MATERIAL PROPERTIES IMPORTANT TO THE DESIGN OF A LARGE SUPERCONDUCTING MAGNET

Introduction:

This monograph is a compilation from the literature, from more general compilations, and from private sources, of electrical and mechanical properties of materials important to the design of a large superconducting magnet for a bubble chamber. It is intended for use by the Magnet Committee of the Bubble Chamber Group, Physics Department, Brookhaven National Laboratory, as a source document during the design of large superconducting magnets for a bubble chamber of 14-foot diameter and a test facility of 7-foot diameter. It will be revised and extended as needed during the design effort.

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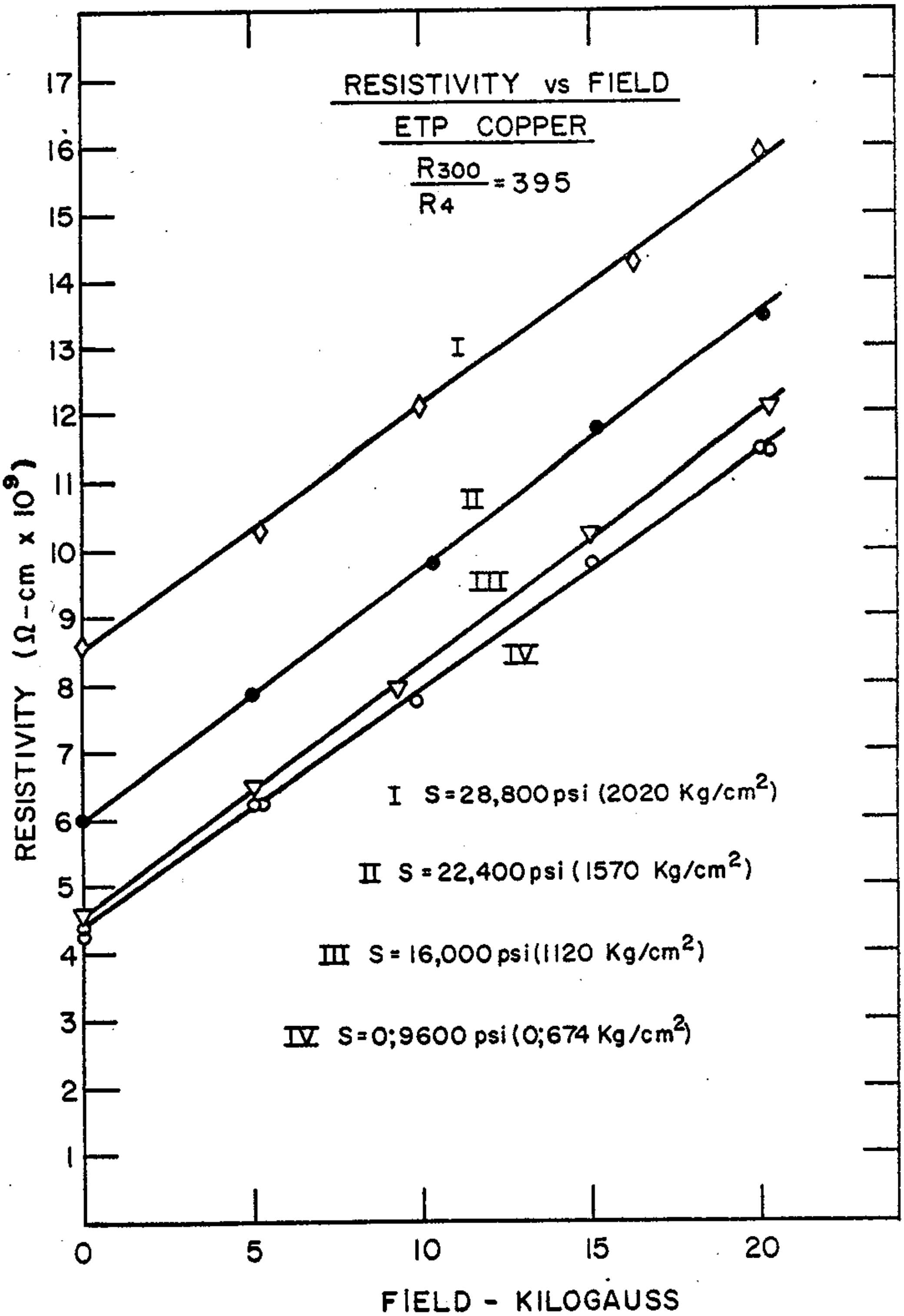

Brooks, J. M. and Purcell, J. R., Stress vs. Resistivity at Liquid Helium Temperature, Argonne Natl. Lab., paper presented at 1966 Cryogenic Conference

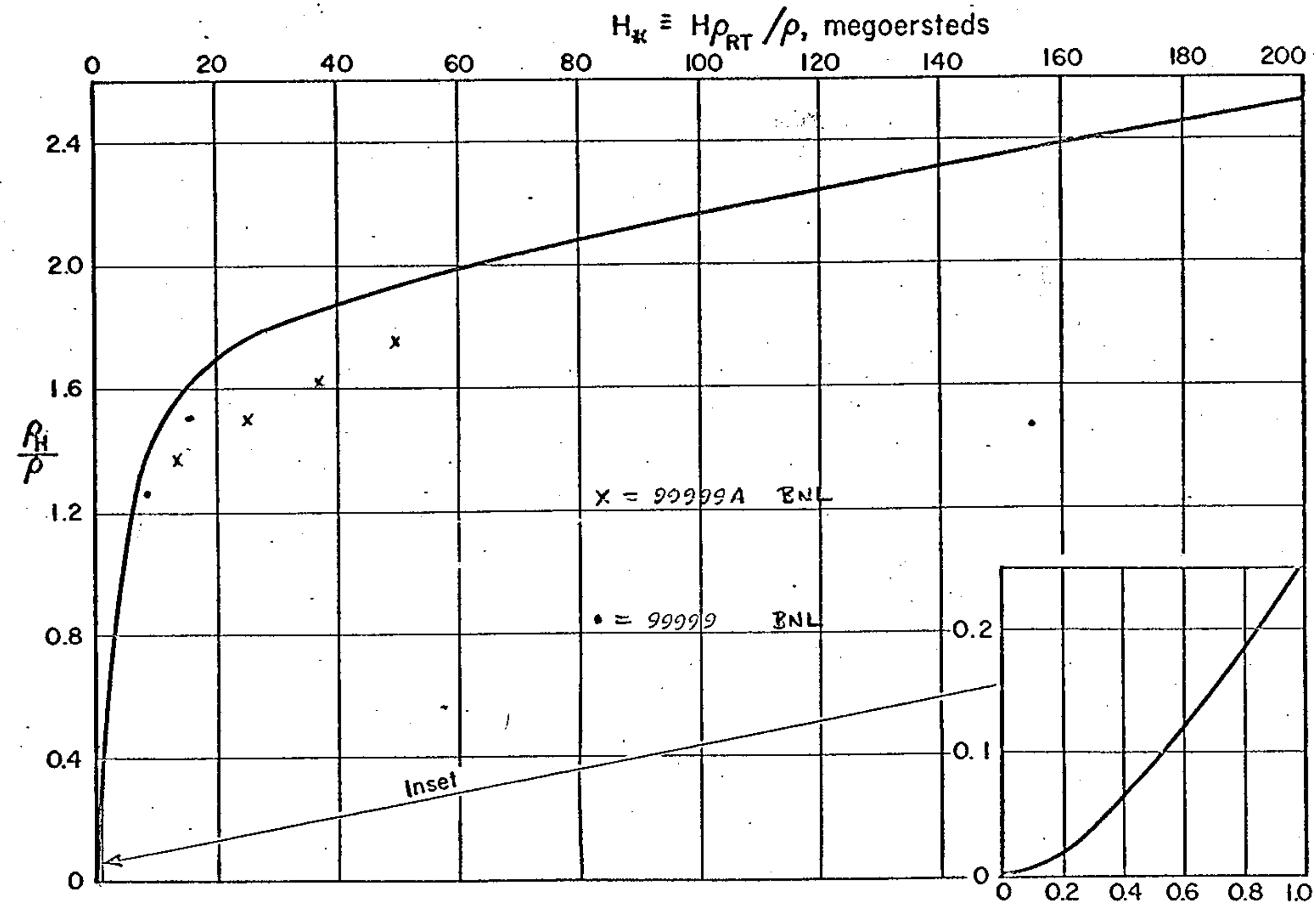

Fig. 3 Transverse magnetoresistance of aluminum as given by equation (6).

$$\rho_\beta = \rho \frac{H_*^2 (1 + .00177\, H_*)}{1.8 + 1.6 H_* + 0.53 H_*^2}$$

N.B.S. TECH NOTE 218
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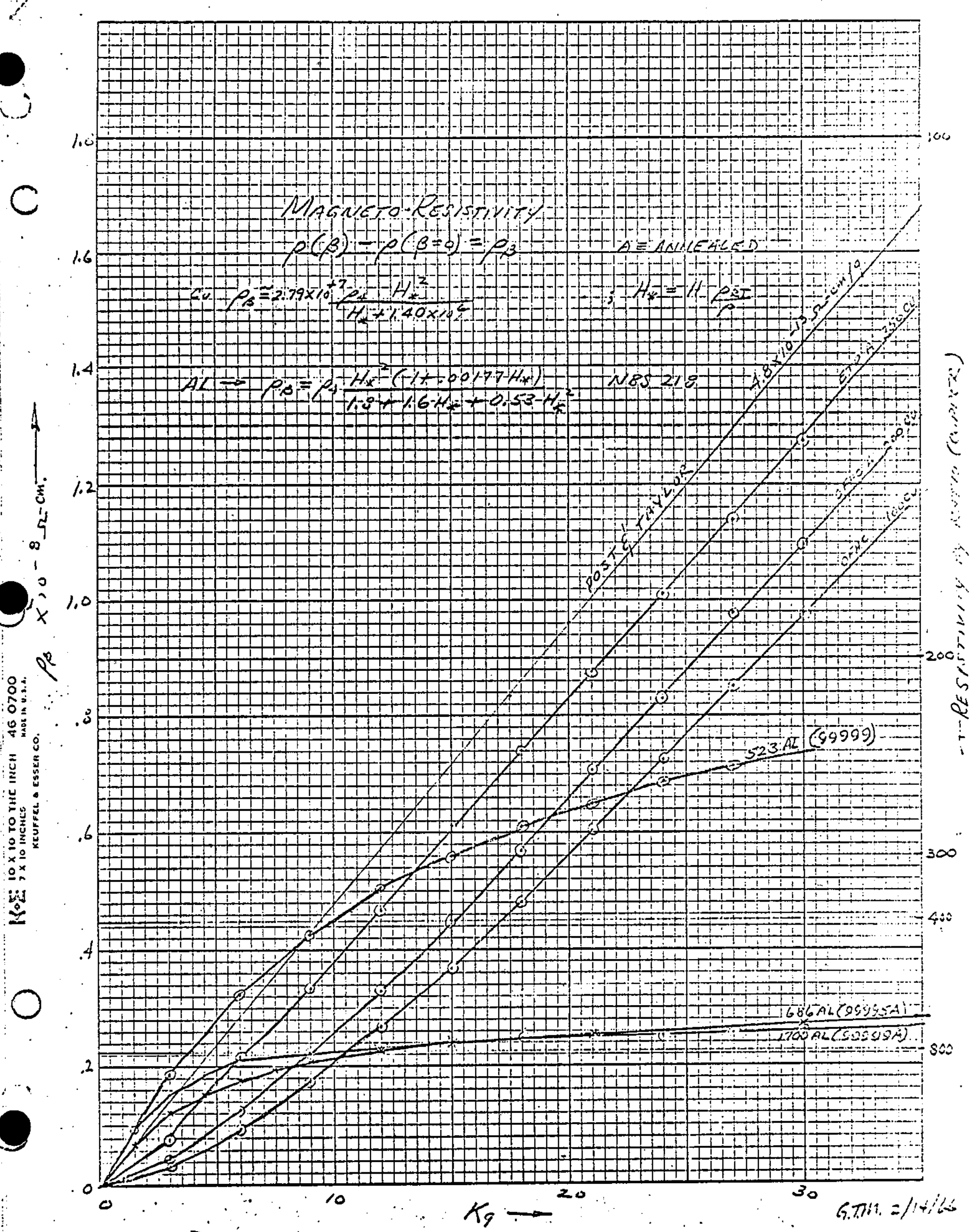
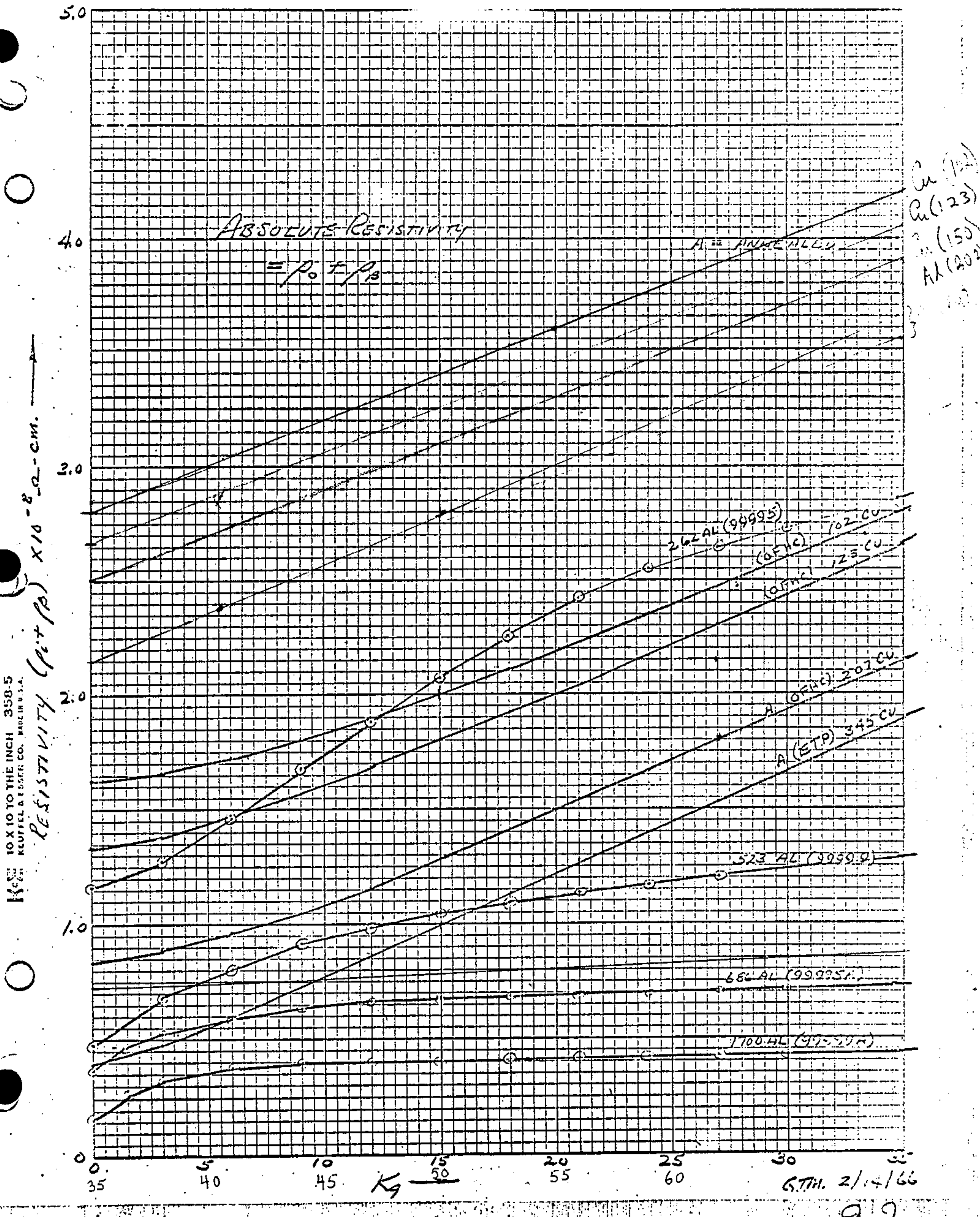
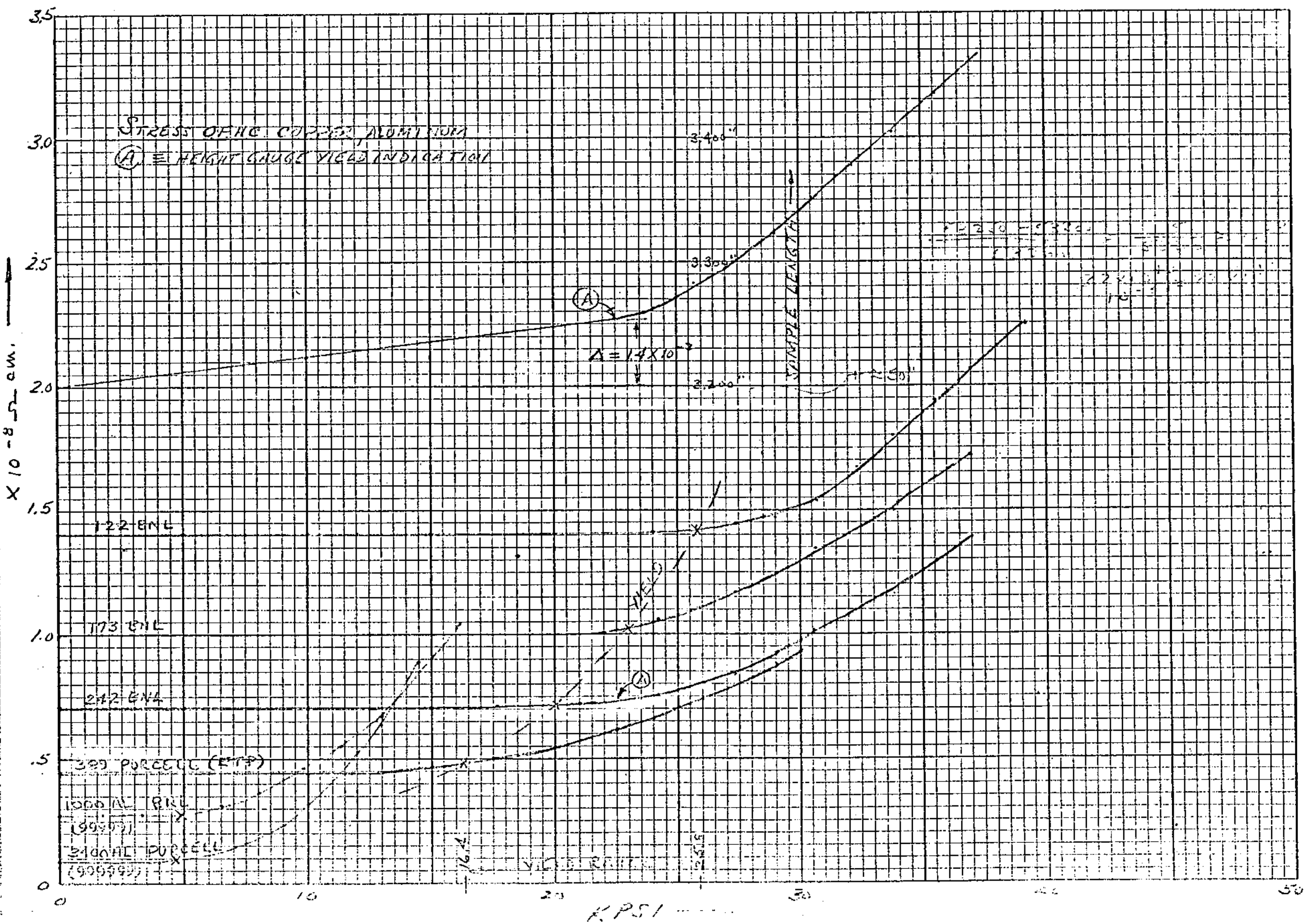

MAGNETO-RESISTIVITY
ρ(B) − ρ(B=0) = ρB
A = ANNEALED
Cu ρB ≅ 2.79×10^+7 ρ+ H*^2 / (H* + 1.40×10^6) ; H* = H ρRT/ρ
AL → ρB = ρ4 H*^2 (1 + .00177 H*) / (1.8 + 1.6 H* + 0.53 H*^2)
NBS 218
POST & TAYLOR
523 AL (99999)
686 AL (99995A)
1700 AL (99999A)
ρB ×10^−8 Ω-CM.
K9
RESISTIVITY
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
10
20
30
100
200
300
400
800
K&E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

G.T.M. 2/14/66


ABSOLUTE RESISTIVITY
= ρ0 + ρB
A = ANNEALED
262 AL (99995)
(OFHC) 102 CU
(OFHC) 123 CU
A (OFHC) 207 CU
A (ETP) 345 CU
1100 AL
RESISTIVITY (ρi + ρB) x10^-8 Ω-cm.
Kg
5.0
4.0
3.0
2.0
1.0
0
0
5
10
15
20
25
30
35
40
45
50
55
60
G.T.H. 2/14/66
10 X 10 TO THE INCH 358-5
KEUFFEL & ESSER CO. MADE IN U.S.A.

K+E 10 X 10 TO THE INCH 46 0700
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



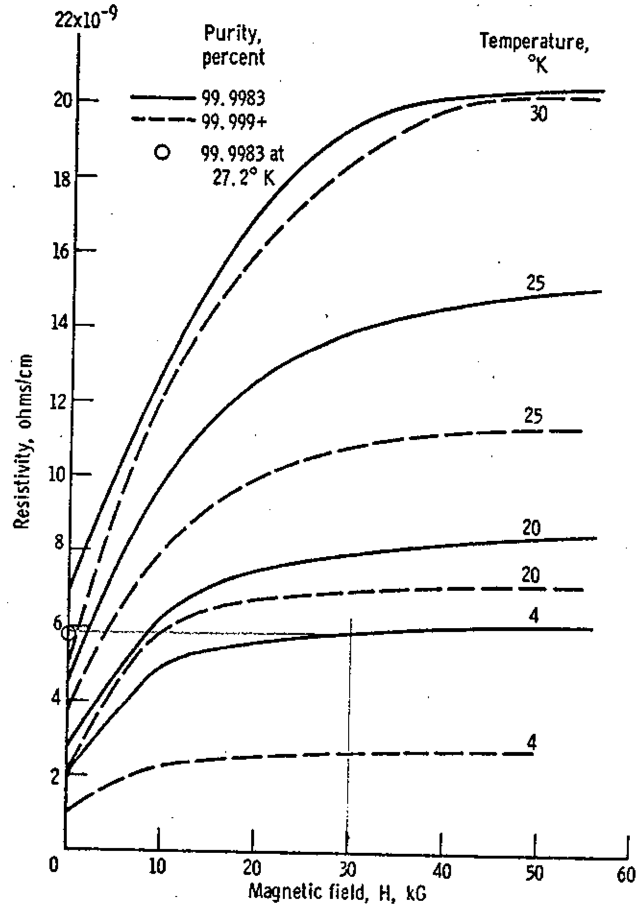


Fig. 1. Magnetoresistance of aluminum.

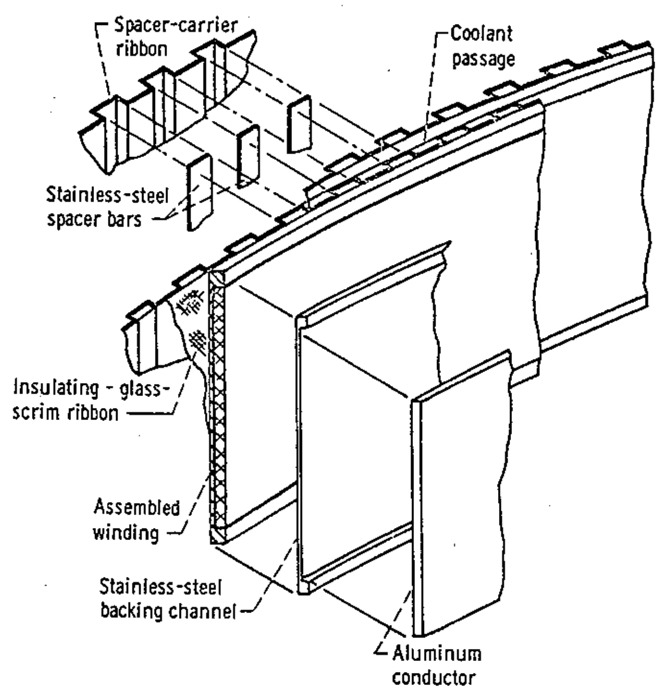


Fig. 2. - Construction of coils of cryogenically-cooled aluminum magnet.

Laurence, J. C. and Coles, W. D., Design, Construction, and Performance of Cryogenically Cooled and Superconducting Electromagnets, NASA TM X-52121 Sept. 1965

E-3111

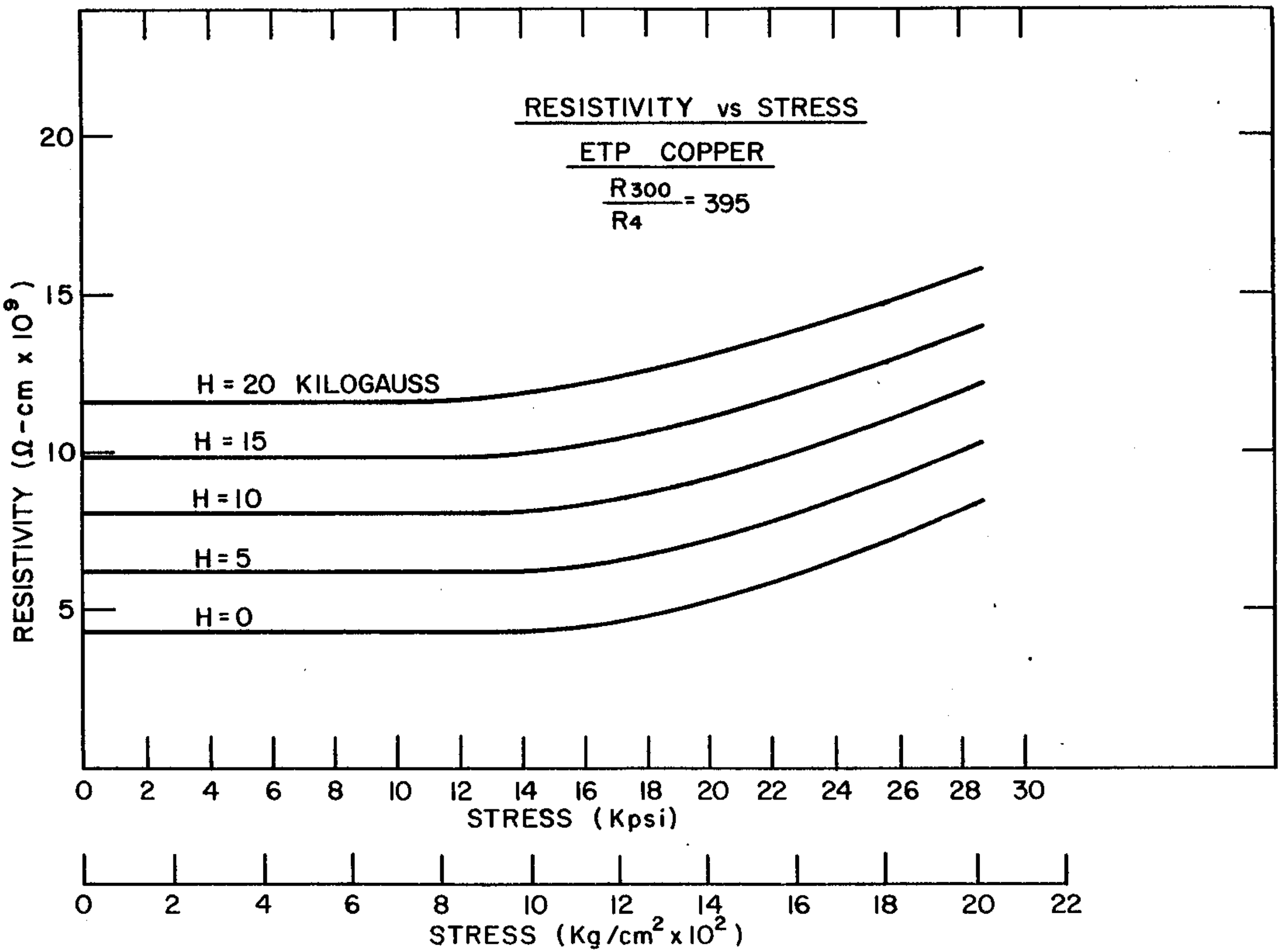

RESISTIVITY vs STRESS
ETP COPPER
$\frac{R_{300}}{R_4} = 395$
H = 20 KILOGAUSS
H = 15
H = 10
H = 5
H = 0
RESISTIVITY (Ω-cm x 10^9)
20
15
10
5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
STRESS (Kpsi)
0
2
4
6
8
10
12
14
16
18
20
22
STRESS (Kg/cm^2 x 10^2)

FIGURE 3

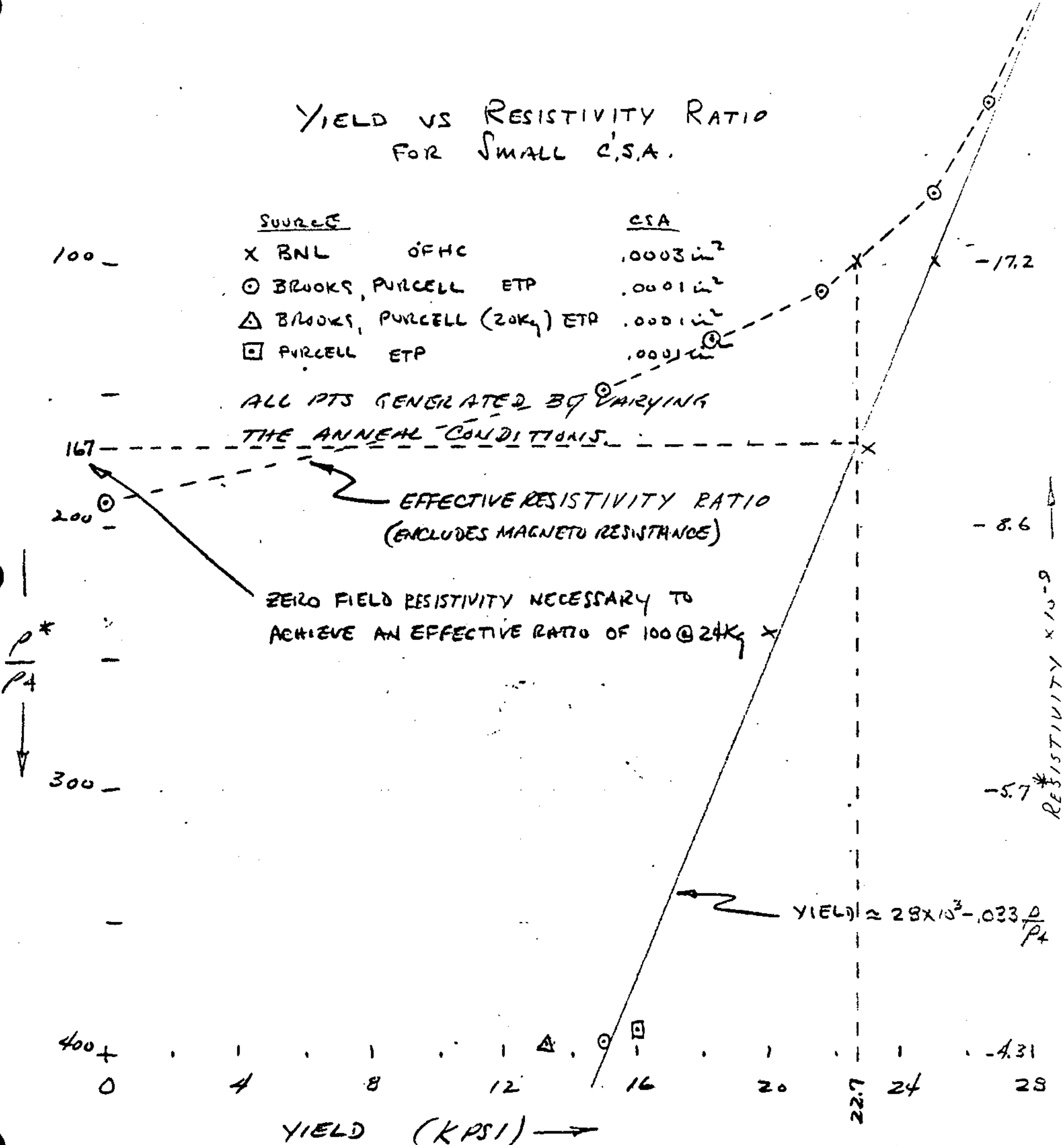
BROOKHAVEN NATIONAL LABORATORY

BY GTM. DATE 6/66 SUBJECT SHEET NO. OF

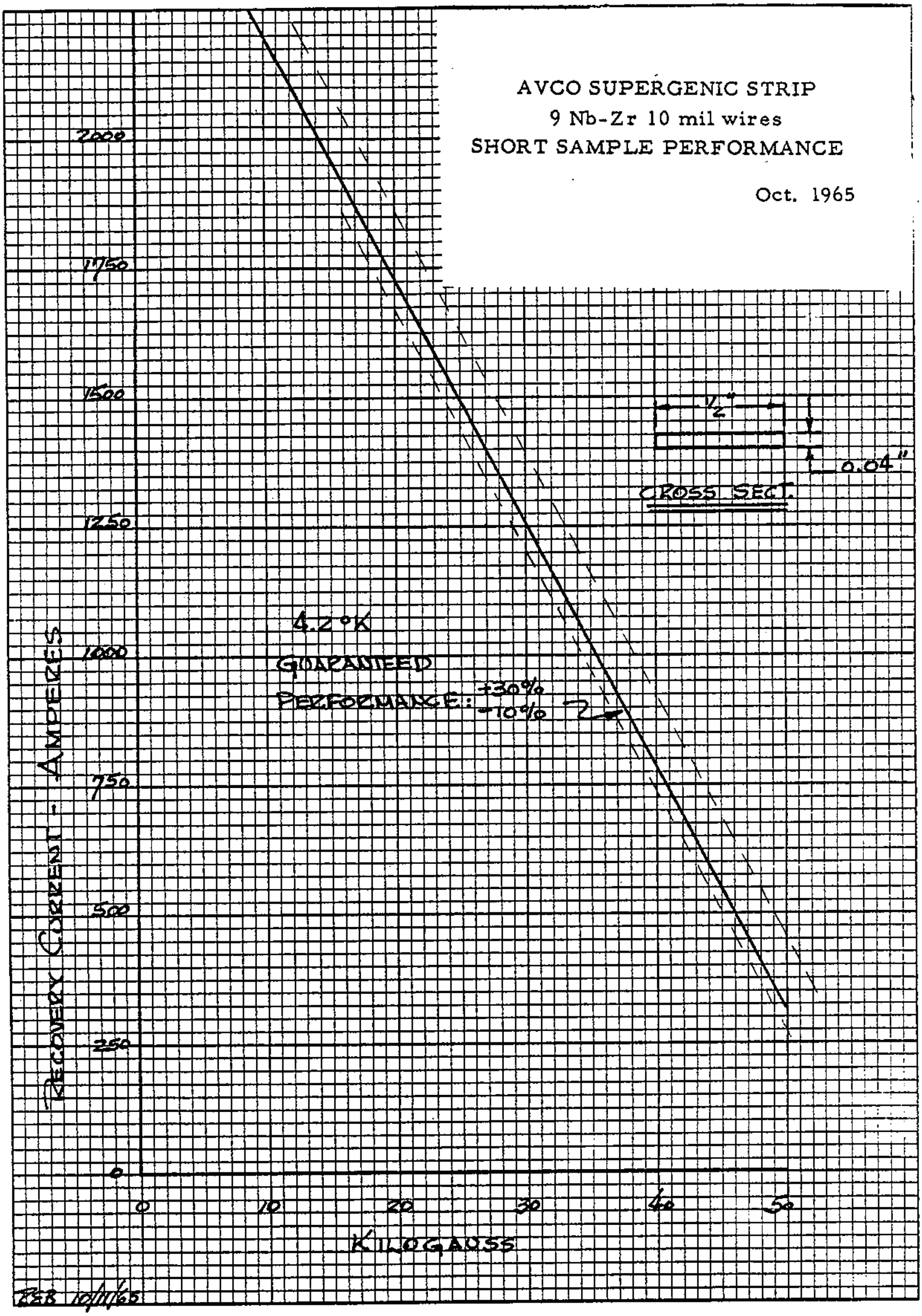
CHKD. BY DATE JOB NO.

