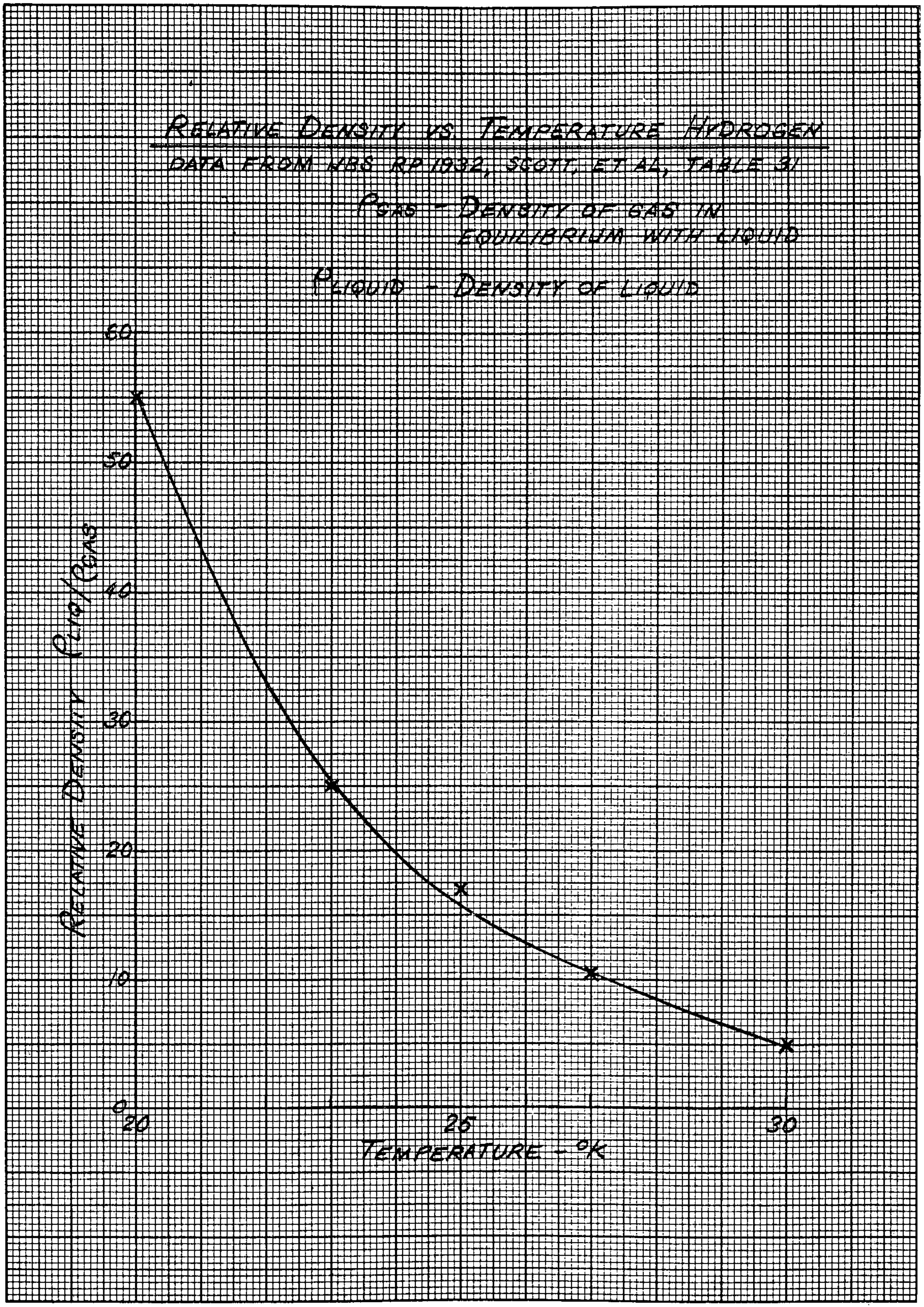

VISCOSITY OF LIQUID HYDROGEN
NBS REPORT 3282 P.7
POISE = GM / CM SEC
250
200
150
100
50
15
20
25
30
TEMPERATURE - °K
VISCOSITY MICROPOISE

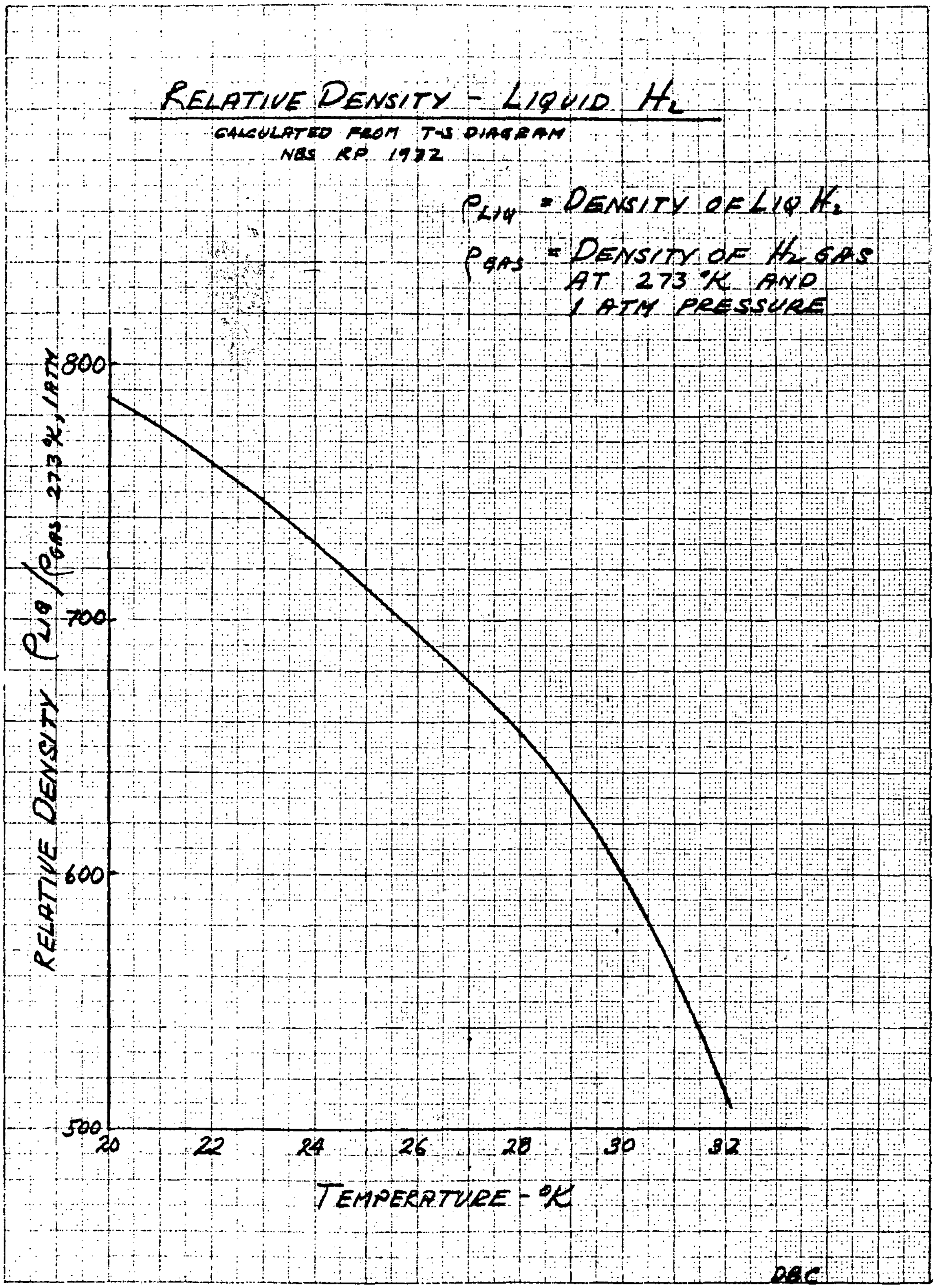

SPECIFIC HEAT OF LIQUID HYDROGEN
NBS RP 1932
FIG. 26 & FIG 27
Cv - SPECIFIC HEAT - CONSTANT VOLUME
Cs - SPECIFIC HEAT - SATURATED LIQUID
Cp - SPECIFIC HEAT - CONSTANT PRESSURE - ACCURATE TO ABOUT 10 ATMOS
Cp
Cs
Cv
SPECIFIC HEAT - WATT-SEC/G °K
18
16
14
12
10
8
6
4
15
20
25
30
TEMPERATURE - °K

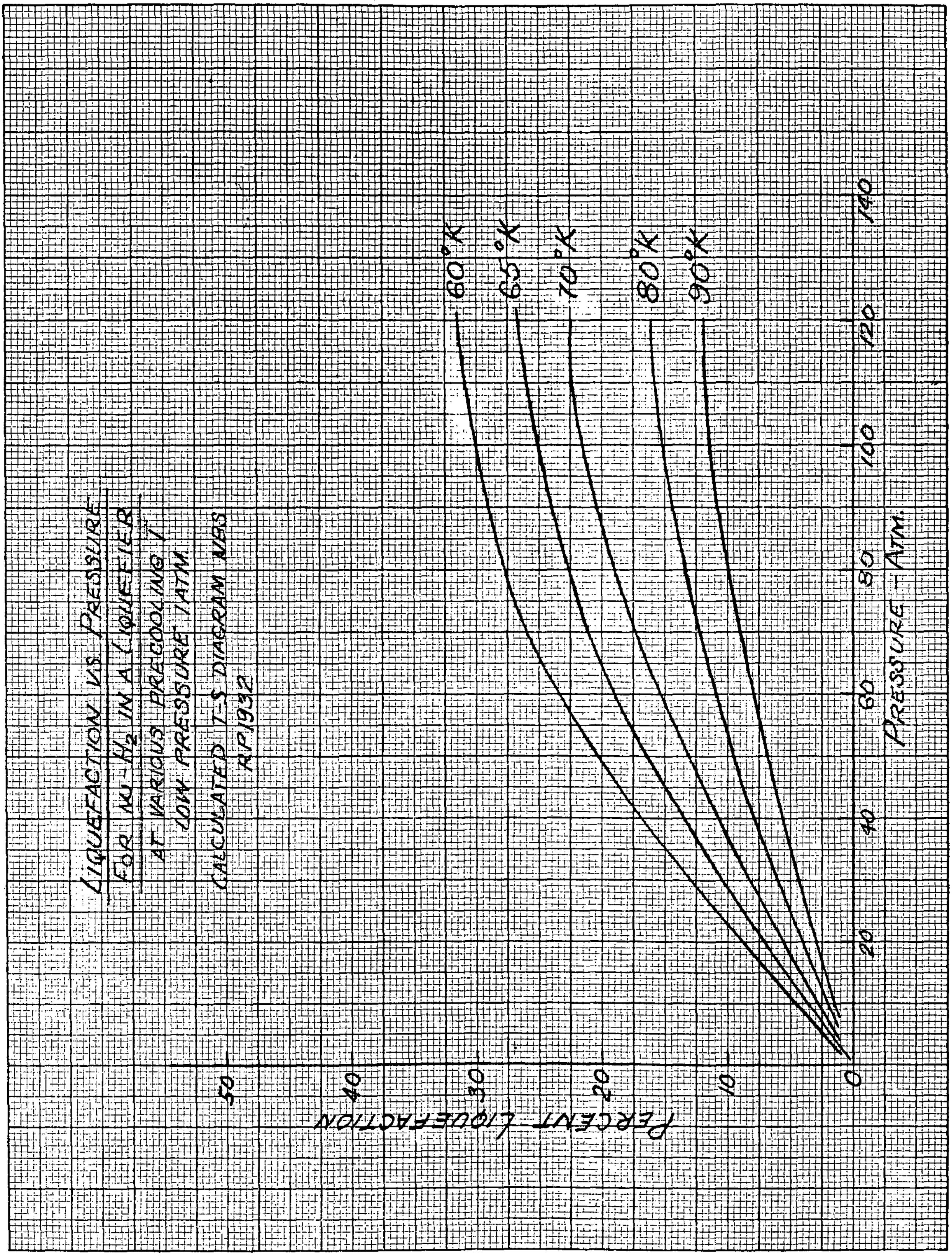
0 0 1 0 1 5 0 0 7 3 8

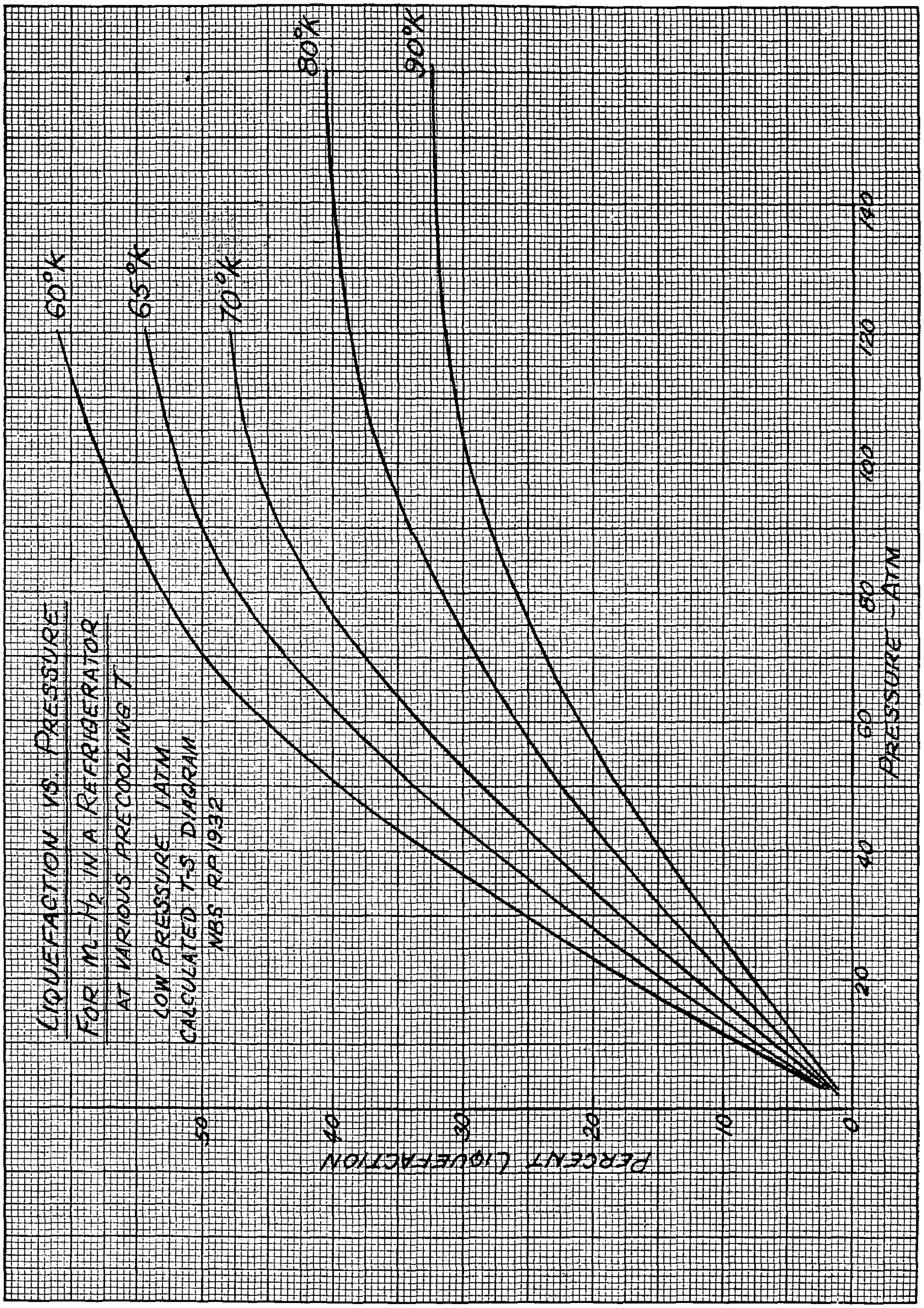


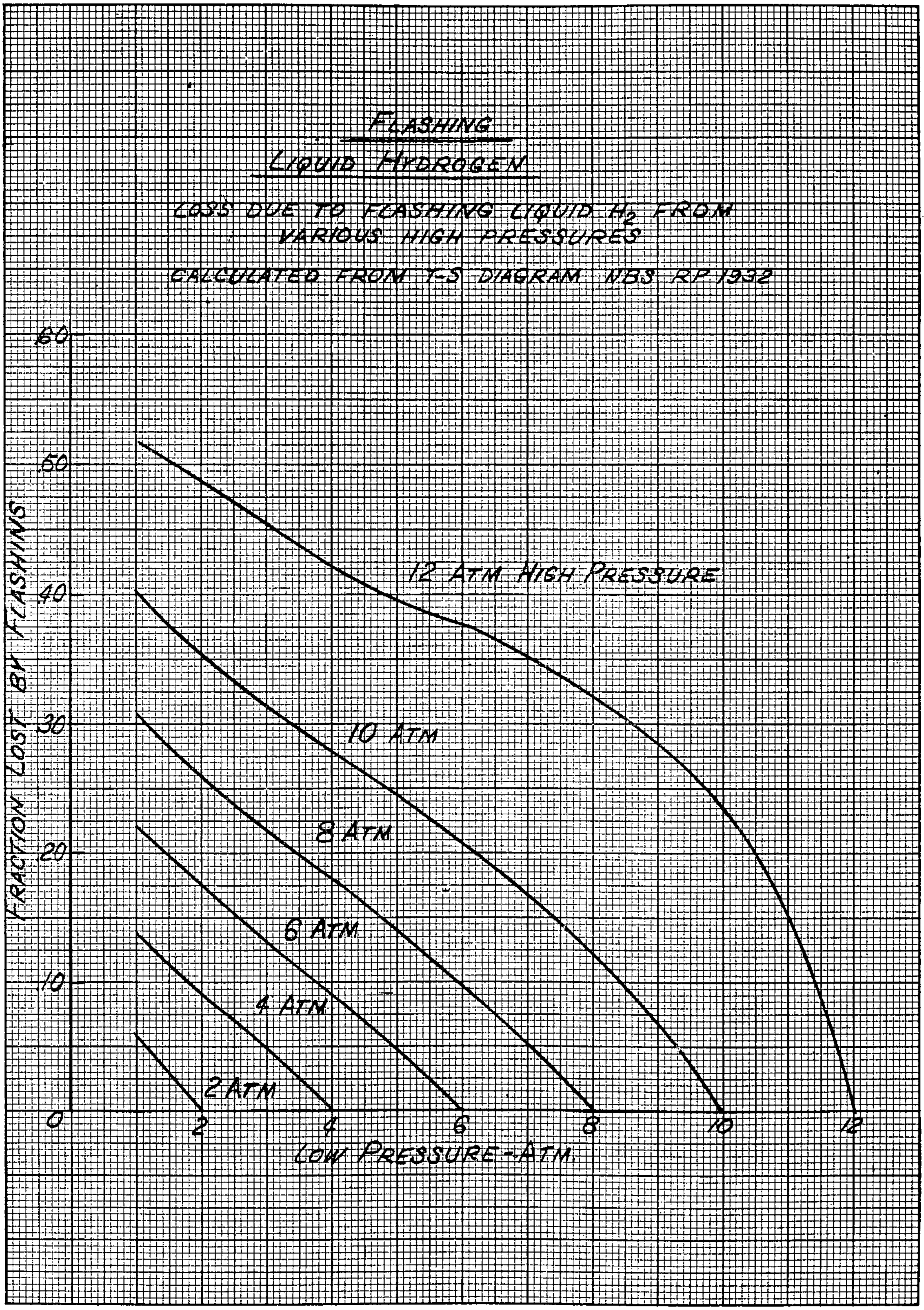

DENSITY OF LIQUID m-HYDROGEN
NBS RP 1932 P.466 TABLE 31
SOLID AT 4.2°K
SOLID AT 13.96°K
CRITICAL
DENSITY G/LITER
90
80
70
60
50
40
30
25
14
18
22
26
30
33
TEMPERATURE - °K

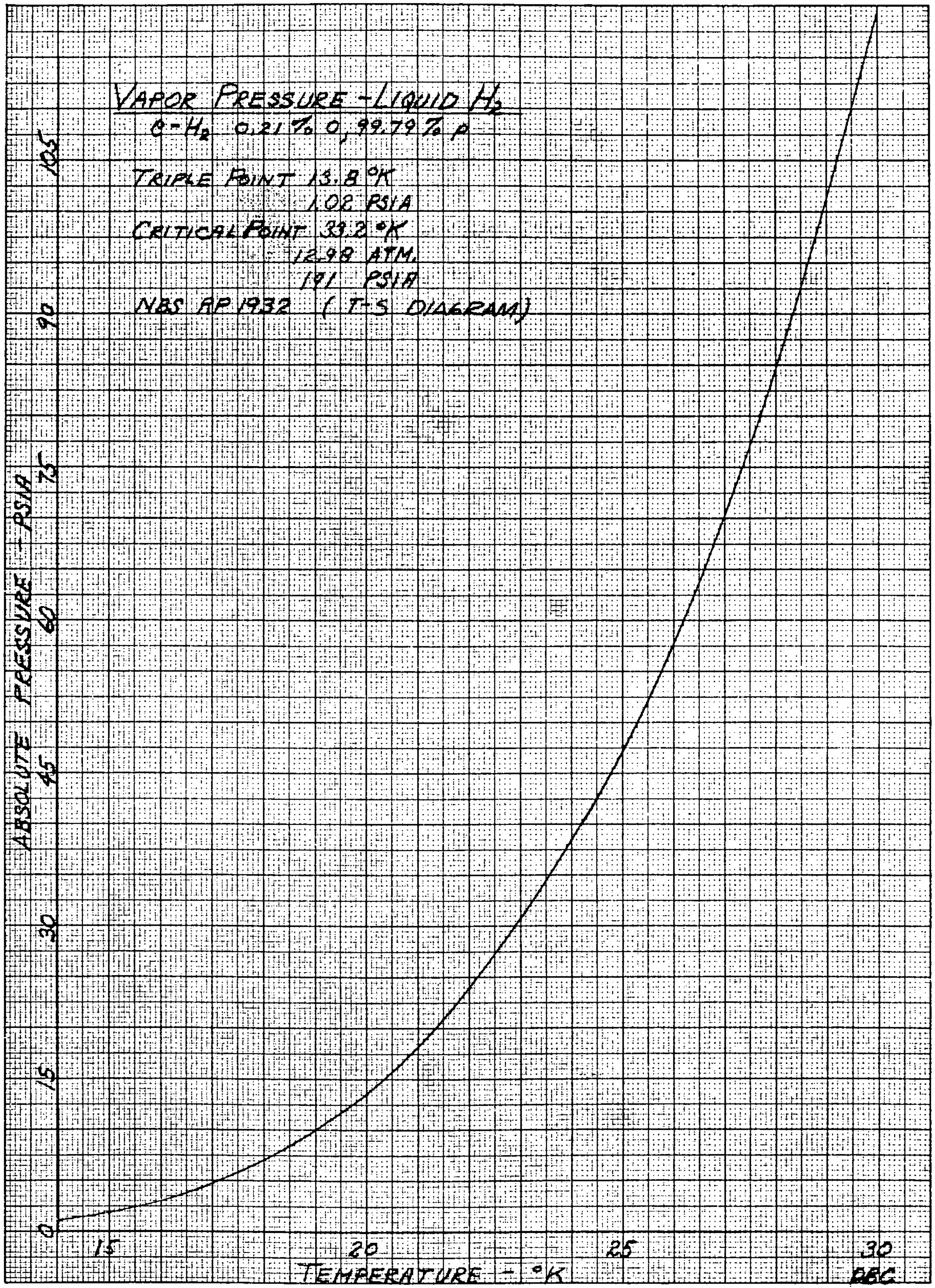

RELATIVE DENSITY VS. TEMPERATURE HYDROGEN
DATA FROM NBS RP 1932, SCOTT, ET AL, TABLE 31
ρGAS - DENSITY OF GAS IN EQUILIBRIUM WITH LIQUID
ρLIQUID - DENSITY OF LIQUID
RELATIVE DENSITY ρLIQ/ρGAS
60
50
40
30
20
10
0
20
25
30
TEMPERATURE - °K

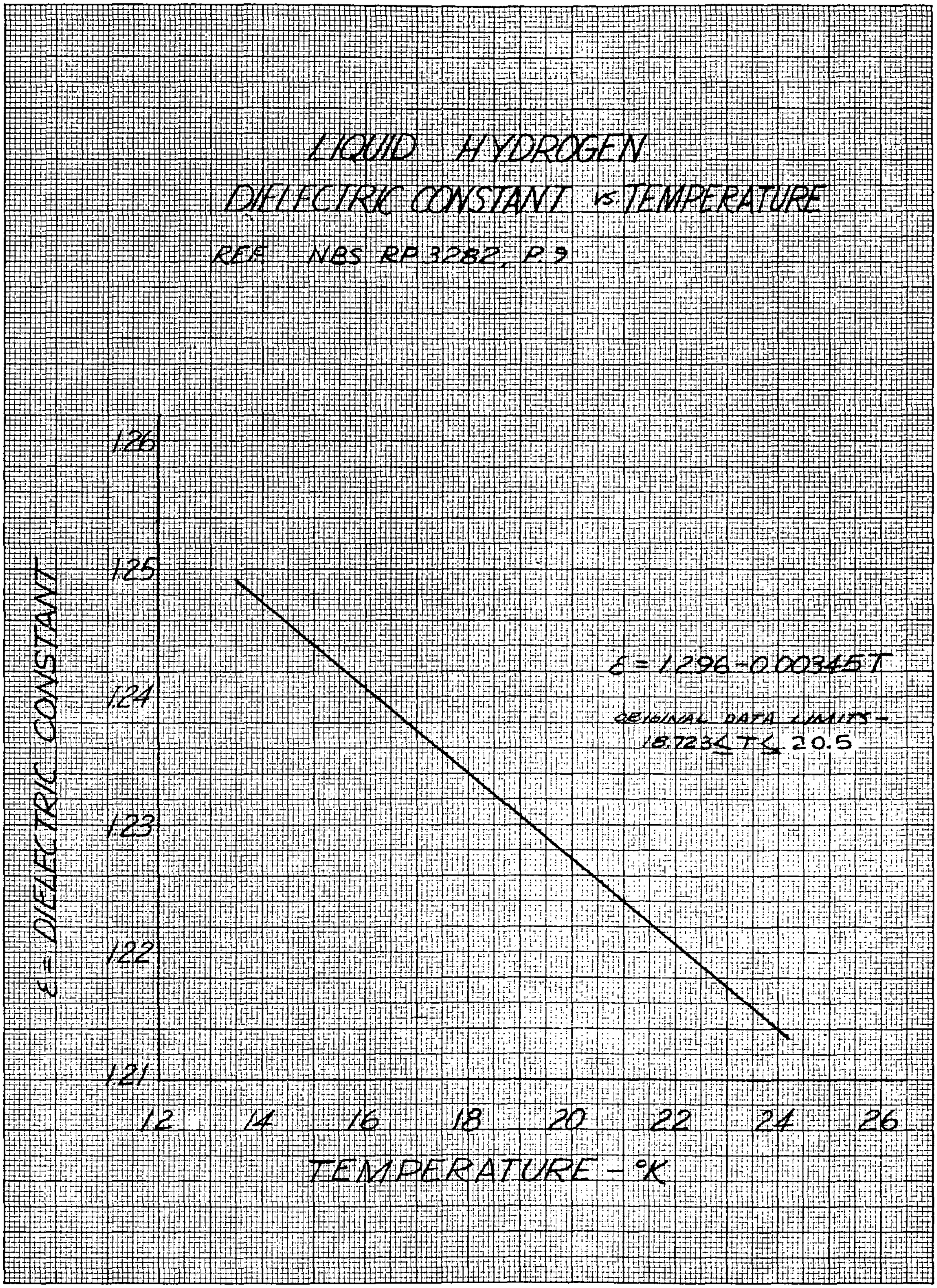

RELATIVE DENSITY - LIQUID H2
CALCULATED FROM T-S DIAGRAM
NBS RP 1932
ρLIQ = DENSITY OF LIQ H2
ρGAS = DENSITY OF H2 GAS AT 273 °K AND 1 ATM PRESSURE
RELATIVE DENSITY ρLIQ/ρGAS 273°K, 1ATM
800
700
600
500
20
22
24
26
28
30
32
TEMPERATURE - °K
DBC

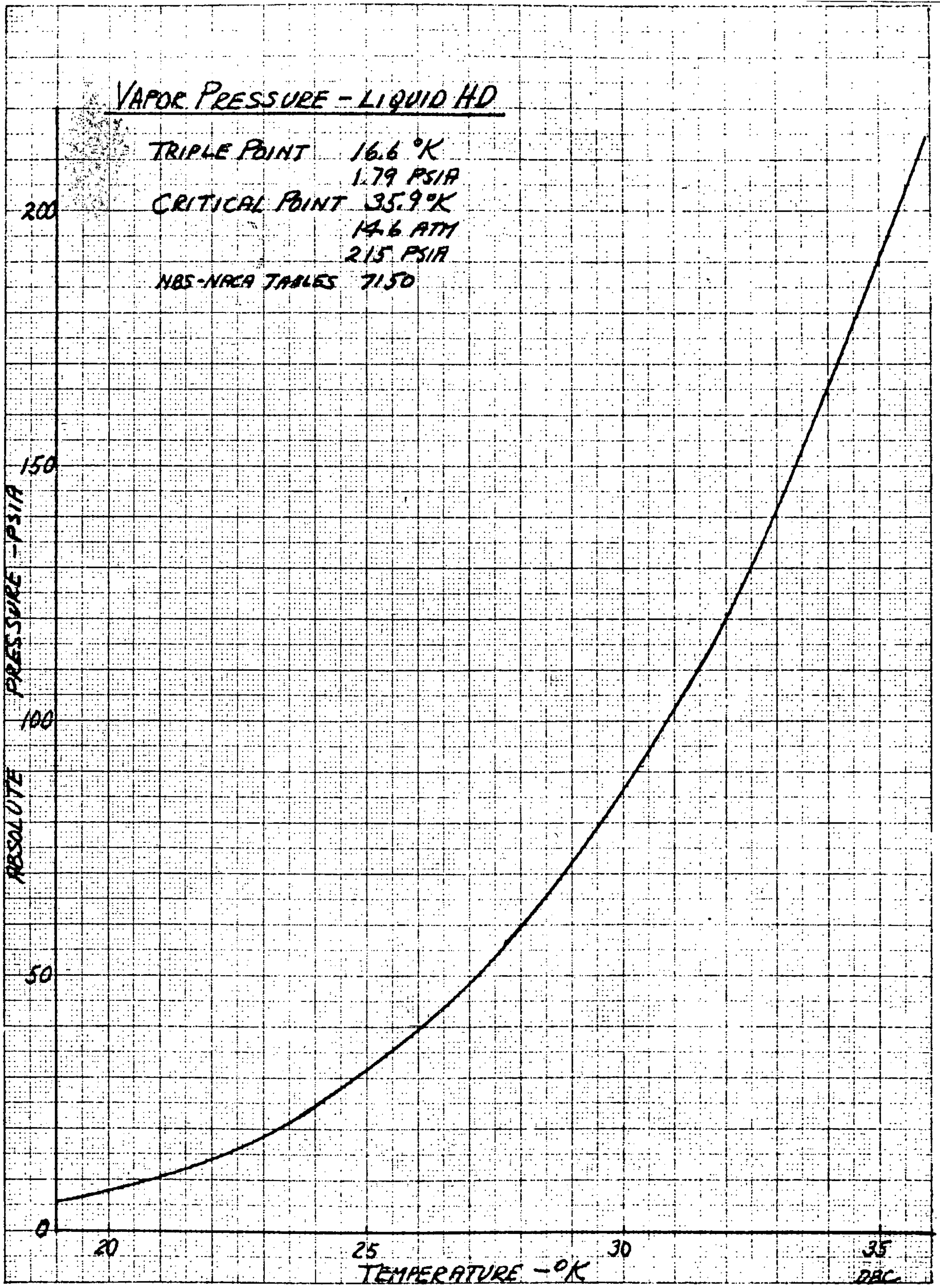

LIQUEFACTION VS PRESSURE
FOR N-H_2 IN A LIQUEFIER
AT VARIOUS PRECOOLING T
LOW PRESSURE 1 ATM.
CALCULATED T-S DIAGRAM NBS
RP1932
60°K
65°K
70°K
80°K
90°K
PERCENT LIQUEFACTION
0
10
20
30
40
50
PRESSURE - ATM.
20
40
60
80
100
120
140

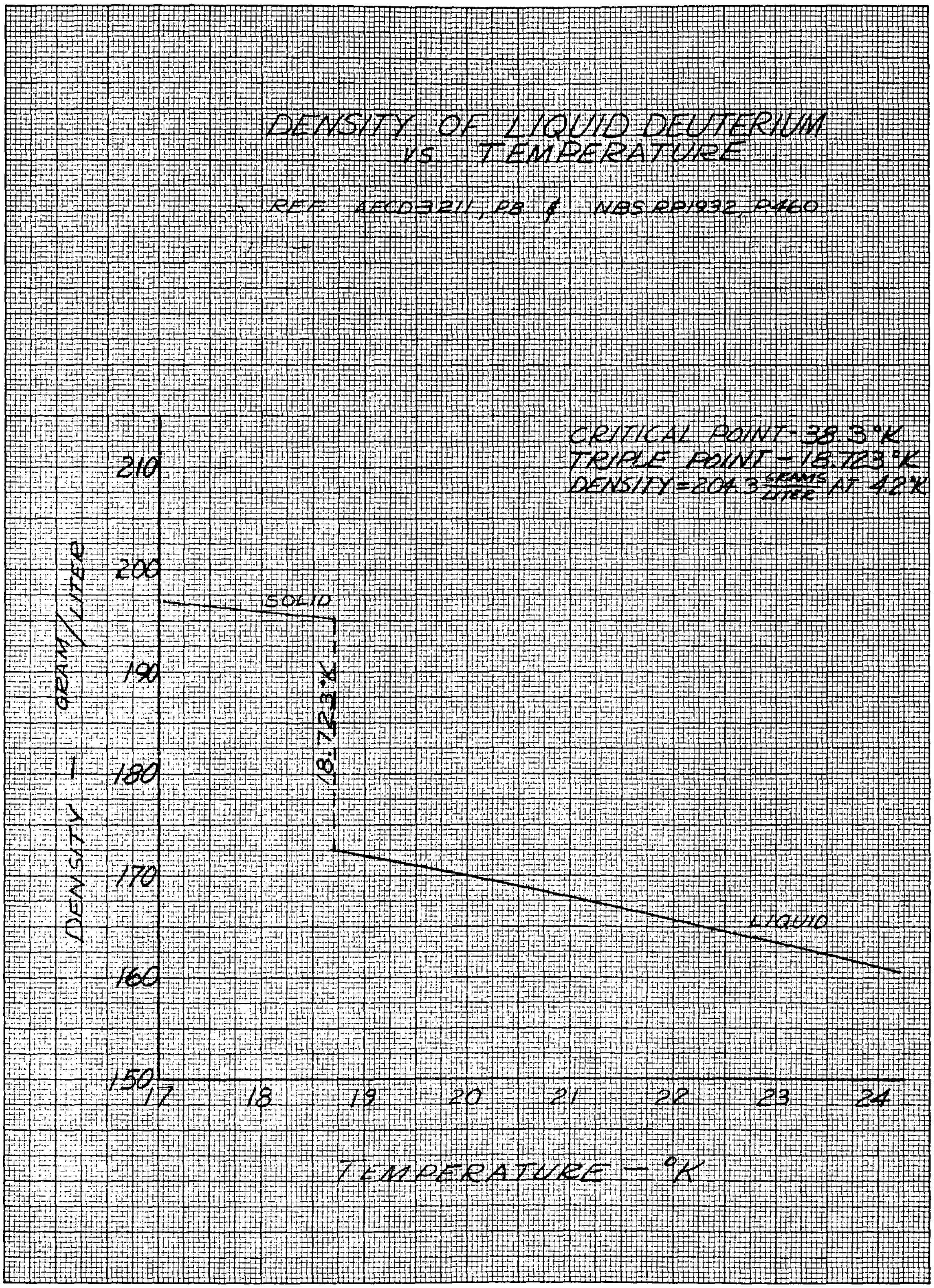

LIQUEFACTION VS. PRESSURE
FOR N-H2 IN A REFRIGERATOR
AT VARIOUS PRECOOLING T
LOW PRESSURE 1 ATM
CALCULATED T-S DIAGRAM
NBS RP1932
60°K
65°K
70°K
80°K
90°K
PERCENT LIQUEFACTION
0
10
20
30
40
50
PRESSURE - ATM
20
40
60
80
100
120
140

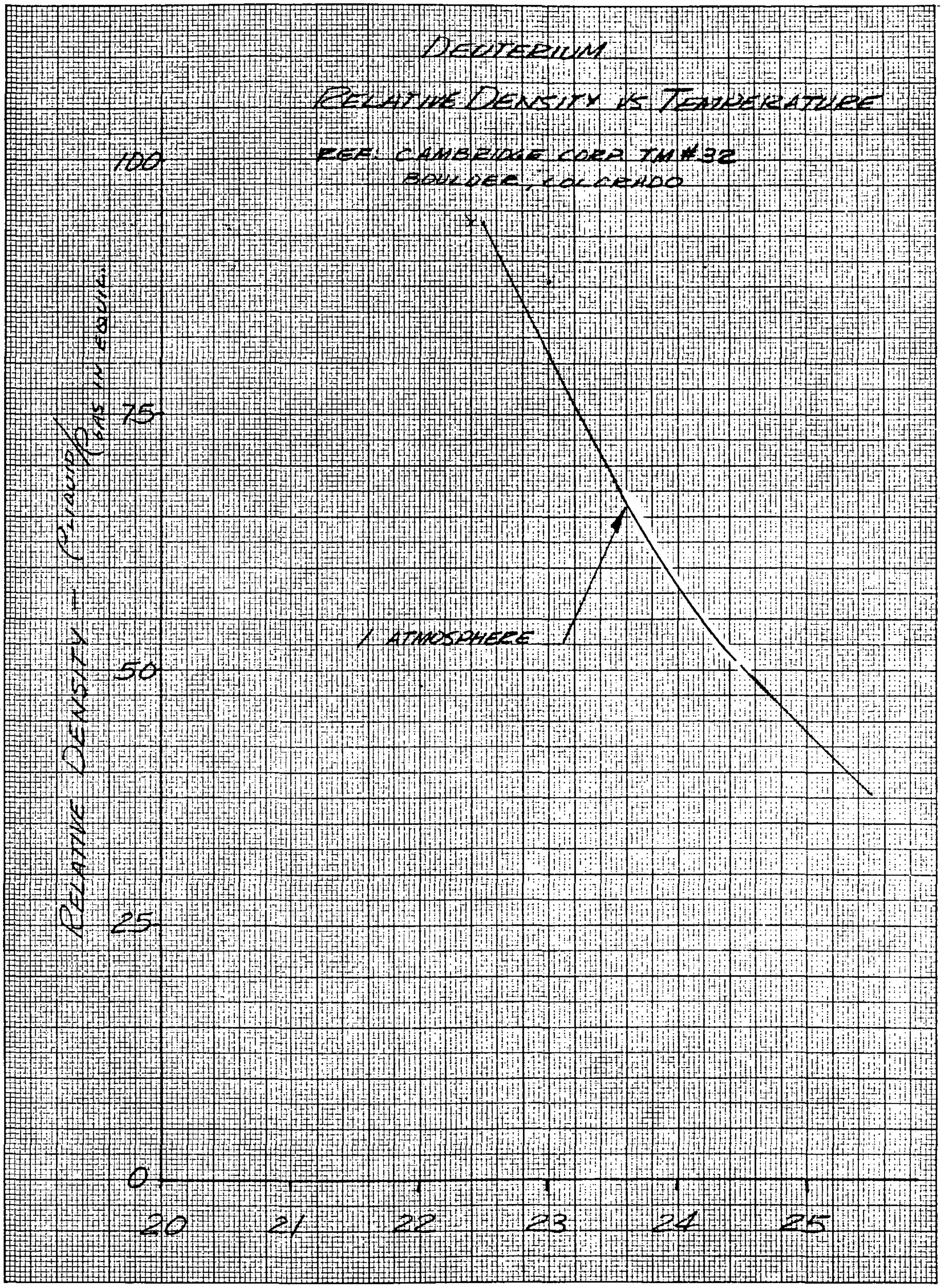

FLASHING
LIQUID HYDROGEN
LOSS DUE TO FLASHING LIQUID H2 FROM VARIOUS HIGH PRESSURES
CALCULATED FROM T-S DIAGRAM NBS RP 1932
12 ATM HIGH PRESSURE
10 ATM
8 ATM
6 ATM
4 ATM
2 ATM
FRACTION LOST BY FLASHING
LOW PRESSURE-ATM.
0
2
4
6
8
10
12
10
20
30
40
50
60

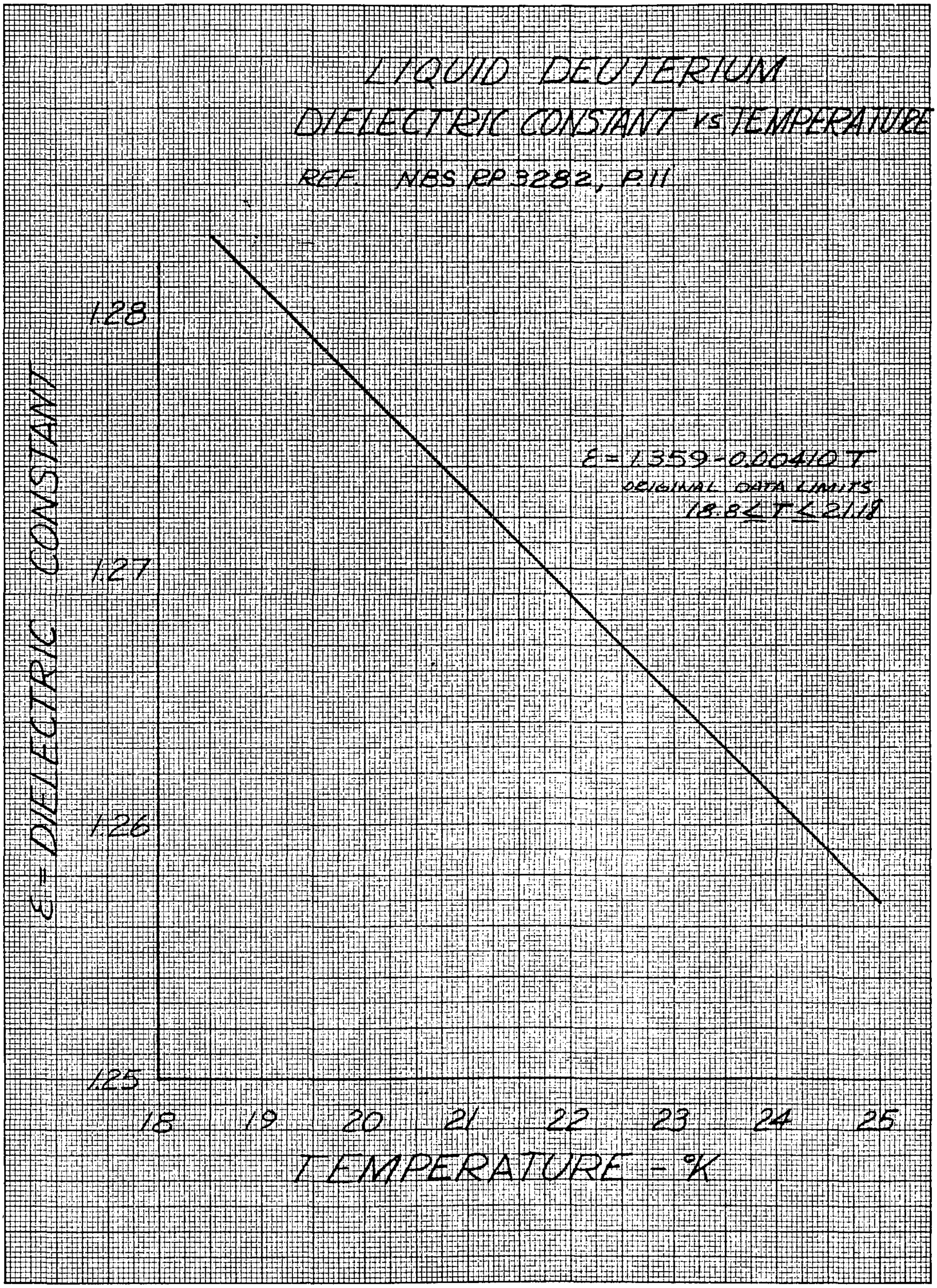

VAPOR PRESSURE - LIQUID H_2
e-H_2 0.21 % o, 99.79 % p
TRIPLE POINT 13.8 °K
1.02 PSIA
CRITICAL POINT 33.2 °K
12.98 ATM.
191 PSIA
NBS RP 1932 (T-S DIAGRAM)
ABSOLUTE PRESSURE - PSIA
0
15
30
45
60
75
90
105
15
20
25
30
TEMPERATURE - °K
BEC

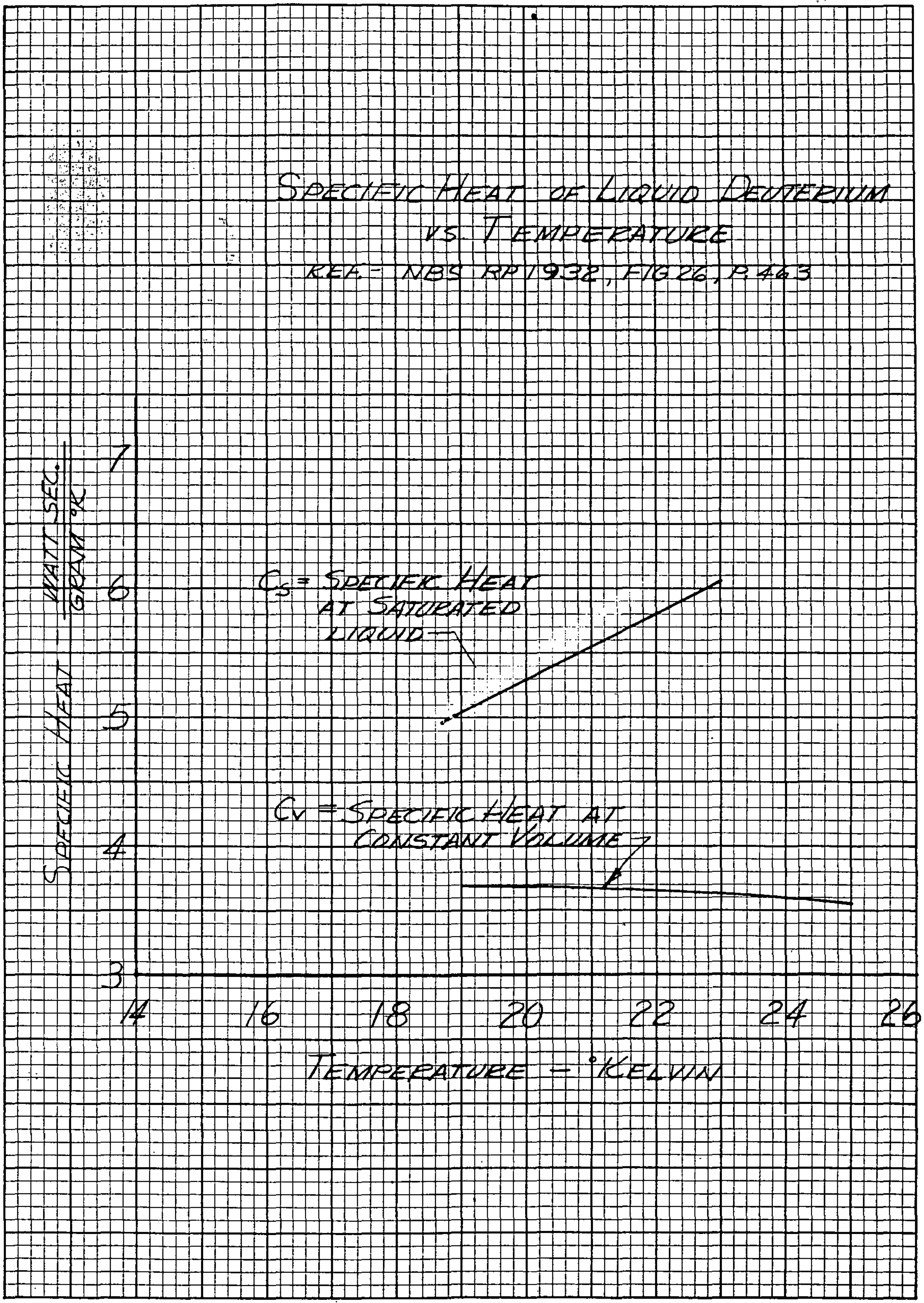

LIQUID HYDROGEN
DIELECTRIC CONSTANT vs TEMPERATURE
REF. NBS RP 3282, P.9
ε = DIELECTRIC CONSTANT
1.26
1.25
1.24
1.23
1.22
1.21
12
14
16
18
20
22
24
26
TEMPERATURE - °K
ε = 1.296 - 0.00345T
ORIGINAL DATA LIMITS -
18.723 ≤ T ≤ 20.5

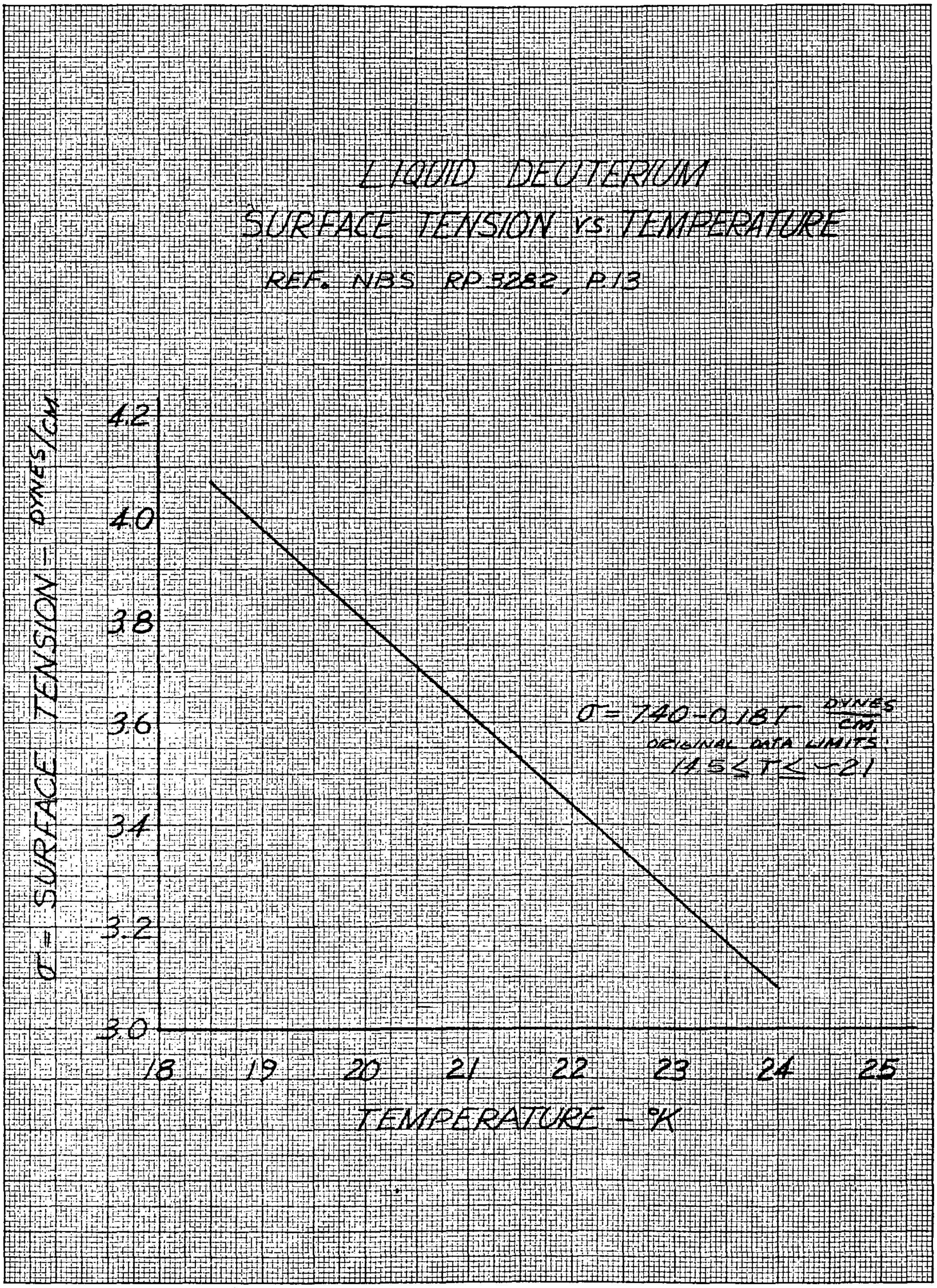

VAPOR PRESSURE - LIQUID HD
TRIPLE POINT 16.6 °K
1.79 PSIA
CRITICAL POINT 35.9°K
14.6 ATM
215 PSIA
NBS-NACA TABLES 7150
ABSOLUTE PRESSURE - PSIA
0
50
100
150
200
20
25
30
35
TEMPERATURE - °K
DBC

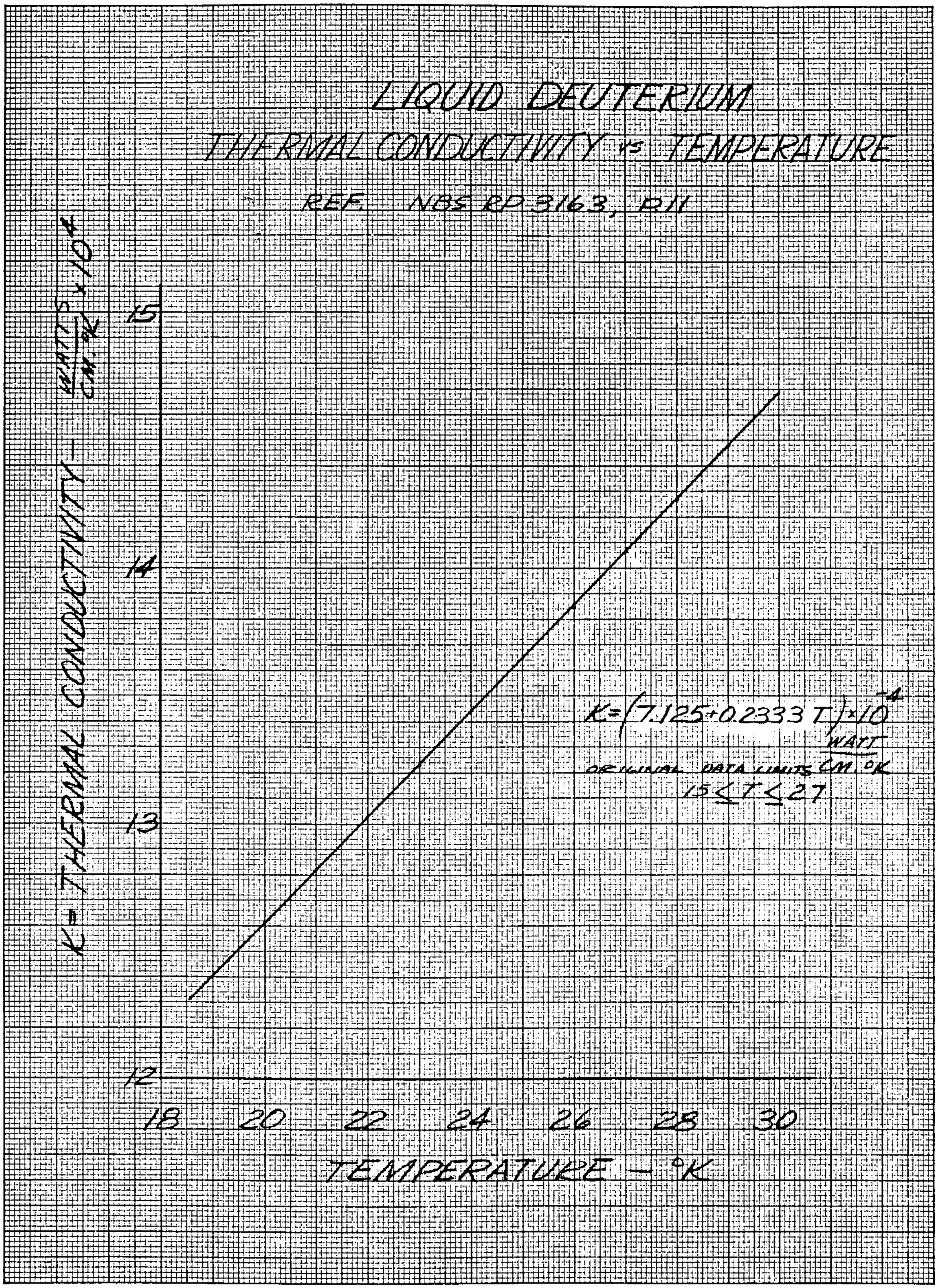

DENSITY OF LIQUID DEUTERIUM
vs. TEMPERATURE
REF. AECD3211, P8 & NBS RP1932, P460
CRITICAL POINT - 38.3°K
TRIPLE POINT - 18.723°K
DENSITY = 204.3 GRAMS/LITER AT 4.2°K
SOLID
18.723°K
LIQUID
DENSITY - GRAM/LITER
210
200
190
180
170
160
150
17
18
19
20
21
22
23
24
TEMPERATURE - °K

