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THERMOPHYSICAL PROPERTIES RESEARCH CENTER

RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

Y. S. TOULOUKIAN
Project Director and Editor

Prepared Under
NBS Sub-Contract No. CST-7590, NASA Order R-45

PURDUE UNIVERSITY LAFAYETTE, INDIANA

February 1966

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PREFACE

This report presents the results of a data search, collection, synthesis and analysis effort conducted over the period of February 1, 1965 to January 31, 1966. The work was performed under NBS Sub-Contract No. CST-7590 of NASA Order R-45 and was administered under the technical direction of the Space Nuclear Propulsion Office, Lewis Research Center. Dr. R. B. Stewart of NBS - Boulder Cryogenic Data Center served as liaison between NASA and TPRC.

It is hoped that the recommended values of the seven thermophysical properties covered by this report will serve as a useful reference tool to designers and engineers working in aerospace applications. It is also felt that as a result of this effort a much needed gap was filled in a small area of thermophsical properties knowledge.

As it is evident from the text discussions, serious gaps of information exist in the literature for several of the properties for most of the materials studied. An effort was made to fill in these gaps wherever feasible through theoretical or semi-empirical considerations. Some of the data were also extrapolated whenever it was felt justifiable within the limits of tolerances set for most engineering applications. In those instances where data were available, serious discord was discovered in nearly all cases, thus making it most difficult to resolve disagreements on the basis of the meager information at hand.

The data reported in this work are to be considered as the "most probable values" recommended by the TPRC staff at this time based on the total evidence known to them. While TPRC assumes full responsibility for its recommendations, it also reserves the right to revise these recommendations in the light of better information that may become available subsequently.

This report will be disseminated through NASA. In the meantime a limited number of copies are available at TPRC for qualified requestors. It should be understood however, that the results of this and similar special reports are always reflected in TPRC's loose-leaf data sheets through its well-known Data Book on Thermophysical Properties of Materials.

The names of contributing senior authors and their collaborators are indicated in each chapter of this report. Special and effective acknowledgment is also made for the invaluable contributions made by TPRC's Scientific Documentation Division and TPRC's supporting staff which made such a major effort possible during such a short time.

Y. S. Touloukian
Project Director and Editor

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MATERIALS	Thermal Conductivity	Viscosity	Thermal Emissivity	Thermal Diffusivity	Specific Heat	Density	Surface Tension
ELEMENTS:							
Aluminum	6	102	136	197	276	434	507
Beryllium	9		139	199	280	436	509
Chromium	11		141	201	283	438	511
Copper	13	104	143	203	286	440	513
Iron	15	106	146	205	290	442	515
Magnesium	18	108	148	207	294	444	517
Manganese	20		149	209	297	446	519
Nickel	22	110	150	211	301	448	521
Niobium	24		153	213	305	450	523
Silicon	27			215	308	452	524
Tin	29	112	156	217	311	454	525
Titanium	32	114	158	219	317	456	527
Zinc	34	116	160	221	320	458	529
ALLOYS:							
Aluminum Alloy 2219-T852	36			223	323	460	
Aluminum Alloy 6061-T6	38		161	225	326	462	
Aluminum Alloy 7075-T6	40		163	227	329	464	
Beryllium Alloy (dilute alloy)	43		167	229	332	466	
Inconel X-750	45		174	231	341	471	
Stainless Steel 304A	47		169	233	335	468	
Stainless Steel 347	49		170	235	338	469	
Titanium Alloy A-110AT	51		176	237	344	473	
OXIDES:							
Aluminum Oxide Al_2O_3	53	118	178	239	347	475	531
Beryllium Oxide BeO	58		180	242	351	477	
Chromium Oxide Cr_2O_3			189		354	479	532
Cupric Oxide CuO			189		356		
Cuprous Oxide Cu_2O			189		358		
Ferrous Oxide FeO		120	189		361	481	533
Ferric Oxide Fe_2O_3	63		189	246	363	483	
Iron Oxide Fe_3O_4	61			244	366		
Magnesium Oxide MgO	65		183	248	368	485	534
Manganese Monoxide MnO	69			250	371	487	
Manganese Dioxide MnO_2					373		
Manganese Sesquioxide Mn_2O_3					375		
Manganomanganic Oxide Mn_3O_4	71			252	377		
Nickel Oxide NiO	73		189	254	379	489	
Niobium Monoxide NbO					381		
Niobium Dioxide NbO_2					383		
Niobium Pentoxide Nb_2O_5			190		385	491	
Silicon Dioxide SiO_2	75	122	185	256	387	493	535
Tin(ous) Oxide SnO					394		
Tin(ic) Oxide SnO_2	80			259	396	495	
Titanium Monoxide TiO					398		
Titanium Dioxide TiO_2	82		187	261	400	497	
Titanium Sesquioxide Ti_2O_3					405		
Titanium Tripentoxide Ti_3O_5					407		
Zinc Oxide ZnO	87		190	264	409		

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TECHNICAL SCOPE OF PROGRAM

The scope of the activity covered by this program consisted of the generation of reference data on seven thermophysical properties of eight alloys, thirteen of their major constituent elements and the twenty-five primary oxides of these elements. Altogether forty-six materials were studied; however, in the case of some of the materials no data could be found on some of the properties and therefore not all of the seven properties could be reported consistently on all of the materials. Initially, it was intended to include the Prandtl Number as one of the properties considered. However, partly due to the paucity of data and primarily because of time limitations, this derived quantity was omitted from the program.

The report is divided into seven chapters, each chapter covering one of the following properties:

Chapter 1. Thermal conductivity
Chapter 2. Viscosity
Chapter 3. Thermal emissivity and emittance
Chapter 4. Thermal diffusivity
Chapter 5. Specific heat (constant pressure)
Chapter 6. Density
Chapter 7. Surface tension

The temperature range covered is from cryogenic temperatures to pass the melting point of the materials. Thus, the coverage includes both the solid and liquid states of the materials based on the availability of information.

Because of the large volume of raw data processed in the overall program it was decided not to report the original data used to arrive at the recommended values. While it is acknowledged that the reporting of the raw data would have been most desirable from an educational point of view it was felt that the extensive time and effort that it would require could not be justified on this limited program. Therefore, it was decided to devote all of the available effort to a broader coverage.

The brief text material at the head of each chapter summarizes the present state of knowledge on the particular property it discusses and gives an estimate of error tolerances of the recommended values. A list of references of the original works used in the study of each property is given at the end of each chapter.

The data on recommended values are reported in both graphical and tabular form. The tabular values are obtained from large working graphs or from analytic equations and reflect the accuracies inherent to the data. The graphical representations simply serve as a visual aid of the trend of the data.

The eight alloys selected by NASA for this program are as follows:

PRIMARY ALLOYS AND THEIR COMPOSITIONS*

	Composition, %
1. Aluminum Alloy 2219-T852	
Aluminum	Balance
Copper	5.8 -6.8
Iron	0.30 (max)
Manganese	0.20-0.40
Silicon	0.20 (max)
Zirconium	0.10-0.25
Zinc	0.10 (max)
Vanadium	0.05-0.15
Titanium	0.02-0.10
Magnesium	0.02 (max)
2. Aluminum Alloy 6061-T6	
Aluminum	Balance
Magnesium	0.8 -1.2
Silicon	0.40-0.8
Copper	0.15-0.40
Iron	0.7
Chromium	0.15-0.35
Zinc	0.25
Titanium	0.15
Manganese	0.15
Other Elements (each)	0.05
Other Elements (total)	0.15

*Heat treatment (temper) "T852" designates that the alloy has been solution heat treated, cold worked, then artificially aged, and then stress-relieved by compressing. The code "T6" designates that the alloy has been solution heat treated and then artificially aged.

	Composition, %
3. Aluminum Alloy 7075-T6	
Aluminum	Balance
Zinc	5.1 -6.1
Magnesium	2.1 -2.9
Copper	1.2 -2.0
Chromium	0.18-0.4
Iron	0.7
Silicon	0.5
Manganese	0.3
Titanium	0.2
4. Beryllium (dilute alloy)	
Beryllium Assay	98.0 (min)
Beryllium Oxide	2.00 (max)
Iron	0.20 (max)
Aluminum	0.18 (max)
Carbon	0.15 (max)
Magnesium	0.08 (max)
Silicon	0.12 (max)
Others (each)	0.04 (max)
5. Inconel X-750	
Nickel	70.0 (min)
Chromium	14.0 -17.0
Iron	5.0 - 9.0
Aluminum	0.40- 1.00
Titanium	2.25- 2.75
Niobium	0.70- 1.20
Cobalt	0.20 (max)
Copper	0.50 (max)
Manganese	1.20 (max)
Silicon	0.50 (max)
Carbon	0.08 (max)
6. Stainless Steel 304A	
Iron	69.0
Chromium	18.0-20.0
Nickel	8.0-11.0
Manganese	2.0
Silicon	0.8

	Composition, %
7. Stainless Steel 347	
Iron	Balance
Chromium	17.0-19.0
Nickel	9.0-13.0
Manganese	2.0
Silicon	1.0
Niobium	10 x C
Phosphorous	0.04
Sulfur	0.03
Carbon	0.08
8. Titanium Alloy A-110AT (Extra Low Interstitial)	
Titanium	Balance
Aluminum	4.75-5.75
Tin	2.20-2.80
Hydrogen	0.015 (max)
Iron	0.25 (max)
Oxygen	0.12 (max)
Carbon	0.050 (max)
Nitrogen	0.040 (max)
Boron	0.010 (max)
Others (each)	0.10 (max)
Others (total)	0.40 (max)

RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER I
THERMAL CONDUCTIVITY

BY

C. Y. HO
R. W. POWELL
M. NALBANTYAN

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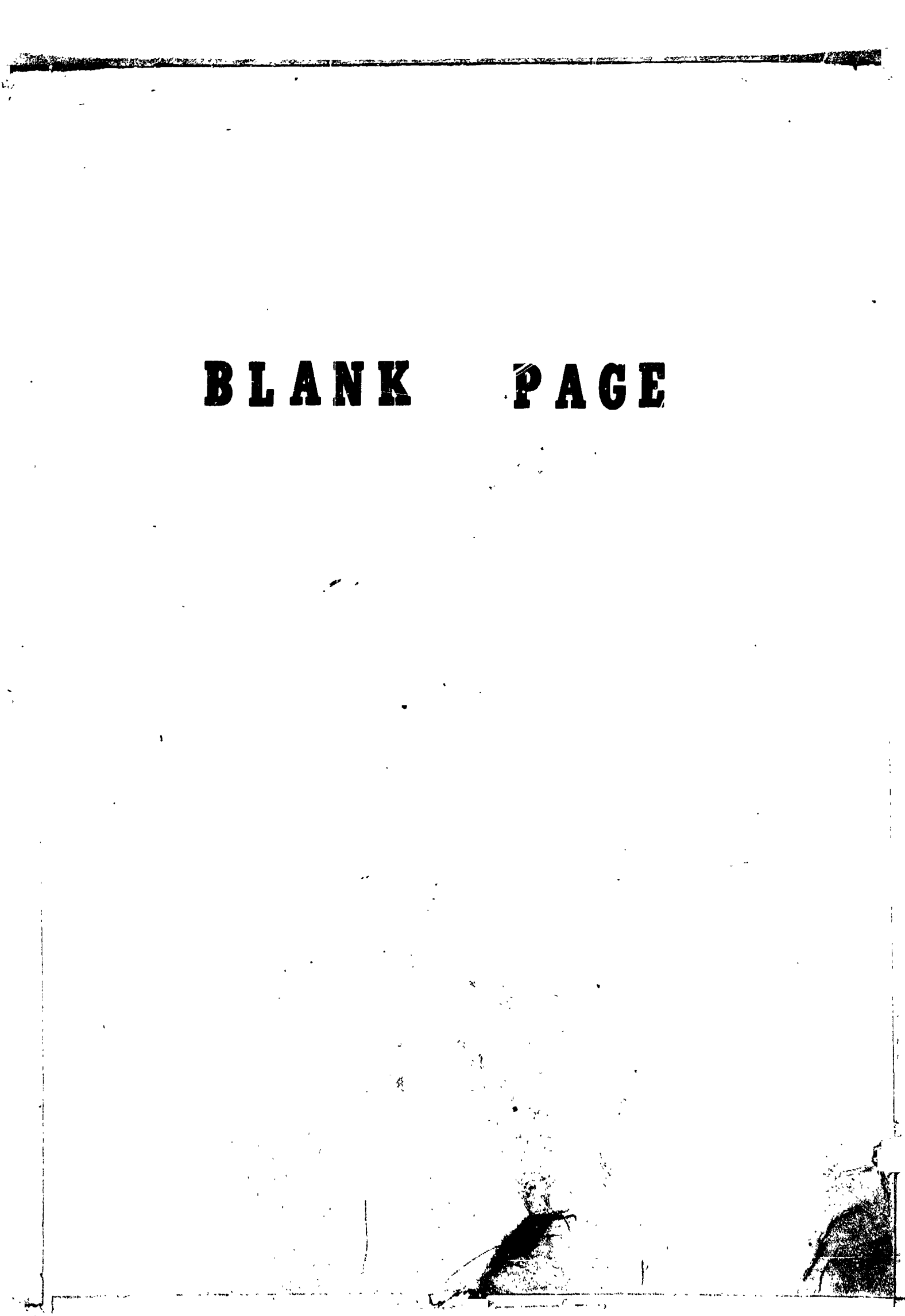

CHAPTER I
THERMAL CONDUCTIVITY

A. INTRODUCTION

A thorough literature search was conducted for the thermal conductivity of thirteen elements, eight alloys and twelve oxides. The results of the evaluation and analysis of the available data are the most probable values recommended for each of the materials considered. The recommended values are presented both in graphical and tabular form.

No experimental thermal conductivity data were uncovered for aluminum alloy 2219-T852 and 6061-T6. For manganese, no data above 90 K were available. For the other elements and alloys, in most cases, experimental data were available only up to about four-fifths of the melting point. Only in the case of the four elements - aluminum, copper, tin and zinc - did experimental data exist over the temperature range from cryogenic temperature to the melting point and above. However, reasonable estimates were made using empirical generalized correlations and semi-theoretical techniques so that recommended values were derived to cover a wide temperature range from absolute zero to above melting point for all elements and alloys except for manganese, silicon, titanium and titanium alloy A-110AT for which the recommended values cover the temperatures from absolute zero to the melting point only.

Limited experimental data were available for the oxides considered. Recommended values for the oxides are mostly limited to the temperature range of the available data.

For the elements the recommended values are for the purest specimens on which thermal conductivity measurements have been made. In order to specify the materials for which the values are recommended, two main criteria, namely, purity and residual electrical resistivity, are specified. Recommended values for the alloys refer to the specific compositions and heat treatments of the various alloys selected by NASA. For oxides, single crystal and polycrystalline specimen are treated separately. For the single crystals the recommended values are for the purest specimens measured, while for the polycrystalline oxides the recommended values are for 99.5% pure, 98% dense specimens whenever available data make the correlation of thermal conductivity with specimen purity and porosity possible.

B. DATA ANALYSIS

The data analysis procedure used involved critical evaluation of the validity of available data and related information from all sources and resolution of the disagreement among conflicting data. In most instances only "original" experimental data were taken into consideration. In one case, i.e., aluminum alloy 6061-T6, a single company-literature value at room temperature was used since no experimental data was available.

In determining the most probable values, consideration was given to all factors which affect thermal conductivity, such as purity (or chemical composition), crystal imperfection, crystal axes orientation, density (or porosity), thermal history, working history, microstructure, etc. It is very unfortunate that, in the majority of cases, the authors do not report all necessary pertinent information to fully characterize the materials for which their data are reported. Data for unspecified materials are of little utility. In the case of aluminum oxide, for example, although 160 sets of experimental data are available, yet only 20 out of 160 sets of data are for specimens for which purity and porosity are reported. Therefore, even for materials for which a large amount of data are seemingly available, the information that can be drawn from the data is meager.

Whenever specimen specifications were available, thermal conductivity data were correlated with the various parameters affecting this property. For the polycrystalline oxides, the data analysis was accomplished mainly by the correlation of thermal conductivity with purity and porosity. At each of several selected temperatures, thermal conductivity data for various specimens were adjusted to values corresponding to a specified density; namely, 98% of the theoretical density of the specimens. The adjusted data were then plotted against the purity of the specimens. Thus several data points were obtained, each corresponding to a 99.5% pure, 98% dense, polyscrystalline sample at each of these selected temperatures and an average curve drawn through these points gave the recommended values. For alloys, correlation of thermal conductivity with composition was made using data of the specific alloy and data of all other alloys of the same base metal. For metallic elements, besides the correlation of thermal conductivity with affecting parameters, the generalized Wiedemann-Franz law was used as a guide.

C. THERMAL CONDUCTIVITY OF SELECTED MATERIALS

For purposes of presentation, the selected materials are divided into three groups: elements, alloys and oxides, and within each group the materials are arranged in alphabetical order by name. For each material the recommended values are presented on a full-page graph followed by the tabular data, at the end of which are given the data source and remarks. The recommended values that are derived from experimental data are represented by a solid curve. Values that are extrapolated or estimated are represented by a broken line and are asterisked in the tabular presentation. Values for the material in superconducting state are represented by a dash-dot line. Recommended values that are derived from experimental data are thought to be accurate to within ±4 percent at room and moderate temperatures and within ±10 percent at extreme temperatures. In the tables the third significant figure is given only for the purpose of comparison and for the smoothness of the table and is not indicative of the degree of accuracy.

In the figures and/or tables several symbols and abbreviations have been used. Their meanings are as follows:

C. P.	Curie point
K	Kelvin temperature
k	thermal conductivity
l	liquid
M. P.	melting point
N. P.	Néel point
s	solid
T	temperature
T. P.	transition point
ρ_o	residual electrical resistivity

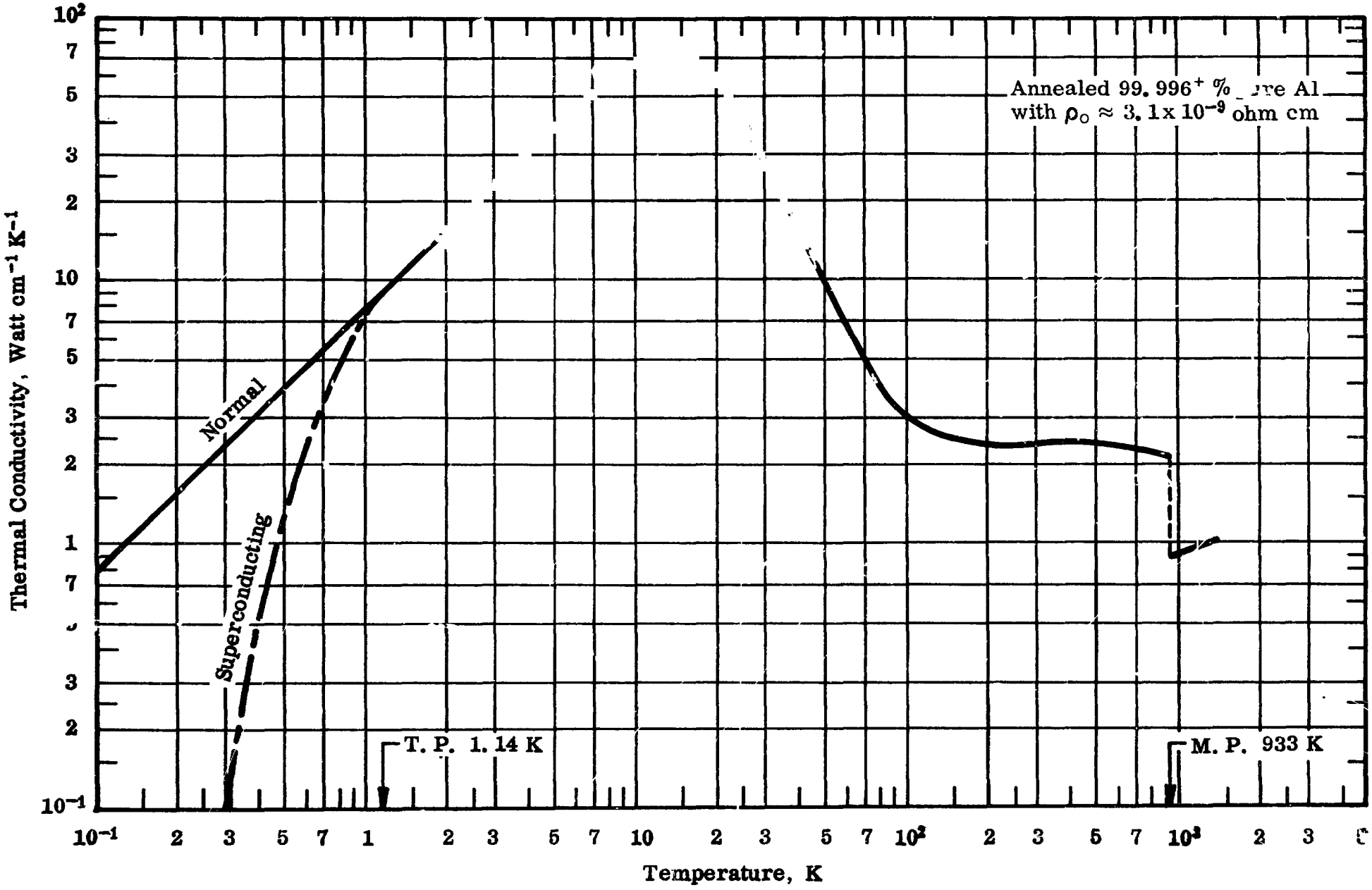

FIG. I-1 THERMAL CONDUCTIVITY OF ALUMINUM

TABLE I-1 THERMAL CONDUCTIVITY OF ALUMINUM

Selected Values for Annealed 99.996+ % Pure Aluminum with $\rho_0 \approx 3.1 \times 10^{-9}$ ohm cm

T, K	k, Watt $cm^{-1} K^{-1}$	T, K	k, Watt $cm^{-1}K^{-1}$
0	0	200	2.37
0.1	0.78*	250	2.34
0.5	3.9	273	2.35
1.0	7.8	300	2.37
5	38	350	2.40
10	66	400	2.40
15	70	450	2.39
20	56.5	500	2.37
25	40	600	2.32
30	28.5	700	2.26
35	21	800	2.20
40	16	900	2.13
45	12.5	(s) 930	2.10
50	10	(l) 950	0.89
60	6.7	1000	0.91
70	5	1100	0.94
80	4	1200	0.97
90	3.4	1300	1.00*
100	3.0	1400	1.02*
150	2.47		

In superconducting state:

T, K	k, Watt $cm^{-1}K^{-1}$	T, K	k, Watt $cm^{-1}K^{-1}$
0	0	0.7	3.4
0.1	0.00019*	0.8	4.6
0.2	0.005	0.9	5.9
0.3	0.089	1.0	7.1
0.4	0.47	1.1	8.5
0.5	1.2	1.14	8.8
0.6	2.2		

* Extrapolated

Data Source and Remarks

Fifty-three sets of experimental data are available. Selected values from 3 to 27 K are derived from the data of Andrews, Webber, and Sophr (1951) [1]*, values from 30 to 150 K from the data of Powers, Schwartz, and Johnston (1951) [2], and from 150 to 873 K the values are taken from the data of Powell, Tye, and Miss Woodman (1965) [3]. For liquid aluminum the values are taken from the data of Powell, Tye, and Metcalf (1965) [4] and values for superconducting aluminum from the data of Zavaritskii (1958) [5].

*Numbers in square brackets designate references appearing under the heading BIBLIOGRAPHY.

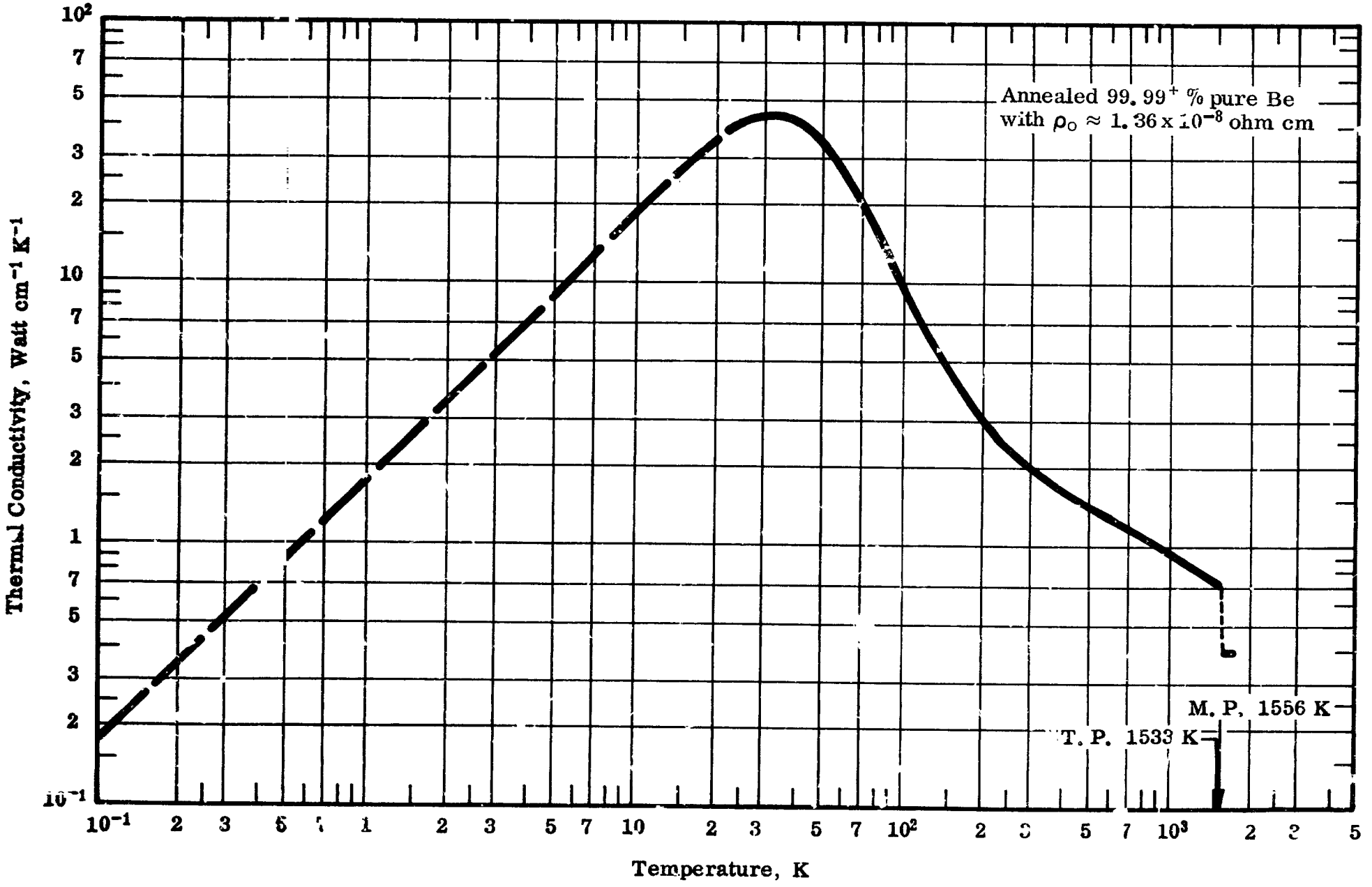

FIG. I-2 THERMAL CONDUCTIVITY OF BERYLLIUM

TABLE I-2 THERMAL CONDUCTIVITY OF BERYLLIUM

Selected Values for Annealed 99.99+ % Pure Beryllium with $\rho_o \approx 1.36 \times 10^{-8}$ ohm cm

T, K	k, Watt $cm^{-1} K^{-1}$	T, K	k, Watt $cm^{-1} K^{-1}$
0	0	250	2.4
0.1	0.18*	273	2.2
1	1.18*	300	2.0
5	9*	350	1.8
10	18*	400	1.65
15	27*	450	1.54
20	35*	500	1.45
25	42	600	1.30
30	45	700	1.18
35	45	800	1.09
40	42	900	1.01
45	39	1000	0.94
50	35	1100	0.89
60	27	1200	0.84
70	21	1300	0.80*
80	16	1400	0.77*
90	12.3	1500	0.74*
100	9.6	(s) 1556	0.72*
150	4.4	(l) 1600	0.36**
200	3.0		

Data Source and Remarks

Twenty-four sets of experimental data are available. Selected values from 23 to 91 K are taken from the data of Griineisen and Erfling (1940) [6]. From 310 to 1240 K the values are derived from the data for less-pure beryllium of Powell (1953) [7], Fieldhouse, Hedge, Lang, and Waterman (1958) [8], and the BMI Sample No. 5 reported by J. Ho and Wright (1960) [9]. There is no measurement on the liquid and the value is estimated.

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* Extrapolated.

** Estimated.

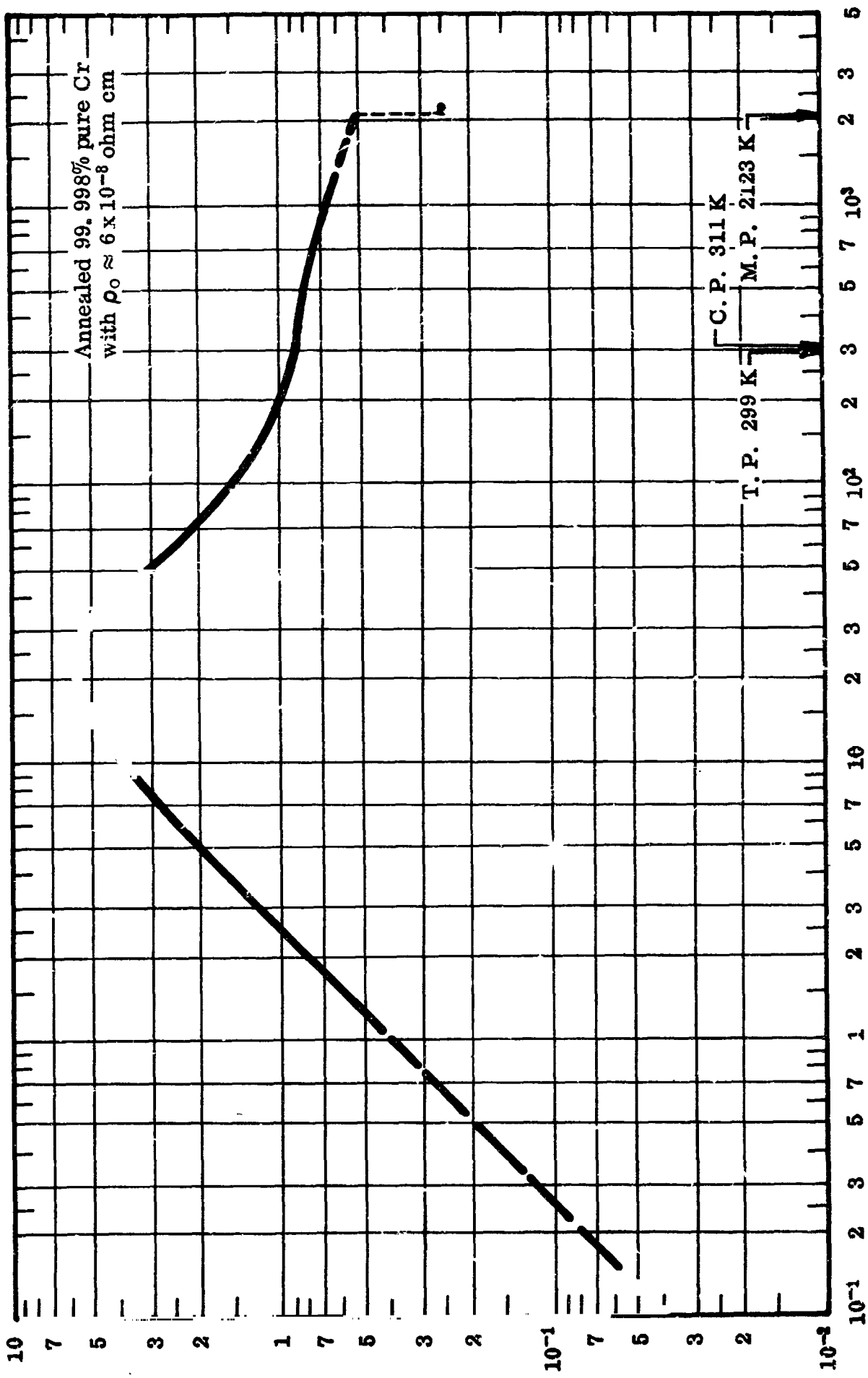

FIG. I-3 THERMAL CONDUCTIVITY OF CHROMIUM

TABLE I-3 THERMAL CONDUCTIVITY OF CHROMIUM

Selected Values for Annealed 99.998% Pure Chromium with $\rho_0 \approx 6 \times 10^{-8}$ ohm cm

T, K	k, Watt $cm^{-1}K^{-1}$		T, K	k, Watt $cm^{-1}K^{-1}$
0	0		300	0.88
0.1	0.04*		350	0.87
1	0.4*		400	0.86
5	2.0		450	0.85
10	3.9		500	0.83
15	5.2		600	0.80
20	5.75		700	0.76
25	5.8		800	0.72
30	5.5		900	0.70
35	4.9		1000	0.67
40	4.2		1100	0.65
45	3.6		1200	0.63
50	3.2		1300	0.62*
60	2.5		1400	0.60*
70	2.1		1500	0.59*
80	1.85		1600	0.58*
90	1.68		1700	0.56*
100	1.54		1800	0.55*
150	1.18		1900	0.54*
200	1.0		2000	0.53*
250	0.92	(s)	2100	0.52*
273	0.90	(l)	2200	0.25**

Data Source and Remarks

Fifteen sets of experimental data are available. Selected values from 2.4 to 150 K are taken from the data of Harper, Kemp, Klemens, Tainsh, and White (1957) [10]. From 323 to 1273 K the values are taken from the data of Powell and Tye (1956) [11] and Lucks and Deem (1956) [12]. The value for liquid chromium is estimated.

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* Extrapolated.

** Estimated.

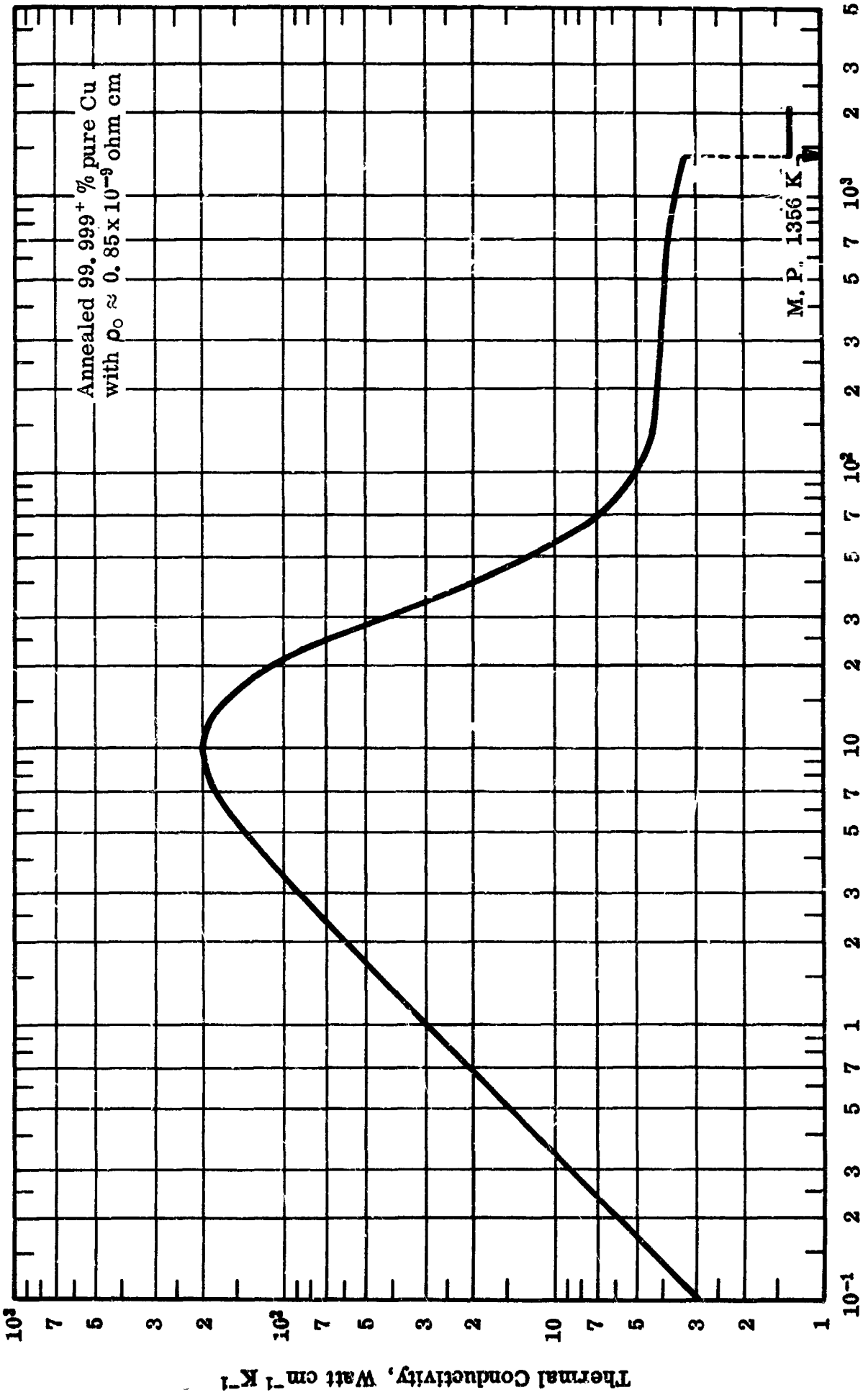

FIG. I-4 THERMAL CONDUCTIVITY OF COPPER

TABLE I-4 THERMAL CONDUCTIVITY OF COPPER

Selected Values for Annealed 99.999+% Pure Copper with $\rho_o \approx 0.85 \times 10^{-9}$ ohm cm

T, K	k, Watt $cm^{-1} K^{-1}$		T, K	k, Watt $cm^{-1}K^{-1}$
0	0		250	4.04
0.1	2.9*		273	4.01
0.5	15		300	3.98
1	29		350	3.94
5	138		400	3.92
10	196		450	3.90
15	156		500	3.88
20	105		600	3.83
25	68		700	3.77
30	43		800	3.71
35	29		900	3.64
40	20.5		1000	3.57
45	15.3		1100	3.50
50	12.2		1200	3.42
60	8.5		1300	3.34
70	6.7	(s)	1350	3.30
80	5.7	(l)	1360	1.4
90	5.1		1400	1.4
100	4.8		1600	1.4
150	4.3		1800	1.4
200	4.1		2000	1.4

Data Source and Remarks

One-hundred and twenty-seven sets of experimental data are available. Selected values from 2 to 55 K are taken from the data of White and Tainsh (1960) [13]. From 55 to 150 K the values are derived from the data of Powell, Roder, and Hall (1959) [14], Powell Rogers, and Coffin (1957) [15], Berman and MacDonald (1952) [16], Lees (1908) [17], and White (1953) [18]. Values from room temperature to the melting point are derived from the data of Mikryukov (1956) [19], Fieldhouse, Hedge, Lang, and Waterman (1956) [20], Sidles and Danielson (1951) [21], Pott (1958) [22], and Smith and Palmer (1935) [23]. For liquid copper the values are the average of the data of Lucks and Deem (1957) [24] and are assumed constant in view of the data of Fieldhouse, Hedge, Lang, and Waterman (1956) [25], and McClelland, Rasor, Dahleen, and Zehms (1957) [26].

*Extrapolated.

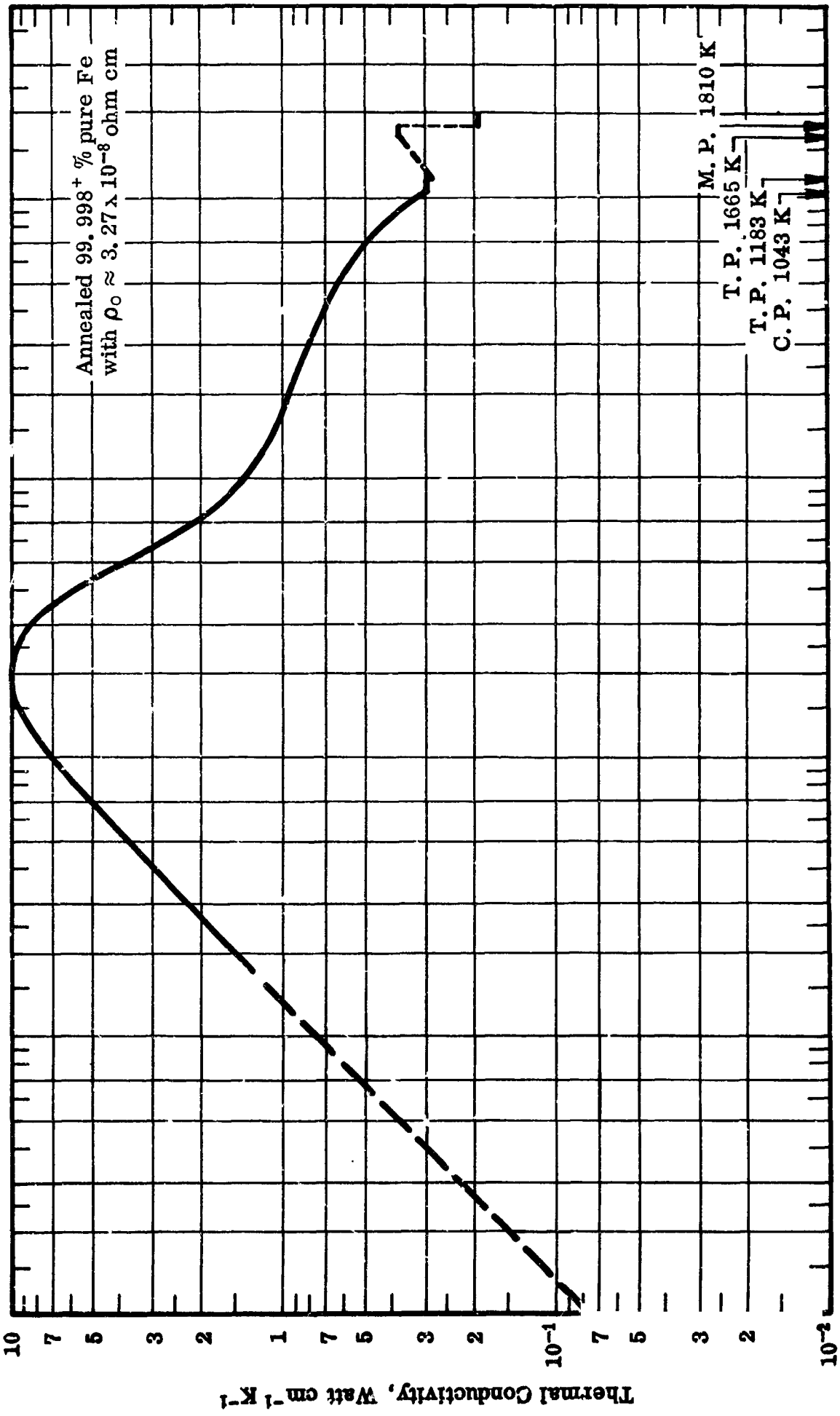

FIG. I-5 THERMAL CONDUCTIVITY OF IRON

TABLE I-5 THERMAL CONDUCTIVITY OF IRON

Selected Values for Annealed 99.998+ % Pure Iron with $\rho_0 \approx 3.27 \times 10^{-8}$ ohm cm

T, K	k, Watt $cm^{-1}K^{-1}$		T, K	k, Watt $cm^{-1}K^{-1}$
0	0		300	0.80
0.1	0.075*		350	0.742
1	0.75*		400	0.694
5	3.7		450	0.652
10	7.1		500	0.613
15	9.3		600	0.547
20	10		700	0.487
25	9.4		800	0.433
30	8.1		900	0.380
35	6.8		1000	0.325
40	5.6		1053	0.296
45	4.5		1100	0.297
50	3.7		1183	0.299
60	2.65		1183	0.279
70	2.05		1200	0.282
80	1.7		1300	0.302
90	1.5		1400	0.322
100	1.35		1500	0.342*
150	1.05		1600	0.362*
200	0.93		1700	0.376**
250	0.85	(s)	1800	0.378**
273	0.83	(l)	1900	0.19**

* Extrapolated.

** Estimated.

Data Source and Remarks

Thirty-eight sets of experimental data are available. The purest iron specimen ever measured with $\rho_0 \approx 3.27 \times 10^{-8}$ ohm cm is that of Arajs, Oliver, and Dunmyre (1965) [27]. The selected values from 1 to 30 K are calculated by using the method of Cezairliyan and Touloukian (1962 . 1965) [28,29] with the impurity-imperfection parameter determined by the above value of the residual electrical resistivity. Values from 30 K to 300 K are derived from the data of Kemp, Klemens, and Tainsh (1959) [30], Richter (1964) [31], and Powers, Ziegler, and Johnston (1951) [32], and values from room temperature to 1200 K from the data of Richter (1964) [31] and Moore, Fulkerson, McElory, and Kollie (1964) [33]. From 1183 to 1665 K in the γ - iron region, the extrapolation is made assuming the slope of the curve as being the same as that of the thermal conductivity curve of Nickel in this temperature range. Selected values for δ - iron and liquid iron are estimated since no data are available.

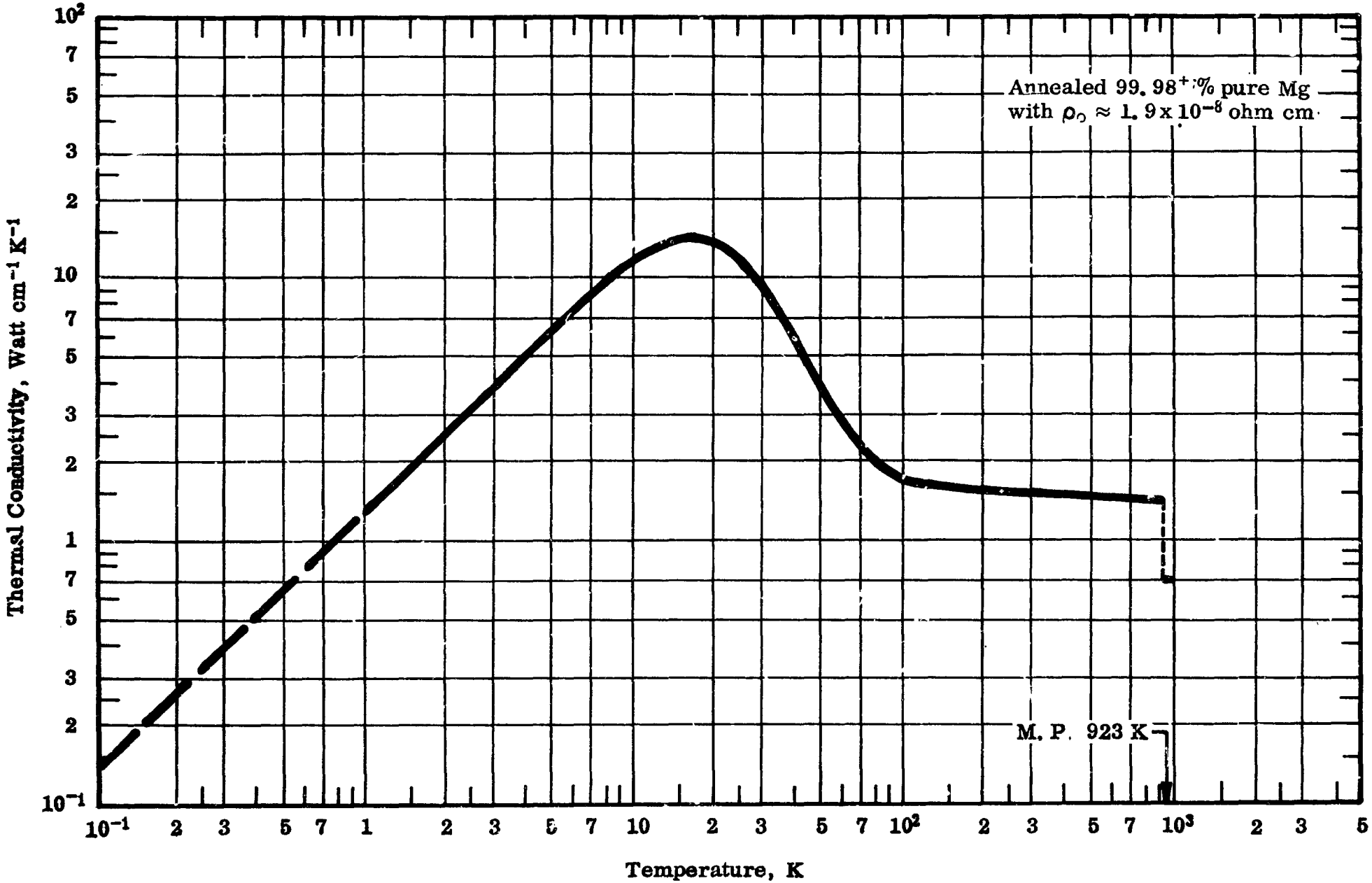

FIG. I-6 THERMAL CONDUCTIVITY OF MAGNESIUM

TABLE I-6 THERMAL CONDUCTIVITY OF MAGNESIUM

Selected Values for Annealed 99.98+% Pure Magnesium with $\rho_o \approx 1.9 \times 10^{-8}$ ohm cm

T,K	k, Watt $cm^{-1} K^{-1}$	T,K	k, Watt $cm^{-1}K^{-1}$
0	0	90	1.78
0.1	0.13*	100	1.69
1	1.3*	150	1.59
5	6.3	200	1.56
10	11.7	250	1.54
15	13.9	273	1.53
20	13.8	300	1.52
25	11.8	350	1.51
30	9.5	400	1.50
35	7.4	450	1.49
40	5.7	500	1.48
45	4.6	600	1.46
50	3.8	700	1.44
60	2.7	800	1.42*
70	2.2	(s) 900	1.40*
80	2.0	(l) 1000	0.7**

Data Source and Remarks

Twenty sets of experimental data are available. Selected values from 2 to 150 K are taken from the data of Kemp, Sreedhar, and White (1953) [34] and values from 323 to 673 K from the data of Powell, Hickman, and Tye (1964) [35]. There are no data available for liquid Magnesium and the selected value is from estimation.

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*Extrapolated.

**Estimated.

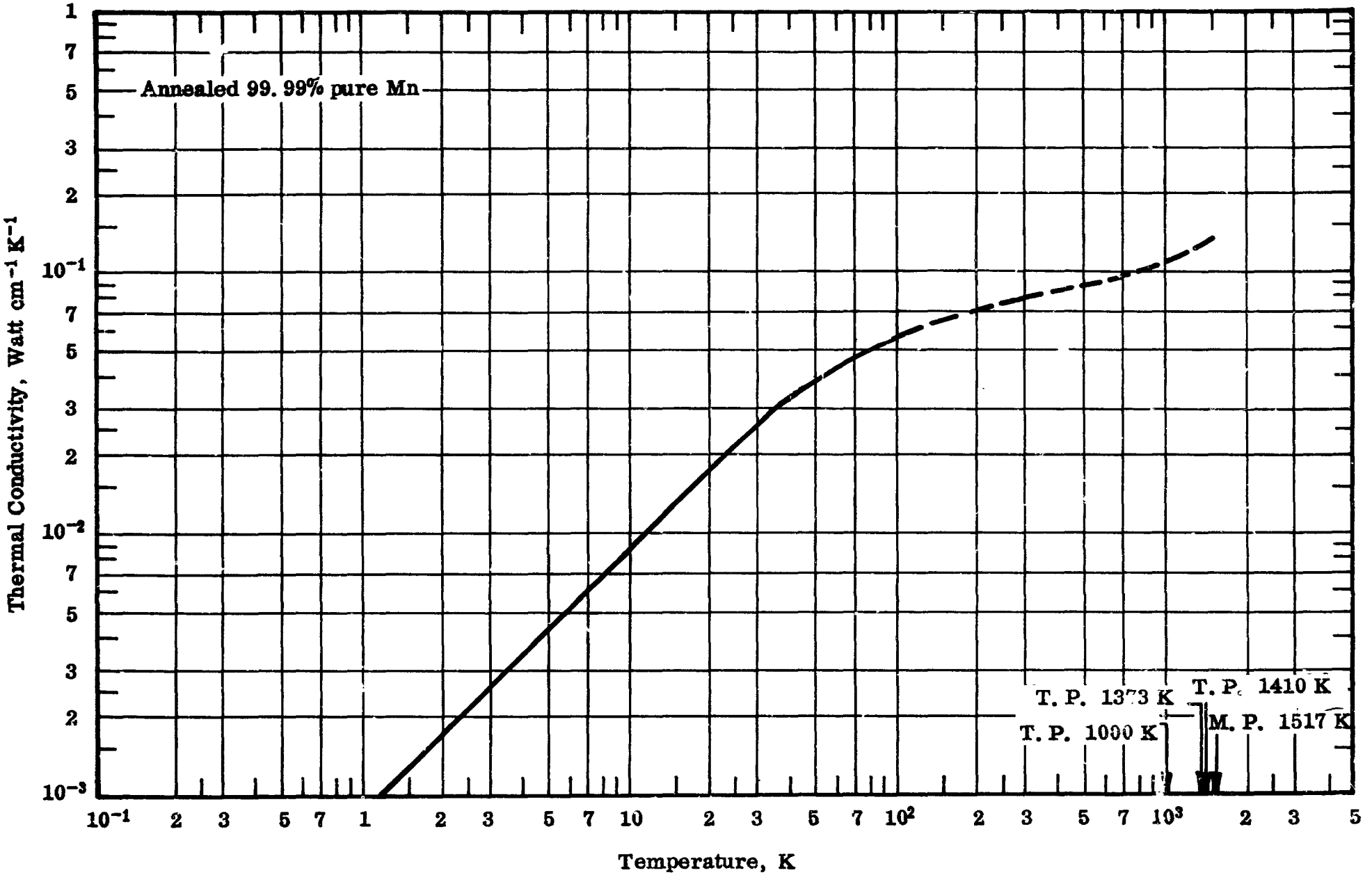

FIG. I-7 THERMAL CONDUCTIVITY OF MANGANESE

TABLE I-7 THERMAL CONDUCTIVITY OF MANGANESE

Selected Values for Annealed 99.99% Pure Manganese

T, K	k, Watt $cm^{-1} K^{-1}$	T, K	k, Watt $cm^{-1} K^{-1}$
0	0	200	0.071
0.1	0.000087*	250	0.075
1	0.00087*	273	0.077
5	0.0044	300	0.079
10	0.0087	350	0.082*
15	0.013	400	0.084*
20	0.017	450	0.087*
25	0.021	500	0.089*
30	0.025	600	0.093*
35	0.029	700	0.097*
40	0.032	800	0.102*
45	0.035	900	0.106*
50	0.038	1000	0.110*
60	0.043	1100	0.115*
70	0.047	1200	0.120*
80	0.051	1300	0.125*
90	0.054	1400	0.130*
100	0.056	1500	0.135*
150	0.065		

Data Source and Remarks

Four sets of experimental data are available. Selected values from 2 to 91 K are taken from the data of Mendelssohn and Rosenberg (1952) [36], Reddemann (1935)[37], and White and Woods (1957) [38]. No data above 91 K are available in the literature. The extrapolation from 91 K to high temperatures is based on a single value, K= 0.78 Watt $cm^{-1} K^{-1}$ at 293 K, measured recently by Tye (1966) [39].

* Extrapolated.

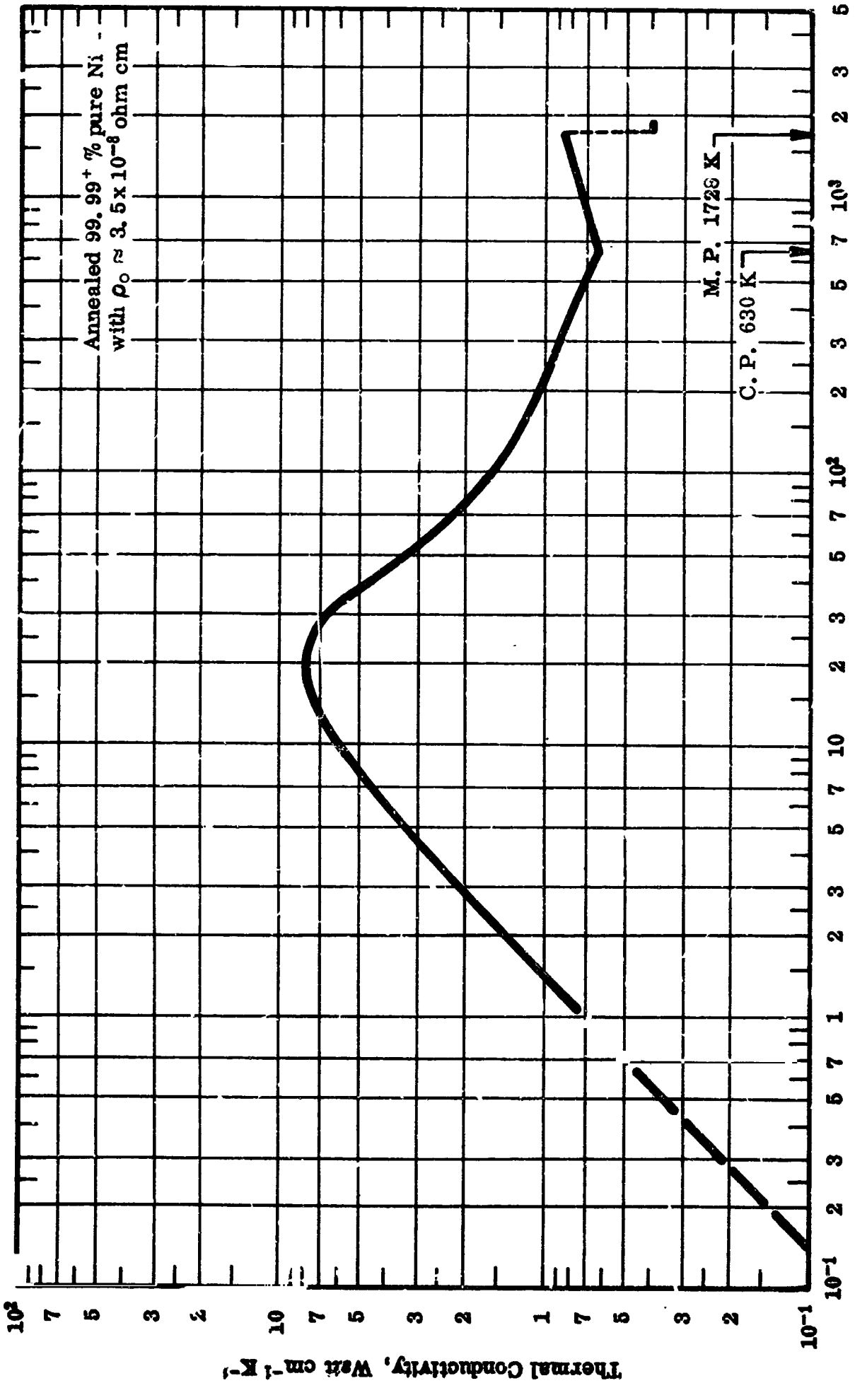

FIG. I-8 THERMAL CONDUCTIVITY OF NICKEL

TABLE I-8 THERMAL CONDUCTIVITY OF NICKEL

Selected Values for Annealed 99.99+ % Pure Nickel with $\rho_o \approx 3.5 \times 10^{-8}$ ohm cm

T,K	k, Watt $cm^{-1}K^{-1}$		T,K	k, Watt cm^{-1} K^{-1}
0	0		273	0.91
0.1	0.07*		300	0.88
1	0.7*		350	0.83
5	3.4		400	0.79
10	6.0		450	0.75
15	7.6		500	0.72
20	8.0		600	0.65
25	7.6		630	0.64
30	6.7		700	0.66
35	5.5		800	0.68
40	4.6		900	0.70
45	3.9		1000	0.72
50	3.4		1100	0.74
60	2.6		1200	0.76
70	2.2		1300	0.78
80	1.9		1400	0.80
90	1.7		1500	0.82
100	1.6		1600	0.84
150	1.2	(s)	1700	0.86*
200	1.03	(l)	1800	0.43**
250	0.94			

Data Source and Remarks

Thirty sets of experimental data are available. Selected values from 5 to 100 K are taken from the data of Kemp, Klemens, and White (1956) [40], and values from 350 to 1300 K from the data of Powell, Tye, and Hickmen (1965) [41]. No data for liquid nickel are available and the selected value is estimated.

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* Extrapolated.

** Estimated.

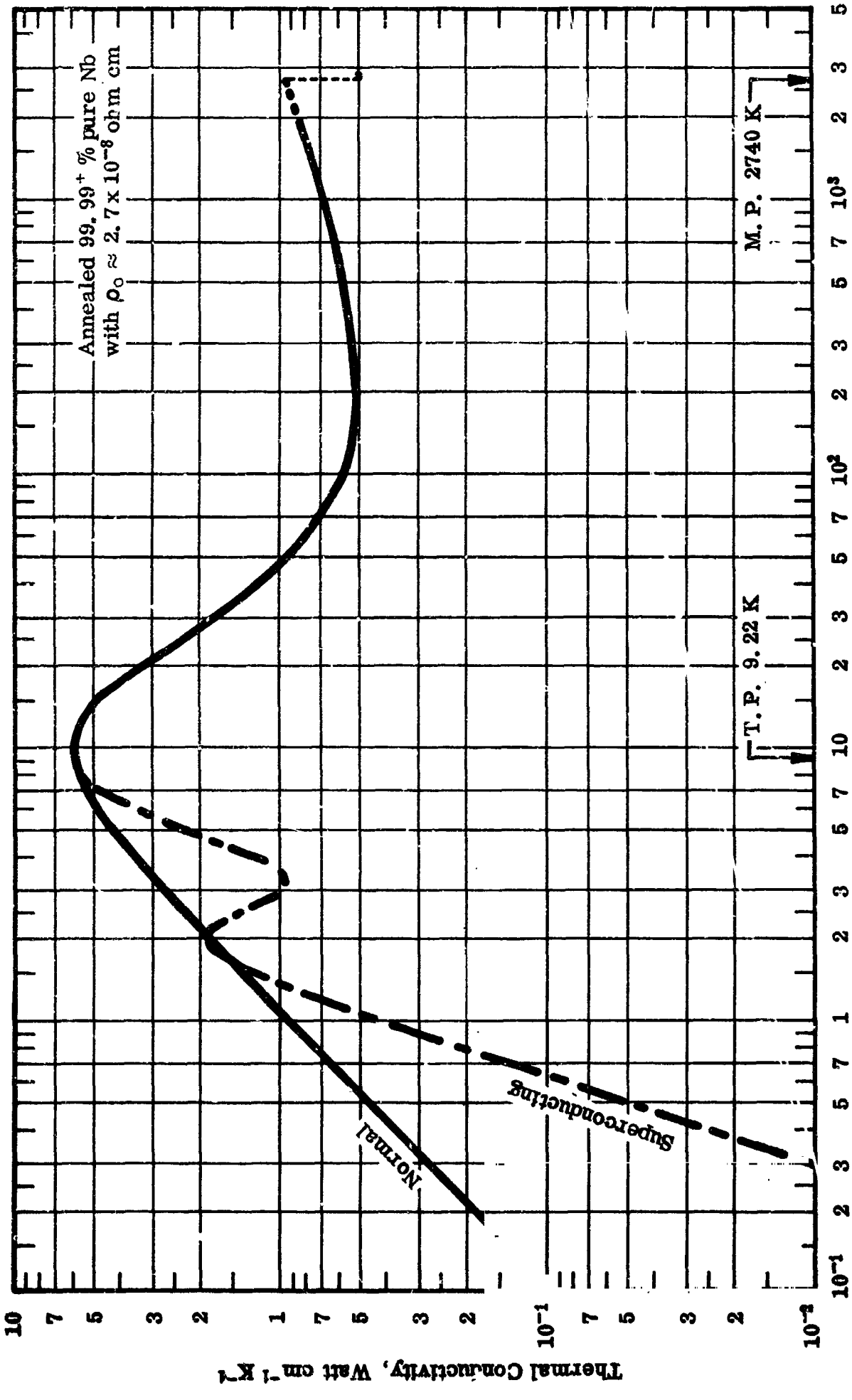

FIG. I-9 THERMAL CONDUCTIVITY OF NIOBIUM

TABLE I-9 THERMAL CONDUCTIVITY OF NIOBIUM

Selected Values for 99.99+% Pure Niobium with $\rho_0 \approx 2.7 \times 10^{-8}$ ohm cm

T, K	k, Watt $cm^{-1} K^{-1}$	T, K	k, Watt $cm^{-1} K^{-1}$
0	0	400	0.55
0.1	0.09*	450	0.56
1	0.9	500	0.57
5	4.3	600	0.59
10	6.0	700	0.61
15	4.7	800	0.63
20	3.1	900	0.65
25	2.25	1000	0.67
30	1.7	1100	0.685
35	1.4	1200	0.70
40	1.18	1300	0.72
45	1.03	1400	0.74
50	0.92	1500	0.76
60	0.78	1600	0.77
70	0.69	1700	0.79
80	0.63	1800	0.81
90	0.60	1900	0.825
100	0.57	2000	0.84*
150	0.52	2200	0.87*
200	0.515	2400	0.90*
250	0.52	2600	0.93*
273	0.525	(s) 2700	0.95*
300	0.53	(l) 2800	0.5**
350	0.54		

*Extrapolated.

**Estimated

In superconducting state:

T,K	k,Watt $cm^{-1} K^{-1}$	T,K	k,Watt $cm^{-1} K^{-1}$
0	0	3.5	0.96
0.1	0.00038*	4	1.2
0.5	0.048	5	2.2
1	0.38	6	3.6
1.5	1.24	7	5.0
2	1.81	8	5.7
2.5	1.32	9	5.9
3	0.95	9.22	5.92

Data Source and Remarks

Forty sets of experimental data are available. Selected values from 1 to 2K for the normal state and from 1 to 9.22 K for the superconducting state are taken from the data of Mendelssohn (1958) [42]. From 273 to 873 K the values are derived from the data of Bell (1955) [43], Powell (1957) [44], and Tye (1961) [45]. No data for liquid Niobium is available and the value is from estimation.

* Extrapolated.

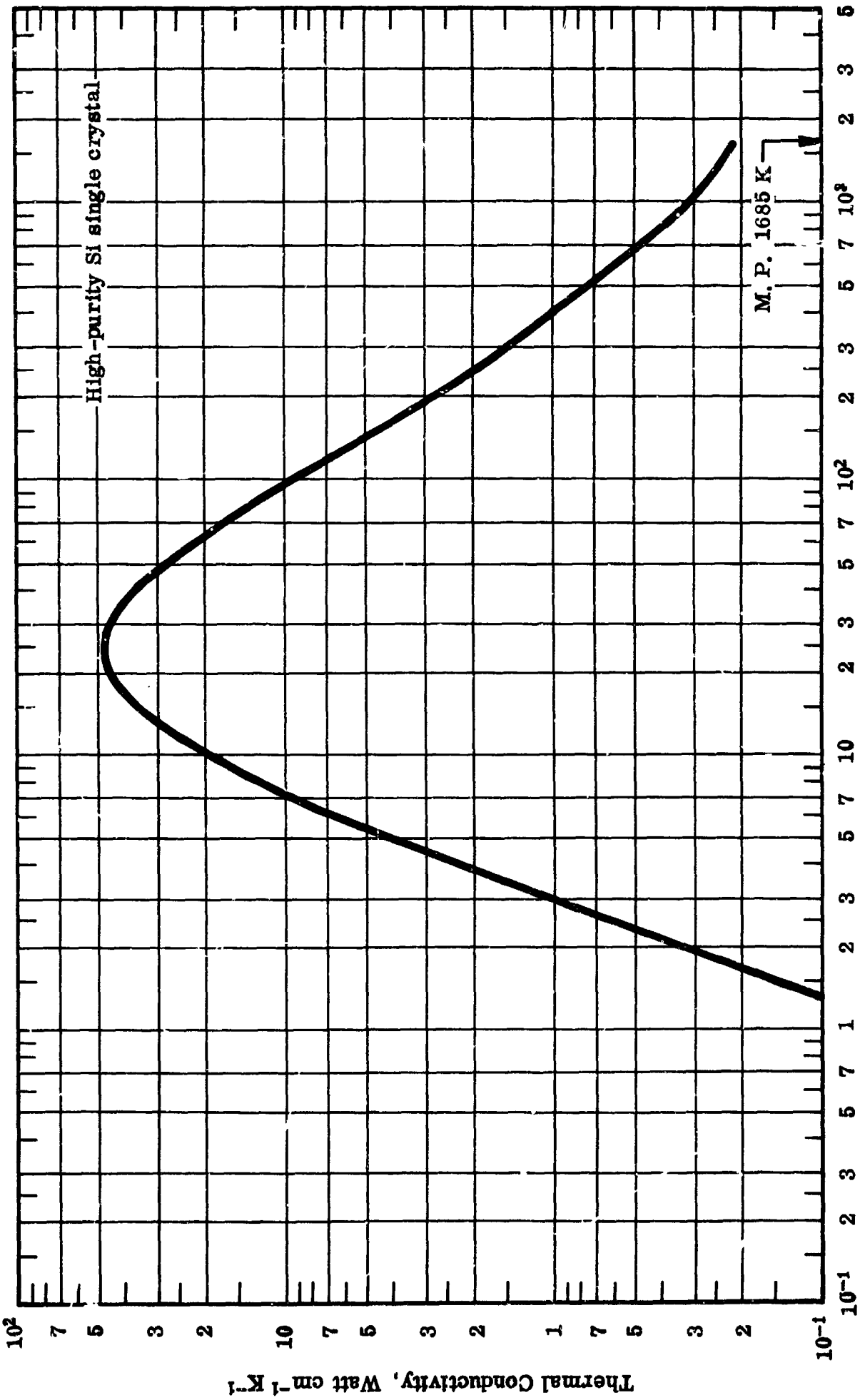

FIG. I-10 THERMAL CONDUCTIVITY OF SILICON

TABLE I-10 THERMAL CONDUCTIVITY OF SILICON

Selected Values for High-Purity Silicon Single Crystal

T, K	k, Watt $cm^{-1}K^{-1}$	T, K	k, Watt $cm^{-1}K^{-1}$
0	0	200	2.7
1	0.05*	250	1.93
3	1.1	273	1.69
5	4.3	300	1.48
7	9.6	350	1.20
10	19.8	400	1.01
15	35.4	450	0.87
20	45.6	500	0.76
25	47.5	600	0.60
30	44.7	700	0.49
35	40.0	800	0.41
40	35.3	900	0.35
45	31.1	1000	0.31
50	27.5	1100	0.28
60	21.5	1200	0.26
70	17.2	1300	0.25
80	13.7	1400	0.24
90	11.2	1500	0.23
100	9.3	1600	0.22
150	4.4	1685	0.215

Data Source and Remarks

Selected values are derived from the data of Glassbrenner and Slack (1964) [46], Holland (1960) [47], Carruthers, Geballe, Rosenberg, and Ziman (1956) [48], and Shanks, Maycock, Sidles, and Danielson (1963) [49].

* Extrapolated.

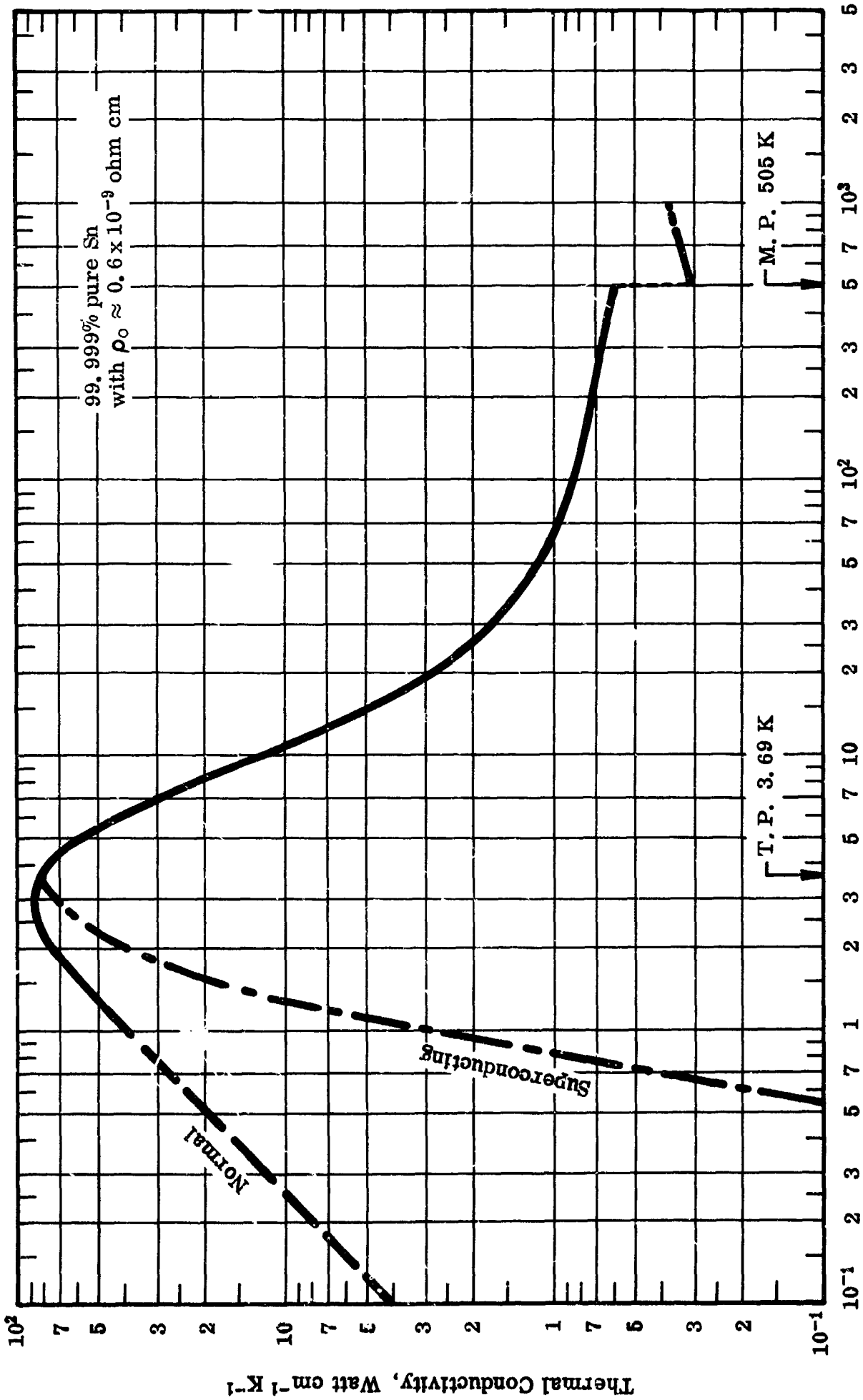

FIG. I-11 THERMAL CONDUCTIVITY OF TIN

TABLE I-11 THERMAL CONDUCTIVITY OF TIN

Selected Values for 99.999% Pure Tin with $\rho_0 \approx 0.61 \times 10^{-9}$ ohm cm

T,K	k, Watt $cm^{-1}K^{-1}$			T,K	k, Watt $cm^{-1}K^{-1}$
	Normal	Superconducting			
0	0	0		60	1.02
0.1	4*	0.0004*		70	0.95
0.3	12*	0.009		80	0.91
0.5	20*	0.06		90	0.87
1	40*	2.8		100	0.84
1.5		18		150	0.77
2	75	40		200	0.72
2.5		59		250	0.69
3	88	72		273	0.67
3.5		80		300	0.66
3.69	82	82		350	0.64
4	77			400	0.62
5	57			450	0.61
10	11.7		(s)	500	0.59
15	4.9		(l)	510	0.31
20	2.9			550	0.315
25	2.06			600	0.322
30	1.68			700	0.336
35	1.46			800	0.350*
40	1.32			900	0.364*
46	1.21			1000	0.378*
50	1.13				

Data Source and Remarks

Eighty-five sets of experimental data are available. Selected values from 1 to 4 K for both the normal and the superconducting state are taken from the data of Rademakers (1949) [50]. In extrapolating the curve for the superconducting state, the data of Zavaritskii (1958, 1960) [51,52] have been used as guidance. Values from 4 to 36 K are derived from the data of Rosenberg (1955) [53].

---

*Extrapolated.

Data Source and Remarks (Continued)

From 100 to 500 K the values are taken from the data of Lees (1903) [54] and Konno (1919) [55]. For liquid tin the values are taken with modifications, from the data of Nikol'skii, Kalakutskaya, Pchelkin, Klassen, and Vel'tishcheva (1959) [56] and some weight is also given to the data of Brown (1923) [57] and Konno (1919) [55].

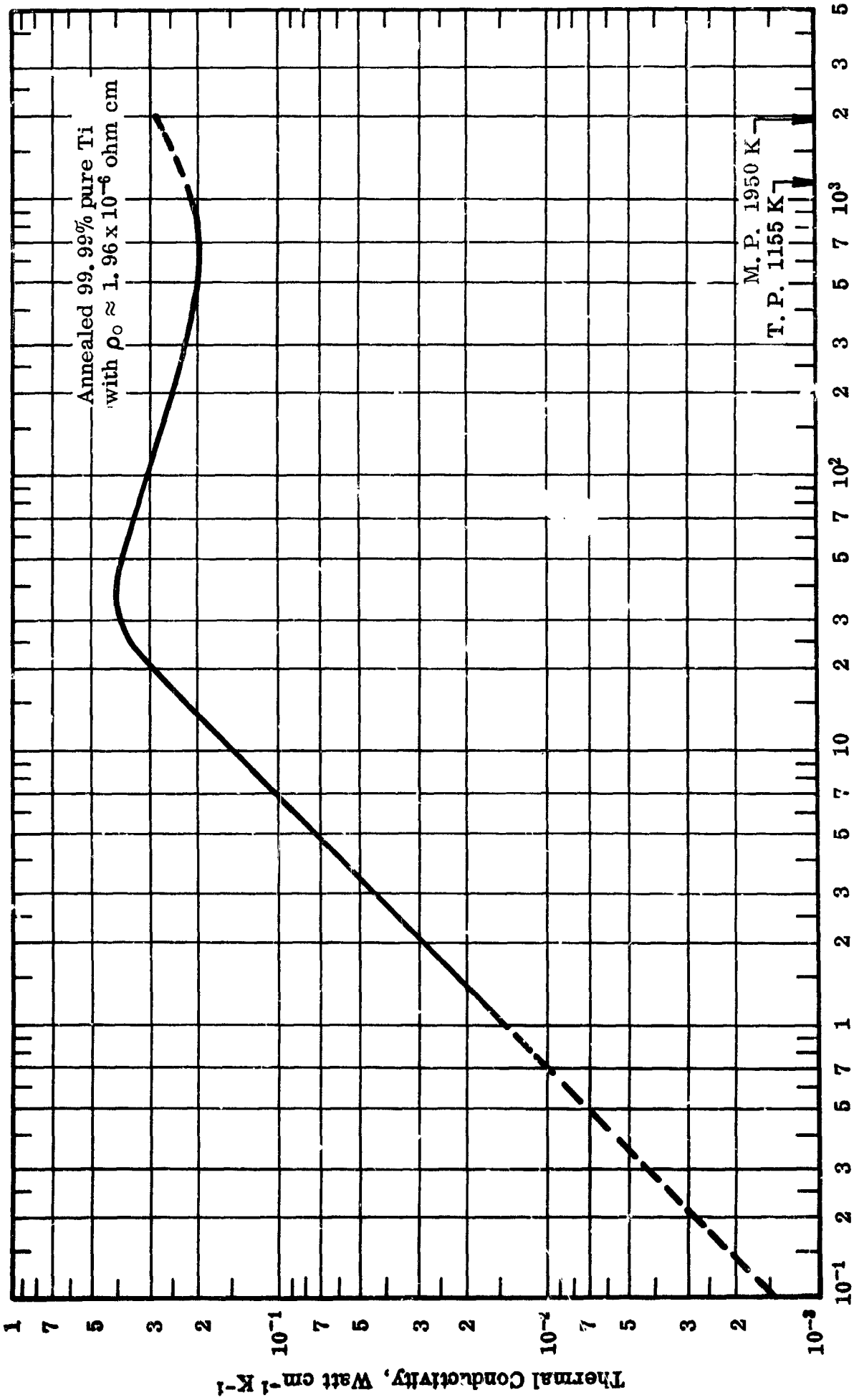

FIG. 1-12 THERMAL CONDUCTIVITY OF TITANIUM

TABLE I-12 THERMAL CONDUCTIVITY OF TITANIUM

Selected Values for Annealed 99.99% Pure Titanium with $\rho_o \approx 1.96 \times 10^{-6}$ ohm cm

T,K	k, Watt $cm^{-1} K^{-1}$	T,K	k, Watt $cm^{-1}K^{-1}$
0	0	273	0.225
0.1	0.0014*	300	0.219
1	0.014*	350	0.211
5	0.072	400	0.205
10	0.144	450	0.201
15	0.216	500	0.199
20	0.288	600	0.196
25	0.350	700	0.196
30	0.380	800	0.198
35	0.393	900	0.202
40	0.390	1000	0.208*
45	0.383	1100	0.214*
50	0.375	1200	0.221*
60	0.360	1300	0.229*
70	0.345	1400	0.238*
80	0.330	1500	0.246*
90	0.317	1600	0.255*
100	0.307	1700	0.263*
150	0.270	1800	0.271*
200	0.247	1900	0.278*
250	0.231	1950	0.281*

Data Source and Remarks

Twenty-five sets of experimental data are available. Selected values from 7 to 150 K are taken from the data of White and Woods (1958) [58]. From 300 to 1000 K the values are derived from the data of Powell and Tye (1961) [59]. Loewen (1956) [60], and Deem, Wood, and Lucks (1958) [61]. No data above 1090 K are available and the extrapolation to higher temperatures is based upon general observation.

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*Extrapolated.

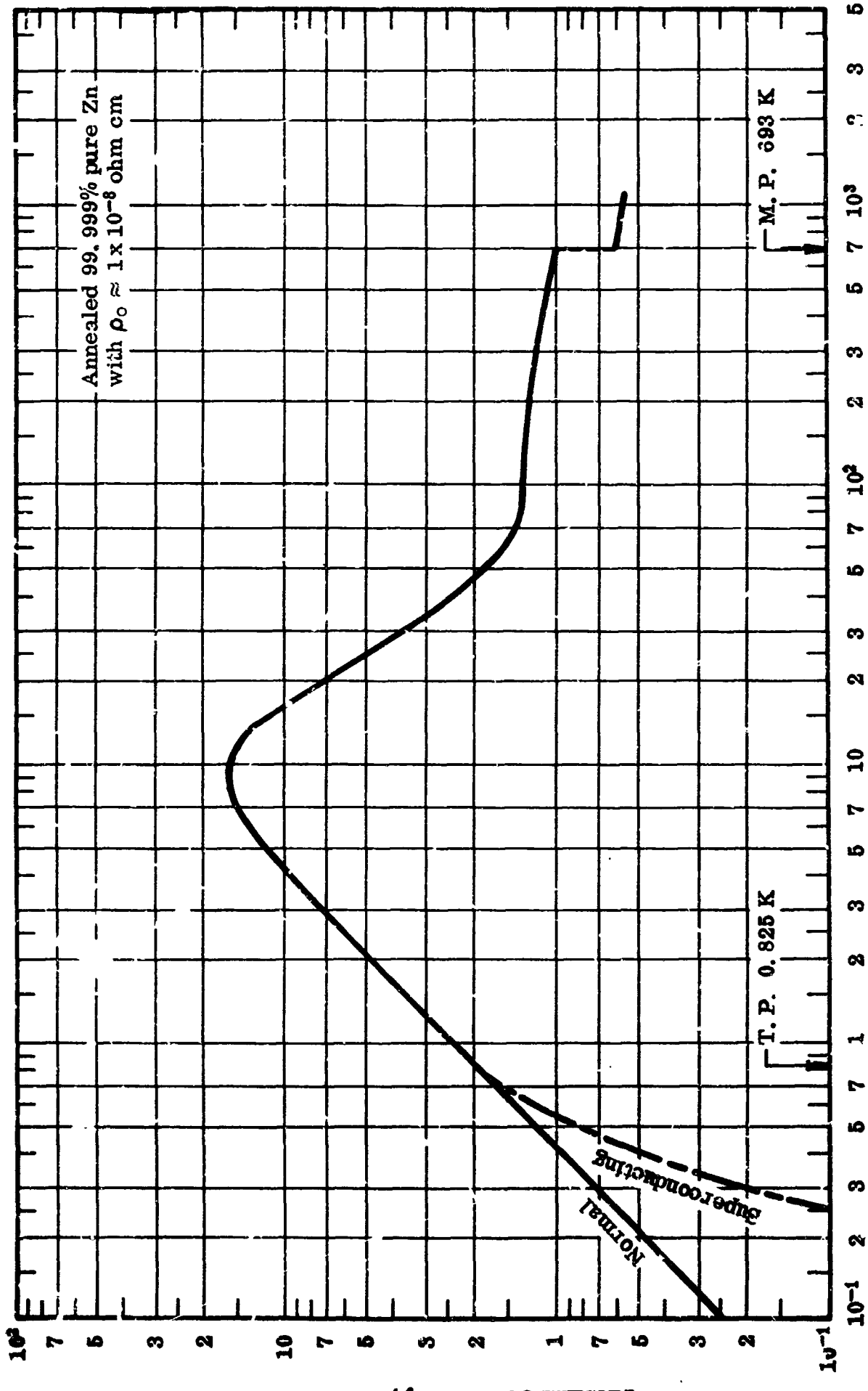

FIG. 1-13 THERMAL CONDUCTIVITY OF ZINC

TABLE I-13 THERMAL CONDUCTIVITY OF ZINC

Selected Values for Annealed 99.999% Pure Zinc with $\rho_0 \approx 1 \times 10^{-8}$ ohm cm

T,K	k, Watt $cm^{-1}K^{-1}$			T,K	k, Watt cm^{-1} K^{-1}
	Normal	Superconducting			
0	0	0		50	1.81
0.1	0.24*	0.00043		60	1.53
0.2	0.48	0.032		70	1.41
0.3	0.72	0.20		80	1.36
0.4	0.96	0.49		90	1.34
0.5	1.20	0.83		100	1.33
0.6	1.44	1.18		150	1.28
0.7	1.68	1.54		200	1.24
0.825	1.97	1.97		250	1.20
1	2.4			273	1.19
3	7.1			300	1.17
5	11.5			350	1.14
7	14.6			400	1.12
9	15.8			450	1.09
10	15.7			500	1.07
15	10.8			600	1.02
20	6.9		(s)	690	0.98
25	4.8		(l)	700	0.60
30	3.6			800	0.585
35	2.9			900	0.576
40	2.4			1000	0.57
45	2.1			1100	0.564*

Data Source and Remarks

Forty-eight sets of experimental data are available. Selected values from 2 to 40 K are taken from the data of Rosenberg (1955) [53] and Mendelssohn and Rosenberg (1952) [36]. From 80 K to the melting point the values are derived from the data of Goens and Grüneisen (1932) [62], Bidwell and Lewis (1939)[63], Bidwell (1939, 1940) [64, 65], Shelton and Swanger (1933) [66], Konno (1919) [55], and Smith (1925) [67]. For liquid zinc the values are the mean values of the data of Konno (1919) [55] and Bidwell (1939, 1940) [64,65]. The values for the superconducting state are derived from the data of Zavaritskii (1958,1960) [5,68].

*Extrapolated.

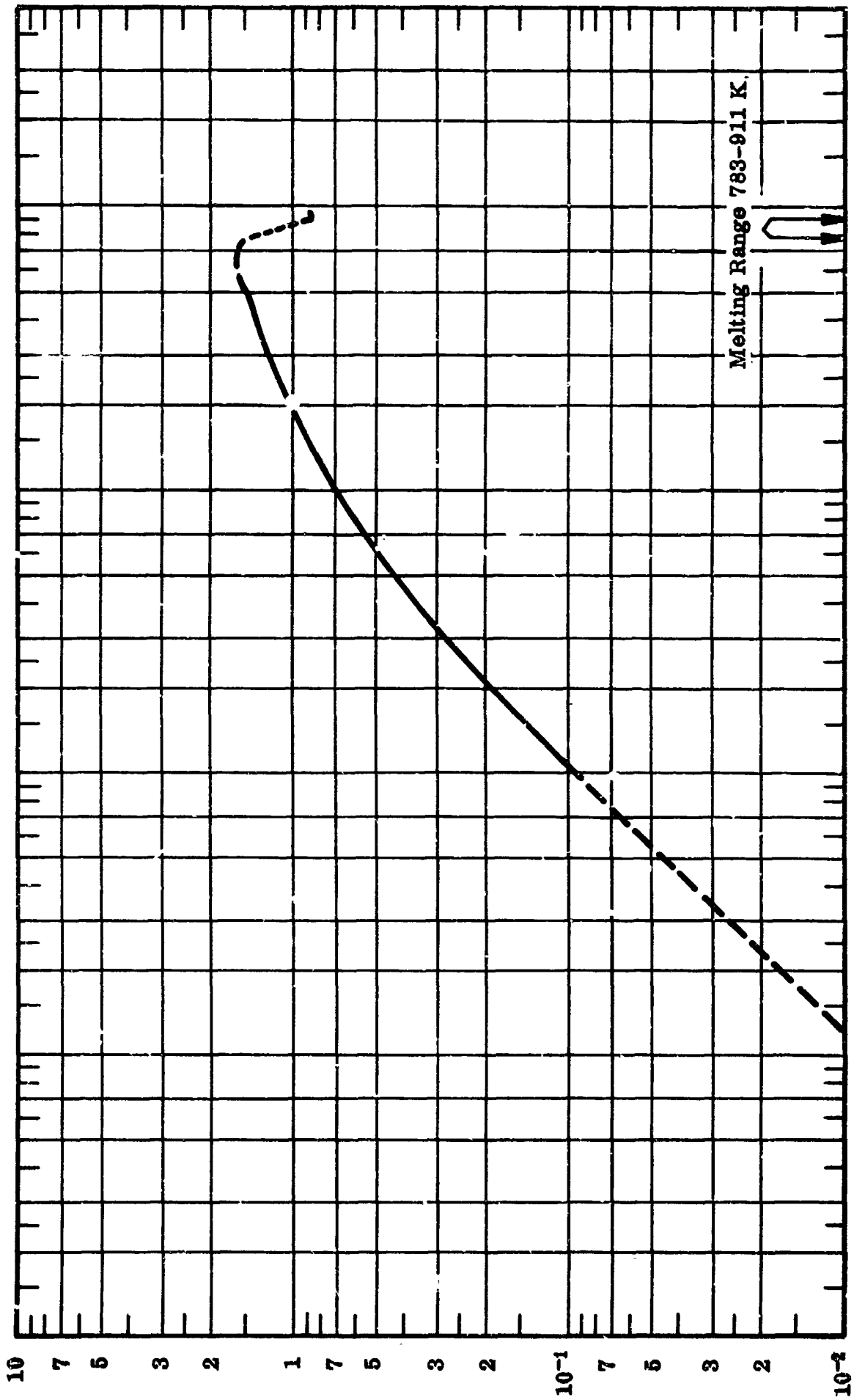

FIG. I-14 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2219-T852

TABLE I-14 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2219-T852

T,K	k, Watt $cm^{-1} K^{-1}$		T,K	k, Watt $cm^{-1}K^{-1}$
0	0		300	1.23
0.1	0.00067*		350	1.31
1	0.008*		400	1.37
5	0.045*		450	1.41
10	0.093*		500	1.46
25	0.23		550	1.52
50	0.43		600	1.56*
75	0.58		650	1.59*
100	0.70		700	1.57*
150	0.87		750	1.54*
200	1.01	(s)	783	1.52*
250	1.13	(l)	925	0.86**
273	1.18		1000	0.88**

Data Source and Remarks

No data are available exactly for this aluminum alloy 2219 - T852‡. Rhodes, Moeller, and Sawer (1965) [69] have measured the thermal conductivity of aluminum alloy 2219-T81, which is different in heat treatment (temper). Selected values from 50 to 600 K are derived from their data. Values for the liquid are estimated. Heating at moderately high temperatures can destroy the "T852"temper of this alloy and consequently the thermal conductivity will be higher after heating (see Figure I-16 for aluminum alloy 7075-T6 for comparison).

---

* Extrapolated.

** Estimated.

‡ The temper "T852"designates that the alloy has been solution heat treated, cold worked, artifically aged, and then stress-relieved by compressing.

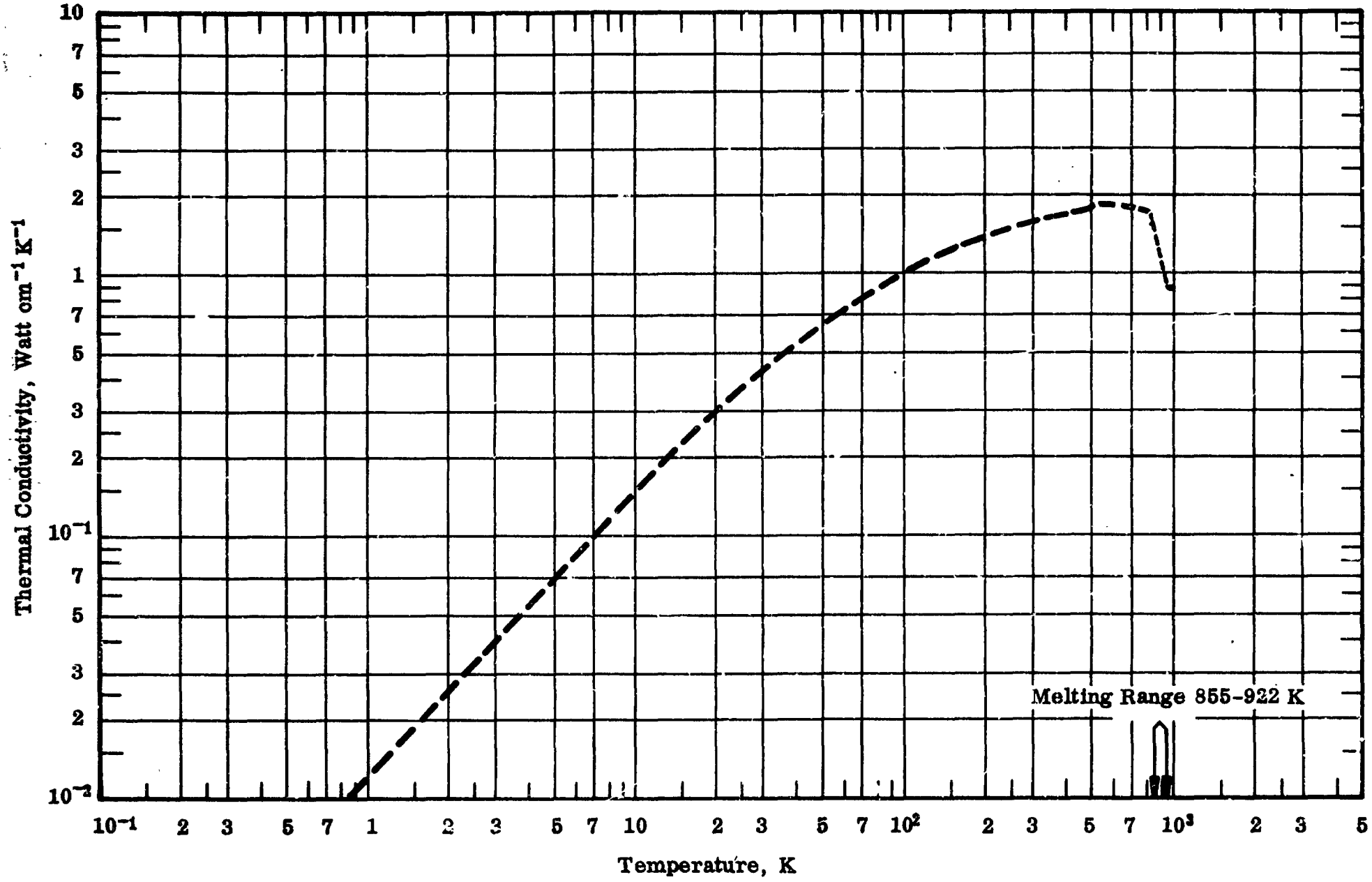

FIG. I-15 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 6061-T6

TABLE I-15 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 6061-T6

T,K	k, Watt $cm^{-1}K^{-1}$		T,K	k, Watt $cm^{-1}K^{-1}$
0	0		350	1.62*
0.1	0.001*		400	1.66*
1	0.012*		450	1.69*
5	0.068*		500	1.80*
10	0.142*		550	1.84*
25	0.35*		600	1.83*
50	0.62*		650	1.81*
75	0.82*		700	1.78*
100	0.98*		750	1.75*
150	1.20*		800	1.72*
200	1.36*	(s)	850	1.68*
250	1.47*	(l)	925	0.86*
273	1.51*		1000	0.88*
300	1.55			

Data Source and Remarks

There are no experimental data available. ALCOA Aluminum Handbook (1957) [70] gives a value of 1.55 Watt cm^{-1} K^{-1} at 298 K and the same value is also reported in Material Properties Handbook (1959) [71], Aluminum Data Book (1959) [72], Metals Handbook (1961) [73], and others. This value is used in estimating the other values. Heating at moderately high temperatures can destroy the "T6" temper of this alloy and consequently the thermal conductivity will become higher after heating (see Figure I-16 for aluminum alloy 7075-T6 for comparison)‡.

---

* Estimated.

‡ The temper "T6" designates that the alloy has been solution heat treated and then artifically aged.

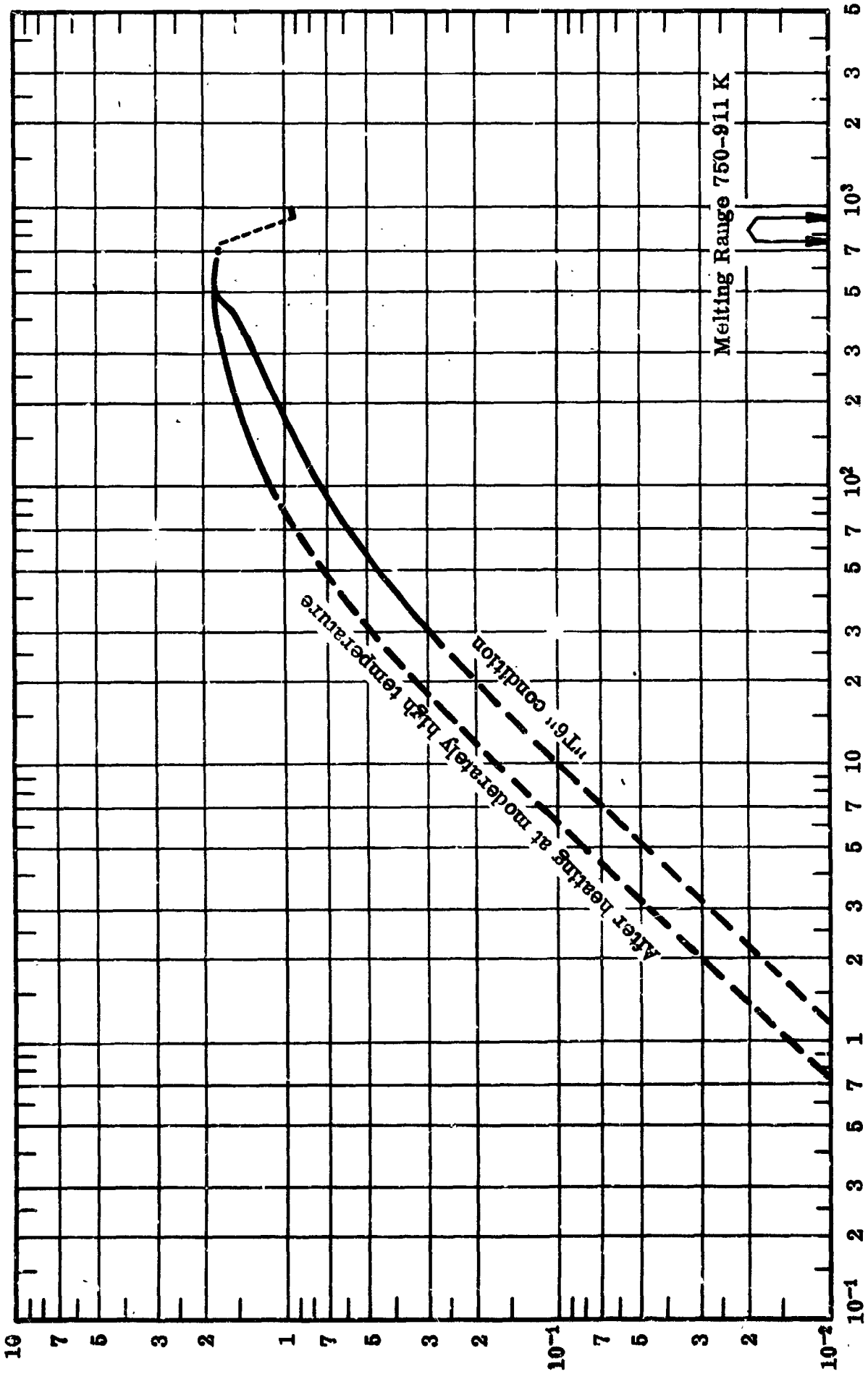

FIG. I-16 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 7075-T6

TABLE I-16 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 7075-T6

T,K	In Condition "T6" k, Watt $cm^{-1}K^{-1}$	After Heating at Moderately High Temperature k, Watt $cm^{-1}K^{-1}$
0	0	0
0.1	0.0007*	0.0012*
1	0.0084*	0.014*
5	0.047*	0.078*
10	0.099*	0.162*
25	0.25*	0.40*
50	0.45	0.70*
75	0.61	0.92*
100	0.73	1.09*
150	0.91	1.32
200	1.06	1.47
250	1.18	1.59
273	1.23	1.63
300	1.28	1.68
350	1.36	1.74
400	1.42	1.78
450	1.65	1.80
500	1.78	1.81
550	1.80	1.80
600	1.78	1.78
650	1.76*	1.76
700	1.73*	1.73
(s) 750	1.70*	1.70*
(l) 925	0.83**	0.83**
1000	0.85**	0.85**

Data Source and Remarks

Four sets of experimental data are available. Selected values from 26 to 600 K for the alloy in "T6" condition are taken from the data of Powers, Ziegler, and Johnston (1951) [74] and Lucks, Thompson, Smith, Cury, Deem, and Bing (1951) [75].

* Extrapolated.

** Estimated.

Data Source and Remarks (Continued)

For the alloy after heating at moderately high temperature the values from 120 to 700 K are taken from the data of Lucks et al. (1951) [75]. The values for the liquid are estimated.

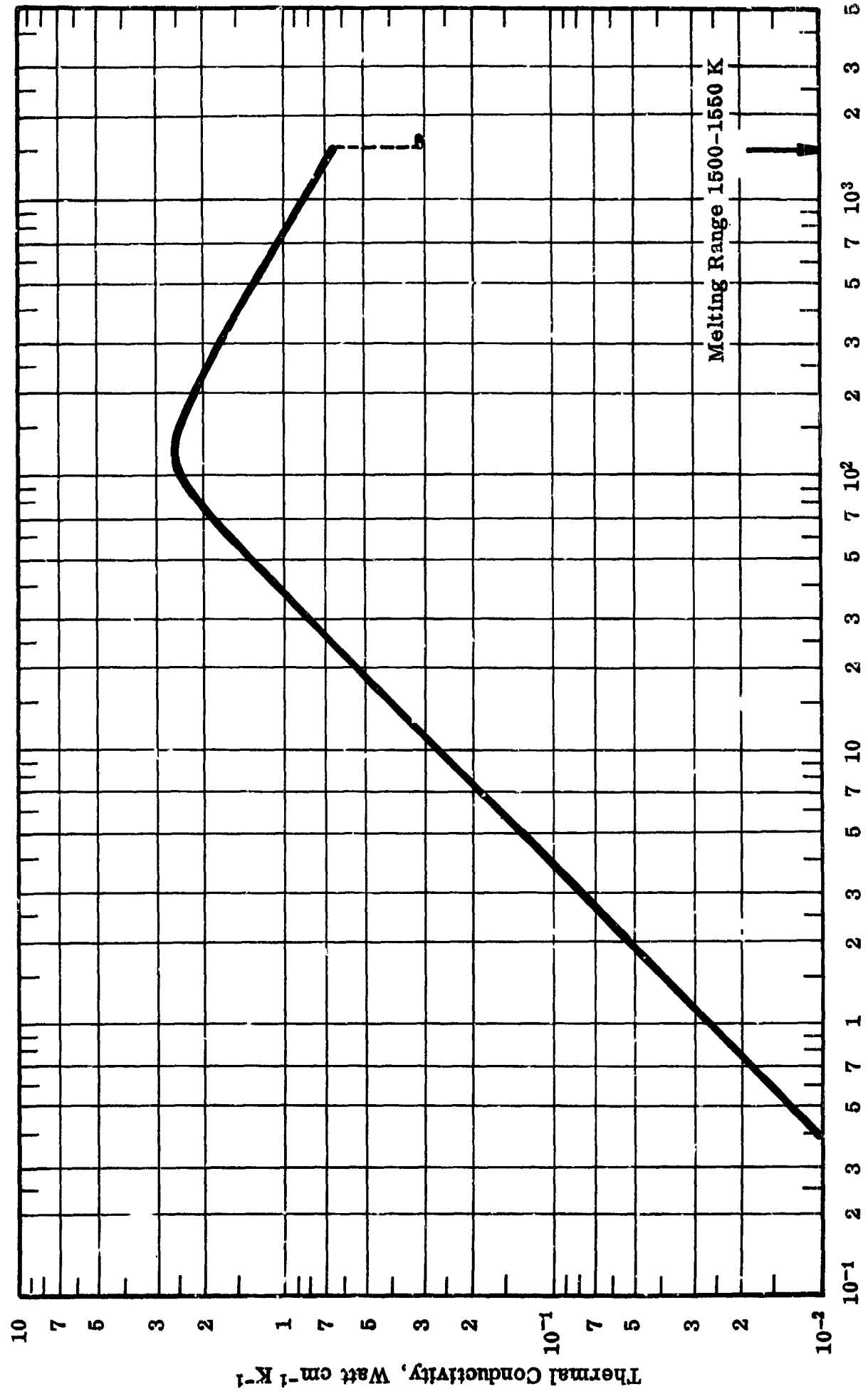

FIG. I-17 THERMAL CONDUCTIVITY OF BERYLLIUM (DILUTE) A LOY

TABLE I-17 THERMAL CONDUCTIVITY OF BERYLLIUM (DILUTE) ALLOY

T,K	k,Watt $cm^{-1}K^{-1}$		T,K	k,Watt $cm^{-1}K^{-1}$
0	0		200	2.11
0.1	0.0026*		250	1.91
1	0.026*		273	1.83
5	0.13		300	1.74
10	0.26		350	1.60
15	0.39		400	1.48
20	0.52		450	1.38
25	0.65		500	1.30
30	0.78		600	1.16
35	0.91		700	1.06
40	1.04		800	0.98
45	1.17		900	0.90
50	1.30		1000	0.84
60	1.56		1100	0.79
70	1.82		1200	0.75
80	2.06		1300	0.71
90	2.18		1400	0.68
100	2.45	(s)	1500	0.65*
150	2.39	(l)	1600	0.32**

Data Source and Remarks

Eleven sets of experimental data are available. Selected values from 4 to 132 K are derived from the data of White and Woods (1955) [76] and Powell, R. L., Harden, and Gibson (1960) [77] and values from 310 to 1240 K from the data of Powell, R. W. (1953) [7], Fieldhouse, Hedge, Lang, and Waterman (1958) [8], and BMI Sample No. 5 reported by J. Ho and Wright (1960) [9]. There is no measurement on the liquid and the value is estimated.

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* Extrapolated.

** Estimated.

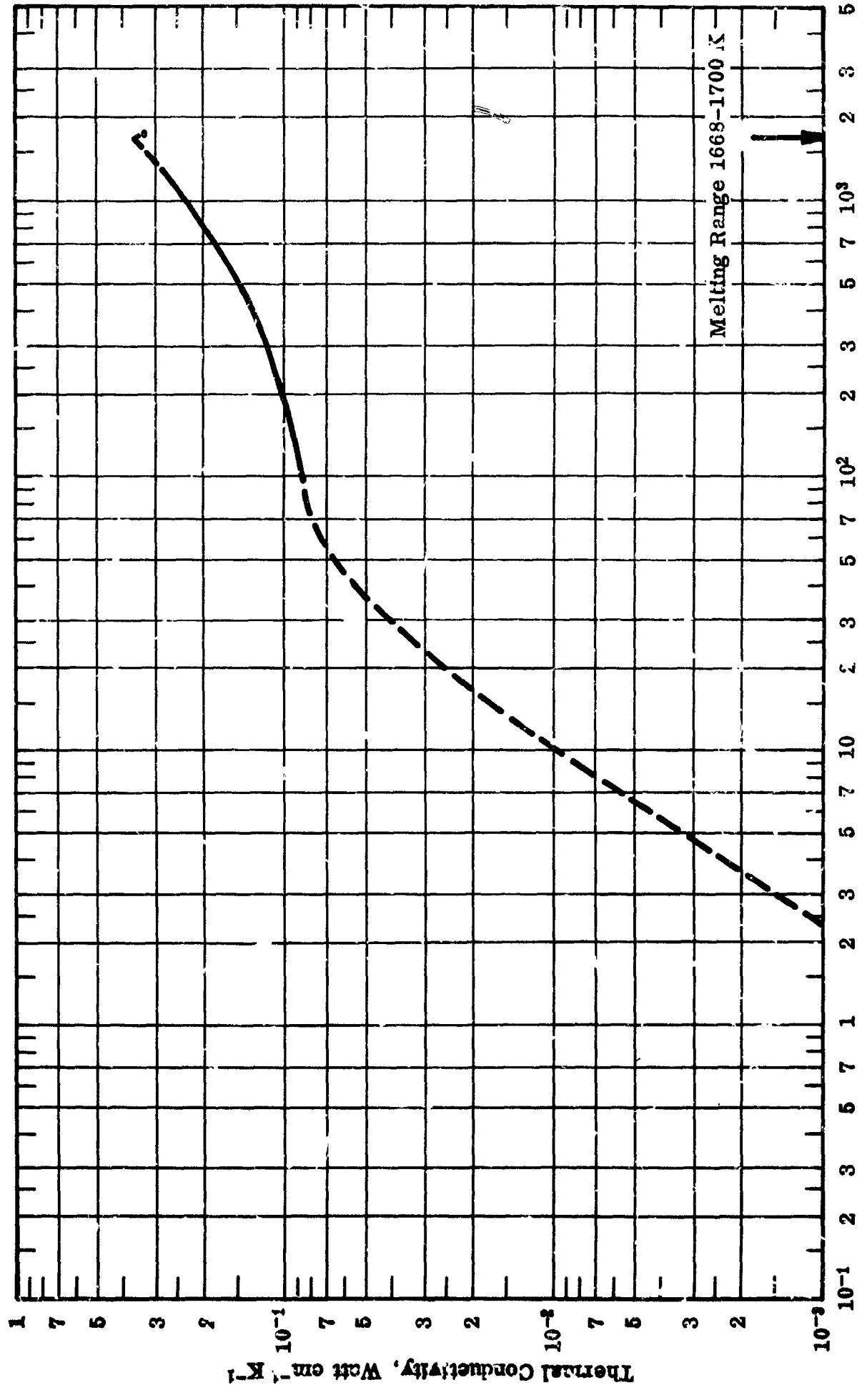

FIG. I-18 THERMAL CONDUCTIVITY OF INCONEL X-750

TABLE I-18 THERMAL CONDUCTIVITY OF INCONEL X-750

T,K	k, Watt $cm^{-1}K^{-1}$		T,K	k, Watt $cm^{-1}K^{-1}$
0	0		450	0.143
0.1	0.000006*		500	0.152
1	0.00024*		600	0.170
5	0.0033*		700	0.188
10	0.0096*		800	0.205
25	0.034*		900	0.223
50	0.066*		1000	0.240
75	0.080*		1100	0.258
100	0.087*		1200	0.276
150	0.096		1300	0.293*
200	0.103		1400	0.311*
250	0.110		1500	0.328*
273	0.113		1600	0.346*
300	0.117	(s)	1665	0.358*
350	0.126	(l)	1800	0.33**
400	0.135			

Data Source and Remarks

Three sets of experimental data are available‡. Selected values from 130 to 1170 K are taken, with modifications, from the data of Lucks, Thompson, Smith, Curry, Deem, and Bing (1951) [75]. There is no measurement on the liquid and the value is estimated.

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* Extrapolated.

** Estimated.

‡ This alloy was previously designated as Inconel X [78].

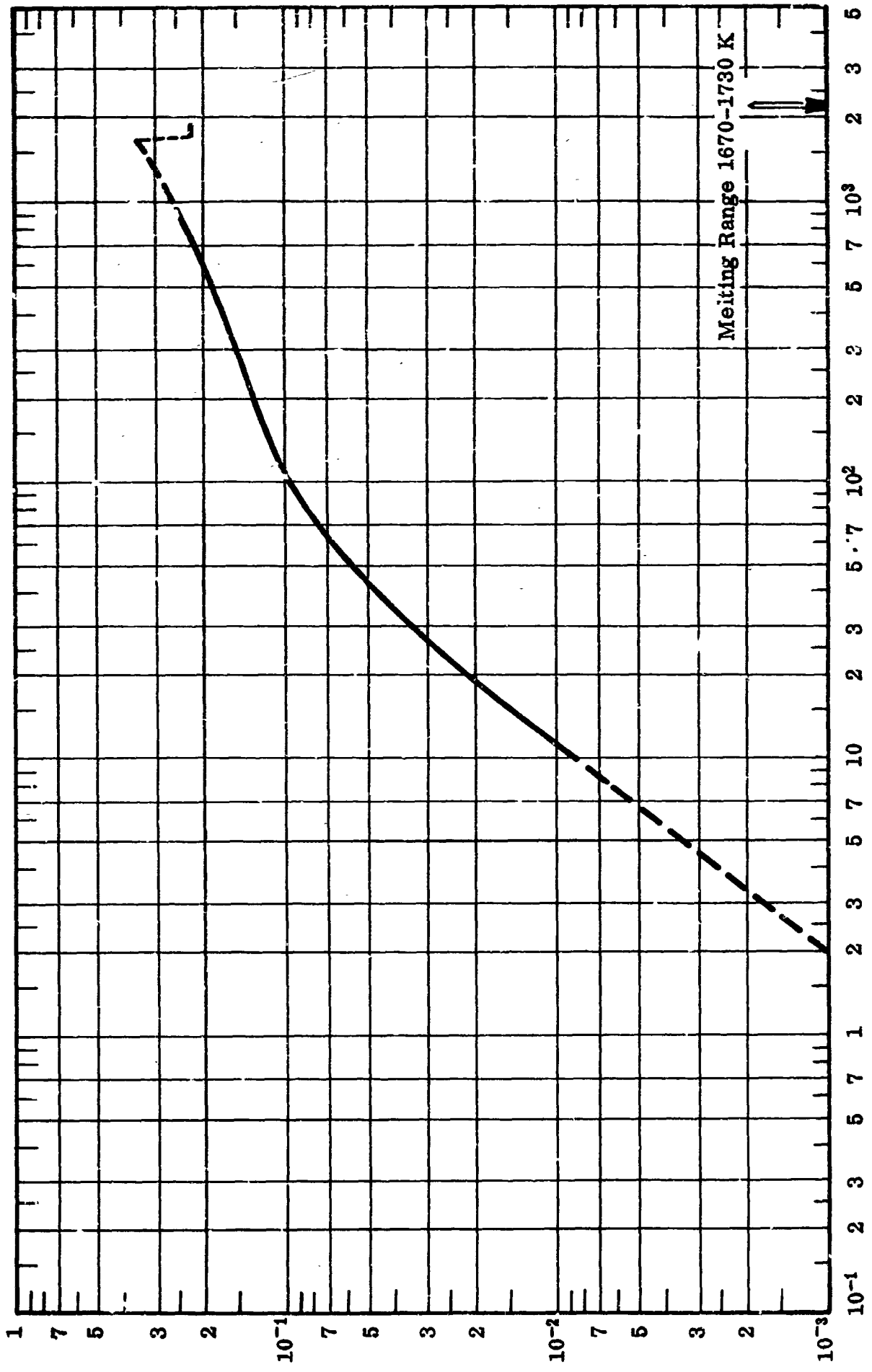

FIG. I-19 THERMAL CONDUCTIVITY OF STAINLESS STEEL 304A

TABLE I-19 THERMAL CONDUCTIVITY OF STAINLESS STEEL 304 A

T,K	k,Watt $cm^{-1}K^{-1}$		T,K	k,Watt $cm^{-1}K^{-1}$
0	0		450	0.177
0.1	0.000017*		500	0.184
1	0.00039*		600	0.198
5	0.0034*		700	0.212
10	0.0085*		800	0.225
25	0.027		900	0.239
50	0.058		1000	0.253*
75	0.080		1100	0.267*
100	0.095		1200	0.281*
150	0.115		1300	0.295*
200	0.130		1400	0.309*
250	0.142		1500	0.323*
273	0.147		1600	0.337*
300	0.152	(s)	1665	0.347*
350	0.162	(l)	1800	0.22**
400	0.170			

Data Source and Remarks

Nine sets of experimental data are available. Selected values from 27 to 250 K are taken from the data of Powers, Ziegler, and Johnston (1951) [32] and values from 373 to 923 K from the data of Ewing, Grand, and Miller (1952) [79] and Deverall (1959) [80]. There is no measurement on the liquid and the value is estimated.

* Extrapolated.

** Estimated.

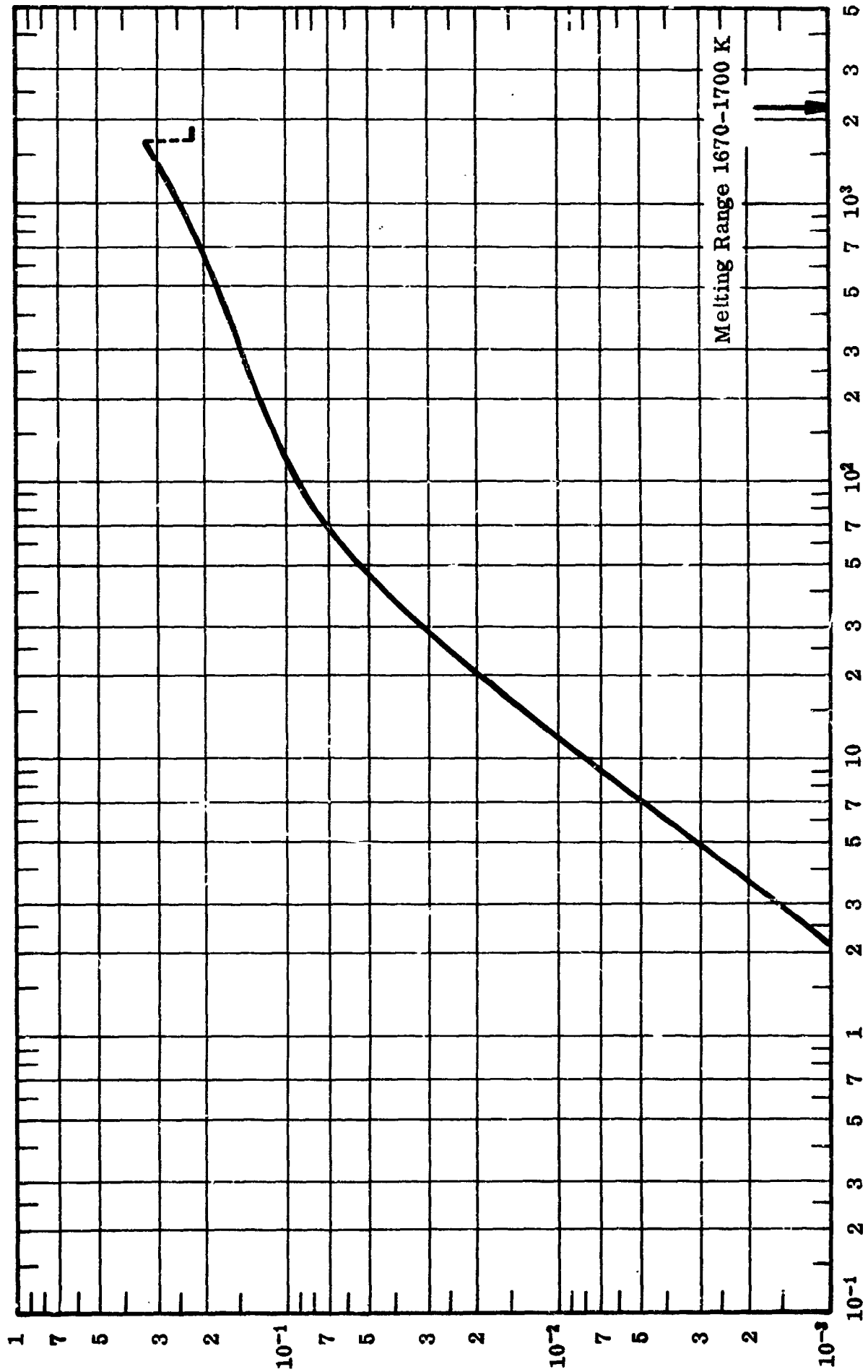

FIG. I-20 THERMAL CONDUCTIVITY OF STAINLESS STEEL 347

TABLE I-20 THERMAL CONDUCTIVITY OF STAINLESS STEEL 347

T, K	k, Watt $cm^{-1} K^{-1}$		T, K	k, Watt $cm^{-1} K^{-1}$
0	0		450	0.172
0.1	0.000015*		500	0.179
1	0.00035*		600	0.192
5	0.0031		700	0.205
10	0.0078		800	0.219
25	0.025		900	0.232
50	0.054		1000	0.246
75	0.076		1100	0.259
100	0.091		1200	0.273
150	0.111		1300	0.286
200	0.126		1400	0.300
250	0.138		1500	0.313
273	0.143		1600	0.327*
300	0.148	(s)	1665	0.336*
350	0.157	(l)	1800	0.22**
400	0.165			

Data Source and Remarks

Six sets of experimental data are available. Selected values from 4 to 300 K are taken, with modification, from the data of Zimmerman (1951) [81] and Powers, Ziegler, and Johnston (1951) [32]. Values from 300 to 1300 K are derived from the data of Lucks, Thompson, Smith, Curry, Deem, and Bing (1951) [75] and Fieldhouse, Hedge, and Lang (1958) [82]. No data are available for the liquid and the value is estimated.

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* Extrapolated.

** Estimated.

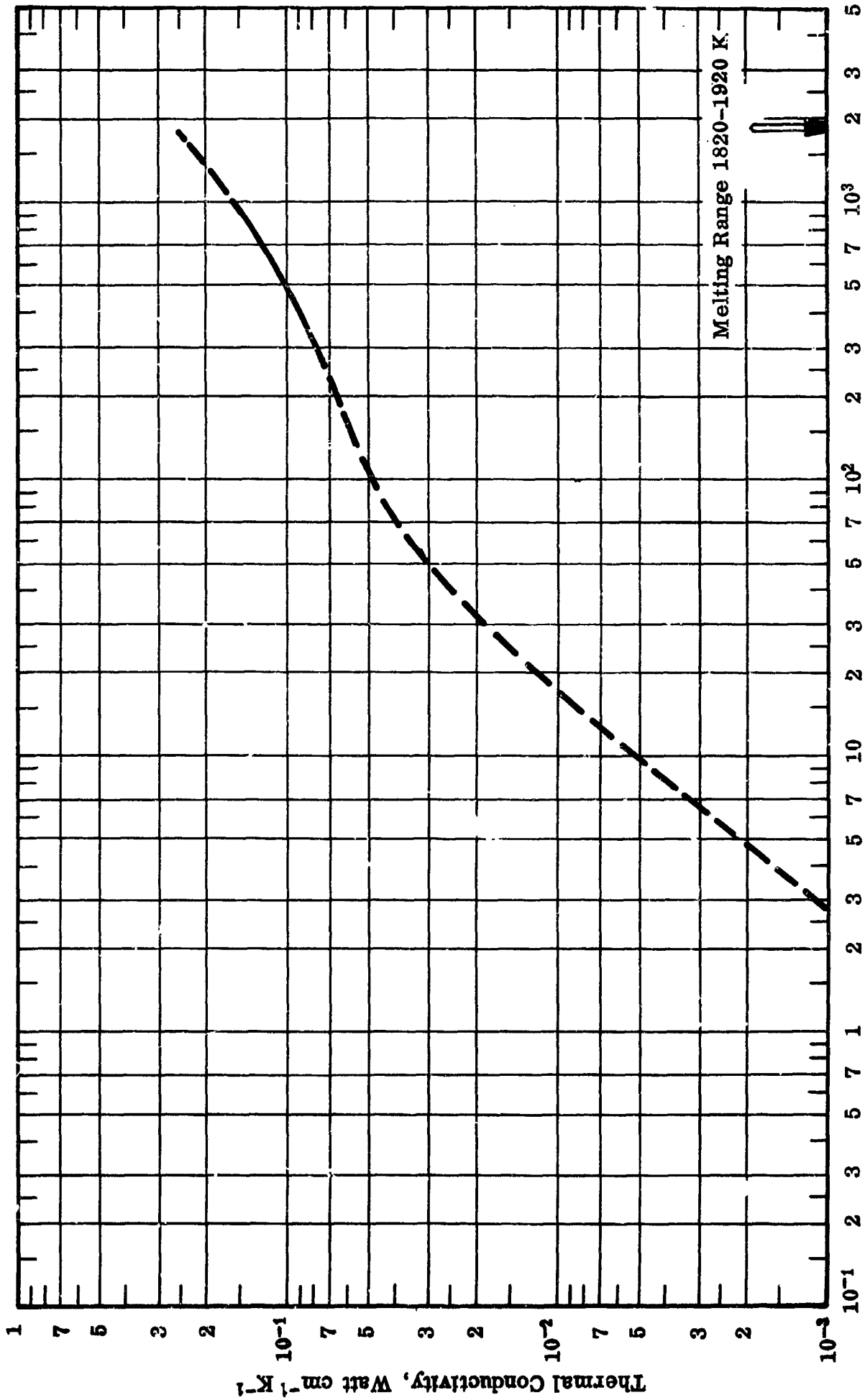

FIG. I-21 THERMAL CONDUCTIVITY OF TITANIUM ALLOY A-110AT

TABLE I-21 THERMAL CONDUCTIVITY OF TITANIUM ALLOY A-110AT

T,K	k, Watt $cm^{-1} K^{-1}$	T,K	k, Watt $cm^{-1} K^{-1}$
0	0	450	0.093
0.1	0.000015*	500	0.098
1	0.00028*	600	0.110
5	0.0021*	700	0.122
10	0.0051*	800	0.133
25	0.015*	900	0.145*
50	0.031*	1000	0.157*
75	0.041*	1100	0.169*
100	0.048*	1200	0.180*
150	0.058*	1300	0.192*
200	0.065*	1400	0.204*
250	0.071	1500	0.216*
273	0.074*	1600	0.227*
300	0.077*	1700	0.239*
350	0.082	1800	0.251*
400	0.087	1820	0.253*

Data Source and Remarks

Only one set of experimental data is available. Selected values from 310 to 810 K are taken from the data of Deem, Wood, and Lucks (1958) [61]. The extrapolation to higher and lower temperatures is based on general observation.

* Extrapolated.