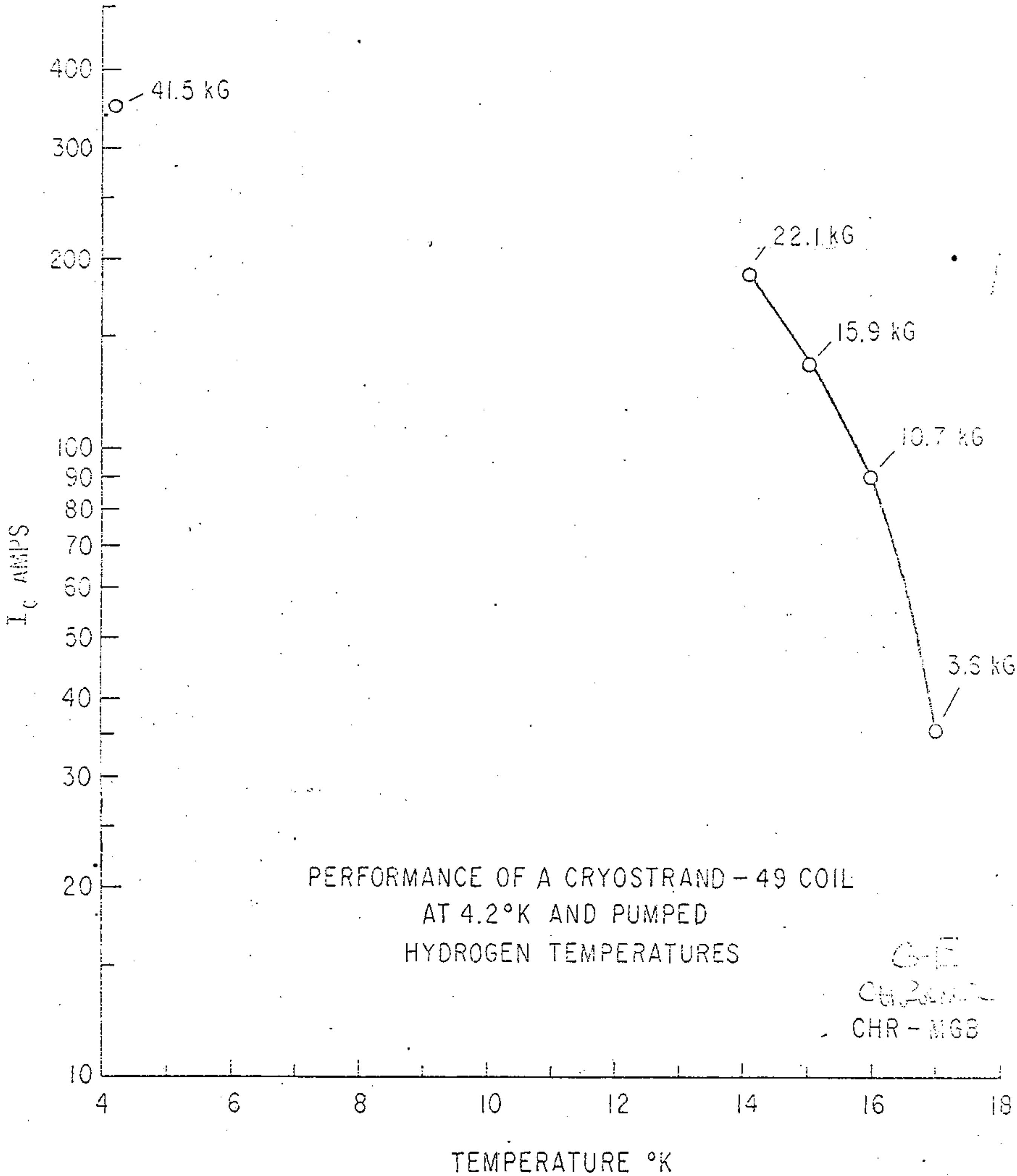
DEPT. OR PROJECT

YIELD VS RESISTIVITY RATIO FOR SMALL C'S.A.

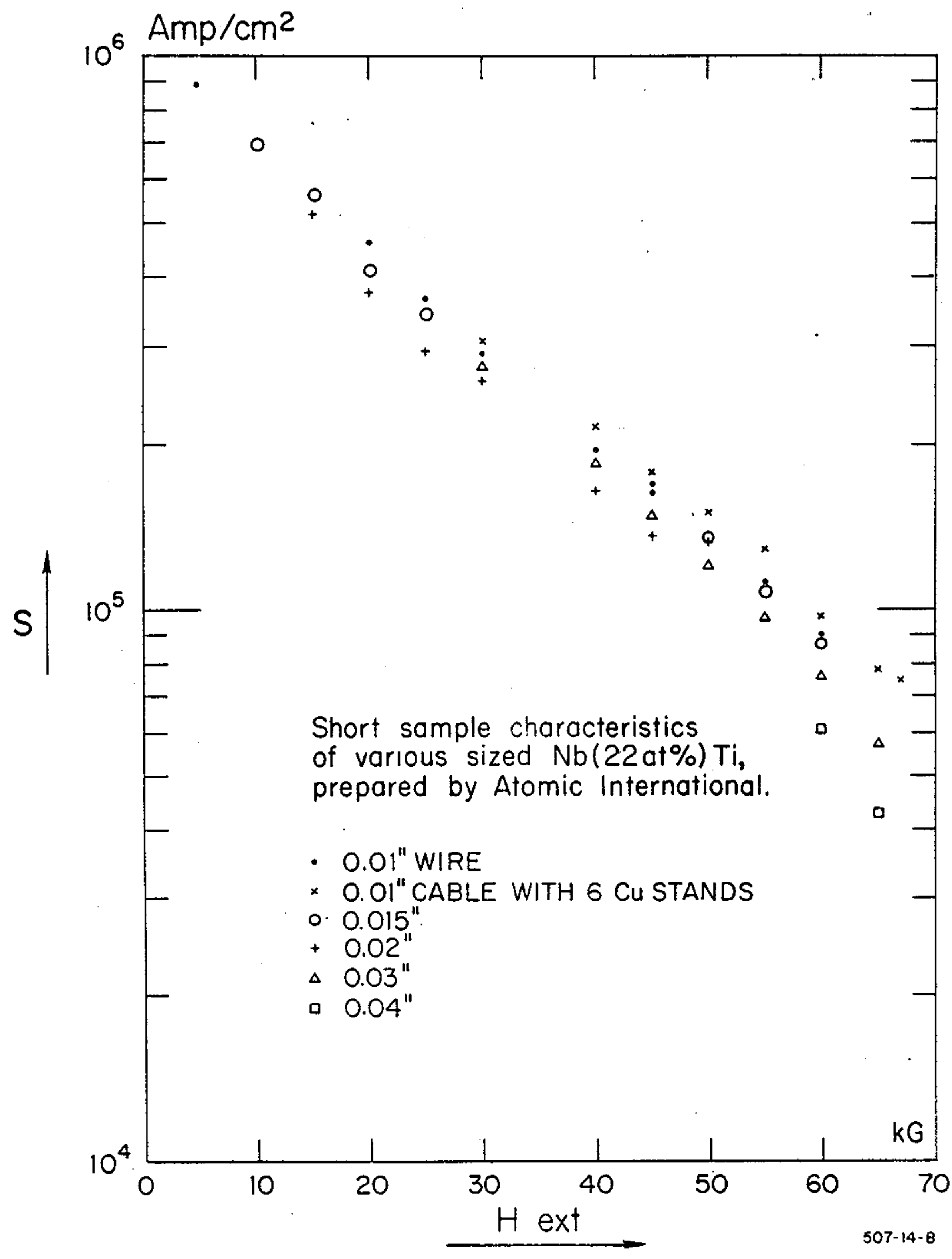


* MAGNETO-R NOT INCLUDED; $\rho_M \cong 4\times10^{-10}\ \Omega\text{-cm/Kg}$
i.e. $\cong 8\times10^{-9}$ @ 20 Kg


AVCO SUPERGENIC STRIP
9 Nb-Zr 10 mil wires
SHORT SAMPLE PERFORMANCE
Oct. 1965
4.2°K
GUARANTEED
PERFORMANCE: +30% -10%
1/2"
0.04"
CROSS SECT.
RECOVERY CURRENT - AMPERES
0
250
500
750
1000
1250
1500
1750
2000
0
10
20
30
40
50
KILOGAUSS
EEB 10/11/65



Dr. C. H. Rosner, The General Electric Co.



Brechna, H., A High Field 1.3m Superconducting Split Coil Magnet with Forced Liquid Helium Cooling, Stanford Linear Accelerator Center, SLAC-PUB-182, April 1966

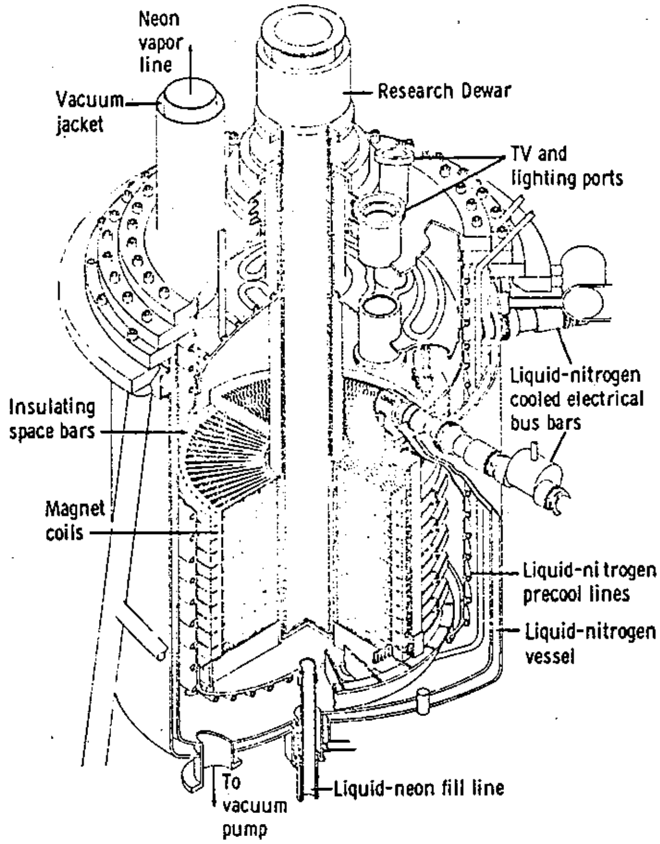


Fig. 1. - 12-in. Coils in magnet vessel.

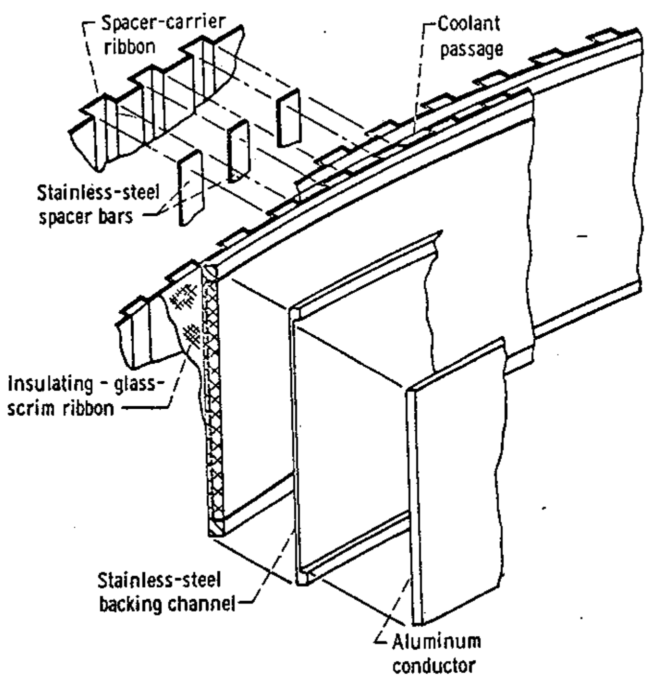


Fig. 2. - Details of coil construction.

Brown, G. V. and Coles, W. D., High-Field Liquid-Neon-Cooled Electromagnets, NASA Tech. Mem. NASA TM X-521

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

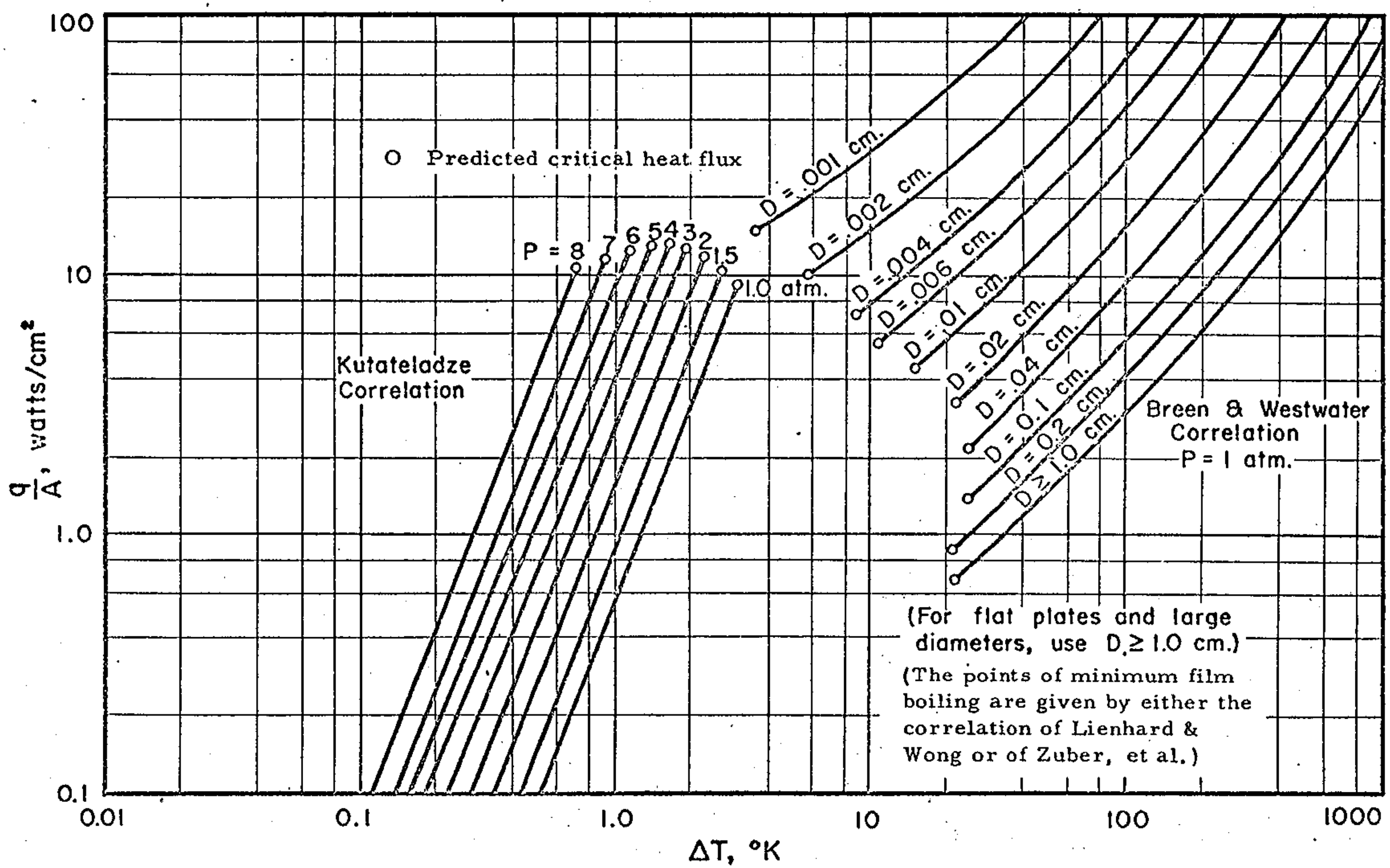


FIGURE 2.7
Predictive Nucleate and Film Pool Boiling Correlations for Hydrogen

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

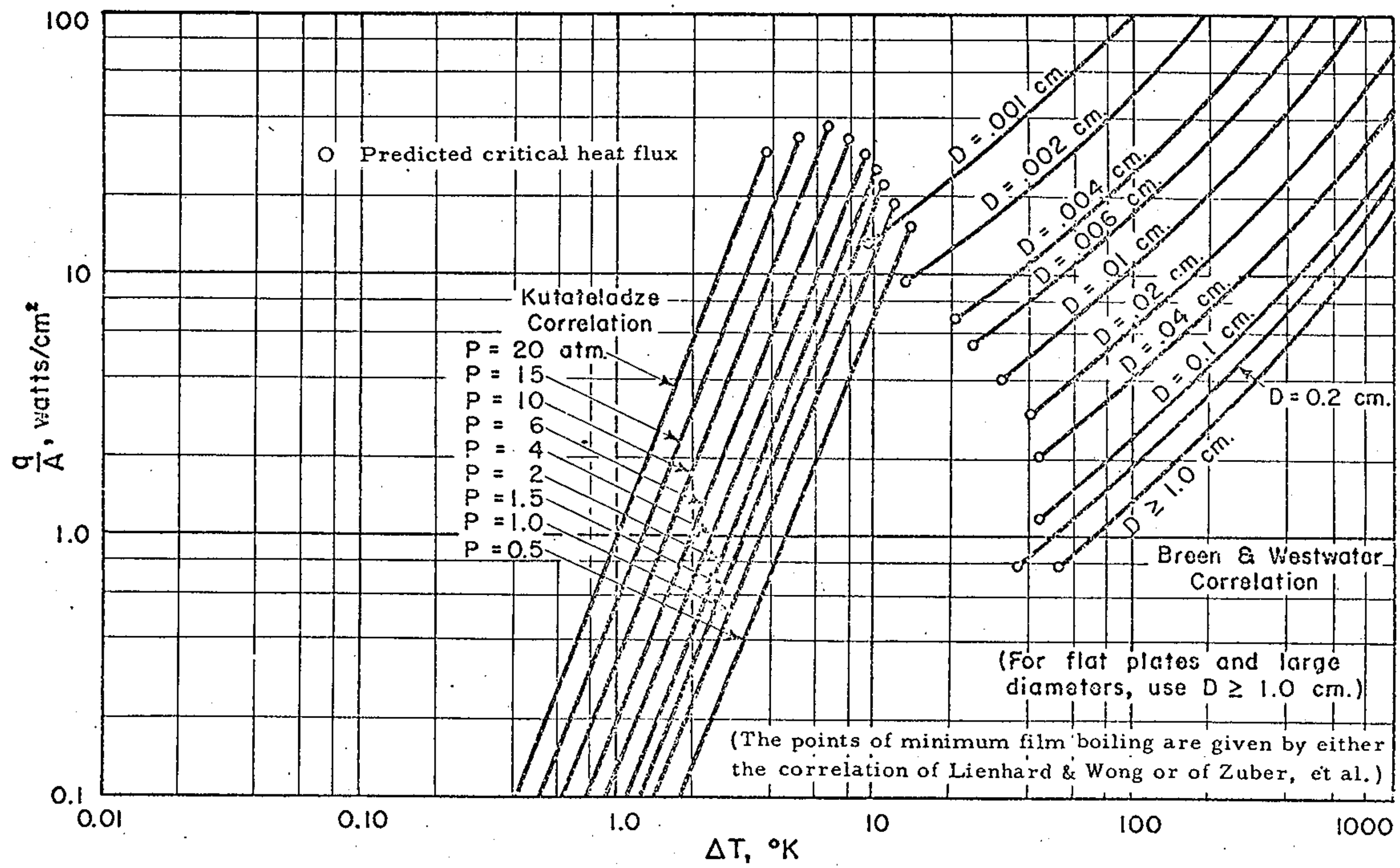


FIGURE 2.6
Predictive Nucleate and Film Pool Boiling Correlations for Nitrogen

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

Brentari, E.G., et al., Boiling Heat Transfer For
...ygen, Nitrogen, Hydrogen, and Helium, NB... Tech.
...e No. 317, Sept. 1965.

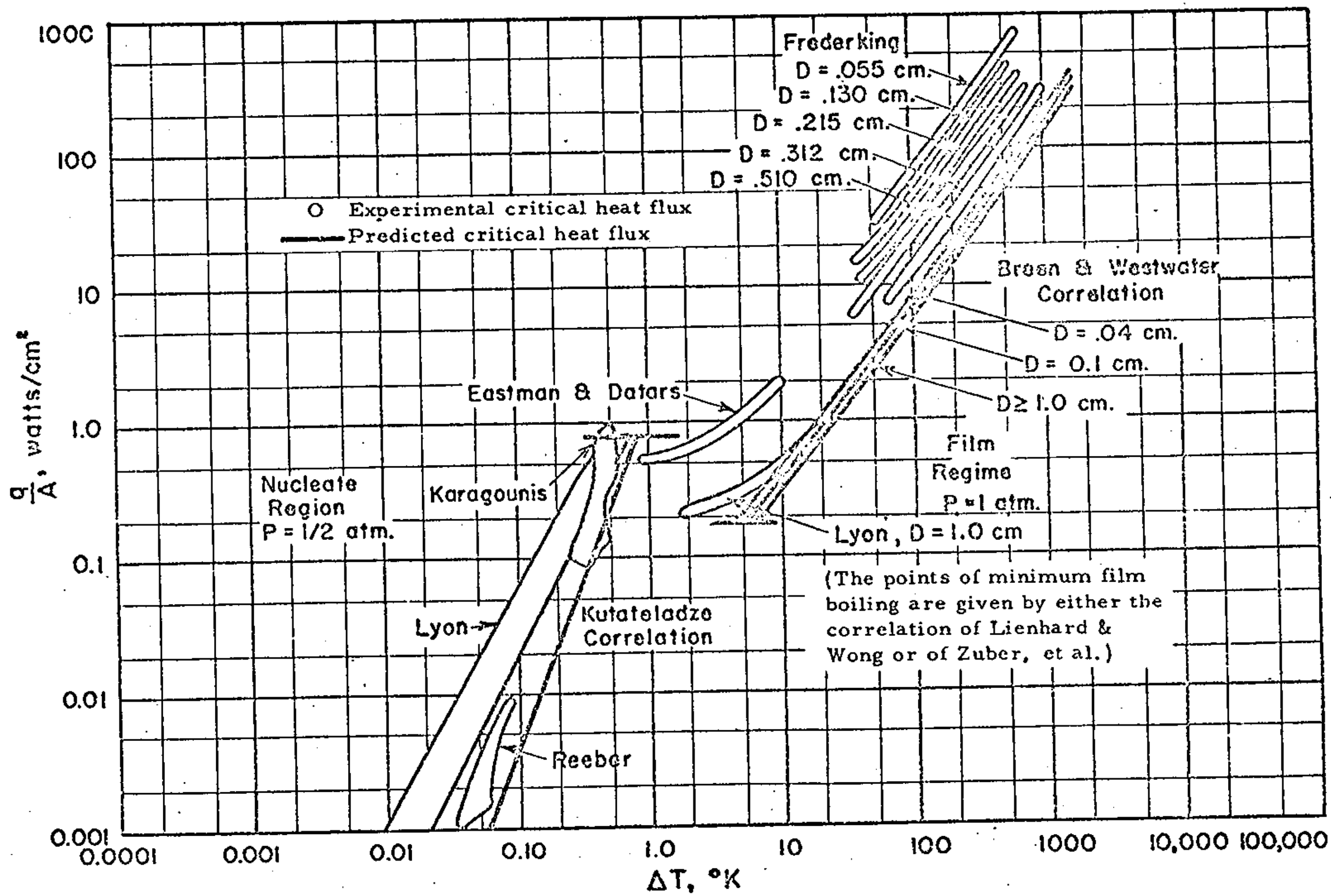


FIGURE 2.4
Experimental Nucleate and Film Pool Boiling of Helium Compared with the Predictive Correlation of Kutatela'ze and Breen and Westwater
Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

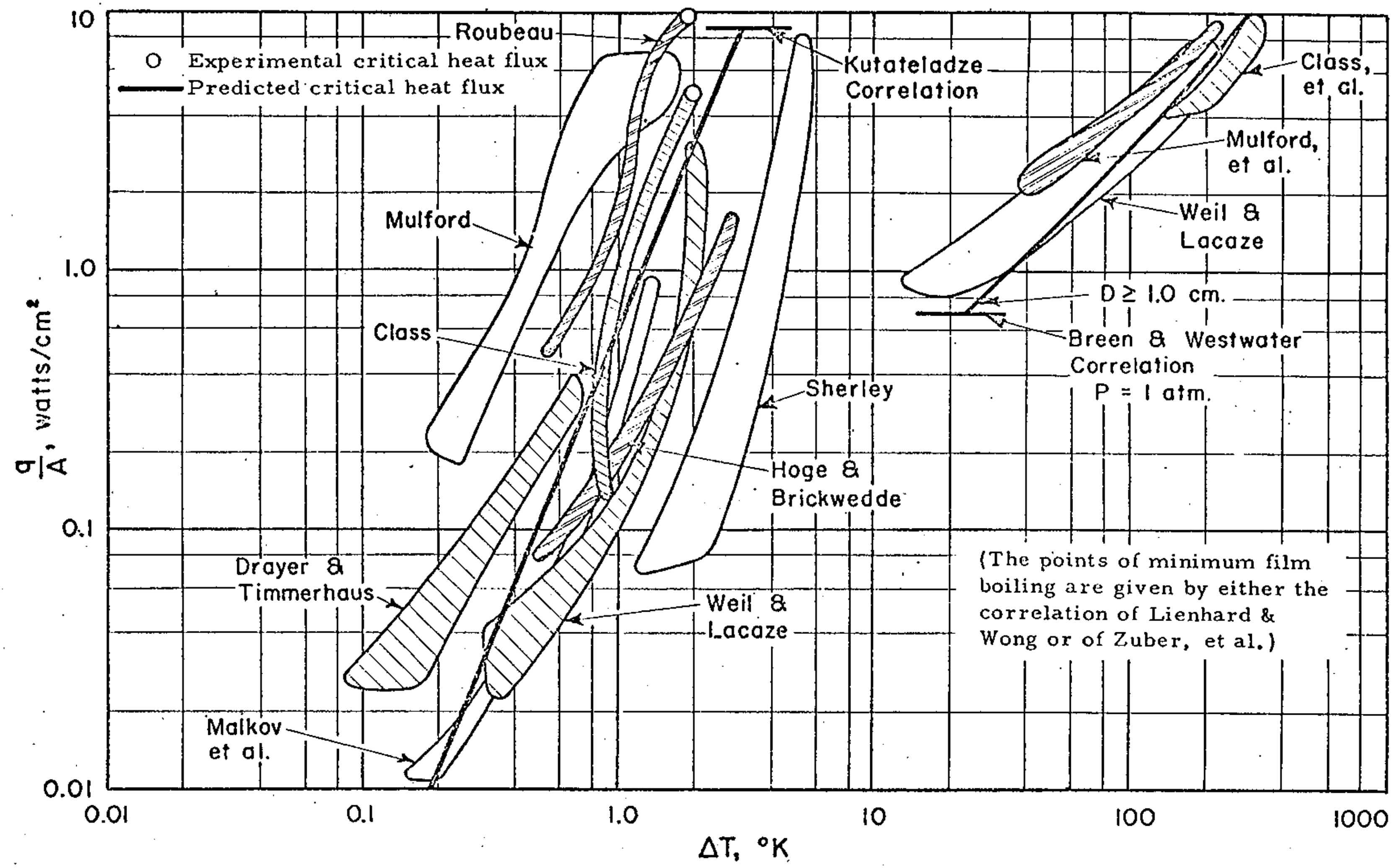


FIGURE 2.3
Experimental Nucleate and Film Pool Boiling of Hydrogen at One Atmosphere Compared with the Predictive Correlations of Kutateladze and Breen and Westwater

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

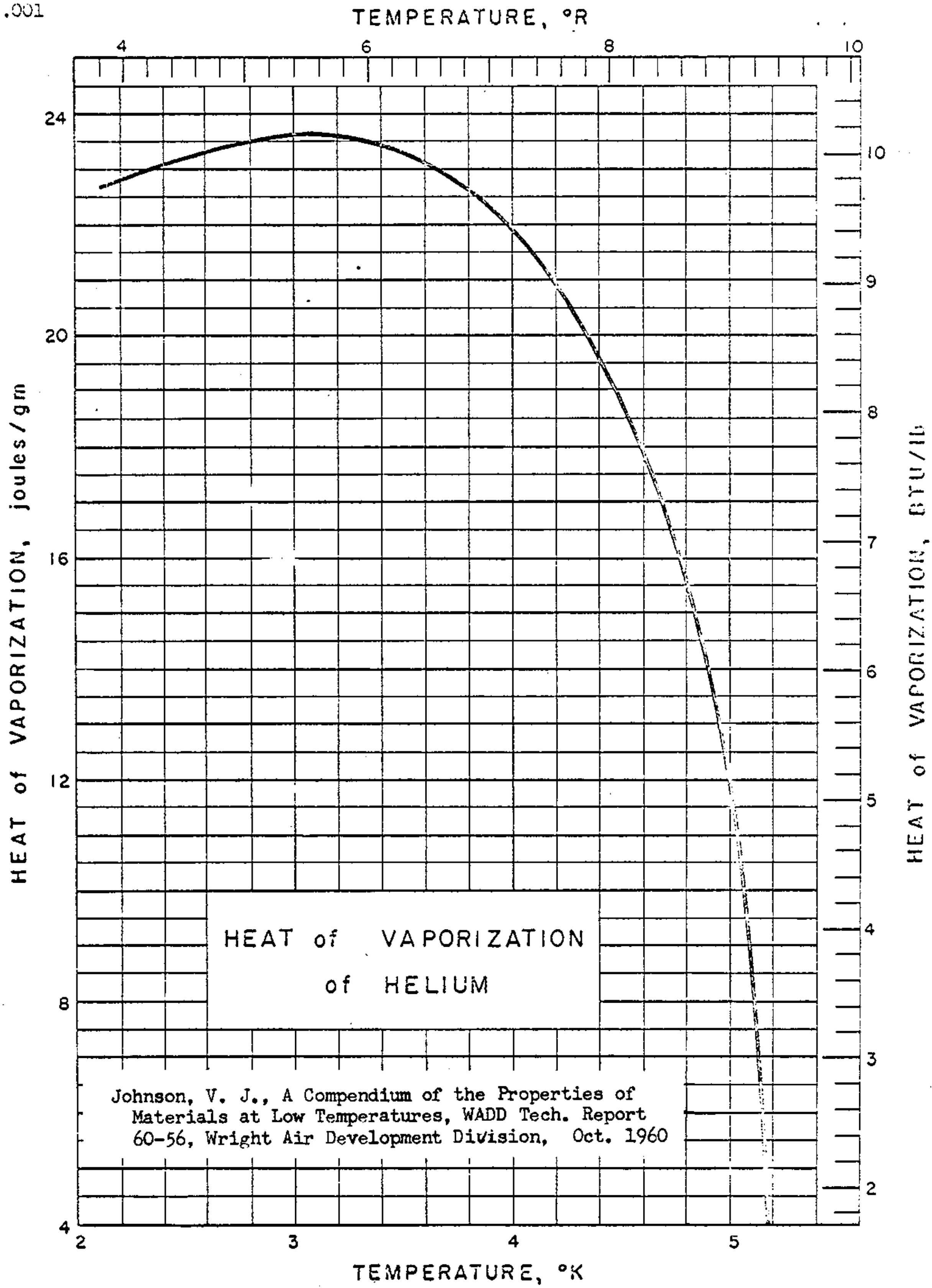
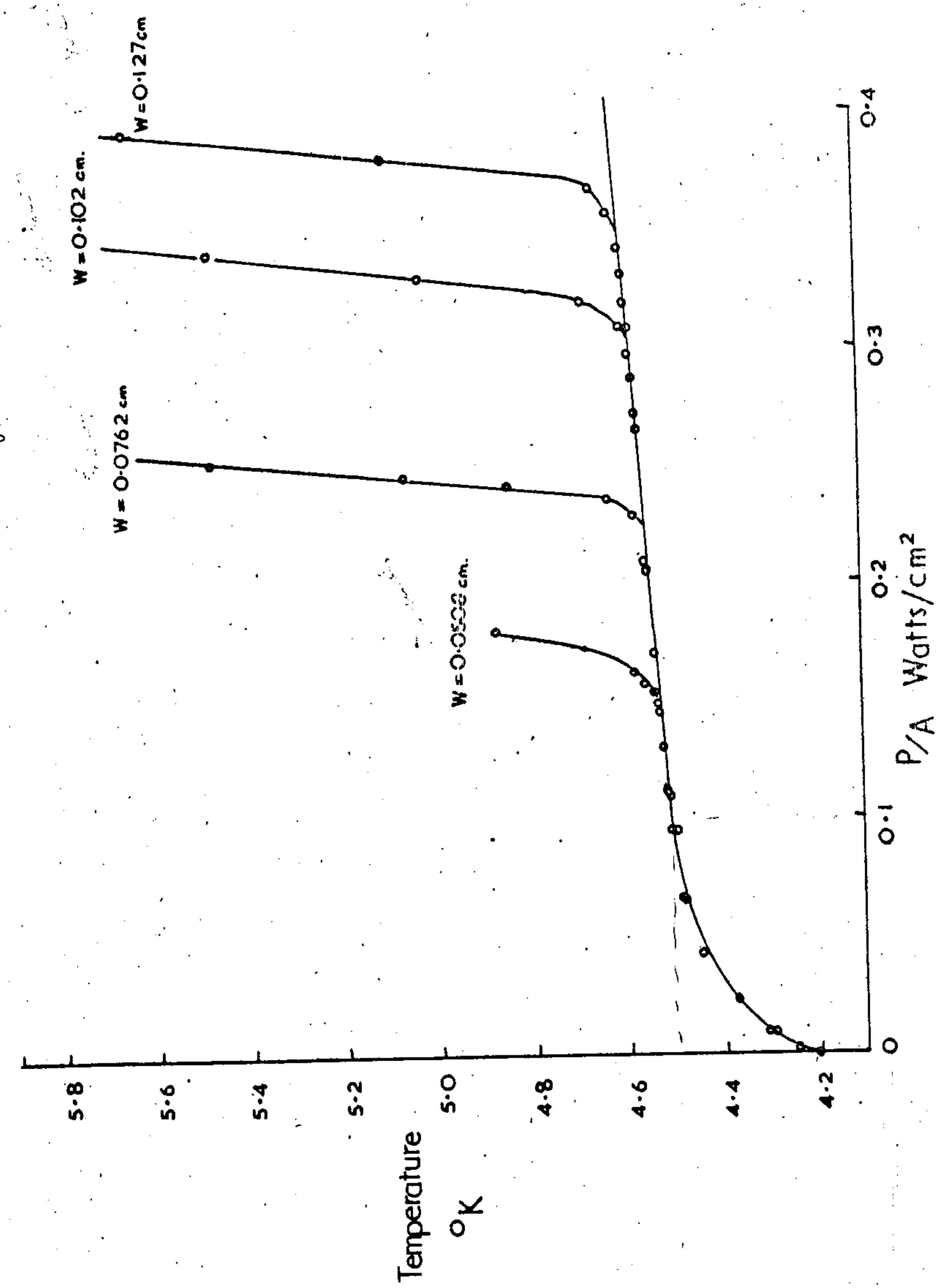

TEMPERATURE, °R
4
6
8
10
24
20
16
12
8
4
10
9
8
7
6
5
4
3
2
HEAT of VAPORIZATION, joules/gm
HEAT of VAPORIZATION, BTU/lb
HEAT of VAPORIZATION
of HELIUM
Johnson, V. J., A Compendium of the Properties of Materials at Low Temperatures, WADD Tech. Report 60-56, Wright Air Development Division, Oct. 1960
2
3
4
5
TEMPERATURE, °K

Fig. 2 Power/cm^2 vs. Temperature.