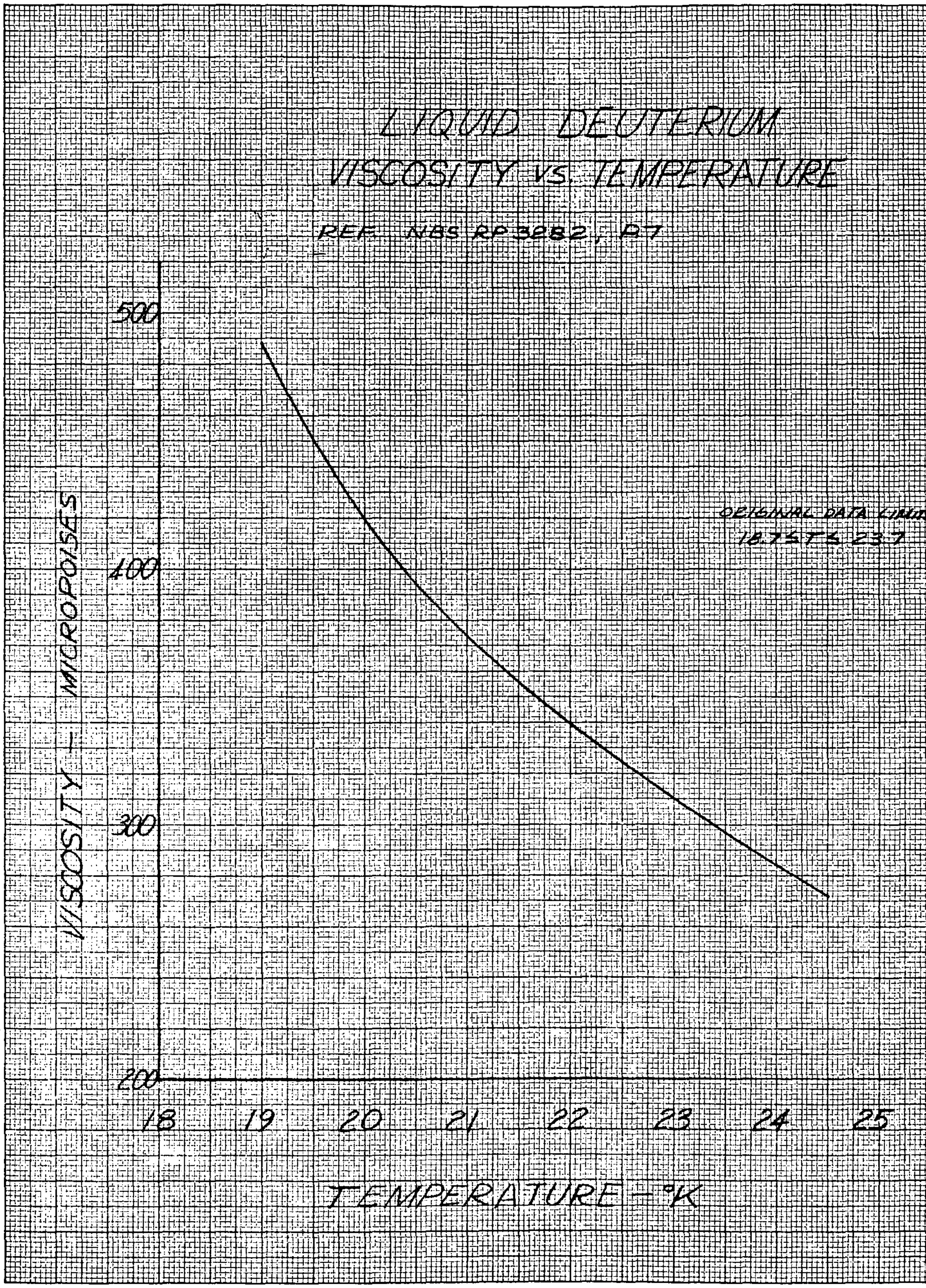

DEUTERIUM
RELATIVE DENSITY VS TEMPERATURE
REF: CAMBRIDGE CORP TM#32
BOULDER, COLORADO
RELATIVE DENSITY = ρ LIQUID / ρ GAS IN EQUIL.
1 ATMOSPHERE
100
75
50
25
0
20
21
22
23
24
25

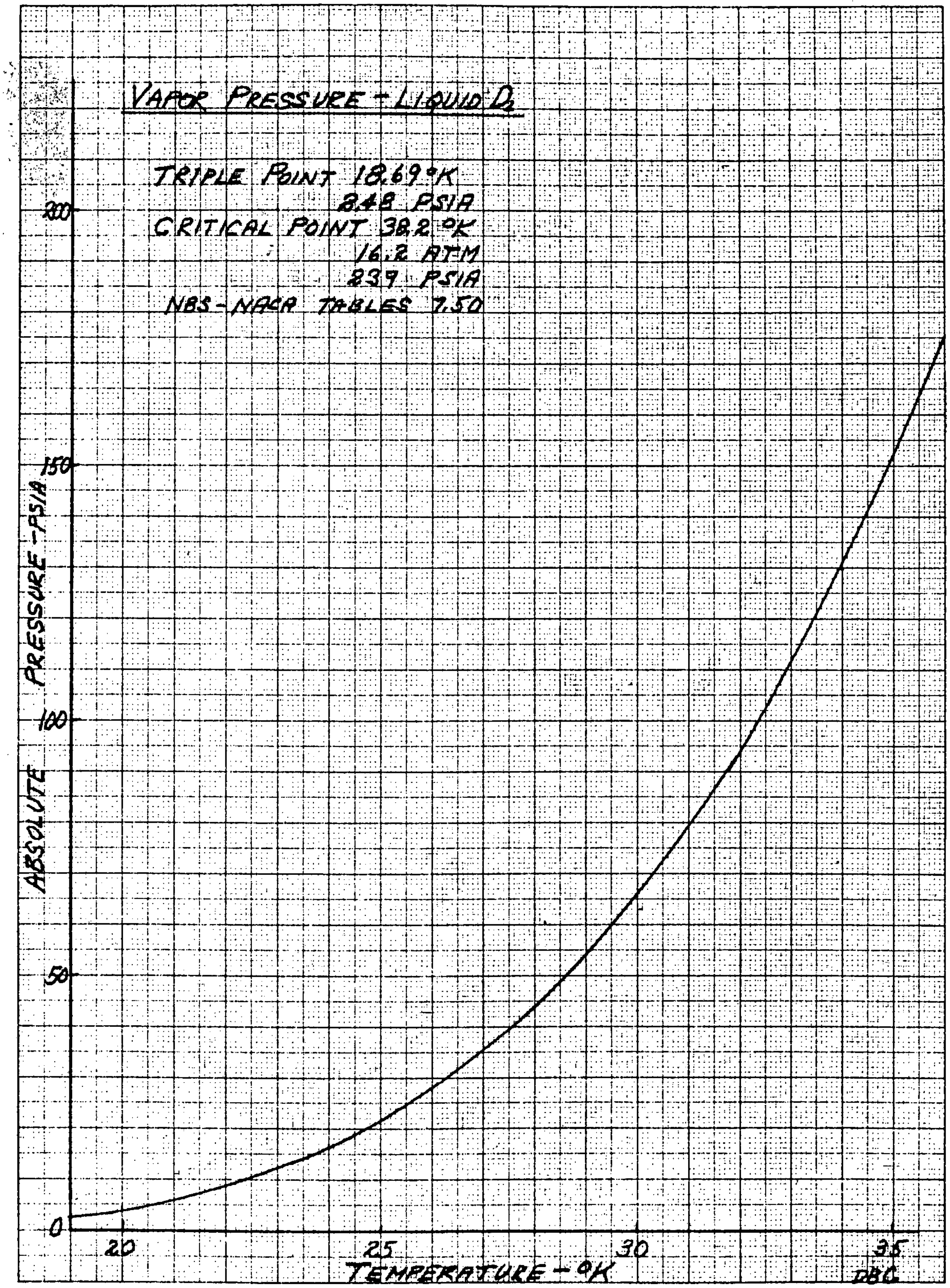

LIQUID DEUTERIUM
DIELECTRIC CONSTANT vs TEMPERATURE
REF. NBS RP 3282, P.11
ε = 1.359 - 0.00410 T
ORIGINAL DATA LIMITS
18.8 ≤ T ≤ 21.18
1.28
1.27
1.26
1.25
ε - DIELECTRIC CONSTANT
18
19
20
21
22
23
24
25
TEMPERATURE - °K

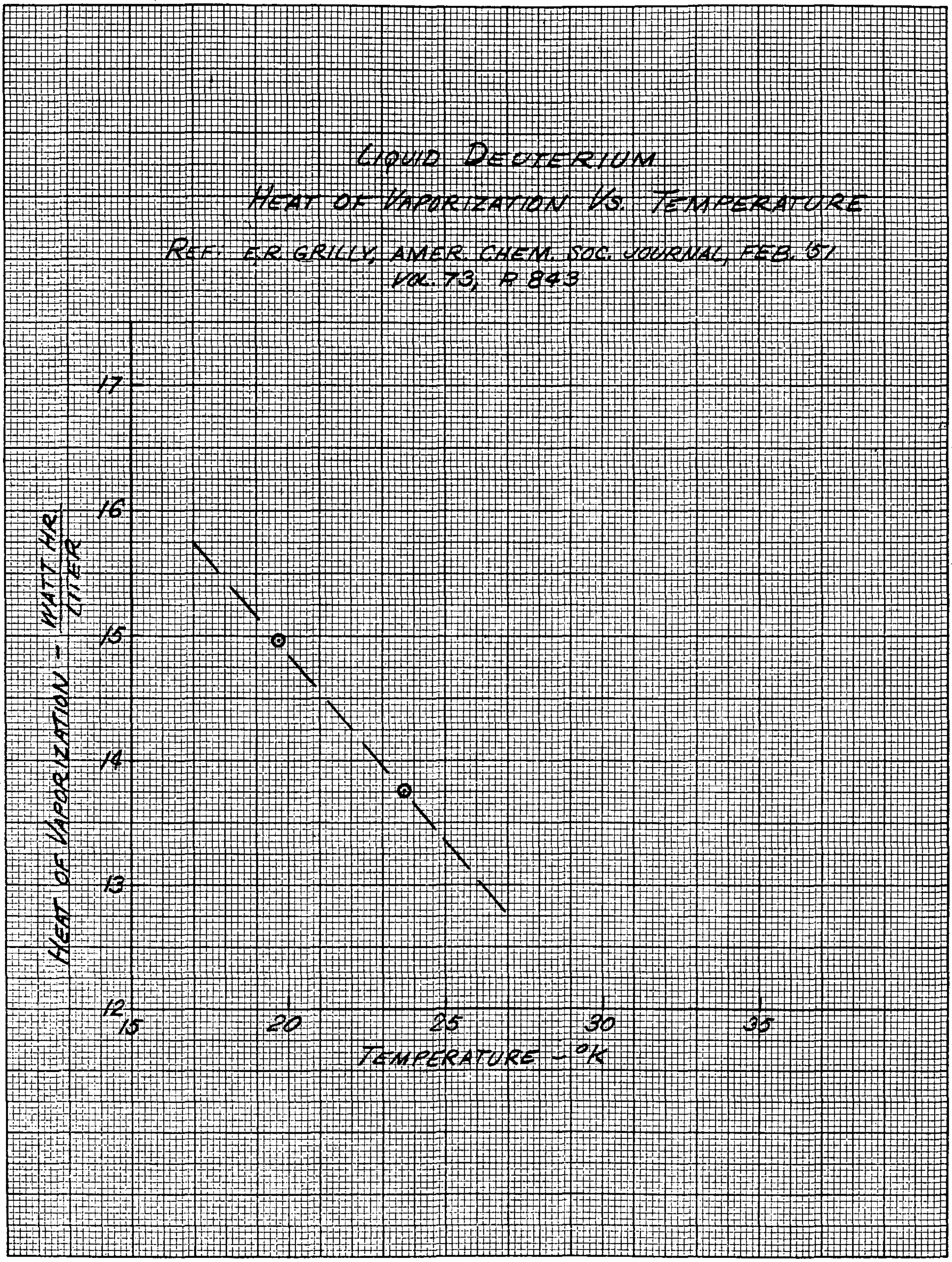

SPECIFIC HEAT OF LIQUID DEUTERIUM
VS. TEMPERATURE
REF. - NBS RP1932, FIG 26, P. 463
SPECIFIC HEAT - WATT SEC. / GRAM °K
7
6
5
4
3
CS = SPECIFIC HEAT AT SATURATED LIQUID
CV = SPECIFIC HEAT AT CONSTANT VOLUME
14
16
18
20
22
24
26
TEMPERATURE - °KELVIN

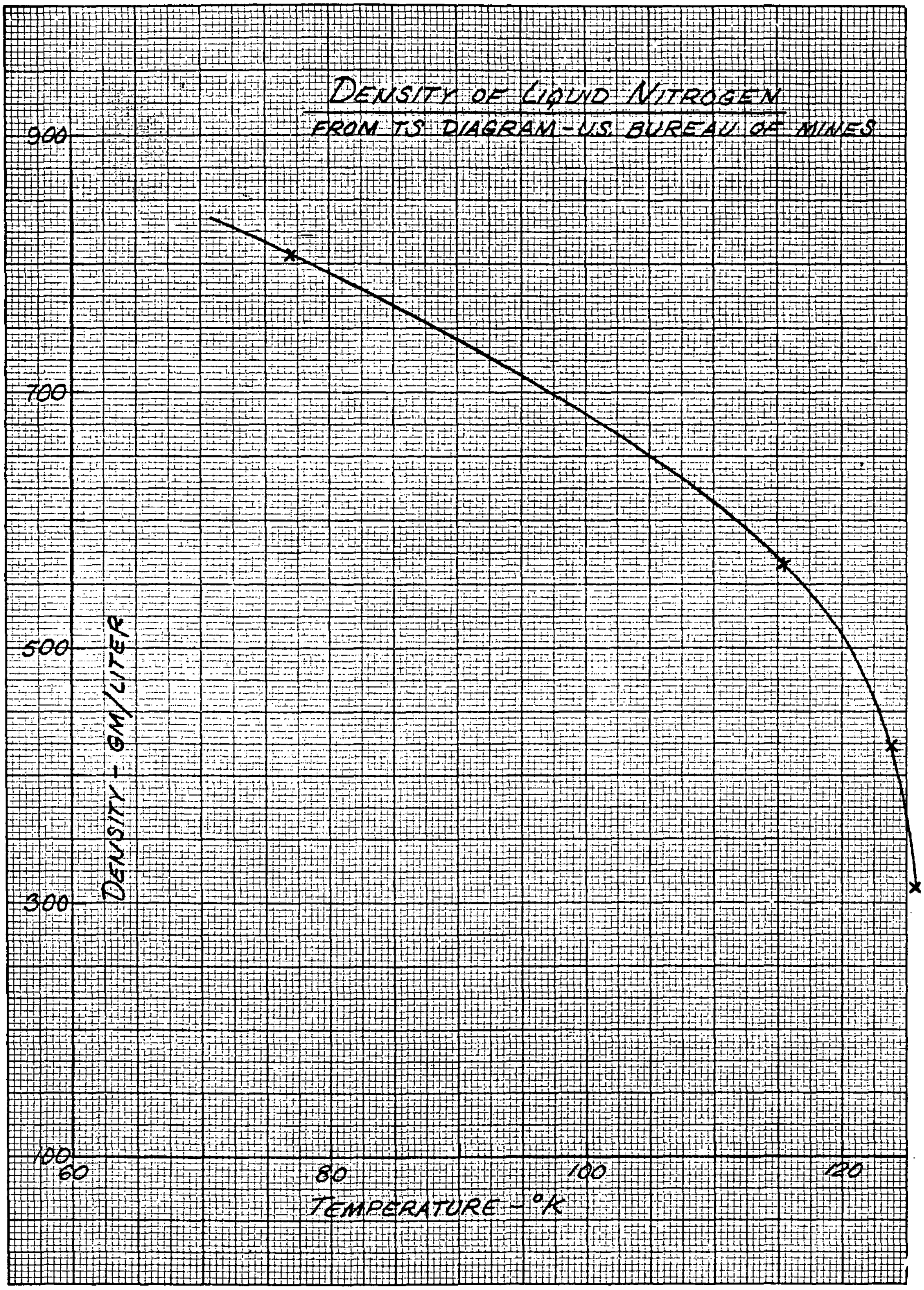

LIQUID DEUTERIUM
SURFACE TENSION vs. TEMPERATURE
REF. NBS RP 5282, P. 13
σ = SURFACE TENSION – DYNES/CM
4.2
4.0
3.8
3.6
3.4
3.2
3.0
18
19
20
21
22
23
24
25
TEMPERATURE – °K
σ = 740-0.18T DYNES/CM.
ORIGINAL DATA LIMITS
14.5 ≤ T ≤ ~21

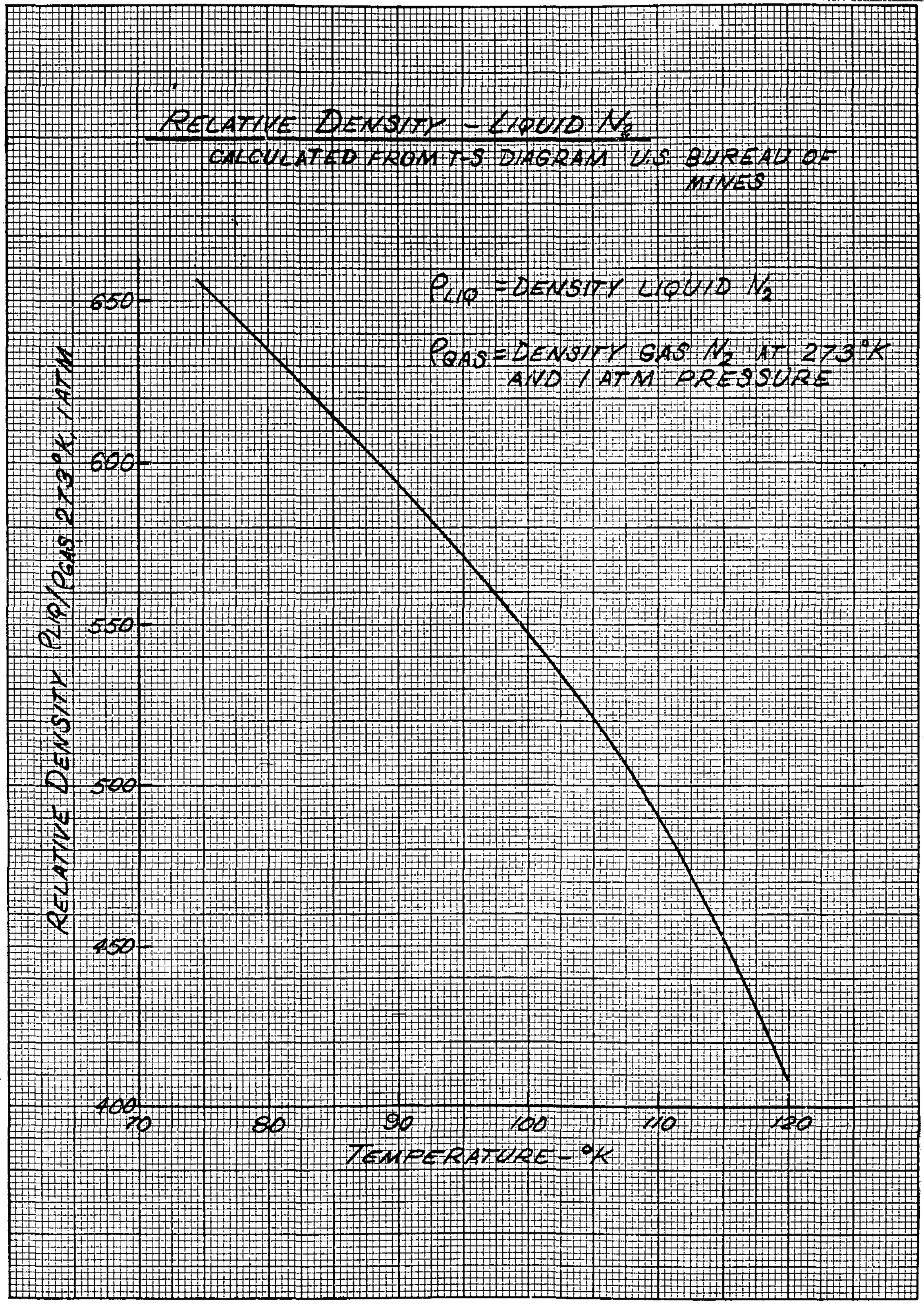

LIQUID DEUTERIUM
THERMAL CONDUCTIVITY vs TEMPERATURE
REF. NBS RP 3163, p11
K = THERMAL CONDUCTIVITY — WATTS/CM °K × 10⁴
15
14
13
12
18
20
22
24
26
28
30
TEMPERATURE — °K
K=(7.125+0.2333 T)×10⁻⁴ WATT/CM °K
ORIGINAL DATA LIMITS 15≤T≤27

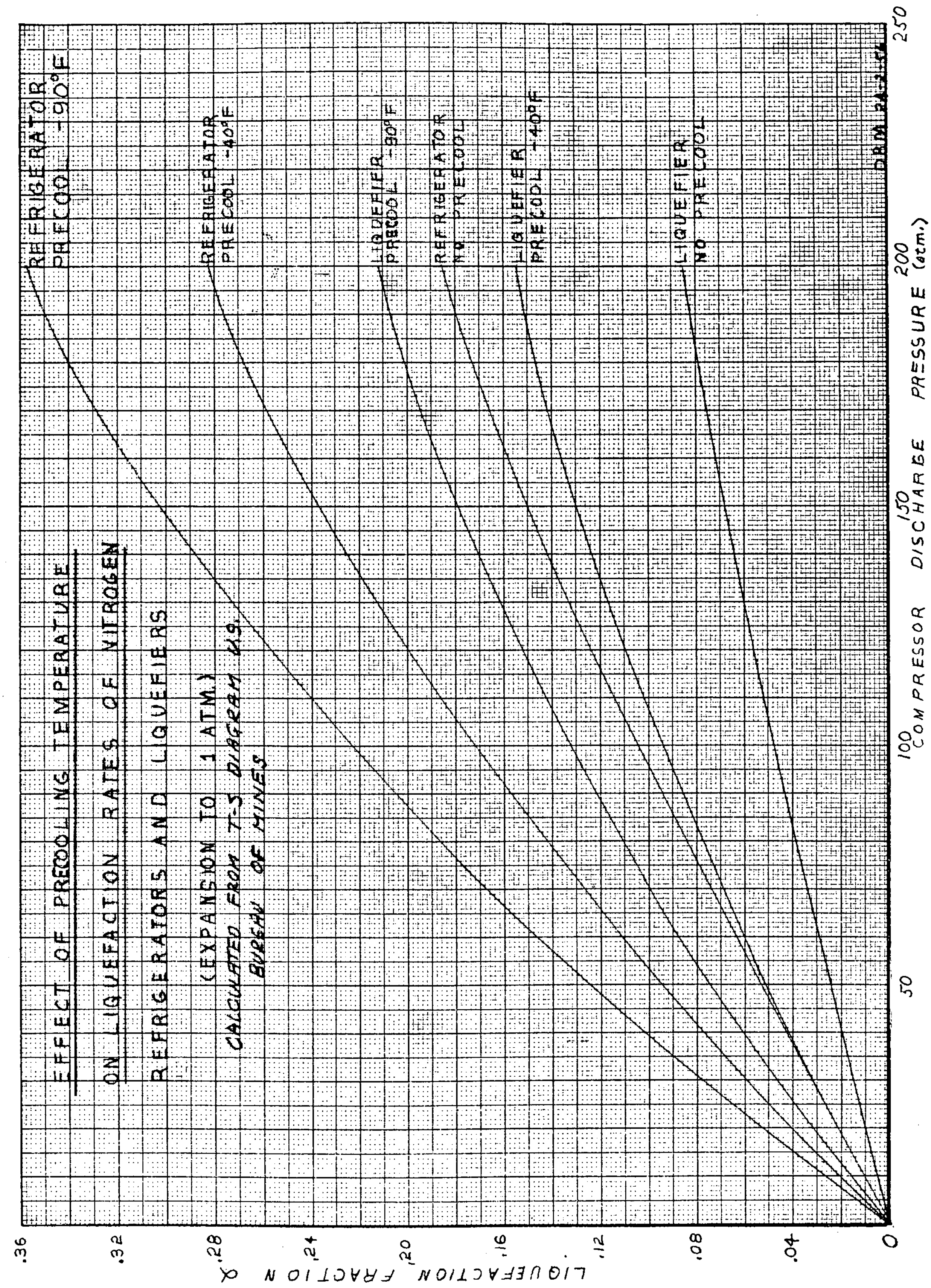

LIQUID DEUTERIUM
VISCOSITY vs. TEMPERATURE
REF. NBS RP 3282, P7
ORIGINAL DATA LIMITS
18.7 ≤ T ≤ 23.7
VISCOSITY — MICROPOISES
500
400
300
200
18
19
20
21
22
23
24
25
TEMPERATURE — °K

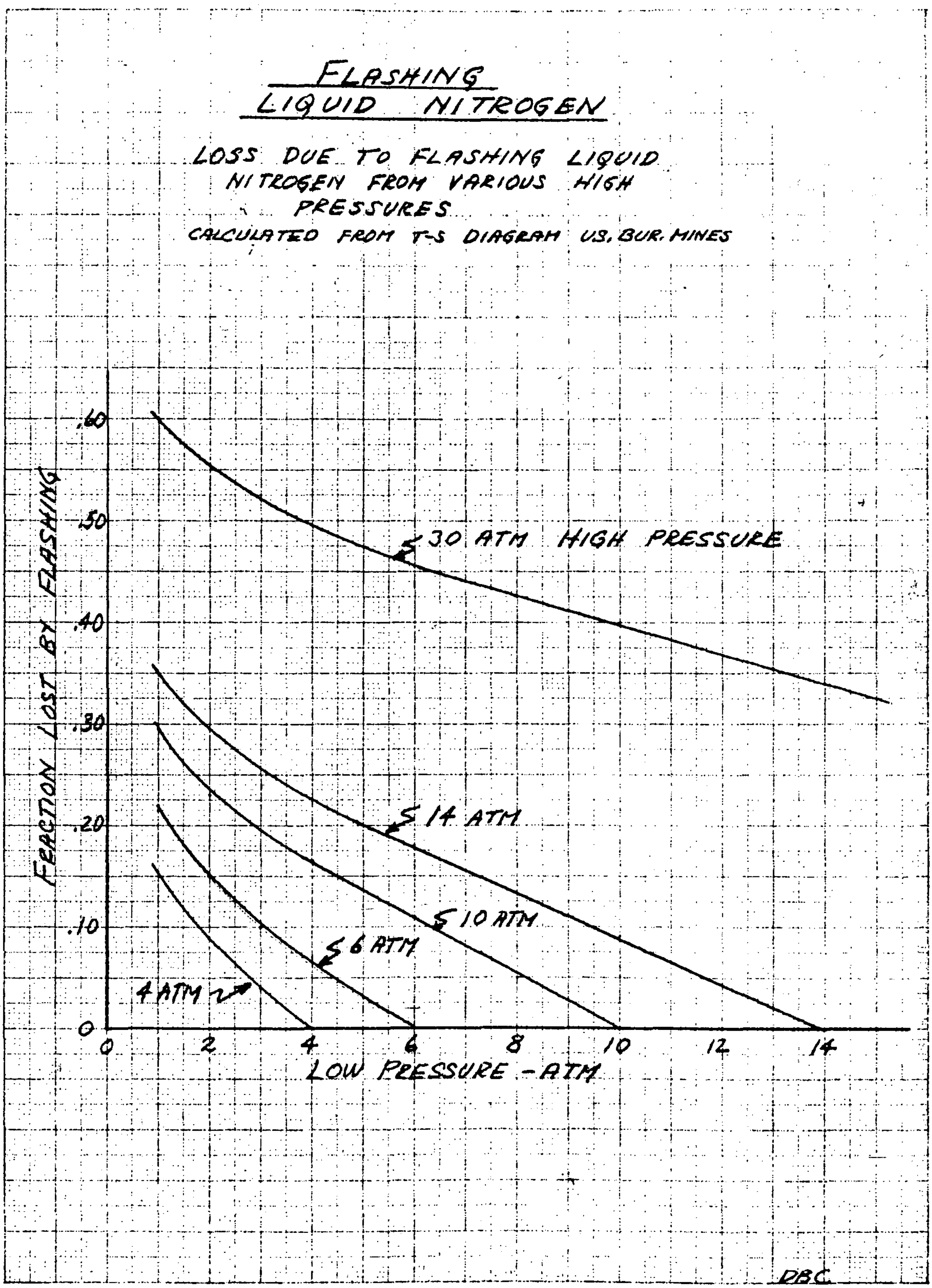

VAPOR PRESSURE - LIQUID D2
TRIPLE POINT 18.69°K
2.48 PSIA
CRITICAL POINT 38.2 °K
16.2 ATM
239 PSIA
NBS-NACA TABLES 7.50
ABSOLUTE PRESSURE - PSIA
200
150
100
50
0
20
25
30
35
TEMPERATURE - °K
DBC

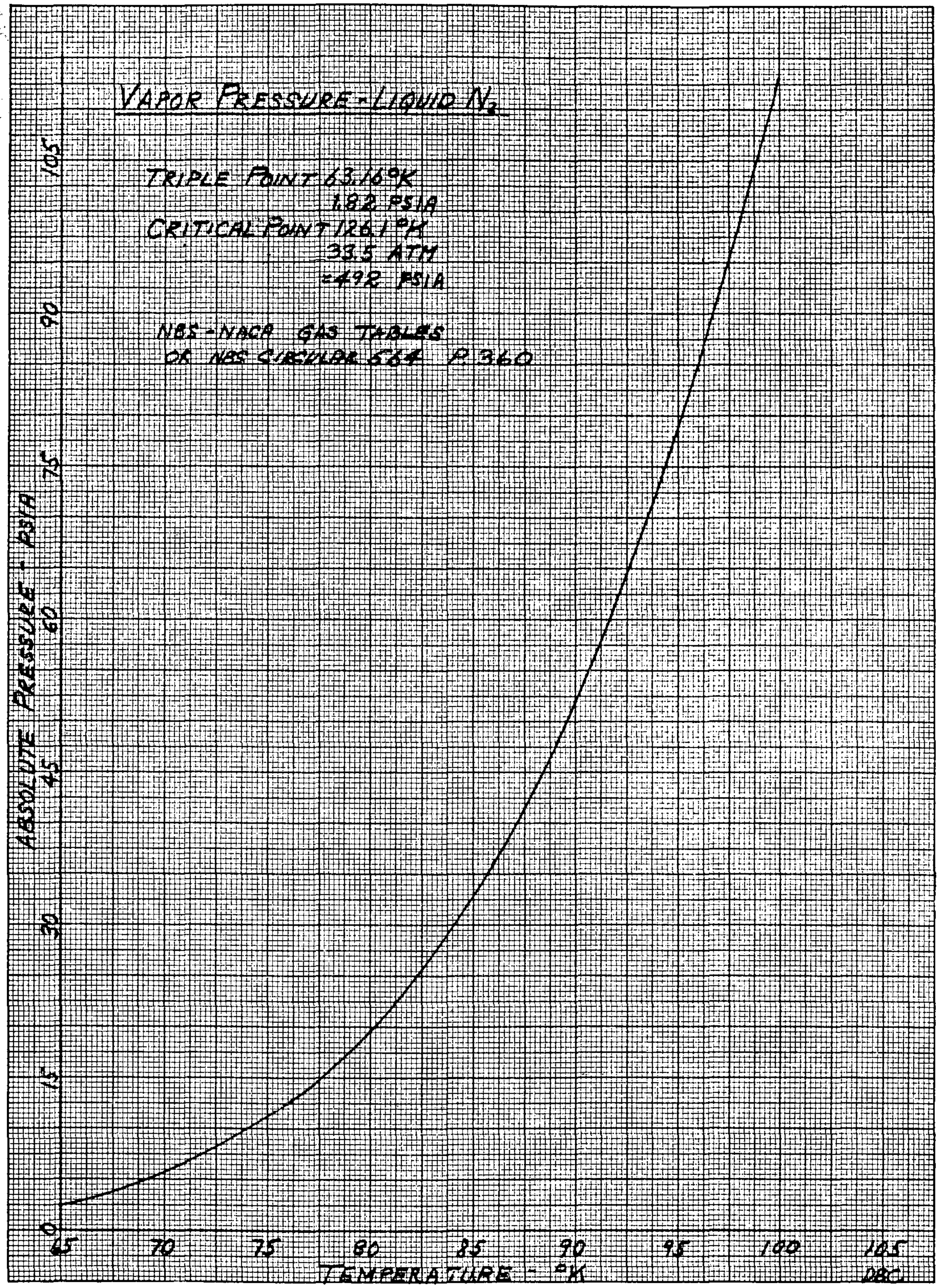

LIQUID DEUTERIUM
HEAT OF VAPORIZATION VS. TEMPERATURE
REF. E.R. GRILLY, AMER. CHEM. SOC. JOURNAL, FEB. '51
VOL. 73, P. 843
HEAT OF VAPORIZATION - WATT HR. / LITER
17
16
15
14
13
12
15
20
25
30
35
TEMPERATURE - °K

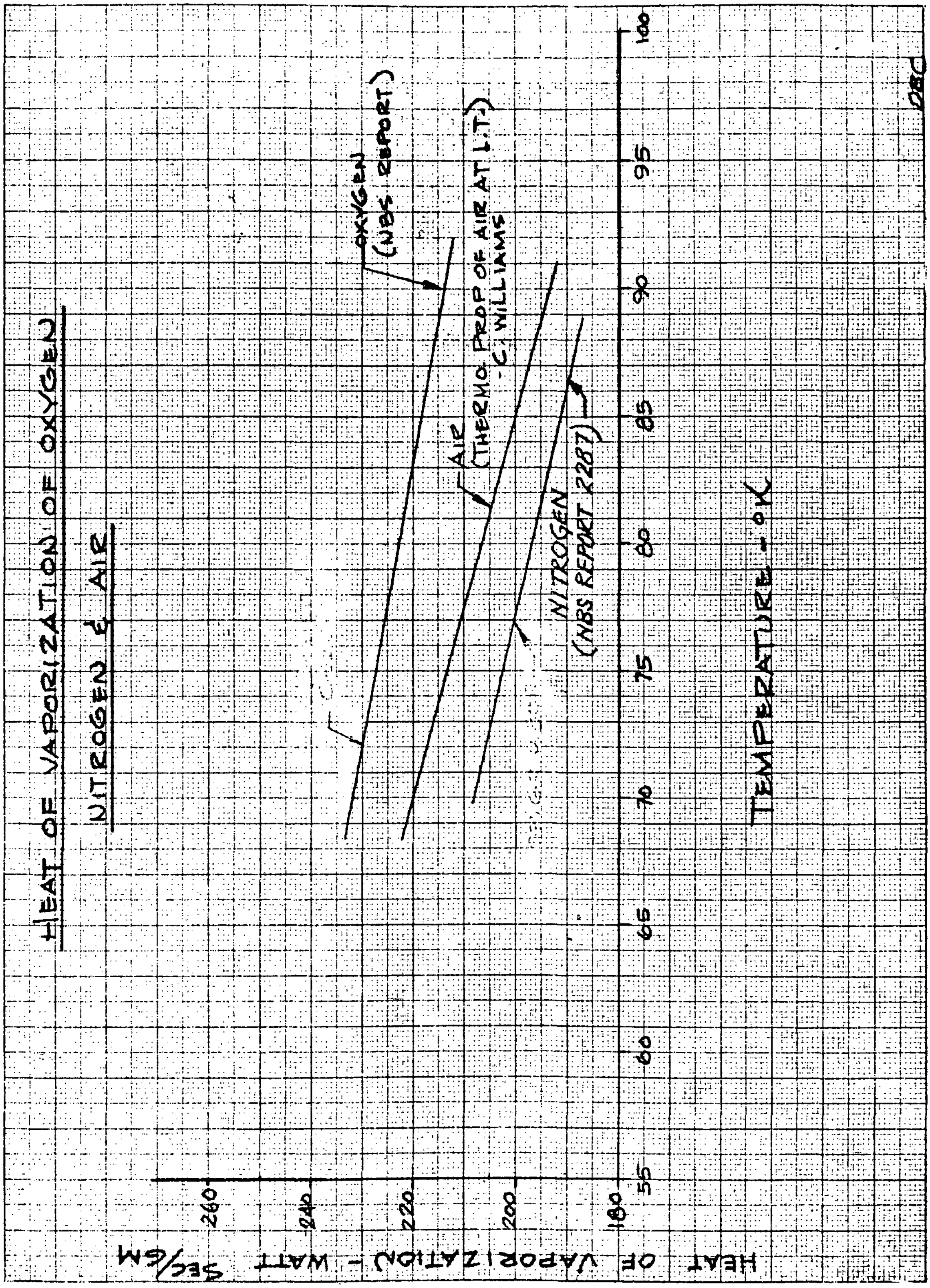

DENSITY OF LIQUID NITROGEN
FROM TS DIAGRAM - US BUREAU OF MINES
900
700
500
300
100
DENSITY - GM/LITER
60
80
100
120
TEMPERATURE - °K

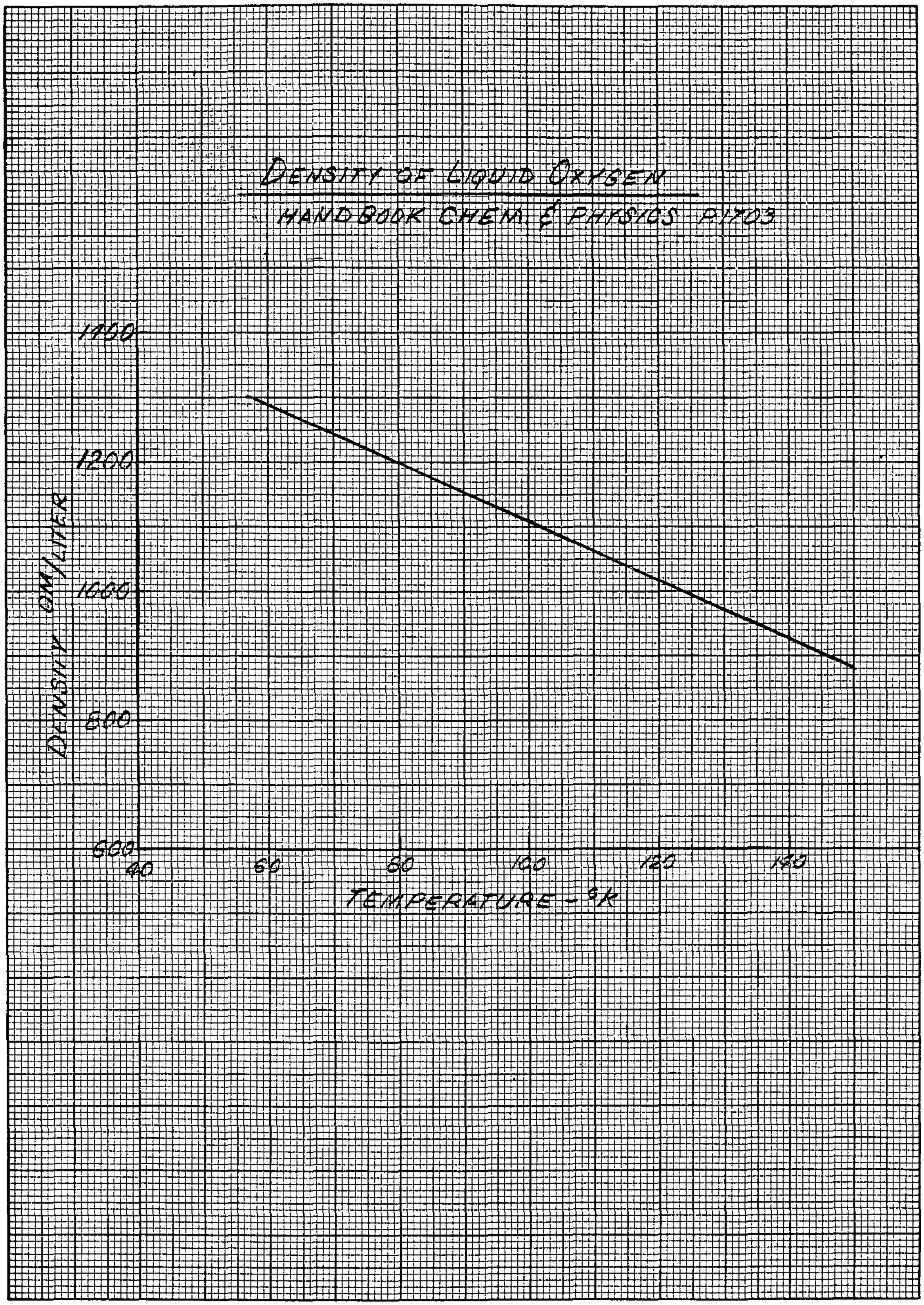

RELATIVE DENSITY - LIQUID N2
CALCULATED FROM T-S DIAGRAM U.S. BUREAU OF MINES
ρLIQ = DENSITY LIQUID N2
ρGAS = DENSITY GAS N2 AT 273°K AND 1 ATM PRESSURE
RELATIVE DENSITY ρLIQ/ρGAS 273°K, 1ATM
650
600
550
500
450
400
70
80
90
100
110
120
TEMPERATURE - °K

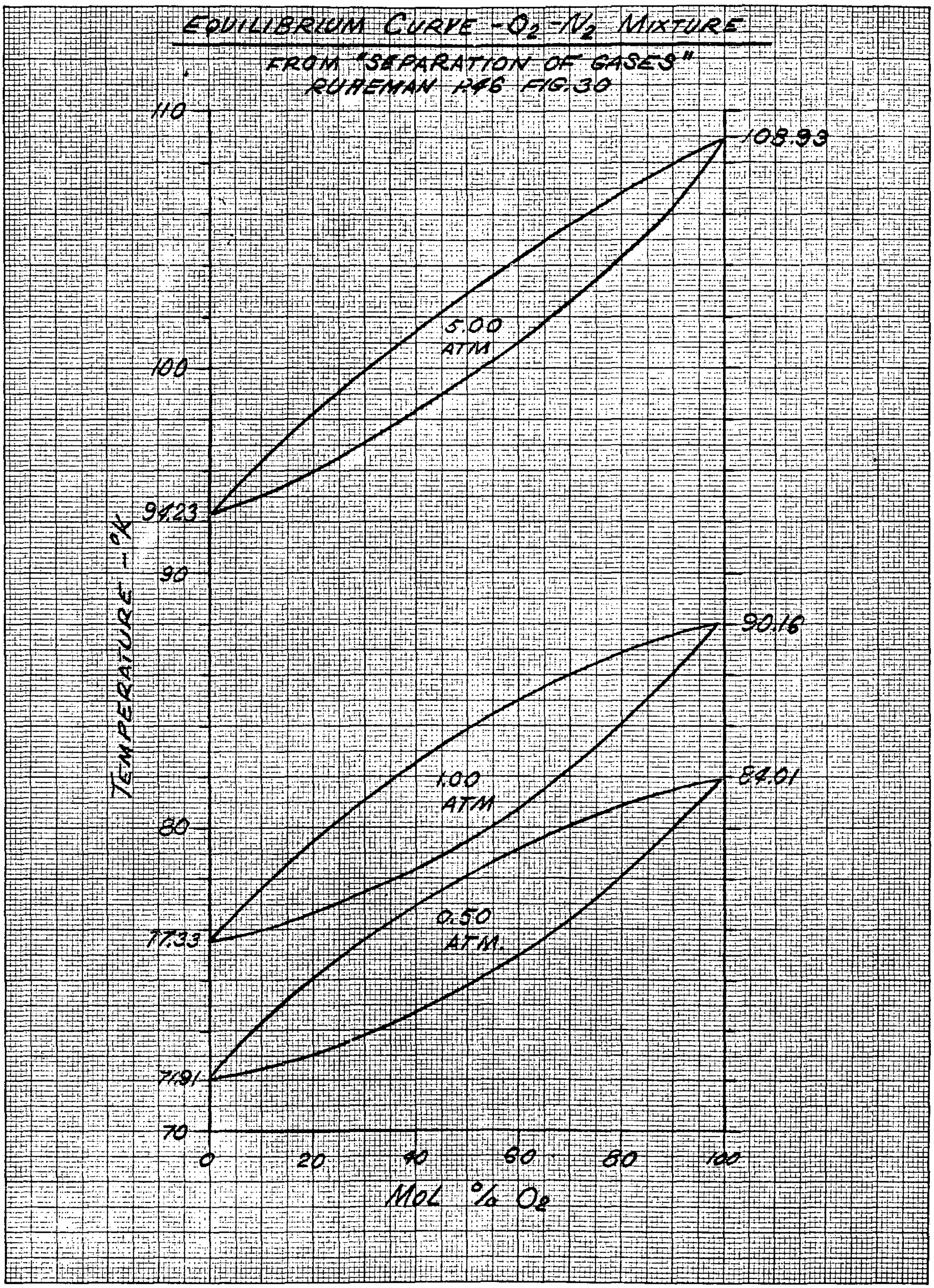

EFFECT OF PRECOOLING TEMPERATURE
ON LIQUEFACTION RATES OF NITROGEN
REFRIGERATORS AND LIQUEFIERS
(EXPANSION TO 1 ATM.)
CALCULATED FROM T-S DIAGRAM U.S. BUREAU OF MINES
REFRIGERATOR PRECOOL -90°F
REFRIGERATOR PRECOOL -40°F
LIQUEFIER PRECOOL -90°F
REFRIGERATOR NO PRECOOL
LIQUEFIER PRECOOL -40°F
LIQUEFIER NO PRECOOL
0
.04
.08
.12
.16
.20
.24
.28
.32
.36
LIQUEFACTION FRACTION α
50
100
150
200
250
COMPRESSOR DISCHARGE PRESSURE (atm.)

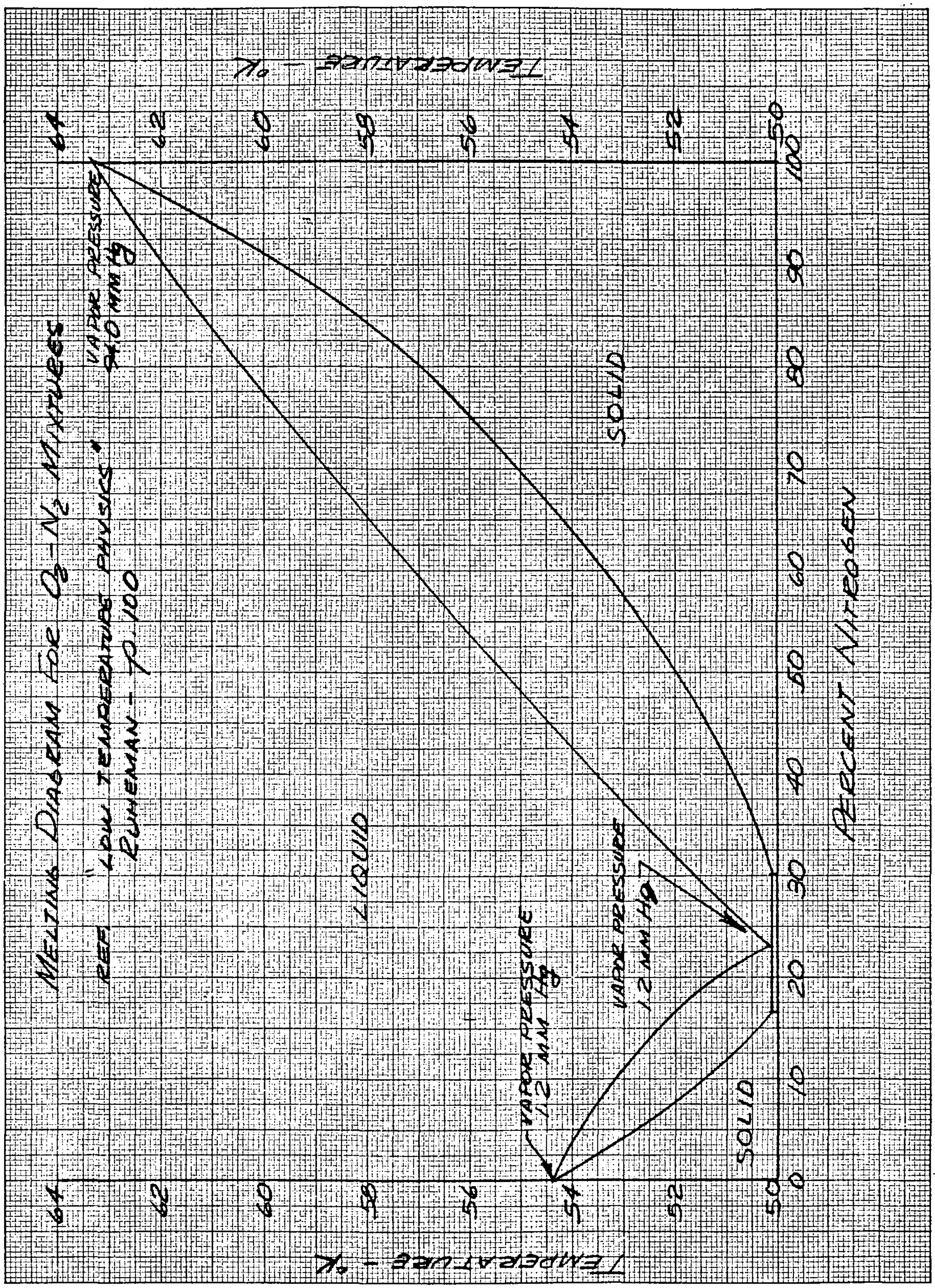

FLASHING
LIQUID NITROGEN
LOSS DUE TO FLASHING LIQUID NITROGEN FROM VARIOUS HIGH PRESSURES
CALCULATED FROM T-S DIAGRAM US. BUR. MINES
30 ATM HIGH PRESSURE
14 ATM
10 ATM
6 ATM
4 ATM
FRACTION LOST BY FLASHING
LOW PRESSURE - ATM
0
.10
.20
.30
.40
.50
.60
0
2
4
6
8
10
12
14
DBC


VAPOR PRESSURE - LIQUID N_2
TRIPLE POINT 63.16°K
1.82 PSIA
CRITICAL POINT 126.1°K
33.5 ATM
=492 PSIA
NBS-NACA GAS TABLES
OR NBS CIRCULAR 564 P. 360
ABSOLUTE PRESSURE - PSIA
0
15
30
45
60
75
90
105
65
70
75
80
85
90
95
100
105
TEMPERATURE - °K
DBC

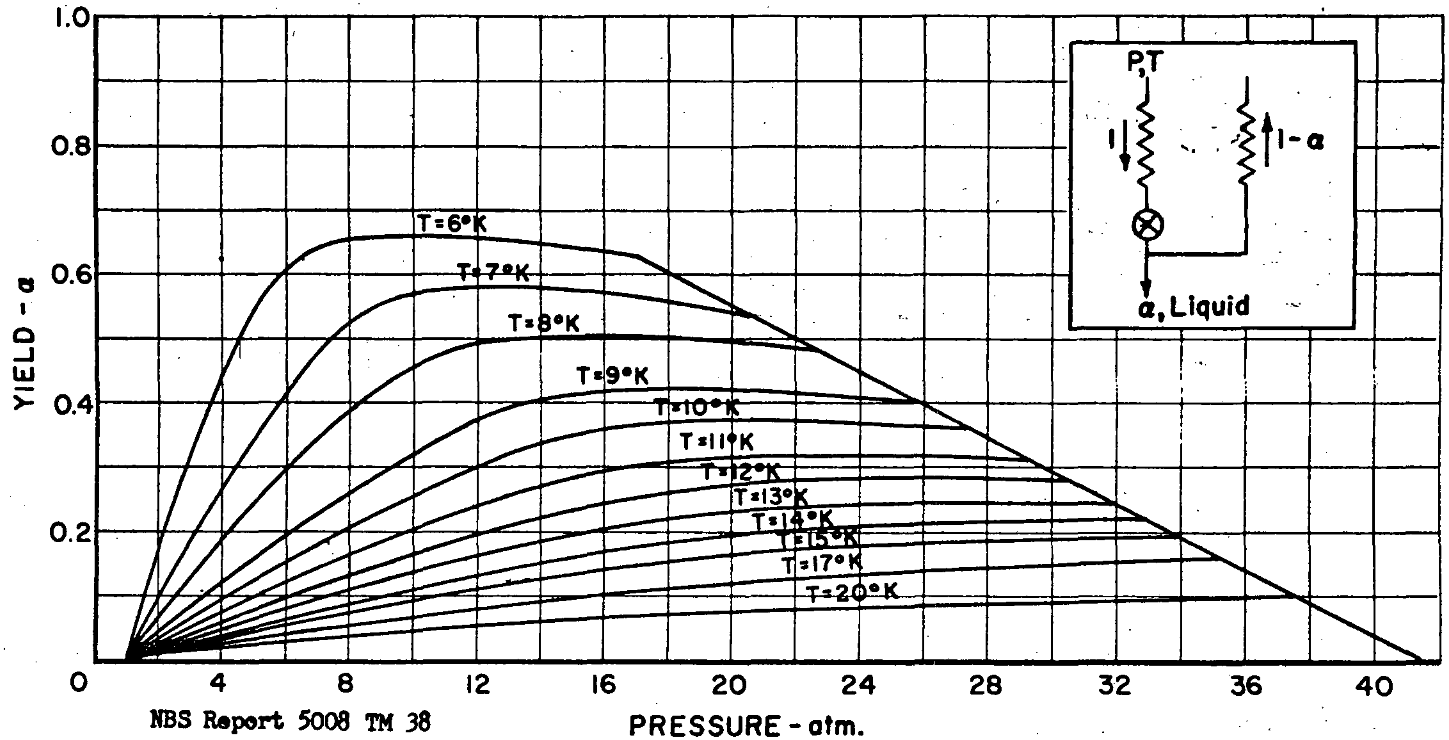

HEAT OF VAPORIZATION OF OXYGEN
NITROGEN & AIR
OXYGEN
(NBS REPORT)
AIR
(THERMO. PROP OF AIR AT L.T.)
-C. WILLIAMS
NITROGEN
(NBS REPORT 2287)
TEMPERATURE - °K
55
60
65
70
75
80
85
90
95
100
180
200
220
240
260
HEAT OF VAPORIZATION - WATT SEC/GM
DBC


DENSITY OF LIQUID OXYGEN
HANDBOOK CHEM. & PHYSICS P.1703
1400
1200
1000
800
600
DENSITY GM/LITER
40
60
80
100
120
140
TEMPERATURE - °K


EQUILIBRIUM CURVE - O_2 - N_2 MIXTURE
FROM "SEPARATION OF GASES"
RUHEMAN P.46 FIG.30
110
100
90
80
70
94.23
77.33
71.91
108.93
90.16
84.01
5.00 ATM
1.00 ATM
0.50 ATM.
TEMPERATURE - °K
0
20
40
60
80
100
MOL % O_2


MELTING DIAGRAM FOR O_2-N_2 MIXTURES
REF "LOW TEMPERATURE PHYSICS"
RUHEMAN - p.100
VAPOR PRESSURE
LIQUID
SOLID
VAPOR PRESSURE
VAPOR PRESSURE
SOLID
PERCENT NITROGEN
TEMPERATURE - °K
TEMPERATURE - °K
64
62
60
58
56
54
52
50
0
10
20
30
40
50
60
70
80
90
100

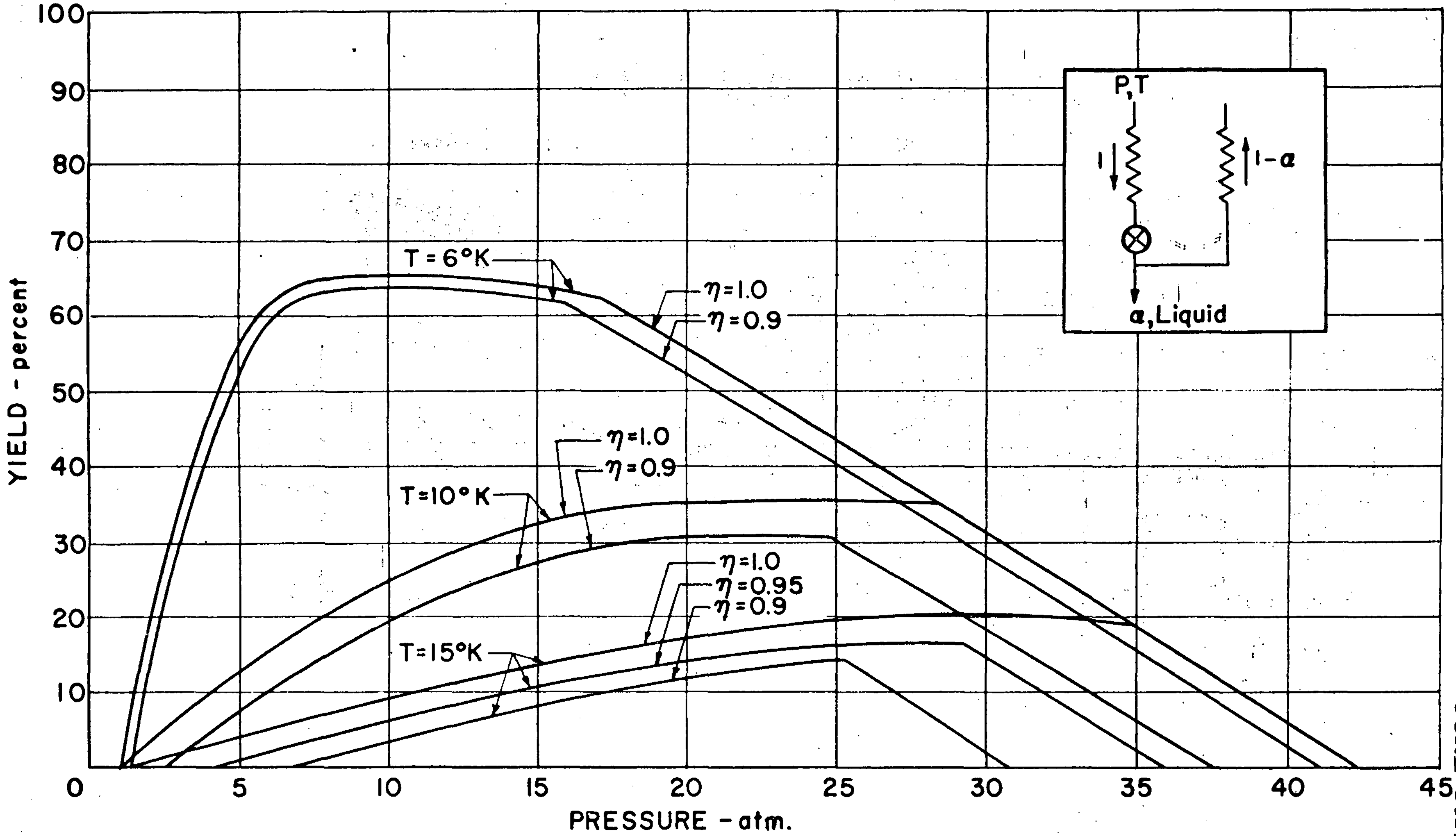
HELIUM GAS LIQUEFACTION



NBS Report 5008 TM 38

Yield α with J-T Heat Exchanger Efficiency η =100 percent
as a Function HP inlet Pressure and Temperature

HELIUM GAS LIQUEFACTION

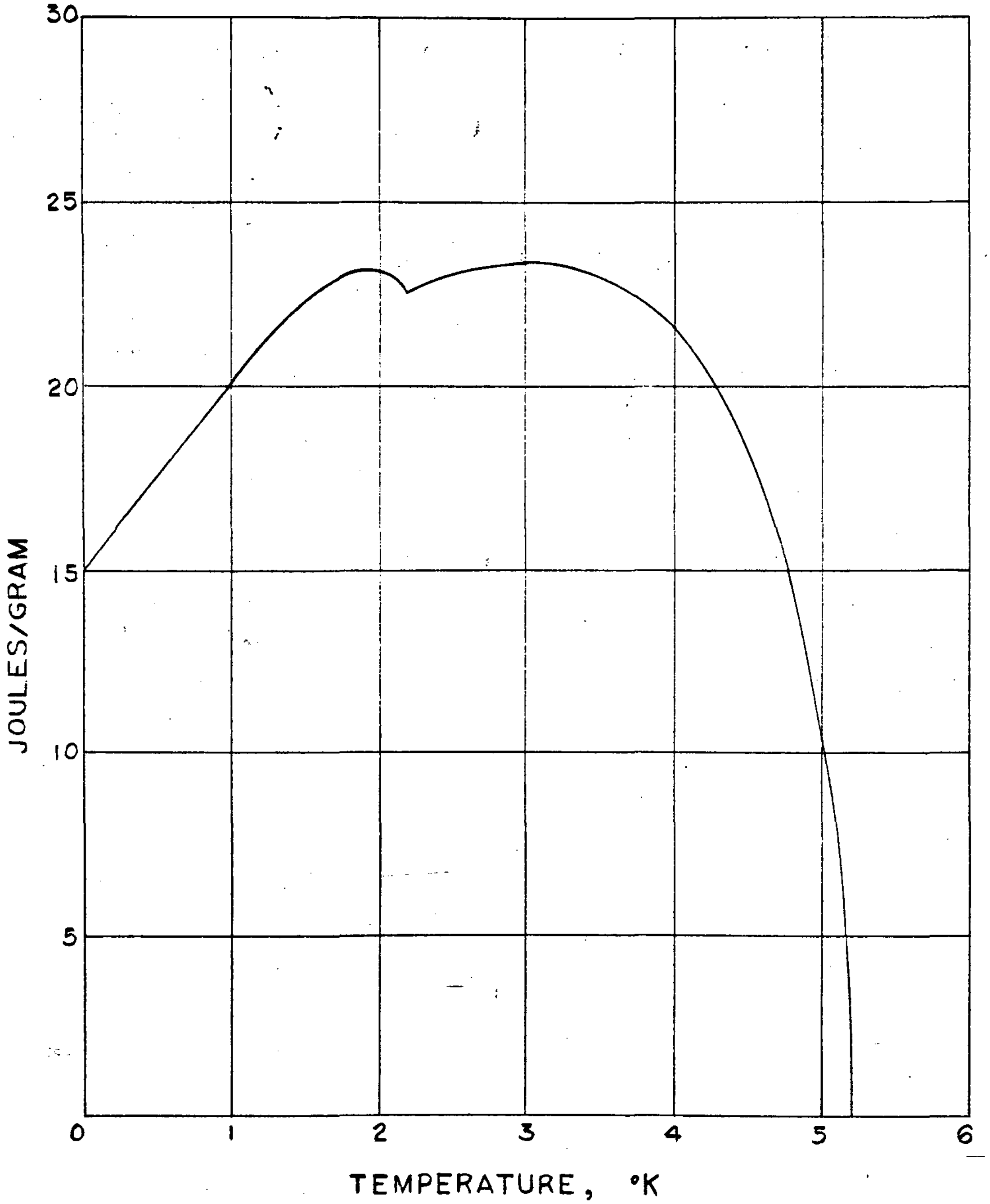


Yield α with J-T Heat Exchanger Efficiencies η = 100 percent and η = 90 percent as a function of HP inlet Temperature and Pressure.