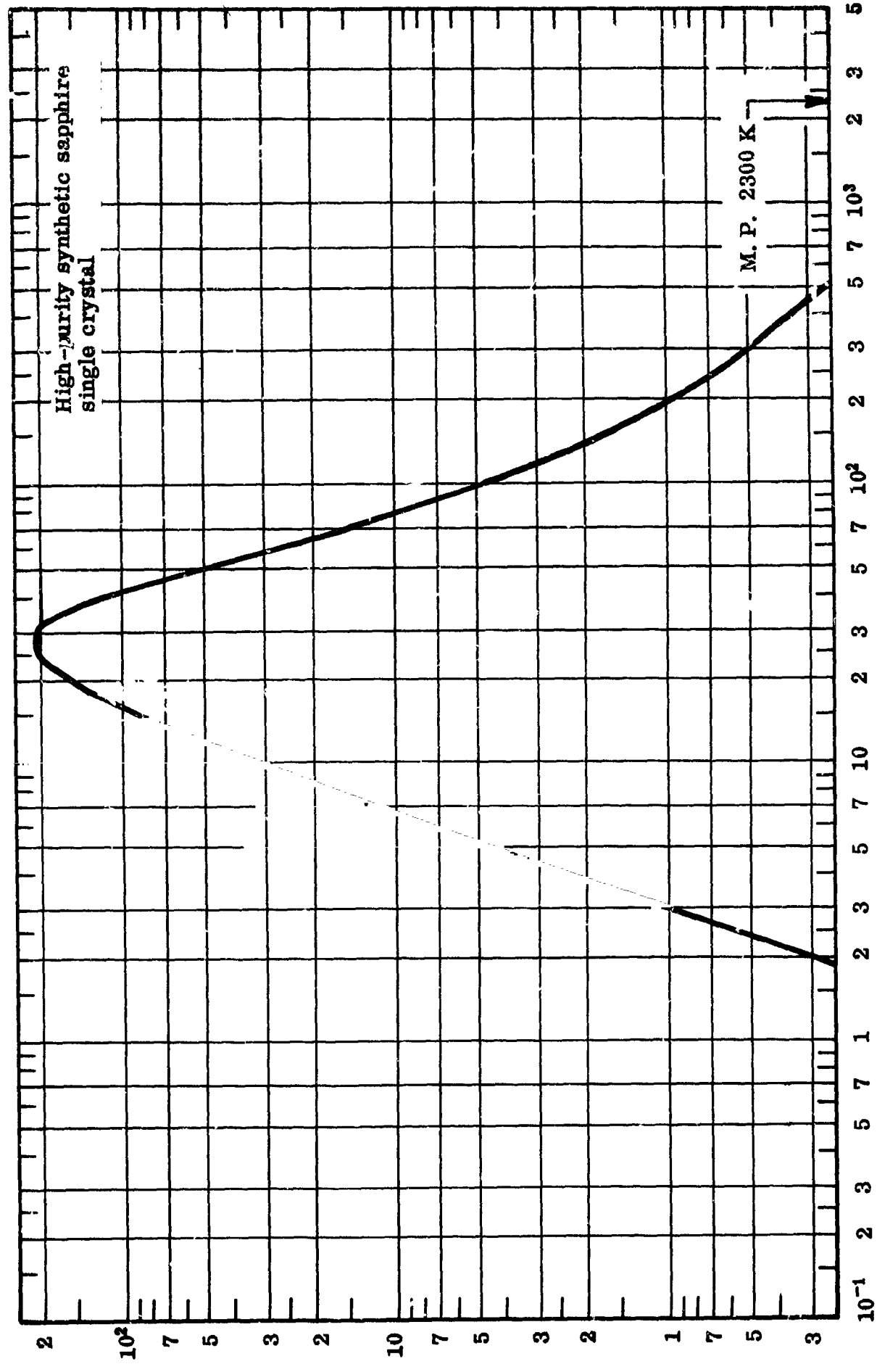

FIG. I-22 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (single crystal) Al_2O_3

TABLE I-22 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (single crystal) Al_2O_3

Selected Values for High-Purity Synthetic Sapphire Single Crystal

T, K	k, Watt $cm^{-1}K^{-1}$	T, K	k, Watt $cm^{-1}K^{-1}$
0	0	70	15.3
0.1	0.000039*	80	9.6
0.5	0.0049*	90	6.4
1	0.039*	100	4.5
5	4.1	150	1.5
10	29	200	0.85
15	87	250	0.60
20	157	273	0.53
25	202	300	0.47
30	207	350	0.39
35	177	400	0.33
40	120	450	0.28
45	77	500	0.25
50	52	600	0.19
60	26.5	700	0.16

Data Source and Remarks

Thirty-four sets of experimental data are available. Selected values from 5 to 90 K are taken from the data of Berman, Foster, Schneidmesser, and Tirmizi (1960) [83]. Above room temperature the values are taken, with modifications, from the data of Lee and Kingery (1960) [84].

*Extrapolated.

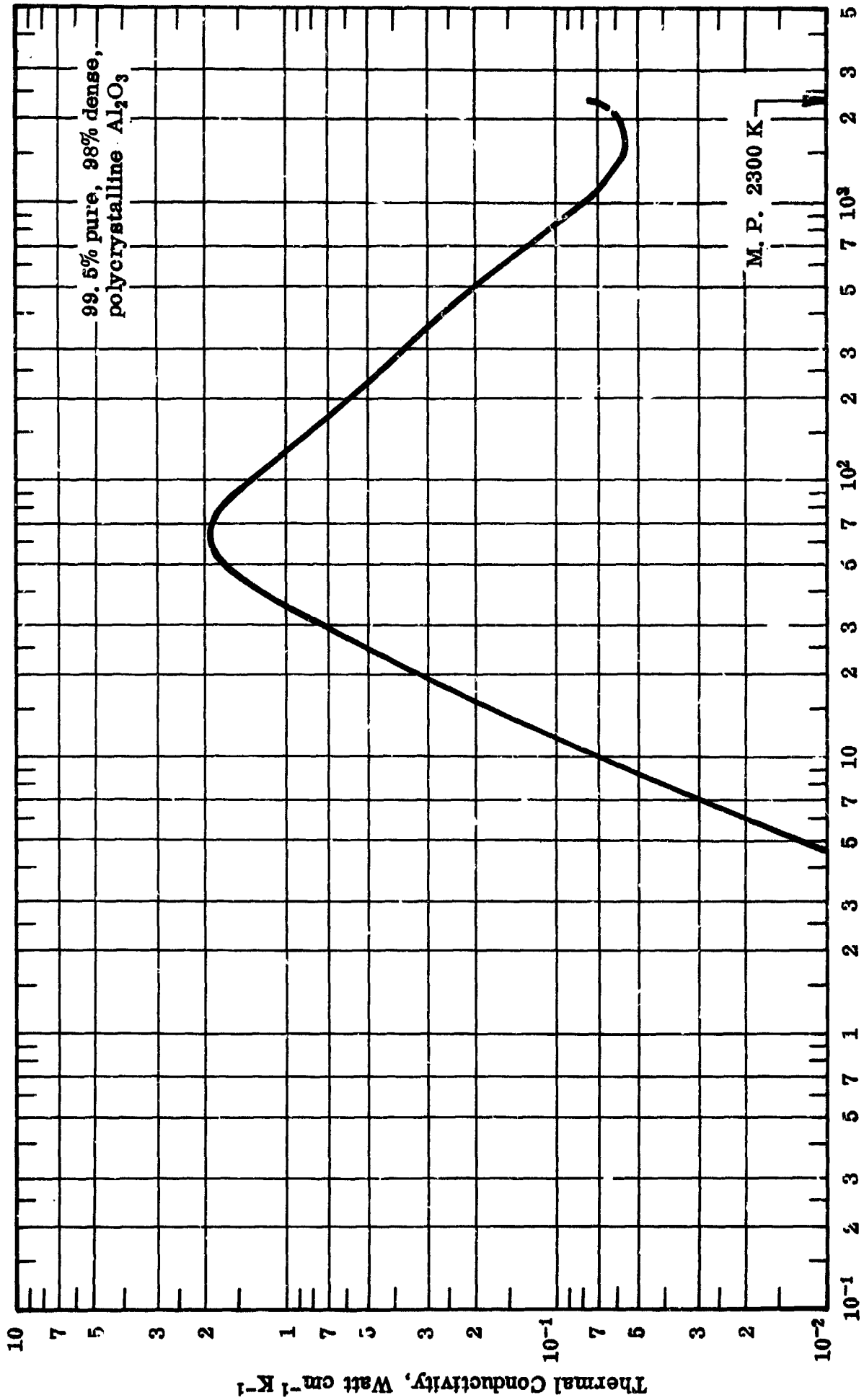

FIG. I-23 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (polycrystalline) Al_2O_3

TABLE I-23 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (polycrystalline) Al_2O_3

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline Al_2O_3

T,K	k, Watt $cm^{-1}K^{-1}$	T,K	k, Watt $cm^{-1}K^{-1}$
0	0	300	0.355
0.1	0.00000013*	350	0.304
0.5	0.000015*	400	0.262
1	0.00013*	450	0.228
5	0.012	500	0.200
10	0.068	600	0.157
15	0.175	700	0.125
20	0.33	800	0.103
25	0.53	900	0.089
30	0.75	1000	0.078
35	0.98	1100	0.071
40	1.23	1200	0.065
45	1.47	1300	0.061
50	1.71	1400	0.059
60	1.92	1500	0.057
70	1.90	1600	0.056
80	1.72	1700	0.056
90	1.50	1800	0.056
100	1.30	1900	0.058
150	0.76	2000	0.060
200	0.54	2100	0.065*
250	0.43	2200	0.072*
273	0.39	2300	0.081*

* Extrapolated.

Data Source and Remarks

One hundred and twenty-six sets of experimental data are available. Selected values from 3 to 200 K are taken from the data of Berman (1952) [85] and Berman, Foster, Schneidmesser and Tirmizi (1960) [83]. Above room temperature the values are the results of the correlation of thermal conductivity and specimen purity and density using the data of Fieldhouse, Hedge, and Lang (1958) [82], Francis, Brown, McNamara, and Tinklepaugh (1958 [86], Sutton (1960) [87], Truesdale, Swica, and Tinklepaugh (1960) [88], Nishijima, Kawada, and Ishihata (1965) [89], Norton (1951) [90], Norton, Fellows, Adams and McQuarrie (1950) [91], Norton and Kingery (1952) [92], Norton, Kingery, McQuarrie, Adams, Loeb, and Francl (1953) [93], Kingery (1954) [94], Kingery (1959) [95], Francl and Kingery (1954) [96, 97], and others.

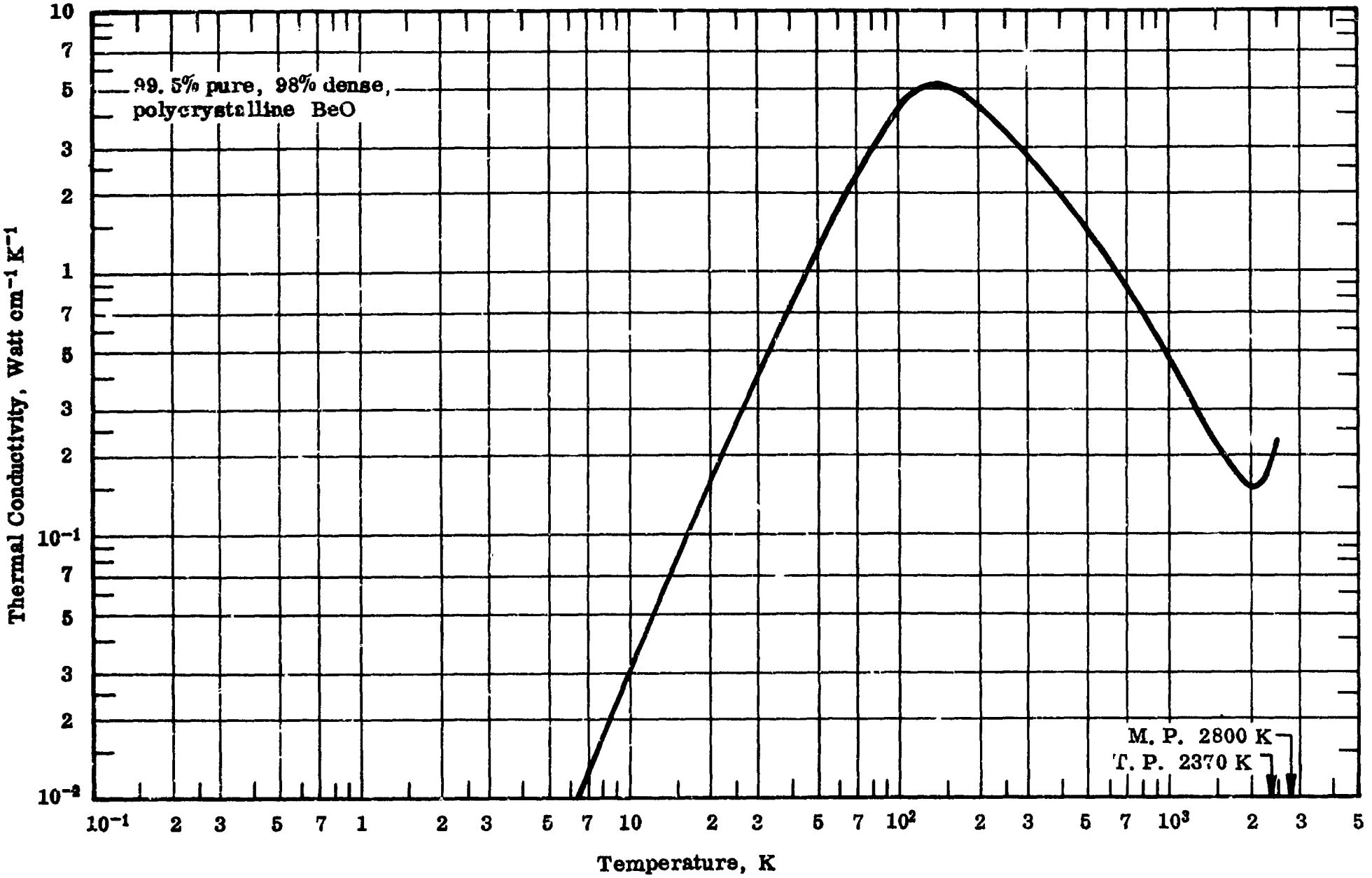

FIG. I-24 THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE BeO

TABLE I-24 THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE BeO

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline BeO

T,K	k,Watt $cm^{-1} K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
0	0	400	1.96
0.1	0.000000063*	450	1.68
0.5	0.0000078*	500	1.46
1	0.000063*	600	1.11
5	0.0052	700	0.87
10	0.030	800	0.70
15	0.081	900	0.57
20	0.16	1000	0.47
25	0.26	1100	0.39
30	0.39	1200	0.33
35	0.55	1300	0.283
40	0.74	1400	0.245
45	0.94	1500	0.215
50	1.18	1600	0.195
60	1.71	1700	0.180
70	2.32	1800	0.167
80	2.96	1900	0.156
90	3.62	2000	0.150
100	4.25	2100	0.150
150	5.17	2200	0.152
200	4.24	2300	0.164
250	3.34	2400	0.180
273	3.02	2500	0.202*
300	2.72	2600	0.230*
350	2.28		

* Extrapolated.

Data Source and Remarks

Forty-nine sets of experimental data are available. Selected values from 3 to 93 K are taken from the data of Berman (1952) [85]. Above room temperature the values are the results of the correlation of thermal conductivity and specimen purity and density using the data of Powell (1954) [98], Taylor (1960) [99], Feith (1964) [100], Hedge, Kostenko, and Lang (1963) [101], Rudkin (1963) [102], Burk (1963) [103], Norton and Kingery (1952) [92], Norton, Kingery, McQuarrie, Adams, Loeb, and Francl (1953) [93], Francl and Kingery (1954) [97], Kingery and Norton (1955) [104], and others.

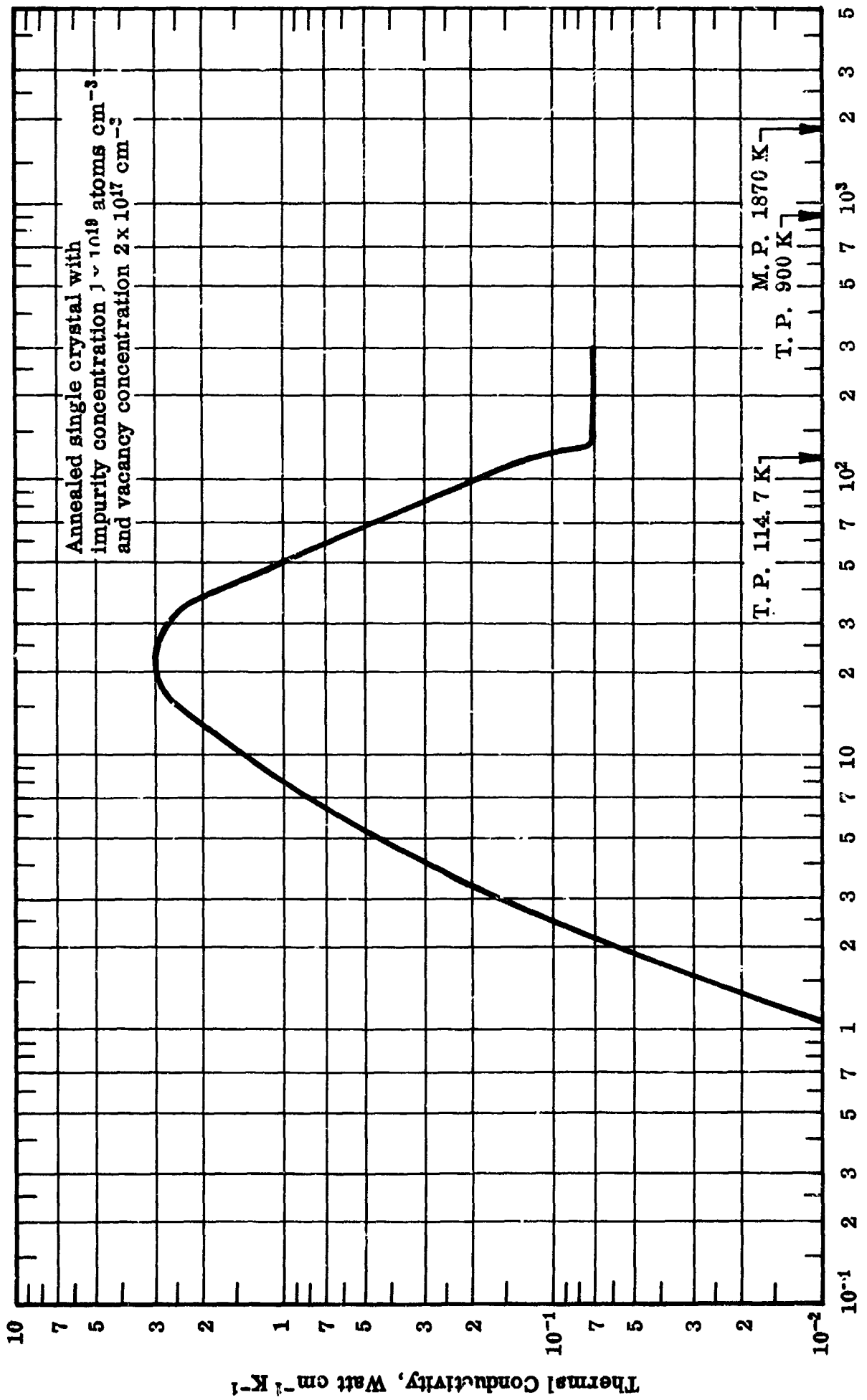

FIG. I-25 THERMAL CONDUCTIVITY OF IRON OXIDE Fe_3O_4

TABLE I-25 THERMAL CONDUCTIVITY OF IRON OXIDE Fe_3O_4

Selected Values for Annealed Single Crystal with Impurity Concentration $1x10^{19}$ atoms cm^{-3} and Vacancy Concentration 2×10^{17} cm^{-3}

T,K	k,Watt cm^{-1} K^{-1}	T,K	k,Watt $cm^{-1}K^{-1}$
0	0	80	0.325
1	0.008*	90	0.243
5	0.47	100	0.188
10	1.35	110	0.150
15	2.53	115	0.134
20	3.03	120	0.115
25	3.02	125	0.091
30	2.76	130	0.073
35	2.30	135	0.0718
40	1.74	140	0.0712
45	1.32	150	0.071
50	1.02	200	0.071
60	0.66	300	0.070
70	0.45		

Data Source and Remarks

Two sets of experimental data from Slack (1961, 1962)[105,106] are available. Selected values are taken from one set of his data.

* Extrapolated.

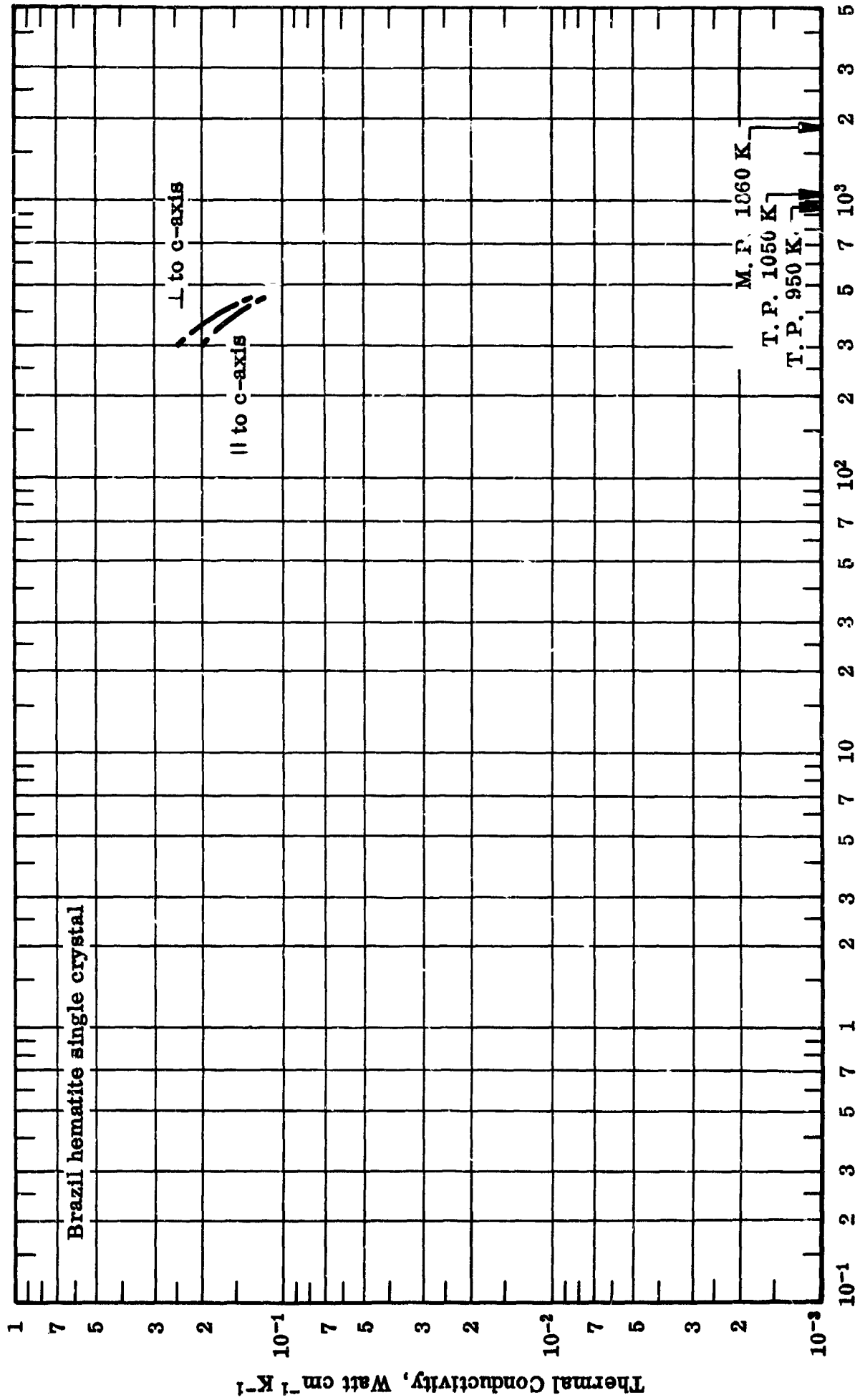

FIG. I-26 THERMAL CONDUCTIVITY OF IRON (IC) OXIDE Fe_2O_3

TABLE I-26 THERMAL CONDUCTIVITY OF IRON (IC) OXIDE Fe_2O_3

Selected Values for Brazil Hematite Single Crystal

T,K	Heat flow parallel to c-axis k, Watt $cm^{-1}K^{-1}$	Heat flow perpendicular to c-axis k, Watt $cm^{-1}K^{-1}$
300	0.199*	0.244*
350	0.171	0.206
400	0.143	0.167
450	0.115*	0.128*

Data Source and Remarks

Selected values are taken from the only two sets of available data from Smoke, Illyn, and Eichbaum (1954) [107].

*Extrapolated.

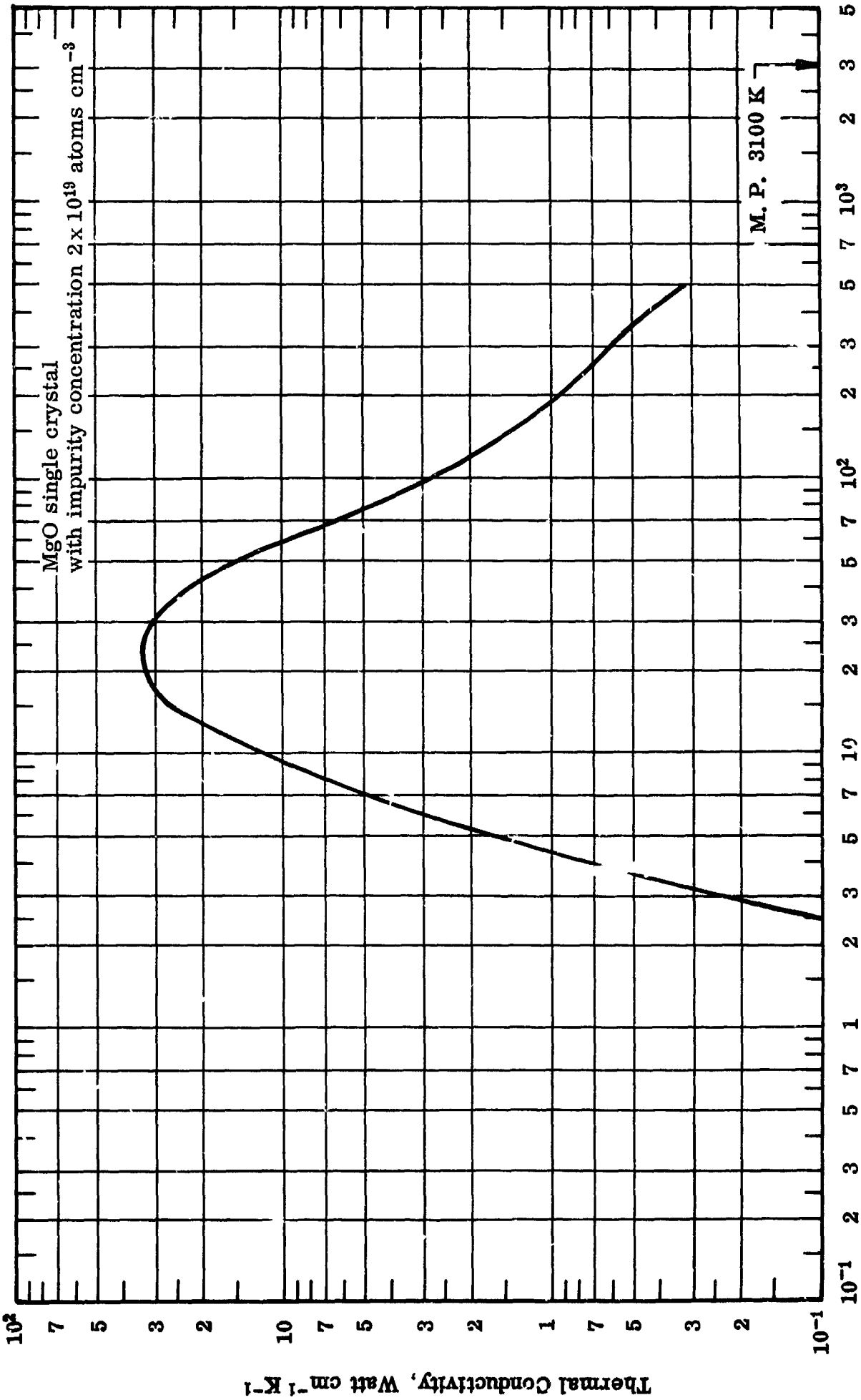

FIG. I-27 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (single crystal) MgO

TABLE I-27 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (single crystal) MgO

Selected Values for MgO Single Crystal with Impurity Concentration 2 x 10^{19} atoms cm^{-3}

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
0	0	60	9.3
0.1	0.000012*	70	6.3
0.5	0.0015*	80	4.5
1	0.012*	90	3.4
5	1.55	100	2.7
10	11.7	150	1.35
15	26.9	200	0.93
20	32.5	250	0.73
25	33.1	273	0.66
30	30.9	300	0.60
35	26.5	350	0.50
40	21.6	400	0.43
45	17.6	450	0.37
50	14.2	500	0.32

Data Source and Remarks

Five sets of experimental data are available. Selected values from 2 to 320 K are taken from the data of Slack (1962) [106]. and values from 423 to 483 K from the data of Makarounis and Jenkins (196[illegible] [108].

*Extrapolated.

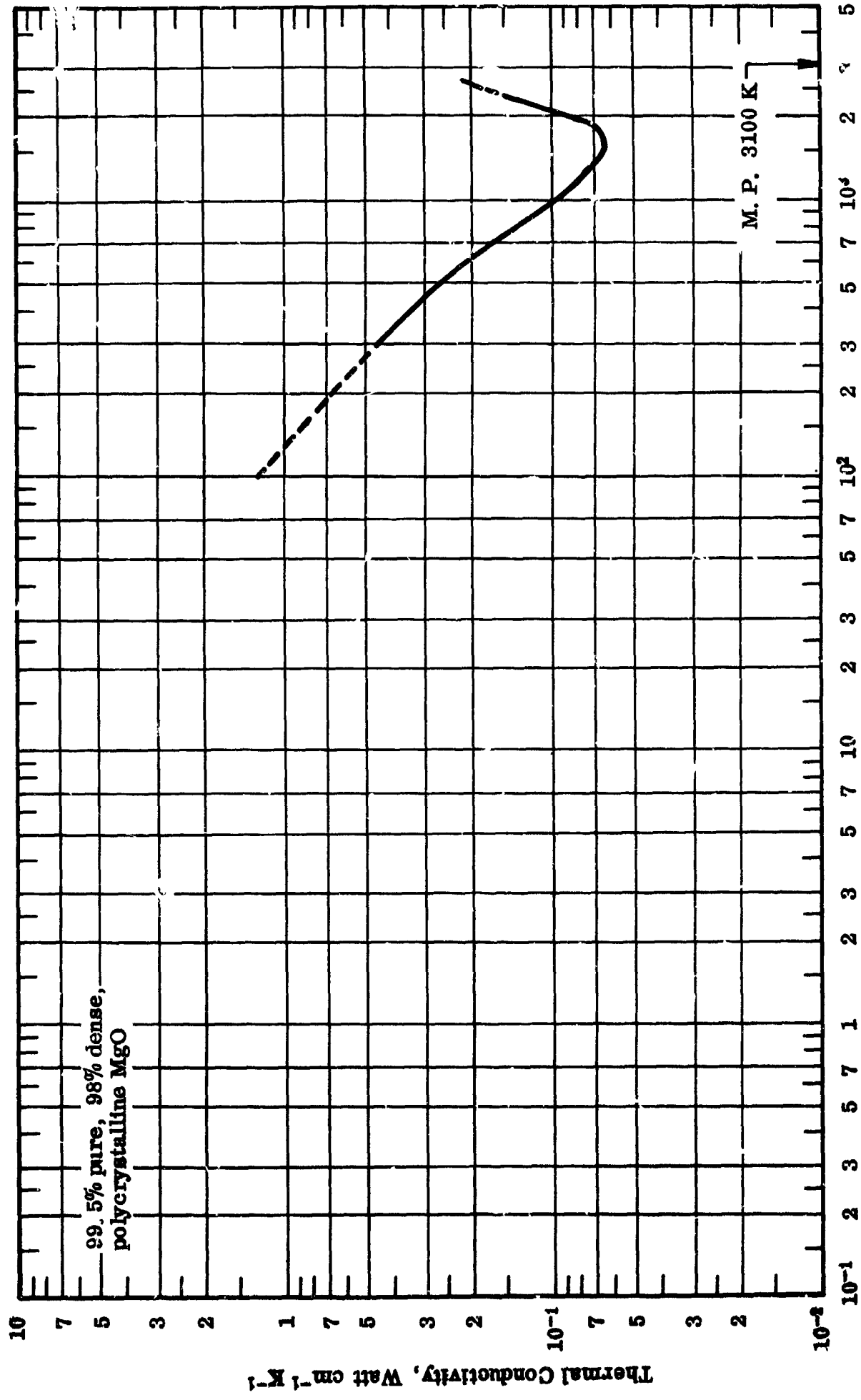

FIG. I-28 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (polycrystalline) MgO

TABLE I-28 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (polycrystalline) MgO

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline MgO

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
100	1.25*	1300	0.072
150	0.85*	1400	0.068
200	0.65*	1500	0.065
250	0.53*	1600	0.064
273	0.488*	1700	0.064
300	0.447	1800	0.066
350	0.386	1900	0.073
400	0.338	2000	0.085
450	0.297	2100	0.099
500	0.260	2200	0.155
600	0.203	2300	0.132
700	0.162	2400	0.150*
800	0.133	2500	0.170*
900	0.112	2600	0.191*
1000	0.096	2700	0.214*
1100	0.085	2800	0.239*
1200	0.077	2900	0.266*

Data Source and Remarks

Thirty-seven sets of experimental data are available, but no measurement has been made below room temperature on polycrystalline MgO. The selected values are the results of the correlation of thermal conductivity and specimen purity and density using the data of Fieldhouse and Lang(1961) [109], Koenig (1953) [110], Norton, Kingery, et al. (1950) [111], Norton, Kingery, et al. (1951) [112], Norton, Kingery, et al. (1953) [93], Francl and Kingery (1954) [97], and others. Charvat and Kingery (1957) [113] measured the thermal conductivity of MgO and investigated the effect of purity, porosity, and microstructure on thermal conductivity. They gave complete specifications to characterize their specimens, which most authors failed to do, and therefore their data should be most valuable. However, their data appear to be very high and the inclusion of their data in the correlation would lead to high results. Consequently, in the present work their data are excluded.

*Extrapolated.

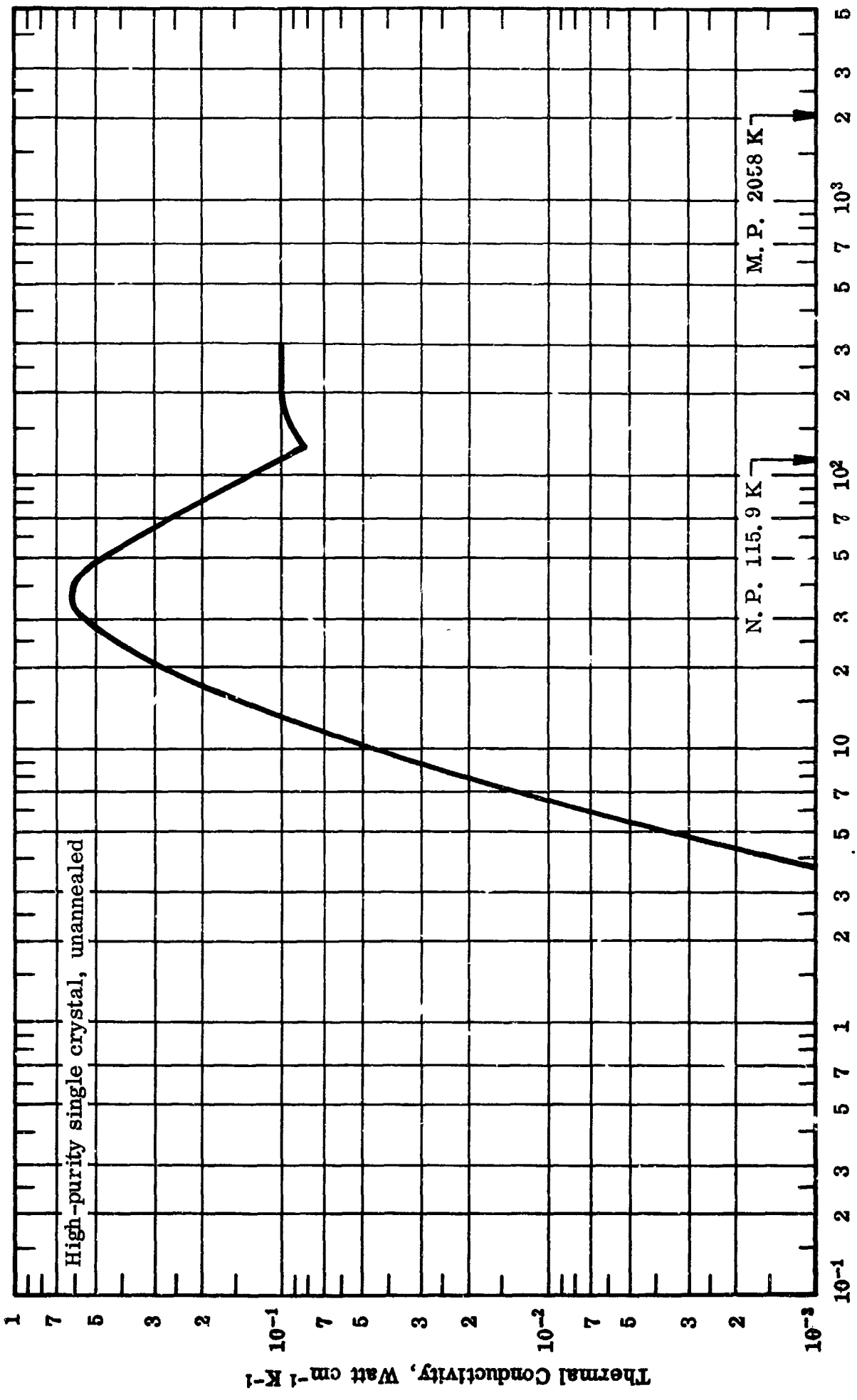

FIG. I-29 THERMAL CONDUCTIVITY OF MANGANESE MONOXIDE MnO

TABLE I-29 THERMAL CONDUCTIVITY OF MANGANESE MONOXIDE MnO

Selected Values for Unannealed High-Purity Single Crystal

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
0	0	70	0.244
1	0.000009*	80	0.190
5	0.0036	90	0.155
10	0.039	100	0.128
15	0.136	110	0.110
20	0.30	120	0.094
25	0.45	130	0.082
30	0.56	140	0.086
35	0.60	150	0.092
40	0.59	170	0.098
45	0.55	200	0.10
50	0.48	250	0.10
60	0.34	300	0.10

Data Source and Remarks

Selected values are taken from the only one set of available data from Slack and Newman (1958) [114].

*Extrapolated

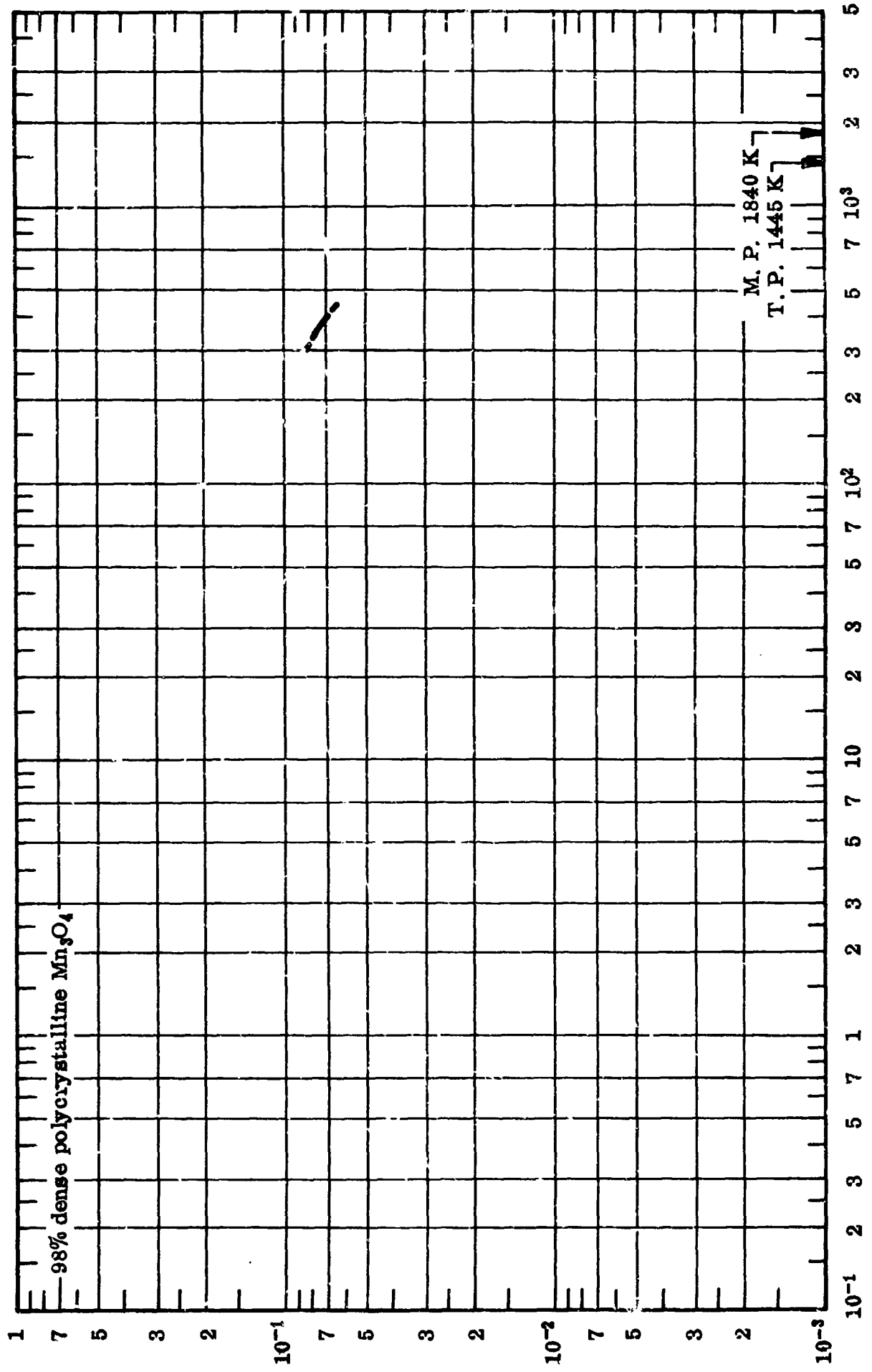

FIG. I-30 THERMAL CONDUCTIVITY OF MANGANOLANGANIC OXIDE Mn_3O_4

TABLE I-30 THERMAL CONDUCTIVITY OF MANGANOMANGANIC OXIDE Mn_3O_4

Selected Values for 98% Dense Polycrystalline Mn_3O_4

T,K	k,Watt cm^{-1} K^{-1}
300	0.083*
350	0.077
400	0.070
450	0.063*

Data Source and Remarks

Two sets of data are available. One set is from Koenig (1952) [115] and the other is from Smoke and Koenig (1958) [116]. These two sets of data differ with each other by about 100% and are with opposite slopes. Selected values are taken with adjustment, from the second set of data. The purity of the specimen was not reported.

*Extrapolated.

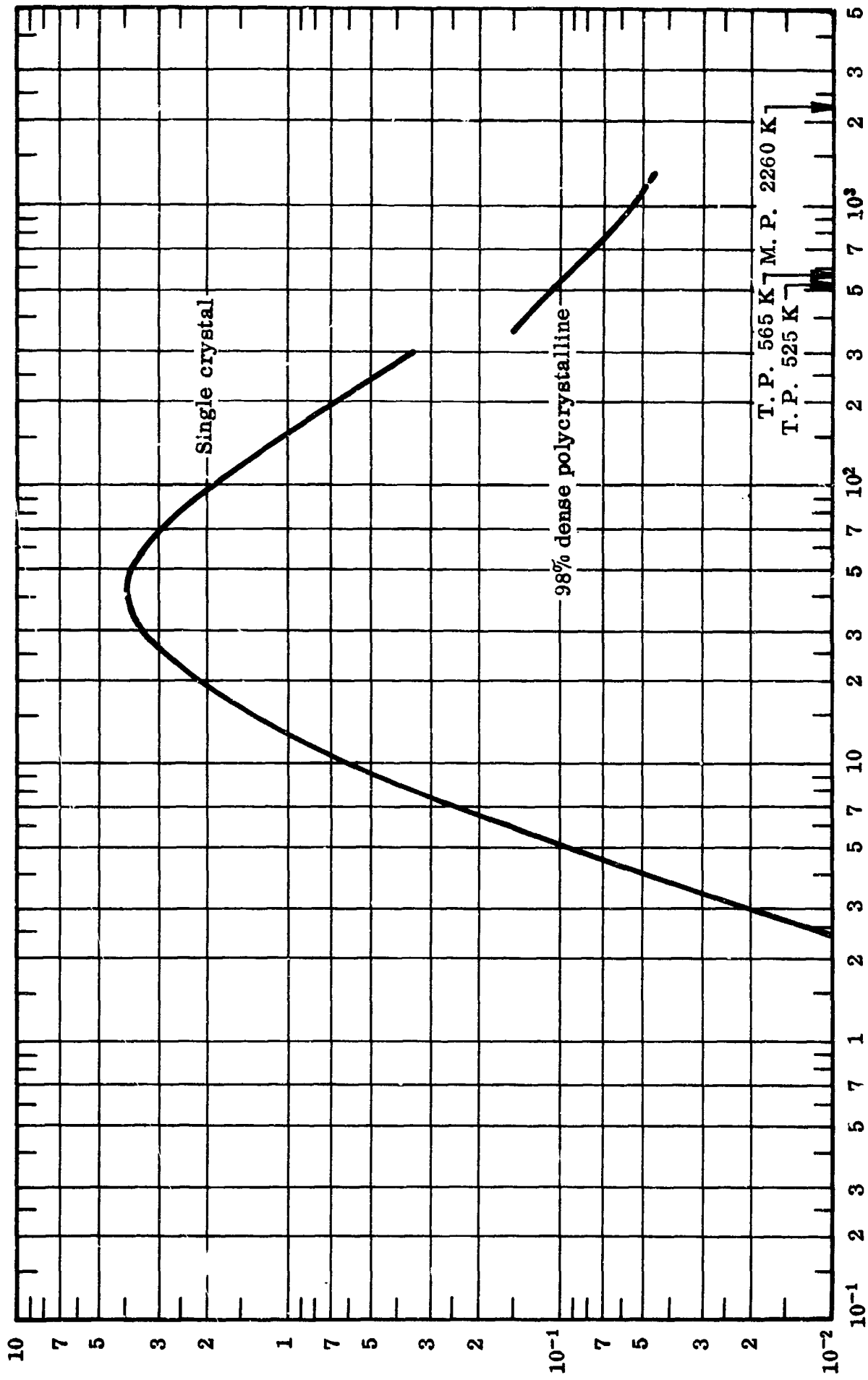

FIG. I-31 THERMAL CONDUCTIVITY OF NICKEL (OUS) OXIDE NiO

TABLE I-31 THERMAL CONDUCTIVITY OF NICKEL (OUS) OXIDE NiO

NiO Single Crystal		98% Dense Polycrystalline NiO	
T, K	k, Watt $cm^{-1}K^{-1}$	T, K	k, Watt $cm^{-1}K^{-1}$
0	0	350	0.150
1	0.00068*	400	0.133
5	0.089	450	0.119
10	0.56	500	0.107
15	1.32	600	0.089
20	2.12	700	0.076
30	3.45	800	0.067
40	3.91	900	0.060
50	3.80	1000	0.054
60	3.38	1100	0.050
70	2.92	1200	0.047
80	2.51	1300	0.045*
90	2.18		
100	1.90		
150	1.06		
200	0.67		
250	0.46		
273	0.40		
300	0.34		

Data Source and Remarks

Selected values for NiO single crystal are taken, with modifications, from the only one set of available experimental data reported by Slacks and Newman (1958) [114]. The impurity and imperfection of the crystal were not reported.

Four sets of experimental data are available for polycrystalline NiO. Selected values are the results of the correlation of thermal conductivity and specimen density based on the data of Kingery, Francl, Coble, and Vasilos (1953) [117] and Francis, Brown, McNamara, and Tinklepaugh (1958) [86]. The purity of the specimens was not reported.

* Extrapolated.

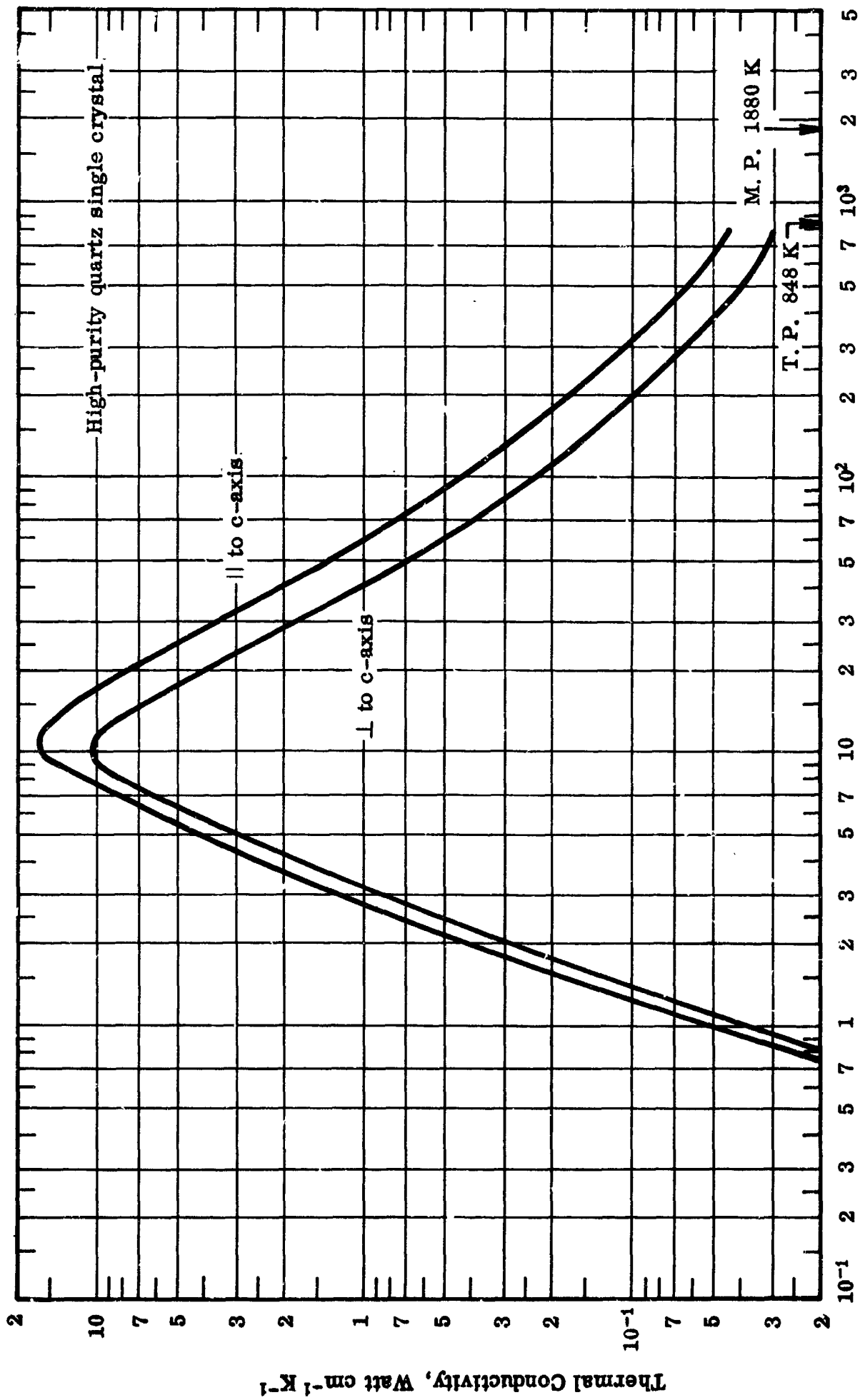

FIG. I-32 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (quartz single crystal) SiO_2

TABLE I-32 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (quartz single crystal) SiO_2

Selected Values for High-Purity Quartz Single Crystal

	Heat flow parallel to c-axis	Heat flow perpendicular to c-axis
T, K	k, Watt $cm^{-1}K^{-1}$	k, Watt $cm^{-1}K^{-1}$
0	0	0
0.1	0.00005*	0.000036*
0.5	0.0063*	0.0045*
1	0.05*	0.036*
5	4.0	3.0
8	10.5	8.6
10	16.5	10.4
15	12.5	6.7
20	7.5	3.9
25	5.0	2.55
30	3.5	1.79
35	2.63	1.32
40	2.04	1.01
45	1.64	0.82
50	1.35	0.68
60	0.97	0.50
70	0.75	0.393
80	0.60	0.324
90	0.50	0.275
100	0.43	0.238
150	0.25	0.141
200	0.174	0.099
250	0.133	0.077
273	0.120	0.070
300	0.108	0.063
350	0.090	0.053
400	0.077	0.047
450	0.068	0.042
500	0.061	0.039

*Extropolated.

TABLE I-32 (continued)

T,K	Heat flow parallel to c-axis k, Watt $cm^{-1}K^{-1}$	Heat flow perpendicular to c-axis k, Watt $cm^{-1}K^{-1}$
600	0.052	0.034
700	0.047	0.032
800	0.044*	0.031*

Data Source and Remarks

Forty-two sets of experimental data are available. Selected values for quartz single crystal with heat flow parallel to c-axis are derived from the data of de Haas and Biermasz (1936) [118], Griffiths and Kaye (1923) [119], Kaye and Higgins (1926) [120], Birch and Clark (1940) [121], Eucken (1911) [122], Koenig (1952, 1954) [115, 107], and others, Values for quartz single crystal with heat flow perpendicular to c-axis are derived from the data of de Haas and Biermasz (1937) [123], Berman (1951) [124] Griffiths and Kaye (1923) [119], Kaye and Higgins (1926) [120], Birch and Clark (1940) [121] Eucken (1911) [122], Ratcliffe (1959) [125], Koenig (1952, 1954) [115,107], Weeks and Seifert (1952) [126], and others.

* Extrapolated.

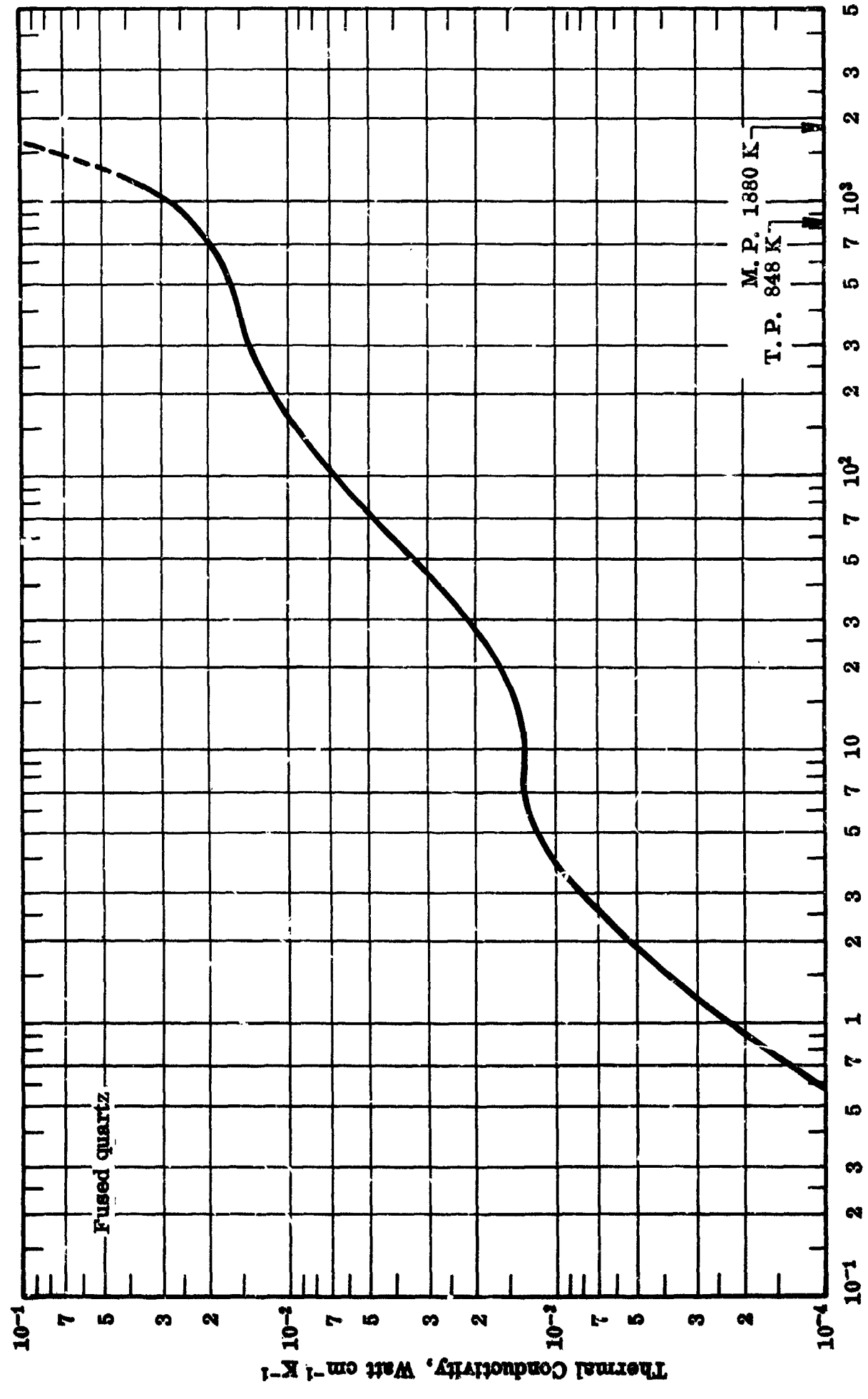

FIG. I-33 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (fused quartz) SiO_2

TABLE I-33 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (fused quartz) SiO_2

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
0	0	350	0.0147
1	0.00024*	400	0.0152
2	0.00054*	450	0.0158
3	0.00080	500	0.0163
5	0.00118	600	0.0177
10	0.00126	700	0.0196
15	0.00136	800	0.0219
20	0.00156	900	0.0248
30	0.0021	1000	0.0289
50	0.0034	1100	0.0337
100	0.0066	1200	0.0400
150	0.0093	1300	0.0493*
200	0.0113	1400	0.0615*
250	0.0128	1500	0.076*
273	0.0133	1600	0.092*
300	0.0138	1700	0.111*

Data Source and Remarks

Fifteen sets of experimental data are available. Selected values are derived from the data of Berman (1951) [124], Devyatkova, Petrov, Smirnov , and Moizhes (1960) [127] Ratcliffe (1959) [125], Kamilov (1963) [128], Norton and Kingery (1953) [129], and others.

* Extrapolated.

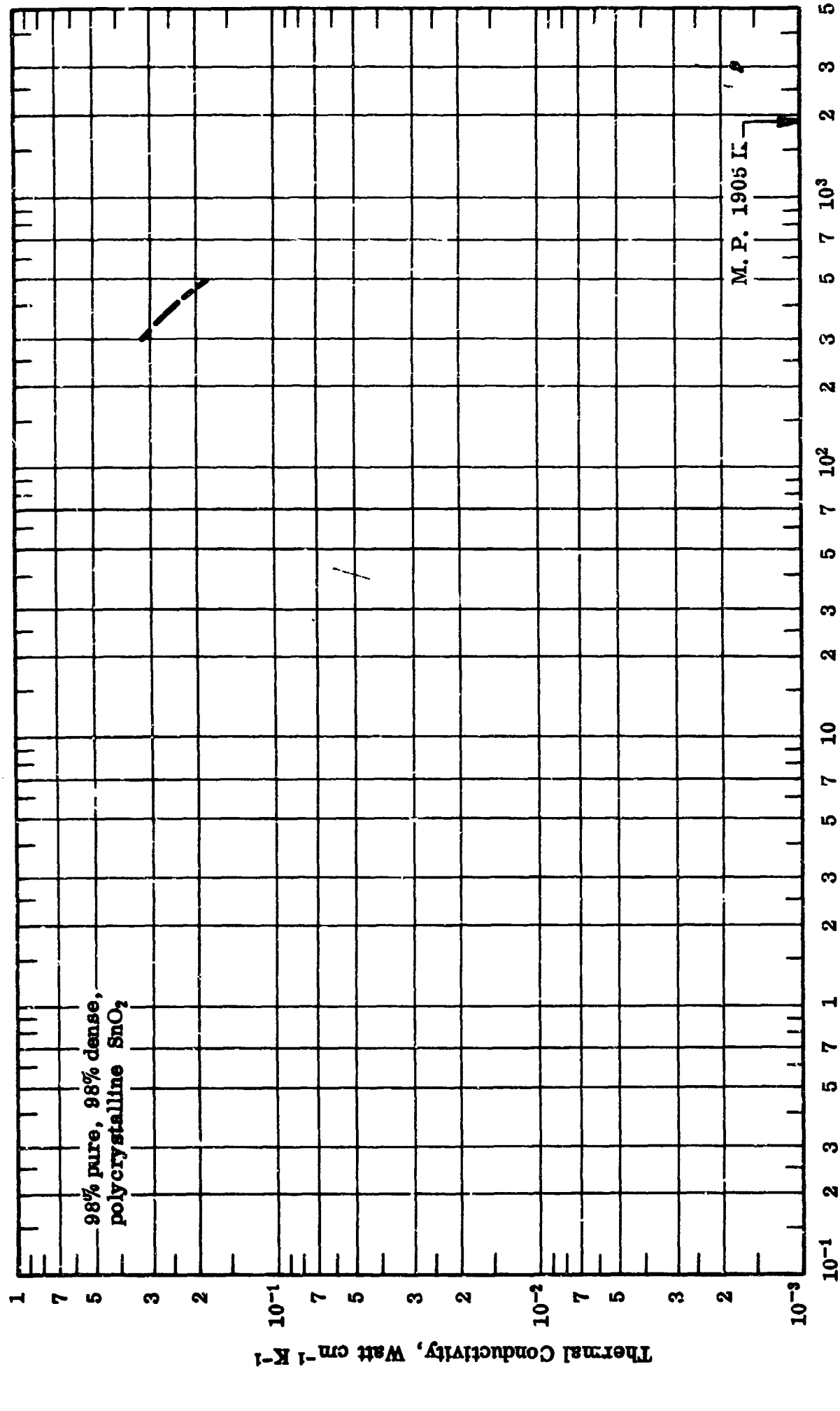

FIG. 1-34 THERMAL CONDUCTIVITY OF TIN (IC) OXIDE SnO_2

TABLE I-34 THERMAL CONDUCTIVITY OF TIN (IC) OXIDE SnO_2

Selected Values for 98% Pure, 98%Dense, Polycrystalline SnO_2

T,K	k,Watt $cm^{-1}K^{-1}$
300	0.32*
350	0.28
400	0.24
450	0.21*
500	0.18*

Data Source and Remarks

Five sets of experimental data are available. Selected values are the results of correlation of thermal conductivity and density using the data of Koenig (1953) [110,130].

* Extrapolated.

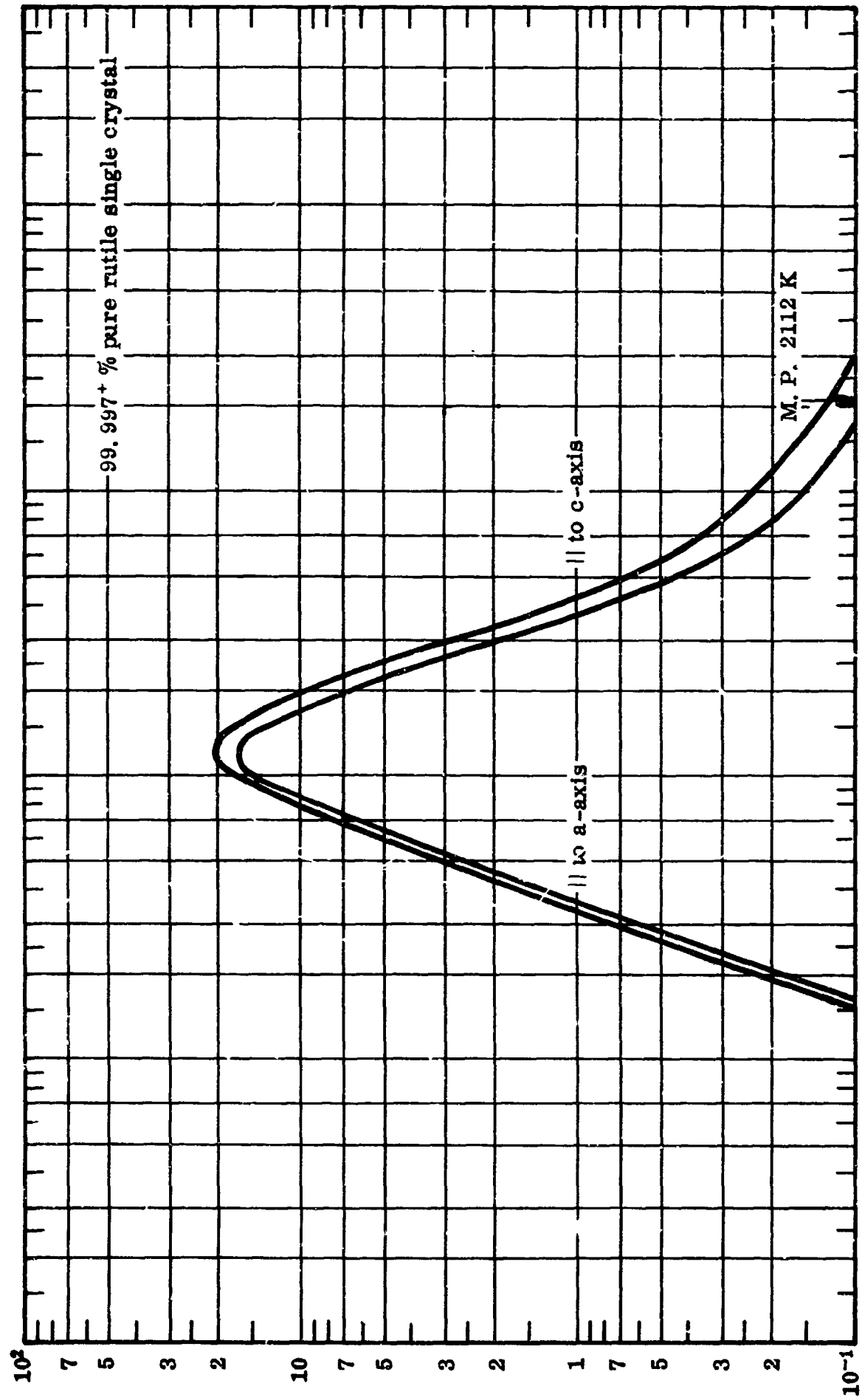

FIG. I-35 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE (single crystal) TiO_2

TABLE I-35 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE single crystal) TiO_2

Selected Values for 99.997+ Pure Rutile Single Crystal

T, K	Heat flow parallel to c-axis k, Watt $cm^{-1} K^{-1}$	Heat flow parallel to a-axis k, Watt $cm^{-1} K^{-1}$
0	0	0
0.1	0.000026*	0.000023*
0.5	0.0032*	0.0028*
1	0.026*	0.023*
5	3.13	2.65
10	17.9	14.6
11	20.0	16.3
12	20.6	17.0
13	20.2	16.5
14	19.1	15.4
15	17.7	13.8
20	10.0	6.9
25	5.4	3.6
30	2.85	1.88
35	1.75	1.17
40	1.17	0.80
45	0.85	0.58
50	0.66	0.45
60	0.45	0.315
70	0.35	0.252
80	0.30	0.213
90	0.264	0.187
100	0.235	0.169
150	0.168	0.120
200	0.137	0.097
250	0.118	0.083
300	0.104	0.074
350	0.094	0.066
400	0.085	0.060

* Extrapolated.

Data Source and Remarks

Twenty-one sets of experimental data are available. Selected values from 2 to 100 K are taken from the data of Thurber and Mante (1965) [131]. No data exists between 100 and 298 K. Values from 300 to 400 K are derived from the data of Yoshida (1960) [132] and Koenig (1953, 1954) [133, 107].

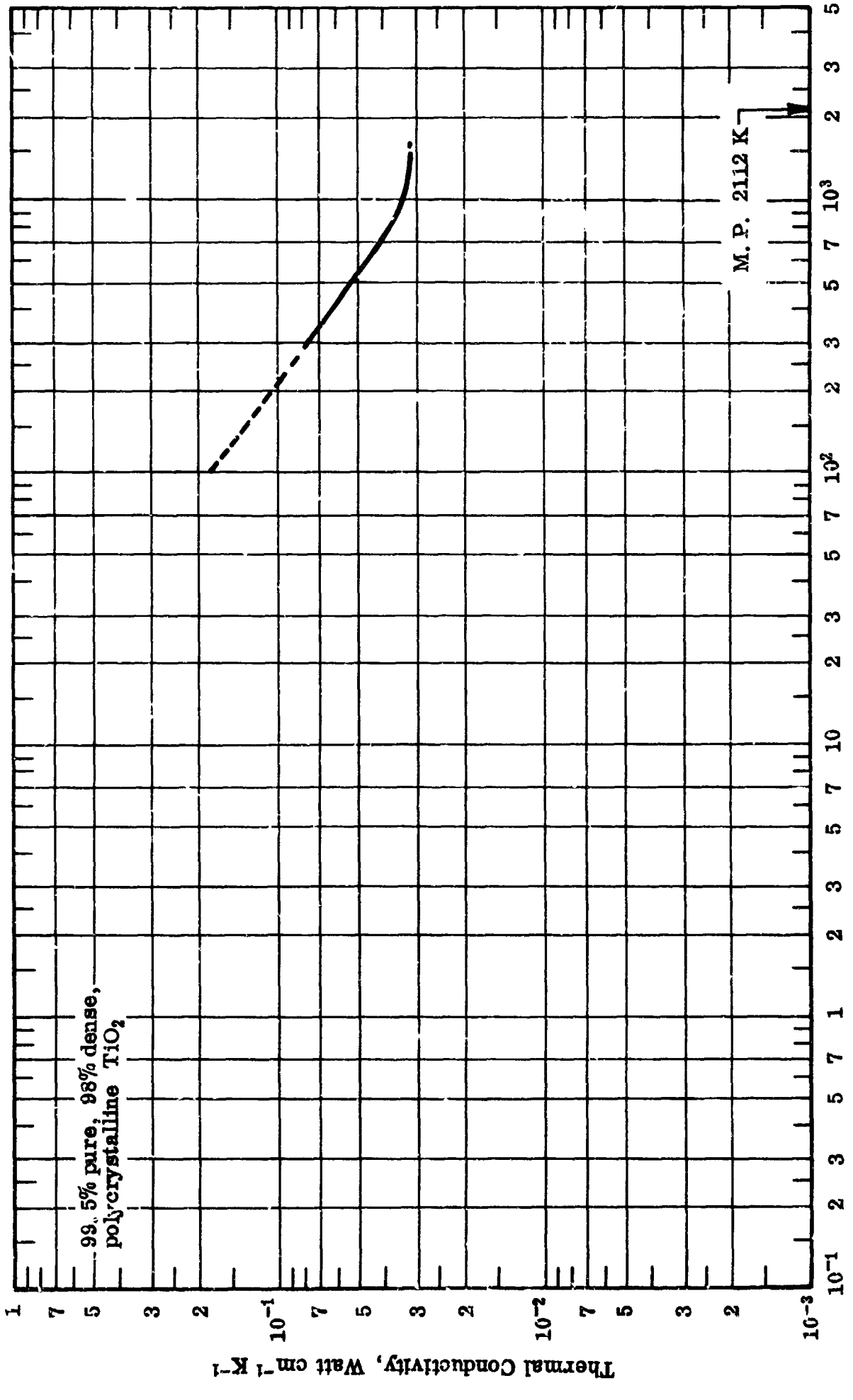

FIG. I-36 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE (polycrystalline) TiO_2

TABLE I-36 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE (polycrystalline) TiO_2

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline TiO_2

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
100	0.18*	600	0.046
150	0.128*	700	0.041
200	0.104*	800	0.038
250	0.088*	900	0.0355
273	0.083*	1000	0.0342
300	0.077	1100	0.0332
350	0.069	1200	0.0325
400	0.063	1300	0.0322
450	0.057	1400	0.0321
500	0.05	1500	0.0320*

Data Source and Remarks

Fifteen sets of experimental data are available. Selected values are derived from the data of Norton, Kingery, et al. (1952) [134], Kingery, Francl, Coble, and Vasilos (1954) [135], and from a part of the data of Charvat and Kingery (1957) [113]. Charvat and Kingery (1957) [113] investigated the effect of purity, porosity, and microstructure on the thermal conductivity of TiO_2. They gave complete specifications to characterize their specimens, which most authors failed to do, and therefore their data should be most useful. However, the data of some of their curves appear to be very high and the inclusion of these high data in the derivation would lead to high results. Consequently, in the present derivation of selected values some of their curves are ignored.

* Extrapolated.

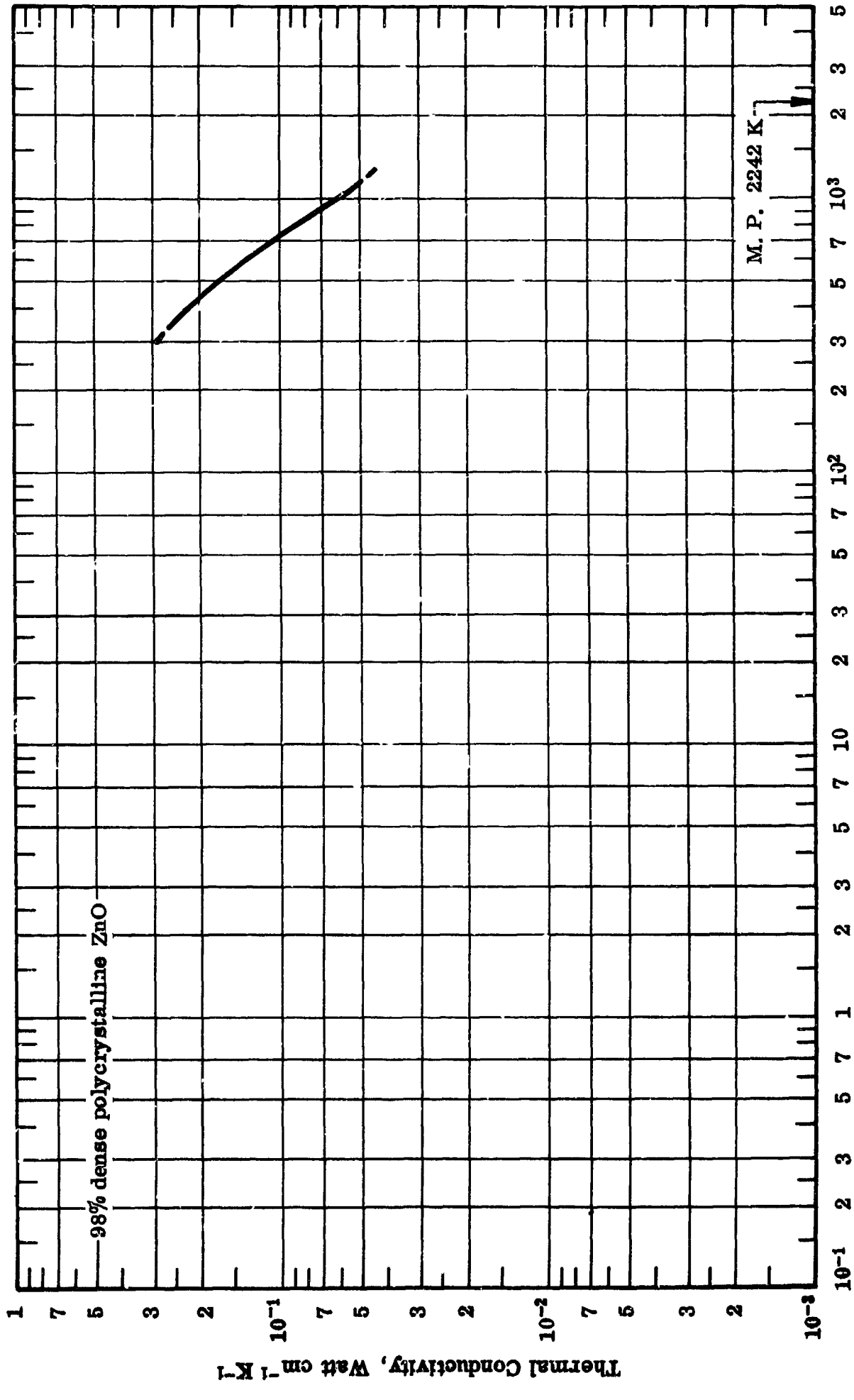

FIG. I-37 THERMAL CONDUCTIVITY OF ZINC OXIDE ZnO

TABLE I-37 THERMAL CONDUCTIVITY OF ZINC OXIDE ZnO

Selected Values for 98% Dense Polycrystalline ZnO

T,K	k,Watt $cm^{-1}K^{-1}$	T,K	k,Watt $cm^{-1}K^{-1}$
300	0.286*	800	0.085
350	0.252	900	0.070
400	0.220	1000	0.059
450	0.192	1100	0.052
500	0.168	1200	0.047
600	0.131	1300	0.043*
700	0.105		

Data Source and Remarks

Four sets of experimental data are available. Selected values are the results of correlation of thermal conductivity and specimen density using the data of Koenig (1953) [130] and Kingery, Francl, Coble, and Vasilos (1953) [117]. The purity of the specimens was not reported.

* Extrapolated.

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RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER II

VISCOSITY

BY

P. HESTERMANS
D. G. CHUA

CHAPTER II
VISCOSITY

A. INTRODUCTION

The literature search has revealed a substantial amount of information on the viscosities of common molten metals, particularly tin, copper, iron, and aluminum. Data were completely lacking for beryllium, chromium, manganese, niobium, and silicon. No information was found on the viscosities of liquid alloys having the required composition. For the oxides, availability of data was limited to aluminum oxide (Al_2O_3), iron oxide (FeO) and silicon oxide (SiO_2).

Values of viscosity are restricted to a short range of temperature below the boiling point. For those metals for which a considerable amount of work has been done, the results show considerable dispersion, even for tin, which is often used as a calibrating liquid. The search for the causes of these discrepancies has been of standing concern to workers in this field. Several hypothesis have been put forward to explain the discrepancies occurring particularly in the region close to the melting point, these are:

a. the possibility of a "pre-freezing" phenomena, in which the liquid acquires an ordering similar to that of the solid, with a resulting increase of viscosity (11)*
b. the influence of insoluble particles (mainly oxides, or the presence of solid phase crystals) causing the metallic liquid to be heterogeneous, the effect is also an increase in viscosity (7)
c. some methodological factors, related to or independent of the two preceding points.**

*Numbers in parentheses refer to the bibliography at the end of this chapter.

**An extensive discussion of this is given in reference (7).

B. DATA ANALYSIS

Bearing in mind the three reasons for the discrepancies found in experimental data, a choice of recommended values was made with due consideration of the purity of samples and of the method used by the authors. Generally the measurements selected were those made by observation of the damping of oscillation of a cylinder filled with the liquid. These were generally more reliable than those made with an oscillating body immersed in the liquid, in which case complications arise due to the influence of surface tension. Unfortunately, the methods based on the damping of a cylinder filled with the liquid are not of equal reliability. It was found that some authors used relative oscillational viscosimeters. The accuracy that can be obtained with these instruments is impaired by the choice of the calibrating liquids. On the other hand, those measurements made with absolute oscillational viscosimeter may be of lower value due to impairments in the experimental conditions.

In order to select the recommended values, graphs were prepared of log μ versus 1/T. A straight line was drawn through the best values. This procedure is based on the acceptance of Andrade's equation

$$\mu = A\, e^{B/T}$$

which was found to represent the data within the scatter of experimental values. In all cases a check was made on a plot of μ versus T.

C. PRESENTATION OF DATA ON THE VISCOSITY OF SELECTED MATERIALS

The elements and oxides for which data are presented can be found in the Page Index to Materials and Properties. No values were found for alloys having the required composition. A first order approximation will be to assume that the viscosities for alloys with a small amount of minor constituents is that of the pure metal. However, it is worth to mention that viscosities in technical conditions (i.e., casting) may be found to deviate widely from the viscosities of pure sample.*

*For the case of aluminum a discussion of this may be found in Reference (7) pp. 99.

Values of the viscosity (in centipoise) versus the absolute temperature (in K) are presented on the following pages, both in graphical and tabular form, at 50 degree intervals. The tables are given as to permit linear or three-point interpolation with acceptable accuracy. The selected values lie generally within ±10 percent of the recommended curves, but the other values may diverge as much as ±20 to 40 percent.

One exception to the preceding rule is the data presentation for silicon oxide. In view of the different order of magnitude and the large variation of viscosities, (from about 10^8 poises at the melting point to 10^4 poises at higher temperature) these were plotted as log μ versus 1/T, while the table gives value of μ versus T. For interpolating purposes an equation is given, and should be used.

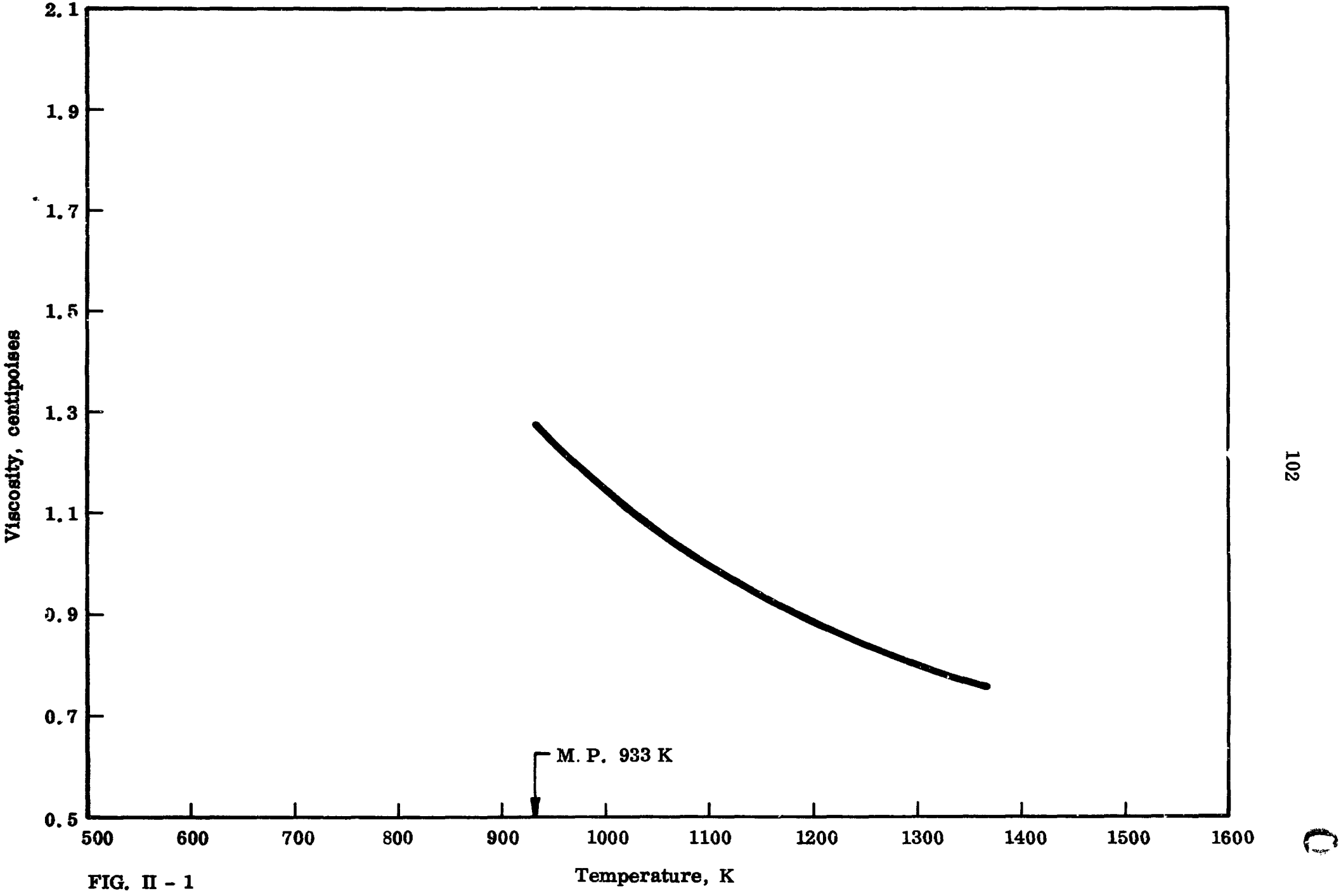

2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
Viscosity, centipoises
M. P. 933 K
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Temperature, K

FIG. II - 1

TABLE II-1. VISCOSITY OF ALUMINUM

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
933(m.p.)	1.27	1200	0.88
950	1.23	1250	0.84
1000	1.14	1300	0.80
1050	1.06	1350	0.77
1100	0.99	1400	0.74
1150	0.93		

SOURCE OF DATA

Selected Values: (a) Glazov, V.M., and Chistiakov, Yu. D. (1); (b) Korolkov, A.M. (2); (c) Rothwell, E. (3); (d) Gebhardt, E., and coll. (4), (5); (e) Sato, T., and Munahata, S. (6); (f) Shvidkovskii, E.G. (7); (g) Tresh, H.R., (8).

Other Values: (h) Polyak, E.V., and Sergueiev, S.V. (9), (10); (i) Yao, T.P., and Kondic, V. (11); (j) Navarro, J.M., and Kondic, V. (12).

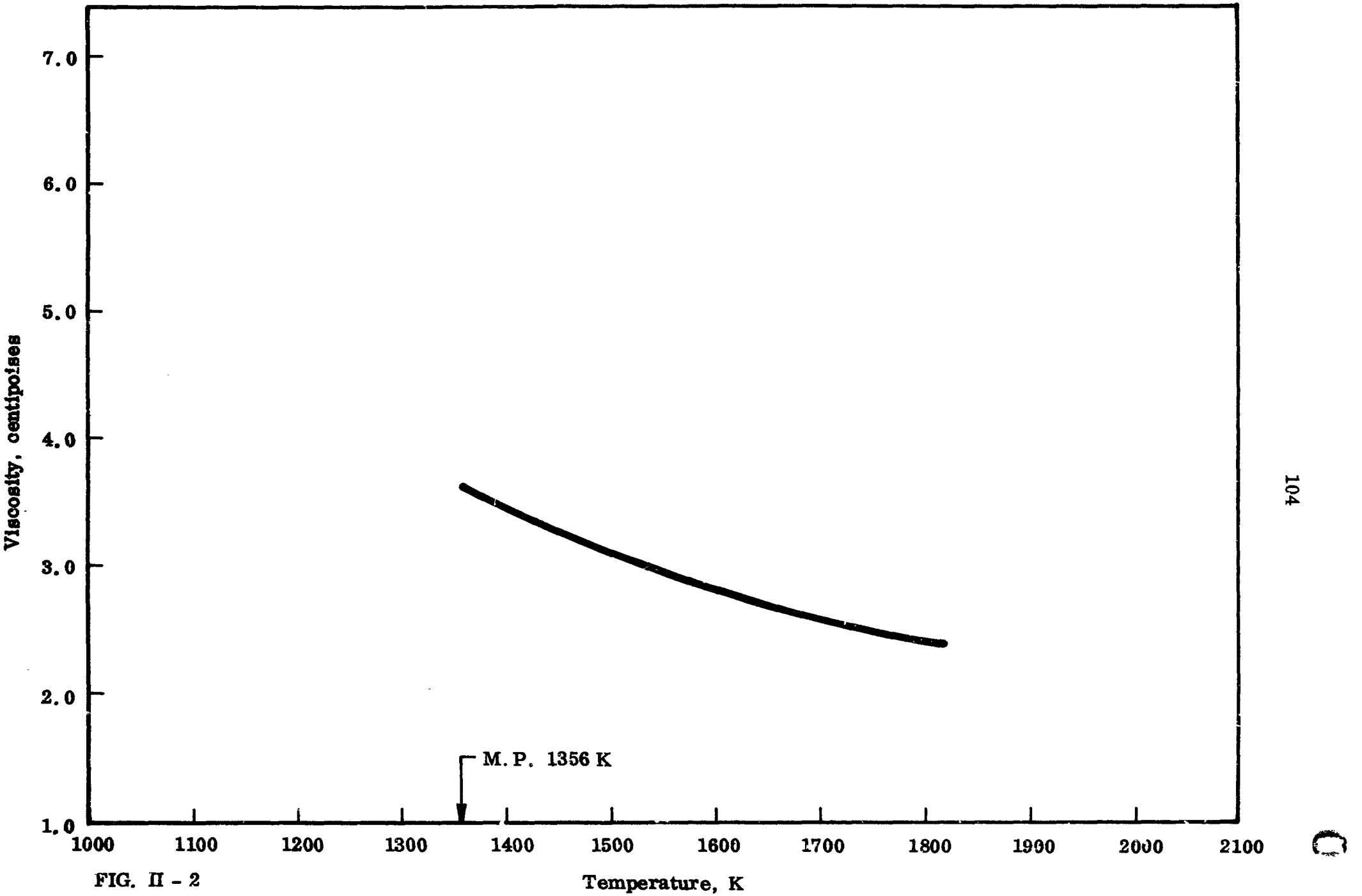

7.0
6.0
5.0
4.0
3.0
2.0
1.0
Viscosity, centipoises
M. P. 1356 K
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Temperature, K

FIG. II - 2

TABLE II-2. VISCOSITY OF COPPER

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
1356(m.p.)	3.64	1600	2.81
1400	3.43	1650	2.69
1450	3.25	1700	2.59
1500	3.08	1750	2.49
1550	2.94	1800	2.40

SOURCE OF DATA

Selected Values: (a) Gebhardt, E., Becker, M., and Schafer, S. (13); Gans, W., Pawlek, F., and Von Roepenack, A. (14); (c) Lipman, M.S. (15); (d) Navarro, J.M., and Kondic, V. (12); (e) Barfield, R.N., and Kitchener, J.A. (16); (f) Vertman, A.A., and Samarin, A.M. (17); (g) Bienias, A., and Sauerwald, F. (18)

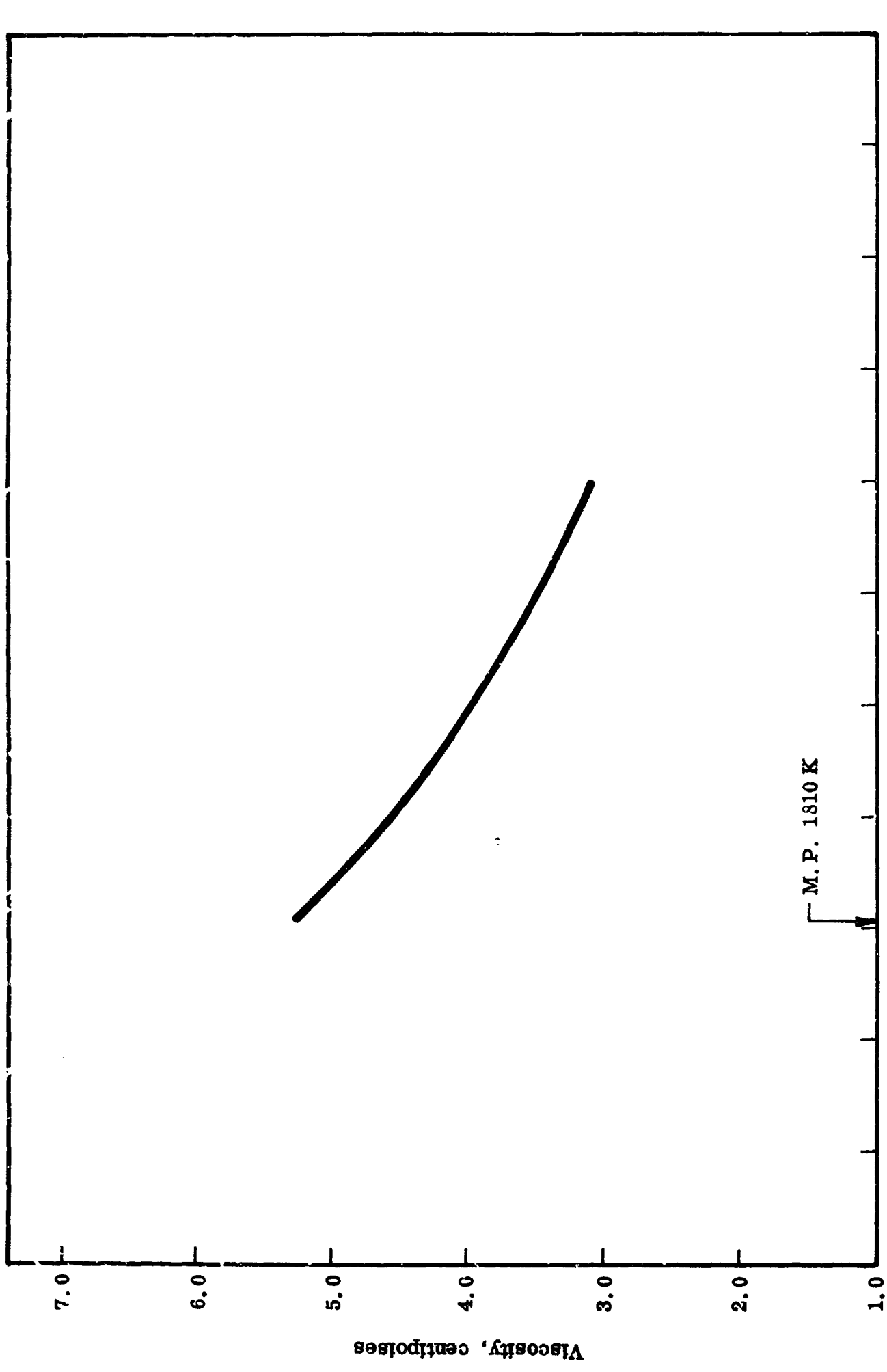

Viscosity, centipoises
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
M.P. 1810 K
Temperature, K

FIG. II - 3

TABLE II-3. VISCOSITY OF IRON

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
1810(m.p.)	5.32	2050	3.70
1850	4.91	2100	3.47
1900	4.55	2150	3.27
1950	4.23	2200	3.08
2000	3.94		

SOURCE OF DATA

Selected Values: (a) Schenck, H., Frohberg, M.G., and Hoffman, K. (19); (b) Samarin, A.M. (20); (c) Thiele, M. (21); (d) Cavalier, G. (22)

Other Values: (e) Barfield, R.N., and Kitchener, J.A. (16); (f) Turovskii, B.M., and Lyubimov, A.D. (23)

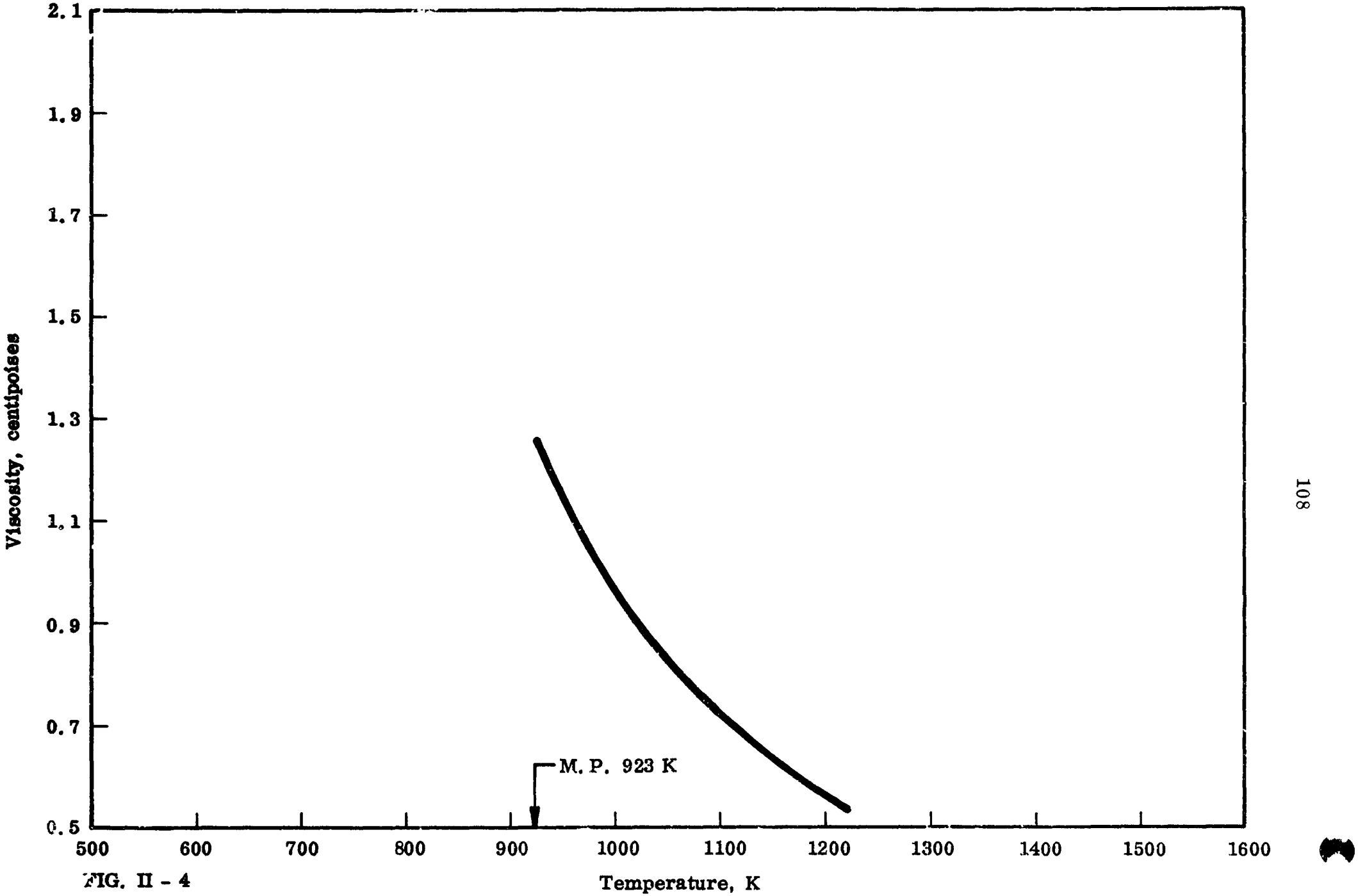

2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
Viscosity, centipoises
M. P. 923 K
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Temperature, K

FIG. II - 4

TABLE II-4. VISCOSITY OF MAGNESIUM

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
923(m.p.)	1.24	1100	0.72
950	1.15	1150	0.63
1000	0.97	1200	0.56
1050	0.83		

SOURCE OF DATA

Selected Values: (a) Culpin, M.F. (24); (b) Gebhardt, E., Becker, M., and Tragner, E. (25); (c) Metals Handbook (26).

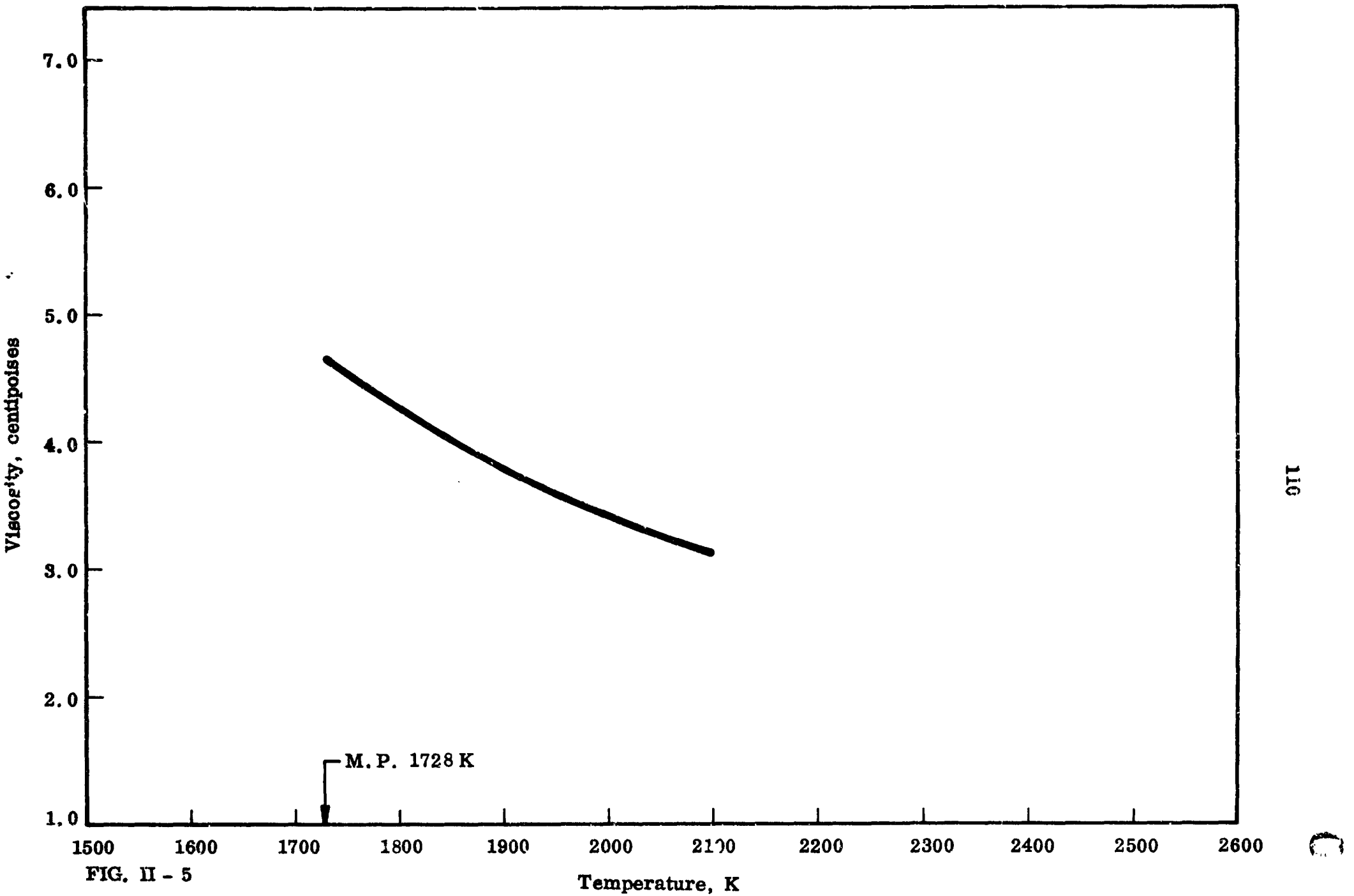

7.0
6.0
5.0
4.0
3.0
2.0
1.0
Viscosity, centipoises
M.P. 1728 K
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
Temperature, K

FIG. II - 5

TABLE II-5. VISCOSITY OF NICKEL

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
1728(m.p.)	4.64	1950	3.59
1750	4.52	2000	3.41
1800	4.25	2050	3.25
1850	4.00	2100	3.10
1900	3.78		

SOURCE OF DATA

Selected Values: (a) Vertman, A.D., and Samarin, A.M. (27); (b) Schenck, H., Frohberg, M.G., and Hoffman, K. (19); (c) Cavalier (28); (d) Lucas, L.D. (29).

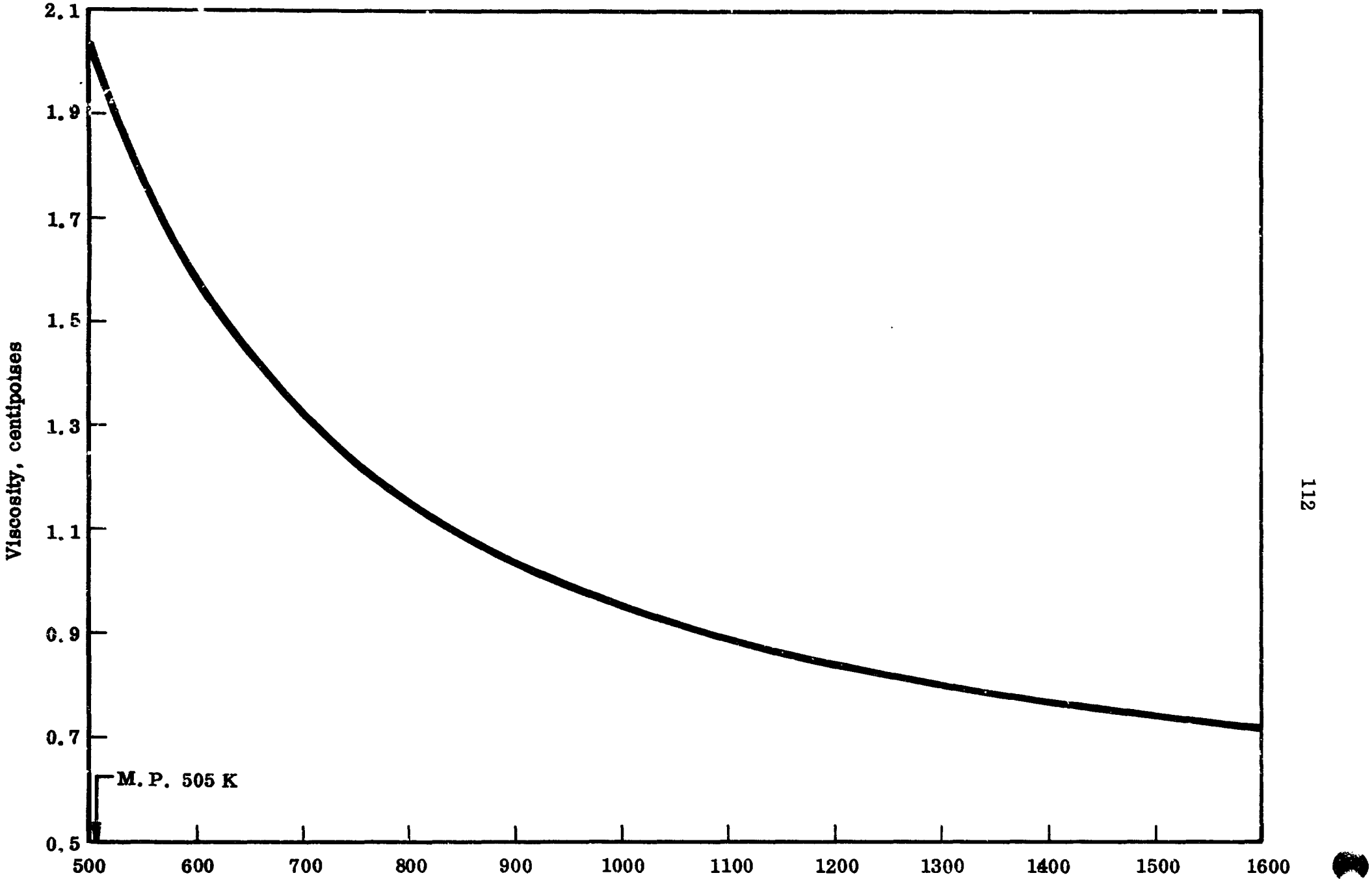

2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
Viscosity, centipoises
M. P. 505 K
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Temperature, K

FIG. II - 6

TABLE II-6. VISCOSITY OF TIN

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
505(m.p.)	2.04	1150	0.86
550	1.77	1200	0.84
600	1.58	1250	0.82
650	1.43	1300	0.80
700	1.32	1350	0.78
750	1.23	1400	0.76
800	1.15	1450	0.75
850	1.09	1500	0.74
900	1.03	1550	0.73
950	0.99	1600	0.72
1000	0.95	1650	0.71
1050	0.92	1700	0.70
1100	0.89		

SOURCE OF DATA

Selected Values: (a) Rothwell, A.M. (3); (b) Yao, T.P., and Kondic, V. (11); (c) Yao, T.P., and Kondic, V. (30); (d) Jones, W.R.D., and Davis, J.B. (31); (e) Lewis, A.J. (32); (f) Culpin, M.F. (33); (g) Bastien, P., Ambruster, J.C., and Azou, P. (34); (h) Hedges, E.S., and Homer, C.E. (35); (i) Shvidkovskii, E.G. (7); (j) Kutateladze, S.S., Barishanskii, V.M., Novikov, I.I., and Fedynskii, O.S. (36); (k) Sauerwald, F., and Topler, K. (37a); Budde, J., Fischer, K., Monz, W., and Sauerwald, F. (37b); (l) Gebhardt, E., Becker, M., and Tragner, E., (38); (m) Gebhardt, E., Becker, M., and Schafer, S. (13); (n) Furth, R. (39); (o) Lipman, M.S. (15); (p) Sergueiev and Polyak (10); (q) Navarro, J.M., and Kondic, V. (12); (r) Sato, T., and Munahata, S. (6).

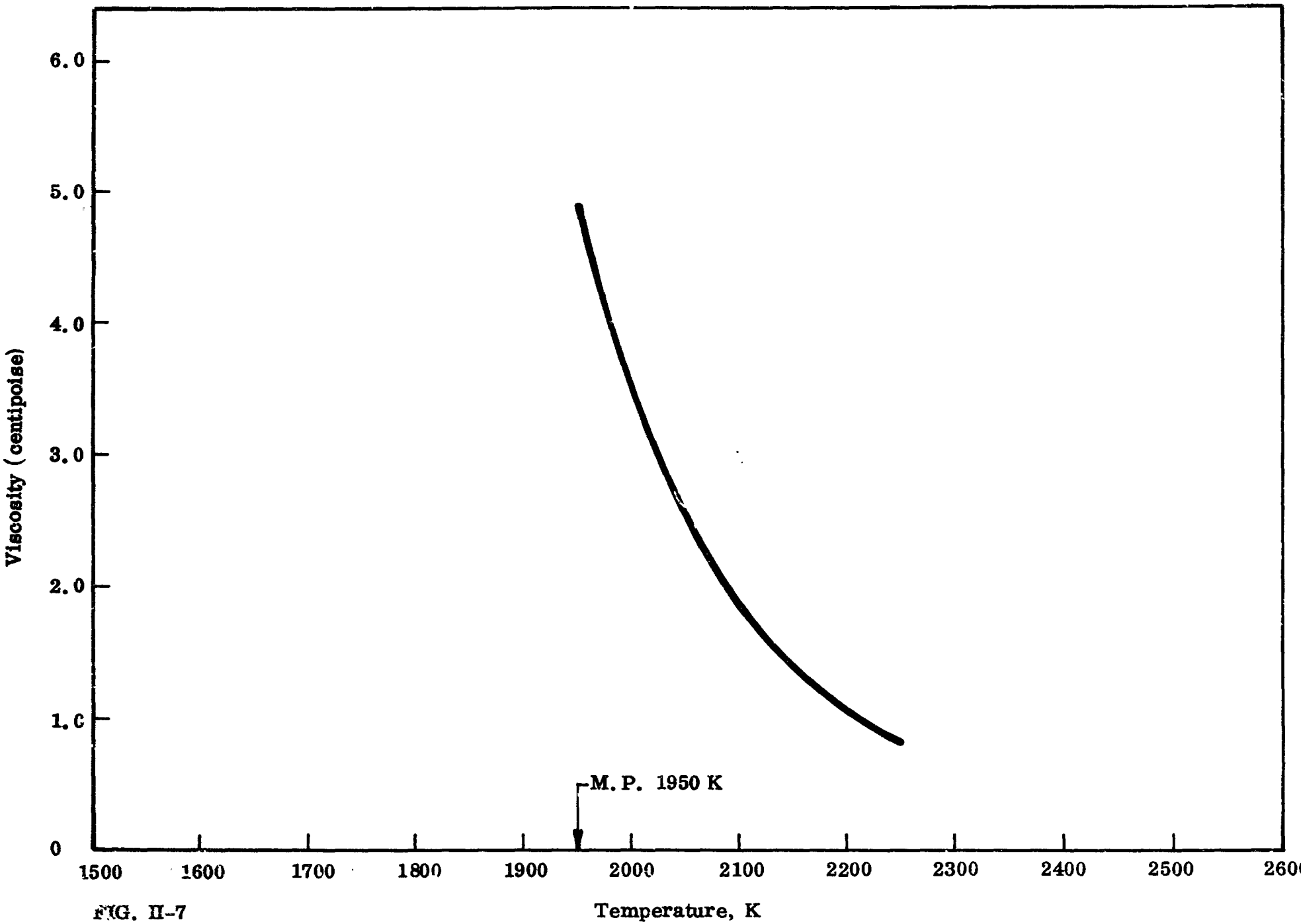

6.0
5.0
4.0
3.0
2.0
1.0
0
Viscosity (centipoise)
M. P. 1950 K
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
Temperature, K

FIG. II-7

TABLE II-7. VISCOSITY OF TITANIUM

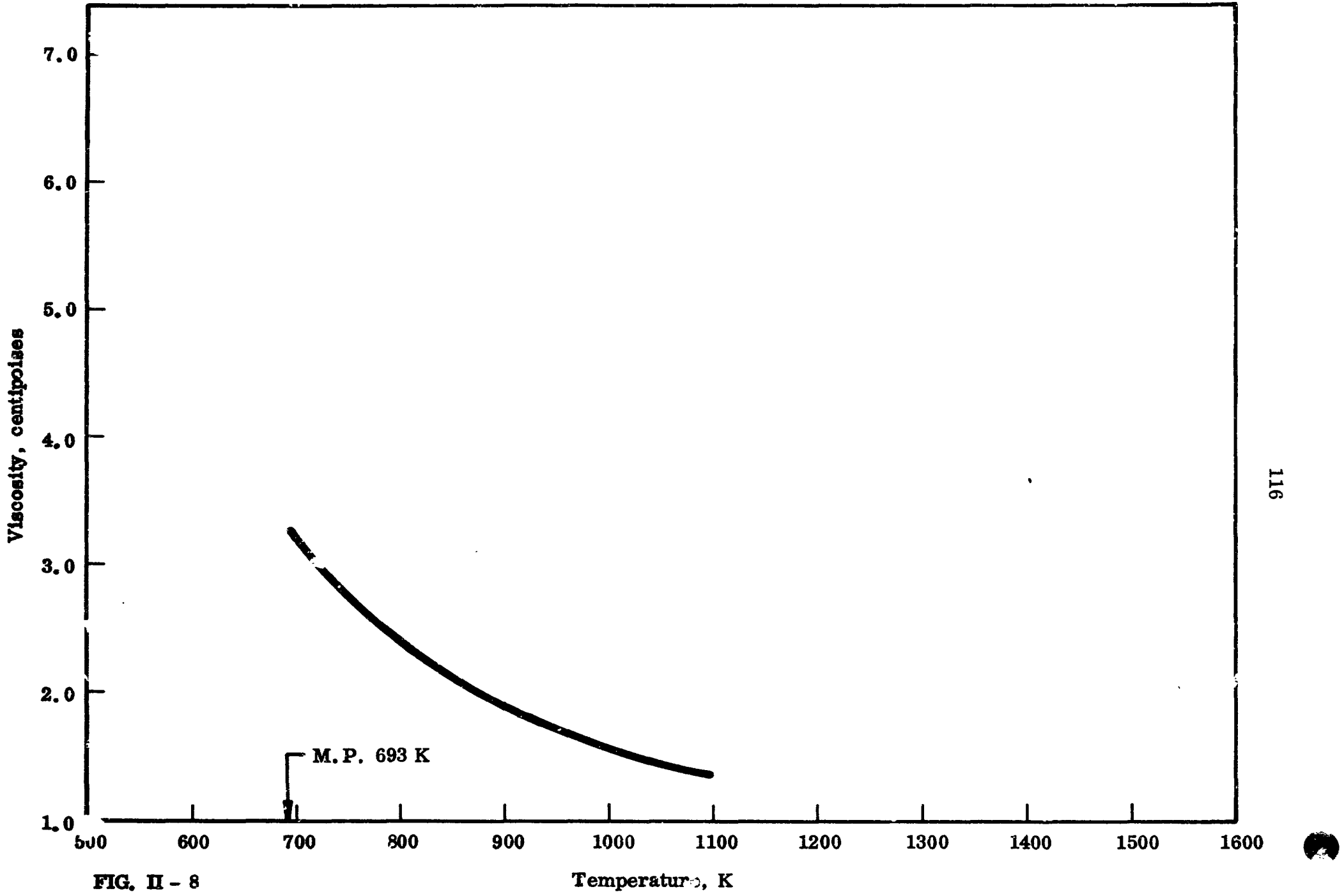
RECOMMENDED VALUES

T(°K)	μ(cp)
1950	4.9
2000	3.5
2050	2.5
2100	1.8
2150	1.4
2200	1.0
2250	0.8

SOURCE OF DATA

Selected Values: (a) Elyutin, V. P., Maurakh, M.A., and Pech'kov, I.A. (52)

Other Values: (b) Grigoriev, G.A., Elyutin, V.P., and Maurakh, M.A. (41)


7.0
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4.0
3.0
2.0
1.0
Viscosity, centipoises
M.P. 693 K
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Temperature, K

FIG. II - 8

TABLE II-8. VISCOSITY OF ZINC

RECOMMENDED VALUES

T(°K)	μ(cp)	T(°K)	μ(cp)
693(m.p.)	3.33	900	1.89
700	3.22	950	1.72
750	2.74	1000	1.57
800	2.39	1050	1.45
850	2.11	1100	1.35

SOURCE OF DATA

Selected Values: (a) Mound Laboratory (42); (b) Korolkov, A.M. (2); (c) Gering, K., and Sauerwald, F. (43); (d) Sato, T., and Munakata, S. (6); (e) Gebhardt, E., and Detering, K. (4); (f) Gebhardt, E., Becker, M., and Dorner (5) (g) Shvidkovskii, E.G. (7).

Other Values: (h) Sato, M. (44); (i) Hopkins, M.R., and Toye, T.C. (45) (j) Yao, T.P., and Kondic, V. (11).

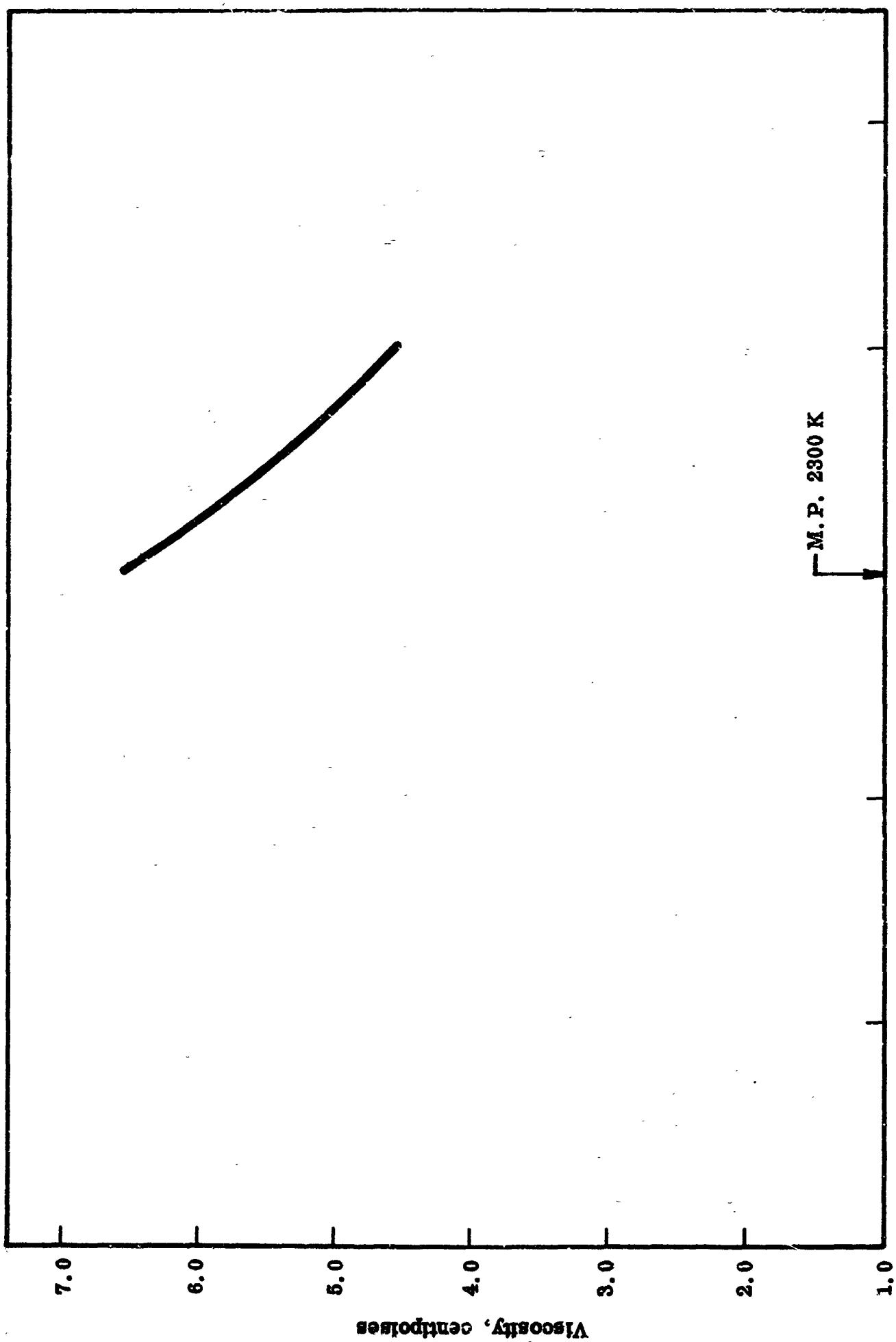
Viscosity, centipoises
7.0
6.0
5.0
4.0
3.0
2.0
1.0
2000
2100
2200
2300
2400
2500
M. P. 2300 K
Temperature, K

FIG. II - 9

TABLE II-9. VISCOSITY OF ALUMINUM OXIDE (Al_2O_3)

RECOMMENDED VALUES

T(°K)	μ(cp)
2309(m.p.)	65.5
2350	54.3
2400	45.4

SOURCE OF DATA

(a) Kozakevitch, P. (46)

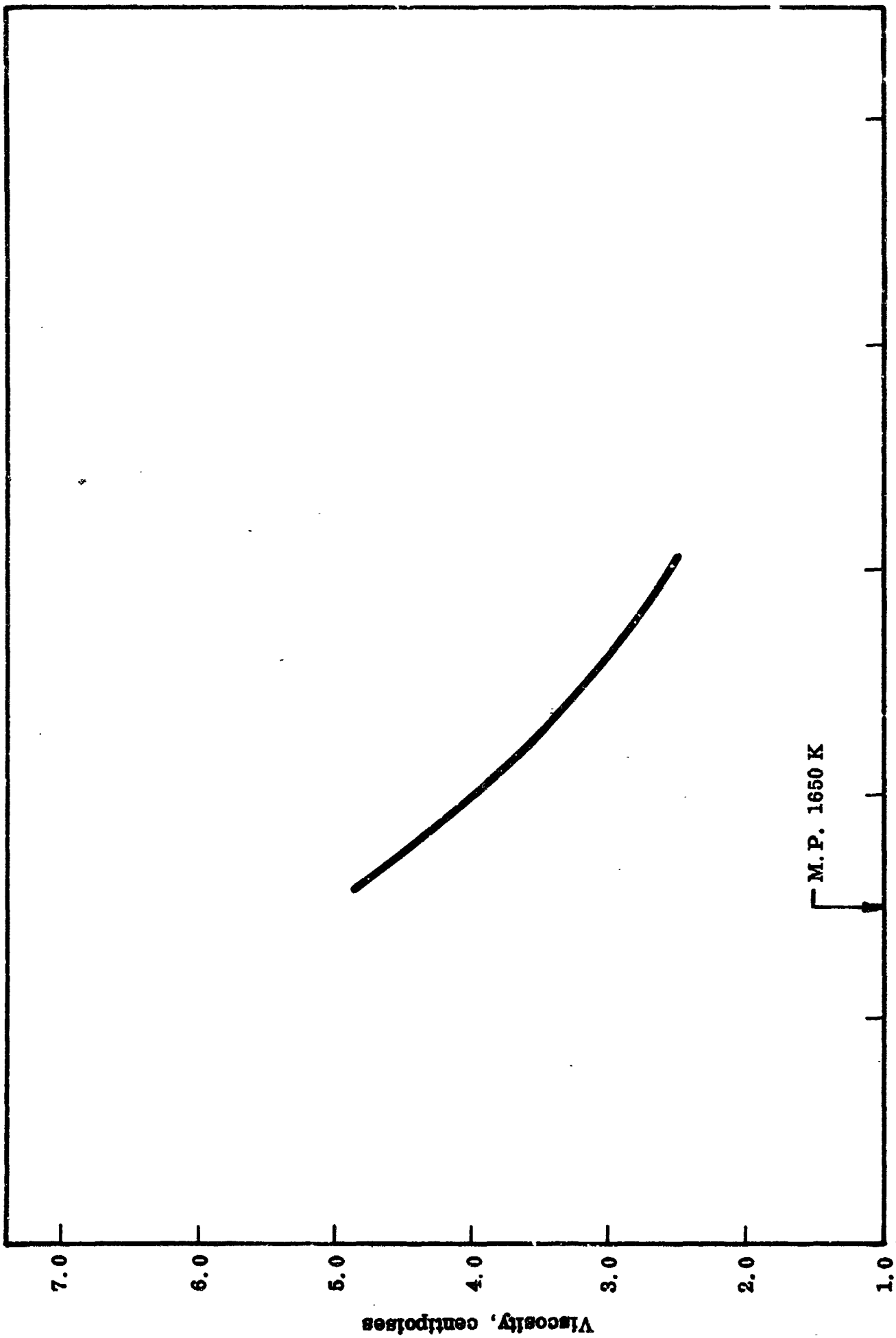
Viscosity, centipoises
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1500
1600
1700
1800
1900
2000
Temperature, K
M.P. 1650 K

FIG. II - 10

TABLE II-10. VISCOSITY OF IRON OXIDE (FeO)

RECOMMENDED VALUES

T(°K)	μ(cp)
1650 (m.p.)	50.4
1700	39.5
1750	31.5
1800	25.3

SOURCE OF DATA

(a) Hermann, S., Frohberg, M.G., and Rohde, W. (47).