Wilson, M. N., Heat Transfer to Boiling Liquid Helium in Narrow Vertical Channels, Rutherford Lab., Berks., England, IIR Commission 1 Meeting June 66

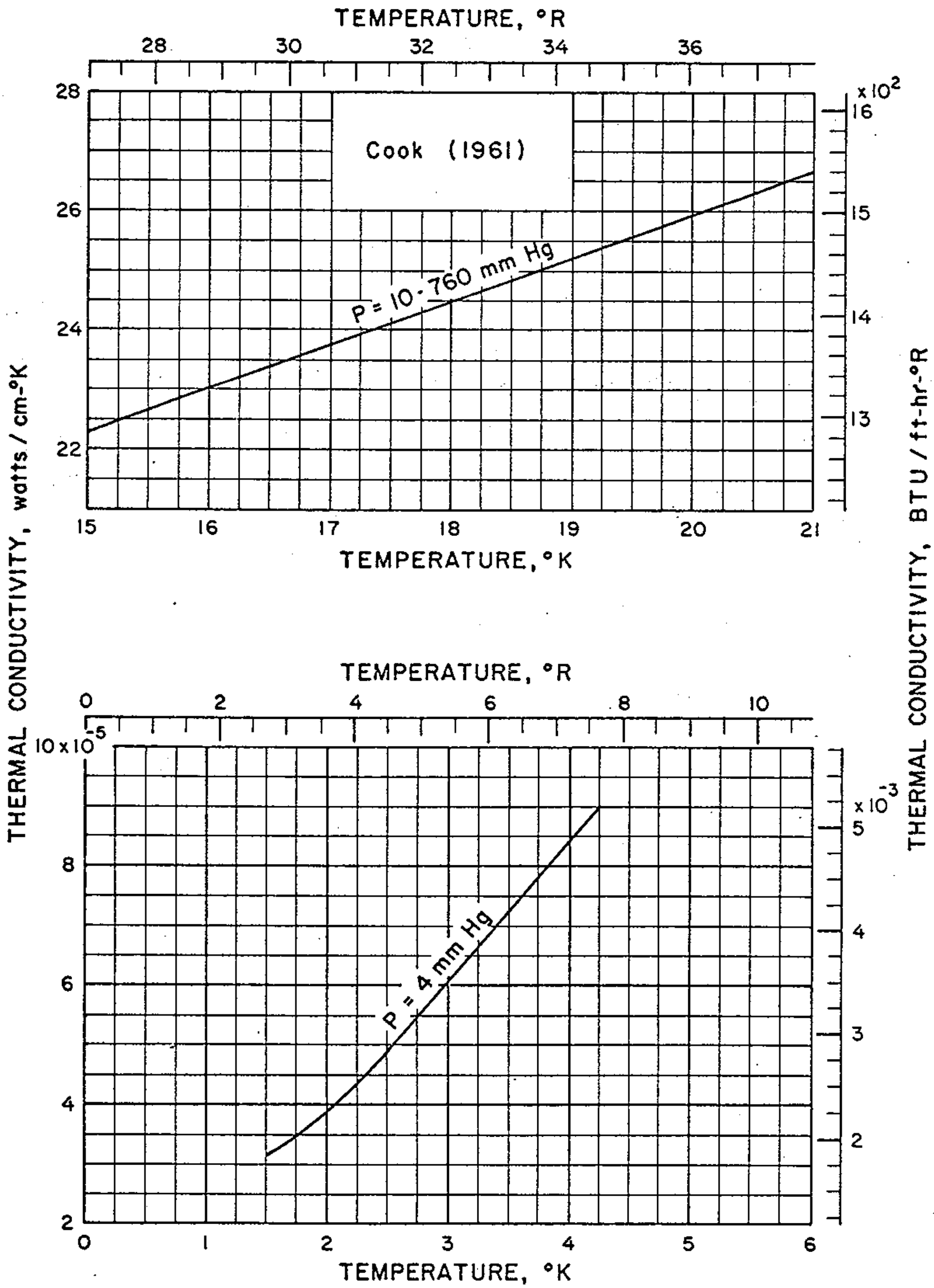


Figure 6.29 Thermal conductivity of gaseous helium from 1.5°K to 21°K

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

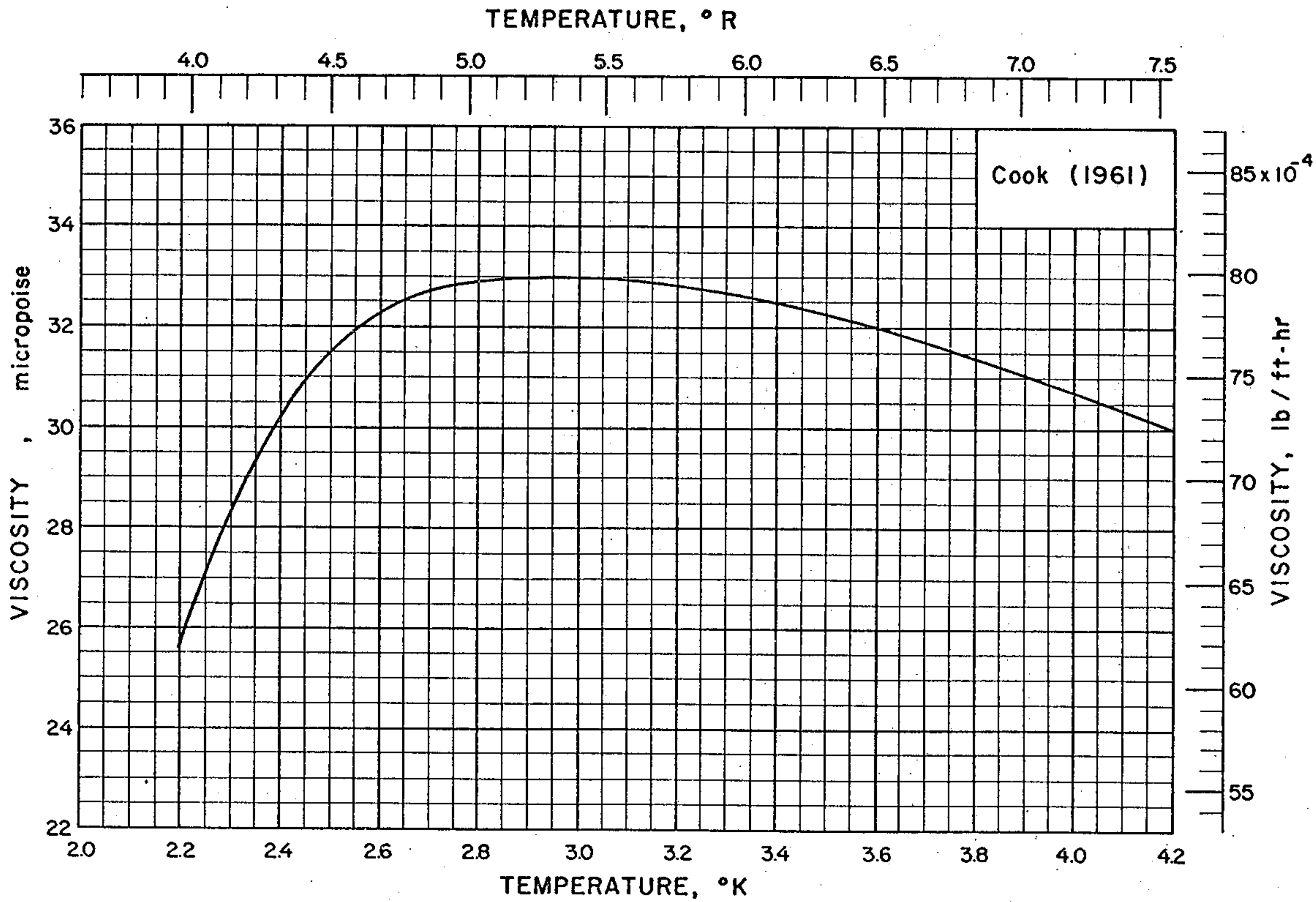
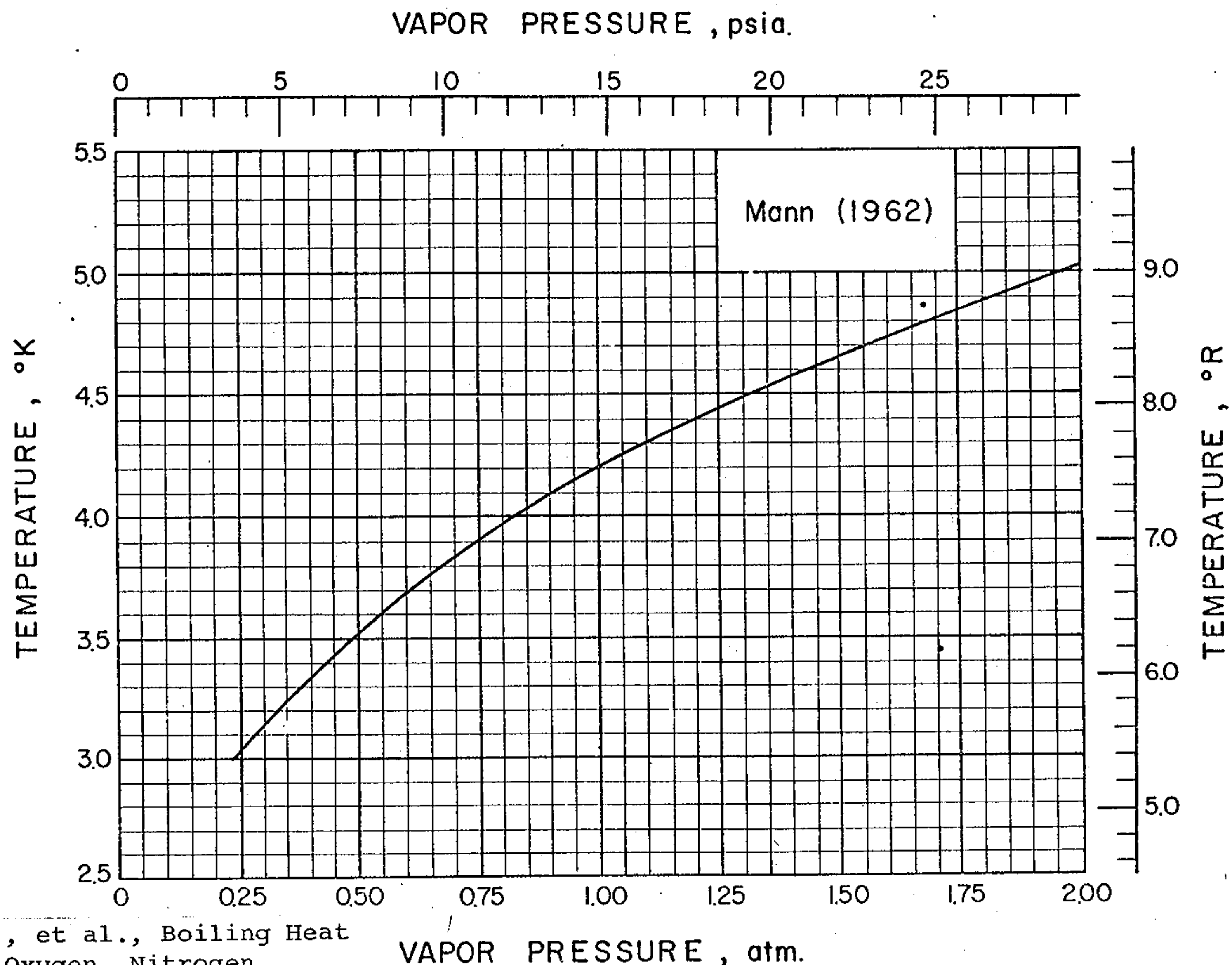


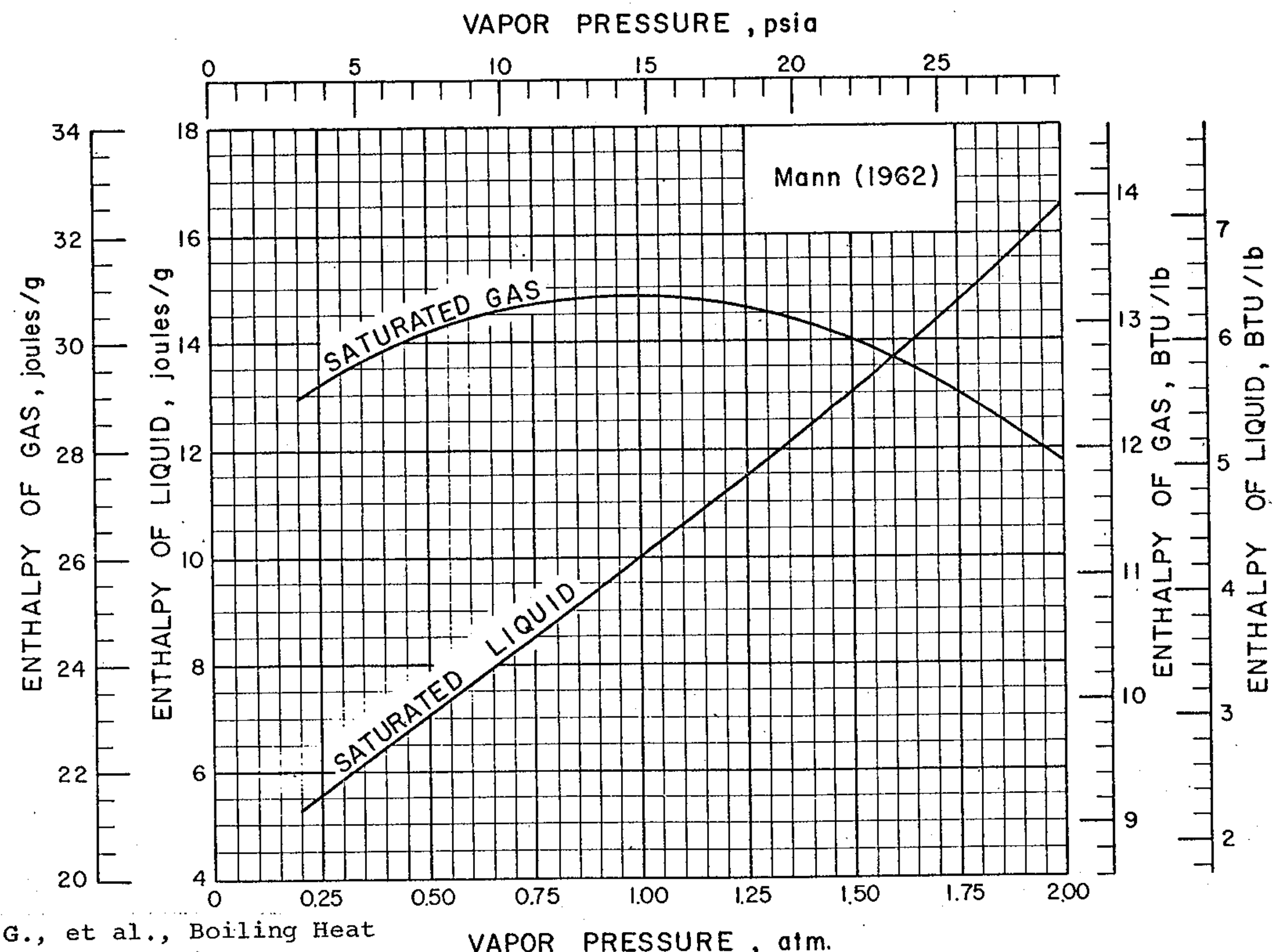
Figure 6.36 Viscosity of saturated liquid helium I

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965



Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen and Helium, NBS Tech. Note No. 317, Sept. 1965.

Figure 6.5 Vapor pressure of helium-4



Brentari, E.G., et al., Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. No. 317, Sept. 1965.

Figure 6.1 Enthalpy of saturated gaseous and saturated liquid helium

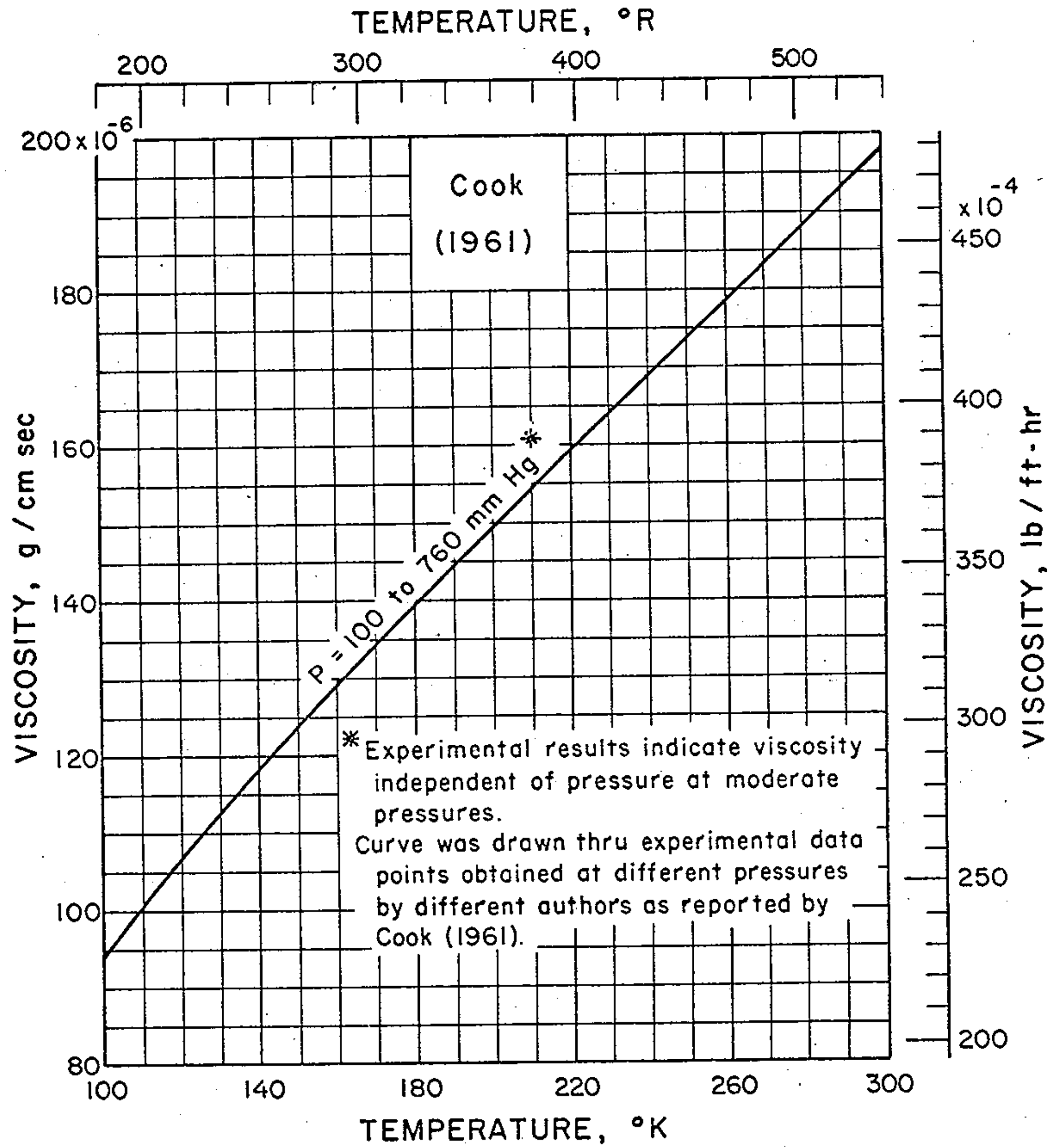


Figure 6.38 Viscosity of gaseous helium from 100° to 300°K

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

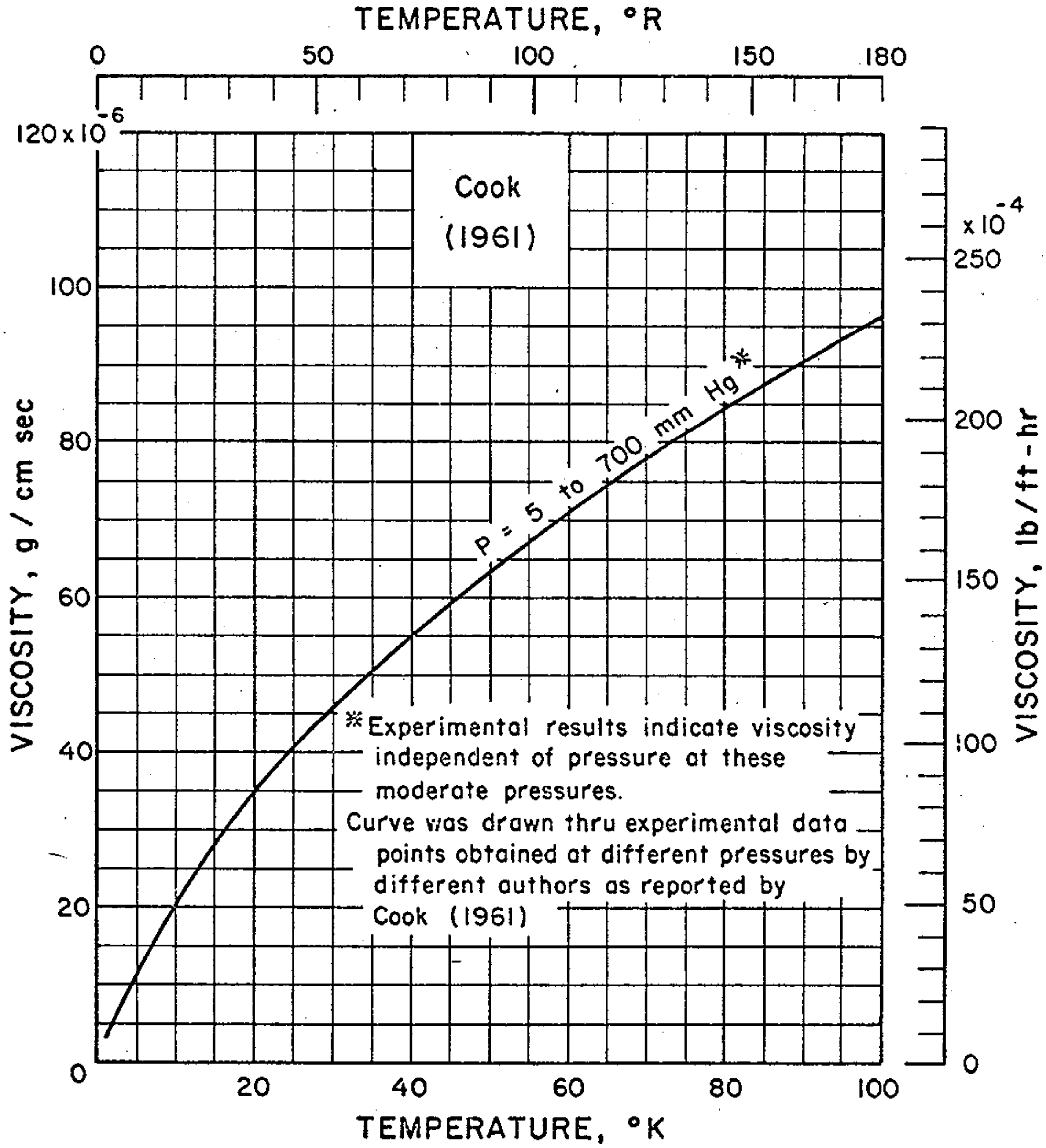


Figure 6.37 Viscosity of gaseous helium from 0° to 100°K

Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

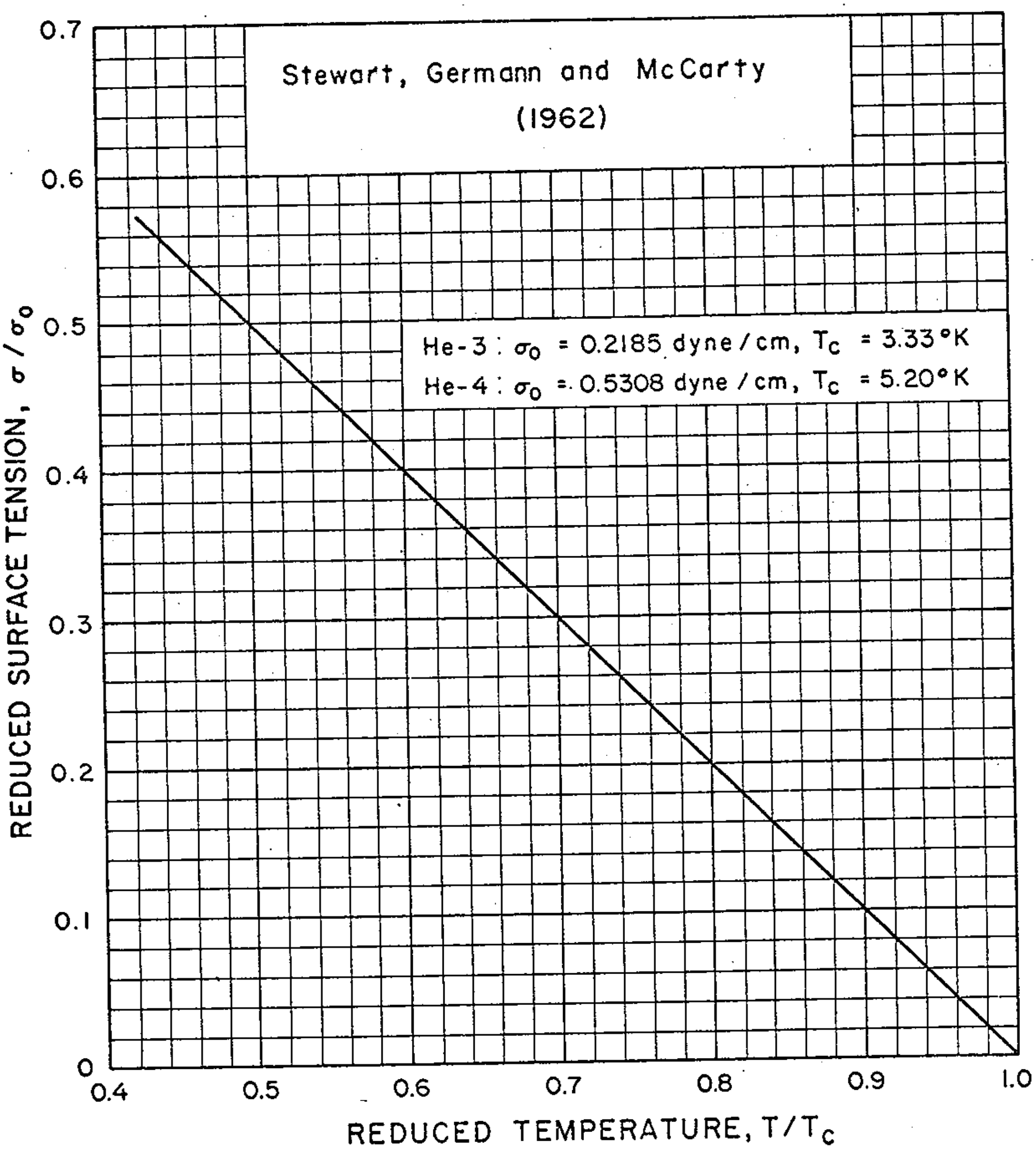
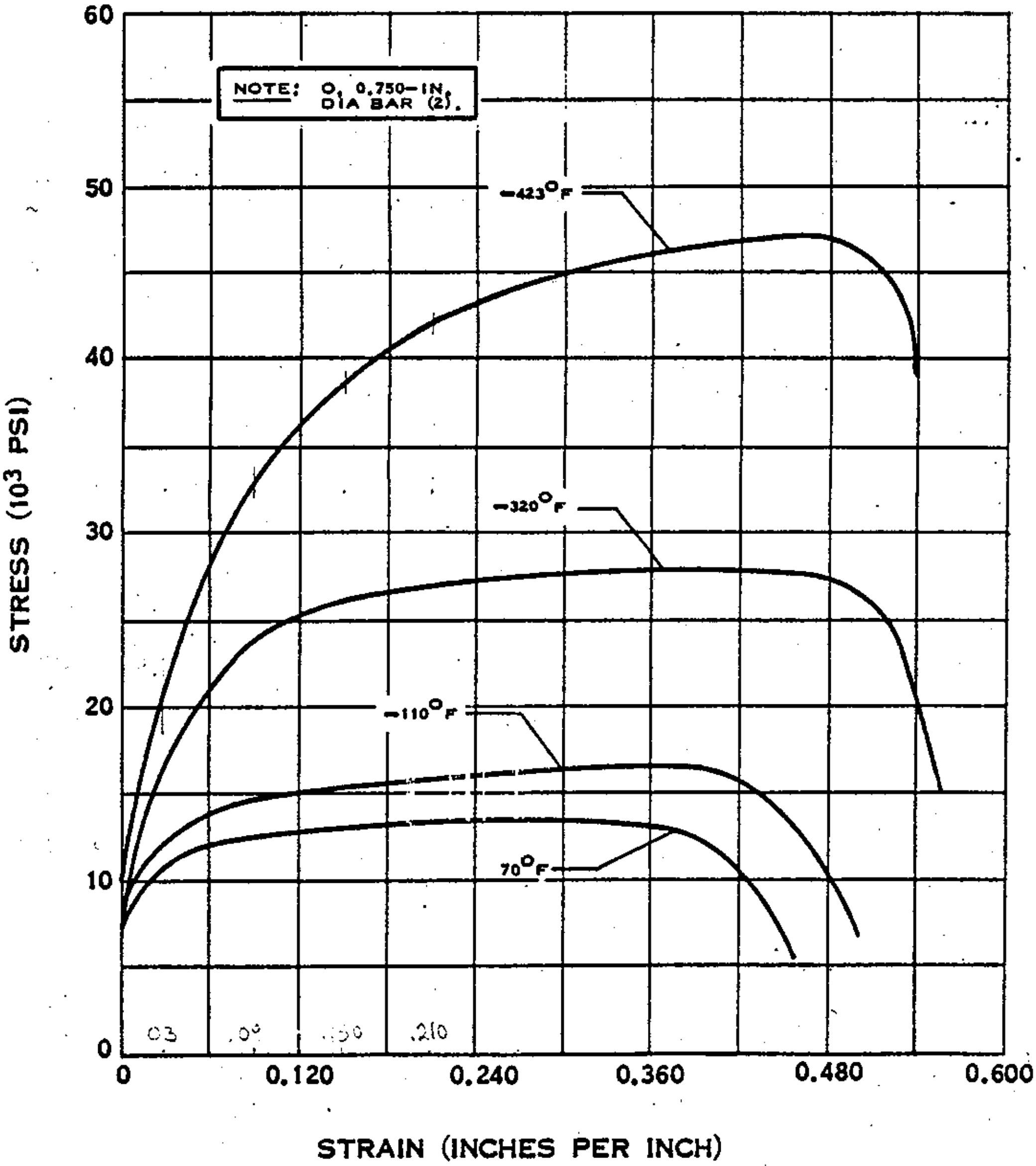


Figure 6.24 Surface tension for helium-3, and helium 4

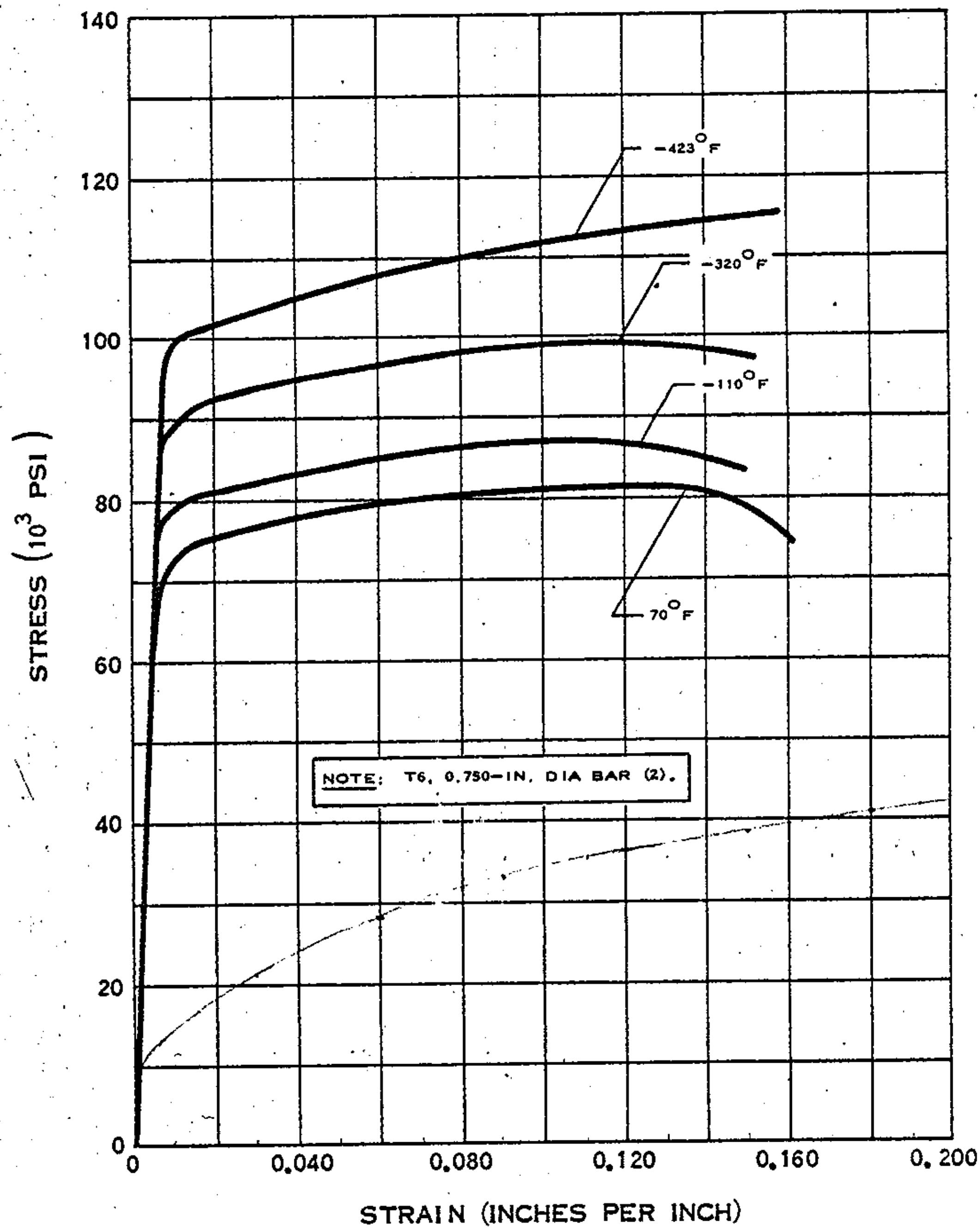
Brentari, E.G., et al., Boiling Heat Transfer For Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, Sept. 1965.