$\eta = \frac{Q \text{ Actual}}{Q \text{ Ideal}}$ NBS Report 5008 TM 38

0 0 1 0 1 5 0 0 / 5 3

Latent Heat of Vaporization of Helium from W. K. Keeson, <u>Helium</u>



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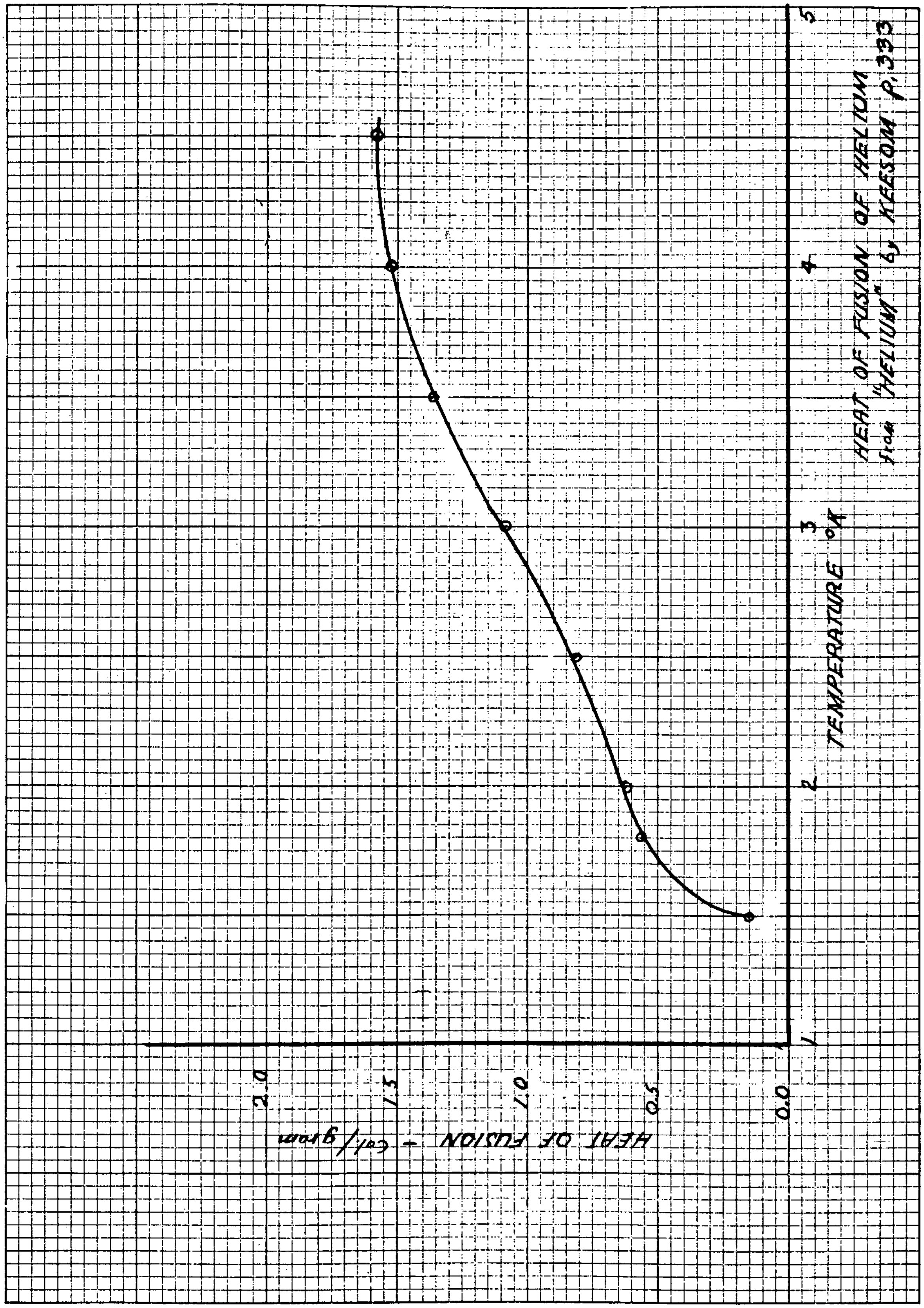
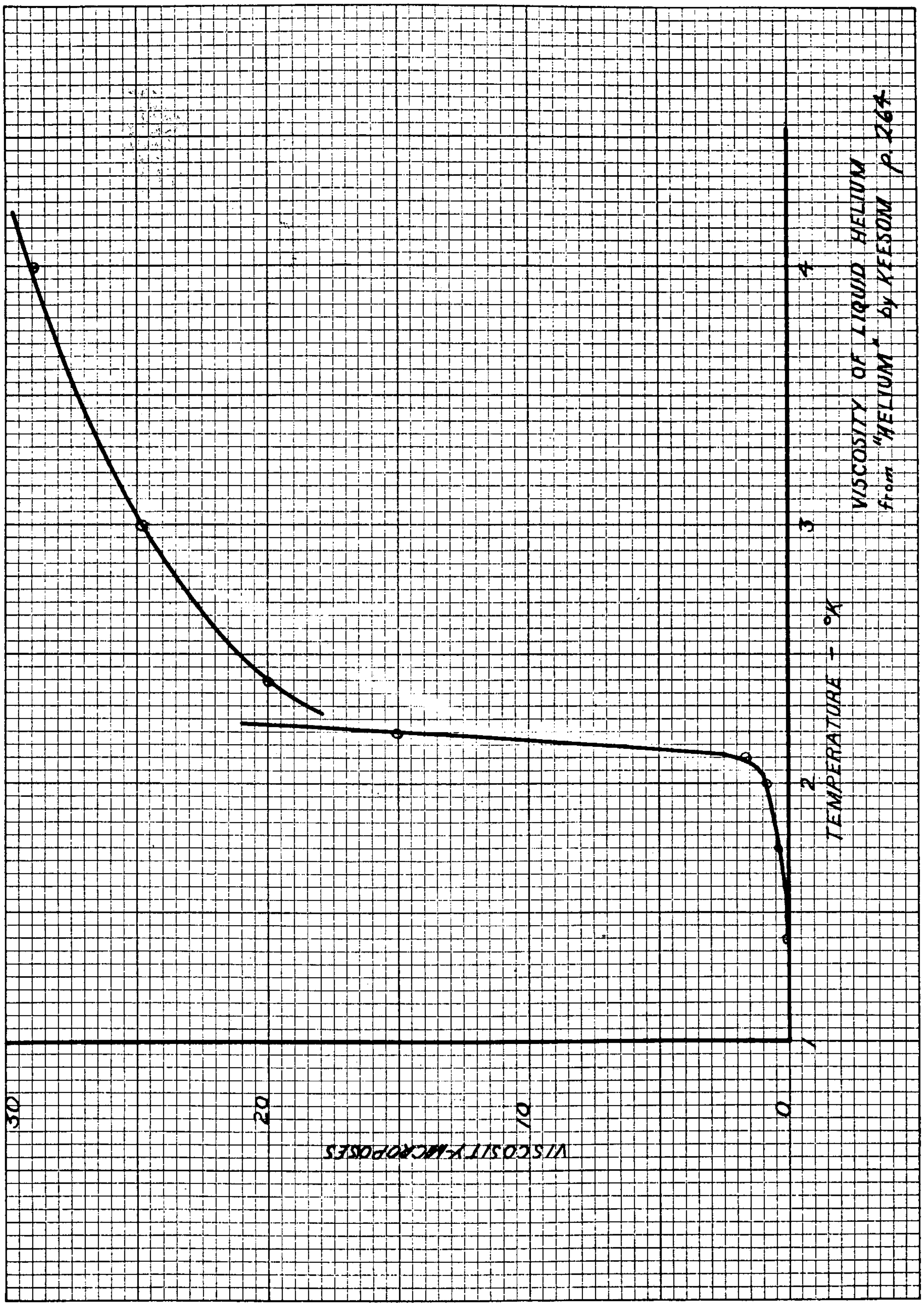
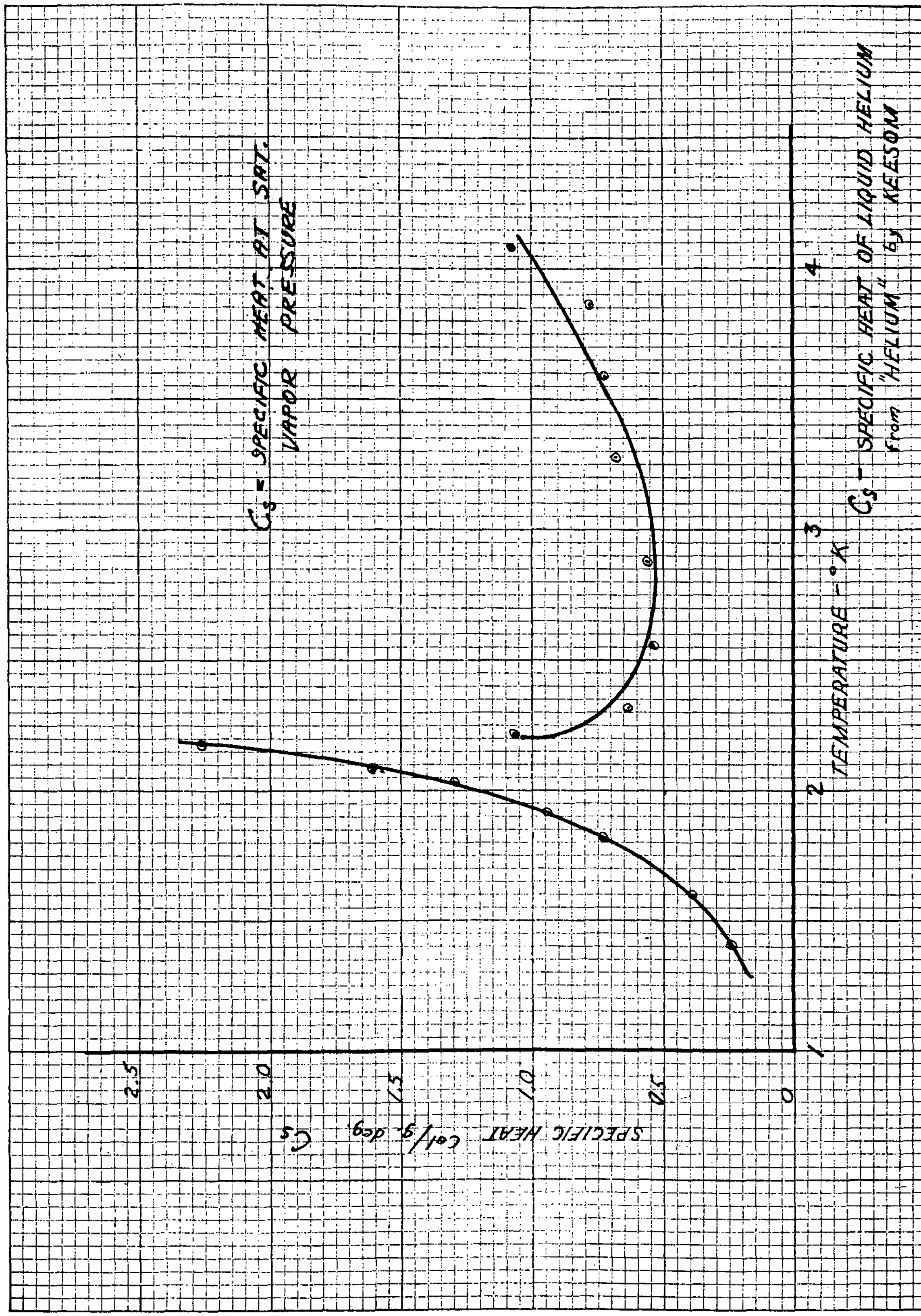
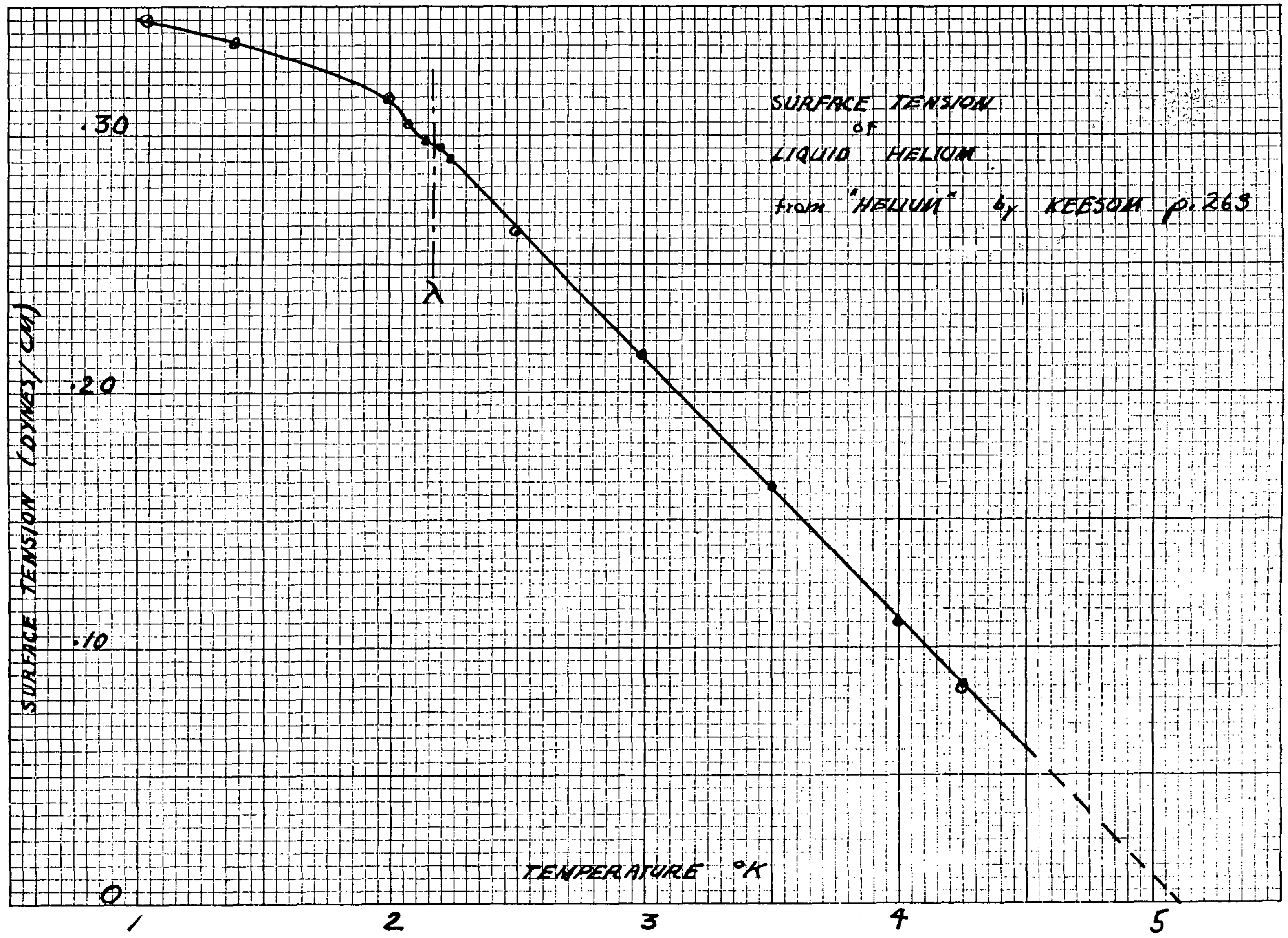
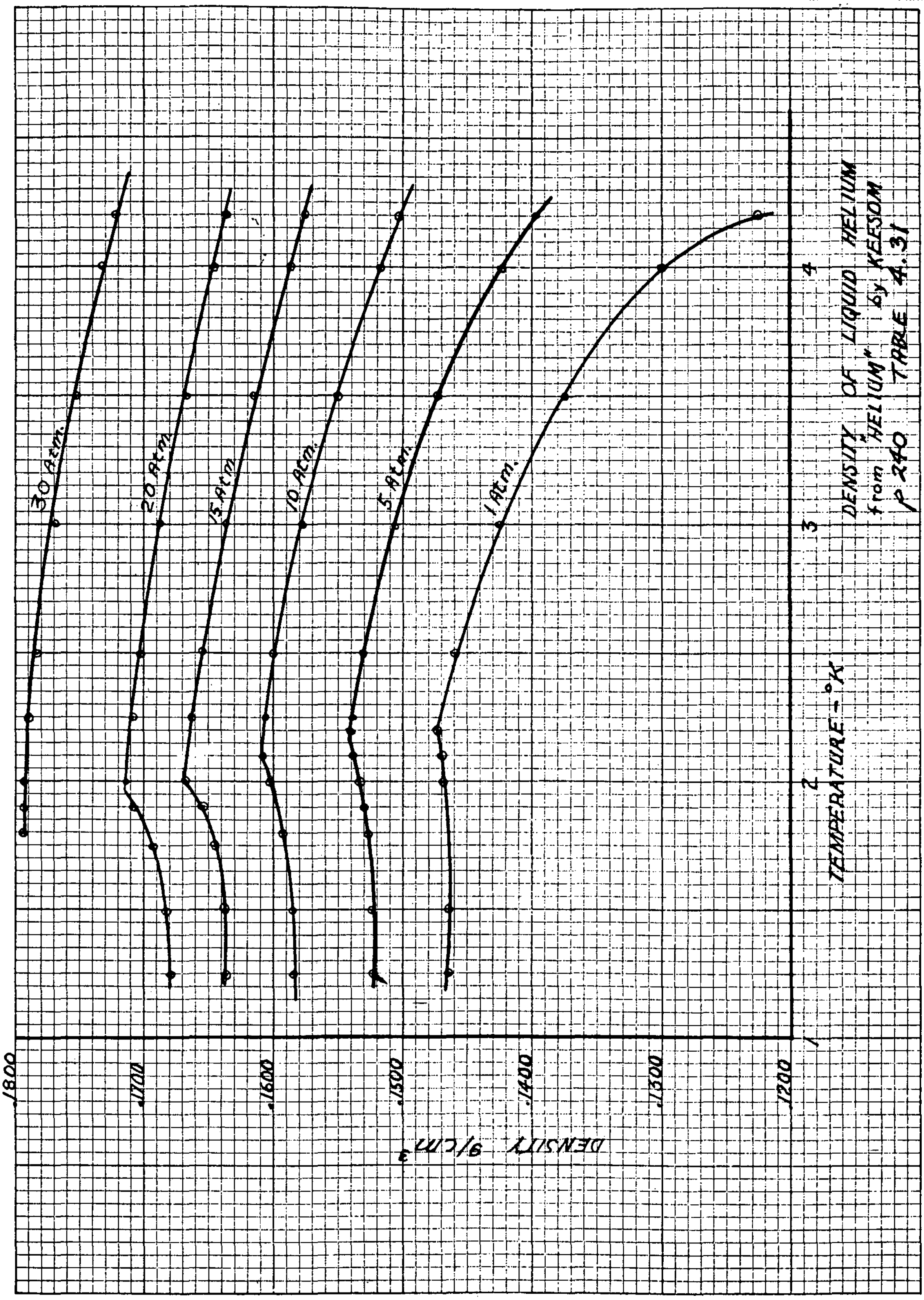
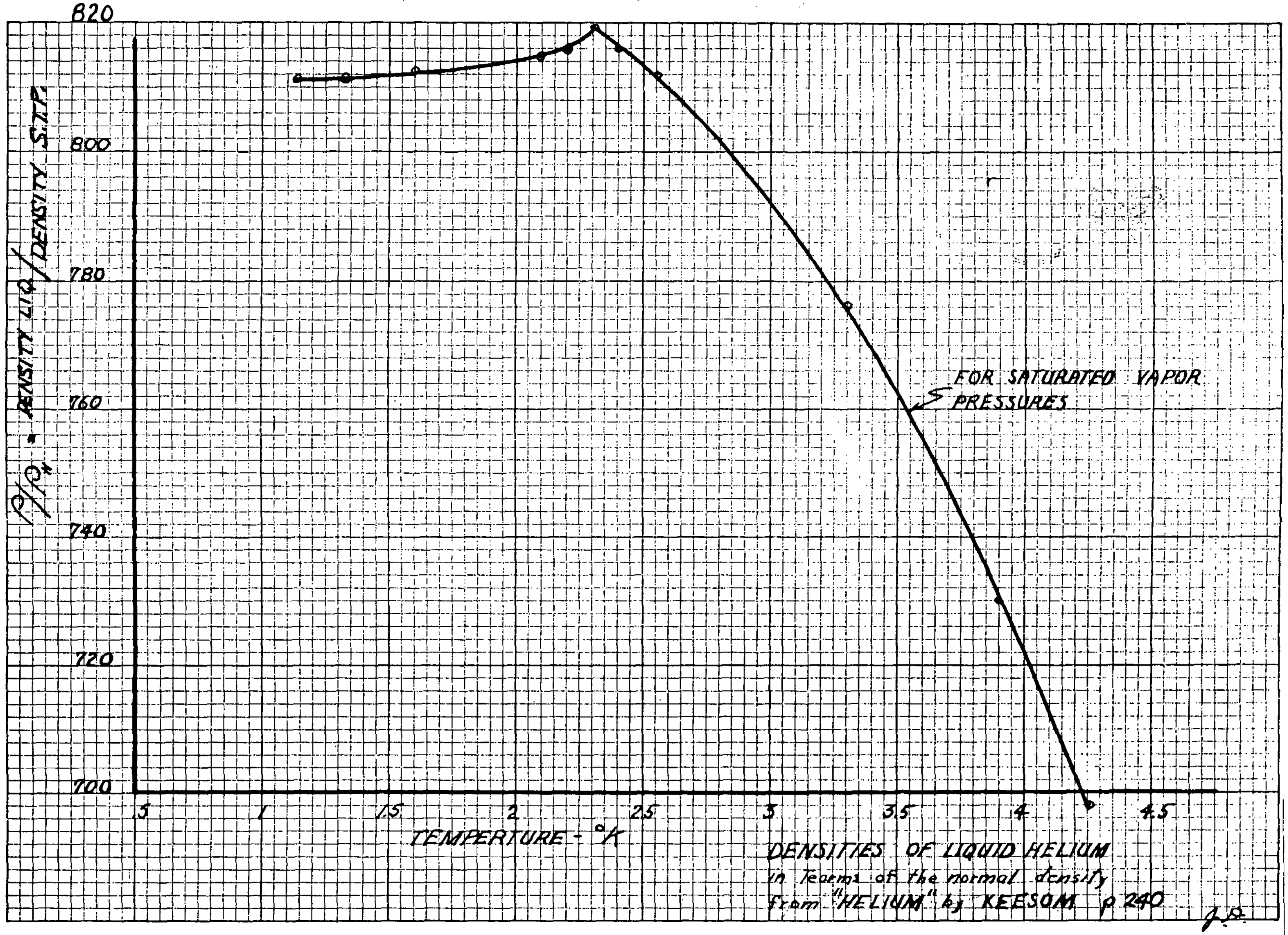

HEAT OF FUSION OF HELIUM
from "HELIUM" by KEESOM P.333
TEMPERATURE °K
1
2
3
4
5
HEAT OF FUSION - cal/gram
0.0
0.5
1.0
1.5
2.0


VISCOSITY OF LIQUID HELIUM
from "HELIUM" by KEESOM p. 264
TEMPERATURE - °K
1
2
3
4
VISCOSITY-MICROPOISES
0
10
20
30


C_s = SPECIFIC HEAT AT SAT. VAPOR PRESSURE
C_s - SPECIFIC HEAT OF LIQUID HELIUM from "HELIUM" by KEESOM
TEMPERATURE - °K
1
2
3
4
SPECIFIC HEAT cal/g. deg, C_s
0
0.5
1.0
1.5
2.0
2.5

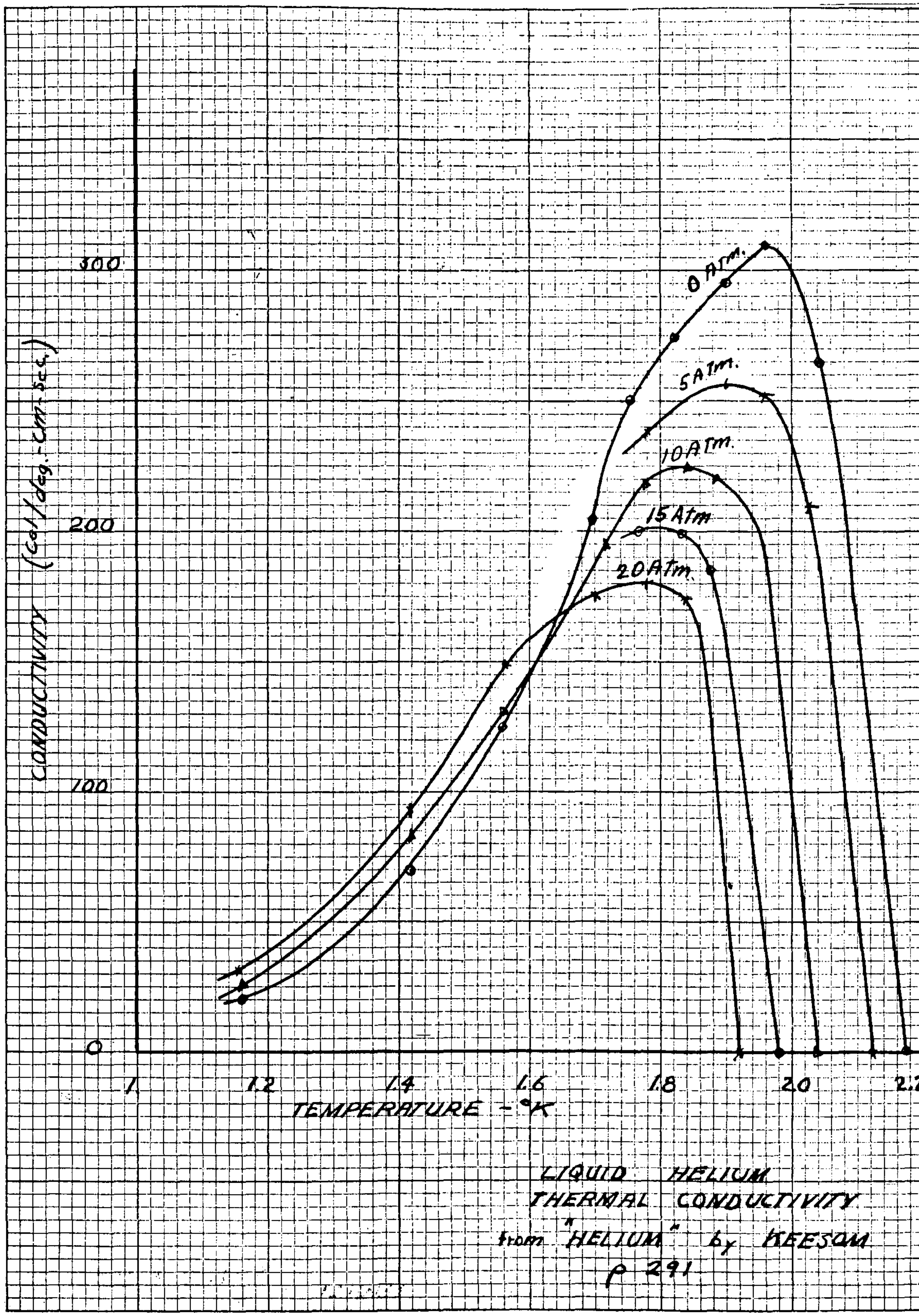

SURFACE TENSION of LIQUID HELIUM
from "HELIUM" by KEESOM p. 263
SURFACE TENSION (DYNES/CM)
.30
.20
.10
0
λ
TEMPERATURE °K
1
2
3
4
5

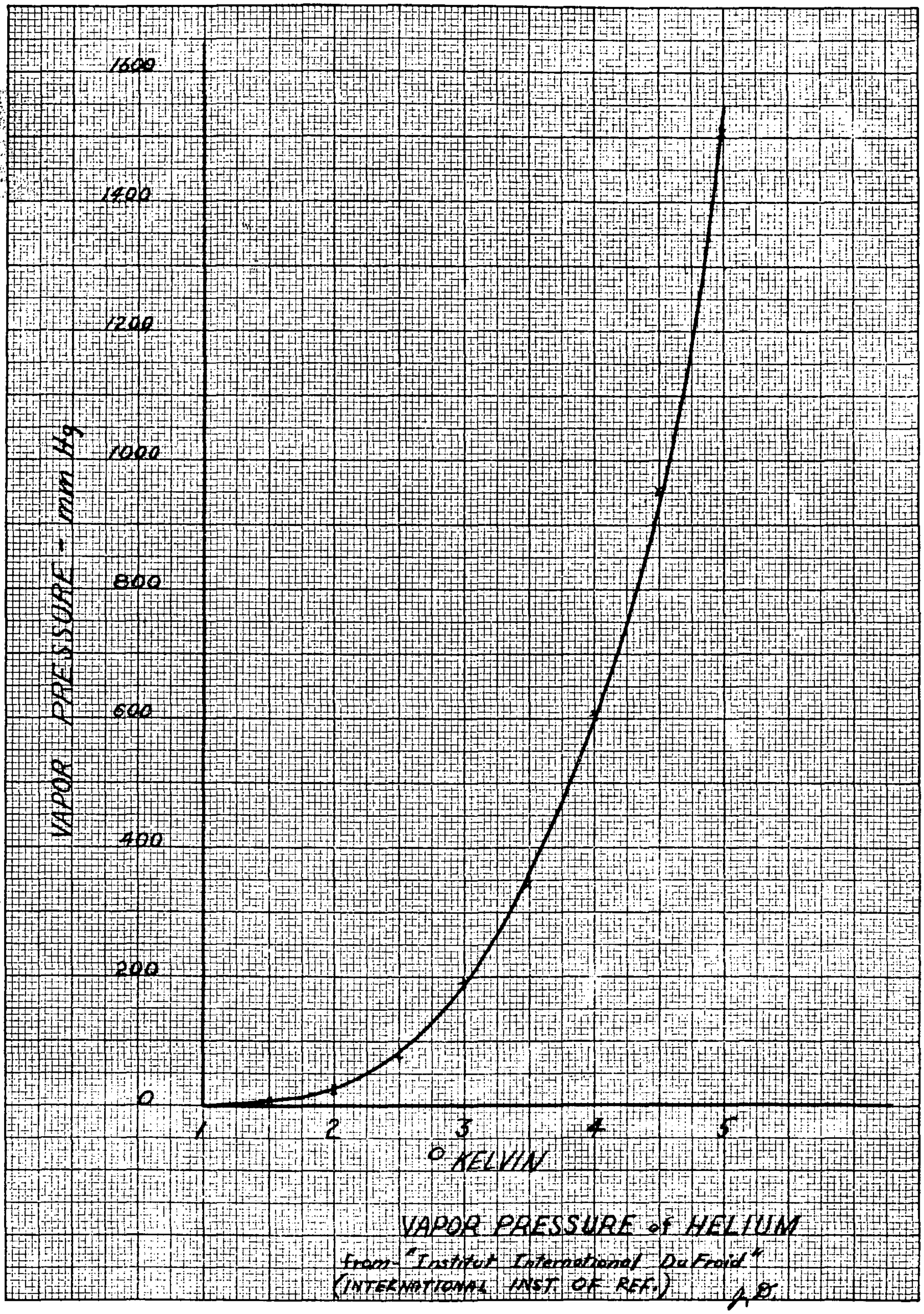

DENSITY OF LIQUID HELIUM
from "HELIUM" by KEESOM
p 240 TABLE 4.31
TEMPERATURE - °K
DENSITY g/cm³
30 Atm.
20 Atm.
15 Atm.
10 Atm.
5 Atm.
1 Atm.
1
2
3
4
.1800
.1700
.1600
.1500
.1400
.1300
.1200



820
800
780
760
740
720
700
ρ/ρ_* = DENSITY LIQ./DENSITY S.T.P.
.5
1
1.5
2
2.5
3
3.5
4
4.5
TEMPERTURE - °K
FOR SATURATED VAPOR PRESSURES
DENSITIES OF LIQUID HELIUM
in Terms of the normal density
from "HELIUM" by KEESOM p 240

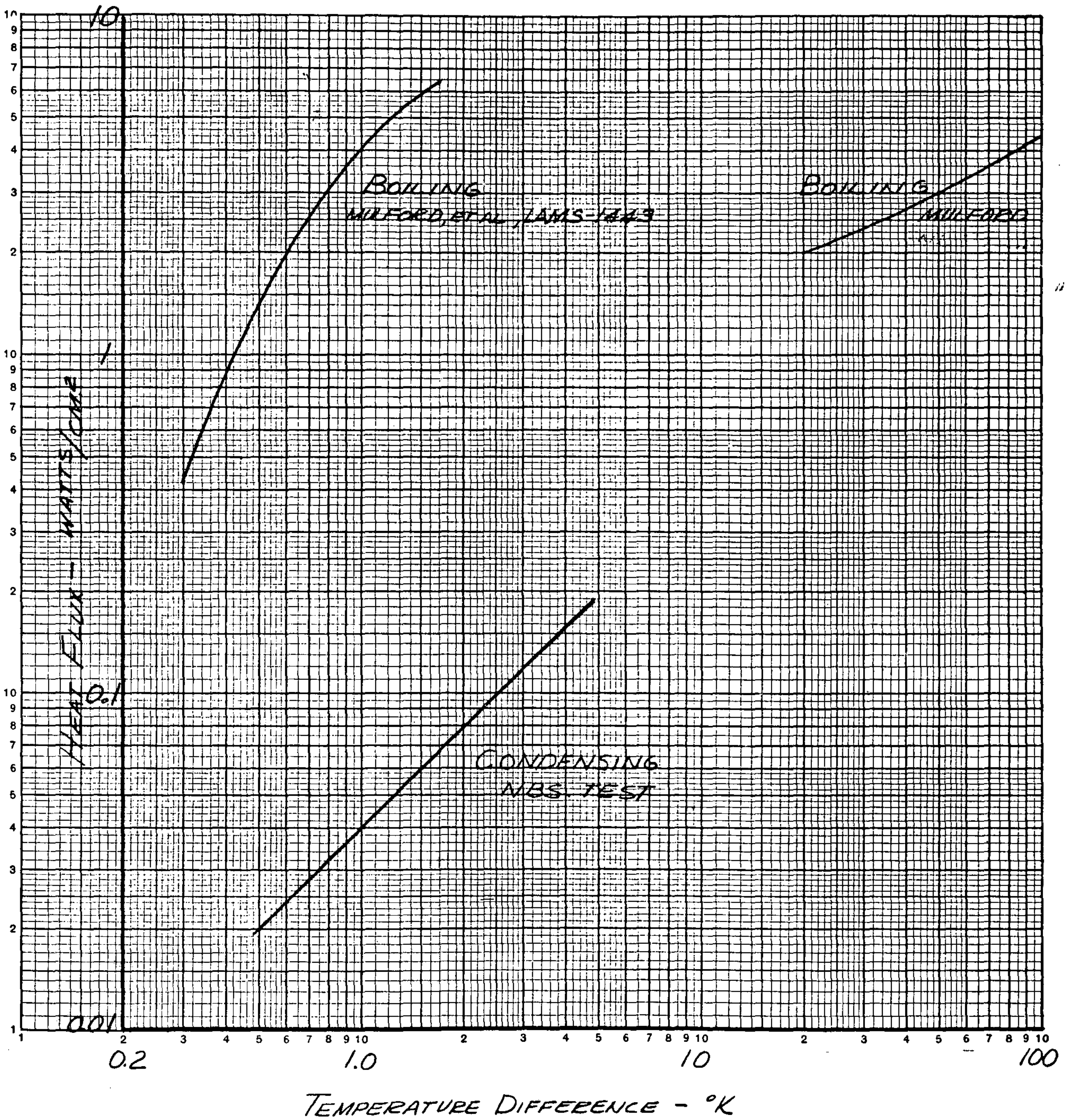
UCRL-3421


0 Atm.
5 Atm.
10 Atm.
15 Atm.
20 Atm.
300
200
100
0
CONDUCTIVITY (cal/deg.-cm.-sec.)
1
1.2
1.4
1.6
1.8
2.0
2.2
TEMPERATURE - °K
LIQUID HELIUM
THERMAL CONDUCTIVITY
from "HELIUM" by KEESOM
p 291

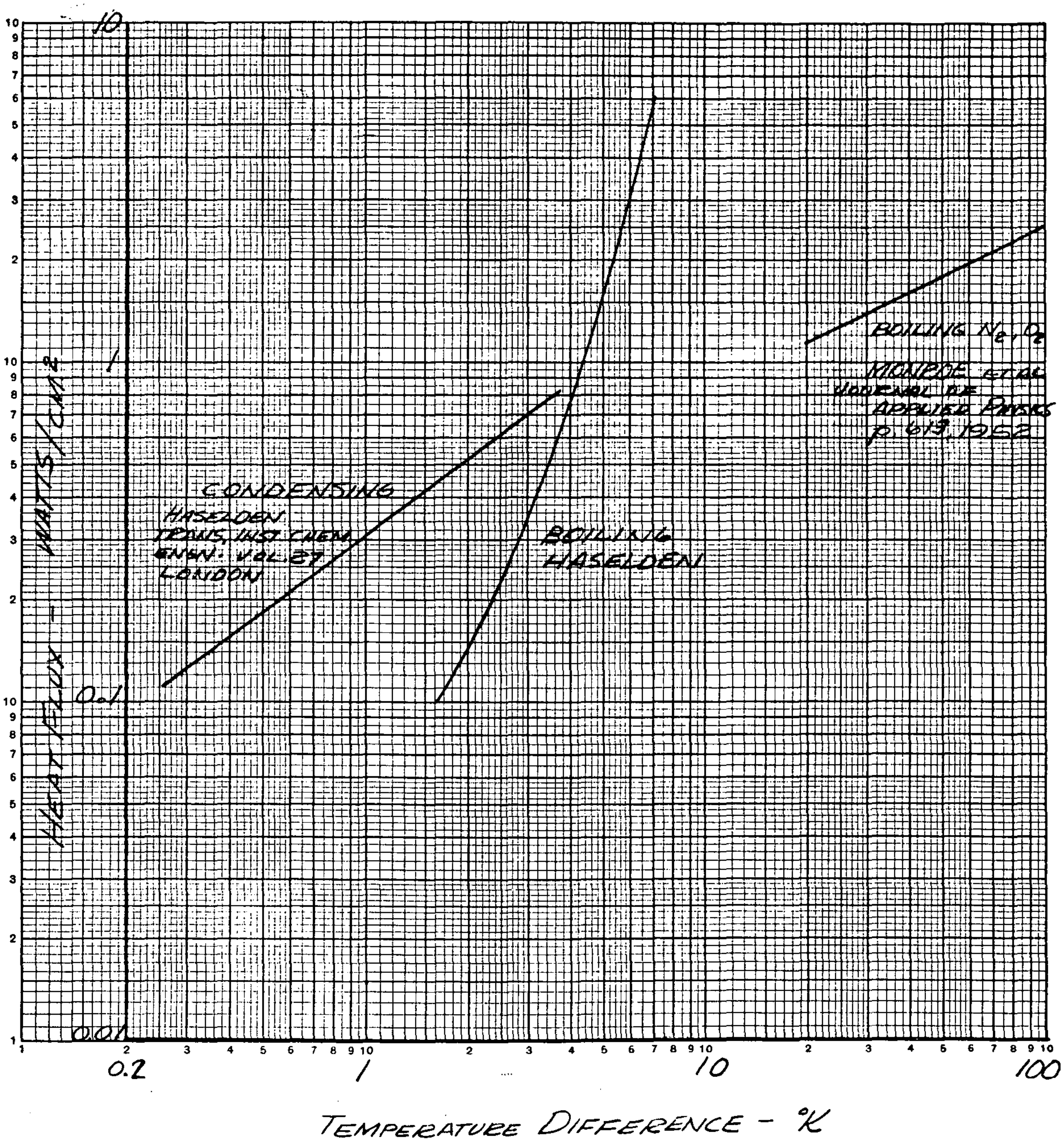

1600
1400
1200
1000
800
600
400
200
0
VAPOR PRESSURE - mm Hg
1
2
3
4
5
° KELVIN
VAPOR PRESSURE of HELIUM
from "Institut International Du Froid"
(INTERNATIONAL INST. OF REF.)

HEAT TRANSFER TO BOILING

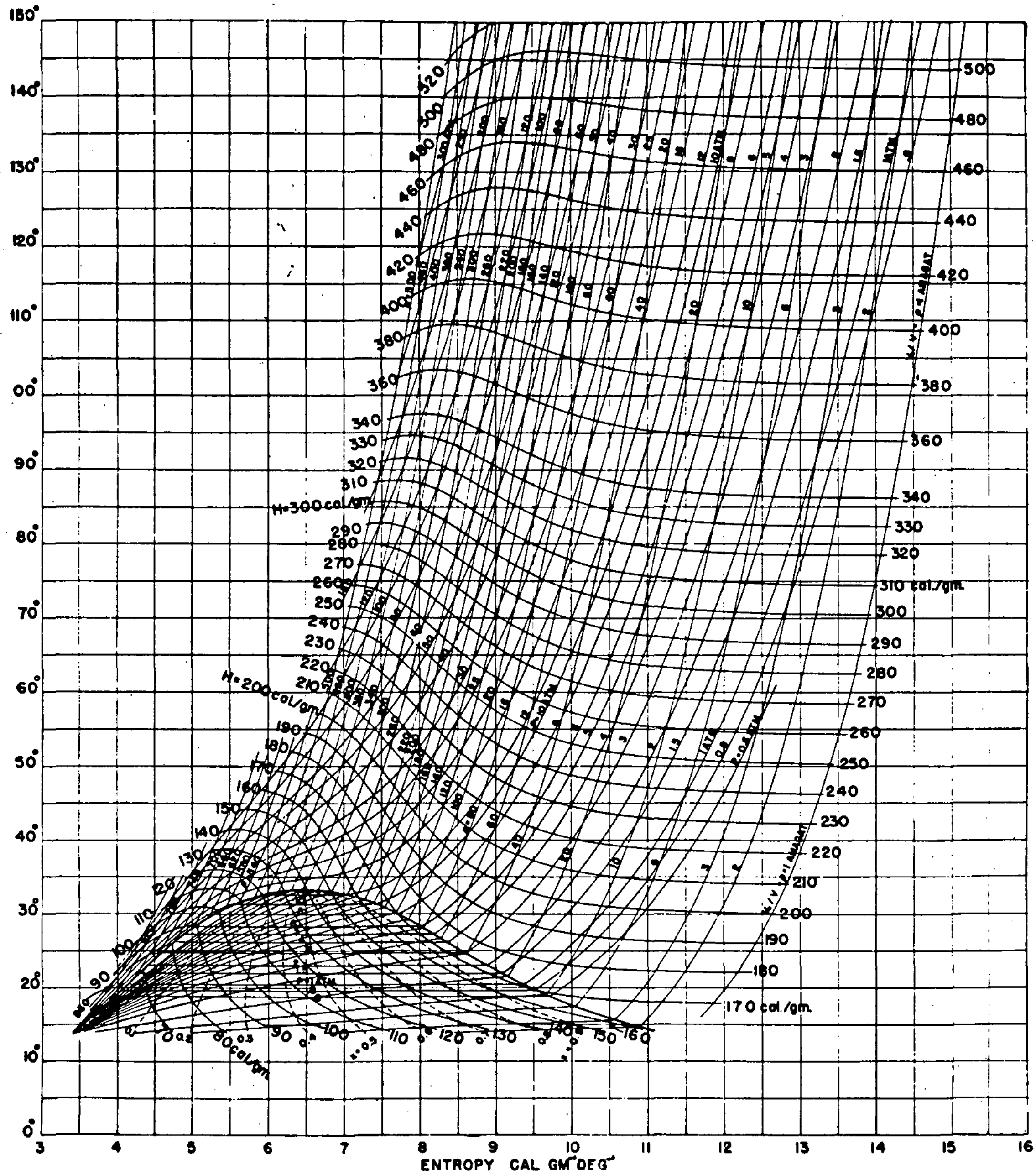
AND CONDENSING HYDROGEN



HEAT TRANSFER TO BOILING AND CONDENSING NITROGEN

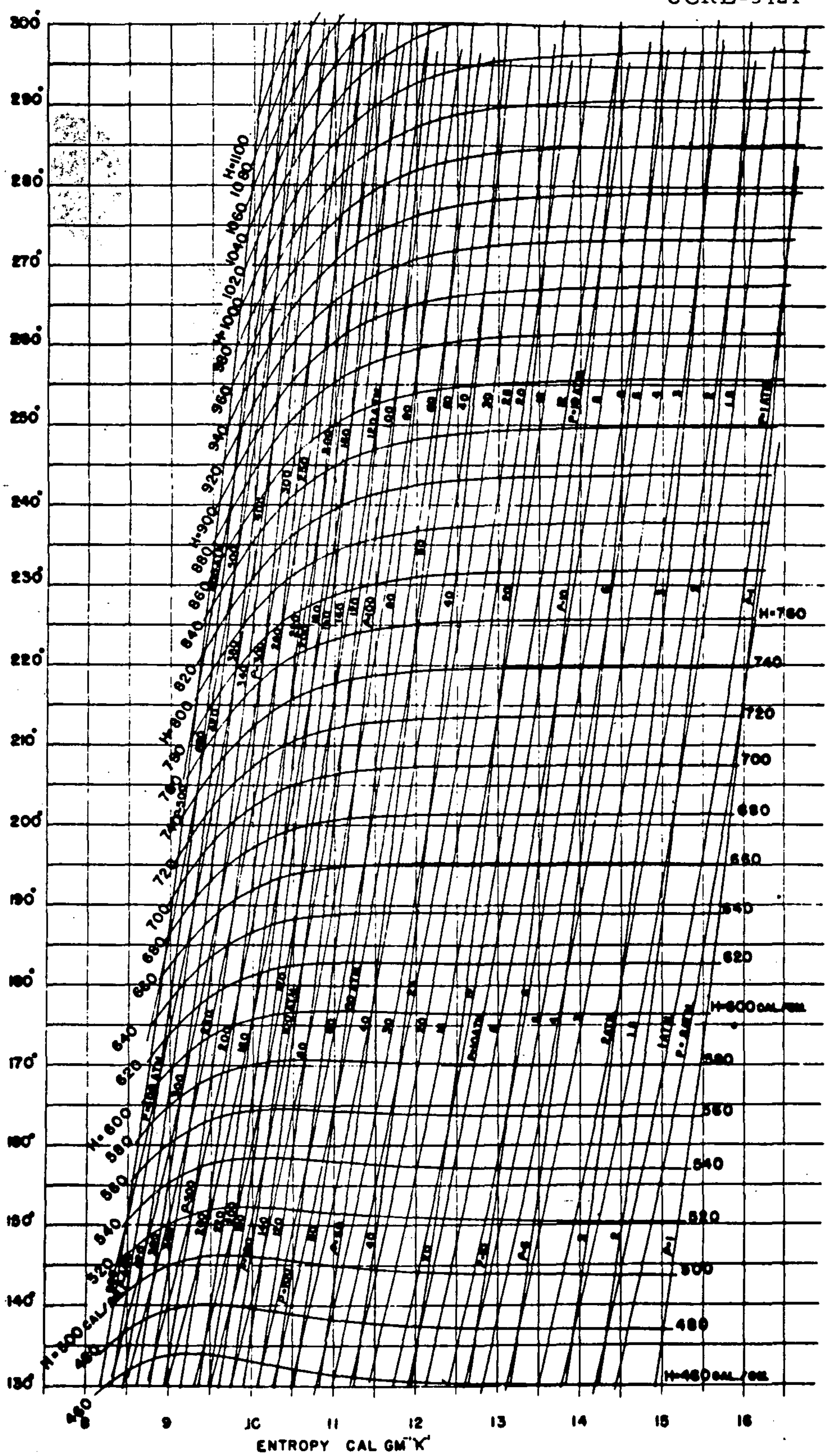


0 0 1 0 1 5 0 0 / 5 9



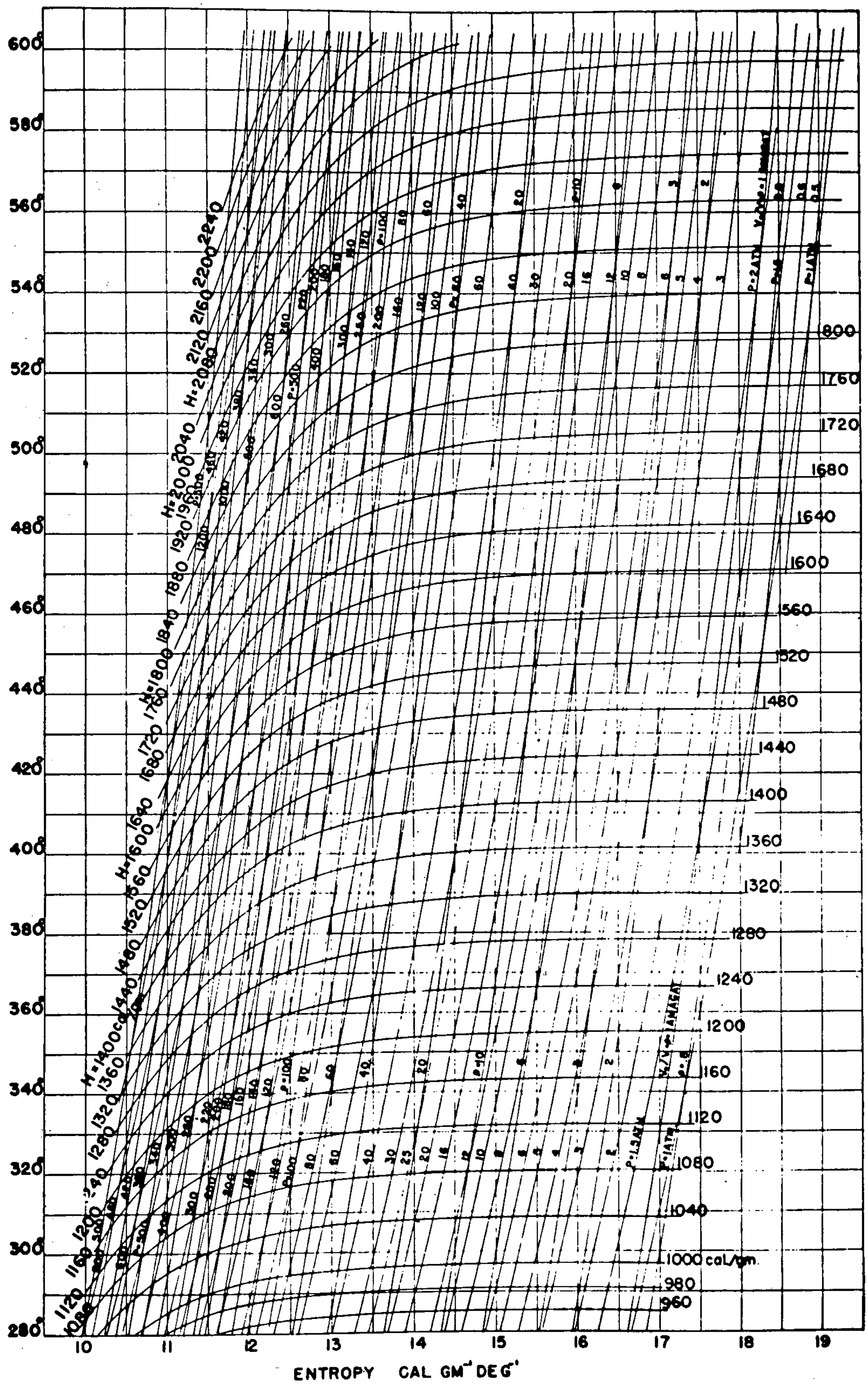
Temperature-entropy diagram for H_2 in the region 0° to 150° K.

REF: NBS RP1932



Temperature-entropy diagram for H_2 in the region 130° to 300° K.