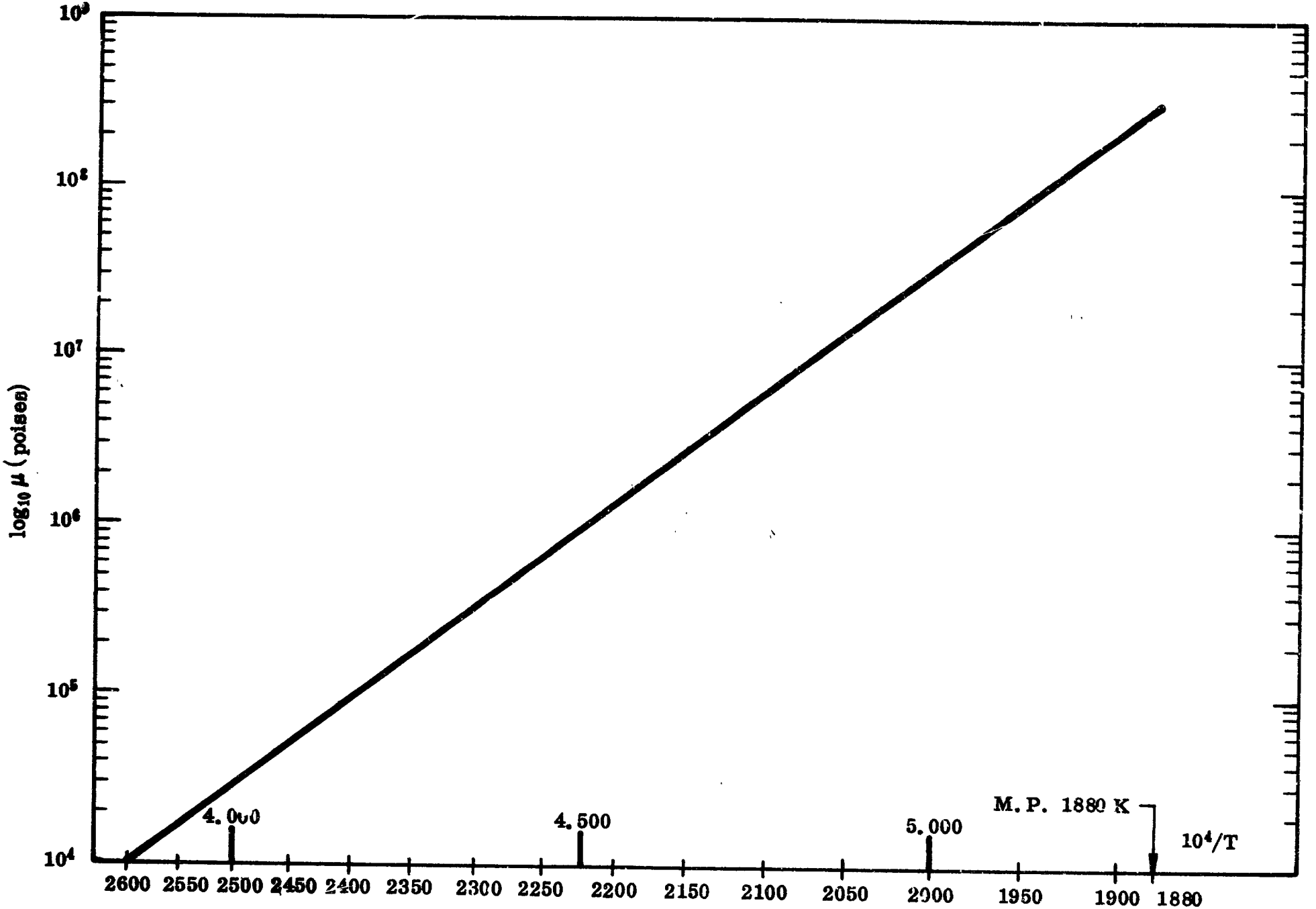
10^9
10^8
10^7
10^6
10^5
10^4
$\log_{10} \mu$ (poises)
4.000
4.500
5.000
M. P. 1880 K
$10^4/T$
2600 2550 2500 2450 2400 2350 2300 2250 2200 2150 2100 2050 2000 1950 1900 1880
Temperature, K

FIG. II-11.

TABLE II-11. VISCOSITY OF SILICON OXIDE (SiO_2)

RECOMMENDED VALUES

T(°K)	μ(poises)	T(°K)	μ(poises)
1880(m.p.)	(3.14×10^8)*	2250	6.68×10^6
1900	(1.98×10^8)	2300	3.38×10^6
1950	(8.21×10^7)	2350	1.77×10^5
2000	3.34×10^7	2400	0.96×10^5
2050	1.42×10^7	2450	5.22×10^4
2100	6.21×10^6	2500	2.95×10^4
2150	2.87×10^6	2550	1.71×10^4
2200	1.36×10^6	2600	1.00×10^4

*figures in parentheses are extrapolated values, outside the experimental range.

SOURCE OF DATA

Selected Values: (a) Hasapis, A.A., Panish, M.B., and Rosen, C. (49); (b) Bacon, J.F., Hasapis, A.A., and Wholley, J.W.,Jr. (50).

Other Values: (c) Bockris, S.D.M., Mackenzie, J.D., and Kitchener, J.A.(48); (d) Solomin, N.V. (51).

REMARKS

The recommended values are from (b) and satisfies the equation

$$\log_{10} \mu = 3.053 \frac{10^4}{T} - 7.7415$$

Values from (c) are 10 times smaller and satisfies the equation

$$\log_{10} \mu = 2.931 \frac{10^4}{T} - 8.2$$

Values from (b) were chosen on ground of lower pick-up from crucible material, better degassing procedure and probable lower water content.

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RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER III
THERMAL EMISSIVITY AND EMITTANCE

BY

D. P. DeWITT
D. G. CHUA
M. E. PARROTT

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CHAPTER III
THERMAL EMISSIVITY AND EMITTANCE

A. INTRODUCTION

The thermal emission properties of a material can be markedly influenced by fabrication technique, surface treatment and the application environment. To add to the complexity, much of the information presently available in the literature is inadequately documented to determine in detail the conditions for which the data are applicable.

The studies on surface characterization - how to uniquely identify the specimen for which data are presented - are among the most critically needed. Until such time that further evidence is amassed either by systematic generation of "critical" data or by correlations of large amounts of data, it will be difficult for the designer to rely on published values to satisfy new applications.

Recent years have seen steady improvement in measurement techniques for higher and lower temperatures; precision of measurements on non-metallic and transparent materials have improved; new experimental devices such as detection systems and pyrometers have been developed and used to advantage. On the other hand, few advances on theoretical models for use as design tools have come forth. Similarly, studies on surface characterization have not been conclusive enought to bring about any break-throughs.

B. APPROACH TO RECOMMENDED VALUES

1. Scope and Definitions

In support of the study presented here - to provide reliable design data - there are few new tools available. The approach to recommended data is through the examination of a large bulk of data, weighed where possible against theoretical prediction. Because of the high sensitivity of the radiative properties to the surface character, and the inability to describe conditions removed from ideality, the significance of recommended or design data must be carefully qualified.

To contain the scope of this study, consideration was given to only hemispherical total emittance, the radiative sub-property of primary importance in determining radiative heat transport. It is important to distinguish between the terms emissivity and emittance. Emissivity is a unique property of a material in its ideal condition - optically smooth surface and homogenous throughout the bulk and sub-surface layers. Emittance is the property of a specimen and cannot be fully identified by specifying the materials but additional characterization of surface roughness, heat treatment, surface contamination, etc., must be considered.

2. Analysis Procedure

This study has addressed itself primarily to providing recommended design data for hemispherical total emissivity. Wherever feasible, emittance data are presented which is indicative of non-ideal conditions that are reasonably reproducible.

For each of the materials considered in this study, comprehensive tables and graphs of available data were examined. Those contributions representative of ideal conditions (emissivity data) were further examined as to the measurement method, environment, and specimen fabrication in an effort to establish a single curve representing the most probable values. For the metals, this curve could be compared with the appropriate theoretical model as described in a following section.

In some instances, there existed little total hemispherical data. In such cases total normal data were considered. Most probable normal data were scrutinized and a recommended curve determined from which hemispherical values were computed by the method described below.

For the oxides, the distinction between normal and hemispherical values is not very great since they are good diffusers. The bulk of literature data is on normal total emittance and no attempt was made to convert to hemispherical values as the difference between them is usually less than the uncertainty in the recommended curve.

Uncertainties in the recommended data were established by an assessment of the concordance of appropriate and compatible data. The magnitude of uncertainties are presented in emittance units rather than percentages.

3. Theoretical Relationships

For the ideal pure metals the hemispherical total emissivity, ϵ_{th}, can be computed with knowledge of the electrical resistivity (ρ) as a function of temperature (T). The Schmidt-Eckert model has been shown to be applicable over a large temperature range even as low as 300 K. The relation‡ is

$$\epsilon_{th} = 0.75(\rho T)^{1/2} - 0.396(\rho T) \qquad 0 < \rho T < 0.2$$

$$\epsilon_{th} = 0.698(\rho T)^{1/2} - 0.266(\rho T) \qquad 0.2 < \rho T < 0.5$$

A similarly styled relation exists for normal total emissivity, ϵ_{tn}; the angular dependency to obtain hemispherical from normal values is through the use of the Fresnell relation. The ratio of $\epsilon_{th}/\epsilon_{tn}$ varies from 1.33 for very small values of ϵ_{tn} to 1.05 as ϵ_{tn} increases. This ratio as a function of ϵ_{tn} is presented graphically in references (45) and (14). The values presented by Eckert and Schmidt in these references have been widely used, but references (10) and (46) have presented evidence that not all metals are in good agreement.

For the alloys, the above models give reasonable results although there is no theoretical basis to justify this approach. Consequently, theoretical predictions using the model for alloys with resistivity data were only used as a coarse indicator during the analysis.

There are no simple models for predicting the emittance of the oxides. However, from experimental results, it is known that the non-metallic materials have a ratio $\epsilon_{th}/\epsilon_{tn}$ which ranges from 1.05 to 0.95 as ϵ_{tn} increases. Further details are presented in references (45) and (14).

In two instances, aluminum oxide and magnesium oxide, it was necessary to use normal spectral data to obtain normal total values. The "100 weighted-ordinate" method described in reference (47) was employed.

4. Utility of the Results

The recommended emissivity data can be obtained in practice only by special care in fabrication of the material and control of the environment. Careful judgement on the part of the user of this information is required to be assured that the data are suitable for use in the many diverse engineering applications

‡In this relation, the units are: ρ, ohm-cm and T, K.

encountered. This situation does not detract seriously from the utility of the study. On the contrary, such data provide design criteria and a basis from which to judge departures caused by real surface effects. The nature of the many conditions which give rise to such effects are not understood, making it very difficult to present generalized guidance to the designer.

C. PRESENTATION OF THE DATA

In subsequent tables and figures, the results of the study are presented in both graphical and tabular form when sufficient data exist.

Where it was possible to arrive at recommended values, the figure shows a heavy curve either solid or dashed. This curve is labeled Recommended Emissivity (1, 2, . . .) where the numbers in parentheses refer to the entries listed in the specification table that follows, giving the sources used to derive the recommended curve. The table also lists the coordinates of the various contributions and the recommended data. The dashed curve implies that the recommendation is less certain as a simple extrapolation or various theoretical techniques were used to estimate the recommended value.

Curves other than the recommended emissivity are represented on the figure indicating conditions typical of various applications, e.g., flame-sprayed, grit-blasted, etc.

Occasionally, a "typical" curve is presented where several independent contributions agree on a non-ideal but well characterized condition. In order to show influences due to real surface effects - flame spraying, grit blasting, oxidation, etc. - original data points are presented. This is not recommended data, but serves only to warn the designer of the large influence the various effects can have on the radiative property.

D. DISCUSSION AND RECOMMENDED DATA ON THE EMISSIVITY OF SELECTED MATERIALS.

1. Elements

The hemispherical total emissivity of the metallic elements is a monotonously increasing function of temperature with a value of zero at absolute zero temperature. There is no evidence that the emissivity changes abruptly or discontinuously due to phase transformation There are no indications of inversions or slope changes at very low temperatures. Consequently, to establish the recommended curve for most of the elements is a fairly straight forward evaluation of available data appropriate to ideal conditions. The Schmidt-Eckert model tends to yield lower values than experimental results, but agreement in many cases is very good. The recommended curve is not extrapolated to very low temperatures without the benefit of experimental evidence. The lack of electrical resistivity data in the higher temperature ranges seriously restricted predictions where they were most needed. As more emissivity and resistivity data are generated, the recommended curves can be established more confidently and over a wider temperature range.

For aluminum, copper, iron, nickel and niobium, the recommended curves are established with confidence over a large temperature range. Beryllium data were somewhat more scarce and the curve for the higher temperature range is presented with less confidence. The chromium curve displays slope changes at lower temperatures. For the 400 to 1100 K region, the curve was established by consideration of normal total data. More data in the entire temperature range is required to establish the recommended curve with any confidence. The curve for tin is established from data at 76 K and follows the temperature dependence as predicted from electrical resistivity data. For titanium, the three significant contributions are widely separated on the temperature scale presenting a difficult situation in establishing recommended values with confidence.

There were insufficient data for the elements magnesium, manganese and zinc to allow analysis toward recommendations. Available literature values are listed in their respective specification tables. No hemispherical total emittance data were uncovered for silicon.

2. Alloys

The general shape of the recommended emissivity curves for alloys is the same as those for the elements. There are less data available for analysis considerations and the theoretical model is not directly applicable. These are the two main factors which give rise to difficulty in establishing recommended curves.

For aluminum alloy 6061-T6 and Inconel X-750 there were sufficient data, but somewhat temperature restricted, to directly prescribe recommended hemispherical total emissivity values. The Inconel recommended curve is inferred from available data but is indicated lower than previous measurements on the strength of theoretical predictions. However, for aluminum alloy 7075-T6 and stainless steel 347, it was necessary to analyze normal total data from which hemispherical total recommended values were calculated as described above. The figures for this normal total data are presented as well as the hemispherical total recommendations. There were insufficient data for the beryllium alloy and titanium alloy A-110AT to allow analyses so that available literature data are presented as extracted from the original sources. No data for aluminum alloy 2219-T852 were located.

3. Oxides

Analysis of data on the oxides is limited by the lack of theoretical models, paucity of data, and lack of understanding of specimen characterization. Grain size, porosity, sintering temperature, and even specimen thickness can markedly influence the measurements. Measurement techniques are not as highly refined as for metallic materials, another factor which causes low quality data available to the analyst.

For the non-metallic materials, especially the oxides, it is simpler to measure normal total data than hemispherical total emittance. Since the oxides are very good diffusers, there is little loss of accuracy in using the two sub-properties interchangeably as suggested above. For aluminum oxide and magnesium oxide there is an abundance of emittance data that were considered in the analysis. In establishing a recommended curve, reliance was given to the NBS data (34) which represents careful measurements on well characterized specimens.

To use these data, one must be careful to have a specimen within the proper porosity limits and grain size. The figure for beryllium oxide presents a typical curve for white colored specimens and two unrelated curves for the black colored. With present information, it is not apparent what shape the black colored typical curve would have. Silicon dioxide data allow establishing a recommended curve with an indication of large grain size influence. Only one contribution for titanium dioxide was uncovered, and this was for the flame sprayed condition.

Literature values as directly extracted from original sources for the remaining oxides are presented in a composit table. From the meager evidence available, it was not possible to construct recommended curves.

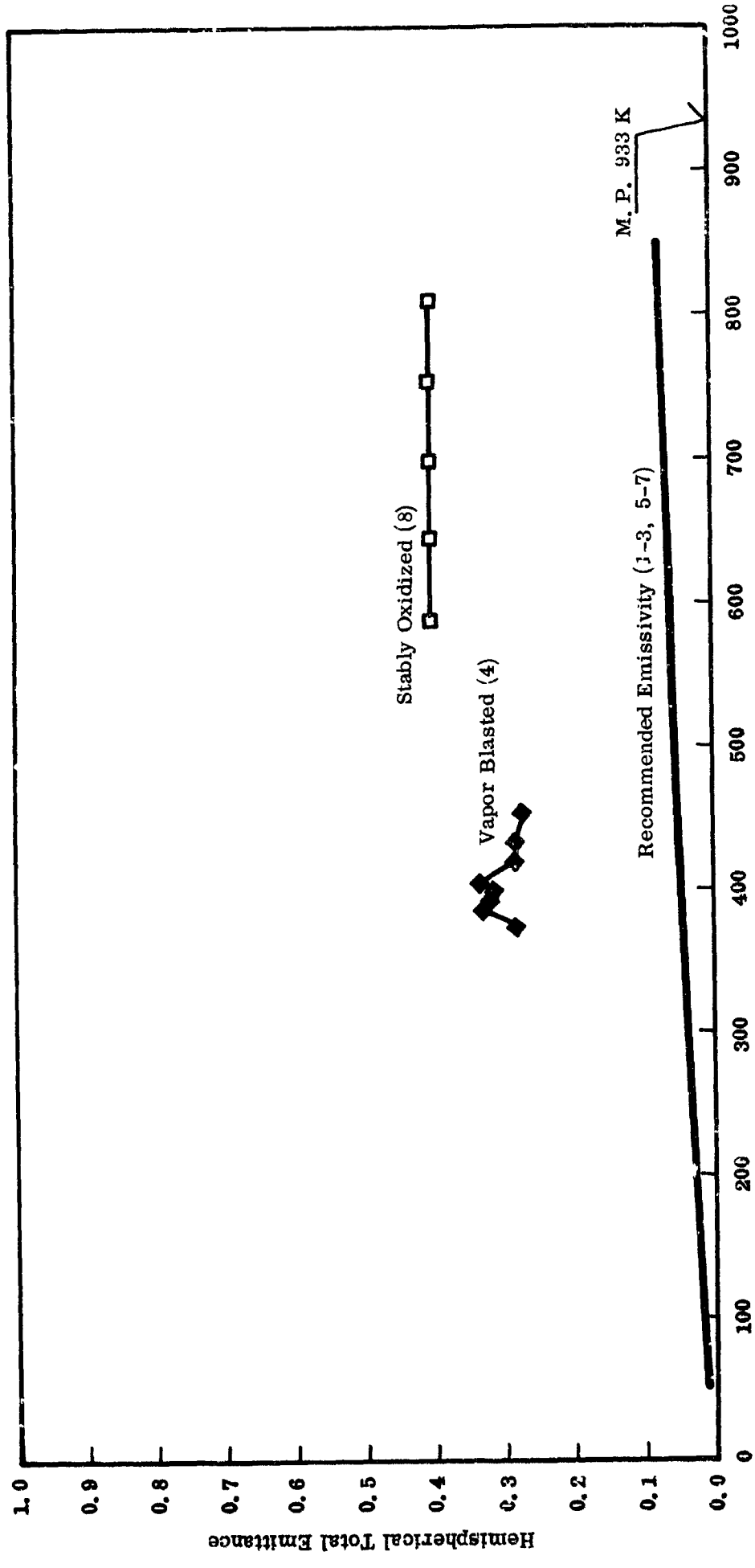

FIG. III-1 HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM

TABLE III-1A HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM

SPECIFICATION TABLE

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	1	76	5	Alcoa No. 2 reflector plate; 0.02 in. thick; emittance for 300 K black body radiation; measured in vacuum, 10^{-6} to 10^{-7} torr.
2*	1	76	5	Same as above; unannealed Kaiser foil; 0.001 in. thickness.
3*	2	227-281	±3	Polished; measured in vacuum.
4	3	375-453	±3	Vapor (alumina suspended in water) blasted for 2 min; measured in vacuum.
5*	3	384-466	±3	Polished by fine abrasive papers and polishing compounds; measured in vacuum.
6*	4	423-623	≤5	Polished mechanically using metallographic procedures; annealed; measured in vacuum.
7*	5	573-873		99.6% purity; computed from spectral reflectance measurements.
8	6	589-811	≤4	AA3003; polished, stably oxidized at 810 K for 30 min; diffuse emitter.

* Not shown on figure

TABLE III-1B HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM DATA TABLE

T (K)	ϵ
RECOMMENDED EMISSIVITY	
50	0.01 ±0.02
100	0.02
200	0.03
300	0.04
400	0.045
500	0.055
600	0.06
700	0.06
800	0.07
850	0.075
CURVE 1*	
76	0.026
CURVE 2*	
76	0.018
CURVE 3*	
281	0.07
266	0.07
260	0.07
252	0.07
244	0.07
234	0.07
227	0.07

T (K)	ϵ
CURVE 4	
375	0.20
385	0.33
393	0.32
398	0.31
403	0.33
419	0.28
433	0.28
453	0.27
CURVE 5	
384	0.17
395	0.18
409	0.18
420	0.18
428	0.17
440	0.17
452	0.16
466	0.15

T (K)	ϵ
CURVE 6*	
423	0.050
473	0.053
523	0.055
573	0.058
623	0.059
CURVE 7*	
573	0.102
673	0.115
773	0.130
873	0.113
CURVE 8	
588.72	0.40
644.27	0.40
699.83	0.40
755.38	0.40
810.94	0.40

*Not shown on figure.

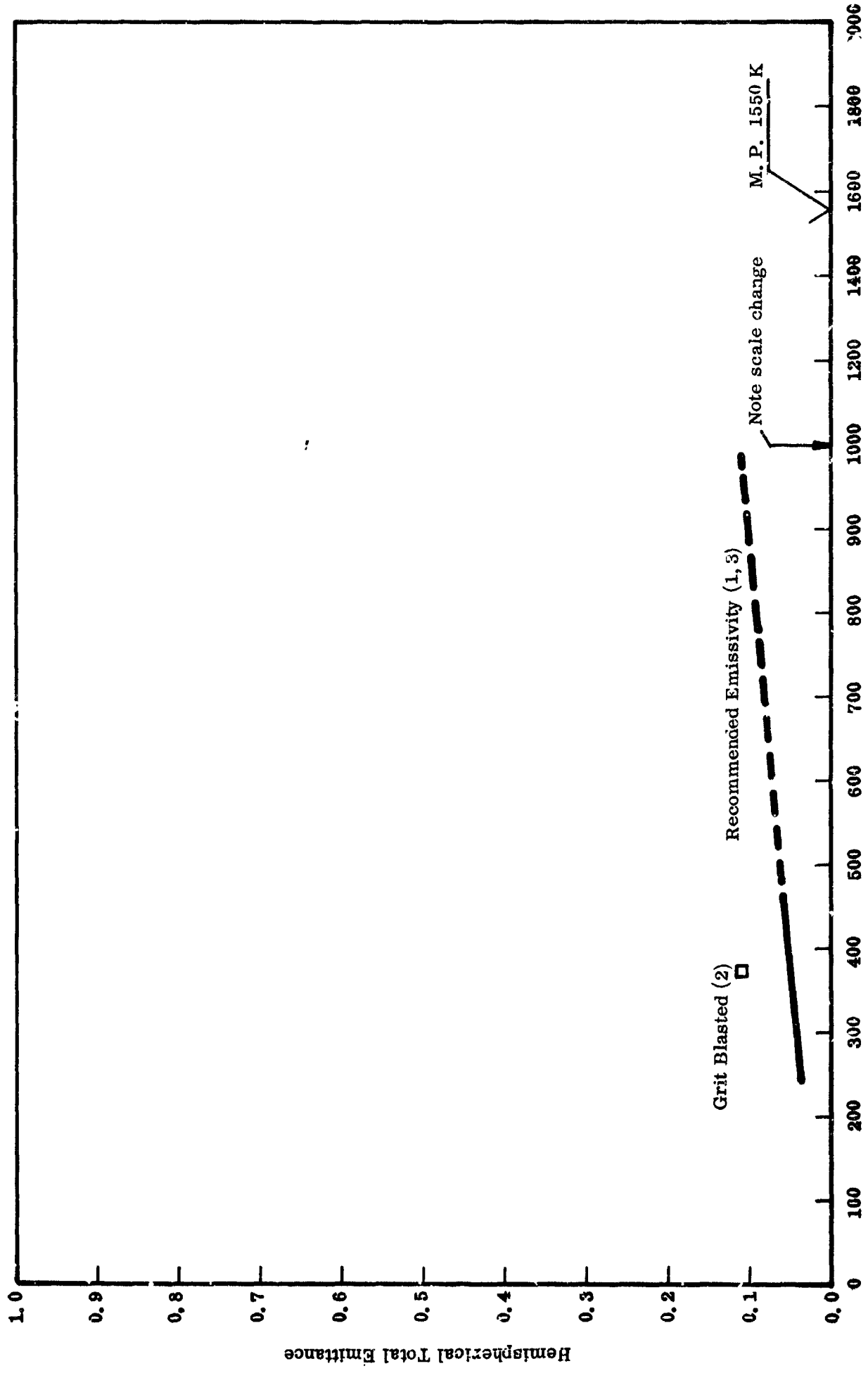

FIG. III-2 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM

TABLE III-2 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	7	277.2	~(0.05)	Chemically and mechanically polished; computed from spectral reflectance measurements.
2	8	373		Grit blasted; computed from spectral reflectance measurements.
3*	8	373		Polished; computed from spectral reflectance measurements.

RECOMMENDED EMISSIVITY

T (K)	ϵ
250	0.04 ±0.02
300	0.045
400	0.055
450	0.06
500	(0.065)
600	(0.075)
700	(0.08)
800	(0.09)
900	(0.10)
1000	(0.12)

CURVE 1*

T (K)	ϵ
277.2	0.063

CURVE 2

T (K)	ϵ
373	0.11

CURVE 3*

T (K)	ϵ
373	0.04

*Not shown on figure

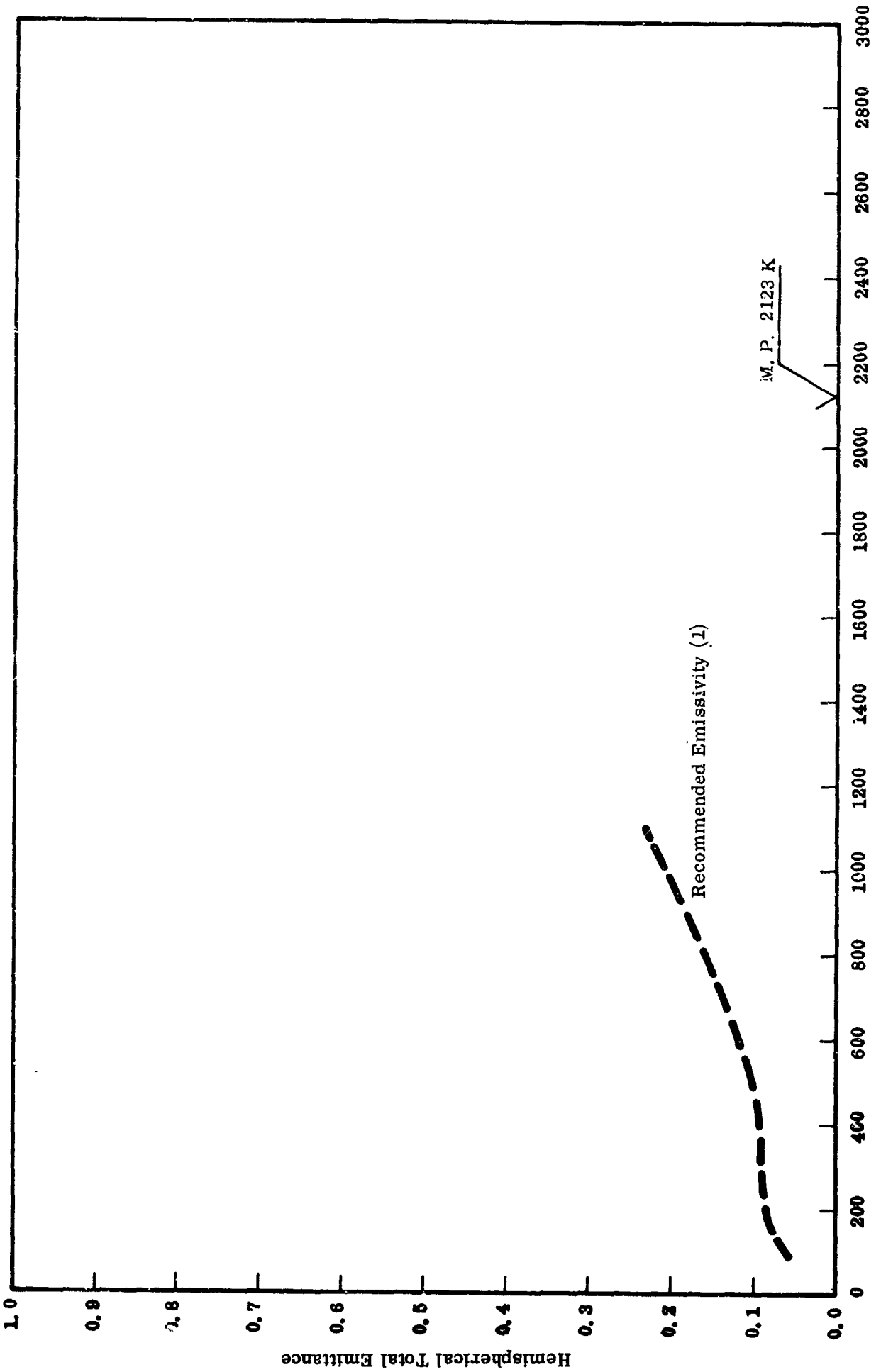

FIG. III-3 HEMISPHERICAL TOTAL EMITTANCE -- CHROMIUM

TABLE III-3 HEMISPHERICAL TOTAL EMITTANCE -- CHROMIUM
SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	1	76	5	Plated on copper; emittance for 300 K black body radiation; measured in vacuum, 10^{-6} to 10^{-7} torr.

RECOMMENDED EMISSIVITY

T (K)	ϵ
100	(0.07) ± 0.02
200	(0.085)
300	(0.09)
400	(0.09)
500	(0.10)
600	(0.12)
700	(0.135)
800	(0.16)
900	(0.18)
1000	(0.22)

CURVE 1*

T (K)	ϵ
76	0.08

*Not shown on figure

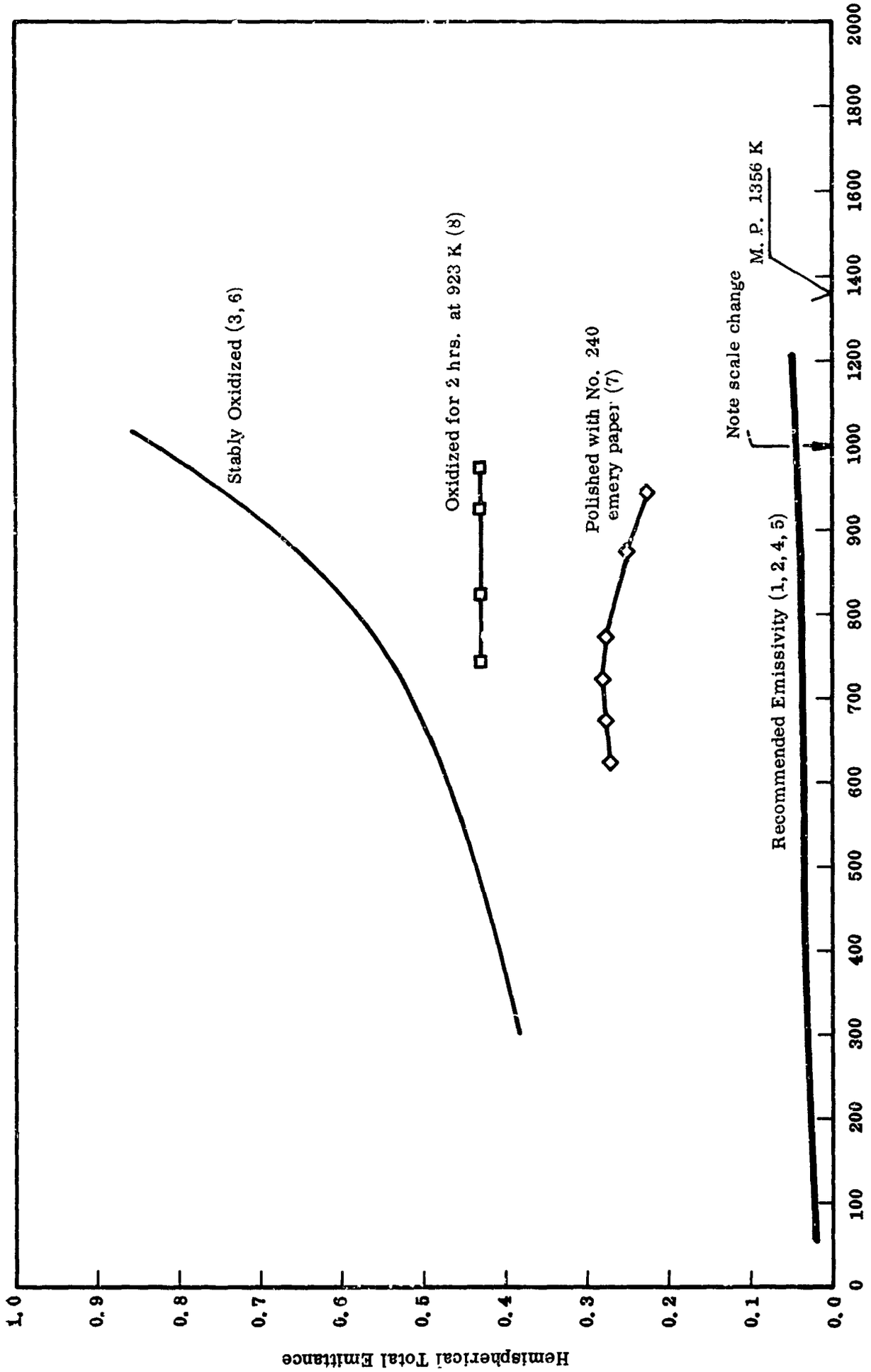

FIG. III-4 HEMISPHERICAL TOTAL EMITTANCE -- COPPER

TABLE III-4A HEMISPHERICAL TOTAL EMITTANCE -- COPPER

SPECIFICATION TABLE

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	1	76	±5	Sheet, 0.005 in. thickness; annealed and cleaned; emittance for 300 K black body radiation; measured in vacuum.
2*	1	76	±5	Same as above; polished.
3*	9	300		Oxidized and corroded.
4*	10	323-1173		Polished; cycled to 1173 K in vacuum several times.
5*	4	373-623	≤5	Polished mechanically; annealed; measured in vacuum.
6*	6	589-1033	≤2	Stably oxidized in quiescent air at 1033 K.
7	11	623-943		Polished with No. 240 grit emery paper; measured in vacuum.
8	11	743-973		Oxidized in air for 2 hrs at 923 K; measured in vacuum.

*Not shown on figure

TABLE III-4B HEMISPHERICAL TOTAL EMITTANCE -- COPPER DATA TABLE

T (K)	ϵ
RECOMMENDED EMISSIVITY	
50	0.02 ±0.01
100	0.025
200	0.03
300	0.03
400	0.035
500	0.035
600	0.04
700	0.04
800	0.04
900	0.04 ±0.02
1000	0.04
1100	0.045
1200	0.045

T (K)	ϵ
CURVE 1*	
76	0.015
CURVE 2*	
76	0.03
CURVE 3*	
300	0.38
CURVE 4*	
323	0.040
473	0.035
673	0.036
873	0.038
1073	0.045
1173	0.050
CURVE 5*	
373	0.030
423	0.030
473	0.031
523	0.031
573	0.032
623	0.032

T (K)	ϵ
CURVE 6*	
588.7	0.495
644.3	0.500
699.8	0.525
755.4	0.545
810.9	0.595
866.5	0.640
922.0	0.710
1033.2	0.855
CURVE 7	
623	0.200
673	0.275
723	0.280
773	0.275
873	0.250
943	0.225
CURVE 8	
743	0.43
823	0.43
923	0.43
973	0.43

*Not shown on figure

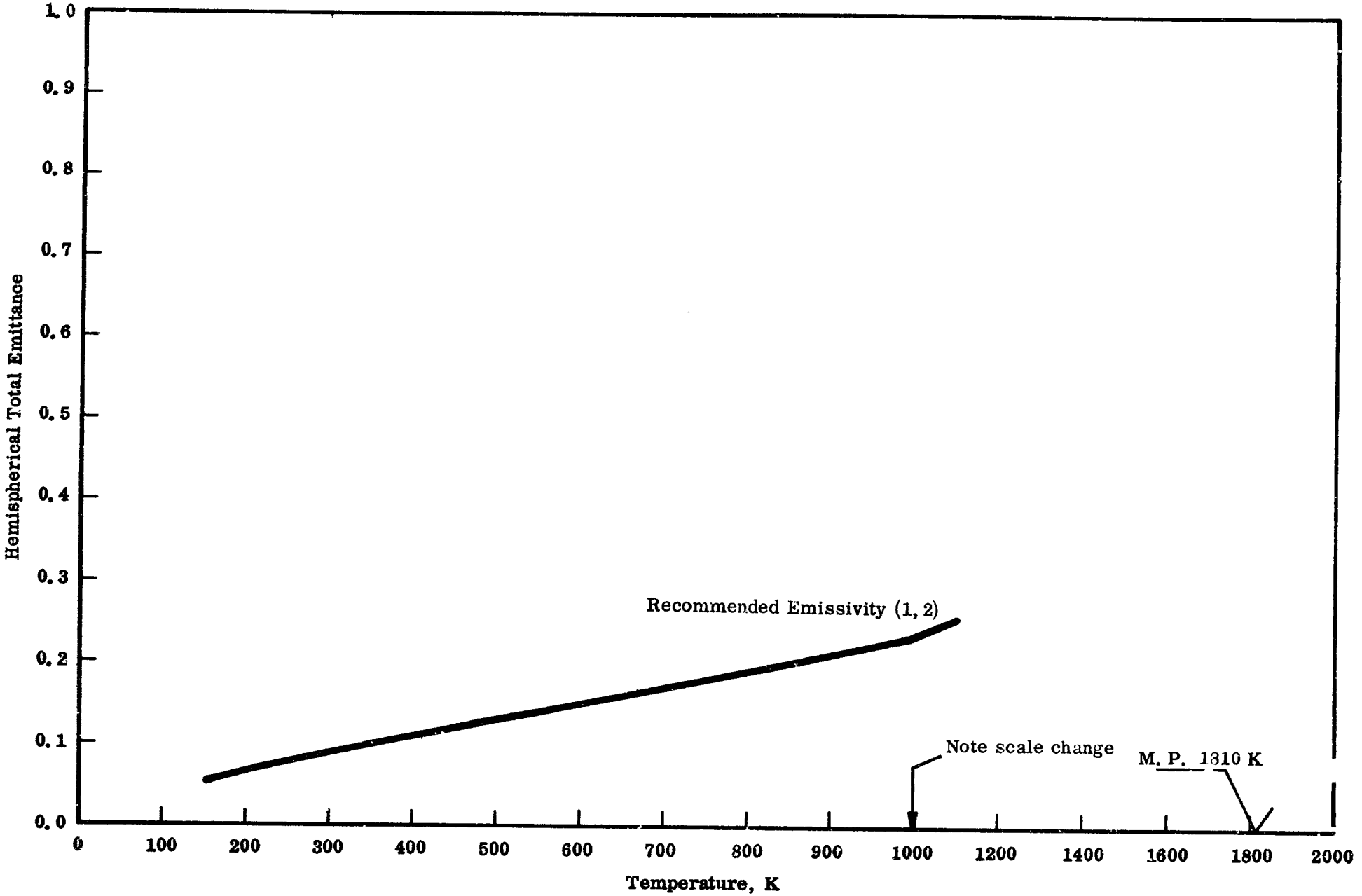

FIG. III-5 HEMISPHERICAL TOTAL EMITTANCE -- IRON

TABLE III-5 HEMISPHERICAL TOTAL EMITTANCE -- IRON
SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	12	168-278	±0.01	Pure, polished; averaged values.
2*	13	468-1093	10%	99.821% purity; Armco iron; ground and polished; measured in vacuum, 10^{-5} torr.

T (K)	∈
RECOMMENDED EMISSIVITY	
150	0.05 ±0.01
200	0.065
300	0.09
400	0.11
500	0.13
600	0.15 ±0.02
700	0.17
800	0.19
900	0.21
1000	0.235
1100	0.255

T (K)	∈
CURVE 1*	
167	0.056
195	0.064
222	0.071
250	0.079
278	0.086
CURVE 2*	
468	0.130
668	0.160
873	0.205
1093	0.255

*Not shown on figure

TABLE III-6 HEMISPHERICAL TOTAL EMITTANCE -- MAGNESIUM SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	3	415-483	±3	Hand polished using fine abrasive papers followed by application of a metal polish; measured in vacuum, 10^{-3} torr.
2*	3	355-478	±3	Hand polished, then vapor blasted; measured in vacuum, 10^{-3} torr.

CURVE 1*

T (K)	ϵ
415	0.12
426	0.13
435	0.12
453	0.12
463	0.12
473	0.12
483	0.12

CURVE 2*

T (K)	ϵ
355	0.31
373	0.31
401	0.33
418	0.31
433	0.31
453	0.30
473	0.28
478	0.27

* No figure presented

TABLE III-7 HEMISPHERICAL TOTAL EMITTANCE -- MANGANESE SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	14	391.9	0.7	Rolled sheet metal; smooth surface.

T (K)	ϵ
CURVE 1*	
391.9	0.0480

*No figure presented

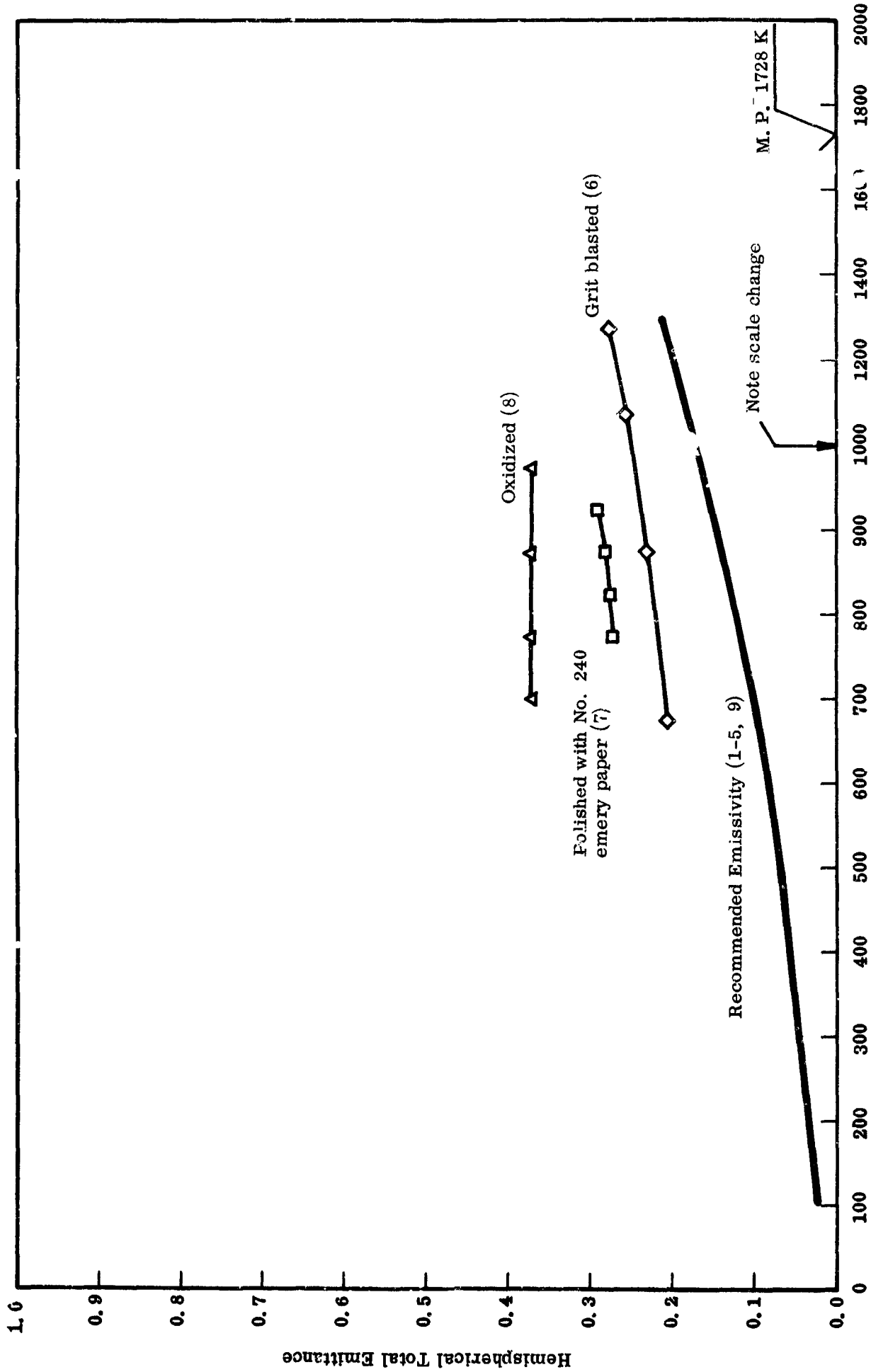

FIG. II-6 HEMISPHERICAL TOTAL EMITTANCE -- NICKEL

TABLE III--8A HEMISPHERICAL TOTAL EMITTANCE -- NICKEL
SPECIFICATION TABLE

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	1	76	5%	Foil, 0.004 in. thickness; cleaned with solvent; emittance for 300 K black body radiation; measured in vacuum, 10^{-6} to 10^{-7} torr.
2*	14	373.5	±0.7%	Plating; polished.
3*	14	373.6	±0.7%	Plating; dull, unpolished.
4*	13	463-1093	< 10%	Ground with 600 grit carborondum; polished with alumina; measured in vacuum, 10^{-5} torr.
5*	15	673-1273	± 2.5%	98.5% purity; bright commercial nickel sheet; vacuum baked for 15 min at 1473 K; measured in vacuum, $< 5. 10^{-6}$ torr.
6	15	673-1273	± 2.5%	Grit blasted sheet; measured in vacuum, $< 5. 10^{-6}$ torr.
7	11	773-923		Polished with No. 240 grit emery paper; measured in vacuum.
8	11	698-973		Same specimen as above; oxidized in air at 923 K for 2 hrs; measured in vacuum.
9*	16	973-1273	± 0.01	Grade A, polished; average of four specimens, measured in vacuum.

*Not shown on figure

TABLE 4I-8B HEMISPHERICAL TOTAL EMITTANCE -- NICKEL

DATA TABLE

T (K)	ϵ
RECOMMENDED EMISSIVITY	
100	0.02 ±0.01
200	0.035
300	0.045
400	0.055
500	0.07 ±0.02
600	0.08
700	0.10
800	0.125
900	0.15
1000	0.17
1100	0.185
1200	0.20
1300	0.21
CURVE 1*	
76	0.022
CURVE 2*	
373.5	0.0532
CURVE 3*	
373.6	0.0463
CURVE 4*	
463	0.10
663	0.12
873	0.13
1093	0.175
CURVE 5*	
673	0.090
723	0.110
813	0.135
973	0.166
1133	0.200
1273	0.233
CURVE 6	
673	0.204
873	0.230
1073	0.254
1273	0.275
CURVE 7	
773	0.270
823	0.275
873	0.280
923	0.290
CURVE 8	
698	0.37
773	0.37
873	0.37
973	0.37
CURVE 9*	
973	0.168
1023	0.171
1073	0.175
1123	0.178
1173	0.181
1223	0.185
1273	0.188

*Not shown on figure

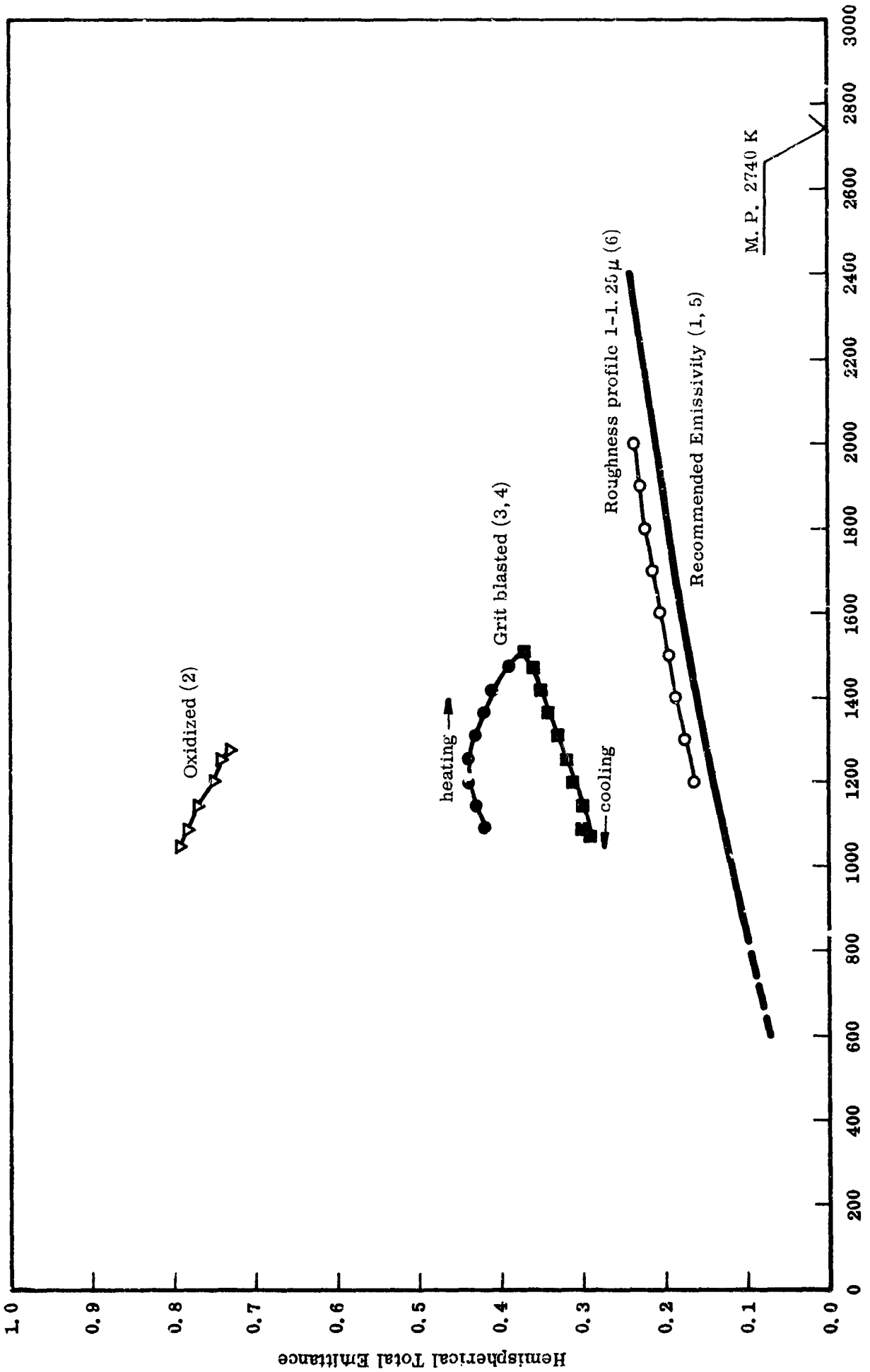

FIG. III-7 HEMISPHERICAL TOTAL EMITTANCE -- NIOBIUM

TABLE III-9A HEMISPHERICAL TOTAL EMITTANCE -- NIOBIUM SPECIFICATION TABLE

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	17	1009-2380		Polished; measured in vacuum.
2	18	1049.8-1266.5		Oxidized in air 5 mins at 922 K; powder oxide, Cb_2O_5, removed by brush to leave black CbO; measured in vacuum.
3	18	1505.4-1072.0		Grit blasted with G-25 grit; data taken during cooling, measured in vacuum.
4	18	1088.7-1505.4		Same as above; data taken during heating.
5*	19	1200-2000	< 1.9	Composition: Nb = 99.26%, Ta = 0.5%, Ti = 0.026%, Fe = 0.06%, Si = 0.03%; mean arithmetical profile, 0.02-0.025 μ; height of irregularities, 0.1-0.125 μ; measured in vacuum.
6	19	1200-2000	< 1.9	Same composition as above; mean arithmetical profile, 1-1.25 μ; height of irregularities 5-6.3 μ; measured in vacuum.

*Not shown on figure

TABLE III-9B HEMISPHERICAL TOTAL EMITTANCE -- NIOBIUM
DATA TABLE

T (K)	ϵ
RECOMMENDED EMISSIVITY	
600	(0.07) ±0.01
800	0.095
1000	0.12
1200	0.14
1400	0.16
1600	0.18 ±0.02
1800	0.195
2000	0.21
2200	0.225
2400	0.24
CURVE 1*	
1009	0.114
1132	0.129
1234	0.143
1322	0.153
1410	0.165
1480	0.176
1560	0.184
1652	0.194
1763	0.205
1860	0.218
1952	0.229

T (K)	ϵ
CURVE 1 (cont.)	
2040	0.242
2142	0.244
2234	0.248
2318	0.252
2380	0.259
CURVE 2	
1049.8	0.74
1088.7	0.73
1144.3	0.72
1199.8	0.70
1255.4	0.69
1266.5	0.68
CURVE 3	
1505.4	0.37
1477.6	0.36
1422.0	0.35
1366.5	0.34
1310.9	0.33
1255.4	0.32
1199.8	0.31
1144.3	0.30
1088.7	0.30
1272.0	0.29

T (K)	ϵ
CURVE 4	
1088.7	0.42
1144.3	0.43
1199.8	0.44
1255.4	0.44
1310.9	0.43
1366.5	0.42
1422.0	0.41
1477.6	0.39*
1505.4	0.37*
CURVE 5*	
1200	0.140
1300	0.151
1400	0.161
1500	0.171
1600	0.180
1700	0.188
1800	0.196
1900	0.203
2000	0.209

T (K)	ϵ
CURVE 6	
1200	0.163
1300	0.175
1400	0.186
1500	0.196
1600	0.205
1700	0.213
1800	0.221
1900	0.228
2000	0.236

*Not shown on figure

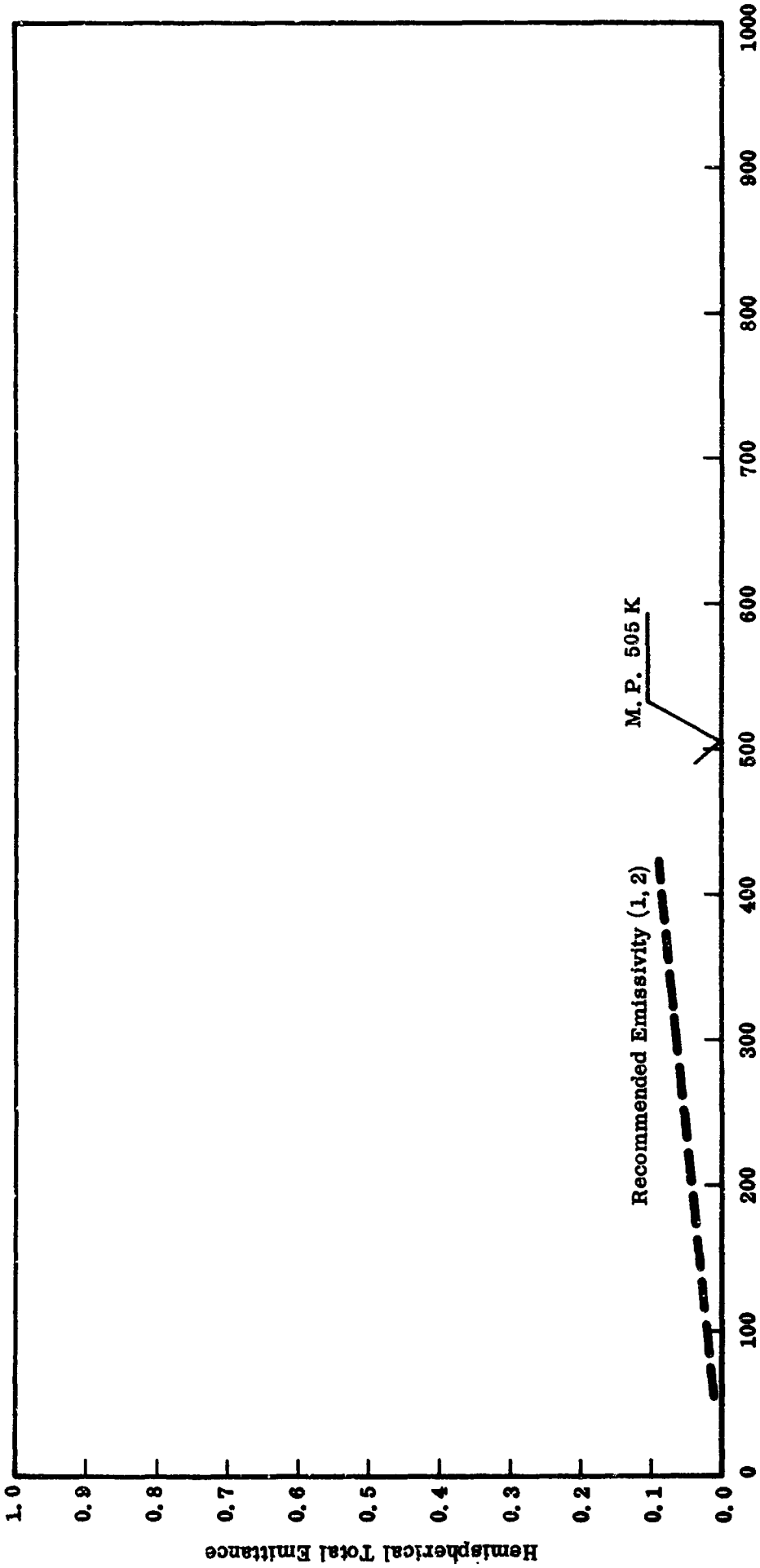

FIG. III-8 HEMISPHERICAL TOTAL EMITTANCE -- TIN

TABLE III-10 HEMISPHERICAL TOTAL EMITTANCE -- TIN

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error %	Specimen Characterization and Remarks
1*	1	76	5	Foil, 0.001 in. thickness; cleaned; emittance for 300 K black body radiation; measured in vacuum, 10^{-6} to 10^{-7} torr.
2*	1	76	5	Same conditions as above; tinned copper.

T (K)	∈
RECOMMENDED EMISSIVITY	
50	(0.01) ±0.02
100	(0.02)
200	(0.04)
300	(0.06)
400	(0.08)

T (K)	∈
CURVE 1*	
76	0.013
CURVE 2*	
76	0.02

*Not shown on figure

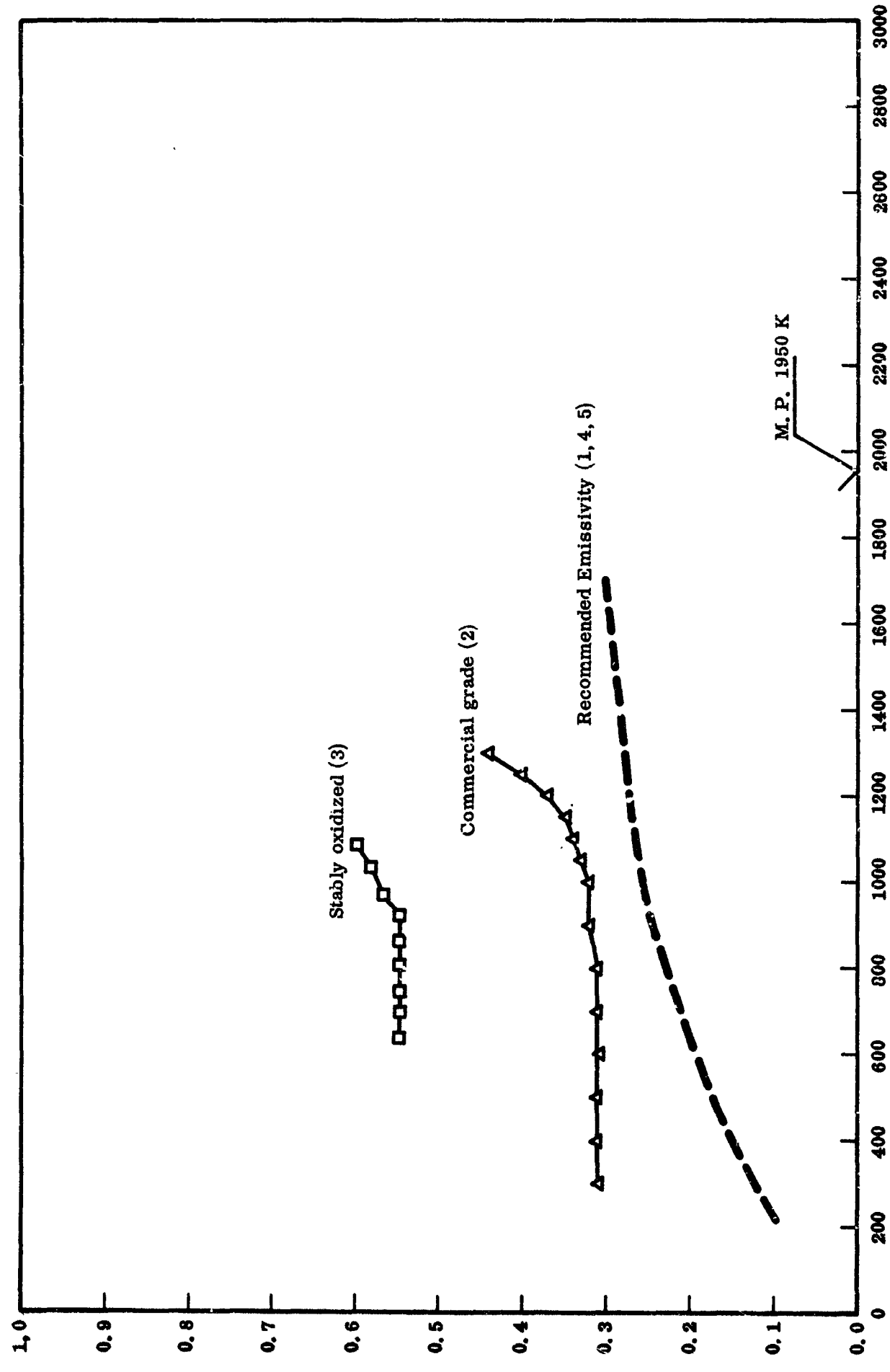

FIG. III-9 HEMISPHERICAL TOTAL EMITTANCE -- TITANIUM

TABLE III-11 HEMISPHERICAL TOTAL EMITTANCE -- TITANIUM SPECIFICATION AND DATA TABLES

Curve No	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	2	241-279	± 3	Pure; measured in vacuum.
2	20	300-1300	±10	Commercial grade; measured in vacuum, 1×10^{-6} torr.
3	6	644-1089	≤ 4	TMCA Ti - 75 A; oxidized in quiescent air at 1089 K; stably oxidized condition; diffuse emitter.
4*	21	891.2	8	Highly polished; measured in vacuum, 1×10^{-5} torr.
5*	22	1700		Pure; measured in vacuum.

RECOMMENDED EMISSIVITY

T (K)	ϵ
200	(0.09) ±0.02
400	(0.15)
600	(0.19)
800	(0.225)
1000	(0.255)
1200	(0.27)
1400	(0.28)
1600	(0.295)
1700	(0.30)

CURVE 1*

T (K)	ϵ
279	0.13
274	0.10
267	0.10
262	0.10
256	0.11
252	0.11
247	0.11
241	0.12

CURVE 2

T (K)	ϵ
300	0.31
400	0.31
500	0.31
600	0.31
700	0.31
800	0.31
900	0.32
1000	0.32
1050	0.33
1100	0.34
1150	0.35
1200	0.37
1250	0.40
1300	0.44

CURVE 3

T (K)	ϵ
644	0.545
700	0.545
755	0.545
811	0.545
866	0.545
922	0.545
978	0.565
1033	0.580
1089	0.595

CURVE 4*

T (K)	ϵ
891.2	0.241

CURVE 5*

T (K)	ϵ
1700	0.30

*Not shown on figure

TABLE III-12 HEMISPHERICAL TOTAL EMITTANCE -- ZINC
SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	1	76	5	Foil, 0.0065 in. thickness; solvent cleaned; emittance for 300 K black body radiation; measured in vacuum, 10^{-6} to 10^{-7} torr.

T (K)	ϵ
CURVE 1*	
76	0.02

*No figure presented

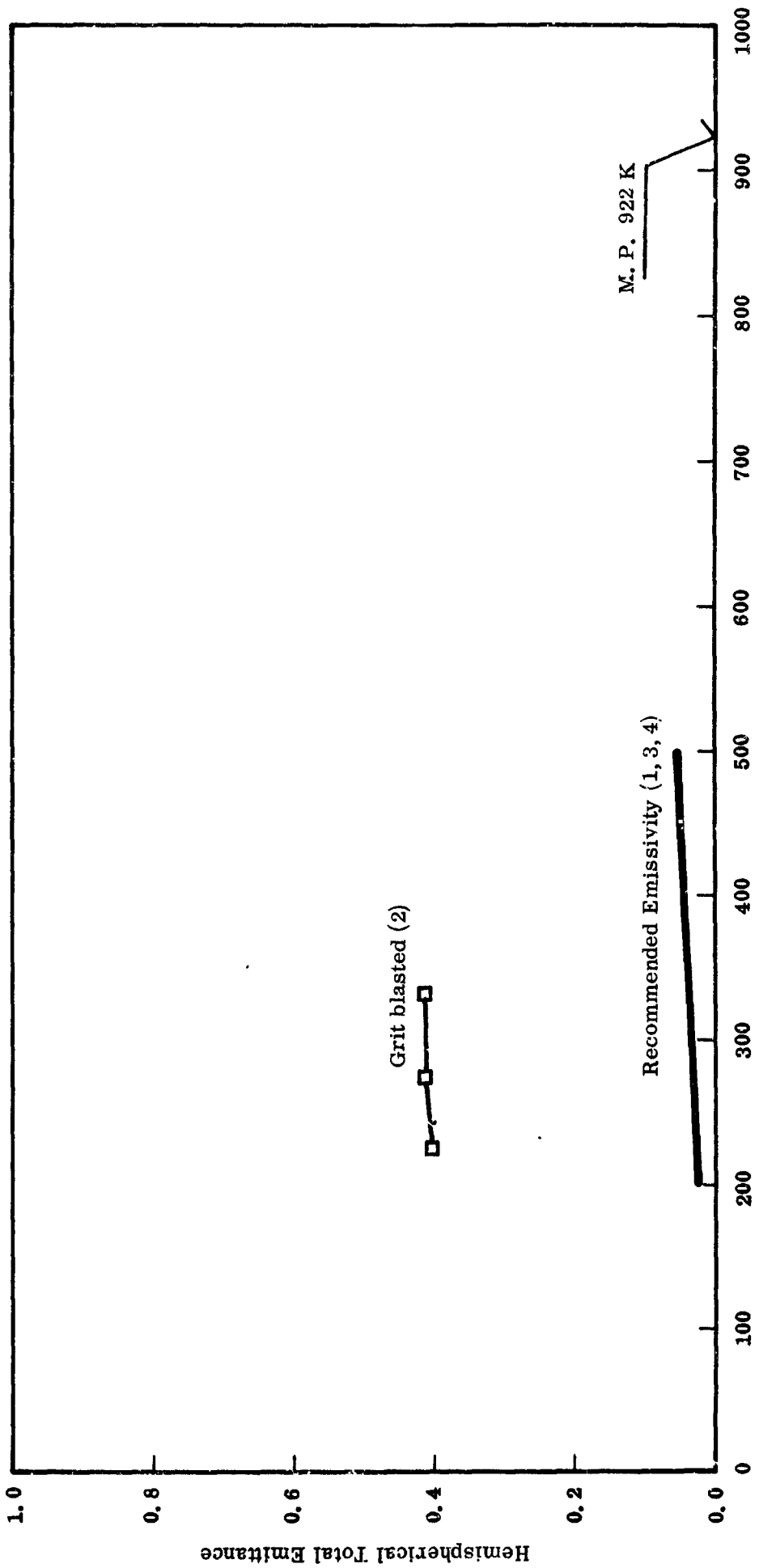

FIG. III-10 HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 6061-T6

TABLE III-13 HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 6061-T6

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	22	222-333	±0.04	Mechanically polished and degreased, representative values; computed from spectral reflectance measurements.
2	22	222-333	±0.04	Same as above; grit blasted, 120-size grit.
3*	22	222-333	±0.06	Same as above; chemically cleaned; rolled alloy.
4*	22	222-333	±0.06	Same as above; forged alloy.

T (K)	ϵ

RECOMMENDED EMISSIVITY

200	0.025 ±0.02
300	0.035
400	0.04
500	0.05

CURVE 1*

222	0.04
278	0.04
333	0.05

T (K)	ϵ

CURVE 2

222	0.40
278	0.41
333	0.41

CURVE 3*

222	0.06
278	0.06
333	0.07

CURVE 4*

222	0.09
278	0.09
333	0.10

*Not shown on figure

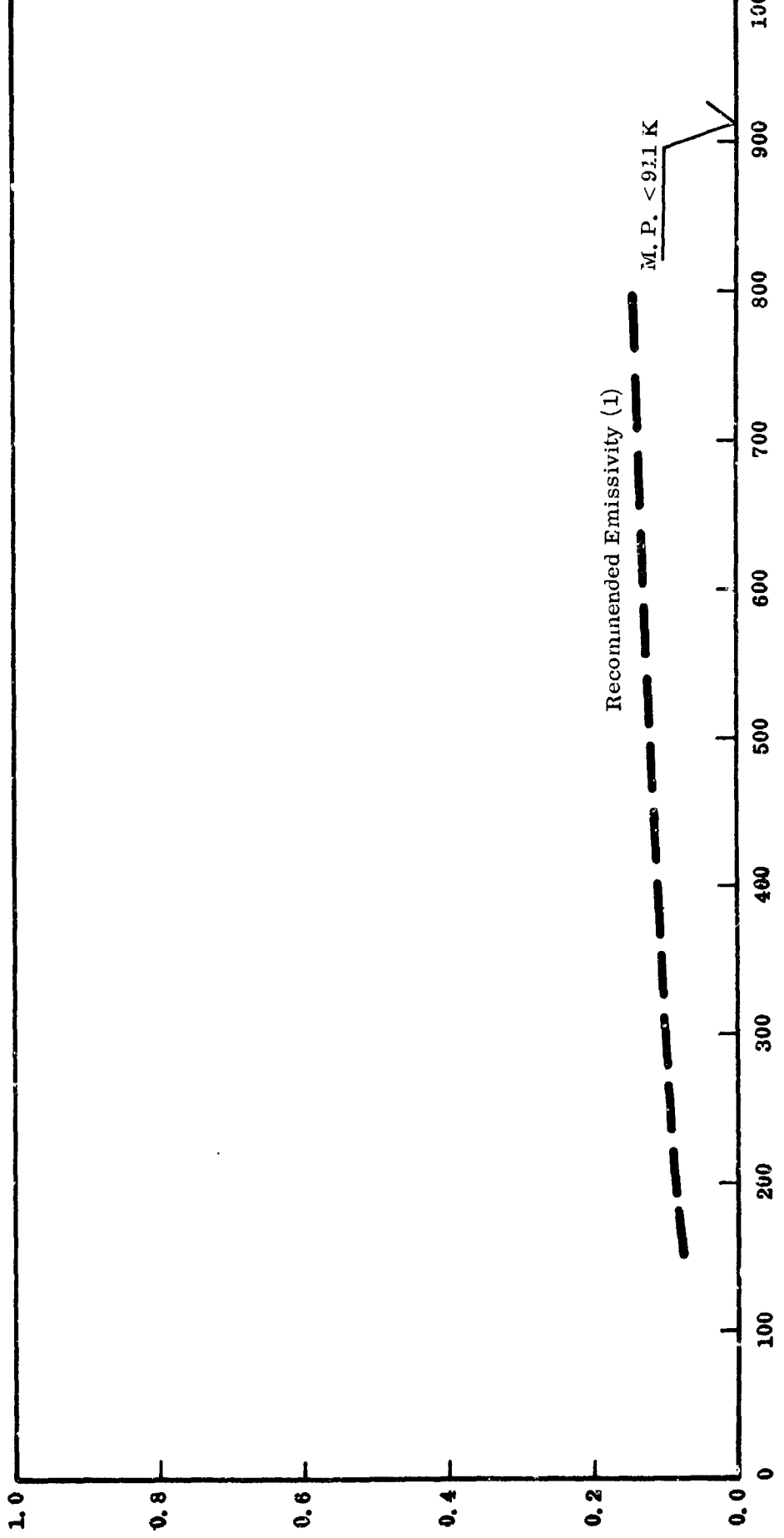

FIG. III-11A HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 7075-T6

TABLE III-14A HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 7075-T6
SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1	--	150-800	±0.02	Computed from normal total emissivity recommended values on following figure and table.

T (K)	ϵ	
RECOMMENDED EMISSIVITY		
150	(0.07)	±0.02
200	(0.09)	
300	(0.10)	
400	(0.11)	
500	(0.12)	
600	(0.12)	
700	(0.13)	
800	(0.14)	

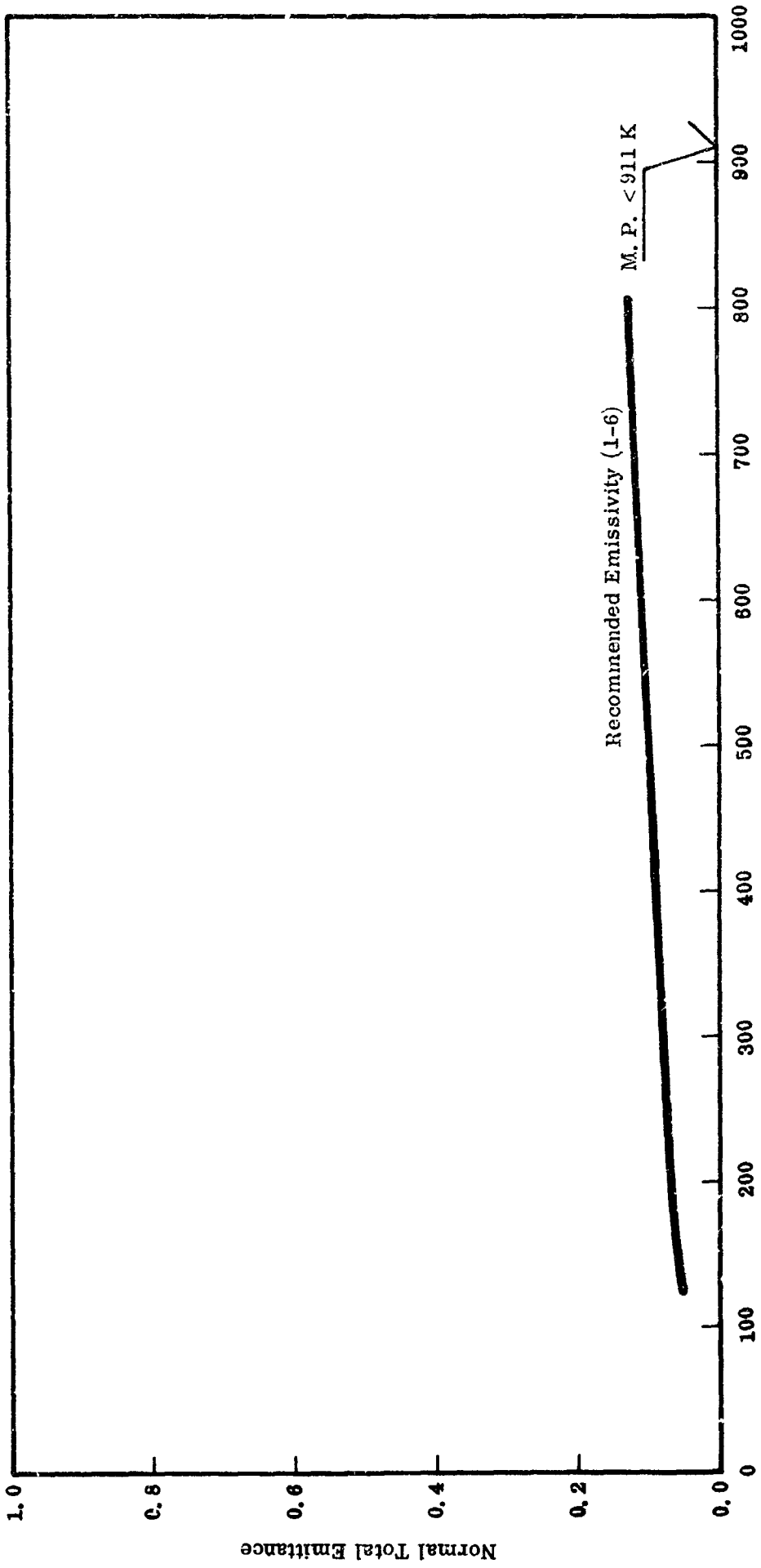

FIG. III-11B NORMAL TOTAL EMITTANCE -- ALUMINUM ALLOY 7075-T6

TABLE III-14B NORMAL TOTAL EMITTANCE -- ALUMINUM ALLOY 7075-T6

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	23	89-805		Polished on buffing wheel, free of scratches, mirror appearance; results during first heating cycle; measured in helium purged atmosphere.
2*	9	301		Polished with Aerobright and Bon Ami.
3*	9	303		Unpolished, as received condition.
4*	24	383-650		Same specimen as Curve 2, different method.
5*	24	386-650		Same specimen as Curve 4; data taken at a different date.
6*	24	428-619		Same specimen as Curve 3, different method.

RECOMMENDED EMISSIVITY

T (K)	ϵ
150	0.06 ±0.02
200	0.07
300	0.08
400	0.09
500	0.10
600	0.11
700	0.115
800	0.125

CURVE 1*

T (K)	ϵ
89	0.06
255	0.08
422	0.09
589	0.10
755	0.12
805	0.12

CURVE 2*

T (K)	ϵ
301	0.07

CURVE 3*

T (K)	ϵ
303	0.02

CURVE 4*

T (K)	ϵ
383	0.13
428	0.11
450	0.14
469	0.14
528	0.145
633	0.16
650	0.175

CURVE 5*

T (K)	ϵ
386	0.09
433	0.095
444	0.098
505	0.12
530	0.105
603	0.125
650	0.13

CURVE 6*

T (K)	ϵ
428	.065
433	0.06

CURVE 6*(cont)

T (K)	ϵ
450	0.06
464	0.055
514	0.06
539	0.06
544	0.06
615	0.065
619	0.065

*Not shown on figure

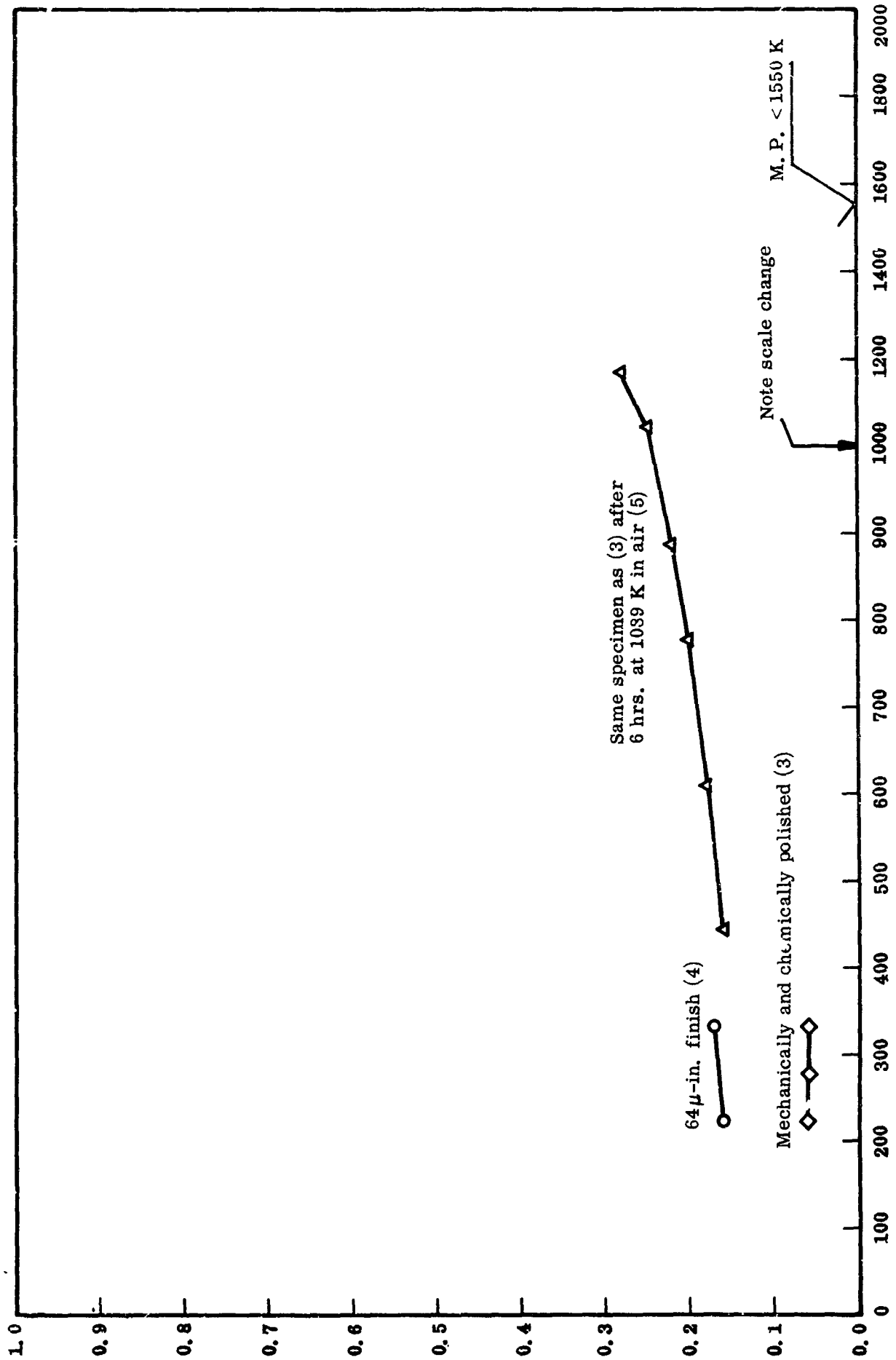

FIG. III-12 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM ALLOY

TABLE III-15 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM ALLOY

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	22	222-333	±0.06	Commercial grade QMV; milled from sintered block; computed from spectral reflectance measurements.
2*	22	222-333	±0.06	Same as Curve 1; rolled plate; chemically milled, followed by chemical polish.
3	22	222-333	±0.06	Same as Curve 1; milled from sintered block, followed by a chemical-mechanical polish.
4	22	222-333	±0.06	Same as Curve 1; 64 μ-in rms finish.
5	22	222-333	±0.06	Same conditions and specimen as 3; maintained at temperature of 1089 K in ambient air for 6 hrs.

T (K)	ϵ
CURVE 1*	
222	0.11
278	0.11
333	0.12
CURVE 2*	
222	0.08
278	0.09
333	0.10

T (K)	ϵ
CURVE 3	
222	0.06
278	0.06
333	0.06
CURVE 4	
222	0.16
333	0.17

T (K)	ϵ
CURVE 5	
222	0.14
333	0.15
445	0.16
611	0.18
778	0.20
889	0.22
1045	0.25
1167	0.28

*Not shown on figure

TABLE III-16 HEMISPHERICAL AND NORMAL TOTAL EMITTANCE -- STAINLESS STEEL 304-A
SPECIFICATION AND DATA TABLES

Ref. No.	Temp. Range, K	HTE	NTE	Reported Error	Specimen Characterization and Remarks
25*	300	0.30		(±0.06)	Immersed in a boiling Dulite 3-0 salt bath; black oxide finish; average of two values computed from reflectance measurements.
26*	811		0.145		Machine finished; measured in helium purged atmosphere.
	811		0.175		
	1128		0.480		
	1400		0.720		
	1444		0.730		

*No figure presented

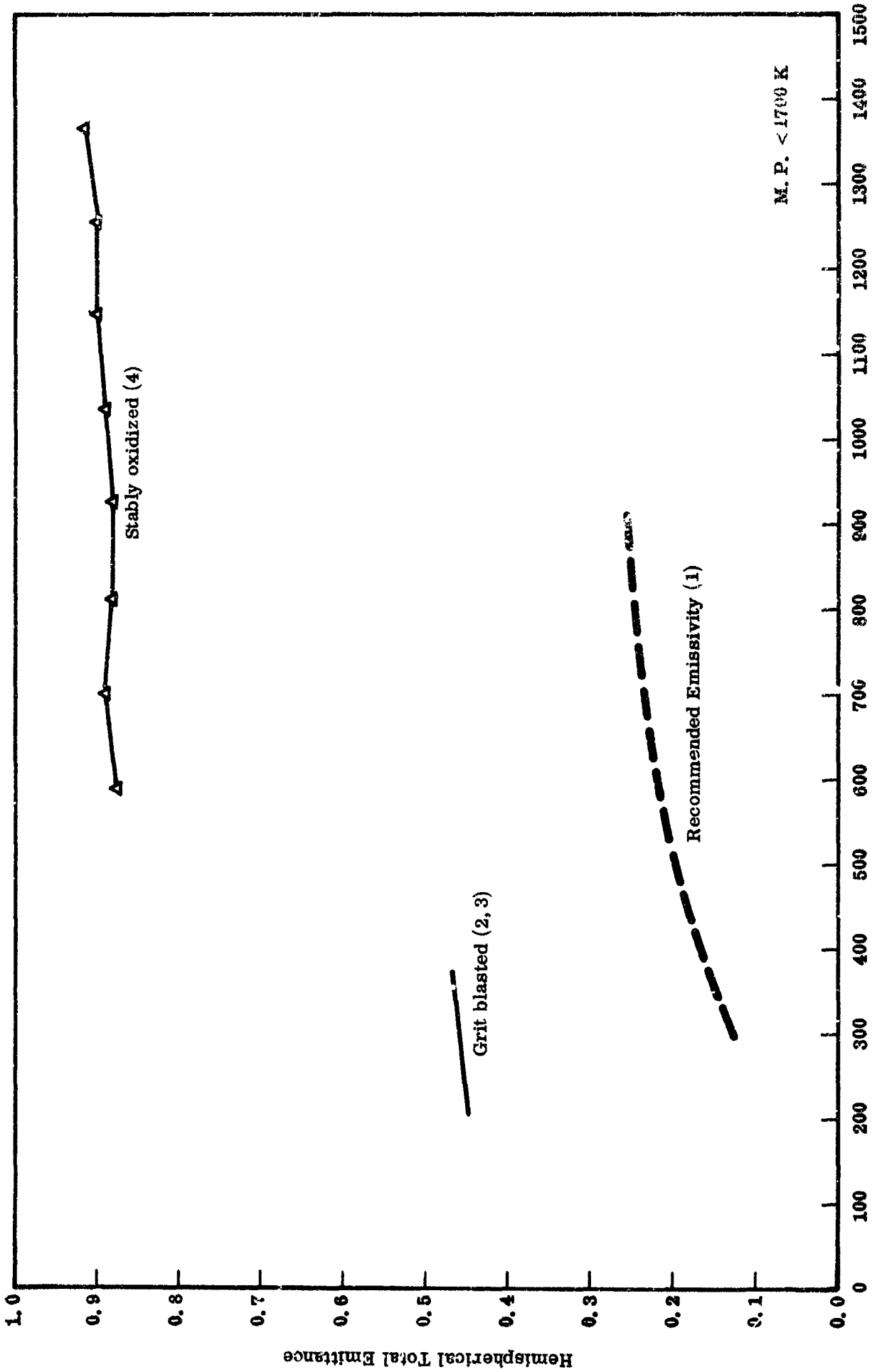

FIG. III-13A HEMISPHERICAL TOTAL EMITTANCE -- STAINLESS STEEL 347

TABLE III-17A HEMISPHERICAL TOTAL EMITTANCE -- STAINLESS STEEL 347

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1	--	300-900	±0.04	Computed from normal total emissivity recommended values on following figure and table.
2*	22	222-333	±0.06	Vapor-degreased in trichlorethylene; grit blasted with 100-mesh grit aluminum oxide nozzle of sandblaster held 12 in. from surface, computed from spectral reflectance measurements.
3*	22	222-333	±0.06	Same as Curve 2; after 5 min. in air-circulating over at 590 K.
4	27	589-1367		Oxidized 30 min. at 1366 K in air; stably oxidized; diffuse emitter.

RECOMMENDED EMISSIVITY

T (K)	∈
300	(0.125) ±0.04
400	(0.165)
500	(0.195) ±0.02
600	(0.215)
700	(0.235)
800	(0.245)
900	(0.255)

CURVE 2*

T (K)	∈
222	0.46
278	0.46
333	0.47

CURVE 3*

T (K)	∈
222	0.44
278	0.45
333	0.46

CURVE 4

T (K)	∈
589	0.875
670	0.890
811	0.880
922	0.880
1033	0.885
1144	0.900
1255	0.900
1367	0.915

*Not shown on figure

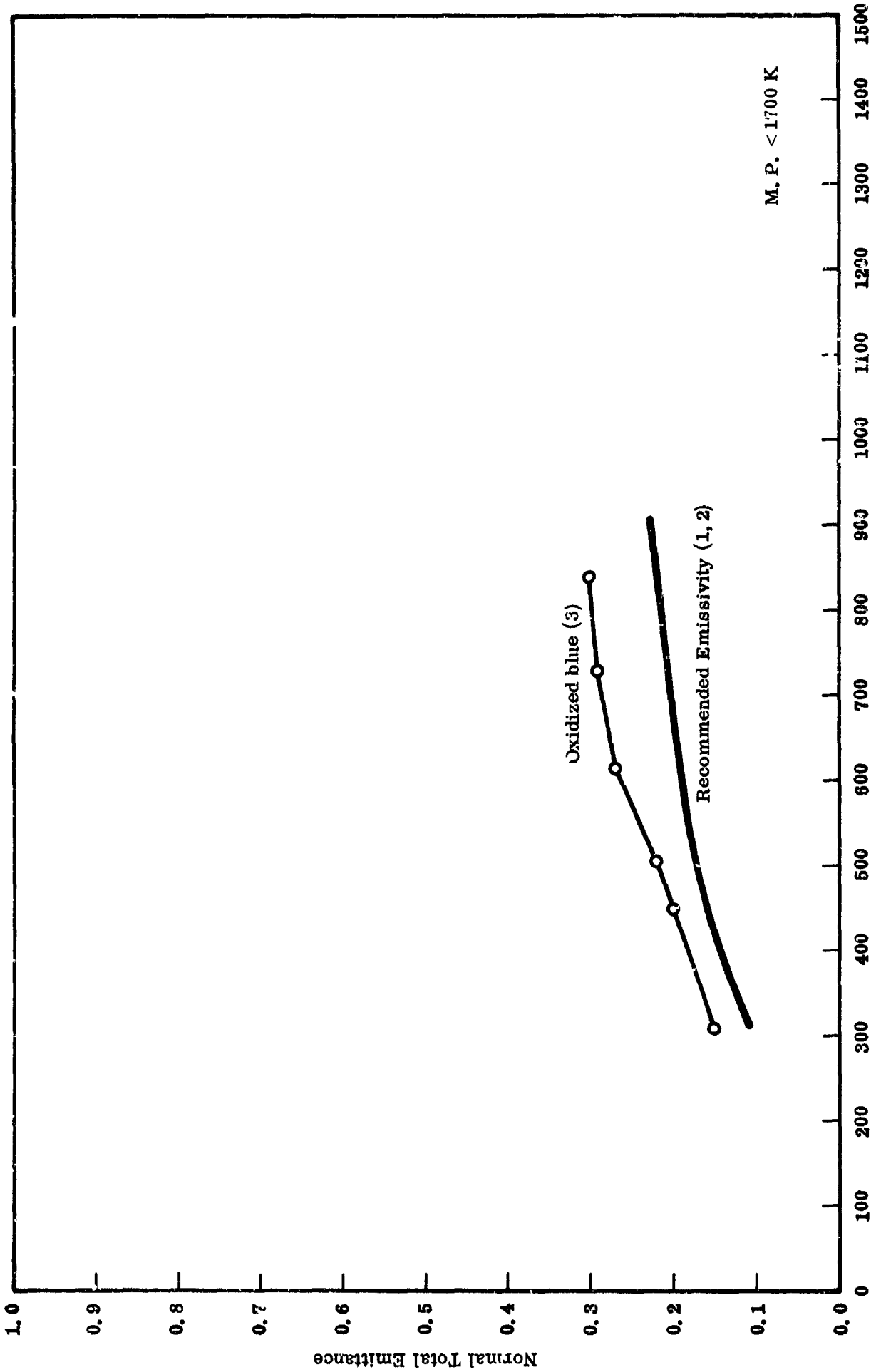

FIG. III-13B NORMAL TOTAL EMITTANCE -- STAINLESS STEEL 347

TABLE III-17B NORMAL TOTAL EMITTANCE -- STAINLESS STEEL 347

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	23	89-1289		Polished with buffing wheel; results during first heating.
2*	28	311-839		Polished.
3	28	311-839		Oxidized blue, 100 hrs at 910 K.

RECOMMENDED EMISSIVITY

T (K)	ϵ
300	0.10 ±0.04
400	0.14
500	0.17 ±0.02
600	0.19
700	0.205
800	0.215
900	0.225

CURVE 1*

T (K)	ϵ
89	0.17
255	0.17
422	0.17
589	0.18
755	0.20
922	0.23
1089	0.33
1289	0.66

CURVE 2*

T (K)	ϵ
311	0.11
450	0.16
505	0.18
617	0.19
728	0.21
839	0.23

CURVE 3

T (K)	ϵ
311	0.15
450	0.20
505	0.22
617	0.27
728	0.29
839	0.30

*Not shown on figure

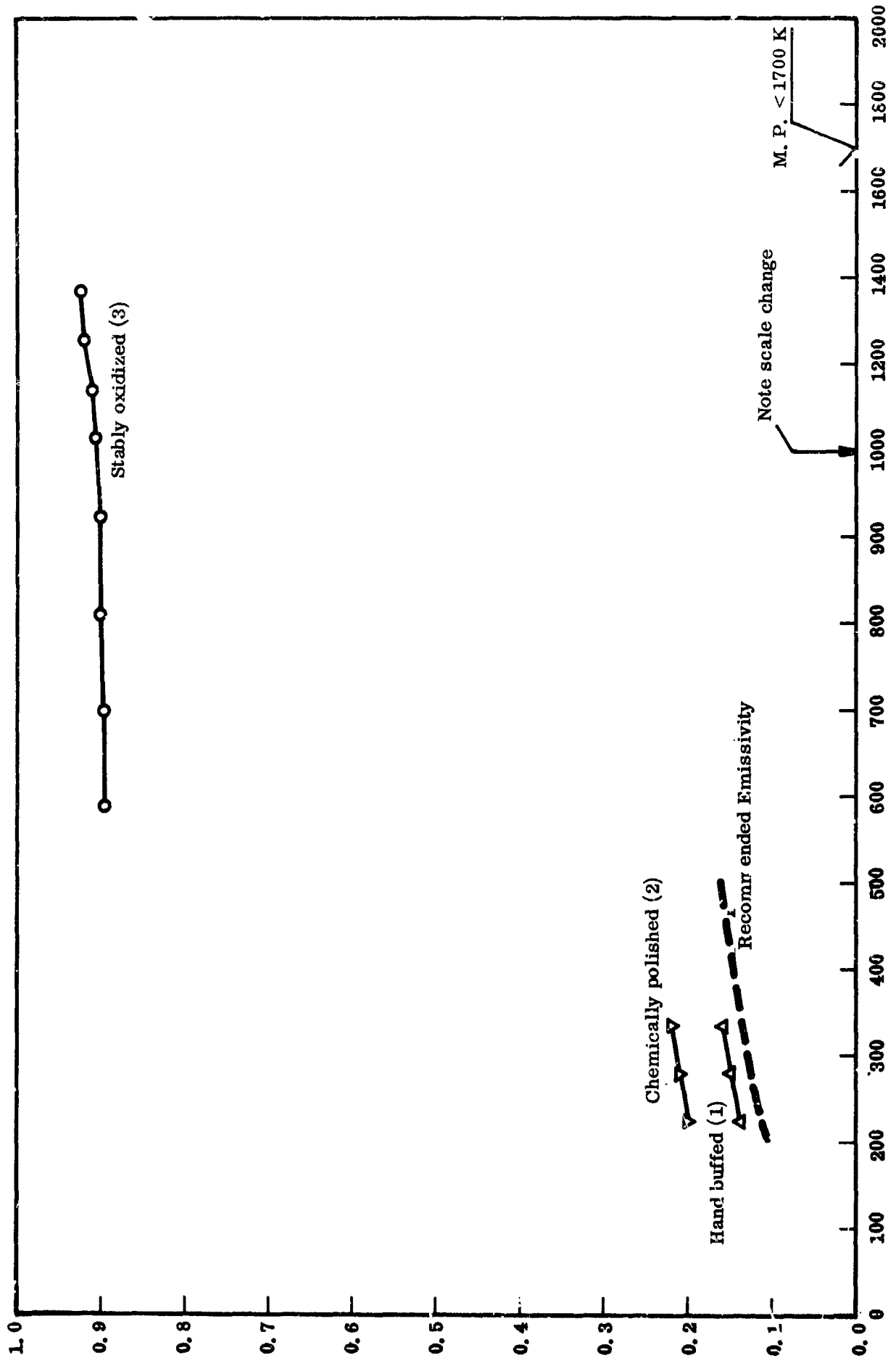

FIG. EI-14 HEMISPHERICAL TOTAL EMITTANCE -- INCONEL X-750

TABLE III-18 HEMISPHERICAL TOTAL EMITTANCE -- INCONEL X-750

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1	22	222-333	±0.07	Foil; hand buffed; computed from spectral reflectance measurements.
2	22	222-333	±0.07	Foil; chemically polished; computed from spectral reflectance measurements.
3	29	589-1367	±2%	Cleaned, polished and oxidized in air at 1366 K for 30 min.; stably oxidized condition; diffuse emitter.

T (K)	∈
RECOMMENDED EMISSIVITY	
200	(0.12) ±0.02
300	(0.13)
400	(0.145)
500	(0.16)
CURVE 1	
222	0.14
278	0.15
333	0.16

T (K)	∈
CURVE 2	
222	0.20
278	0.21
333	0.22
CURVE 3	
589	0.69
700	0.705
811	0.730
922	0.755
1033	0.765
1144	0.795
1255	0.820

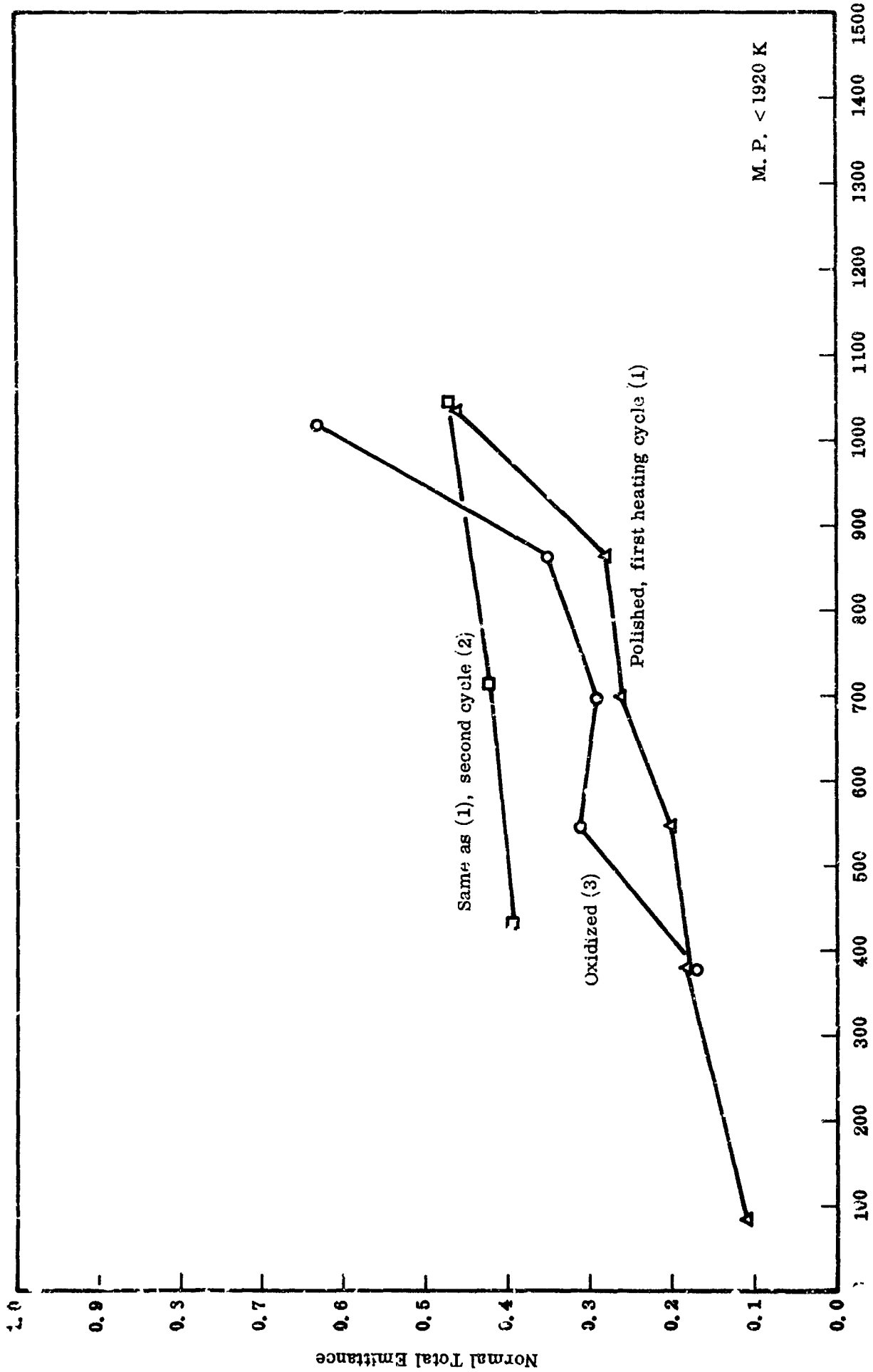

FIG. III-15 NORMAL TOTAL EMITTANCE -- TITANIUM ALLOY A-110AT

TABLE III-19 NORMAL TOTAL EMITTANCE -- TITANIUM ALLOY A-110AT

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1	30	89-1033		Polished; first heating.
2	30	436-1047		Polished; second heating of same specimen as above.
3	30	380-1019		Oxidized; first heating; subsequent cycles show large increase in emittance.

T (K)	ϵ
CURVE 1	
89	0.11
380	0.18
539	0.20
700	0.26
867	0.28
1033	0.46
CURVE 2	
436	0.39
714	0.42
1047	0.47

T (K)	ϵ
CURVE 3	
380	0.17
547	0.31
700	0.29
867	0.35
1019	0.63

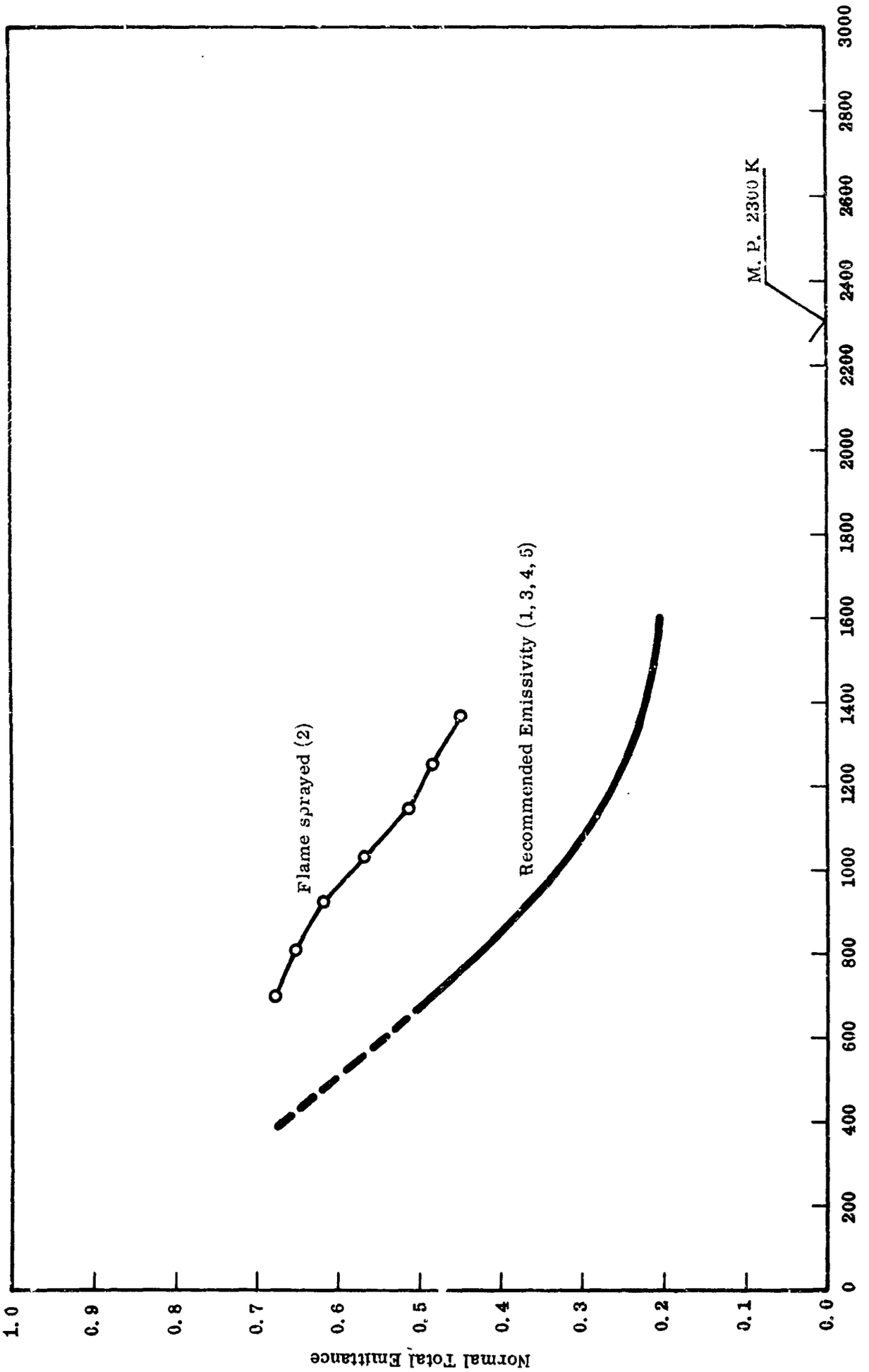

FIG. III-16 NORMAL TOTAL EMITTANCE -- ALUMINUM OXIDE

TABLE III-20 NORMAL TOTAL EMITTANCE -- ALUMINUM OXIDE

SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	31	673-1073		Powder coating on nimonic 75 strip.
2	27	700-1366		Flame sprayed coating on oxidized inconel strip.
3*	32	958-1158		Norton E111 alumina, cold pressed and sintered at 2000 K; 14% porosity.
4*	33	1200		Sintered 1 hr at 1623 K; same results for measurements in vacuum (10^{-5} torr) and in air.
5*	34	1200-1600	±0.02	99+ Al_2O_3, 0.1 SiO_2, 0.07 CaO, 0.4 FeO; sintered 27 hrs at 1865 K; 30% porosity; computed from spectral emittance measurements.

T (K)	∈
RECOMMENDED EMISSIVITY	
400	(0.66) ±0.04
600	(0.54)
800	0.43
1000	0.33
1200	0.26
1400	0.22
1600	0.20

T (K)	∈
CURVE 1*	
673	0.48
773	0.41
873	0.39
973	0.34
1073	0.30
CURVE 2	
700	0.676
811	0.650
922	0.615
1033	0.565

T (K)	∈
CURVE 2 (cont.)	
1144	0.510
1255	0.480
1366	0.445
CURVE 3*	
958	0.37
1158	0.37
CURVE 4*	
1200	0.32

T (K)	∈
CURVE 5*	
1200	0.26
1400	0.22
1600	0.20

*Not shown on figure

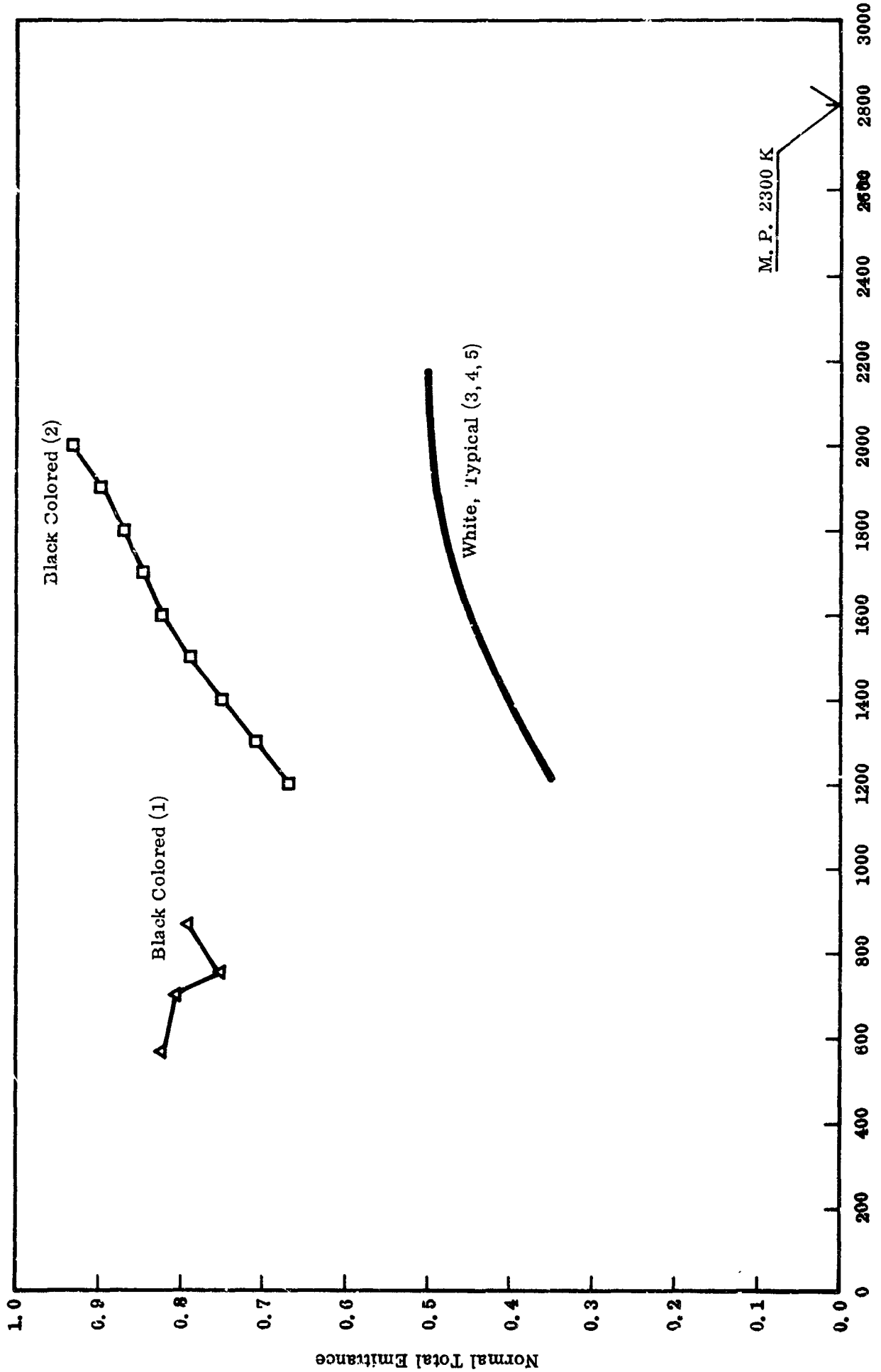

FIG. III-17 NORMAL TOTAL EMITTANCE -- BERYLLIUM OXIDE

TABLE III-21A NORMAL TOTAL EMITTANCE -- BERYLLIUM OXIDE
SPECIFICATION TABLE

Curve No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1	35	561-867		Color not specified, but probably black.
2	36	1200-2000	20	Polished; fabricated by hot-pressing high fired beryllia powder in graphite forms; density 2.85 gm cm^{-3}, black colored; measured in vacuum.
3*	36	1200-2150	20	Same as above; fabricated by hot-pressing Brush S. P. powdered beryllia; density 2.844 gm cm^{-3}; white colored.
4*	36	1200-2150	20	Same as No. 3; fabricated as in 3, annealed by ceramic firing; density 2.778 gm cm^{-3}; white colored.
5*	37	1223	± 8	Sintered at 1973 K for 2 hrs; measured in argon atmosphere.

*Not shown on figure

TABLE III-21B NORMAL TOTAL EMITTANCE -- BERYLLIUM OXIDE

DATA TABLE

T (K)	∈
WHITE, TYPICAL	
1200	0.35 ±0.02
1400	0.40
1600	0.445
1800	0.48
2000	0.495
2200	0.50
CURVE 1	
561	0.82
700	0.805
755	0.80
867	0.79
CURVE 2	
1200	0.665
1300	0.706
1400	0.746
1500	0.785
1600	0.819
1700	0.843
1800	0.867
1900	0.894
2000	0.931

T (K)	∈
CURVE 3*	
1200	0.351
1300	0.383
1400	0.405
1500	0.425
1600	0.447
1700	0.474
1800	0.499
1900	0.513
2000	0.517
2100	0.514
2150	0.509
CURVE 4*	
1200	0.336
1300	0.36..
1400	0.392
1500	0.420
1600	0.439
1700	0.453
1800	0.463
1900	0.470
2000	0.474
2100	0.475
2150	0.475

T (K)	∈
CURVE 5*	
1223	0.34

*Not shown on figure

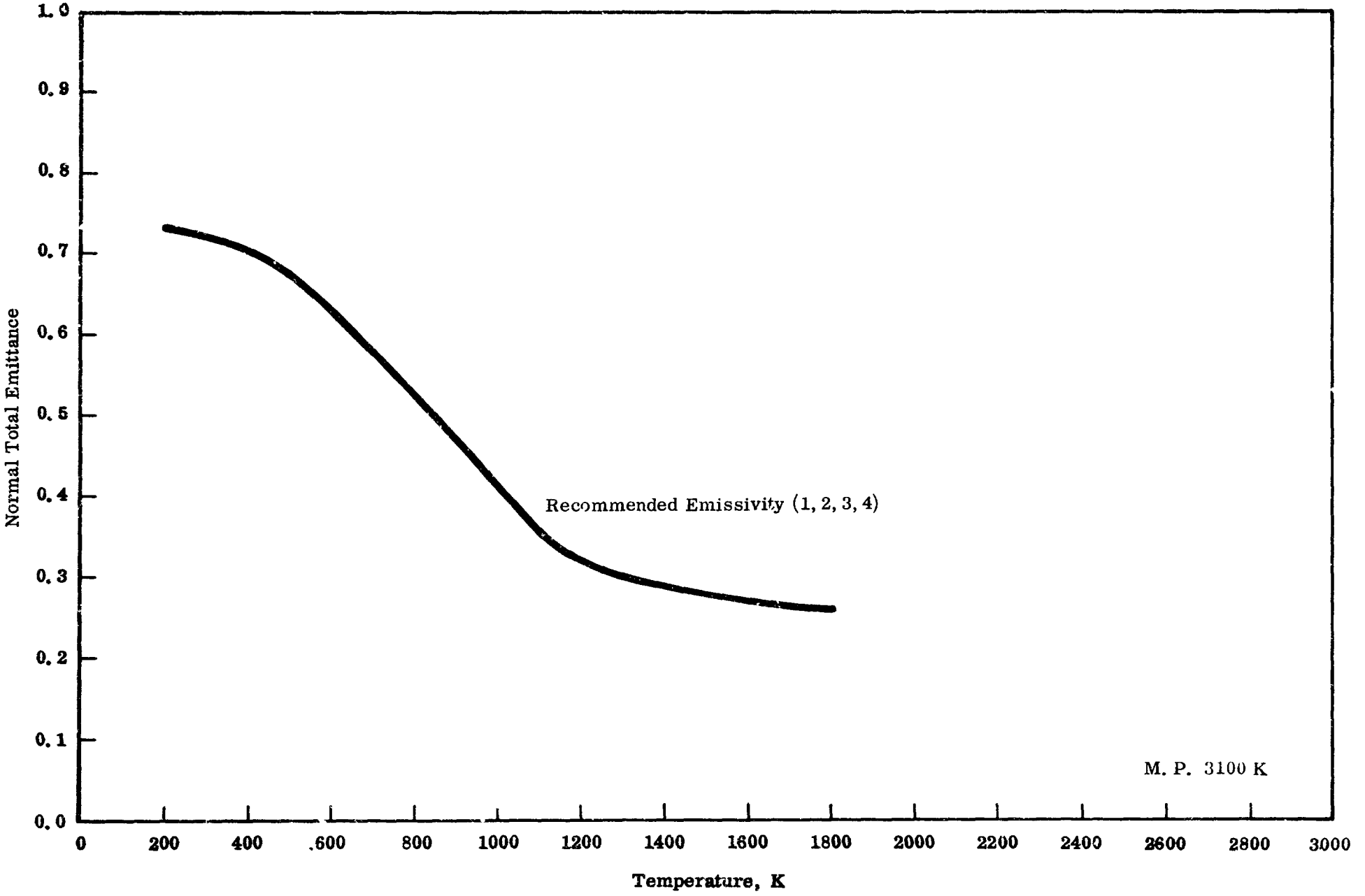

FIG. III-18 NORMAL TOTAL EMITTANCE -- MAGNESIUM OXIDE

TABLE III-22 NORMAL TOTAL EMITTANCE -- MAGNESIUM OXIDE
SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	30	75-1019		As received; first cycle, increasing temperature.
2*	35	89-1755	4%	Fused; same specimen as used in Curve 1; smoothed curve.
3*	31	673-1073		Powder coating on nimonic 75 strip; prepared from super pure Mg.
4*	34	1200-1600	±0.02	99.2 MgO, 0.1 Al_2O_3, 0.4 SiO_2, 0.1 CaO, 0.1 Fe_2O_3; sintered 27 hrs at 1623 K; 30% porosity; computed from spectral emittance measurements.

T (K)	∈
RECOMMENDED EMISSIVITY	
200	0.73 ±0.03
400	0.705
600	0.63
800	0.52
1000	0.41
1200	0.32 ±0.04
1400	0.285
1600	0.27
1800	0.26

T (K)	∈
CURVE 1*	
758	0.700
378	0.726
542	0.700
694	0.555
866	0.505
1019	0.490
CURVE 2*	
89	0.74
422	0.70
589	0.63
755	0.55
922	0.47

T (K)	∈
CURVE 2* (cont.)	
1089	0.40
1255	0.36
1422	0.33
1589	0.32
1755	0.31
CURVE 3*	
673	0.60
773	0.55
873	0.51
973	0.46
1073	0.42

T (K)	∈
CURVE 4*	
1200	0.26
1400	0.25
1600	0.24

*Not shown on figure

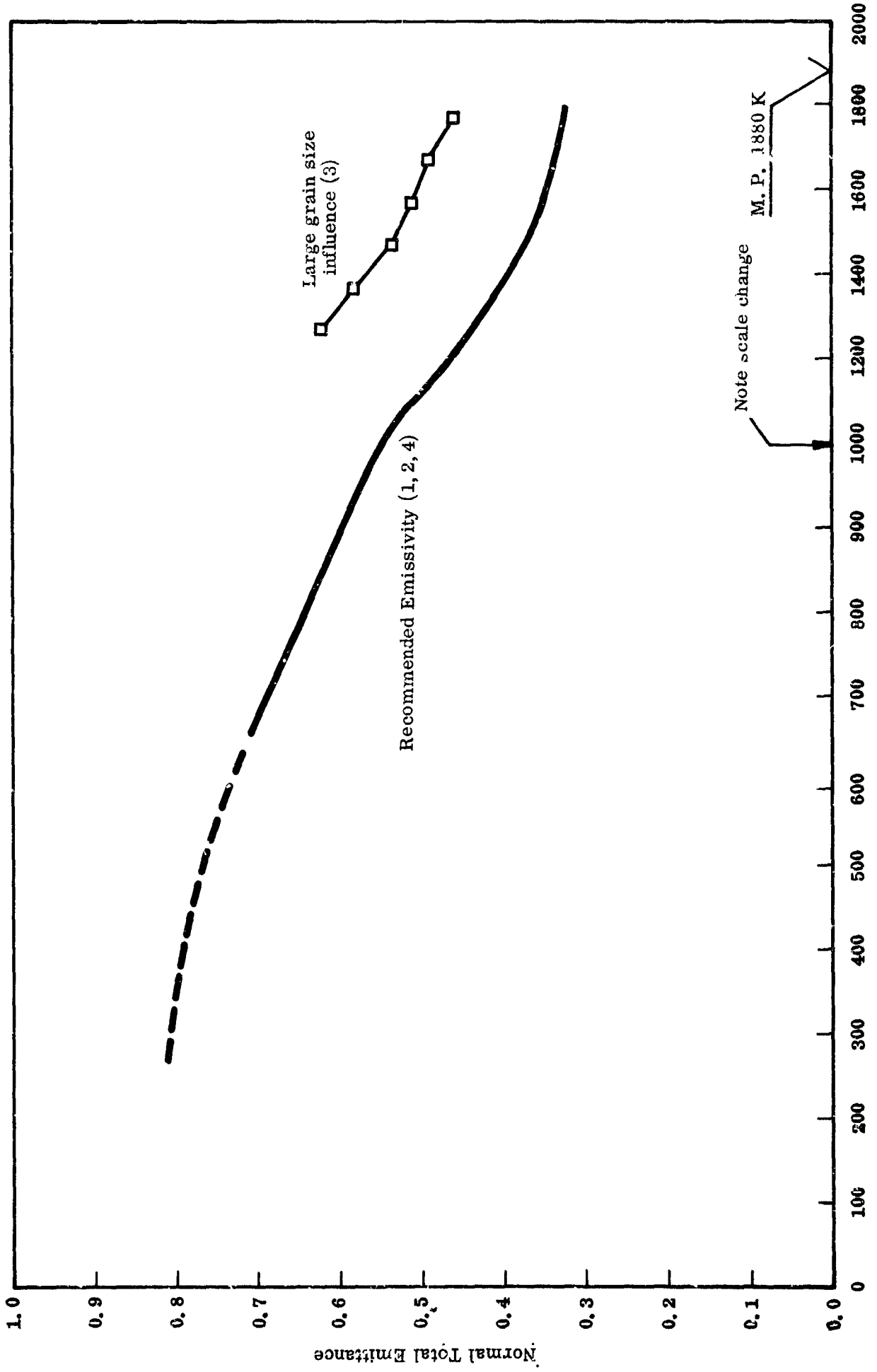

FIG. III-19 NORMAL TOTAL EMITTANCE -- SILICON DIOXIDE

TABLE III-23 NORMAL TOTAL EMITTANCE -- SILICON DIOXIDE

SPECIFICATION AND DATA TABLES

Curv No.	Ref. No.	Temp. Range, K	Reported Error, %	Specimen Characterization and Remarks
1*	31	673-1073		Crushed silica; milled into powder and treated with 50% HCl; powder coating on nimonic 75 strip; heated in air.
2*	37	1273	±8	Sintered at 1823 K for 1 hr; measured in argon atmosphere.
3	38	1273-1773		98% purity; cut from industrial bricks; results of 4 samples of different grain size, 0.08 to 0.6 mm dia.
4*	38	1273-1773		Same as above; grain size of sample < 20 micron diameter.

T (K)	ϵ
RECOMMENDED EMISSIVITY	
250	(0.81) ±0.04
300	(0.805)
400	(0.79)
500	(0.775)
600	(0.73)
700	(0.685) ±0.01
800	0.645
900	0.600
1000	0.55
1200	0.465 ±0.03
1400	0.39
1600	0.345
1800	0.315

T (K)	ϵ
CURVE 1*	
673	0.69
773	0.65
873	0.62
973	0.57
1073	0.50
CURVE 2*	
1273	0.37

T (K)	ϵ
CURVE 3	
1273	0.62
1373	0.58
1473	0.535
1573	0.51
1673	0.49
1773	0.46

T (K)	ϵ
CURVE 4*	
1273	0.42
1373	0.42
1473	0.41
1573	0.35
1673	0.34
1773	0.33

*Not shown on figure

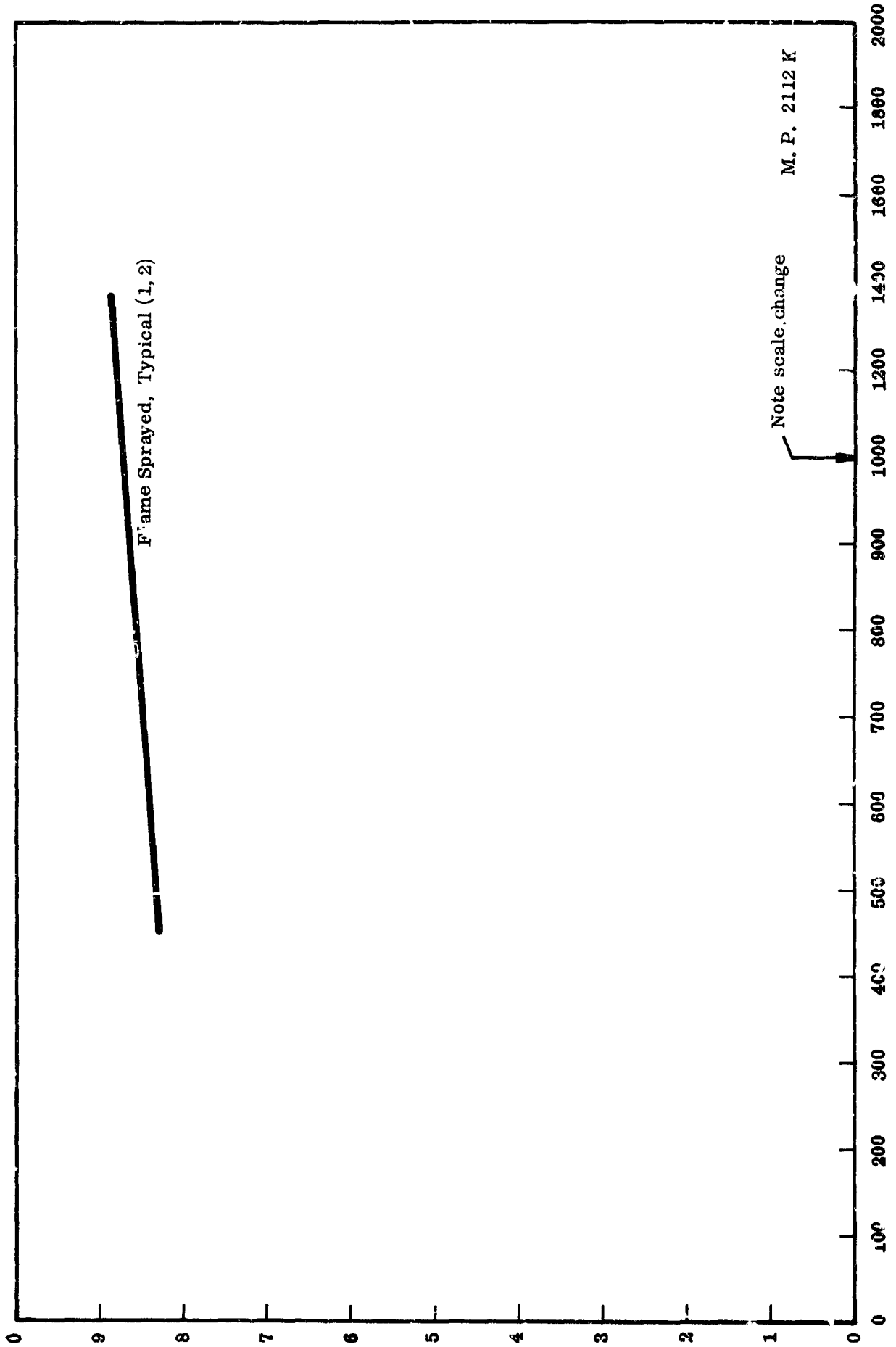

FIG. III-20 HEMISPHERICAL TOTAL EMITTANCE — TITANIUM DIOXIDE

TABLE III-24 HEMISPHERICAL TOTAL EMITTANCE -- TITANIUM DIOXIDE SPECIFICATION AND DATA TABLES

Curve No.	Ref. No.	Temp. Range, K	Reported Error	Specimen Characterization and Remarks
1*	39	445-570		Flame sprayed; coating 0.0025 in. thickness on type 310 stainless steel; measured in vacuum, ($9.0 \times 3.4 \times 10^{-7}$ torr); run No. 1A.
2*	39	1261-649		Same as above; run No. 4B.