A.1.h



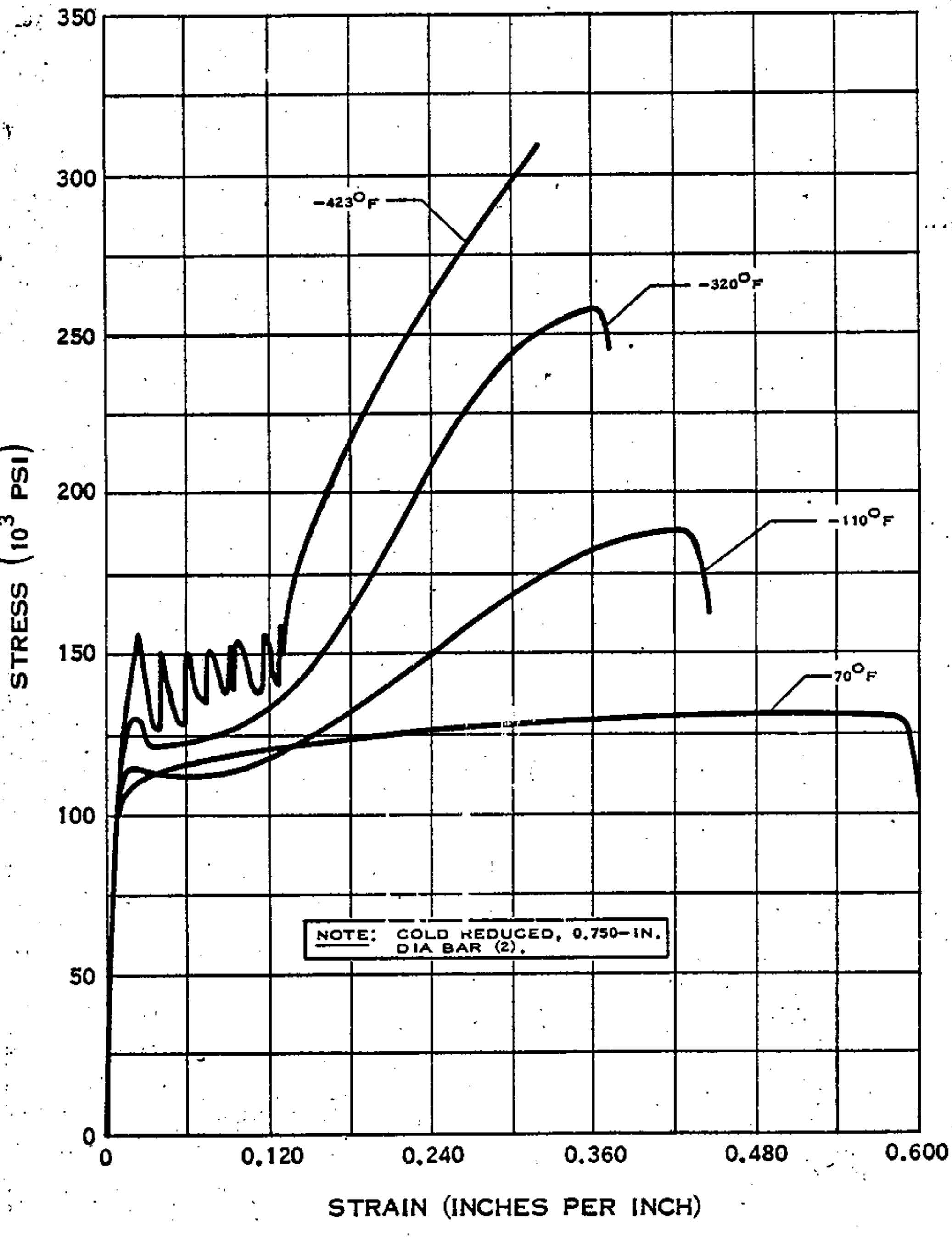
STRESS-STRAIN DIAGRAM FOR 1100 ALUMINUM

A.16.h

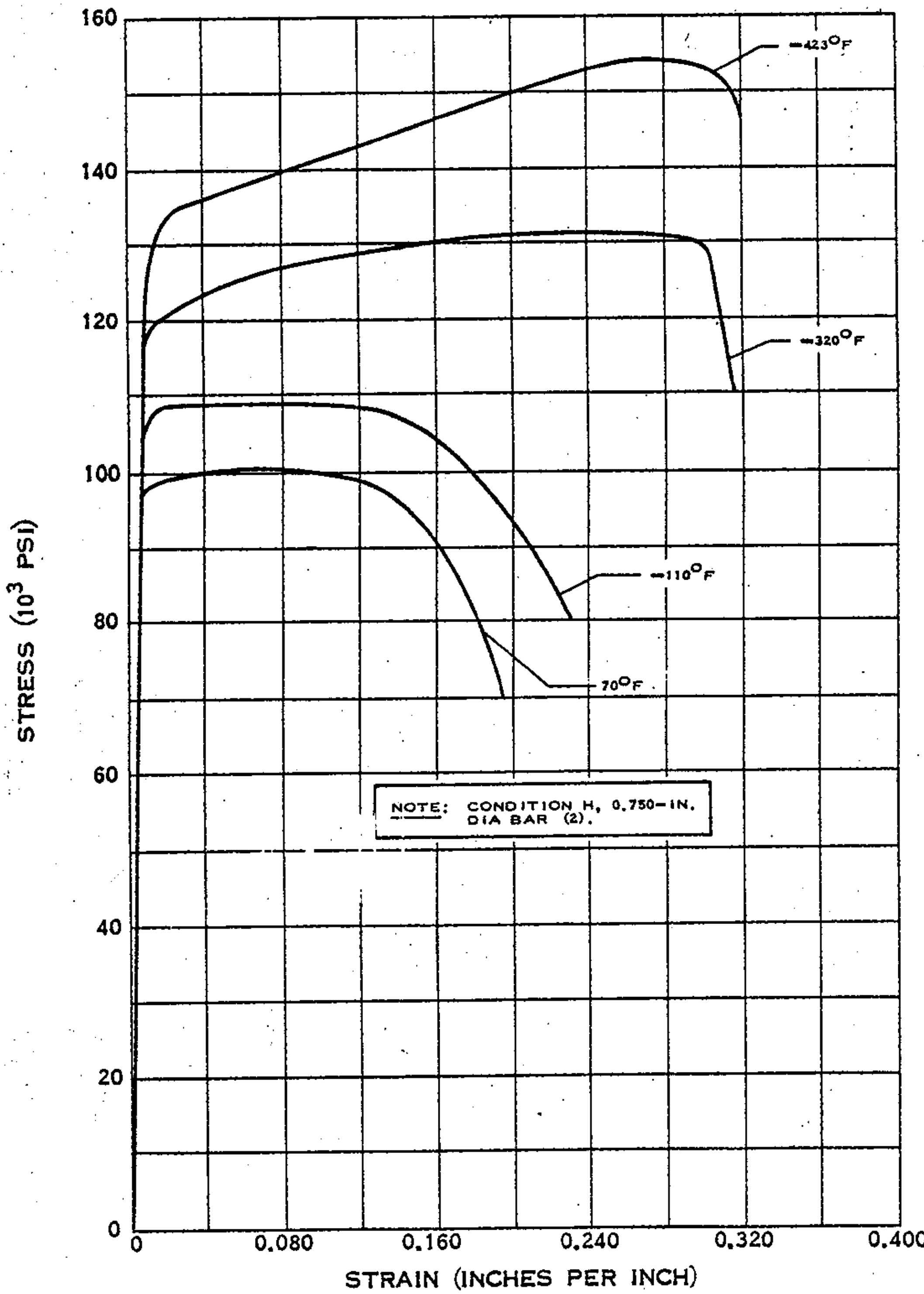


STRESS-STRAIN DIAGRAM FOR 7075 ALUMINUM

(7-64)

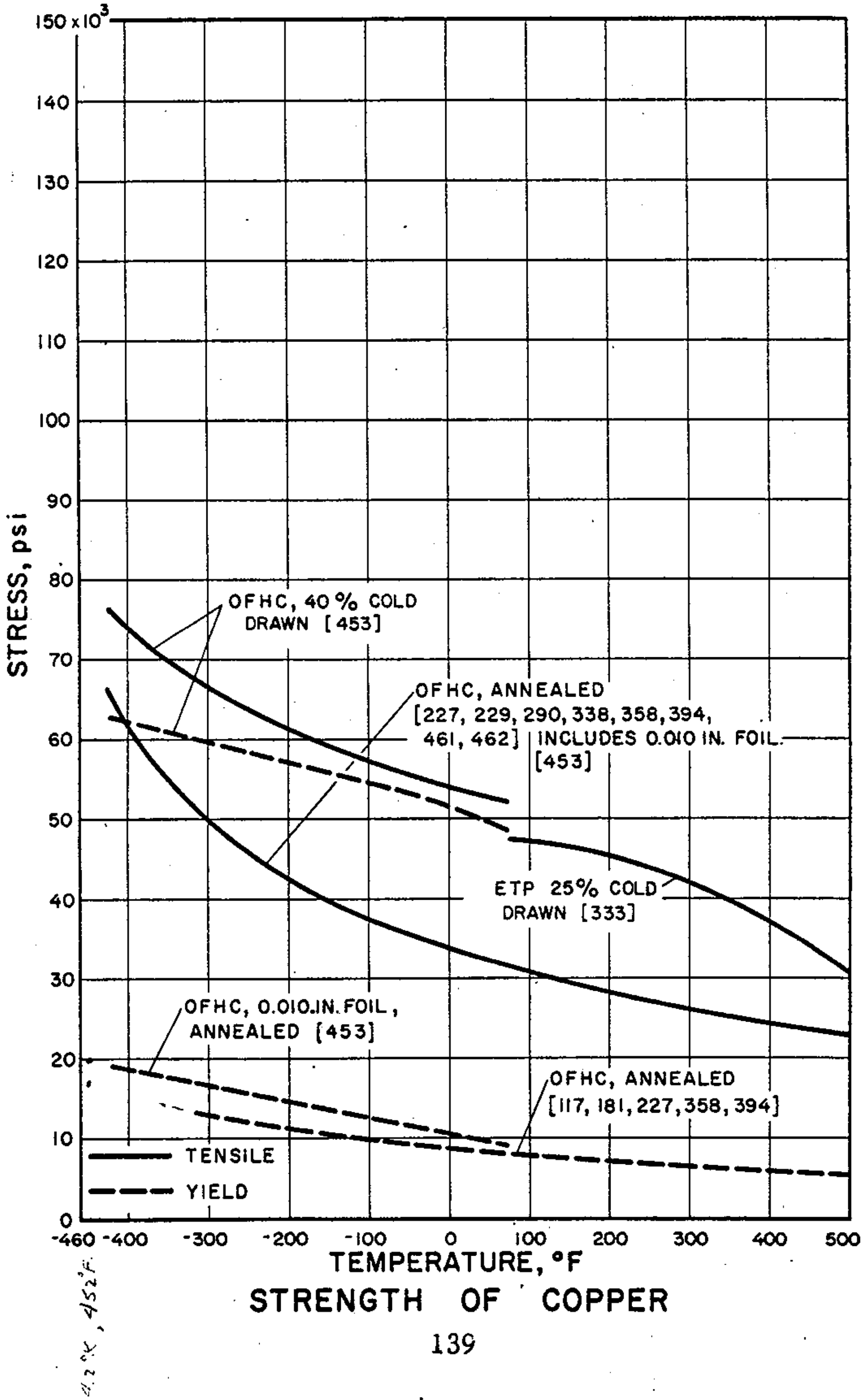


STRESS-STRAIN DIAGRAM FOR 302 STAINLESS STEEL



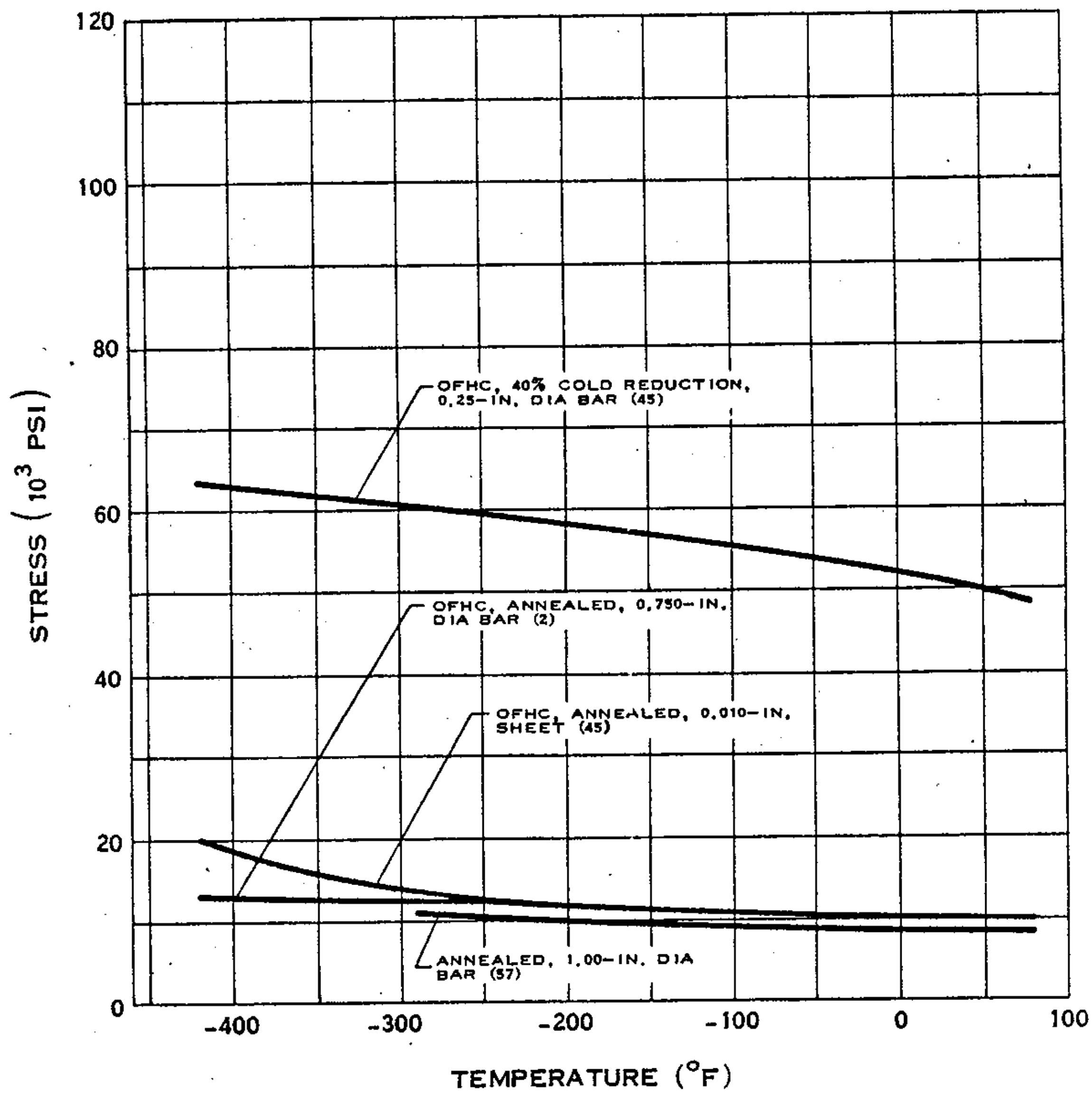
STRESS-STRAIN DIAGRAM FOR BERYLLIUM COPPER

From Cryo Mat. H.B.
Mc Clinton Reed et, Al



STRENGTH OF COPPER

F.1.a

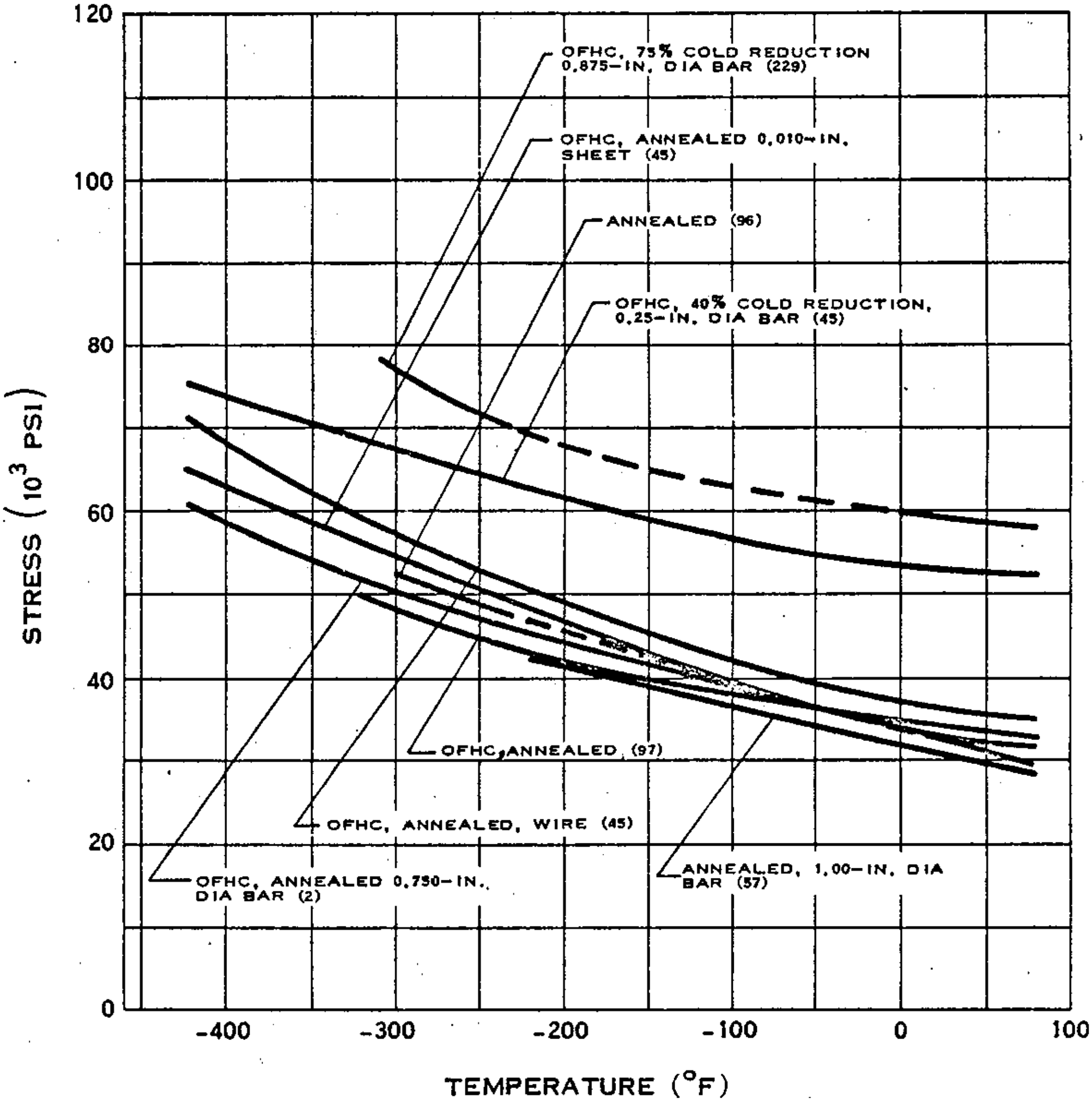


YIELD STRENGTH OF COPPER

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

F.1.b

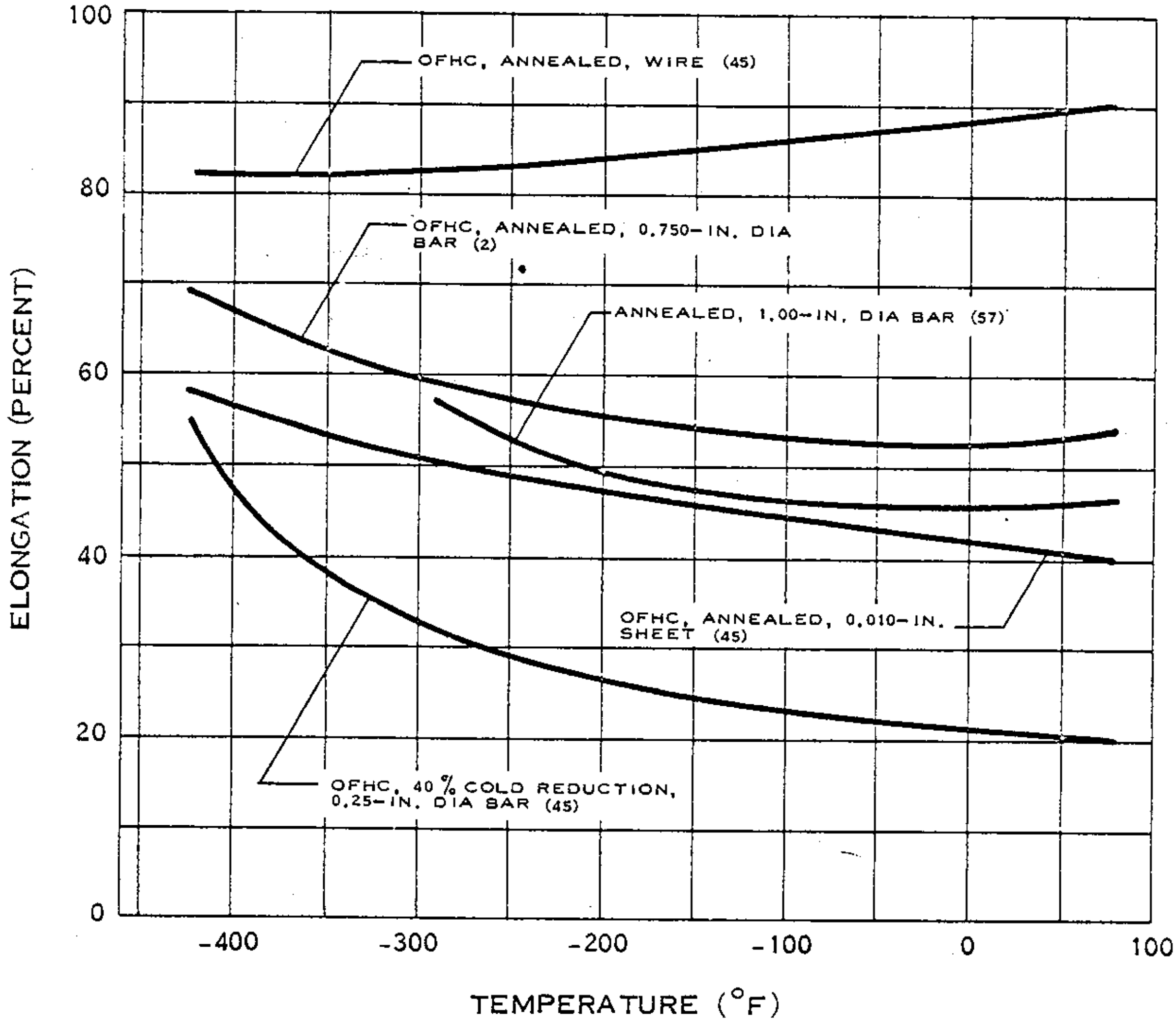


TENSILE STRENGTH OF COPPER

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

F.1.c

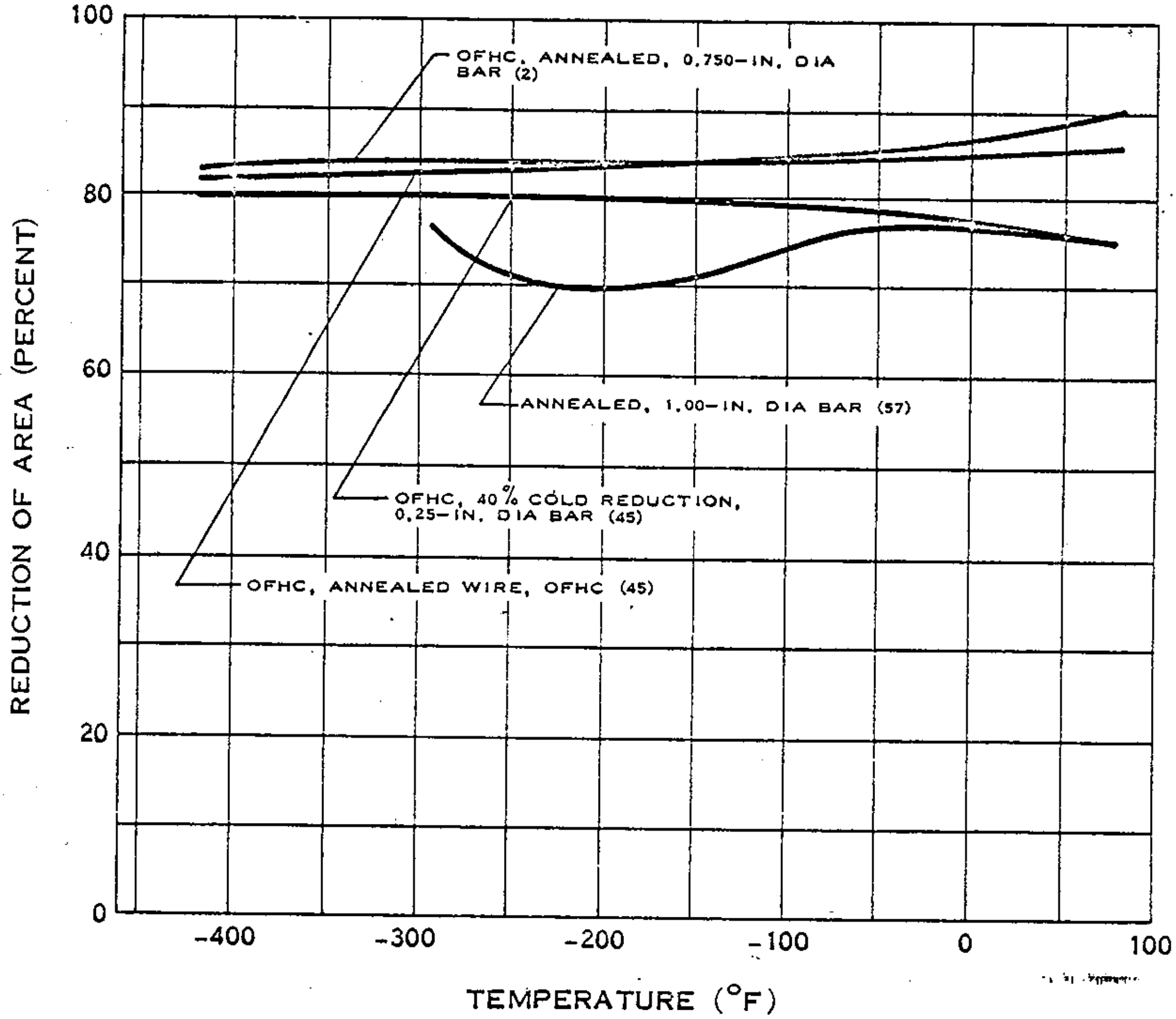


ELONGATION OF COPPER

(7-64)

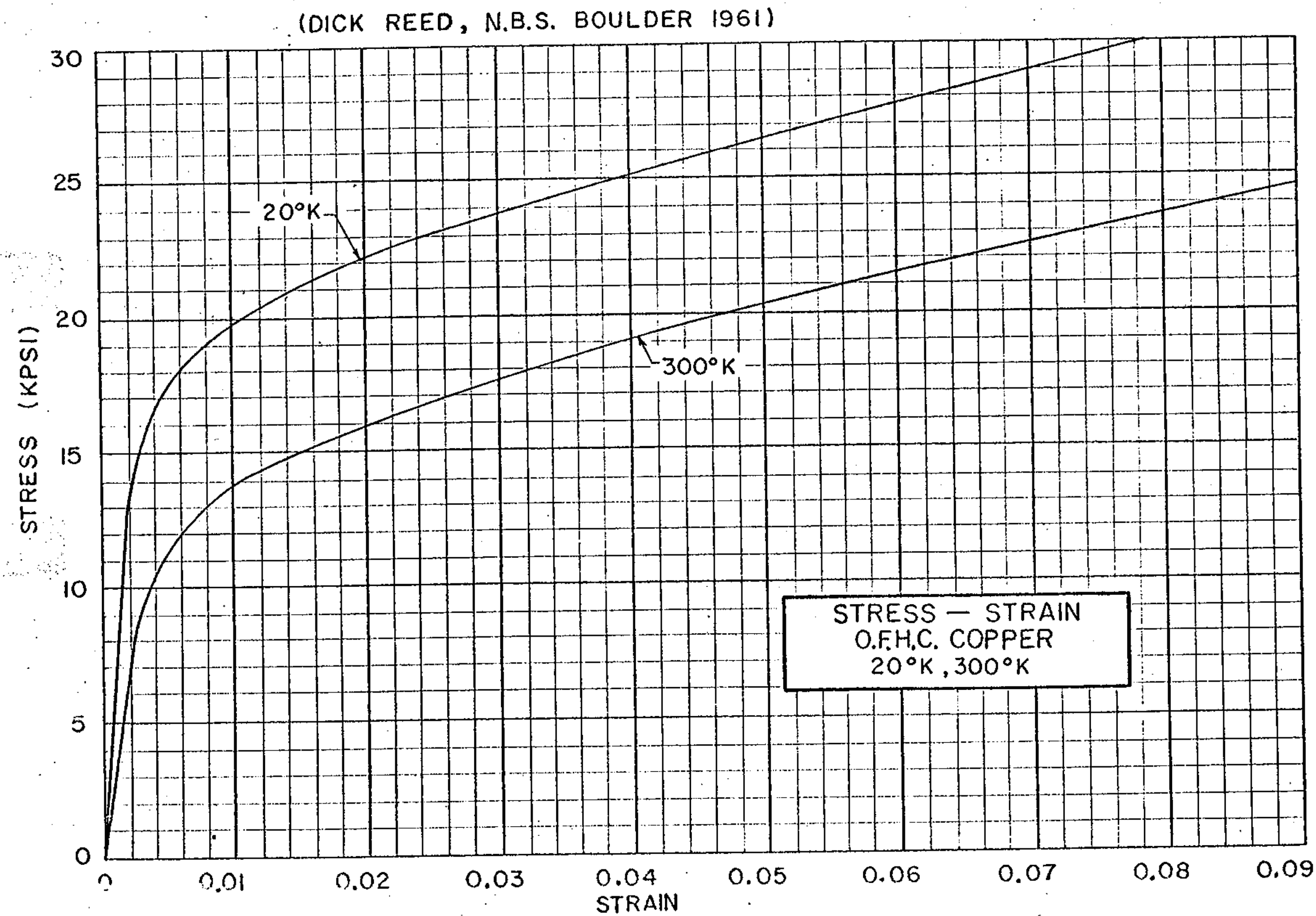
Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

F.1.d

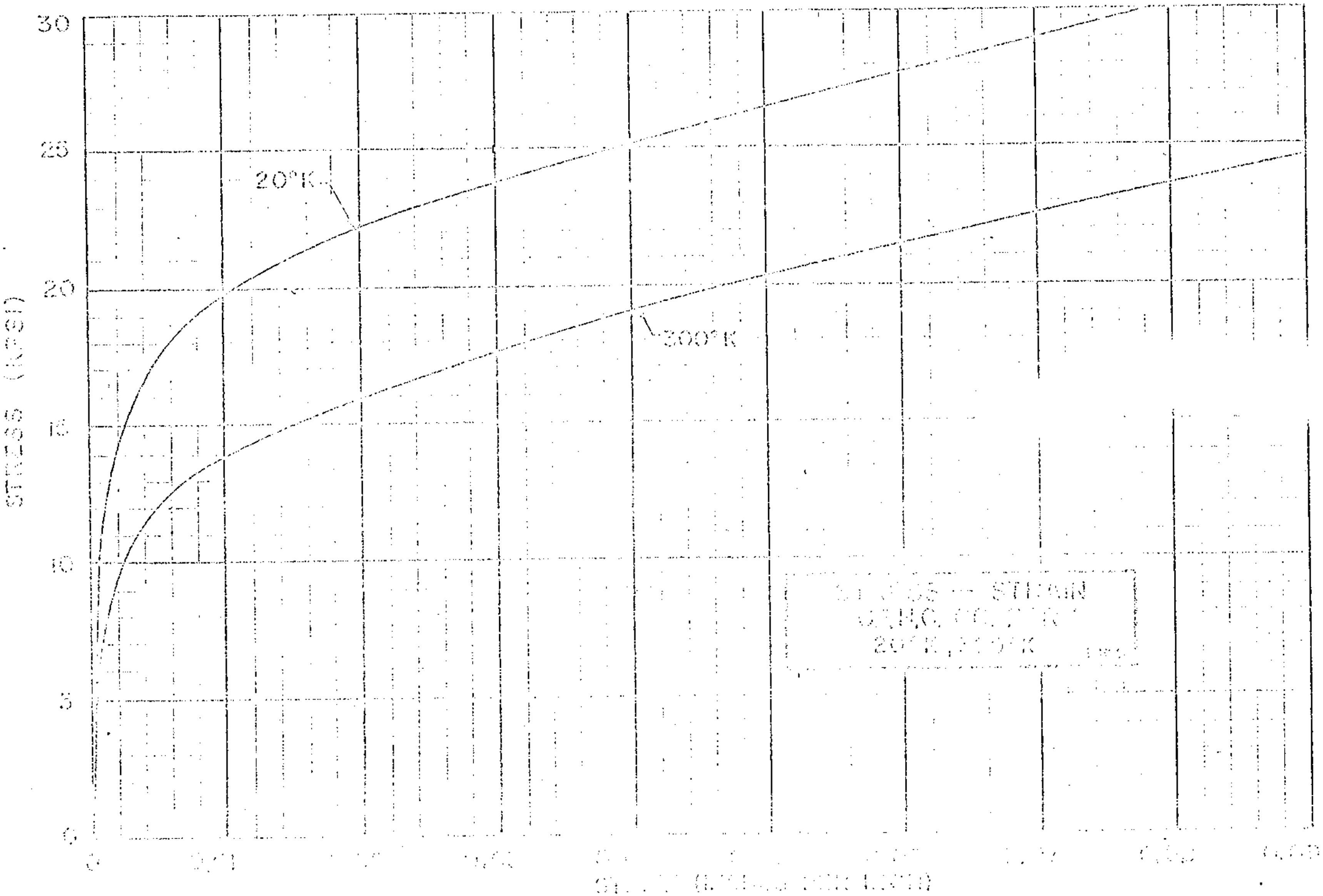


REDUCTION OF AREA OF COPPER

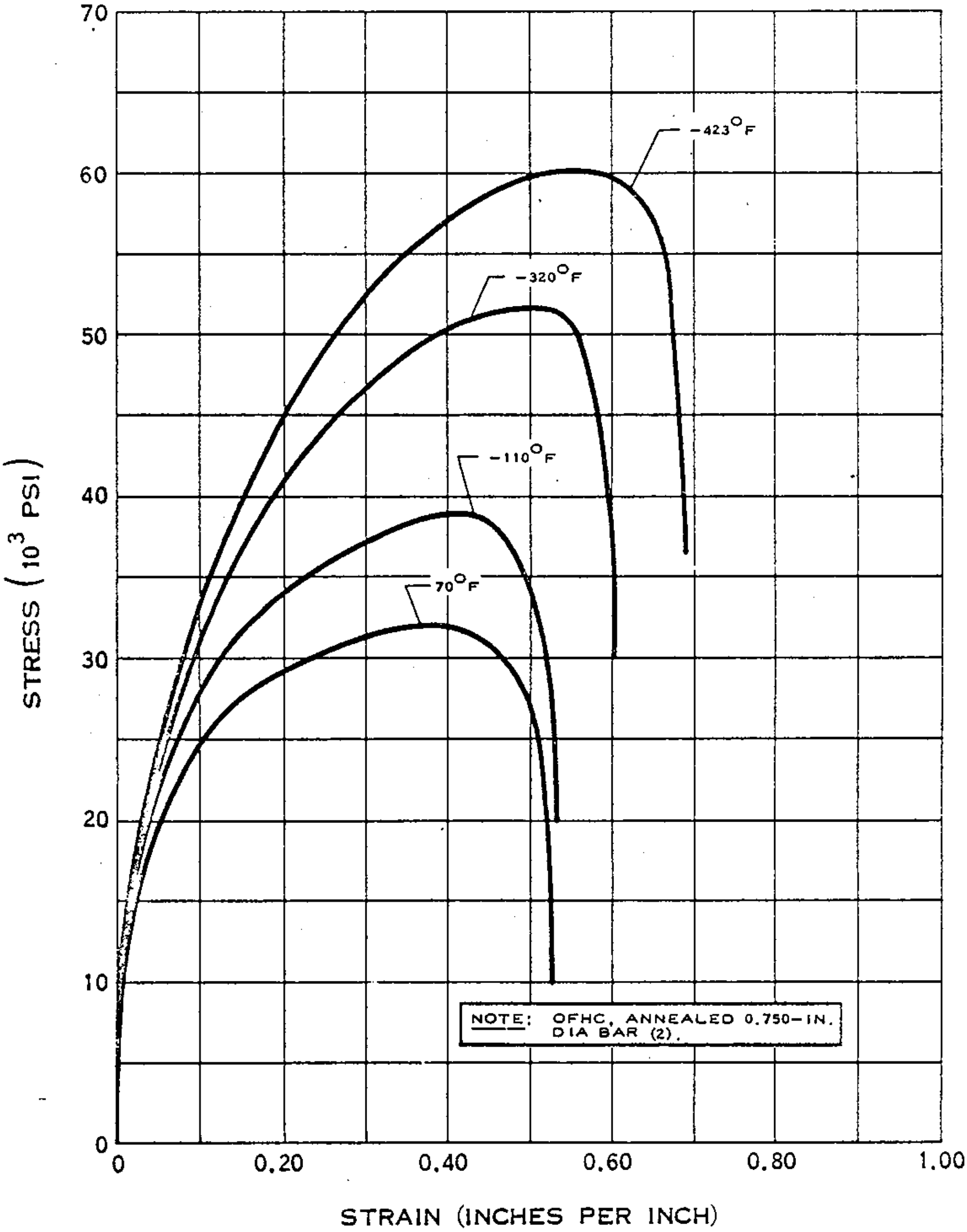
Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964


(DICK REED, N.B.S. BOULDER 1961)
STRESS (KPSI)
30
25
20
15
10
5
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
STRAIN
20°K
300°K
STRESS — STRAIN
O.F.H.C. COPPER
20°K, 300°K

(DICK REED, N.B.S. BOULDER 1961)



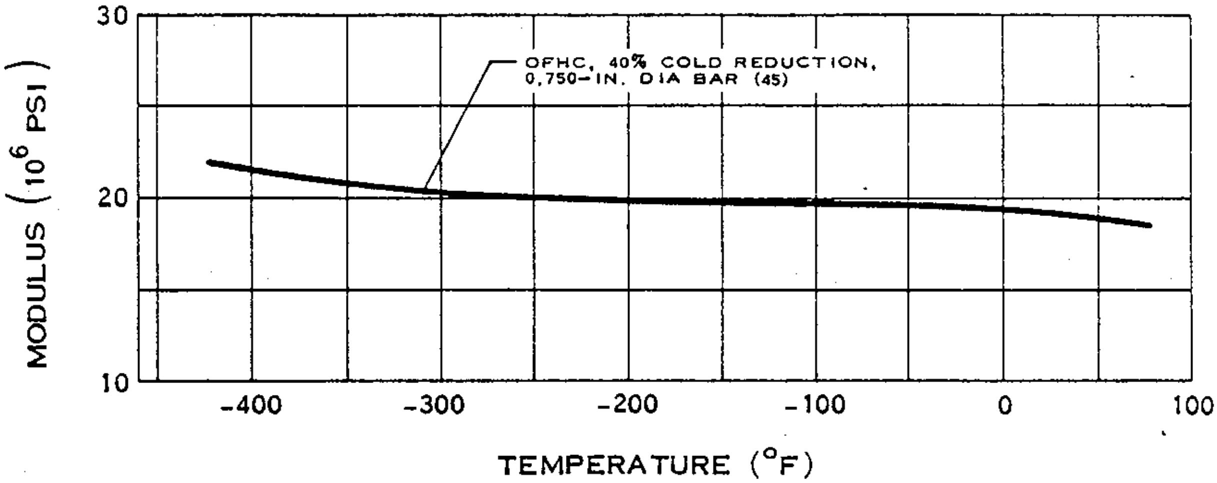
F.1.h



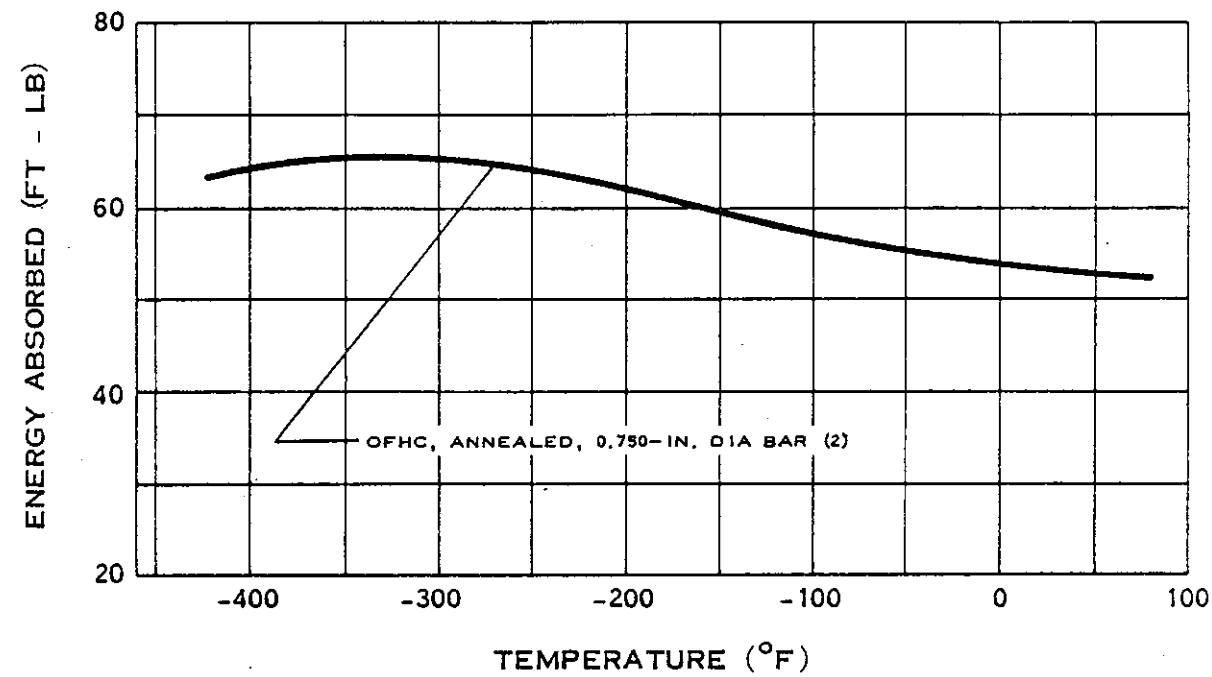
STRESS-STRAIN DIAGRAM FOR COPPER

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964.