REF: NBS RP1932

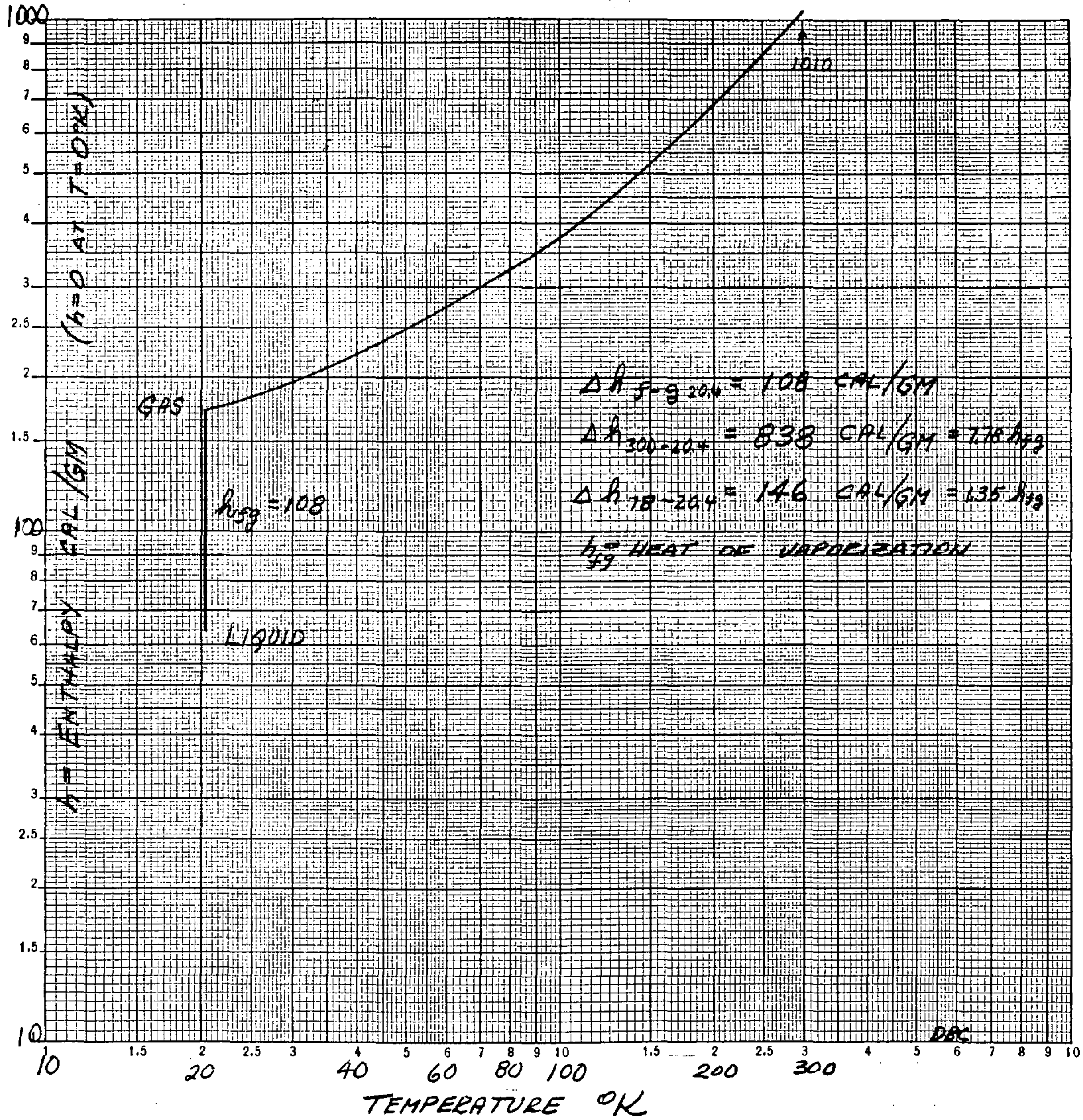


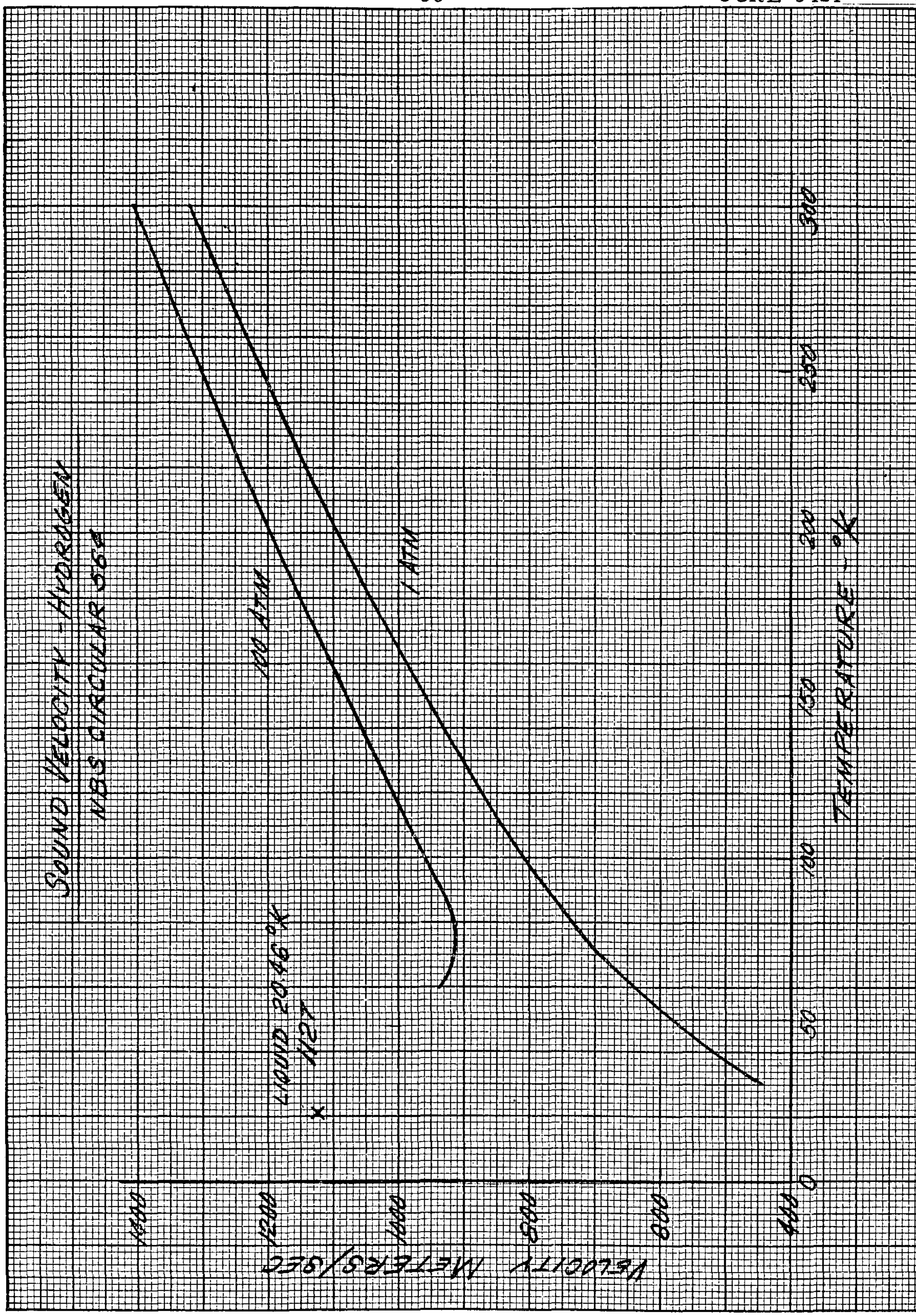
Temperature-entropy diagram for H_2 in the region 280° to 600° K.

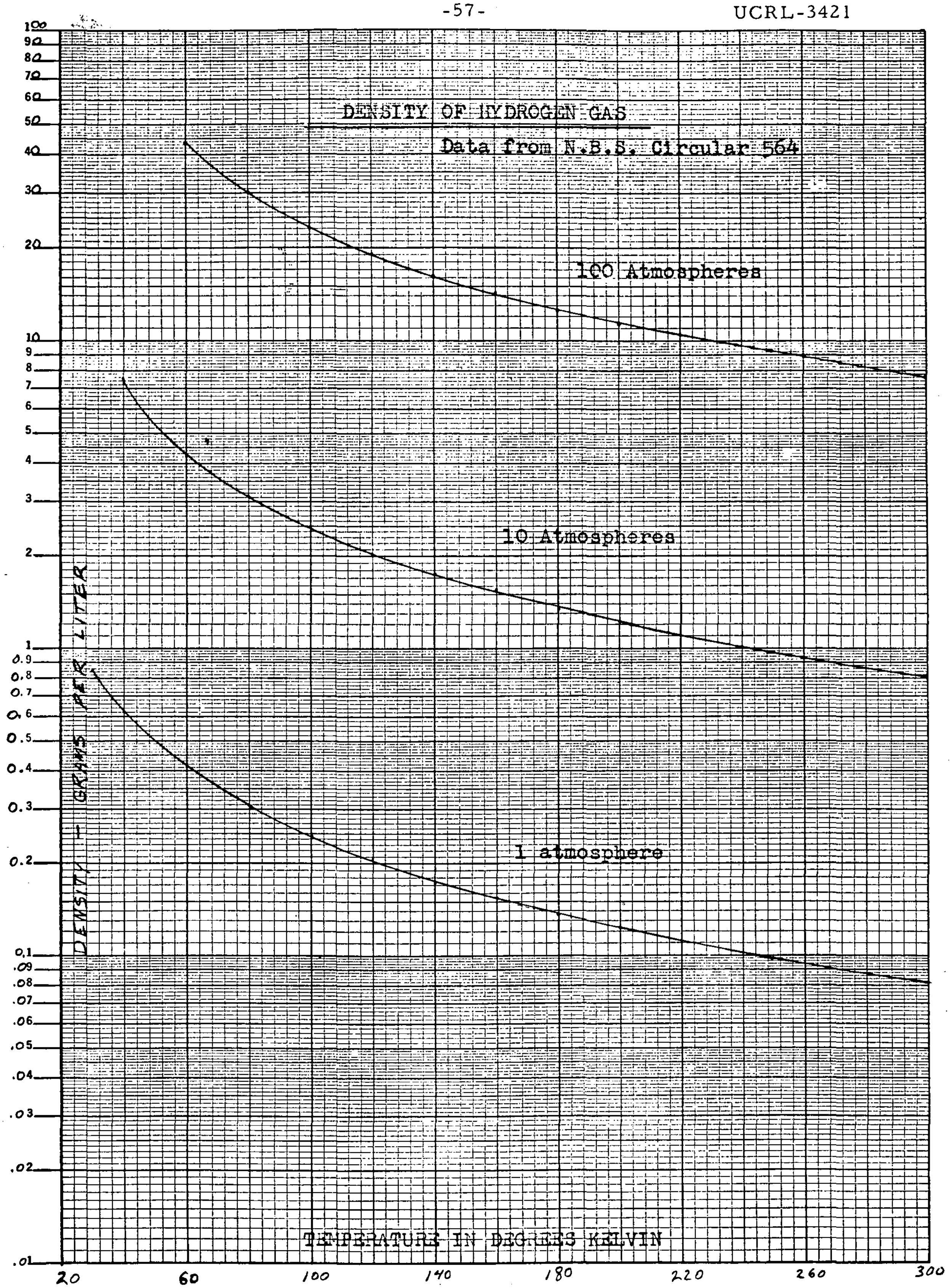
REF: NBS RP1932

ENTHALPY - HYDROGEN

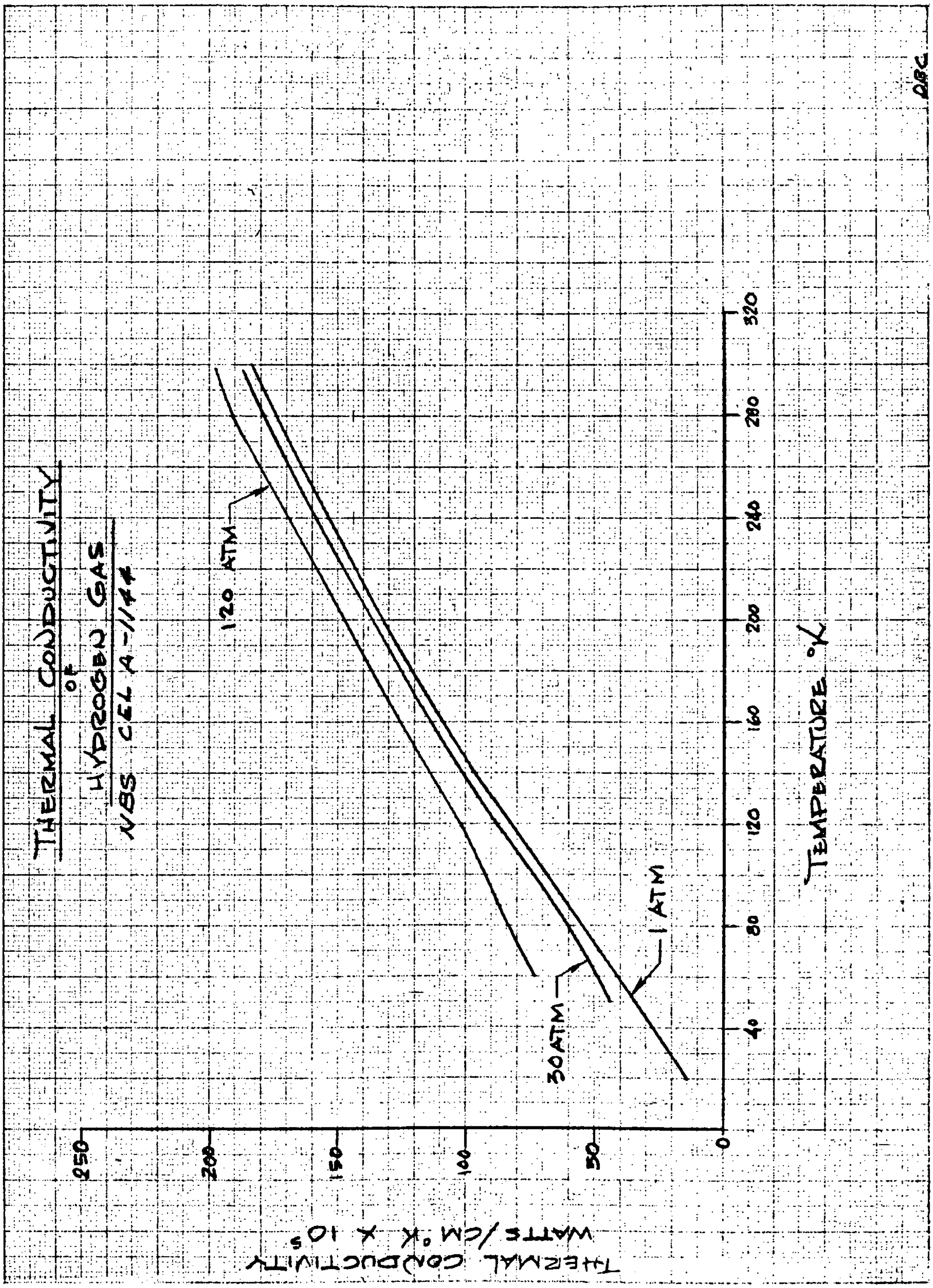
1 ATM PRESSURE
NBS CIRCULAR 564

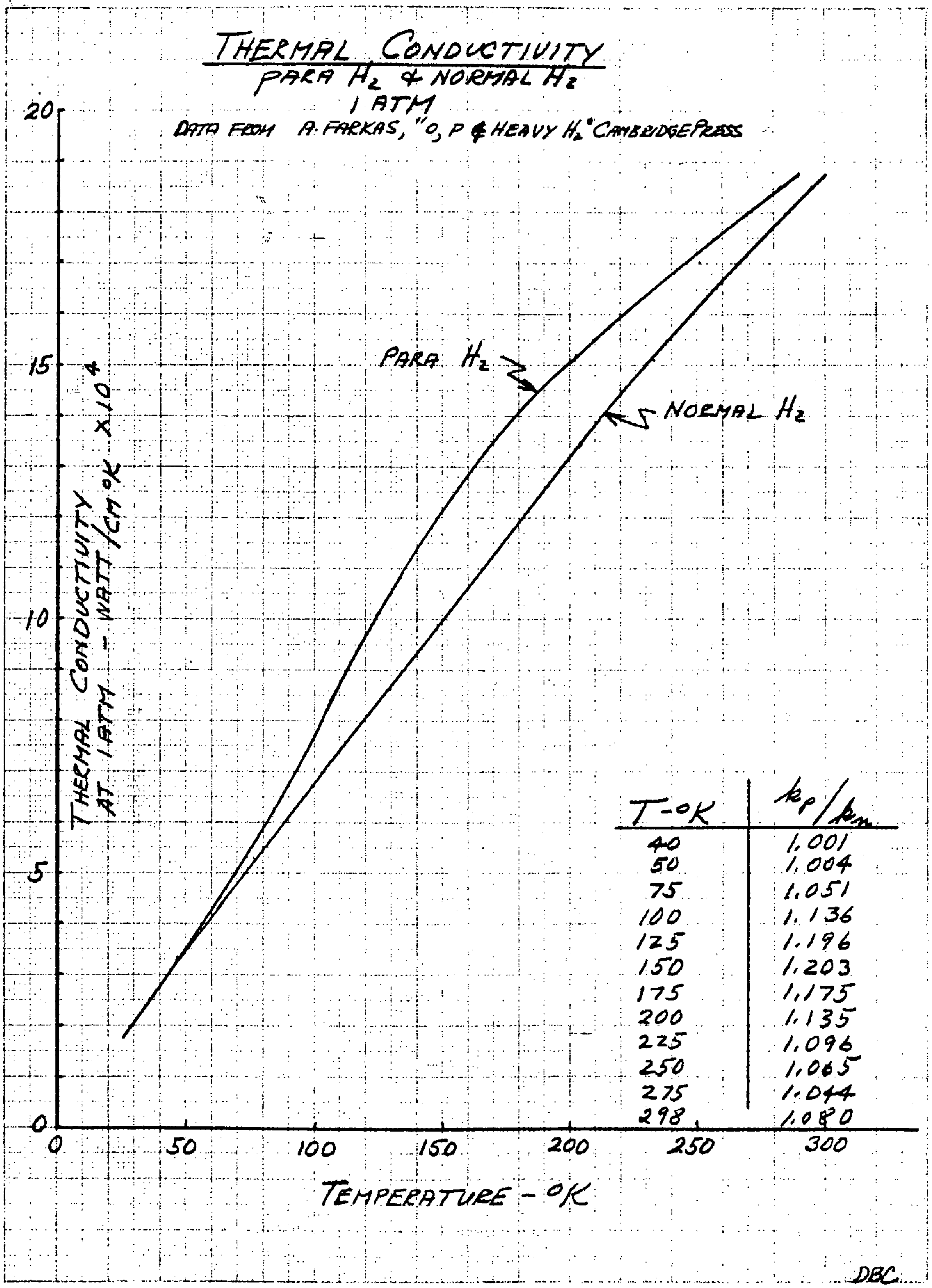



SOUND VELOCITY - HYDROGEN
NBS CIRCULAR 564
100 ATM
1 ATM
LIQUID 20.46 °K
TEMPERATURE - °K
0
50
100
150
200
250
300
VELOCITY METERS/SEC
1400
1200
1000
800
600
400

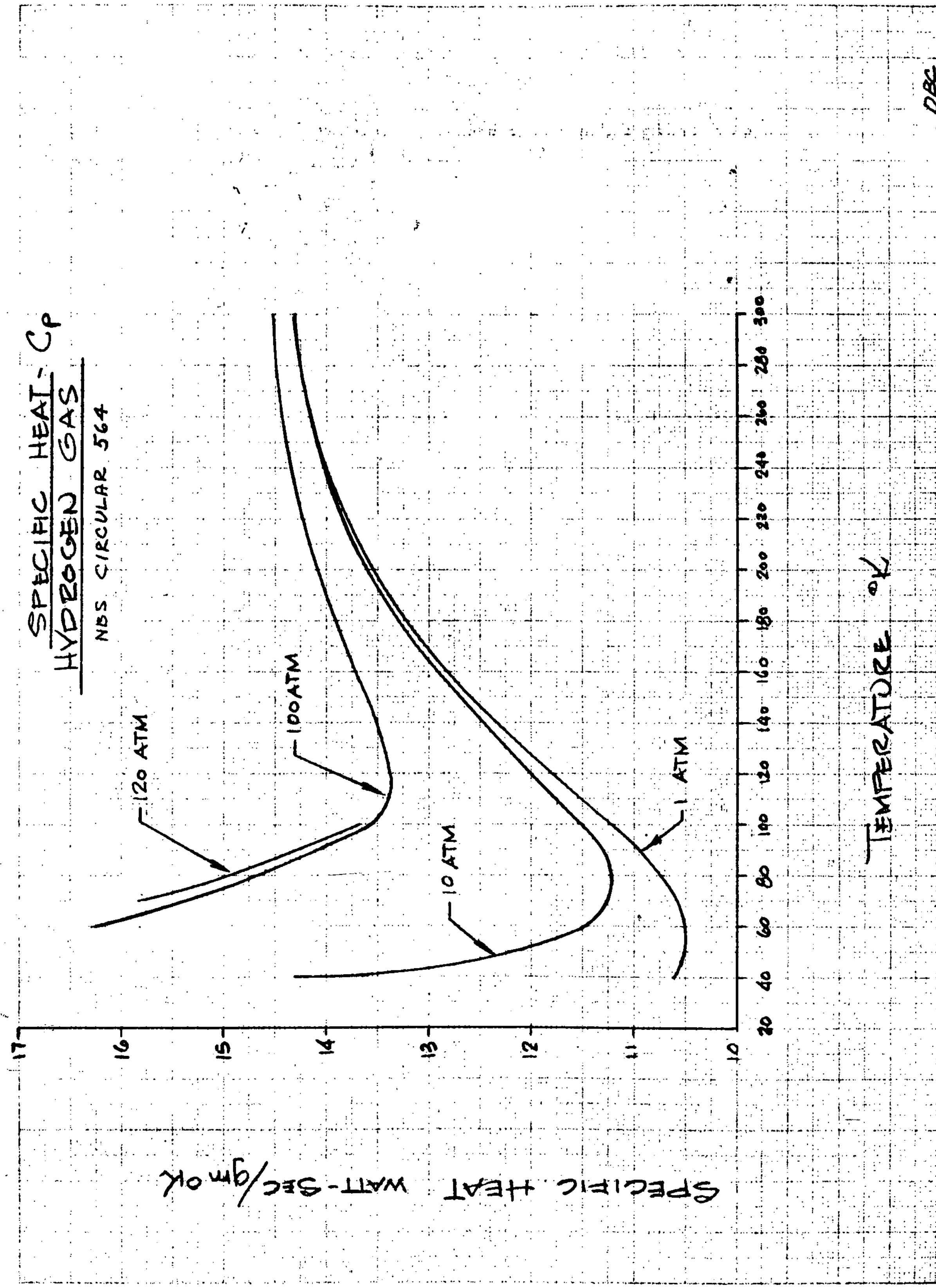

DENSITY OF HYDROGEN GAS
Data from N.B.S. Circular 564
100 Atmospheres
10 Atmospheres
1 atmosphere
DENSITY - GRAMS PER LITER
TEMPERATURE IN DEGREES KELVIN
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
20
60
100
140
180
220
260
300

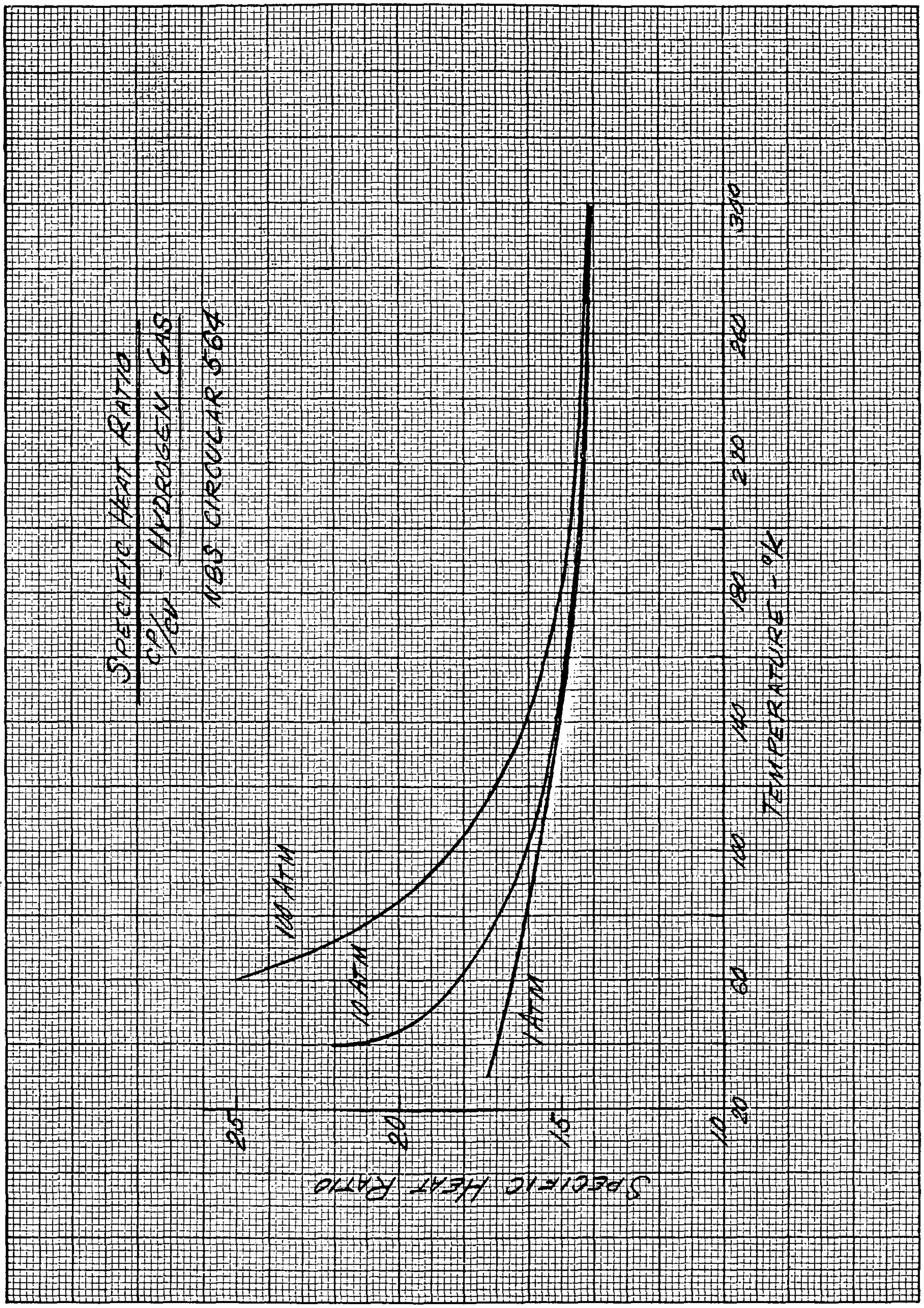
0 0 1 0 1 5 0 0 / 6 2

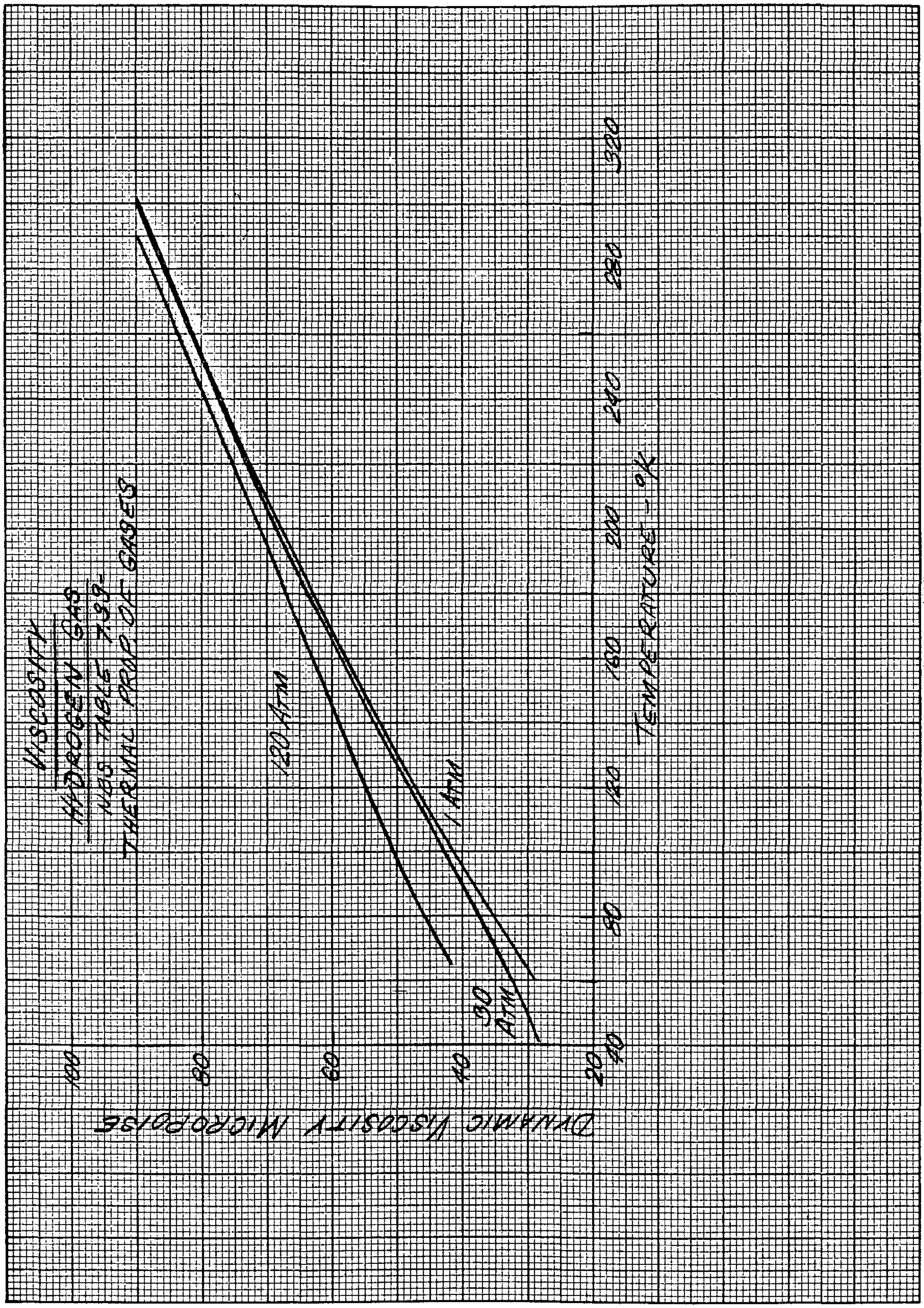

THERMAL CONDUCTIVITY
OF
HYDROGEN GAS
NBS CEL A-1144
120 ATM
30 ATM
1 ATM
TEMPERATURE °K
0
40
80
120
160
200
240
280
320
0
50
100
150
200
250
THERMAL CONDUCTIVITY
WATTS/CM °K × 10⁵
DBC



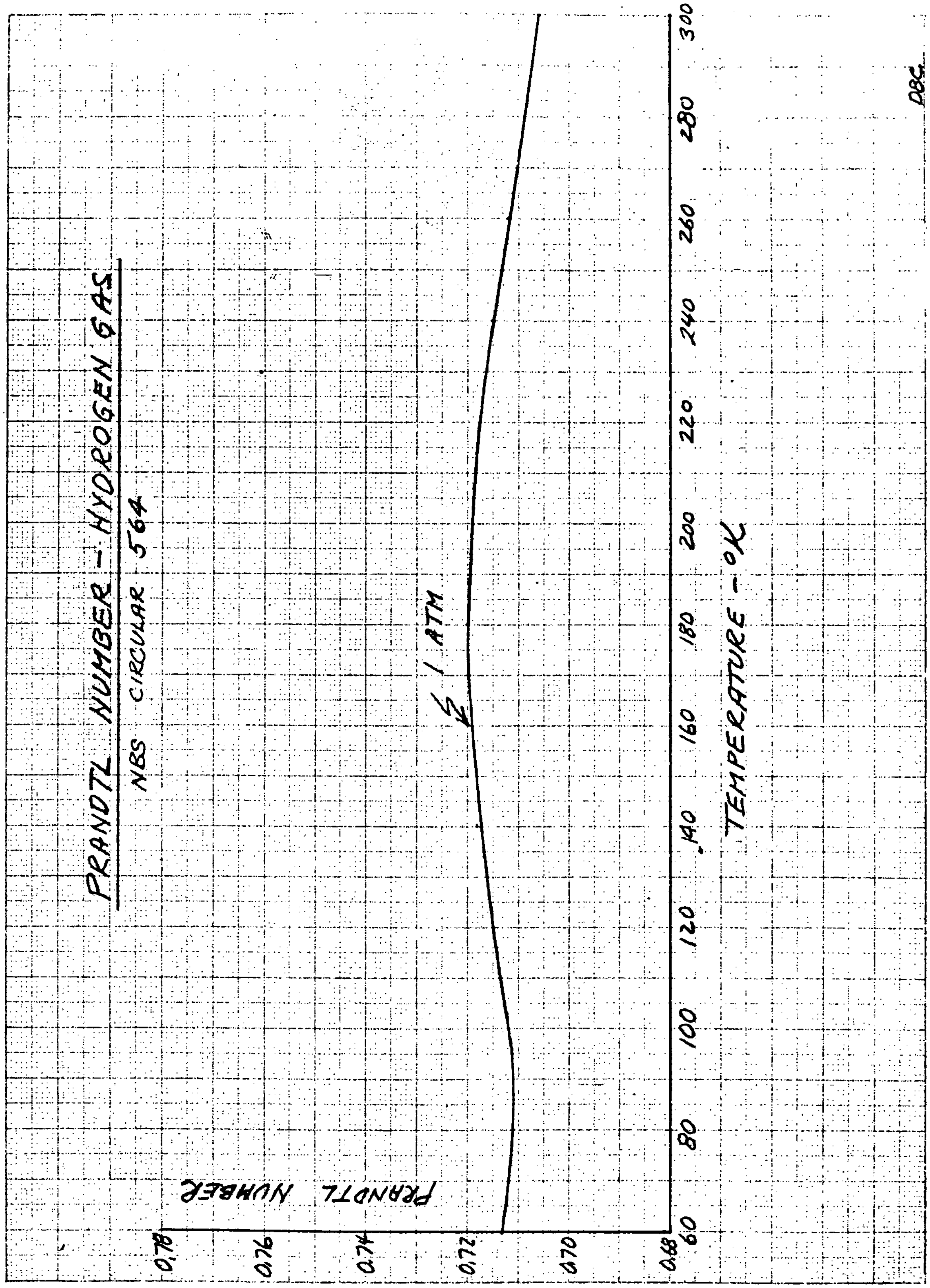
T-°K	k_p/k_n
40	1.001
50	1.004
75	1.051
100	1.136
125	1.196
150	1.203
175	1.175
200	1.135
225	1.096
250	1.065
275	1.044
298	1.080

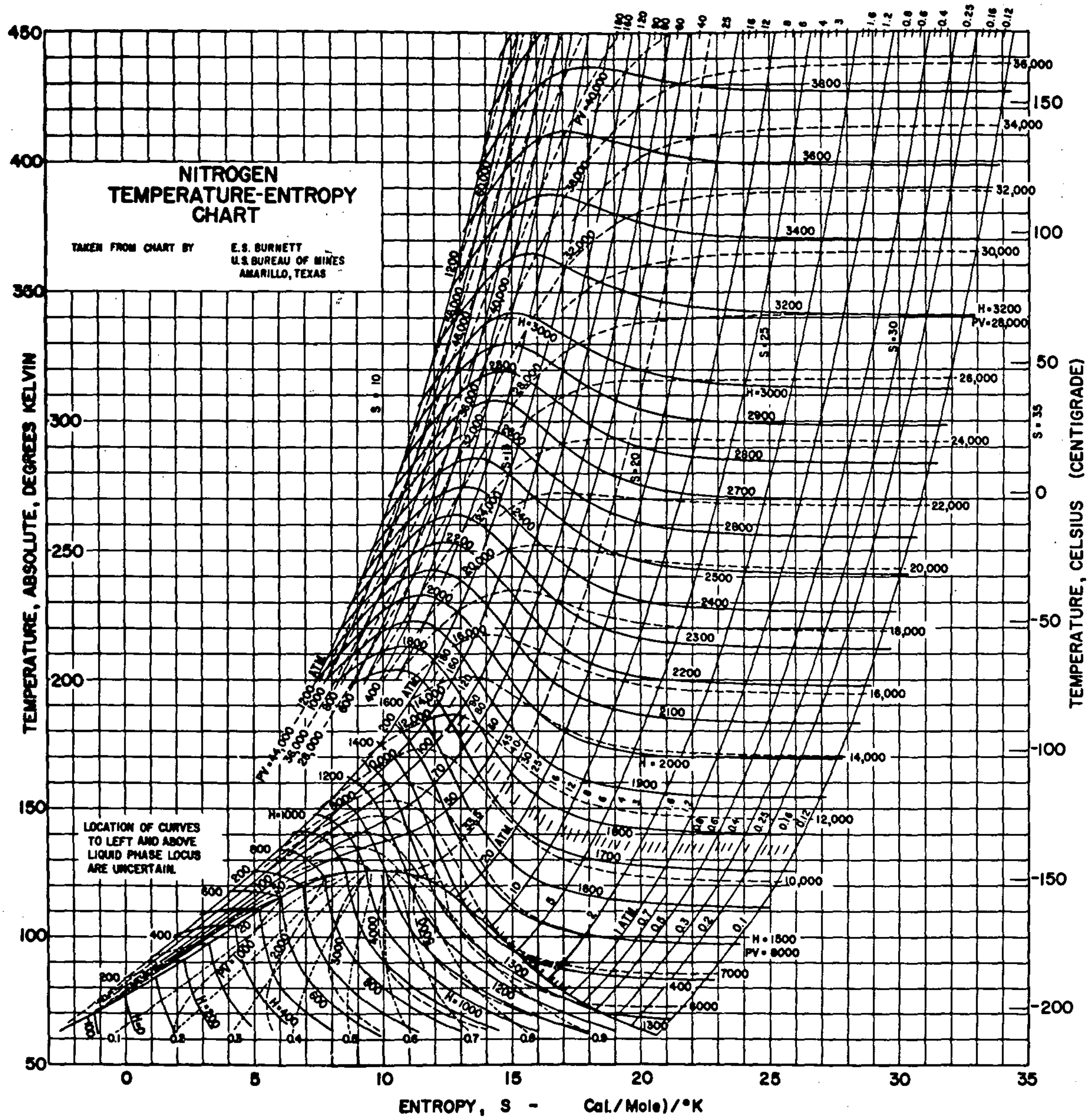

SPECIFIC HEAT - C_P
HYDROGEN GAS
NBS CIRCULAR 564
120 ATM
100 ATM
10 ATM
1 ATM
TEMPERATURE °K
SPECIFIC HEAT WATT-SEC/gm °K
17
16
15
14
13
12
11
10
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
DBC


SPECIFIC HEAT RATIO
Cp/Cv - HYDROGEN GAS
NBS CIRCULAR 564
100 ATM
10 ATM
1 ATM
20
60
100
140
180
220
260
300
TEMPERATURE - °K
1.0
1.5
2.0
2.5
SPECIFIC HEAT RATIO



VISCOSITY
HYDROGEN GAS
NBS TABLE 7.33
THERMAL PROP. OF GASES
120 ATM
1 ATM
30 ATM
TEMPERATURE - °K
40
80
120
160
200
240
280
320
DYNAMIC VISCOSITY MICROPOISE
20
40
60
80
100


PRANDTL NUMBER - HYDROGEN GAS
NBS CIRCULAR 564
1 ATM
TEMPERATURE - °K
PRANDTL NUMBER
0.78
0.76
0.74
0.72
0.70
0.68
60
80
100
120
140
160
180
200
220
240
260
280
300
DBC


NITROGEN
TEMPERATURE-ENTROPY
CHART
TAKEN FROM CHART BY E.S. BURNETT
U.S. BUREAU OF MINES
AMARILLO, TEXAS
LOCATION OF CURVES TO LEFT AND ABOVE LIQUID PHASE LOCUS ARE UNCERTAIN.
TEMPERATURE, ABSOLUTE, DEGREES KELVIN
TEMPERATURE, CELSIUS (CENTIGRADE)
ENTROPY, S - Cal./Mole)/°K
H=3200
PV=28,000
H=1500
PV=8000
H=2000
H=3000
PV=44,000
20 ATM
1 ATM

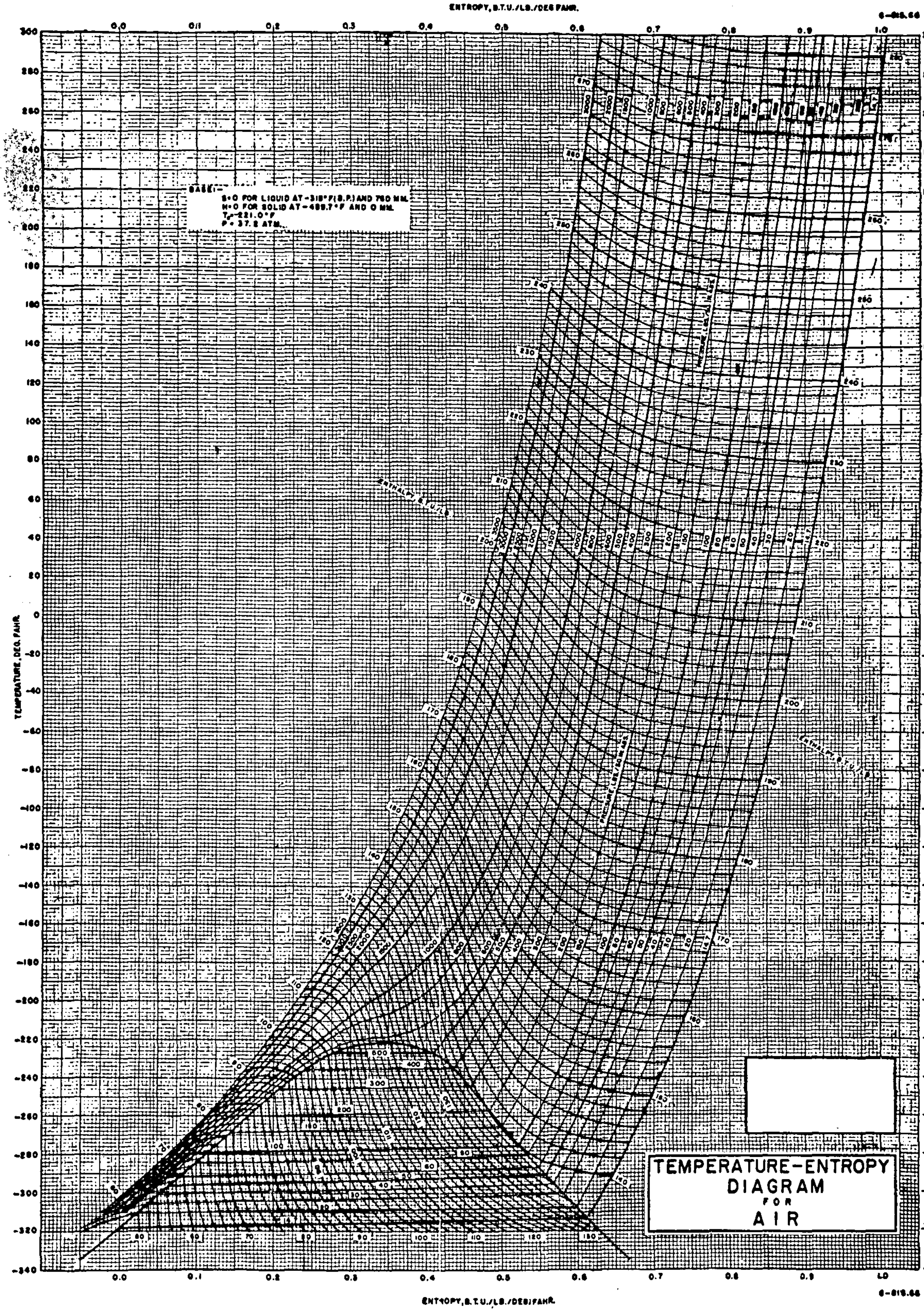
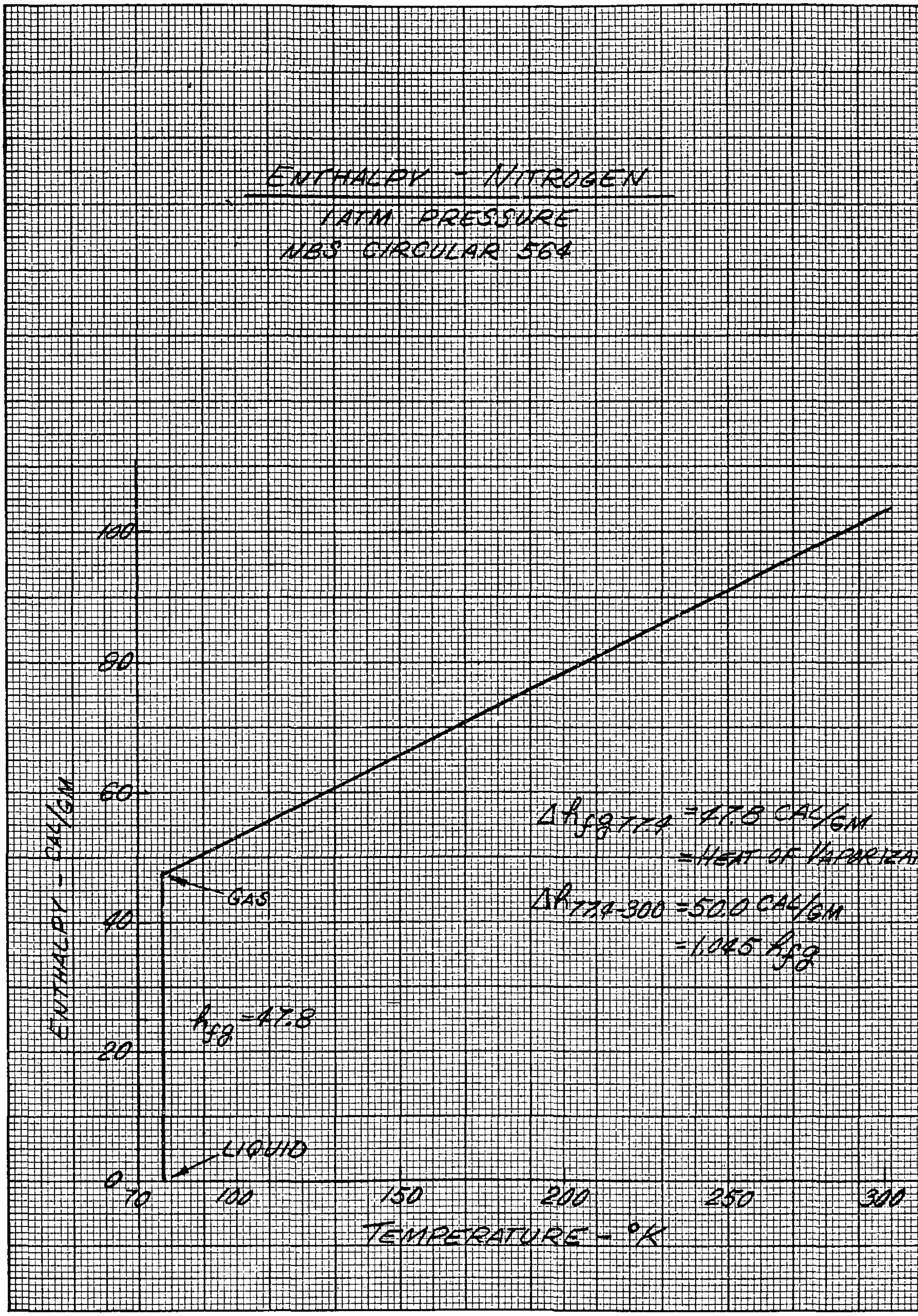
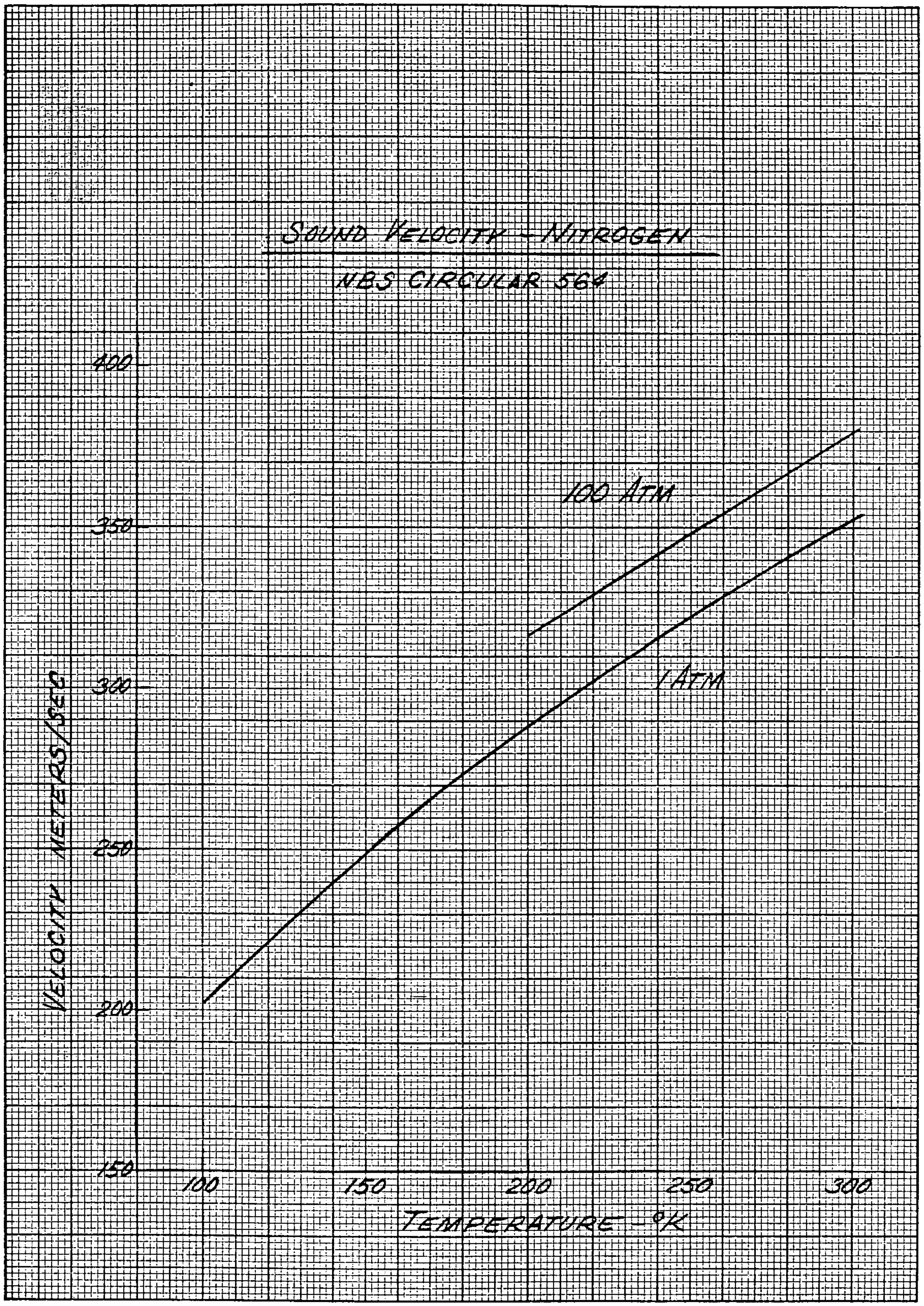
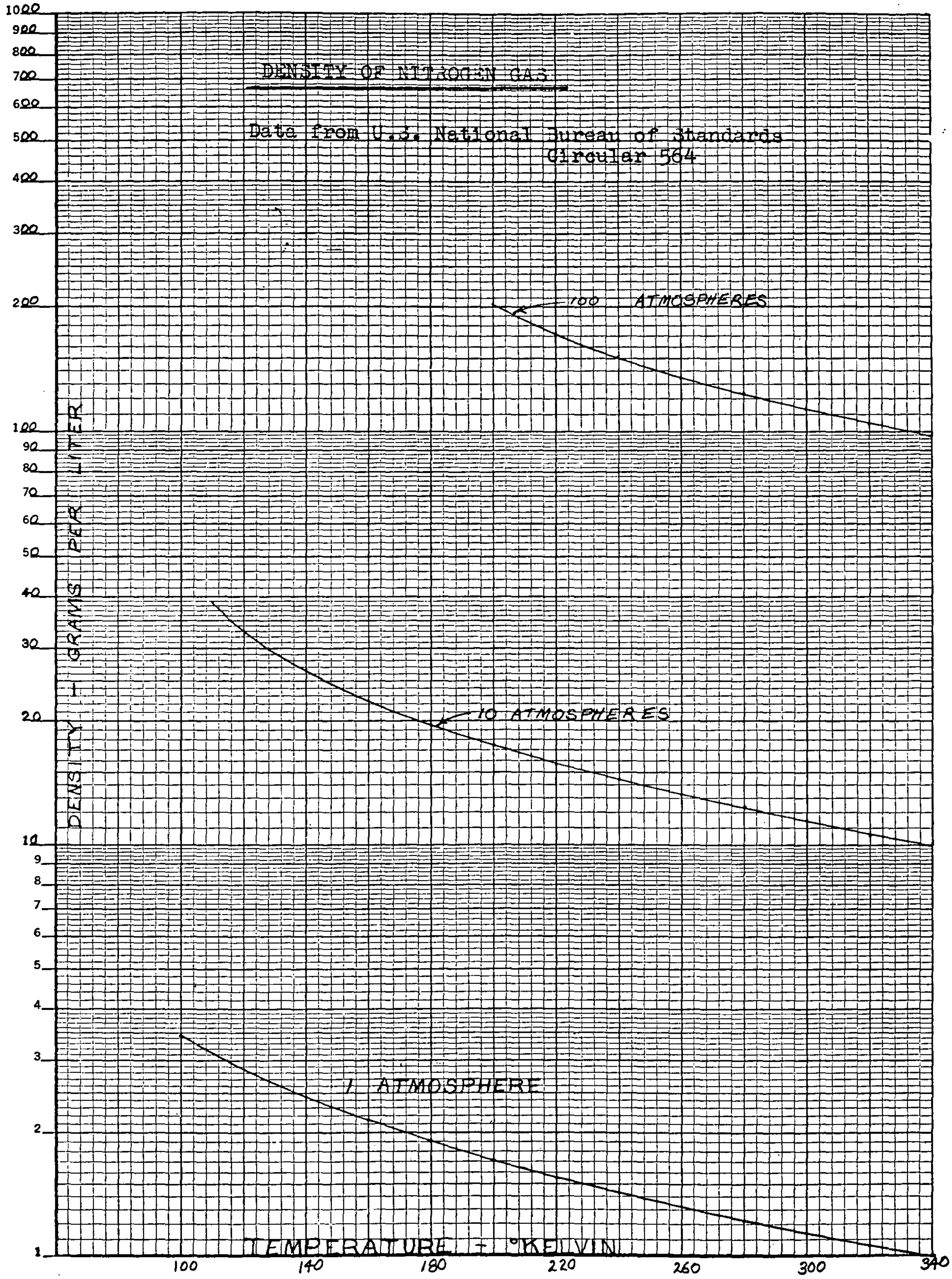
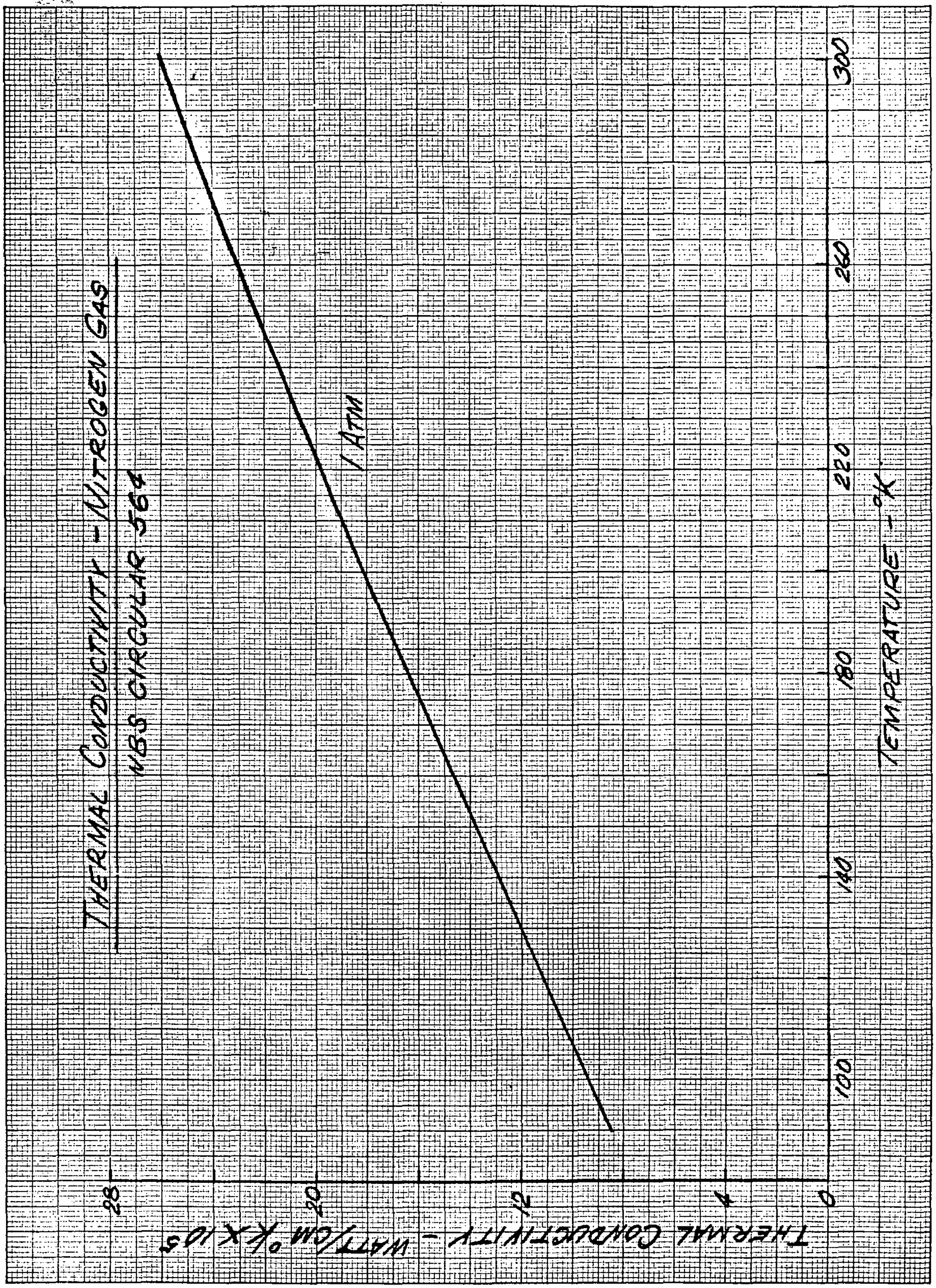


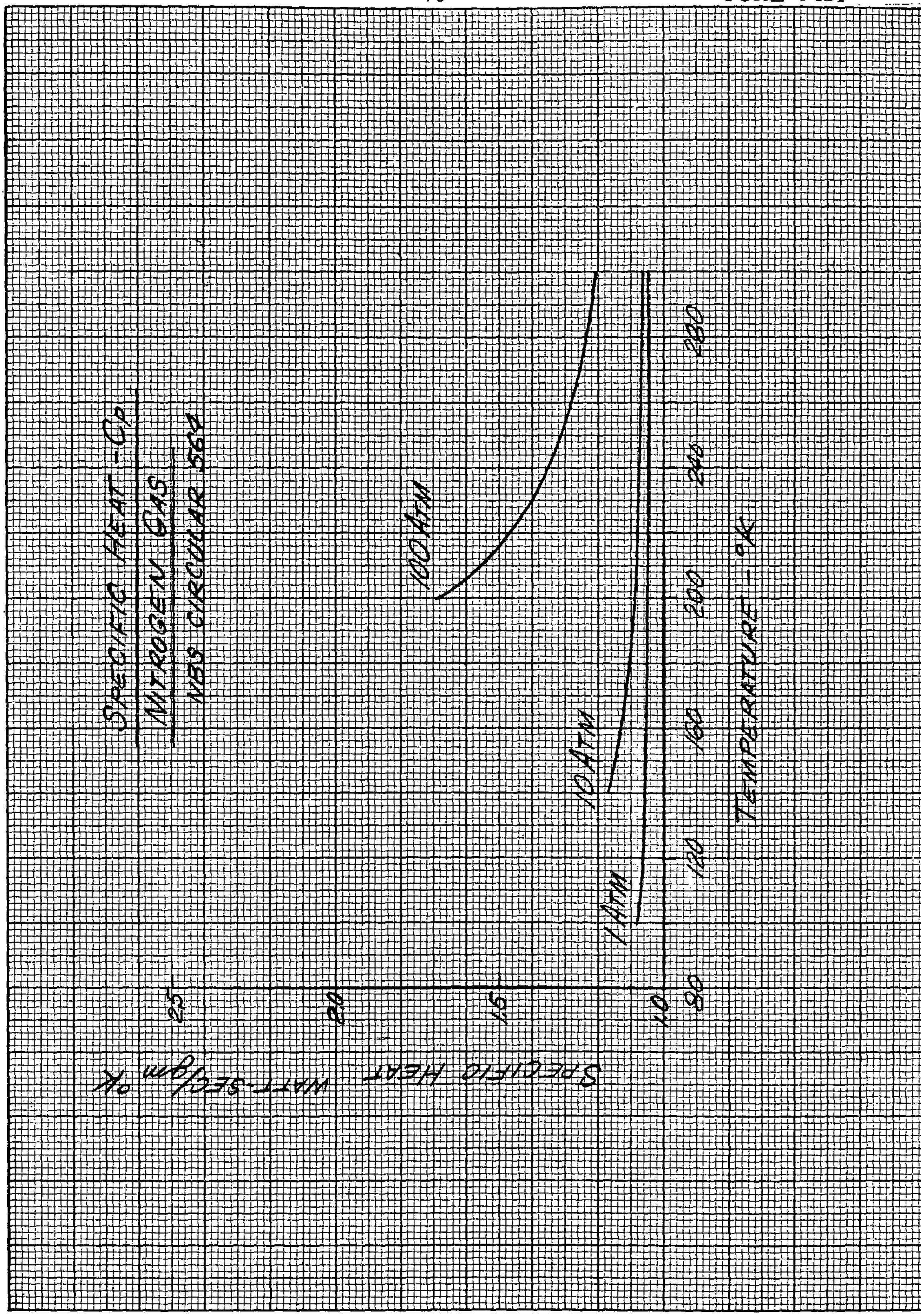
Fig. 16.5. Temperature-entropy diagram for air. Courtesy M. W. Kellogg Co.