T (K)	ϵ
FLAME SPRAY, TYPICAL	
400	0.825 ±0.02
500	0.83
600	0.84
700	0.85
800	0.855
900	0.86
1000	0.87
1200	0.88
1400	0.89

T (K)	ϵ
CURVE 1*	
445	0.837
493	0.844
526	0.834
570	0.835

T (K)	ϵ
CURVE 2*	
1261	0.883
1225	0.888
1187	0.897
1140	0.891
1121	0.875
1060	0.885
999	0.882
999	0.882
956	0.886
913	0.873
864	0.874
812	0.854
766	0.843
708	0.832
649	0.828

*Not shown on figure

TABLE III-25 NORMAL TOTAL EMITTANCE FOR OXIDES OF CHROMIUM, COPPER, IRON, NICKEL, NIOBIUM, ZINC*

Ref.	T (K)	ϵ	Reported Error	Specimen Characterization and Remarks
CHROMIUM OXIDE, Cr_2O_3				
40	873	0.85		Sintered at 2173 K for 2 hrs.
	1073	0.90		
	1273	0.80		
CUPRIC OXIDE, CuO				
14	406	0.759	0.7%	Cu plate with smooth, thick, dark blue oxide layer.
CUPROUS OXIDE, Cu_2O				
41	1073	0.66		Thin coating on bulk material; computed from total radiation pyrometer measurements.
	1173	0.60		
	1273	0.56		
	1373	0.54		
FERROUS OXIDE, FeO				
42	673	0.90		Black.
FERRIC OXIDE, Fe_2O_3				
33	1200	0.67		Sintered 2 hrs at 1273 K
33	1200	0.88		Same as above but measured in vacuum, 1×10^{-5} torr.
NICKEL OXIDE, NiO				
43	873	0.53	±0.02	Ni strip heated electrically in air to form fairly thick coating; composition 99.2 NiO, 0.8 FeO.
	1073	0.68		
	1273	0.75		
	1573	0.87		

* No figure presented

TABLE III-25 (Continued)

Ref.	T (K)	ϵ	Reported Error	Specimen Characterization and Remarks
NIOBIUM PENTOXIDE, Nb_2O_5				
33	1200	0.36		Sintered 2 hrs at 1573 K.
	1200	0.52		Same as above but measured in vacuum, 1×10^{-5} torr.
ZINC OXIDE, ZnO				
44	1140	0.91		Crystal; measured in vacuum, 1×10^{-4} torr; computed from spectral emittance measurements.
	1240	0.81		
	1330	0.82		
33	1200	0.75		Sintered 1 hr at 1573 K.
	1200	0.56		Same as above bu . asured in vacuum, 1.2×10^{-5} torr.

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RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER IV
THERMAL DIFFUSIVITY

BY

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CHAPTER IV
THERMAL DIFFUSIVITY

A. INTRODUCTION

A thorough literature search was conducted for the thermal diffusivity of thirteen elements, eight alloys and twelve oxides. The results of the evaluation and analysis of the available data are the most probable values recommended for each of the materials considered. The recommended values are presented in graphical and tabular form.

Although the recommended values for the elements and alloys cover a wide temperature range from cryogenic temperature to the melting point or above and somewhat more limited temperature ranges are covered by the oxides, the available experimental data are extremely scanty. In fact, no experimental data are available for beryllium, chromium, magnesium, manganese, niobium, silicon, tin, aluminum alloys 2219-T852, 6061-T6, and 7075-T6, beryllium dilute alloy, titanium alloy A-110AT, and the oxides Fe_3O_4, Fe_2O_3, MnO, Mn_3O_4, NiO, SnO_2, TiO_2, and ZnO. In other words, there are no experimental data for twenty of the thirty-three materials investigated. Even for those materials for which data are available, the temperature ranges covered are very narrow, and no measurements have ever been made on these materials in the liquid state.

B. DATA ANALYSIS

Since experimental data are very scanty, the determination of recommended values relies heavily on calculations. For those materials for which no experimental data are available, the recommended thermal diffusivity values are derived from the recommended values of thermal conductivity, density, and specific heat. The results are not always reported as first calculated and adjustments are made for internal consistency by smoothing the resultant curves or for complying with theoretical considerations especially in those temperature ranges where the data for one or more of the properties, thermal conductivity, density, or specific heat were obtained from extensive extrapolation or estimation. For those materials for which experimental data are directly available, the recommended values are derived from both the direct measurements and the derived values.

C. THERMAL DIFFUSIVITY OF SELECTED MATERIALS

The selected materials are divided into three groups: elements, alloys, and oxides, and within each group the materials are arranged in alphabetical order by name. For each material the recommended values are reported on a full-page graph followed by a tabular presentation. Information on data source and remarks are given at the end of each table. The recommended values that are derived from experimental data are represented by a solid curve. Values that are obtained from calculations or estimations are represented by a broken line and are asterisked in the table. For the material in superconducting state the values are represented by a dash-dot line. Recommended values that are derived from experimental data are thought to be accurate to within ±5 percent at room and moderate temperatures and within ±10 percent at high temperatures. In the tables the third significant figure is given only for the purpose of comparison and for the smoothness of the table and is not indicative of the degree of accuracy.

In the figures and/or tables several symbols and abbreviations have been used. Their meanings are as follows:

bcc	body-centered cubic crystal structure
bct	body-centered tetragonal crystal structure
c	cubic crystal structure
C. P.	Curic point
cph	close-packed hexagonal crystal structure
fcc	face-centered cubic crystal structure
K	Kelvin temperature
l	liquid
M. P.	melting point
N. P.	Néel point
s	solid
T	temperature
T. P.	transition point
α	thermal diffusivity
ρ_0	residual electrical resistivity

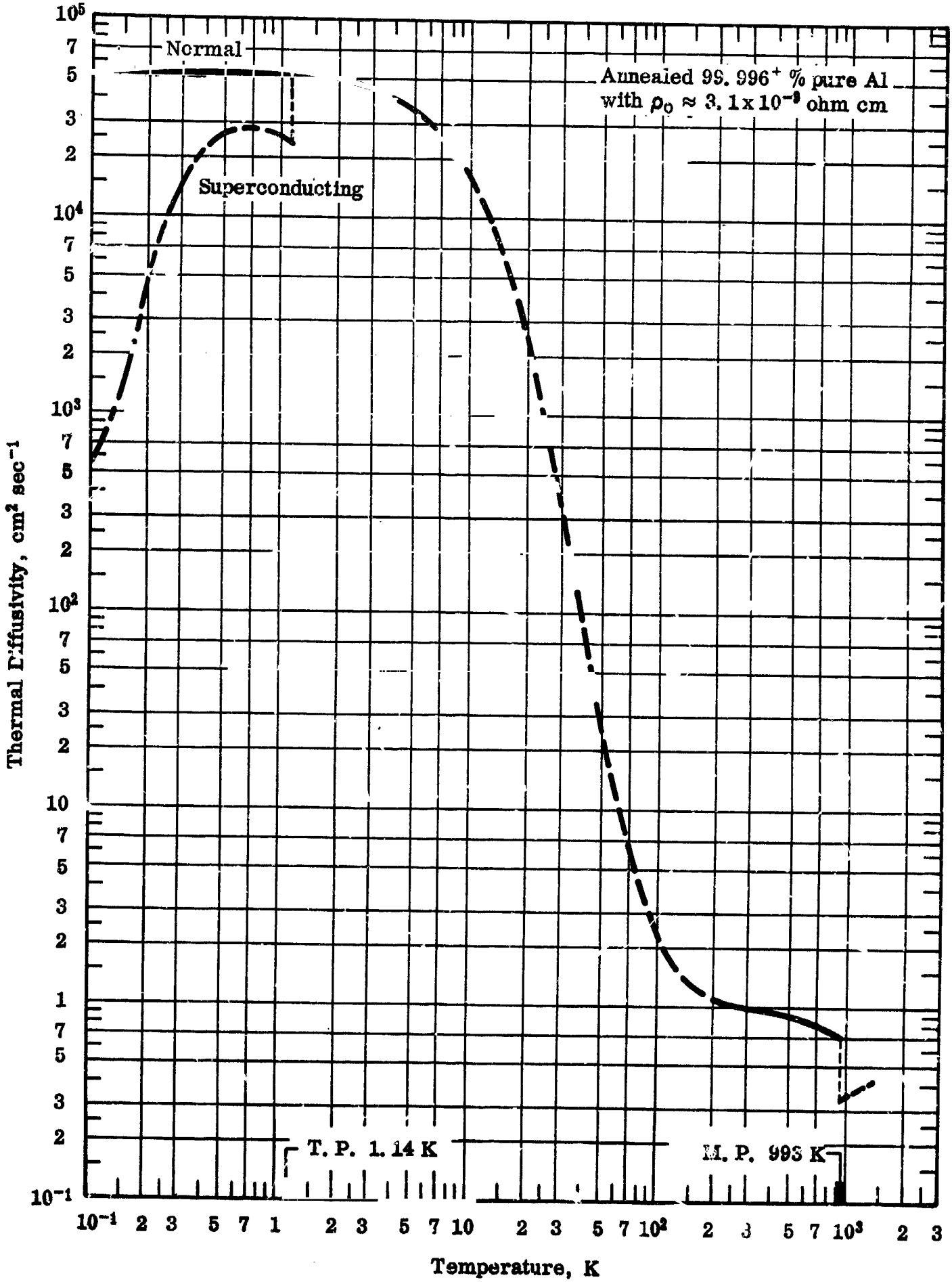

FIG. IV-1 THERMAL DIFFUSIVITY OF ALUMINUM

TABLE IV. 1 THERMAL DIFFUSIVITY OF ALUMINUM

Selected Values for Annealed 99.996+ % Pure Aluminum with $\rho_o \approx 3.1 \times 10^{-9}$ ohm cm

T,K	α, $cm^2\ sec^{-1}$			T,K	α, $cm^2\ sec^{-1}$
	Normal	Superconducting			
0.1	52000*	550*		70	6.3*
0.2		4400		80	4.0*
0.3		15100		90	2.9*
0.4		22400		100	2.27*
0.5	56000	26200		150	1.32*
0.6		27800		200	1.09*
0.7		28000		300	0.97
0.8		27400		400	0.94
0.9		26400		500	0.90
1.0	55000	25300		600	0.84
1.1		23600		700	0.80
1.14		23000		800	0.75
5	36000*		(fcc)	930	0.69*
10	16000*		(l)	940	0.35*
20	2500*			1000	0.36*
30	330*			1100	0.37*
40	76*			1200	0.39*
50	26*			1300	0.40*
60	11.4*			1400	0.42*

Data Source and Remarks

Eight sets of experimental data are available over the temperature ranges 0.2 to 4.1 K and 295 to 830 K. Selected values at the lowest temperatures lie between the data of Zavaritskii (1958) [1]$ and Howling, Mendoza, and Zimmerman (1955) [2]. From 295 to 830 K selected values lie close to the data of Sonnenschein and Winn (1960) [3], Jenkins and Parker (1961) [4], and Schmidt (1961) [5], noting that the selected values are for purer alumirum than those measured by these authors.

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* Calculated or estimated.

$ Numbers in square brackets designate references appearing under the heading BIBLIOGRAPHY.

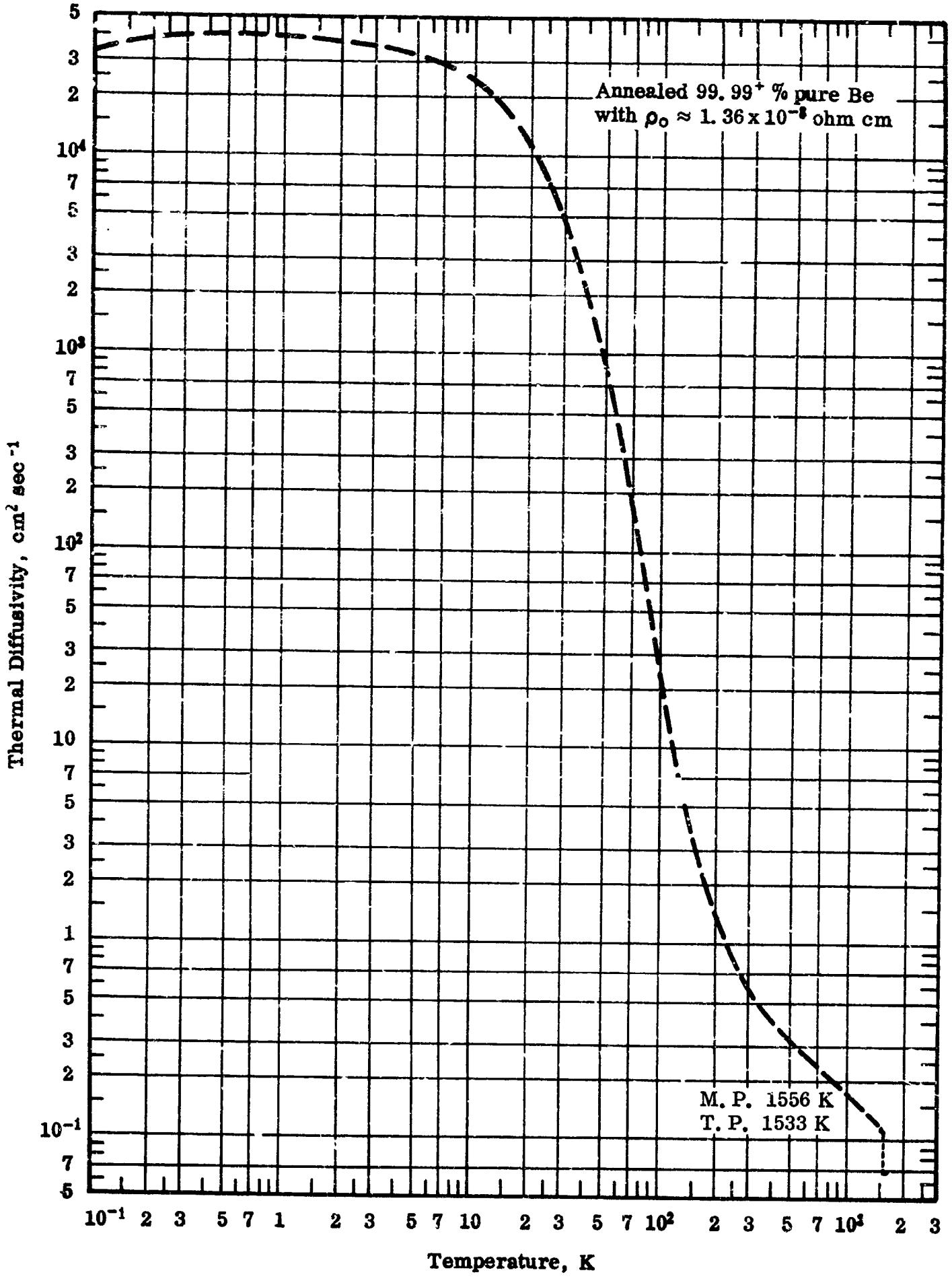

FIG. IV-2 THERMAL DIFFUSIVITY OF BERYLLIUM

TABLE IV-2 THERMAL DIFFUSIVITY OF BERYLLIUM

Selected Values for Annealed 99.99+ % Pure Beryllium with $\rho_o \approx 1.36 \times 10^{-8}$ ohm cm*

T, K	α, cm^2 sec^{-1}	T, K	α, cm^2 sec^{-1}
0.1	33000*	400	0.41
1	40000	500	0.33
5	34000	600	0.28
10	25000	700	0.24
20	11700	800	0.22
30	5100	900	0.19
40	2300	1000	0.17
50	1010	1100	0.16
60	430	1200	0.15
70	200	1300	0.14
80	97	1400	0.13
90	48	1500	0.121
100	25	(cph)1532	0.119
150	3.7	(bcc)1534	0.113
200	1.47	(bcc)1550	0.111
250	0.84	(l) 1600	0.067
300	0.60		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

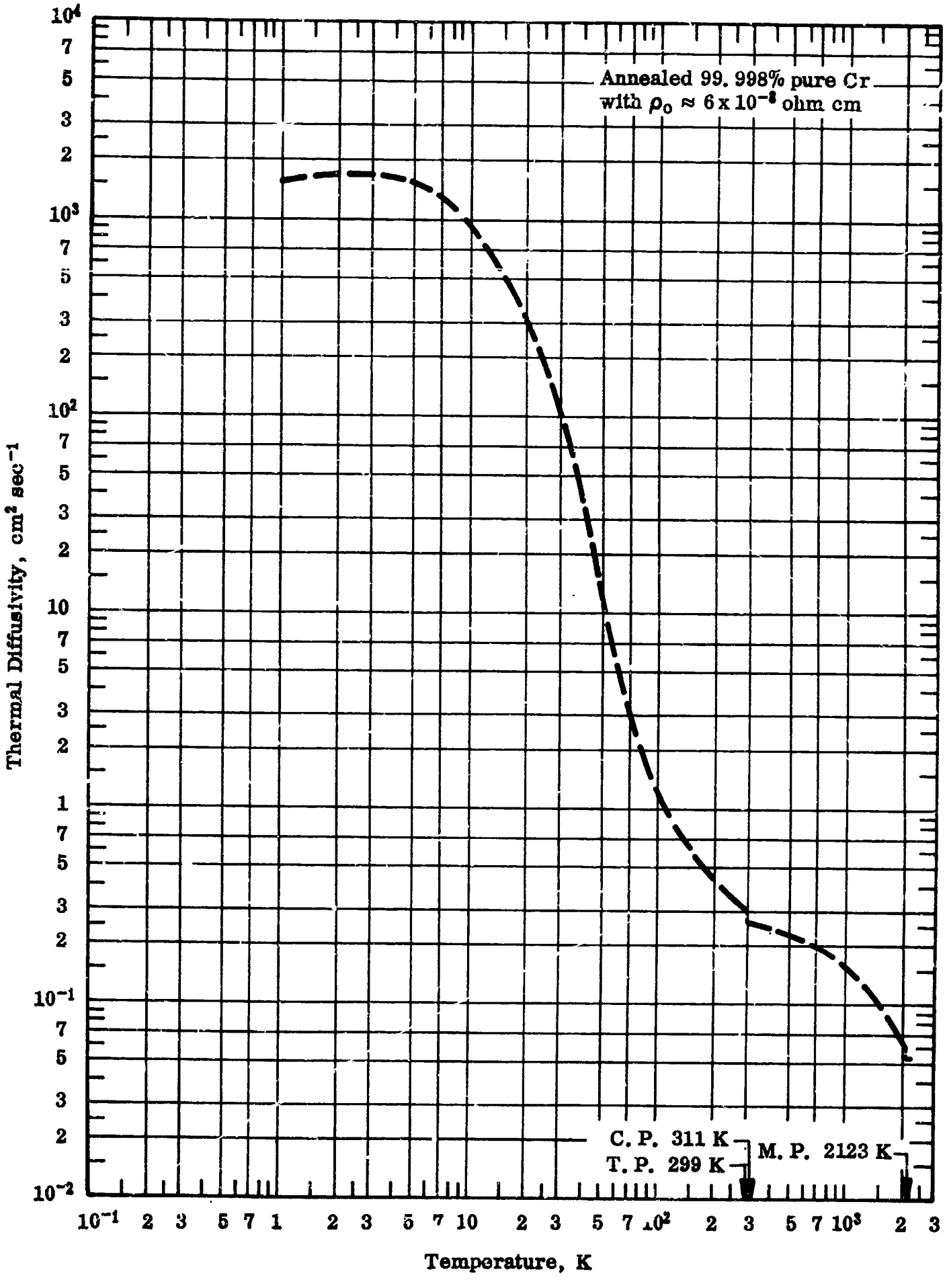

FIG. IV-3 THERMAL DIFFUSIVITY OF CHROMIUM

TABLE IV-3 THERMAL DIFFUSIVITY OF CHROMIUM

Selected Values for Annealed 99.998% Pure Chromium with $\rho_o \approx 6 \times 10^{-8}$ ohm cm*

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
1	1550*	500	0.225
5	1530	600	0.212
10	910	700	0.198
15	510	800	0.185
20	300	900	0.170
30	118	1000	0.157
40	35	1100	0.145
50	13	1200	0.133
60	5.9	1300	0.122
70	3.4	1400	0.112
80	2.2	1500	0.103
90	1.62	1600	0.095
100	1.24	1700	0.087
150	0.61	1800	0.080
200	0.43	1900	0.073
250	0.35	2000	0.067
(cp')290	0.33	(bcc) 2100	0.060
(bcc)300	0.27	(l) 2200	0.054
400	0.24		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

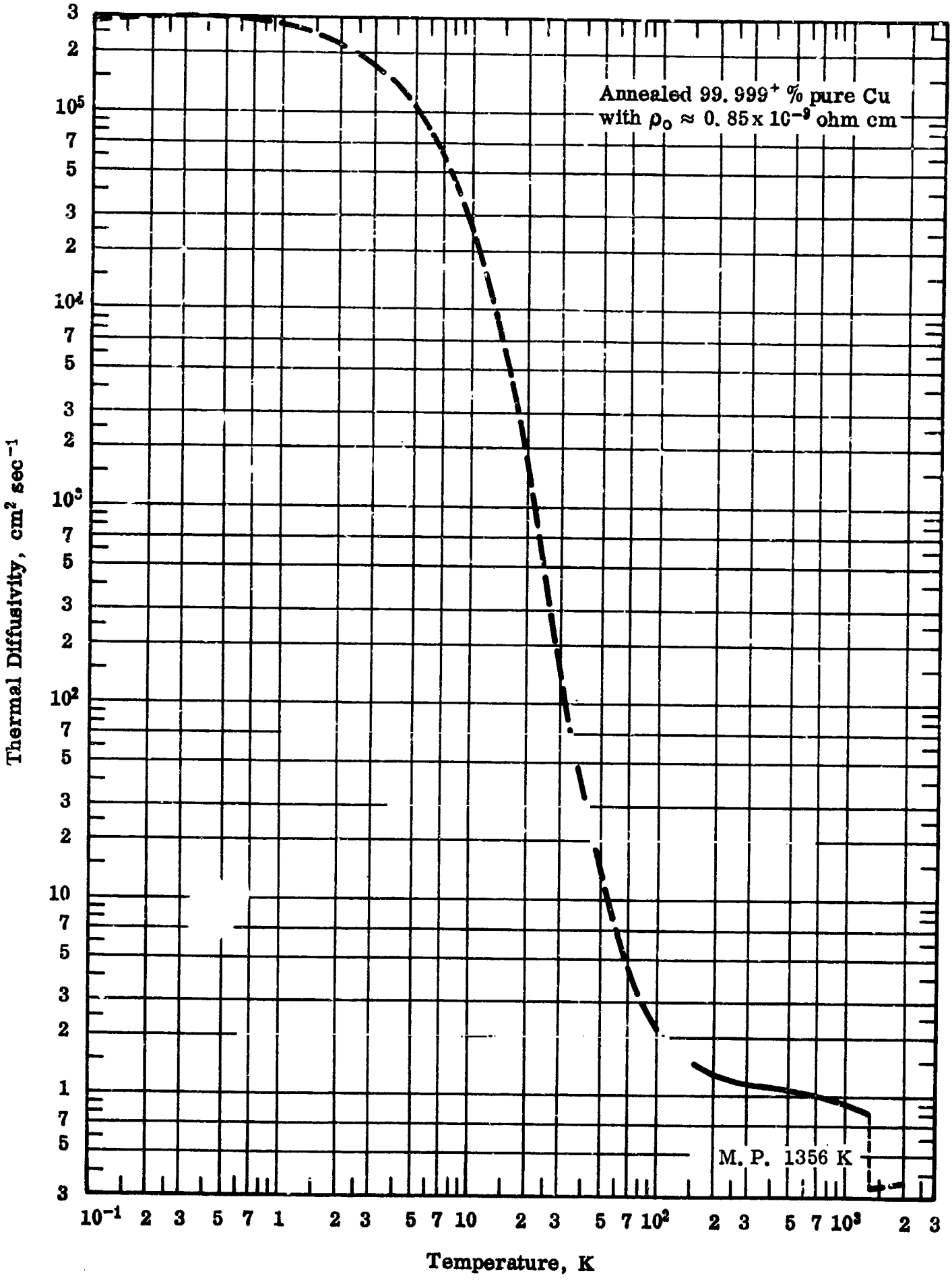

FIG. IV-4 THERMAL DIFFUSIVITY OF COPPER

TABLE IV-4 THERMAL DIFFUSIVITY OF COPPER

Selected Values for Annealed 99.999+ % Pure Copper with $\rho_o \approx 0.85 \times 10^{-9}$ ohm cm

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
0.1	280000*	500	1.08
0.5	287000*	600	1.04
1	275000*	700	1.01
5	105000*	800	0.98
10	25200*	900	0.94
15	6200*	1000	0.91
20	1570*	1100	0.89
30	174*	1200	0.85
40	38*	1300	0.82
50	13.6*	(fcc)1350	0.80*
60	6.9*	(l) 1360	0.342*
70	4.3*	1400	0.344*
80	3.1*	1500	0.347*
90	2.5*	1600	0.351*
100	2.1*	1700	0.354*
150	1.48*	1800	0.358*
200	1.28*	1900	0.362*
300	1.15	2000	0.366*
400	1.11		

Data Source and Remarks

Thirty-five sets of experimental data are available over the temperature range 295 to 1284 K. Selected values lie close to the data of Sidles and Danielson (1960, 1953, 1951) [6,7,8], Butler and Inn (1957) [9], Mrozawski, Andrew, Fund, Sato , Strauss, and Tsuzuku (1963) [10] Moser and Kruger (1963) [11], El-hifini and Chao (1956) [12], Sonnenschein and Winn (1960) [3], and Jenkins and Parker (1961) [4]. It is noted that the selected values are for purer copper than those measured by these authors.

* Calculated or estimated.

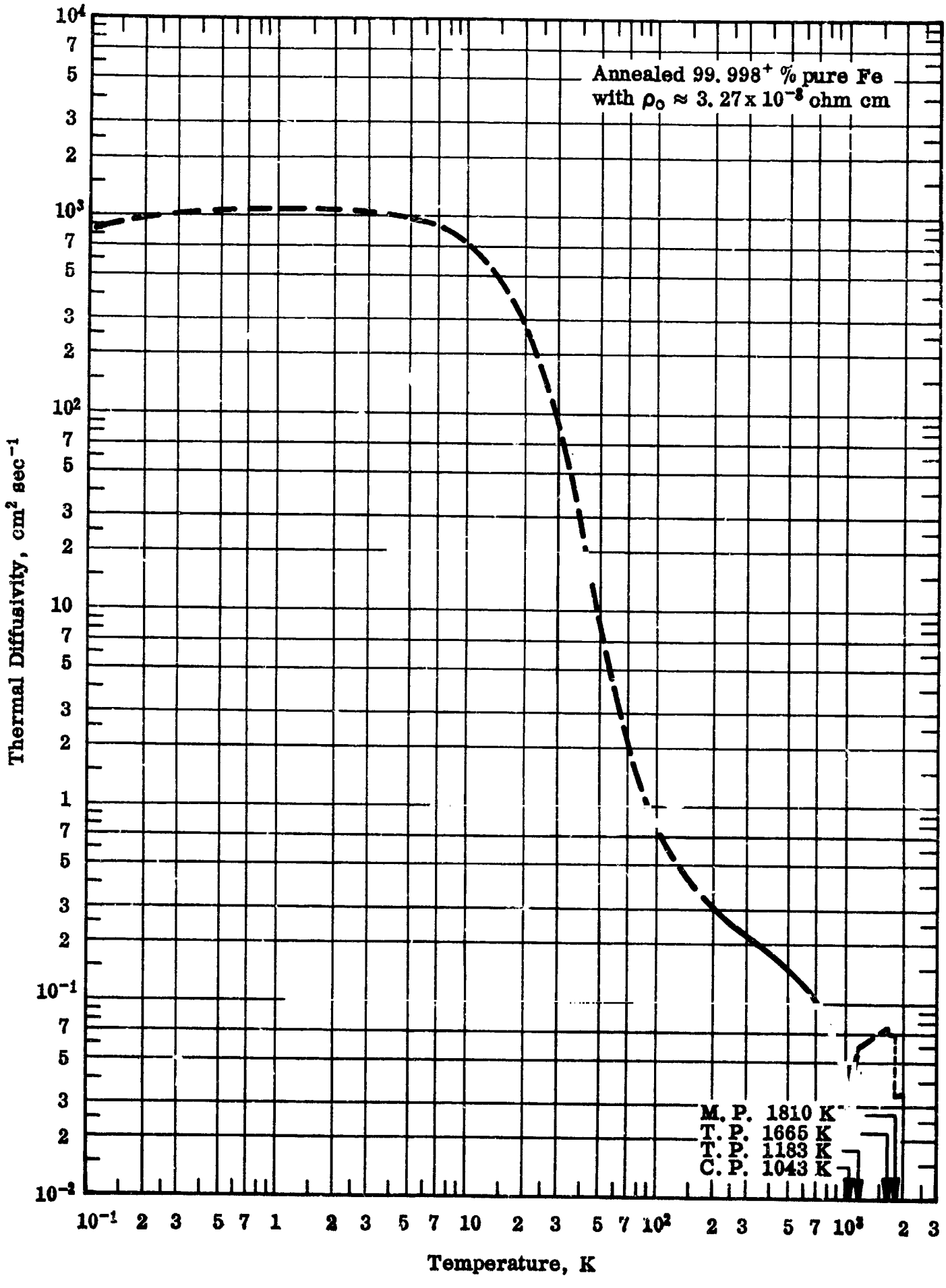

FIG. IV-5 THERMAL DIFFUSIVITY OF IRON

TABLE IV-5 THERMAL DIFFUSIVITY OF IRON

Selected Values for Annealed 99.998+% Pure Iron with $\rho_o \approx 3.27 \times 10^{-8}$ ohm cm

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
0.1	840*	500	0.149
1	1040*	600	0.125
5	950*	700	0.102
10	710*	800	0.082
20	273*	900	0.063
25	145*	1000	0.042
30	77*	1043	0.030
35	53*	1053	0.037
40	24*	1100	0.051
45	18*	(bcc) 1182	0.057
50	8.8*	(fcc) 1184	0.060
60	3.9*	1200	0.061
70	2.2*	1300	0.064
80	1.41*	1400	0.068*
90	1.02*	1500	0.071*
100	0.79*	1600	0.075*
150	0.41*	(fcc) 1664	0.077*
200	0.303*	(bcc) 1666	0.070*
250	0.256*	1700	0.070*
300	0.224	(bcc) 1800	0.069*
400	0.182	(l) 1900	0.035*

Data Source and Remarks

Twenty sets of experimental data are available over the temperature range 252 to 1460 K. Selected values lie close to the data of Sidles and Danielson (1960) [6], Abeles, Beers, Cody, Novak, and Rosi (1960, 1959) [13,14], Chiotti and Carlson (1956) [15], Kennedy (1960) [16] Dennis, Hirschman, Derksen, and Monahan (1960) [17], Moser and Kruger (1963) [11], and others. It is noted that most of these authors' data are for Armco iron while the selected values are for much purer iron.

*Calculated or estimated.

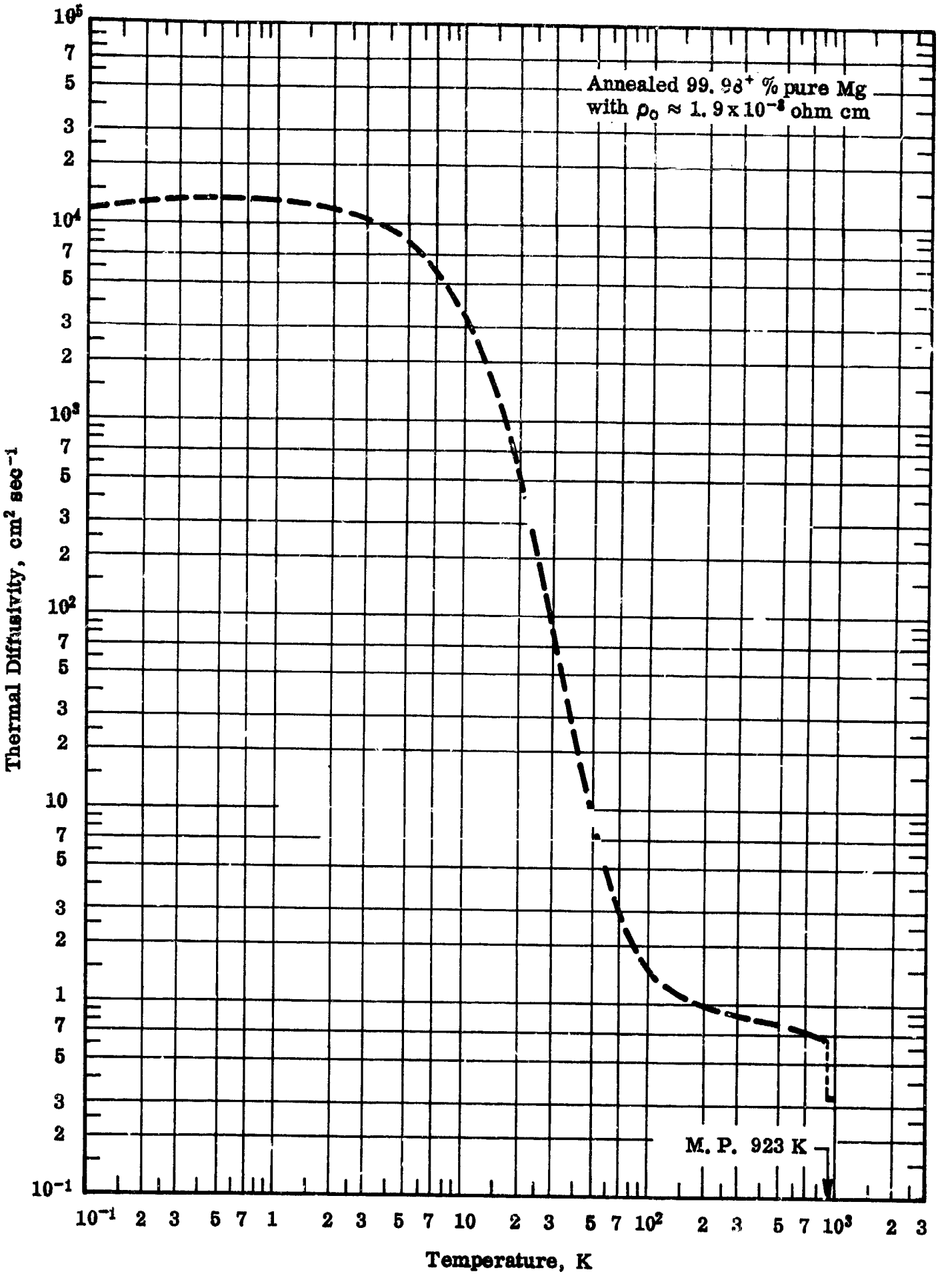

FIG. IV-6 THERMAL DIFFUSIVITY OF MAGNESIUM

TABLE IV-6 THERMAL DIFFUSIVITY OF MAGNESIUM

Selected Values for Annealed 99.98+ % Pure Magnesium with $\rho_o \approx 1.9 \times 10^{-8}$ ohm cm*

T, K	α, $cm^2 sec^{-1}$	T, K	α, $cm^2 sec^{-1}$
0.1	11500*	100	1.5
1	13000	150	1.1
5	8000	200	0.96
10	3500	300	0.86
20	530	400	0.81
30	92	500	0.78
40	23	600	0.74
50	9	700	0.71
60	4.6	800	0.67
70	2.9	900	0.64
80	2.2	(cph) 920	0.63
90	1.7	(l) 1000	0.33

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

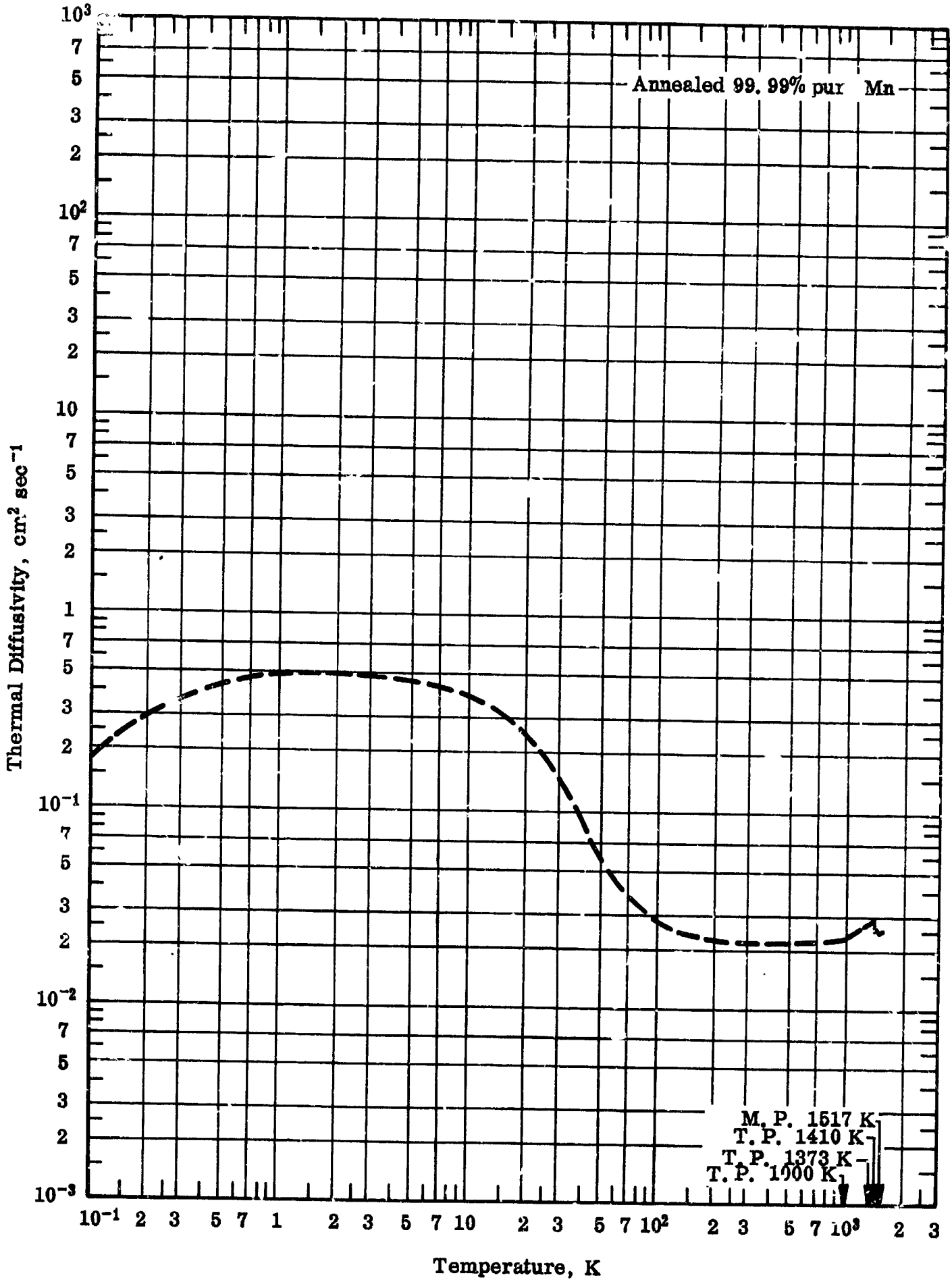

FIG. IV-7 THERMAL DIFFUSIVITY OF MANGANESE

TABLE IV-7 THERMAL DIFFUSIVITY OF MANGANESE

Selected Values for Annealed 99.99% Pure Manganese*

T,K	α, $cm^2 sec^{-1}$		T,K	α, $cm^2 sec^{-1}$
0.1	0.18*		400	0.0220
1	0.49		500	0.0220
5	0.44		600	0.0222
10	0.38		700	0.0224
15	0.31		800	0.0227
20	0.26		900	0.0230
30	0.14	(c)	995	0.0231
40	0.084	(c)	1005	0.0239
50	0.057		1100	0.0252
60	0.045		1200	0.0266
70	0.037		1300	0.0281
80	0.032	(c)	1370	0.0293
90	0.029	(fct)	1375	0.0256
100	0.0274		1400	0.0260
150	0.0237	(fct)	1409	0.0262
200	0.0227	(bcc)	1411	0.0254
300	0.0221		1500	0.0267

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

*All values are calculated or estimated.

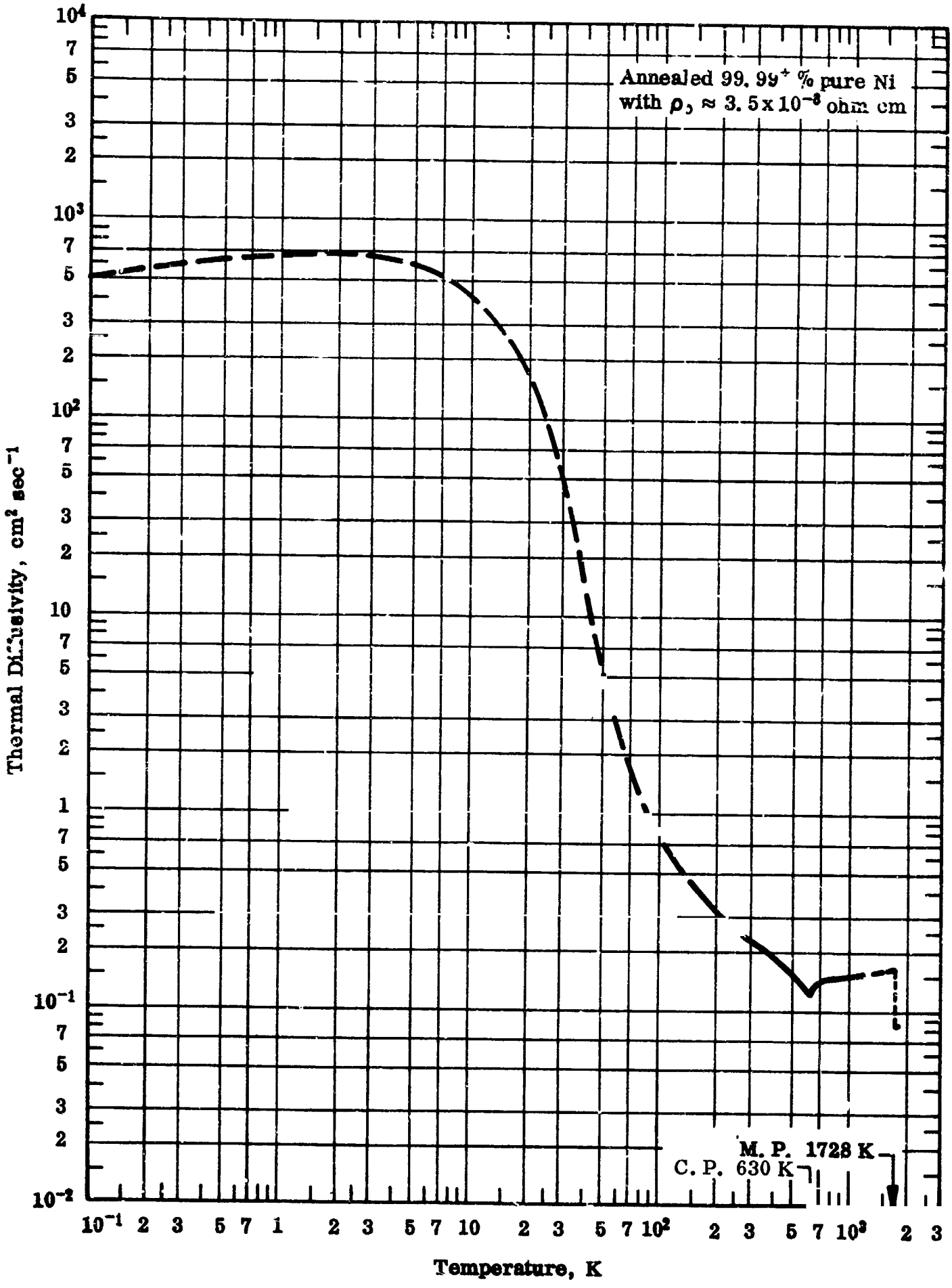

FIG. IV-8 THERMAL DIFFUSIVITY OF NICKEL

TABLE IV-8 THERMAL DIFFUSIVITY OF NICKEL

Selected Values for Annealed 99.99+ % Pure Nickel with $\rho_o \approx 3.5 \times 10^{-8}$ ohm cm

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
0.1	500*	400	0.183
1	650*	500	0.154
5	590*	600	0.124
10	410*	630	0.110
15	274*	635	0.127
20	163*	700	0.142
30	46*	800	0.145
40	13.6*	900	0.147
50	5.6*	1000	0.149
60	2.83*	1100	0.151
70	1.76*	1200	0.152
80	1.25*	1300	0.154*
90	0.94*	1400	0.156*
100	0.76*	1500	0.158*
150	0.42*	1600	0.160*
200	0.30*	(fcc) 1700	0.162*
300	0.22	(l) 1800	0.084*

Data Source and Remarks

Four sets of experimental data are available over the temperature range 298 to 1273 K. Selected values agree pretty well with the data of Sidles and Danielson (1930) [6].

* Calculated or estimated.

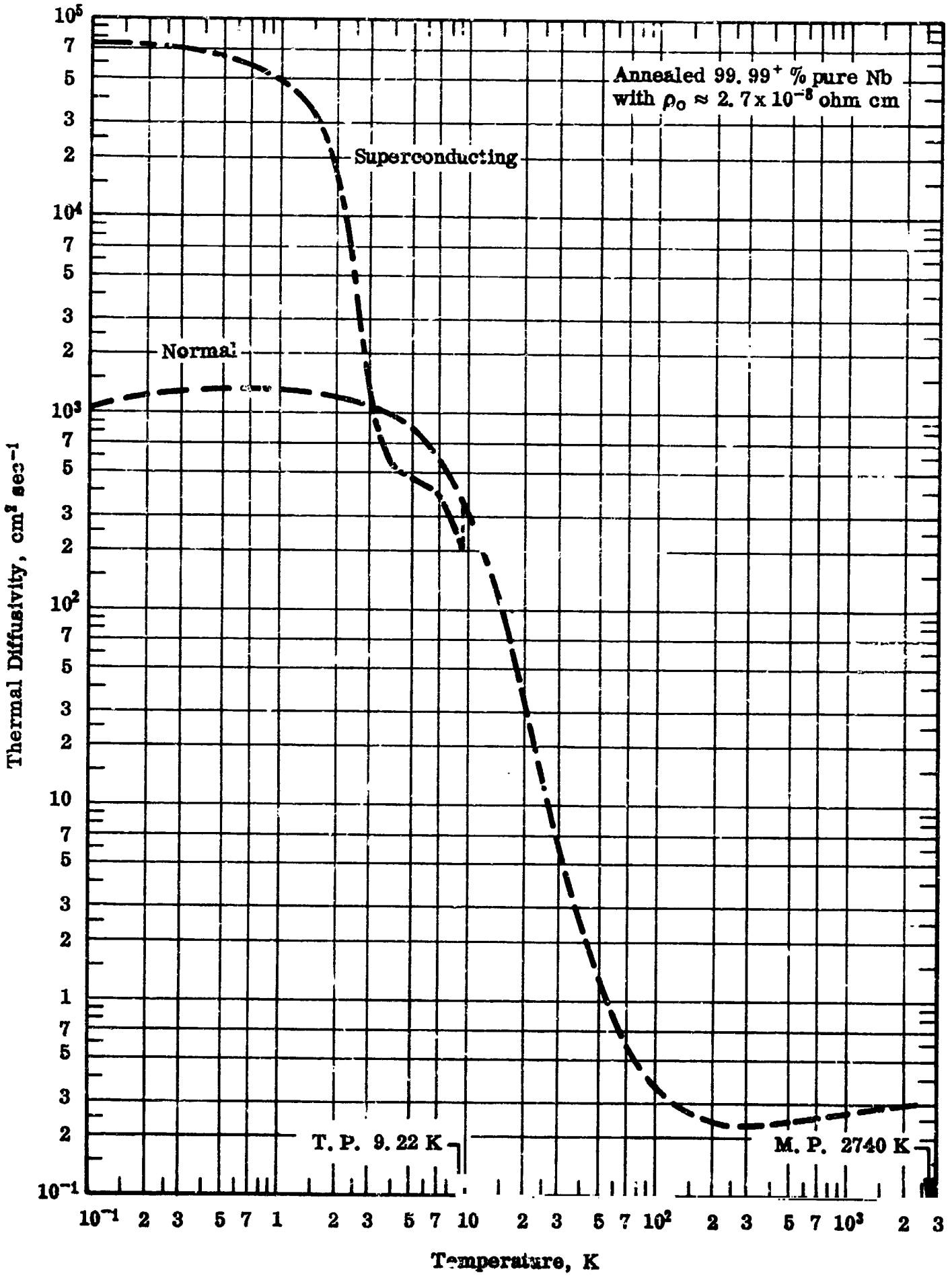

FIG. IV-9 THERMAL DIFFUSIVITY OF NIOBIUM

TABLE 17-9 THERMAL DIFFUSIVITY OF NIOBIUM

Selected Values for Annealed 99.99+ % Pure Niobium with $\rho_0 \approx 2.7 \times 10^{-8}$ ohm cm*

T,K	α, $cm^{-2}sec^{-1}$		T,K	α, $cm^2\ sec^{-1}$
	Normal	Superconducting		
0.1	1620*	75000	100	0.353
1	1290	48000	150	0.264
1.5		33000	200	0.242
2		14000	300	0.234
2.5		4200	400	0.236
3		1260	500	0.241
4		530	600	0.246
5	860	460	700	0.252
6		440	800	0.256
7		380	900	0.261
8		300	1000	0.266
9		210	1100	0.270
9.22		200	1200	0.274
10	310		1300	0.278
15	97		1400	0.281
20	34		1500	0.284
30	6.8		1600	0.287
40	2.5		1700	0.290
50	1.26		1800	0.292
60	0.81		1900	0.294
70	0.59		2000	0.296
80	0.47		2200	0.298
90	0.40		2400	0.300

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

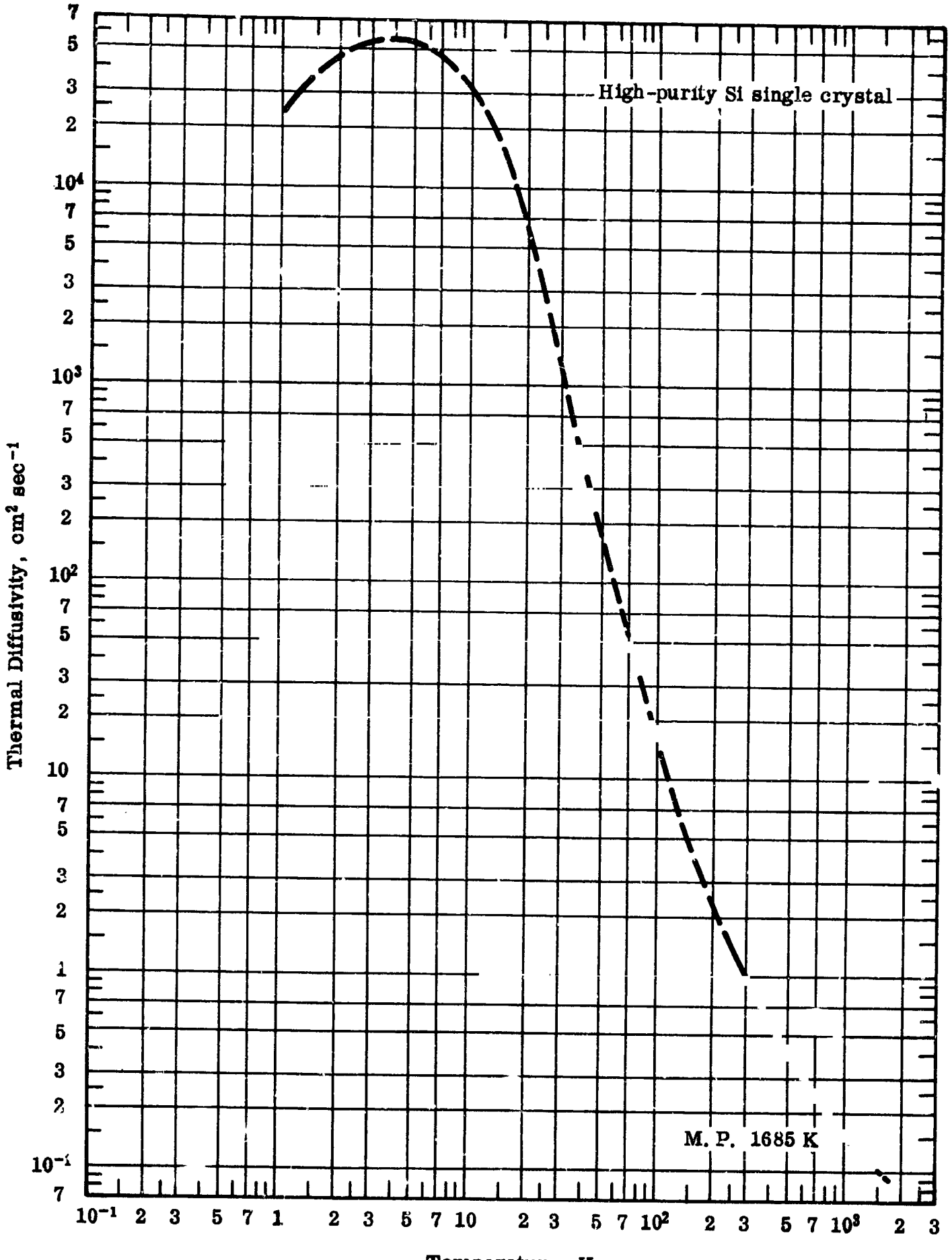

FIG. IV-10 THERMAL DIFFUSIVITY OF SILICON

TABLE IV-10 THERMAL DIFFUSIVITY OF SILICON

Selected Values for High-Purity Silicon Single Crystal

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	24000*	200	2.08*
2	46000*	300	0.38
3	53700*	400	0.55
5	54500*	500	0.40
7	45000*	600	0.30
10	31000*	700	0.24
15	14200*	800	0.20
20	5900*	900	0.168
30	1120*	1000	0.146
40	350*	1100	0.133
50	152*	1200	0.121
60	80*	1300	0.112
70	49*	1400	0.104*
80	31*	1500	0.099*
90	21.3*	1600	0.094*
100	15.1*	1680	0.091*
150	4.4*		

Data Source and Remarks

Four sets of experimental data are available over the temperature range 300 to 1390 K. Selected values from 300 to 1100 K agree well with the data of Shanks, Maycock, Sidles, and Danielson (1963) [18].

*Calculated or estimated.

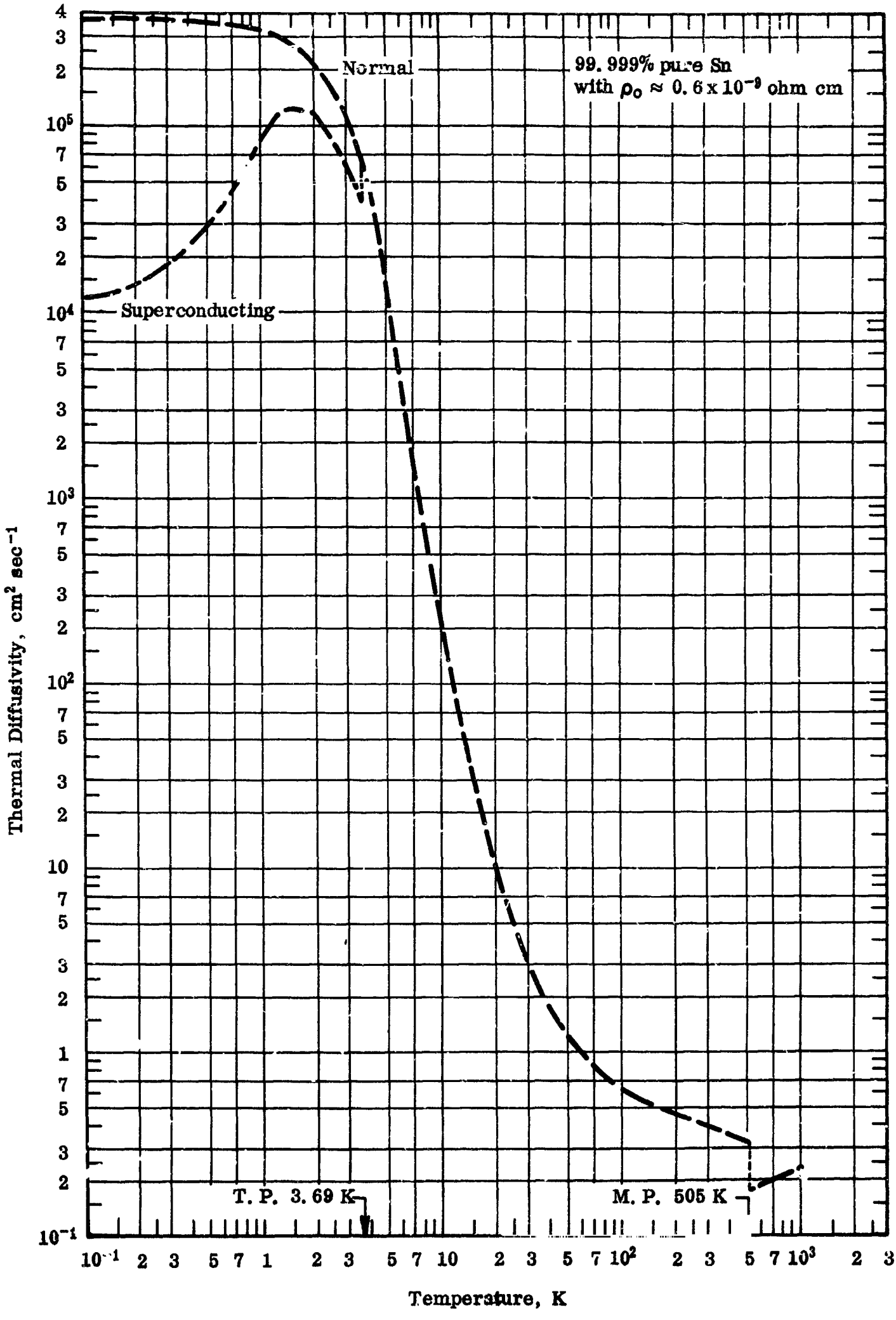
Normal
Superconducting
99.999% pure Sn
with $\rho_o \approx 0.6 \times 10^{-9}$ ohm cm
T. P. 3.69 K
M. P. 505 K
Thermal Diffusivity, $cm^2\ sec^{-1}$
Temperature, K

TABLE IV-11 THERMAL DIFFUSIVITY OF TIN

Selected Values for 99.999% Pure Tin with $\rho_o \approx 0.6 \times 10^{-9}$ ohm cm*

T,K	α, $cm^2 sec^{-1}$		T,K	α, $cm^2 sec^{-1}$
	Normal	Superconductivity		
0.1	360000*	12300	50	1.18
0.3		17700	60	0.93
0.5	350000	28400	70	0.80
1	320000	87000	80	0.72
1.5		123000	90	0.66
2	216000	112000	100	0.61
2.5		89000	150	0.51
3	109000	64000	200	0.46
3.5		44000	300	0.40
3.69		39000	400	0.35
4	44000		500	0.32
5	13200		(bct) 504	0.32
10	190		(l) 506	0.176
15	30		600	0.190
20	10		700	0.202
25	4.8		800	0.213
30	3.0		900	0.224
40	1.7		1000	0.235

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

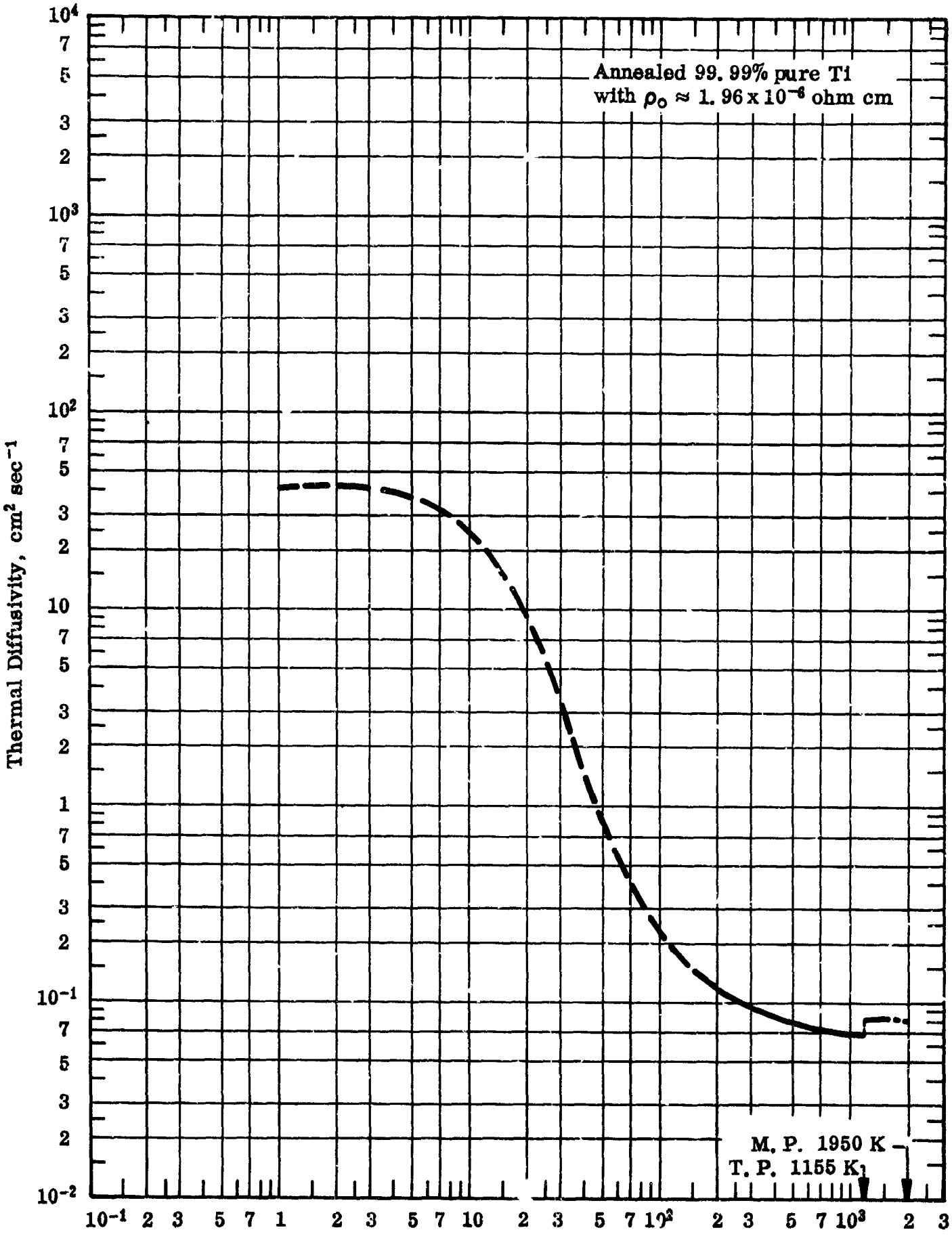

FIG. IV-12 THERMAL DIFFUSIVITY OF TITANIUM

TABLE IV-12 THERMAL DIFFUSIVITY OF TITANIUM

Selected Values for Annealed 99.99% Pure Titanium with $\rho_o \approx 1.96 \times 10^{-6}$ ohm cm

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ Sec^{-1}$
1	41*	500	0.077
5	37*	600	0.074
10	24.4*	700	0.072
15	15.5*	800	0.070
20	9.0*	900	0.070
30	3.4*	1000	0.069
40	1.53*	1100	0.069
50	0.85*	(cph) 1150	0.069
60	0.55*	(bcc) 1160	0.081
70	0.40*	1200	0.081
80	0.32*	1300	0.082
90	0.26*	1400	0.083
100	0.225*	1500	0.084
150	0.147*	1600	0.084*
200	0.118*	1700	0.084*
300	0.093	1800	0.084*
400	0.083	1900	0.083*

Data Source and Remarks

Four sets of experimental data are available over the temperature range 253 to 1598 K. Selected values from 500 to 800 K lie close to the data of Karagezyan (1962) [19] and values from 1400 to 1600 K close to the data of Rudkin, Parker, and Jenkins (1963) [20].

*Calculated or estimated.

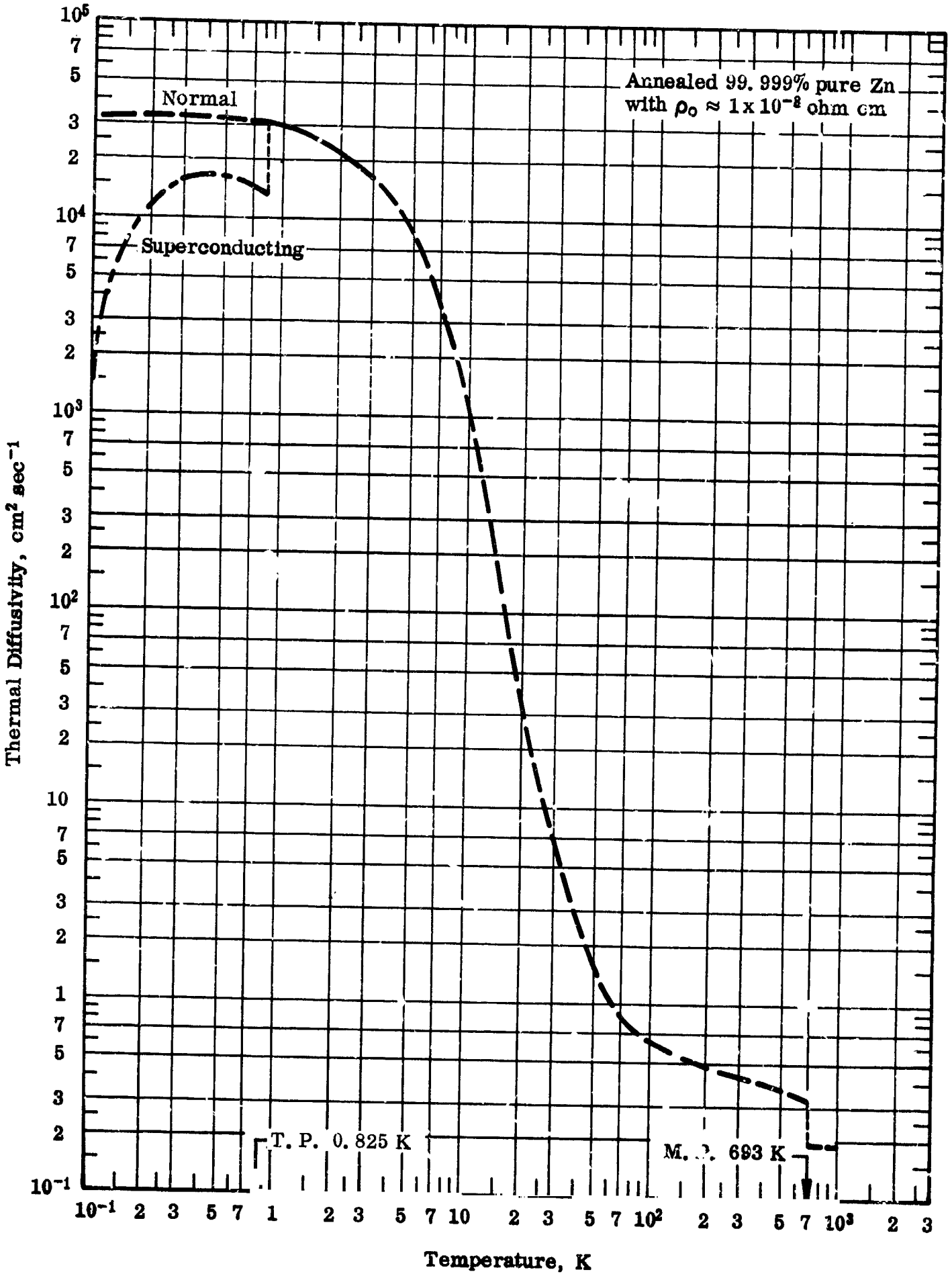

FIG. IV-13 THERMAL DIFFUSIVITY OF ZINC

TABLE IV-13 THERMAL DIFFUSIVITY OF ZINC

Selected Values for Annealed 99.999% Pure Zinc with $\rho_0 \approx 1 \times 10^{-8}$ ohm cm

T,K	α, cm^2 sec^{-1}			T,K	α, cm^2 sec^{-1}
	Normal	Superconducting			
0.1	32000*	1410*		40	2.64*
0.2		11100		50	1.47*
0.3		15600		60	1.03*
0.4		16500		70	0.83*
0.5	31500*	15900		80	0.72*
0.6		15000		90	0.66*
0.7		14100		100	0.63*
0.8		13300		150	0.52*
0.825		13000		200	0.47*
1	29600			300	0.42
3	16000*			400	0.39
5	8100*			500	0.37*
7	3900*			600	0.34*
9	1430*		(cph)	690	0.32*
10	900*		(l)	700	0.19*
15	130*			800	0.19*
20	34			900	0.19*
30	6.7*			1000	0.19*

Data Source and Remarks

Six sets of experimental data are available over the temperature ranges 0.15 to 2 K and 295 to 408 K. Selected values from 295 to 408 K agree well with the data of Jenkins and Parker (1961) [4] and Frazier (1933) [21]. In the low temperature range selected values are higher than the data of Zavaritskii (1958) [1] since the selected values are for purer zinc.

* Calculated or estimated.

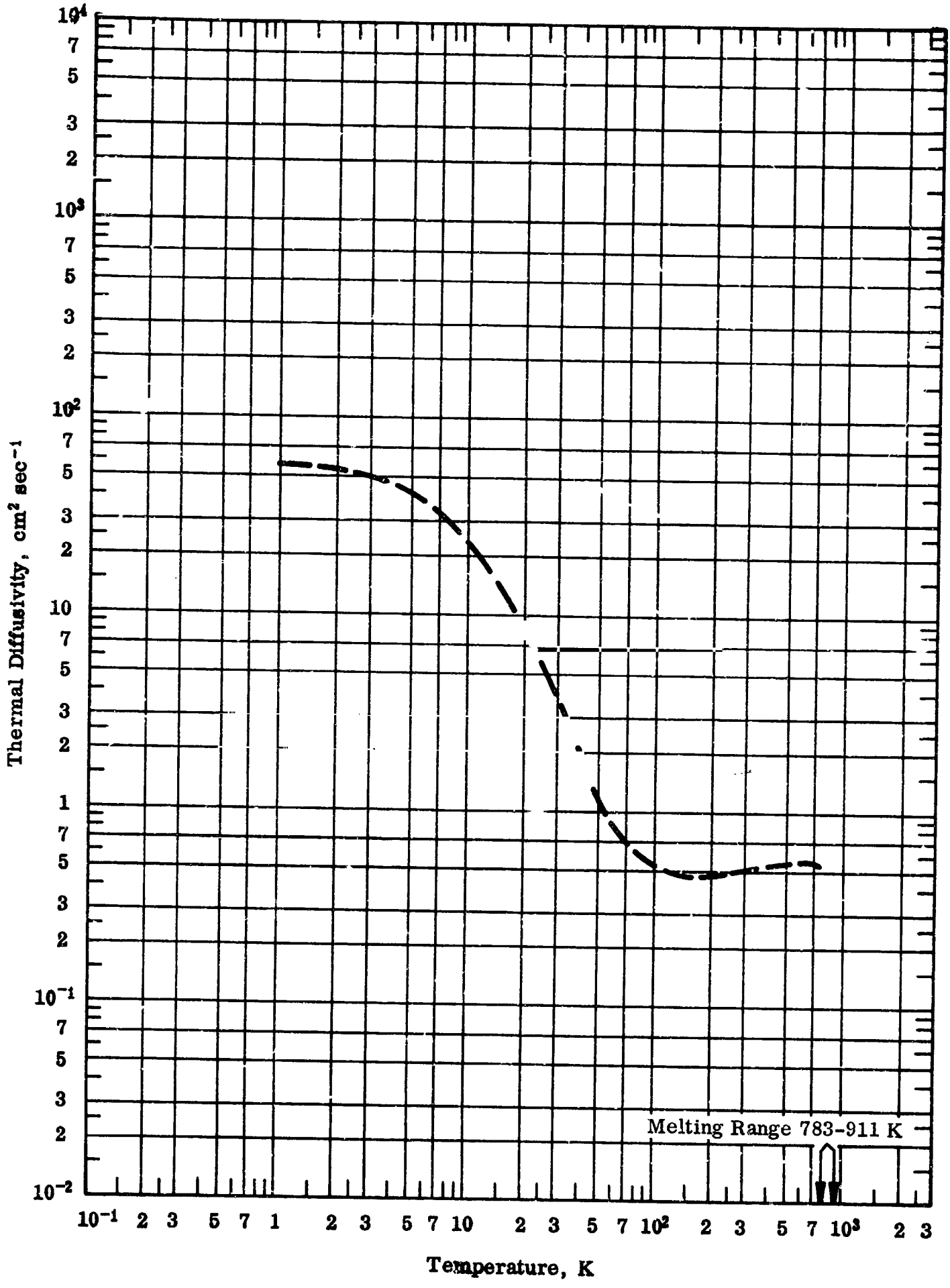

FIG. IV-14 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2219-T852

TABLE IV-14 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2219-T852*

T,K	α, $cm^2\ sec^{-1}$
1	56*
5	41
10	22
25	5.3
50	1.09
75	0.64
100	0.52
150	0.46
200	0.46
250	0.48
300	0.50
400	0.54
500	0.55
600	0.57
700	0.55
780	0.53

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated. Heating at moderately high temperature can destroy the "T852" temper and the thermal conductivity will consequently become higher (see Fig. IV-16 for aluminum alloy 7075-T6 for comparison).

* All values are calculated or estimated.

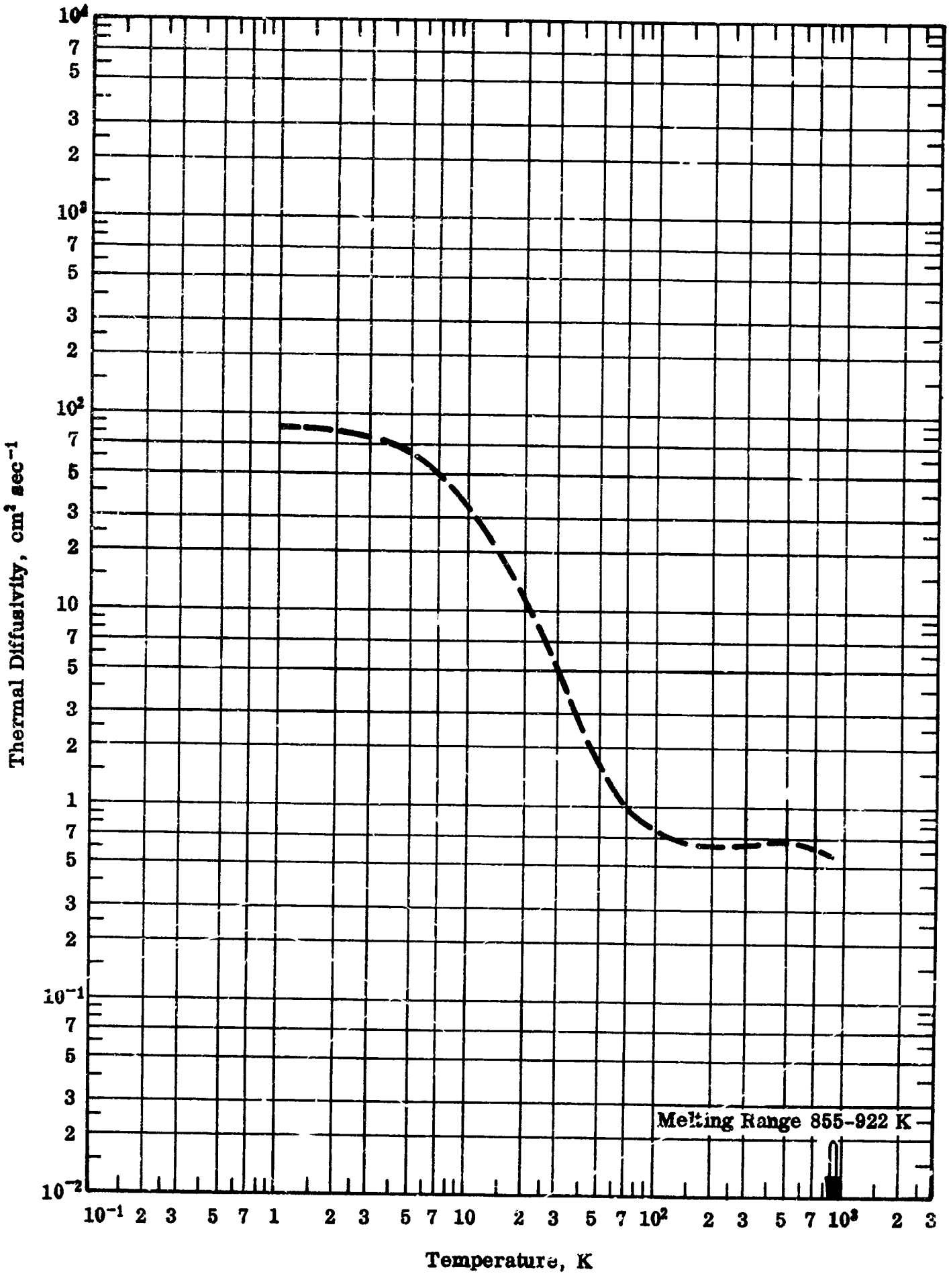

FIG. IV-15 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 6061-T6

TABLE IV-15 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 6061-T6*

T,K	α, $cm^2\ sec^{-1}$
1	85*
5	64
10	34
25	7.7
50	1.61
75	0.92
100	0.75
150	0.65
200	0.63
250	0.64
300	0.64
400	0.66
500	0.69
600	0.67
700	0.63
800	0.60
850	0.58

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated. Heating at moderately high temperature can destroy the "T6" temper and the thermal conductivity will consequently become higher (see Fig. IV-16 for aluminum alloy 7075-T6 for comparison).

* All values calculated or estimated.

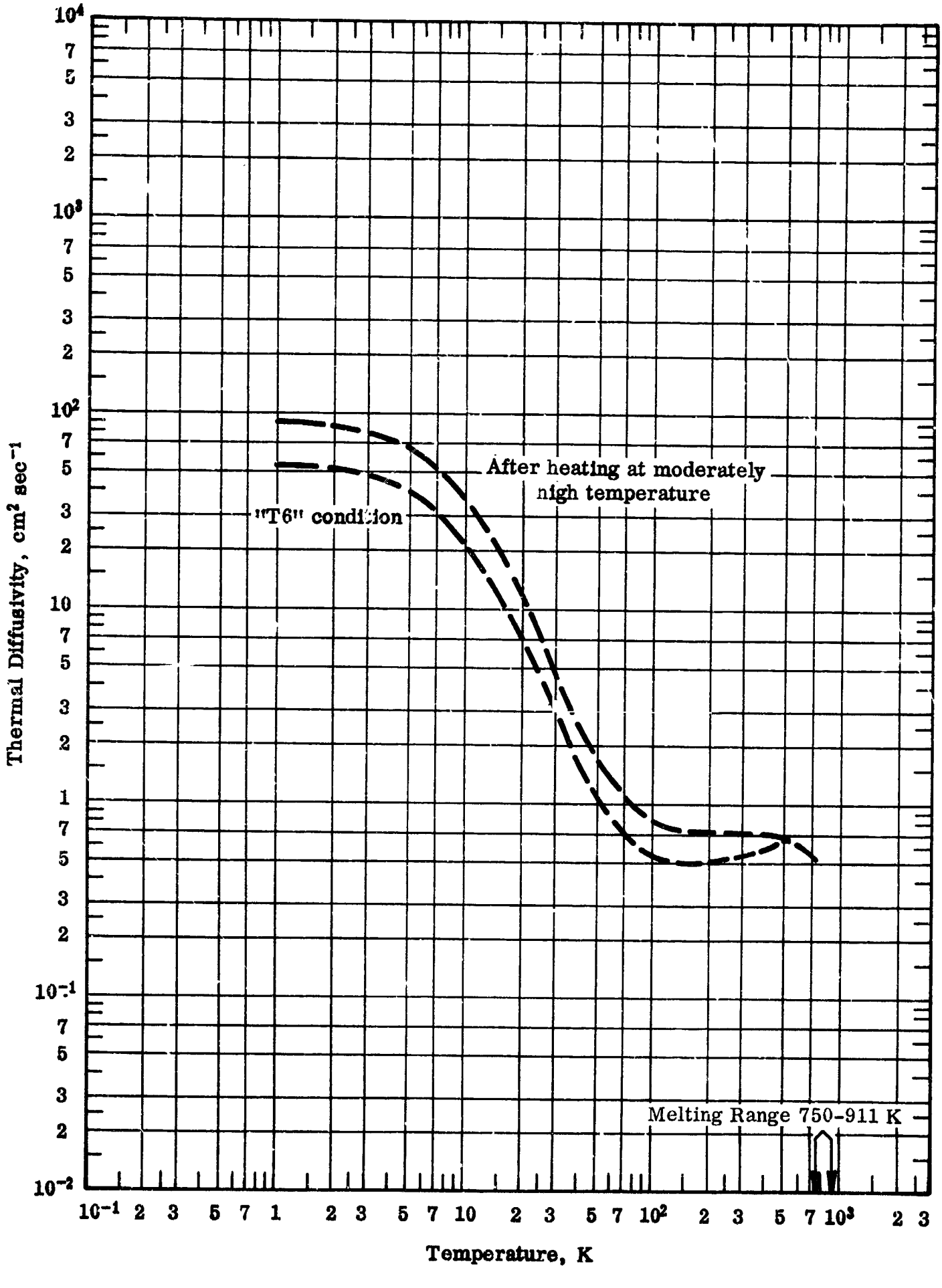

FIG. IV-16 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 7075-T6

TABLE IV-16 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 7075-T6*

"T6" Condition		After Heating at Moderately High temperature	
T, K	α, $cm^2\ sec^{-1}$	T, K	α, $cm^2\ sec^{-1}$
1	53*	1	88
5	40	5	66
10	21	10	35
25	4.6	25	7.5
50	1.1	50	1.7
75	0.65	75	0.98
100	0.54	100	0.81
150	0.50	150	0.72
200	0.51	200	0.72
250	0.52	250	0.72
300	0.53	300	0.72
400	0.56	400	0.71
500	0.66	500	0.68
600	0.62	600	0.62
700	0.55	700	0.55
745	0.52	745	0.52

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

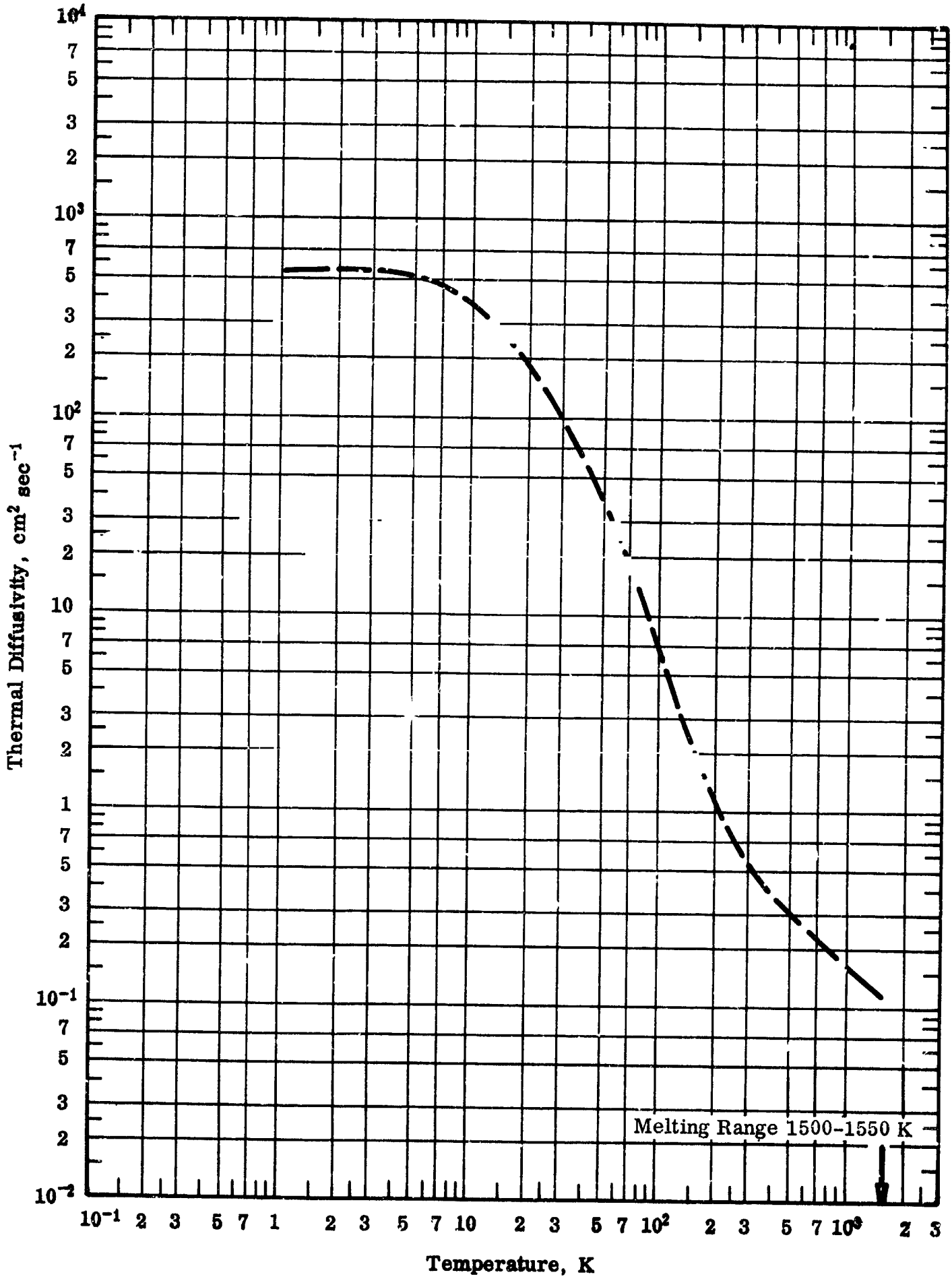

FIG. IV-17 THERMAL DIFFUSIVITY OF BERYLLIUM (DILUTE) ALLOY

TABLE IV-17 THERMAL DIFFUSIVITY OF BERYLLIUM (DILUTE) ALLOY*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	530*	250	0.69
5	500	300	0.52
10	370	400	0.37
15	250	500	0.30
20	176	600	0.25
30	96	700	0.22
40	58	800	0.192
50	38	900	0.173
60	25	1000	0.157
70	17	1100	0.144
80	12	1200	0.133
90	8.6	1300	0.123
100	6.5	1400	0.117
150	2.12	1495	0.110
200	1.04		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

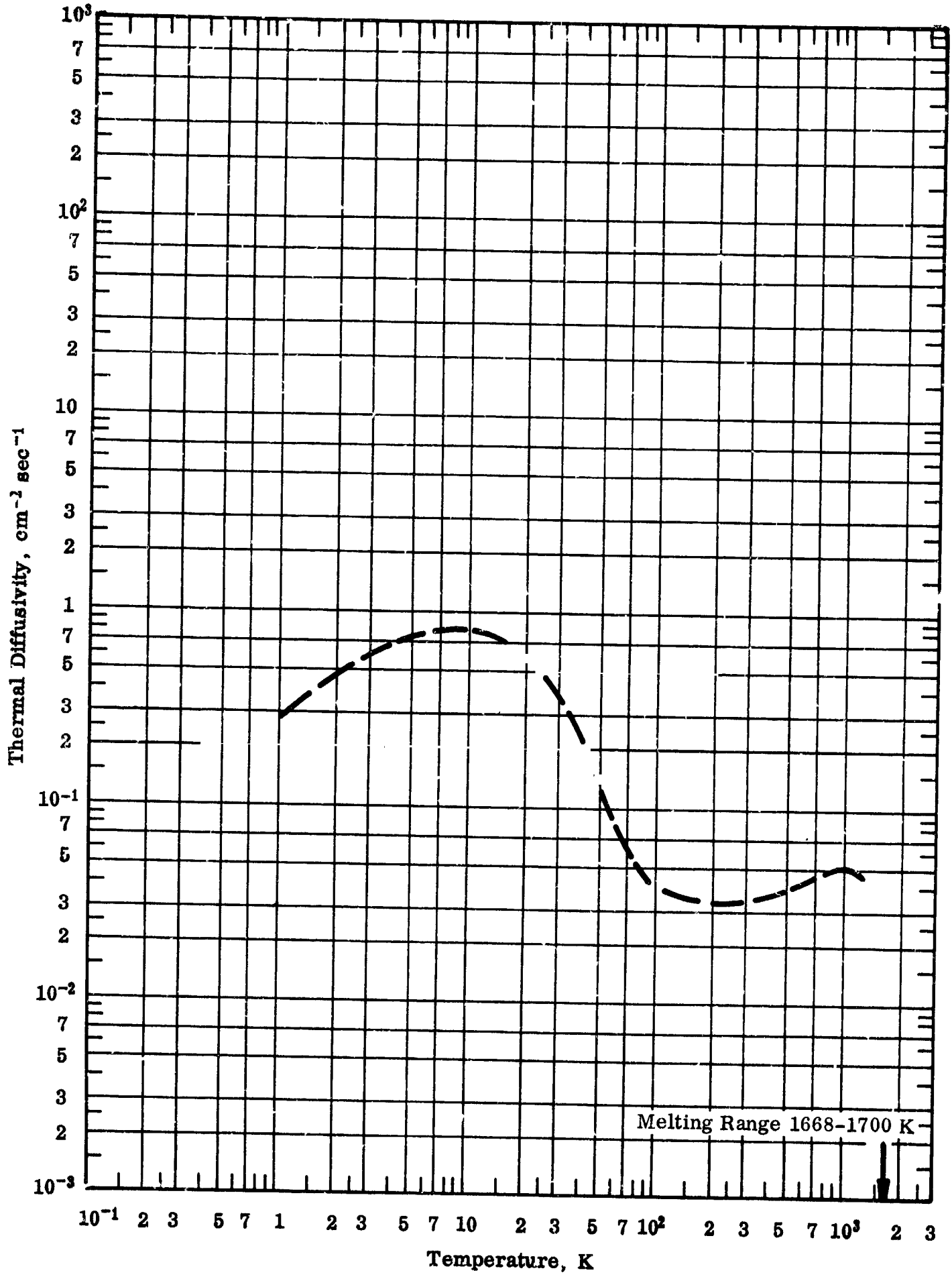

FIG. IV-18 THERMAL DIFFUSIVITY OF INCONEL X-750

TABLE IV-18 THERMAL DIFFUSIVITY OF INCONEL X-750*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	0.28*	400	0.035
5	0.71	500	0.038
10	0.79	600	0.041
25	0.47	700	0.044
50	0.124	800	0.047
75	0.055	900	0.048
100	0.038	1000	0.048
150	0.034	1100	0.048
200	0.033	1200	0.046
250	0.033	1300	0.042
300	0.033		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

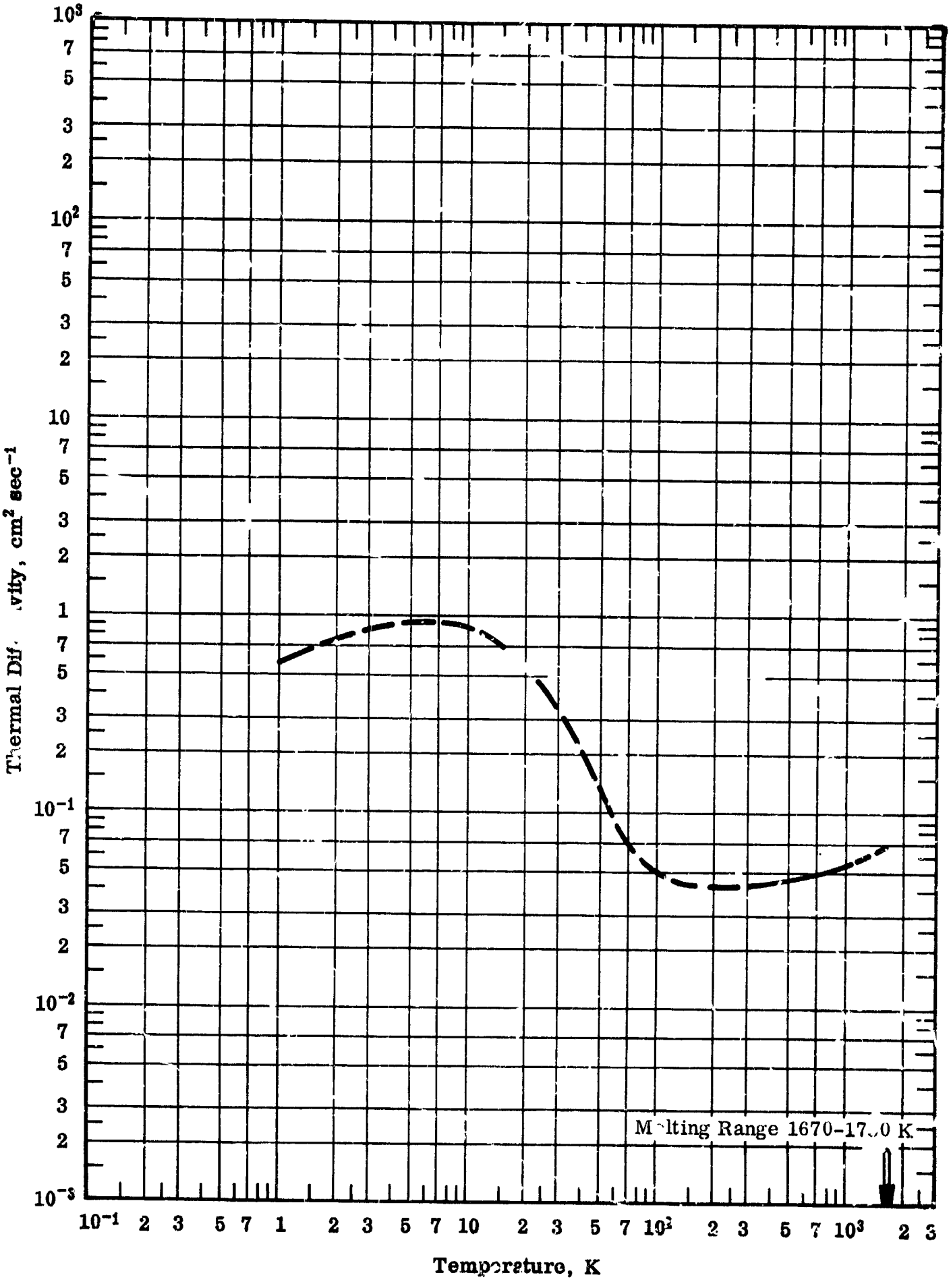

FIG. IV-19 THERMAL DIFFUSIVITY OF STAINLESS STEEL 304A

TABLE IV-19 THERMAL DIFFUSIVITY OF STAINLESS STEEL 304 A

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	0.56*	300	0.042
5	0.91*	400	0.043
10	0.88*	500	0.044
25	0.44*	600	0.045
50	0.138*	700	0.047
75	0.060*	800	0.049
100	0.047*	900	0.050
150	0.042*	1000	0.051
200	0.041*	1100	0.052
250	0.041*	1200	0.053

Data Source and Remarks

There are two sets of available experimental data from Jenkins and Parker (1961) [4] over the temperature range 293 to 1263 K. Selected values above room temperature are derived from their data with modifications and adjustments.

*Calculated or estimated.

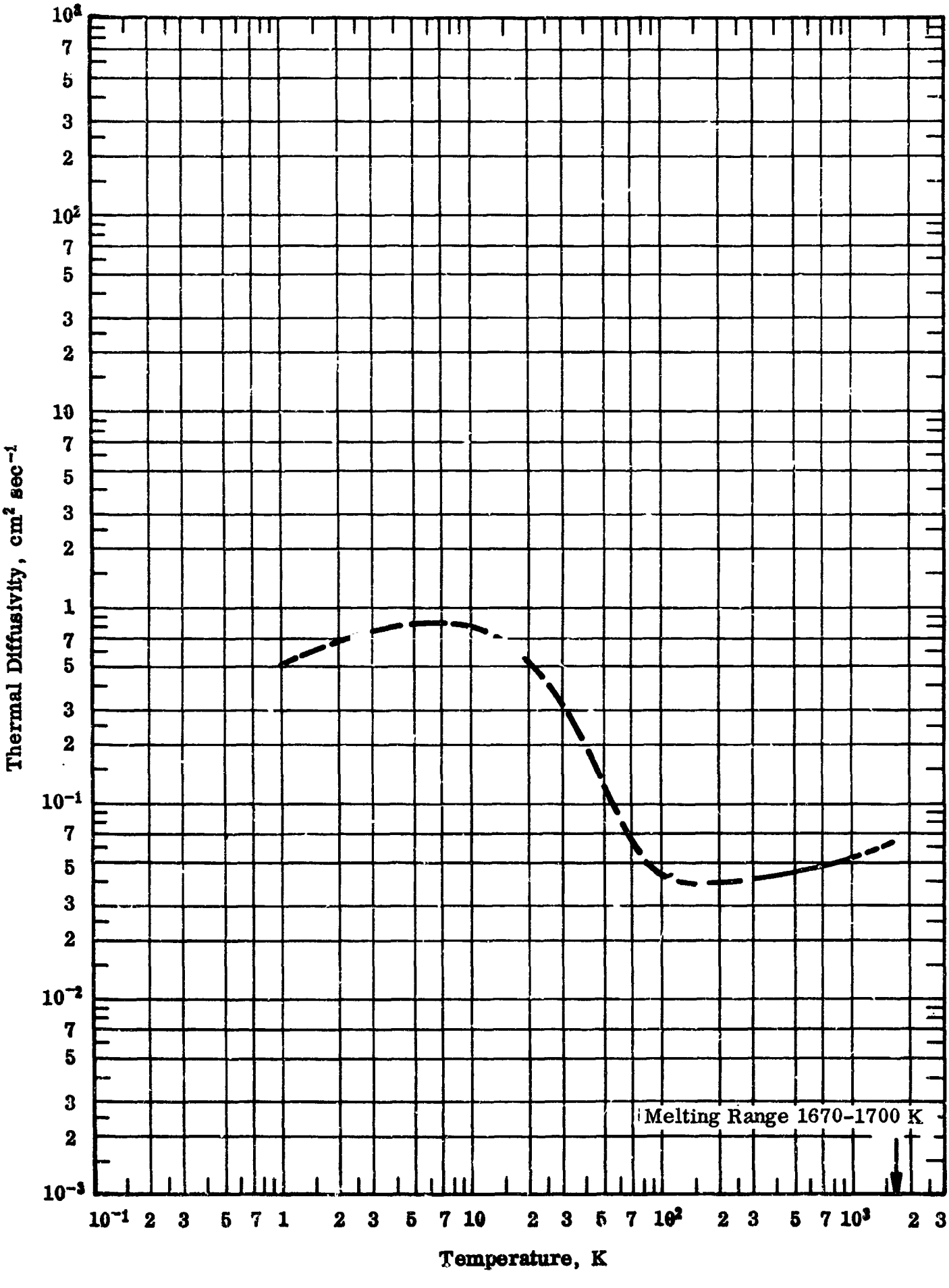

FIG. IV-20 THERMAL DIFFUSIVITY OF STAINLESS STEEL 347

TABLE IV-20 THERMAL DIFFUSIVITY OF STAINLESS STEEL 347

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	0.50*	300	0.041
5	0.82*	400	0.042
10	0.79*	500	0.043
25	0.41*	600	0.045
50	0.13*	700	0.047
75	0.056*	800	0.049
100	0.043*	900	0.050
150	0.039*	1000	0.051
200	0.039*	1100	0.052
250	0.040*	1200	0.053

Data Source and Remarks

There are two sets of available experimental data from Jenkins and Parker (1961) [4] over the temperature range 298 to 1200 K. Selected values at high temperatures are derived from their data.

*Calculated or estimated.

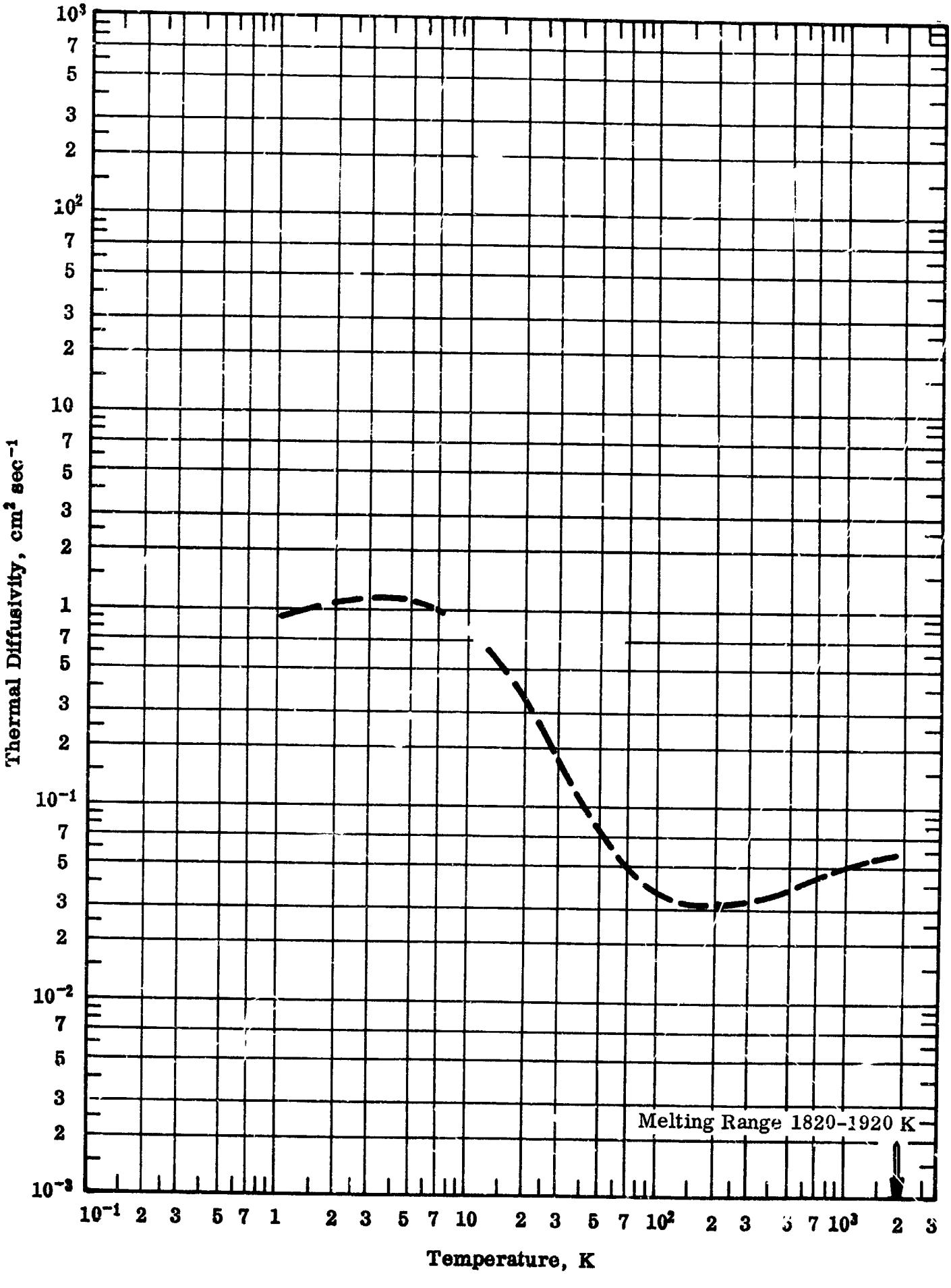

FIG. IV-21 THERMAL DIFFUSIVITY OF TITANIUM ALLOY A-110AT

TABLE IV-21 THERMAL DIFFUSIVITY OF TITANIUM ALLOY A-110AT*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	0.88*	600	0.041
5	0.08	700	0.044
10	0.76	800	0.046
20	0.33	900	0.048
25	0.22	1000	0.050
50	0.069	1100	0.052
75	0.042	1200	0.053
100	0.035	1300	0.054
150	0.031	1400	0.055
200	0.031	1500	0.056
250	0.032	1600	0.056
300	0.033	1700	0.057
400	0.035	1800	0.057
500	0.038		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

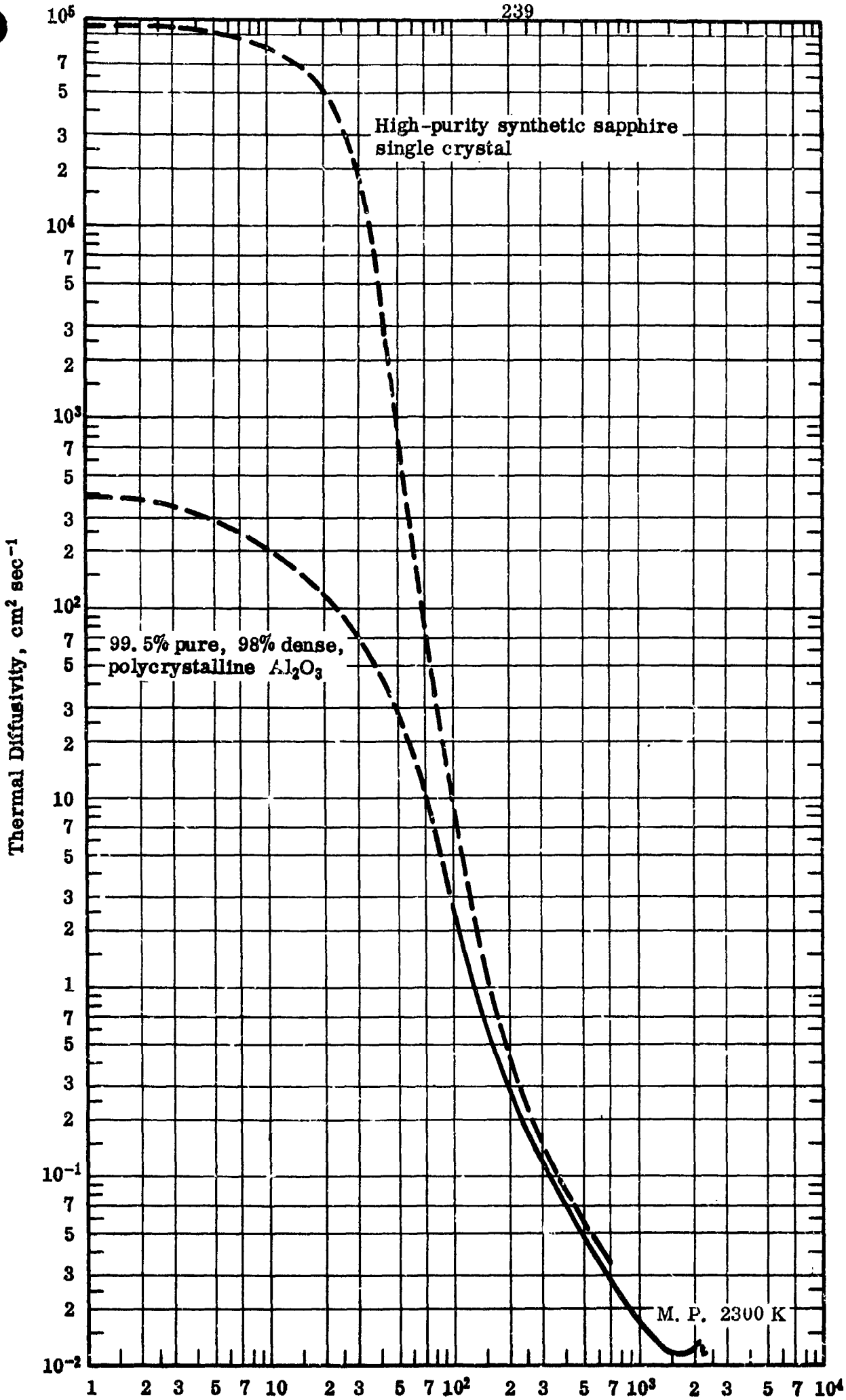

FIG. IV-22 THERMAL DIFFUSIVITY OF ALUMINUM OXIDE Al_2O_3

TABLE IV-22 THERMAL DIFFUSIVITY OF ALUMINUM OXIDE Al_2O_3

	99.5% Pure, 98% Dense, Polycrystalline Al_2O_3	High-Purity Synthetic Sapphire Single Crystal
T,K	α, $cm^2\ sec^{-1}$	α, $cm^2\ sec^{-1}$
1	380*	111000*
5	290*	104000*
10	200*	86000*
15	150*	69000*
20	120*	53000*
25	96*	36000*
30	74*	20200*
35	58*	10300*
40	46*	4400*
45	37*	1900*
50	29*	890*
60	17.5*	244*
70	10.6*	86*
80	6.5*	36*
90	4.0	16.9*
100	2.64	9.0*
150	0.62	1.2*
200	0.28	0.43*
250	0.17	0.23*
300	0.118	0.15*
350	0.090	0.112*
400	0.072	0.087*
450	0 060	0.071*
500	0.050	0.060*
600	0.037	0.044*
700	0.0284	0.034*
800	0.0227	
900	0.0194	
1000	0.0168	

* Calculated or estimated.

TABLE IV-22 (Continued)

T,K	99.5% Pure, 98% Dense, Polycrystalline Al_2O_3 α, $cm^2\ sec^{-1}$	High-Purity Synthetic Sapphire Single Crystal α, $cm^2\ sec^{-1}$
1100	0.0150	
1200	0.0137	
1300	0.0128	
1400	0.0122	
1500	0.0117	
1600	0.0115	

Data Source and Remarks

Forty sets of experimental data for polycrystalline aluminum oxide are available over the temperature range 84 to 1998 K. Selected values from 80 to 250 K lie close to the data of Soxman (1957) [22] and values at high temperatures close to the data of Rudkin, Parker, and Jenkins (1963) [20], Rudkin (1963) [23], Crandall and Ging (1955) [24], and Fitzsimmons (1950) [25]. There are no data available for alumina single crystal.

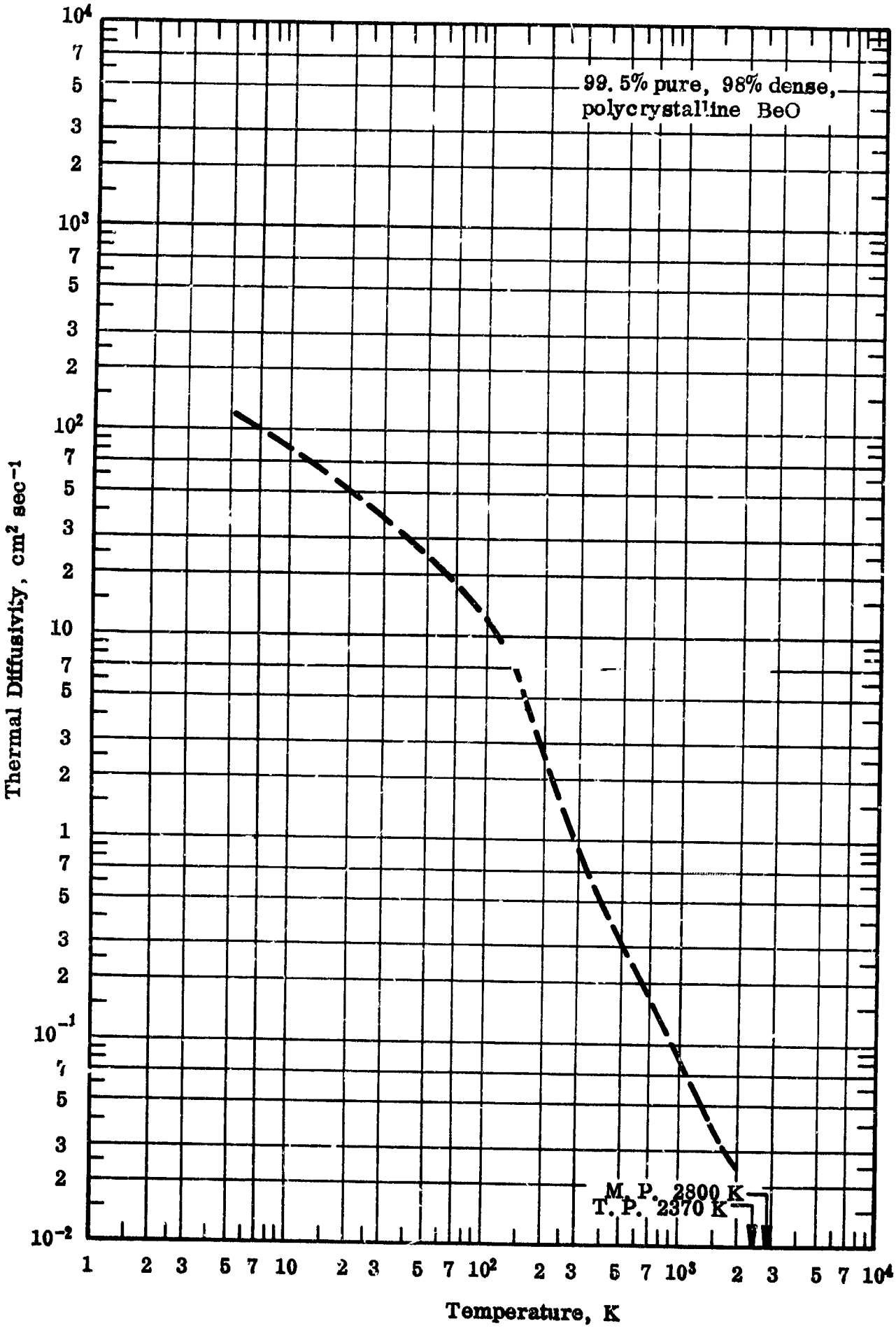

FIG. IV-23 THERMAL DIFFUSIVITY OF BERYLLIUM OXIDE BeO

TABLE IV-23 THERMAL DIFFUSIVITY OF BERYLLIUM OXIDE BeO

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline BeO

T, K	α, $cm^2\ sec^{-1}$	T, K	α, $cm^2\ sec^{-1}$
1	170*	400	0.50
5	120*	450	0.39
10	33*	500	0.32
15	64*	600	0.224
20	52*	700	0.168
30	38*	800	0.130
40	30*	900	0.102
50	25*	1000	0.082
60	21*	1100	0.068
70	18*	1200	0.056
80	16*	1300	0.048
90	14.4*	1400	0.041
100	12.6*	1500	0.036
150	5.8*	1600	0.033
200	2.5*	1700	0.030
250	1.4*	1800	0.028
300	0.90	1900	0.026
350	0.65	2000	0.025

Data Source and Remarks

Four sets of experimental data are available over the temperature range 293 to 2200 K. Selected values lie close to the data of Elston and Caillat (1958) [26] and Rudkin (1963) [23].

*Calculated or estimated.

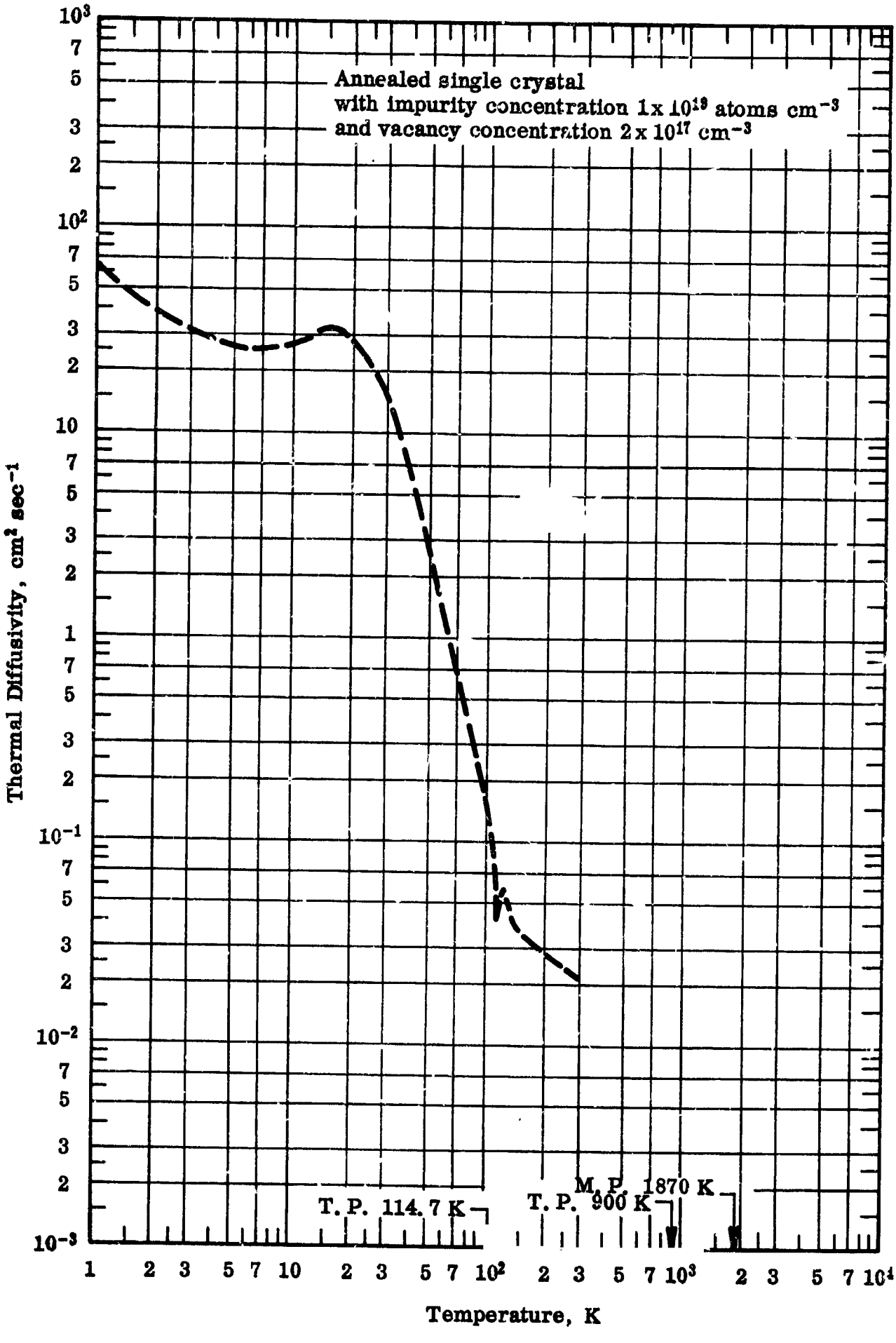

FIG. IV-24 THERMAL DIFFUSIVITY OF IRON OXIDE Fe_3O_4

TABLE IV-24 THERMAL DIFFUSIVITY OF IRON OXIDE Fe_3O_4

Selected Values for Annealed Single Crystal with Impurity Concentration 1×10^{19} atoms cm^{-3} and Vacancy Concentration 2×10^{17} cm^{-3}*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	65*	100	0.15
5	26	110	0.085
10	27	114	0.045
15	33	114.7	0.040
20	28	116	0.049
30	15	120	0.059
40	6	130	0.041
50	2.6	140	0.037
60	1.3	150	0.035
70	0.68	200	0.028
80	0.39	300	0.021
90	0.24		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

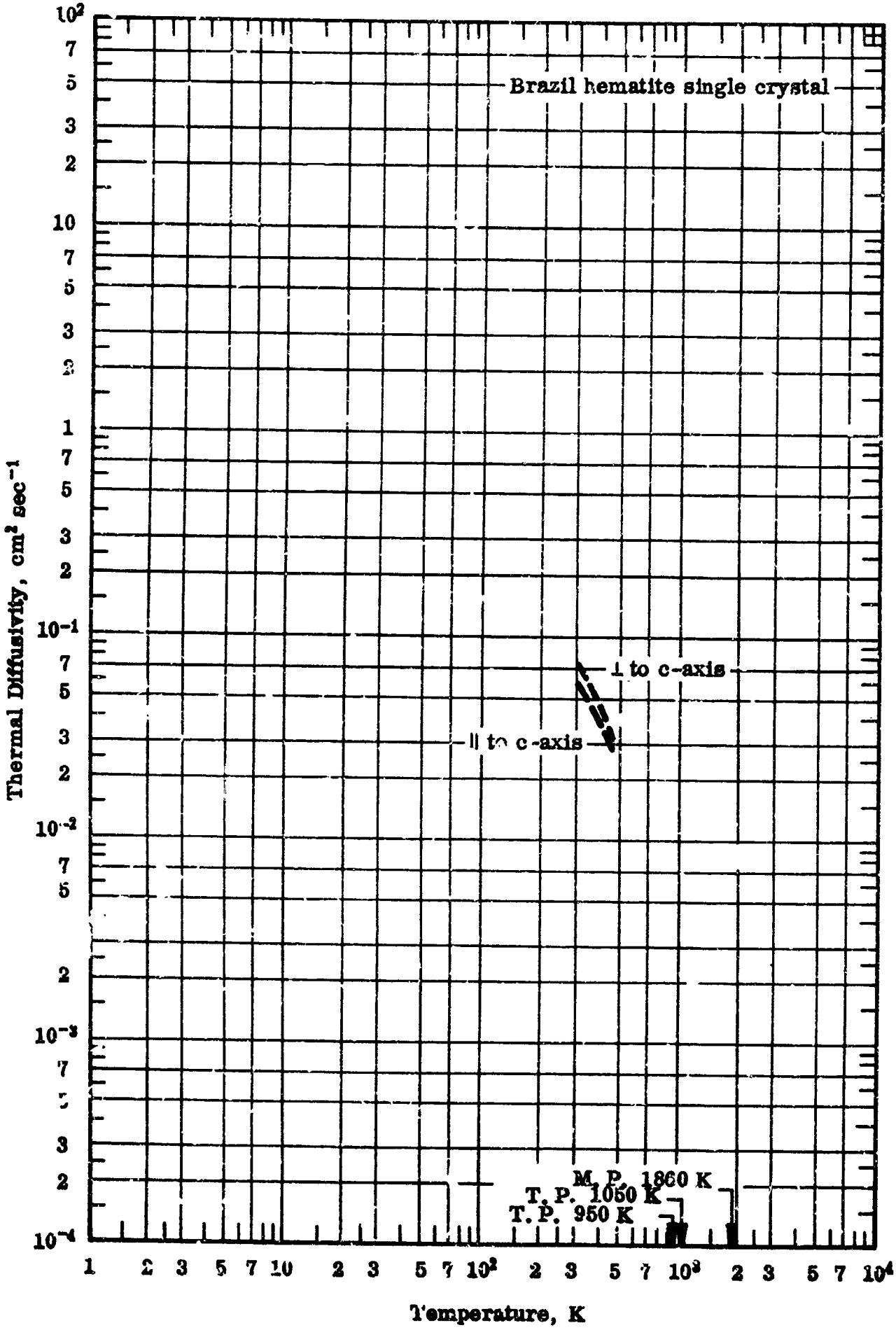

Fig. IV-25 THERMAL DIFFUSIVITY OF IRON (IC) OXIDE Fe_2O_3

TABLE IV-25 THERMAL DIFFUSIVITY OF IRON (IC) OXIDE Fe_2O_3

Selected Values for Brazil Hematite Single Crystal

	Heat flow parallel to c-axis	Heat flow perpendicular to c-axis
T,K	α, $cm^2\ sec^{-1}$	α, $cm^2\ sec^{-1}$
300	0.058*	0.072*
350	0.046*	0.055*
400	0.036*	0.042*
450	0.027*	0.030*

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* Calculated or estimated.

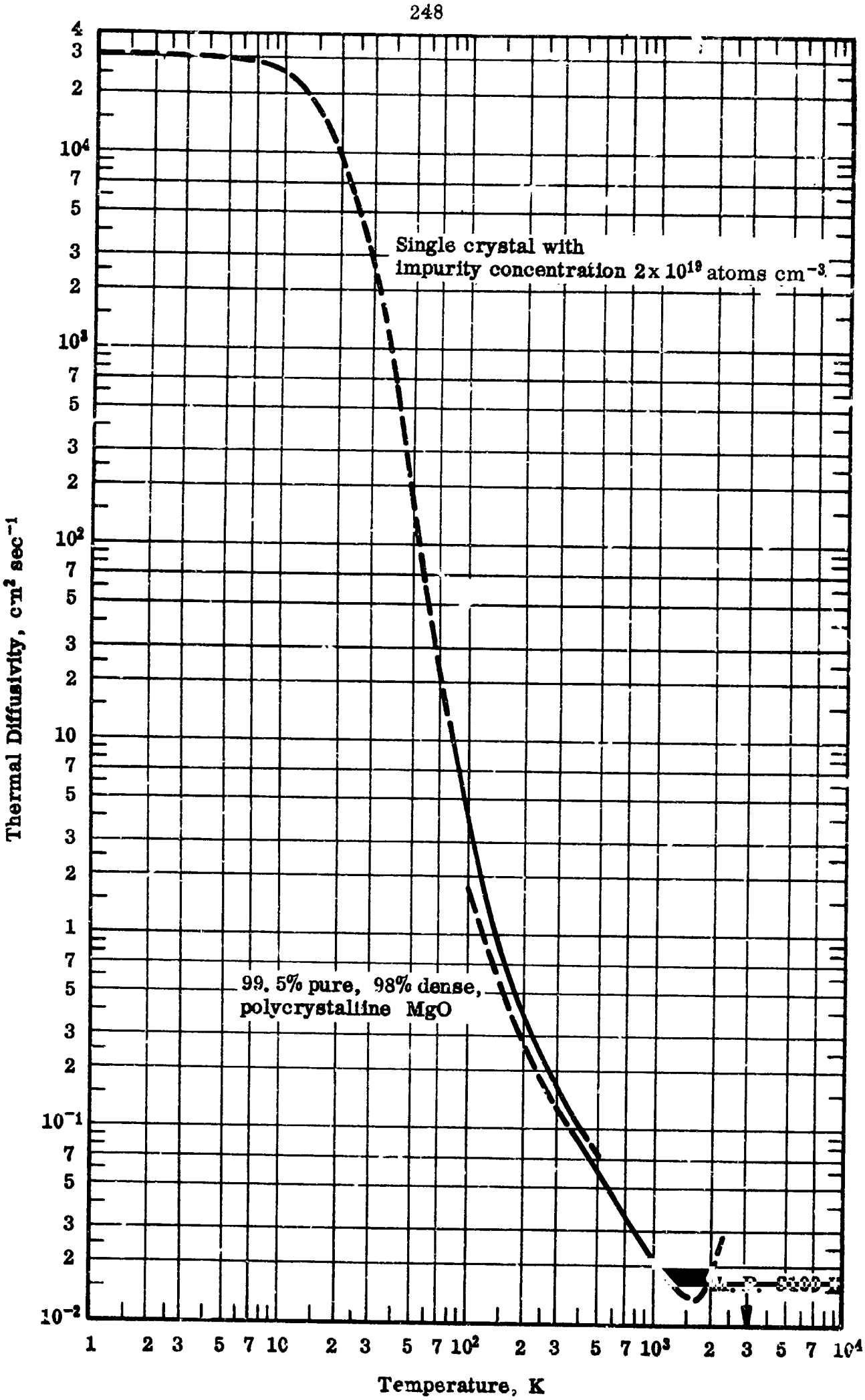

FIG. IV-26 THERMAL DIFFUSIVITY OF MAGNESIUM OXIDE MgO

TABLE IV-26 THERMAL DIFFUSIVITY OF MAGNESIUM OXIDE MgO

Selected Values for MgO Single Crystal with Impurity Concentration 2×10^{19} atoms cm^{-3}

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
1	32200*	70	26*
5	31800*	80	12*
10	27300*	90	6.4*
15	17900*	100	3.8
20	9800*	150	0.88
30	2500*	200	0.39
40	650*	300	0.18
50	190*	400	0.113
60	65*	500	0.079*

Selected Values for 99.5 % Pure, 98% Dense, Polycrystalline MgO

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
100	1.83*	900	0.026
150	0.57*	1000	0.022
200	0.28*	1100	0.0195
300	0.137	1200	0.0176
400	0.092	1300	0.0164
500	0.066	1400	0.0155
600	0.050	1500	0.0149
700	0.039	1600	0.0146
800	0.031		

Data Source and Remarks

One set of experimental data from Makarounis and Jenkins (1962) [27] is available for MgO single crystal over the temperature range 94 to 478 K. Selected values from 200 to 500 K agree well with their data.