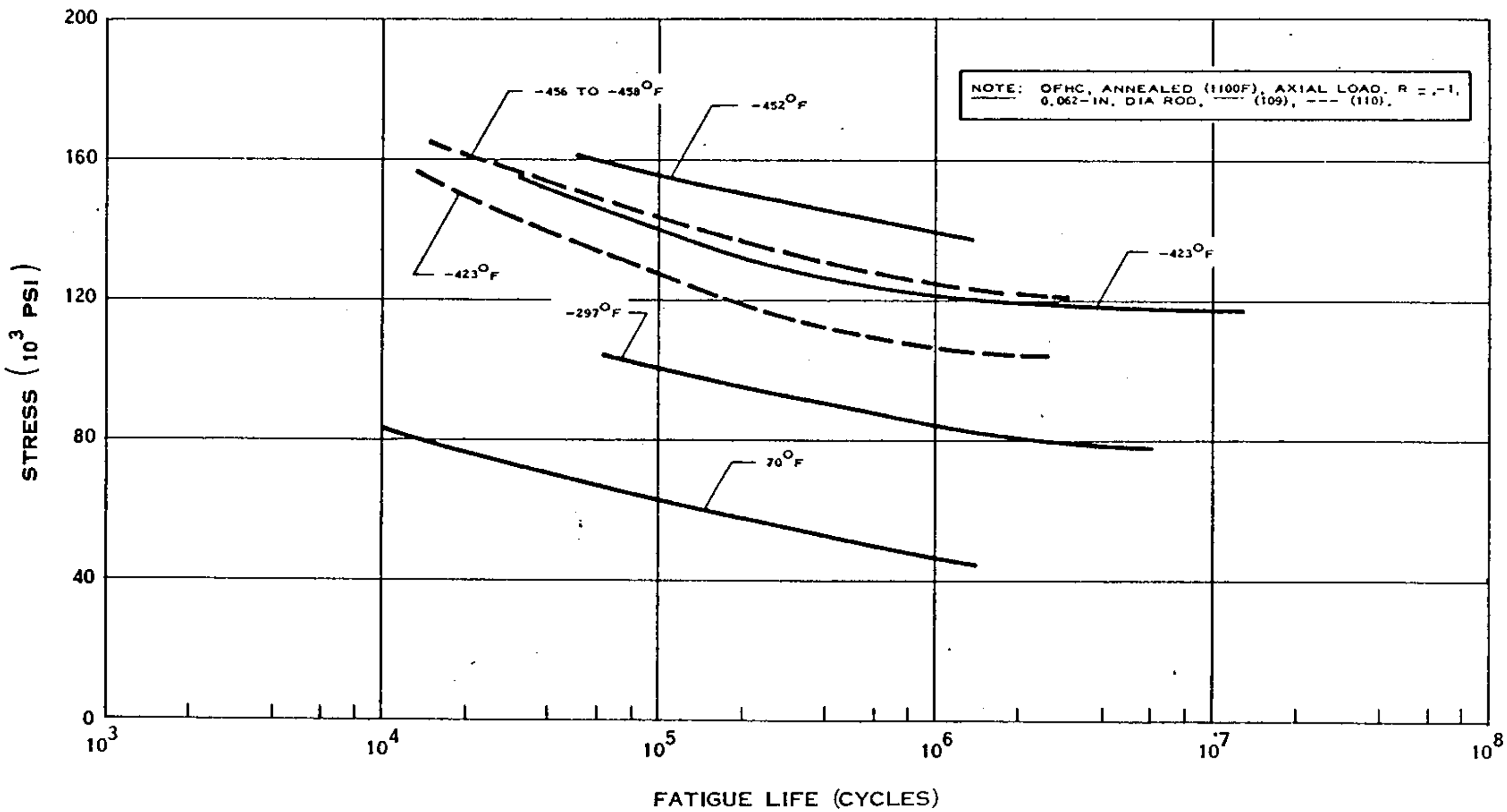
MODULUS OF ELASTICITY OF COPPER



IMPACT STRENGTH OF COPPER

(7-64)

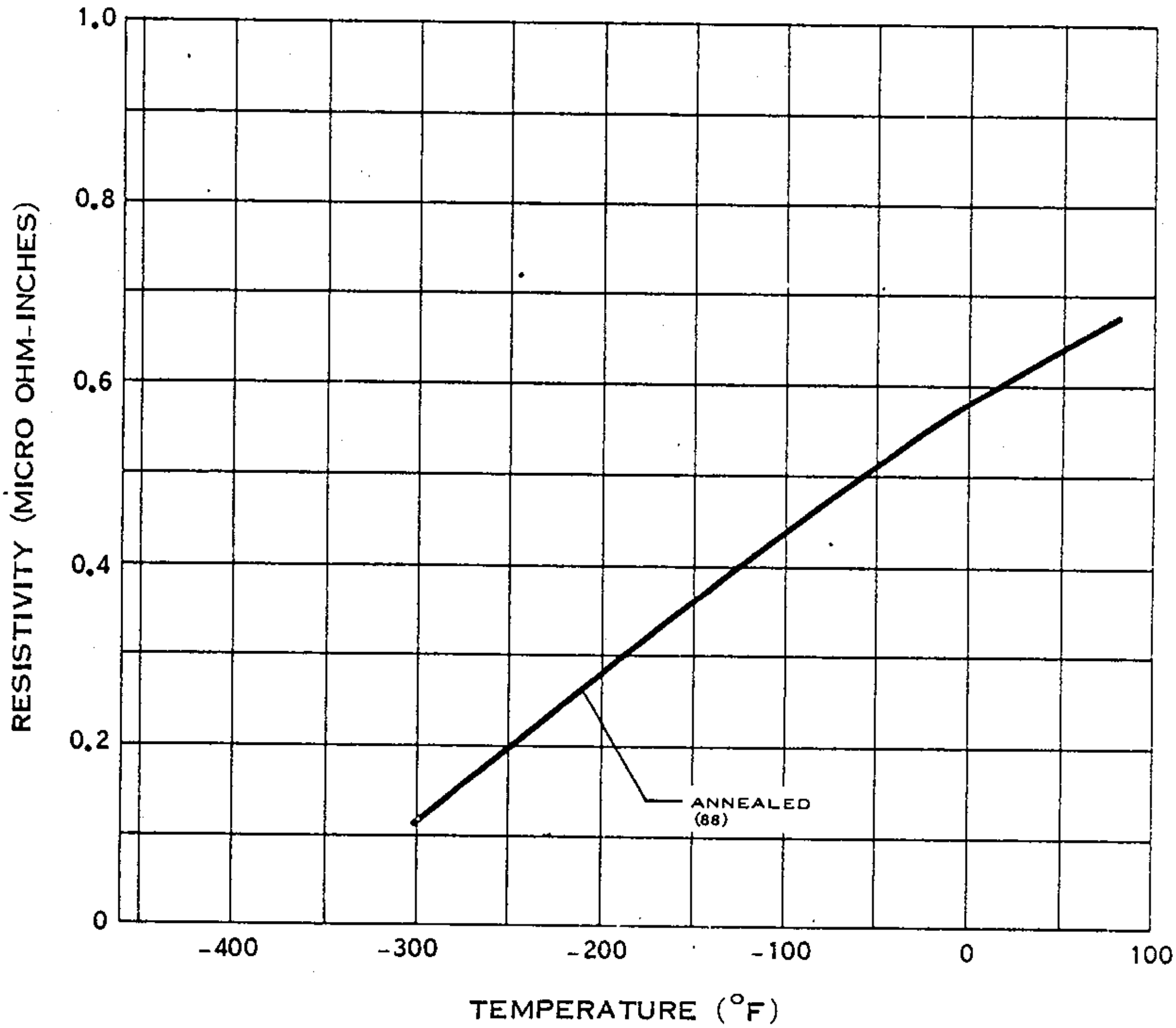
Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964.



FATIGUE STRENGTH OF COPPER

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., August 1964.

F.1.w



ELECTRICAL RESISTIVITY OF COPPER

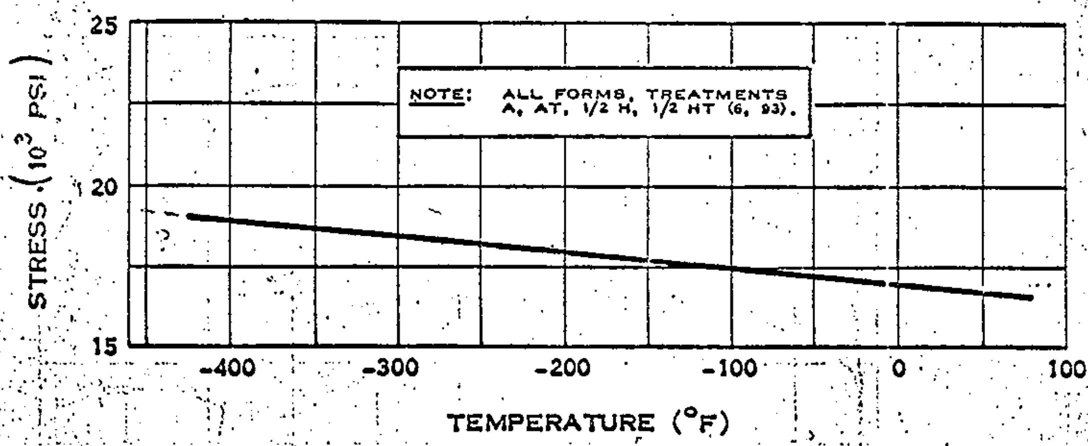
Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964.

(7-64)

AGP

SECTION 11

STIFFENERS



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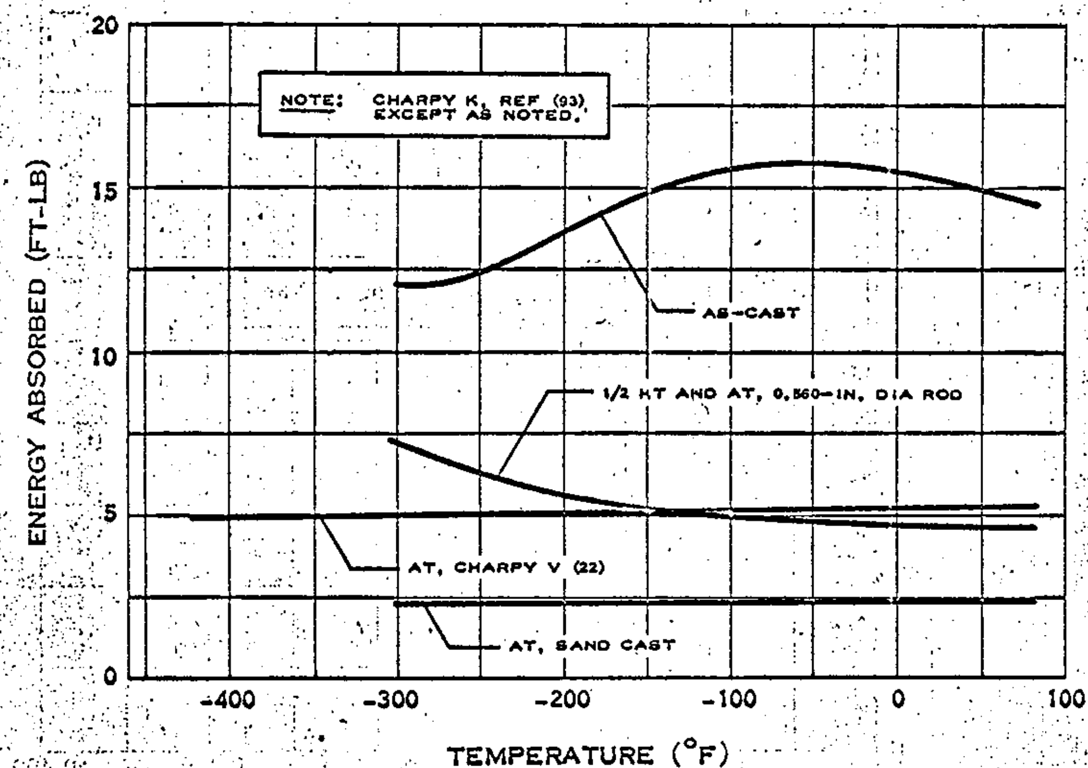
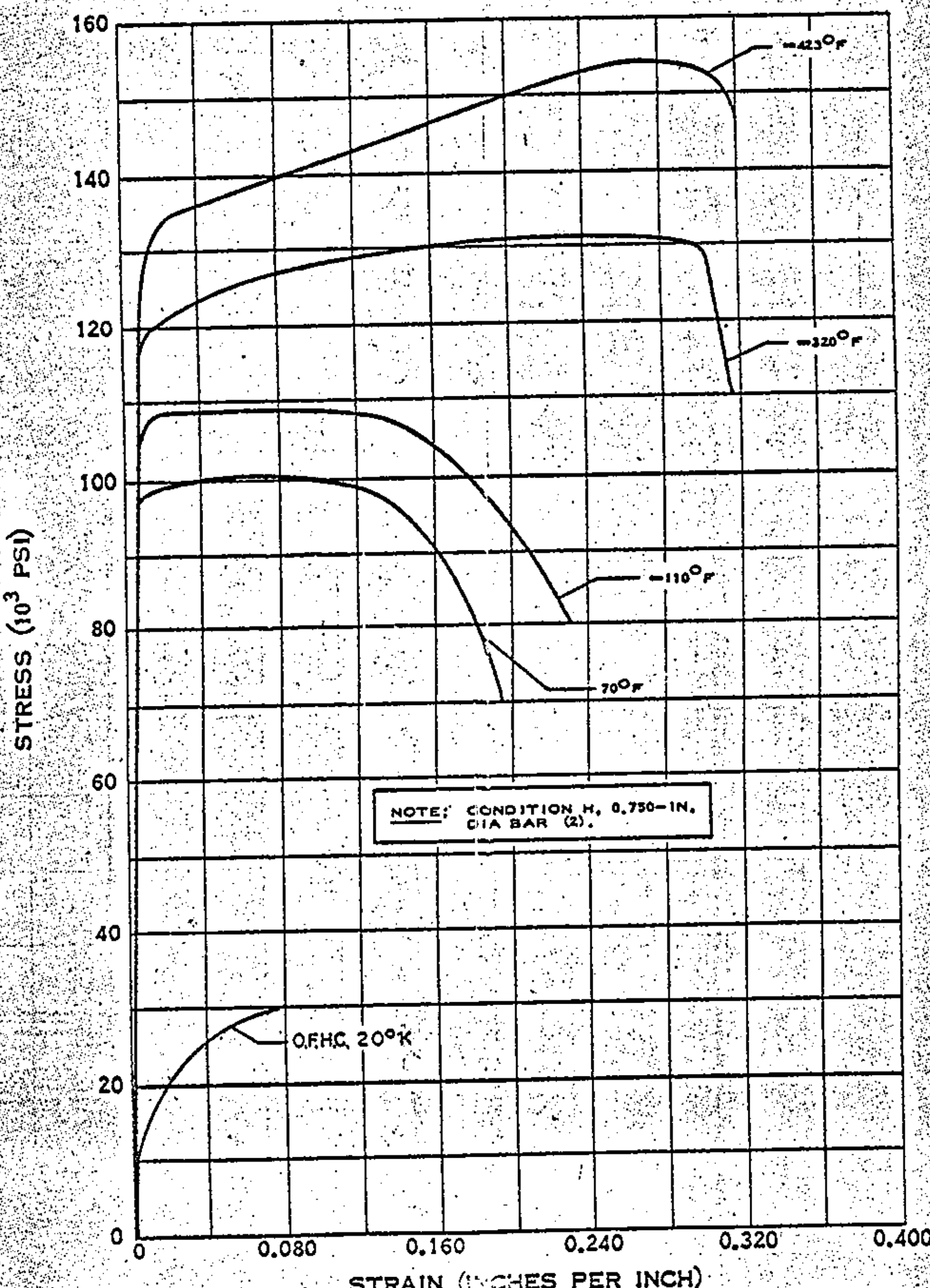


IMPACT STRENGTH OF BERYLLIUM COPPER

(7-64) Schwartzberg, et al., Cryogenic Material Data Handbook,
Tech. Doc. Report ML-TDR-64-280 AD609562,
Air Force Materials Lab., Aug. 1964

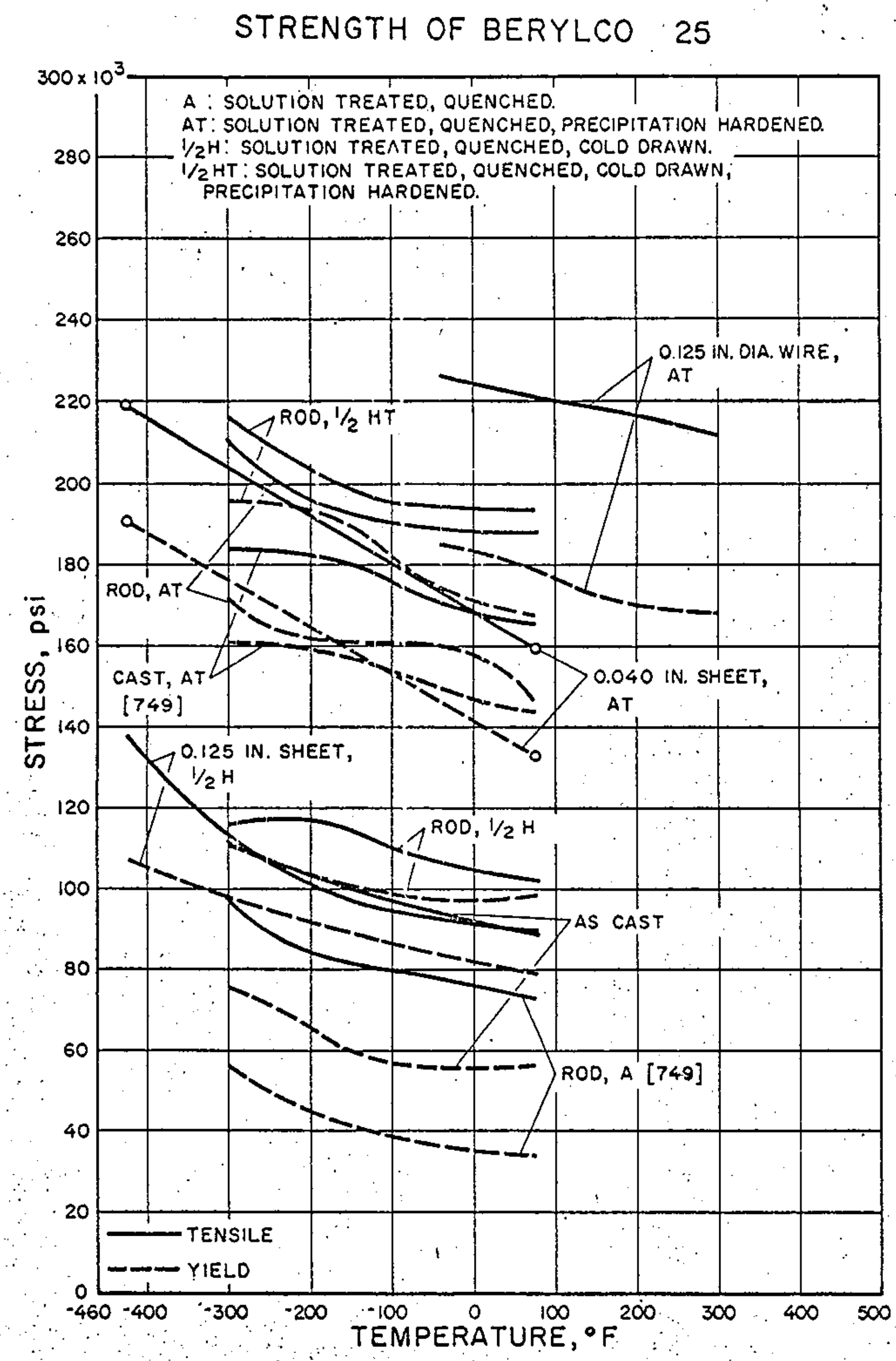
F.2.h-1



STRESS-STRAIN DIAGRA FOR BERYLLIUM COPPER

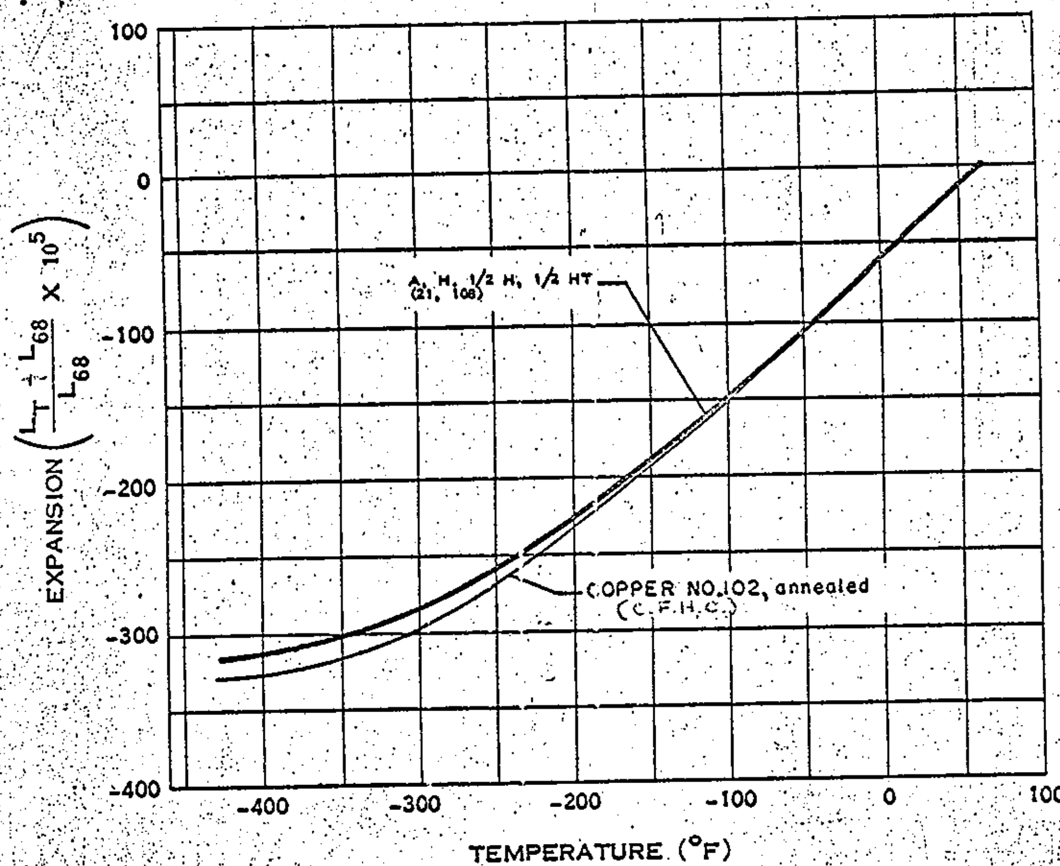
(7-64)

Schwartzberg, et. al., Cry enic Material Data Handbook, Tech. Doc. Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



BERYLCO TECH. BUL. 1040A

F.2.t

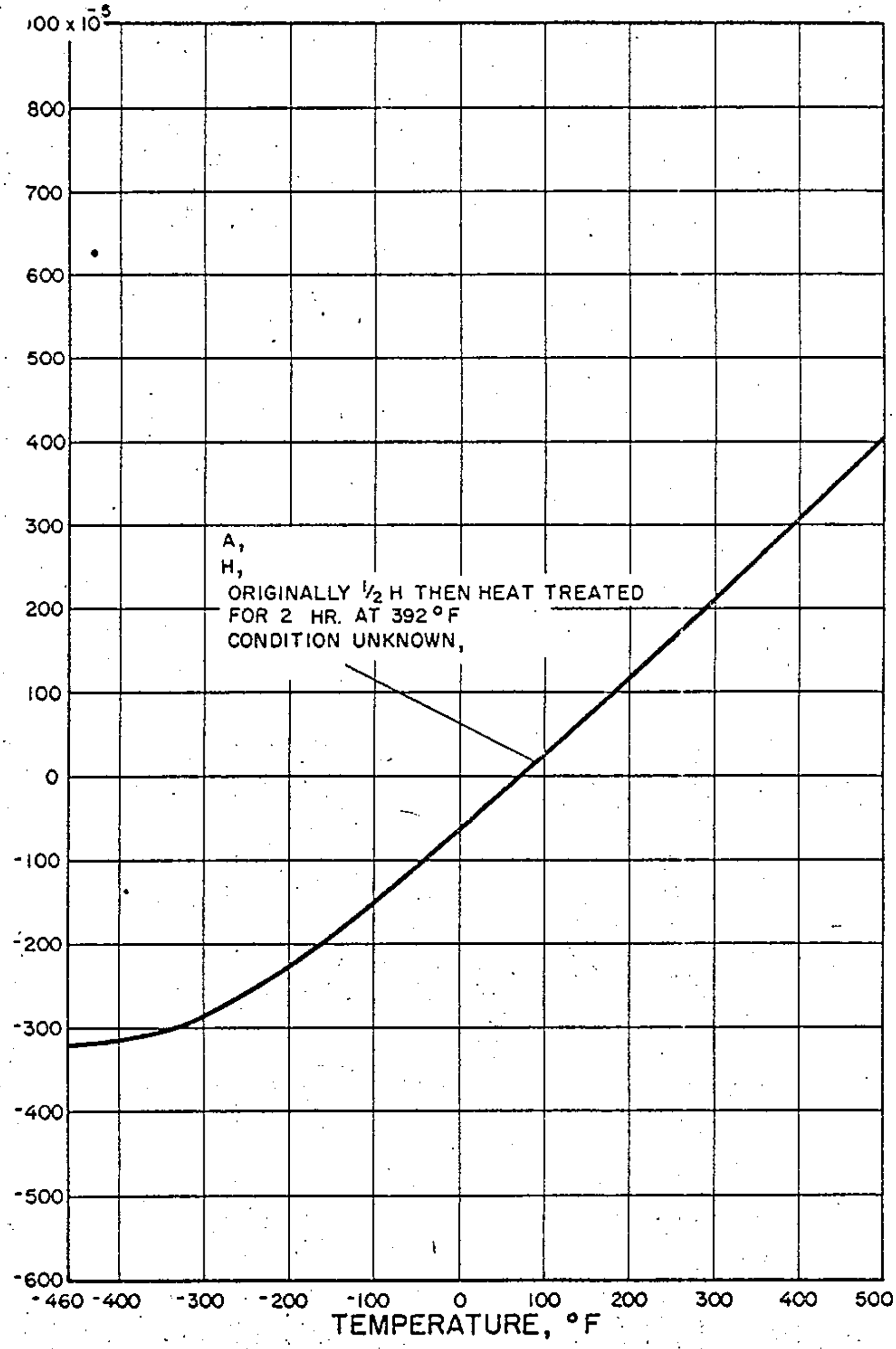


THERMAL EXPANSION OF BERYLLIUM COPPER

Schwartzberg, et. al., Cryogenic Material Data Handbook,
Tech. Doc. Report ML-TDR-64-280 AD609562,
Air Force Materials Lab., Aug. 1964

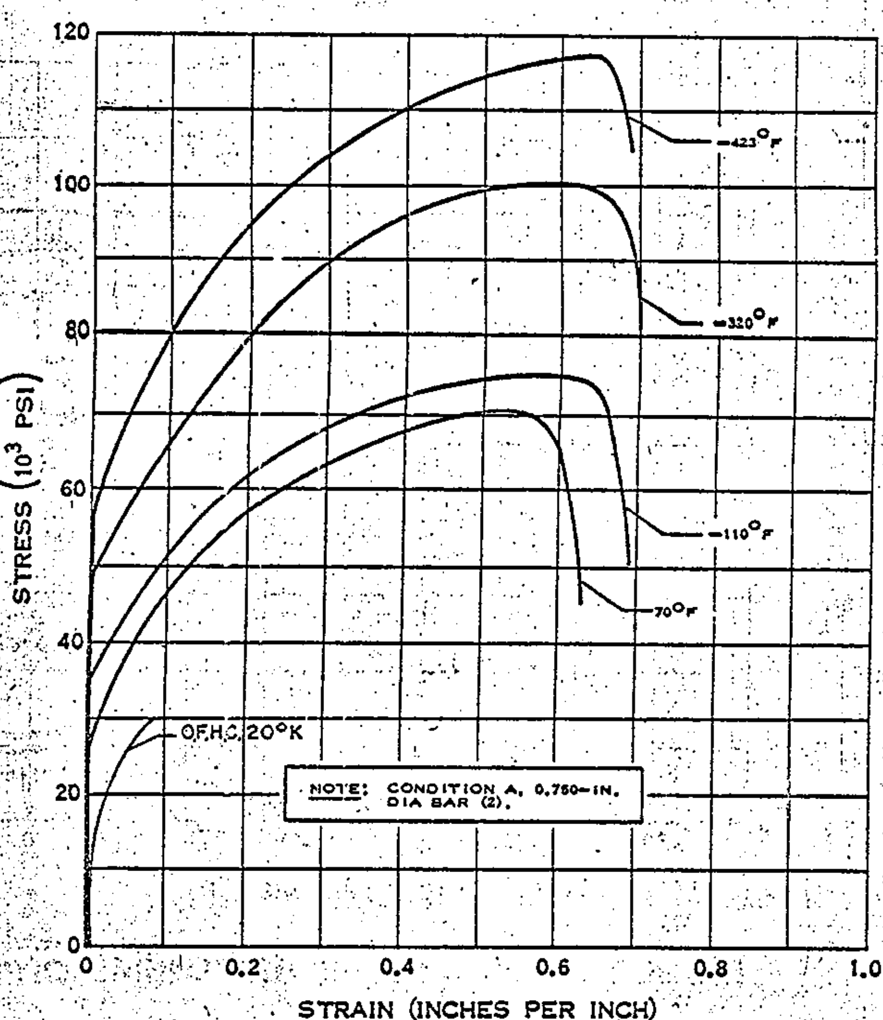
(7-64)

THERMAL EXPANSION OF BERYLCO 25



Berylco Tech, Bul. 1040A.