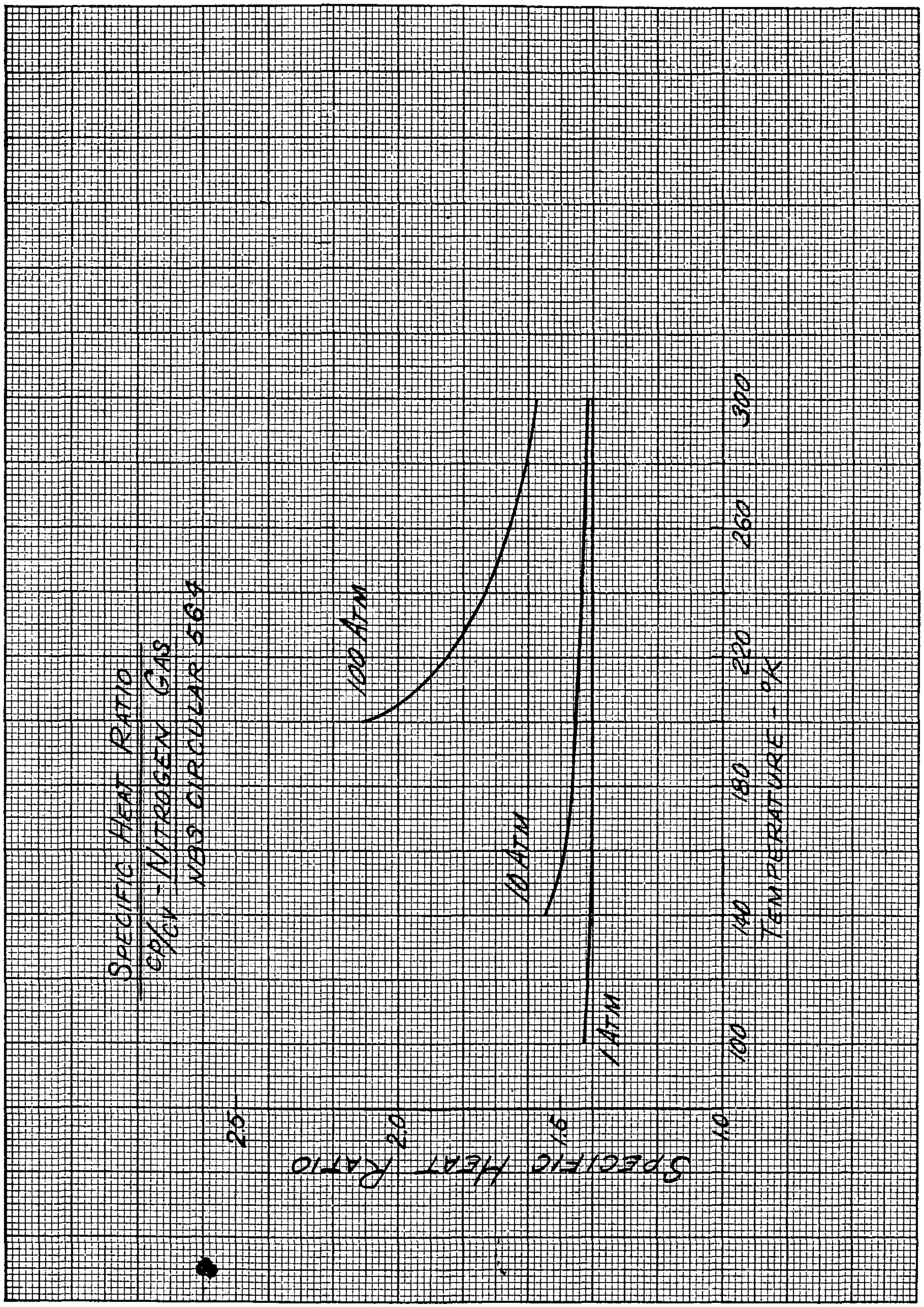

ENTHALPY - NITROGEN
1 ATM PRESSURE
NBS CIRCULAR 564
ENTHALPY - CAL/GM
TEMPERATURE - °K
0
20
40
60
80
100
70
100
150
200
250
300
GAS
LIQUID
h_{fg} = 47.8
$\Delta h_{fg\,77.4}$ = 47.8 CAL/GM
= HEAT OF VAPORIZATION
$\Delta h_{77.4-300}$ = 50.0 CAL/GM
= 1.045 h_{fg}

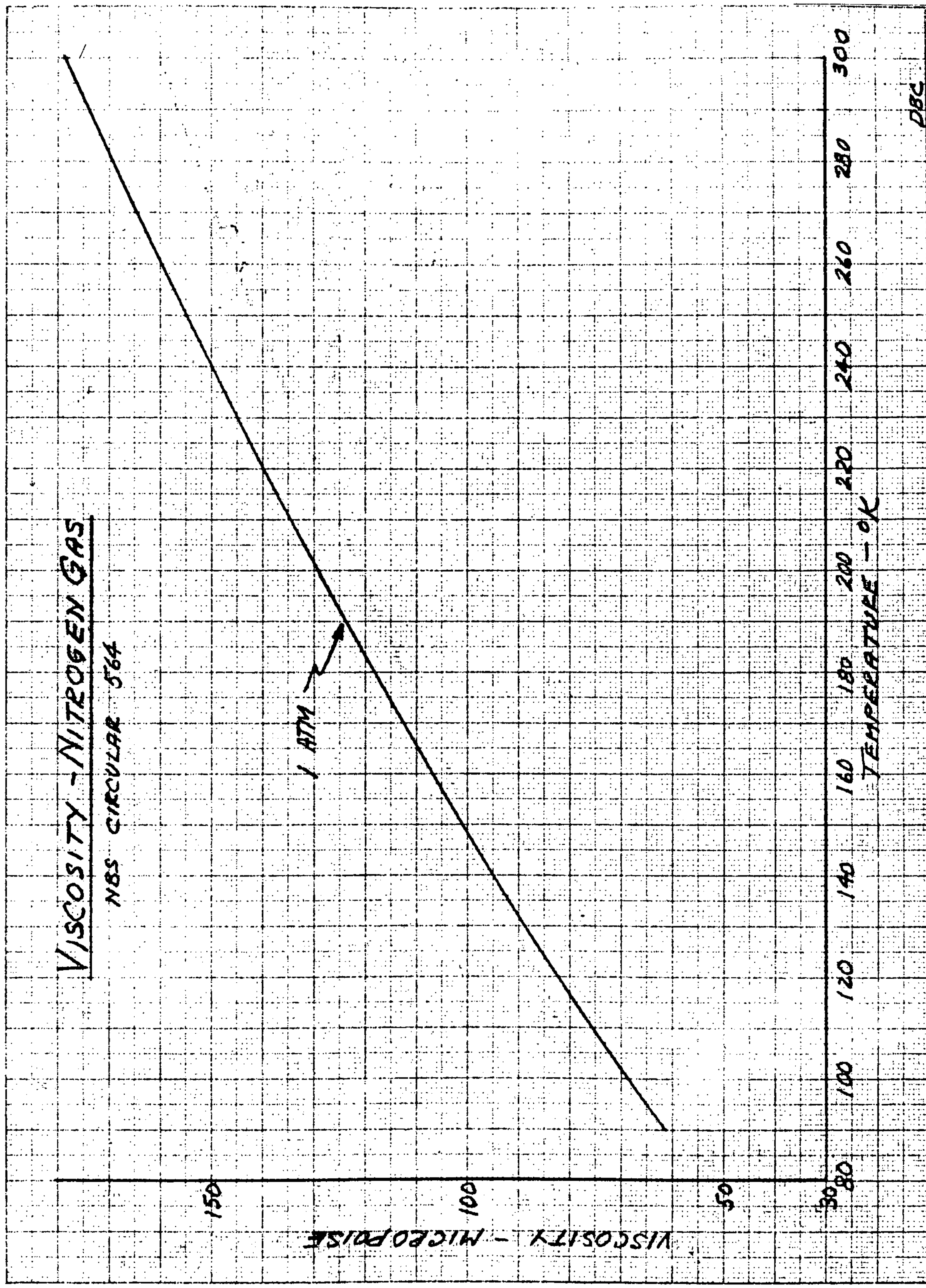

SOUND VELOCITY - NITROGEN
NBS CIRCULAR 564
100 ATM
1 ATM
VELOCITY METERS/SEC
400
350
300
250
200
150
100
150
200
250
300
TEMPERATURE - °K

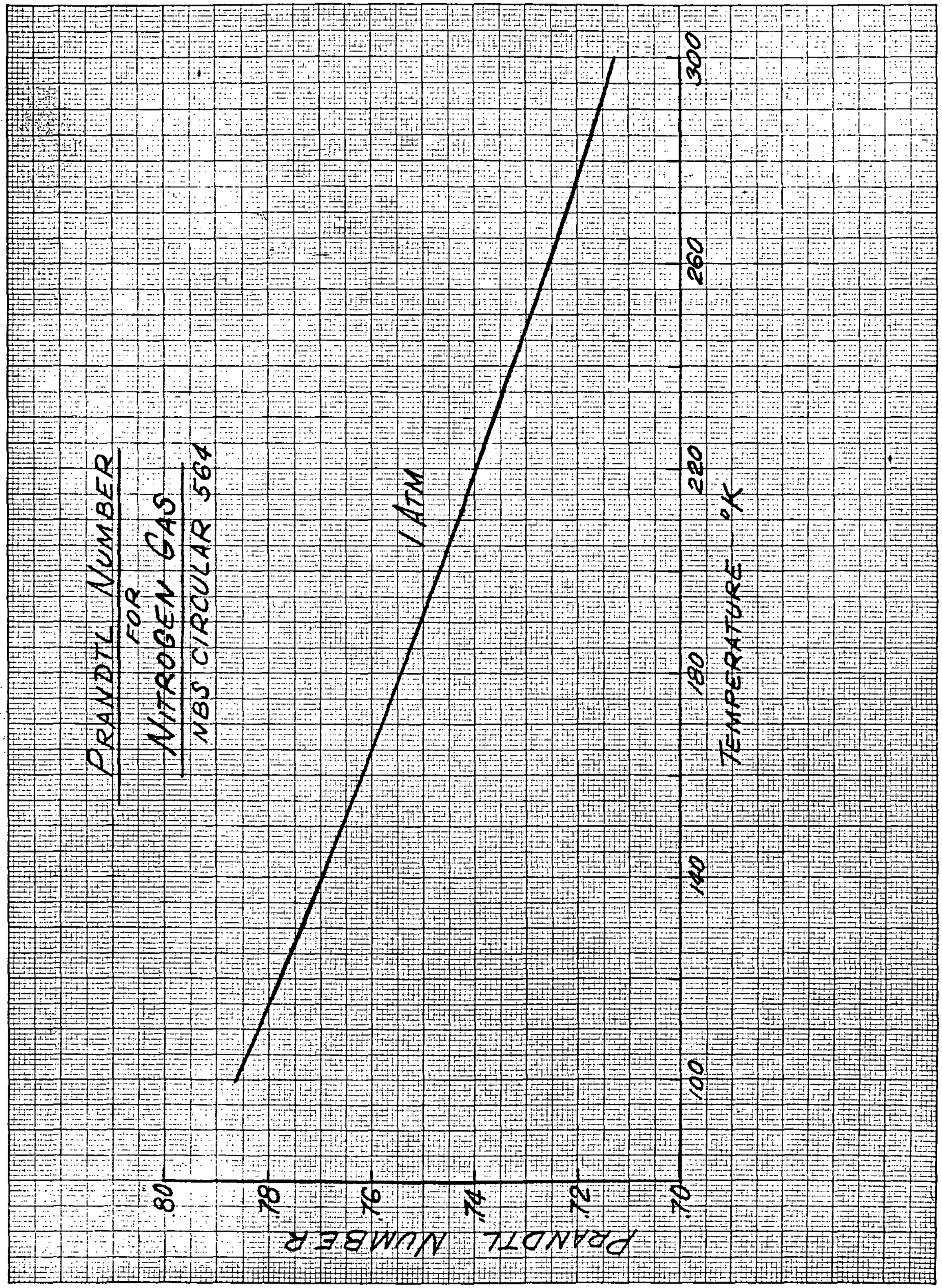

DENSITY OF NITROGEN GAS
Data from U.S. National Bureau of Standards Circular 564
100 ATMOSPHERES
10 ATMOSPHERES
1 ATMOSPHERE
DENSITY - GRAMS PER LITER
TEMPERATURE - °KELVIN
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
100
140
180
220
260
300
340

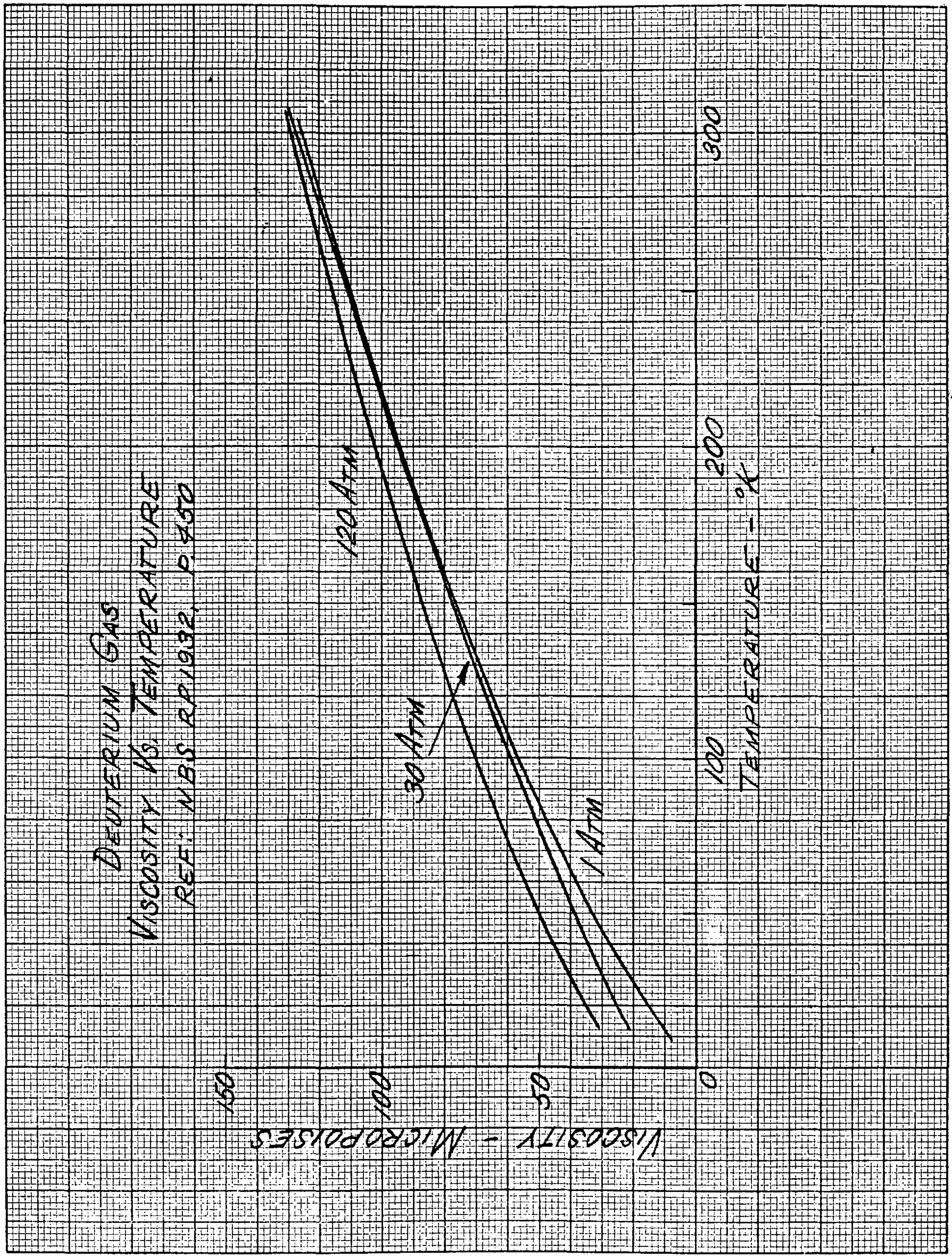

THERMAL CONDUCTIVITY - NITROGEN GAS
NBS CIRCULAR 564
1 ATM
TEMPERATURE - °K
300
260
220
180
140
100
THERMAL CONDUCTIVITY - WATT/CM °K X 10⁵
28
20
12
4
0


SPECIFIC HEAT - Cp
NITROGEN GAS
NBS CIRCULAR 564
100 ATM
10 ATM
1 ATM
TEMPERATURE - °K
80
120
160
200
240
280
SPECIFIC HEAT WATT-SEC/gm °K
1.0
1.5
2.0
2.5


SPECIFIC HEAT RATIO
CP/CV - NITROGEN GAS
NBS CIRCULAR 564
100 ATM
10 ATM
1 ATM
100
140
180
220
260
300
TEMPERATURE - °K
2.5
2.0
1.5
1.0
SPECIFIC HEAT RATIO

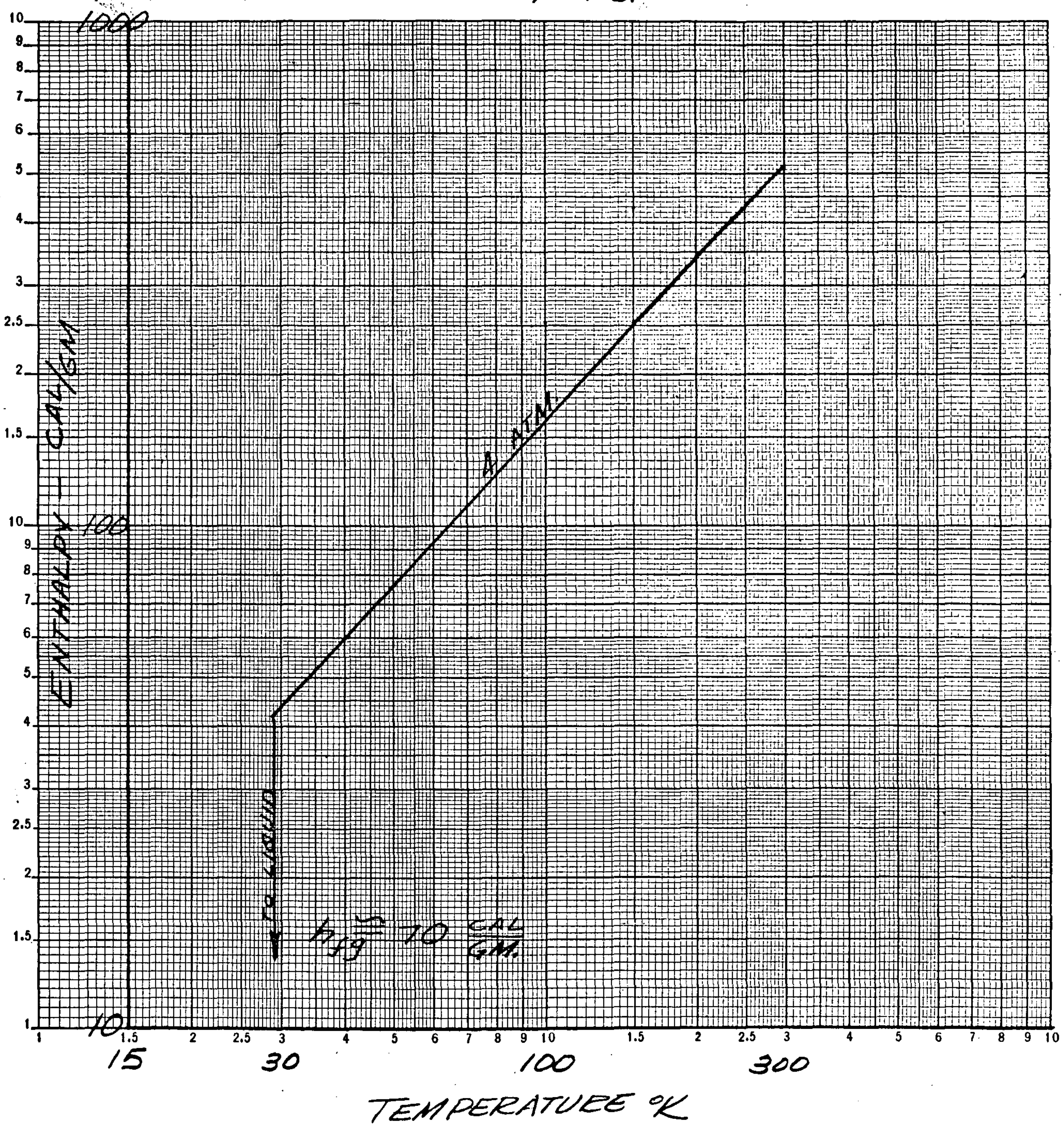

VISCOSITY - NITROGEN GAS
NBS CIRCULAR 564
1 ATM
TEMPERATURE - °K
VISCOSITY - MICROPOISE
80
100
120
140
160
180
200
220
240
260
280
300
30
50
100
150
DBC

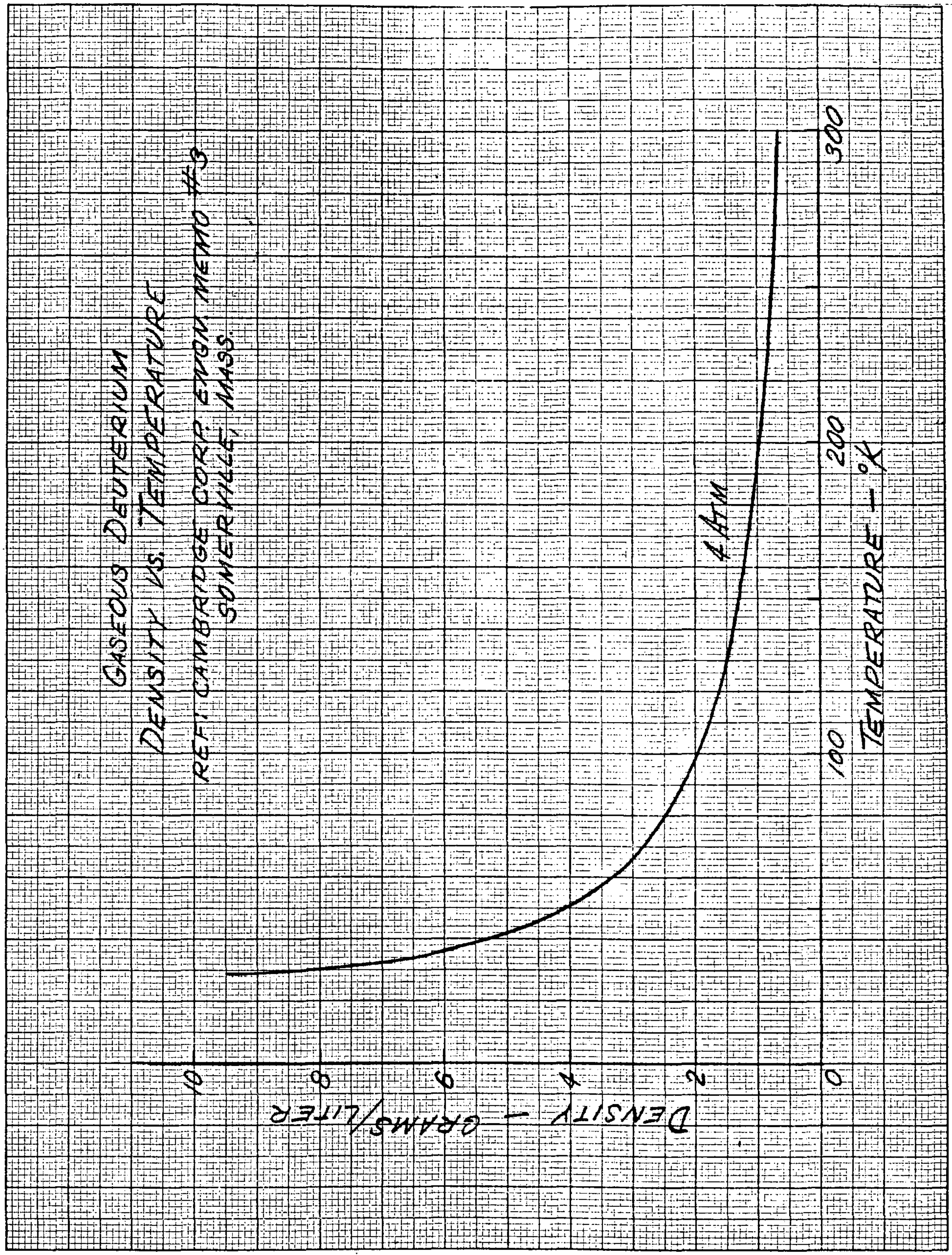

PRANDTL NUMBER
FOR
NITROGEN GAS
NBS CIRCULAR 564
1 ATM
TEMPERATURE °K
100
140
180
220
260
300
PRANDTL NUMBER
80
78
76
74
72
70


Deuterium Gas
Viscosity Vs. Temperature
Ref: NBS RP1932, P.450
120 Atm
30 Atm
1 Atm
0
100
200
300
Temperature - °K
50
100
150
Viscosity - Micropoises

GASEOUS DEUTERIUM
ENTHALPY VS. TEMPERATURE

REF: CAMBRIDGE CORP. ENGN. MEMO. #3
SOMERVILLE, MASS.




GASEOUS DEUTERIUM
DENSITY VS. TEMPERATURE
REF: CAMBRIDGE CORP. ENGN. MEMO #3
SOMERVILLE, MASS.
4 ATM
100
200
300
TEMPERATURE — °K
0
2
4
6
8
10
DENSITY — GRAMS/LITER

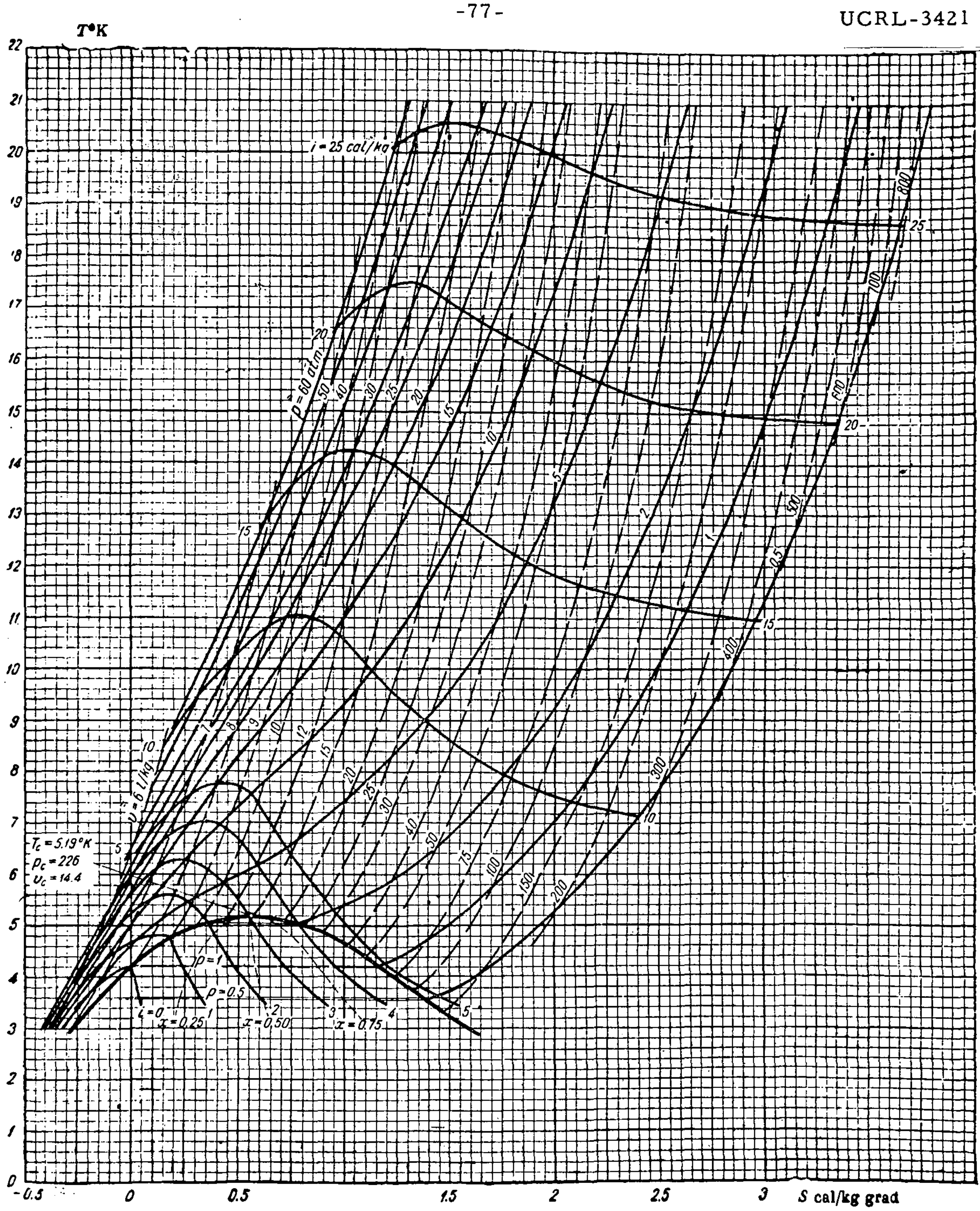
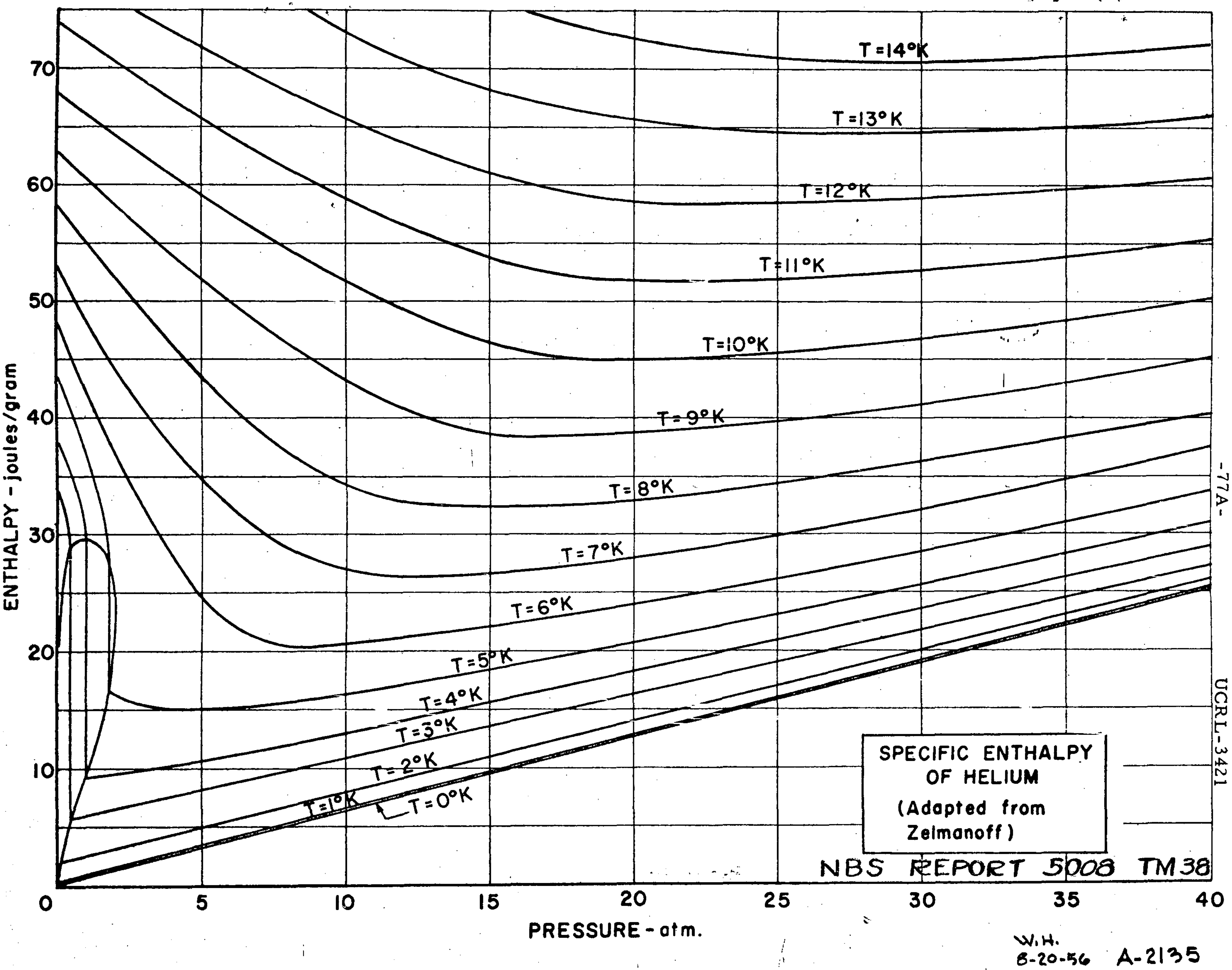


Fig. 2. $T-S$ diagram of helium



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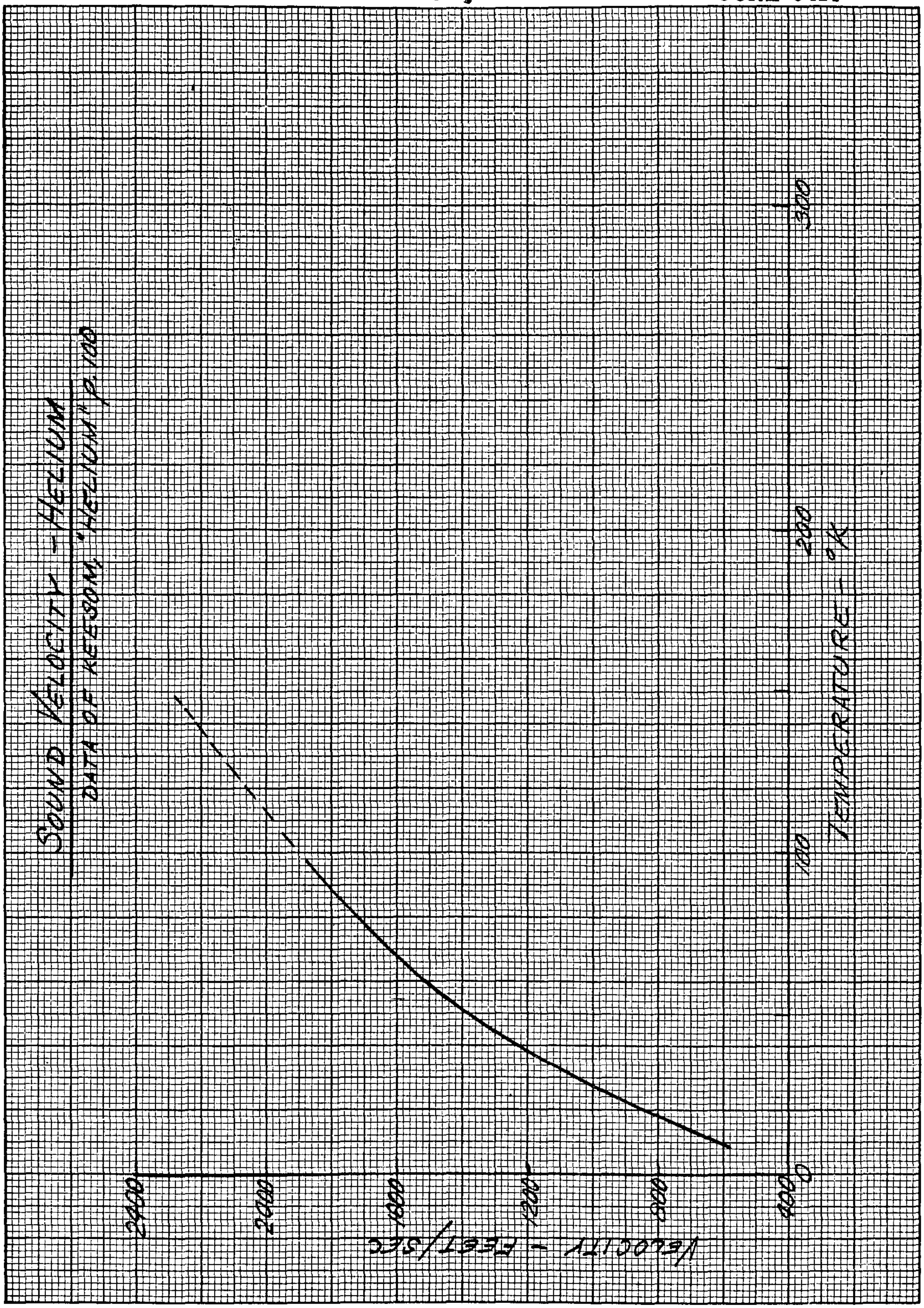
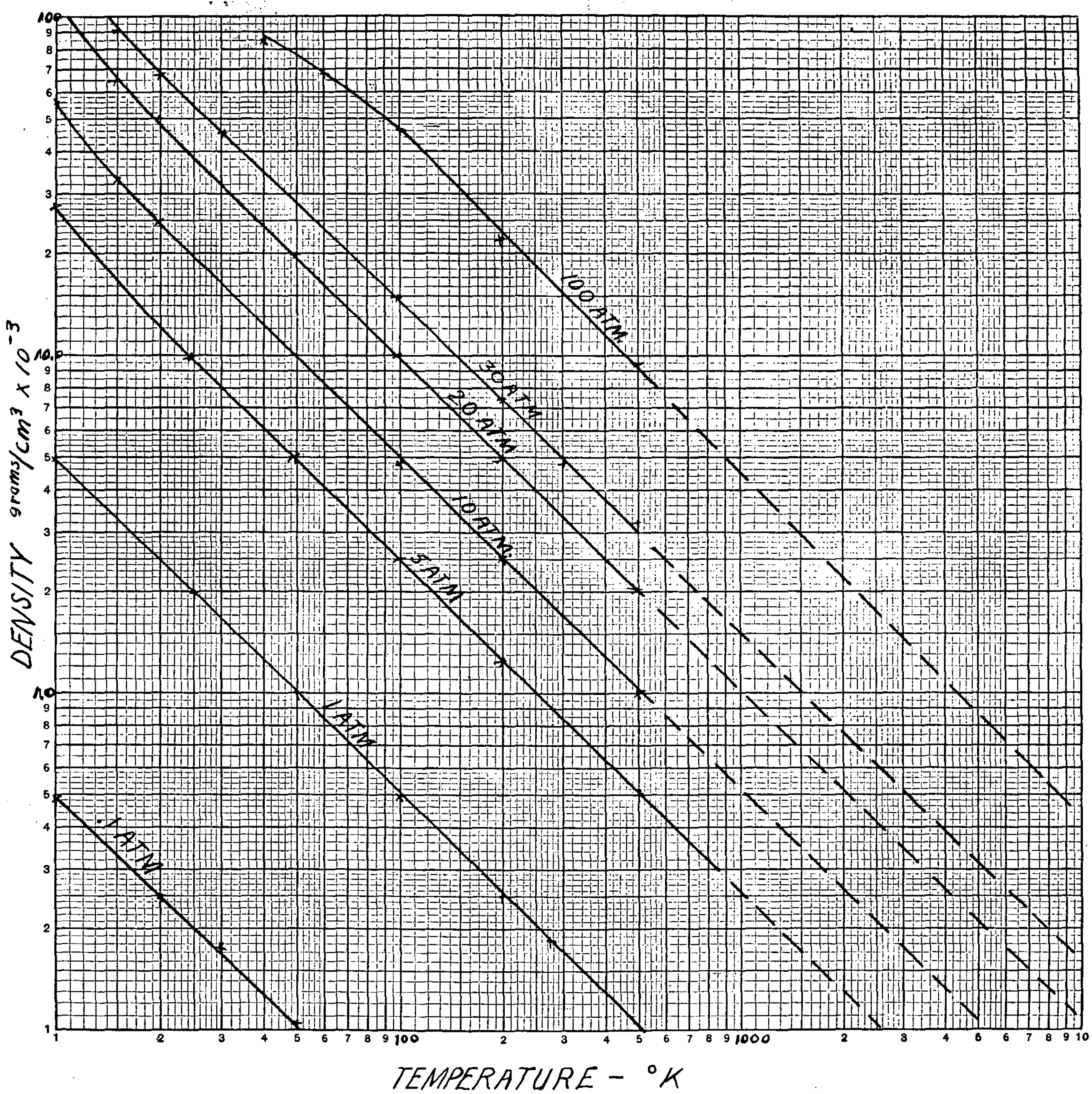
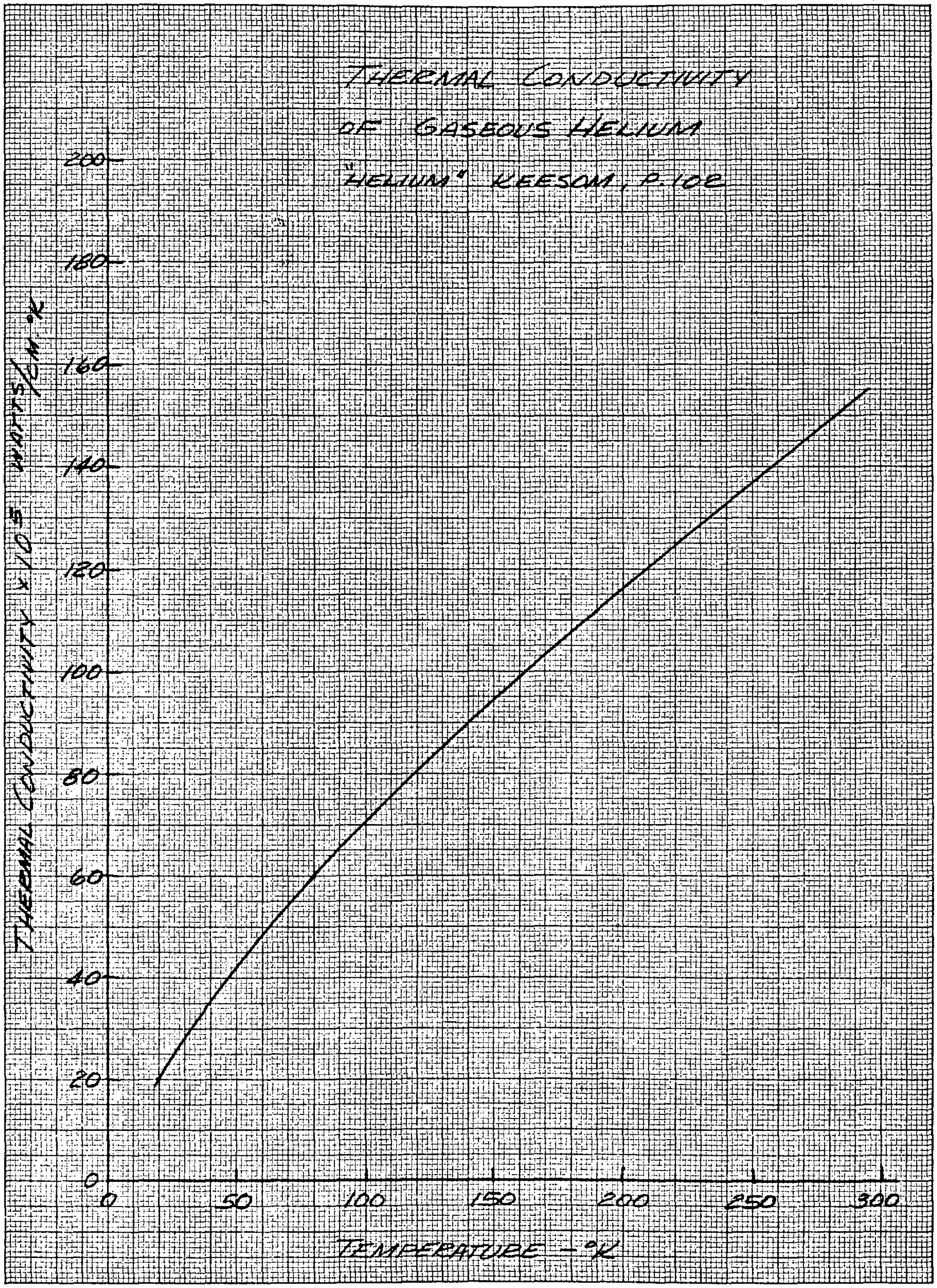
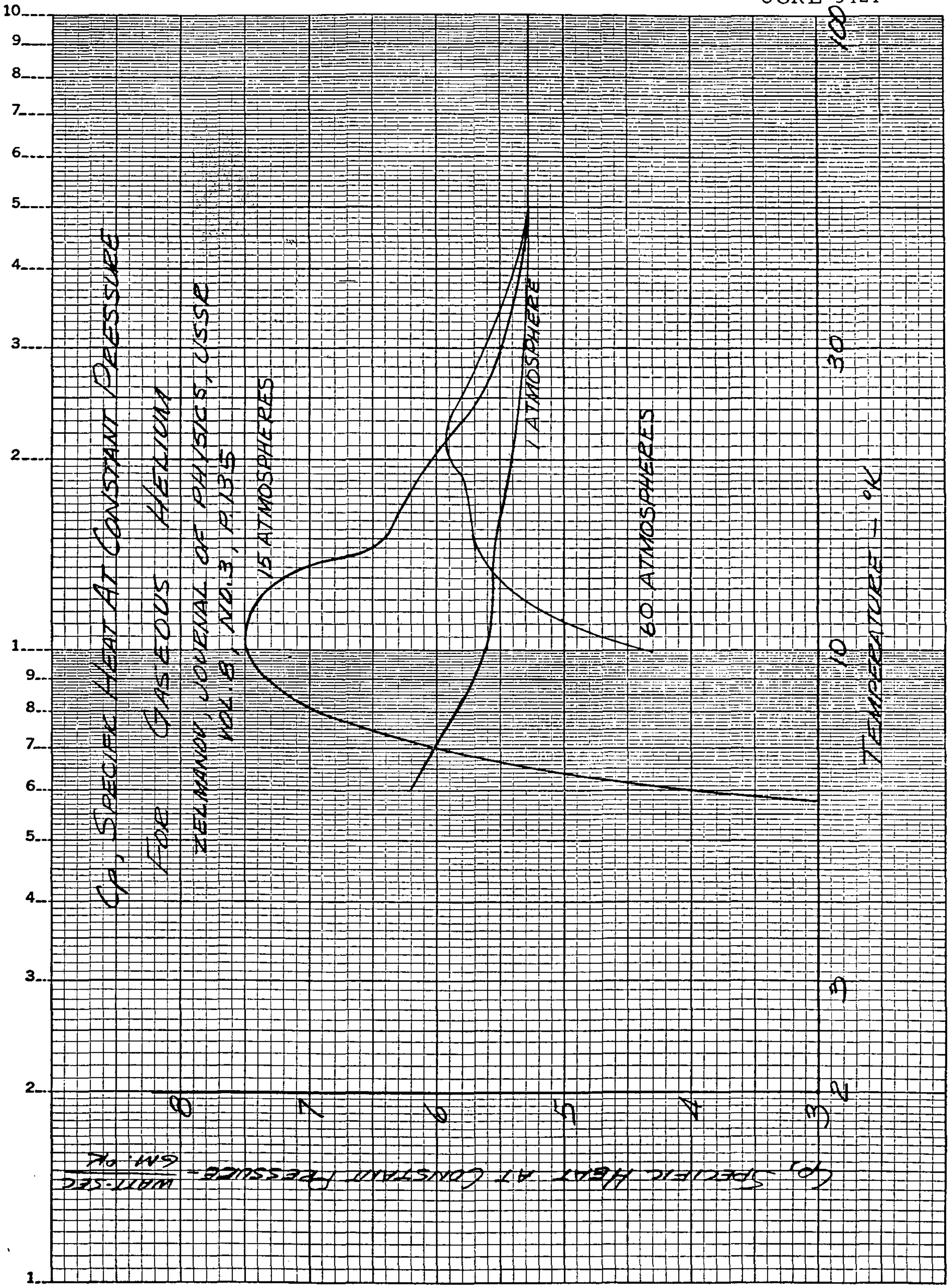

SOUND VELOCITY - HELIUM
DATA OF KEESOM, "HELIUM" p. 100
TEMPERATURE - °K
0
100
200
300
VELOCITY - FEET/SEC
400
800
1200
1600
2000
2400



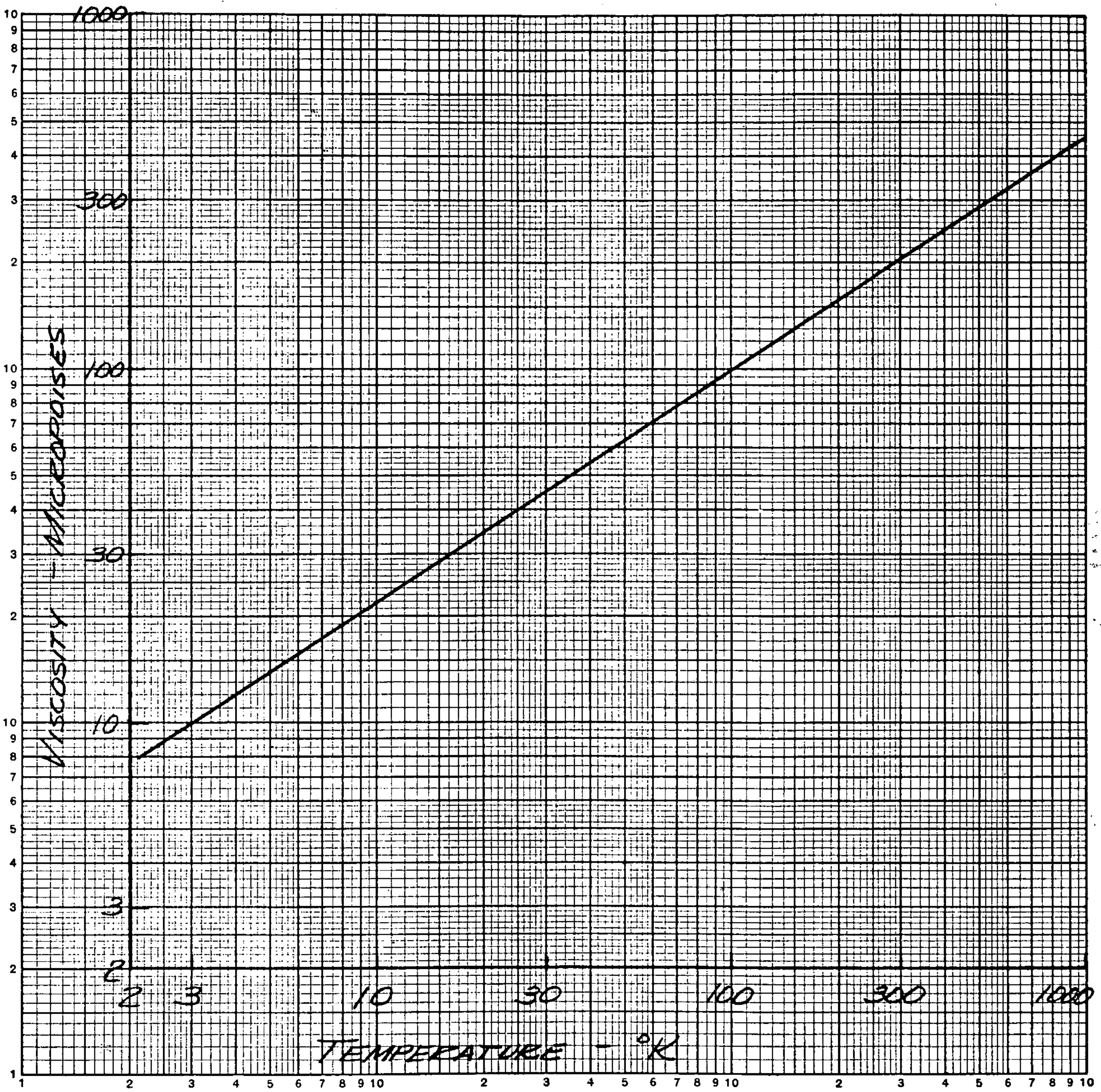
DENSITY OF GASEOUS HELIUM
from- "Institut International Du Froid"
(INTERNATIONAL INST. OF REF.)