Five sets of experimental data are available for polycrystalline MgO over the temperature range 298 to 1643 K. Selected values from 300 to 500 K lie close to the data of Plummer, Campbell, and Comstock (1962) [28] and values above 800 K close to the data of Fitzsimmons (1950) [25] and Rudkin (1953) [23]

* Calculated or estimated.

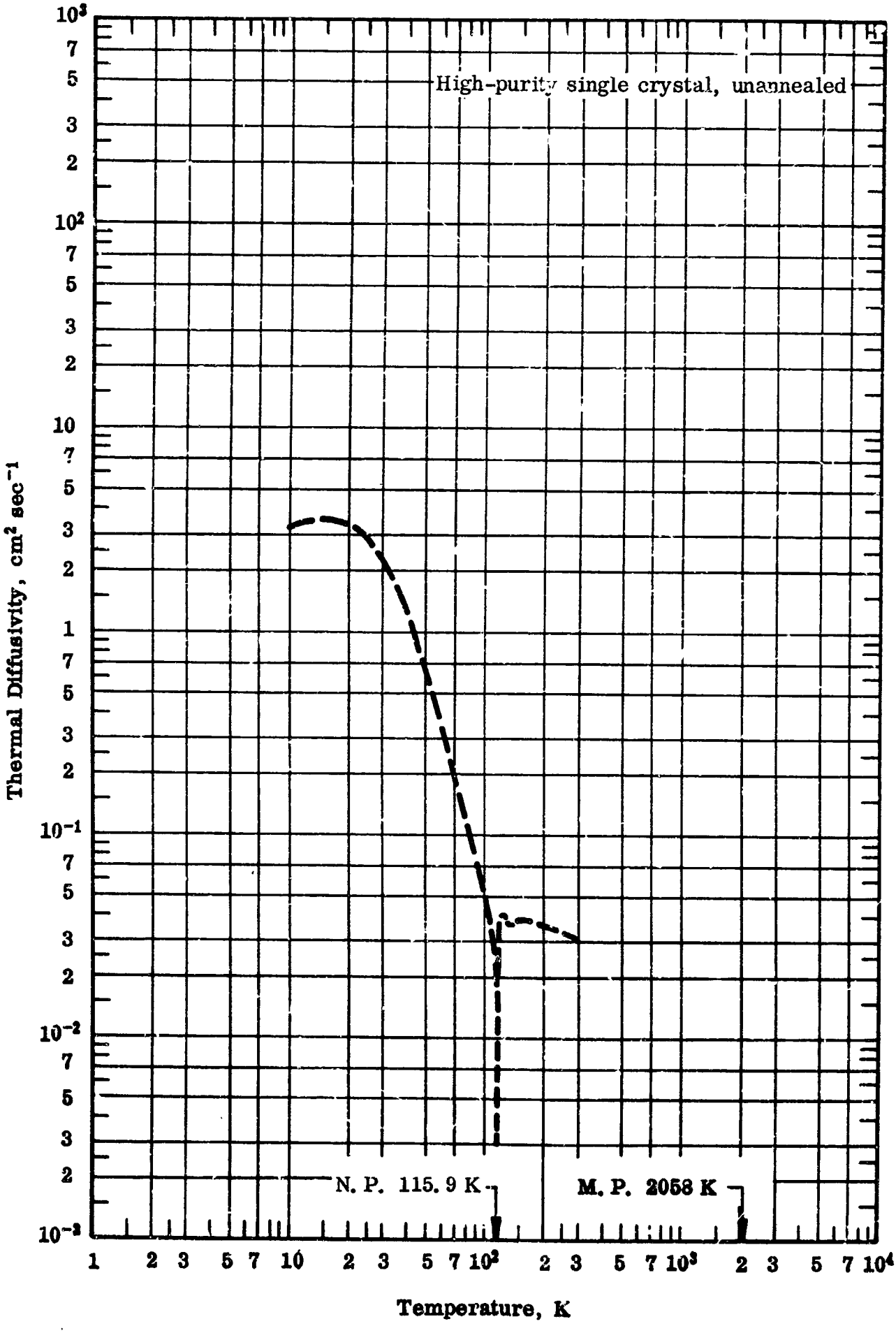

FIG. IV-27 THERMAL DIFFUSIVITY OF MANGANESE MONOXIDE MnO

TABLE IV-27 THERMAL DIFFUSIVITY OF MANGANESE MONOXIDE MnO

Selected Values for Unannealed High-Purity Single Crystal*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
10	3.2*	114	0.027
15	3.6	115	0.024
20	3.4	115.9	0.003
30	2.3	116	0.014
40	1.3	120	0.041
50	0.67	130	0.036
60	0.34	140	0.036
70	0.19	150	0.038
80	0.12	200	0.036
90	0.08	250	0.033
100	0.054	300	0.031
110	0.038		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

*All values are calculated or estimated.

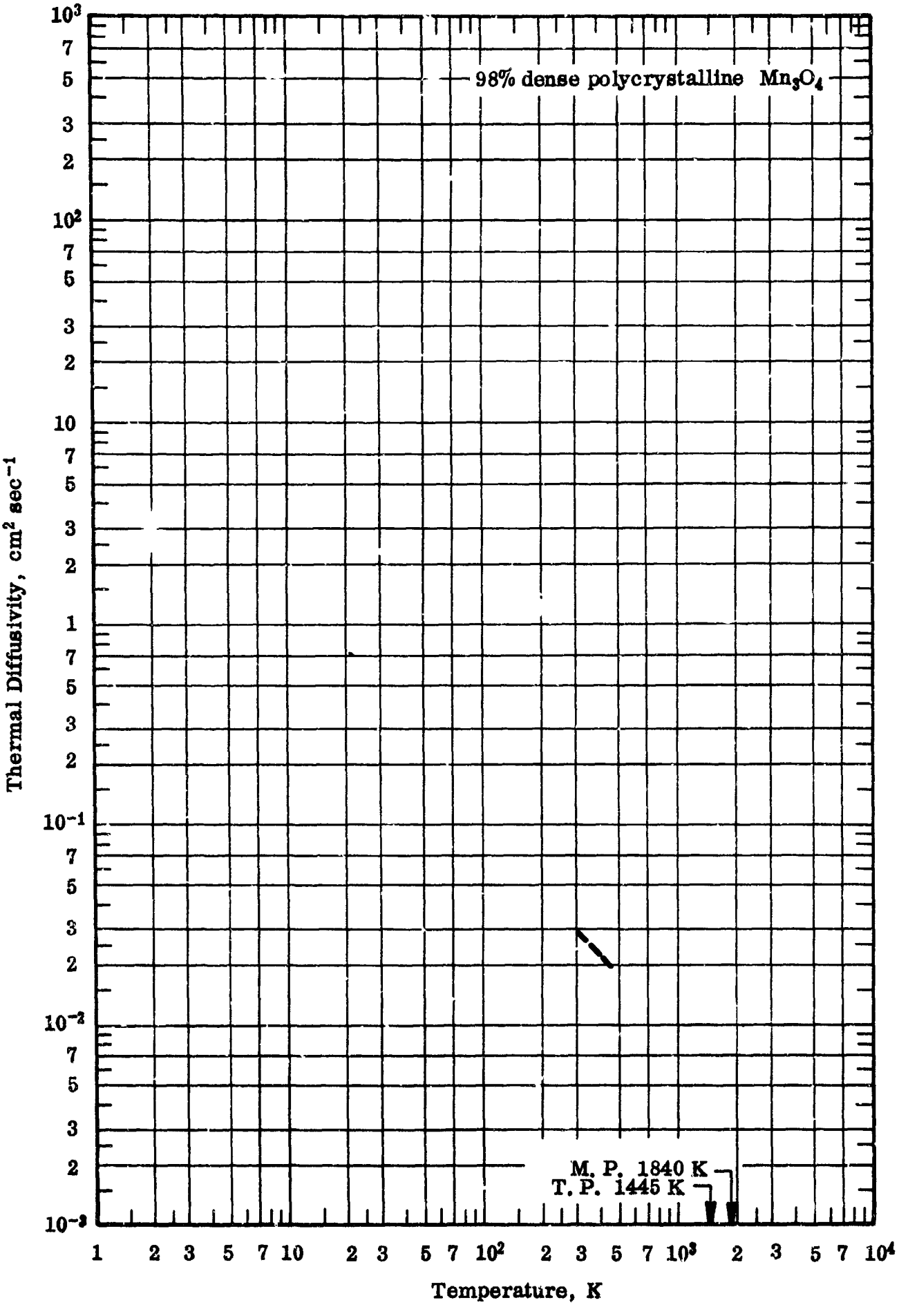

FIG. IV-28 THERMAL DIFFUSIVITY OF MANGANOMANGANIC OXIDE Mn_3O_4

TABLE IV-28 THERMAL DIFFUSIVITY OF MANGANOMANGANIC OXIDE Mn_3O_4

Selected Values for 98% Dense Polycrystalline Mn_3O_4

T,K	α, $cm^2\ sec^{-1}$
300	0.029*
350	0.025*
400	0.022*
450	0.019*

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* Calculated or estimated.

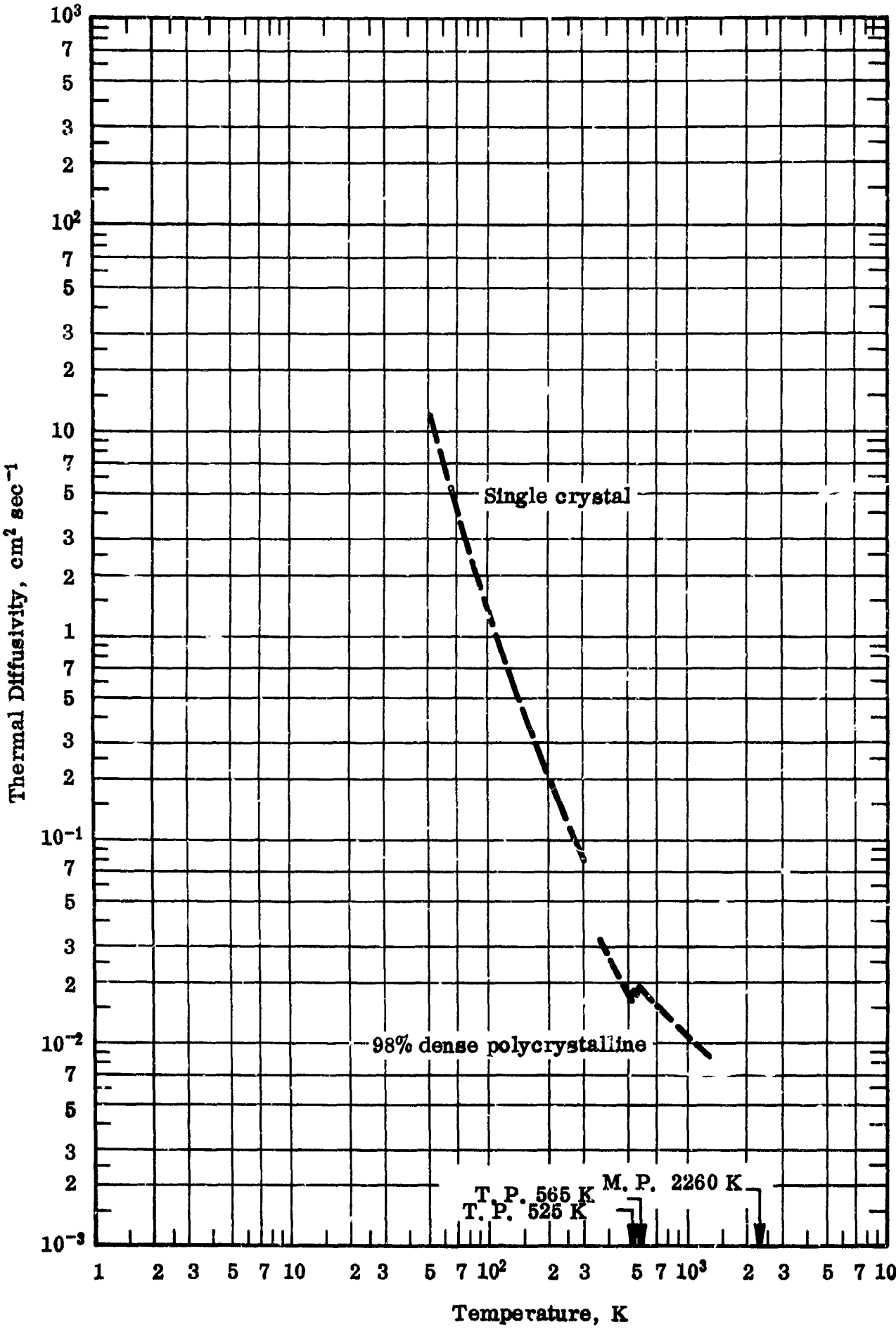

FIG. IV-29 THERMAL DIFFUSIVITY OF NICKEL (OUS) OXIDE NiO

TABLE IV-29 THERMAL DIFFUSIVITY OF NICKEL (OUS) OXIDE NiO

Selected Values for High-Purity NiO Single Crystal*

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
50	12*	100	1.3
60	6.5	150	0.44
70	3.9	200	0.20
80	2.6	300	0.077
90	1.8		

Selected Values for 98% Dense Polycrystalline NiO*

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
350	0.032*	600	0.0178
400	0.026	700	0.0151
450	0.021	800	0.0132
500	0.017	900	0.0117
(α) 524	0.0156	1000	0.0103
(β) 526	0.0182	1100	0.0095
550	0.0173	1200	0.0088
(β) 564	0.0169	1300	0.0084
(γ) 566	0.0192		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

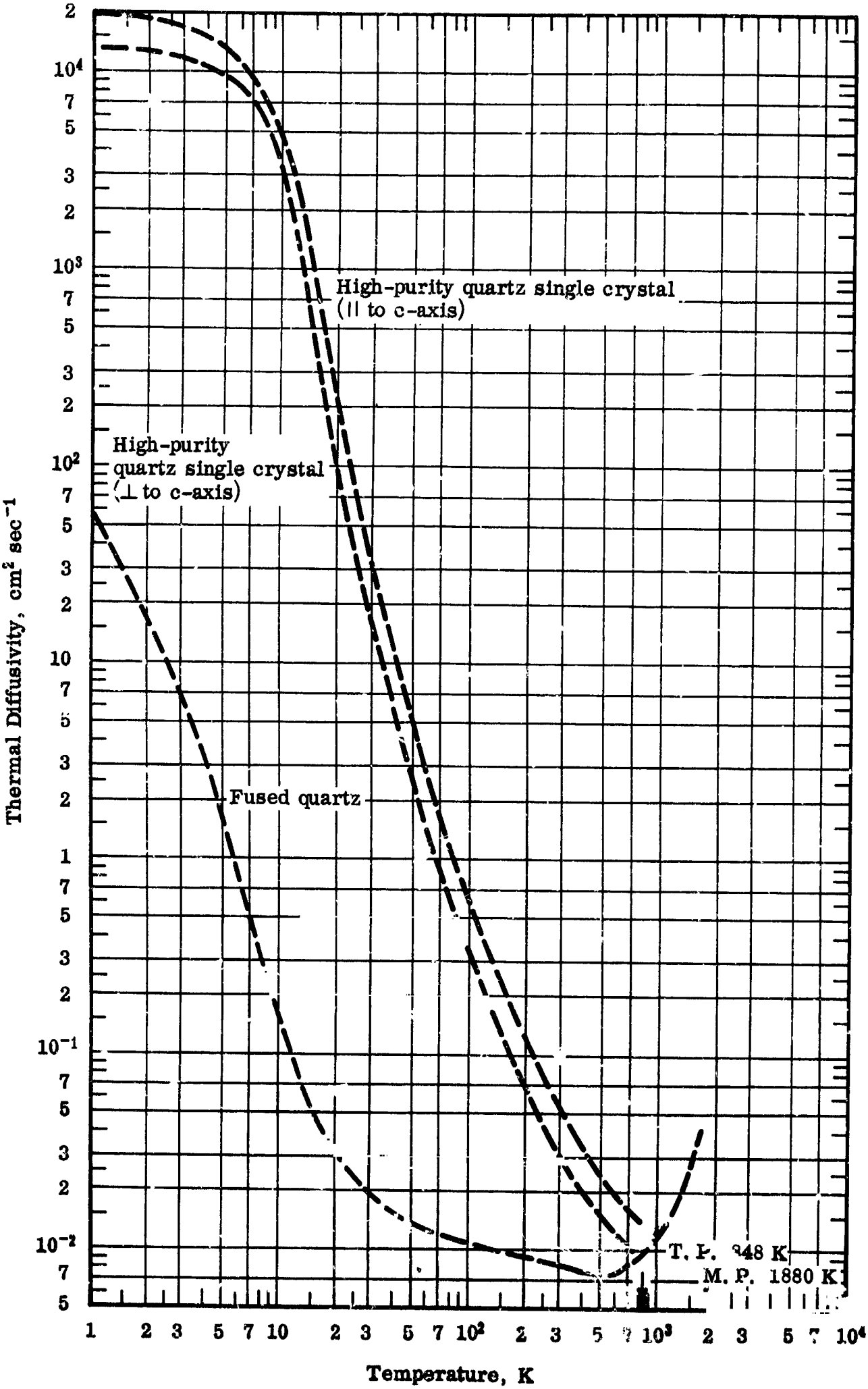

FIG. IV-30 THERMAL DIFFUSIVITY OF SILICON DIOXIDE SiO_2

TABLE IV-30 THERMAL DIFFUSIVITY OF SILICON DIOXIDE SiO_2

	Fused Quartz	High-Purity Quartz Single Crystal parallel to c-axis	perpendicular to c-axis
T, K	α, $cm^2\ sec^{-1}$	α, $cm^2\ sec^{-1}$	α, $cm^2\ sec^{-1}$
1	59*	19000*	13000*
2	15.8		
3	7.1*		
5	1.55*	13000*	9400*
8		7000*	5700*
10	0.146*	4300*	700*
15	0.051*	760*	400*
20	0.029*	190*	96*
30		33*	17*
40		11*	5.4*
50	0.0138*	5*	2.5*
60		2.8*	1.4*
70		1.7*	0.89*
80		1.15*	0.62*
90		0.81*	0.45*
100	0.0110*	0.61*	0.34*
150	0.0101*	0.23*	0.13*
200	0.0094*	0.12*	0.066*
273	0.0087*	0.065*	0.037*
300	0.0084	0.055*	0.032*
400	0.0078	0.033*	0.020*
500	0.0077	0.0235*	0.015*
600	0.0077*	0.0185*	0.012*
700	0.0083*	0.016*	0.0105*
800	0.0090*	0.014*	0.0094*
900	0.0100*		
1000	0.0114*		
1100	0.0130*		
1200	0.0152*		
1300	0.0185*		
1400	0.023*		
1500	0.028*		
1600	0.034*		
1700	0.040*		

*Calculated or estimated

Data Source and Remarks

Two sets of experimental data from Schmidt (1961) [5] and Hartunian and Varwig (1962) [29] are available for fused quartz over the temperature range 297 to 589 K. Selected values lie close to their data. There are no experimental data available for quartz single crystal for which all values are calculated or estimated.

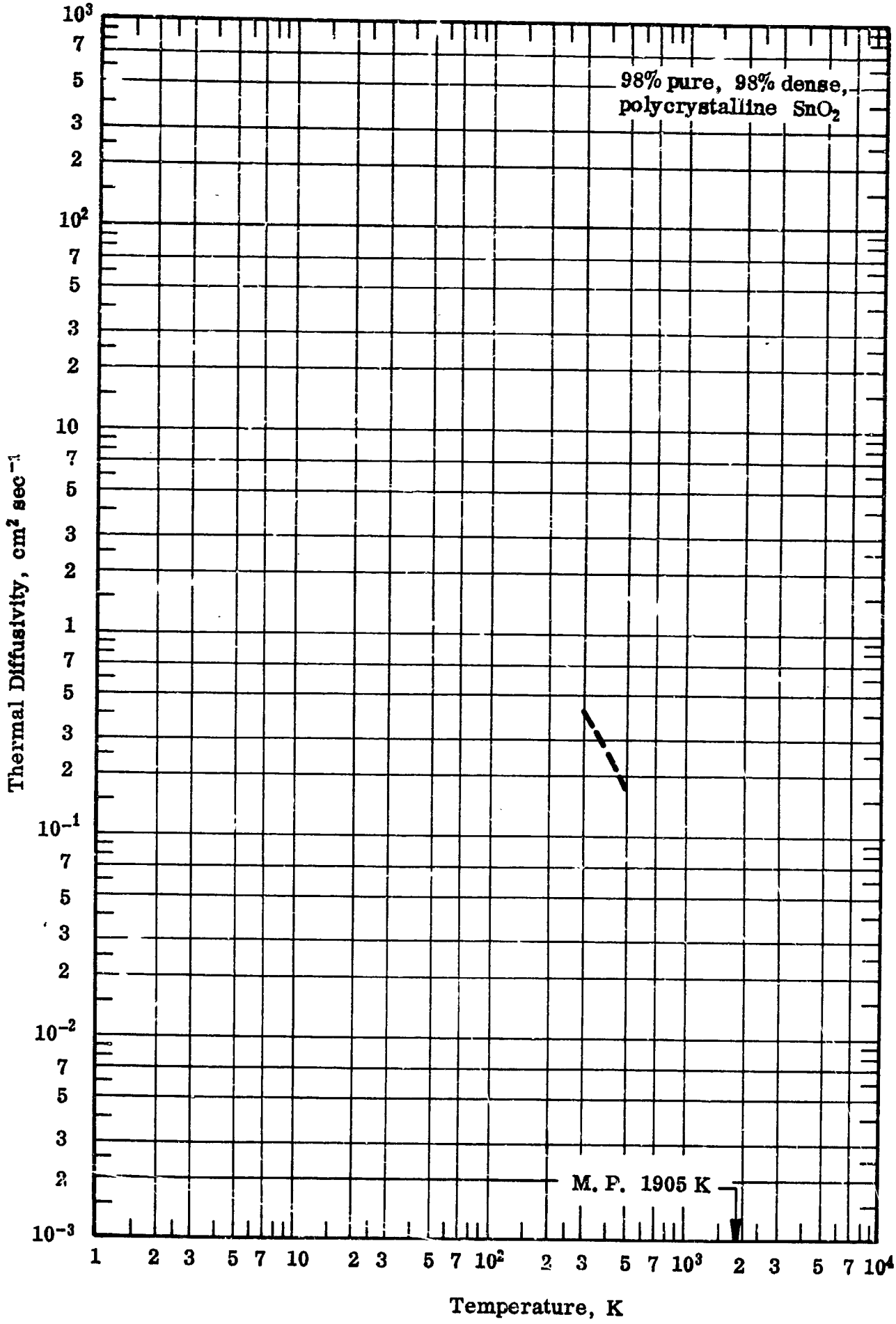

FIG. IV-31 THERMAL DIFFUSIVITY OF TIN (IC) OXIDE SnO_2

TABLE IV-31 THERMAL DIFFUSIVITY OF TIN (IC) OXIDE SnO_2

Selected Values for 98% Pure, 98% Dense, Polycrystalline SnO_2

T,K	α, $cm^2\ sec^{-1}$
300	0.42*
350	0.33*
400	0.26*
450	0.21*
500	0.17*

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

*Calculated or estimated.

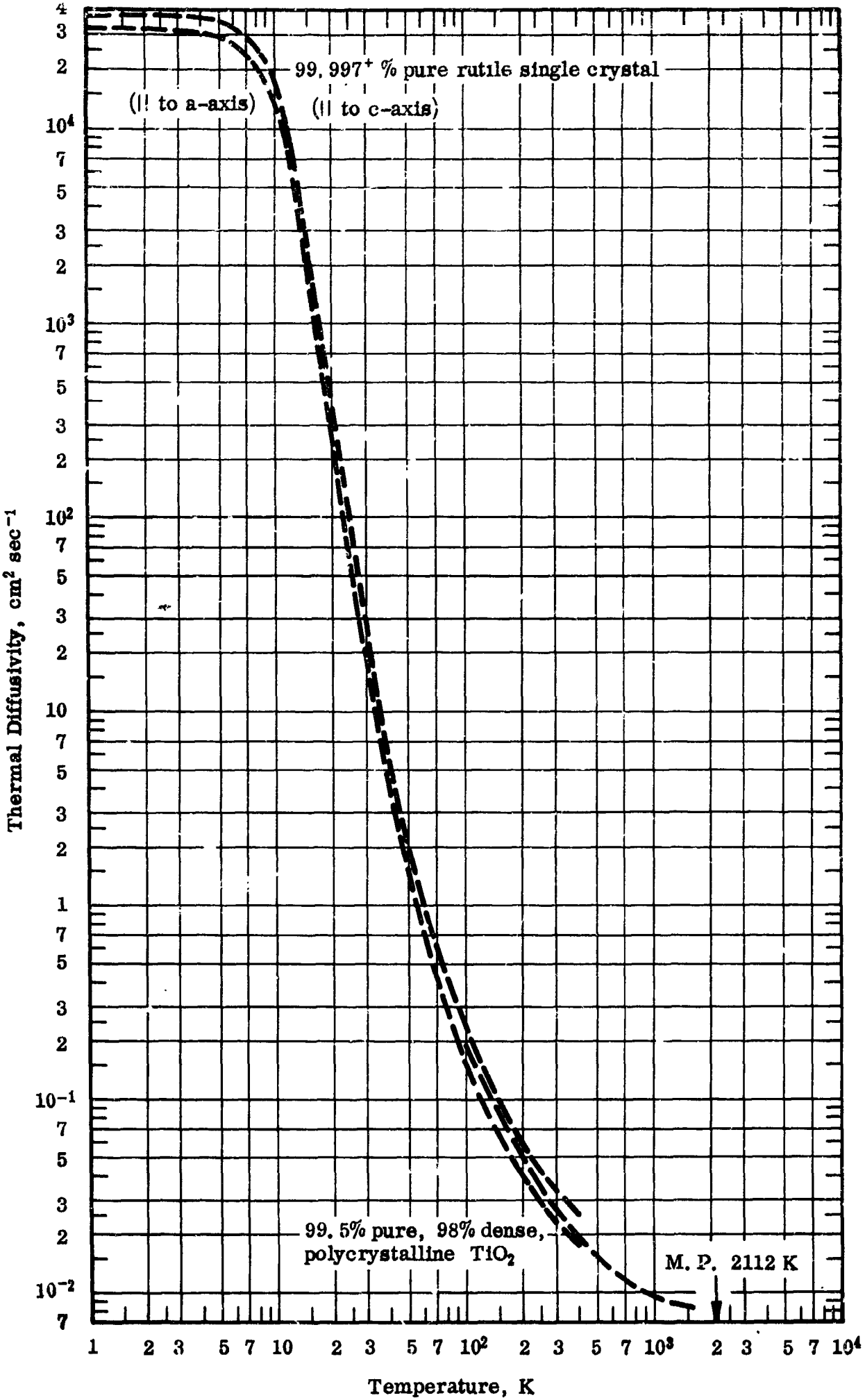

FIG. IV-32 THERMAL DIFFUSIVITY OF TITANIUM DIOXIDE TiO_2

TABLE IV-32 THERMAL DIFFUSIVITY OF TITANIUM DIOXIDE TiO_2

Selected Values for 99.997+ % Pure Rutile Single Crystal*

T,K	α, $cm^2\ sec^{-1}$	
	Parallel to c-axis	Parallel to a-axis
1	35500*	31300
5	35000	29600
10	19100	15600
13	6100	5000
15	2540	1970
20	430	296
30	31	20.2
40	5.8	4.0
50	2.02	1.39
60	0.99	0.70
70	0.60	0.43
80	0.42	0.31
90	0.31	0.22
100	0.24	0.17
150	0.099	0.071
200	0.061	0.043
273	0.039	0.028
300	0.034	0.025
400	0.025	0.018

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline TiO_2*

T,K	α, $cm^2 sec^{-1}$	T,K	α, $cm^2\ sec^{-1}$
100	0.185*	800	0.0101
150	0.077	900	0.0094
200	0.047	1000	0.0090
273	0.029	1100	0.0087
300	0.026	1200	0.0084
400	0.0187	1300	0.00831
500	0.0149	1400	0.00824
600	0.0127	1500	0.0082
700	0.0111	1600	0.0082

* All values are calculated or estimated.

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

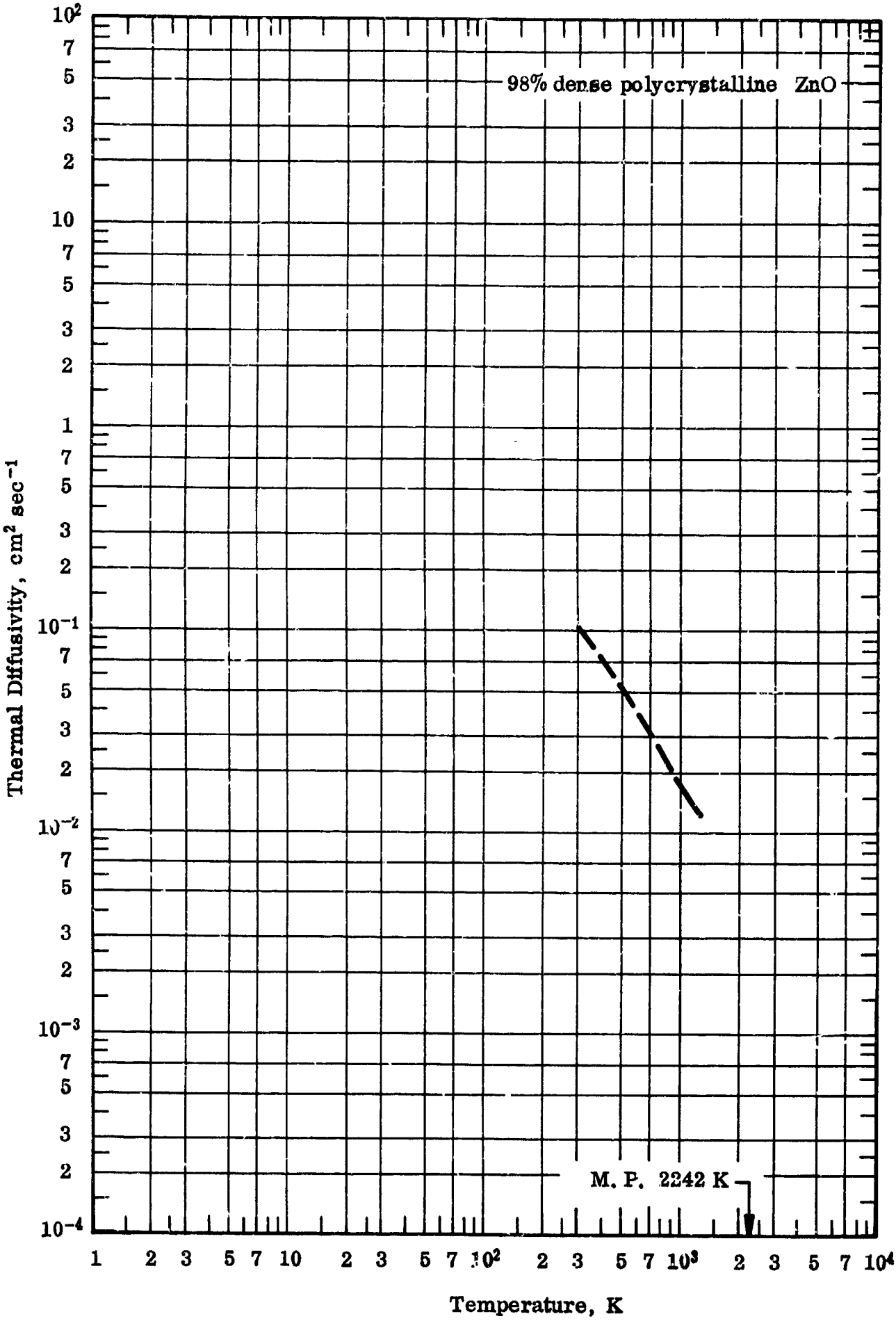

FIG. IV-33 THERMAL DIFFUSIVITY OF ZINC OXIDE ZnO

TABLE IV-33 THERMAL DIFFUSIVITY OF ZINC OXIDE ZnO

Selected Values for 98% Dense Polycrystalline ZnO*

T,K	α, $cm^2\ sec^{-1}$	T,K	α, $cm^2 sec^{-1}$
300	0.105*	900	0.020
400	0.071	1000	0.017
500	0.052	1100	0.014
600	0.039	1200	0.013
700	0.031	1300	0.012
800	0.025		

Data Source and Remarks

No experimental data are available. Selected values are calculated or estimated.

* All values are calculated or estimated.

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RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER V
SPECIFIC HEAT

E. H. BUYCO
C. E. VOLK
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CHAPTER V

SPECIFIC HEAT

A. INTRODUCTION

This chapter contains selected specific heat values for the elements aluminum, beryllium, chromium, copper, iron, magnesium, manganese, nickel, niobium, silicon, tin, titanium, zinc, their various stable oxides; and the alloys Aluminum Alloy 2219-T852, Aluminum Alloy 6061-T6, Aluminum Alloy 7075-T6, Beryllium Alloy, Stainless Steel 304-A, Stainless Steel 347, Inconel X-750, and Titanium Alloy A-110AT. The range of temperature covered is from 0 K to the melting point and above.

Previous compilations of the specific heat of substances have been reported by Eldgridge, E.A., and Deem, H.W. (1) for metals and alloys from cryogenic to elevated temperatures; Furukawa, G.T., et al., (2) for light elements and their compounds; Goldsmith, A., et al., (3) for substances melting above 750 K; Hultgren, R., et al., (4) for metals and binary alloys; Kelley, K.K. (5) for elements and their compounds at high temperatures; Loser, L.B., et al., (6) for thermal insulating materials; Johnson, V.J. (7) for low temperature materials; and Wood, W.D., and Deem, H.W. (8) for high temperature materials.

The sources of specific heat data contained in this report came from published technical literature, United States Government Publications, Doctoral and Masters' dissertations, data supplied by private companies and organizations, and special collections, compendia and reference works of major research centers throughout the world. The present comprehensive literature search includes published experimental specific heat results on a current basis. Most recent data that have not appeared in previous compilations are reported here. This report also contains specific heat data over a wider range of temperature than in previous compilations. The selected specific heat values are presented in both tabular and graphical forms.

B. DATA ANALYSIS

In selecting the "best" values from the available experimental and calculated data, consideration was given to the characterization of the specimens, (purity of the specimens, thermal history of the specimens, and final state of the specimens) and existence of magnetic and phase transitions. Consistency with results obtained over different temperature ranges and with results obtained by the different methods of measurements were also given considerable weight in the analysis of the data. For instance, measurements made with the Nernst adiabatic calorimeter for the temperature range $0 < T \leq 350$ K, should join smoothly with high temperature ($T \geq 298$ K) data which were obtained by the drop method or the cooling rate technique. It was also observed that some individuals and laboratories produced results which were more reliable than others.

After carefully applying the above mentioned criteria, recommended specific heat curves were drawn. Specific heat values are also presented in tabular form for the convenience of the users. The specific heat values are given in cal $g^{-1} K^{-1}$ (1 cal = 4.1840 absolute joules, ice point 273.15 K) and the temperature in degrees Kelvin. No corrections have been applied to specific heat data reported in the literature which were based on ice point of 273.16 K and calorie unit equal to 4.1868 absolute joules, since the error introduced is insignificant compared with the experimental errors.

Exact estimates of the most probable error or uncertainty are very difficult to calculate. Various individuals reported estimates of error ranging from 0.1 percent up to about 5 percent with others reporting 2 to 3 percent. Measurements with estimates of error over 5 percent were considered unreliable and were ignored in analyzing the data. The selected specific heat values may be taken to represent at most ±5 percent uncertainty.

Over the range of temperature $0 < T \leq 10$ K, the constant volume specific heat C_v, and the constant pressure specific heat, C_p, may be taken to be equal for solids without appreciable error. In the absence of specific heat data over this low temperature range, the equations

$$C_v = \beta T^3 + \gamma T \text{ and}$$

$$C_v = \frac{234R}{M} \frac{T^3}{\theta}$$

may be used for metals and oxides respectively, where,

C_v = constant volume heat capacity, cal $mol^{-1} K^{-1}$,

T = temperature, K,

β, γ = constants,

R = 1.98 cal $mol^{-1} K^{-1}$,

M = molecular or atomic weight, g mol^{-1},

θ = Debye temperature.

The expression βT^3 represents the lattice specific heat and obeys a cube law while the terms γT, the electronic specific heat has a linear temperature dependence. For oxides and nonmetals, the electronic term is negligible so that the cube law is applicable.

At higher temperatures (T > 300 K), the specific heat levels off to almost a constant value. This value varies for various substances but for some metals it is approximately 6.5 cal $mol^{-1} K^{-1}$.

The Kopp-Newman Law may be used to approximate the specific heat of alloys. According to this law, the heat capacity of ideal solutions is equal to the sum of the specific heat of each constituent multiplied by its mole fraction that is:

$$C_p = \sum_1^n X_i C_{p_i} , \qquad [1]$$

where

X_i = mole fraction of the i'th element,

C_{p_i} = specific heat of the i'th element,

Although Equation [1] is exact for ideal solutions, it is good approximation for some nonideal solutions, such as metal alloys. It must be applied with care especially when magnetic or phase transitions are present in the temperature range under investigation.

C. SPECIFIC HEATS OF SELECTED MATERIALS

In this chapter, the specific heat of a group of selected materials are presented in Figures V-1 to V-49 and Tables V-1 to V-46. Both the graphical and tabular values are expressed in terms of calorie - gram - degree Kelvin units.

Most of the original specific heat data published prior to 1961 were based on the chemical system of atomic weights (oxygen atomic weight = 16). Recent measurements were based on a new set of atomic weights, based on $C^{12} = 12$ as adopted by International Union of Pure and Applied Chemistry, 1961. This change of the reference base would lead only to small changes in the fundamental constants and would not have any significant effect on tabulated values of specific heat.

The transition temperatures are indicated by Greek letters α, β, γ, and δ, and the solid and liquid phases by the letters "s" and "l" respectively. Extrapolated and interpolated values are indicated by paranthesis and calculated values by an asterisk.

Substances existing in more than one stable form are indicated by their common name or their chemical name. For instance, titanium dioxide; rutile and anatase; silicon dioxide; quartz crystal, quartz glass, cristobalite, and tridymite, etc.

ELEMENTS

For a number of metals, it has been possible to give the specific heat values for both the normal and super conducting states at very low temperatures ($T < 2$ K). Transformation of this type is second order and involves no heat changes at the normal critical temperatures. In the region below the critical temperature, the normal specific heats are usually measured with introduction of an external magnetic field. Specific heat information above the melting temperature of metals are rather scanty and sometimes totally nonexistent. The values estimated by Kelley, K.K. (5) are recommended for most metals in the absence of available data. These values are identified by a parenthesis in the data tables. For metals, further measurements are clearly desirable beyond the melting temperature.

ALLOYS

The recommended specific heat values for the alloys have been based on scanty information which may prove to be inadequate and should be accepted only as an attempt to make the most of existing knowledge and hence subject to modification in the light of future work. No available specific heat data were found in the literature for the low temperature range ($T < 300$ K) nor values above their melting temperatures. Values recommended were obtained by calculations from the data on the elements with the aid of Kopp - Newman mixing rule. There was no way of checking the validity of the results obtained from these calculations for temperatures below 300 K inasmuch as no data were available. The specific heat measurements of DuChatenier, F. G., et al., (203) on stainless steel between 1 to 90 K provides the only results available for comparison with the calculated values for AISI 347. The composition of the stainless steel specimen used by DuChatenier, however, was not exactly the same as AISI 347. Above 300 K and below phase transition temperatures, the calculated and the experimental values agreed reasonably well. There are no recommended values for the alloys above their melting point because of a complete absence of experimental data. For alloys, further measurements are required immediately above their melting points and below room temperature.

METAL OXIDES

Most measurements were made above 5 K and below melting temperatures. In many instances, measurements were made up to 300 K with no data below 50 K. For some of these oxides it was not possible to predict the values of the specific heat below 50 K.

For oxides with available experimental specific heat values around 5 K it is possible to calculate the Debye temperature, θ, and use this value to calculate the specific heat at low temperatures ($0 < T < 10$ K). The C_p equations obtained from Kelley's least square fit of the enthalpy measurements made on some oxides (285, 293, 327, 331, 336, 339) were used to calculate their true specific heat over the applicable temperature range.

No recommended values are given above the melting point of the oxides because of lack of available information. Further measurements are required below 10 K and beyond the melting point for metallic oxides.

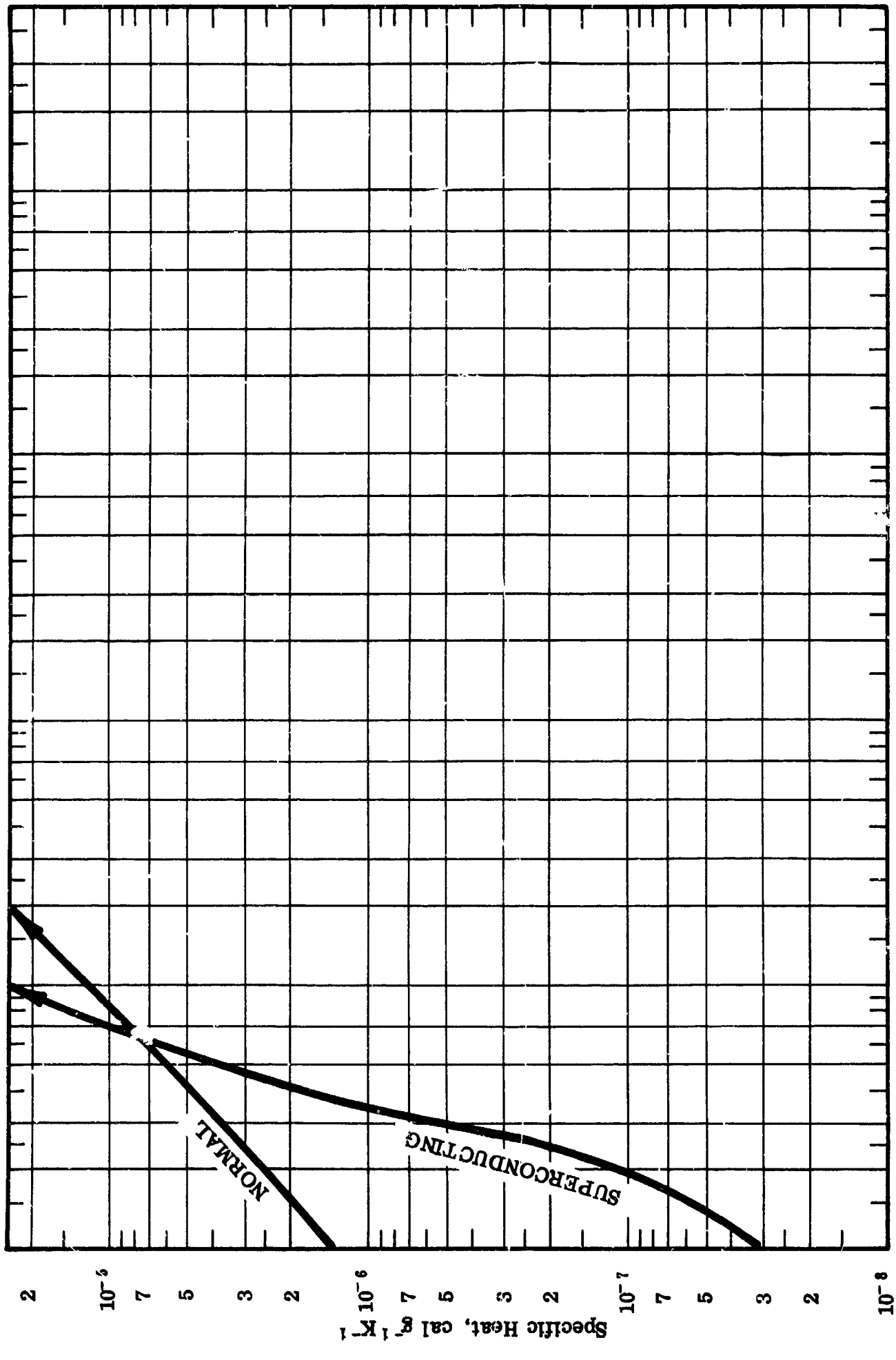

FIG. V - 1 (a)

SPECIFIC HEAT -- ALUMINUM

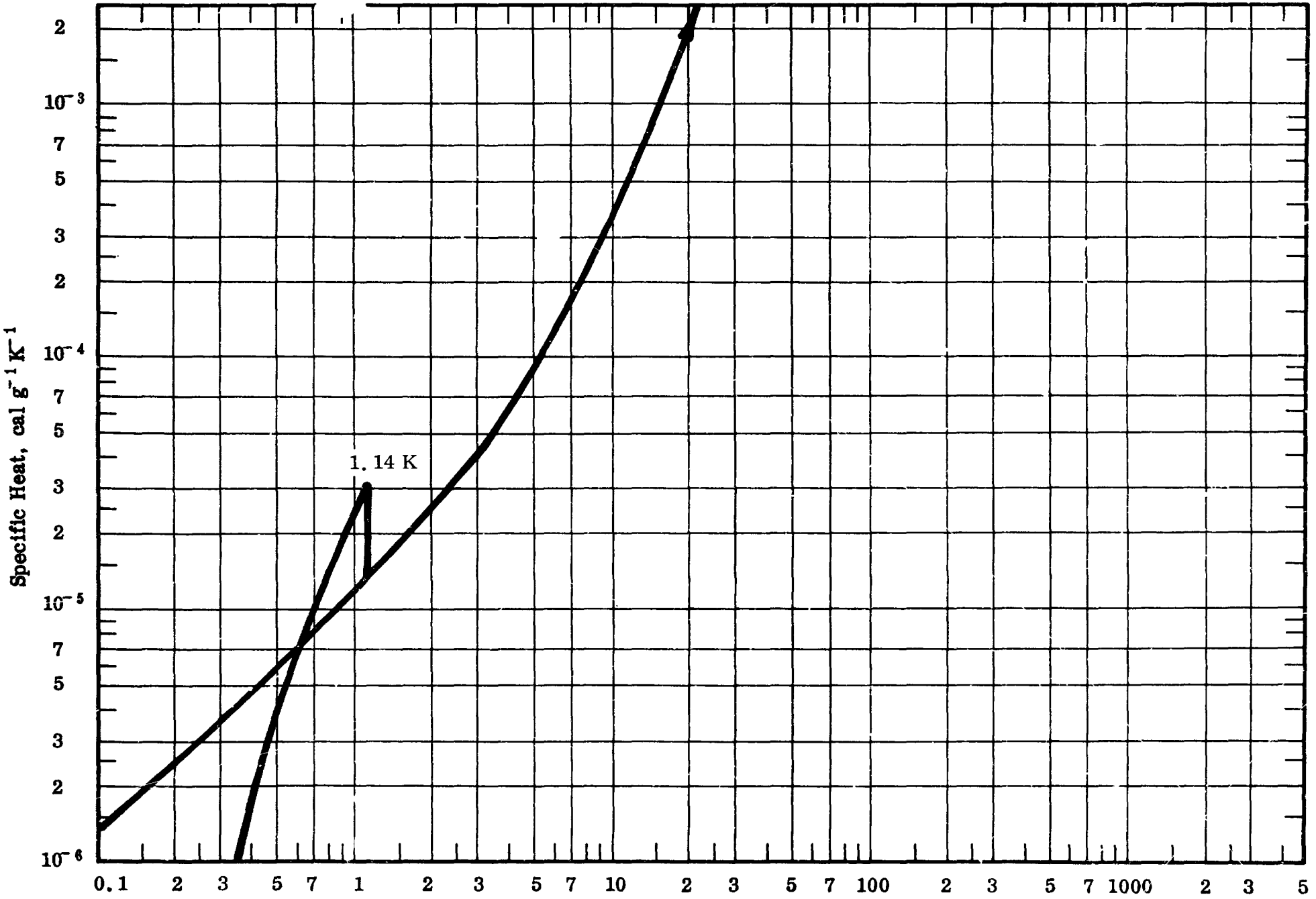

FIG. V - 1 (b)

SPECIFIC HEAT -- ALUMINUM

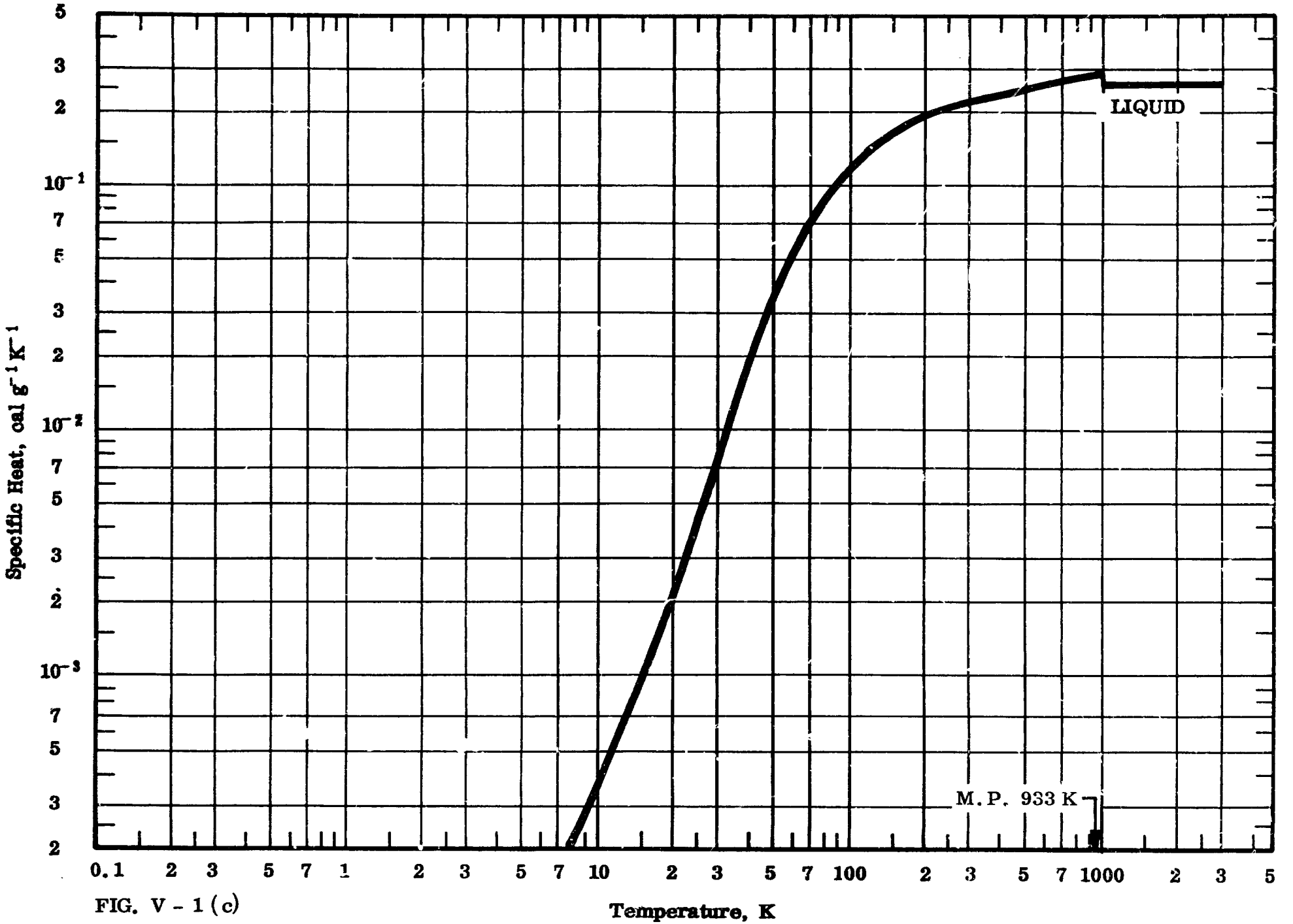

FIG. V - 1 (c)

SPECIFIC HEAT -- ALUMINUM

TABLE V-1. SPECIFIC HEAT OF ALUMINUM

T °K	NORMAL C_p, cal $g^{-1} K^{-1}$	SUPERCONDUCTING C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
0.1	$(1.32 \times 10^{-6})^{\dagger}$	$(3.02 \times 10^{-8})^{\dagger}$	300	2.17×10^{-1}
0.2	2.50	1.00×10^{-7}	400	2.27
0.3	3.68	5.10×10^{-7}	500	2.38
0.4	4.85	1.83×10^{-6}	600	2.49
0.5	6.05	4.01	700	2.60
0.6	6.95	6.90	800	2.71
0.7	8.50	1.03×10^{-5}	900	2.82
0.8	9.70	1.47	(s) 933	2.85
0.9	1.10×10^{-5}	1.95	(l) 933	$(2.59 \times 10^{-1})^{\ddagger}$
1.0	1.24	2.45	1000	(2.59)
1.14		3.18	1100	(2.59)
1.5	1.84		1200	(2.59)
2	2.50		1300	(2.59)
3	4.10		1400	(2.59)
4	6.10		1500	(2.59)
5	9.38		1600	(2.59)
6	1.27×10^{-4}		1700	(2.59)
7	1.71		1800	(2.59)
8	2.27		1900	(2.59)
9	2.86		2000	(2.59)
10	3.63		2100	(2.59)
20	2.00×10^{-3}		2200	(2.59)
30	7.50		2300	(2.59)
40	1.85×10^{-2}		2400	(2.59)
50	3.38		2500	(2.59)
60	5.15		2600	(2.59)
70	7.00		2700	(2.59)
80	8.70		2800	(2.59)
90	1.03×10^{-1}		2900	(2.59)
100	1.16		3000	(2.59)
200	1.91			

Investigators: Avramescu, A., (9) [373-873 K]; Eastman, E.D. et al (10) [373-873 K]; Giauque, W.F., and Meads, P.F., (11) [15-302 K]; Hopkins, D.C. (12) [Normal, 1-1.2 K, Superconducting 1-1.2 K]; Kok, J.A., and Keesom, W.H., (13) [1-19 K]; Phillips, N.E. (14) [Normal 0.1-4 K Superconducting 0.2-1.2 K]; Pochapsky, T.E., (15) [273-673 K]; Quinney, H., and Taylor, G.I. (16) [398-673 K]; Rorer, D.C., et al (17) [Superconducting 1.1-1.2 K]; Yurkov, V.A., and Invoniskaya, L.A., (18) [323-573 K].

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†Extrapolated

‡Estimated (5)

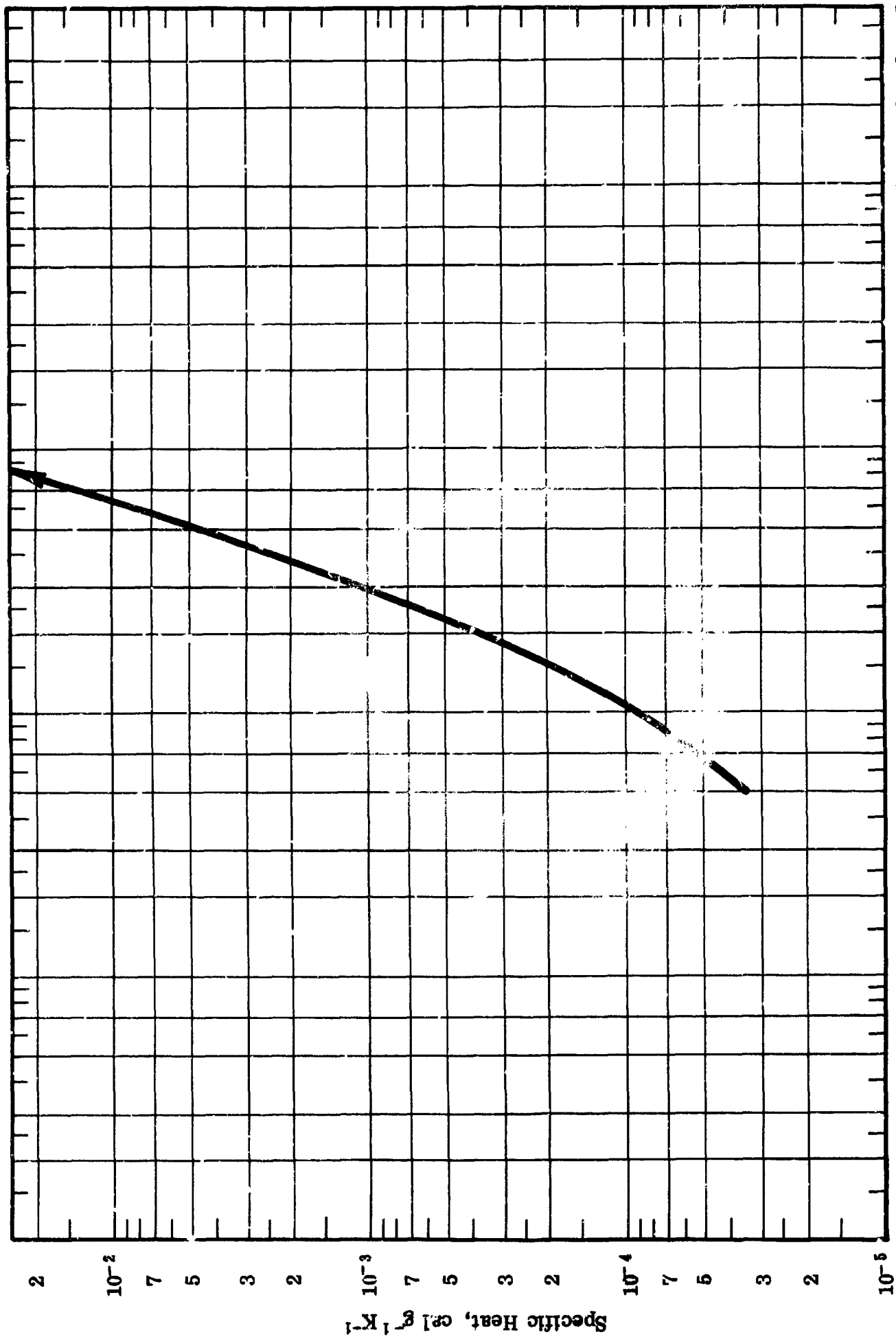

FIG. V - 2 (a)

SPECIFIC HEAT-- BERYLLIUM

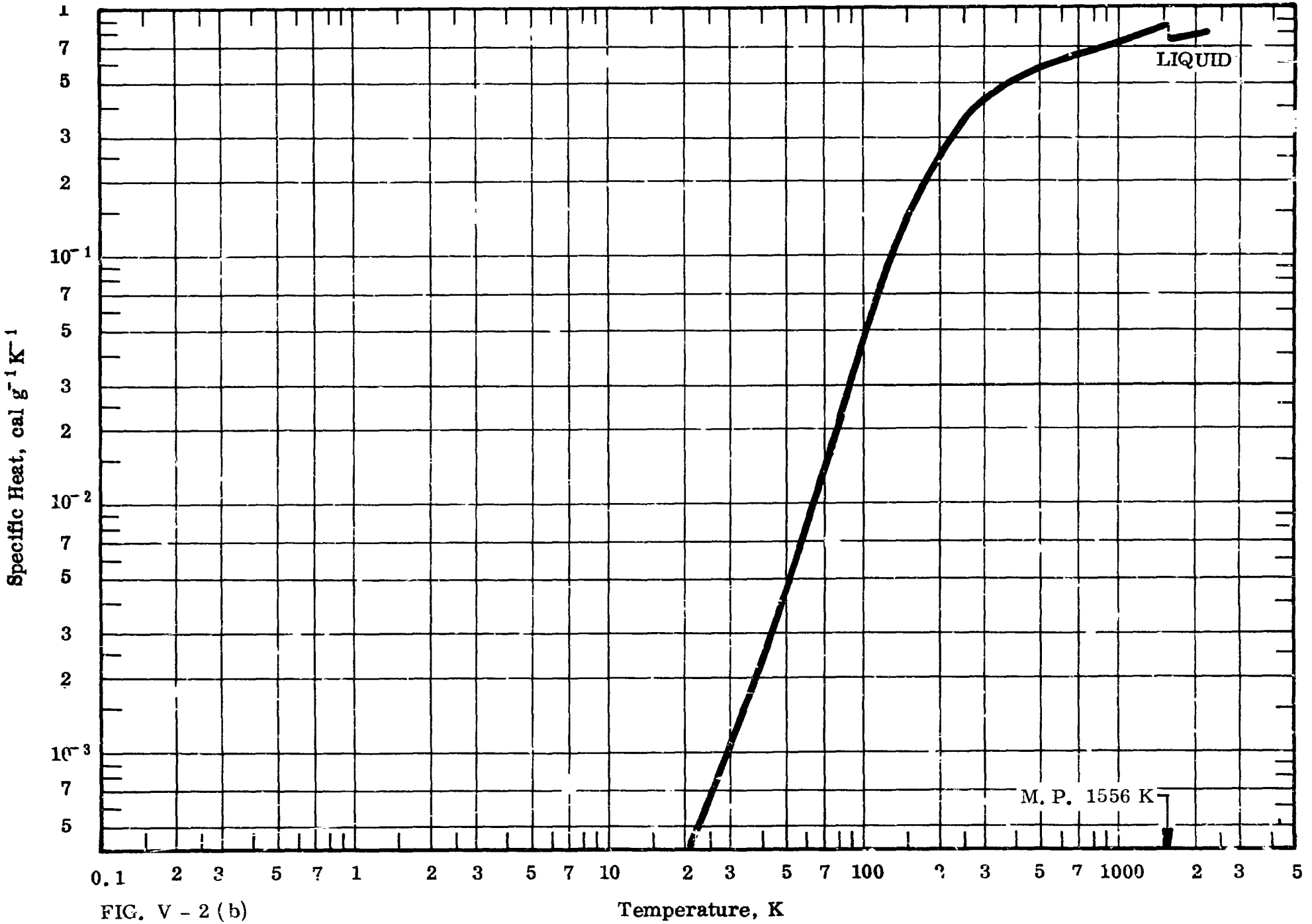

FIG. V - 2 (b)

SPECIFIC HEAT -- BERYLLIUM

TABLE V-2. SPECIFIC HEAT OF BERYLLIUM

T °K	C_p, cal $g^{-1} K^{-1}$		T °K	C_p, cal $g^{-1} K^{-1}$
5	3.4×10^{-5}		700	6.49×10^{-1}
10	9.2		800	6.73
20	3.83×10^{-4}		900	6.97
30	1.13×10^{-3}		1000	7.22
40	2.40		1100	7.46
50	4.45		1200	7.70
60	8.14		1300	7.94
70	1.37×10^{-2}		1400	8.18
80	2.16		1500	8.42
90	3.30	(s)	1556	8.57
100	4.85	(l)	1556	7.64
150	1.52×10^{-1}		1600	7.66
200	2.66		1700	7.72
250	3.67		1800	7.77
300	4.38		1900	7.83
400	5.25		2000	7.89
500	5.77		2100	7.94
600	6.15		2200	8.00

Investigators: Ginnings, D.C., et al (19) [373-1173K]; Hill, R.W., and Smith, P.L. (20) [5-300K]; Jaeger, F.M., and Rosenbohm, E. (21) [273-1073K]; Kantor, P.B., et al (22) [600-2200K]; Mit'Kina, E.A. (23) [323-773K].

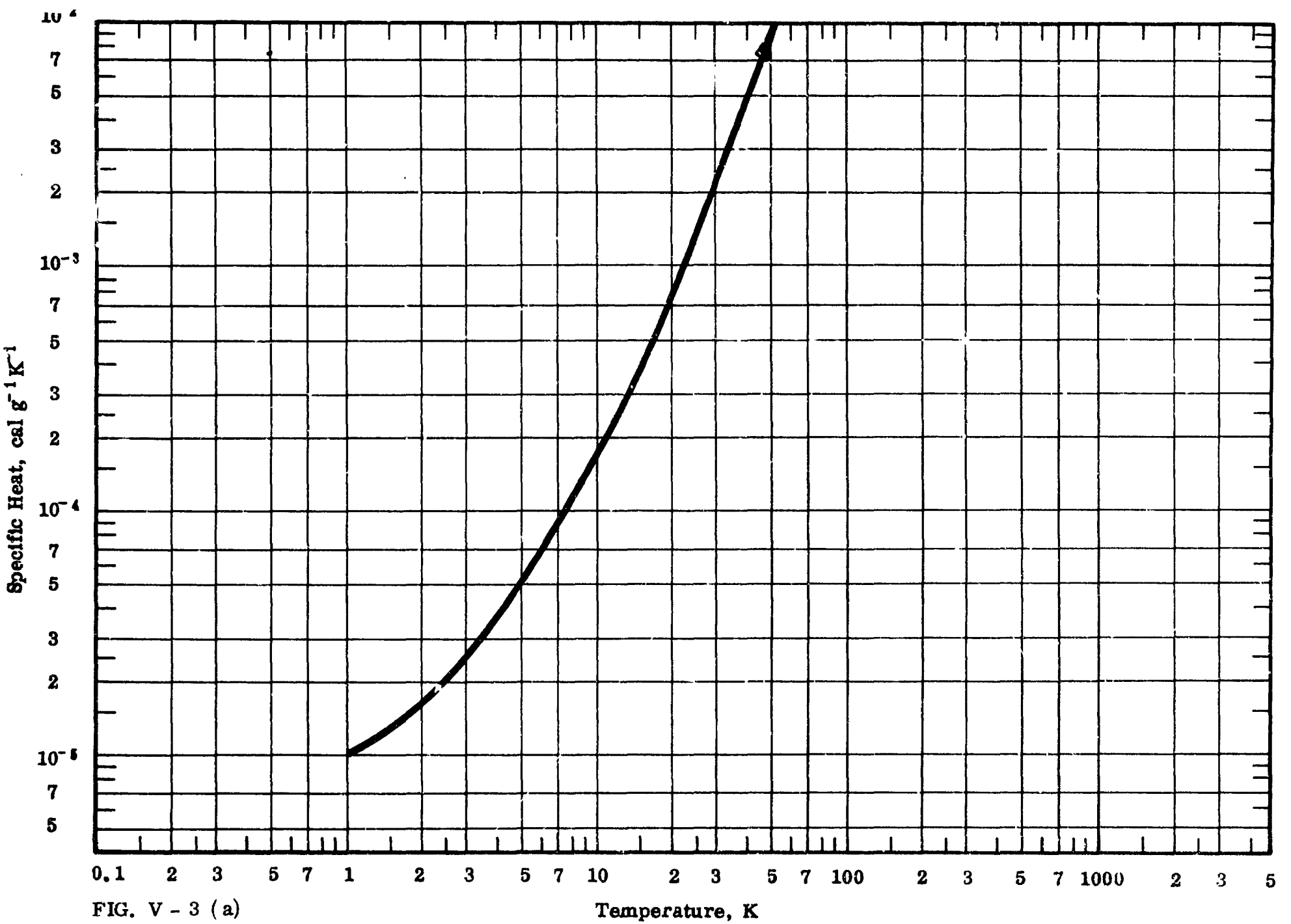

FIG. V - 3 (a)

SPECIFIC HEAT -- CHROMIUM

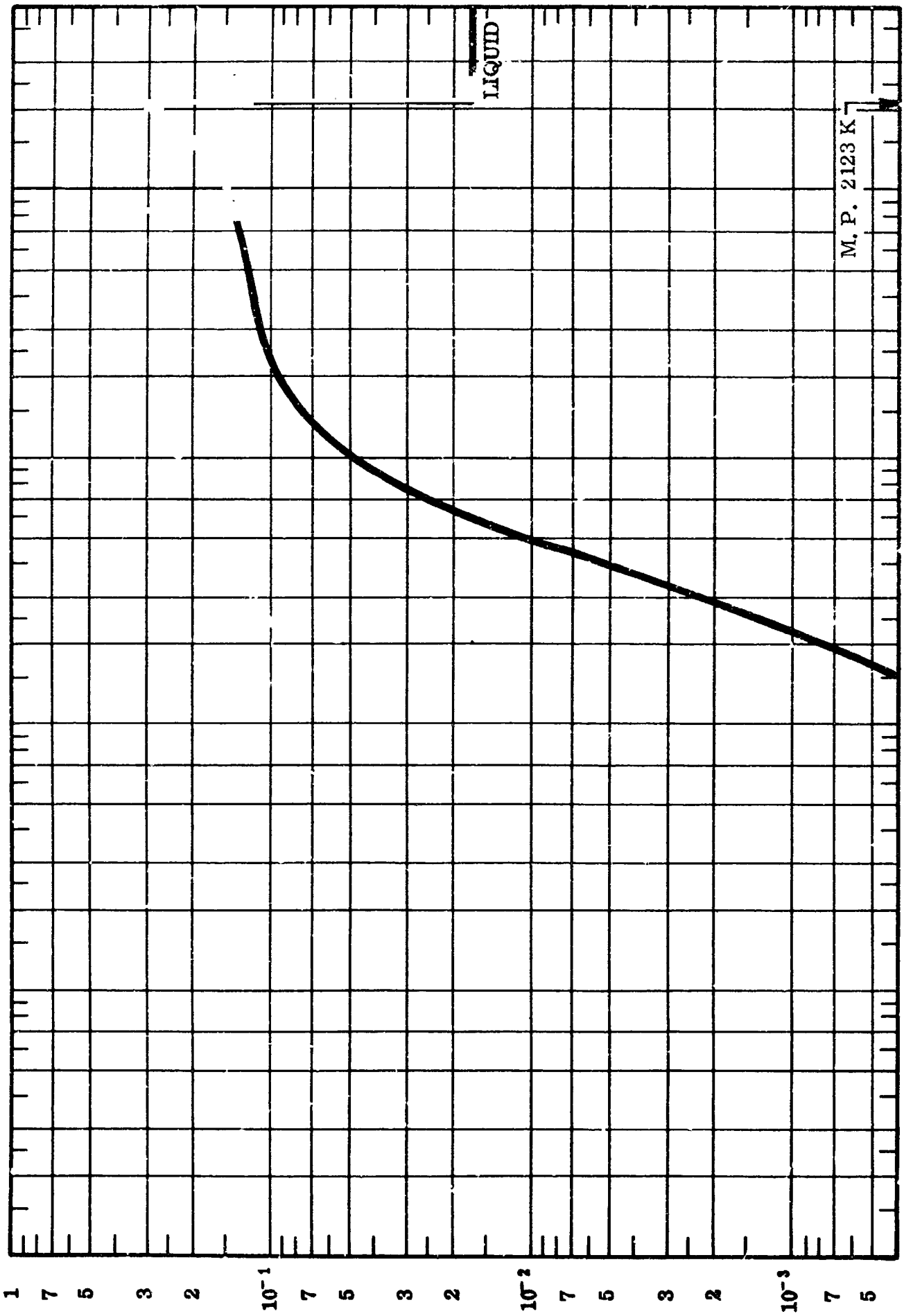

FIG. V - 3 (b)

SPECIFIC HEAT -- CHROMIUM

TABLE V-3. SPECIFIC HEAT OF CHROMIUM

T°K	C_p, cal g^{-1} K^{-1}	T°K	C_p, cal g^{-1} K^{-1}
1	(1×10^{-5})†	800	1.31×10^{-1}
2	1.58	900	1.38
3	2.50	1000	1.45
4	3.70	1100	1.53
5	(5.10)‡	1200	1.63
6	(6.90)	1300	1.72
7	(8.90)	1400	1.84
8	(1.12×10^{-4})	1500	1.96
9	(1.36)	1600	2.10
10	(1.65)	1700	2.27
15	(4.00)	1800	2.45
20	7.44	1900	2.65
30	2.99×10^{-3}	2000	(2.82)†
40	4.72	2100	(3.03)
50	9.37	(s) 2123	(3.18)
60	1.64×10^{-2}	(l) 2123	(1.81)††
70	2.41	2200	(1.81)
80	3.23	2300	(1.81)
90	4.05	2400	(1.81)
100	4.84	2500	(1.81)
150	7.62	2600	(1.81)
200	9.08	2700	(1.81)
300	1.08×10^{-1}	2800	(1.81)
400	1.17	2900	(1.81)
500	1.23	3000	(1.81)
600	1.27		
700	1.28		

Investigators: Amstrong, L. D., and Grayson-Smith, H. (24) [273-1073K]; Anderson, C. T. (25) [56-291K]; Beaumont, R. H. (26) [268-324K]; Clusius, K., and Franzosini, P. (27) [14-274K]; Conway, J. B., and Hein, R. A. (28) [1273-2103K]; Estermann, I., et al (29) [1.8-3.9K]; Friedberg, S. A. (30) [20-200K]; Hultgren, R., and Land, C. (31) [800-1500K]; Krauss, F. (32) [964-1598K]; Lucks, C. F., and Deem, H. W. (33) [297-1922K].

†Extrapolated

‡Interpolated

††Estimated (5)

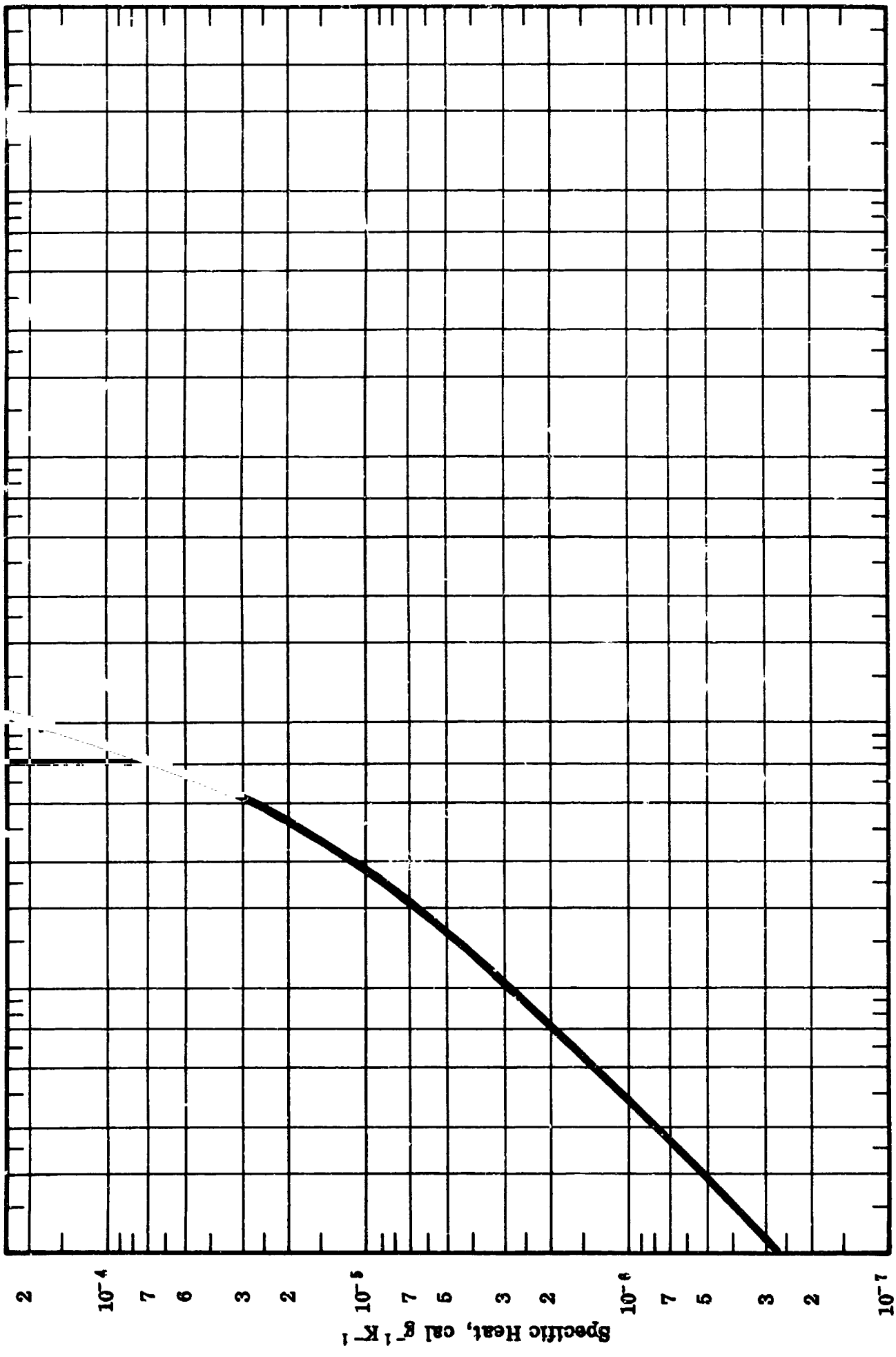

FIG. V - 4 (a)

SPECIFIC HEAT -- COPPER

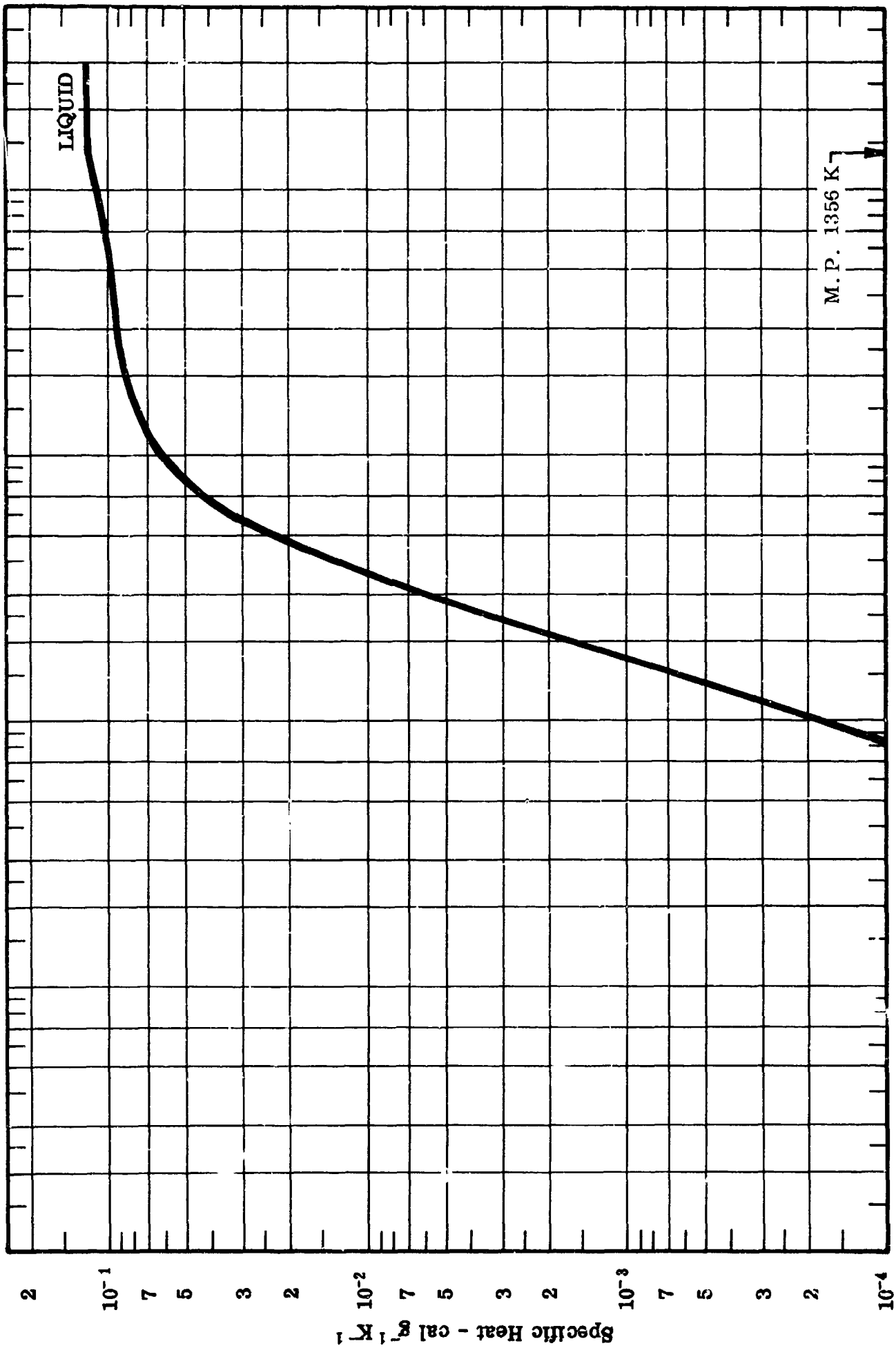

FIG. V - 4 (b)

SPECIFIC HEAT -- COPPER

TABLE V-4. SPECIFIC HEAT OF COPPER

T °K	C_p, cal $g^{-1} K^{-1}$		T °K	C_p, cal $g^{-1} K^{-1}$
0.1	2.70×10^{-7}		300	9.23×10^{-2}
0.2	5.30		400	9.46
0.3	7.95		500	9.71
0.4	1.05×10^{-6}		600	9.95
0.5	1.32		700	1.02×10^{-1}
0.6	1.59		800	1.04
0.7	1.88		900	1.07
0.8	2.15		1000	1.09
0.9	2.46		1100	1.11
1	2.75		1200	1.14
2	6.59		1300	1.16
3	1.26×10^{-5}	(s)	1356	1.18 †
4	2.17	(l)	1356	(1.18)†
5	3.45		1400	(1.18)
6	5.45		1500	(1.18)
7	8.00		1600	(1.18)
8	1.14×10^{-4}		1700	(1.18)
9	1.56		1800	(1.18)
10	2.05		1900	(1.18)
15	6.63		2000	(1.18)
20	1.76×10^{-3}		2100	(1.18)
30	6.53		2200	(1.18)
40	1.42×10^{-2}		2300	(1.18)
50	2.36		2400	(1.18)
60	3.45		2500	(1.18)
70	4.10		2600	(1.18)
80	4.35		2700	(1.18)
90	5.50		2800	(1.18)
100	6.06		2900	(1.18)
200	8.55		3000	(1.18)

Investigators: Avramescu, A. (34) [373-1273K]; Bell, I.P. (35) [288-701K]; Booker, J., et al (36) [727-1210K]; Butler, C.P., and Inn, E.C.Y. (37) [337-946K]; Dockerty, S.M. (38) [201-389K]; Dockerty, S.M. (39) [28-194K]; Eder, F.X. (40) [30-300K]; Esterman, I., et al (41) [2.2-3.6K]; Eucken, A., and Werth, H. (42) [94-219K]; Fieldhouse, I.B., et al (43) [811-1311K]; Fieldhouse, I.B., et al (44) [1366-1922K]; Giauque, W.F., and Meads, P.F. (45) [15-300K]; Howse, P.T., et al (46) [366-544K]; Jaeger, F.M., et al (47) [573-1173K];

†Estimated (5)

Investigators: (continued) (COPPER)
Kok, J.A., and Keesom, W.H., (48) [1-20 K]; Klinkhardt, H. (49) [373-1073K]; Lucks, C.F., and Deem, H.W. (50) [297-1310K]; Lucks, C.F. and Deem, H.W. (51) [273-1338K]; Lyusternik, V.E. (52) [323-1273K]; Masuda, Y. (53) [473-973K]; Martin, D.L. (54) [20-300 K]; Martin, D.L. (55) [10-30K]; Neel, D.S., et al (56) [533-1089K]; O'Neal, H.R. (57) [0.1-1.0K]; Pawel, R.E. (58) [363-883K]; Picklesimer, M.L. (59) [373-1203K]; Quinney, H., and Taylor, G.I. (60) [410-673K]; Sandenaw, T.A. (61) [5-298K]; Trice, J.B., et al (62) [589-794K].

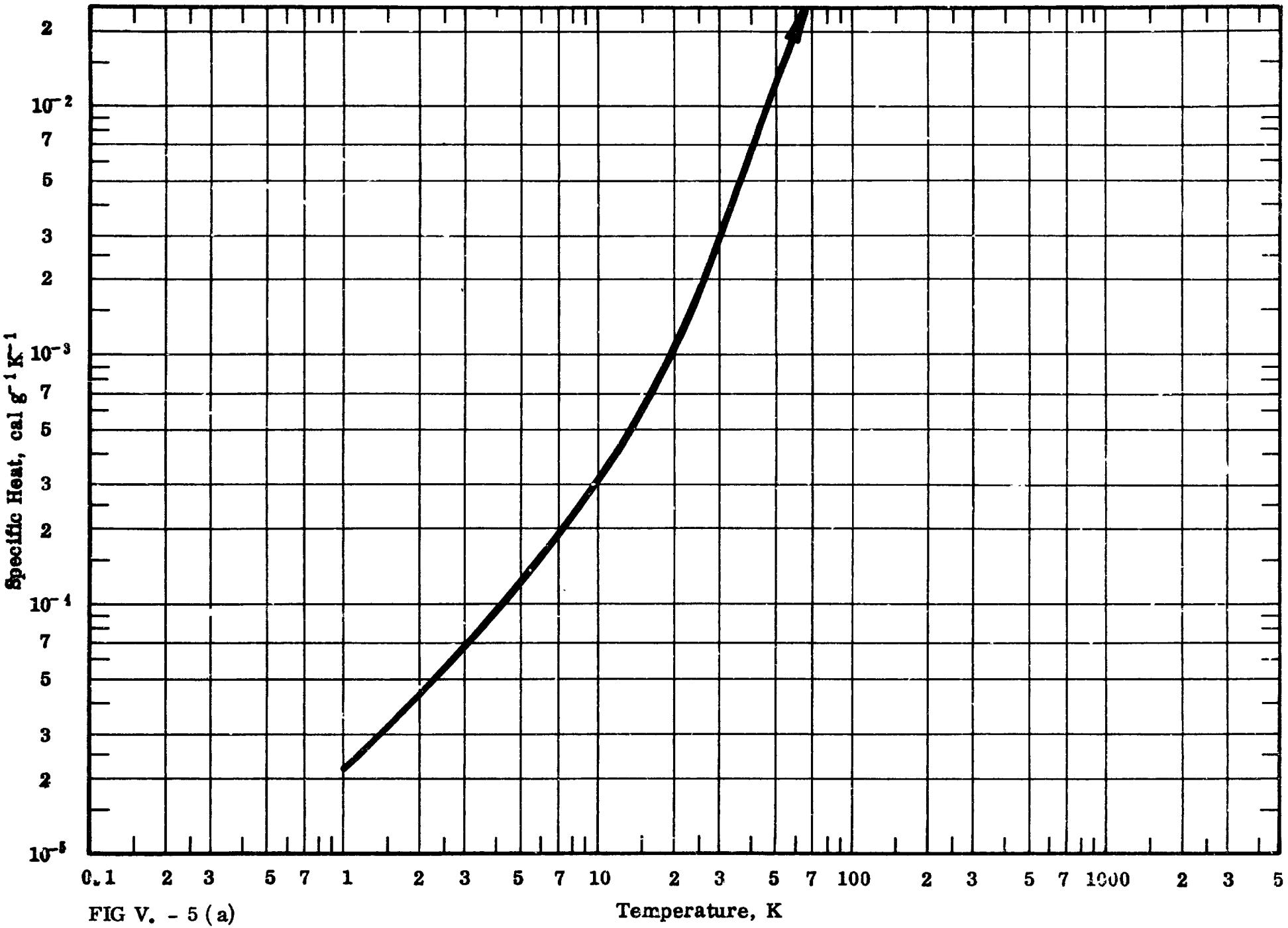

FIG V. - 5 (a)

SPECIFIC HEAT -- IRON

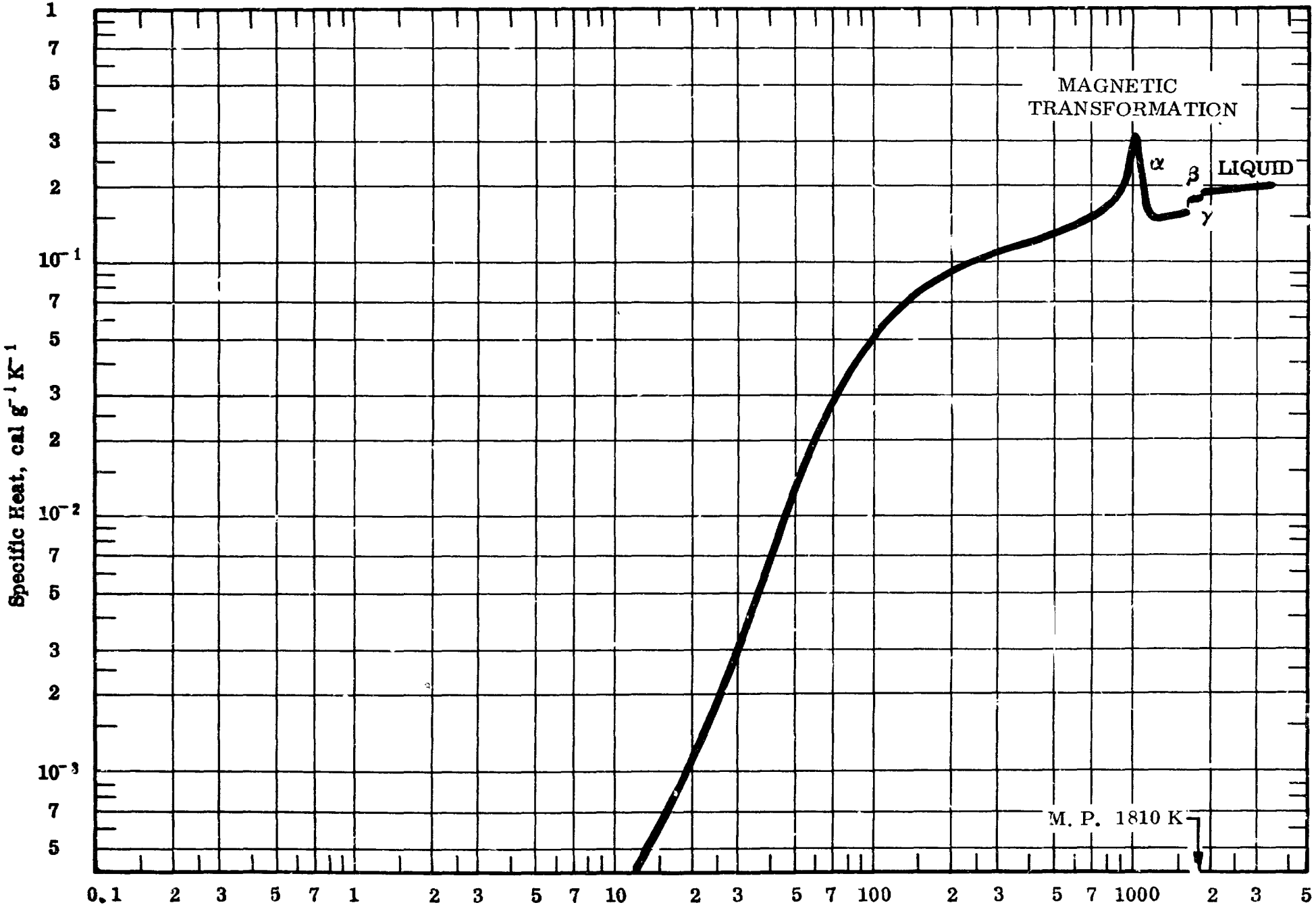

FIG. V - 5 (b)

SPECIFIC HEAT -- IRON

TABLE V-5. SPECIFIC HEAT OF IRON

T °K	C_p, cal $g^{-1}K^{-1}$	T °K	C_p, cal $g^{-1}K^{-1}$
1	(2.18×10^{-5})†	900	1.88×10^{-1}
1.5	3.27	1000	2.43
2	4.37	1020	2.79
3	6.68	1033	3.19
4	9.13	1040	2.97
5	1.18×10^{-4}	1060	2.38
6	1.50	1080	1.97
7	1.82	1100	1.83
8	2.16	1120	1.75
9	2.52	1140	1.71
10	2.99	1160	1.69
15	6.03	(α) 1183	1.67
20	1.10×10^{-3}	(γ) 1183	1.46
30	3.19	1200	1.46
40	7.09	1300	1.49
50	1.27×10^{-2}	1400	1.51
60	2.04	1500	1.54
70	2.84	1600	1.57
80	3.65	(γ') 1665	1.59
90	4.45	(δ) 1665	1.75
100	5.16	1800	1.79
150	7.75	(δ) 1810	1.79
200	9.18	(l) 1810	1.88
250	1.01×10^{-1}	1900	1.89
300	1.08	2000	1.89
400	1.16	2300	(1.92)‡
500	1.26	2600	(1.94)
600	1.36	3000	(1.97)
700	1.48	3148	(1.98)
800	1.64	3500	(2.00)

Investigators: Anderson, P.D., and Hultgren, R. (63) [298-1904 K]; Awbery, J.H., and Challoner, A.R. (64) [348-1223 K]; Awbery, J.H., and Griffiths, E. (65) [373-1223 K]; Dench, W.A., and Kubaschewski, O. (66) [1073-1693 K]; Duyckaerts, G. (67) [1.5-20 K]; Duyckaerts, G. (68) [1.5-20 K]; Eucken, A., and Werth, H. (69) [17-206 K]; Jaeger, F.M., et al (70) [278-1773 K]; Keesom, W.H., and Kurrelmeyer, B. (71) [1-20 K]; Kelley, K.K. (72) [54-295 K]; Klinkhardt, H. (73) [373-1273 K]; McElroy, D.L. (74) [353-1173 K]; Kohlhaas, R., and Braun, M. (75) [20-1663 K]; Kohlhaas, R., Braun, M. (76) [20-1663 K]; Lyubimov, A.P., and Belashchenko, D.K. (77) [618-973 K] Pallister, P.R. (78) [273-1539]; Pallister, P.R.,

†Extrapolated

‡Estimated (5)

Investigators(continued) (IRON)
(79) [901-923 K]; Picklesimer, M. L. (80) [70-935 K]; Quinney, H , and Taylor, G. T. (81) [773-973 K]; Rodebush, W. H., and Mickalek, J. C. (82) [73-200 K]; Schroder, K. (83) [173-623 K]; Tretyakov, Yu D., et al (84) [800-1071 K]; Umino, S. (85) [112-1833 K]; Wallace, D.C., et al (86) [298-1323 K]) Zuithoff, A.J. (87) [378-1773 K].

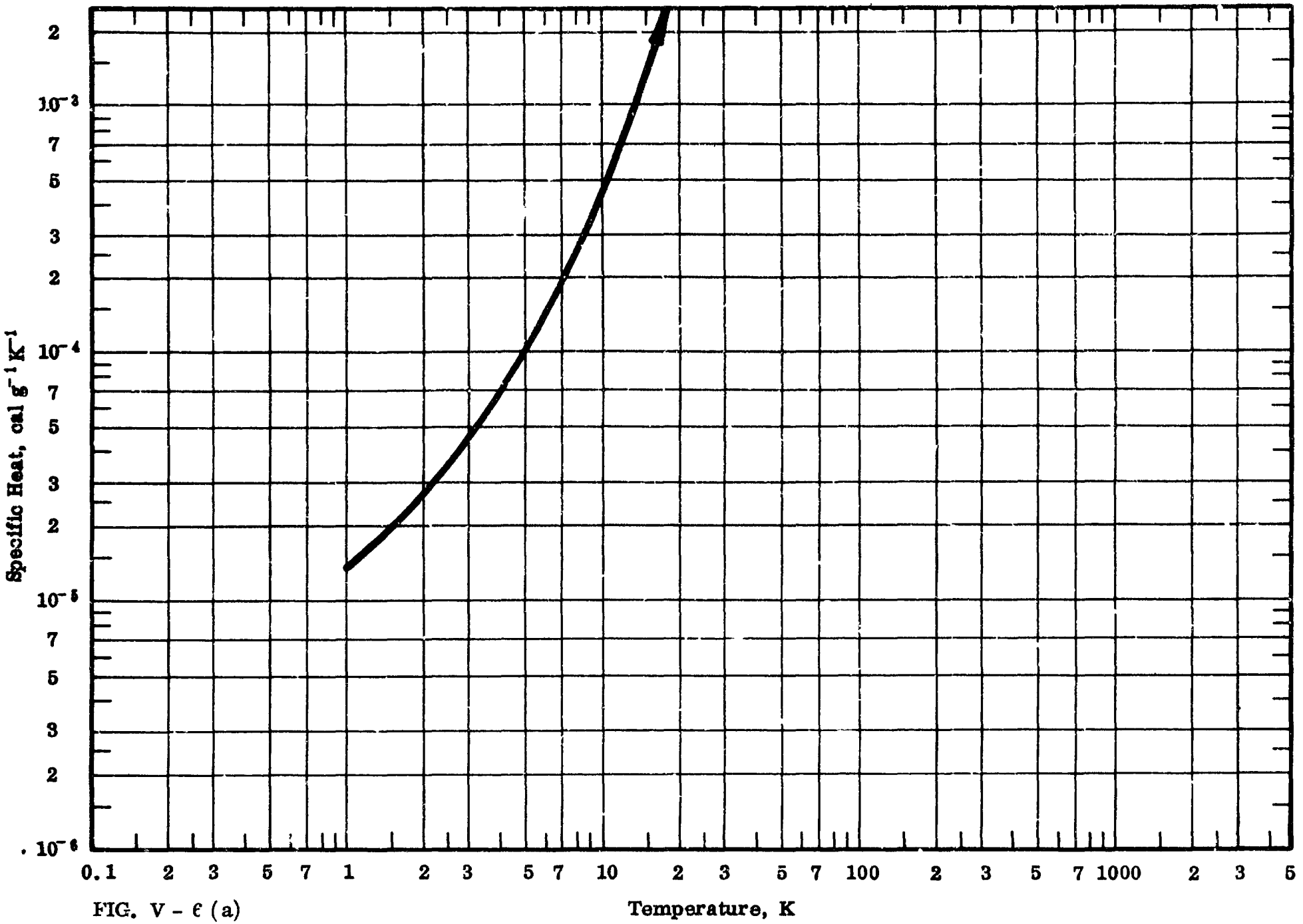

FIG. V - ϵ (a)

SPECIFIC HEAT MAGNESIUM

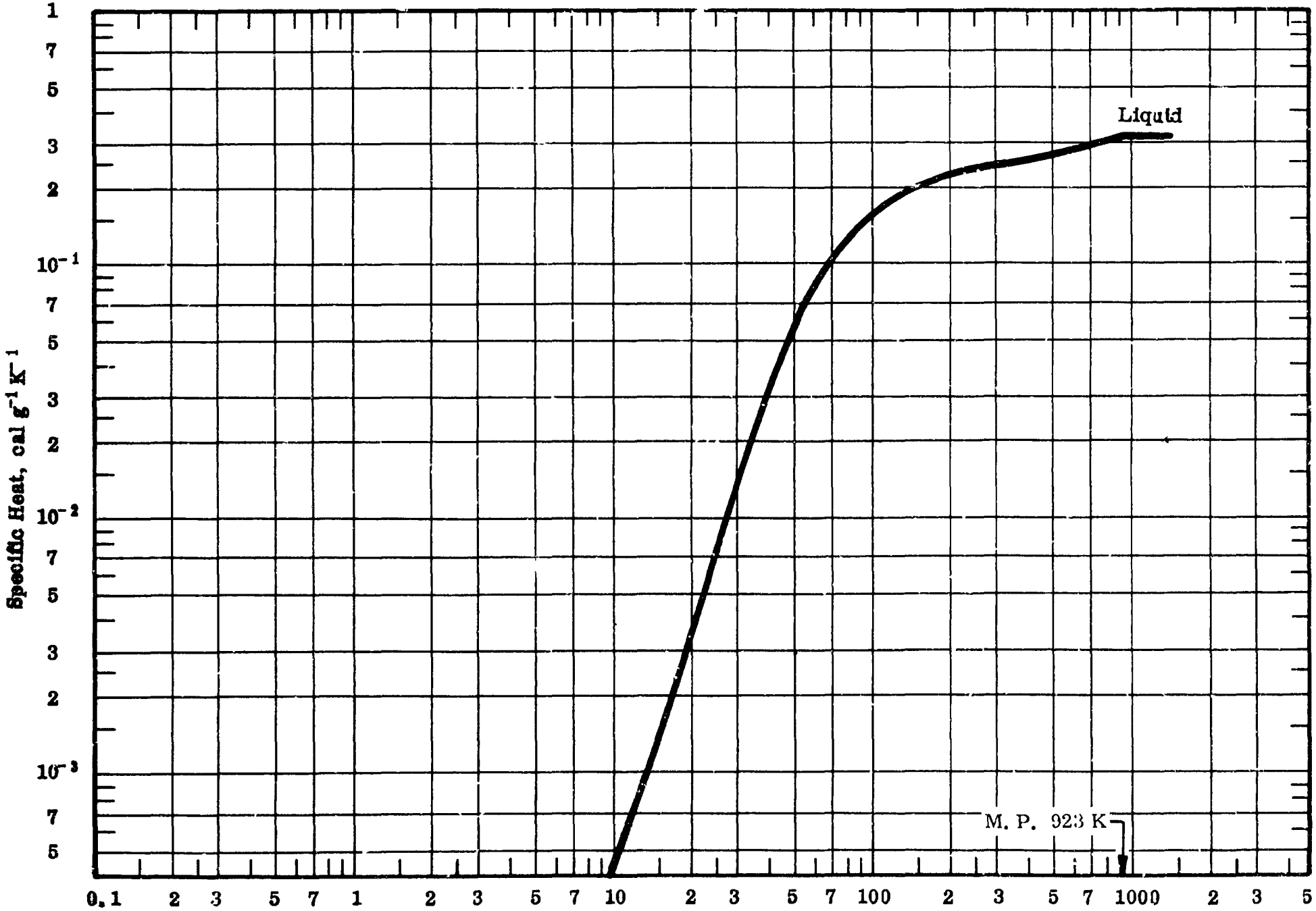

FIG. V - 6 (b)

SPECIFIC HEAT -- MAGNESIUM

TABLE V-6. SPECIFIC HEAT OF MAGNESIUM

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
1	1.33×10^{-5}	200	2.23×10^{-1}
2	2.85	300	2.44
3	4.77	400	2.57
4	7.32	500	2.66
5	1.07×10^{-4}	600	2.78
10	4.52	700	2.91
20	3.55×10^{-3}	800	3.05
30	1.40×10^{-2}	900	3.21
40	3.31	(s) 923	3.23
50	5.67	(l) 923	(3.20)†
60	8.03	1000	(3.20)
70	1.03×10^{-1}	1100	(3.20)
80	1.23	1200	(3.20)
90	1.40	1300	(3.20)
100	1.55	1400	(3.20)

Investigators: Baker, H. (88) [700-1100K]; Clusius, K., and Vaughen, J. V. (89) [11-22?K]; Craig, R.S., et al (90) [12-320K]; Esterman, I., et al (91) [3-3.6K]; Eastman, E.D., et al (92) [373-873K]; Jaeger, F.M., and Poppema, T.J. (93) [273-873K]; Logan, J.K., et al (94) [3-13K]; Manchen, W., and Bornkessel, K. (95) [190-300K]; Poppema, T.J., and Jaeger, F.M. (96) [273-87?K]; Smith, P.L. (97) [1.3-20K]; Stull, D.R., and McDonald, R.A. (98) [700-1100K]; Wallace, W.E., et al (99) [278-543K].

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†Estimated (5)

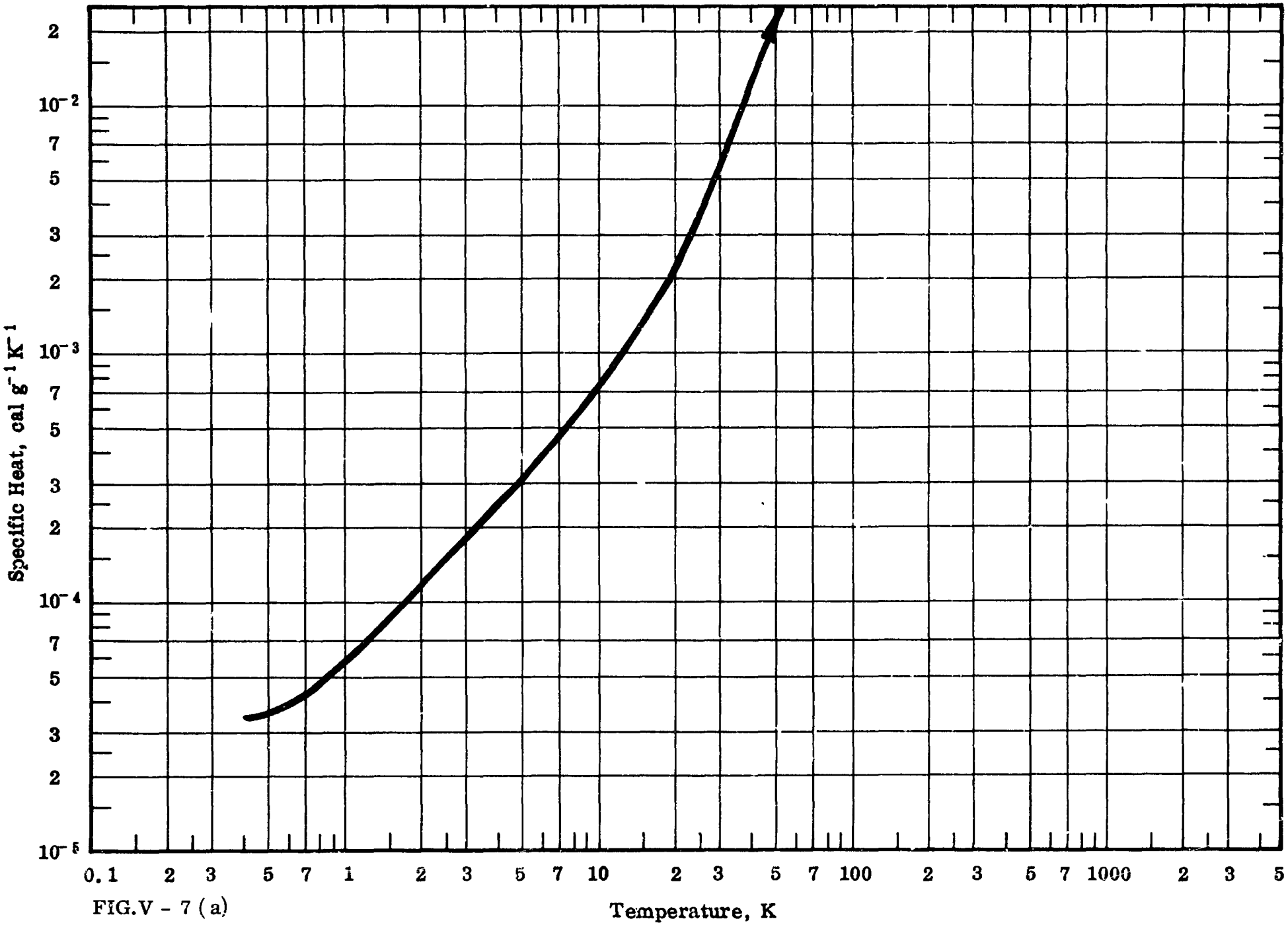

FIG.V - 7 (a)

SPECIFIC HEAT -- MANGANESE

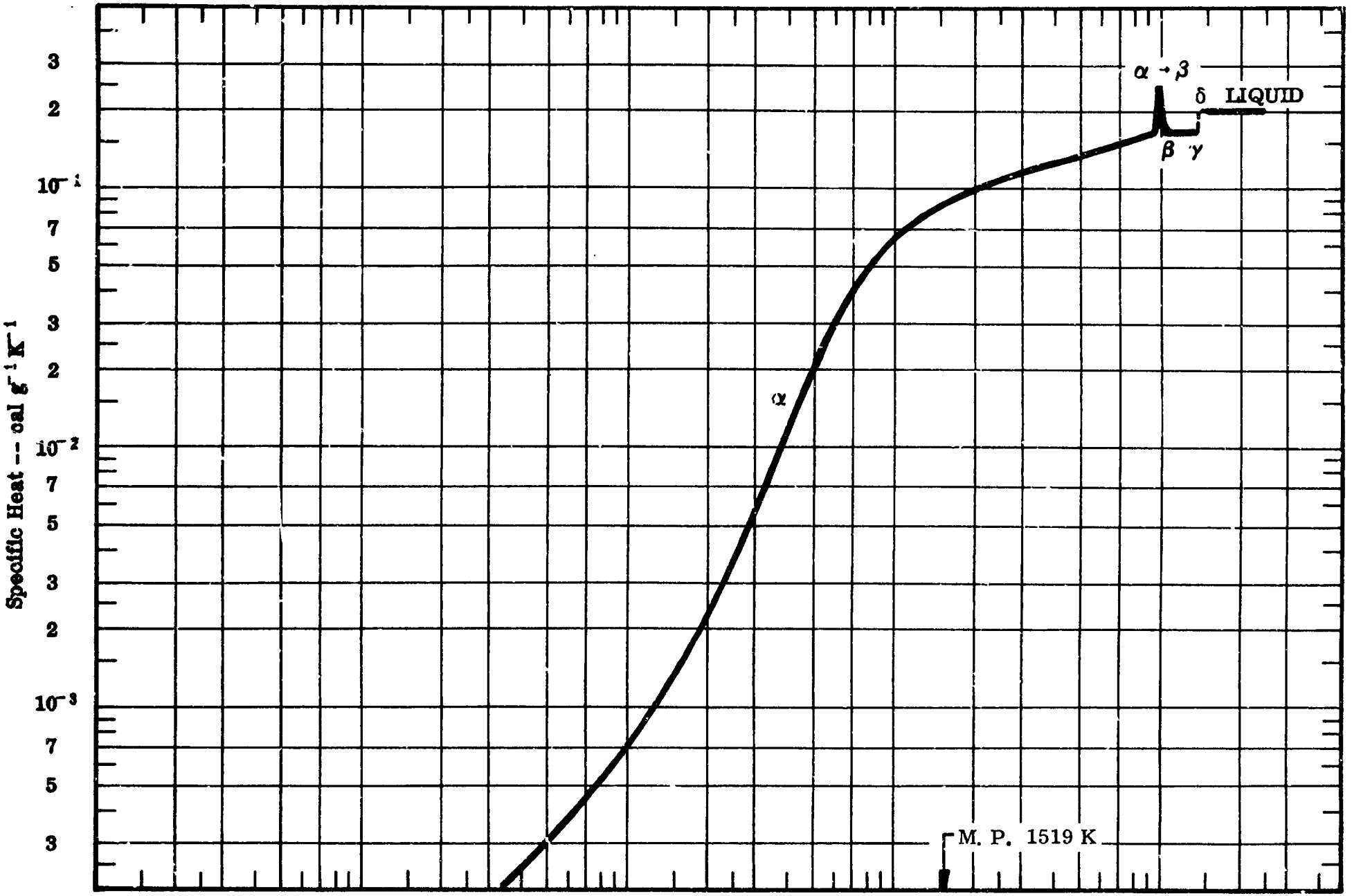

FIG. V - 7 (b)

SPECIFIC HEAT . . MANGANESE

TABLE V-7. SPECIFIC HEAT OF MANGANESE

T °K		C_p, cal g^{-1} K^{-1}	T °K		C_p, cal g^{-1} K^{-1}
(α)	0.4	3.48×10^{-5}			
	0.5	3.52			
	0.6	3.80			
	0.7	4.19			
	0.8	4.64			
	0.9	5.13			
	1.0	5.66			
	1.2	6.77			
	1.4	7.96			
	1.6	9.22			
	1.8	1.06×10^{-4}			
	2.0	1.20			
	3.0	(1.82)††			
	4.0	(2.48)			
	5.0	(3.15)			
	6.0	(3.90)			
	7.0	(4.60)			
	8.0	(5.45)			
	9.0	(6.30)			
	10	7.20	(γ)	10	6.55×10^{-4}
	15	1.31×10^{-3}		15	1.22×10^{-3}
	20	2.13		20	2.22
	30	5.72		30	6.30
	40	1.21×10^{-2}		40	1.35×10^{-2}
	50	2.11		50	2.20
	60	3.06		60	3.20
	70	4.07		70	4.16
	80	5.00		80	5.06
	90	5.70		90	5.88
	100	6.41		100	6.44
	150	8.72		150	8.88
	200	1.00×10^{-1}		200	1.03×10^{-1}
	300	1.15		300	1.21
	400	1.24		400	(1.31)‡
	500	1.32		500	(1.39)
	600	1.39		600	(1.47)
	700	1.45		700	(1.53)
	800	1.52		800	(1.60)
	900	1.58		900	(1.67)
(α)	1000	1.65		1000	(1.74)
(β)	1000	1.64×10^{-1}			
	1100	1.65		1100	(1.80)

†Extrapolated

‡Estimated (5)

††Interpolated

TABLE V-7. SPECIFIC HEAT OF MANGANESE (continued)

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
(β) 1200	1.66×10^{-1}	(γ) 1200	(1.87×10^{-1})
1300	1.67	1300	(1.94)
(β) 1374	1.68		
(γ) 1374	1.95×10^{-1}		
1400	1.95		
(γ) 1410	1.95		
(δ) 1410	2.06×10^{-1}		
1500	2.06		
(δ) 1517	2.06		
(l) 1517	(2.00×10^{-1})‡		
1600	(2.00)		
1700	(2.00)		
1800	(2.00)		
1900	(2.00)		
2000	(2.00)		
2100	(2.00)		
2200	(2.00)		
2300	(2.00)		
2400	(2.00)		
(l) 2500	(2.00)		

Investigators: Amstrong, L.D., and Grayson-Smith, H. (100) [273-1073K]; Amstrong, L.D. (101) [15-22K]; Booth, G.L., et al (102) [12-20K]; Elson, R.G., et al (103) [16-22K]; Franzosini, P., et al (104) [10-273K]; Heer, C.V. (105) [0.4-2.0K]; Kelley, K.K. (106) [54-290K]; Kelley, K.K., et al (107) [54-1410K].

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‡Estimated (5)

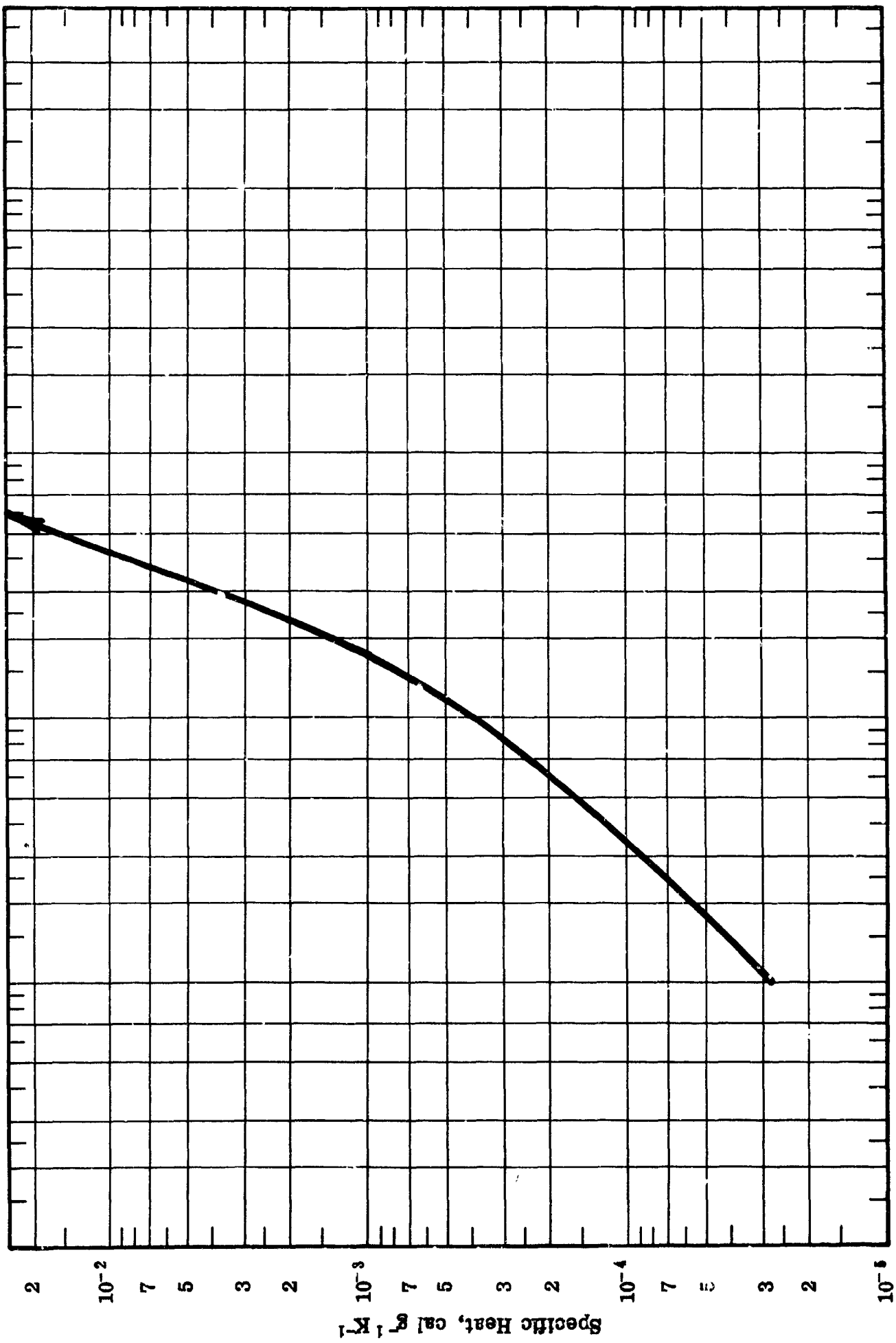

FIG. V - 8 (a)

SPECIFIC HEAT -- NICKEL

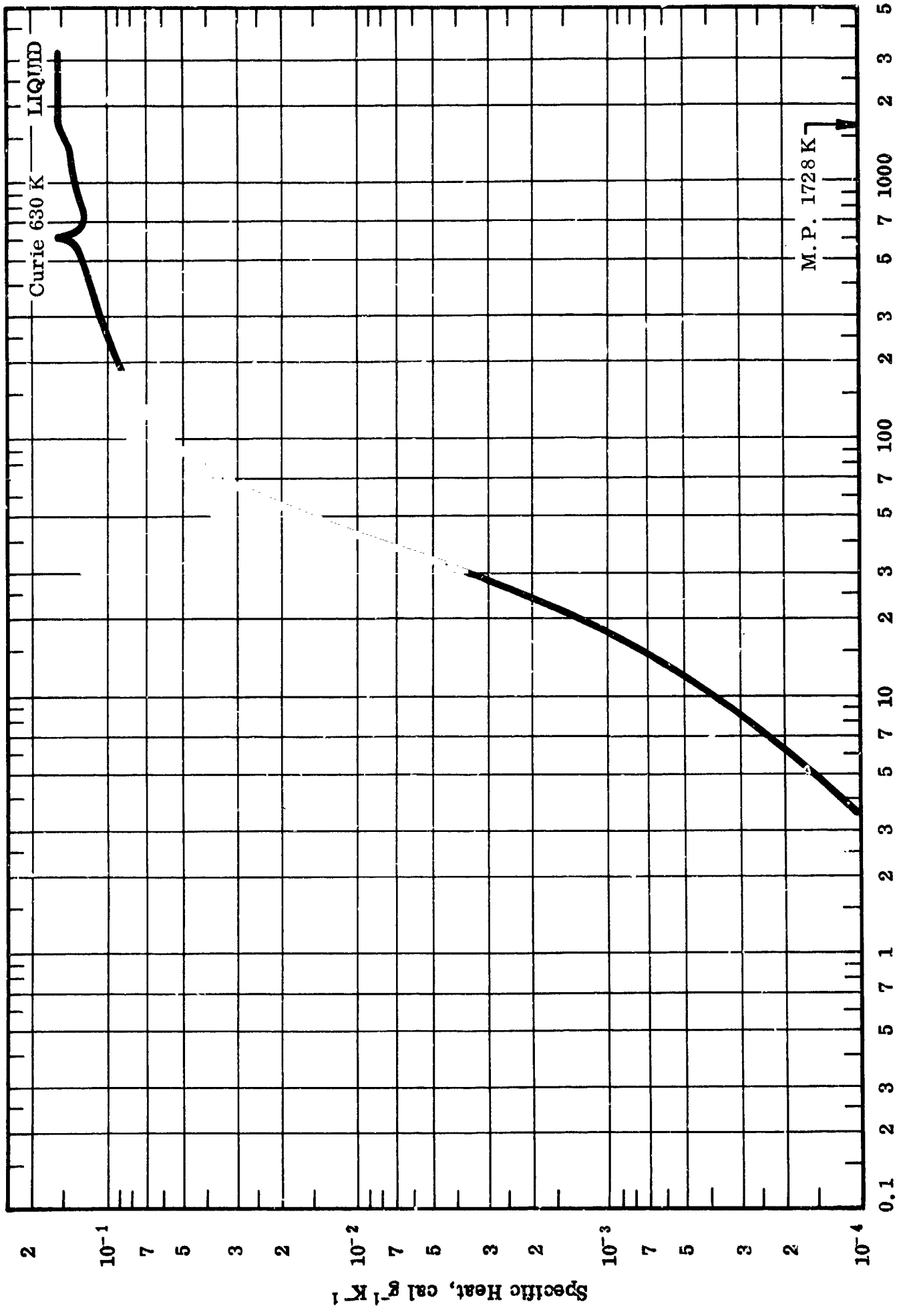

FIG. V - 8 (b)

SPECIFIC HEAT -- NICKEL

TABLE V-8. SPECIFIC HEAT OF NICKEL

T ° K	C_p, cal $g^{-1} K^{-1}$	T ° K	C_p, cal $g^{-1} K^{-1}$
1	2.88×10^{-5}	640	1.34×10^{-1}
2	5.79	650	1.30
3	8.84	700	1.26
4	1.20×10^{-4}	800	1.27
5	1.55	900	1.30
6	2.04	1000	1.34
7	2.48	1100	1.37
8	2.92	1200	1.40
9	3.40	1300	1.43
10	3.92	1400	1.46
15	7.39	1500	(1.49)†
20	1.31×10^{-3}	1600	(1.51)
30	3.93	1700	(1.54)
40	9.04	(s) 1728	(1.54)
50	1.63×10^{-2}	(l) 1728	(1.57)
60	2.45	1800	(1.57)
70	2.34	1900	(1.57)
80	4.08	2000	(1.57)
90	4.90	2100	(1.57)
100	5.55	2200	(1.57)
200	9.14	2300	(1.57)
300	1.06×10^{-1}	2400	(1.57)
400	1.16	2500	(1.57)
500	1.26	2600	(1.57)
600	1.42	2700	(1.57)
610	1.44	2800	(1.57)
620	1.48	2900	(1.57)
625	1.51	3000	(1.57)
630	1.58	3100	(1.57)
635	1.37	3200	(1.57)

Investigators: Booker, J., et al (108) [466-1584 K]; Bronson, H. L., et al (109) [336-773 K]; Bronson, H. L., and Wilson, A. J. C. (110) [203-383 K]; Busey, R. H. (111) [13-302 K]; Butler, C. P., and Inn, E. C. Y. (112) [337-1164 K]; Eucken, A., and Werth, H. (113) [15-204 K]; Ewert, M. (114) [373-1273 K]; Fieldhouse, I. B., et al (115) [811-1644 K]; Grew, K. E. (116) [86-726K]; Hagel, K. E. (117) [673-1123 K]; Haltgren, R., and Land, C. (118) [800-1500 K]; Keesom, W. H., and Clark, C. W. (119) [1-19 K]; Keesom, W. H., and Kok, J. A. (120) [11-42 K]; Krauss, F., and Warncke, H. (121) [770-1437 K]; Lapp, C. (122) [98-733 K]; Moser, H. (123) [325-923 K];

†Estimated (5)

Investigators: (continued) (NICKEL)
Neel, L. (124) [287-813 K]; Pawel, R. E. (125) [323-883 K]; Persoz, B. (126) [698-1280 K]; Rayne, J. A., and Kemp, W. R. G. (127) [1.4-4.2 K]; Sucksmith, W., and Potter, H. H. (128) [291-673 K]; Sykes, C., and Wilkinson, H. (129) [333-875 K].