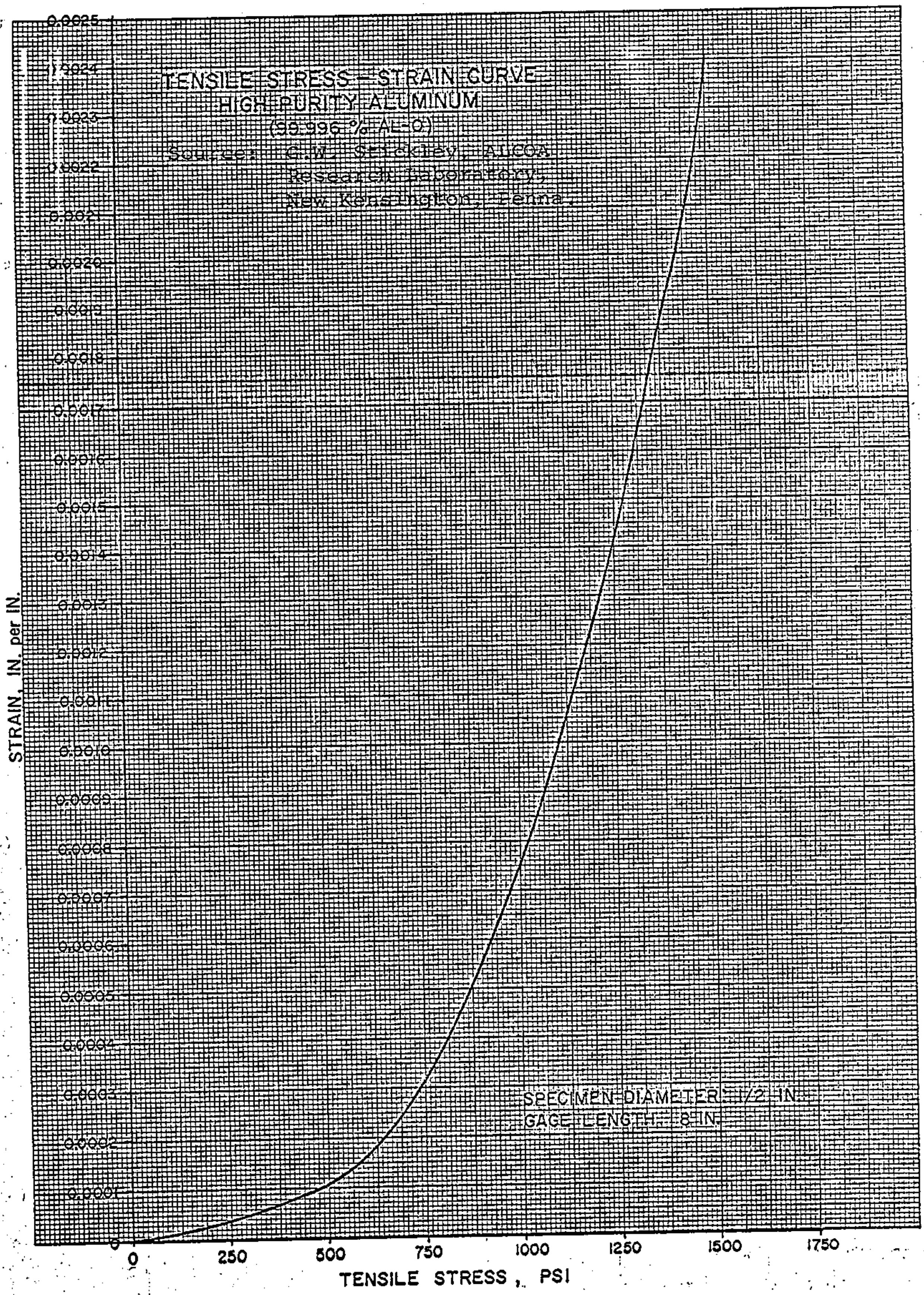
F.2-h



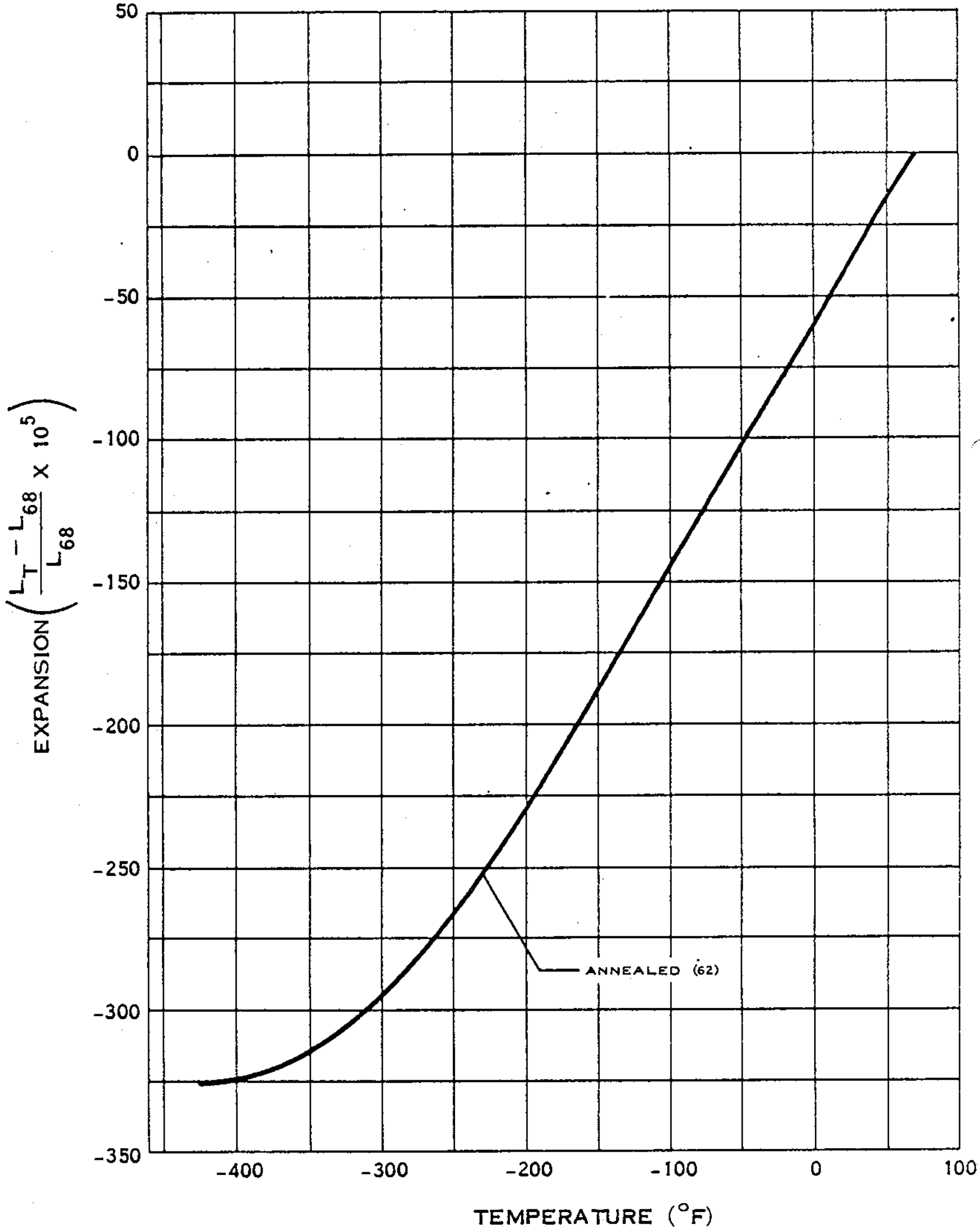
STRESS-STRAIN DIAGRAM FOR BERYLLIUM COPPER

Schwartzberg, et. al., Cryogenic Material Data Handbook,
Tech. Doc. Report ML-TDR-64-280 AD609562,
Air Force Materials Lab., Aug. 1964

(7-64)



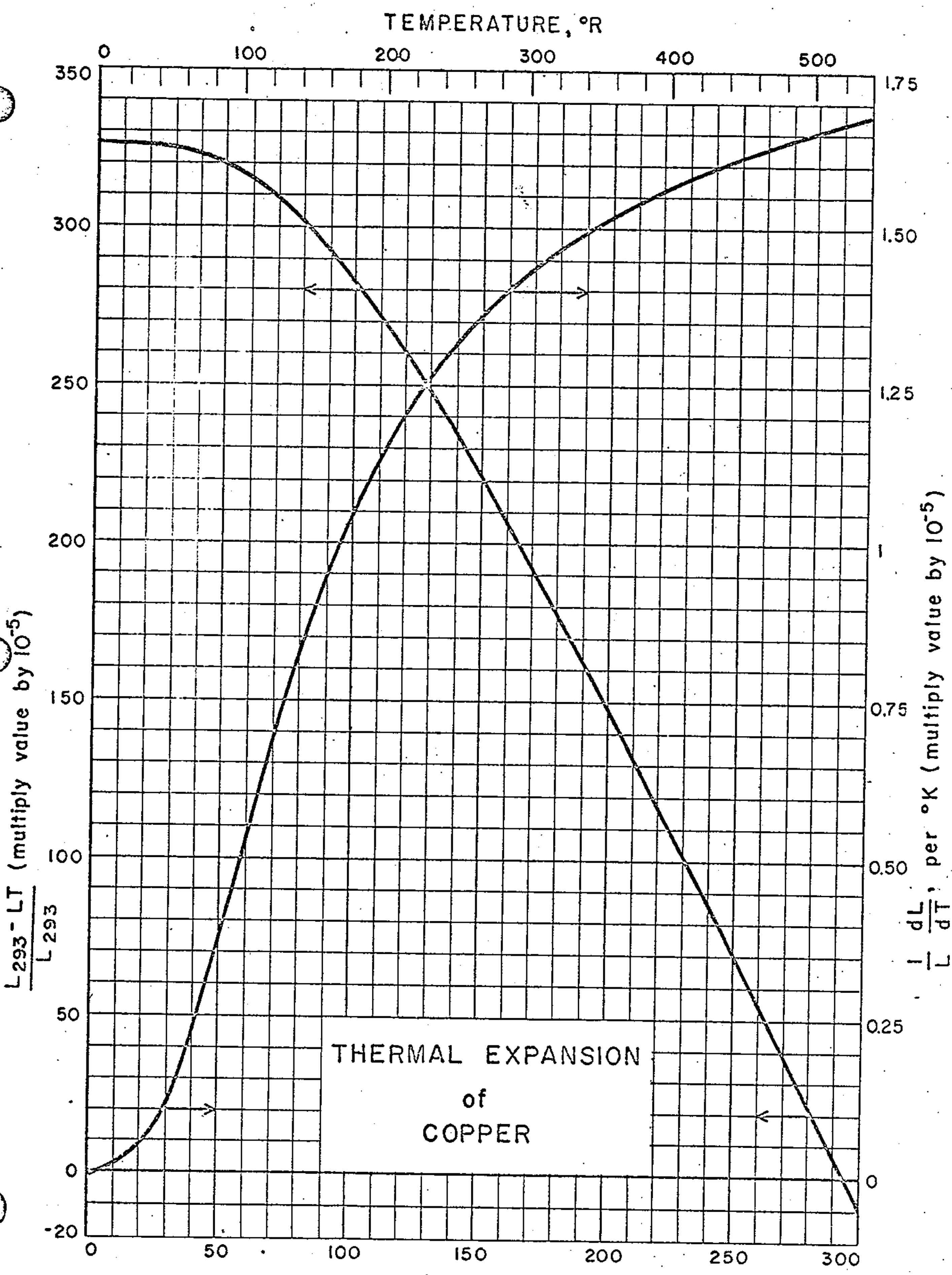
K&E 10 X 10 TO THE CENTIMETER 46 1513
18 X 25 CM. MADE IN U.S.A.
KEUFFEL & ESSER CO.



THERMAL EXPANSION OF COPPER

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964.



Johnson, V.J., A Compendium of
the Properties of Materials at Low Temperatures, WADD
Tech. Rpt. 60-56, Wright Air Dev. Div., Oct. 1960

TABLE 2.2. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Alloys

T	Steel, SAE 52100 [b]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, SAE 52100 [b]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Steel, AISI 301 [c]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, AISI 301 [c]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Steel, AISI 302 [d]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, AISI 302 [d]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Steel, AISI 304 [e]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, AISI 304 [e]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		deg⁻¹ K		deg⁻¹ K		deg⁻¹ K		deg⁻¹ K
0					[a]316	0	[a]296	0
10					316	[a]0.01	296	[a]0.01
20					316	[a].09	296	.02
30					316	.5	296	.62
40					315	1.4	296	1.1
50					313	2.7	294	2.3
60					309	4.3	291	4.7
70					304	6.5	285	6.1
80	198	6.2			296	8.3	279	7.5
90	192	6.6	267	9.0	287	9.6	271	8.7
100	185	6.9	257	10.1	277	10.4	261	9.6
120	171	7.3	236	11.0	255	11.6	241	10.9
140	156	7.6	213	11.8	231	12.4	218	12.0
160	140	8.2	188	12.5	206	13.2	193	12.8
180	123	8.9	163	13.1	179	13.8	167	13.4
200	105	9.7	136	13.6	151	14.5	139	14.0
220	84.4	10.6	109	14.1	121	15.2	111	14.5
240	62.4	11.3	80.1	14.5	89.6	16.0	84.7	14.9
260	39.4	11.7	50.5	15.0	57.0	16.7	54.4	15.3
273	24.0	11.9	30.9	15.3	35.0	17.2	31.4	15.5
280	15.6	12.0	20.2	15.4	22.9	17.4	20.5	15.6
293	0.0	12.1	0.0	15.7	0.0	17.9	0.0	15.9
300	−8.5	12.1	−11.0	15.8	−12.7	18.1	−11.1	16.0
Sources of above data	Werner 1924		Furman 1959		Beenakker and Swenson 1955		Altman, Rubin, and Johnston 1954; Beenakker and Swenson 1955	
Other refs.			Lucks and Deem 1958				Fontana 1953; Fontana, Bishop, and Spretnak 1953; Furman 1959	

T	Steel, AISI 310 [f]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, AISI 310 [f]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Steel, AISI 316 [g]: $10^5\frac{L_{293}-L_T}{L_{293}}$	Steel, AISI 316 [g]: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Aluminum: $10^5\frac{L_{293}-L_T}{L_{293}}$	Aluminum: $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Copper: $10^5\frac{L_{293}-L_T}{L_{293}}$	Copper: $\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		deg⁻¹ K		deg⁻¹ K		deg⁻¹ K		deg⁻¹ K
0			[a]297	0	[a]415	0	[a]326	0
10			297	[a]0.01	[a]415	[a]0.05	[a]326	[a]0.01
20			297	[a].09	415	.2	326	.3
30			297	.5	414	.9	325	1.0
40			296	1.4	413	2.2	324	2.3
50			294	2.7	410	3.8	321	3.8
60			290	4.3	405	5.6	316	5.5
70			285	6.5	399	7.4	310	7.0
80			277	8.2	391	9.1	302	8.4
90	246	8.9	269	9.4	381	10.7	293	9.5
100	237	9.1	259	10.2	370	12.2	283	10.5
120	218	9.8	237	11.3	343	14.6	260	12.0
140	198	10.7	214	12.1	312	16.5	235	13.2
160	176	11.4	189	12.7	277	17.9	208	14.1
180	152	12.1	163	13.2	240	19.0	179	14.7
200	127	12.7	136	13.6	201	20.0	149	15.2
220	101	13.2	109	14.1	160	20.8	118	15.6
240	74.5	13.6	80.1	14.5	118	21.5	87	15.9
260	46.9	14.0	50.6	15.0	75	22.1	55	16.2
273	28.6	14.2	30.9	15.3	45	22.5	33	16.4
280	18.7	14.3	20.2	15.4	30	22.7	22	16.5
293	0.0	14.5	0.0	15.7	0	23.0	0	16.7
300	−10.2	14.6	−11.0	15.8	−16	23.2	−11	16.8
Sources of above data	Furman 1959		Beenakker and Swenson 1955		Altman, Rubin, and Johnston 1954		Rubin, Altman, and Johnston 1954	
Other refs.			Furman 1959; Lucks and Deem 1958		Ayres 1905; Bijl and Pullan 1955; Buffington and Latimer 1926; Ebert 1928; Figgins, Jones, and Riley 1956; Gibbons 1958; Henning 1907; Hordon, Lement, and Averbach 1958; Hume-Rothery and Strawbridge 1947; Lindemann 1911; Nix and MacNair 1941; Shearer 1905		Adenstedt 1936; Aoyama and Ito 1939; Beenakker and Swenson 1955; Bijl and Pullan 1955; Borelius and Johansson 1924; Buffington and Latimer 1926; Dorsey 1907; Fraser and Hollis-Hallet 1955; Henning 1907; Keesom, Van Agt, and Jansen 1926; Keyston, MacPherson, and Guptill 1959; Kupkowska and de Haas 1928; Lindemann 1911; Nix and MacNair 1941; Simmons and Balluffi 1957; Simon and Bergmann 1930	

[a] Estimated.

[b] The measurements were made on a German steel that approximated the specifications of SAE 52100. Its composition was 0.94 C, 0.27 Si, 0.34 Mn, 0.95 Cr, bal. Fe. The above data adequately represent two "hard" samples, one of which was "heated at 780 °C", the other "quenched from 850 °C in oil and tempered at 630 °C". The expansion coefficients in the "soft" condition were also measured and were about 8% lower than the above values at 80 °K, about the same from 125 to 200 °K, and about 10% lower at 300 °K.

[c] 0.13 C, 0.80 Mn, 0.54 Si, 16.9 Cr, 7.25 Ni, bal. Fe. Annealed 20 min at 1950 °F and water quenched. After cooling to 19 °K and rewarming to room temperature a small permanent expansion was found to have occurred due to irreversible formation of ferrite.

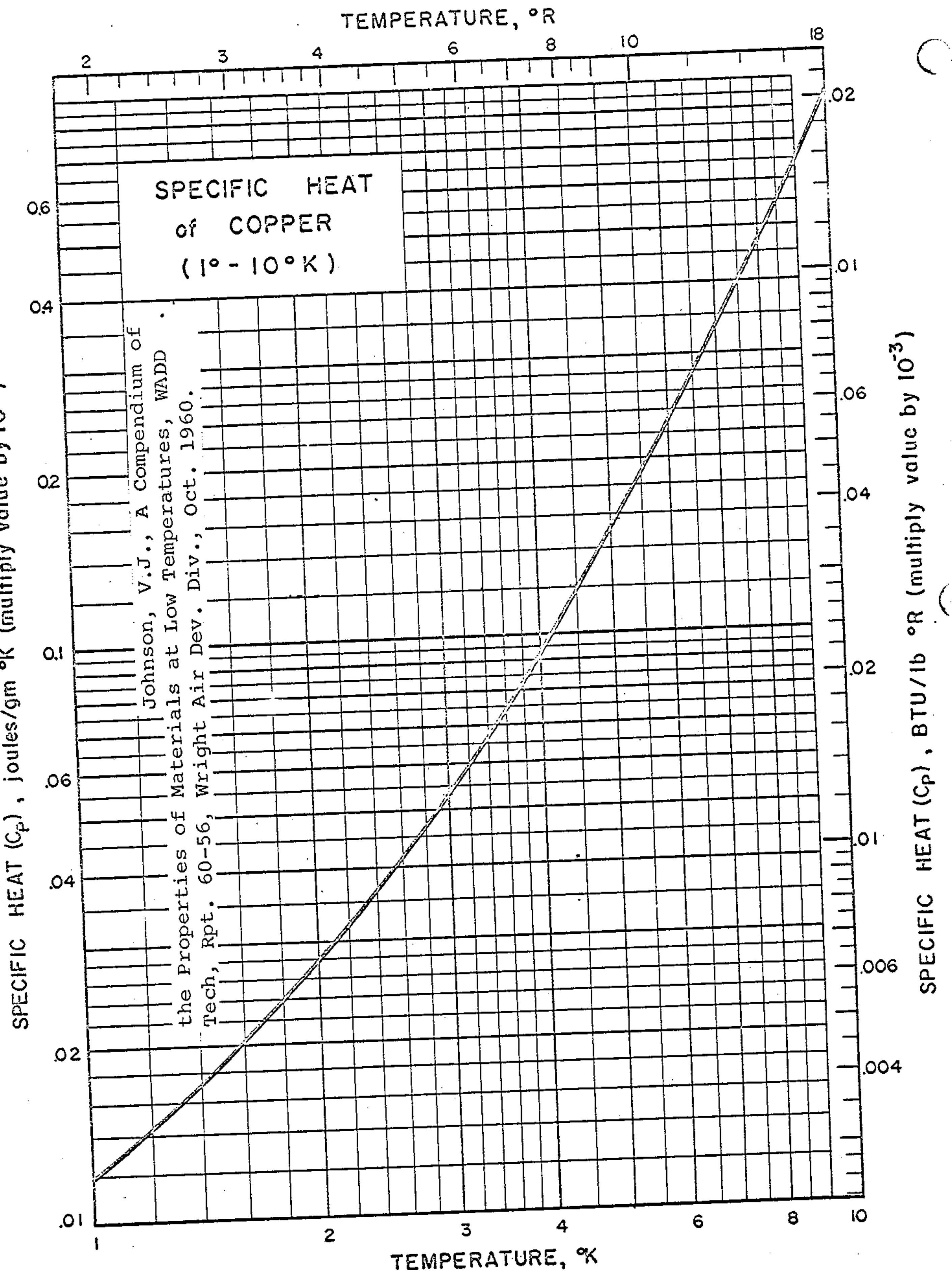
[d] Composition and heat treatment of sample not stated. Composition limits for this alloy are: 0.08-0.20 C, 2 (max.) Mn, 1 (max.) Si, 17-19 Cr, 8-10 Ni, bal. Fe.

[e] Composition limits for this alloy are: 0.08 (max.) C, 2 (max.) Mn, 1 (max.) Si, 18-20 Cr, 8-11 Ni. Altman et al., found small irreversible effects and, below 35 °K, small negative values of expansion coefficient. While we have given their results inferior weight in this region, the effects were undoubtedly real and attributable to martensitic transformation on cooling [Reed and Mikesell, 1958]. In this alloy the extent of transformation that is produced by cooling is sensitive to composition and has been found to vary from zero to about 50% [R. P. Reed, private communication]. Complete transformation would be accompanied by a mean increase in linear dimension of roughly 1% [Ward, Jepson, and Rait, 1952; and Fiedler, Averbach, and Cohen, 1955].

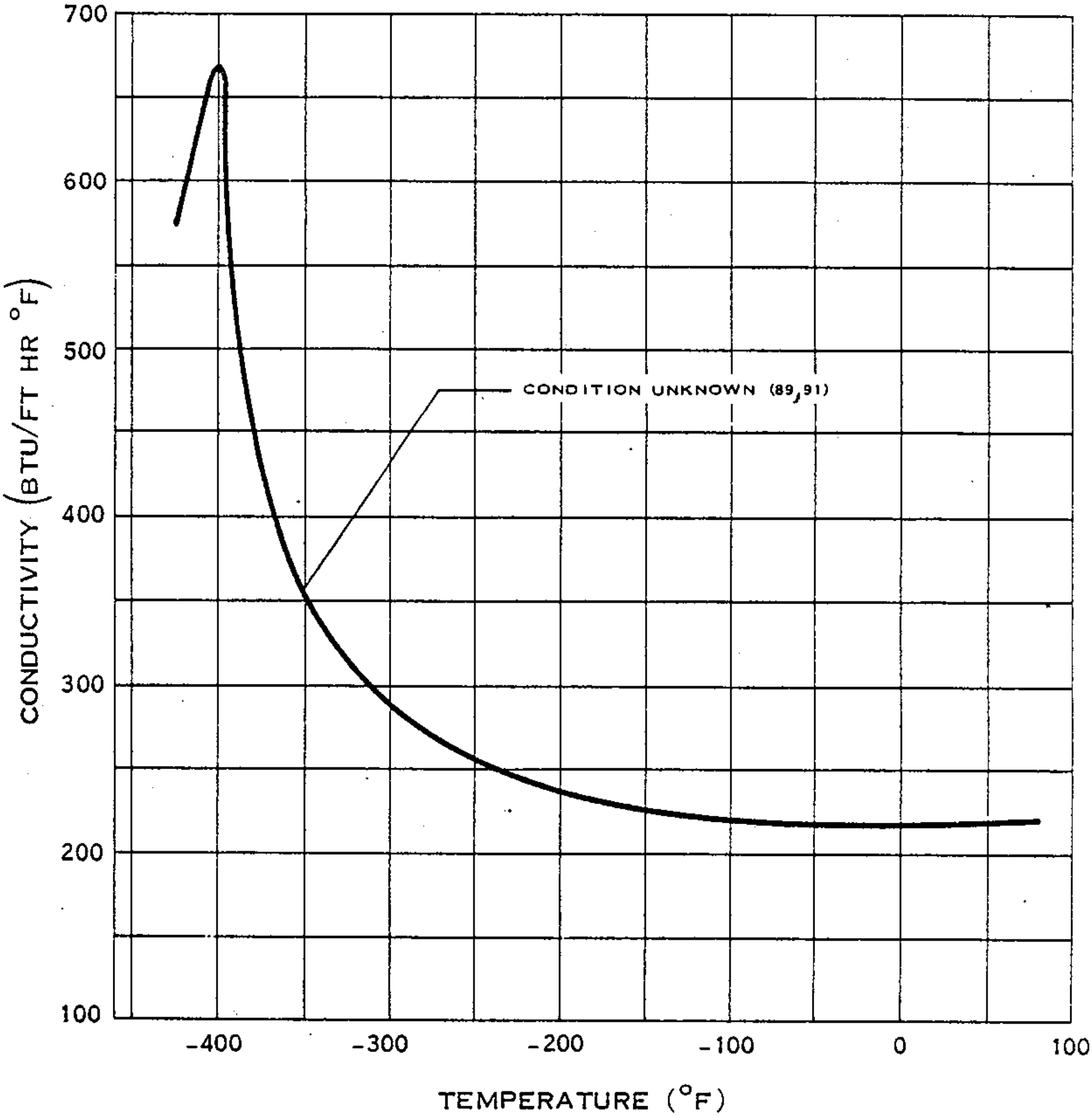
[f] 0.11 C, 1.51 Mn, 0.42 Si, 0.01 S, 0.02 P, 27.2 Cr, 21.6 Ni, bal. Fe. Annealed 30 min at 1950 °F and water quenched.

[g] Composition and heat treatment of sample not stated. Composition limits for this alloy are: 0.10 (max.) C, 2 (max.) Mn, 1 (max.) Si, 16-18 Cr, 10-14 Ni, 2-3 Mo, bal. Fe.

Corruccini, R. J. and Gniewek, J. J.,
Thermal Expansion of Technical Solids at Low Temp
A Compilation from the Literature, NBS Mono. 29
May, 1961

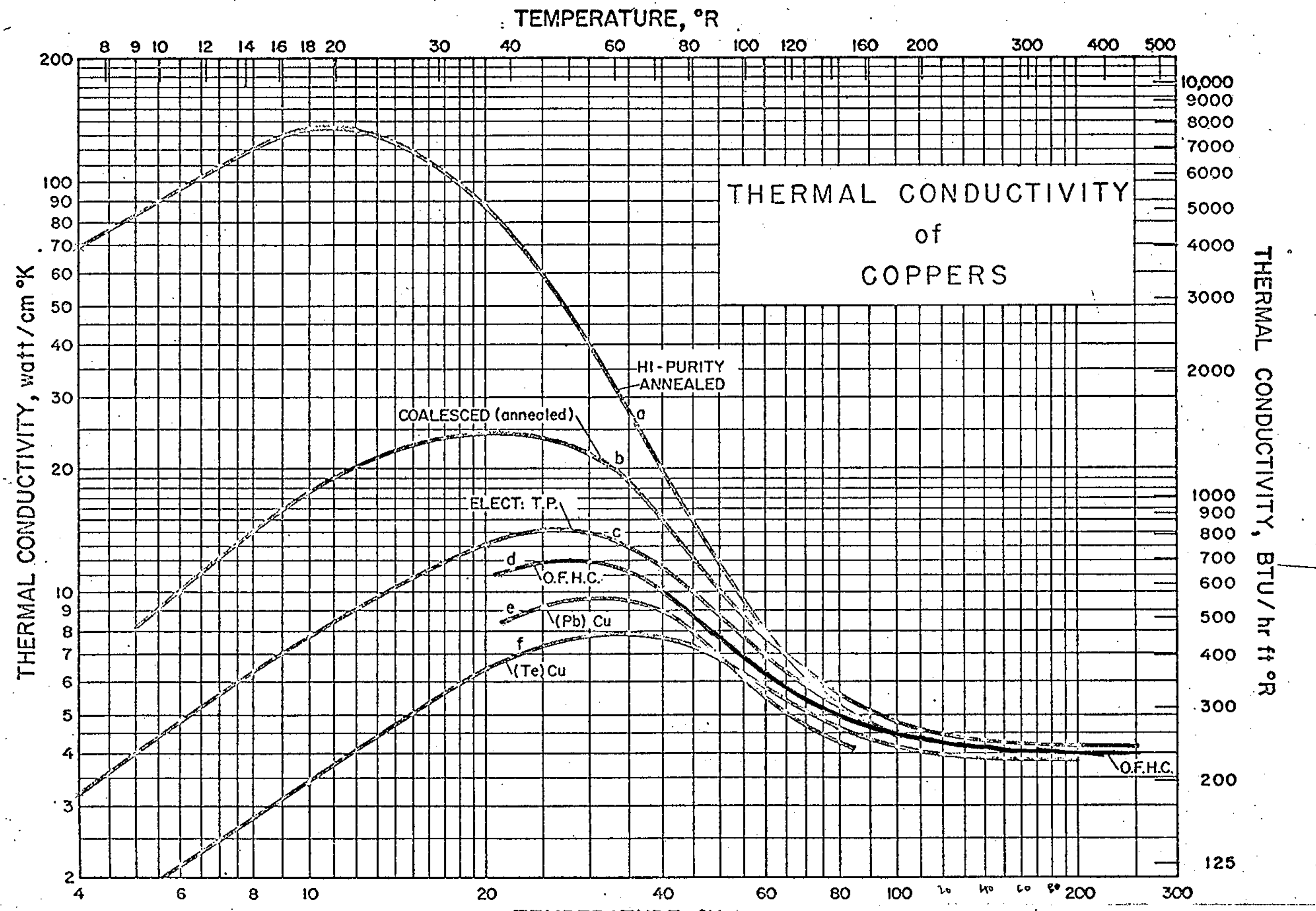

TEMPERATURE, °R
2
3
4
6
8
10
18
SPECIFIC HEAT
of COPPER
(1° - 10°K)
Johnson, V.J., A Compendium of
the Properties of Materials at Low Temperatures, WADD
Tech, Rpt. 60-56, Wright Air Dev. Div., Oct. 1960.
SPECIFIC HEAT (C_p), joules/gm °K (multiply value by 10^{-3})
0.6
0.4
0.2
0.1
.06
.04
.02
.01
SPECIFIC HEAT (C_p), BTU/lb °R (multiply value by 10^{-3})
.02
.01
.06
.04
.02
.01
.006
.004
1
2
3
4
6
8
10
TEMPERATURE, °K

F.1.v

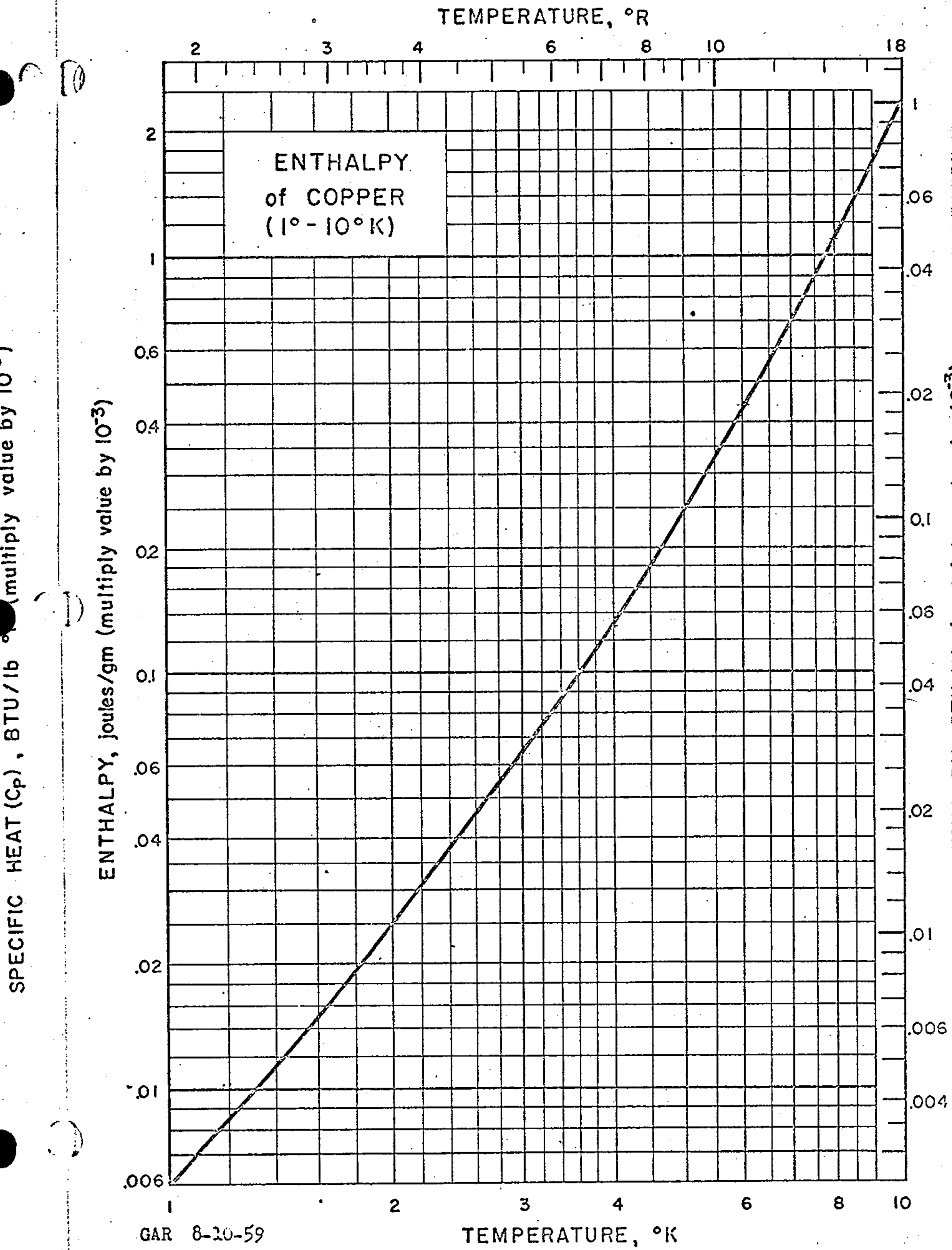


THERMAL CONDUCTIVITY OF COPPER

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964.



Johnson, V.J., A Compendium of the Properties of Materials at Low Temperatures, WADD Tech. Rpt. 60-56, Wright Air Dev. Div., Oct. 1960.



Johnson, V.J., A Compendium of the Properties of Materials at Low Temperatures, WADD

HEAT LOSS FOR MULTISTAGE COOLED LEADS*

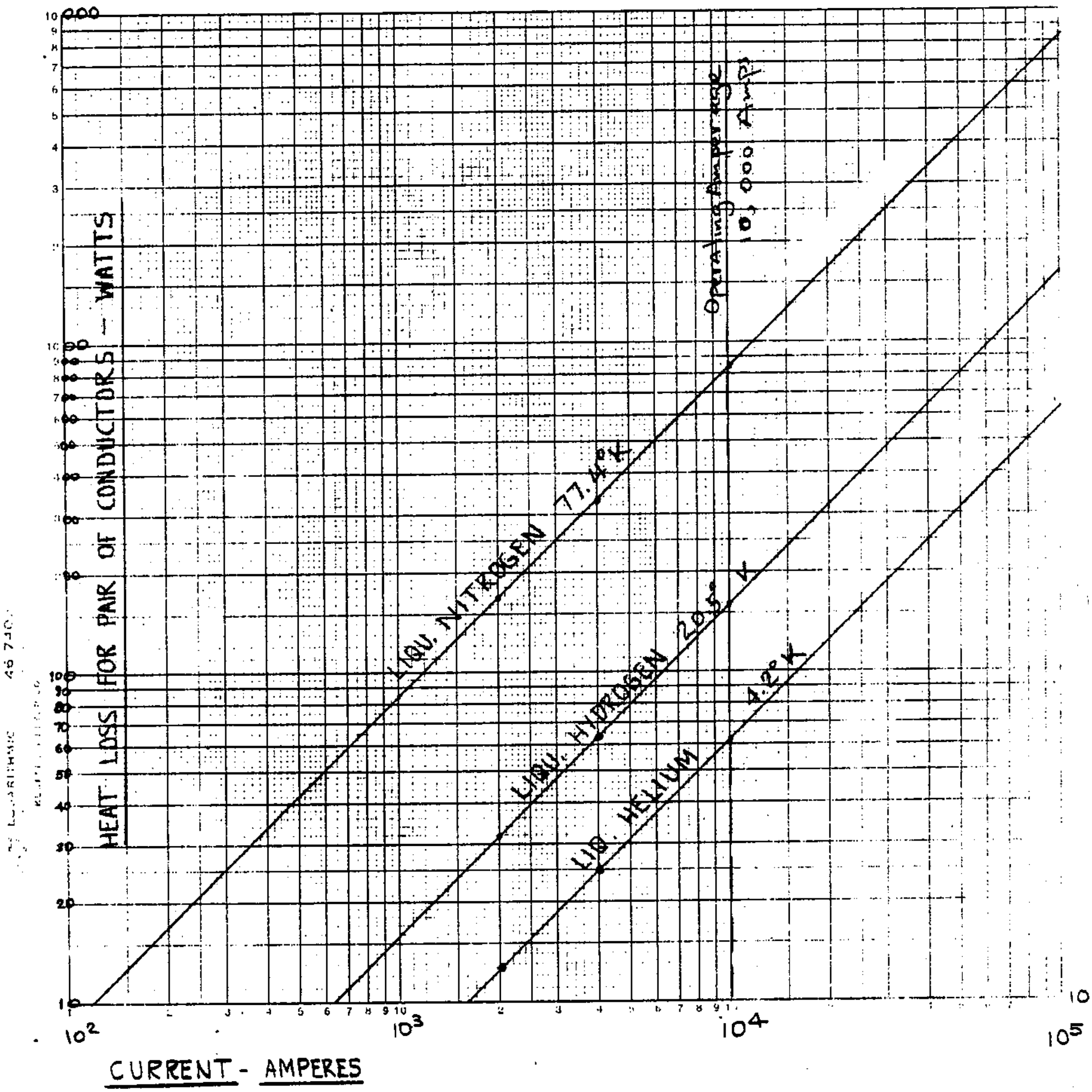
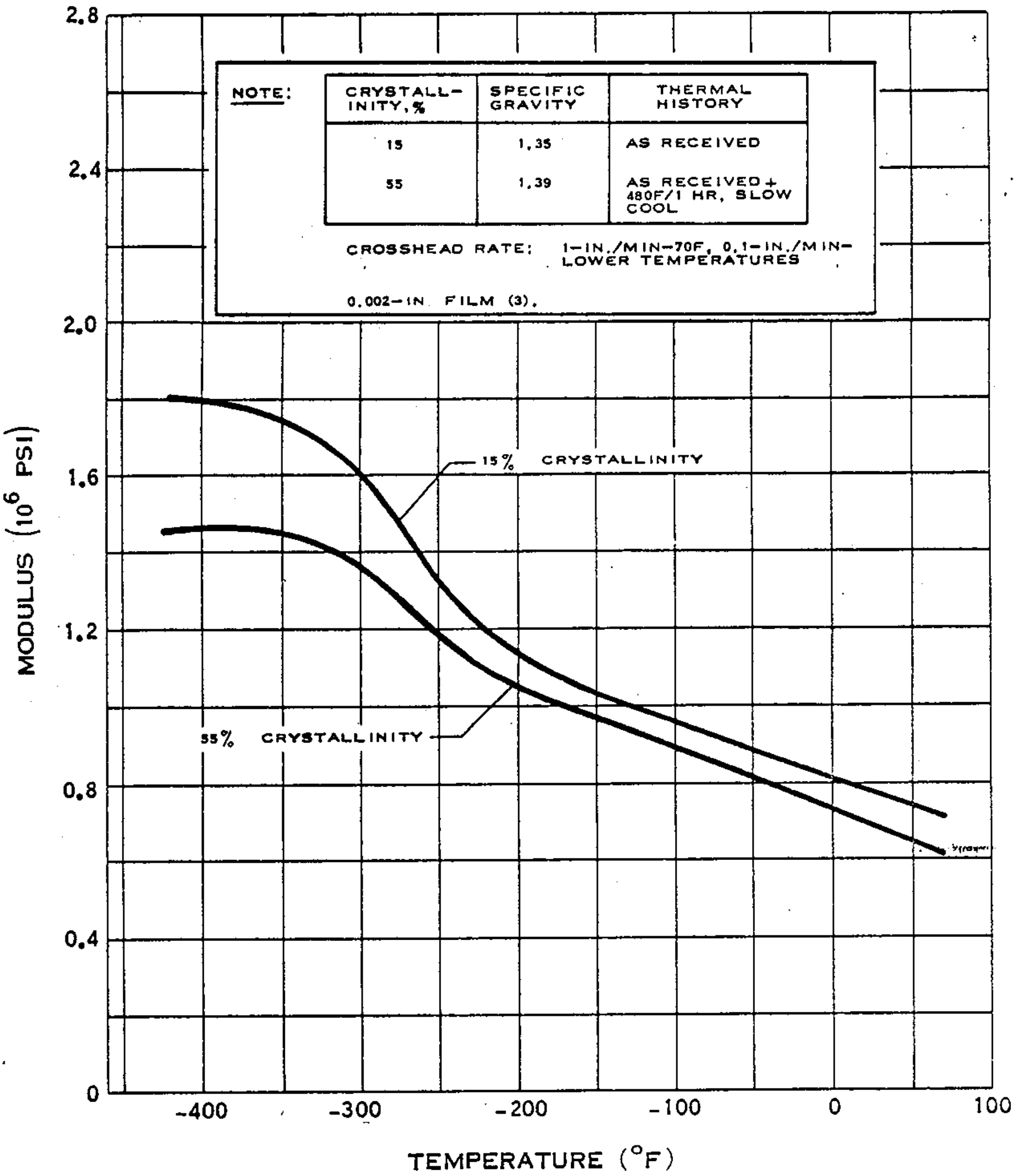