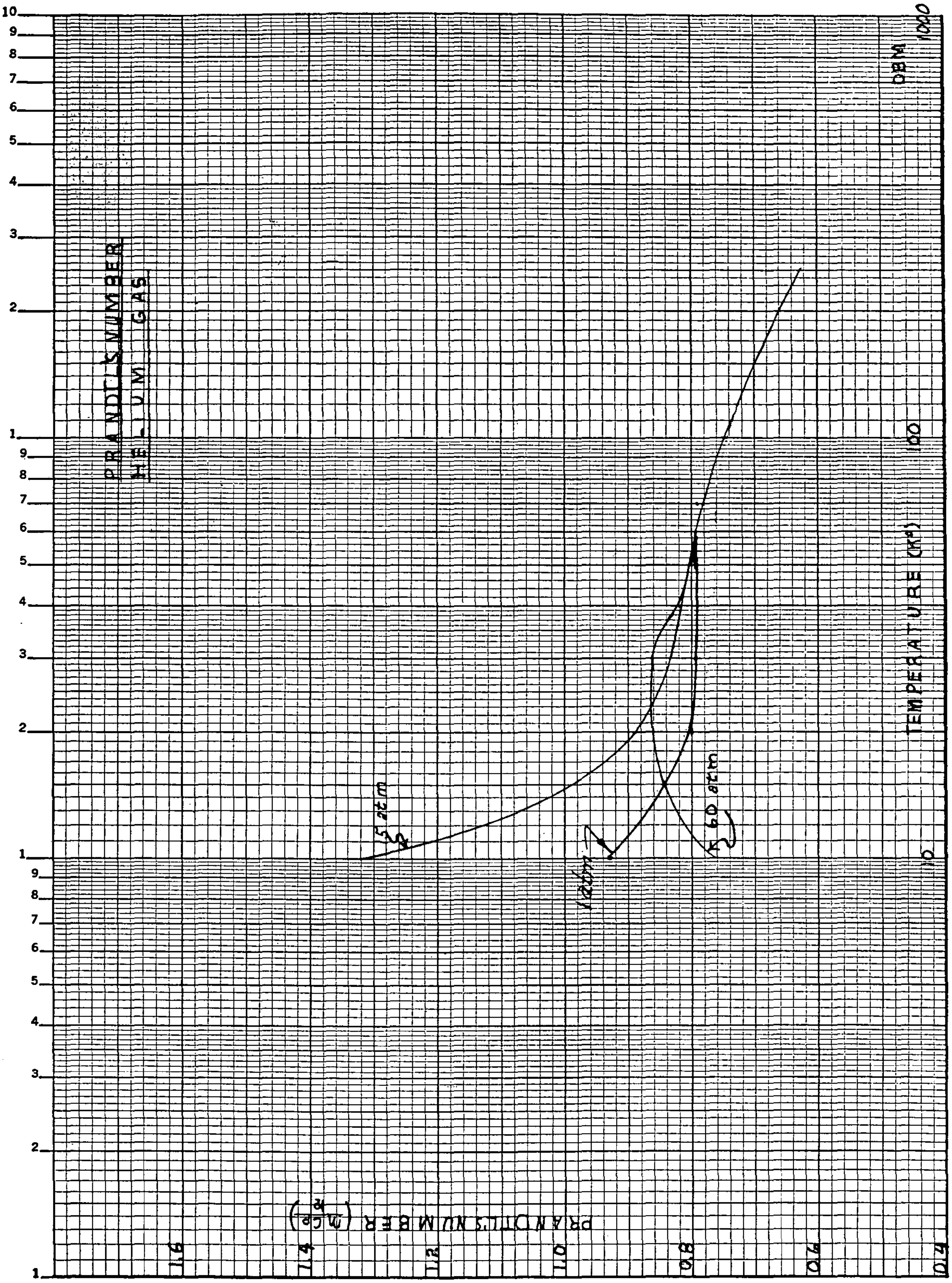

THERMAL CONDUCTIVITY
OF GASEOUS HELIUM
"HELIUM" KEESOM, P.102
THERMAL CONDUCTIVITY × 10^5 WATTS/CM·°K
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
TEMPERATURE — °K

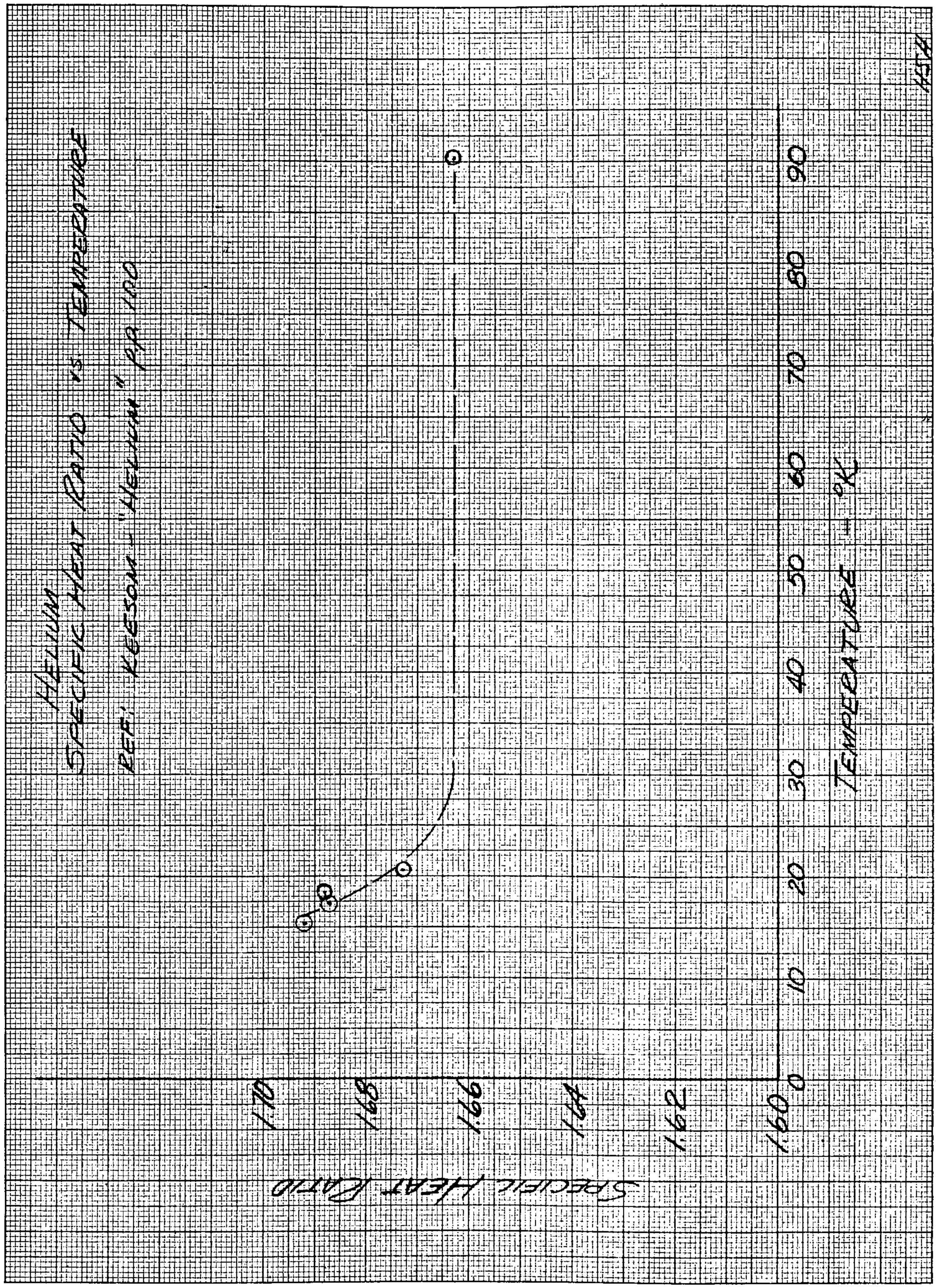

Cp, Specific Heat At Constant Pressure
For Gaseous Helium
Zelmanov, Journal of Physics, USSR
Vol. 8, No. 3, P. 135
15 Atmospheres
1 Atmosphere
60 Atmospheres
Temperature – °K
Cp, Specific Heat At Constant Pressure – Watt-Sec / Gm·°K

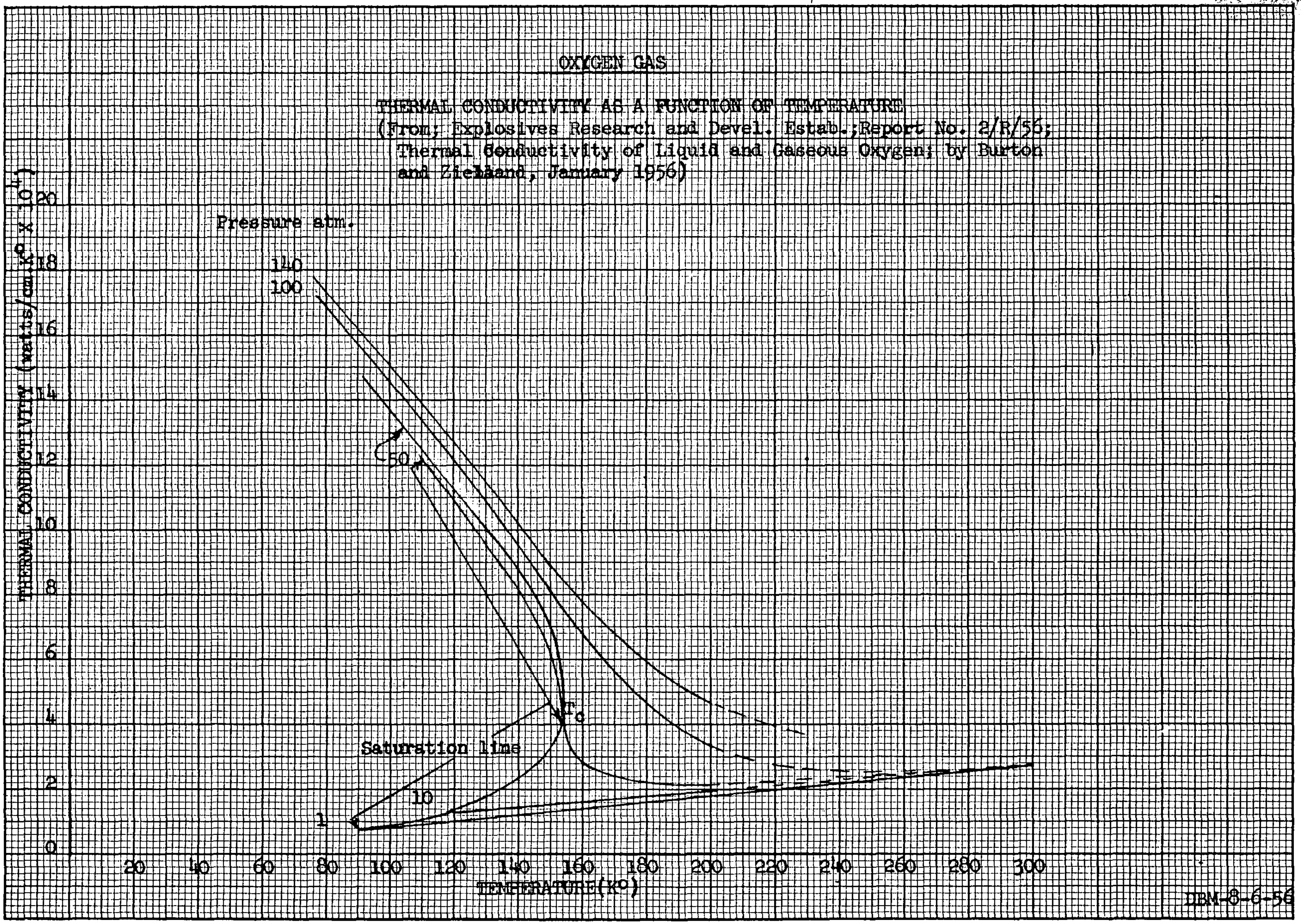
VISCOSITY OF GASEOUS HELIUM

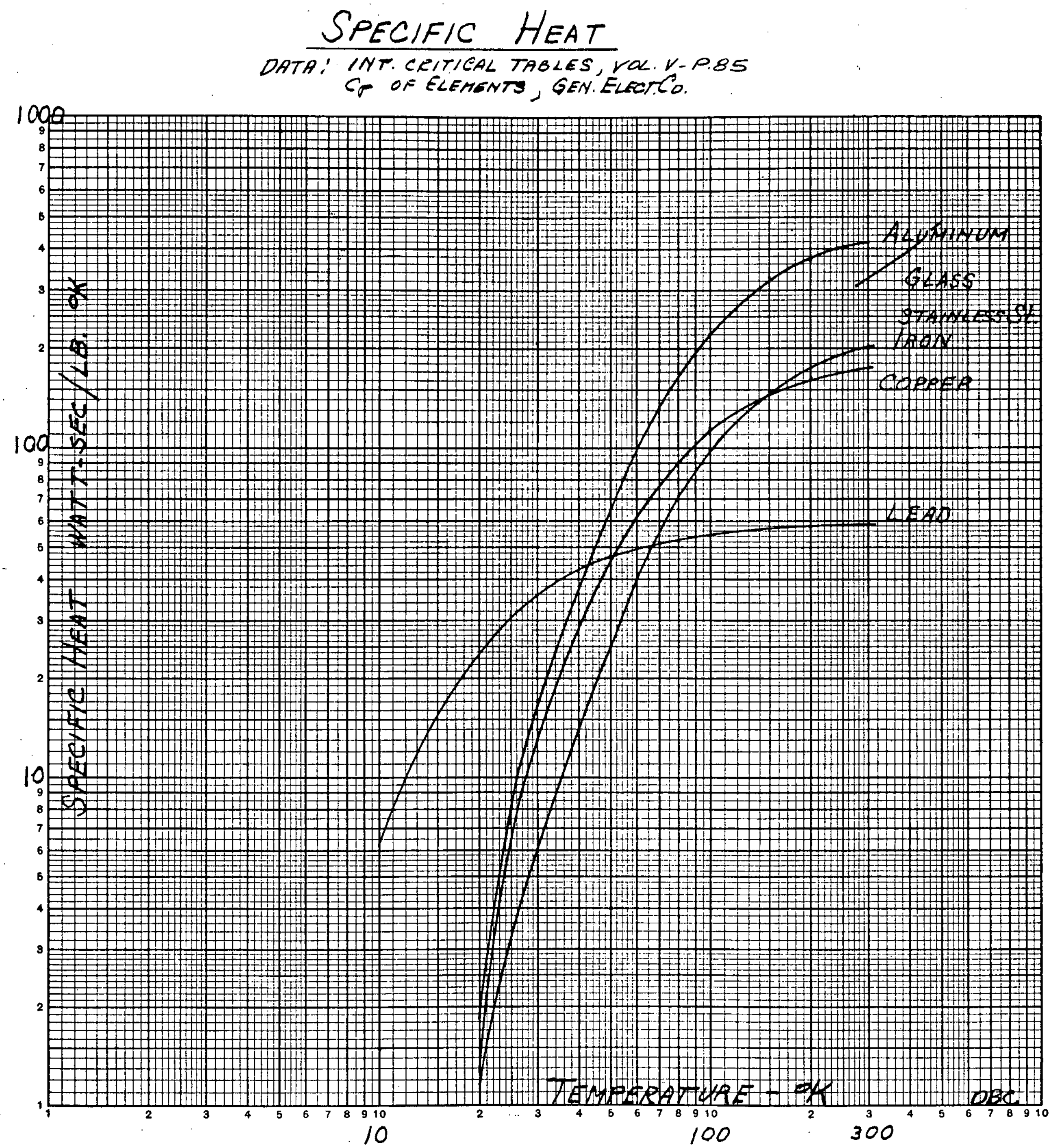
"HELIUM", p. 108 - KEESOM




PRANDTL'S NUMBER
HELIUM GAS
TEMPERATURE (K°)
PRANDTL'S NUMBER (μCp/k)
5 atm
60 atm
1 atm
1.6
1.4
1.2
1.0
0.8
0.6
0.4
10
100
1000


HELIUM
SPECIFIC HEAT RATIO VS. TEMPERATURE
REF: KEESOM - "HELIUM" PP 100
TEMPERATURE - °K
SPECIFIC HEAT RATIO
0
10
20
30
40
50
60
70
80
90
1.60
1.62
1.64
1.66
1.68
1.70


OXYGEN GAS
THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE
(From; Explosives Research and Devel. Estab.;Report No. 2/R/56;
Thermal Conductivity of Liquid and Gaseous Oxygen; by Burton
and Zielaand, January 1956)
Pressure atm.
110
100
50
10
1
T_c
Saturation line
THERMAL CONDUCTIVITY (watts/cm.K° x 10^4)
TEMPERATURE(K°)
0
2
4
6
8
10
12
14
16
18
20
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
DBM-8-6-56


SPECIFIC HEAT
DATA: INT. CRITICAL TABLES, VOL. V - P.85
C_p OF ELEMENTS, GEN. ELECT. CO.
ALUMINUM
GLASS
STAINLESS ST.
IRON
COPPER
LEAD
SPECIFIC HEAT WATT-SEC/LB. °K
TEMPERATURE - °K
10
100
300
DBC

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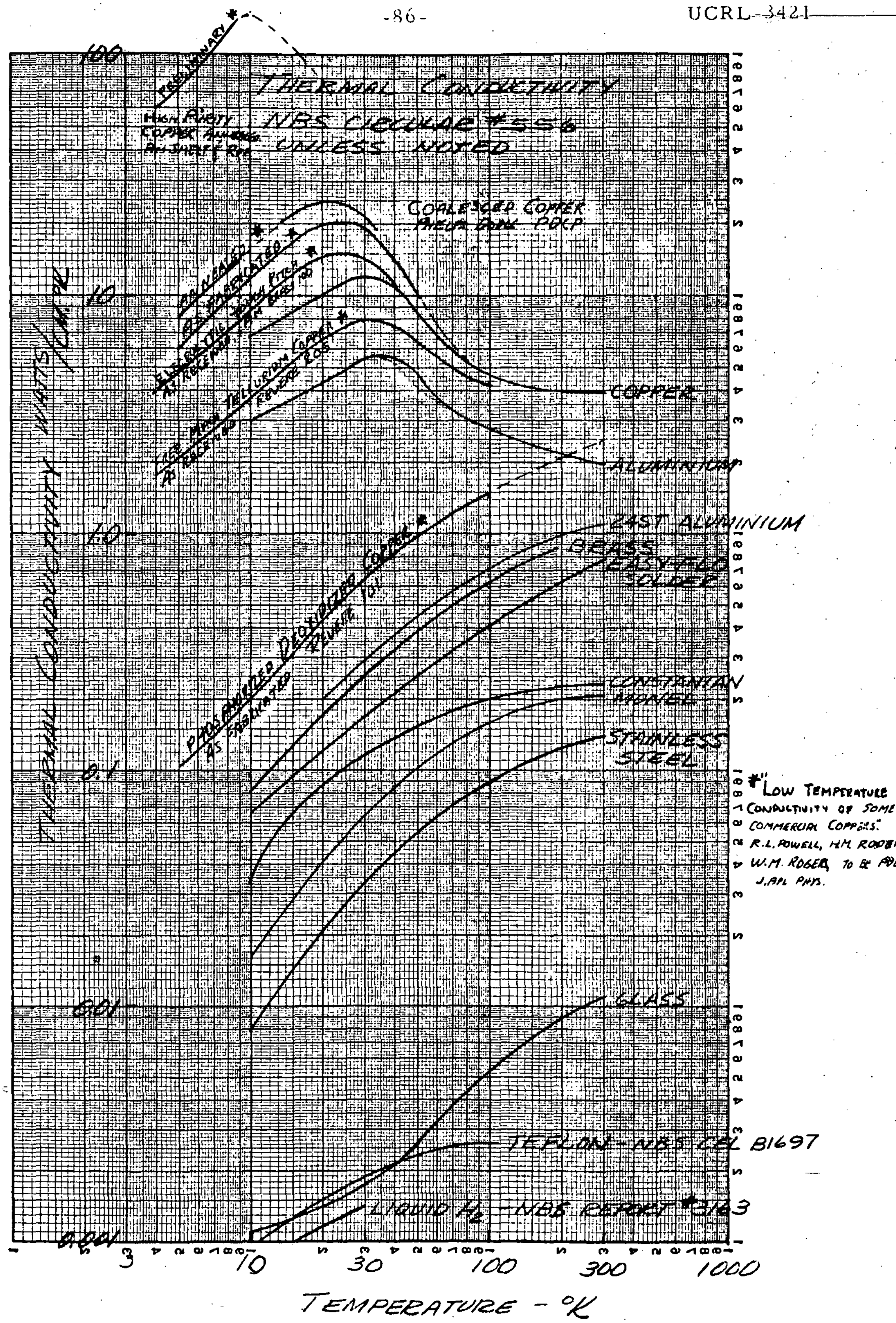
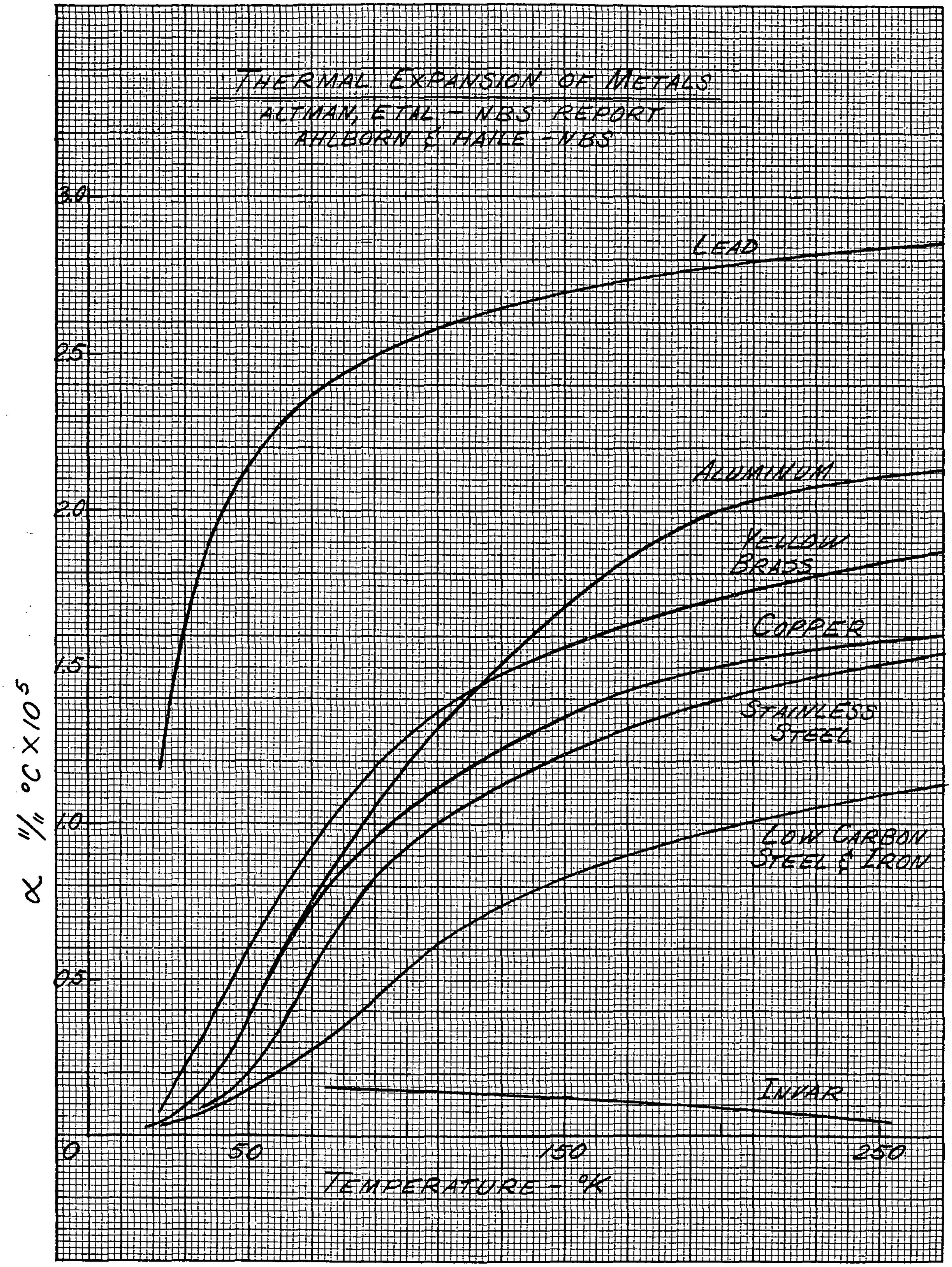
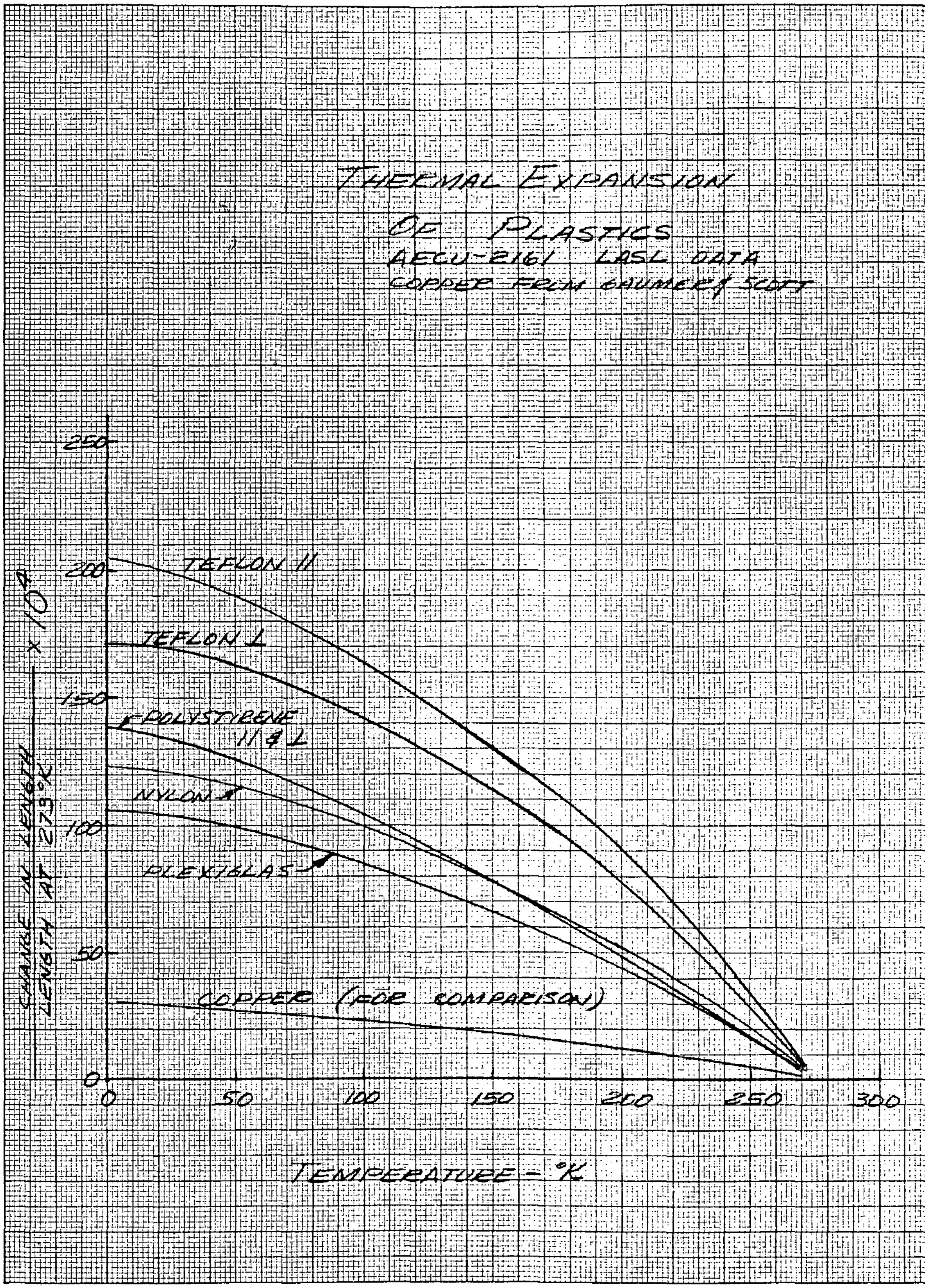
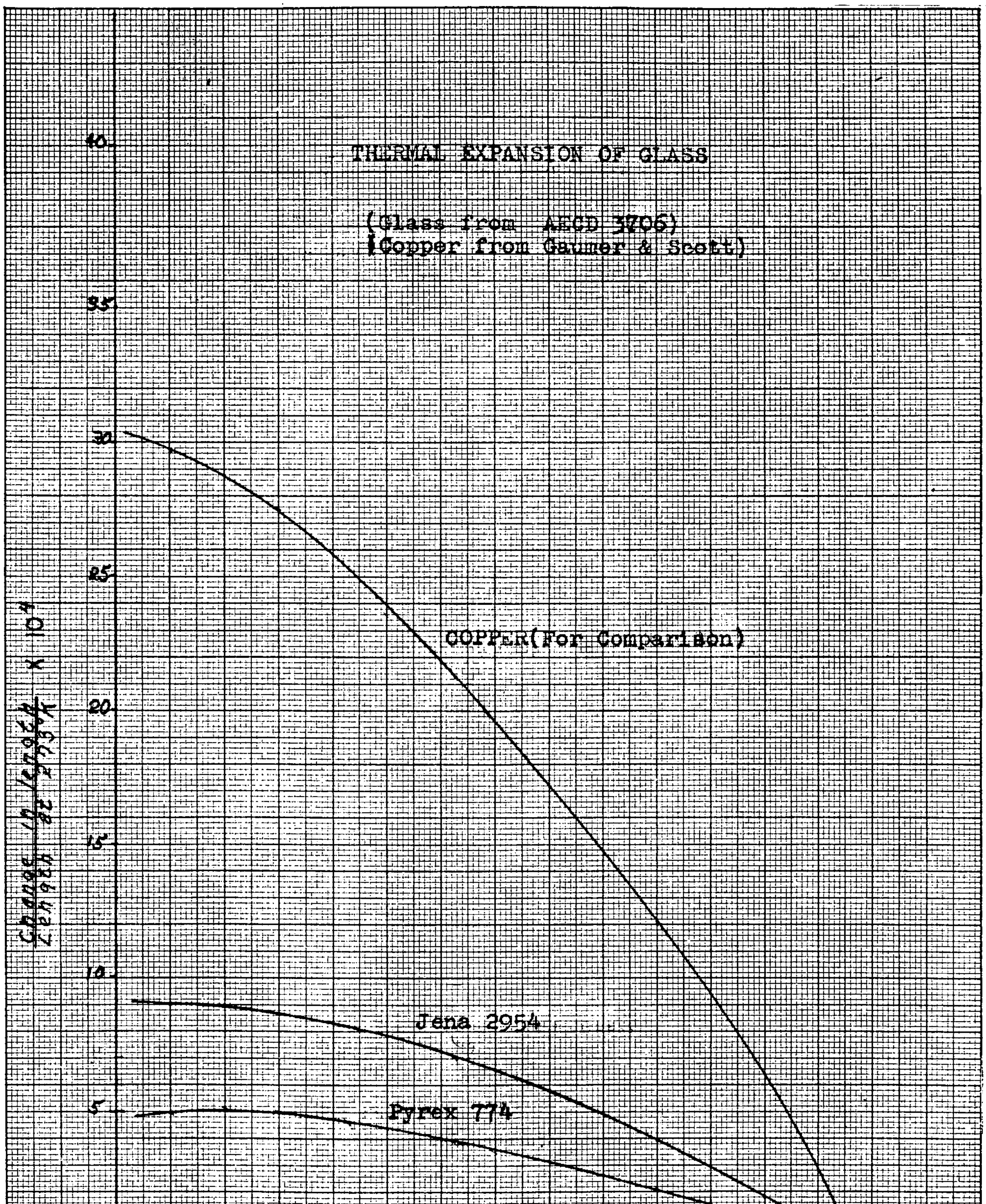
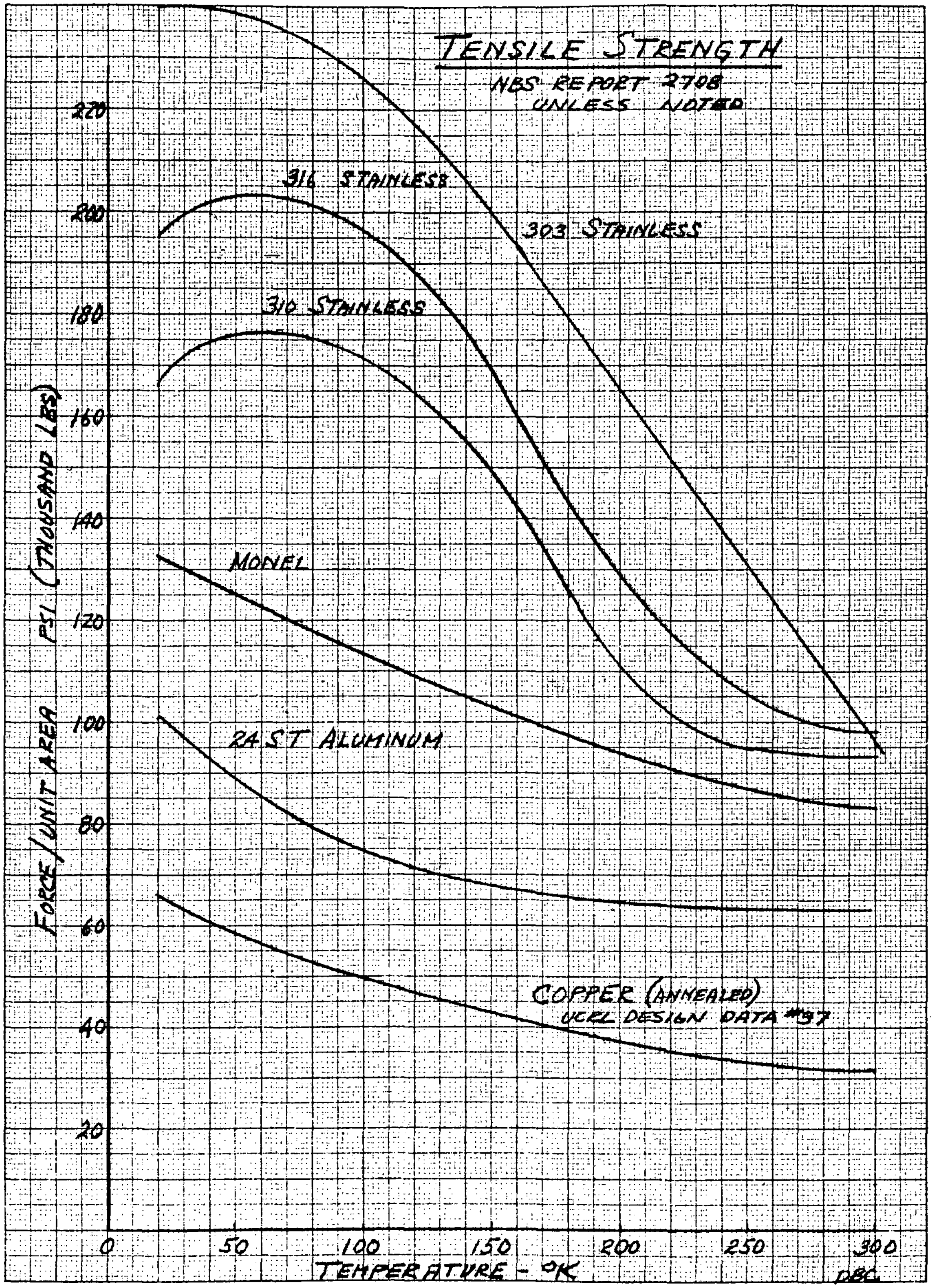
0 0 1 0 1 5 0 0 / 7 8


THERMAL CONDUCTIVITY
NBS CIRCULAR #556
UNLESS NOTED
High Purity Copper Annealing
COALESCED COPPER
COPPER
ALUMINUM
24ST ALUMINIUM
BRASS
EASYFLO SOLDER
CONSTANTAN
MONEL
STAINLESS STEEL
GLASS
TEFLON - NBS CEL B1697
LIQUID H2 - NBS REPORT #3163
PHOSPHORIZED DEOXIDIZED COPPER
THERMAL CONDUCTIVITY WATTS/CM°K
TEMPERATURE - °K
100
10
1.0
0.1
0.01
0.001
3
10
30
100
300
1000
*"Low Temperature Conductivity of Some Commercial Coppers." R.L. Powell, H.M. Roder, W.M. Roger, to be pub J. Apl Phys.

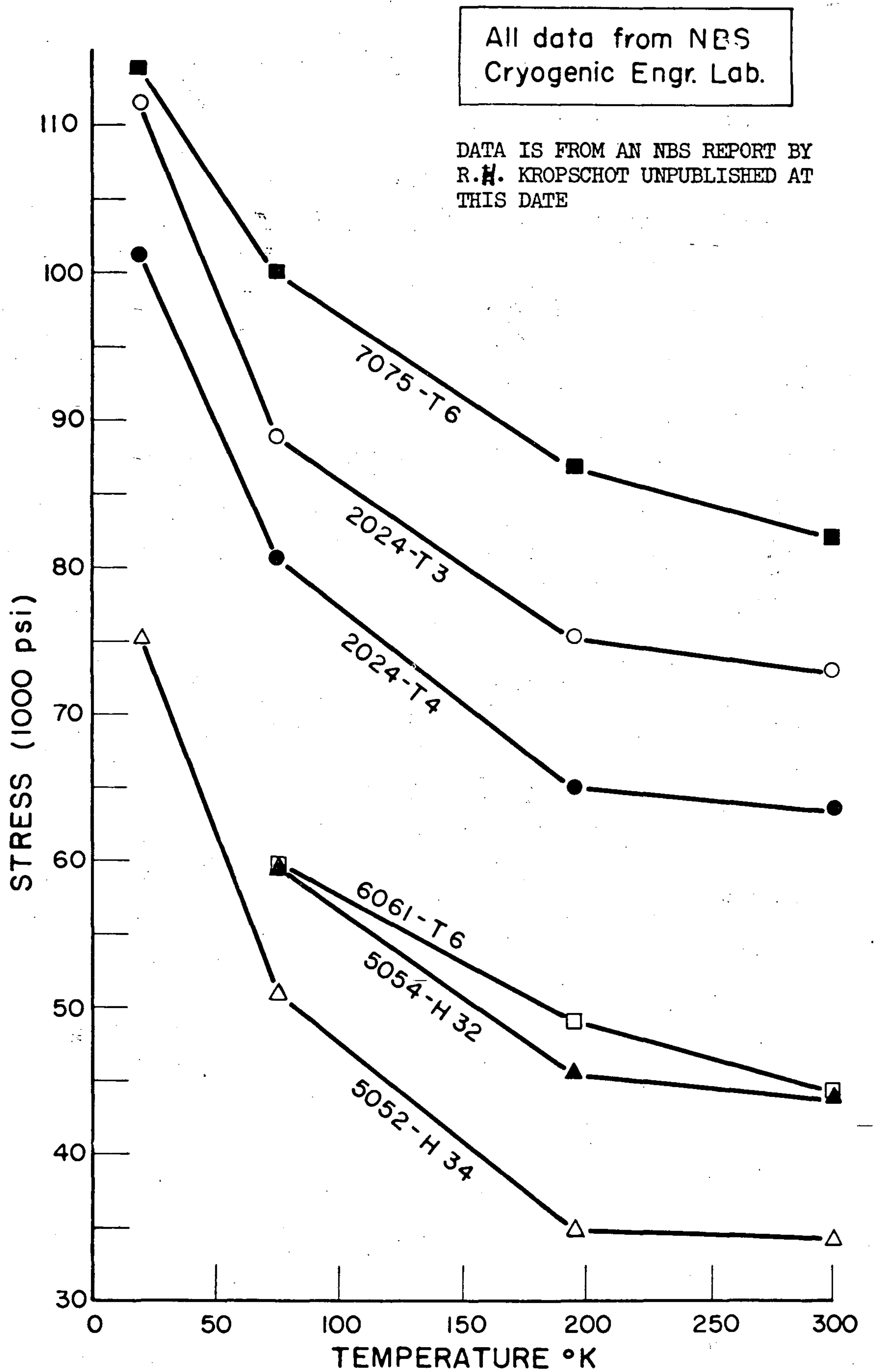

THERMAL EXPANSION OF METALS
ALTMAN, ETAL - NBS REPORT
AHLBORN & HAILE - NBS
LEAD
ALUMINUM
YELLOW BRASS
COPPER
STAINLESS STEEL
LOW CARBON STEEL & IRON
INVAR
3.0
2.5
2.0
1.5
1.0
0.5
0
50
150
250
α "/" °C × 10⁵
TEMPERATURE - °K


THERMAL EXPANSION
OF PLASTICS
AECU-2161 LASL DATA
COPPER FROM GAUMER & SCOTT
TEFLON ||
TEFLON ⊥
POLYSTIRENE
|| & ⊥
NYLON
PLEXIGLAS
COPPER (FOR COMPARISON)
CHANGE IN LENGTH / LENGTH AT 273°K × 10⁴
0
50
100
150
200
250
300
TEMPERATURE - °K


THERMAL EXPANSION OF GLASS
(Glass from AECD 3706)
(Copper from Gaumer & Scott)
COPPER(For Comparison)
Jena 2954
Pyrex 774
40
35
30
25
20
15
10
5
50
100
150
200
250
300
Temperature - K°
DBM

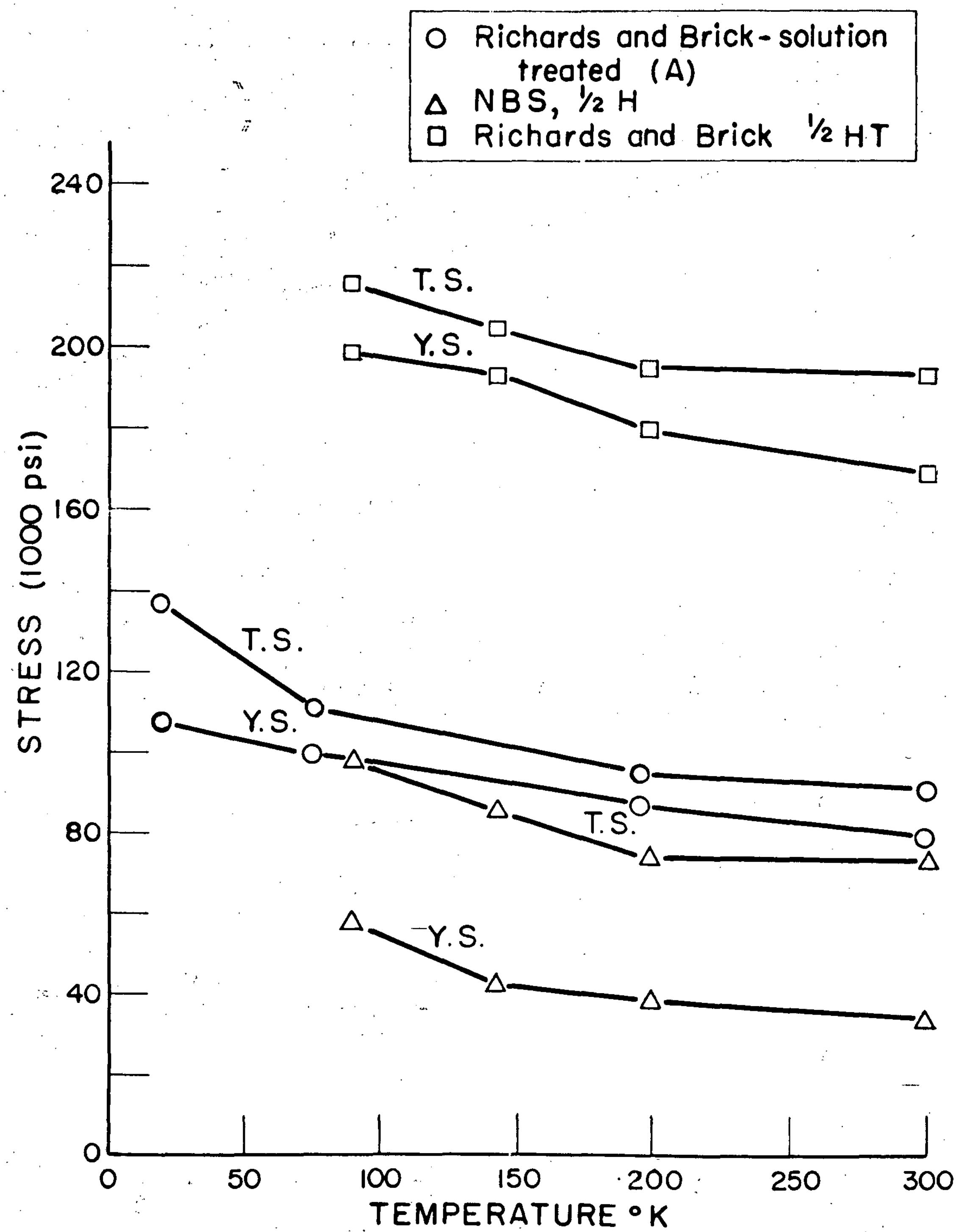


TENSILE STRENGTH
NBS REPORT 2708
UNLESS NOTED
316 STAINLESS
303 STAINLESS
310 STAINLESS
MONEL
24 ST ALUMINUM
COPPER (ANNEALED)
UCRL DESIGN DATA #97
FORCE / UNIT AREA PSI (THOUSAND LBS)
220
200
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
TEMPERATURE - °K
DBC

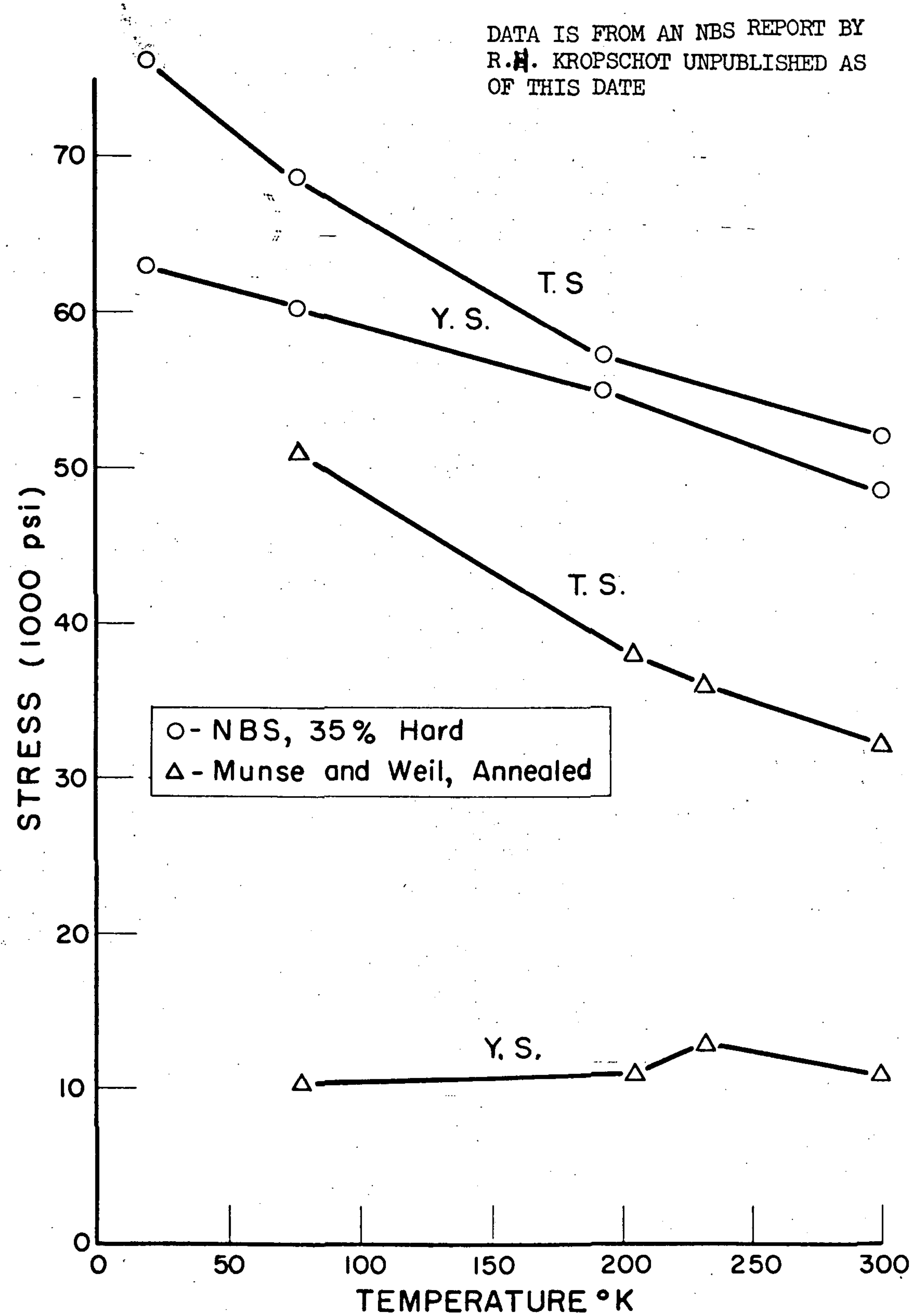


TENSILE STRENGTH OF ALUMINUM ALLOYS

DATA IS FROM A NBS REPROKT BY R.H. Kropschot
UNPUBLISHED AS OF THIS DATE

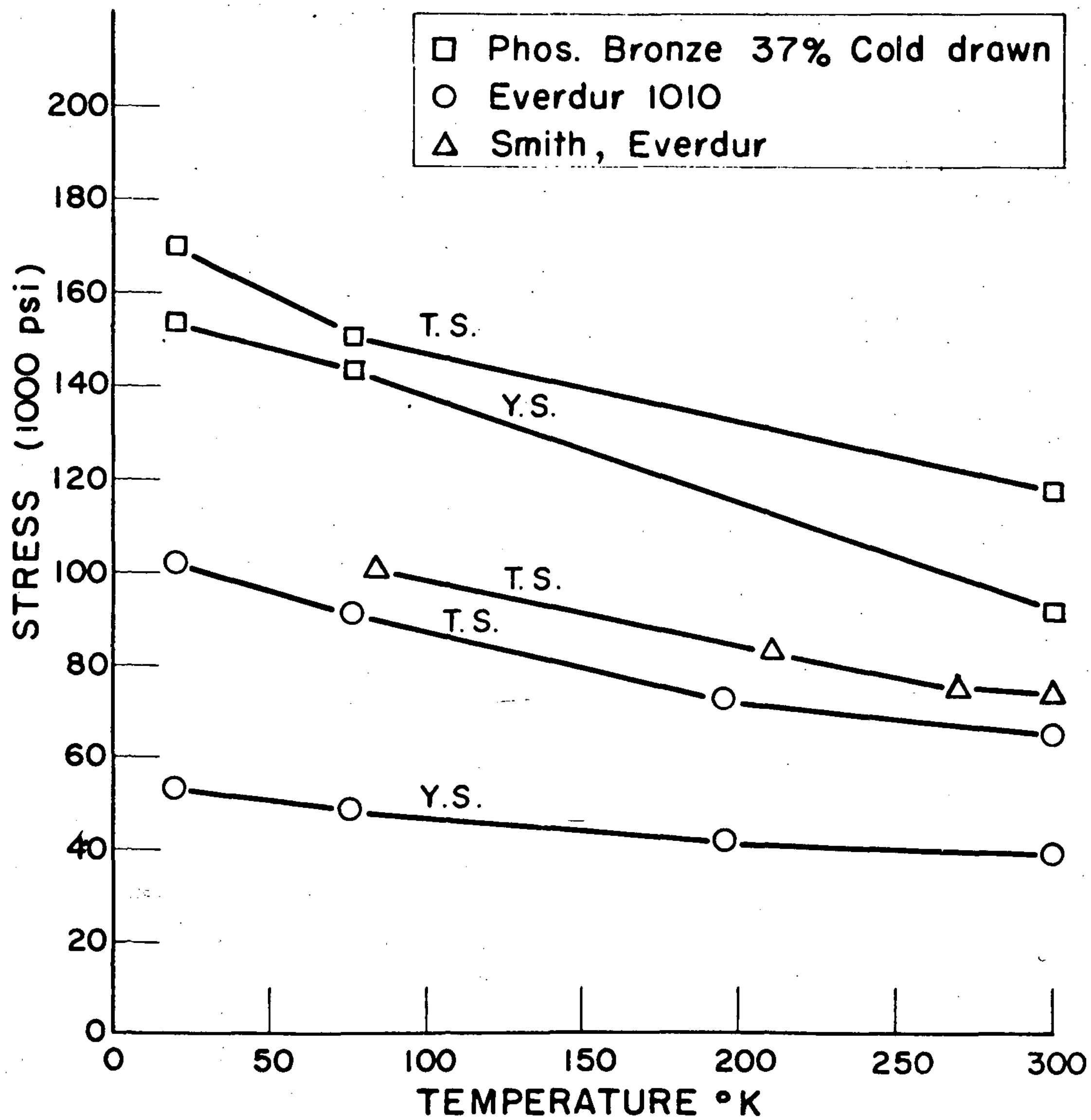


TENSILE AND YIELD STRENGTH
OF
BERYLLIUM COPPER (BERYLCO 25)



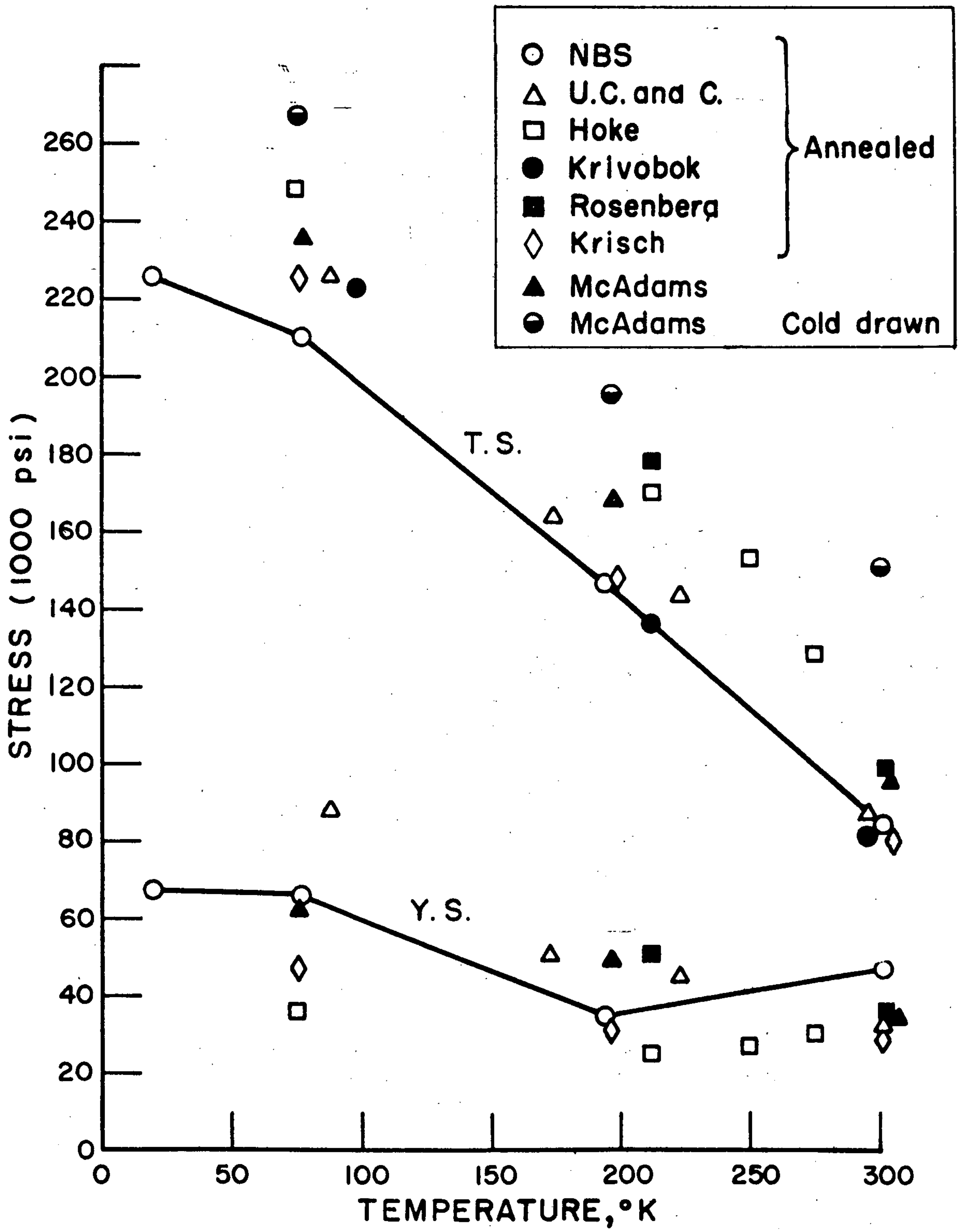
TENSILE AND YIELD STRENGH
OF
O.F. H.C. COPPER