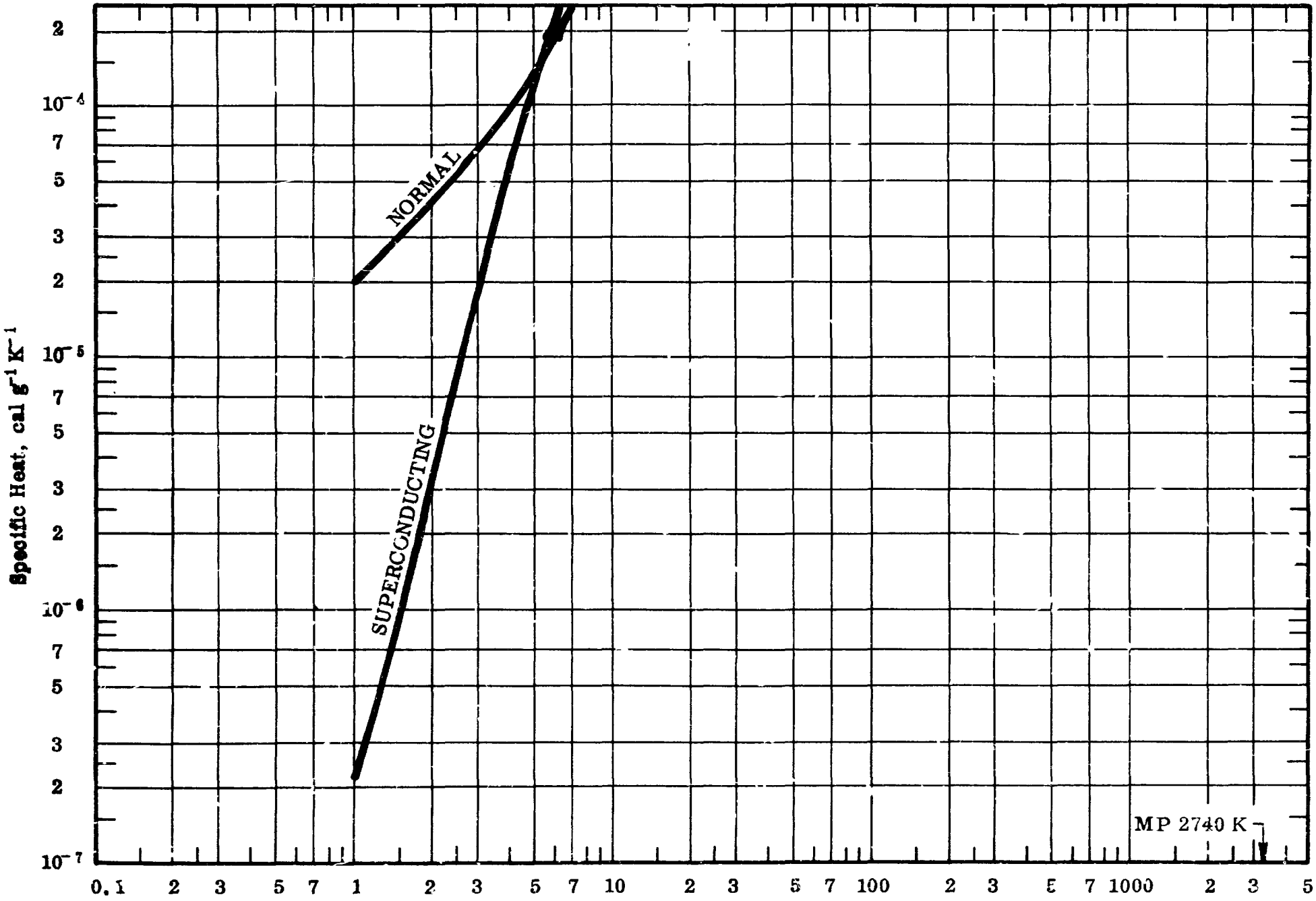

FIG. V - 9 (a)

SPECIFIC HEAT -- NIOBIUM

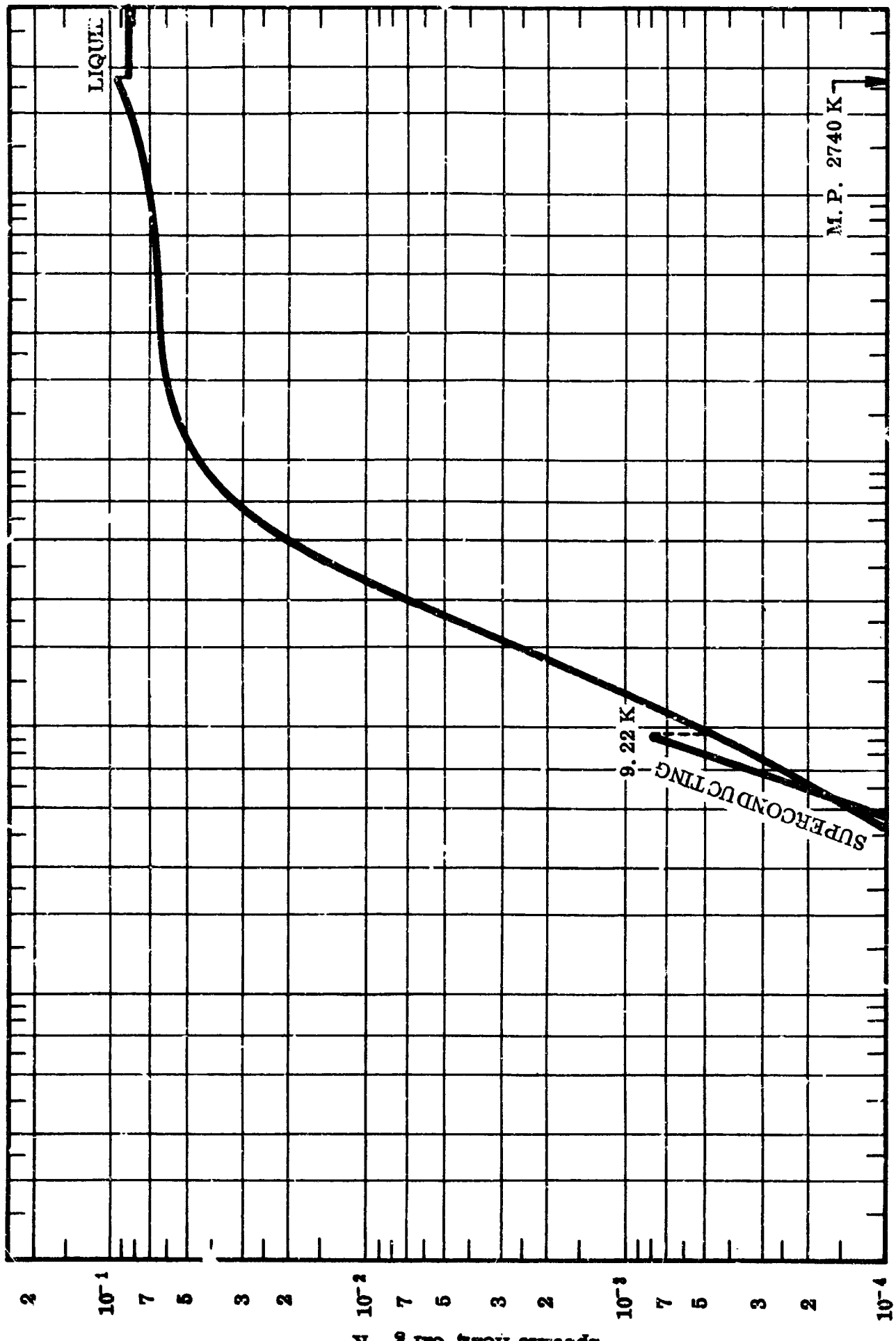
LIQUID
M. P. 2740 K
SUPERCONDUCTING
9.22 K
Specific Heat, cal g⁻¹ K⁻¹
Temperature, K
0.1
1000

FIG. V - 9 (b)

TABLE V-9. SPECIFIC HEAT OF NIOBIUM

	NORMAL	SUPERCONDUCTING		
T °K	C_p, cal $g^{-1} K^{-1}$	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
1	1.97×10^{-5}	2.2×10^{-7}	800	6.93×10^{-2}
2	4.13	3.6×10^{-6}	900	7.03
3	6.72	2.1×10^{-5}	1000	7.14
4	9.90	6.29	1100	7.23
5	1.39×10^{-4}	1.32×10^{-4}	1200	7.34
6	1.89	2.29	1300	7.45
7	2.52	3.62	1400	7.55
8	3.28	5.36	1500	7.65
9	4.22	7.65	1600	7.75
9.22		8.12	1700	7.86
10	5.33		1800	7.97
15	1.35×10^{-3}		1900	(8.30)†
20	2.52		2000	(8.40)
30	6.96		2100	(8.50)
40	1.33×10^{-2}		2200	(8.65)
50	2.02		2300	(8.80)
60	2.68		2400	(8.95)
70	3.25		2500	(9.10)
80	3.72		2600	(9.20)
90	4.15		2700	(9.30)
100	4.49		(s) 2740	(9.40)
150	5.49		(l) 2740	(8.61×10^{-2})‡
200	5.94		2800	(8.61)
300	6.32		2900	(8.61)
400	6.52		3000	(8.61)
500	6.63		4000	(8.61)
600	6.72		5000	(8.61)
700	6.82			

Investigators: Brown, A., et al (130) [3-9K]; Brown, A., et al (131) [normal, 3-9K; superconducting, 2.5-8.7K]; Chou, C., et al (132) [normal, 1-10K; superconducting, 1-11K]; Clusius, K., et al (133) [11-270K]; Conway, J.B., and Hein, R.A. (134) [1273-2593K]; Fieldhouse, T.B., et al (135) [454-1885K]; Lowenthal, G.C. (136) [1200-2400K]; Yeager, F.H., and Veenstra, W.A. (137) [273-1873K].

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†Extrapolated

‡Estimated (5)

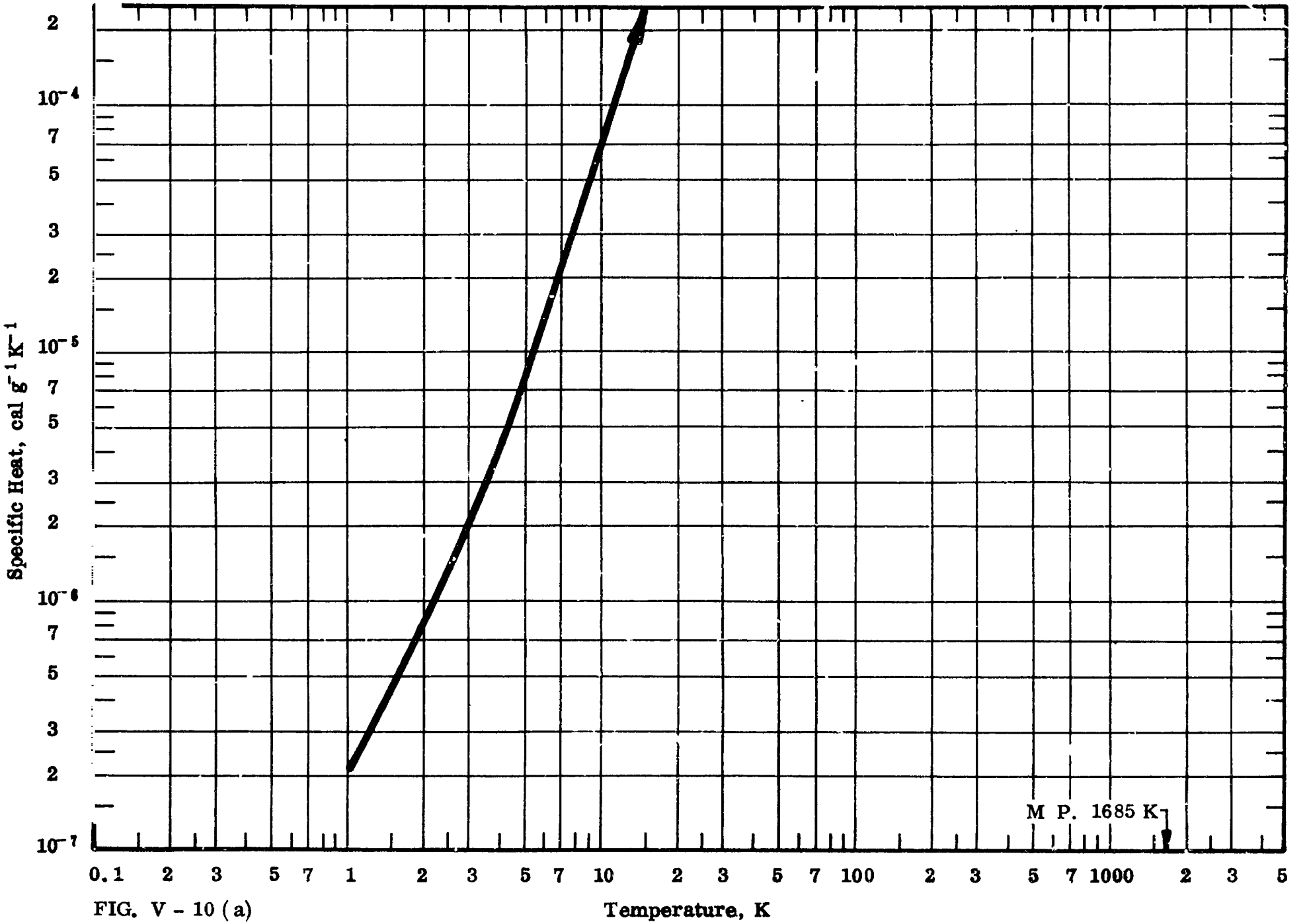

FIG. V - 10 (a)

SPECIFIC HEAT -- SILICON

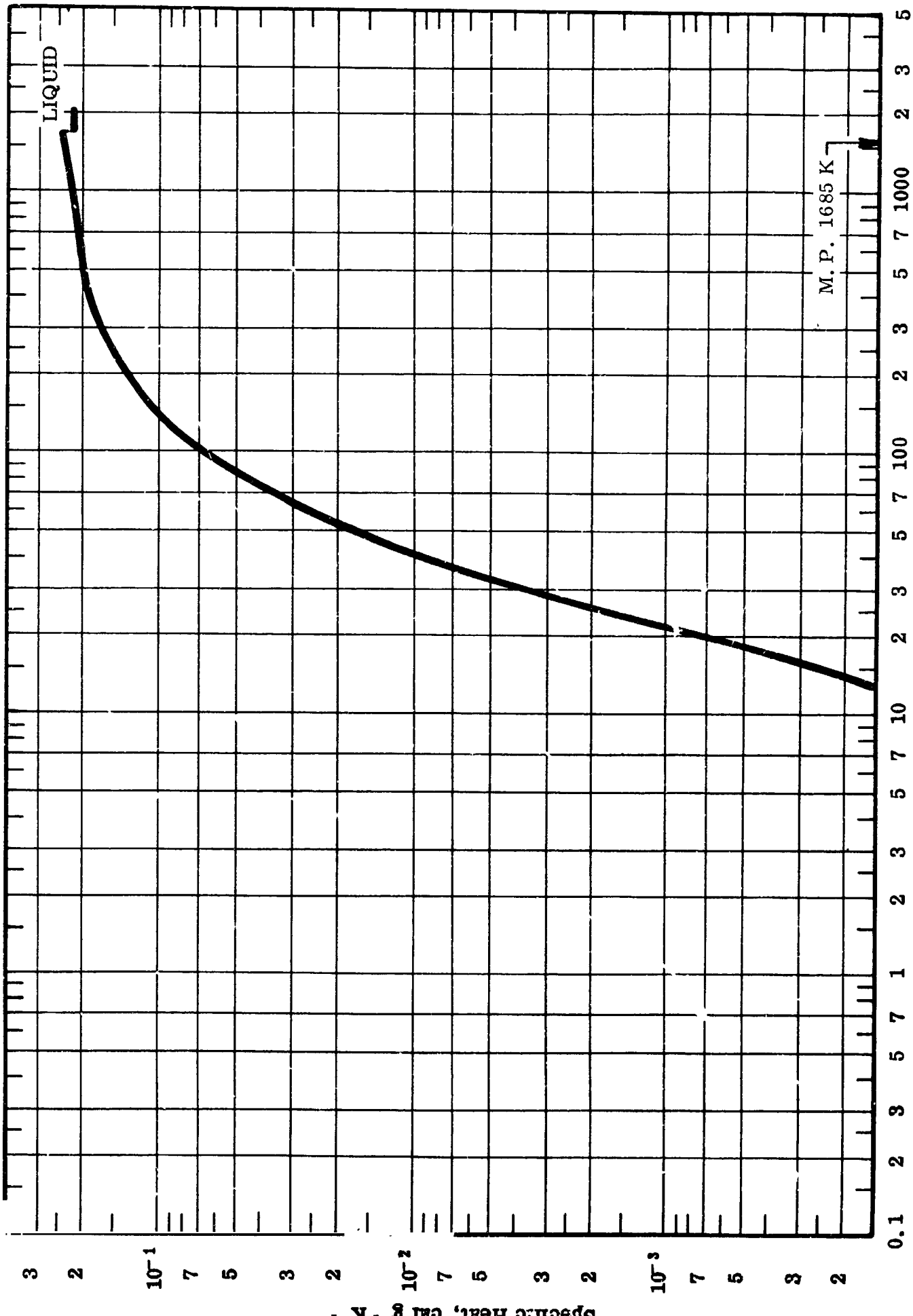

FIG. V – 10 (b)

SPECIFIC HEAT -- SILICON

TABLE V-10. SPECIFIC HEAT OF SILICON

T °K	C_p, cal $g^{-1} K^{-1}$		T °K	C_p, cal $g^{-1} K^{-1}$
1	$(2.18 \times 10^{-7})^{\dagger}$		200	1.33×10^{-1}
1.5	(4.58)		300	1.72
2	8.07		400	1.88
3	2.08×10^{-6}		500	1.97
4	4.40		600	2.04
5	8.10		700	2.08
6	1.38×10^{-5}		800	2.11
7	2.20		900	2.15
8	3.30		1000	2.19
9	4.70		1100	2.20
10	6.55		1200	2.25
15	2.55×10^{-4}		1300	2.30
20	8.00		1400	2.35
30	4.08×10^{-3}		1500	2.38
40	1.05×10^{-2}		1600	2.42
50	1.86	(s)	1685	2.46
60	2.75	(l)	1685	$(2.17 \times 10^{-1})^{\ddagger}$
70	3.64		1700	(2.17)
80	4.52		1800	(2.17)
90	5.40		1900	(2.17)
100	6.30		2000	(2.17)
150	1.02×10^{-1}			

Investigators: Anderson, C. T. (138) [61-296K]; Dismukes, J. P., et al (139) [295-889K]; Flubacher, P., et al (140) [8-300K]; Gultyaev, P. V., and Petrov, A. V. (141) [80-310K]; Kantor, P. B., et al (142) [1100-1900K]; Pearlman, N., and Keesom, P. H. (143) [1.7-5.0K]; Shanks, H. R. (144) [273-1373K].

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†Extrapolated

‡Estimated (5)

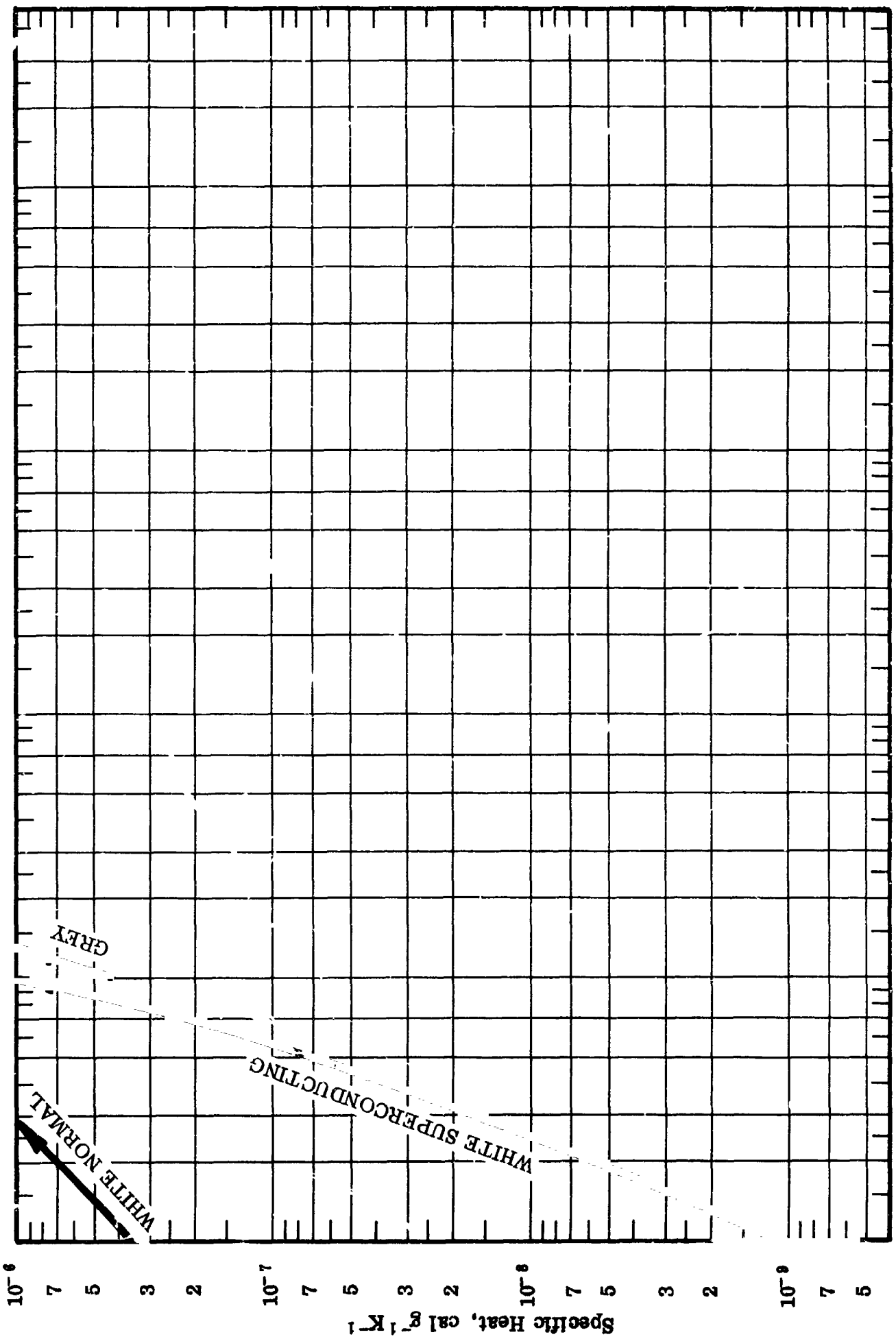

FIG. V - 11 (a)

SPECIFIC HEAT -- TIN

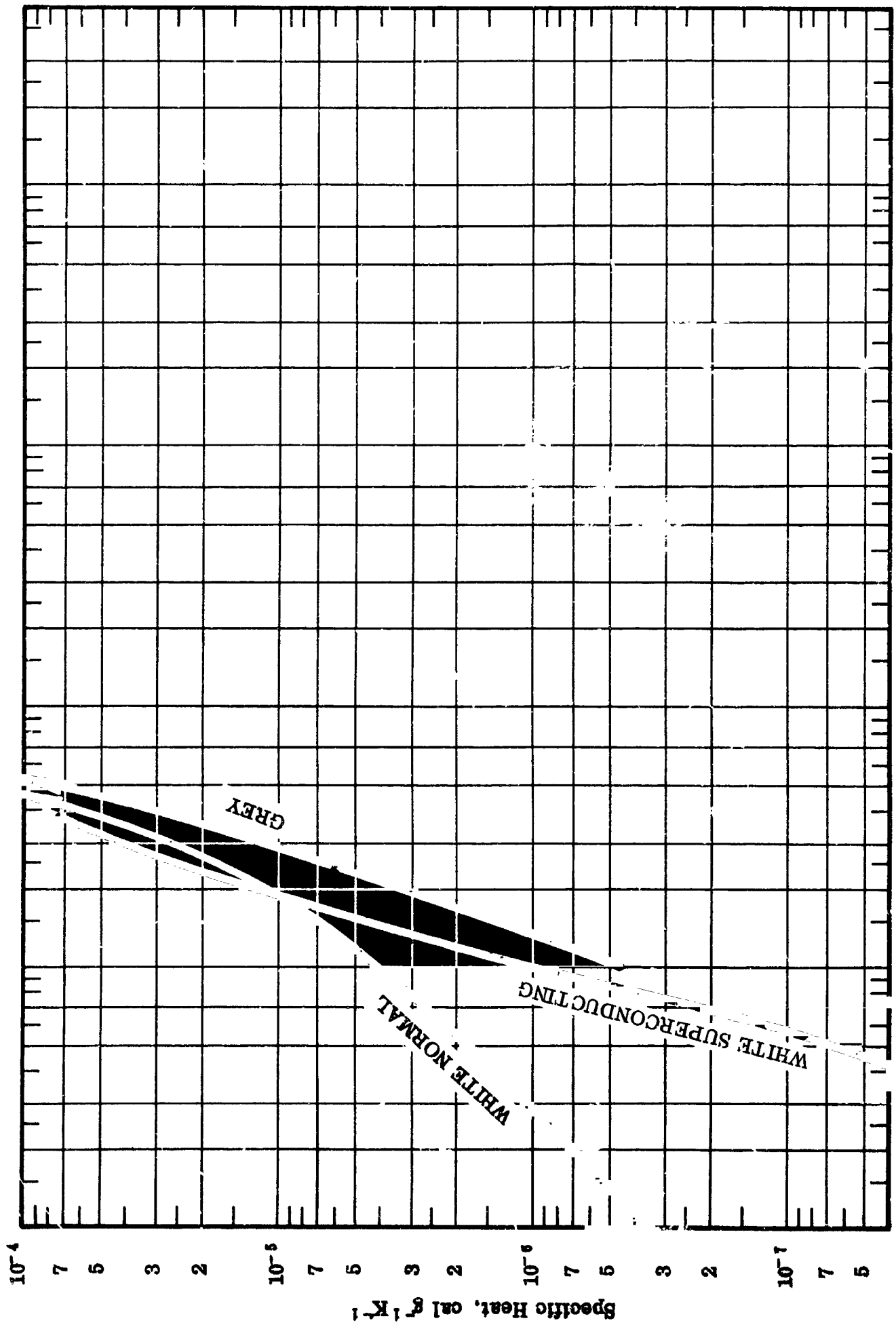
SPECIFIC HEAT -- TIN
Specific Heat, cal g⁻¹ K⁻¹
Temperature, K
GREY
WHITE NORMAL
WHITE SUPERCONDUCTING
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.1
1000

FIG. V - 11 (b)

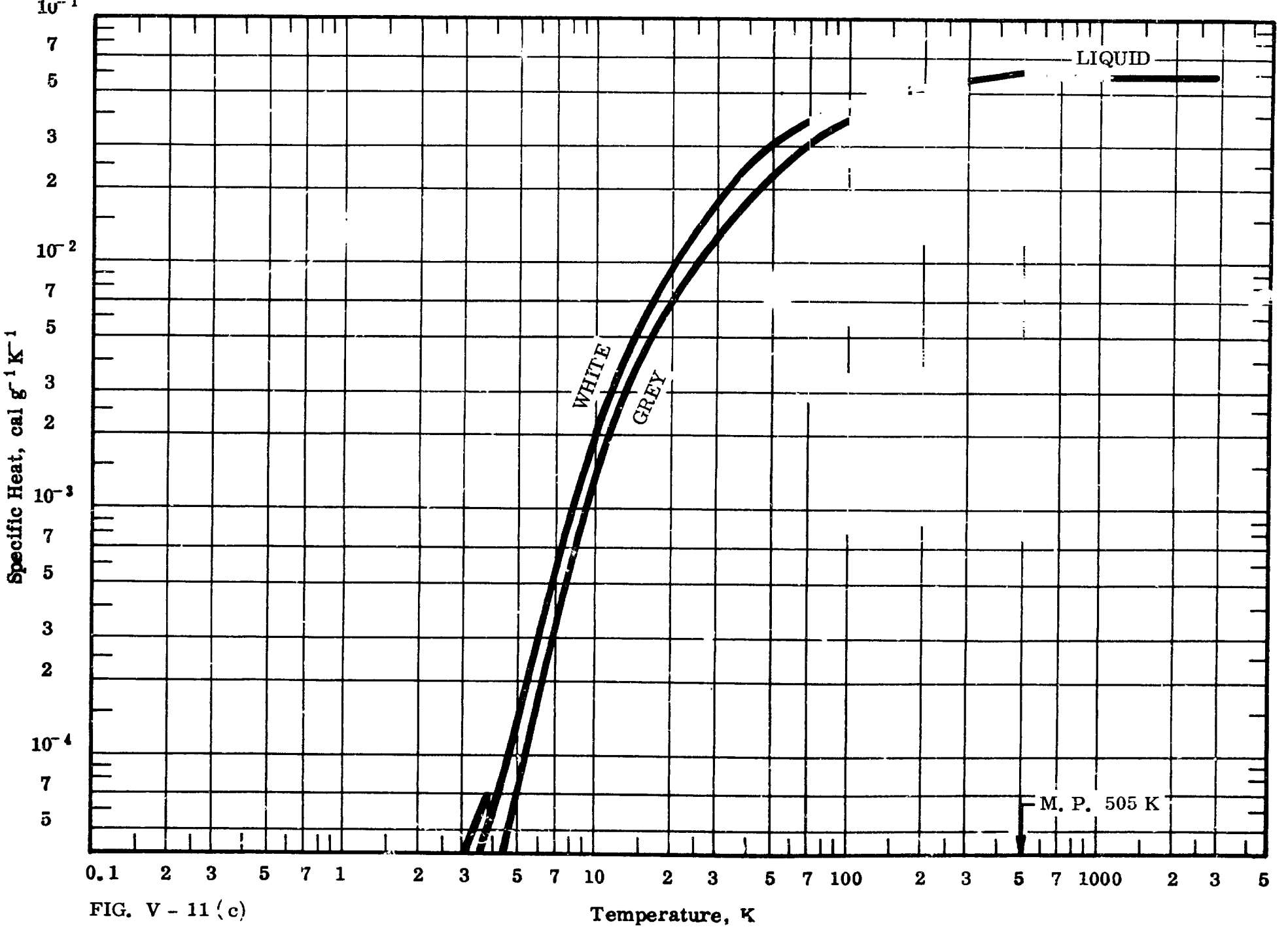

FIG. V - 11 (c)

SPECIFIC HEAT -- TIN

TABLE V-11. SPECIFIC HEAT OF TIN

	WHITE NORMAL	WHITE SUPERCONDUCTING	GREY
T °K	C_p, cal $g^{-1} K^{-1}$	C_p, cal $g^{-1} K^{-1}$	C_p, cal $g^{-1} K^{-1}$
0.1	3.55×10^{-7}	1.05×10^{-9}	
0.2	7.10	5.90	
0.3	1.08×10^{-6}	1.64×10^{-8}	
0.4	1.45	3.52	
0.5	1.85	6.82	
0.6	2.25	1.28×10^{-7}	
0.7	2.68	2.30	
0.8	3.14	4.00	
0.9	3.60	6.60	
1.0	4.06	1.04×10^{-6}	4.20×10^{-7}
1.2			7.40
1.4			1.18×10^{-6}
1.5	7.05	4.70	1.42
1.6			1.75
1.8			2.45
2.0	1.12×10^{-5}	1.15×10^{-5}	3.34
2.5	1.70	2.15	6.45
3.0	2.59	3.61	1.11×10^{-5}
3.5		5.80	
3.69	4.67	6.77	2.27
4	5.65		2.95
5	1.39×10^{-4}		7.60
6	2.92		1.75×10^{-4}
7	5.55		3.45
8	9.15		6.10
9	1.38×10^{-3}		9.40
10	1.97×10^{-3}		1.35
15	5.21		4.20
20	9.35		7.46
25	1.39×10^{-2}		
30	1.80		1.30×10^{-2}
40	2.51		1.79

TABLE V-11. SPECIFIC HEAT OF TIN (continued)

T °K	WHITE NORMAL C_p cal $g^{-1} K^{-1}$	WHITE SUPERCONDUCTING C_p cal $g^{-1} K^{-1}$	GREY C_p cal $g^{-1} K^{-1}$
50	3.10×10^{-2}		2.25×10^{-2}
60	3.54		2.70
70	3.86		3.10
80	4.12		3.40
90	4.30		3.65
100	4.48		3.91
125			4.31
150	4.94		4.58
200	5.14		4.90
250			5.06
300	5.44		5.20
400	5.81		
500	6.15		
(s) 505	6.19		
(l) 505	$(6.00 \times 10^{-2})^{\dagger}$		
600	(5.85)		
700	(5.77)		
800	(5.77)		
900	(5.77)		
1000	(5.77)		
1100	(5.77)		
1200	(5.77)		
1300	(5.77)		
1400	(5.77)		
1500	(5.77)		
1600	(5.77)		
1700	(5.77)		
1800	(5.77)		
1900	(5.77)		
2000	(5.77)		
2100	(5.77)		
2200	(5.77)		
2300	(5.77)		
2400	(5.77)		
2500	(5.77)		
2600	(5.77)		
2700	(5.77)		
2800	(5.77)		
2900	(5.77)		

†Estimated (5)

Investigators: (TIN)
Corak, W.S., and Satterthwaite, N.E. (145) [Superconducting 1.1-4.3K]; Fritz, L. (146) [15-284K]; Heffan, H. (147) [506-800K]; Hill, R.W., and Parkinson, D.H. (148) [7-100K]; Jaeger, F.M., and Bottema, J.A. (149) [273-505K]; Keesom, W.H., and Ende, Van den, J.N. (150) [1-20K]; Keesom, W.H., and Laer Van, P.H. (151) [1-4K]; Kutateladze, S.S., et al (152) [513-973K]; O Neal, H.R. (153, 154) [normal, 0.1-1.1K; superconducting, 0.14-1.1K]; Rodebush, W.H. (155) [69-100K]; Webb, F.J., and Wilkes, J. (156) [1.5-4.0K]; Yaqub, M. (157) [normal, 0.6-1.6K; superconducting, 0.8-2.1K].

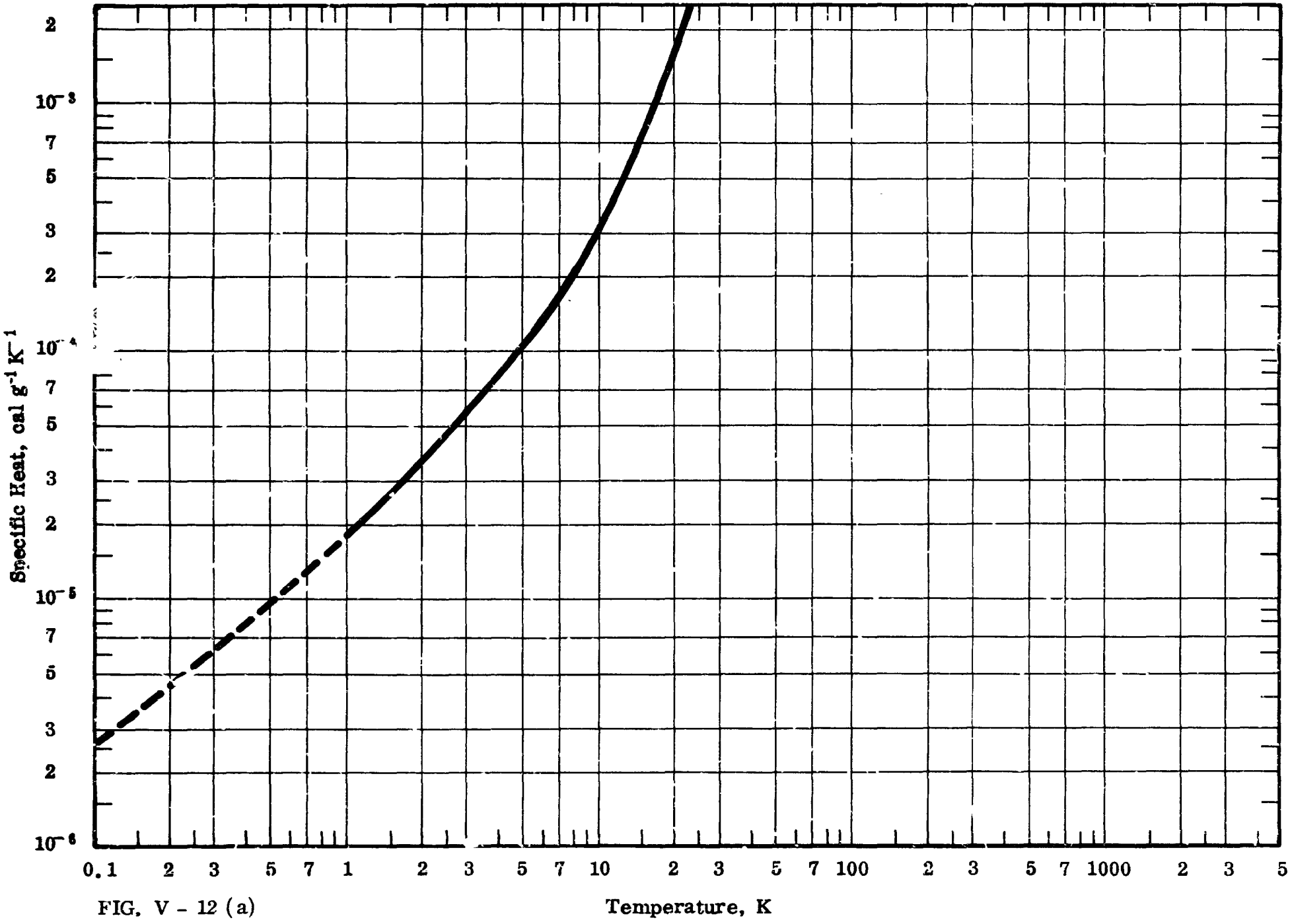

FIG. V - 12 (a)

SPECIFIC HEAT -- TITANIUM

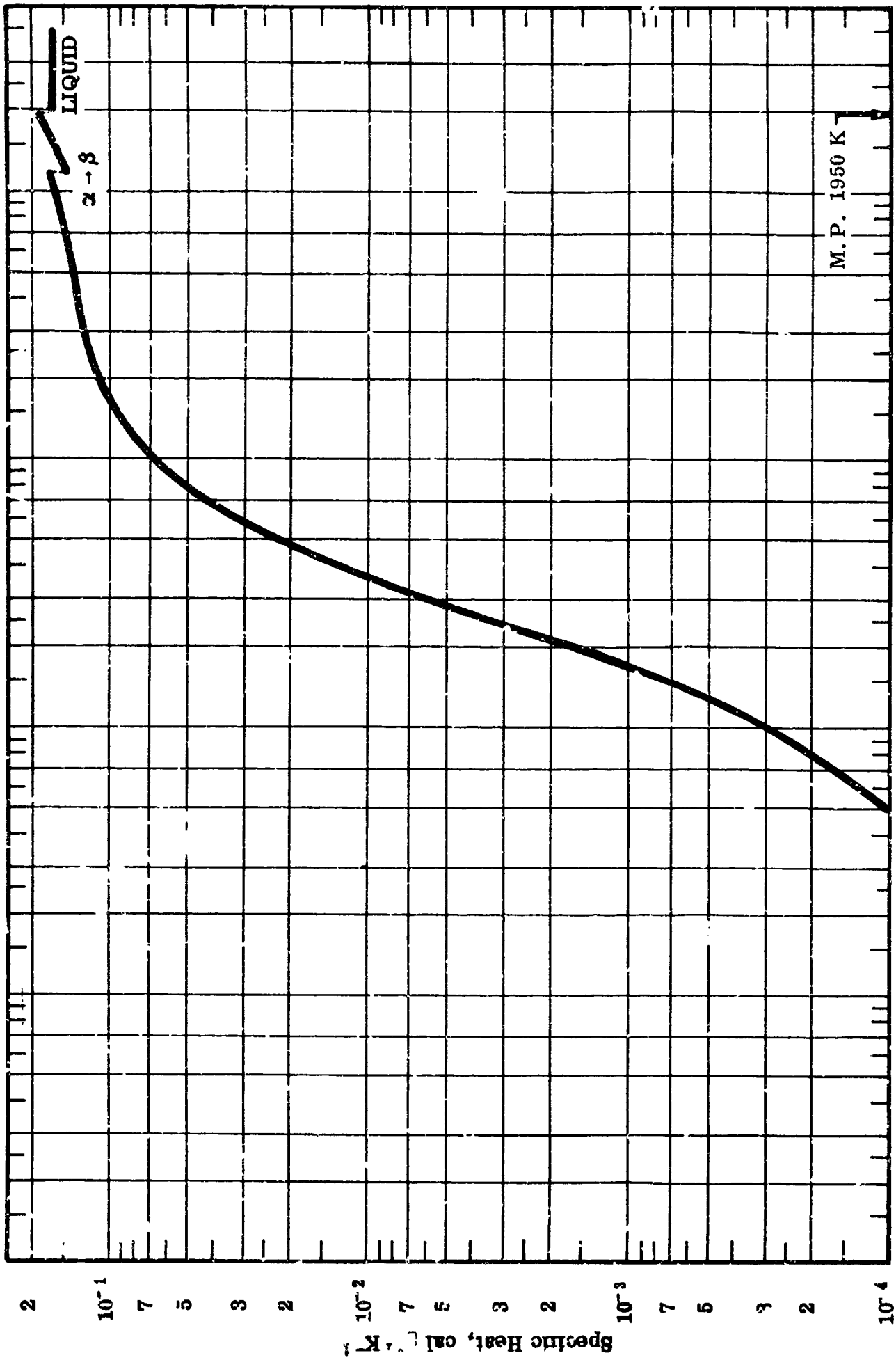

FIG. V - 12 (b)

SPECIFIC HEAT -- TITANIUM

TABLE V-12. SPECIFIC HEAT OF TITANIUM

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
1	1.78×10^{-5}	600	1.42×10^{-1}
2	3.63	700	1.47
3	5.63	800	1.52
4	7.85	900	1.57
5	1.03×10^{-4}	1000	1.62
6	1.34	1100	1.67
7	1.68	(α) 1155	1.70
8	2.08	(β) 1155	1.48
9	2.57	1200	1.50
10	3.11	1300	1.54
15	7.35	1400	1.58
20	1.69×10^{-3}	1500	1.63
30	5.85	1600	1.68
40	1.34×10^{-2}	1700	1.74
50	2.34	1800	1.82
60	3.45	1900	1.89
70	4.52	(β) 1950	1.92
80	5.52	(l) 1950	$(1.67 \times 10^{-1})^{\dagger}$
90	6.50	2000	(1.67)
100	7.12	2200	(1.67)
150	9.71	2400	(1.67)
200	1.11×10^{-1}	2600	(1.67)
300	1.25	2800	(1.67)
400	1.32	3000	(1.67)
500	1.36		

Investigators: Aven, M.H., et al (158) [4-15K]; Backhurst, I. (159) [868-1348K]; Clusius, K., and Franzosini, P. (160) [14-273K]; Golutrin, Y.M. (161) [298-1400K]; Holland, L.R. (162) [599-1066K]; Jaeger, F.M., et al (163) [573-1090K]; Kelley, K.K. (164) [53-297K]; Kothen, C.W. (165) [298-1900K]; Kothen, C.W., and Johnston, H.L. (166) [15-305K]; Loewen, E.G. (167) [311-1033K]; Parker, R. (168) [343-1073K]; Rea, J.A. (169) [422-977K]; Serebryannikov, N.N., and Geld, P.V. (170) [294-1923K]; Scott, J.L. (171) [323-1273K]; Wolcott, N.M. (172) [1.2-21K].

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†Estimated (5)

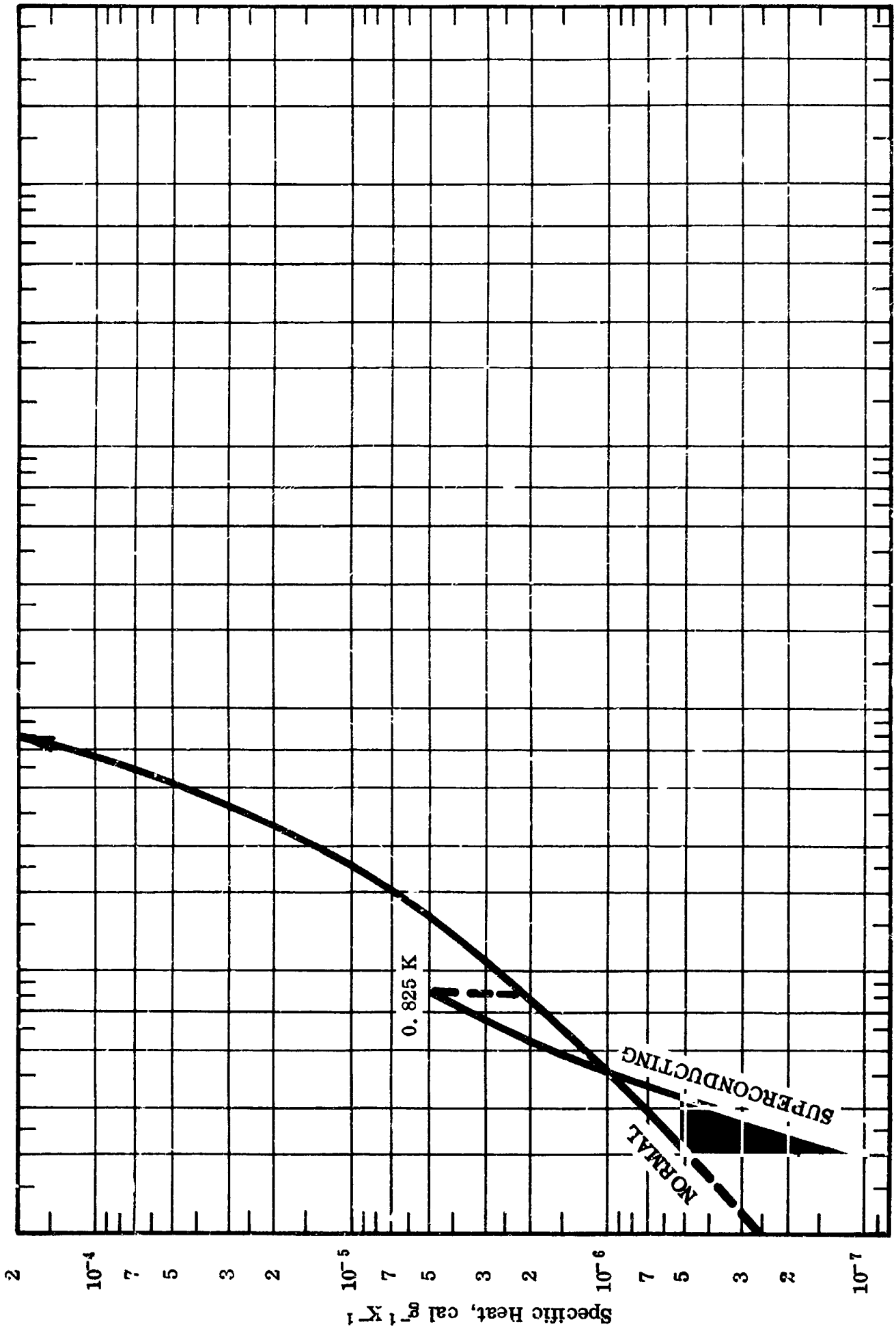

FIG. V - 13 (a)

SPECIFIC HEAT -- ZINC

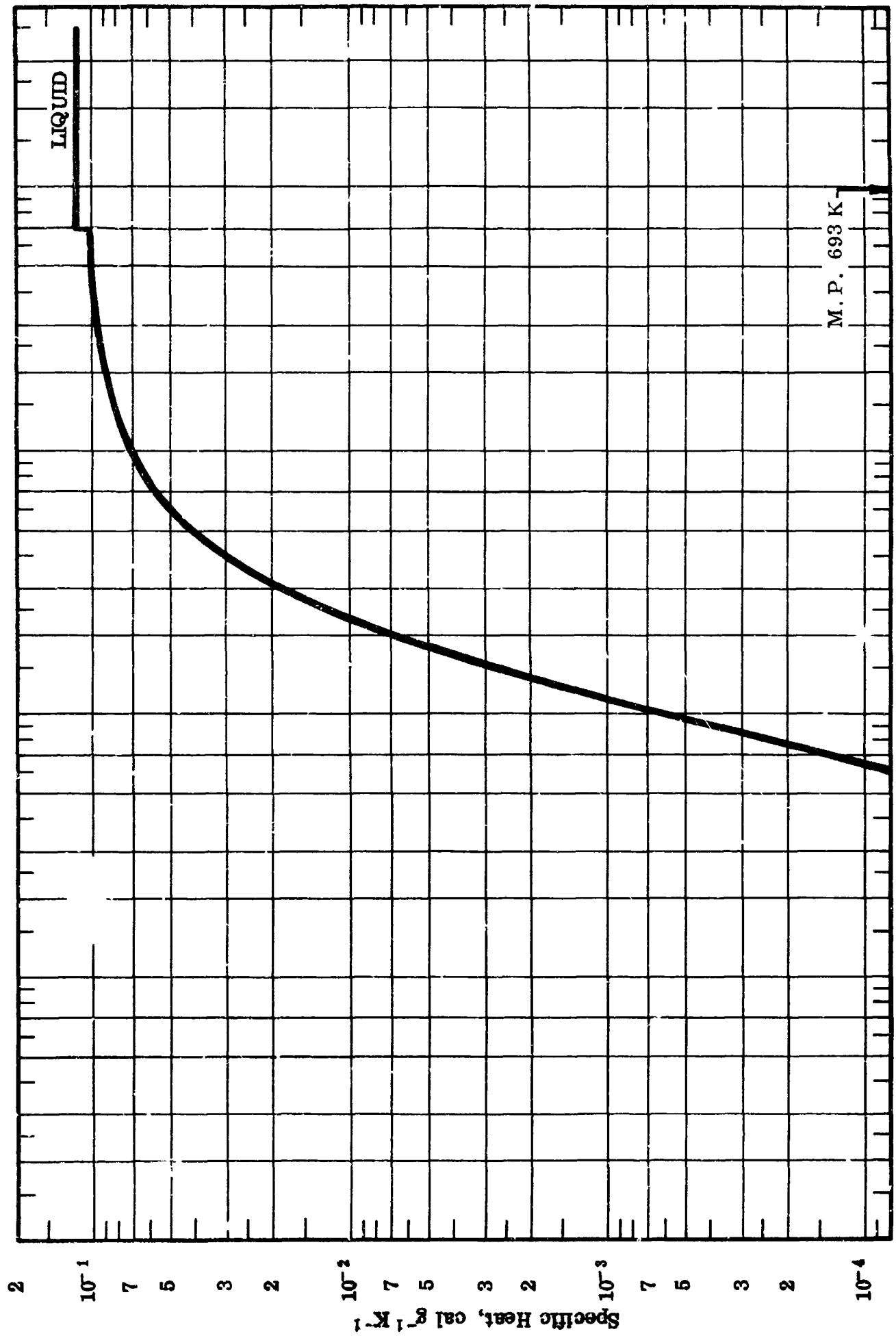

FIG. V - 13 (b)

SPECIFIC HEAT -- ZINC

TABLE V-12. SPECIFIC HEAT OF ZINC

	NORMAL	SUPERCONDUCTING		
T °K	C_p, cal $g^{-1} K^{-1}$	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
0.1	2.46×10^{-7}		40	2.93×10^{-2}
0.2	4.85	9.5×10^{-8}	50	4.05
0.3	7.30	4.2×10^{-7}	60	4.90
0.4	9.82	9.78×10^{-7}	70	5.60
0.5	1.25×10^{-6}	1.74×10^{-6}	80	6.20
0.6	1.50	2.57	90	6.70
0.7	1.78	3.60	100	7.02
0.8	2.06	4.57	150	8.10
0.825	2.13	4.97	200	8.75
1	2.66		300	9.30
2	6.91		400	9.65
3	1.46×10^{-5}		500	1.00×10^{-1}
4	2.71		600	1.04
5	4.67		(s) 693	1.07
6	7.60		(l) 693	(1.15)†
7	1.23×10^{-4}		700	(1.15)
8	2.34		800	(1.15)
9	3.85		900	(1.15)
10	5.54		1000	(1.15)
15	2.72×10^{-3}		1100	(1.15)
20	6.64		1200	(1.15)
30	1.79×10^{-2}			

Investigators: Bronson, H.L., and Wilson, A.J.C. (173) [193-393K]; Clusius, K., and Harteck, P. (174) [20-202K]; Eastman, E.D., et al (175) [373-673K]; Eichanuer, W., and Schulze, M. (176) [12-273K]; Jaeger, F.M., and Poppema, T.J. (177) [373-673K]; Keesom, W.H., and Ende, Van den, J.N. (178) [1-20K]; Keesom, W.H., and Kok, J.A. (179) [2-6K]; Phillips, N.E. (180) [0.15-1.1K]; Poppema, T.J., and Jaeger, F.M. (181) [373-673K]; Silvidi, A.A., and Daunt, J.G. (182) [1.5-4K]; Smith, P.L. (183) [5-19K]; Srinivasan, T.M. (184) [1.2-4.2K]; Zavaritsky, N.V. (185) [0.15-1.5K].

†Estimated (5)

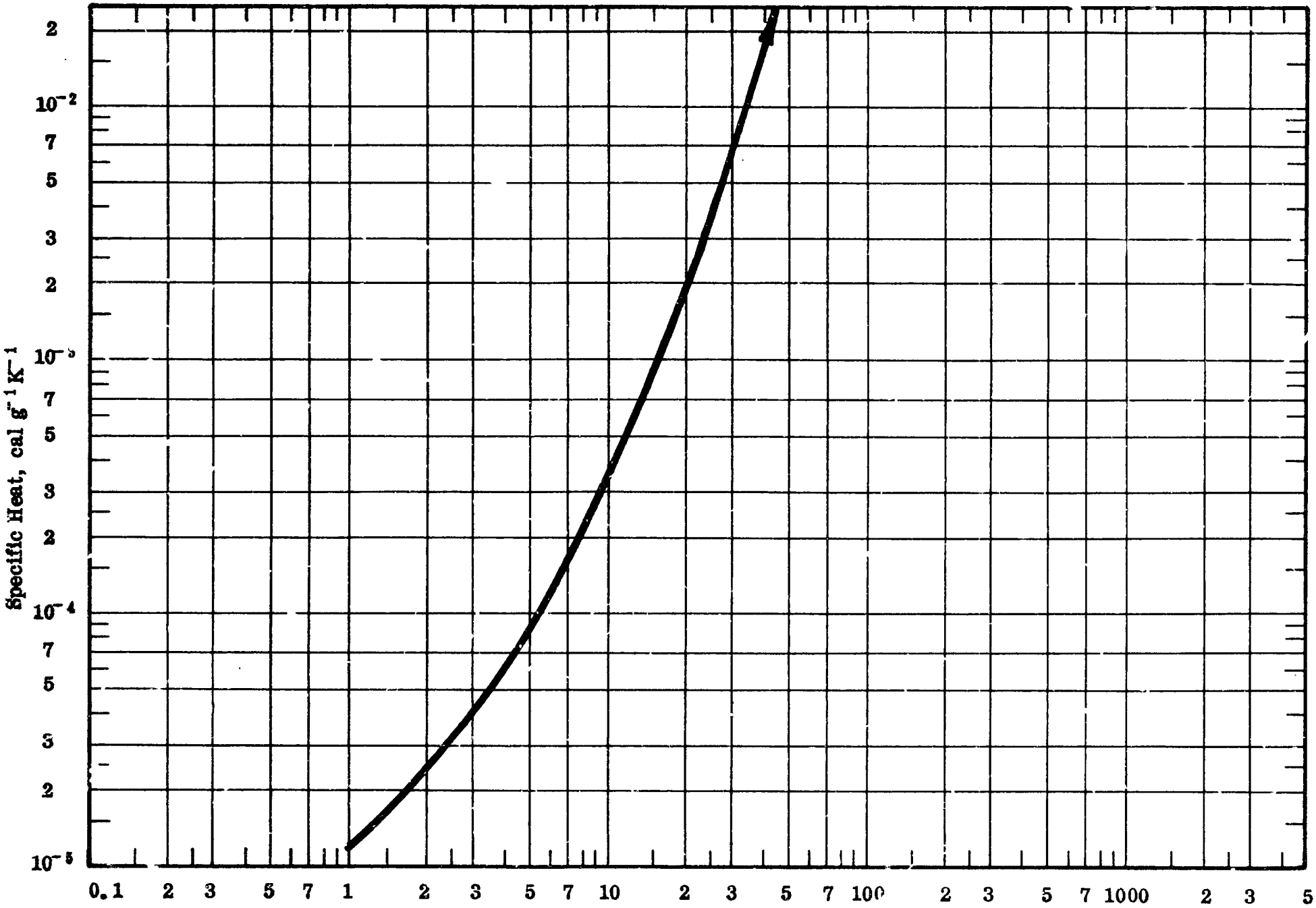

FIG. V - 14 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 2219 - T852

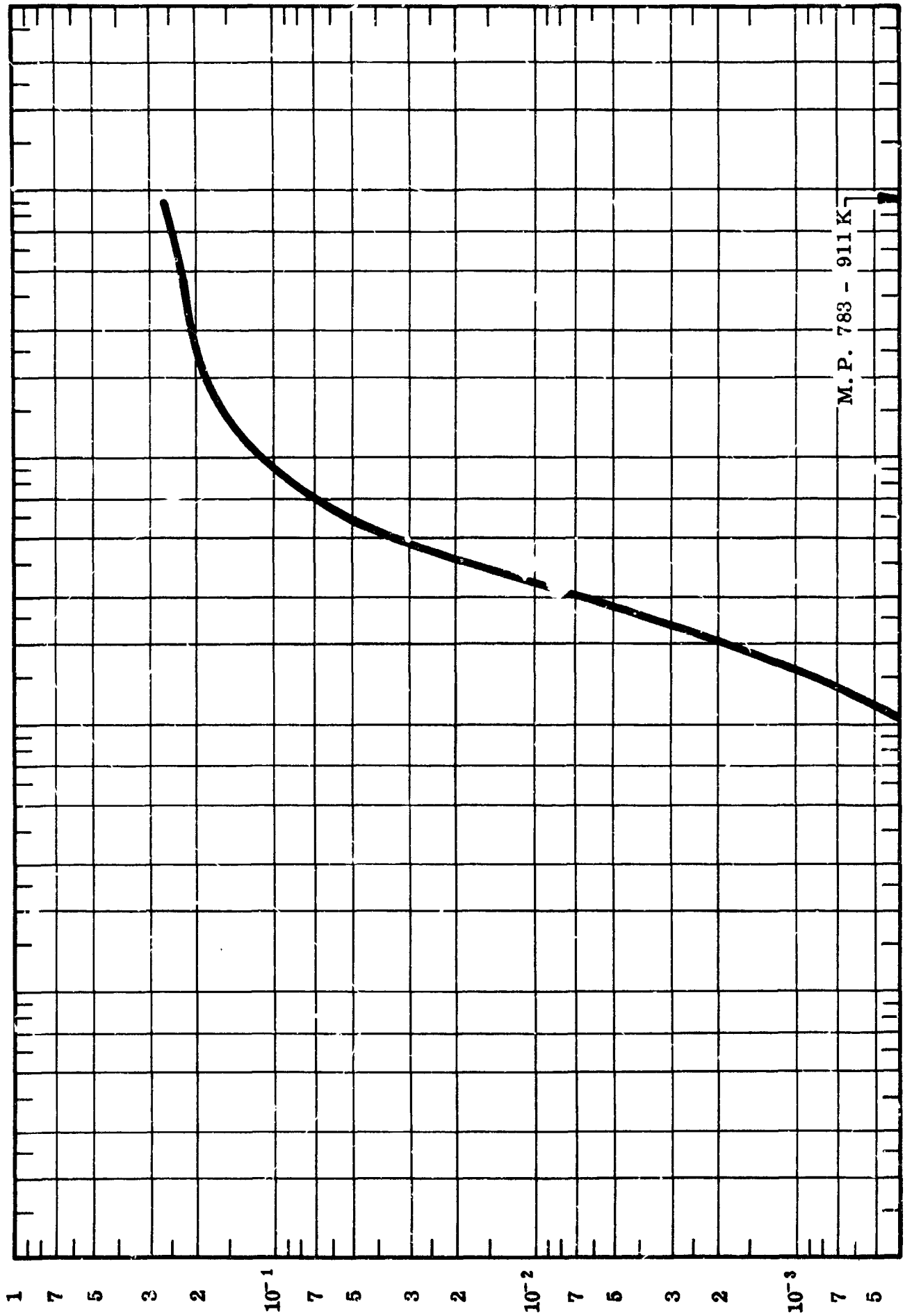

FIG. V – 14 (b)

SPECIFIC HEAT -- ALUMINUM ALLOY 2219 - T852

TABLE V-14. SPECIFIC HEAT OF ALUMINUM ALLOY 2219-T852

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1	1.19×10^{-5} *	60	5.13×10^{-2} *
2	2.42*	70	6.92*
3	3.97*	80	8.37*
4	5.92*	90	9.94
5	9.07	100	1.12×10^{-1} *
6	1.23×10^{-4} *	150	1.60*
7	1.66*	200	1.83*
8	2.21*	300	2.08*
9	2.78*	400	2.17*
10	3.53*	500	2.28*
15	9.00	600	2.38*
20	1.98×10^{-3} *	700	2.48*
30	7.41*	800	2.59*
40	1.81×10^{-2}*	900	2.69*
50	3.30		

Investigators: Honda, K. and Tokunaga, M. (186) [298 K]

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*Calculated using Kopp-Newman Law

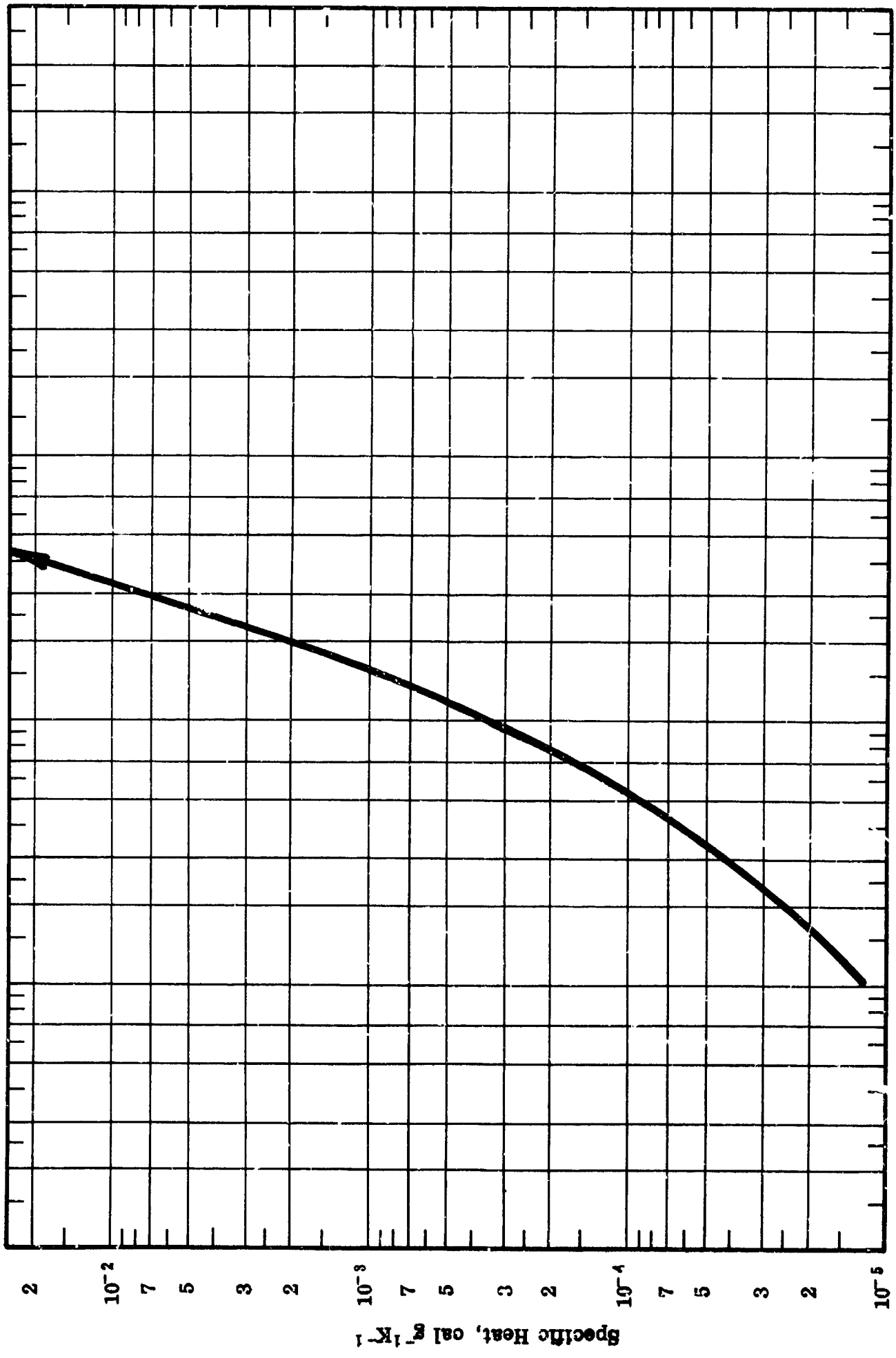

FIG. V - 15 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 6061 - T6

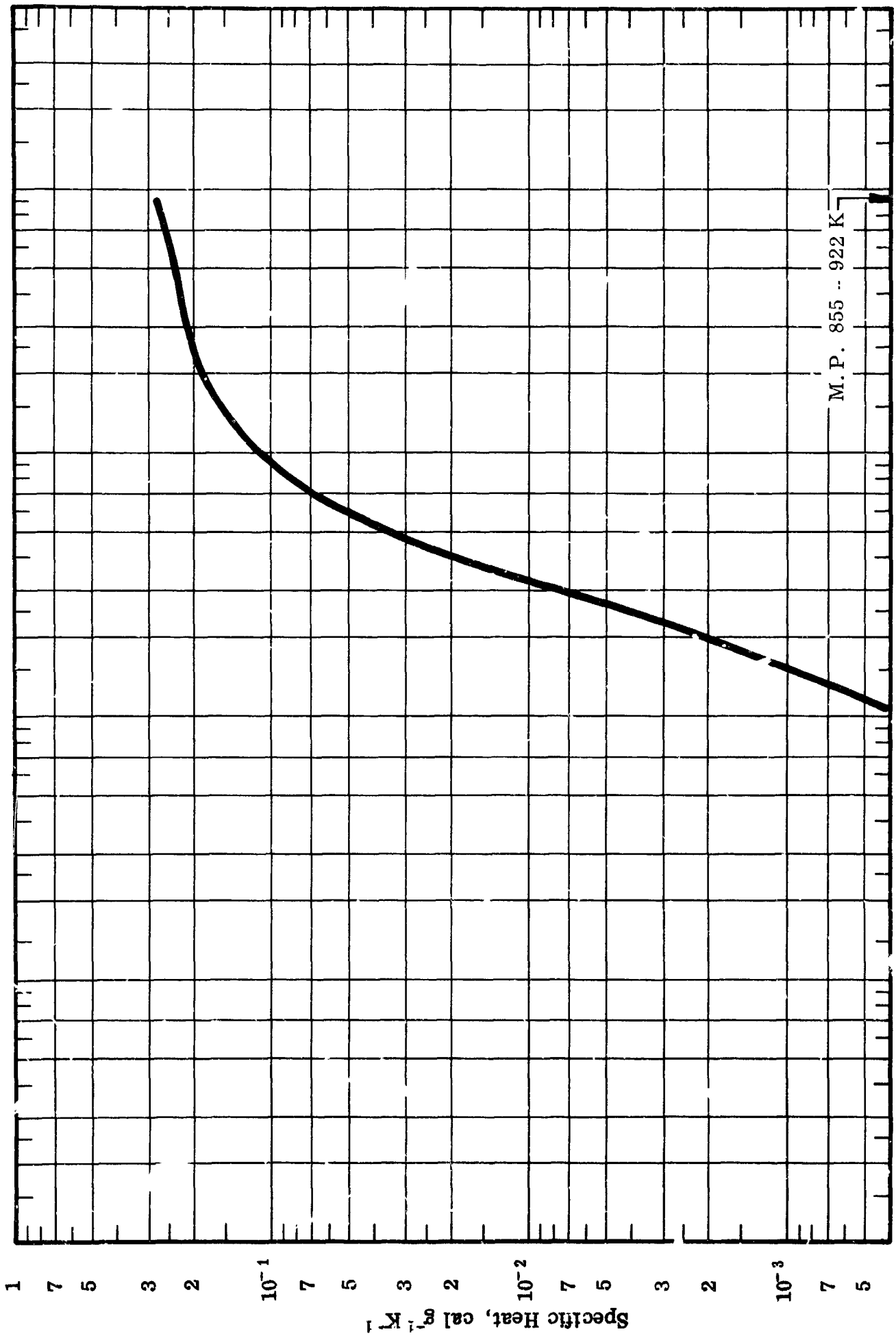

FIG. V - 15 (b)

SPECIFIC HEAT -- ALUMINUM ALLOY 6061 - T6

TABLE V-15. SPECIFIC HEAT OF ALUMINUM ALLOY 6061-T6

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1	1.23×10^{-5} *	60	5.14×10^{-2} *
2	2.49*	70	6.97*
3	4.08*	80	8.65*
4	6.07*	90	1.02×10^{-1}*
5	9.31*	100	1.15*
6	1.26×10^{-4} *	150	1.62*
7	1.70*	200	1.90*
8	2.25*	300	2.15*
9	2.84*	400	2.25*
10	3.61*	500	2.36*
15	9.40*	600	2.47*
20	2.01×10^{-3} *	700	2.58*
30	7.54*	800	2.69*
40	1.35×10^{-2} *	900	2.80*
50	3.38*		

Investigators: Johnson, E.W. (187) [33-311 K]; Materials Design Eng. (188) [373 K]; Materials Properties Handbook (189) [373 K].

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*Calculated using Kopp-Newman Law

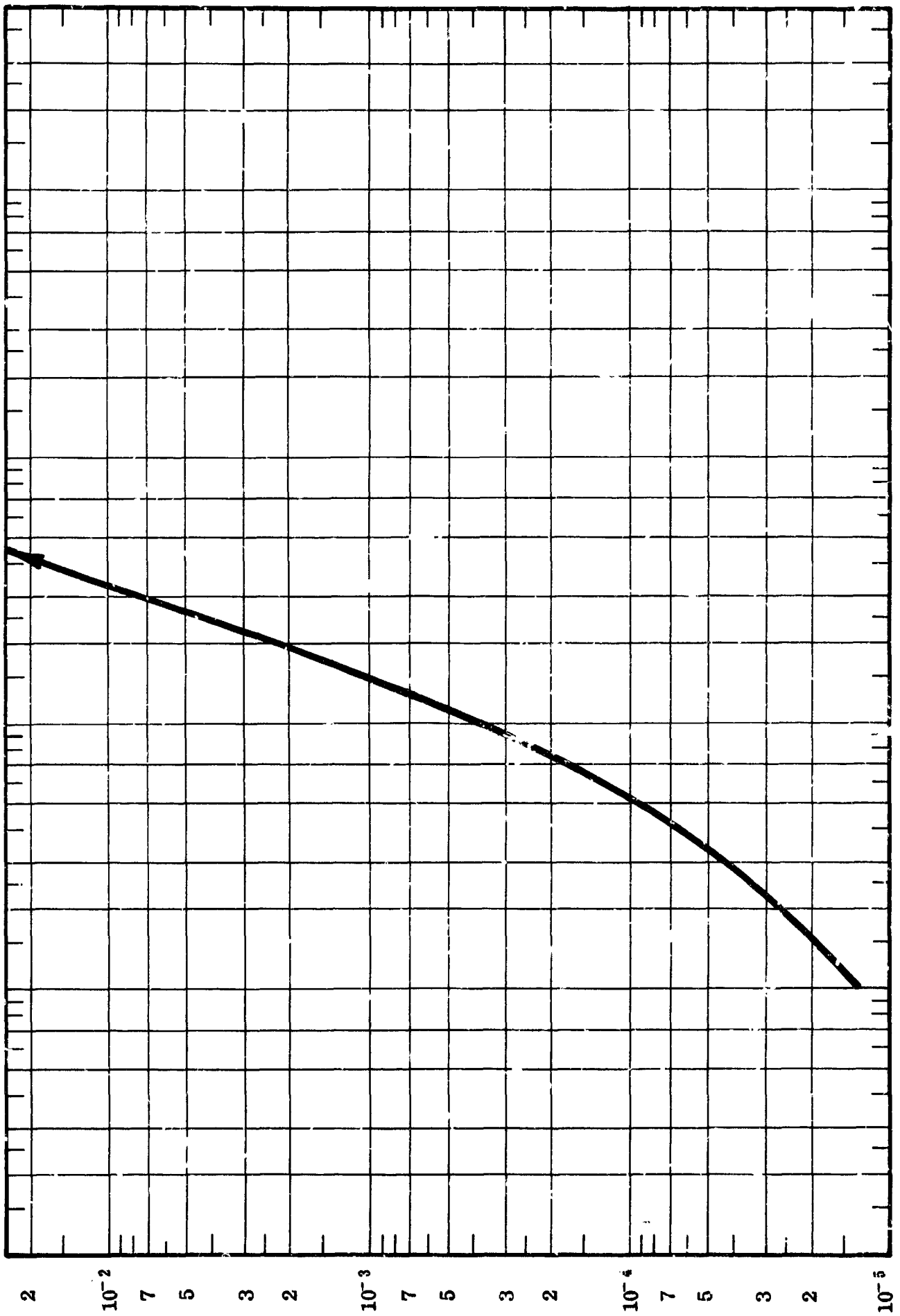

FIG. V – 16 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 7075 - T6

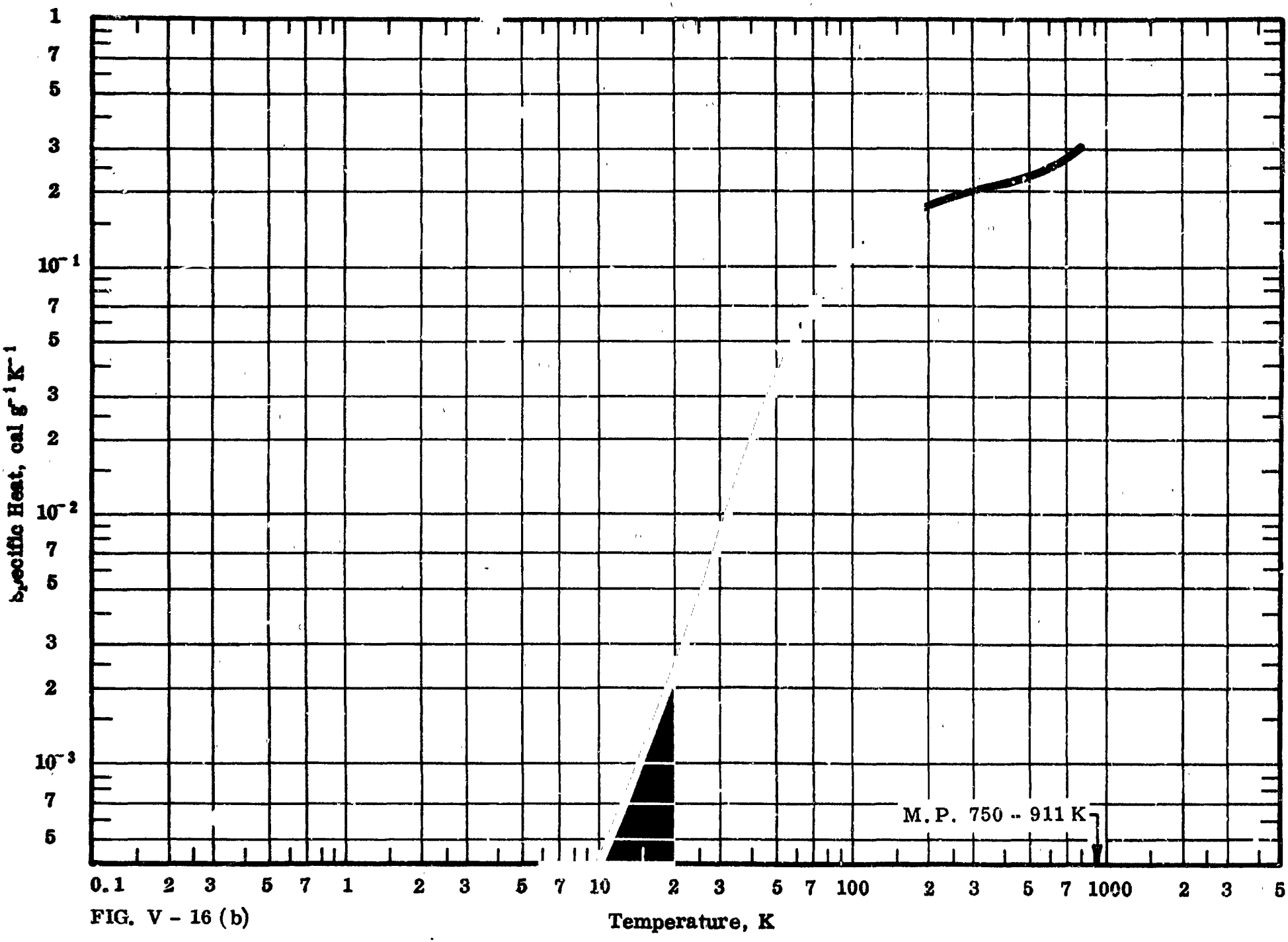

FIG. V - 16 (b)

SPECIFIC HEAT ALUMINUM ALLOY 7075 T

TABLE V-16. SPECIFIC HEAT OF ALUMINUM ALLOY 7075-T6

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1	1.33×10^{-5}*	50	3.44×10^{-2}*
2	2.71*	60	5.40*
3	4.42*	70	7.10*
4	6.54*	80	8.56*
5	9.87*	90	1.01×10^{-1}*
6	1.34×10^{-4}*	100	1.13*
7	1.79*	150	1.55
8	2.40*	200	1.75
9	3.06*	300	2.00
10	3.90*	400	2.19
15	1.10×10^{-3}*	500	2.29
20	2.33*	600	2.50
30	8.24*	700	2.78
40	1.93×10^{-2}*	800	(3.10×10^{-1})†

Investigators: Lucks, C. F. and Deem, H. W. (190) [73-725 K]; Lucks, C. F. et al. (191) [116-700 K]; Materials Design Eng. (192) [373 K]; Materials Properties Handbook (193) [373 K].

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*Calculated by Kopp-Newman Law

†Extrapolated

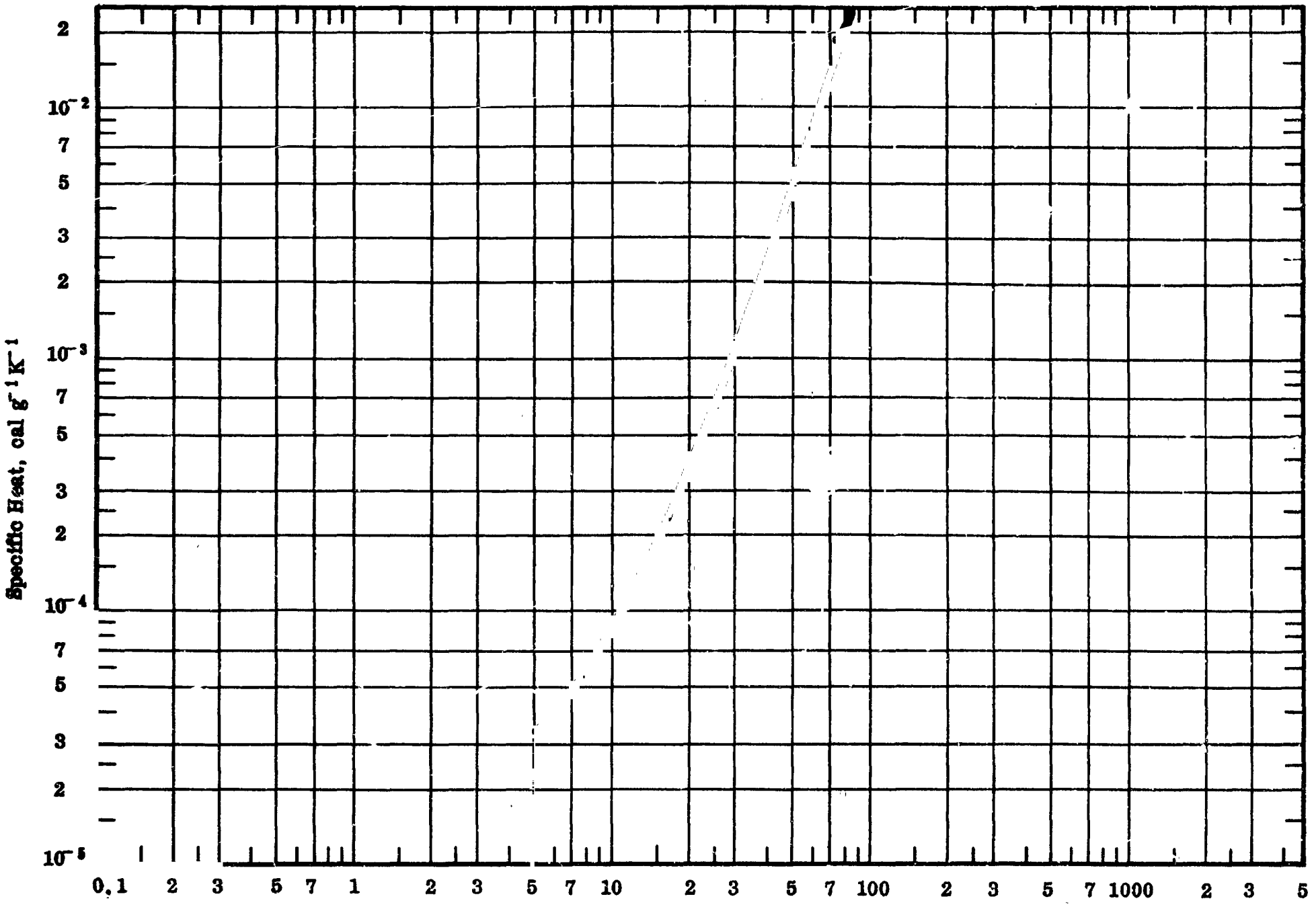

FIG. V - 17 (a)

SPECIFIC HEAT -- BERYLLIUM ALLOY

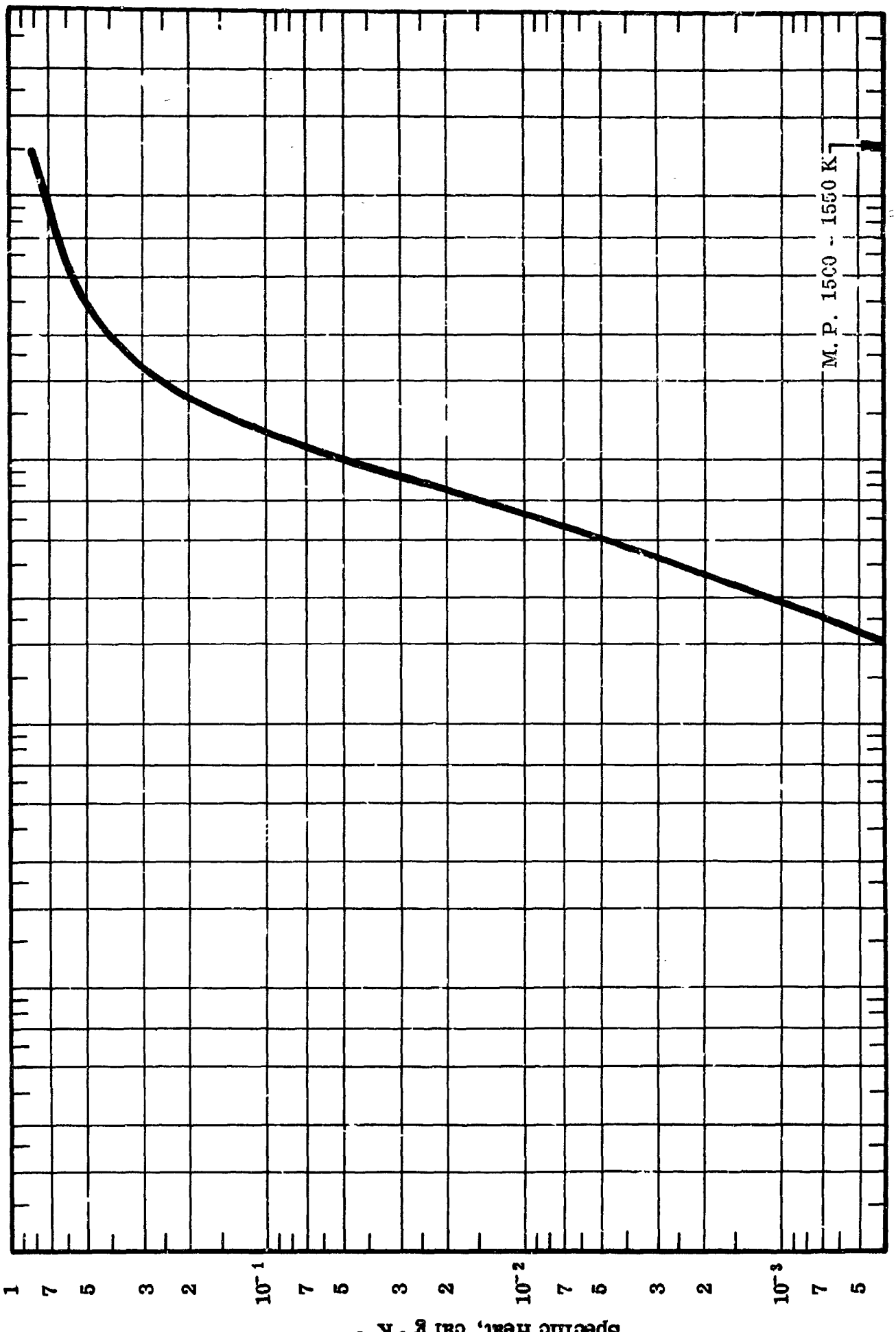

FIG. V - 17 (b)

SPECIFIC HEAT -- BERYLLIUM ALLOY

TABLE V-17. SPECIFIC HEAT OF BERYLLIUM ALLOY

T °K	C_p, cal $g^{-1} K^{-1}$	T°K	C_p, cal $g^{-1} K^{-1}$
5	3.35×10^{-5}*	150	1.45×10^{-1}*
6	4.10*	200	2.63*
7	5.05*	300	4.34
8	6.20*	400	5.21
9	7.50*	500	5.70
10	9.10*	600	6.11
15	1.99×10^{-4}*	700	6.45
20	3.80*	800	6.68
30	1.12×10^{-3}*	900	6.92
40	2.34*	1000	7.17
50	4.44*	1100	7.41
60	8.11*	1200	7.64
70	1.36×10^{-2}*	1300	7.88
80	2.14*	1400	8.00
90	3.27*	1500	(8.20×10^{-1})†
100	4.79*		

Investigators: Fieldhouse, I.B. et al. (194) [478-1311 K]; Kanazawa, E. and Packer, C.M. (195) [373-1373 K]; Walker, B.E., Jr., et al. (196) [303-1075 K].

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*Calculated from Kopp-Newman Law

†Extrapolated

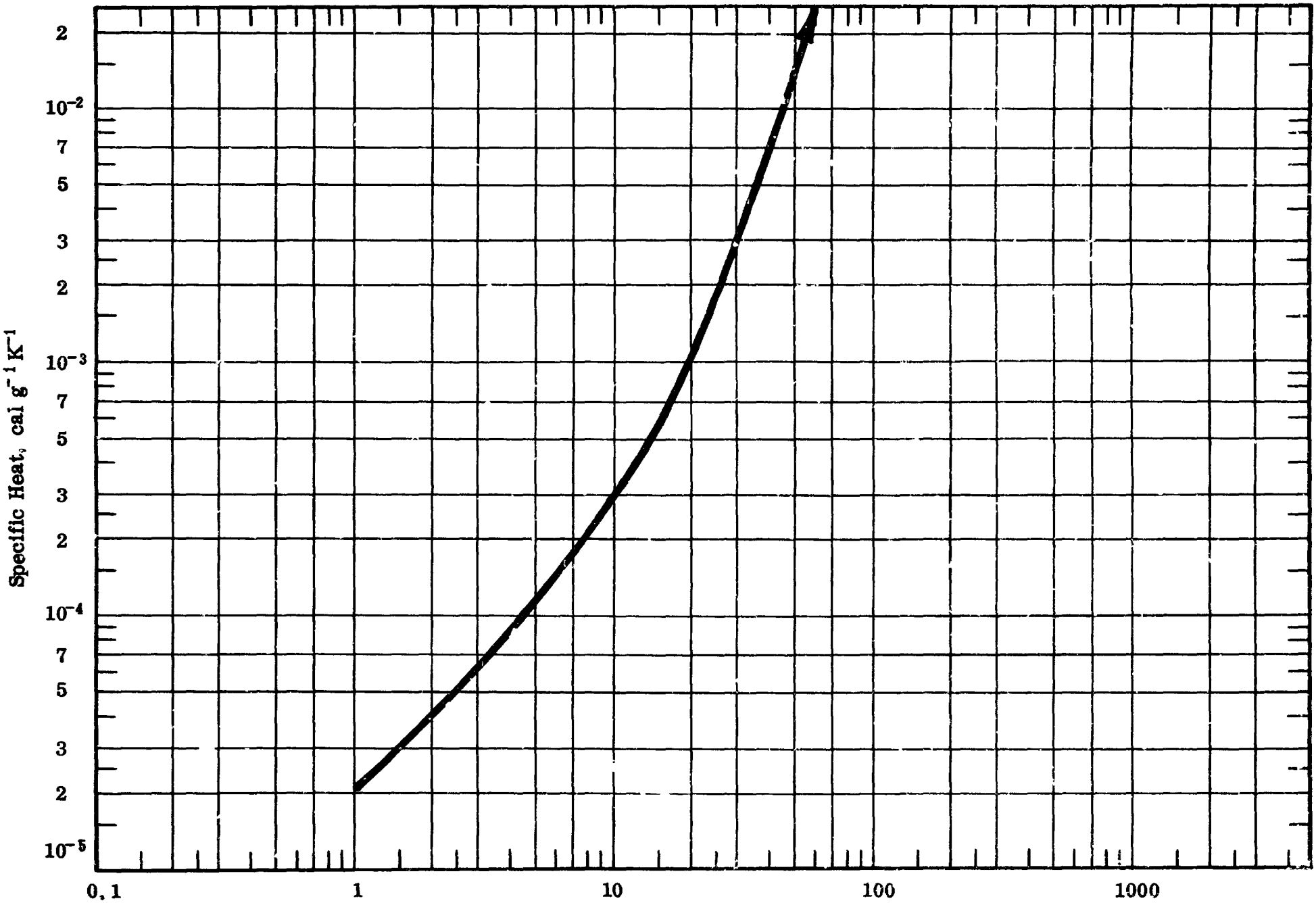

FIG. V - 18 (a)

SPECIFIC HEAT -- STAINLESS STEEL AISI 304A

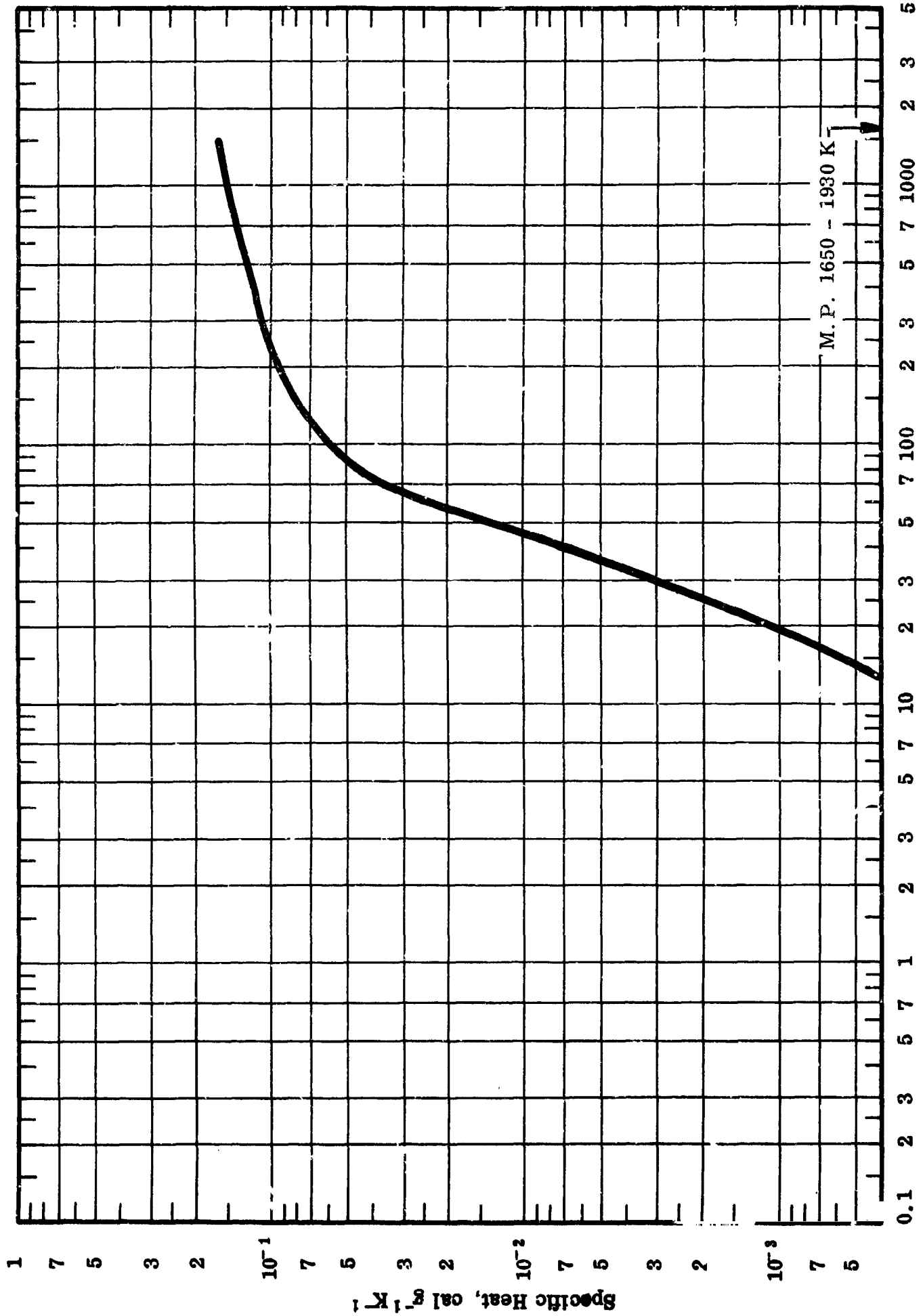

FIG. V – 18 (b)

SPECIFIC HEAT -- STAINLESS STEEL AISI 304A

TABLE V-18. SPECIFIC HEAT OF STAINLESS STEEL, AISI 304 A

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal^{-1} K^{-1}
1	2.07×10^{-5}*	90	5.17×10^{-2}*
2	4.09*	100	5.85*
3	6.26*	150	8.10*
4	8.60*	200	9.30*
5	1.12×10^{-4}*	300	1.08×10^{-1}*
6	1.43*	400	1.17
7	1.75*	500	1.26
8	2.09*	600	1.33
9	2.44*	700	1.38
10	2.89*	800	1.42
15	5.90*	900	1.48
20	1.07×10^{-3}*	1000	1.50
30	3.09*	1100	1.52
40	6.96*	1200	1.54
50	1.26×10^{-2}*	1300	1.57
60	2.58*	1400	1.60
70	3.57*	(1500	1.62×10^{-1})†
80	4.45*		

Investigators: Neel, D. S. et al. (197) [533-1366 K]; Thornburg, D. L. et al. (198) [373-1273 K]; Venturi, R. and Seibel, R. D. (199) [366-1366 K].

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*Calculated using Kopp-Newman Law

†Extrapolated

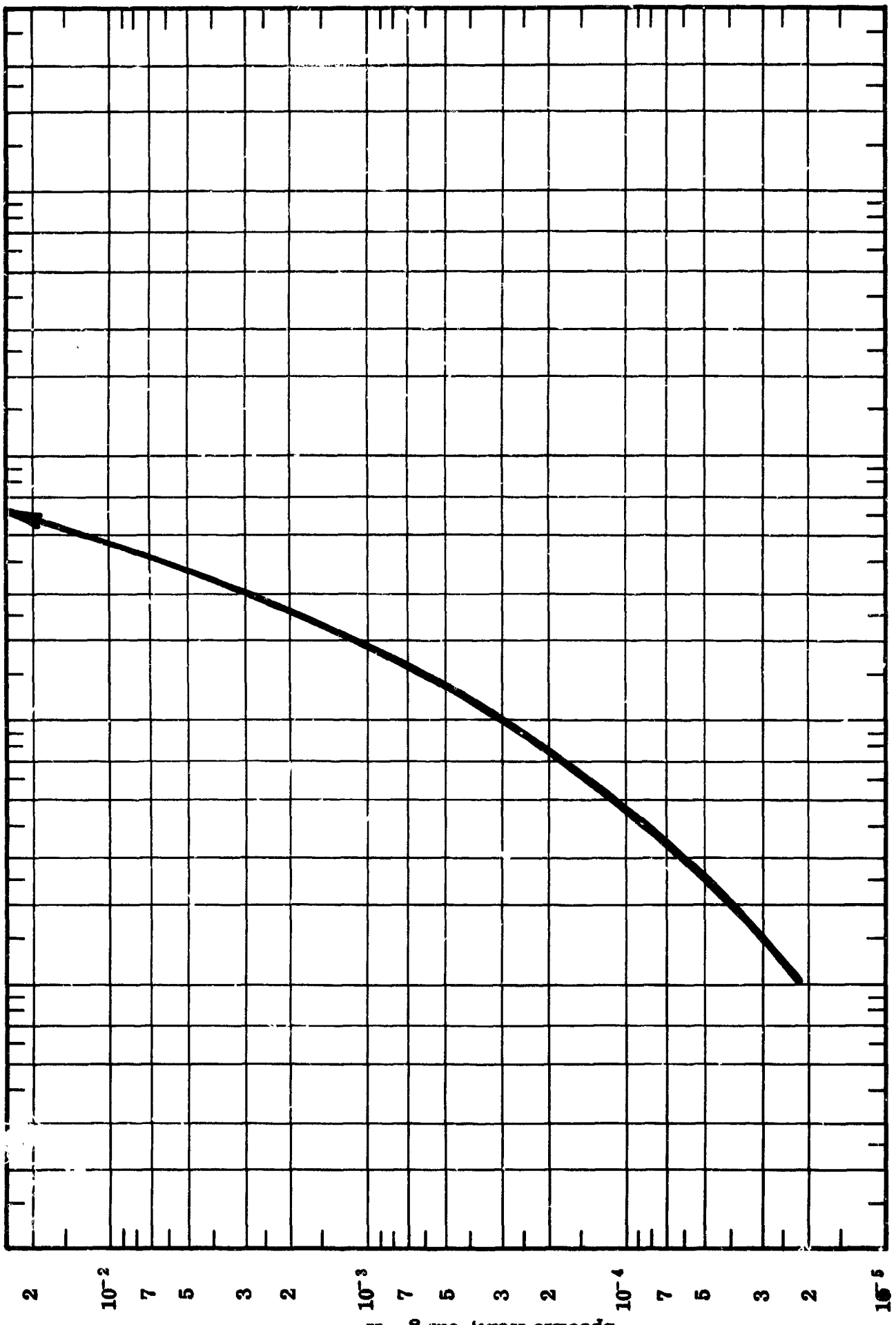

FIG. V – 19 (a)

SPECIFIC HEAT -- STAINLESS STEEL AISI 347

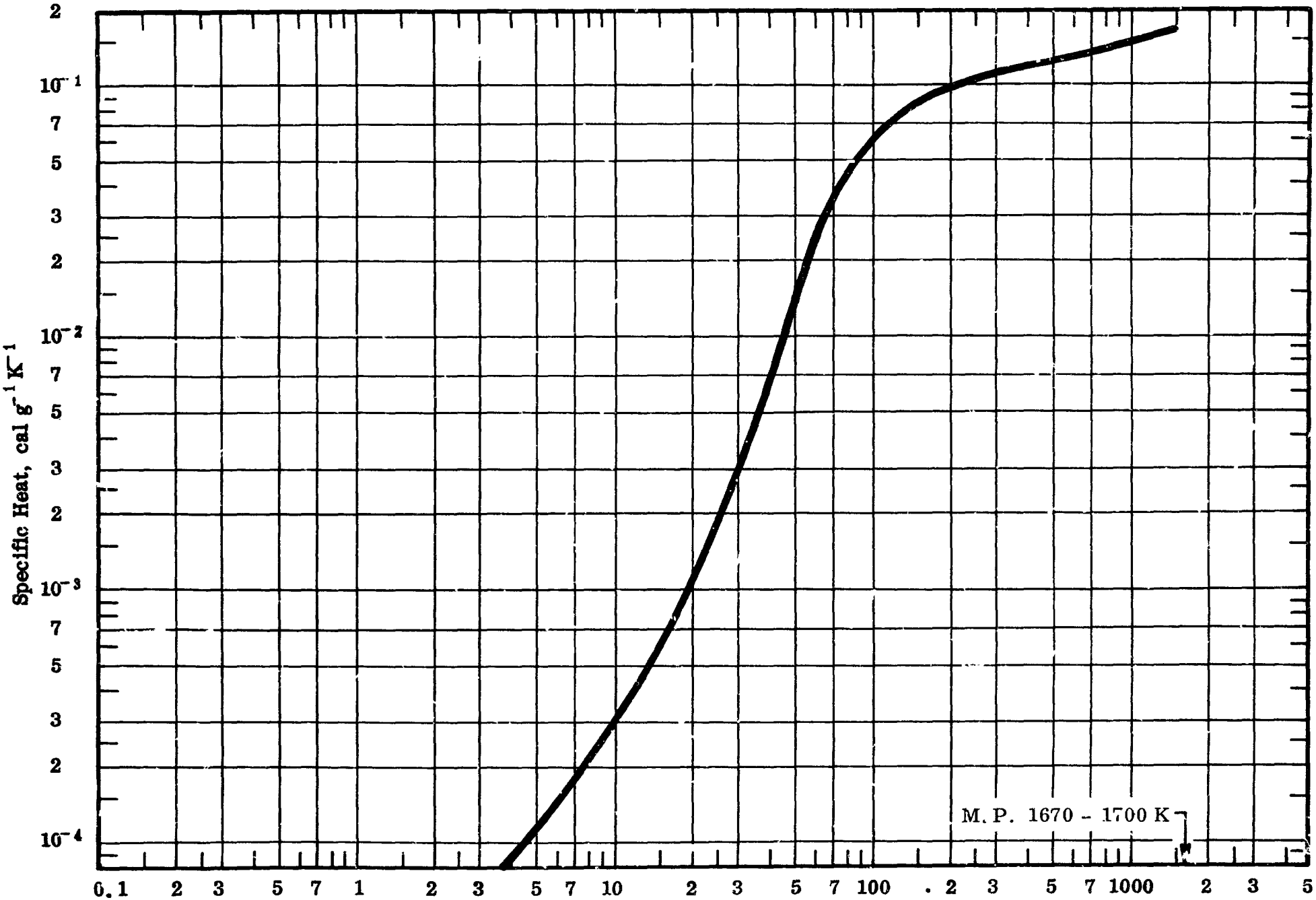

FIG. V - 19 (b)

SPECIFIC HEAT -- STAINLESS STEEL AISI 347

TABLE V-19. SPECIFIC HEAT OF STAINLESS STEEL, AISI 347

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1	2.09×10^{-5}*	90	5.40×10^{-2}*
2	4.13*	100	6.30*
3	6.33*	150	8.70
4	8.70*	200	9.70
5	1.13×10^{-4}*	300	1.08×10^{-1}
6	1.45*	400	1.17
7	1.77*	500	1.23
8	2.12*	600	1.30
9	2.48*	700	1.35
10	2.94*	800	1.40
15	5.90*	900	1.45
20	1.09×10^{-3}*	1000	1.49
30	3.15*	1100	1.52
40	7.08*	1200	1.56
50	1.28×10^{-2}*	1300	1.60
60	2.60*	1400	1.64
70	3.59*	1500	1.68
80	4.46*		

Investigators: Douglas, T. B. and Dever, J. L. (200, 201) [273-1173 K]; Douglas, T. B. and Victor, A. C. (202) [273-1173 K]; DuChatenier, F. J., et al. (203) [1-90 K]; Fieldhouse, I. B. et al. (204) [451-1494 K]; Lang, J. I. (205) [451-1494 K]; Lucks, C. F. and Deem, H. W. (206) [116-1255]; Lucks, C. F. et al. (207) [73-1123 K].

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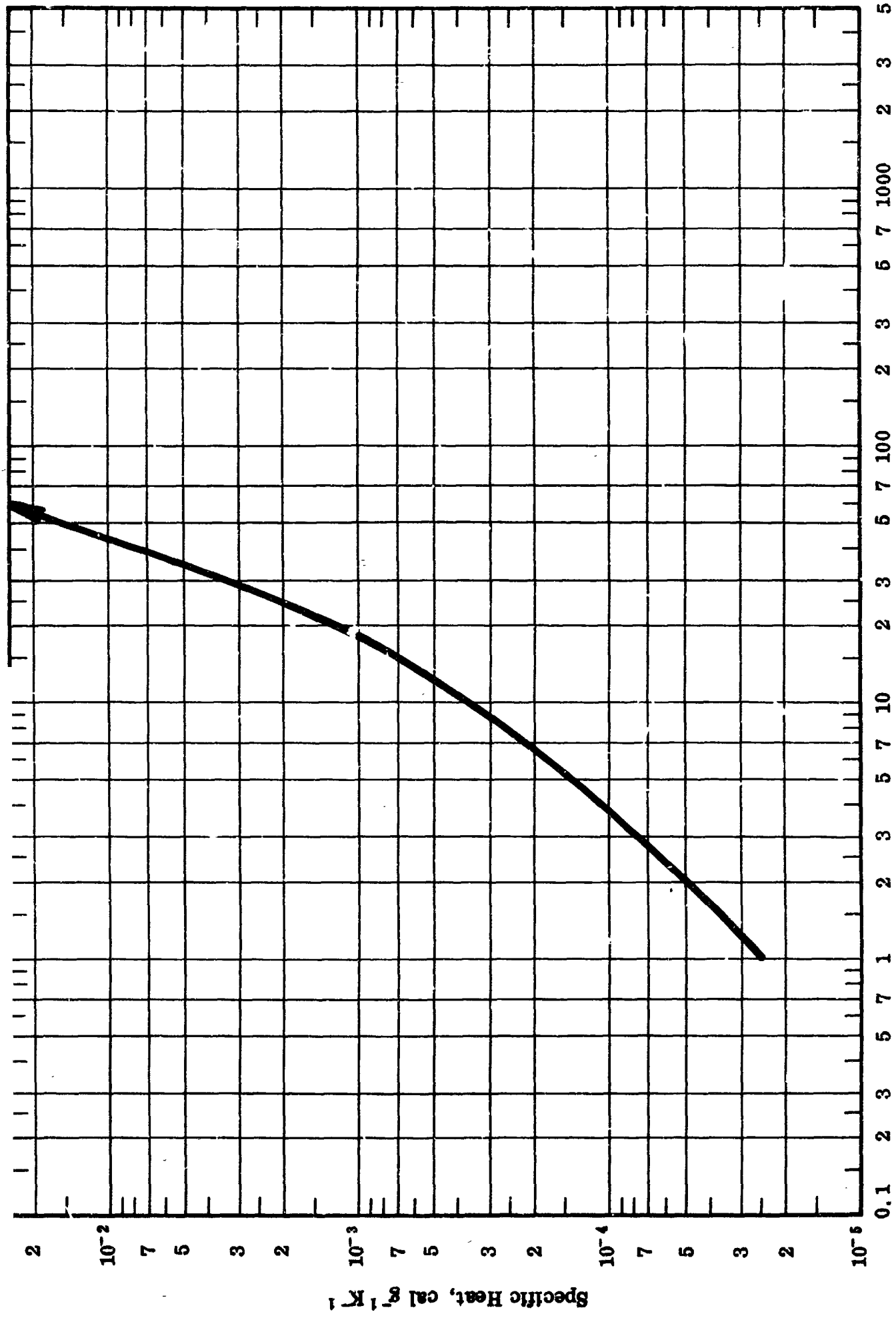
*Calculated using Kopp-Newman Law



Temperature, K

FIG. V - 20 (a)

SPECIFIC HEAT -- INCONEL X - 750

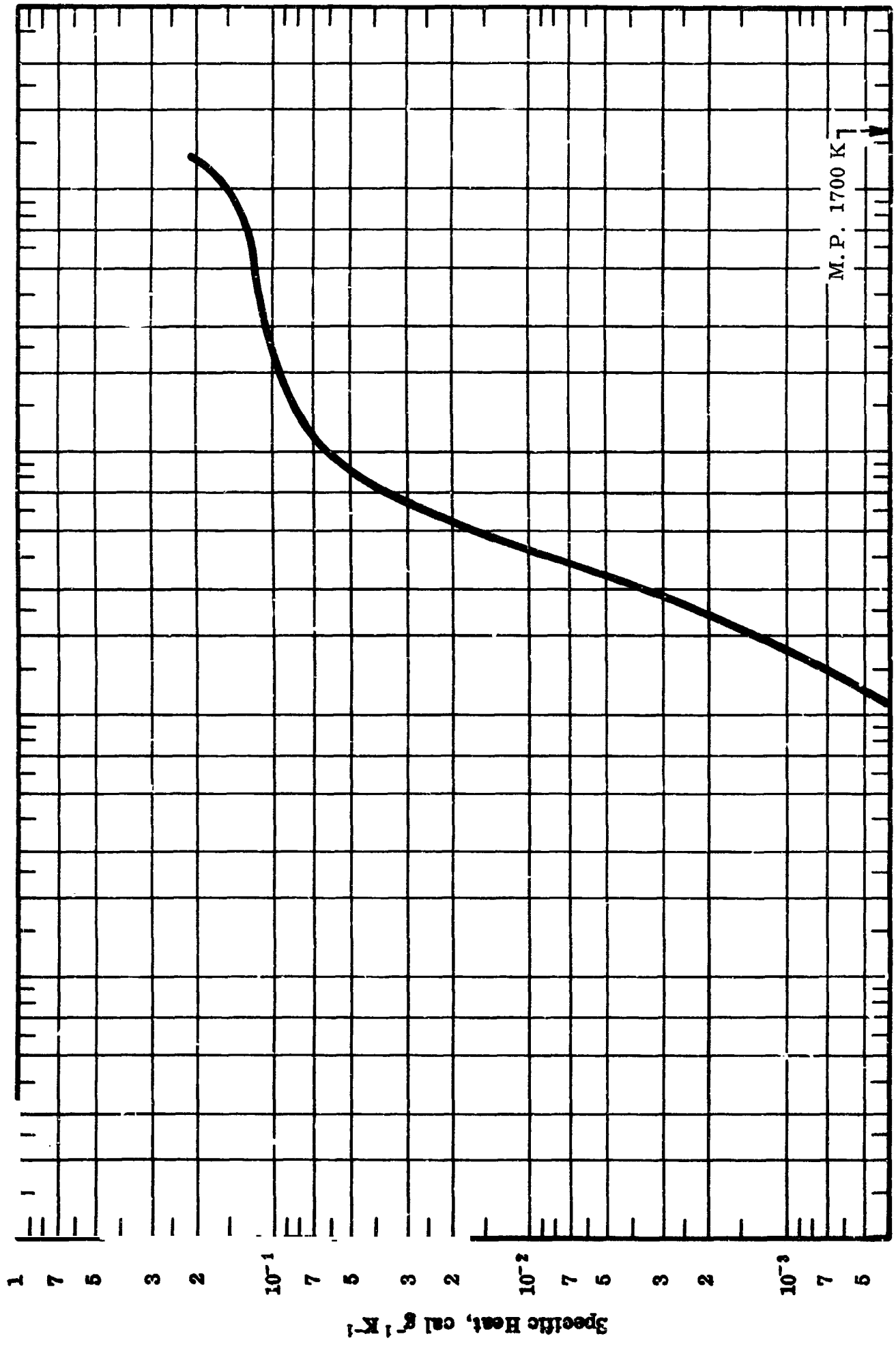


FIG. V - 20 (b)

SPECIFIC HEAT -- INCONEL X - 750

TABLE V-20. SPECIFIC HEAT OF INCONEL X-750

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
1	2.47×10^{-5}*	80	4.70×10^{-2}*
2	4.91*	90	5.65*
3	7.52*	100	6.55
4	1.03×10^{-4}*	150	8.20
5	1.34*	200	9.10
6	1.76*	300	1.04×10^{-1}
7	2.15*	400	1.12
8	2.55*	500	1.18
9	2.99*	600	1.20
10	3.48*	700	1.25
15	7.00*	800	1.30
20	1.24×10^{-3}*	900	1.40
30	3.68*	1000	1.49
40	8.43*	1100	1.60
50	1.53×10^{-2}*	1200	1.80
60	2.67*	1300	(2.15×10^{-1})†
70	3.65*		

Investigators: Lucks, C. F. and Deem, H. W. (208) [116-1255 K]; Lucks, C. F. et al. (209) [73-1123 K]; Venturi, R. and Seibel, R. D. (210) [366-1366 K].

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*Calculated from Kopp-Newman Law

†Extrapolated

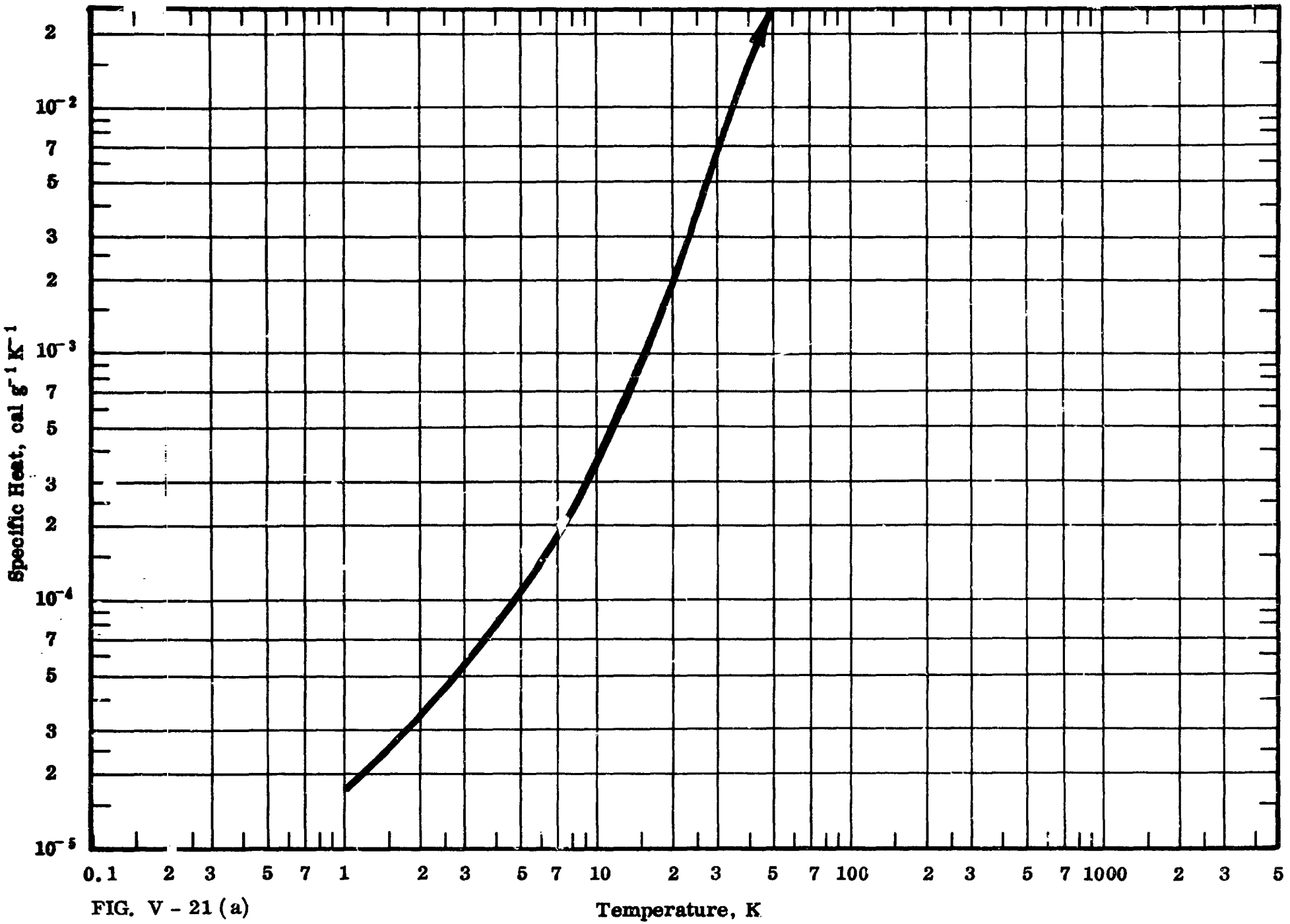

FIG. V - 21 (a)

SPECIFIC HEAT -- TITANIUM ALLOY A-110AT

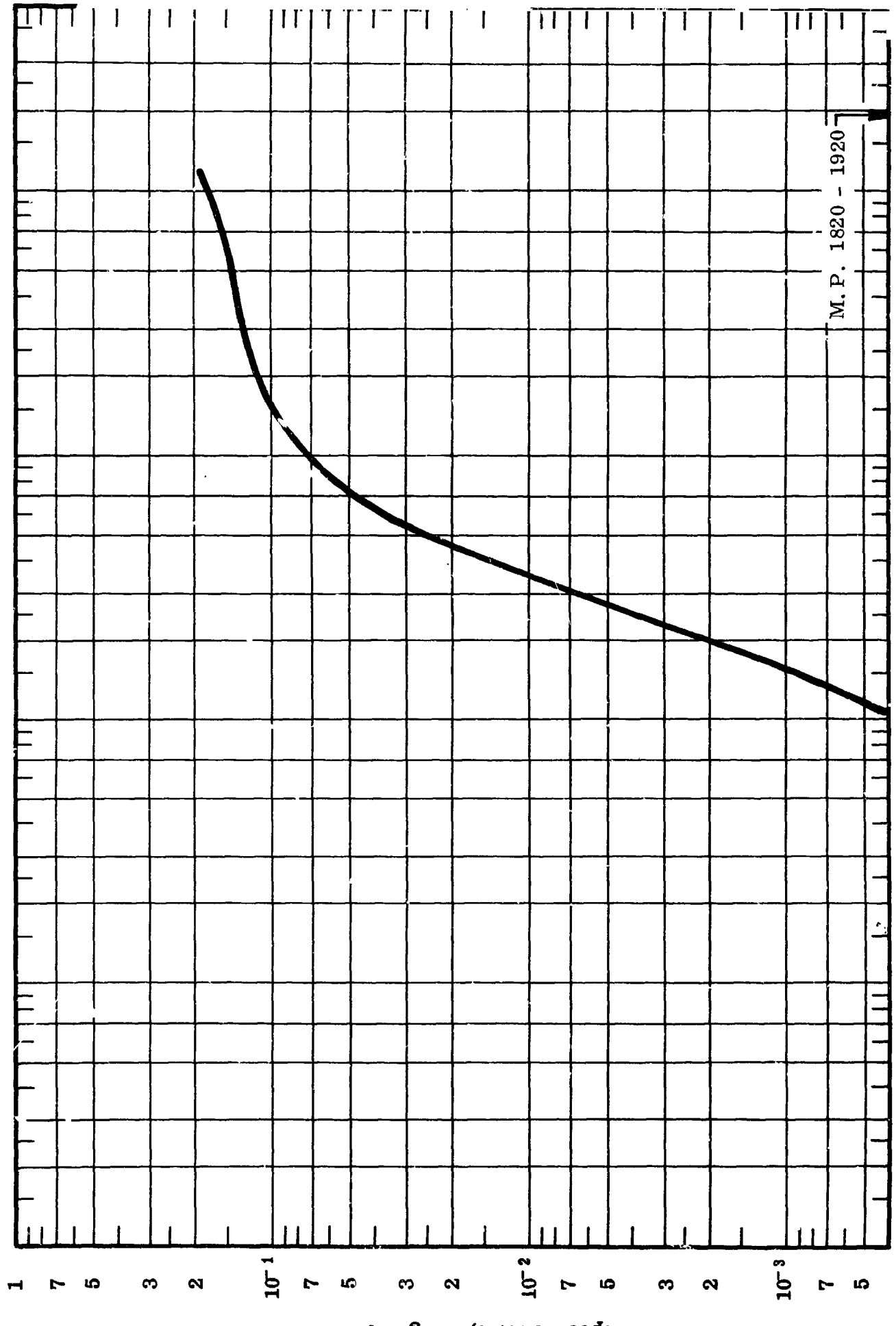

FIG. V - 21 (b)

SPECIFIC HEAT -- TITANIUM ALLOY A-110AT

TABLE V-21. SPECIFIC HEAT OF TITANIUM ALLOY A-110 AT

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1	1.71×10^{-5}*	70	4.64×10^{-2}
2	3.50*	80	5.66*
3	5.46*	90	6.65*
4	7.69*	100	7.30*
5	1.04×10^{-4}	150	1.00×10^{-1}
6	1.38*	200	1.14*
7	1.79*	300	1.28
8	2.29*	400	1.35
9	2.90*	500	1.40
10	3.60*	600	1.46
15	8.80*	700	1.51
20	1.92×10^{-3}*	800	1.60
30	6.28*	900	1.68
40	1.40×10^{-2}*	1000	1.76
50	2.42*	1100	1.82
60	3.55*	1200	1.91

Investigators: Crucible Steel Co. (211) [273-1116 K]; Deem, H. W. and Lucks, C. F. (212) [273-1116 K].

*Calculated from Kopp-Newman Law

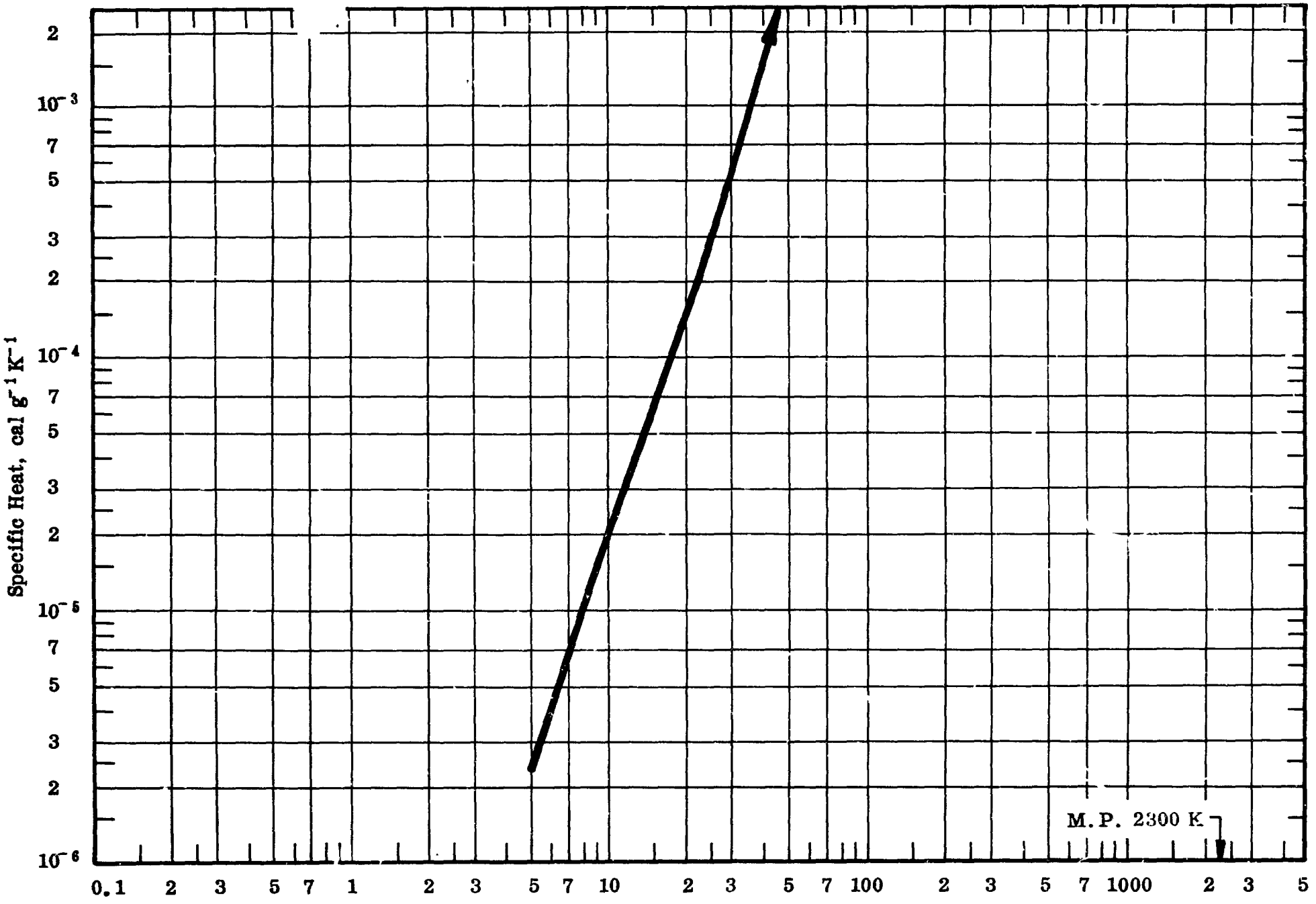

FIG. V - 22 (a)

SPECIFIC HEAT -- ALUMINUM OXIDE, Al_2O_3

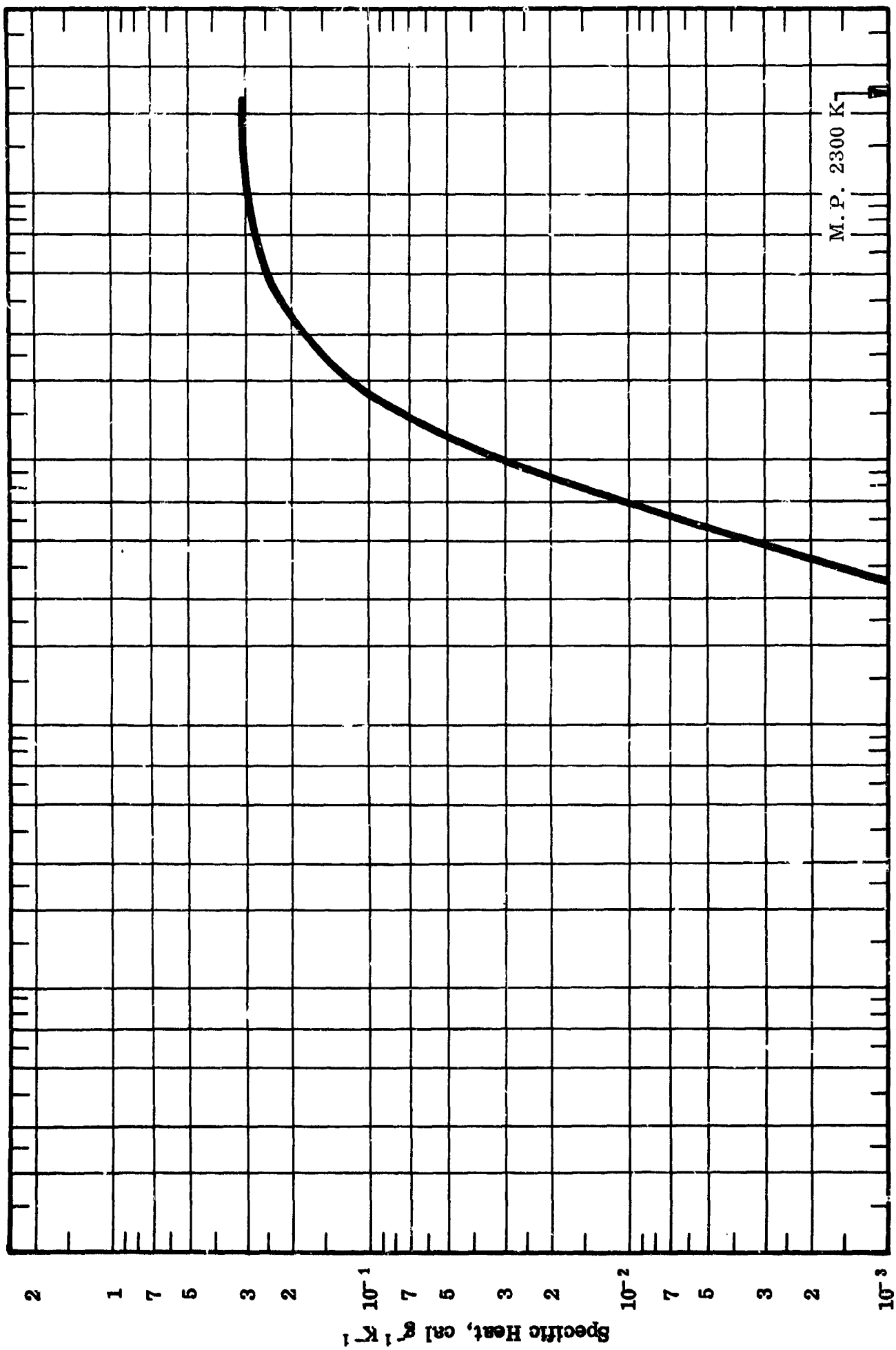

FIG. V - 22 (b)

SPECIFIC HEAT -- ALUMINUM OXIDE, Al_2O_3

TABLE V-22. SPECIFIC HEAT OF ALUMINUM OXIDE, Al_2O_3

T° K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
5	2.35×10^{-6}	300	1.86×10^{-1}
10	2.11×10^{-5}	310	1.91
15	7.03	320	1.96
20	1.78×10^{-4}	330	2.00
25	3.33	340	2.04
30	6.16	350	2.08
35	1.03×10^{-3}	360	2.12
40	1.62	370	2.16
45	2.44	380	2.19
50	3.50	390	2.22
55	4.85	400	2.25
60	6.51	420	2.33
65	8.48	440	2.36
70	1.07×10^{-2}	460	2.40
75	1.33	480	2.45
80	1.62	500	2.48
85	1.93	550	2.57
90	2.27	600	2.64
95	2.63	650	2.69
100	3.01	700	2.74
110	3.82	750	2.78
120	4.70	800	2.82
130	5.62	850	2.85
140	6.55	900	2.88
150	7.50	950	2.90
160	8.43	1000	2.92
170	9.36	1100	2.96
180	1.03×10^{-1}	1200	2.99
190	1.11	1300	3.01
200	1.20	1400	3.03
210	1.28	1500	3.04
220	1.36	1600	3.06
230	1.43	1700	3.07
240	1.50	1800	3.07
250	1.57	1900	3.08
260	1.64	2000	3.08
270	1.70	2100	3.09
280	1.75	2200	3.09
290	1.81	2300	3.09

Investigators: (Aluminum Oxide, Al_2O_3)

Anthony, F. M., et al (213) [533-1228K]; Bogge, J. F., and Wiebelt, J. A. (214) [1089-1700K]; Edwards, J. W., and Kington, G. L. (215) [53-291K]; Ewing, C. T., et al (216) [552-1286K]; Fieldhouse, I. B., et al (217) [435-1883K]; Fieldhouse, I. B., et al (218) [533-1228K]; Furukawa, G. T., et al (219) [5-1200K]; Ginnings, D. C., and Corruccini, R. J. (220) [273-1173K]; Ginnings, D. C., and Furukawa, G. I. (221) [5-1200K]; Hoch, M., and Johnston, H. L. (222) [1273-2273K]; Kerr, E. C., et al (223) [20-295K]; Komanovskii, V. A., and Tarasov, V. V. (224) [65-300K]; Martin, D. L. (225) [283-303K]; Neel, D. S., et al (226) [553-1922K]; Oettig, F. L. (227) [342-764K]; Parks, G. S., and Kelley, K. K. (228) [91-291K]; Pears, C. D., and Neel, D. S. (229) [533-1922K]; Prophet, H. and Stull, D. R. (230) [1300-2000K]; Roth, W. A., and Bertram, W. W. (231) [369-1187K]; Schmidt, N. E., and Sokolov, V. A. (232) [326-987K]; Shomate, C. H., and Naylor, B. F. (233) [298-1800K]; Sterrett, K. F., et al (234) [10-360K]; Walker, B. F., et al (235) [337-923K]; Walker, B. F., et al (236) [337-923K]; West, E. D., and Ginnings, D. C. (237) [311-689K]; Wiebelt, J. A. (238) [1089-1700K].