FIG. 2

* Per McFee - Review of Scient. Inst. Vol. 30 No. 2



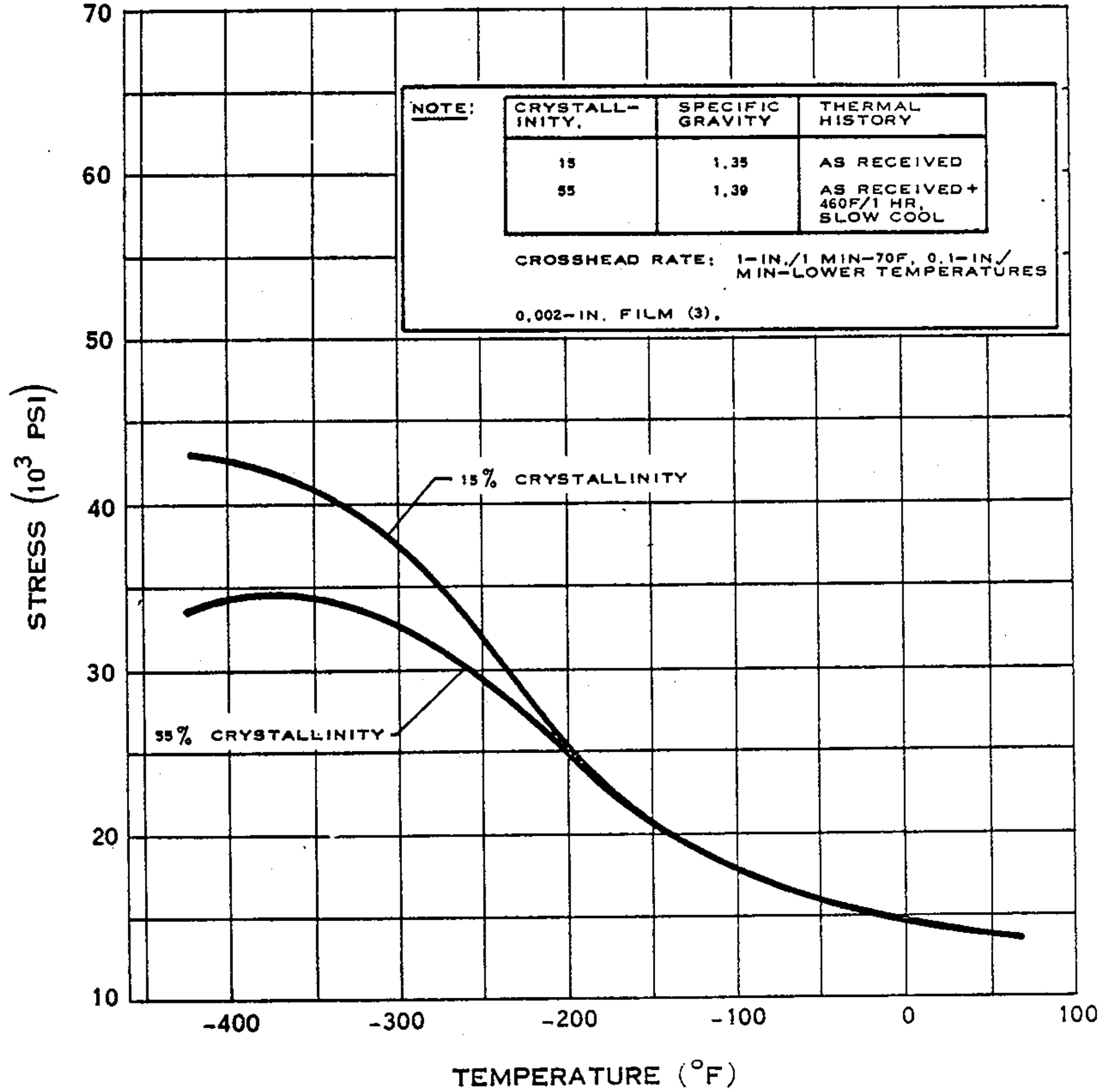
MODULUS OF ELASTICITY OF MYLAR*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et. al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

G.2.a



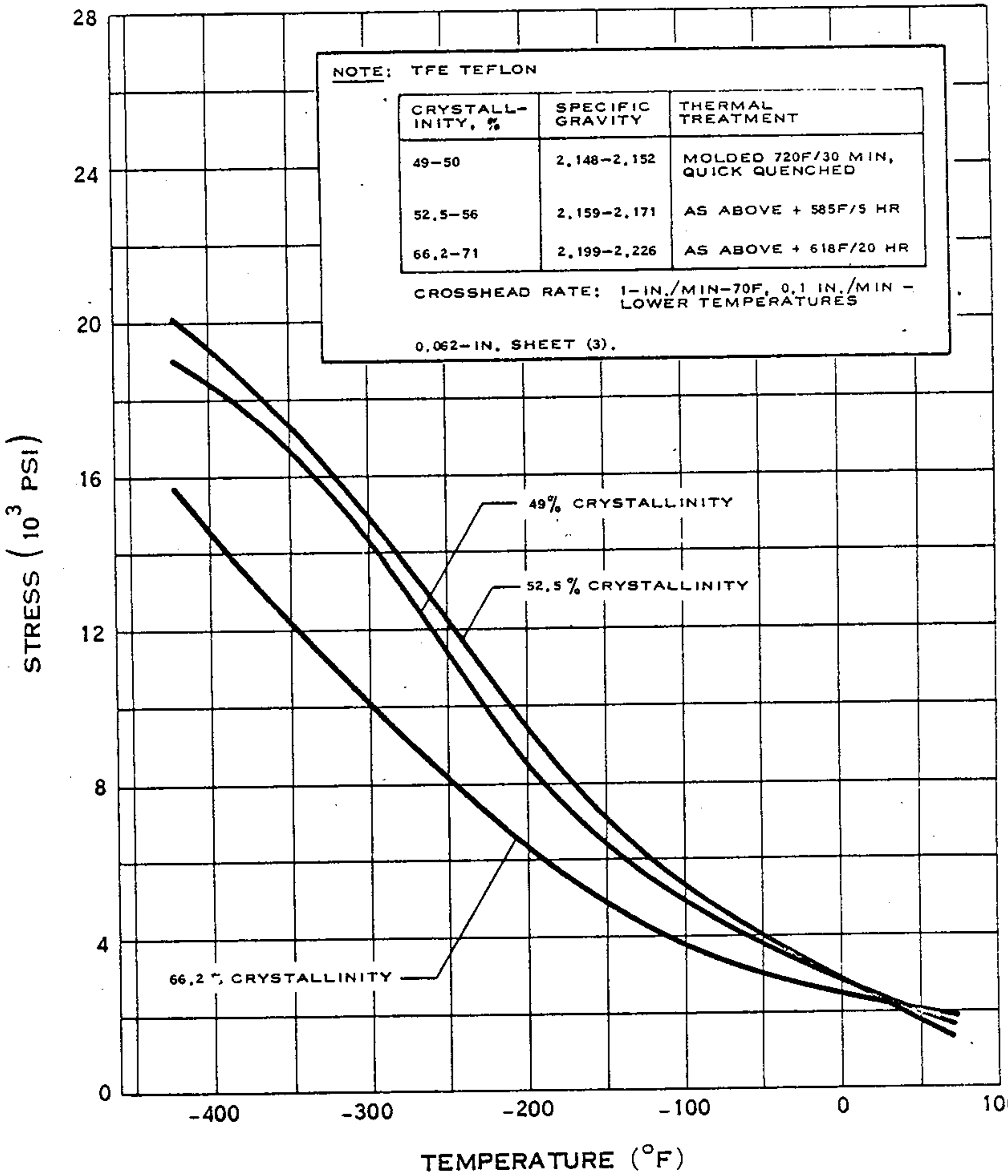
YIELD STRENGTH OF MYLAR*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et. al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

G.3.a



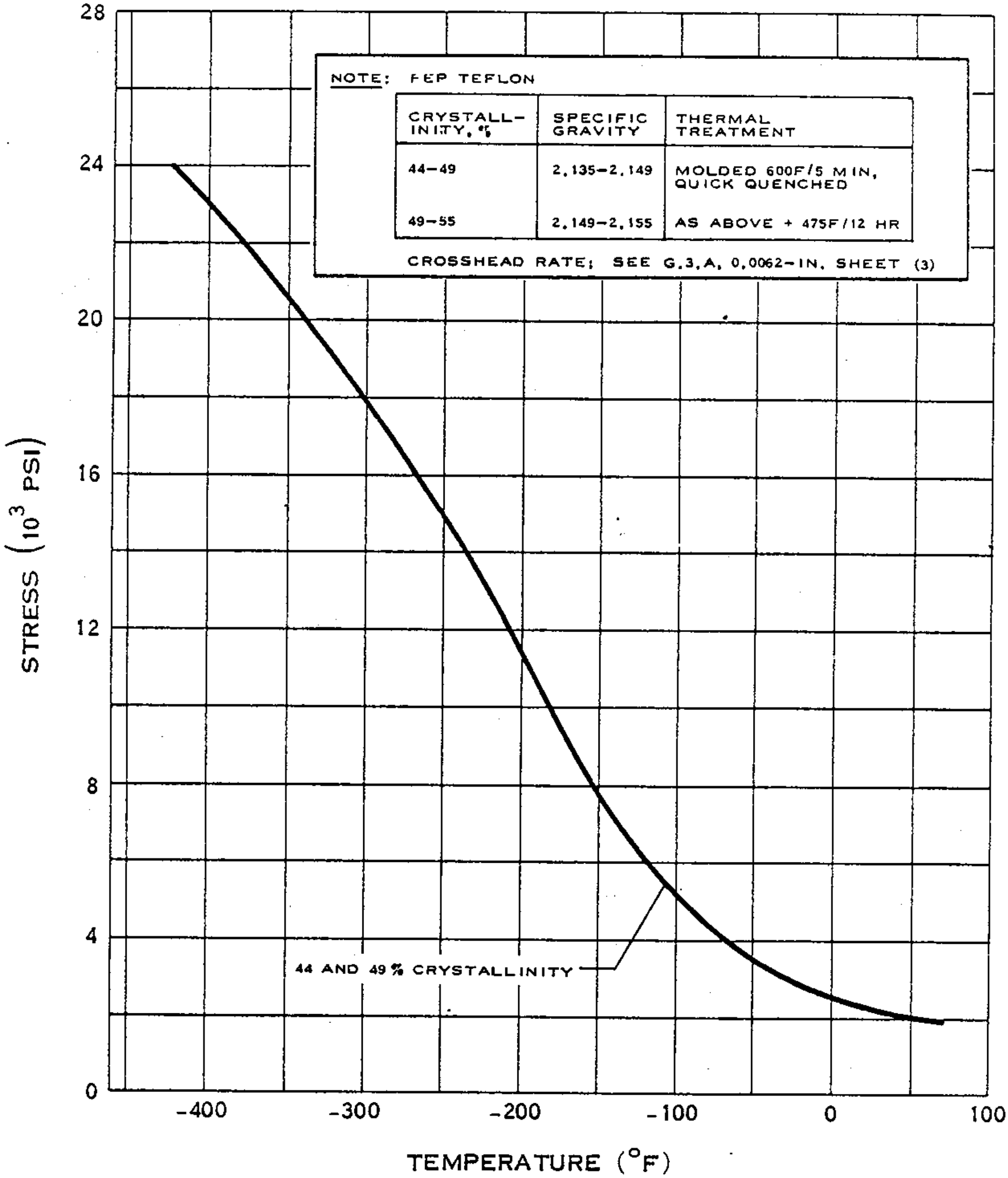
YIELD STRENGTH OF TEFLON* (TFE)

* T.M. E. I. DUPONT DE NEMOURS AND CO.

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

(7-64)

G.3.a-1

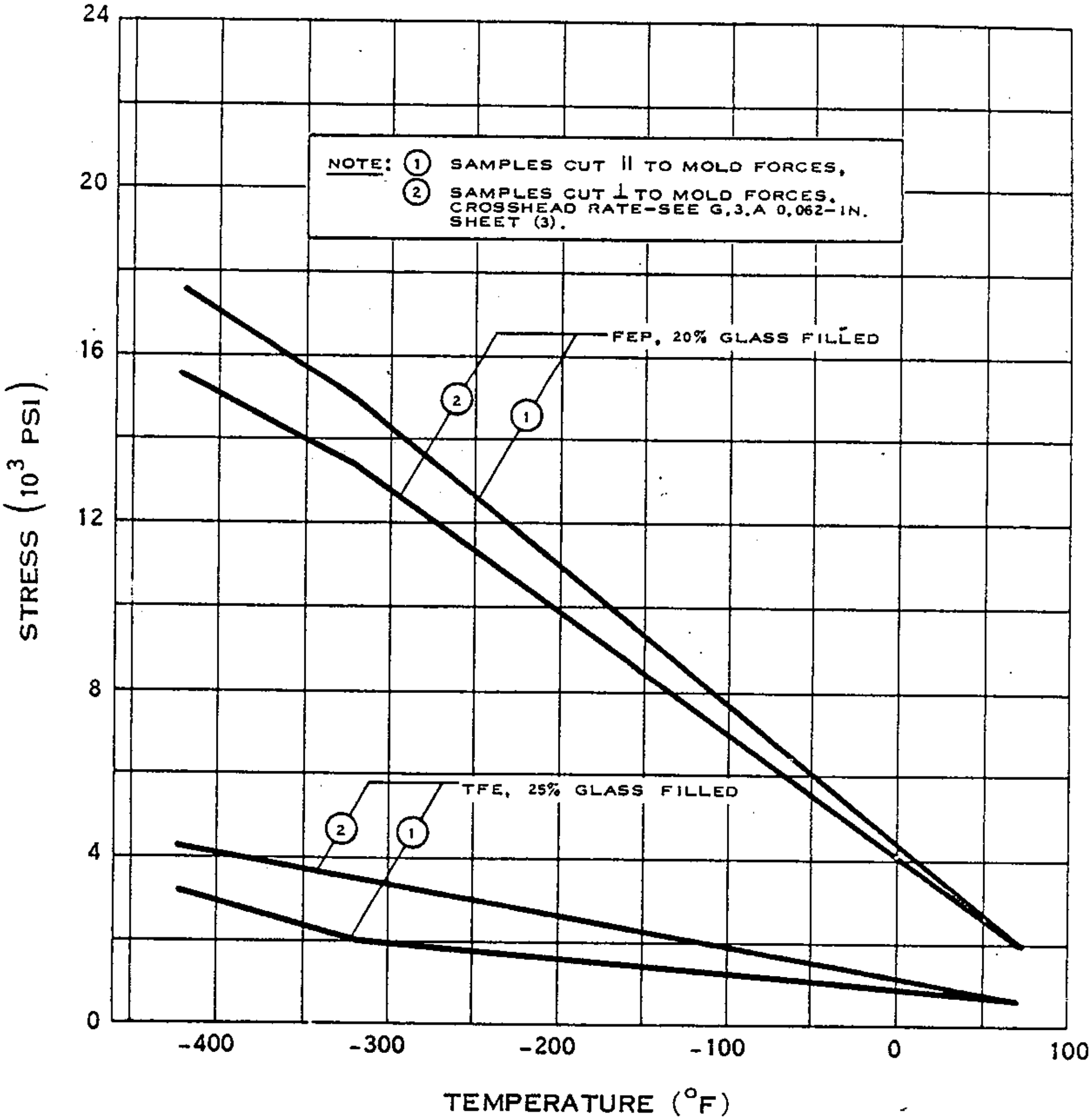


YIELD STRENGTH OF TEFLON* (FEP)

*T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

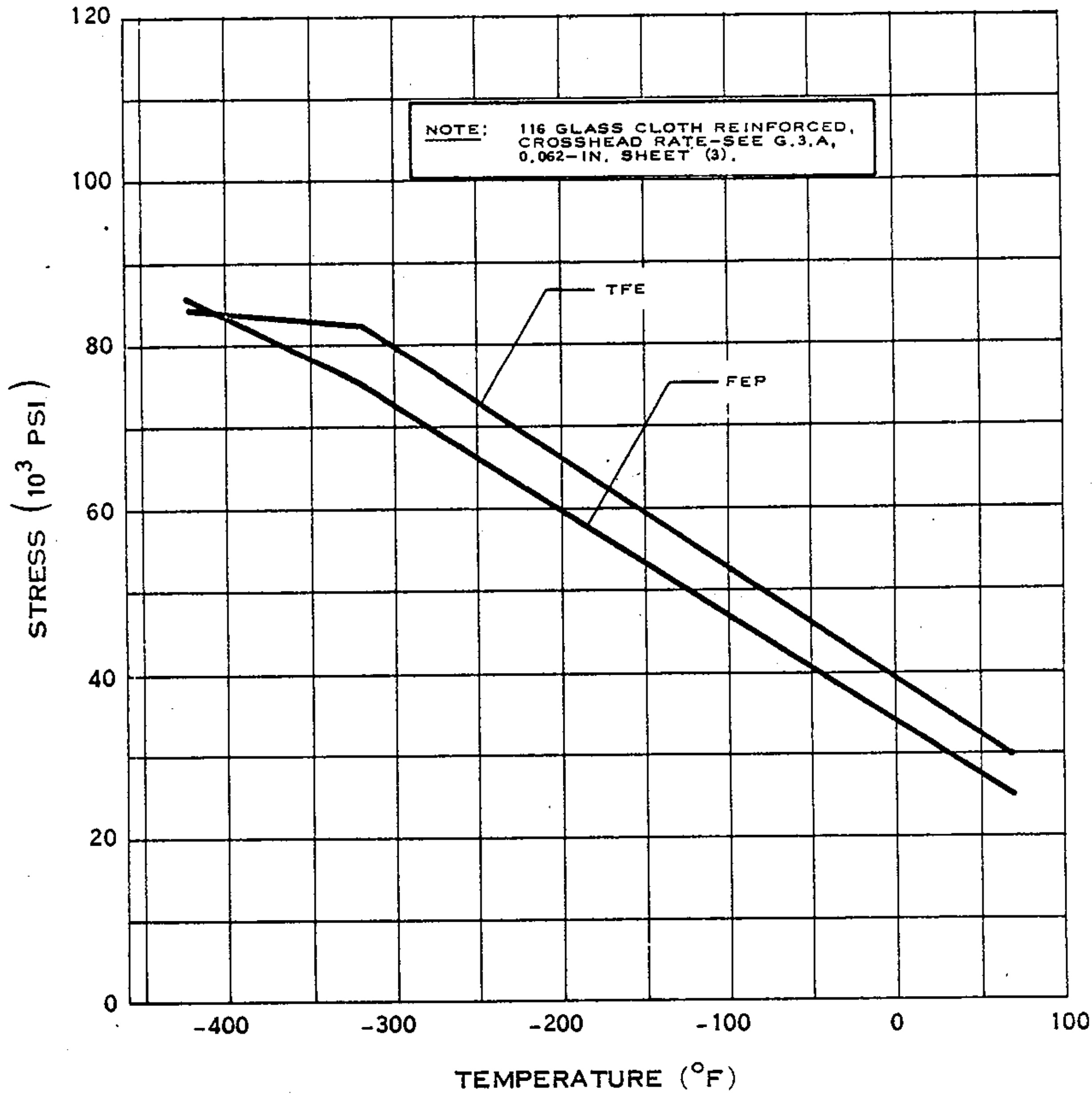
Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



YIELD STRENGTH OF TEFLON*

Schwartzberg., et al., Cryogenic Material Data Handbook, Tech. Doc. Rpt. ML-TDR-64-208 AD609562, Air Force Materials Lab., Aug. 1964

* T.M. E. I. DUPONT DE NEMOURS AND CO.

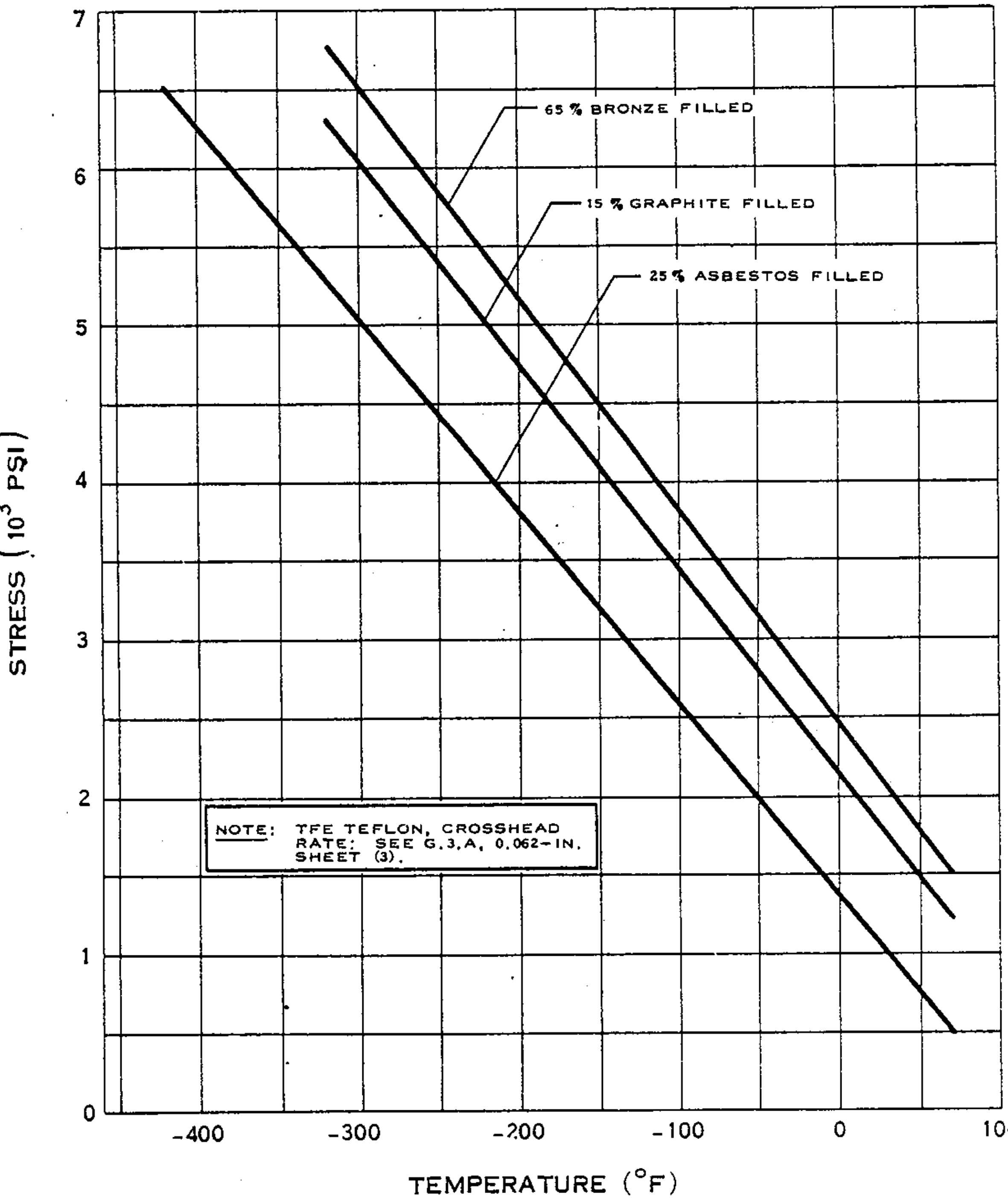


YIELD STRENGTH OF TEFLON*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et al., Cryogenic Materials Data Handbook, Tech. Documentary Report ML-TDR-64-280 · AD609562, Air Force Materials Lab., Aug. 1964

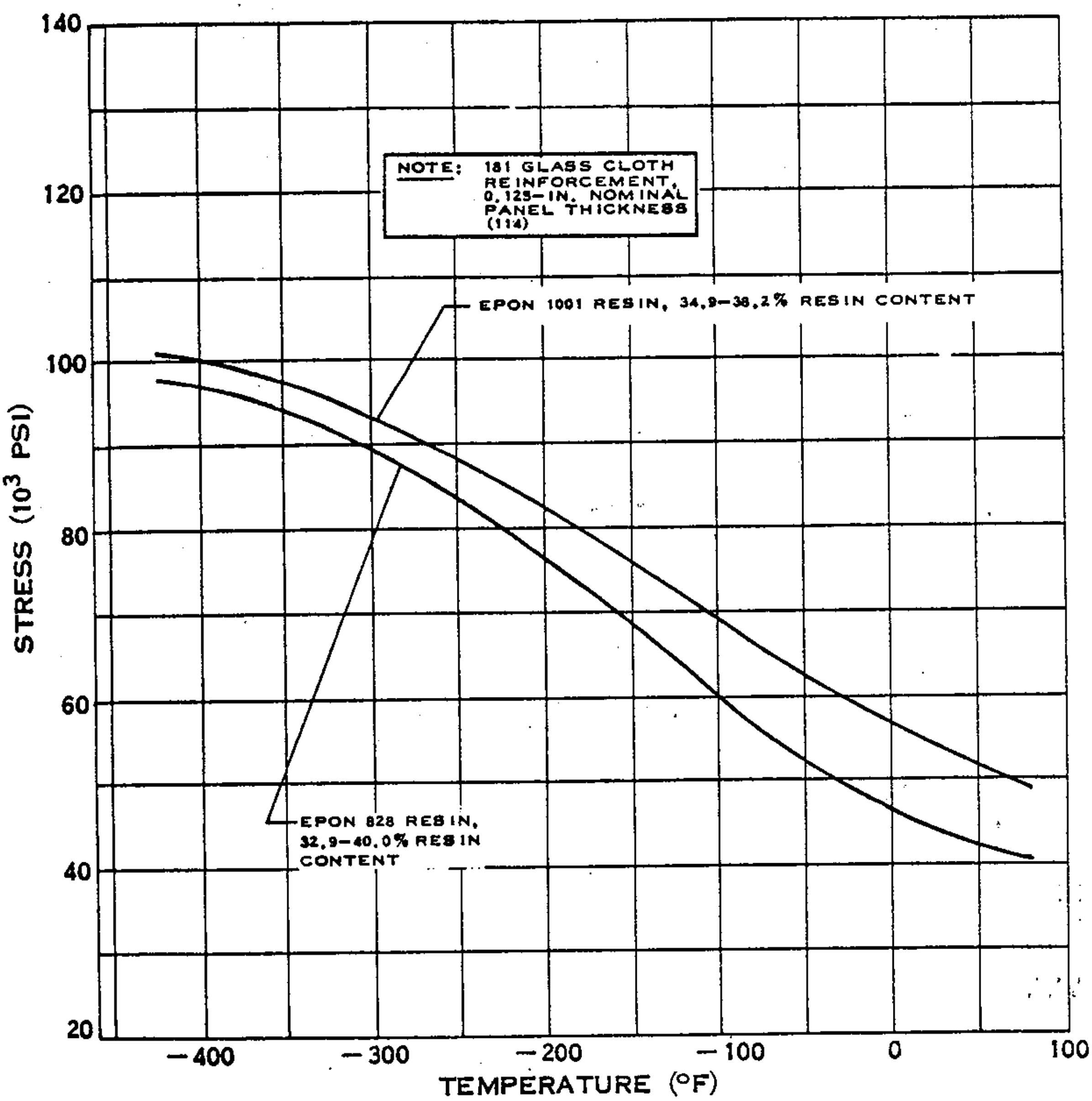


YIELD STRENGTH OF TEFLON* (TFE)

Schwartzberg, F. et al, Cryogenic Material Data Handbook,
Tech. Doc. Rpt. ML-TDR-64-208 AD609562,
Air Force Materials Lab., Aug. 1964

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

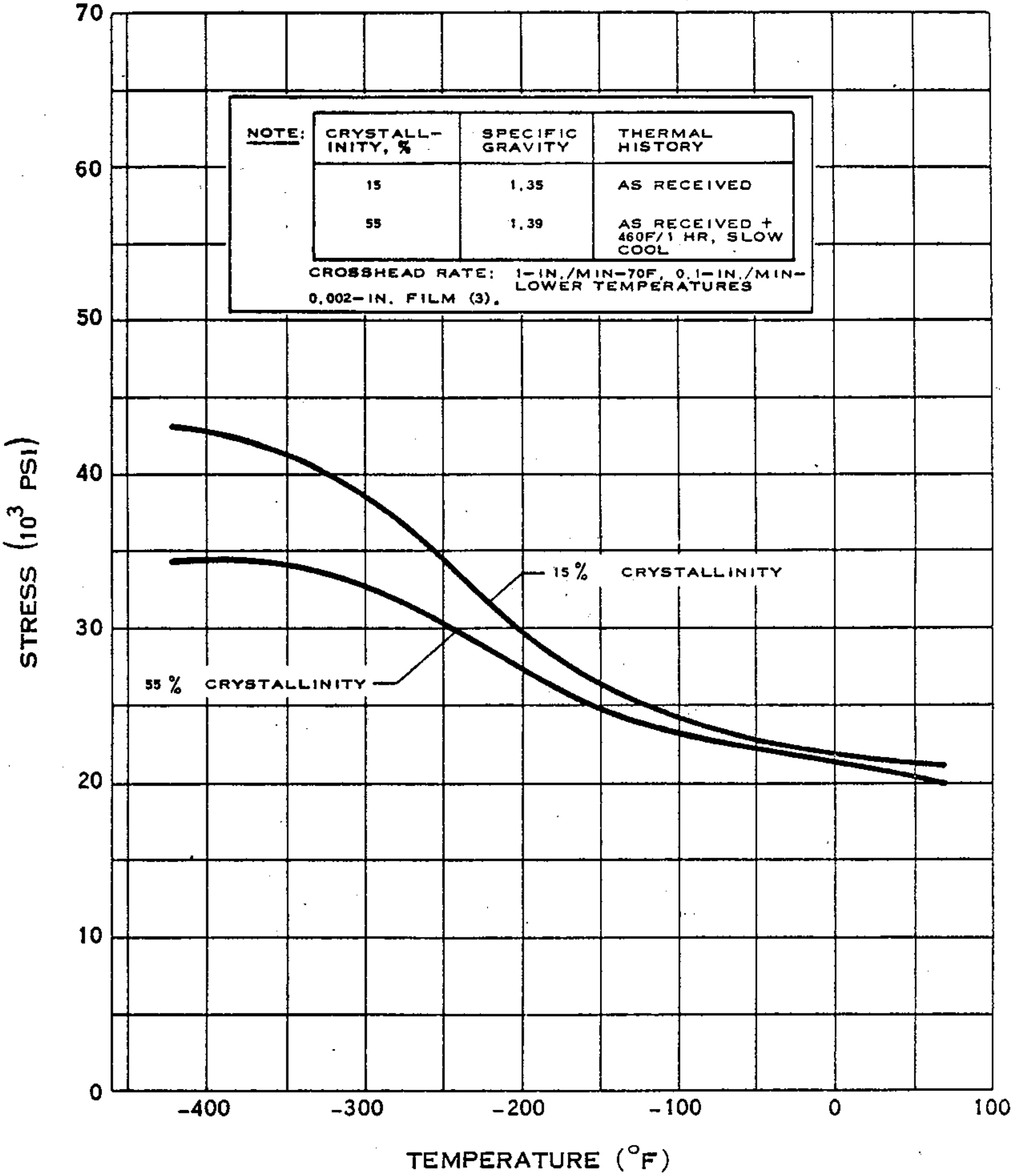
H.1.b



TENSILE STRENGTH OF EPOXY - FIBERGLASS LAMINATE

(7-64)

Schwartzberg, et. al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



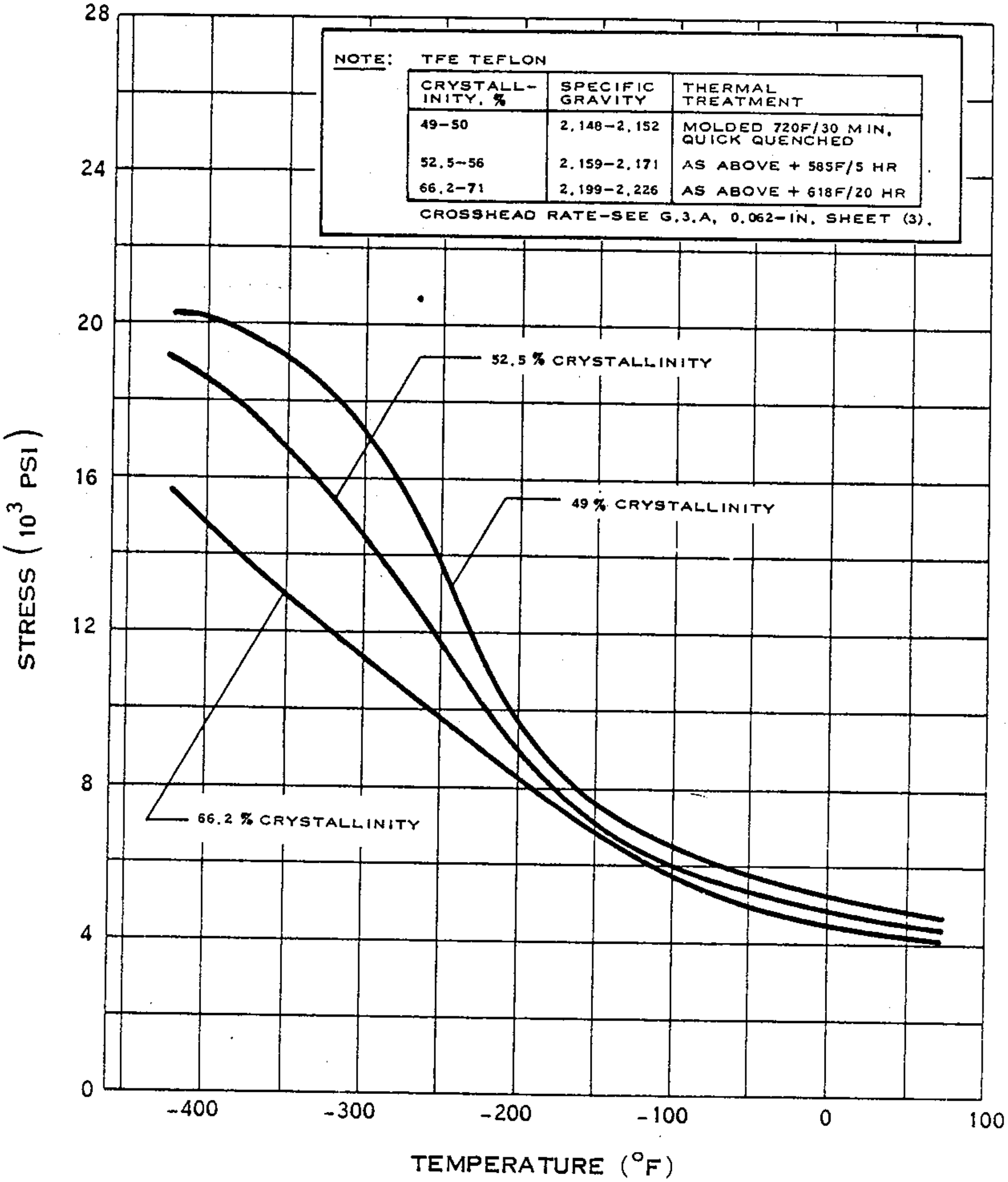
TENSILE STRENGTH OF MYLAR*

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et. al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