DATA IS FROM AN NBS REPORT BY R. H. KROPSCHOT
UNPUBLISHED AS OF THIS DATE

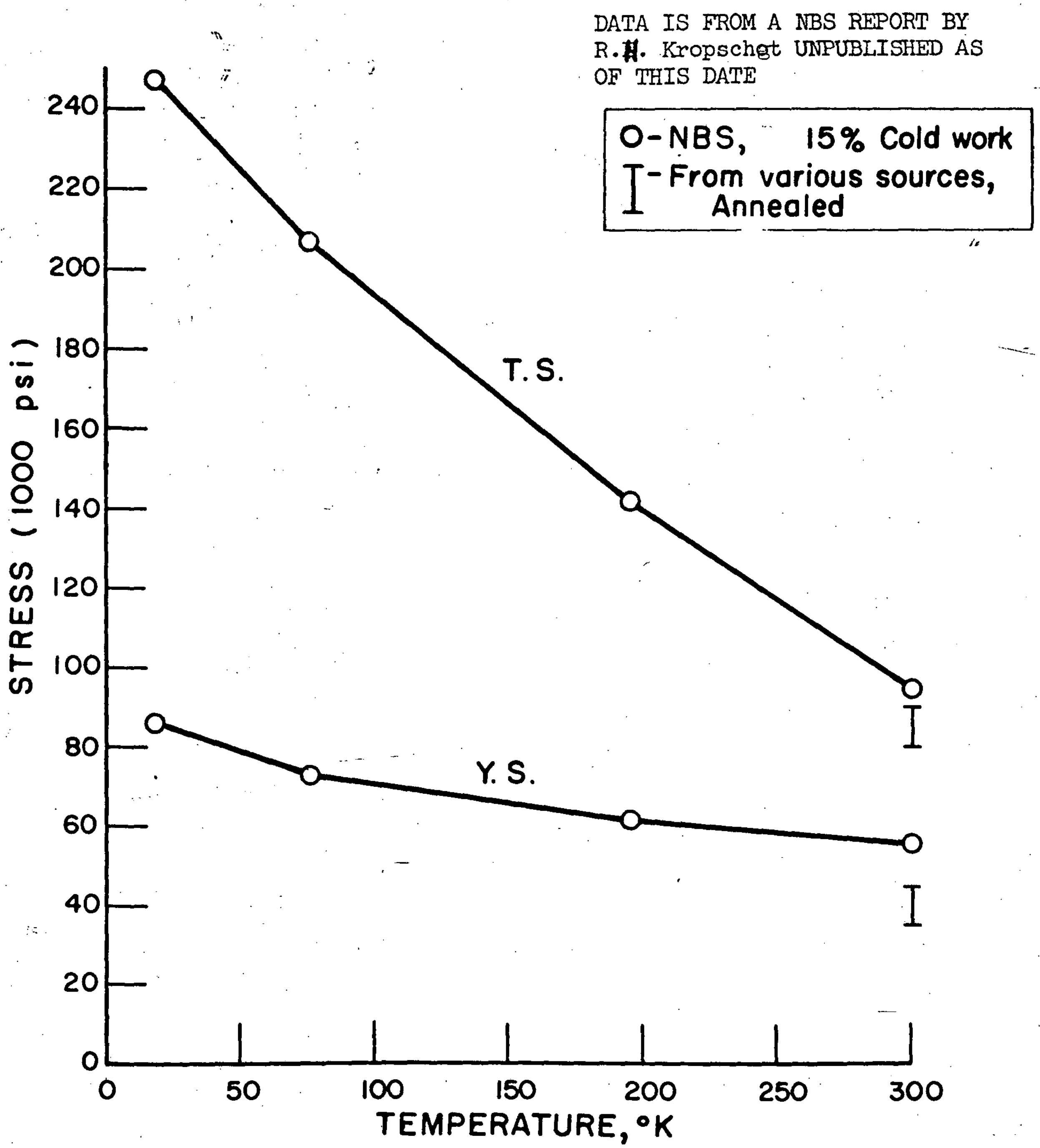


TENSILE AND YIELD STRENGTH
OF
EVERDUR AND PHOSPHOR BRONZE ASTM B-139

DATA IS FROM AN NBS REPORT BY R.H.KROPSCHOT UNPUBLISHED AS OF THIS DATE

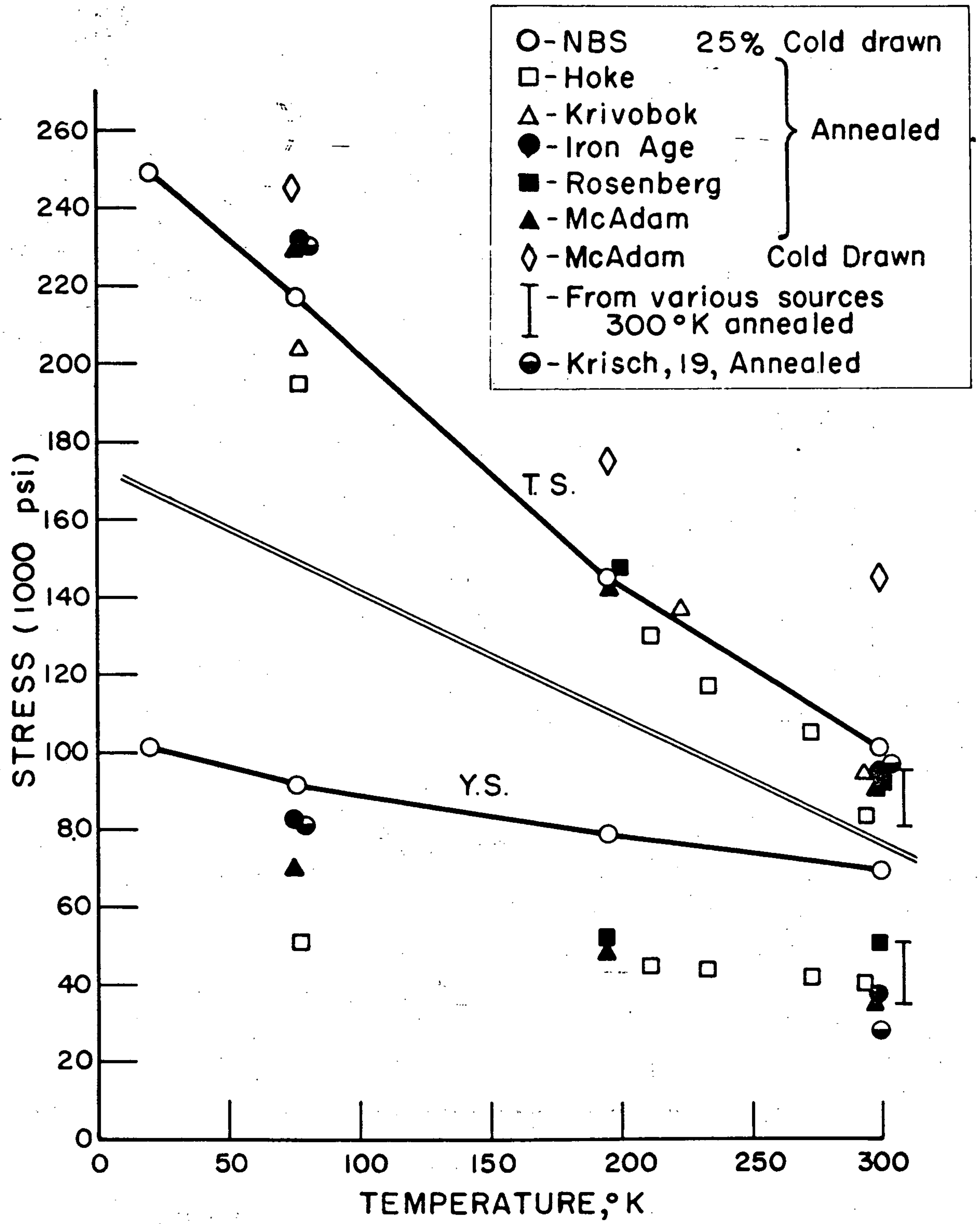


TENSILE AND YIELD STRENGTH OF 304 STAINLESS STEEL



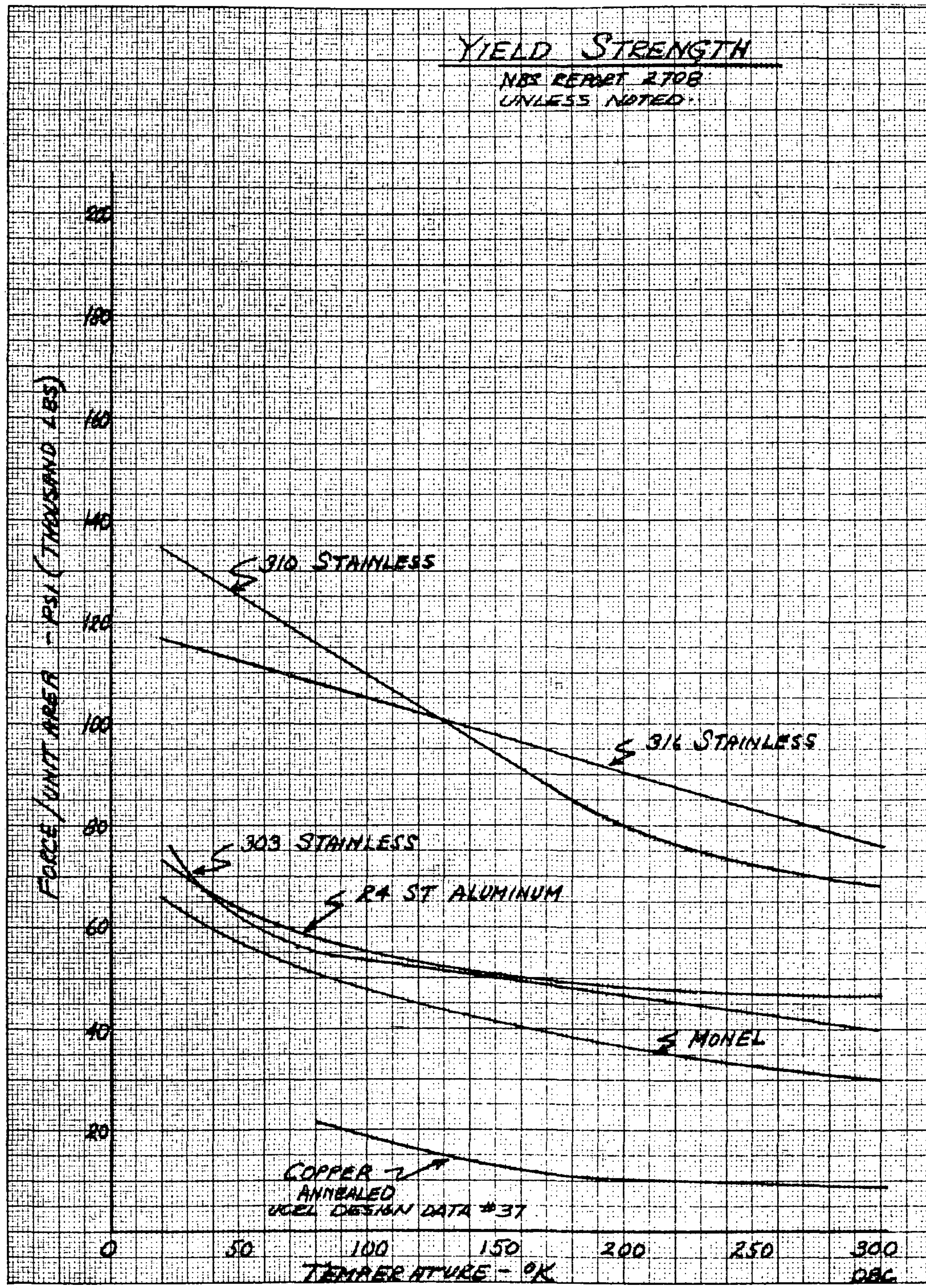
TENSILE AND YIELD STRENGTH OF 308 STAINLESS STEEL

DATA IS FROM AN NBS REPORT BY
R.M. KROPSCHOT UNPUBLISHED AT
THIS DATE

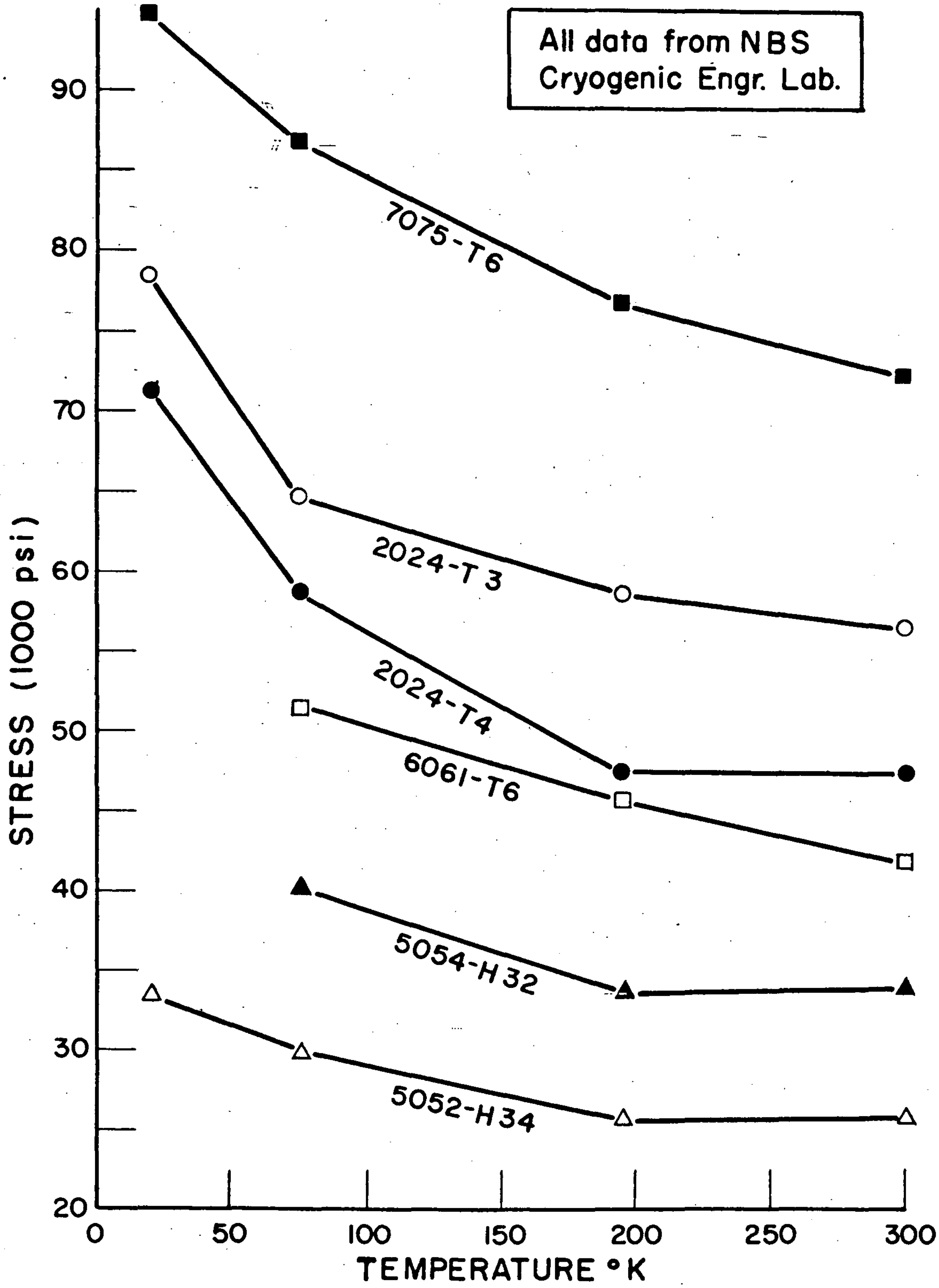


TENSILE AND YIELD STRENGTH
OF
347 STAINLESS STEEL

0 0 1 0 1 5 0 0 / 8 4

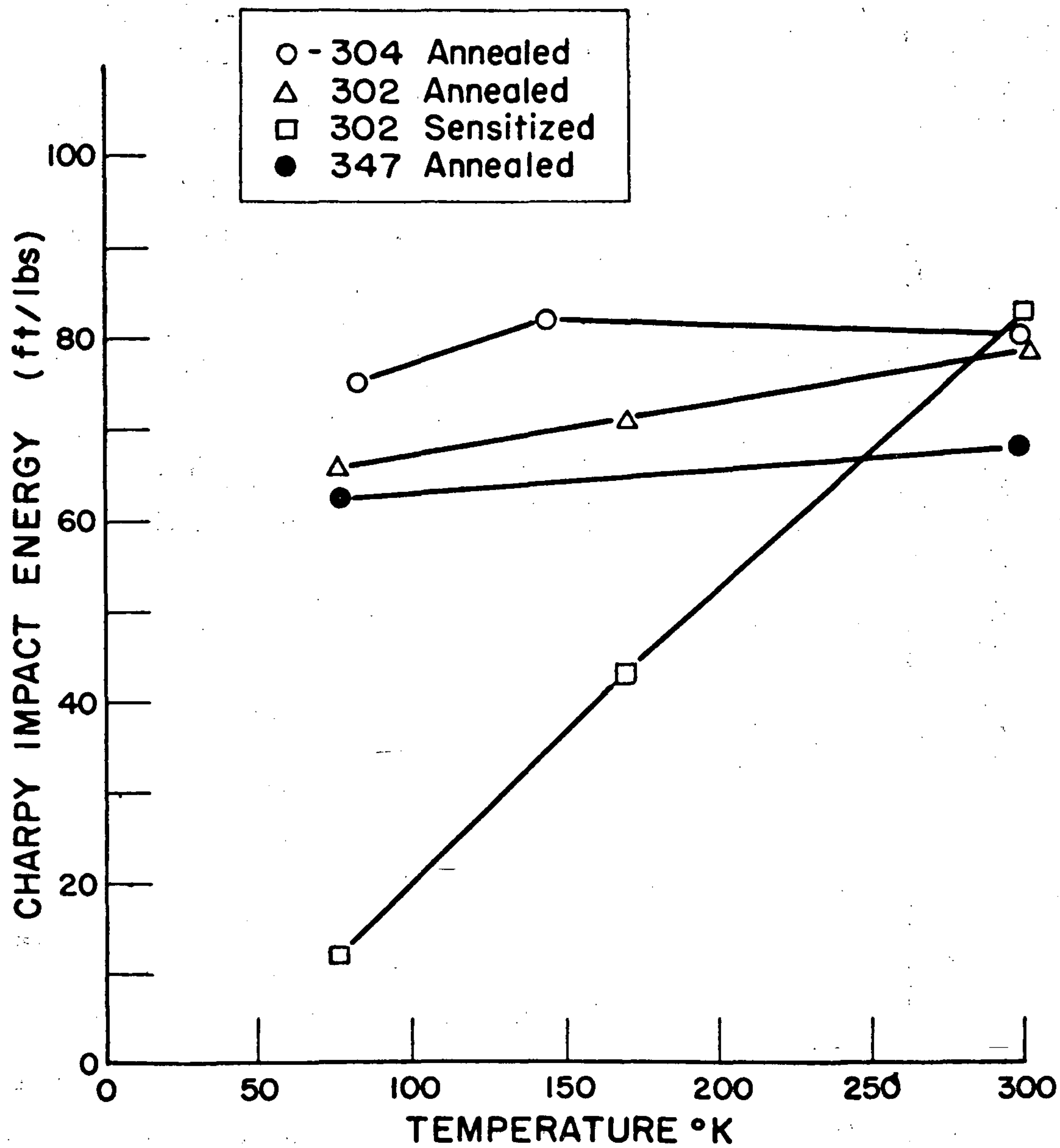

YIELD STRENGTH
NBS REPORT 2708
UNLESS NOTED.
FORCE / UNIT AREA - PSI (THOUSAND LBS)
200
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
TEMPERATURE - °K
310 STAINLESS
316 STAINLESS
303 STAINLESS
24 ST ALUMINUM
MONEL
COPPER ANNEALED
UCEL DESIGN DATA #37
DBC

DATA IS FROM AN NBS REPORT BY R.H. KROPSCHOT
UNPUBLISHED AS OF THIS DATE



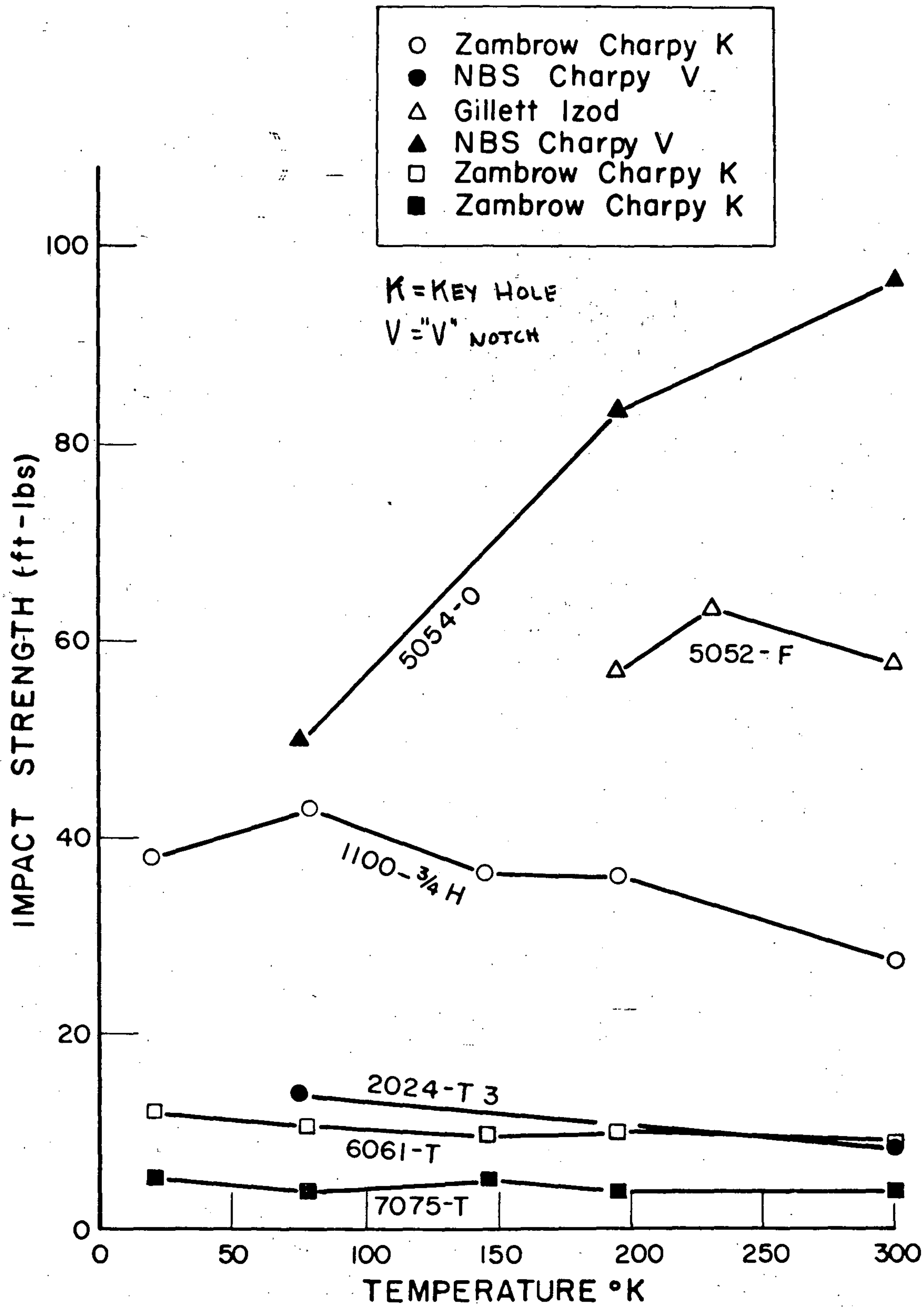
YIELD STRENGTH OF ALUMINUM ALLOYS

DATA IS FROM AN NBS REPORT BY R.H.KROPSCHOT
UNPUBLISHED AS OF THIS DATE



IMPACT STRENGTH OF ANNEALED AND SENSITIZED STAINLESS STEEL

DATA IS FROM AN NBS REPORT BY R.#. KROPSCHOT
UNPUBLISHED AS OF THIS DATE



IMPACT STRENGTH OF ALUMINUM ALLOYS

From; R. H. Kropschot, AN EXPERIMENTAL STUDY OF THE STRENGTH AND FATIGUE OF GLASS AT VERY LOW TEMPERATURES, NBS REPORT 3590, June 22, 1956

Condition	Rate Stress increase lb/in^2-sec.	Breaking Stress lb/in^2			
		296°K	194°K	76°K	20°K
A	800	7,500	9,500	10,400	10,400
A	10	5,500	7,500	10,400	10,600
A	1	5,000	6,400	10,400	10,200
U	800	10,400		18,000	

Breaking stress of BSC-2 optical glass.
Median values from probability plots.
A - abraded; U - unabraded.

D. Chelton
March 8, 1956

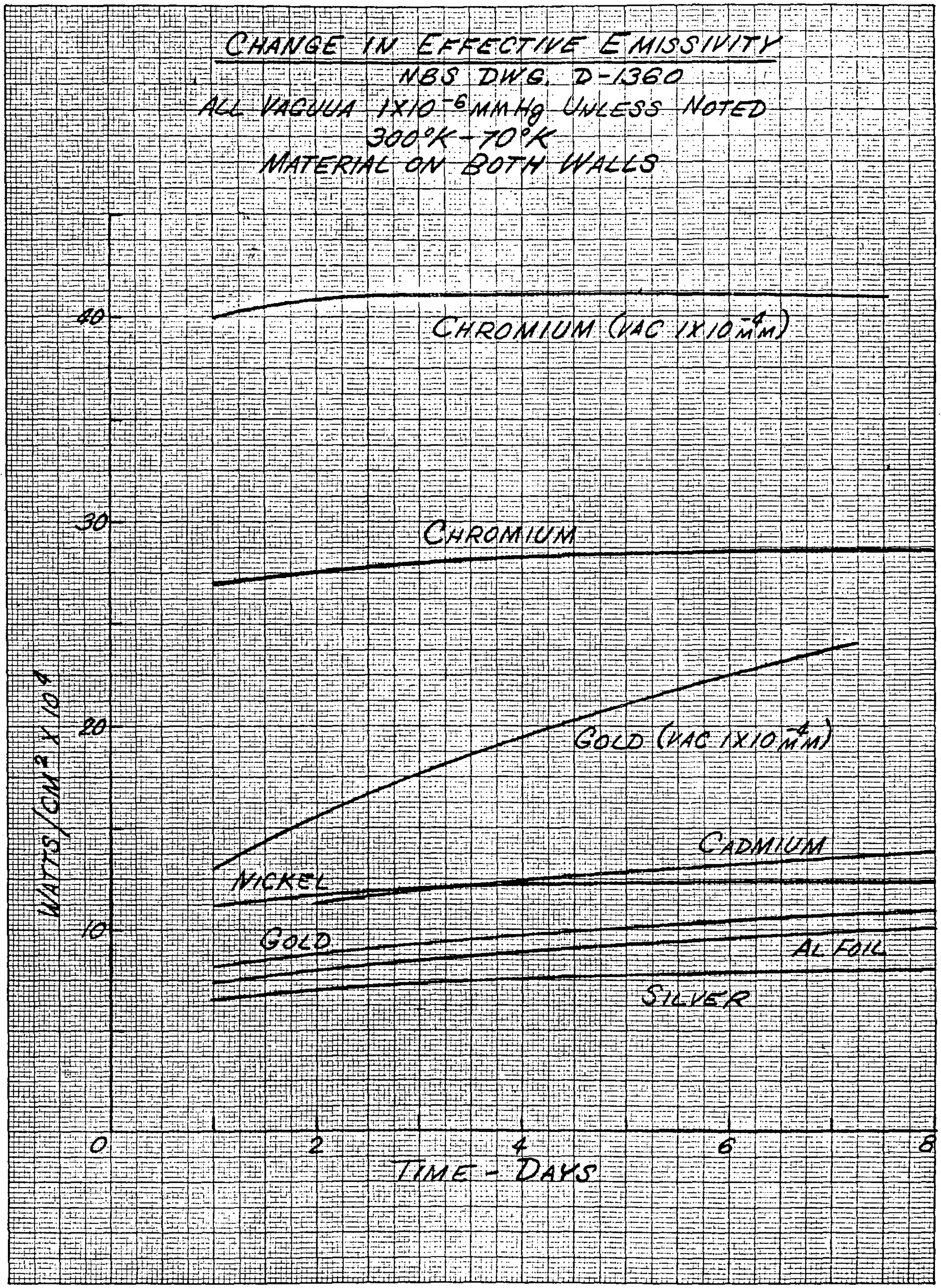
EMISSIVITIES OF MATERIALS
Measured Values For Radiation Between 300°K and 76°K

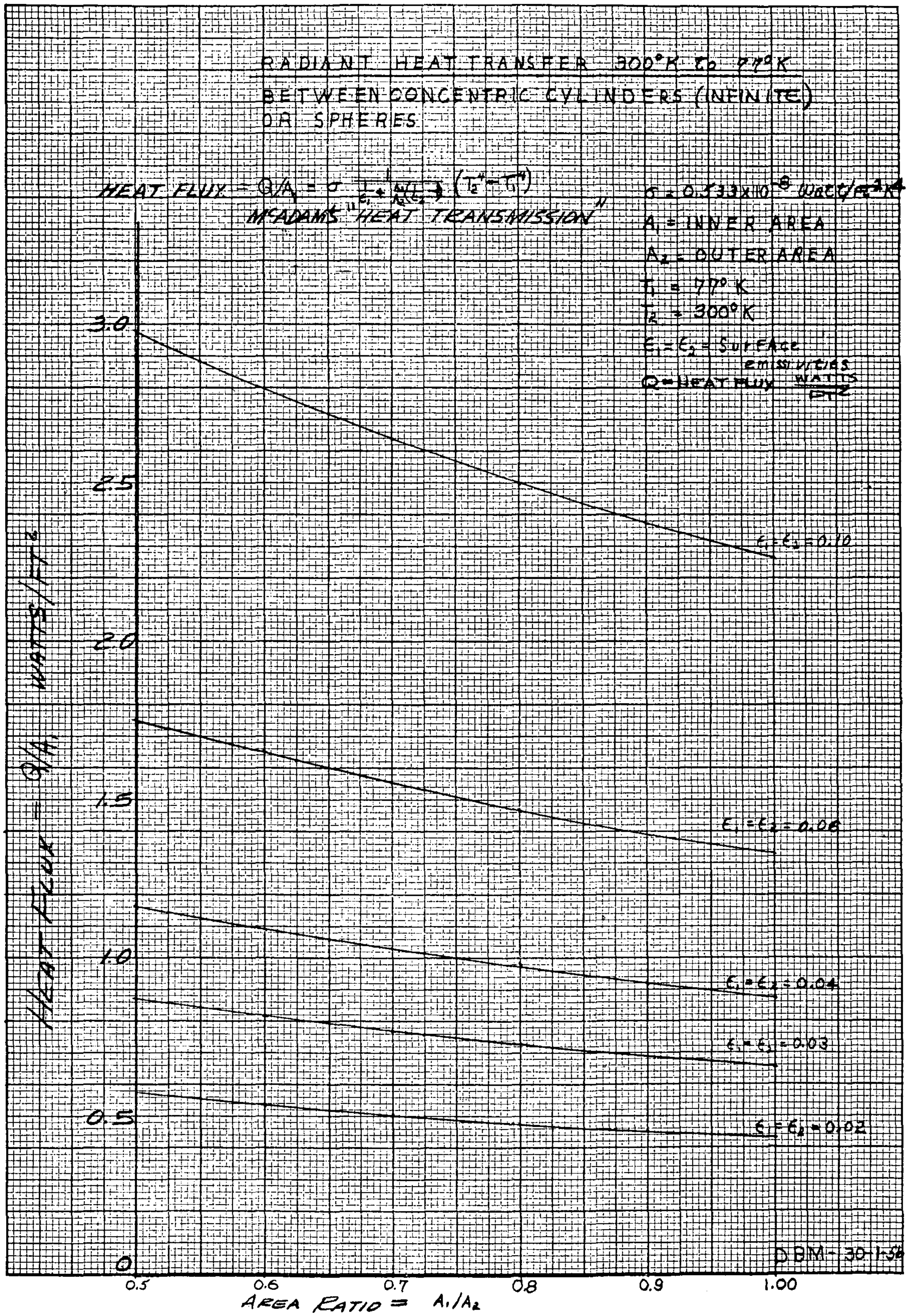
Data Taken From NBS, Cryogenic Laboratory, TM16

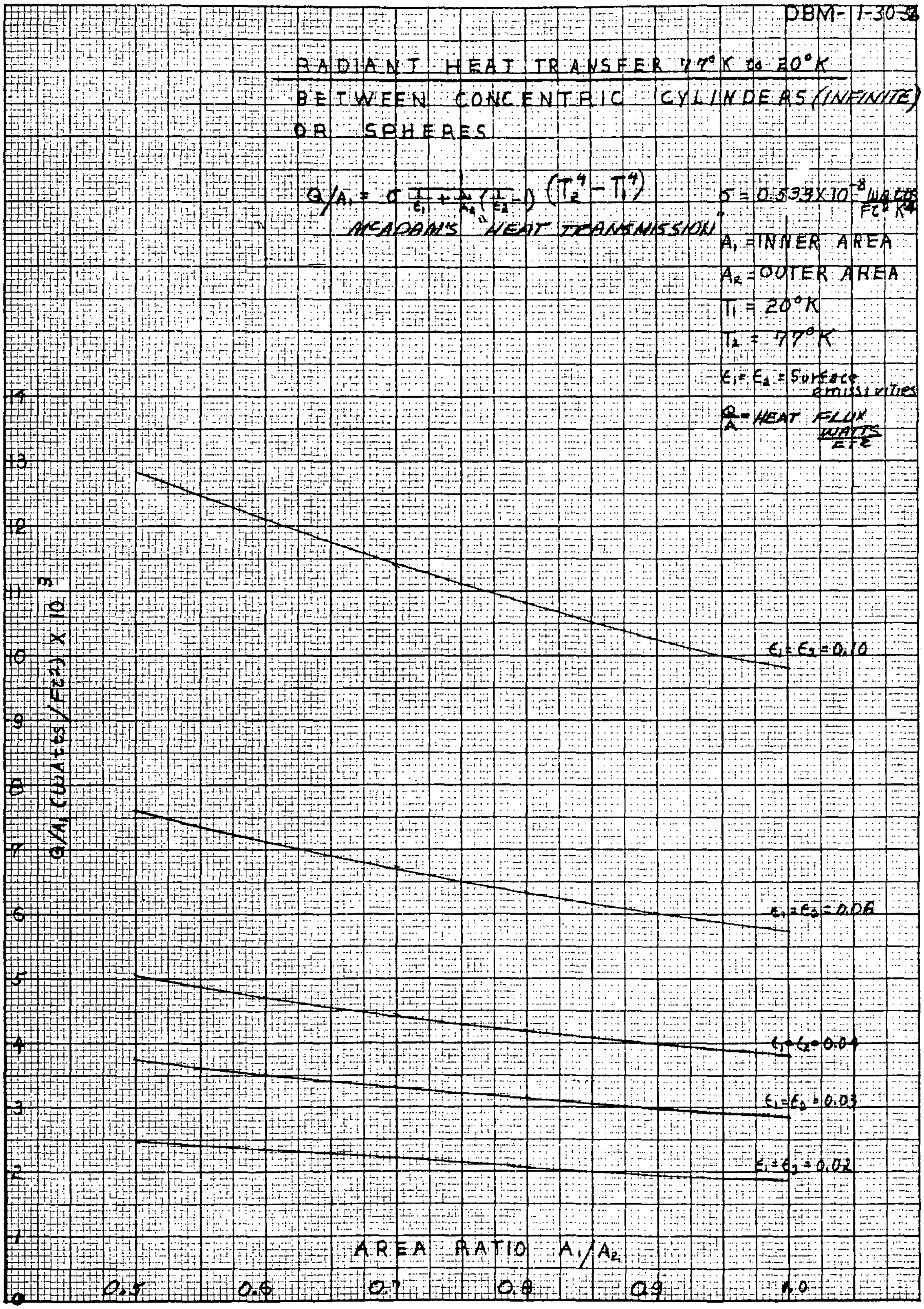
Metal	Surface Finish	Apparent ε
Al	Cockron foil .0015"	.0204
Al on Mylar	1/2 mil plastic, Al vaporized on both sides	.0399
Au on Mylar	1/2 mil plastic, Au vaporized on both sides	.0205
Au	.0015, solvent cleaned	.0099
Sn	.001", mill foil	.0136
Sn	Same sample, partially covered with frost from a condensible gas	.105
Stainless Steel	.005", type 302, solvent cleaned	.0485
Lucite	Plastic dewar, solvent cleaned — — — — (ε outside =0.978)*	.60
Cu	.005", dilute chromic acid dip	.0176
Cu	.005", wet polished with Dr. Lyons tooth powder	.0185
Cu	.005", dry polished with plastic polishing wax-abrasive	.0192
Cu	.005", electrolytic cleaned, (this value may be high as trace of frost was observed)	.0178
Al	.00075", Kaiser home foil	.0186
Al	.001", Kaiser foil unannealed	.0184
Al	.001", Kaiser foil unannealed	.0213
Al	.0015", Cockron home foil	.0186
Al	.0015", Cockron home foil	.0204
Al	.0015", Hurwich home foil, mat side	.0212
Al	.0015", Hurwich home foil, bright side	.0217
Al	.020", cold acid cleaned	.0283
Al	.020", Hot acid cleaned, Alco process	.0294
Al	.020", cold acid cleaned	.0317
Al	.020", Alco No. 2 reflector plate ($\epsilon_{25^\circ C}^{\text{visible light}}$ =.30)	.0327
Al	.020", Alkali cleaned	.0356
Al	.020", wire brush - emery paper - steel wool - cold acid	.0452
Al	.020", wire brush - emery paper - steel wool	.0615
Al	.020", wire brush	.0615
Al	.020", electrolytic polish, light anodize	.2082
Al	.020", electrolytic polish, heavy anodize	.324

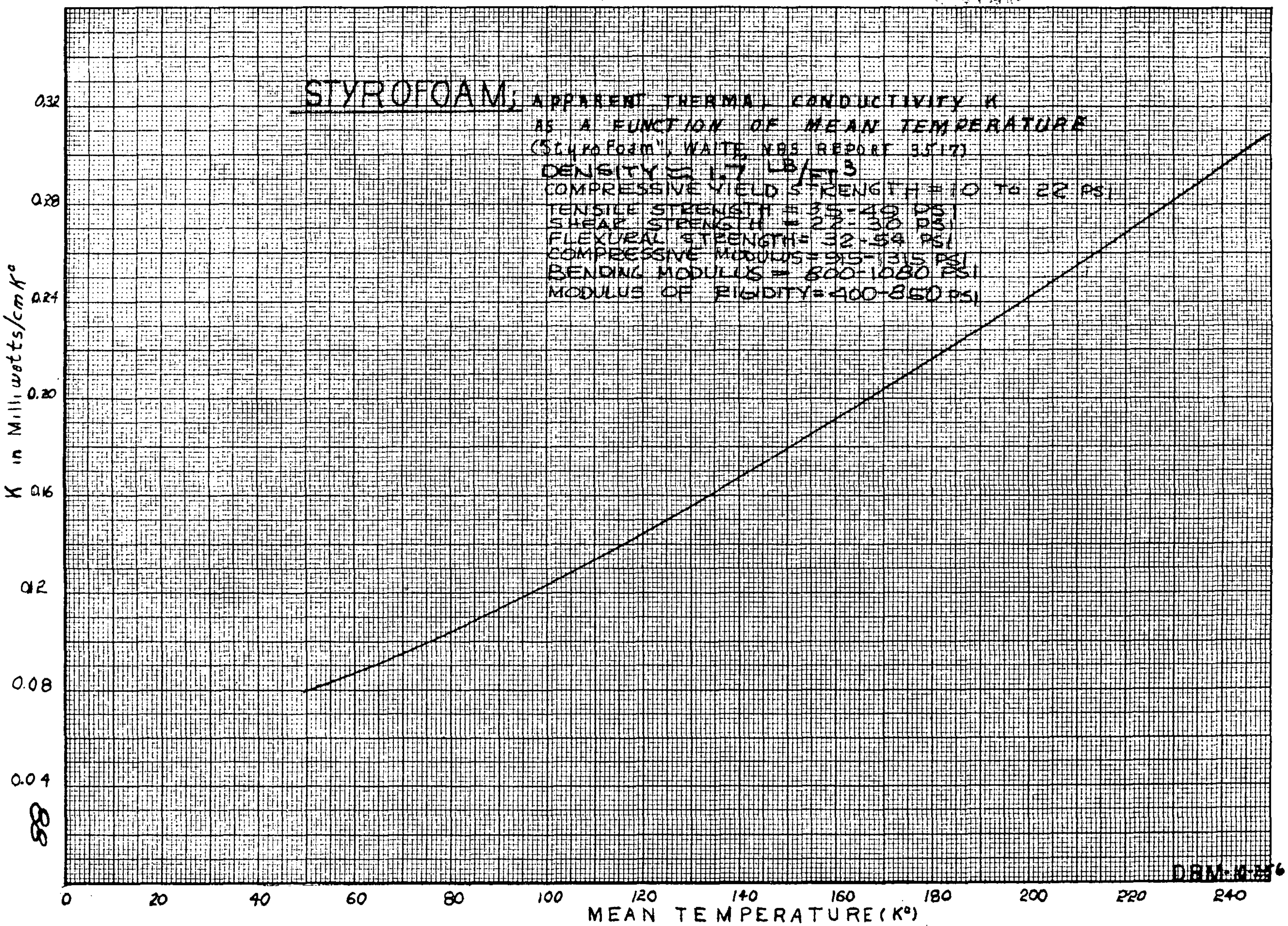
* This value is the computed effective emissivity. During this measurement the radiation was so great that the temperature of the outer wall fell to 279°K. In all other measurements the wall remained at room temperature.

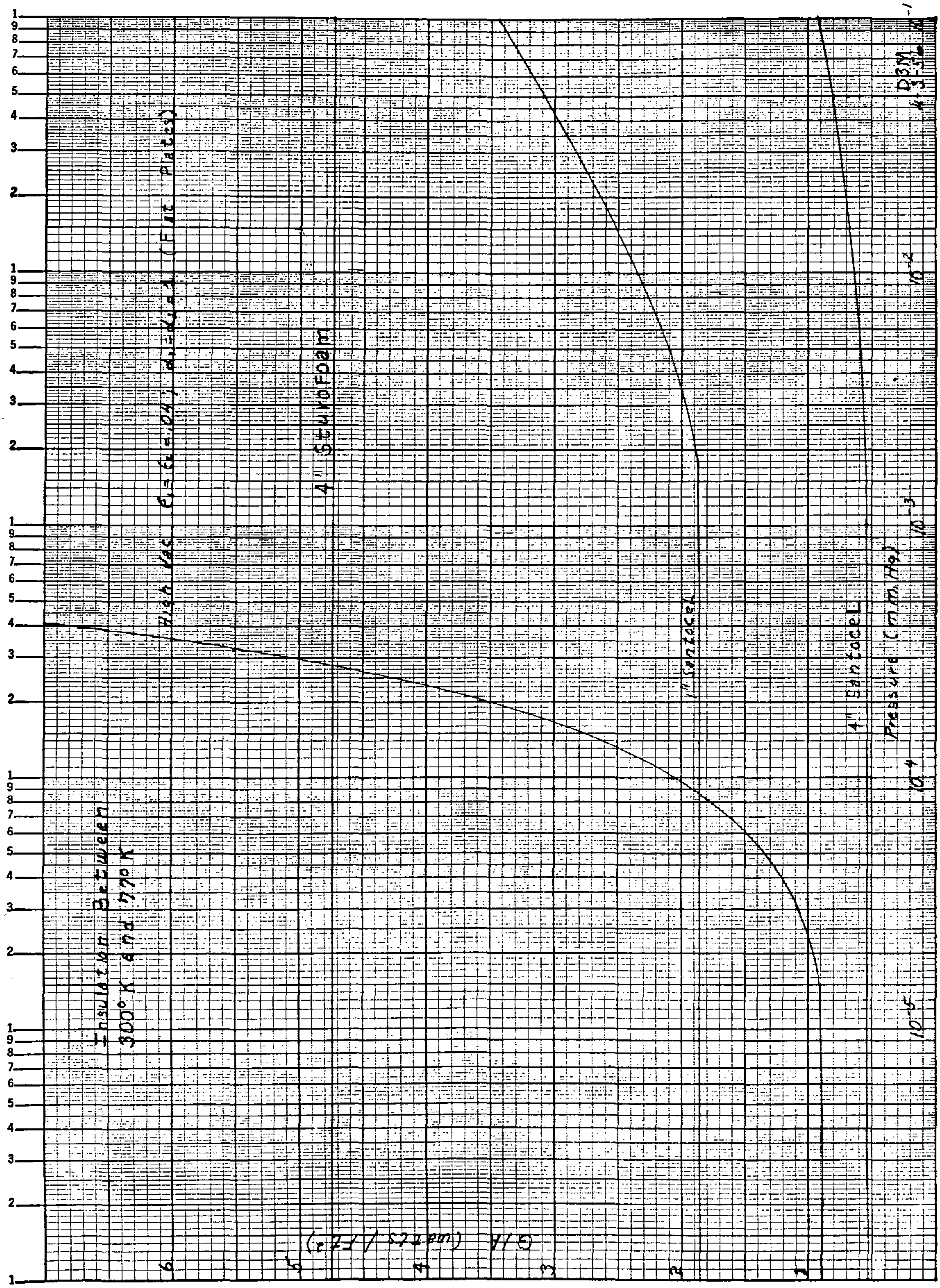
0 0 1 0 1 5 0 0 7 8 7

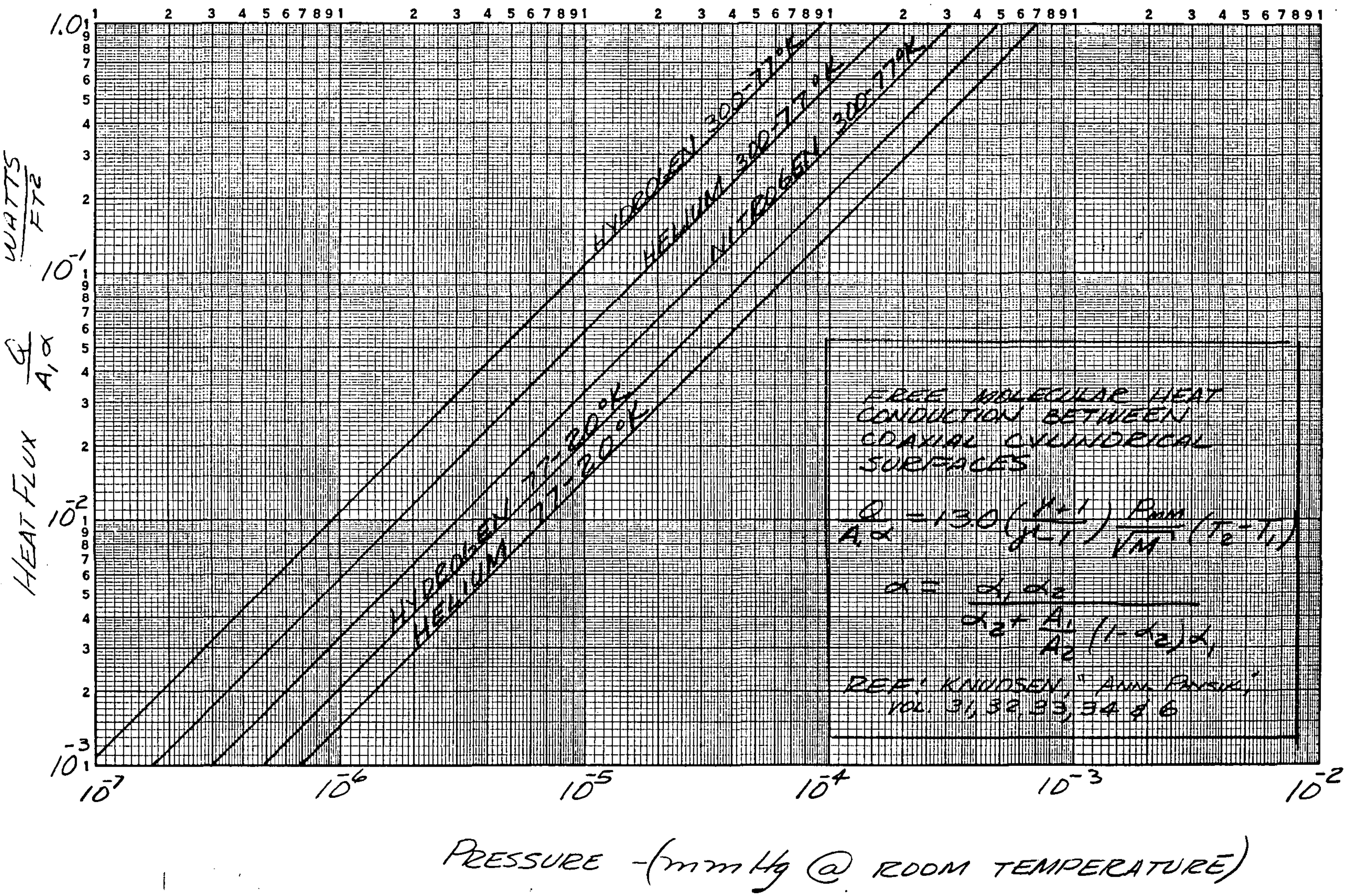



RADIANT HEAT TRANSFER 300°K to 77°K
BETWEEN CONCENTRIC CYLINDERS (INFINITE) OR SPHERES
HEAT FLUX = Q/A₁ = σ 1/(1/ε₁ + A₁/A₂(1/ε₂ − 1)) (T₂⁴ − T₁⁴)
McADAMS "HEAT TRANSMISSION"
σ = 0.533 x 10⁻⁸ watts/ft² °K⁴
A₁ = INNER AREA
A₂ = OUTER AREA
T₁ = 77° K
T₂ = 300° K
ε₁ = ε₂ = Surface emissivities
Q = HEAT FLUX WATTS/FT²
ε₁ = ε₂ = 0.10
ε₁ = ε₂ = 0.06
ε₁ = ε₂ = 0.04
ε₁ = ε₂ = 0.03
ε₁ = ε₂ = 0.02
HEAT FLUX = Q/A₁ WATTS/FT²
AREA RATIO = A₁/A₂
0
0.5
1.0
1.5
2.0
2.5
3.0
0.5
0.6
0.7
0.8
0.9
1.00
DBM-30-1-56

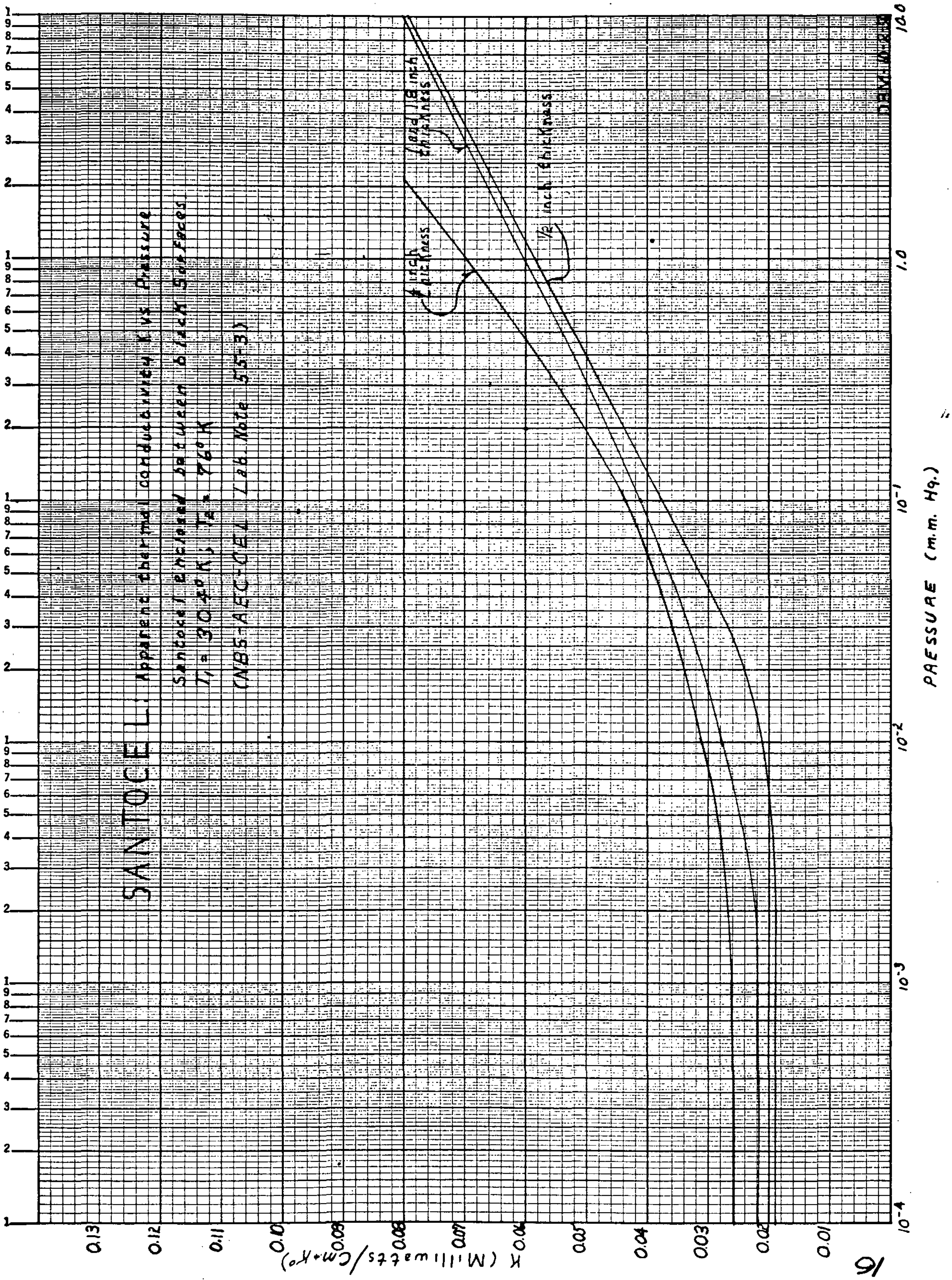

DBM- 1-30-5
RADIANT HEAT TRANSFER 77°K to 20°K
BETWEEN CONCENTRIC CYLINDERS (INFINITE)
OR SPHERES
Q/A₁ = σ (1/ε₁ + A₁/A₂ (1/ε₂ - 1)) (T₂⁴ - T₁⁴)
McADAM'S "HEAT TRANSMISSION"
σ = 0.533 X 10⁻⁸ watts/Ft² K⁴
A₁ = INNER AREA
A₂ = OUTER AREA
T₁ = 20°K
T₂ = 77°K
ε₁ = ε₂ = Surface emissivities
Q/A = HEAT FLUX watts/Ft²
Q/A₁ (watts/Ft²) X 10⁻³
ε₁ = ε₂ = 0.10
ε₁ = ε₂ = 0.06
ε₁ = ε₂ = 0.04
ε₁ = ε₂ = 0.03
ε₁ = ε₂ = 0.02
AREA RATIO A₁/A₂
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0.5
0.6
0.7
0.8
0.9
1.0

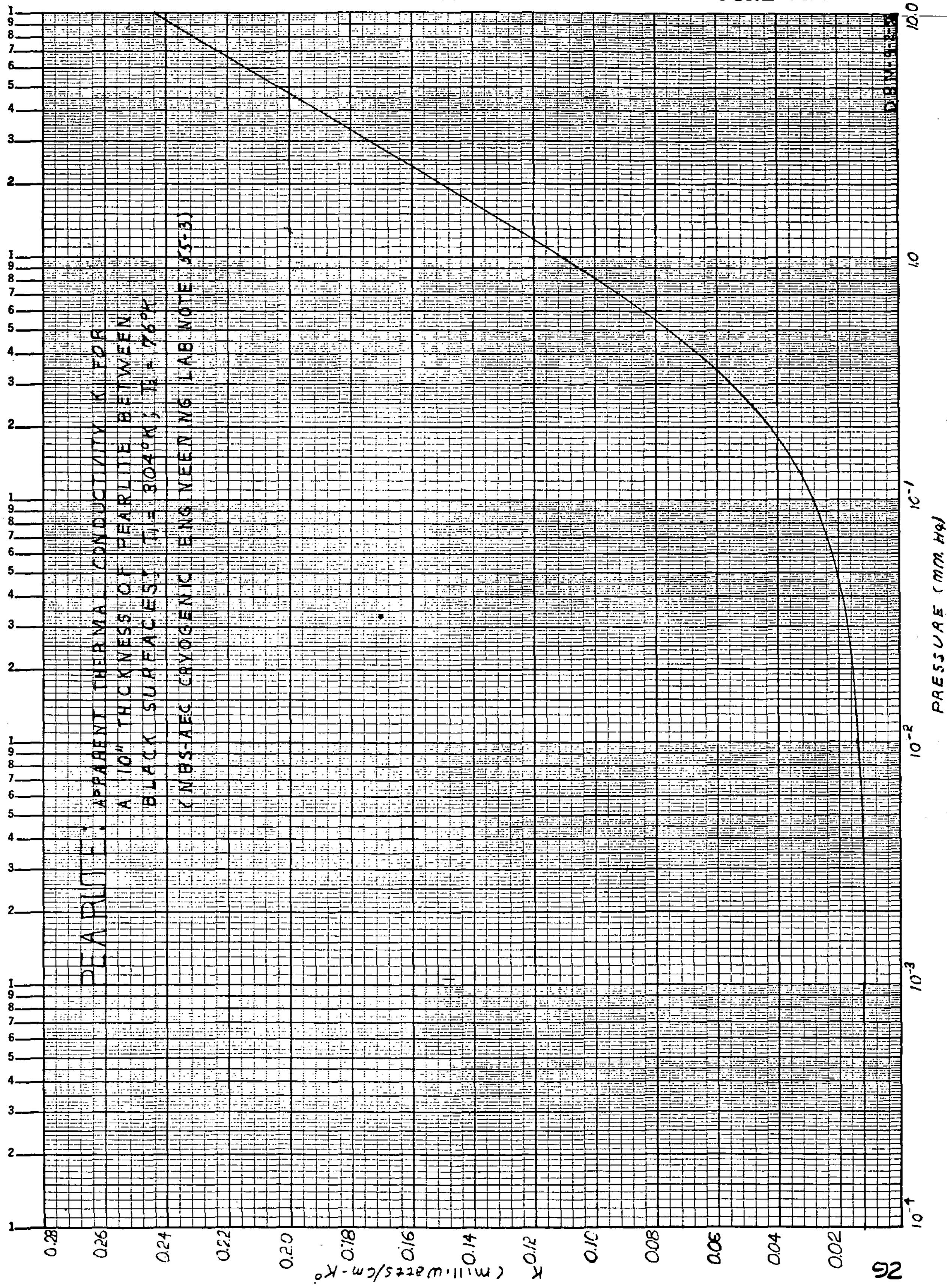

STYROFOAM; APPARENT THERMAL CONDUCTIVITY K
AS A FUNCTION OF MEAN TEMPERATURE
("StyroFoam", WAITE, NBS REPORT 3517)
DENSITY ≅ 1.7 LB/FT3
COMPRESSIVE YIELD STRENGTH = 10 TO 22 PSI
TENSILE STRENGTH = 35-49 PSI
SHEAR STRENGTH = 22-30 PSI
FLEXURAL STRENGTH = 32-54 PSI
COMPRESSIVE MODULUS = 915-1315 PSI
BENDING MODULUS = 600-1080 PSI
MODULUS OF RIGIDITY = 400-860 PSI
K in Milliwatts/cm K°
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0
20
40
60
80
100
120
140
160
180
200
220
240
MEAN TEMPERATURE (K°)
88

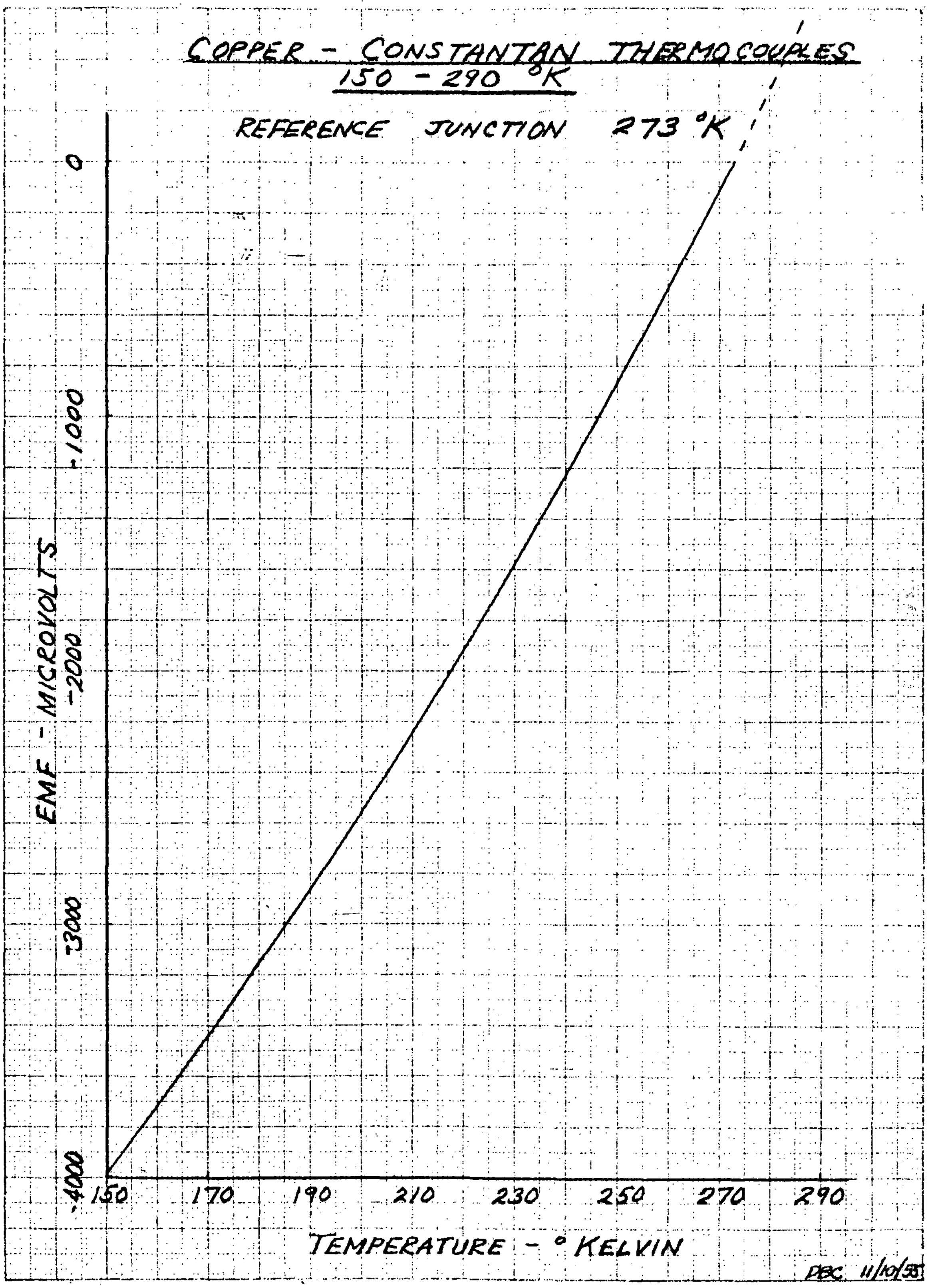

Insulation Between
300° K and 77° K
High Vac
(Flat Plates)
4" Styrofoam
1" Santocel
4" Santocel
Pressure (mm Hg)
Q/A (watts / ft²)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
6
5
4
3
2
1