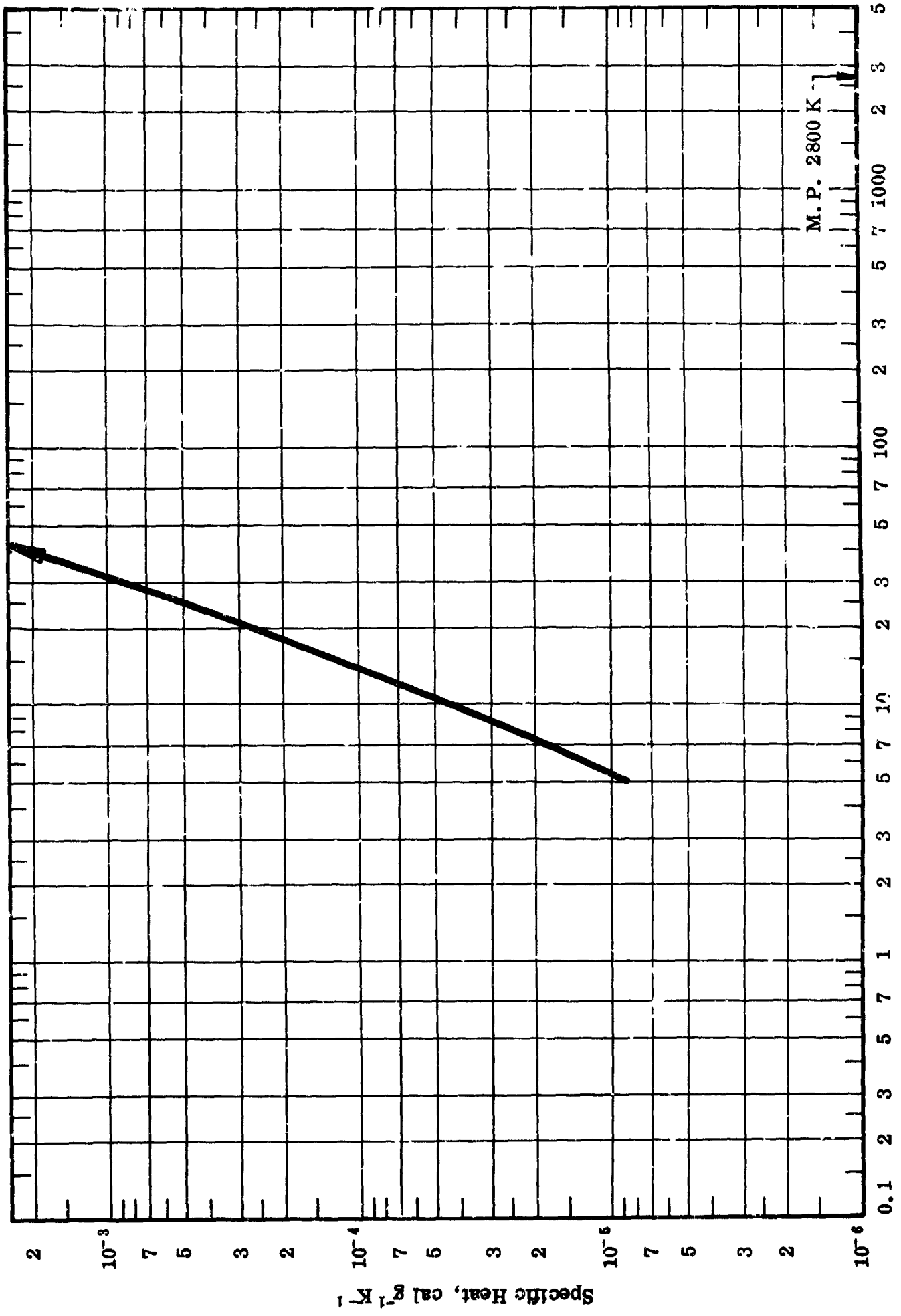

FIG. V - 23 (a)

SPECIFIC HEAT -- BERYLLIUM OXIDE, BeO

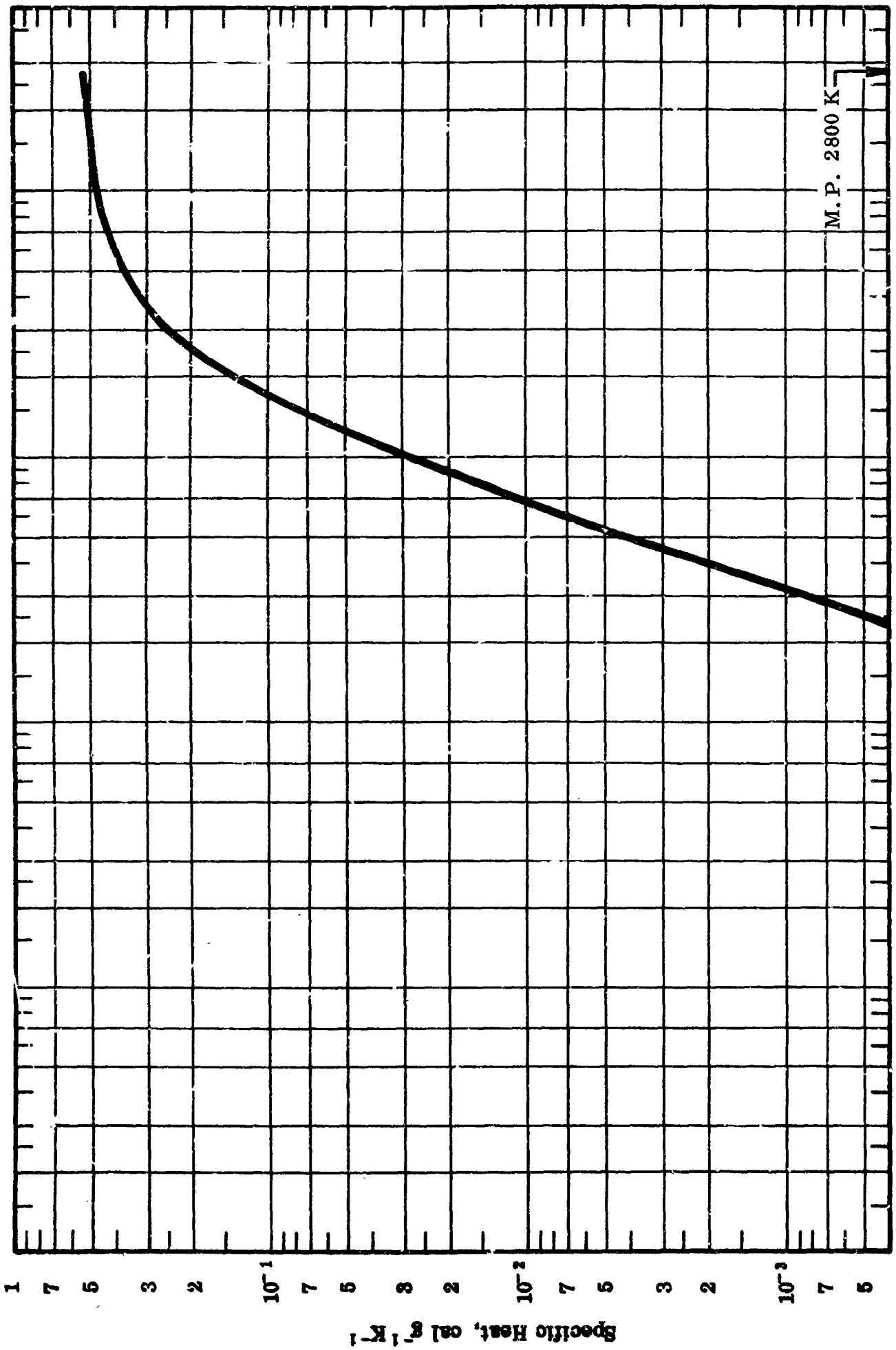

FIG. V - 23 (b)

SPECIFIC HEAT -- BERYLLIUM OXIDE, BeO

TABLE V-23. SPECIFIC HEAT OF BERYLLIUM OXIDE, BeO

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
5	(8.40×10^{-6})†	750	4.38×10^{-1}
10	4.00×10^{-5}	800	4.46
15	1.20×10^{-4}	850	4.53
20	2.40	900	4.60
30	8.40	950	4.66
40	2.00×10^{-3}	1000	4.71
50	3.90	1100	4.80
60	6.67	1200	4.88
70	1.03×10^{-2}	1300	4.94
80	1.48	1400	5.00
90	2.03	1500	5.05
100	2.70	1600	5.09
150	7.62	1700	5.13
200	1.36×10^{-1}	1800	5.17
250	1.95	1900	5.20
300	2.46	2000	5.23
350	2.88	2100	5.26
400	3.23	2200	5.28
450	3.50	2300	5.30
500	3.72	2400	5.32
550	3.90	2500	5.34
600	4.05	2600	5.36
650	4.18	2700	5.38
700	4.28	2800	5.40

Investigators: Hedge, J.C., et al (239) [527-2278K]; Kandyba, V.V., et al (240) [1142-2820K]; Kelley, K.K. (241) [55-292K]; Magnus, A., and Danz. H., (242) [293-1175K], Pears, C.D. (243) [533-2200K]; Victor, A.C., and Douglas, T.B. (244) [298-1200K]; Walker, B.E., et al (245) [303-1075K].

†Extrapolated

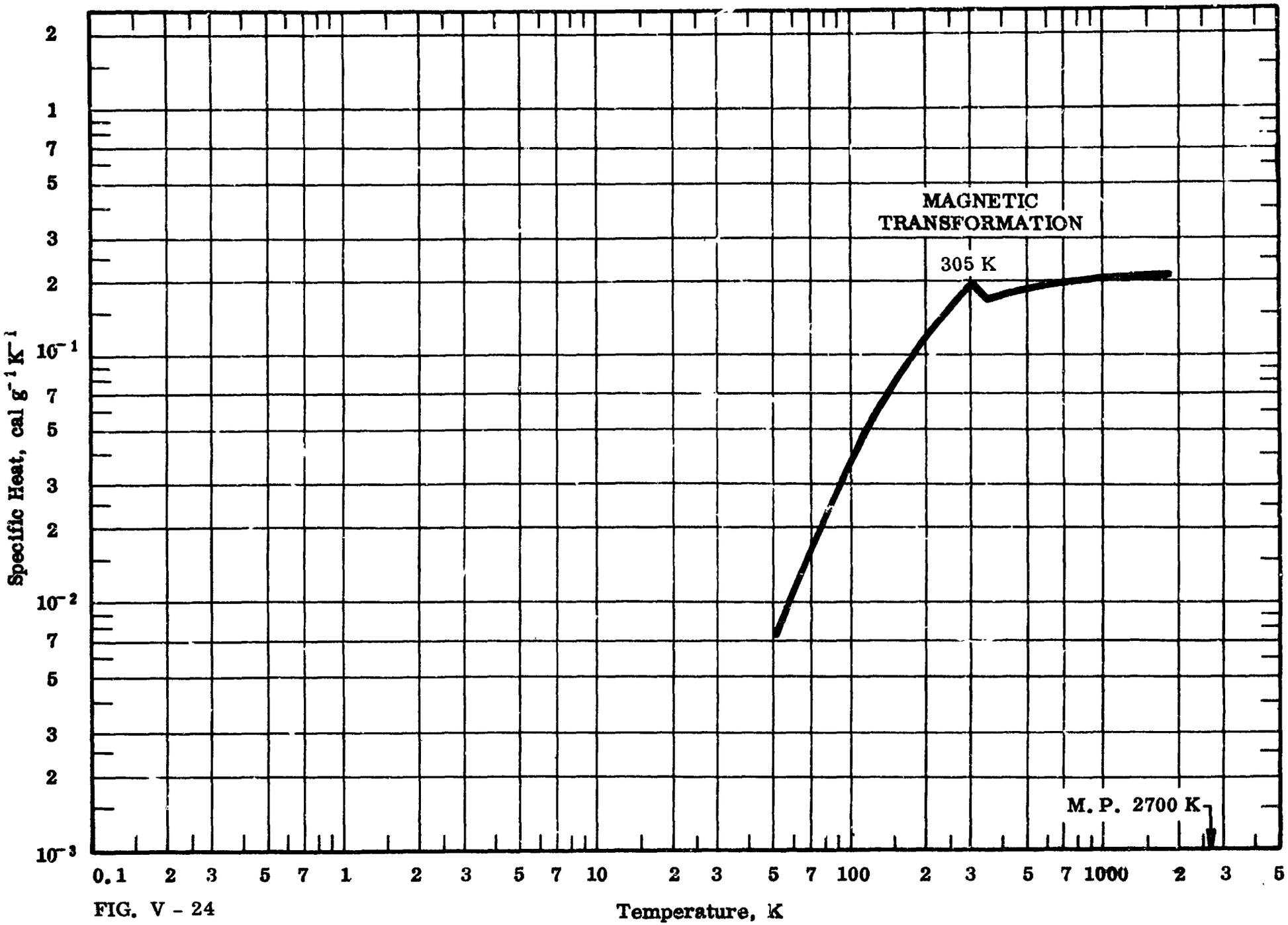

FIG. V - 24

SPECIFIC HEAT ... CHROMIUM OXIDE, Cr_2O_3

TABLE V-24. SPECIFIC HEAT OF CHROMIUM OXIDE, Cr_2O_3

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
50	(7.30×10^{-3}) †	330	1.68×10^{-1}
60	1.08×10^{-2}	350	1.67
70	1.70	400	1.78
80	2.45	500	1.85
90	3.10	600	1.90
100	3.85	700	1.93
120	5.40	800	1.95
150	8.00	900	1.98
160	8.80	1000	1.99
180	1.02×10^{-1}	1100	2.02
200	1.20	1200	2.03
250	1.55	1300	2.05
300	1.91	1400	2.07
305	1.98	1500	2.08
310	1.81	1600	2.10
315	1.74	1700	2.12
320	1.69	1800	2.13

Investigators: Anderson, C. T. (246) [56-335K]; Kelley, K.K., et al (247) [298-1800K]; Volger, J. (248) [98-322K].

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†Extrapolated

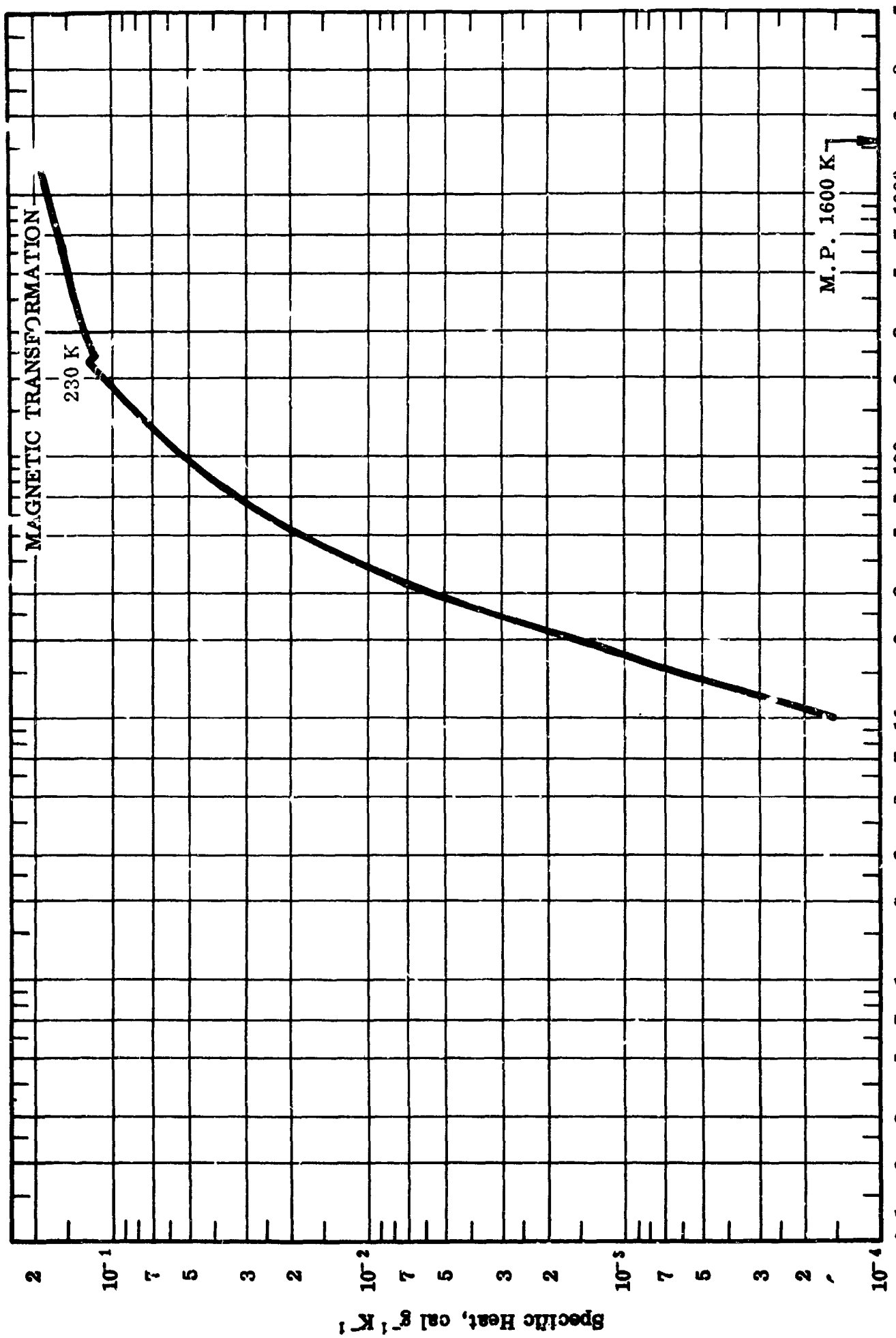
MAGNETIC TRANSFORMATION
230 K
M.P. 1600 K
Specific Heat, cal g⁻¹ K⁻¹
Temperature, K
10⁻¹
10⁻²
10⁻³
10⁻⁴
0.1
1000

FIG. V - 25

TABLE V-25. SPECIFIC HEAT OF CUPRIC OXIDE, CuO

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
10	(1.5×10^{-4})†	240	1.17×10^{-2}
15	6.29×10^{-4}	250	1.19
20	1.55×10^{-3}	260	1.21
25	3.12	270	1.22
30	5.80	280	1.24
40	1.20×10^{-2}	290	1.26
50	1.85	300	1.28
60	2.59	400	1.41×10^{-1}
70	3.20	500	1.47
80	3.90	600	1.53
90	4.50	700	1.59
100	5.00	800	1.65
150	8.00	900	1.71
200	1.07	1000	1.77
210	1.12	1100	1.83
220	1.17	1200	1.89
230	1.24	1253	1.92

Investigators: Assayag, G., and Bizette, H. (249) [200-300K]; Clusius, K., and Hasteck, P. (250) [30-200K]; Hu, J.H., and Johnston, H. L. (251) [15-297K]; Millar, R.W. (252) [71-301K]; Wohler, L., and Jochum, N. (253) [298-1253K].

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†Extrapolated

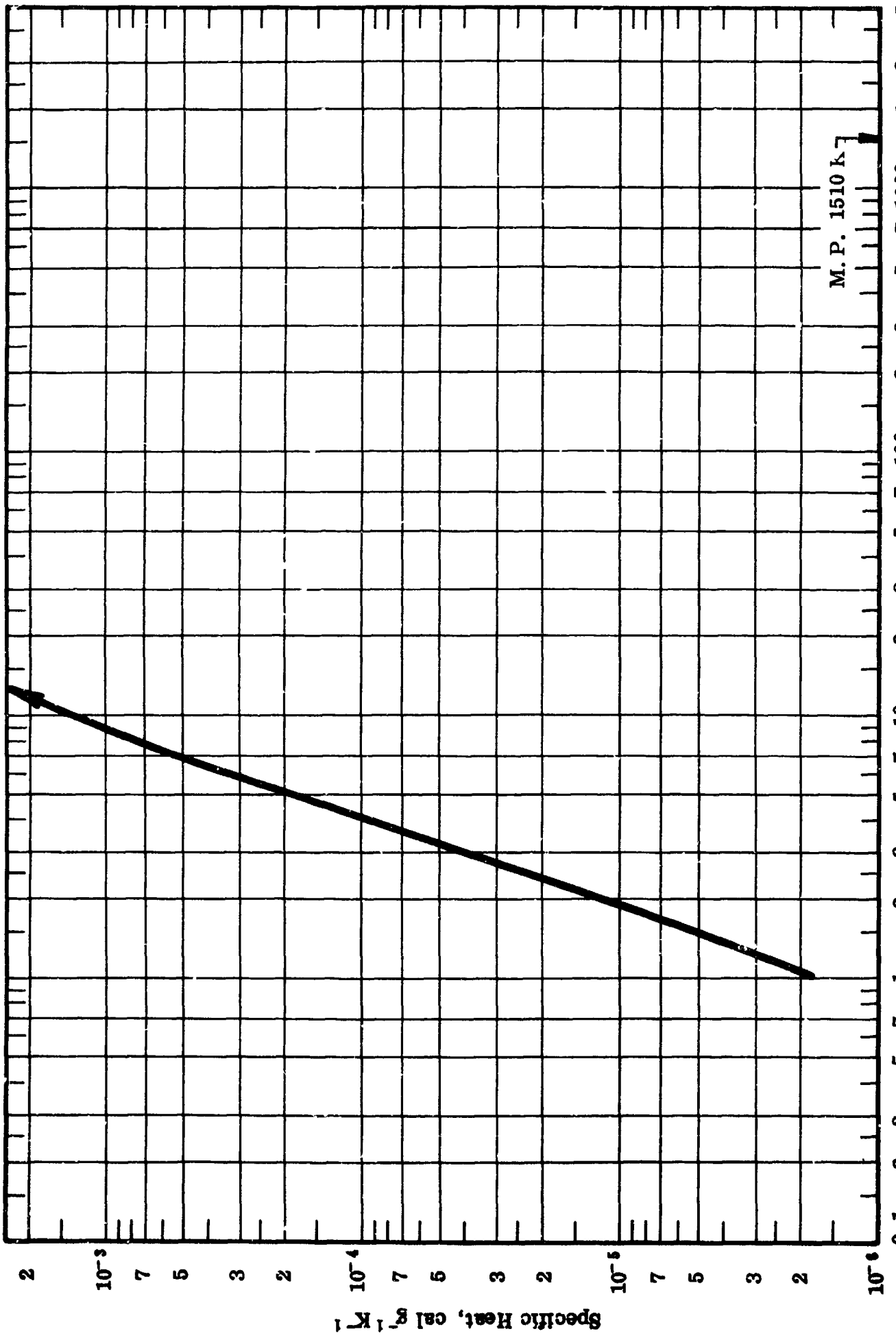

FIG. V - 26 (a)

SPECIFIC HEAT -- CUPROUS OXIDE, Cu_2O

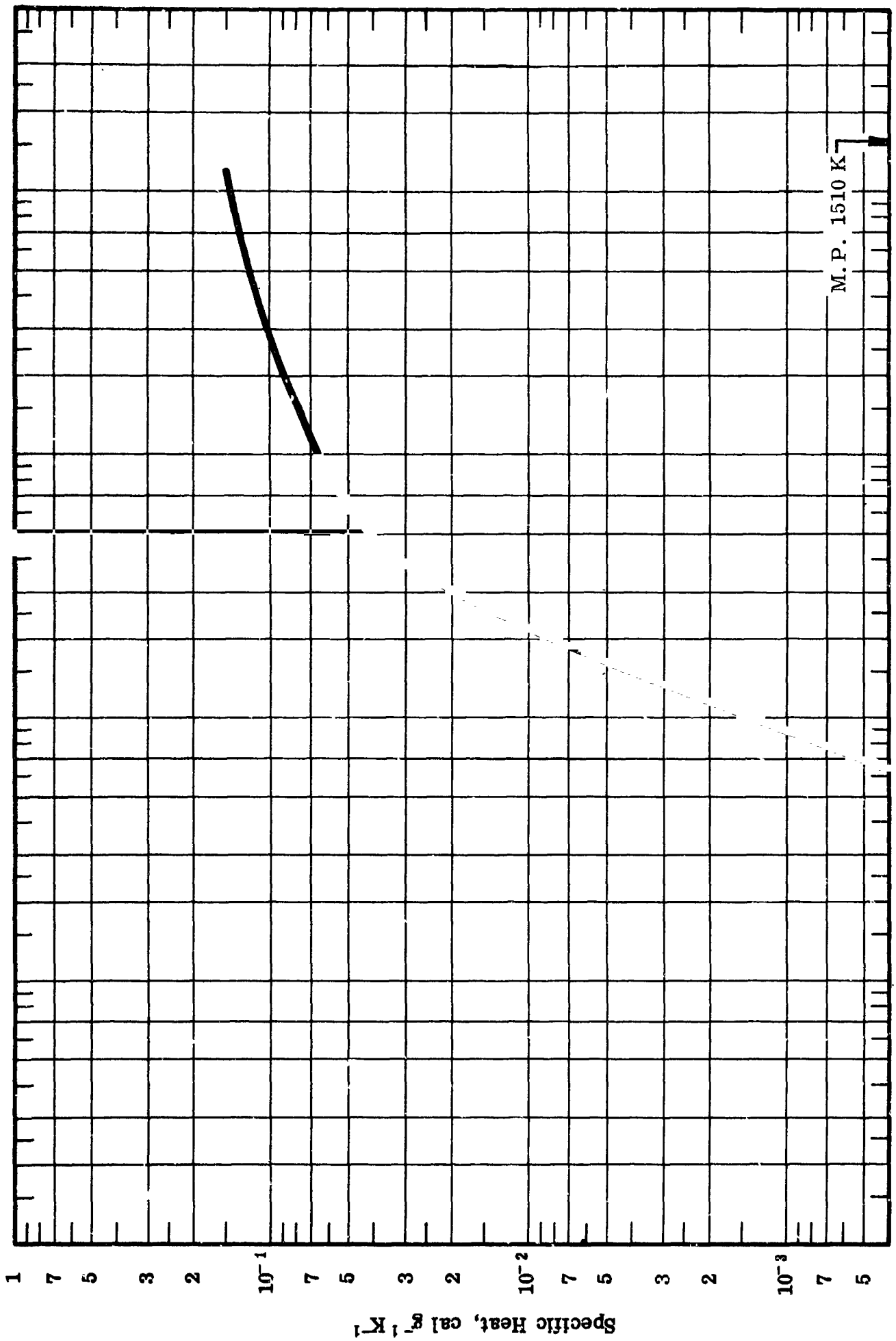

FIG. V - 26(b).

SPECIFIC HEAT -- CUPROUS OXIDE, Cu_2O

TABLE V-26. SPECIFIC HEAT OF CUPROUS OXIDE, Cu_2O

T °K	C_p, $cal^{-1} K^{-1}$	T °K	C_p, $cal\ g^{-1} K^{-1}$
1	(1.80×10^{-6})†	100	6.70×10^{-2}
1.5	(5.20×10^{-6})	120	7.20
2	(1.17×10^{-5})	140	7.70
3	3.90	160	8.10
4	9.50	180	8.50
5	1.92×10^{-4}	200	8.95
6	3.34	220	9.40
7	5.40	240	9.75
8	7.60	260	1.00×10^{-1}
9	1.02×10^{-3}	280	1.02
10	1.32	300	1.06
15	4.00	400	1.19
20	8.40	500	1.23
30	2.05×10^{-2}	600	1.28
40	3.28	700	1.32
50	4.16	800	1.36
60	4.92	900	1.40
70	5.50	1000	1.44
80	5.95	1100	1.48
90	6.30	1200	1.52

Investigators: Gregor, L. V. (254) [2-21K]; Hu, J. H., and Johnston, H. L. (255) [15-300K]; Millar, R. W. (256) [76-291K]; Wohler, L., and Jochum, N. (257) [298-1200K].

†Extrapolated

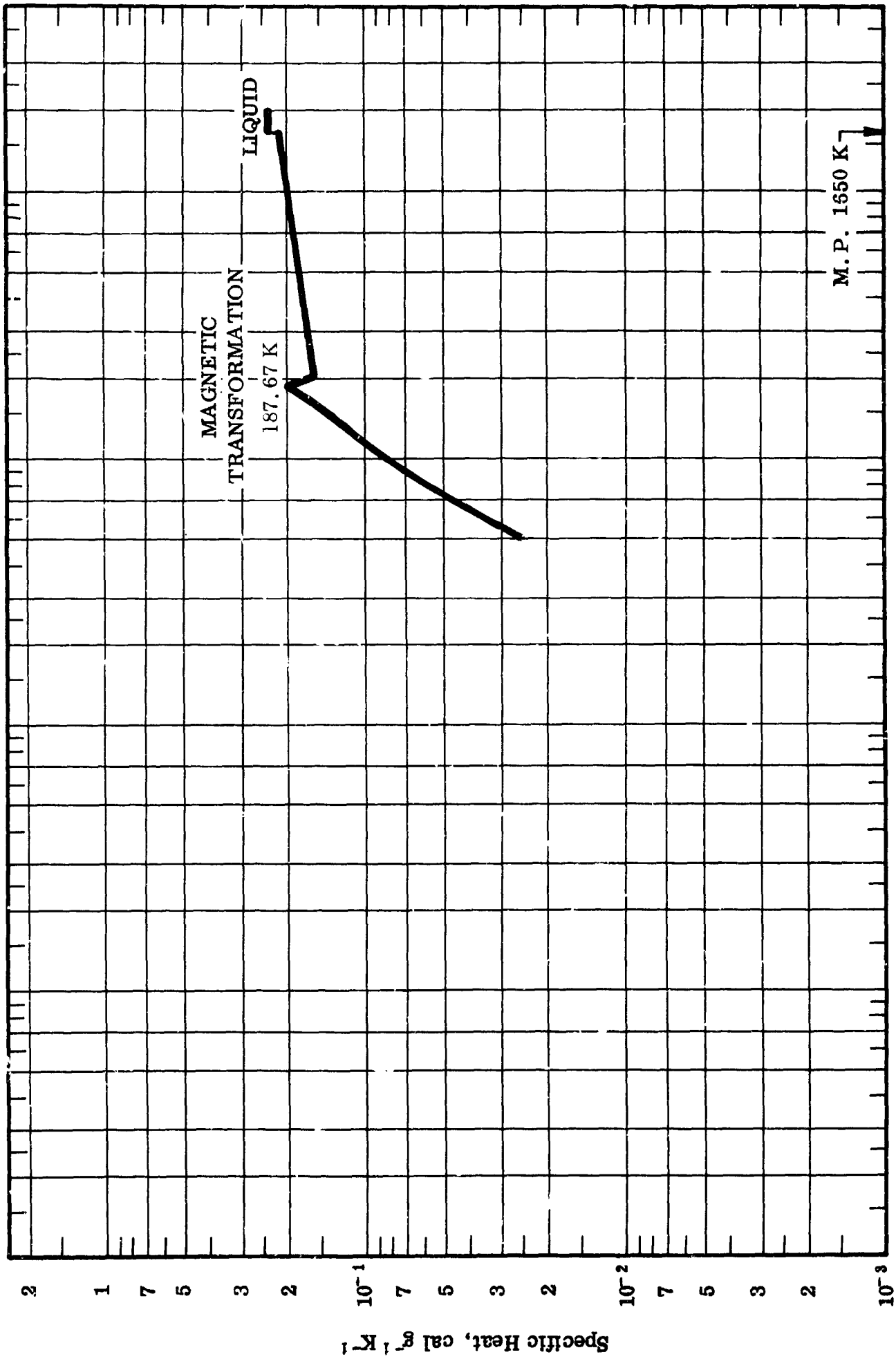

FIG. V - 27

SPECIFIC HEAT -- FERROUS OXIDE, $Fe_{0.947}O$

TABLE V-27. SPECIFIC HEAT OF FERROUS OXIDE, $Fe_{0.947}O$

T °K	C_p cal $g^{-1} K^{-1}$	T °K	C_p cal $g^{-1} K^{-1}$
50	2.45×10^{-2}	700	1.88
60	3.55	800	1.91
70	4.80	900	1.94
80	5.80	1000	1.97
90	7.10	1100	2.00
100	8.30	1200	2.03
150	1.45×10^{-1}	1300	2.06
160	1.58	1400	2.09
180	1.85	1500	2.12
187.67	2.02	1600	2.15
190	1.98	(s) 1650	2.17
200	1.59	(l) 1650	2.37
300	1.67	1700	2.37
400	1.75	1800	2.37
500	1.79	1900	$(2.37 \times 10^{-1})^{\dagger}$
600	1.84	2000	(2.37×10^{-1})

Investigators: Coughlin, J.P., et al (258) [298–1800K]; Millar, R.W. (259) [71–302K]; Todd, S.S., and Bonnickson, K.R. (260) [54–298K]; White, W.P. (261) [303–1173K].

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†Extrapolated

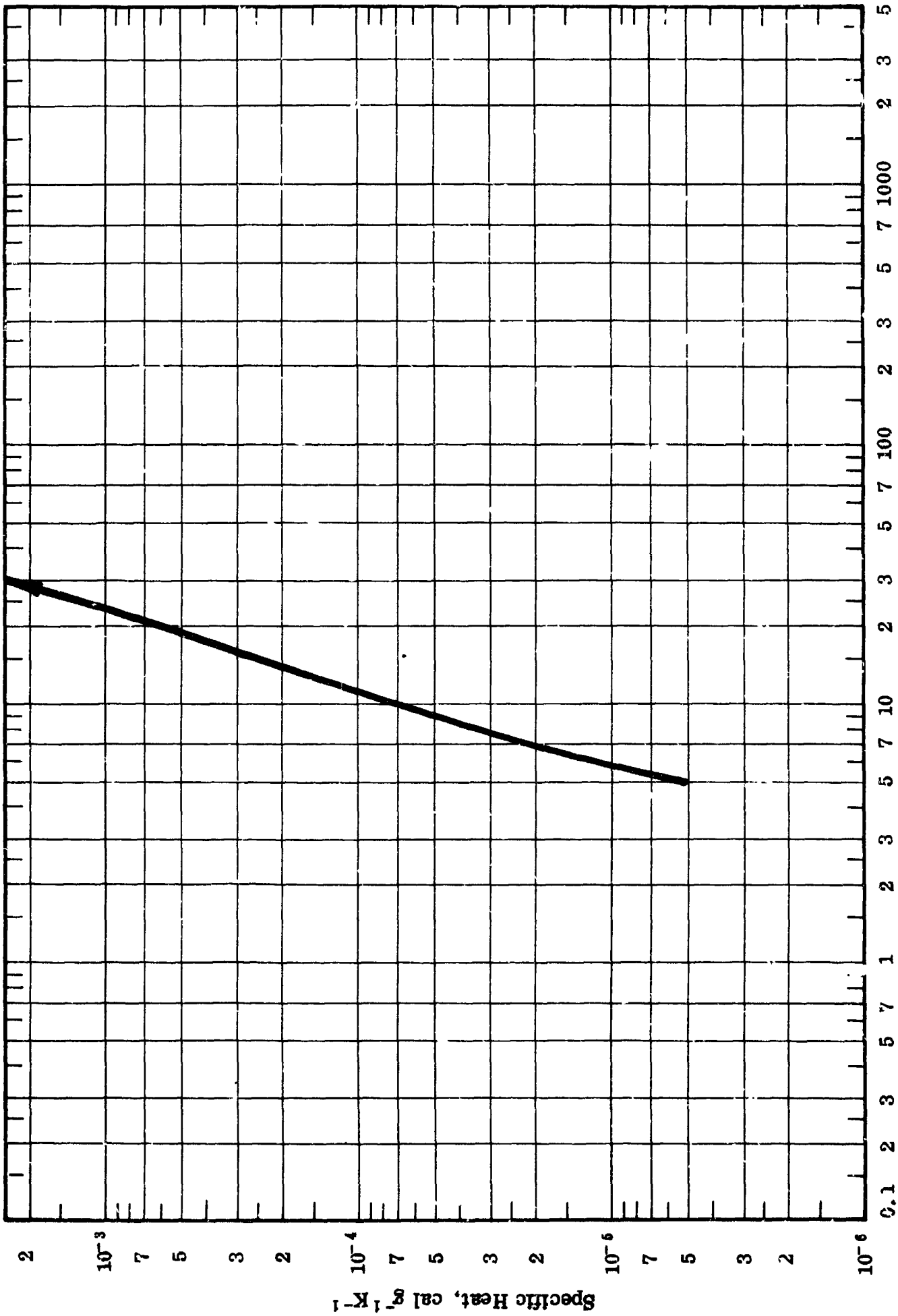

FIG. V - 28 (a)

SPECIFIC HEAT -- FERRIC OXIDE, Fe_2O_3

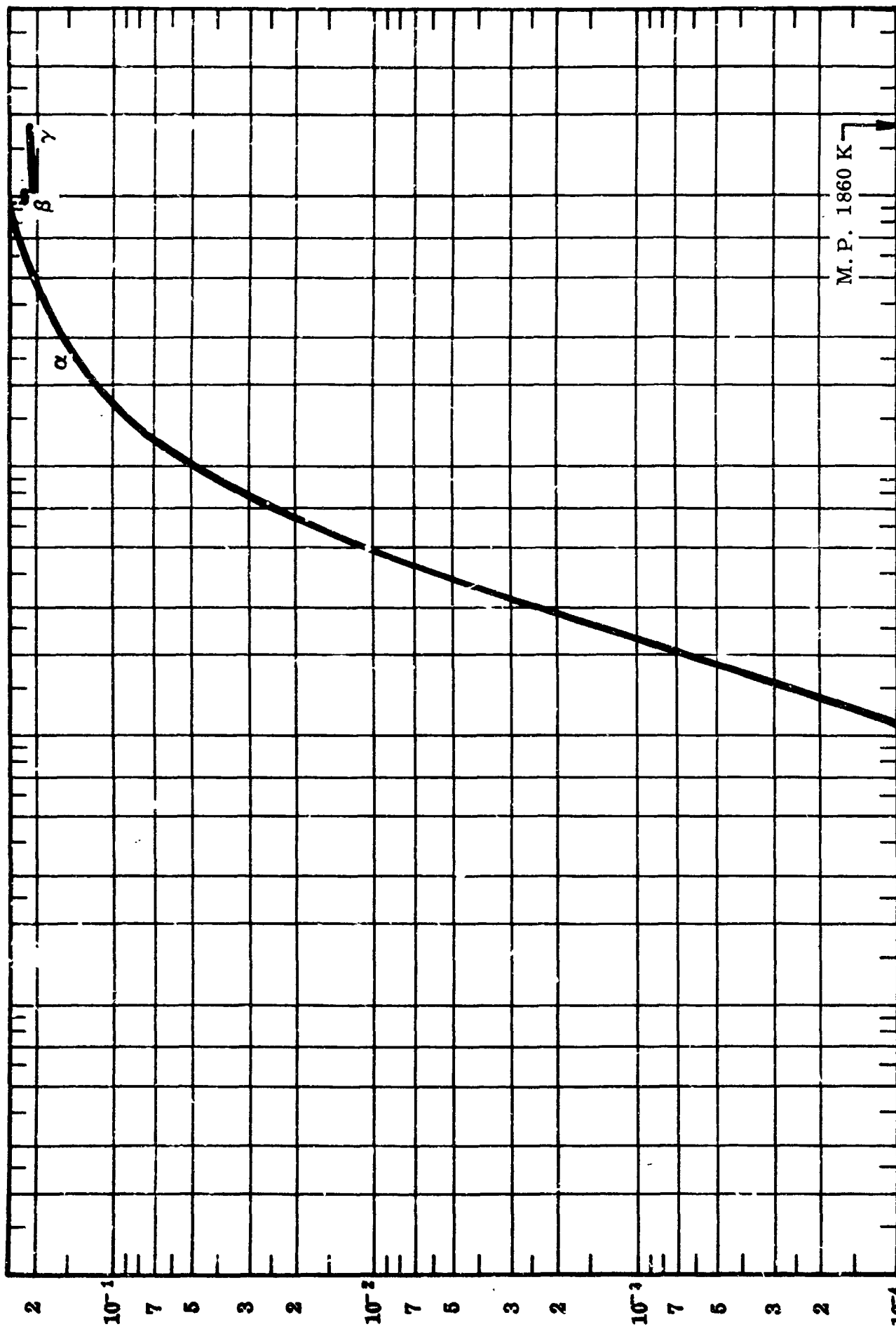

FIG. V - 28 (b)

SPECIFIC HEAT -- FERRIC OXIDE, Fe_2O_3

TABLE NO. V-28. SPECIFIC HEAT OF FERRIC OXIDE Fe_2O_3

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
5	5.00×10^{-6}	(α) 700	2.28×10^{-1}
10	7.51×10^{-5}	800	2.40
15	2.67×10^{-4}	900	2.52
20	5.70	(α) 950	2.58
30	2.38×10^{-3}	(β) 950	2.25
40	5.96	1000	2.25
50	1.10×10^{-2}	(β) 1050	2.25
60	1.72	(γ) 1050	2.10
70	2.42	1100	2.11
80	3.17	1200	2.12
90	3.95	1300	2.13
(α) 100	4.71	1400	2.14
150	8.42	1500	2.15
200	1.14×10^{-1}	1600	2.16
300	1.56	1700	2.17
400	1.85	(γ) 1750	2.18
500	2.04		
600	2.16		

Investigators: Brown, G. G. and Furnas, C. C. (262) [273-923 K]; Coughlin, J. P. et al. (263) [298-1750 K]; Gronvold, F. and Westrum, E. F., Jr., (264) [5-350 K]; Parks, G. S. and Kelley, K. K. (265) [90-292 K]; Roth, W. A. and Bertram, W. W. (266) [293-1097 K].

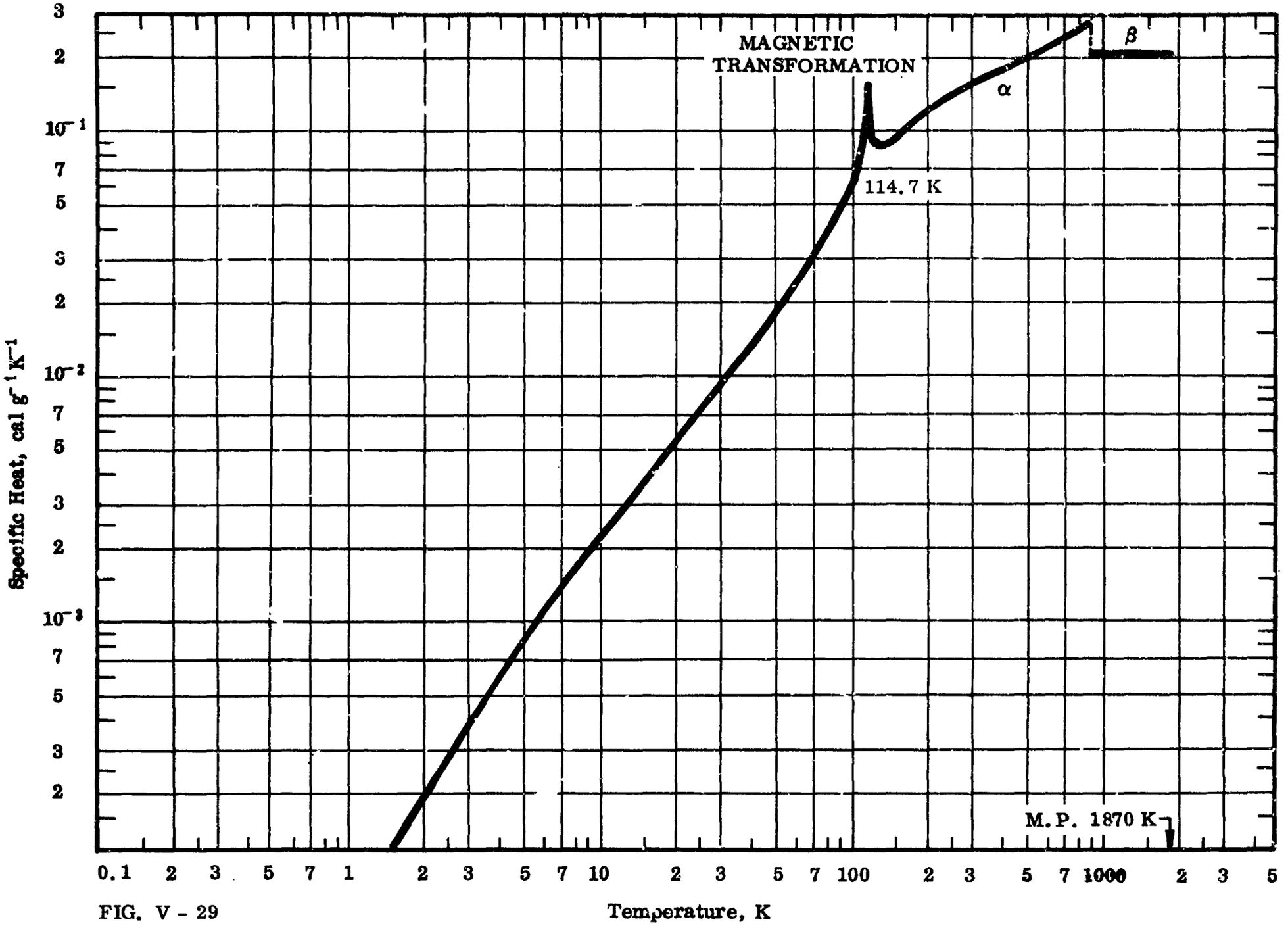

FIG. V - 29

SPECIFIC HEAT -- IRON OXIDE (MAGNETITE) Fe_3O_4

TABLE V-29. SPECIFIC HEAT OF IRON OXIDE (MAGNETITE) Fe_3O_4

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
1.0	$(5.80 \times 10^{-5})^{\dagger}$	114.7	1.57×10^{-1}
1.5	$(1.19 \times 10^{-4})^{\dagger}$	116	1.27
2	1.95	119	9.29×10^{-2}
3	3.90	120	9.25
4	6.20	130	8.50
5	8.50	140	9.00
6	$(1.10 \times 10^{-3})^{\ddagger}$	150	9.60
7	$(1.36 \times 10^{-3})^{\ddagger}$	200	1.20×10^{-1}
8	$(1.65 \times 10^{-3})^{\ddagger}$	(α) 300	1.57
9	$(1.92 \times 10^{-3})^{\ddagger}$	400	1.78
10	$(2.40 \times 10^{-3})^{\ddagger}$	500	1.99
15	$(3.60 \times 10^{-3})^{\ddagger}$	600	2.19
20	$(5.20 \times 10^{-3})^{\ddagger}$	700	2.40
30	$(8.90 \times 10^{-3})^{\ddagger}$	800	2.61
40	$(1.34 \times 10^{-2})^{\ddagger}$	($\sim$) 900	2.82
50	$(1.85 \times 10^{-2})^{\ddagger}$	(β) 900	2.07
60	2.37×10^{-2}	1000	2.07
70	3.10	1100	2.07
80	3.90	1200	2.07
90	4.80	1300	2.07
100	6.00	1400	2.07
105	6.56	1500	2.07
110	8.30	1600	2.07
112	1.06×10^{-1}	1700	2.07
114	1.42	(β)1800	2.07

Investigators: Coughlin, J. P. et al. (267) [298-1800 K]; Kouvel, J. S. (268) [1.8-4.2 K]; Millar, R. W. (269) [60-300 K]; Okamura, T. and Torizuka, Y. (270) [89-125 K]; Parks, G. S. and Kelley, K. K. (271) [90-295 K]; Roth, W. A. and Berman, W. W. (272) [293-1056 K].

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†Extrapolated

‡Interpolated

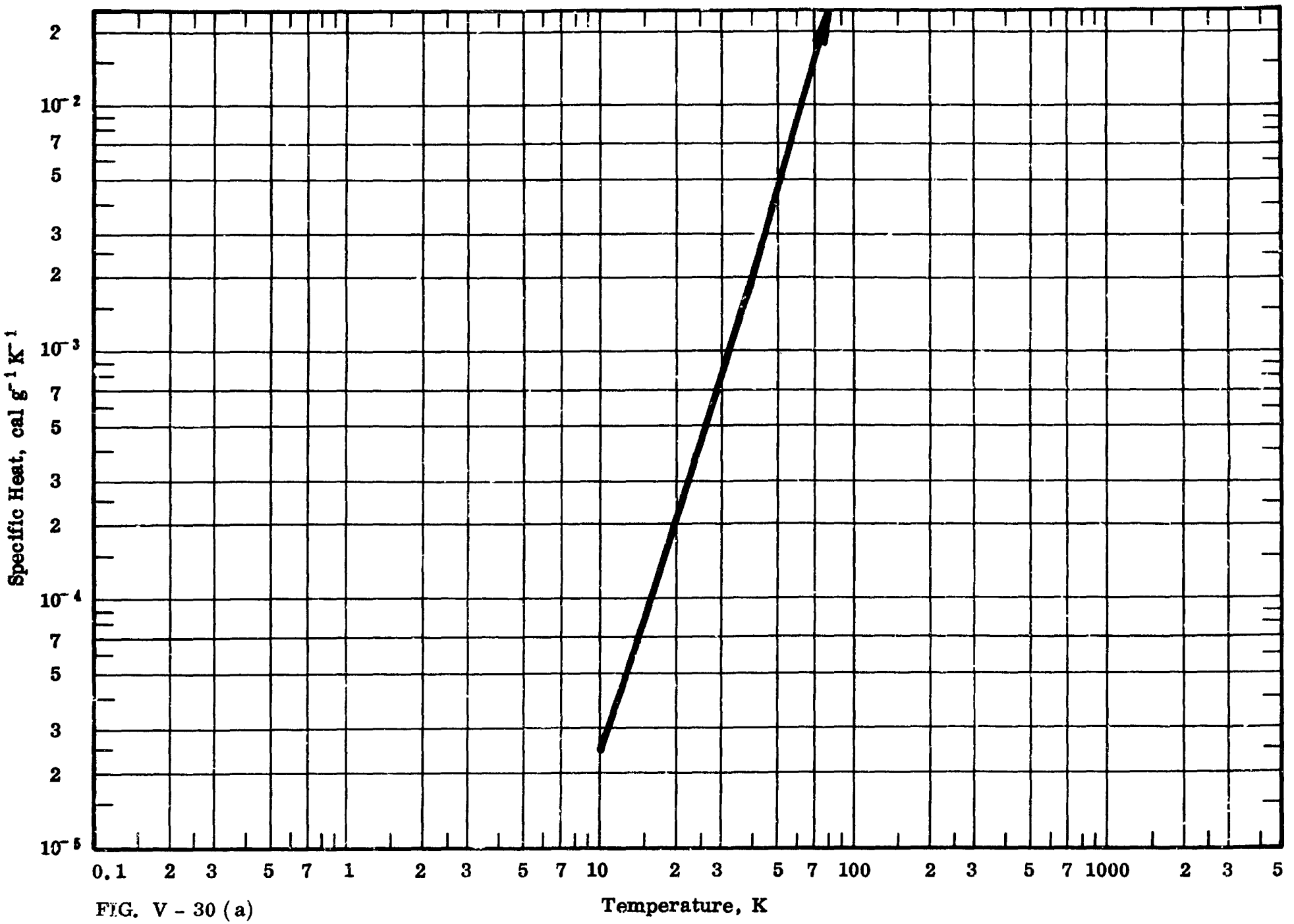

FIG. V - 30 (a)

SPECIFIC HEAT ... M[illegible]GNESIUM OXIDE ...

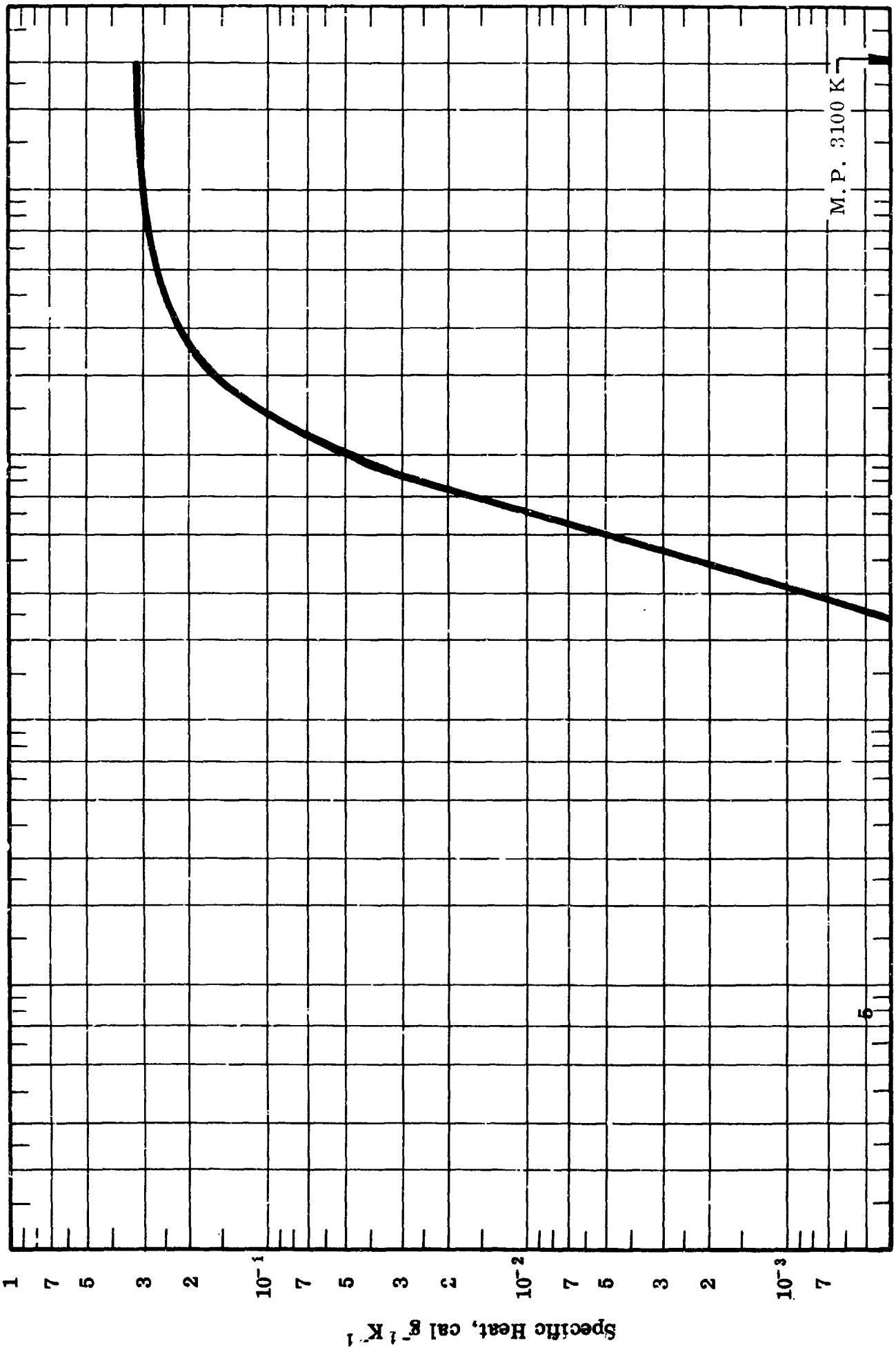

FIG. V - 30 (b)

SPECIFIC HEAT -- MAGNESIUM OXIDE, MgO

TABLE V-30. SPECIFIC HEAT OF MAGNESIUM OXIDE MgO

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
10	2.50×10^{-5}	1100	3.07×10^{-1}
15	9.90	1200	3.10
20	2.20×10^{-4}	1300	3.12
30	8.20	1400	3.13
40	2.20×10^{-3}	1500	3.15
50	4.94	1600	3.16
60	9.52	1700	3.18
70	1.62×10^{-2}	1800	3.19
80	2.48	1900	3.19
90	3.49	2000	3.20
100	4.62	2100	3.21
150	1.02×10^{-1}	2200	3.22
200	1.58	2300	3.22
300	2.22	2400	3.23
400	2.52	2500	3.23
500	2.69	2600	3.24
600	2.81	2700	3.24
700	2.89	2800	3.24
800	2.95	2900	3.25
900	3.00	3000	3.25
1000	3.04		

Investigators: Arthur, J.S. (273) [473-773 K]; Barron, T.H.K. et al. (274) [10-270 K]; Fieldhouse, I.B. and Lang, J.I. (275) [475-1812 K]; Giauque, W.F. and Archibald, R.C. (276) [20-500 K]; Lien, W.H., (277) [1.3-4.2 K]; Makarounis, O and Jenkins, R.J. (278) [90-482 K]; Pankratz, L.B. and Kelley, K.K. (279) [293-1800 K]; Parks, G.S. and Kelley, K.K. (280) [94-291 K]; Pears, C.D. (281) [533-2478 K]; Victor, A.C. and Douglas, T.B. (282) [298-1200 K]; Victor, A.C. and Douglas, T.B. (283) [273-1173 K].

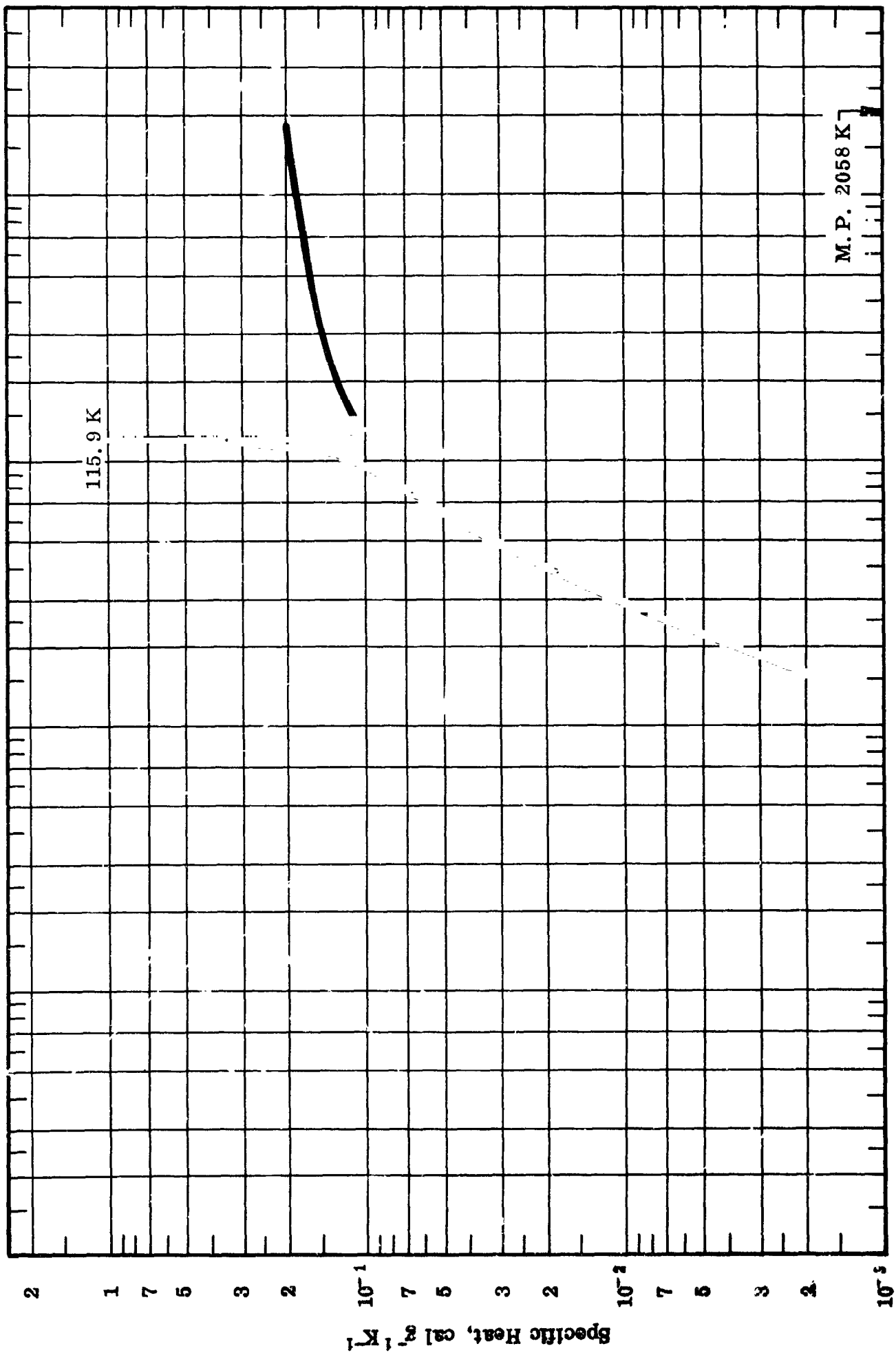

FIG. V - 31

SPECIFIC HEAT -- MANGANOUS OXIDE, MnO

TABLE V-31. SPECIFIC HEAT OF MANGANESE MONOXIDE MnO

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
10	(5.64×10^{-4})	150	1.12×10^{-1}
15	(1.75×10^{-3})	200	1.28
20	(3.95×10^{-3})	250	1.40
30	(1.09×10^{-2})	300	1.49
40	(2.05×10^{-2})	400	1.60
50	(3.20×10^{-2})	500	1.65
60	4.50×10^{-2}	600	1.70
70	5.90	700	1.73
80	7.50	800	1.76
90	8.80	900	1.80
100	1.09×10^{-1}	1000	1.83
110	1.34	1100	1.86
112	1.55	1200	1.89
114	1.76	1300	1.91
115	1.94	1400	1.94
115.9	1.52×10^{0}	1500	1.97
116	3.37×10^{-1}	1600	2.00
120	1.05	1700	2.03
130	1.04	1800	2.05
140	1.09		

Investigators: Millar, R.W. (284) [70-300 K]; Southard, J.C. and Shomate, C.H. (285) [ΔH, 298-1800 K]; Todd, S.S. and Bonnickson, K.R. (286) [55-298 K].

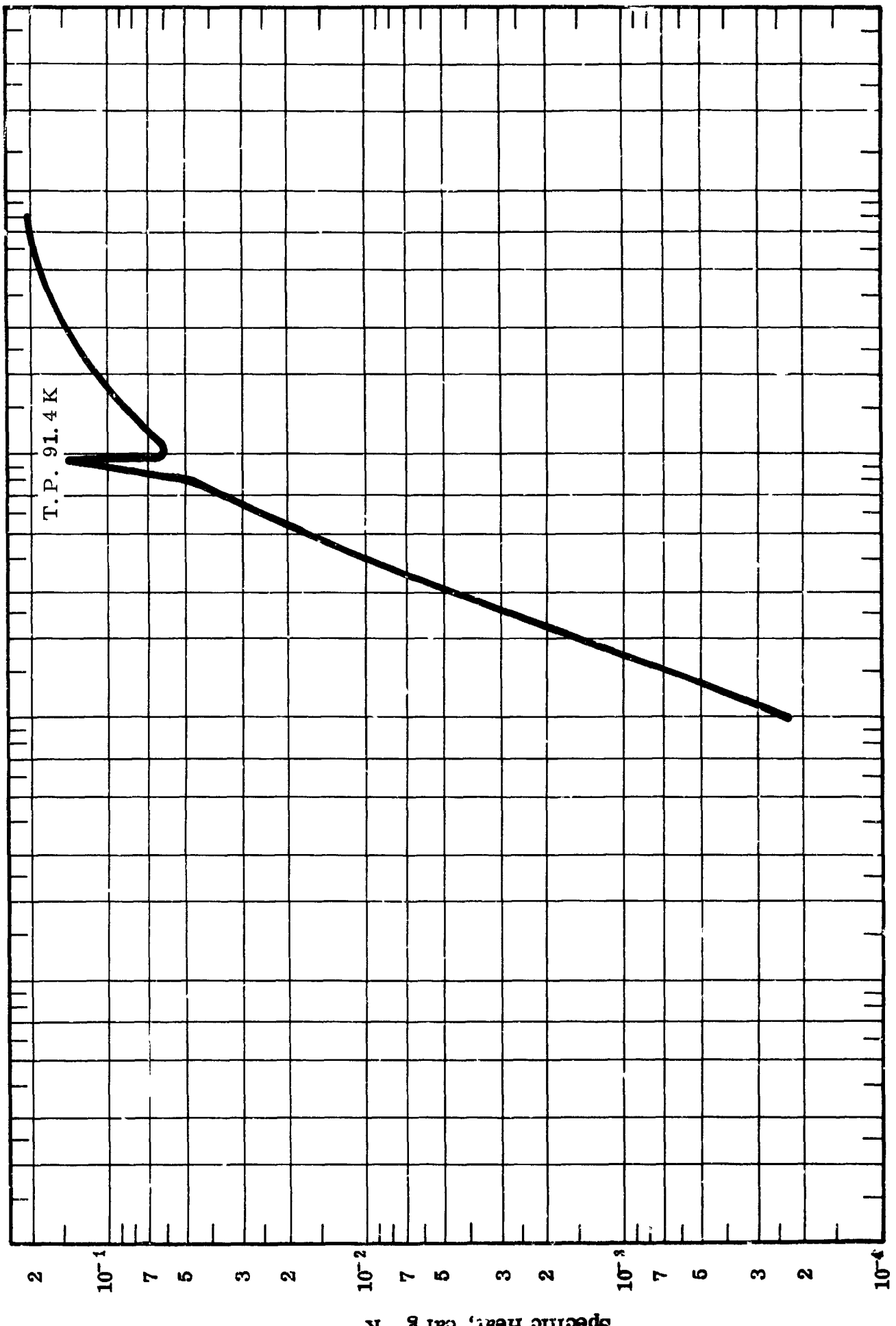

FIG. V - 32

SPECIFIC HEAT -- MANGANESE DIOXIDE, MnO_2

TABLE V-32. SPECIFIC HEAT OF MANGANESE DIOXIDE MnO_2

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
10	$(2.30 \times 10^{-4})^{\dagger}$	92.1	1.26×10^{-1}
15	$(7.20 \times 10^{-4})^{\dagger}$	97.4	6.06×10^{-2}
20	$(1.55 \times 10^{-3})^{\dagger}$	100	5.95
30	$(4.70 \times 10^{-3})^{\dagger}$	150	8.50
40	$(1.02 \times 10^{-2})^{\dagger}$	200	$1.1? \times 10^{-1}$
50	1.76×10^{-2}	300	1.50
60	2.70	400	1.74
70	3.90	500	1.87
80	5.28	600	1.95
90	1.01×10^{-1}	700	2.02
91.4	1 31	800	2.06

Investigators: Kelley, K.K. and Moore, G.E. (287) [53-295 K]; Millar, R.W. (288) [72-293 K]; Moore, G.E. (289) [298-780 K].

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†Extrapolated

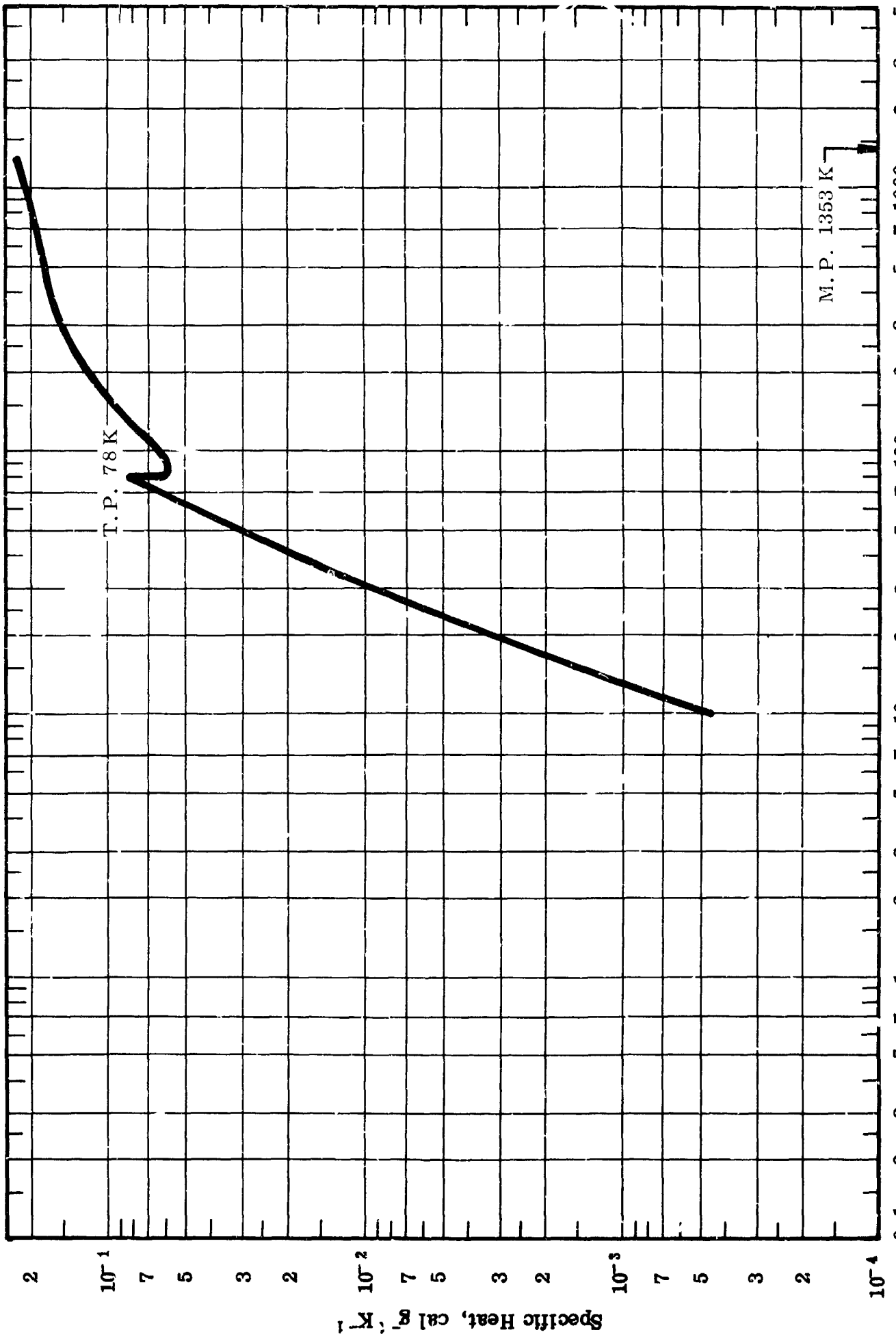

FIG. V - 33

SPECIFIC HEAT -- MANGANESE SESQUIOXIDE, Mn_2O_3

TABLE V-33. SPECIFIC HEAT OF MANGANESE SESQUIOXIDE Mn_2O_3

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
10	(4.43×10^{-4})†	90	5.90×10^{-2}
15	(1.50×10^{-3})	100	6.30
20	(3.15×10^{-3})	150	9.30
30	(9.10×10^{-3})	200	1.19×10^{-1}
40	(1.84×10^{-2})	300	1.50
50	3.00×10^{-2}	400	1.65
60	4.30	500	1.75
70	6.20	600	1.83
75	7.05	700	1.90
76	7.27	800	1.96
77	7.65	900	2.02
78	8.12	1000	2.08
79	7.80	1100	2.13
80	5.99	1200	2.19
82	5.78	1300	2.24
84	5.73		

Investigators: King, E. G. (290) [54-298 K]; Orr, R. L. (291) [298-1300 K].

†Extrapolated

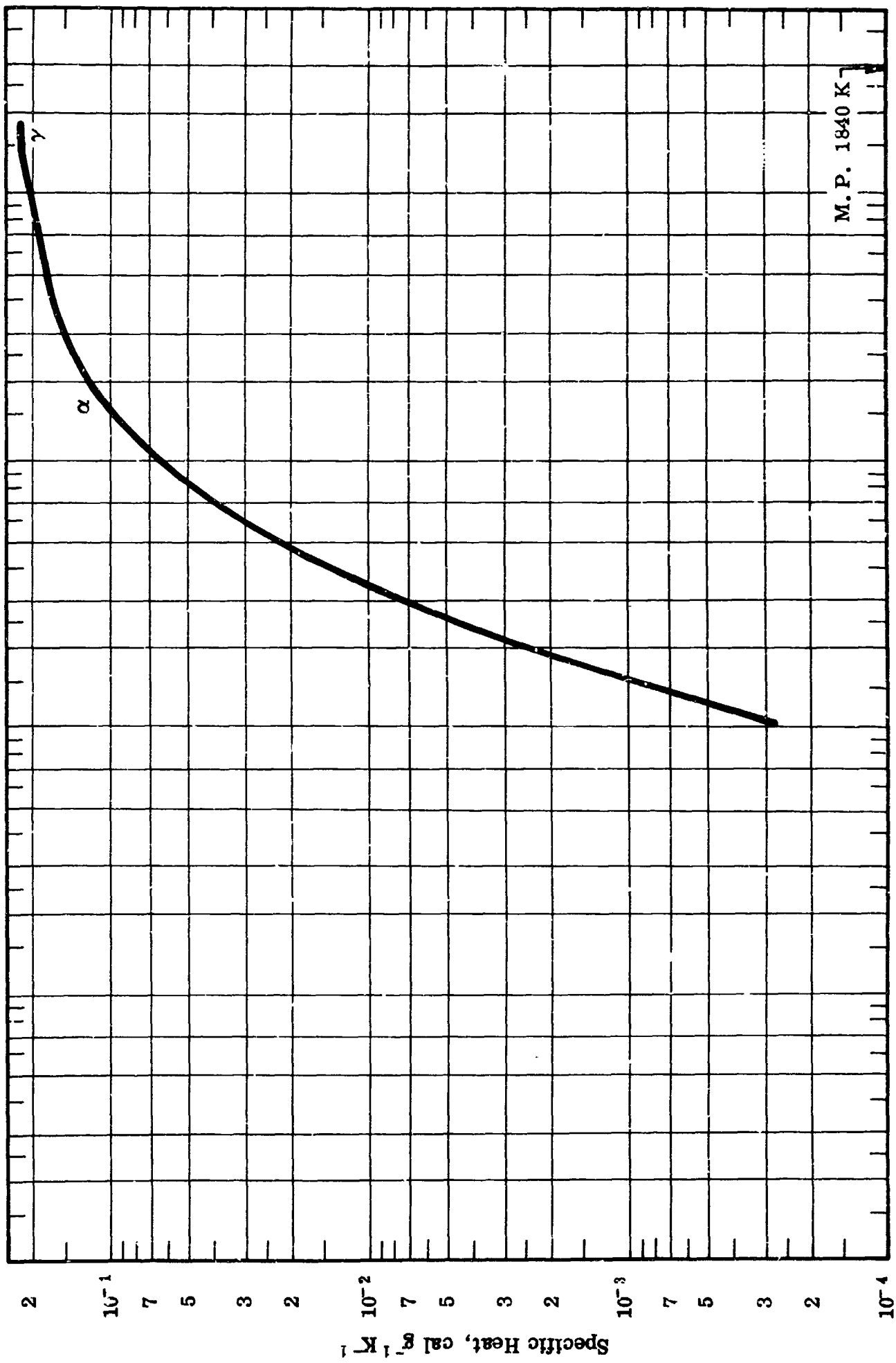

FIG. V - 34

SPECIFIC HEAT -- MANGANOMANGANIC OXIDE, Mn_3O_4

TABLE V-34. SPECIFIC HEAT OF MANGANOMANGANIC OXIDE Mn_3O_4

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
10	2.62×10^{-4}	(α) 600	1.77×10^{-1}
15	9.20	700	1.82
20	2.40×10^{-3}	800	1.88
30	7.10	900	1.93
40	1.44×10^{-2}	1000	1.98
50	2.26	1100	2.03
60	3.15	1200	2.08
70	4.00	1300	2.12
80	4.85	1400	2.17
90	5.60	(α) 1445	2.19
(α) 100	6.40	(β) 1145	2.20×10^{-1}
150	9.60	1500	2.20
200	1.19×10^{-1}	1600	2.20
300	1.46	1700	2.20
400	1.64	(β) 1800	2.20
500	1.71		

Investigators: Millar, R.W. (292) [72-305 K]; Southard, J.C. and Moore, G.E. (293) [ΔH, 298-1768 K].

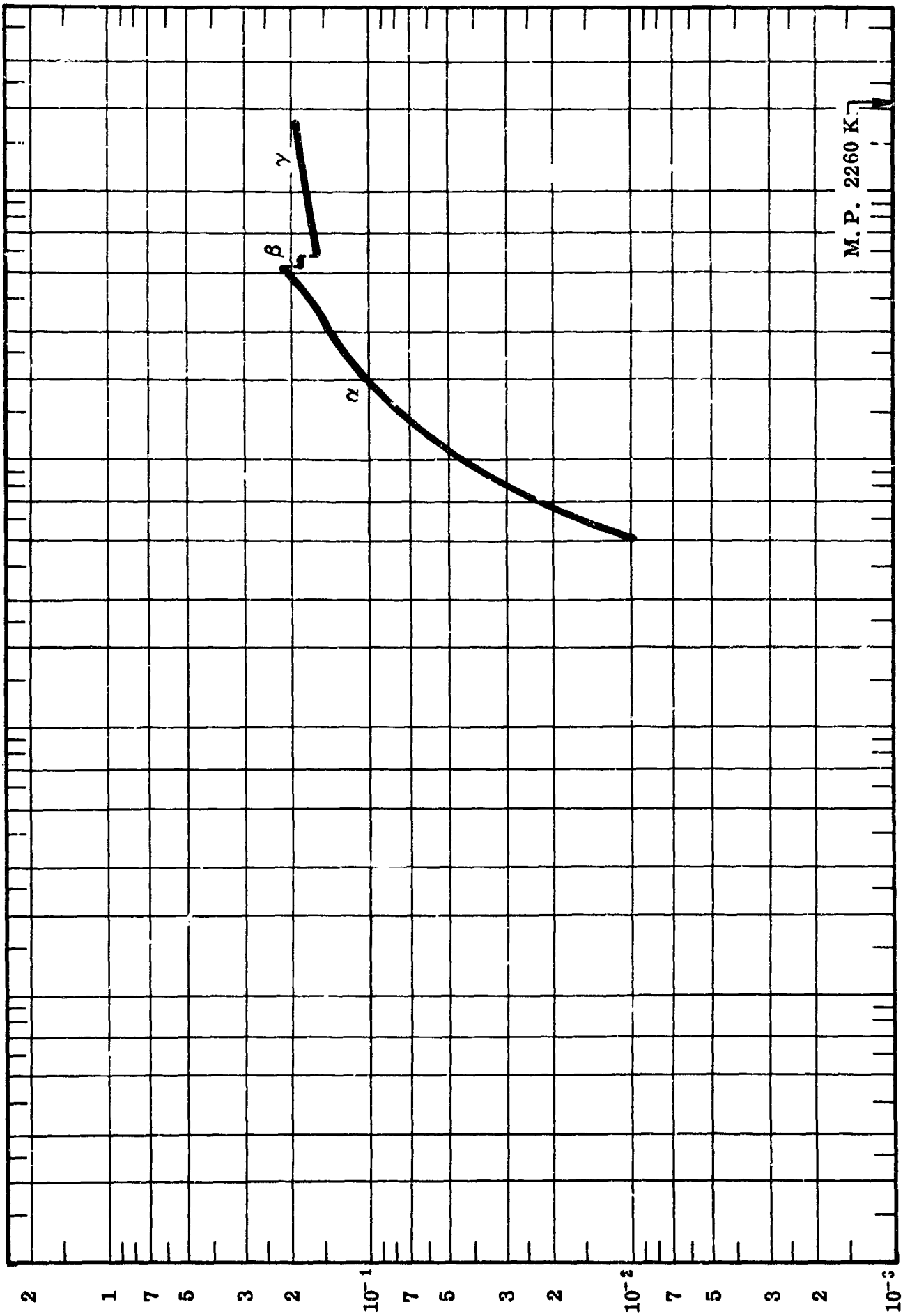

FIG. V - 35

SPECIFIC HEAT -- NICKEL OXIDE, NiO

TABLE V-35. . SPECIFIC HEAT OF NICKEL OXIDE NiO

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
(α) 50	9.90×10^{-3}	(γ) 565	1.64×10^{-1}
60	1.65×10^{-2}	600	1.65
70	2.40	700	1.68
80	3.05	800	1.70
90	3.80	900	1.73
100	4.60	1000	1.76
150	7.80	1100	1.78
200	1.06×10^{-1}	1200	1.81
300	1.42	1300	1.84
400	1.67	1400	1.86
500	2.06	1500	1.89
(α) 525	2.16	1600	1.92
(β) 525	1.86×10^{-1}	1700	1.94
550	1.86	(γ) 1800	1.97
(β) 565	1.86		

Investigators: Kapustinsky, A. F. and Novosel'tsev, K. A. (294) [295-1395 K]; King, E. G. (295) [54-296 K]; King, E. G. and Christensen, A. V., Jr. (296) [298-1800 K]; Tomlinson, J. R. et al. (297) [273-1100 K]; Zeltz, H. et al. (298) [68-297 K].

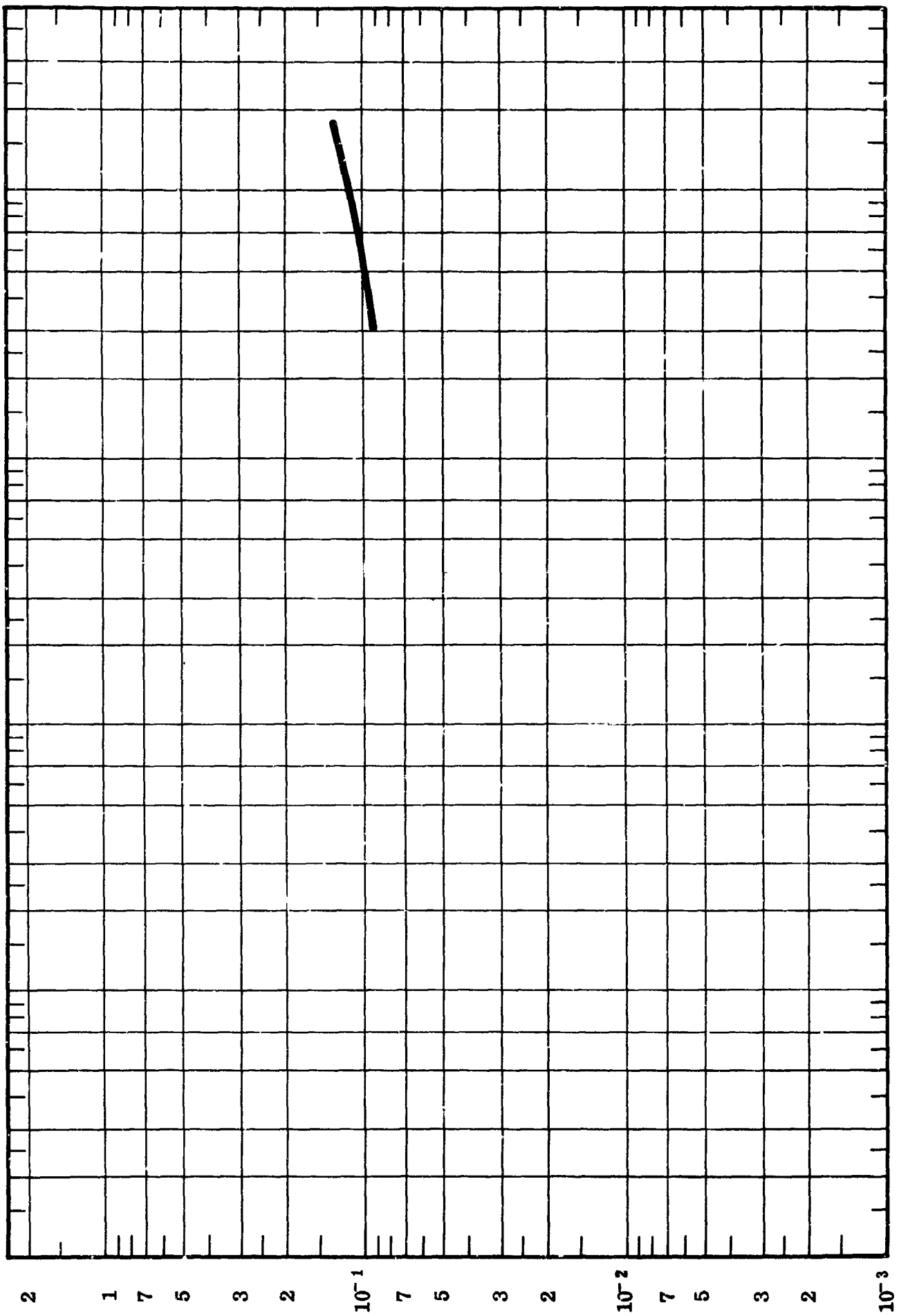

FIG. V - 36

SPECIFIC HEAT -- NIOBIUM MONOXIDE, NbO

TABLE V-36. SPECIFIC HEAT OF NIOBIUM MONOXIDE NbO

T °K	C_p, cal $g^{-1} K^{-1}$	T °K	C_p, cal $g^{-1} K^{-1}$
300	9.06×10^{-2}	1100	1.15×10^{-1}
400	9.63	1200	1.18
500	1.00×10^{-1}	1300	1.20
600	1.03	1400	1.22
700	1.06	1500	1.24
800	1.08	1600	1.26
900	1.11	1700	1.29
1000	1.13	1800	1.31

Investigators: Gel'd, P. V. and Kusenko, F. G. (299) [300-1800 K].

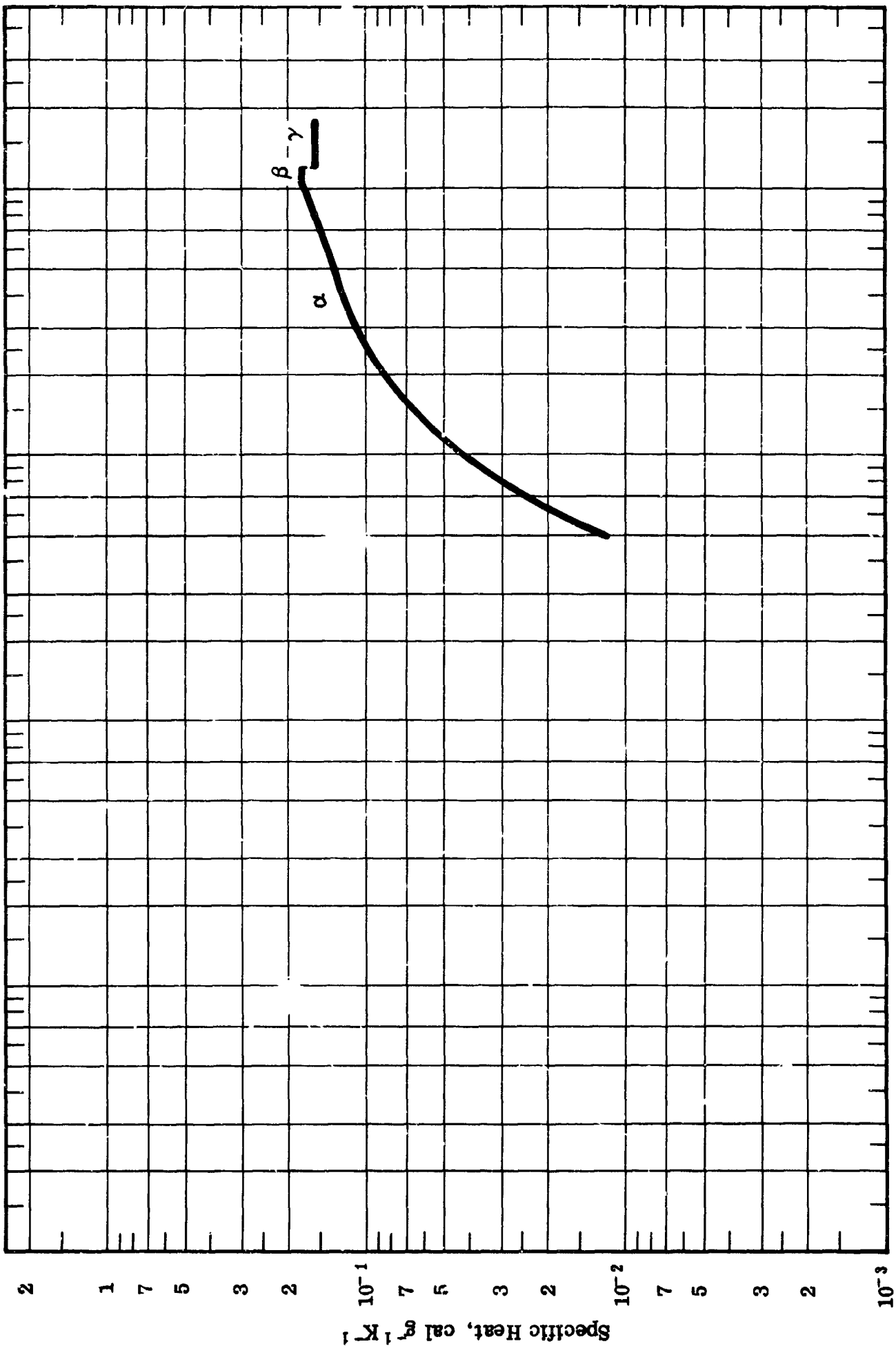

FIG. V - 37

SPECIFIC HEAT -- NIOBIUM DIOXIDE, NbO_2

TABLE V-37. . SPECIFIC HEAT OF NIOBIUM DIOXIDE NbO_2

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
(α) 50	1.19×10^{-2}	(α) 900	1.62×10^{-1}
60	1.75	950	1.66
70	2.30	(α) 1090	1.71
80	2.92	(β) 1090	1.78
90	3.50	1100	1.78
100	4.10	(β) 1200	1.78
150	6.65	(γ) 1200	1.59
200	8.60	1300	1.59
300	1.11×10^{-1}	1400	1.59
400	1.21	1500	1.59
500	1.30	1600	1.59
600	1.38	1700	1.59
700	1.46	(γ) 1800	1.59
(α) 800	1.54		

Investigators: Gel'd, P. V. and Kusenko, F. G. (300) [298-1500 K]; King, E. G. (301) [53-298 K]; King, E. G. and Christensen, A. U. (302) [298-1800 K]; Kusenko, F. G. and Gel'd, P. V. (303) [298-1500 K].

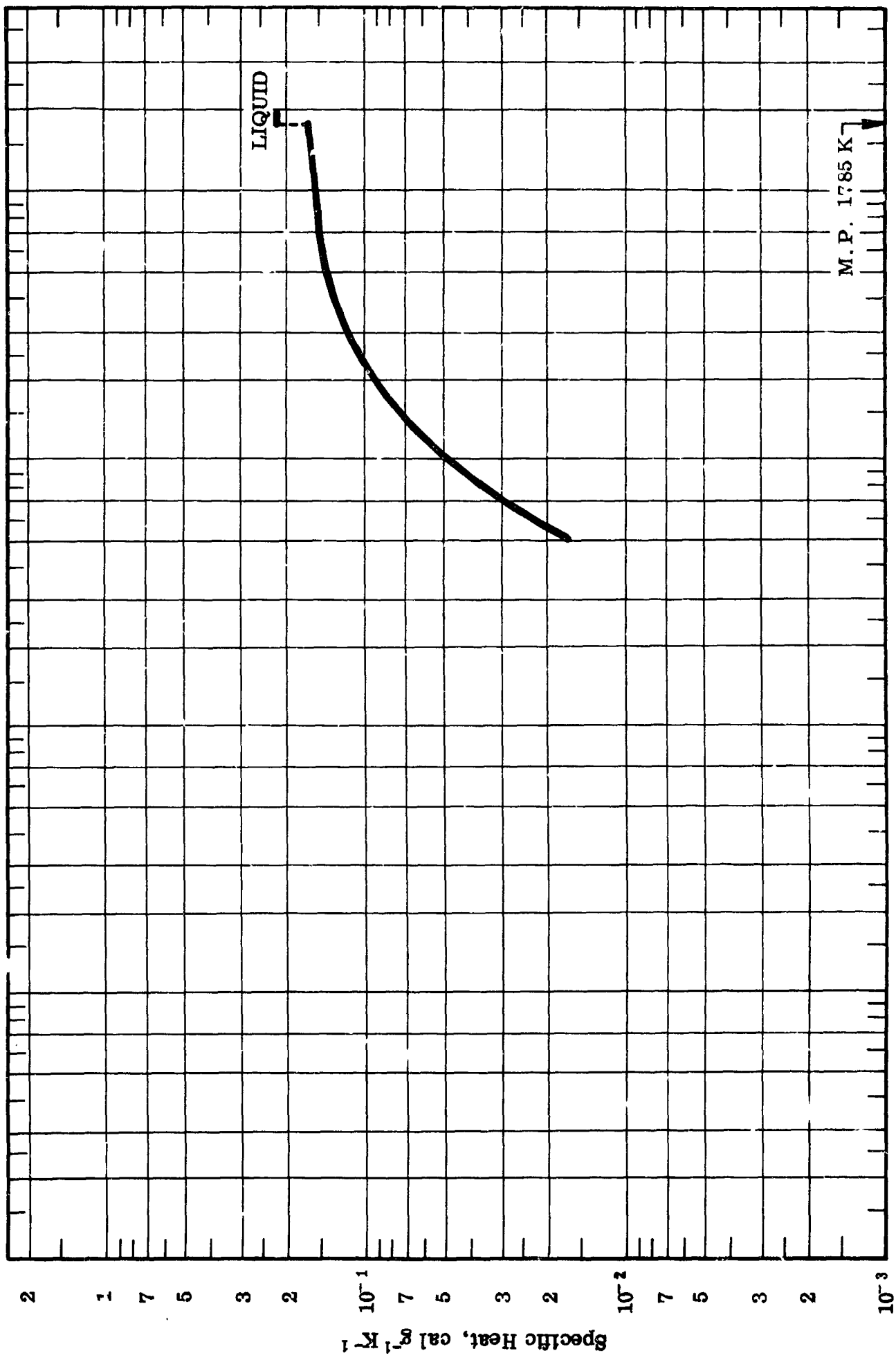

FIG. V - 38

SPECIFIC HEAT -- NIOBIUM PENTOXIDE, Nb_2O_5

TABLE V-38. SPECIFIC HEAT OF NIOBIUM PENTOXIDE Nb_2O_5

	T °K	C_p, cal g^{-1} K^{-1}		T °K	C_p, cal g^{-1} K^{-1}
(s)	50	$(1.65 \times 10^{-2})^{\dagger}$	(s)	900	1.54×10^{-1}
	60	2.35×10^{-2}		1000	1.56
	70	3.00		1100	1.58
	80	3.65		1200	1.60
	90	4.20		1300	1.62
	100	4.80		1400	1.63
	150	7.55		1500	1.65
	200	9.50		1600	1.66
	300	1.19×10^{-1}		1700	1.68
	400	1.34	(s)	1785	1.68
	500	1.42	(l)	1785	2.18×10^{-1}
	600	1.46		1800	2.18
	700	1.50		1900	2.18
	800	1.52	(l)	2000	2.18

Investigators: Gel'd, P. V. and Kusenko, F. G. (304) [300-1700 K]; King, E. G. (305) [53-298 K]; Orr, R. L. (306) [298-1810 K].

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†Extrapolated

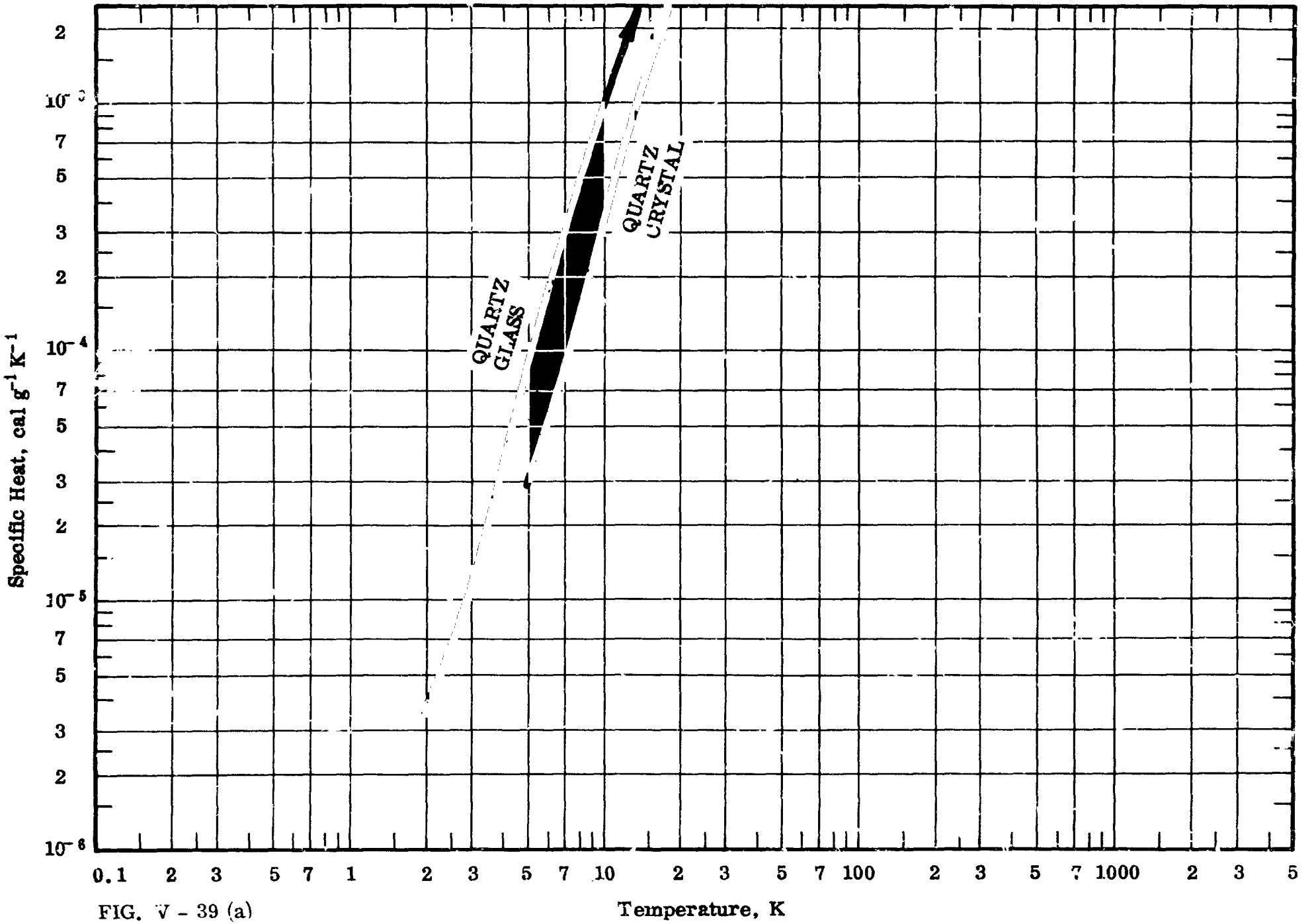

FIG. V - 39 (a)

SPECIFIC HEAT -- SILICON DIOXIDE

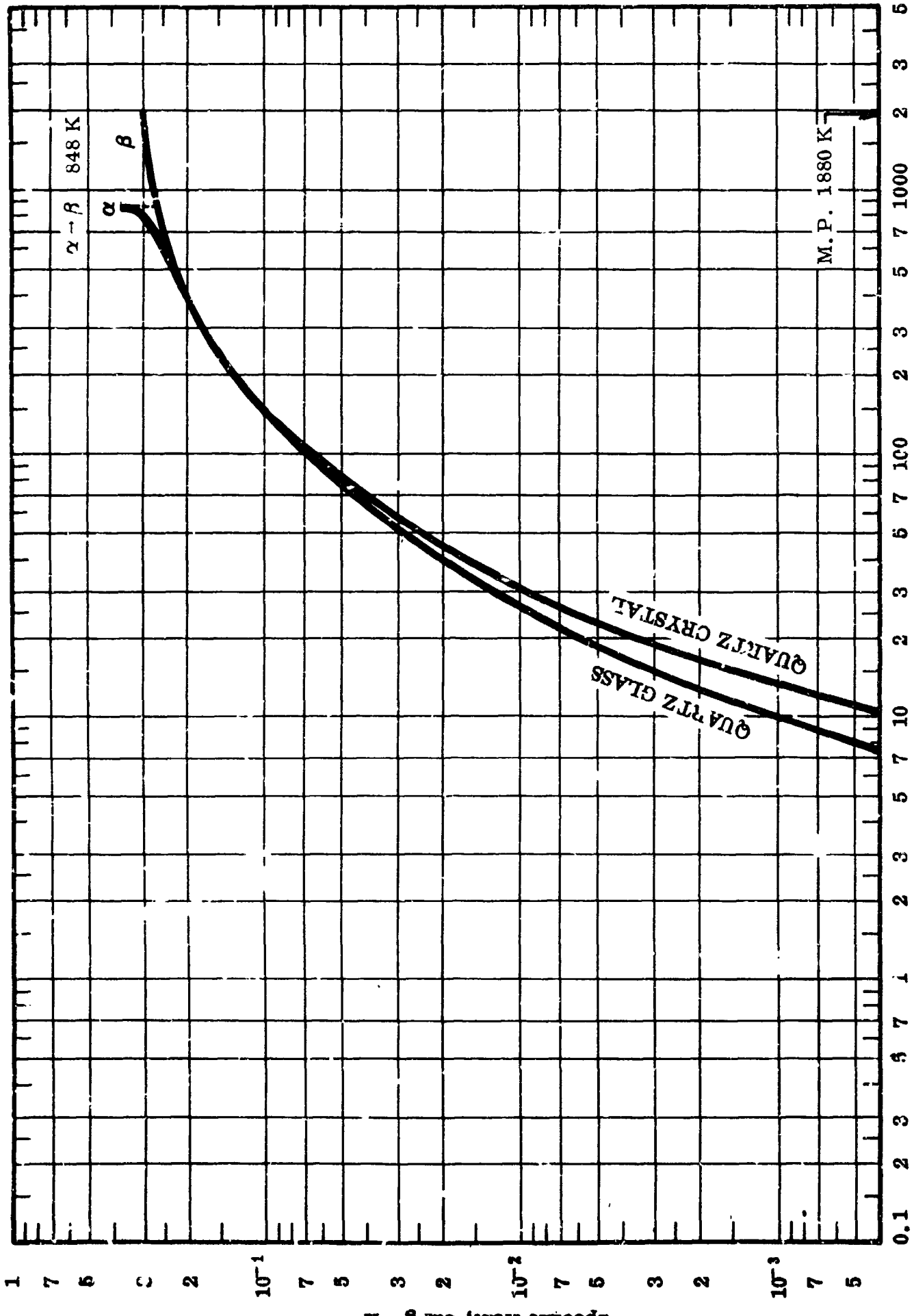

FIG. V - 39 (b)

SPECIFIC HEAT -- SILICON DIOXIDE

TABLE V-39. SPECIFIC HEAT OF SILICON DIOXIDE SiO_2

	QUARTZ GLASS	QUARTZ CRYSTAL
T °K	C_p, cal g^{-1} K^{-1}	C_p, cal g^{-1} K^{-1}
2	(3.55×10^{-6})†	
3	1.22×10^{-5}	
4	3.40	
5	8.40	2.85×10^{-5}
6	1.65×10^{-4}	4.90
7	2.90	7.95
8	4.64	1.35×10^{-4}
9	6.90	2.25
10	9.70	3.42
15	2.98×10^{-3}	1.48×10^{-3}
20	5.95	3.65
30	1.30×10^{-2}	9.30
40	2.02	1.68×10^{-2}
50	2.67	2.40
60	3.50	3.15
70	4.30	3.95
80	5.05	4.70
90	5.80	5.50
100	6.50	6.30
150	1.00×10^{-1}	1.00×10^{-1}
200	1.31	1.31
300	1.78	1.78
400	2.12	2.13
500	2.31	2.37
600	2.48	2.56
700	2.57	2.73
800	2.64	3.00
848		(α) 3.61
848		(β) 2.67
900	2.70×10^{-1}	2.69
1000	2.76	2.72
1100	2.81	2.75
1200	2.86	2.78
1300	2.90	2.82
1400	2.94	2.85
1500	2.98	2.88
1600		(2.92×10^{-1})†
1700		(2.95×10^{-1})
1800		(2.98×10^{-1})
1900		(3.01×10^{-1})
2000		(3.045×10^{-1})

†Extrapolated

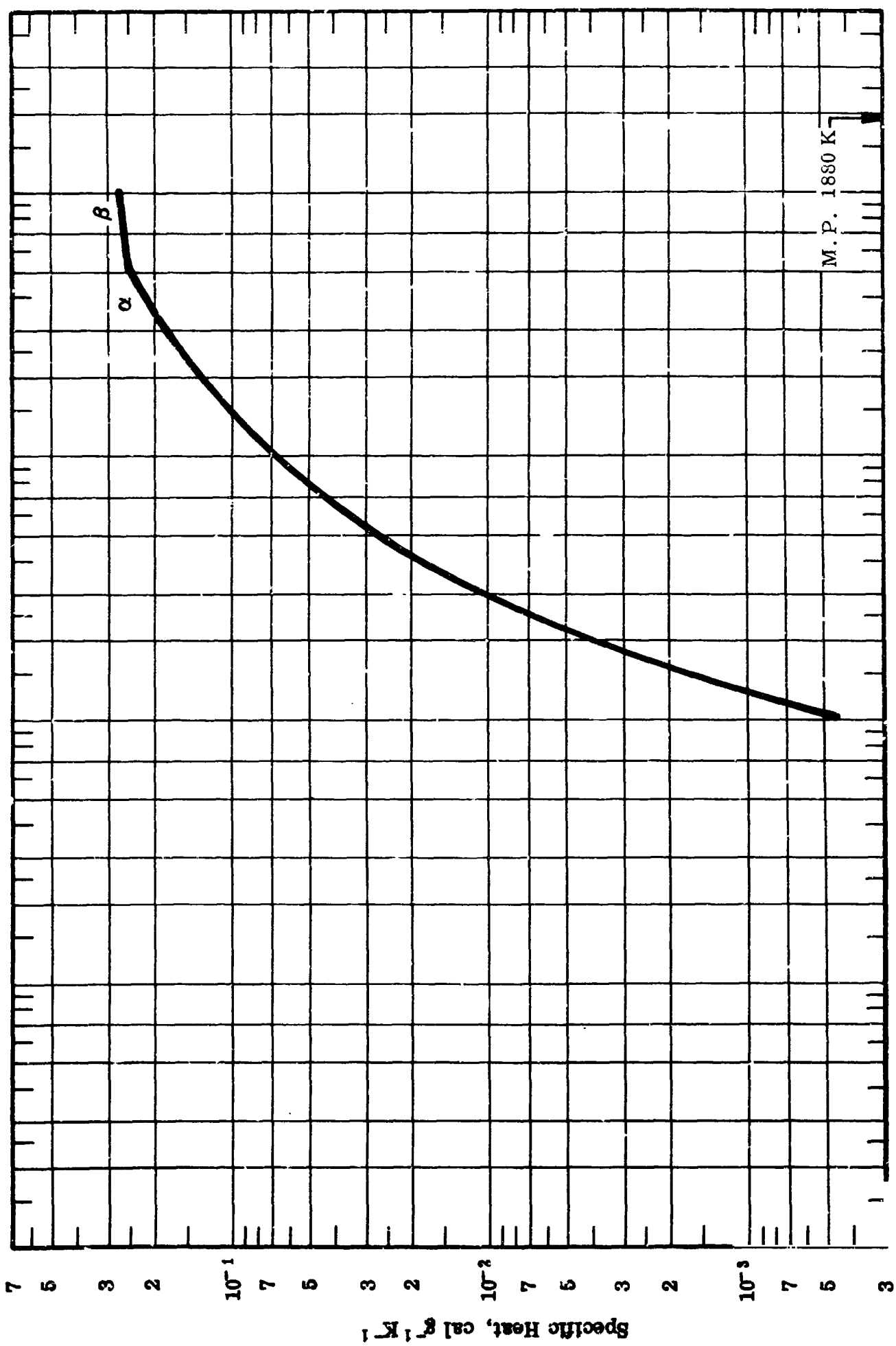

FIG. V - 40

SPECIFIC HEAT ... SILICON DIOXIDE (CRISTOBALITE)

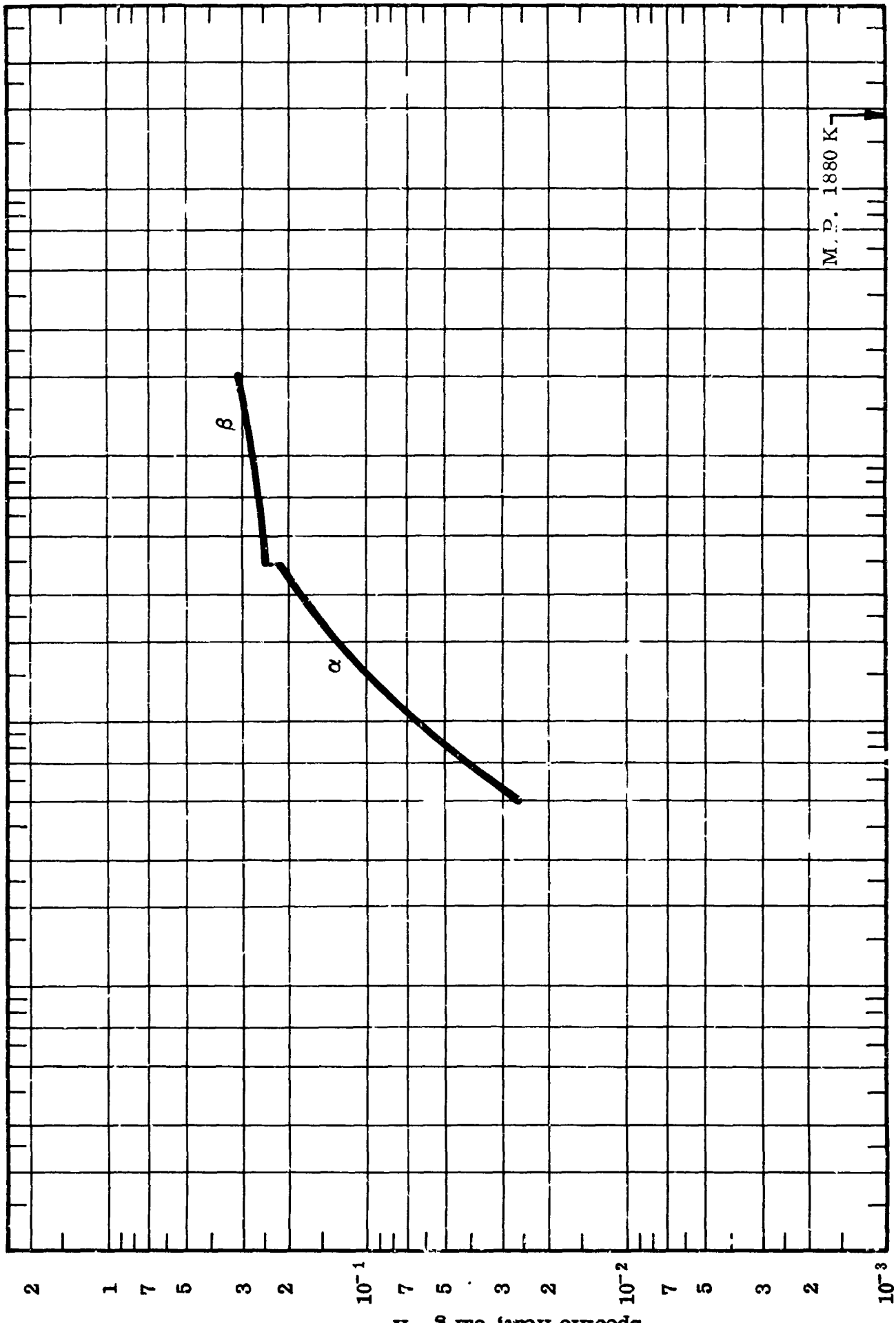

FIG. V - 41

SPECIFIC HEAT -- SILICON DIOXIDE (TRIDYMITE)

TABLE V-39. SPECIFIC HEAT OF SILICON DIOXIDE SiO_2 (continued)

	CRISTOBALITE	TRIDYMITE
T °K	C_p, cal g^{-1} K^{-1}	C_p, cal g^{-1} K^{-1}
10	4.50×10^{-4}	
15	1.70×10^{-3}	
20	3.70	
30	1.10×10^{-2}	
40	1.85	
50	2.57	2.60×10^{-2}
60	3.40	3.35
70	4.26	4.10
80	5.06	4.90
90	5.85	5.70
100	6.43	6.50
120	7.93	
140	9.36	
150		1.00×10^{-1}
160	1.08×10^{-1}	
180	1.21	
200	1.34	1.32×10^{-1}
220	1.44	
240	1.54	
260	1.64	
300	1.76	1.78×10^{-1}
390		(α) 2.15
390		(β) 2.44
400	2.11×10^{-1}	2.45
500	2.46	2.49
523	(α) 2.54	
523	(β) 2.57	
600	2.60	2.53×10^{-1}
700	2.63	2.58
800	2.67	2.62
900	2.70	2.66
1000	2.74	2.71
1100	2.77	2.75
1200	2.80	2.80
1300	2.84	2.84
1400	2.87	2.88
1500	2.91	2.93
1600	2.94	2.97
1700	2.97	3.02
1800	3.01	3.06
1900	3.04	3.10
2000	3.08	3.15

Investigators: Anderson, C. T. (307) [quartz crystal, 53-296 K; cristobalite, 55-297 K; tridymite, 54-295 K]; Clark, A. E. and Starkna, R. E. (308) [silica, 12-21 K]; Flubacher, P. et al. (309) [vitreous

Investigators: (Silicon Dioxide SiO_2)

silica, 2-19 K]; Lord, R.C. and Morrow, J.C. (310) [calculated; vitreous silica, quartz crystal, 10-700 K]; Lucks, C.F. et al. (311) [fused silica, 111-1144 K]; Moser, H. (312) [quartz crystal, 317-950 K; quartz glass, 324-936 K]; Mosesman, M.A. and Pitzer, K.S. (313) [quartz, cristobalite, and tridymite, 298-2000 K]; Nernst, W. (314) [glass, 63-273 K]; Simon, F. (315) [quartz glass, 19-288 K, crystobalite, 29-117 K]; Sinel'nikov, N.N. (316) [303-922 K]; Southard, J.C. (317) [silica glass, 298-1520 K]; Spedding, F.H. and Miller, C.F. (318) [commercial quartz, 273-400 K]; Westrum, E.F., Jr. (319) [irradiated quartz, 5-344 K]; Wietzel, R. (320) [quartz glass, 10-273 K; quartz crystal, 10-273 K, crystobalite, 10-273 K].

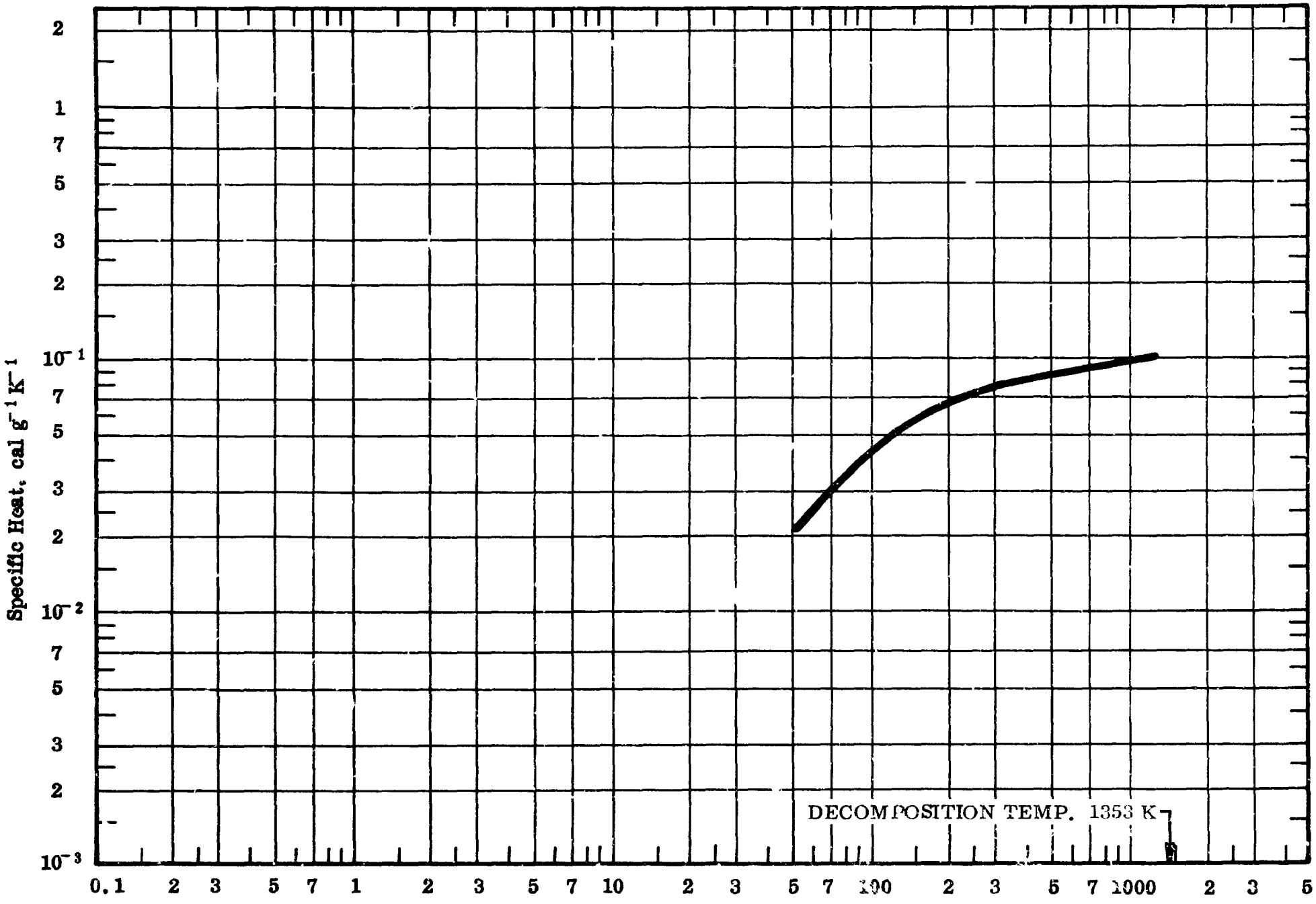

FIG. V - 42

SPECIFIC HEAT -- TIN OXIDE, SnO

TABLE V-40. SPECIFIC HEAT OF TIN (STANNOUS) OXIDE, SnO

T°K	C_p, cal $g^{-1}K^{-1}$	T°K	C_p, cal $g^{-1}K^{-1}$
50	2.09×10^{-2}	*500	(8.39×10^{-2})
60	2.59	*600	8.65
70	3.10	*700	8.91
80	3.58	*800	9.17
90	3.90	*900	9.43
100	4.42	*1000	9.69
150	5.98	*1100	9.95
200	6.90	*1200	1.03×10^{-1}
300	7.80	*1273	1.04
*400	8.13×10^{-2}		

Investigators: Kelley, K. K. (321) [298-1273 K] ; Millar, R. W. (322) [70-292 K].

*Calculated (5)

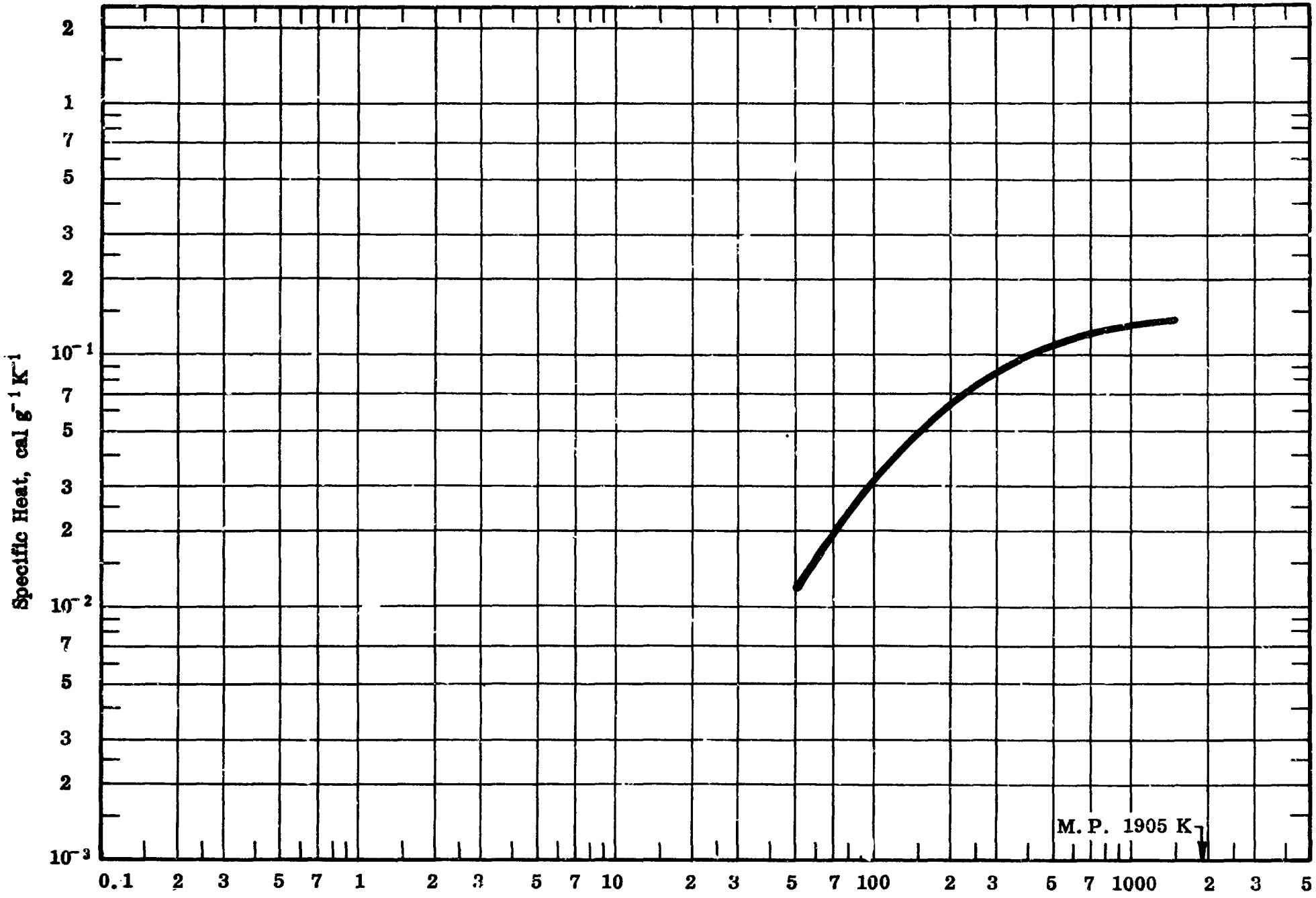

FIG. V - 43

SPECIFIC HEAT -- TIN DIOXIDE, SnO_2

TABLE V-41. SPECIFIC HEAT OF TIN(STANNIC) OXIDE, SnO_2

T°K	C_p, cal g^{-1} K^{-1}	T°K	C_p, cal g^{-1} K^{-1}
50	$(1.17 \times 10^{-2})^{\dagger}$	600	1.17×10^{-1}
60	1.58×10^{-2}	700	1.21
70	2.00	800	1.25
80	2.44	900	1.27
90	2.86	1000	1.30
100	3.30	1100	1.32
150	5.10	1200	1.34
200	6.50	1300	1.36
300	8.39	1400	1.38
400	1.02×10^{-1}	1500	1.40
500	1.11		

Investigators: Huttig, G. F. et al (323) [273-623 K]; Kapustinsky, A. F. (324) [295-1495 K]; Millar, R. W. (325) [69-292 K].