G.3.b



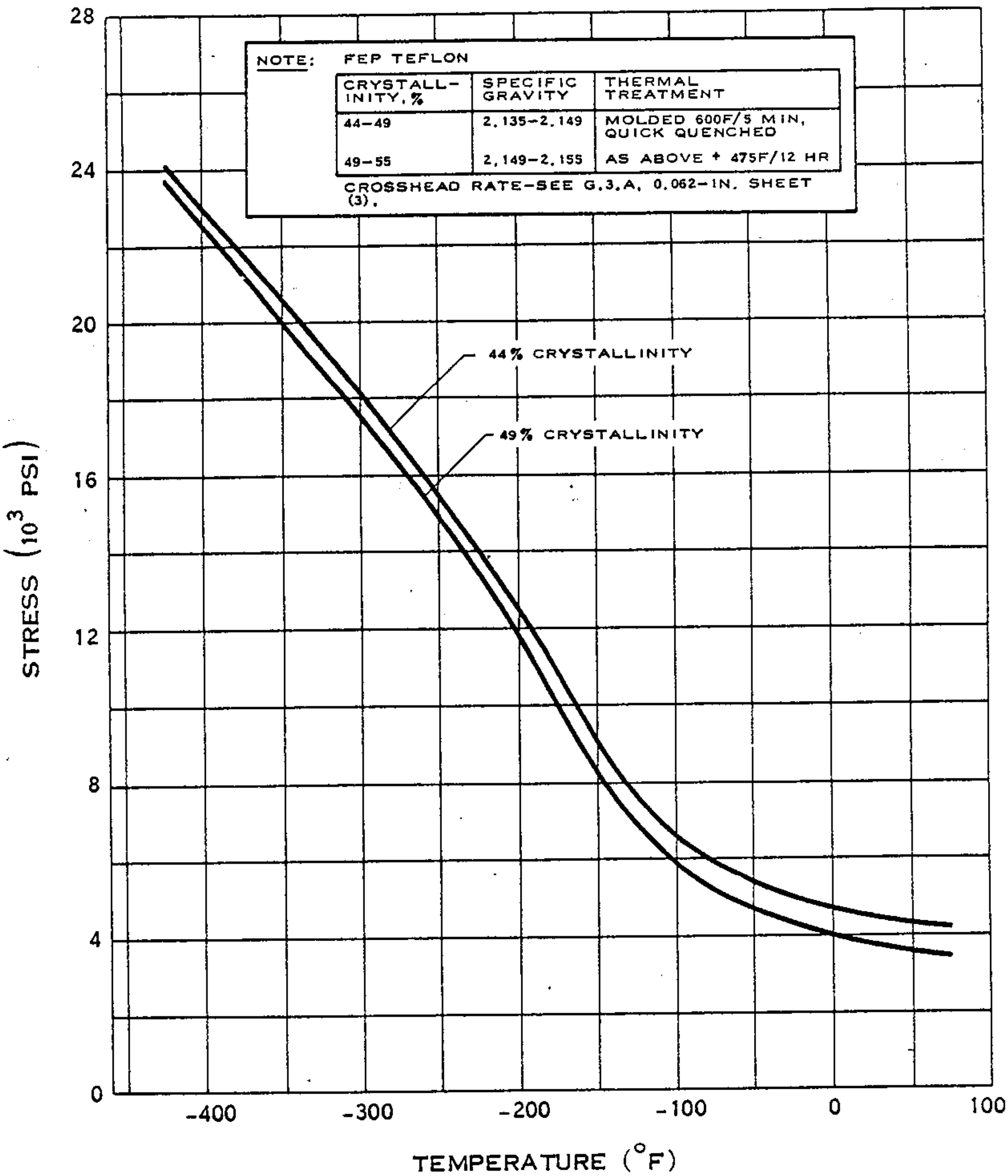
TENSILE STRENGTH OF TEFLON* (TFE)

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7–64)

Schwartzberg, et al., Cryogenic Materials Data Handbook, Tech. Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

G.3.b-1

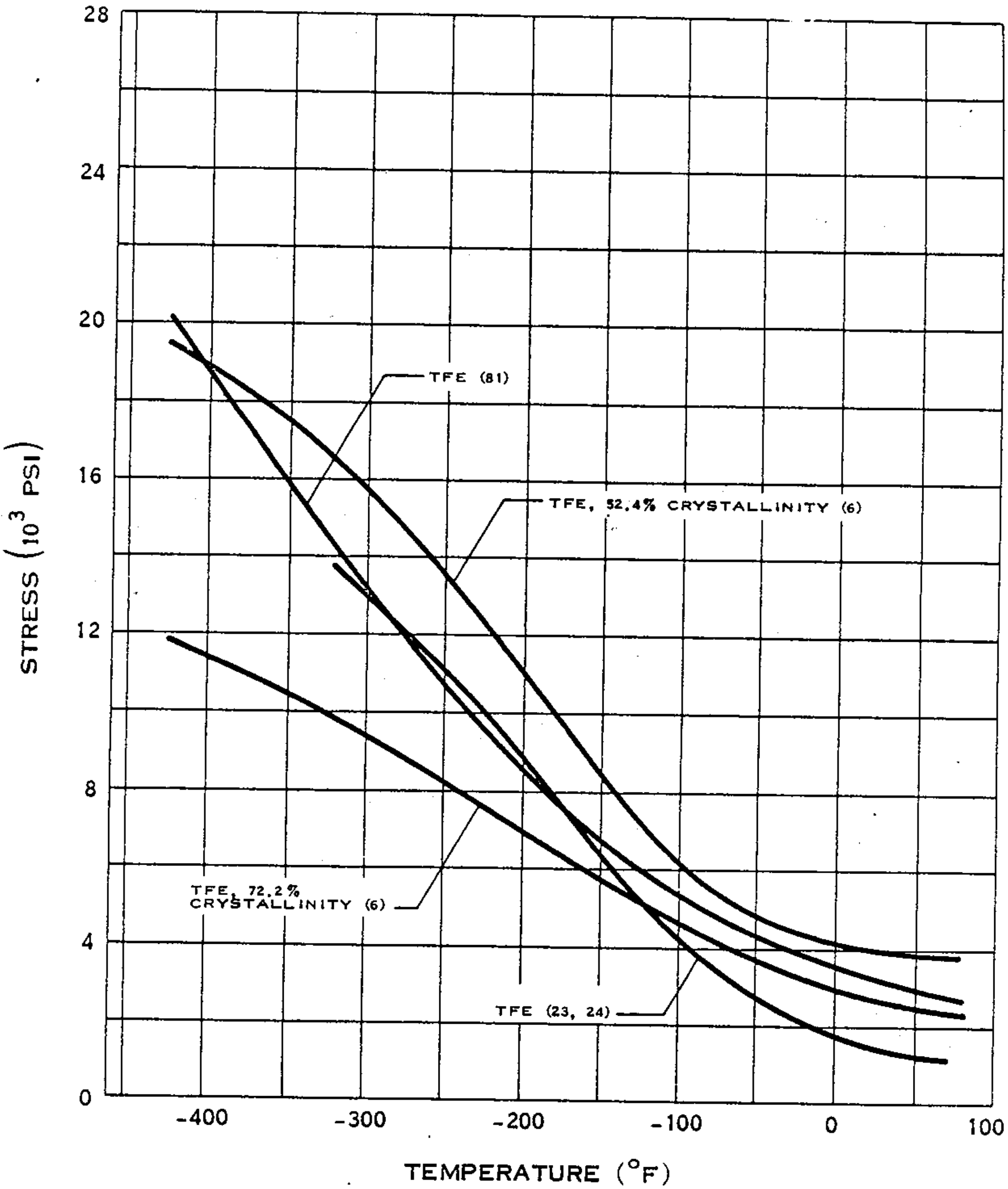


TENSILE STRENGTH OF TEFLON* (FEP)

*T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg., et al., Cryogenic Material Data Handbook,
Tech. Doc. Rpt. ML-TDR-64-280 AD609562,
Air Force Materials Lab., Aug. 1964

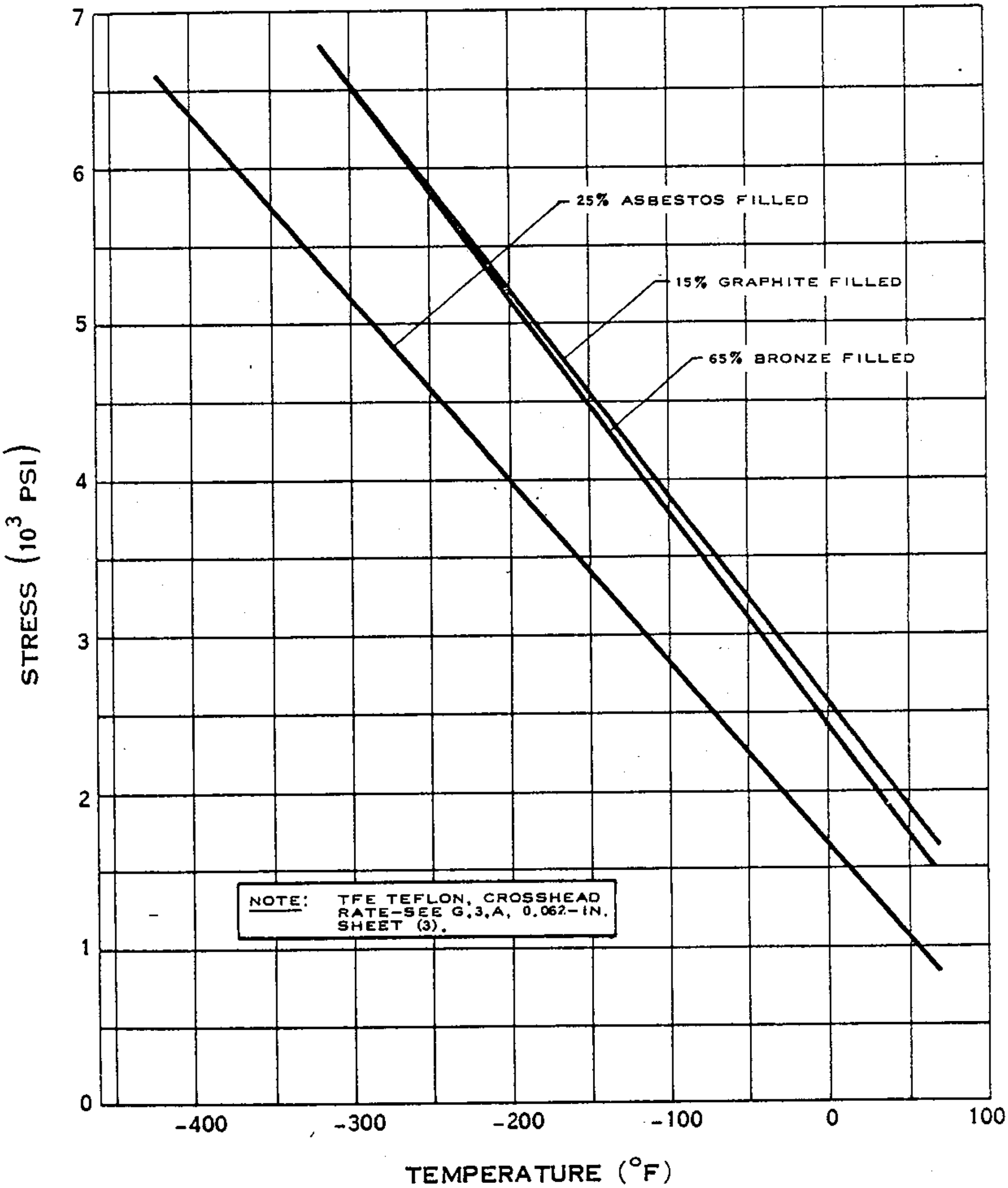


TENSILE STRENGTH OF TEFLON* (TFE)

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg., et al., Cryogenic Material Data Handbook, Tech, Doc. Rpt. ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



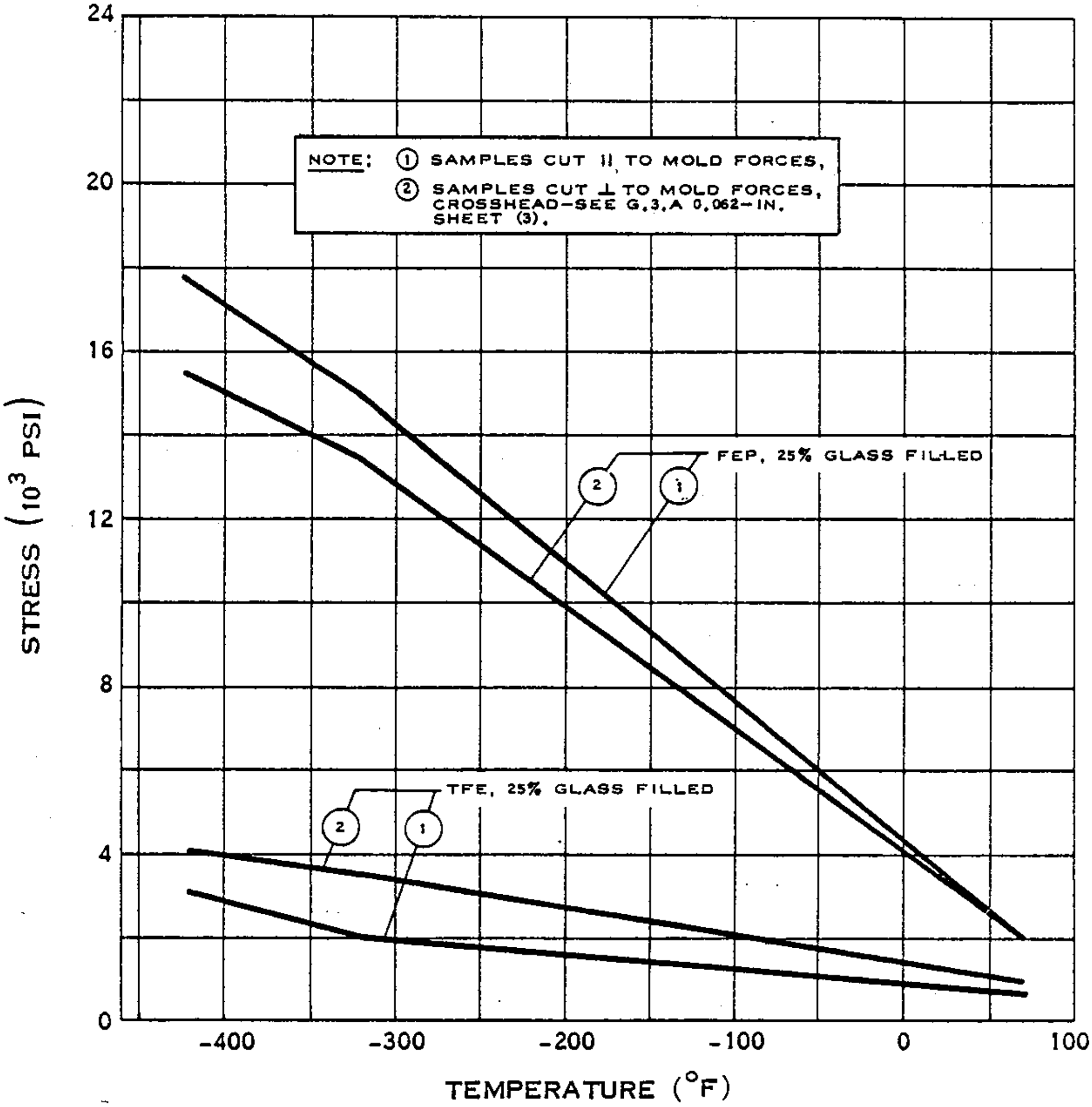
TENSILE STRENGTH OF TEFLON* (TFE)

* T.M. E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Tech. Doc. Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964

G.3.b-4



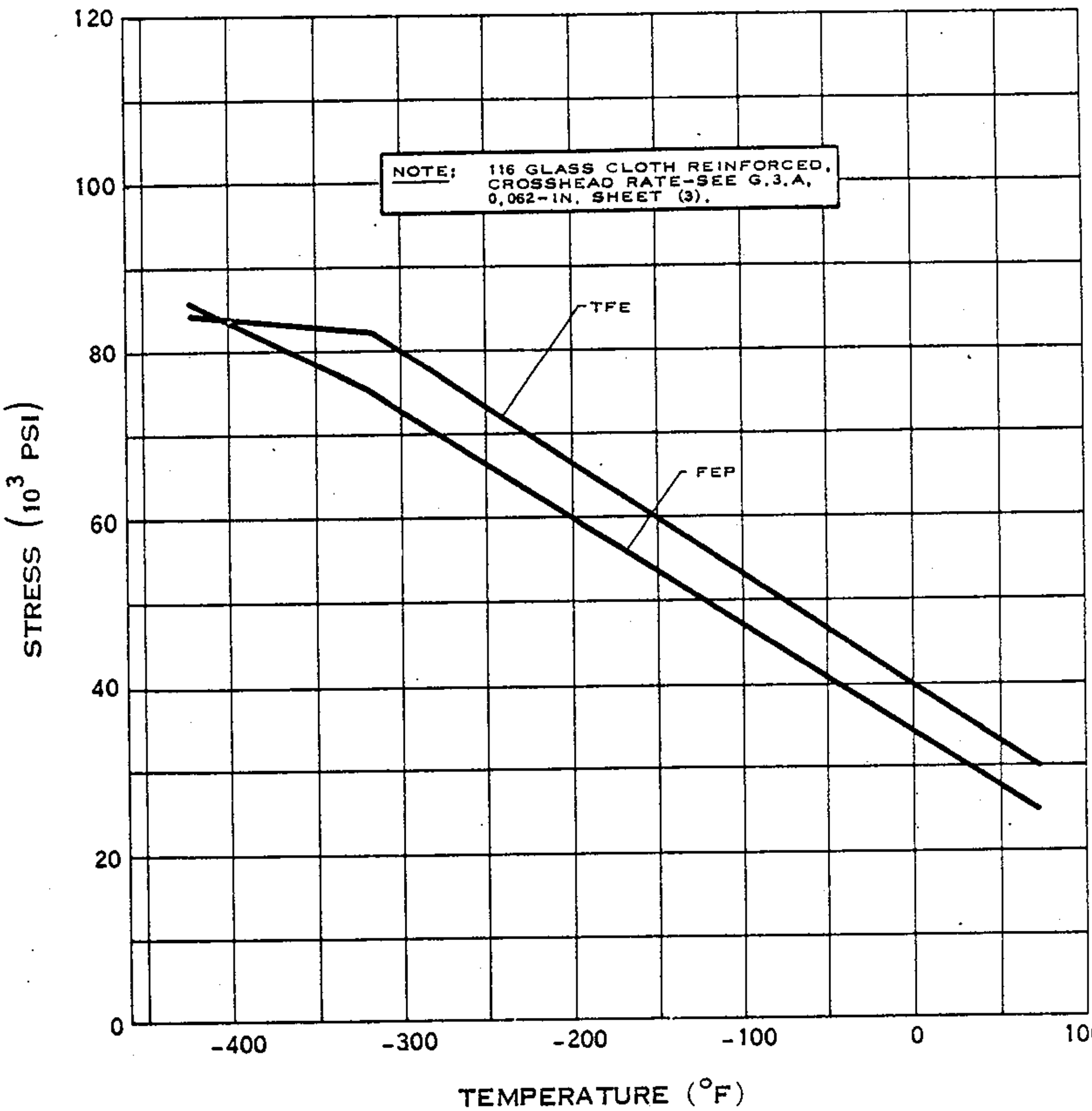
TENSILE STRENGTH OF TEFLON*

* T.M.
E. I. DUPONT DE NEMOURS AND CO.

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook,
Tech. Doc. Report ML-TDR-64-280 AD609562,
Air Force Materials Lab., Aug. 1964

G.3.b-5



TENSILE STRENGTH OF TEFLON*

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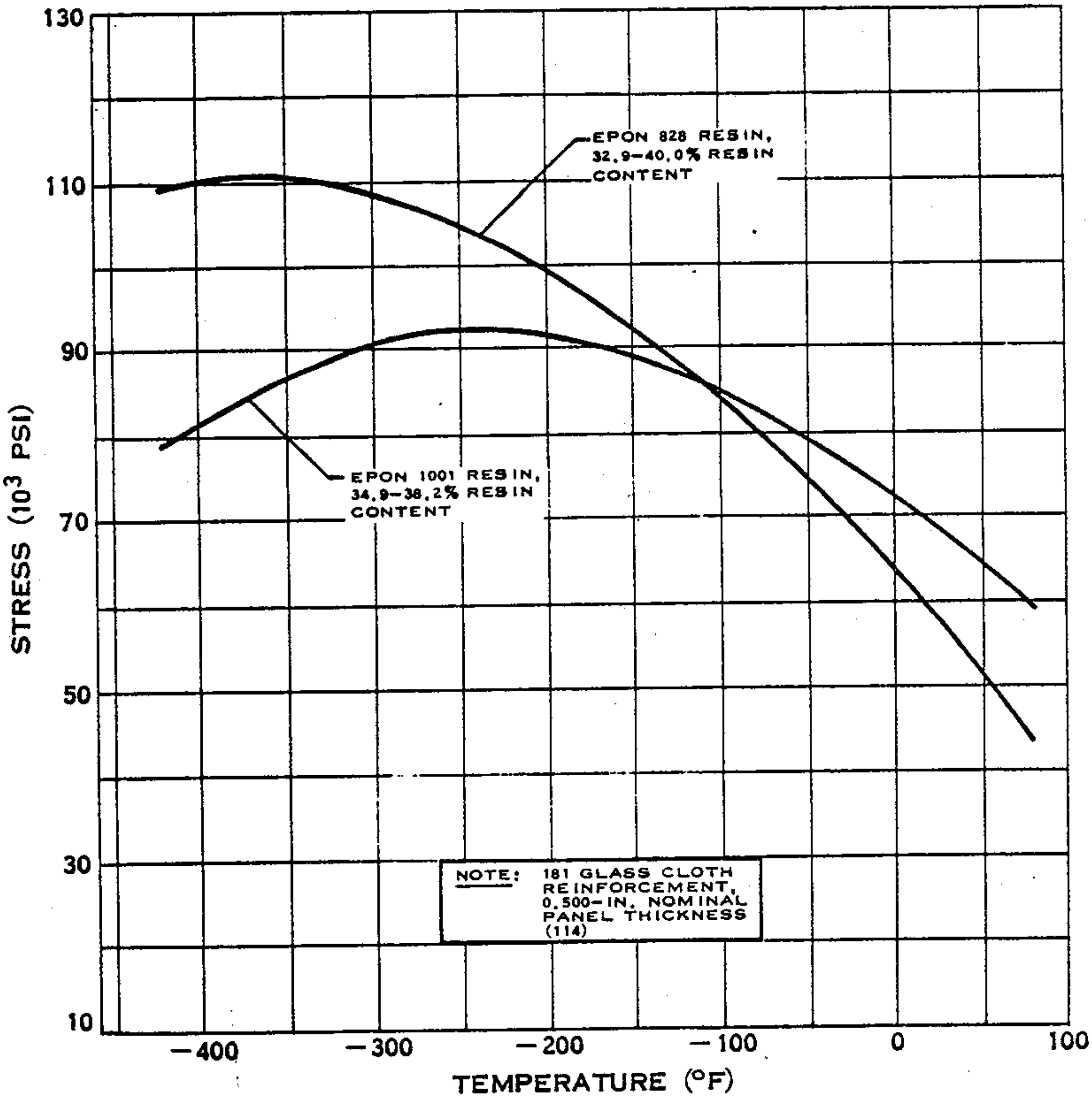
Schwartzberg, et al., Cryogenic Materials Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug., 1964

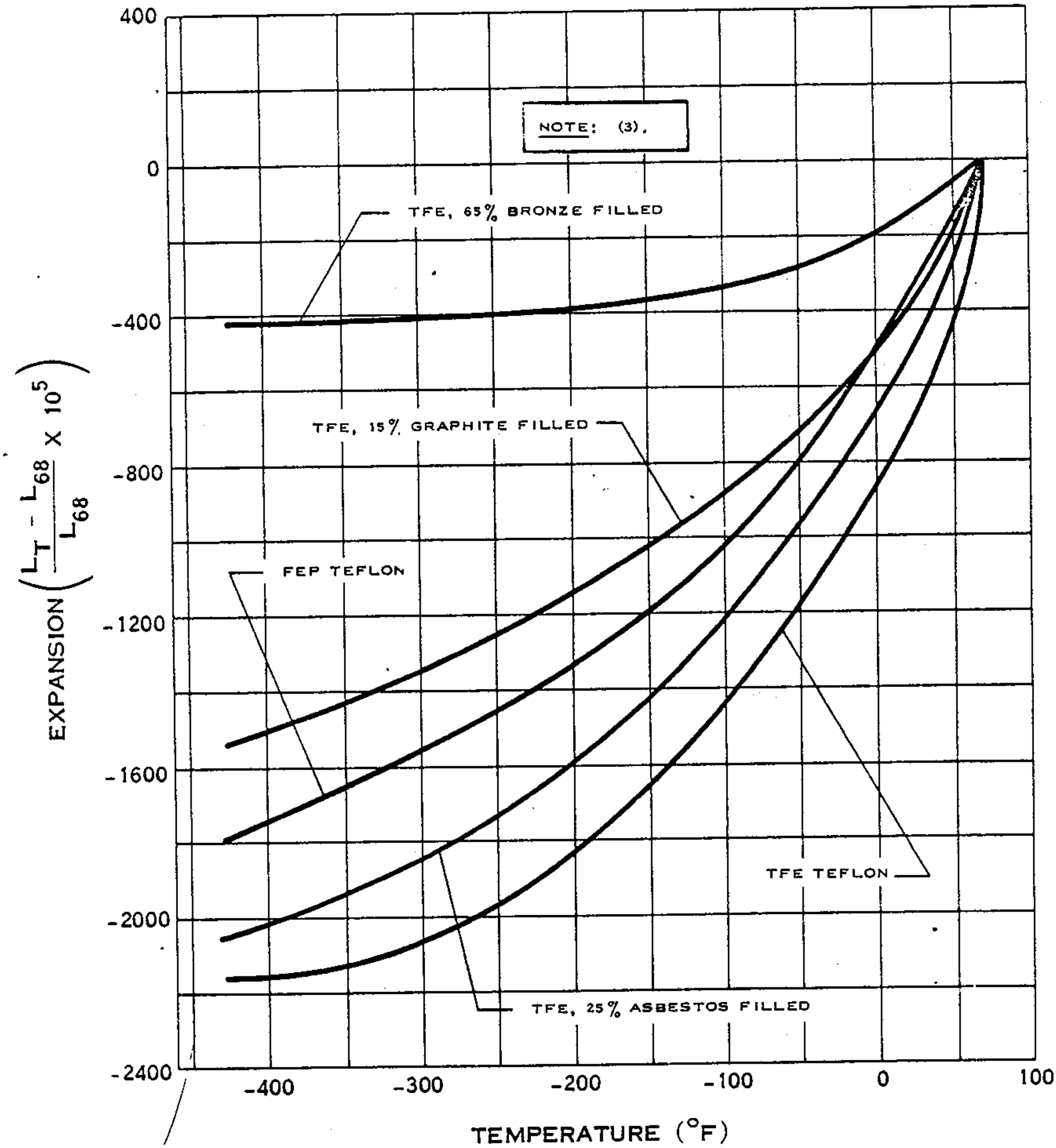
(7-64)



COMPRESSIVE STRENGTH OF EPOXY - FIBERGLASS LAMINATE

(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



THERMAL EXPANSION OF TEFLON*

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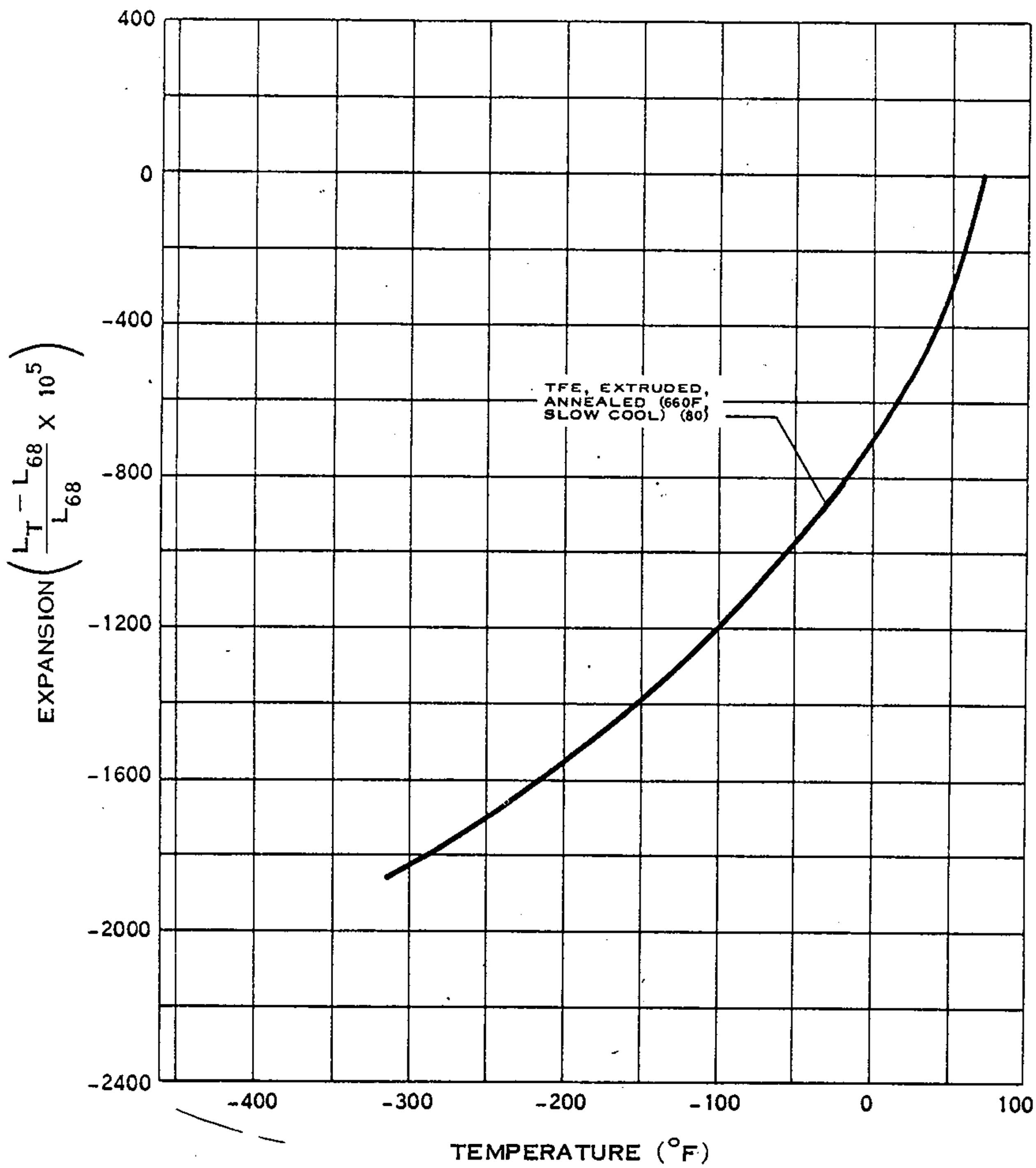
(7-64)

Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964



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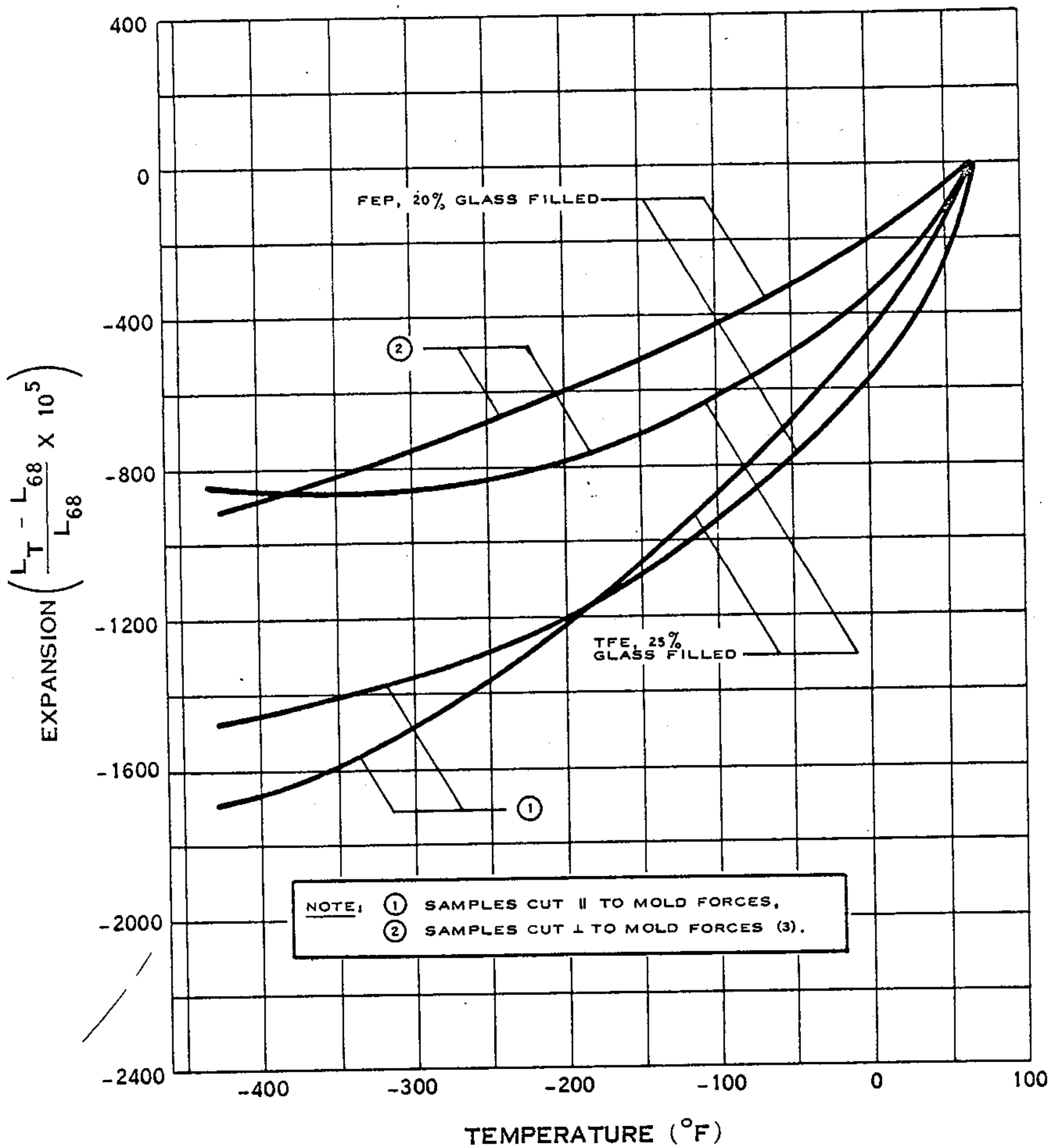

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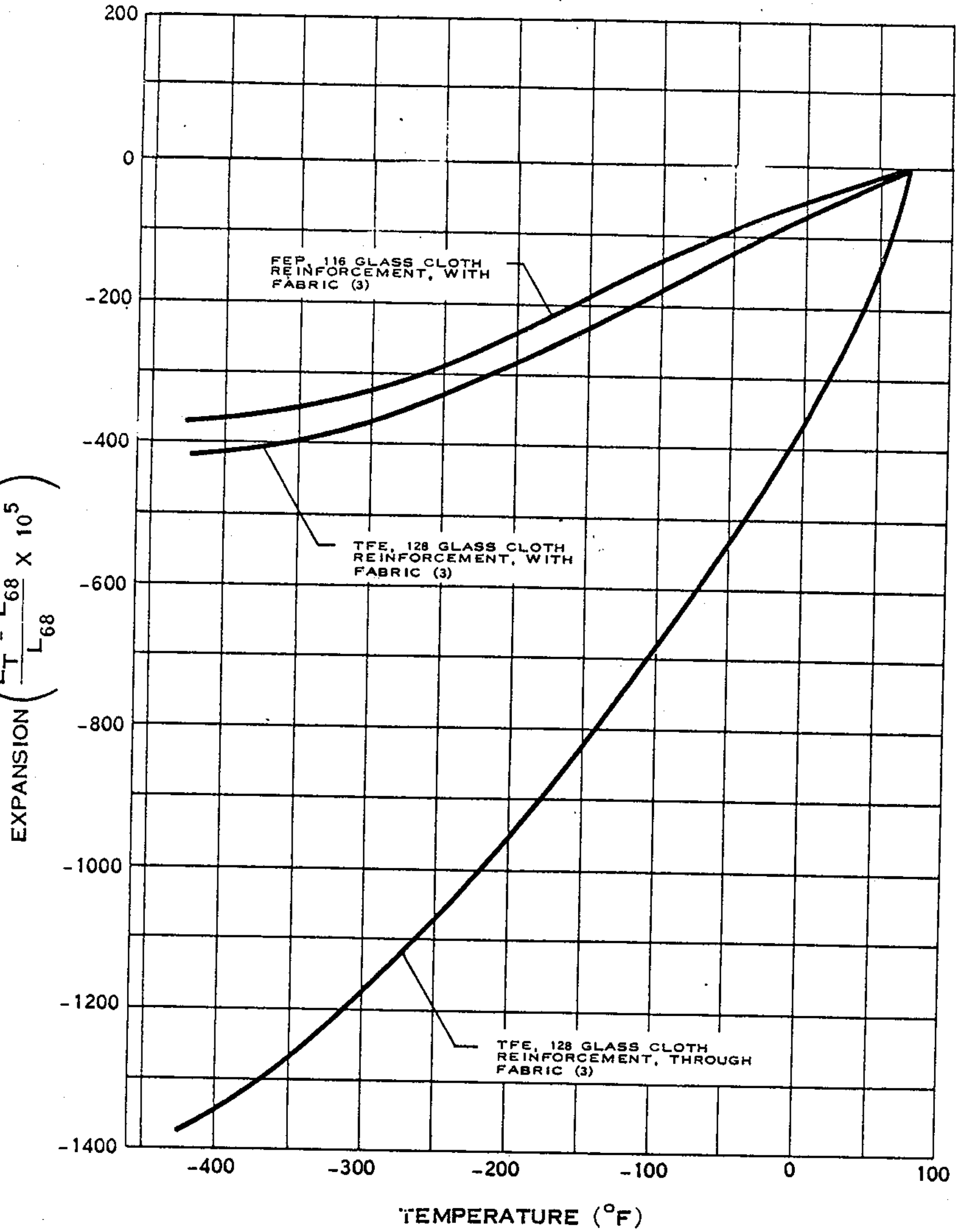

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Schwartzberg, et al., Cryogenic Material Data Handbook, Technical Documentary Report ML-TDR-64-280 AD609562, Air Force Materials Lab., Aug. 1964