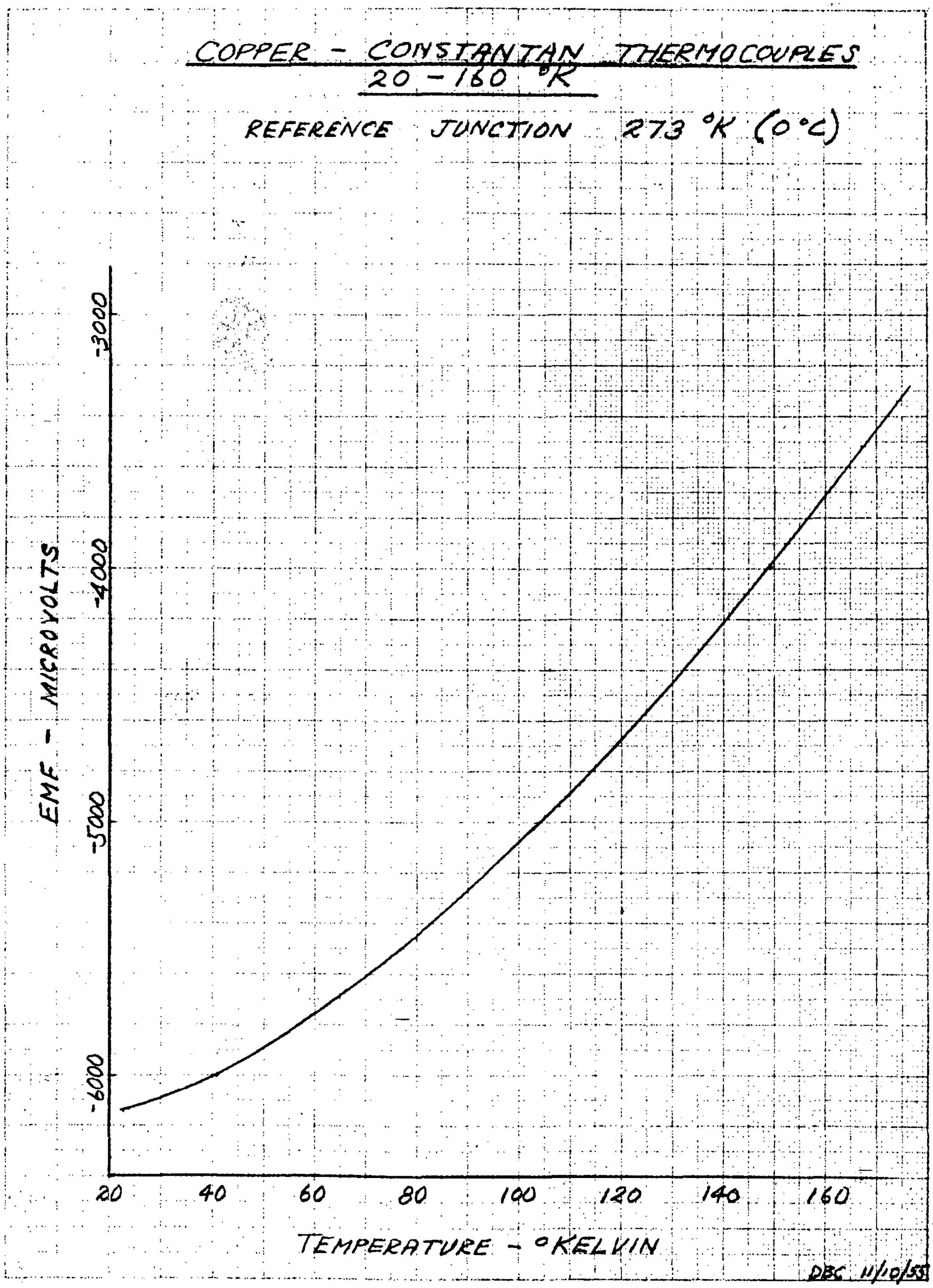

HEAT FLUX $\frac{Q}{A_1 \alpha}$ $\frac{WATTS}{FT^2}$
PRESSURE -(mm Hg @ ROOM TEMPERATURE)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
1.0
10^{-1}
10^{-2}
10^{-3}
HYDROGEN 300-77°K
HELIUM 300-77°K
NITROGEN 300-77°K
HYDROGEN 77-20°K
HELIUM 77-20°K
FREE MOLECULAR HEAT CONDUCTION BETWEEN COAXIAL CYLINDRICAL SURFACES
$\frac{Q}{A\alpha} = 13.0\left(\frac{\gamma+1}{\gamma-1}\right)\frac{P_{mm}}{\sqrt{M}}(T_2 - T_1)$
$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \frac{A_1}{A_2}(1-\alpha_2)\alpha_1}$
REF: KNUDSEN, "ANN. PHYSIK,"
VOL. 31, 32, 33, 34 & 6

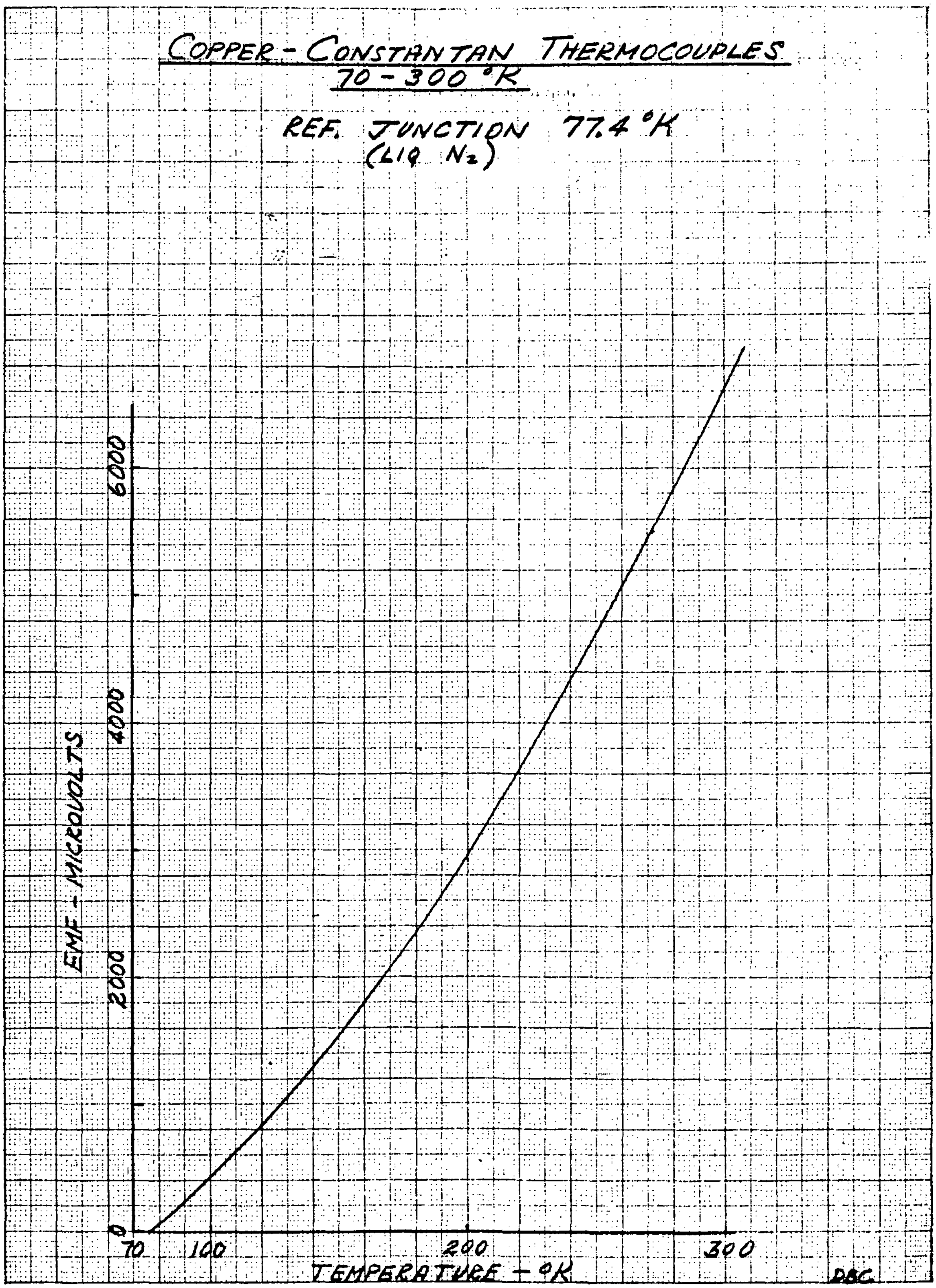
0 0 1 0 1 5 0 0 7 9 0



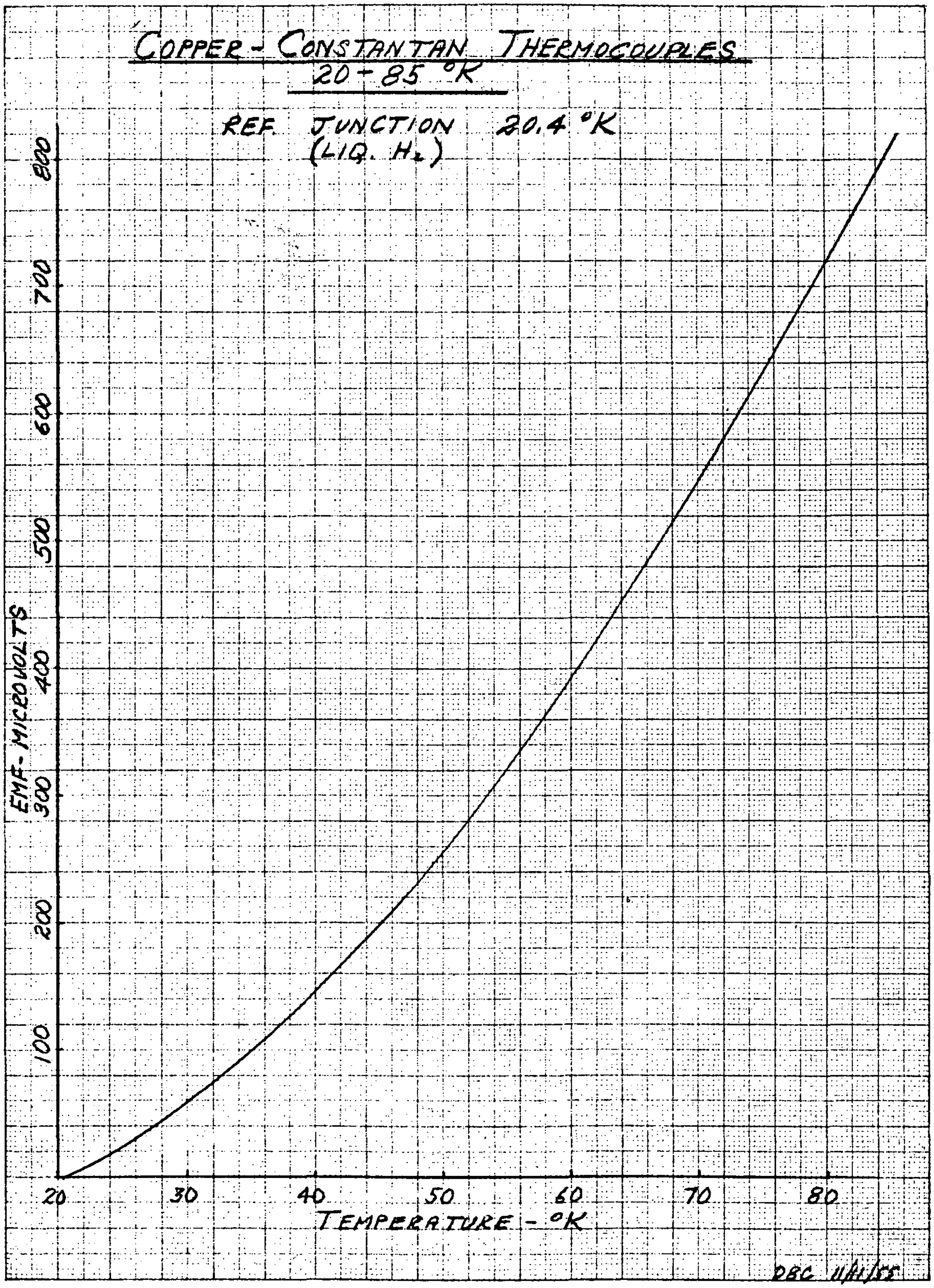

PEARLITE: APPARENT THERMAL CONDUCTIVITY K FOR
A 10" THICKNESS OF PEARLITE BETWEEN
BLACK SURFACES: T1 = 304°K; T2 = 76°K
(NBS-AEC CRYOGENIC ENGINEERING LAB NOTE 55-3)
PRESSURE (mm. Hg)
K (milliwatts/cm-K°)
10.0
1.0
10^-1
10^-2
10^-3
10^-4
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02


COPPER - CONSTANTAN THERMOCOUPLES
150 - 290 °K
REFERENCE JUNCTION 273 °K
0
-1000
-2000
-3000
-4000
EMF - MICROVOLTS
150
170
190
210
230
250
270
290
TEMPERATURE - ° KELVIN
DBC 11/10/55

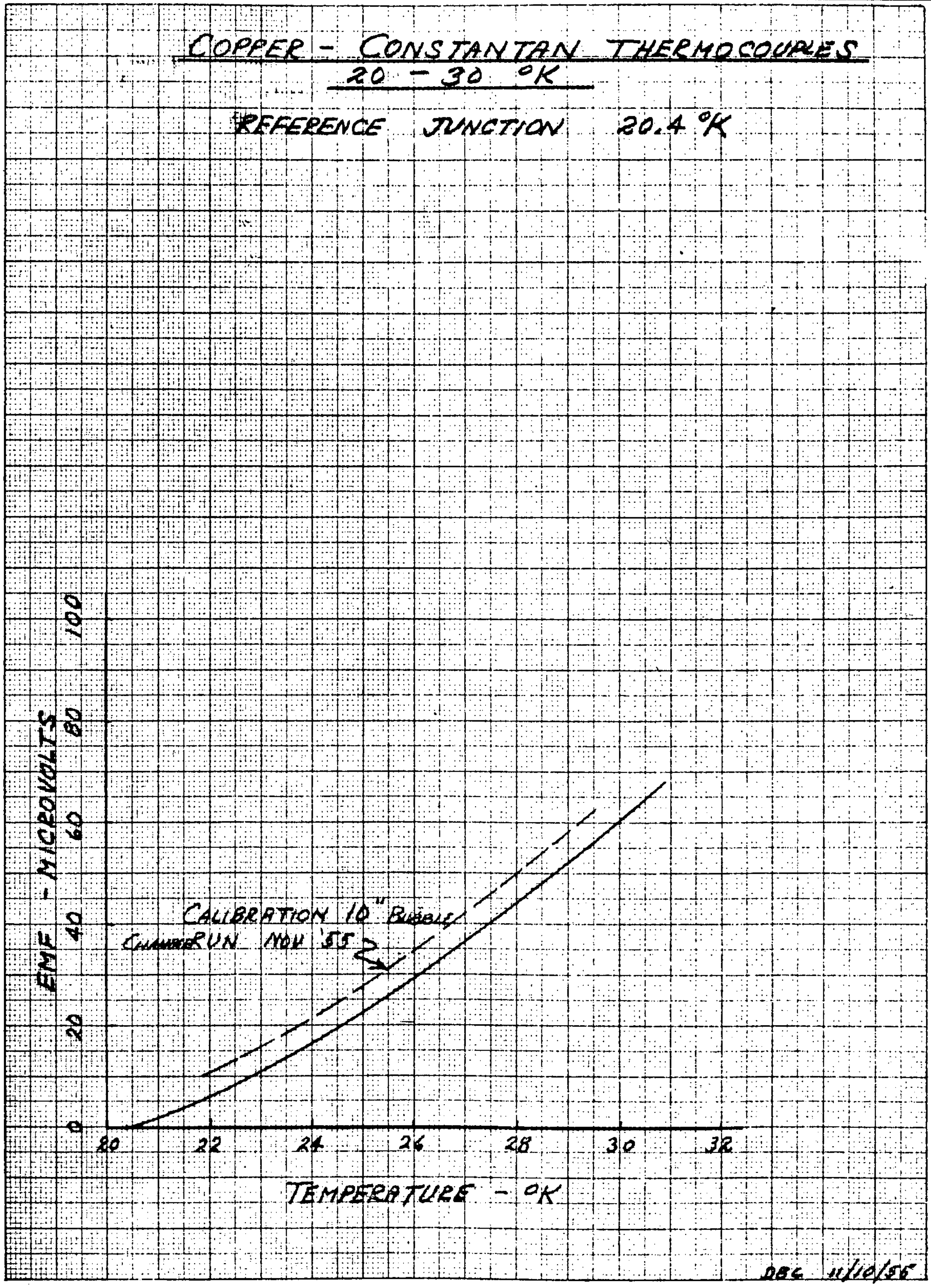

COPPER - CONSTANTAN THERMOCOUPLES
20 - 160 °K
REFERENCE JUNCTION 273 °K (0 °C)
EMF - MICROVOLTS
-3000
-4000
-5000
-6000
20
40
60
80
100
120
140
160
TEMPERATURE - °KELVIN
DBC 11/10/55



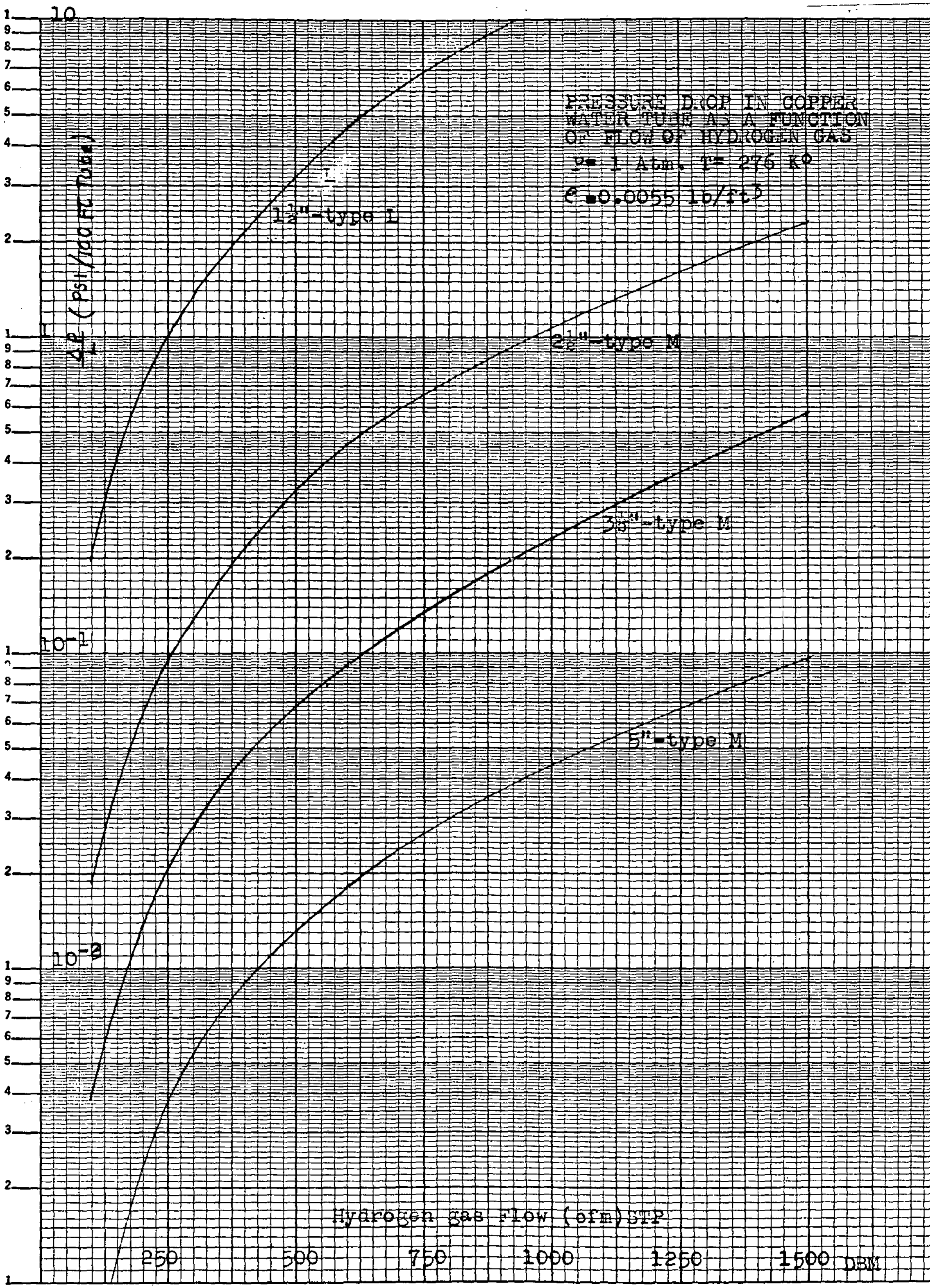
COPPER - CONSTANTAN THERMOCOUPLES
70 - 300 °K
REF. JUNCTION 77.4 °K
(LIQ N₂)
EMF - MICROVOLTS
0
2000
4000
6000
70
100
200
300
TEMPERATURE - °K
DBC

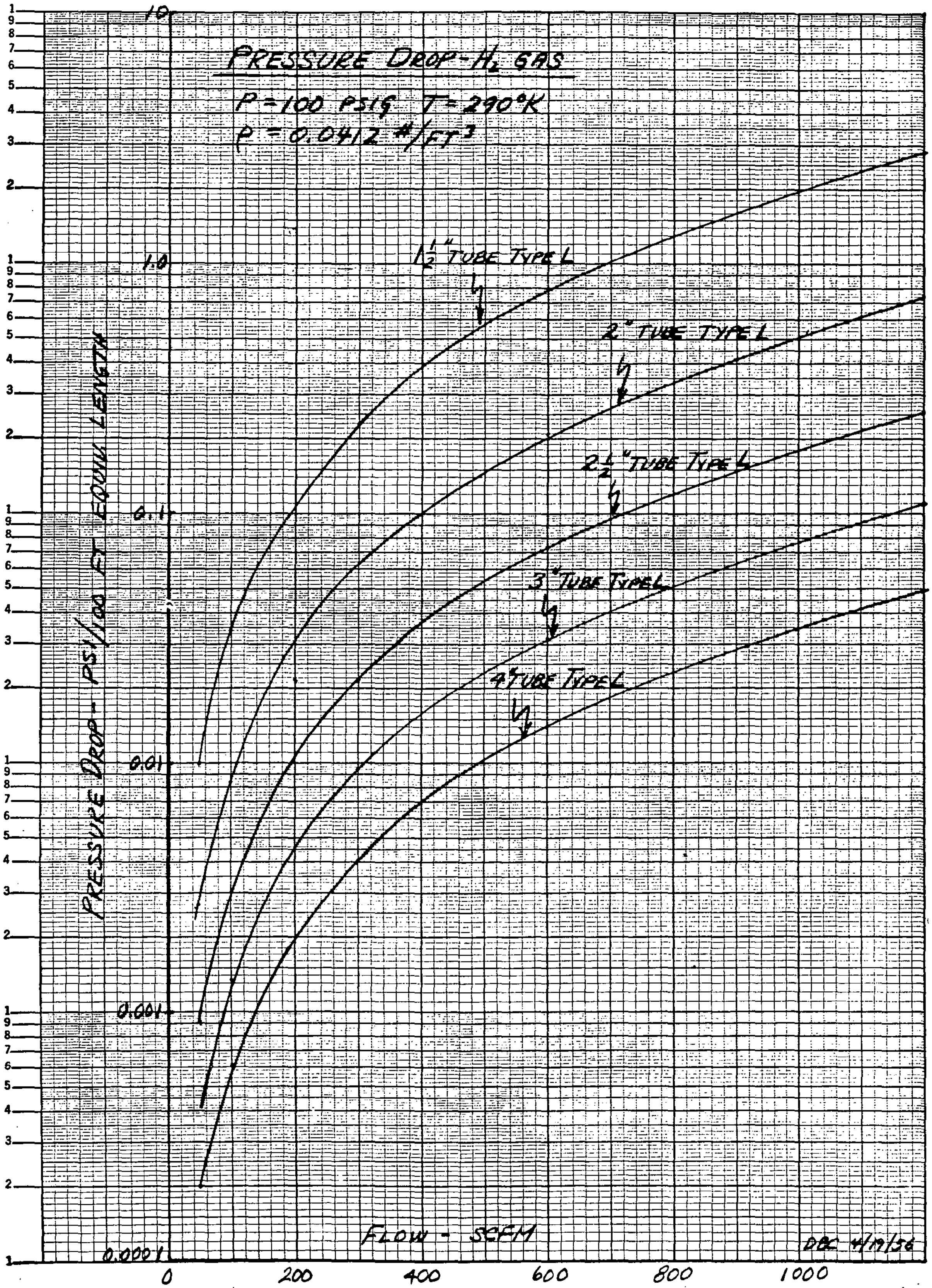


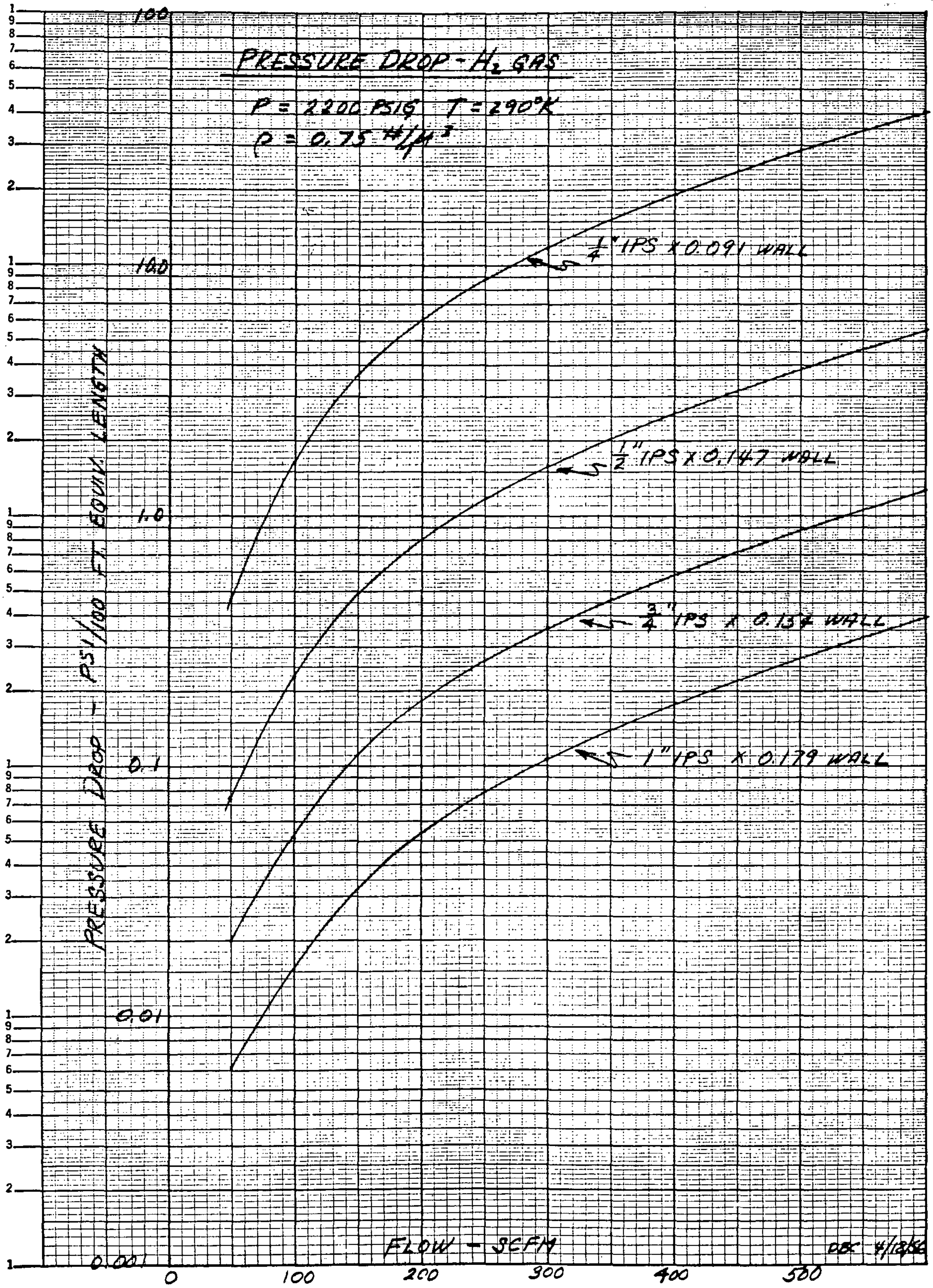
COPPER - CONSTANTAN THERMOCOUPLES
20 - 85 °K
REF. JUNCTION 20.4 °K
(LIQ. H₂)
EMF - MICROVOLTS
100
200
300
400
500
600
700
800
20
30
40
50
60
70
80
TEMPERATURE - °K

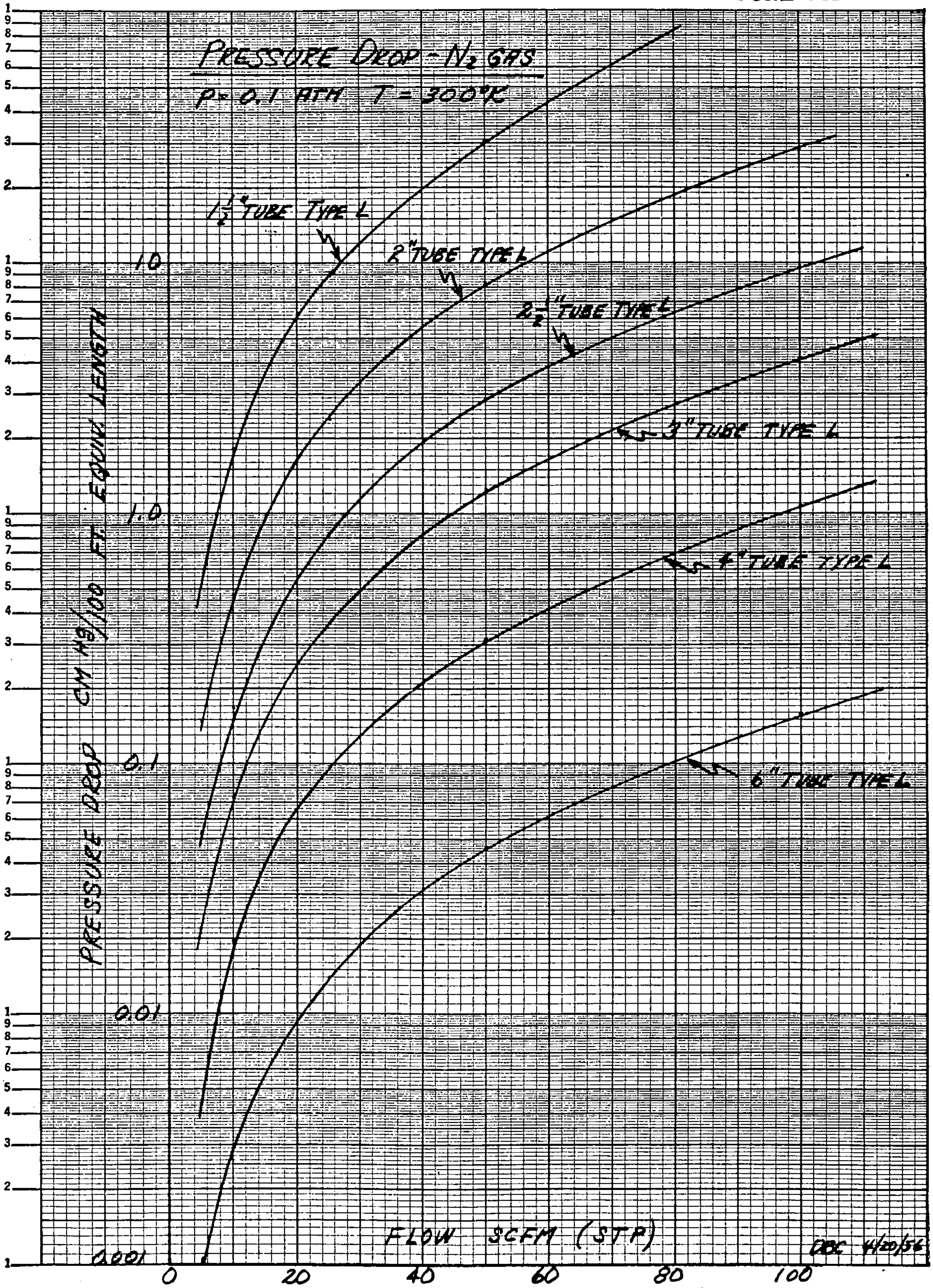

COPPER - CONSTANTAN THERMOCOUPLES
20 - 30 °K
REFERENCE JUNCTION 20.4 °K
EMF - MICROVOLTS
0
20
40
60
80
100
20
22
24
26
28
30
32
TEMPERATURE - °K
CALIBRATION 10" BUBBLE
CHAMBER RUN NOV '55
DBC 11/10/56

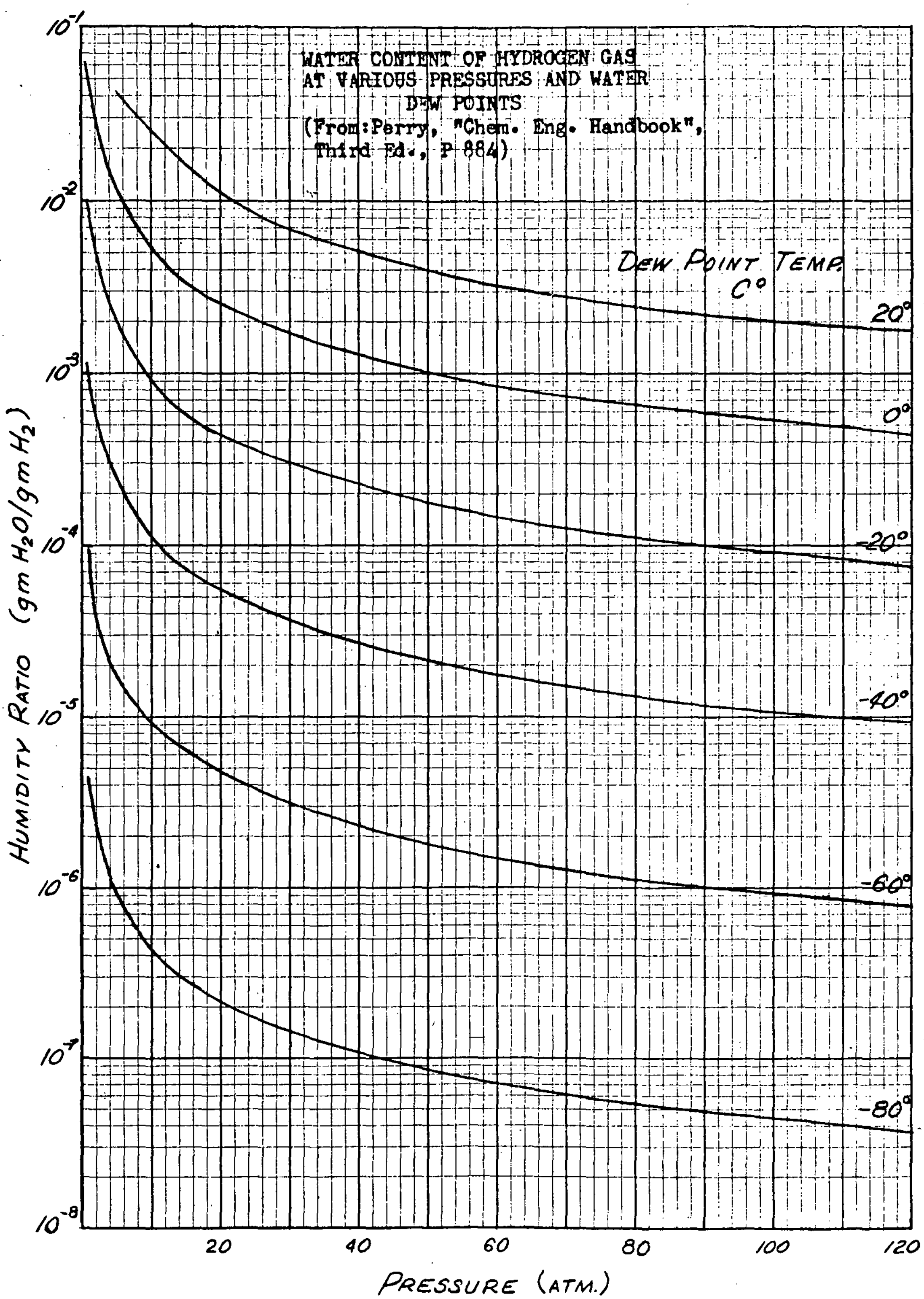

DIFFERENTIAL THERMAL E.M.F.
GOLD + 2.1% COBALT VS. COPPER
NBS UNPUBLISHED DATA
MICROVOLTS / °K
30
20
10
0
20
40
60
TEMPERATURE – °K


PRESSURE DROP IN COPPER WATER TUBE AS A FUNCTION OF FLOW OF HYDROGEN GAS
P= 1 Atm. T= 276 K°
ρ =0.0055 lb/ft³
1½"-type L
2½"-type M
3½"-type M
5"-type M
ΔP/L (PSI/100 Ft Tube)
10
1
10⁻¹
10⁻²
Hydrogen gas Flow (cfm)STP
250
500
750
1000
1250
1500


PRESSURE DROP-H_2 GAS
P=100 PSIG T=290°K
ρ=0.0412 #/FT³
1½" TUBE TYPE L
2" TUBE TYPE L
2½" TUBE TYPE L
3" TUBE TYPE L
4" TUBE TYPE L
PRESSURE DROP - PSI/100 FT EQUIV LENGTH
FLOW - SCFM
10
1.0
0.1
0.01
0.001
0.0001
0
200
400
600
800
1000
DBC 4/19/56


PRESSURE DROP - H_2 GAS
P = 2200 PSIG T = 290°K
ρ = 0.75 #/ft³
1/4" IPS x 0.091 WALL
1/2" IPS x 0.147 WALL
3/4" IPS x 0.134 WALL
1" IPS x 0.179 WALL
PRESSURE DROP - PSI/100 FT. EQUIV. LENGTH
FLOW - SCFM
100
10
1.0
0.1
0.01
0.001
0
100
200
300
400
500
DBC 4/12/56


PRESSURE DROP - N₂ GAS
P = 0.1 ATM T = 300°K
1½" TUBE TYPE L
2" TUBE TYPE L
2½" TUBE TYPE L
3" TUBE TYPE L
4" TUBE TYPE L
6" TUBE TYPE L
PRESSURE DROP CM Hg/100 FT. EQUIV. LENGTH
10
1.0
0.1
0.01
0.001
FLOW SCFM (STP)
0
20
40
60
80
100
DBC 4/20/56


WATER CONTENT OF HYDROGEN GAS
AT VARIOUS PRESSURES AND WATER
DEW POINTS
(From: Perry, "Chem. Eng. Handbook",
Third Ed., P 884)
DEW POINT TEMP.
C°
20°
0°
-20°
-40°
-60°
-80°
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
HUMIDITY RATIO (gm H2O/gm H2)
20
40
60
80
100
120
PRESSURE (ATM.)

STAINLESS STEEL CHARACTERISTICS

Type	302	304L	304	310	316	321	347
Carbon	~0.2	0.03	0.08	0.25	0.10	0.08	0.08
Ni	8-10	12-14	8-11	19-22	10-14	8-11	9-12
Cr	17-19	18-20	18-20	24-26	16-18	17-19	17-19
Stabilizer					MO	Ti	Cb
Nitrogen Should be limited to	0.03-0.08	→	→	→	→	→	→
Welding	poor c percip.	good	fair	good	good 1st poor 2nd	good 1st poor 2nd Ti oxidize	good
Weld after cold work		1		2			3
Hard Soldering annealed, 1st solder only	OK	→	→	→	→	→	→
Soft Solder 430 Solder recom.	poor	OK	→	→	→	→	→
Magnetic prop. at low temp.	L	L ~1.002 perm.	L	H ~1.02 perm.	H ~1.02 perm.	H	H ~1.02 perm.
COST $/100 lbs sheet stocks 10 ga. 36" x 120" size 2 B finish, 100 lbs-299 lbs. lots	72.75	80.75	75.50	107.00	96.50*	82.50	98.75

*316 ELC - 101.75

430 - 65.00

Note: 303 is poor material

FLUID PROPERTIES

REF: NBS TM No. 36, p. 41

Properties	Liquid Hydrogen	Liquid Nitrogen	Water	Oxygen	Freon-11	Freon-22
Heat of Vaporization (cal./gr.)	106.5	47.6	586	50.8	43.5	55.9
Vapor Pressure (mm Hg)	760	760	18.8	760	760	760
Molecular Weight (gr./gr.mole)	2	28	18	32	137.4	86.5
Specific Volume (cc/gr.)	14.1	1.24	1.00	0.871	0.673	0.706
Temperature (^{o}K)	20	77	294 (70^{o}F)	90.13	297	232
C_p - Specific Heat (cal./gr.^{o}K)	2.3	0.49	1.00	0.405	0.210	0.255
Viscosity (centipoises)	0.0130	0.158	0.98	0.190	0.429	———

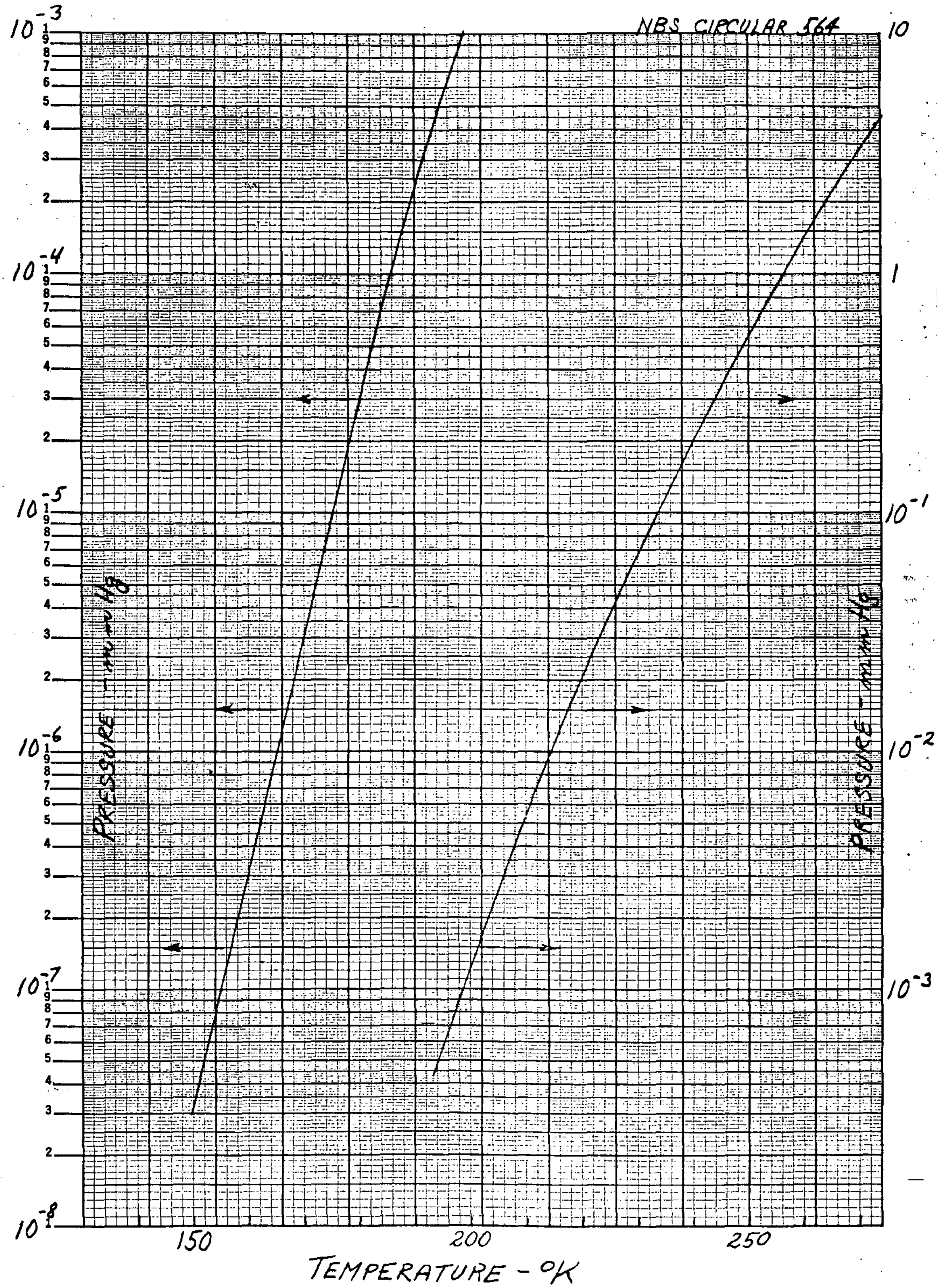
BOILING POINTS OF GASES

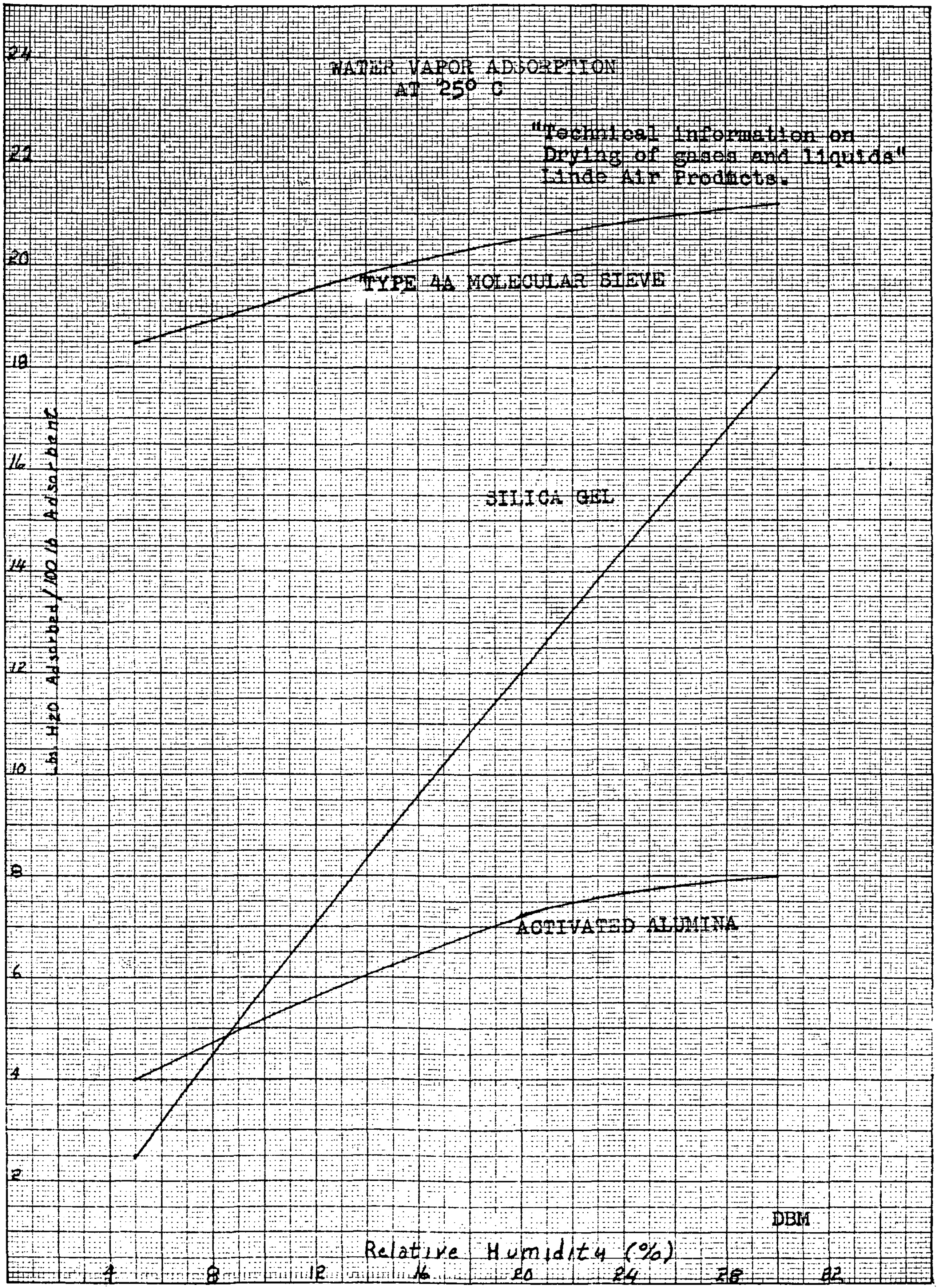
Gas		Boiling Point at 1 atm.			Mass Of Liquid C	Volume Of Gas(STP) Produced	Heat Of Vaporization
		C°	F°	K°	gm/liter	Cu.Ft./liter	cal/liter
Helium	He^3	-269.9	-453.8	3.2			
Helium	He^4	-268.9	-452.0	4.2	125.2	24.7	650
Hydrogen	H_2	-252.7	-422.9	20.4	70.8	27.5	7640
Deuterium	D_2	-249.5	-417.1	23.6	164	32.5	12,000
Tritium	T_2	-248.0	-414.4	25.1			
Neon	Ne	-245.9	-410.6	27.2	1204	47.3	26,300
Nitrogen	N_2	-195.8	-320.4	77.3	808	23.05	38,600
Carbon Monoxide	CO	-192.0	-313.6	81.1	793	22.4	40900
Fluorine	F_2	-187.0	-304.6	86.0	1108	23.1	47,500
Argon	A	-185.7	-302.3	87.4	1410	27.9	56300
Oxygen	O_2	-183.0	-297.4	90.1	1140	28.2	58,100
Methane	CH_4	-161.4	-258.5	111.7	415	20.5	50,500
Krypton	Kr	-151.8	-241.1	121.3	2155	20.5	59,400
Xenon	Xe	-109.1	-164.4	164.0	3520	21.2	83,400
Ethylene	C_2H_4	-103.8	-154.8	169.3	566	16.1	65,000
Nitrous Oxide	N_2O	- 90.7	-129.1	183.6	1226	22.5	110,000
Ethane	C_2H_6	- 88.3	-126.9	184.8	547	14.3	64,000
Acetylene*	C_2H_2	- 84.0	-119.2	189.1	620.8	18.7	
Carbon Dioxide*	CO_2	- 78.5	-109.3	194.6	1560	27.8	214,000
Propylene	C_3H_6	- 47.0	- 52.6	226.1			
Propane	C_3H_8	- 42.3	- 44.1	230.8			
Ketene	C_2H_2O	- 41.0	- 41.8	232.1			
Freon22	$CHClF_2$	- 40.6	- 41.0	232.5			
Ammonia	NH_3	- 33.3	- 27.9	239.8			
Freon12	CCl_2F_2	- 30.0	- 22.0	243.1			
Methyl Chloride	CH_3Cl	- 23.7	- 10.7	249.4			
Isobutane	$(CH_3)_2C_2H_4$	- 10.2	13.6	262.9			
Sulphur Dioxide	SO_2	- 10.0	14.0	263.1			
Butane	C_4H_{10}	- 0.6	30.9	272.5			

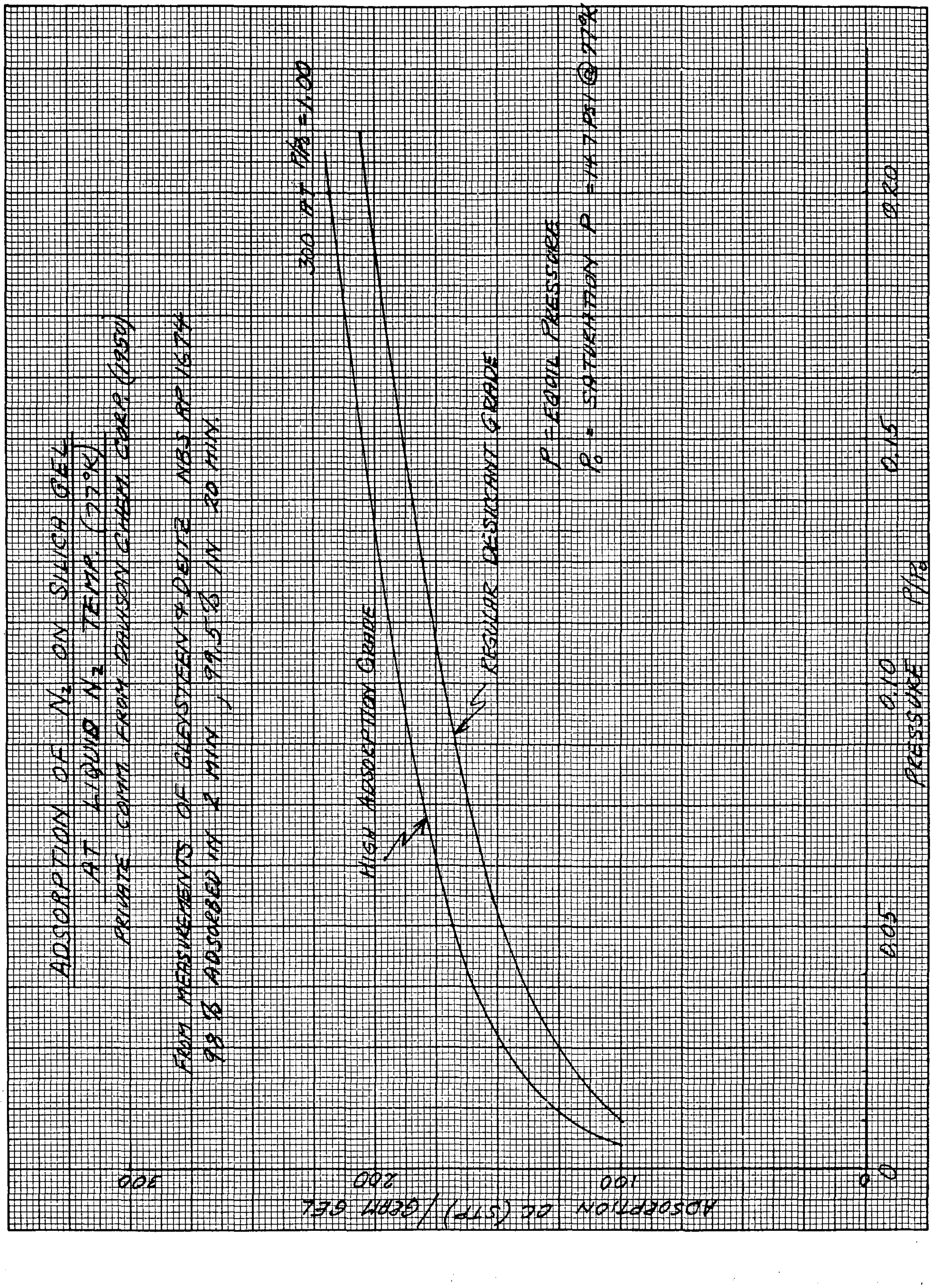
*Sublimes

0 0 1 0 1 5 0 0 / 9 8

VAPOR PRESSURE OF ICE




WATER VAPOR ADSORPTION
AT 25° C
"Technical information on Drying of gases and liquids" Linde Air Products.
TYPE 4A MOLECULAR SIEVE
SILICA GEL
ACTIVATED ALUMINA
lbs H2O Adsorbed / 100 lb Adsorbent
Relative Humidity (%)
DBM
2
4
6
8
10
12
14
16
18
20
22
24
4
8
12
16
20
24
28
32


ADSORPTION OF N_2 ON SILICA GEL
AT LIQUID N_2 TEMP. (77°K)
PRIVATE COMM FROM DAVISON CHEM. CORP. (1954)
FROM MEASUREMENTS OF GLEYSTEEN & DEITZ NBS RP 1674
98% ADSORBED IN 2 MIN, 99.5% IN 20 MIN.
HIGH ADSORPTION GRADE
REGULAR DESICCANT GRADE
300 AT P/P_0 = 1.00
P - EQUIL PRESSURE
P_0 = SATURATION P = 14.7 PSI @ 77°K
0
0.05
0.10
0.15
0.20
PRESSURE P/P_0
100
200
300
ADSORPTION CC (STP) / GRAM GEL

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