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†Extrapolated

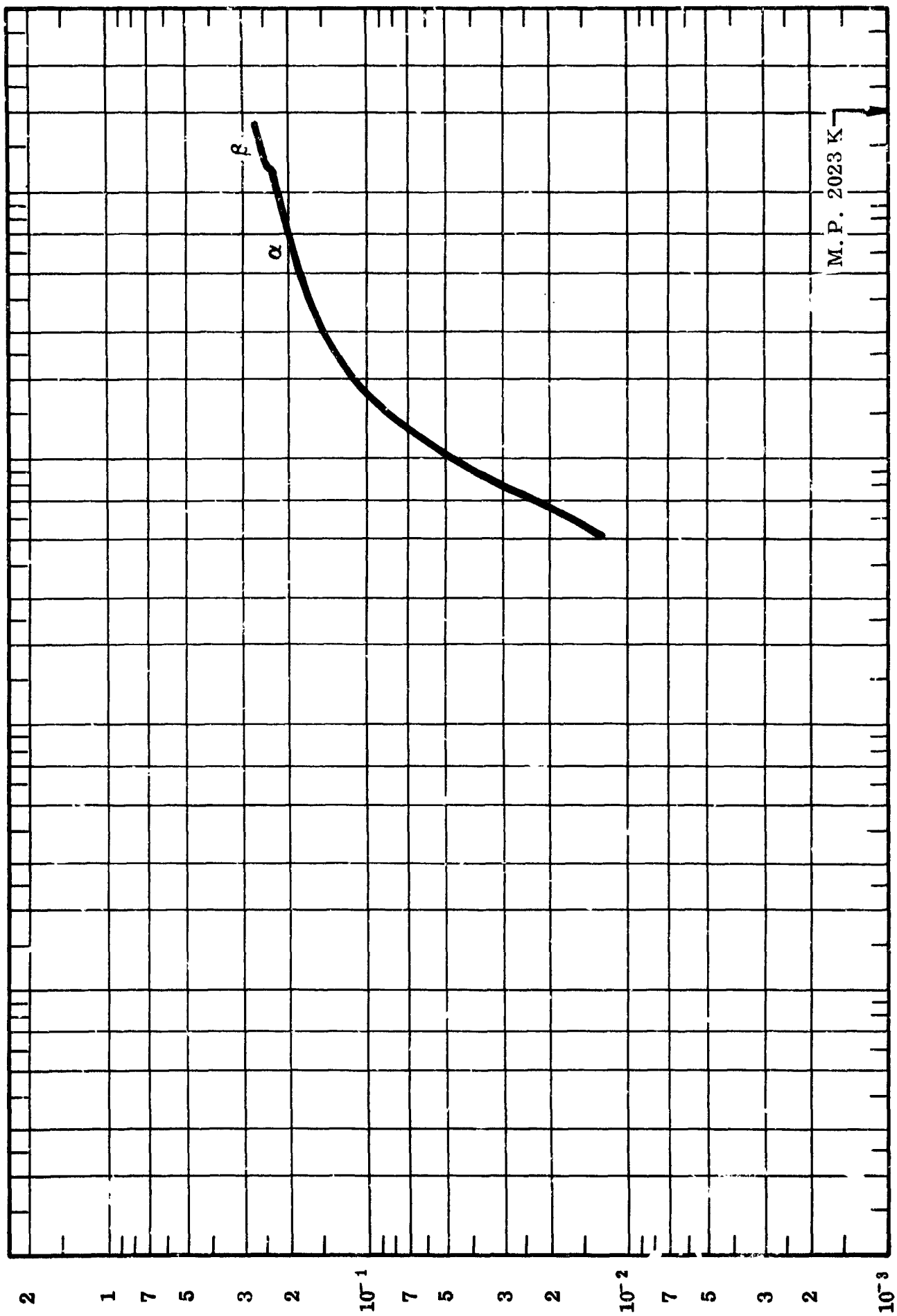

FIG. V - 44

SPECIFIC HEAT -- TITANIUM MONOXIDE, TiO

TABLE V-42. SPECIFIC HEAT OF TITANIUM MONOXIDE, TiO

T°K	C_p, cal $g^{-1}K^{-1}$	T°K	C_p, cal $g^{-1}K^{-1}$
(α) 50	1.02×10^{-2}	800	2.06×10^{-1}
60	1.65	900	2.12
70	2.40	1000	2.19
80	3.14	1100	2.25
90	3.95	1200	2.31
100	4.80	(α) 1264	2.35
150	8.50	(β) 1264	2.45
200	1.15×10^{-1}	1300	2.46
300	1.50	1400	2.51
400	1.70	1500	2.56
500	1.82	1600	2.61
600	1.91	1700	2.65
700	1.99	(β) 1800	2.70

Investigators: Naylor, B. F. (326) [298-1800 K]; Kelley, K. K. and Mah, A. D. (327) [ΔH, 298-2000 K]; Shomate, C. H. (328) [52-293 K].

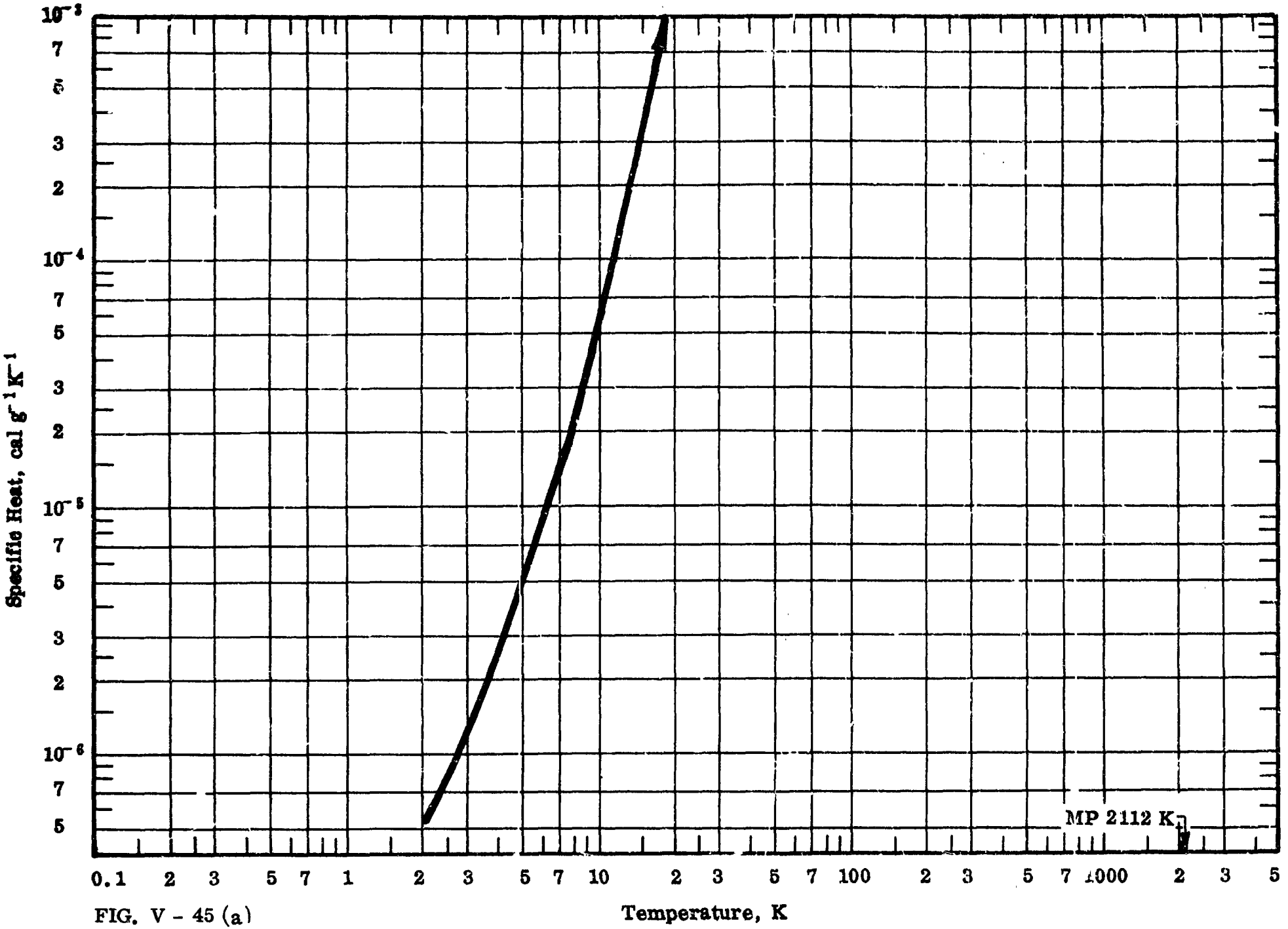

FIG. V - 45 (a)

SPECIFIC HEAT -- TITANIUM DIOXIDE (RUTILE) TiO_2

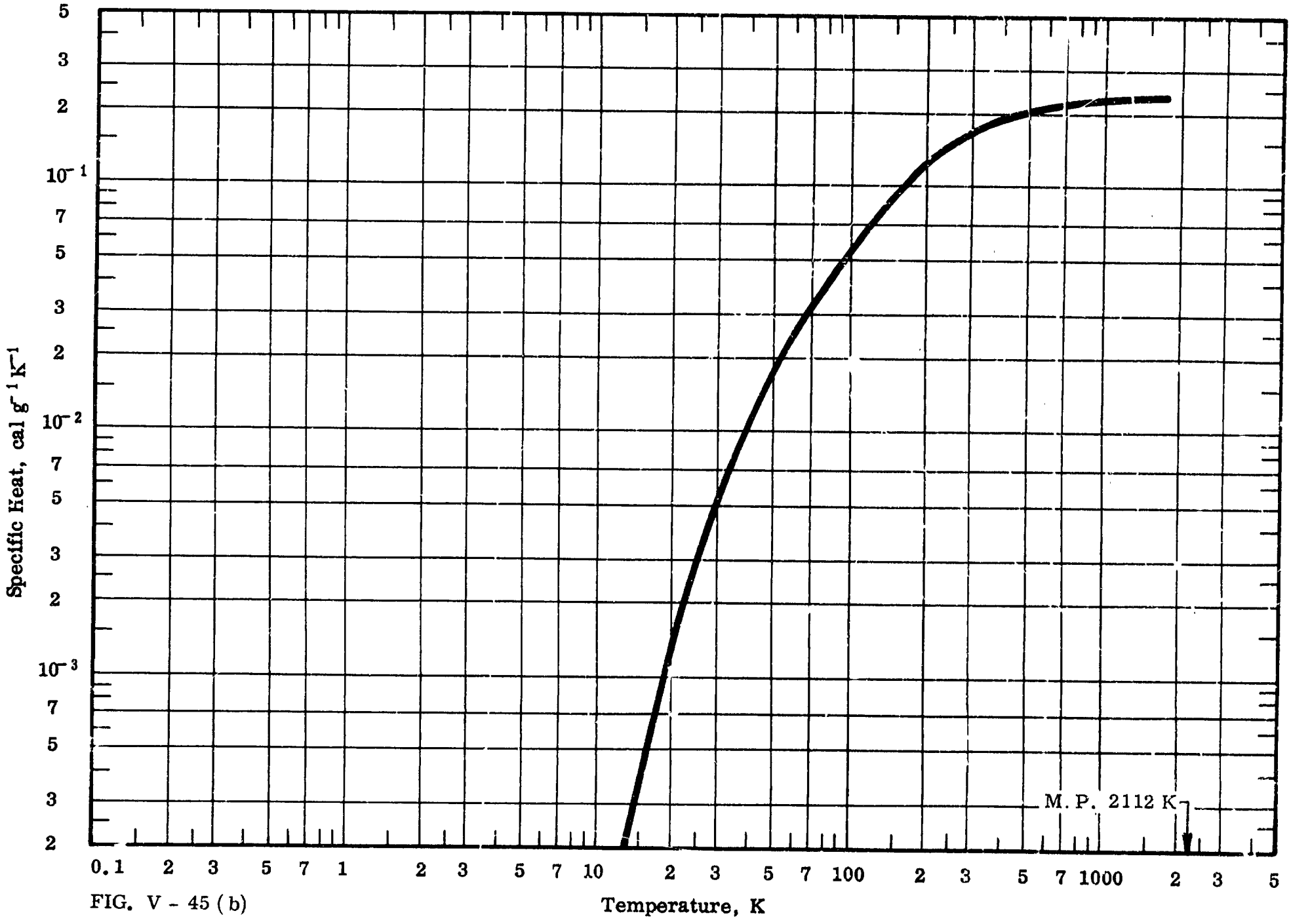

FIG. V - 45 (b)

SPECIFIC HEAT -- TITANIUM DIOXIDE (RUTILE) TiO_2

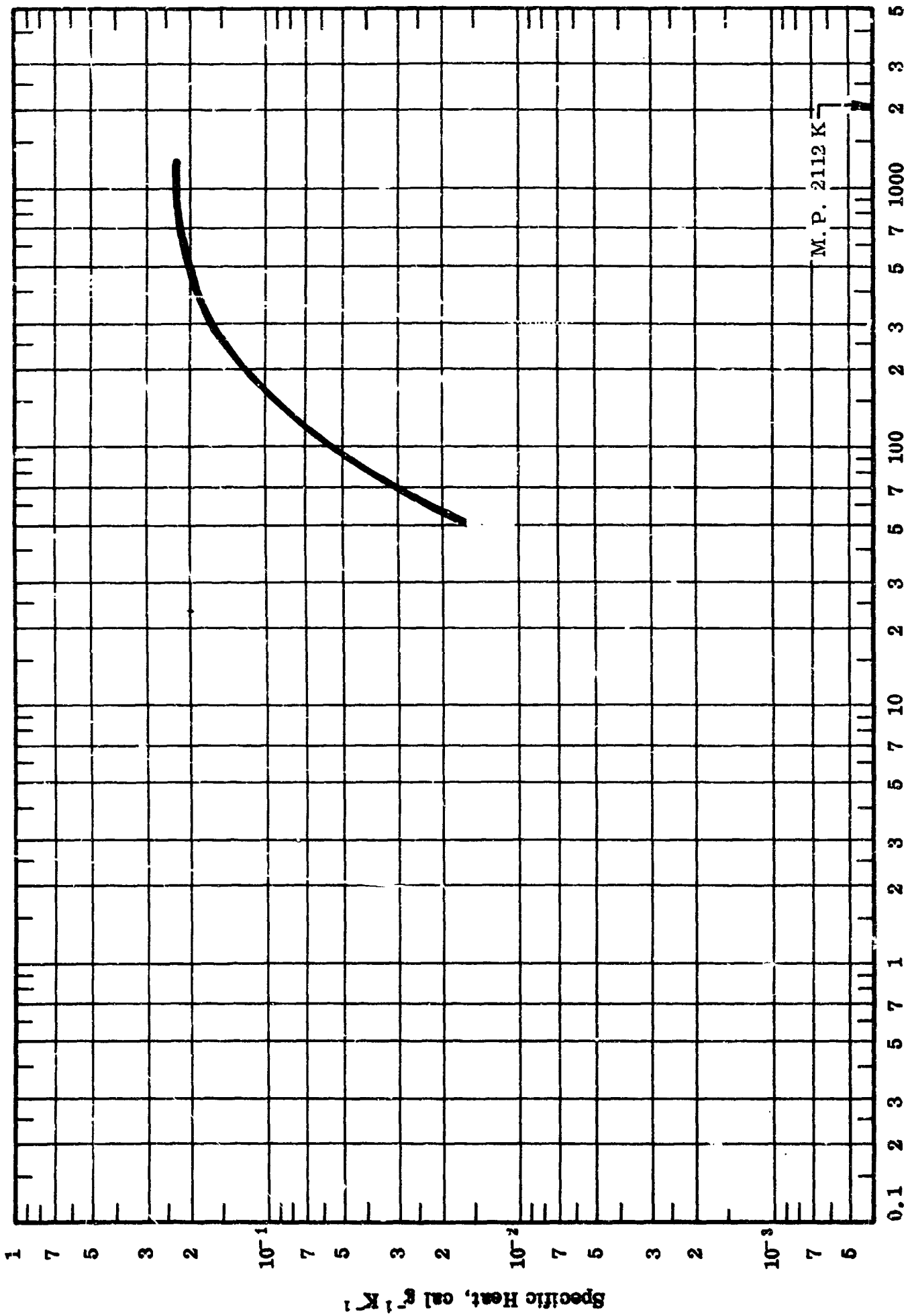

FIG. V -- 46

SPECIFIC HEAT -- TITANIUM DIOXIDE (ANATASE)

TABLE V-43. SPECIFIC HEAT OF TITANIUM DIOXIDE, TiO_2

	RUTILE	ANATASE
T °K	C_p, cal $g^{-1} K^{-1}$	C_p, cal $g^{-1} K^{-1}$
2	5.30×10^{-7}	
3	1.20×10^{-6}	
4	2.70	
5	5.00	
6	8.80	
7	1.45×10^{-5}	
8	2.35	
9	3.55	
10	5.25	
15	3.90×10^{-4}	
20	1.30×10^{-3}	
30	5.20	
40	1.12×10^{-2}	
50	1.82	1.52×10^{-2}
60	2.52	2.30
70	3.25	3.10
80	3.90	3.90
90	4.70	4.80
100	5.55	5.70
150	9.51	9.60
200	1.26×10^{-1}	1.23×10^{-1}
250		1.48
300	1.69	1.69
400	1.92	1.93
500	2.03	2.04
600	2.10	2.11
700	2.14	2.16
800	2.17	2.19
900	2.20	2.22
1000	2.22	2.24
1100	2.24	2.26
1200	2.26	2.28
1300	2.28	2.30
1400	2.29	
1500	2.31	
1600	2.32	
1700	2.34	
1800	2.35	

Investigators: (TITANIUM DIOXIDE)
Arthur, J.S. (329) [200-500K]; Keesom, P.H., and Pearlman, N. (330) [rutile, 1-20K]; Kelley, K.K., and Mah, A.D. (331) [anatase ΔH, 298-1300K; rutile ΔH, 298-2000K]; Lietz, J. (332) [anatase, 393-993K; rutile, 293-1193K]; McDonald, H.J., and Seltz, H. (333) [69-292K]; Naylor, B.F. (334) [anatase, 298-1300K; rutile, 298-1800K]; Shomate, C.H. (335) [anatase, 52-298K; rutile, 52-298K].

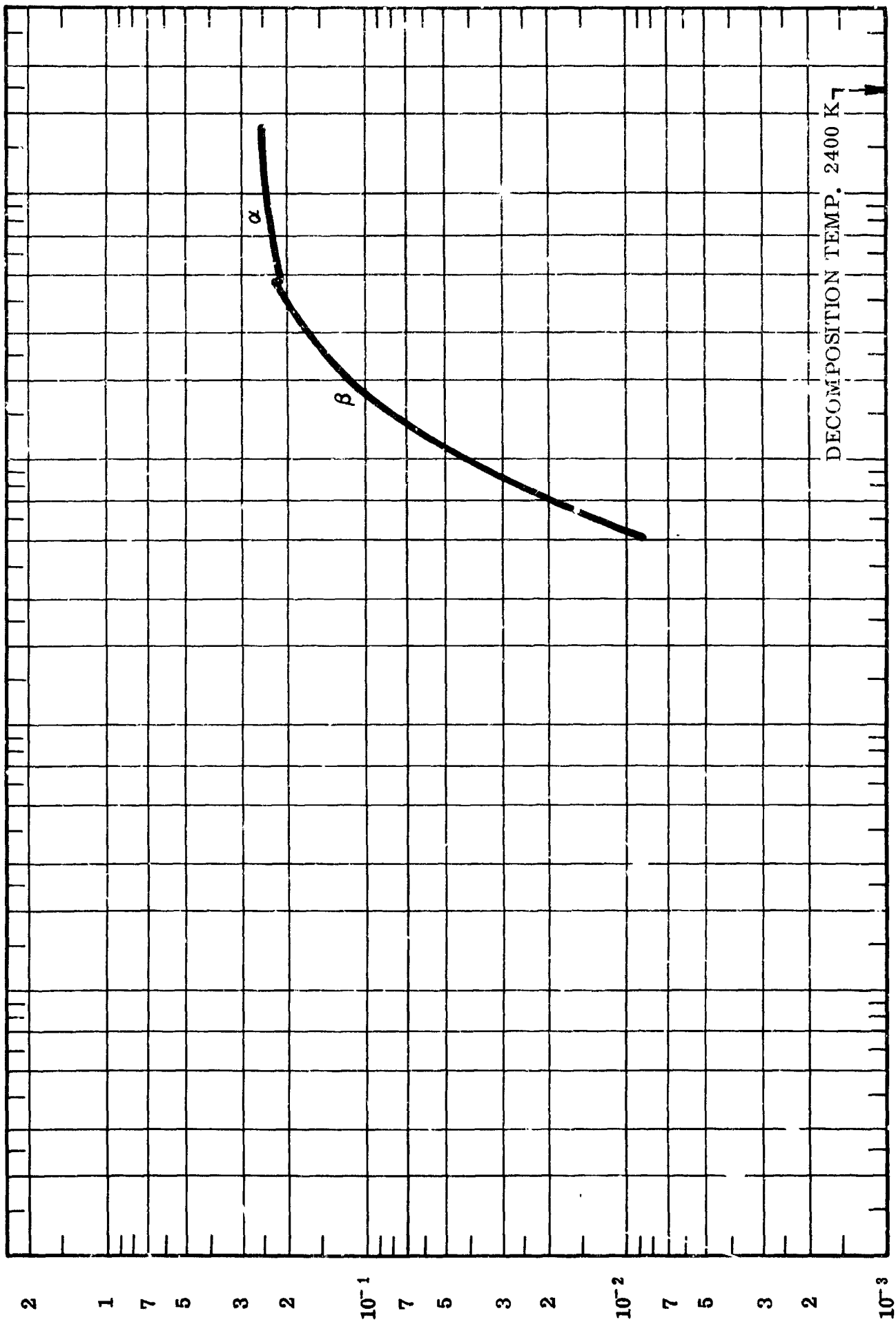

FIG. V - 47

SPECIFIC HEAT -- TITANIUM SESQUIOXIDE, Ti_2O_3

TABLE V-44. . SPECIFIC HEAT OF TITANIUM SESQUIOXIDE Ti_2O_3

	T °K	C_p, cal g^{-1} K^{-1}		T °K	C_p, cal g^{-1} K^{-1}
	50	8.60×10^{-3}	(β)	600	2.27×10^{-1}
	60	1.39×10^{-2}		700	2.33
	70	2.04		800	2.37
	80	2.79		900	2.40
(α)	90	3.55		1000	2.43
	100	4.39		1100	2.45
	150	8.00		1200	2.47
	200	1.19×10^{-1}		1300	2.49
	300	1.62		1400	2.50
	400	2.00		1500	2.52
(α)	473	2.27		1600	2.53
(β)	473	2.14		1700	2.54
	500	2.17	(β)	1800	2.55

Investigators: Kelley, K. K. and Mah, A. D. (336) [ΔH, 298-2000 K]; Naylor, B. F. (337) [298-1800 K]; Shomate, C. H. (333) [53-298 K].

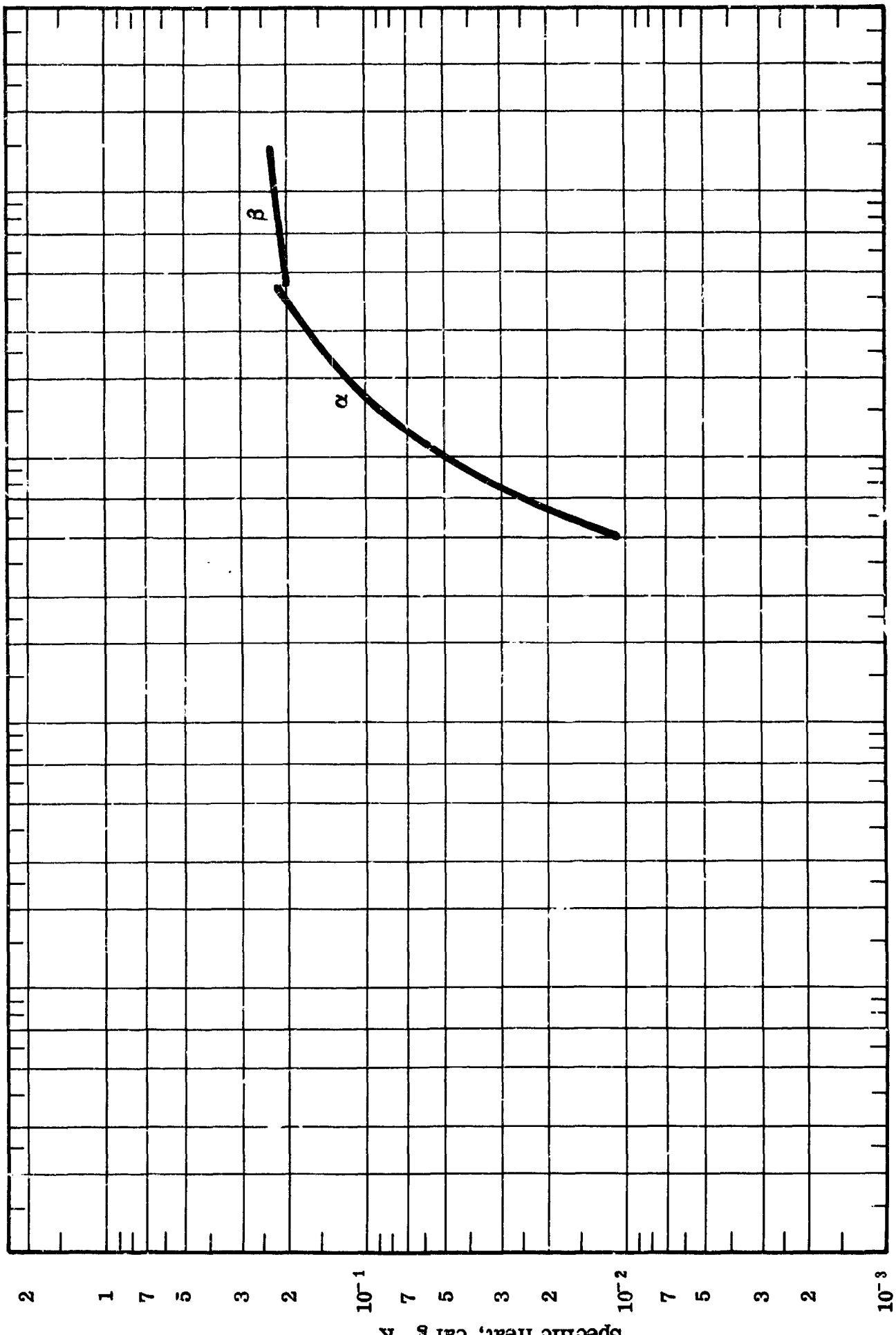

FIG. V - 48

SPECIFIC HEAT -- TITANIUM TRIPENTOXIDE, Ti_3O_5

TABLE V-45. SPECIFIC HEAT OF TITANIUM TRIPENTOXIDE Ti_3O_5

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
(α) 50	1.05×10^{-2}	(β) 450	2.02×10^{-1}
60	1.73	500	2.04
70	2.50	600	2.07
80	3.32	700	2.11
90	4.10	800	2.15
100	5.00	900	2.18
150	9.00	1000	2.22
200	1.20×10^{-1}	1100	2.25
300	1.66	1200	2.29
400	2.08	1300	2.32
(α) 450	2.18	1400	2.36
		(β) 1500	(2.39×10^{-1})

Investigators: Kelley, K. K. and Mah, A. D. (339) [ΔH, 298-2000 K]; Naylor, B. F. (340) [298-1800 K]; Shomate, C. H. (341) [53-298 K].

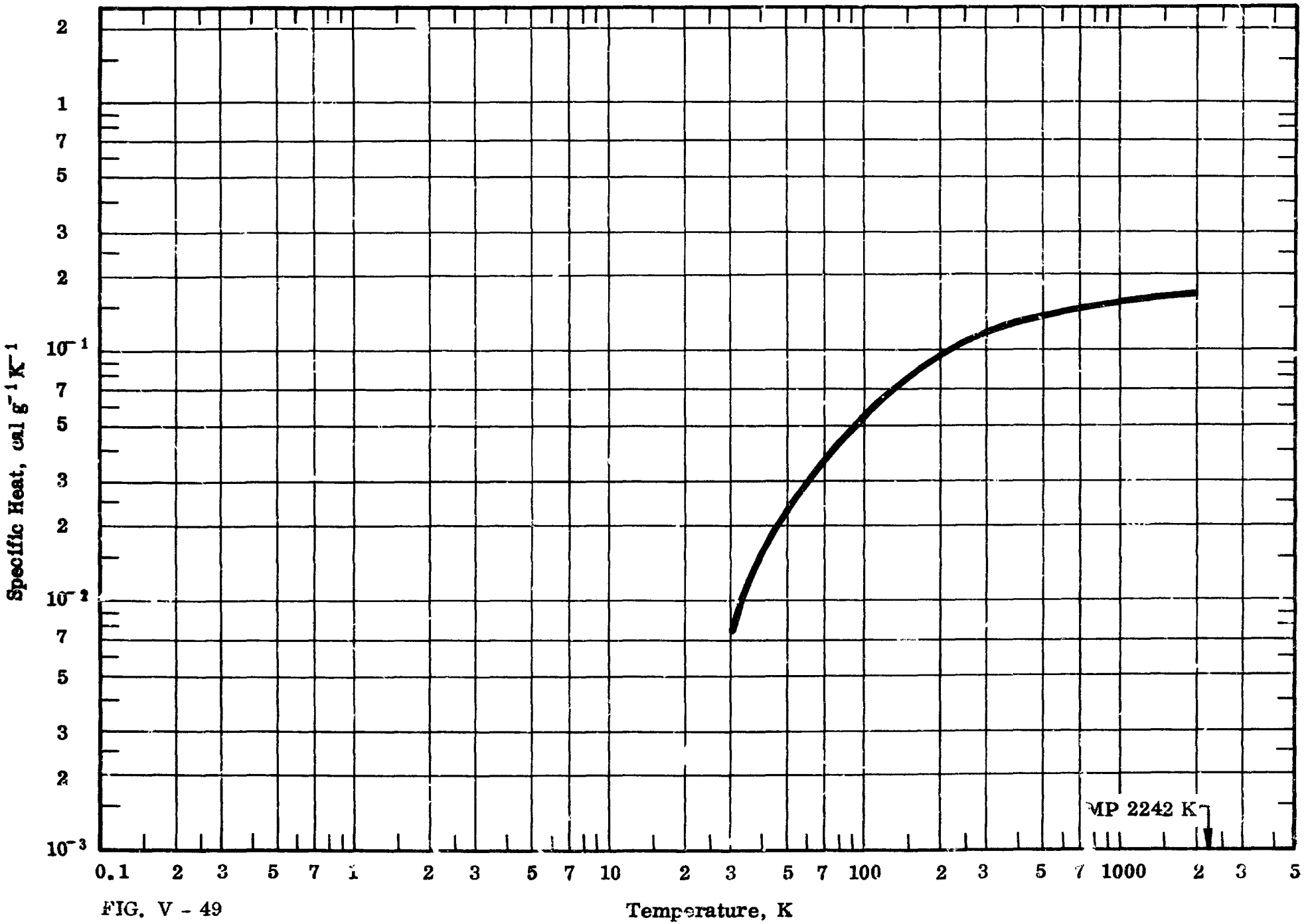

FIG. V - 49

SPECIFIC HEAT -- ZINC OXIDE, ZnO

TABLE V-46. SPECIFIC HEAT OF ZINC OXIDE ZnO

T °K	C_p, cal g^{-1} K^{-1}	T °K	C_p, cal g^{-1} K^{-1}
30	7.40×10^{-3}	700	1.49×10^{-1}
40	1.62×10^{-2}	800	1.52
50	2.43	900	1.54
60	3.15	1000	1.56
70	3.76	1100	1.58
80	4.30	1200	1.60
90	4.79	1300	1.62
100	5.33	1400	1.64
150	7.91	1500	1.65×10^{-1} †
200	9.95	1600	1.67 †
300	1.19×10^{-1}	1700	1.68 †
400	1.33	1800	1.70 †
500	1.41	1900	1.72 †
600	1.45	2000	1.73 †

Investigators: Clusius, K. and Harteck, P. (342) [30-200 K]; Maier, C. G. and Ralston, O. C. (343) [298-1573 K]; Millar, R. W. (344) [90-298 K].

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†Extrapolated

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238.	29885	Wiebelt, J. A., PhD Thesis, Oklahoma State Univ., 1-91, 1960.
		BERYLLIUM OXIDE
239.	25961	Hedge, J. C., Kostenko, C. and Lang, J. I., ASD-TDR-63-597, 1-128, 1963. [AD 424375]
240.	15021	Kandyba, V. V., Kantor, P. B., Krasovitskaya, R. M., and Fomichev, E. N., AEC-TR-4310 (English Transl. Doklady Akad. Nauk., SSSR, 131 (3), 566-7, 1960), 1-4, 1960.
241.	11861	Kelley, K. K., J. Am. Chem. Soc., 61, 1217-8, 1939.
242.	21405	Magnus, A. and Danz, H., Ann Physik, 81, 407-24, 1926.
243.	26008	Pears, C. D., ASD-TDR-62-765, 1-429, 1962. [AD 298061]
244.	30541	Victor, A. C. and Douglas, T. B., J. Res. Natl. Bur. Std., 67A (4), 325-9, 1963.
245.	29978	Walker, B. E., Jr., Ewing, C. T. and Miller, R. R., J. Chem. Eng. Data, 7, 595-7, 1962.

Ref. No.	TPRC No.	
		CHROMIUM OXIDE
246.	12111	Anderson, C. T., J. Am. Chem. Soc., 59, 488-91, 1937.
247.	1871	Kelley, K. K., Boericke, F. S., Moore, G. E., Huffman, E. H. and Bangert, W. M., U. S. Bur. Mines, Tech. Paper 662, 1-43, 1944.
248.	521	Volger, J., Nature, 170, 1027, 1952.
		CUPRIC OXIDE
249.	1213	Assayag, G. and Bizette, H., Compt. Rend., 239, 238-40, 1954.
250.	7025	Clusius, K. and Harteck, P., Z. Physik. Chem., 134, 243-63, 1928.
251.	932	Hu, J. H. and Johnston, H. L., J. Am. Chem. Soc., 75, 2471-3, 1953.
252.	21814	Millar, R. W., J. Am. Chem. Soc., 51, 215-22, 1929.
253.	20978	Wohler, L. and Jochum, N., Z. Physik. Chem. (Leipzig), A167 (3), 169-79, 1933.
		CUPROUS OXIDE
254.	27444	Gregor, L. V., J. Phys. Chem., 66, 1645-7, 1962.
255.	7768	Hu, J. H. and Johnston, H. L., J. Am. Chem. Soc., 73, 4450-1, 1951.
256.	21814	Millar, R. W., J. Am. Chem. Soc., 51, 215-22, 1929.
257.	20978	Wohler, L. and Jochum, N., Z. Physik. Chem., 167A, 169-, 1933.
		FERROUS OXIDE
258.	1296	Coughlin, J. P., King, E. G. and Bonnickson, K. R., J. Am. Chem. Soc., 73, 3891-3, 1951.
259.	21814	Millar, R. W., J. Am. Chem. Soc., 51, 215-22, 1929.
260.	1295	Todd, S. S. and Bonnickson, K. R., J. Am. Chem. Soc., 73, 3894-5, 1951.
261.	14383	White, W. P., J. Am. Chem. Soc., 55, 1047-53, 1933.
		FERRIC OXIDE
262.	19866	Brown, G. G. and Furnas, C. C., Trans. Am. Inst. Chem. Eng., 18, 309-46, 1926.
263.	1296	Coughlin, J. P., King, E. G. and Bonnickson, K. R., J. Am. Chem. Soc., 73, 3891-3, 1951.

Ref. No.	TPRC No.	FERRIC OXIDE (continued)
264.	18139	Gronvold, F. and Westrum, E. F., Jr., J. Am. Chem. Soc., 81, 1780-3, 1959.
265.	21864	Parks, G. S. and Kelley, K. K., J. Phys. Chem., 30, 47-55, 1926.
266.	22766	Roth, W. A. and Bertram, W. W., Z. Elektrochem., 35, 297-308, 1929.
		IRON OXIDE (Magnetite)
267.	1296	Coughlin, J. P., King, E. G. and Bonnickson, K. R., J. Chem. Soc., 73, 3891-3, 1951.
268.	1000	Kouvel, J. S., Phys. Rev., 102 (6), 1489-90, 1956.
269.	21814	Millar, R. W., J. Am. Chem. Soc., 51, 215-22, 1929.
270.	975	Okamura, T. and Torizuka, Y., Sci. Repts. Res. Inst., Tohoku Univ., A2, 352-60, 1950.
271.	21864	Parks, G. S. and Kelley, K. K., J. Phys. Chem., 30, 47-55, 1926.
272.	22766	Roth, W. A. and Bertram, W. W., Z. Electrochem., 35, 297-308, 1929.
		MAGNESIUM OXIDE
273.	1550	Arthur, J. S., J. Appl. Phys., 21 (8), 732-3, 1950.
274.	19407	Barron, T. H. K., Berg, W. T. and Morrison, J. A., Proc. Roy. Soc., A250, 70-83, 1959.
275.	24812	Fieldhouse, I. B. and Lang, J. I., WADD TR 60-904, 1-119, 1961. [AD 268304]
276.	12112	Giauque, W. F. and Archibald, R. C., J. Am. Chem. Soc., 59, 561-9, 1937.
277.	19870	Lien, W. H., U. S. At. Energy Comm. Rept., UCRL-9880, 1-78, 1962.
278.	25901	Makarounis, O. and Jenkins, R. J., NRDL-TR-599, 1-24, 1962. [AD 295887]
279.	31606	Pankratz, L. B. and Kelley, K. K., U. S. Bur. Mines, Rept. Invest. 6295, 1-5, 1963.
280.	21864	Parks, G. S. and Kelley, K. K., J. Phys. Chem., 30, 47-55, 1926.
281.	26008	Pears, C. D., ASD-TDR-62-765, 1-420, 1962. [AD 298061]
282.	30541	Victor, A. C. and Douglas, T. B., J. Res. Natl. Bur. Std., 67A (4), 325-9, 1963.
283.	18701	Victor, A. C. and Douglas, T. B., WADC TR 57-374, Pt. 6, 1-16, 1960. [AD 258383]

Ref. No.	TPRC No.	
		MANGANESE MONOXIDE
284.	21807	Millar, R.W., J. Am. Chem. Soc., 50, 1875-83, 1928.
285.		Southard, J.C. and Shomate, C.H., J. Am. Chem. Soc., 64, 1770-4, 1942.
286.	1295	Todd, S.S. and Bonnickson, K.R., J. Am. Chem. Soc., 73, 3894-5, 1951.
		MANGANESE DIOXIDE
287.	28381	Kelley, K.K. and Moore, G.E., J. Am. Chem. Soc., 65, 782-5, 1943.
288.	21807	Millar, R.W., J. Am. Chem. Soc., 50, 1875-83, 1928.
289.	23113	Moore, G.E., J. Am. Chem. Soc., 65, 1398-9, 1943.
		MANGANESE SESQUIOXIDE
290.	386	King, E.G., J. Am. Chem. Soc., 76, 3289-91, 1954.
291.	30770	Orr, R.L., J. Am. Chem. Soc., 76, 857-8, 1954.
		MANGANOMANGANIC OXIDE
292.	21807	Millar, R.W., J. Am. Chem. Soc., 50, 1875-83, 1928.
293.		Southard, J.C. and Moore, G.E., J. Am. Chem. Soc., 64, 1769-70, 1942.
		NICKEL OXIDE
294.	13607	Kapustinsky, A.F. and Novosel'tsev, K.A., J. Phys. Chem. (USSR), 11, 61, 1938.
295.	1351	King, E.G., J. Am. Chem. Soc., 79, 2399-400, 1957.
296.	9764	King, E.G. and Christensen, A.V., Jr., J. Am. Chem. Soc., 80, 1800-1, 1958.
297.	633	Tomlinson, J.R., Domash, L., Hay, R.G. and Montgomery, C.M., J. Am. Chem. Soc., 77, 909-10, 1955.
298.	20445	Zeltz, H., DeWitt, B.J. and McDonald, H.J., J. Am. Chem. Soc., 62, 88-9, 1940.
		NIOBIUM MONOXIDE
299.	25326	Gel'd, P.V. and Kusenko, F.G., (English Transl. Izvest. Akad. Nauk. SSSR, Otdel. Tekh. Nauk., Met. i Toplivo, (2), 79-86, 1960), Rus. Met. Fuels, 2 (2), 43-5, 1960.

Ref. No.	TPRC No.	
		NIOBIUM DIOXIDE
300.	25326	Gel'd, P. V. and Kusenko, F. G., (English Transl., Izvest. Akad. Nauk. SSSR, Otdel. Tekh. Nauk. Met. i Toplivo, (2), 79-86, 1960), Rus. Met. Fuels, 2 (2), 43-5, 1960.
301.	18112	King, E. G., J. Am. Chem. Soc., 80 (8), 1799-1800, 1958.
302.	29312	King, E. G. and Christensen, A. U., U. S. Bur. Mines, RI-5789, 1-6, 1961.
303.	20317	Kusenko, F. G. and Gel'd, P. V., Izv. Vysshikh. Uchebn. Zavedenii, Tsvetn. Met., 3 (4), 102-6, 1960.
		NIOBIUM PENTOXIDE
304.	25326	Gel'd, P. V. and Kusenko, F. G., (English Transl., Izvest. Akad. Nauk. SSSR, Otdel. Tekh. Nauk. Met. i Topliva, (2), 79-86, 1960), Rus. Met. Fuels, 2 (2), 43-5, 1960.
305.	386	King, E. G., J. Am. Chem. Soc., 76, 3289-91, 1954.
306.	529	Orr, R. L., J. Am. Chem. Soc., 75, 2808-9, 1953.
		SILICON DIOXIDE
307.	15366	Anderson, C. T., J. Am. Chem. Soc., 58, 568-70, 1936.
308.	26662	Clark, A. E. and Starkna, R. E., Phys. Chem. Glasses, 3 (4), 121-6, 1962.
309.	23932	Flubacher, P., Leadbetter, A. J., Morrison, J. A. and Stoicheff, B. P., J. Phys. Chem. Solids, 12 (1), 53-65, 1959.
310.	296	Lord, R. C. and Morrow, J. C., J. Chem. Phys., 26 (2), 230-2, 1957.
311.	10947	Lucks, C. F., Deem, H. W. and Wood, W. D., Am. Ceram. Soc. Bull., 39 (6), 313-9, 1960.
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313.	30160	Mosesman, M. A. and Pitzer, K. S., J. Am. Chem. Soc., 63, 2348-56, 1941.
314.	29642	Nernst, W., Ann. Physik, 36 (4), 395-439, 1911.
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316.	619	Sinel'nikov, N. N., Doklady Akad. Nauk. SSSR, 92, 369-72, 1953.
317.	25447	Southard, J. C., J. Am. Chem. Soc., 63, 3142, 1941.
318.	10853	Spedding, F. H. and Miller, C. F., U. S. At. Energy Comm., ISC-167, 1-131, 1951.
319.	26210	Westrum, E. F., Jr., IV^{e} Congr. Intern. du Verre, Paris, 396-9, 1956.
320.	30241	Wietzel, R., Z. Anorg. Chem., 116, 71-95, 1921.

Ref. No.	TPRC No.	
		TIN MONOXIDE
321.	28478	Kelley, K.K., U.S. Bur. Mines, Bull. 584, 1-232, 1960.
322.	21815	Millar, R.W., J. Am. Chem. Soc., 51, 207-14, 1929.
		TIN DIOXIDE
323.	22875	Huttig, G.F., Magierkiewict, S. and Fichmann, J., Z. Physik. Chem., 141A, 1-32, 1929.
324.	30598	Kapustinsky, A.F., Trudy Vsesoyoz. Nauch. Issledovatel Inst. Mineral. Syr'ya, (109), 68, 1936.
325.	21815	Millar, R.W., J. Am. Chem. Soc., 51, 207-14, 1929.
		TITANIUM MONOXIDE
326.	5622	Naylor, B.F., J. Am. Chem. Soc., 68, 1077-80, 1946.
327.		Kelley, K.K. and Mah, A.D., U.S. Bur. Mines Rept. Invest. 5490, 1-20, 1959.
328.	7830	Shomate, C.H., J. Am. Chem. Soc., 68, 310-2, 1946.
		TITANIUM DIOXIDE
329.	1550	Arthur, J.S., J. Appl. Phys., 21 (8), 732-3, 1950.
330.	19225	Keesom, P.H., and Pearlman, N., Phys. Rev., 112 (12), 300-4, 1958.
331.		Kelley, K.K. and Mah, A.D., U.S. Bur. Mines Rept. Invest. 5490, 1-20, 1959.
332.	887	Lietz, J., Hamburger Beitr. Angew. Mineral u. Kristallphys., 1, 229-38, 1956.
333.	11873	McDonald, H.J. and Seltz, H., J. Am. Chem. Soc., 61, 2405-7, 1939.
334.	5622	Naylor, B.F., J. Am. Chem. Soc., 68, 1077-80, 1946.
335.	32767	Shomate, C.H., J. Am. Chem. Soc., 69, 218-9, 1947.
		TITANIUM SESQUIOXIDE
336.		Kelley, K.K. and Mah, A.D., U.S. Bur. Mines Rept. Invest. 5490, 1-20, 1959.
337.	5622	Naylor, B.F., J. Am. Chem. Soc., 68, 1077-80, 1946.
338.	7830	Shomate, C.H., J. Am. Chem. Soc., 68, 310-2, 1946.

Ref. No.	TPRC No.	
		TITANIUM TRIPENTOXIDE
339.		Kelley, K. K. and Mah, A. D., U. S. Bur. Mines Rept. Invest. 5490, 1-20, 1959.
340.	5622	Naylor, B. F., J. Am. Chem. Soc., 68, 1077-80, 1946.
341.	7830	Shomate, C. H., J. Am. Chem. Soc., 68, 310-2, 1946.
		ZINC OXIDE
342.	7025	Clusius, K. and Harteck, P., Z. Physik. Chem., 134, 243-63, 1928.
343.	30400	Maier, C. G. and Ralston, O. C., J. Am. Chem. Soc., 48, 364-74, 1926.
344.	21806	Millar, R. W., J. Am. Chem. Soc., 50, 2653-6, 1928.

RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER VI
DENSITY

BY

P. HESTERMANS
C. E. VOLK

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CHAPTER VI
DENSITY

A. INTRODUCTION

Although density is a basic property, surprisingly little data exist giving density as a function of temperature. The bulk of the available data in the literature pertain to the liquid state, and there is a dearth of data for the solid state.

Fortunately, the knowledge of the linear thermal expansion coefficient of solids permits an evaluation of the temperature dependence of density. The experimental values of the liquid densities are generally reliable.

With few exceptions, enough data were available to establish the temperature dependence of density both in the liquid and solid state, for the elements. Data for the metal oxides with only two exceptions were not available for the whole solid range and nonexistent for the liquid range. Some data exist for the alloys in the solid state; however, the main sources of these data were compilations similar to the present report, or information available from commercial sources.

Density as a function of temperature has been evaluated for the elements, alloys, and oxides covered in this work. No data was found for the liquid state of niobium, chromium and silicon. For manganese the data in both states were particularly scarce. The selected values are presented both in tabular and graphical form.

B. DATA ANALYSIS

The selection of recommended values from available data was made with due consideration to the purity of specimens, and after critical analysis of the accuracy claimed by the authors.

As was already pointed out, the data in the solid range were restricted to densities near room temperature (about 300 K).

For the elements and oxides, available values come from direct measurements (generally by Archimedean methods) or from lattice parameters. To fill the gap between room temperature and the melting point, thermal expansion data were used.

Precautions were taken to record all the phase transitions, which are clearly indicated in graphs and tables. From reported value of volume change on phase transition and on melting, together with the knowledge of the liquid density at the melting point, it was generally possible to construct a smooth curve from normal temperature to the melting point. Where data were available, the procedure was found to agree fairly well with the computed values. In the liquid range, a linear dependence on temperature was assumed, as the reported values covered only a small part of the liquid range, lying well below the boiling point.

For alloys, whenever possible, a similar procedure was followed. No liquid densities were available. Except for the stainless steel and Inconel, an attempt was made to evaluate these densities by means of the mixing rule established by Solet and Saint Clair (8)* for two component liquid alloys.

This very simple rule is:

$$\rho = \sum_i \rho_i x_i$$

where ρ = density of the alloy

ρ_i = density of the i-th pure component

x_i = mole fraction of the i-th pure component.

It was found that the use of this mixing rule was permissible for alloys containing a small amount of minor constituents. Although the procedure may be questionable in the solid state (the values obtained were found to be in error by as much as 4 percent in some cases), use was made of the mixing rule to establish the form of the function, and then by bringing the function in coincidence with data in the solid state considered as reliable, the value of the liquid density was plotted. However, the values so obtained should be used with caution.

No attempt was made to evaluate the liquid densities of the stainless steels and Inconel, the mixing rules failing badly in the solid state.

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*Numbers in parentheses refer to Bibliography at the end of this chapter.

C. PRESENTATION OF DATA ON THE DENSITY OF SELECTED MATERIALS

The recommended values are presented in graphical form. Accompanying each graph is a table of values at 100 degree K intervals. Linear interpolation in these tables is acceptable. With each table, a list of references is given. References to general sources of information (handbooks, compilations) is given in Roman numerals, references to original papers are in Arabic numerals, both can be found in the Bibliography at the end of this chapter. Whenever necessary, comments on the selection of values are given in the form of special remarks under the author listing.

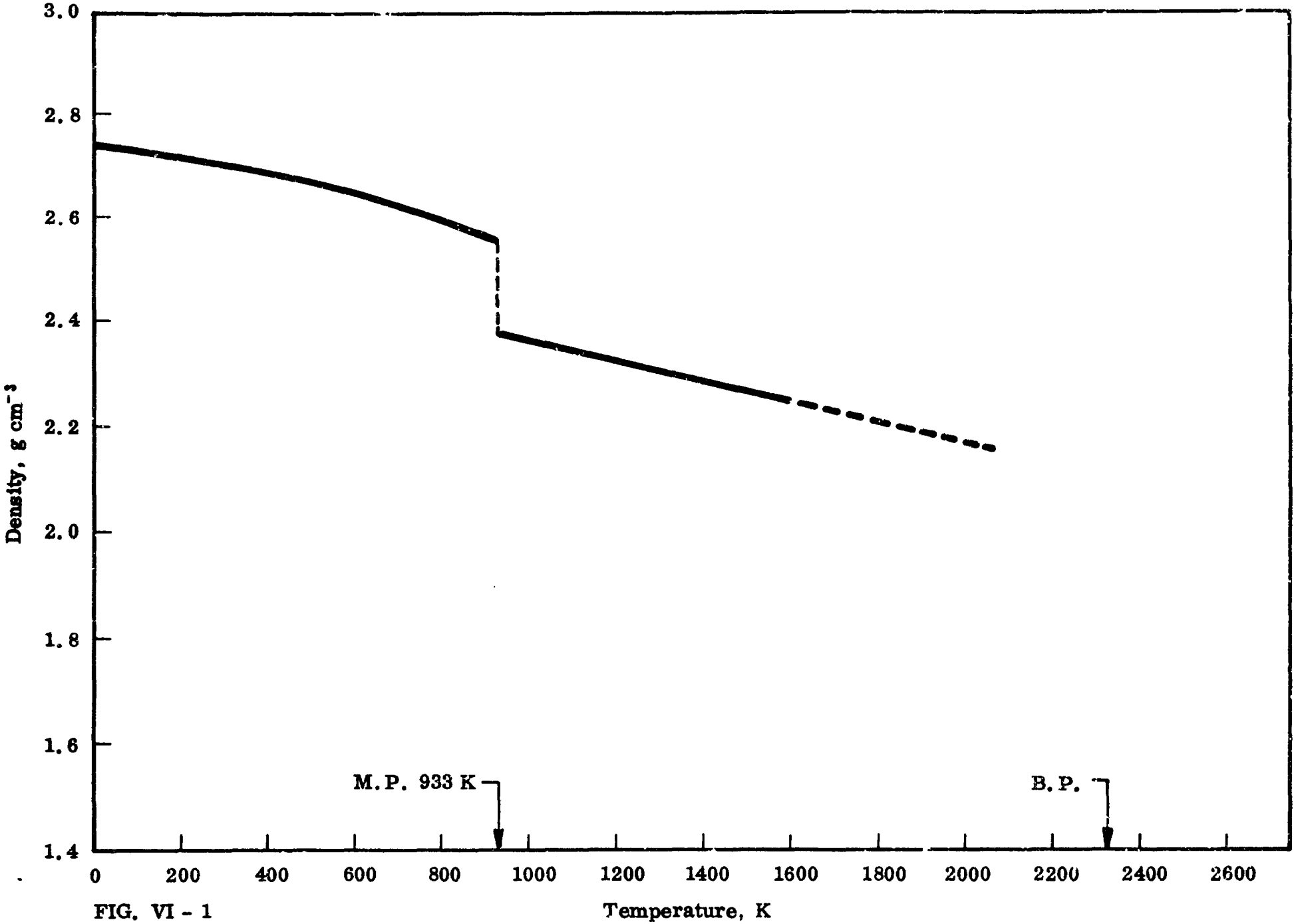

FIG. VI - 1

DENSITY -- ALUMINUM

TABLE VI-1. DENSITY OF ALUMINUM

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 2.735	931(m.p.)	(1) 2.379
100	2.725	1000	2.360
200	2.713	1100	2.341
300	2.698	1200	2.322
400	2.681	1300	2.303
500	2.662	1400	2.284
600	2.640	1500	2.265
700	2.616	1600	2.246
800	2.590		
900	2.552		
931(m.p.)	2.542	2329(n.b.p.)	(2.102)

SOURCE OF DATA

1) Value at room temperature:

   (a) Snoek, J.L. (1); (b) Smakula, A. and Sils, V. (2); (c) Miller, P.N., and Dumond, J.N.M. (3); (d) Foote, F., and Jette, E.R. (4).

2) Solid range:

   (e) from thermal expansion data (III)

3) Volume change on melting.

   (f) Edwards, J.D., and Moorman, T.A. (5).

4) Liquid range:

   (g) Kanda, K.A., and Keller, D.V. (6); (h) Gebhardt, E., Becker, M., and Dorner, S. (7); (i) Solet, I.S., and St Clair, H.W., (8); (j) Naidich, Yu. V., and Eremenko, V.N. (9); (k) Bornemann, K., and Sauerwald, F. (10).

REMARKS: Accuracy solid range ± .5% or better.
liquid range ± .1% or better.

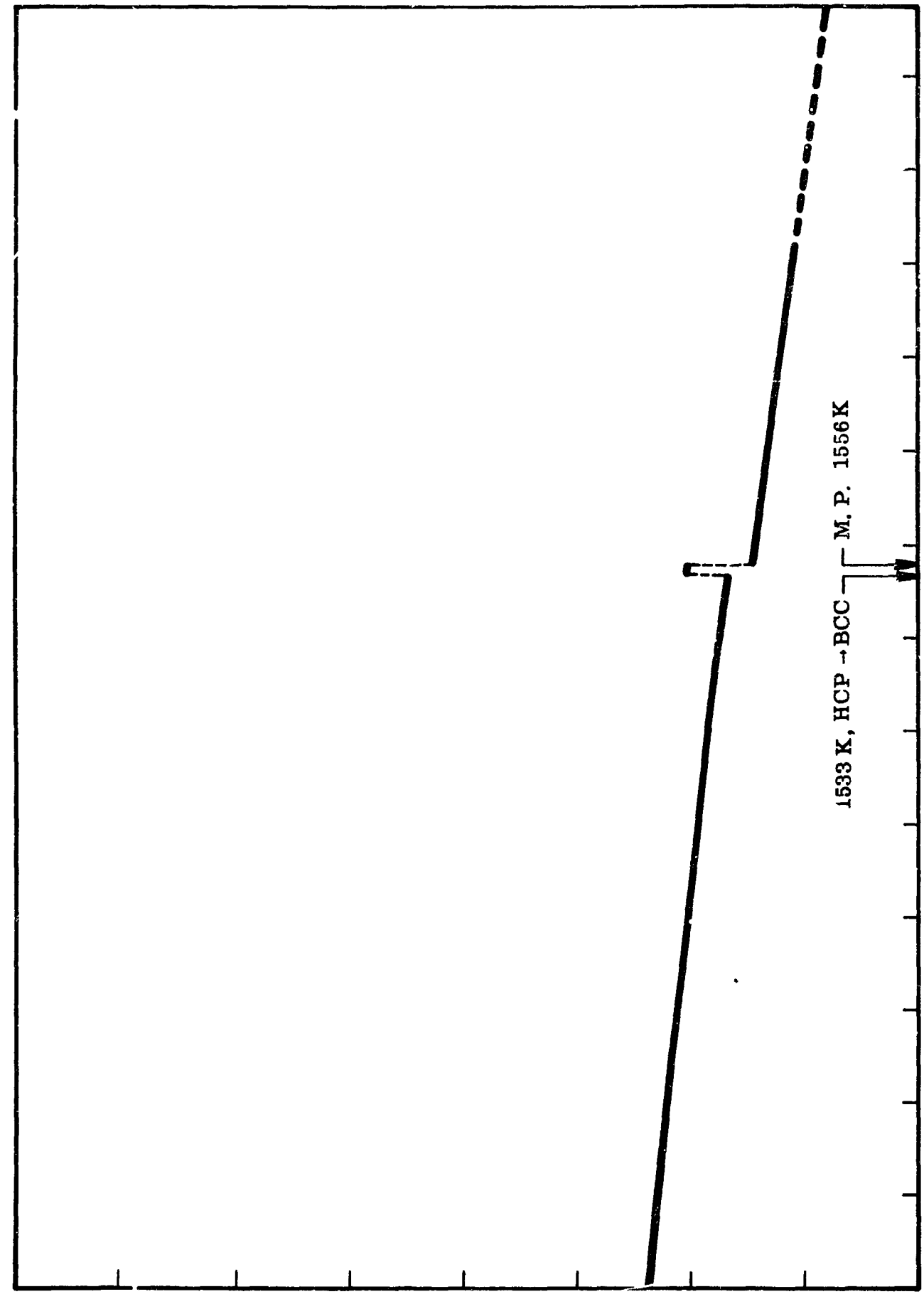

FIG. VI - 2

DENSITY -- BERYLLIUM

TABLE VI-2. DENSITY OF BERYLLIUM

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s,HCP) (1.873)	1400	1.741
100	(1.864)	1500	1.730
200	(1.855)	1533	(s, HCP) 1.725
300	1.846	1533	(s, BCC) 1.803
400	1.837	1556 (m.p.)	(s) 1.805
500	1.828	1556 (m.p.)	(l) 1.690
600	1.819	1600	1.685
700	1.810	1700	1.674
800	1.801	1800	1.662
900	1.792	1900	1.651
1000	1.783	2000	1.639
1100	1.773	2100	1.627
1200	1.763	2200	1.616
1300	1.752		

SOURCE OF DATA

1) Value at room temperature:

   (a) Metals handbook(I); (b) Handbook of Chemistry (IV).

2) Solid range:

   (c) from thermal expansion data (III); (d) Martin, A.Y., and Moore, H. (11)

3) Volume change i) transition HCP→BCC (d) Martin, A.Y. and Moore, A. (11); ii) melting point; (e) Grosse, A.V. and Cahill, J.A. (12)

4) Liquid range

   (e) Grosse, A.V. and Cahill, J.A. (12)

REMARKS: Value below 300°K are extrapolated

Accuracy = Solid range ± .5%
liquid range ± 4%

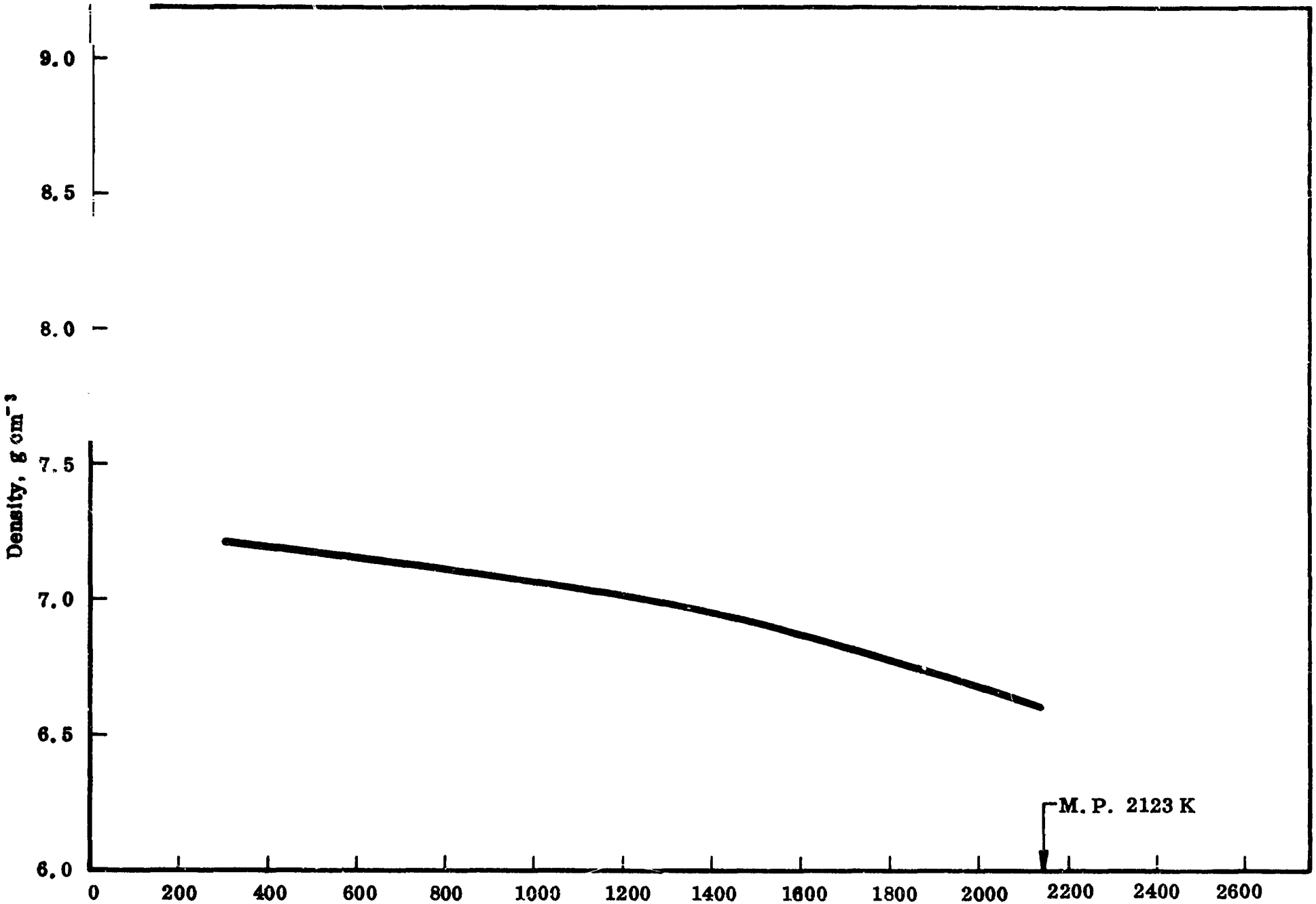

FIG. VII - 3

DENSITY -- CHROMIUM

TABLE VI-3. DENSITY OF CHROMIUM

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
299	(s, HCP) 6.08	1300	6.98
299	(s, BCC) 7.21	1400	6.94
300	7.21	1500	6.91
400	7.20	1600	6.87
500	7.18	1700	6.83
600	7.16	1800	6.78
800	7.11	1900	6.74
900	7.09	2000	6.69
1000	7.07	2100	6.63
1100	7.04	2123(m.p.)	(s) 6.61
1200	7.01		
		2223	(l) 6.00 ± 0.13

SOURCE OF DATA

1) Value at room temperature:

   (a) Metals handbook (I); (b) Handbook of Chemistry (IV)

2) Solid range:

   (c) from thermal expansion data (III)

3) liquid range: (one value, see table)

   (d) Eremenko, V.N. and Naidich, Yu. V. (48)

REMARKS: The data at room temperature are non-original and may be in error as much as ± 1%. Since no values are available for the phase transition near room temperature the curve was not drawn below 300° K. Since no values were available for the change of volume on fusion, no recommended curve was drawn, in the liquid range. These values should be used with caution.

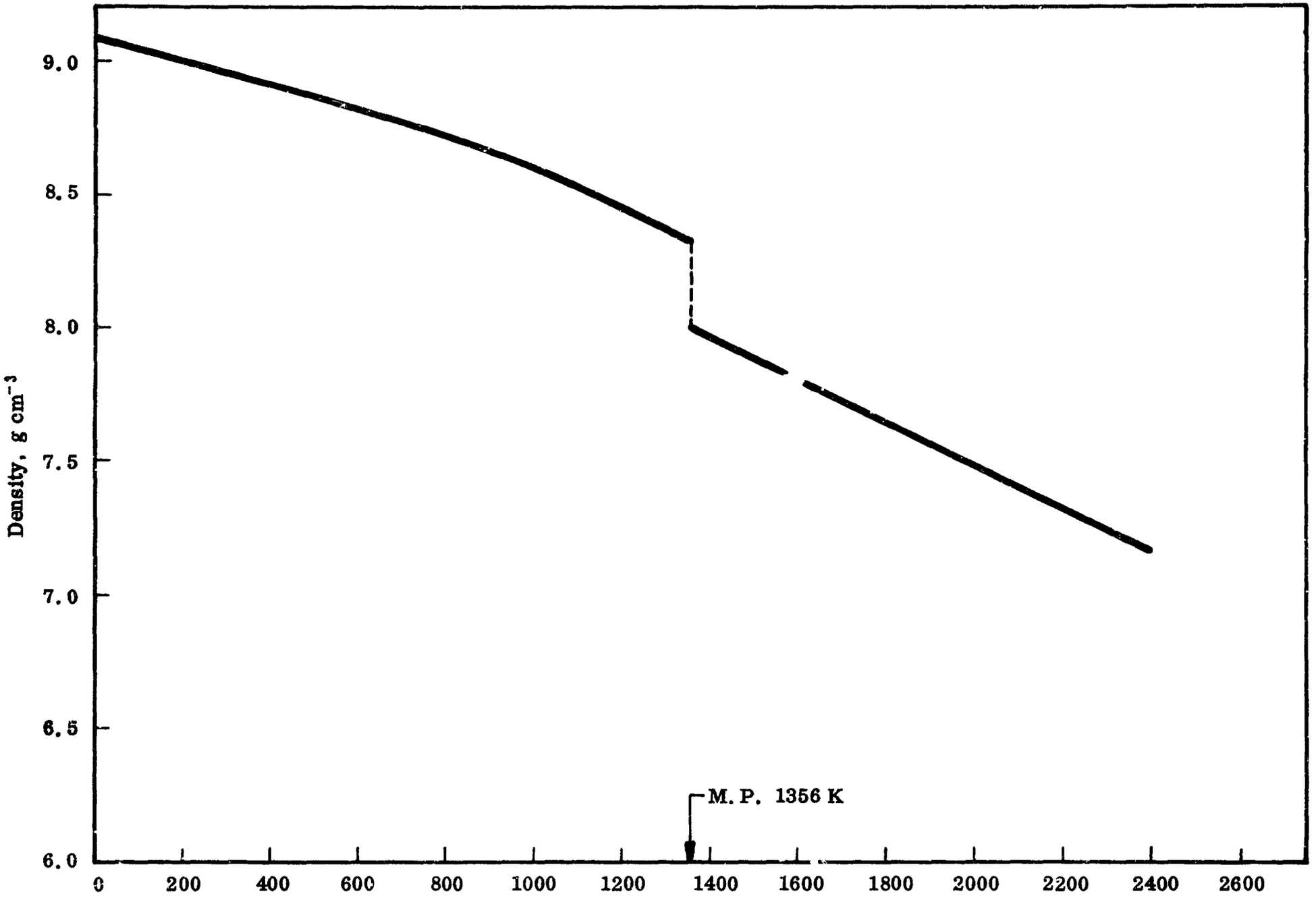

FIG. VI - 4

DENSITY -- COPPER

TABLE VI-4. DENSITY OF COPPER

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 9.08	1300	8.37
100	9.04	1356 (m.p.)	(s) 8.32
200	9.00	1356 (m.p.)	(l) 7.99
300	8.96	1400	7.96
400	8.91	1500	7.88
500	8.87	1600	7.80
600	8.82	1700	7.72
700	8.76	1800	7.64
800	8.71	1900	7.56
900	8.65	2000	7.48
1000	8.58	2100	7.46
1100	8.51	2200	7.22
1200	8.44	2300	7.24
		2400	7.16

SOURCE OF DATA

1) Value at room temperature:

   (a) Smart, J.S., Smith, A.A., and Phillips, A.J. (13);
   (b) Metals Handbook (I);
   (c) Foote, F. and Jette, E.R. (4).

2) Solid range:

   (d) from thermal expansion data (III);
   (e) Bornemann, K. and Sauerwald (10).

3) Liquid range:

   (f) Lucas, L.D. (14); (g) Gebhardt, E., Becker, M. and Schafer, S. (15); (h) Cahill, J.A. and Kirshenbaum, A.D. (16); (i) Allen, B.C. and Kingery, W.D. (17); (j) Bornemann, K. and Sauerwald, F. (10)

REMARKS: Accuracy solid and liquid range = ± .5% or better.

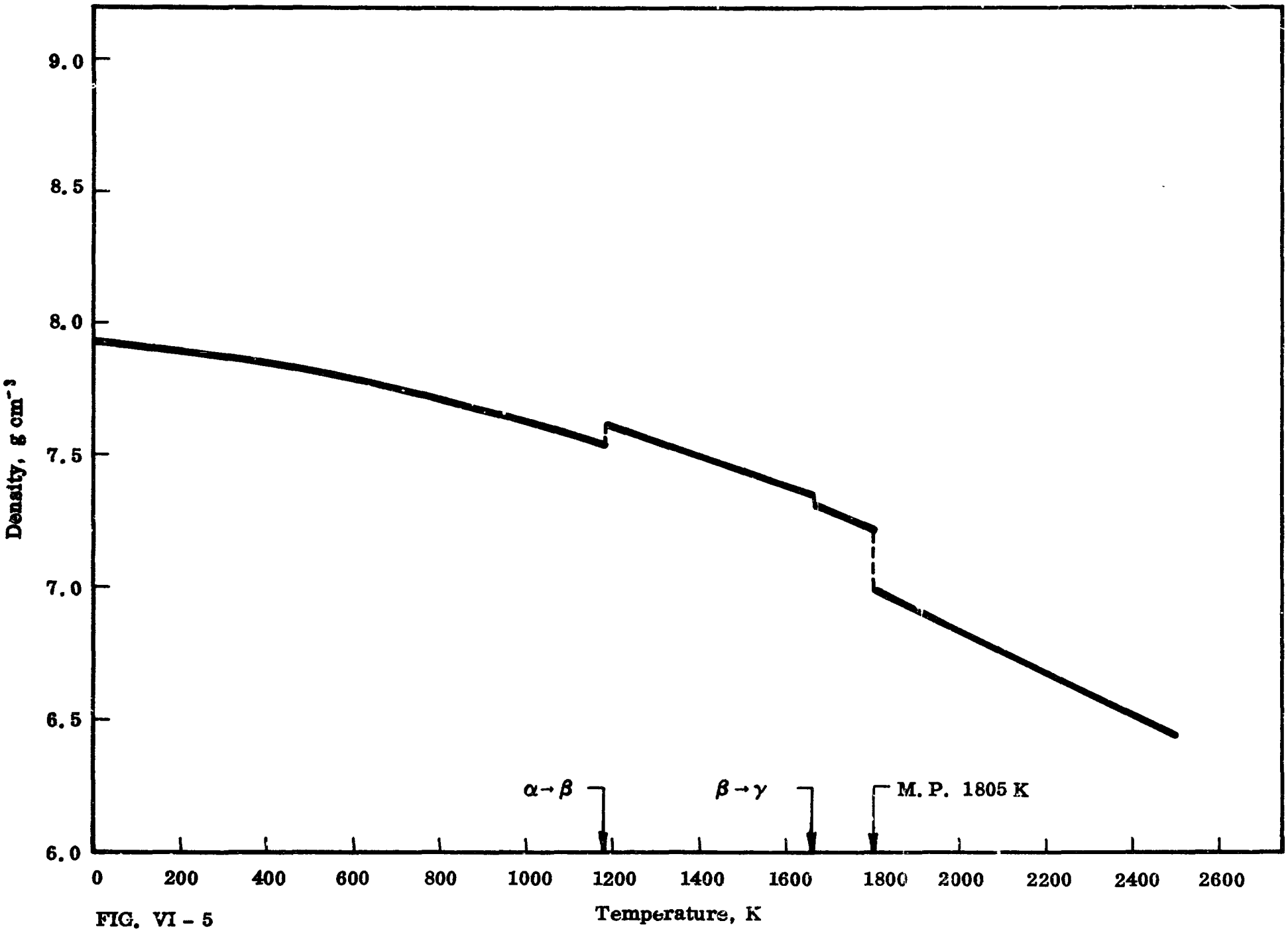

FIG. VI - 5

DENSITY -- IRON

TABLE VI-5. DENSITY OF IRON

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s, BCC) 7.928	1500	7.433
100	7.910	1600	7.377
200	7.889	1663	(s, FCC) 7.341
300	7.865	1663	(s, BCC) 7.304
400	7.838	1700	7.290
500	7.808	1805(m.p.)	(s, BCC) 7.260
600	7.715	1805(m.p.)	(l) 7.014
700	7.739	1900	6.935
800	7.700	2000	6.851
900	7.658	2100	6.768
1000	7.613	2200	6.684
1100	7.565	2300	6.601
1183	(s, BCC) 7.523	2400	6.517
1183	(s, FCC) 7.598	2500	6.433
1200	7.589		
1300	7.539	(3273) (n.b.p.)	(5.828)
1400	7.487		

SOURCE OF DATA

1) Value at room temperature:

   (a) Metals handbook (I); (b) Keeler, J.H. and Davis, A.M. (18)

2) Volume change on phase transformation

   (c) - BCC-FCC and FCC-BCC from Metals handbook (I)
   (d) - solid-liquid: Kirschenbaum, A.D. and cahill, J.A. (19)

3) liquid range: see (d); (e) Stott, V.H. and Randall, J.N. (20); (f) Kozakevitch, P. and Urbain, G. (21); (g) Lucas, L.D. (22) (h) Allen, B.C. and Kingery, W.D. (17); (i) Benedicks, C., Berlin, D.W., and Phragmen, G. (23); (j) Desch, C.H. and Smith, B.S. (24)

REMARKS: Accuracy: solid range: .5% or better
liquid range: 1% or better

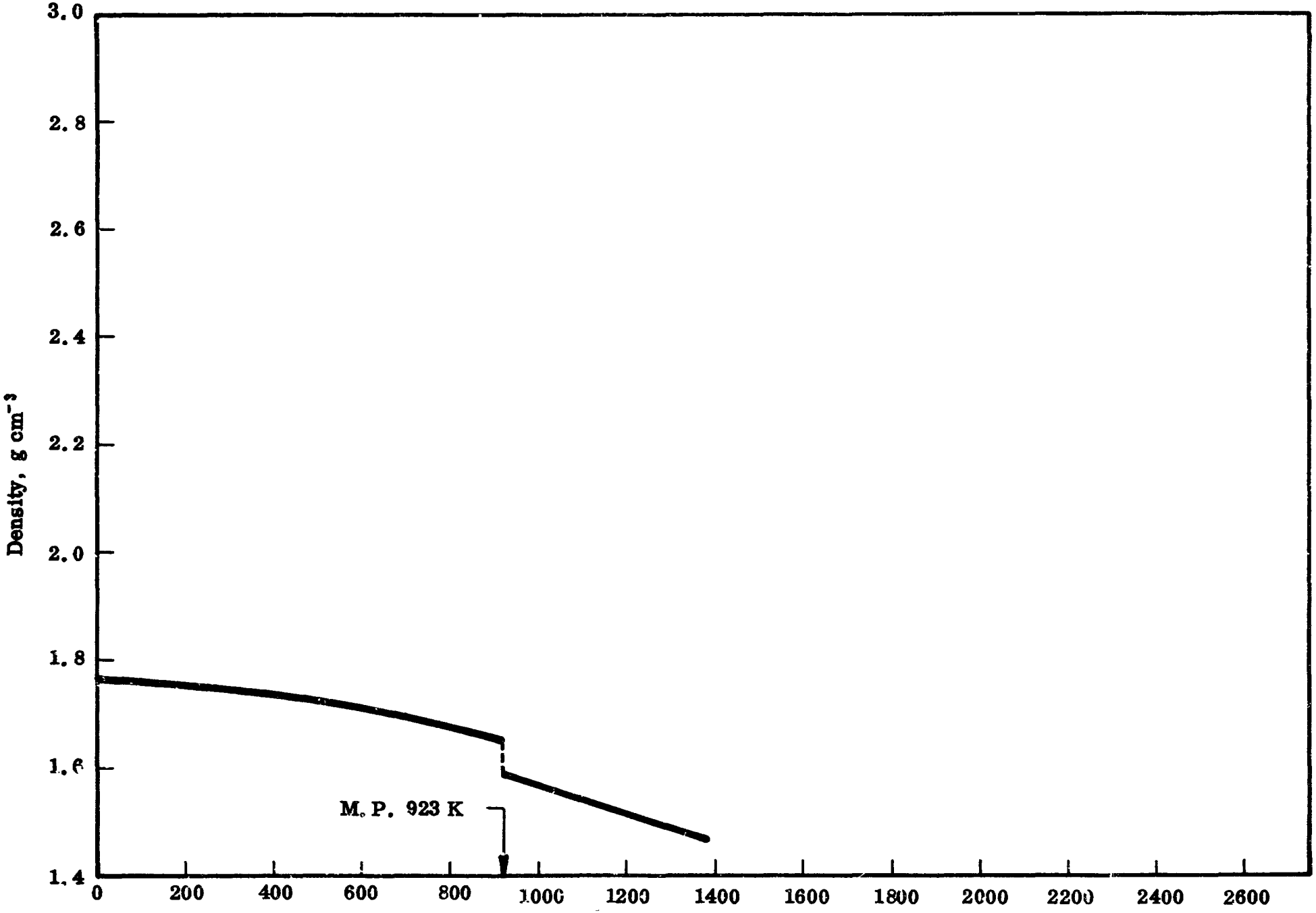

FIG. VI - 6

DENSITY -- MAGNESIUM

TABLE VI-6. DENSITY OF MAGNESIUM

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 1.762	923(m.p.)	(s) 1.637
100	1.756	923(m.p.)	(l) 1.590
200	1.748	1000	1.569
300	1.738	1100	1.543
400	1.726	1200	1.516
500	1.712	1300	1.490
600	1.696	1390 (n.b.p.)	1.466
700	1.678	(1500)	(1.438)
800	1.657	(3500)	(0.815)
900	1.643		

SOURCE OF DATA

1) Solid range: (a) Seddon, B.J. and Francis, E.L. (25); (b) Metals handbook (I); (c) Pelzel, E. and Sauerwald, F. (26); (d) Edwards, J.D. and Taylor, C.S. (27); (e) Batuecas, T. and Casado, F.L. (28); (f) Foote, F. and Jette, E.R. (4); (g) from thermal expansion data (III)

2) Volume change on fusion: (h) McGonigal, P.J., Kirshenbaum, A.D. and Grosse, A.V. (29).

3) liquid range: see (a); (b); (c); (d); (h);
(i) Arndt, K. and Ploetz, G. (30);
(j) Gebhardt, E., Becker, M., Tragner F., (31)
(k) Grothe, H. and Mangelsdorf, C. (32).

REMARKS: Accuracy: solid range: ± .5% or better
liquid range: ± .5% or better
Values above boiling point are from (h) and are extrapolated values.

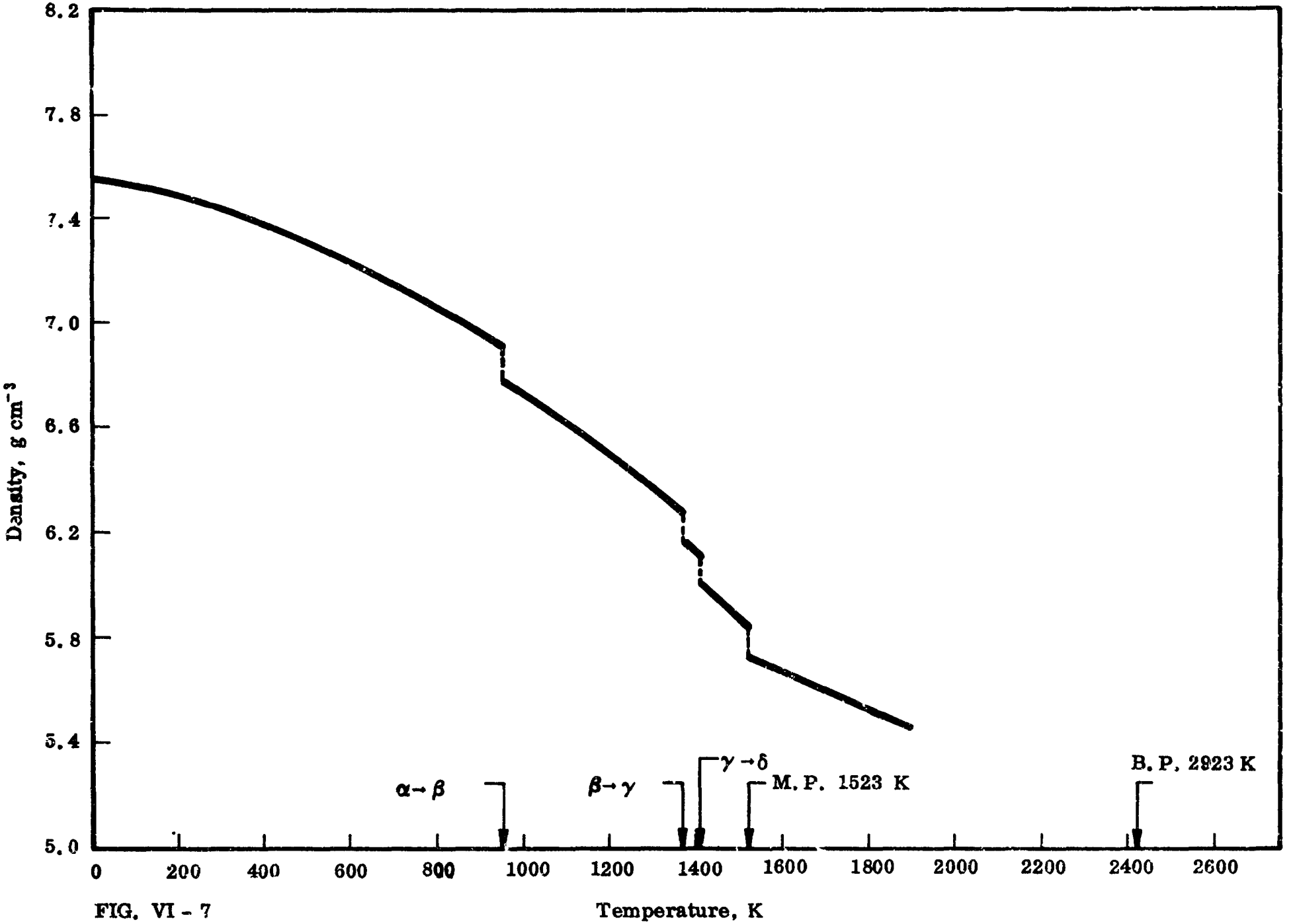
8.2
7.8
7.4
7.0
6.6
6.2
5.8
5.4
5.0
Density, g cm⁻³
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Temperature, K
α→β
β→γ
γ→δ
M. P. 1523 K
B. P. 2923 K

FIG. VI - 7

TABLE VI-7. DENSITY OF MANGANESE

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s,α) 7.55	1200	6.49
100	7.52	1300	6.36
200	7.48	1373	(s,β) 6.27
300	7.43	1373	(s,γ) 6.17
400	7.37	1400	6.12
500	7.30	1411	(s,γ) 6.10
600	7.23	1411	(s,δ) 6.00
700	7.15	1500	5.87
800	7.06	1518 (m.p.)	(s) 5.83
900	6.96	1518 (m.p.)	(l) 5.72
951	(s,α) 6.90	1600	5.67
951	(s,β) 6.77	1700	5.60
1000	6.72	1800	5.53
1100	6.61	1900	5.46

SOURCE OF DATA

1) Values at room temperature: for α, β, γ, from Metal Handbook (I)

2) Solid range: from thermal expansion coefficient (up to 1000°K) (III)

3) liquid range: Popel', S.I. Tsarevskiy, B.V. and Dzhenilev, N.K. (33)

REMARKS: Up to 951°K the curve was constructed using the value of α-Mn at 25° c (from Metal Handbook (I), apparently computed from lattice parameter) and thermal expansion coefficient from, (III). The values in the liquid range are taken from Popel'. Between 951°K and the melting point smooth curves were drawn using the volume change on fusion given in Metal Handbook, assuming for the β, γ, and δ phases, behavior similar to the α phase. No accuracy can be evaluated in this case. The values should be considered as tentative values and used with caution.

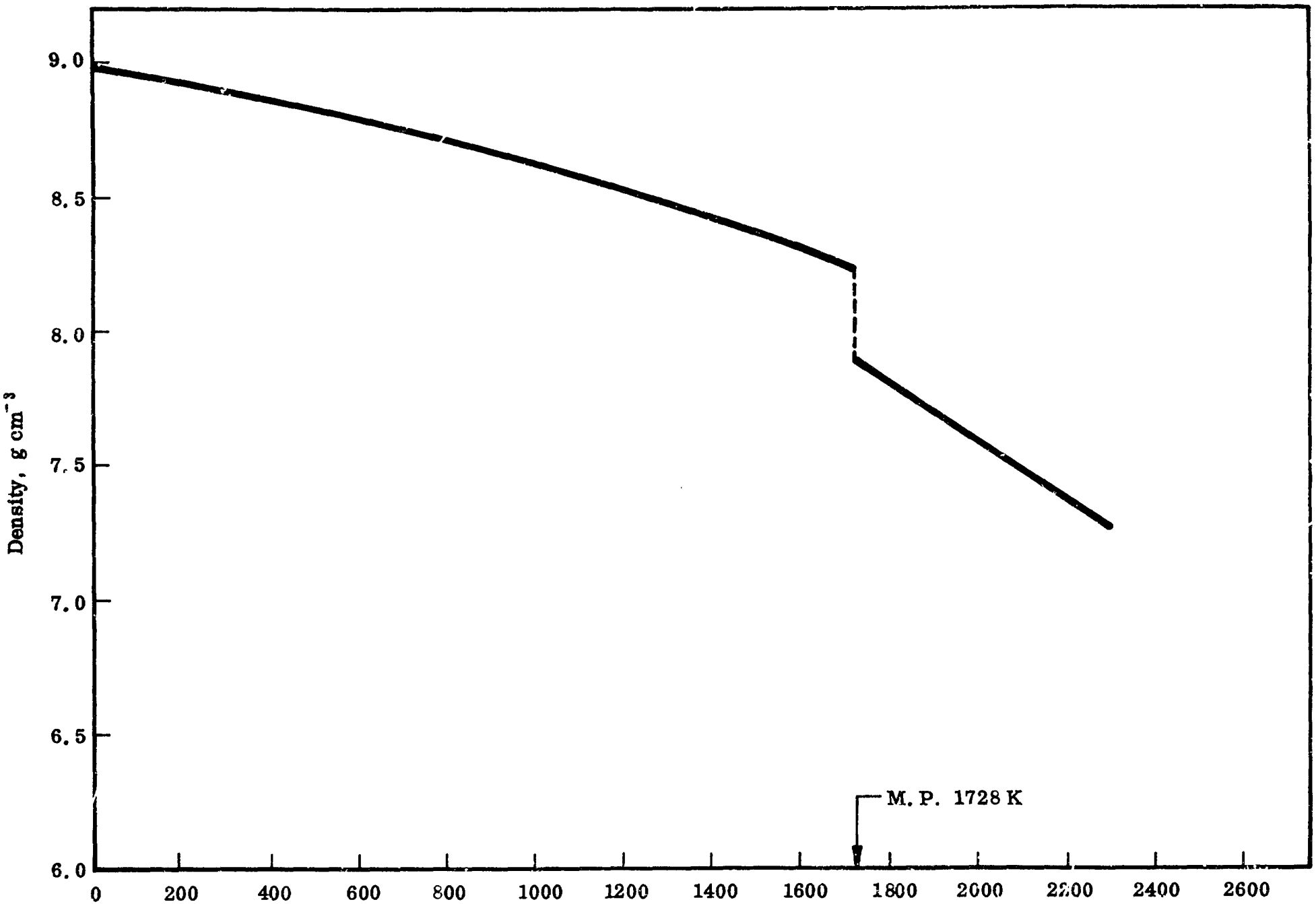

FIG. VI - 8

DENSITY — NICKEL

TABLE VI-8. DENSITY OF NICKEL

RECOMMENDED VALUES

T(°C)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 8.976	1300	8.477
100	8.953	1400	8.421
200	8.928	1500	8.362
300	8.901	1600	8.301
400	8.870	1700	8.237
500	8.836	1728 (m.p.)	(s) 8.220
600	8.800	1728 (m.p.)	(l) 7.898
700	8.761	1800	7.814
800	8.720	1900	7.696
900	8.677	2000	7.518
1000	8.631	2100	7.460
1100	8.582	2200	7.342
1200	8.531	2300	7.224

SOURCE OF DATA

1) Value at room temperature: (a) Metals Handbook (I); (b) Handbook of Chemistry (IV); (c) Jordan, L. and Swanger, W.H. (34); (d) Foote, F. and Jette, E.R. (4);
2) Solid range: (e) from thermal expansion data (III);
3) liquid range: (f) Grosse, A.V. and Kirshenbaum, A.D. (35); (g) Kozakevitch, P. and Urbain, G. (21); (h) Eremenko, V.N. and Nizhenko, V.I. (36)

REMARKS: Accuracy: solid range: ± .5%
liquid range: ± 1.0%

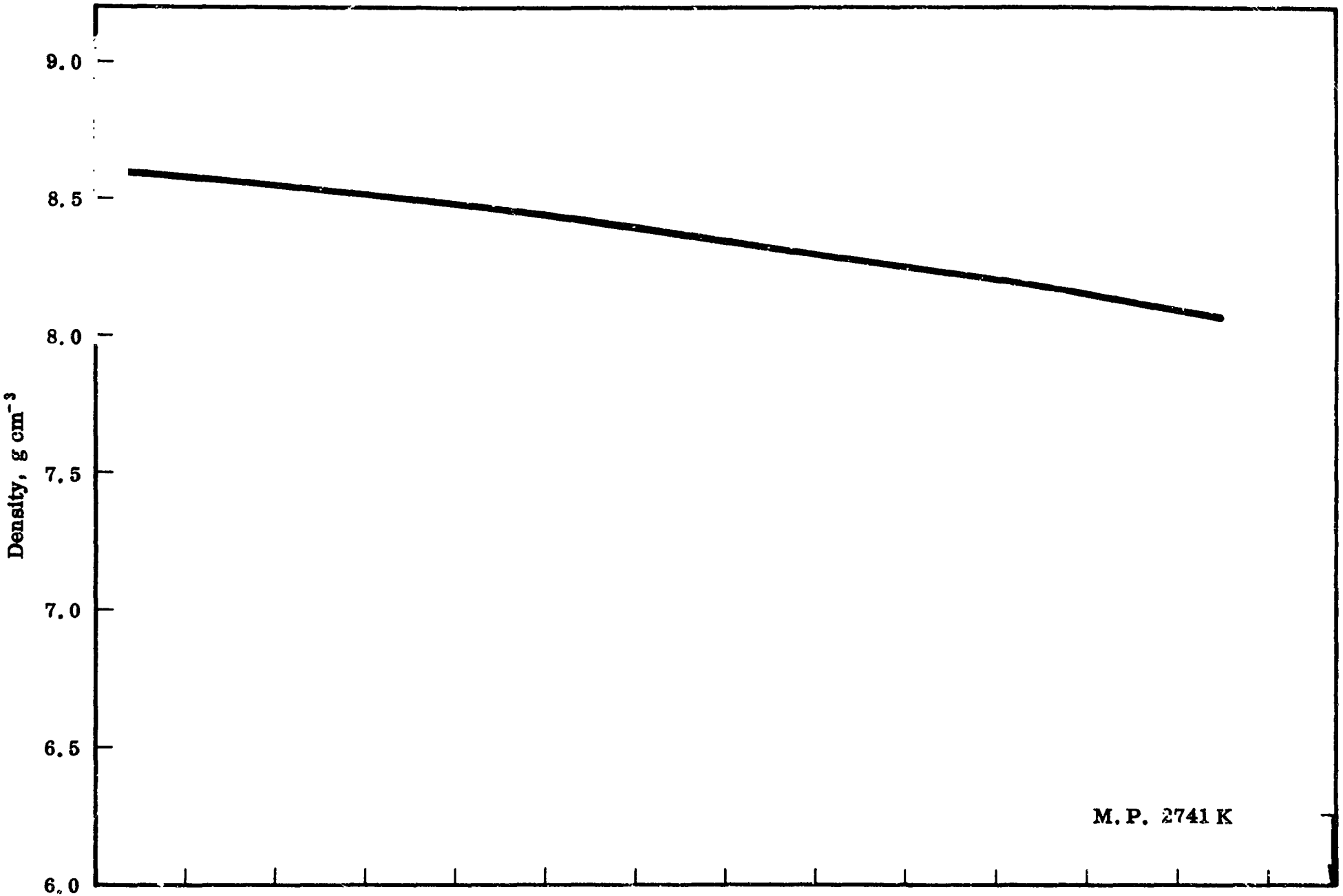

FIG. VI - 9

DENSITY -- NIOBIUM

TABLE VI-9. DENSITY OF NIOBIUM

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 8.61	1300	8.37
100	8.60	1400	8.34
200	8.59	1500	8.32
300	8.58	1600	8.29
400	8.56	1700	8.27
500	8.54	1800	8.24
600	8.52	1900	8.22
700	8.50	2000	8.19
800	8.48	2100	8.17
900	8.46	2200	8.14
1000	8.44	2300	8.11
1100	8.42	2400	8.09
1200	8.40	2500	(s) 8.05

SOURCE OF DATA

1) Value at room temperature: (a) Schrijner, A.J. and Middelhoek, A. (37)
2) Solid range: (b) from thermal expansion coefficient of Tietz, T.E. and Wilson, J.W. (38)

REMARKS: Accuracy: ± .5%

No value in liquid range (m.p. is 2740°K)

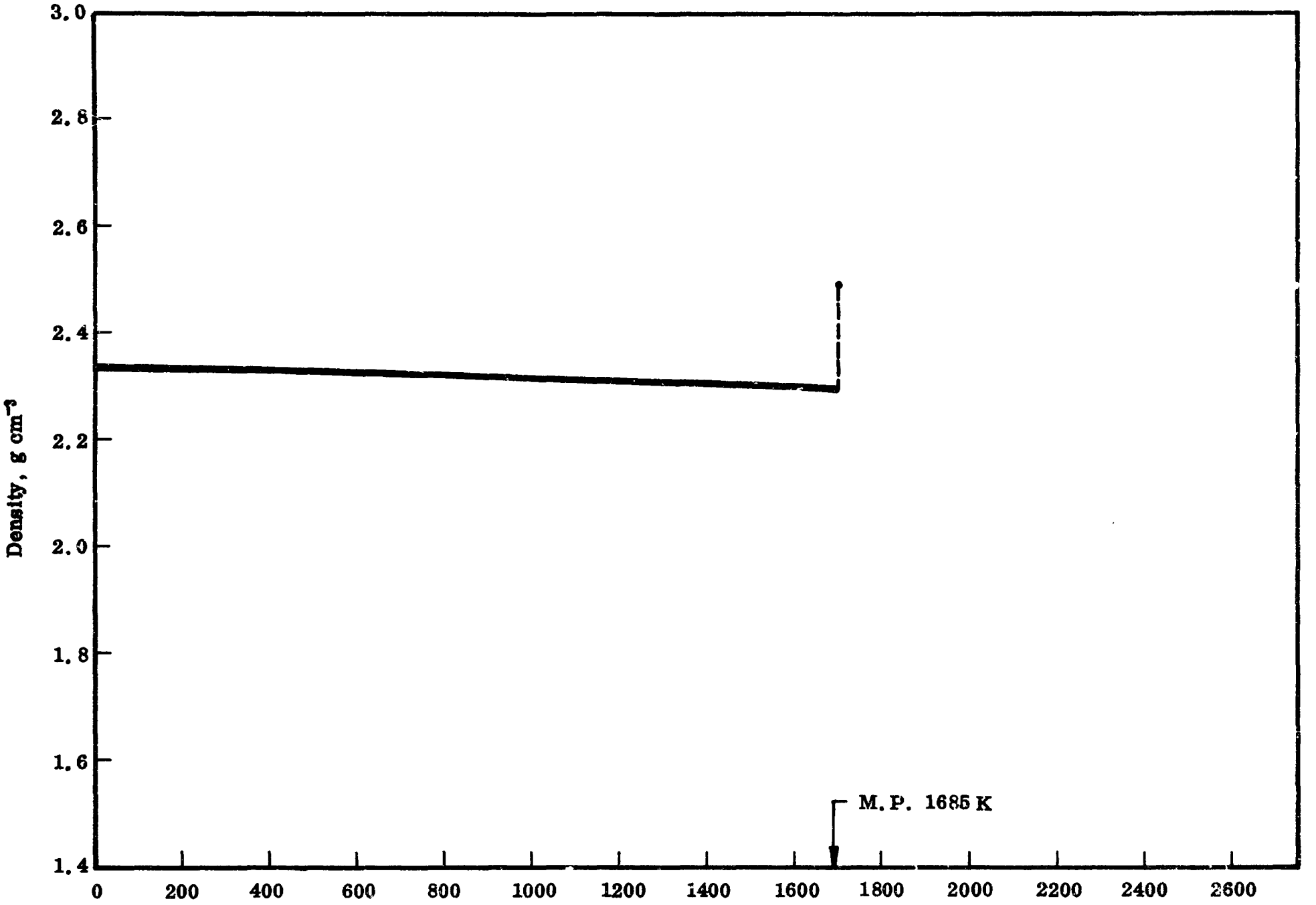

FIG. VI - 10

DENSITY -- SILICON

TABLE VI - 10. DENSITY OF SILICON

RECOMMENDED VALUES

T(°K)	ρ(g, cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 2.332	900	2.315
100	2.331	1000	2.312
200	2.330	1100	2.309
300	2.329	1200	2.306
400	2.327	1300	2.302
500	2.325	1400	2.298
600	2.323	1500	2.294
700	2.321	1600	2.290
800	2.318	1688 (m.p.)	(s) 2.286
		1688 (m.p.)	(l) 2.49

SOURCE OF DATA

1) Value at room temperature: (a) Prener, J.S. and William, F.E. (39); (b) Smakula, A. and Sils, V. (2); (c) Horn, F.H. (40); (d) Smakula, A., Kalnass, J., and Sils, V. (41)

2) Solid range: (e) from thermal expansion coefficient (III)

3) Change of volume on fusion: (f) Logan, R.A. and Bond, W.L. (42)

REMARKS: Accuracy = ± 0.5% or better.

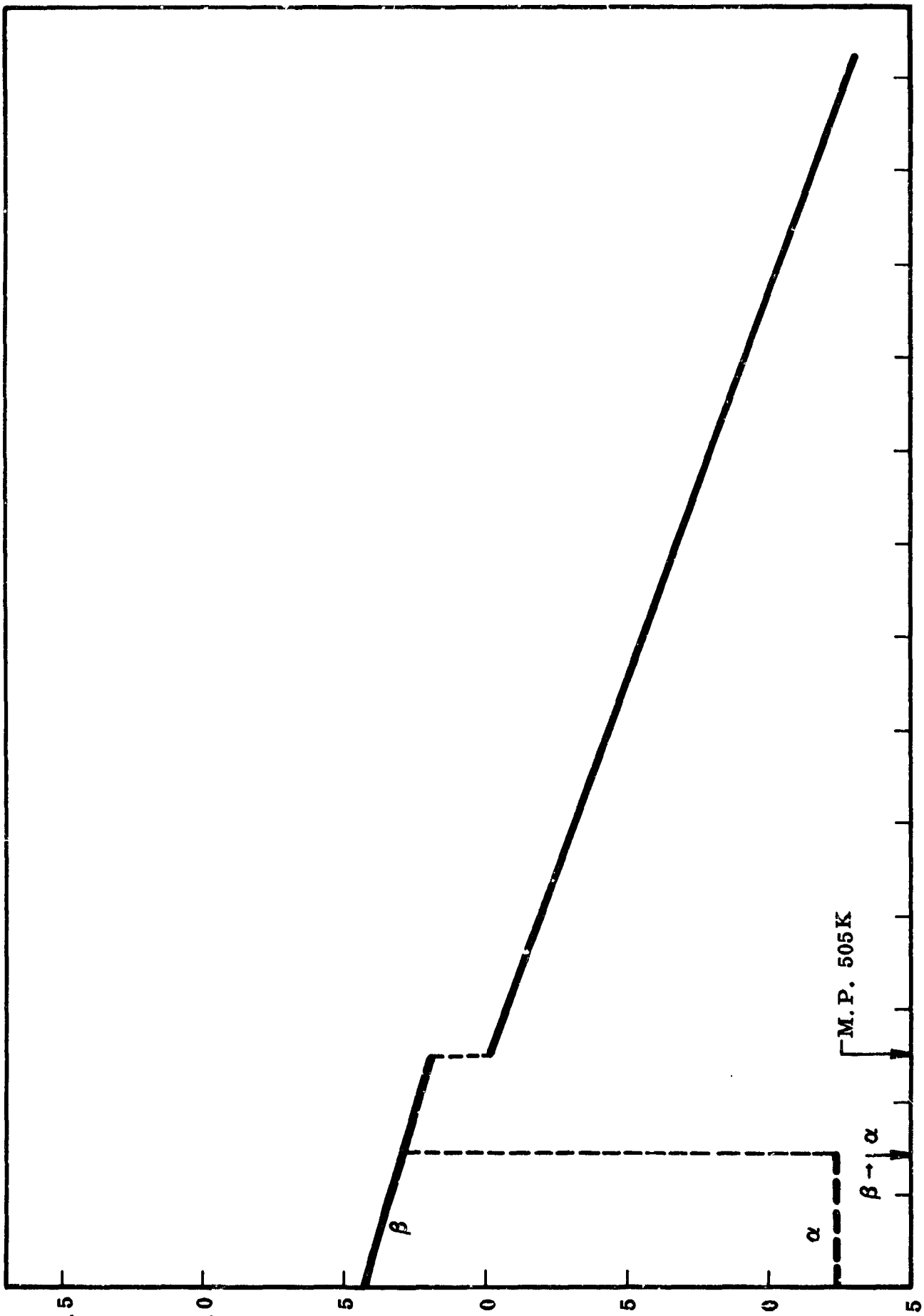

FIG. VI - 11

DENSITY -- TIN

TABLE VI-11. DENSITY OF TIN

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s,α)7.418	1200	6.563
100	7.375	1300	6.503
200	7.331	1400	6.443
286.36*	7.290	1500	6.383
300	7.283	1600	6.323
400	7.234	1700	6.263
500	7.185	1800	6.203
505 (m.p.)	(s) 7.182	1900	6.143
505 (m.p.)	(l) 6.980	2000	6.083
600	6.923	2100	6.023
700	6.863	2200	5.963
800	6.803	2300	5.903
900	6.743	2400	5.843
1000	6.683	2753 (n.b.p.)	(5.622)
1100	6.623		

*below 286K, white tin (α - tin) transforms to gray tin (β - tin) but the transformation is slow. The density of β - tin at 286.36 is 5.765 g cm^{-3}

SOURCE OF DATA

1) Value near room temperature:

β-tin (tetragonal) and α-tin (cubic)
(a) Metals Handbook (I) : (b) Handbook of Chemistry (IV) ;
(c) Hedges, E.S. and Homer, C.F. (43)

2) Solid range: see (a) (b) (c)

3) Volume change on fusion: see (a) and discussion by (d) Kirshenbaum, A.D. and Cahill, J.A. (44) and (e) Matuyama, Y. (45)

4) Liquid range : see (d) (e) ; and (f) Bornemann, K. and Siebe, P. (46) ; (g) Hogness, T.R. (47) ; (h) Bornemann, K. and Sauerwald, F. (10) ; (i) Allen, B.C. and Kingery, W.D. (17) ; (j) Kanda. F.A. and Keller, D.V. (6) ; (k) Ubelacker, E. and Lucas, L.D. (48) ; (l) Gebhardt, E. Becker, M. and Schafer, S. (15) ; (m) Kutateladze, S.S., Borishanskii, V.M. and Novikov, I.J. (50) ; (n) Atterton, D.V. and Hoar, T P. (51) ; (o) Pascal, P., and Jouniaux, A. (52) ; (p) Herezynska, E. (53) ; (q) Gamertsfelder, C. (54) ; (r) Majima, M. (55) ; (s) Pluss, M. (56) ; (t) Sosman, R.B., Day, A.L. and Hostetter, J.C. (57)

REMARKS: Accuracy: Both liquid and solid range: ± .5% or better

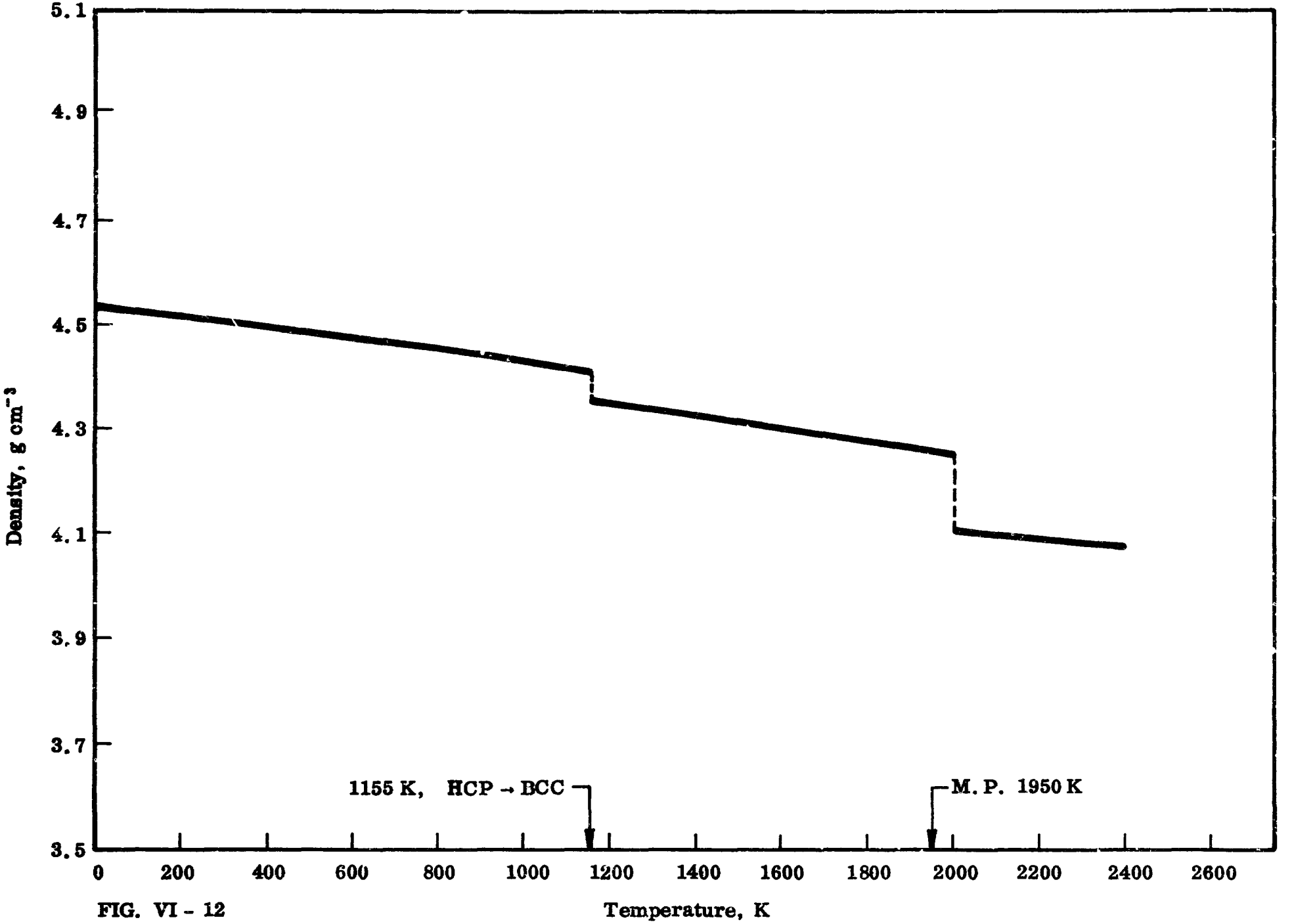

FIG. VI - 12

DENSITY -- TITANIUM

TABLE VI-12. DENSITY OF TITANIUM

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s, HCP) 4.54	1300	4.334
100	4.53	1400	4.323
200	4.52	1500	4.312
300	4.50	1600	4.300
400	4.49	1700	4.288
500	4.48	1800	4.276
600	4.47	1900	4.263
700	4.46	1950(m.p.) (s)	4.257
800	4.45	1950(m.p.) (l)	4.113
900	4.43	2000	4.110
1000	4.42	2100	4.102
1100	4.41	2200	4.097
1155	(s, HCP) 4.41	2300	4.087
1155	(s, BCC) 4.350	2400	4.073
1200	4.345		

SOURCE OF DATA

1) Value at room temperature: (a) Metals Handbook (I)
2) Solid range: (b) from thermal expansion coefficient (III)
3) liquid range: (c) Yelyutin, V.P. and Maurakh, M.A. (58)
   (d) Maurakh, M.A. (59)

REMARKS: for the solid above 1155°K (BCC) nearly the same slope as for the (HCP) phase was assumed.

Accuracy: solid range (HCP): ± .5%
(BCC): non evaluable
liquid range: non evaluable

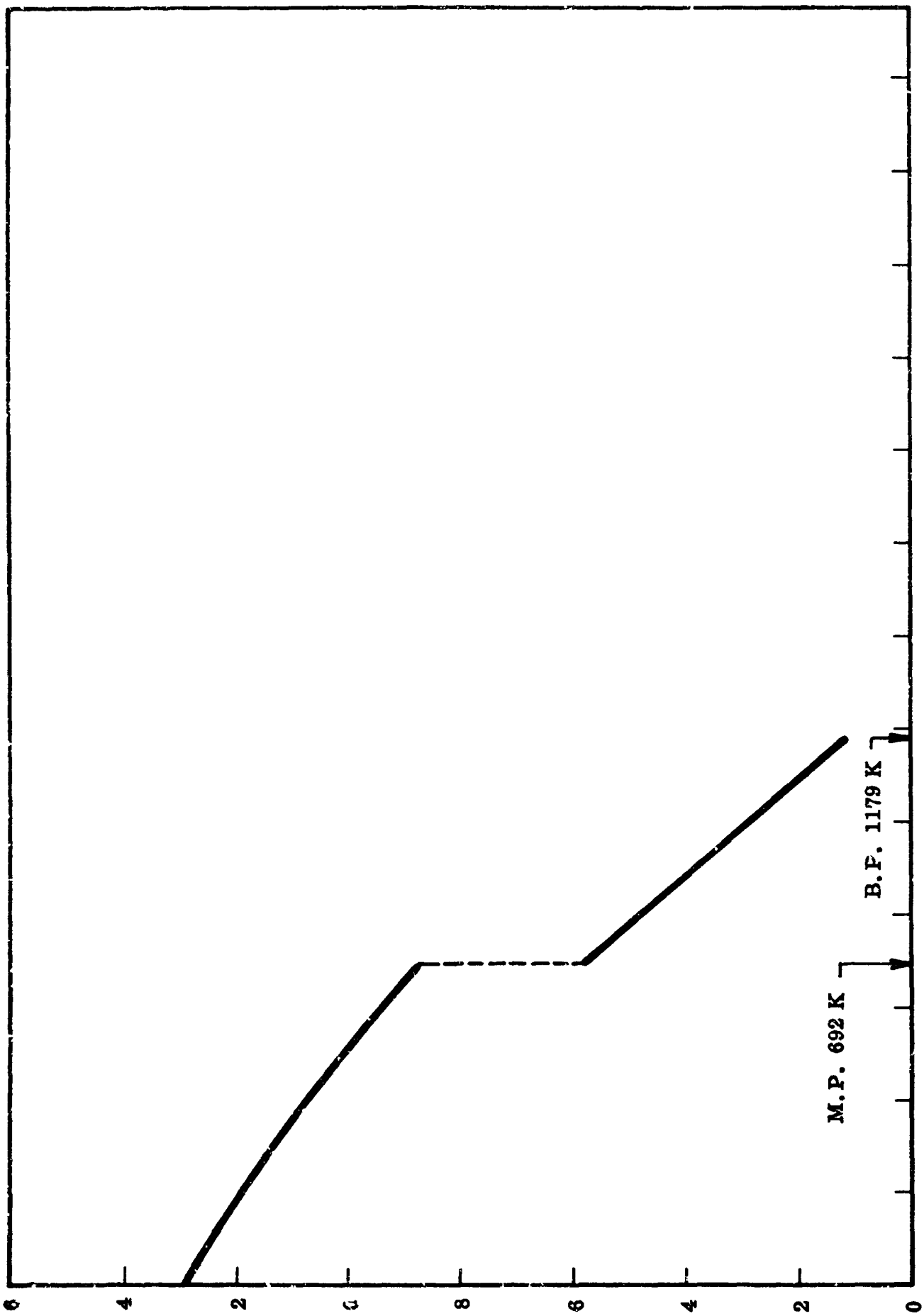

FIG. VI - 13

DENSITY -- ZINC

TABLE VI-13. DENSITY OF ZINC

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 7.290	692(m.p.)	(1) 6.585
100	7.241	700	6.577
200	7.188	800	6.480
300	7.131	900	6.384
400	7.070	1000	6.287
500	7.005	1100	6.191
600	6.936	1179(n.b.p.)	6.115
692(m.p.)	6.869		

SOURCE OF DATA

1) Value at room temperature: (a) Metals handbook (I)

2) Solid range: (b) from thermal expansion data in American Institute of Physics Handbook (V)

3) liquid range: (c) Gebhardt, E., Becker, M. and Dorner, S. (7); (d) Mound laboratory (60); (e) Ubelacker and Lucas, L.D. (49); (f) Solet, J.S. and St. Clair, A.W. (8); (g) Hogness, T.R. (47)

REMARKS: Accuracy, liquid and solid range: ± 1%

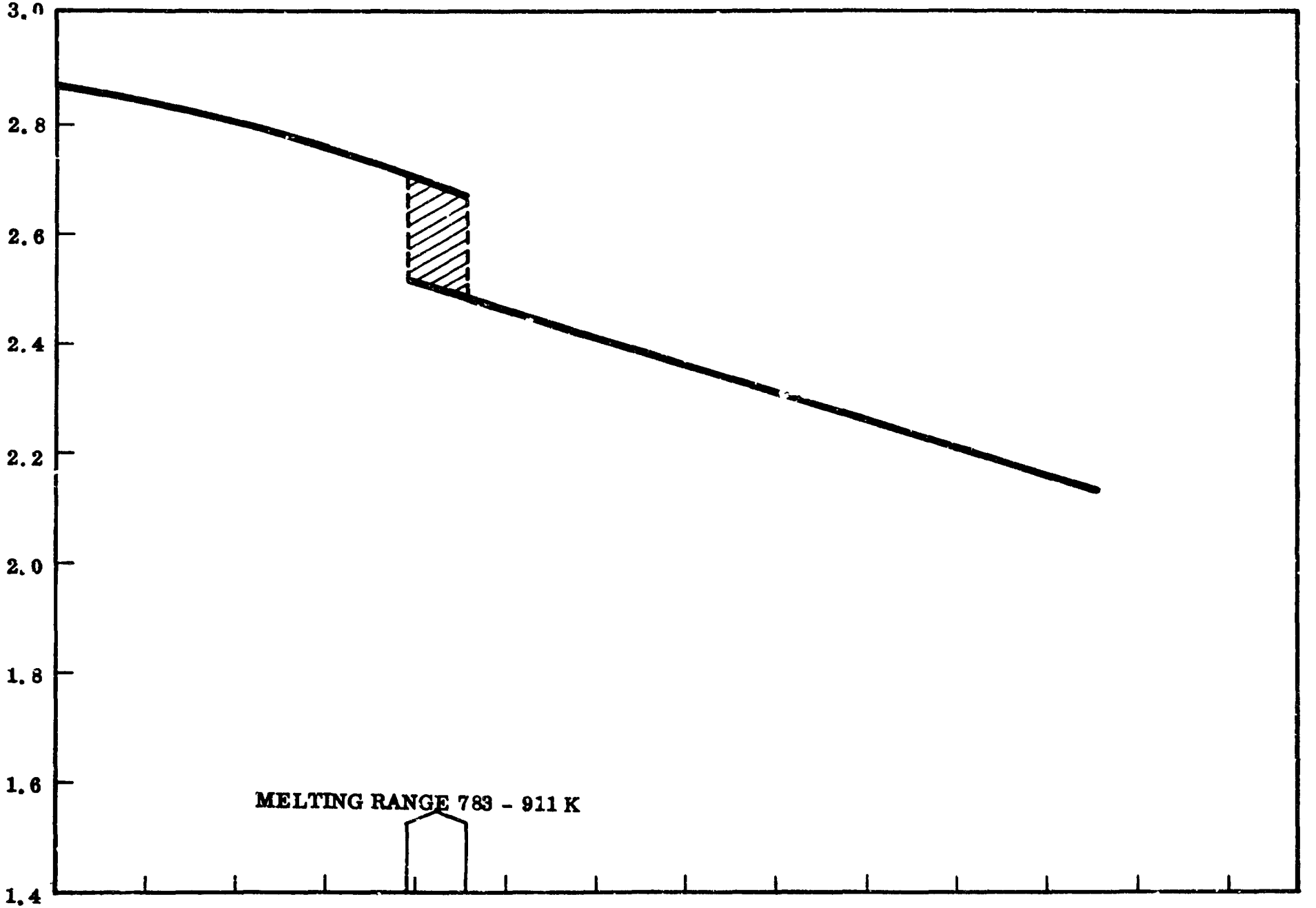

FIG. VI - 14

DENSITY -- ALUMINUM ALLOY 2219-T852

TABLE VI-14. DENSITY OF ALUMINUM ALLOY 2219-T852

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 2.87	1400	2.36
100	2.85	1500	2.34
200	2.84	1600	2.31
300	2.82	1700	2.28
400	2.80	1800	2.26
500	2.78	1900	2.24
600	2.76	2000	2.21
700	2.73	2100	2.28
Melting range 783-911°K		2200	2.16
1000	(l) 2.46	2300	2.14
1100	2.44		
1200	2.41		
1300	2.38		

SOURCE OF DATA

1) Value at room temperature: (a) Levy, A.V. (61)
2) Solid range: (b) from thermal expansion coefficient (III)
3) liquid range: (c) computed from mixing rule.

REMARKS: The value computed from mixing rule was found from 1.25 to 3% higher at room temperature, depending on composition. No accuracy can be stated. These data are only tentative values.

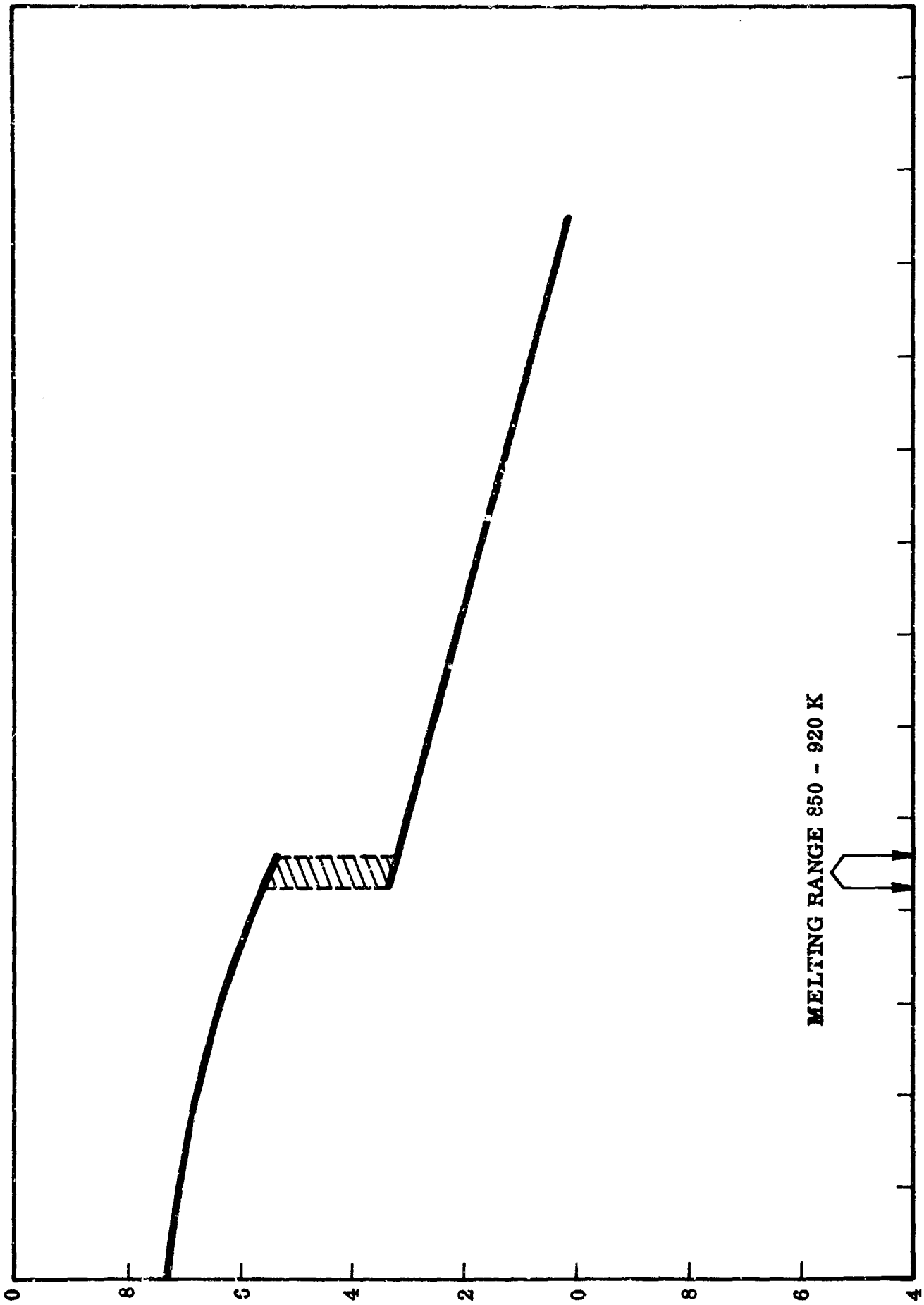

FIG. VI - 15 DENSITY -- ALUMINUM ALLOY 6061-T6

TABLE VI-15. DENSITY OF ALUMINUM ALLOY 6061-T6

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 2.73	1200	2.25
100	2.72	1300	2.23
200	2.71	1400	2.21
300	2.70	1500	2.19
400	2.68	1600	2.17
500	2.66	1700	2.15
600	2.63	1800	2.12
700	2.60	1900	2.10
800	2.57	2000	2.08
Melting range 850°K-920°K		2100	2.06
1000	(l) 2.30	2200	2.04
1100	2.28	2300	2.01

SOURCE OF DATA

1) Solid range: Material properties Handbook (62)
2) Melting range: from Metals handbook (I)
3) liquid range: computed from mixing rule.

REMARKS: The values obtained from mixing rule calculations were 1.25% higher at all temperature in the solid range.
No accuracy can be stated. These data are only tentative values.

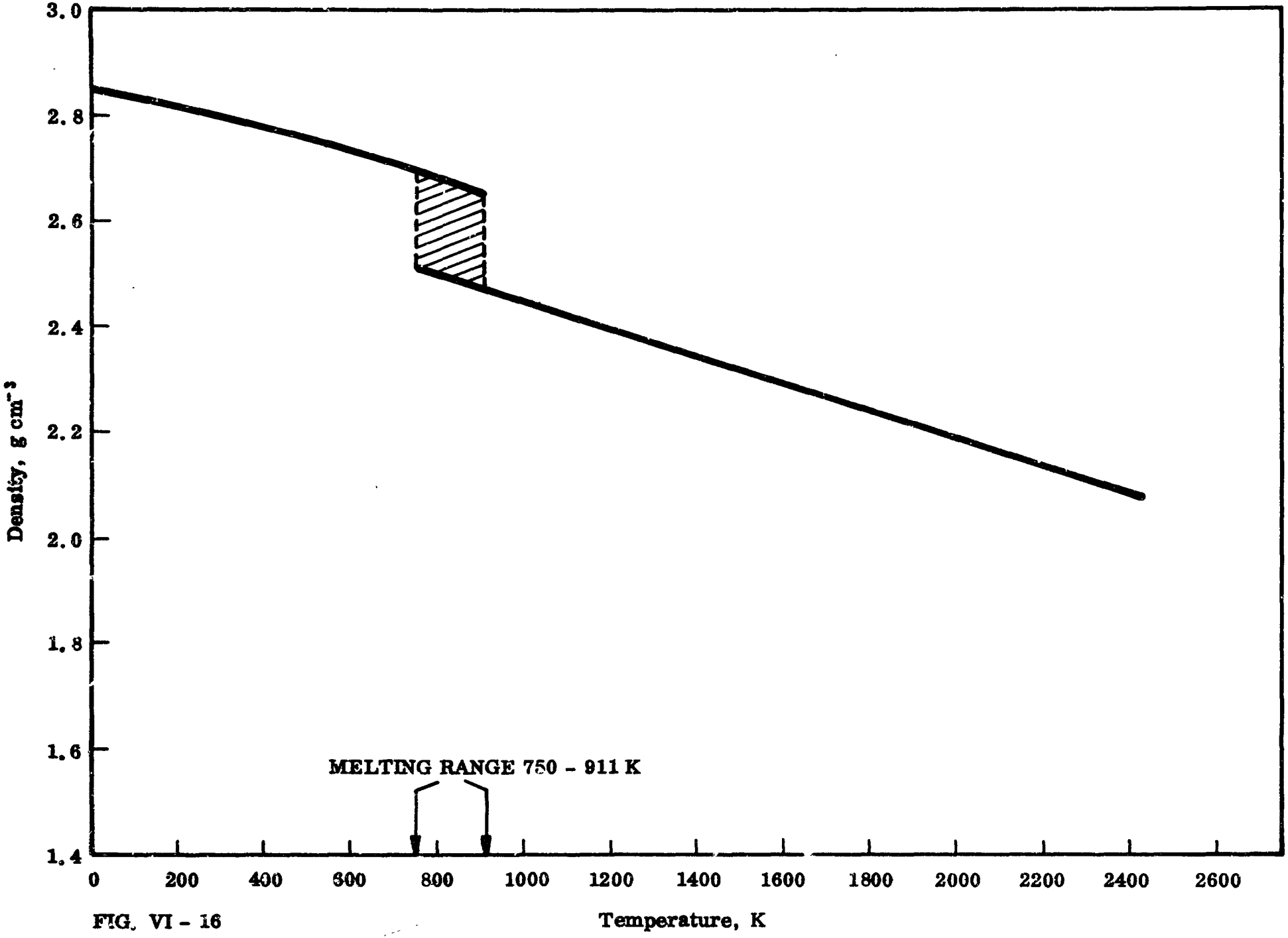

FIG. VI - 16

DENSITY -- ALUMINUM ALLOY 7075 - T6

TABLE VI-16. DENSITY OF ALUMINUM ALLOY 7075-T6

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 2.85	1300	2.37
100	2.84	1400	2.34
200	2.82	1500	2.31
300	2.80	1600	2.29
400	2.78	1700	2.26
500	2.76	1800	2.24
600	2.74	1900	2.21
700	2.71	2000	2.18
Melting range 750-911 °K		2100	2.16
1000	(1) 2.44	2200	2.13
1100	2.42	2300	2.11
1200	2.39	2400	2.08

SOURCE OF DATA

1) Solid range: from Material properties handbook (62)
2) Melting range: from Metals Handbook (I)
3) liquid range: computed from mixing rule

REMARKS: The values obtained from mixing rule calculation were 2 to 3% higher at all temperature in the solid range, depending on composition.
No accuracy can be stated. The data are only tentative values.

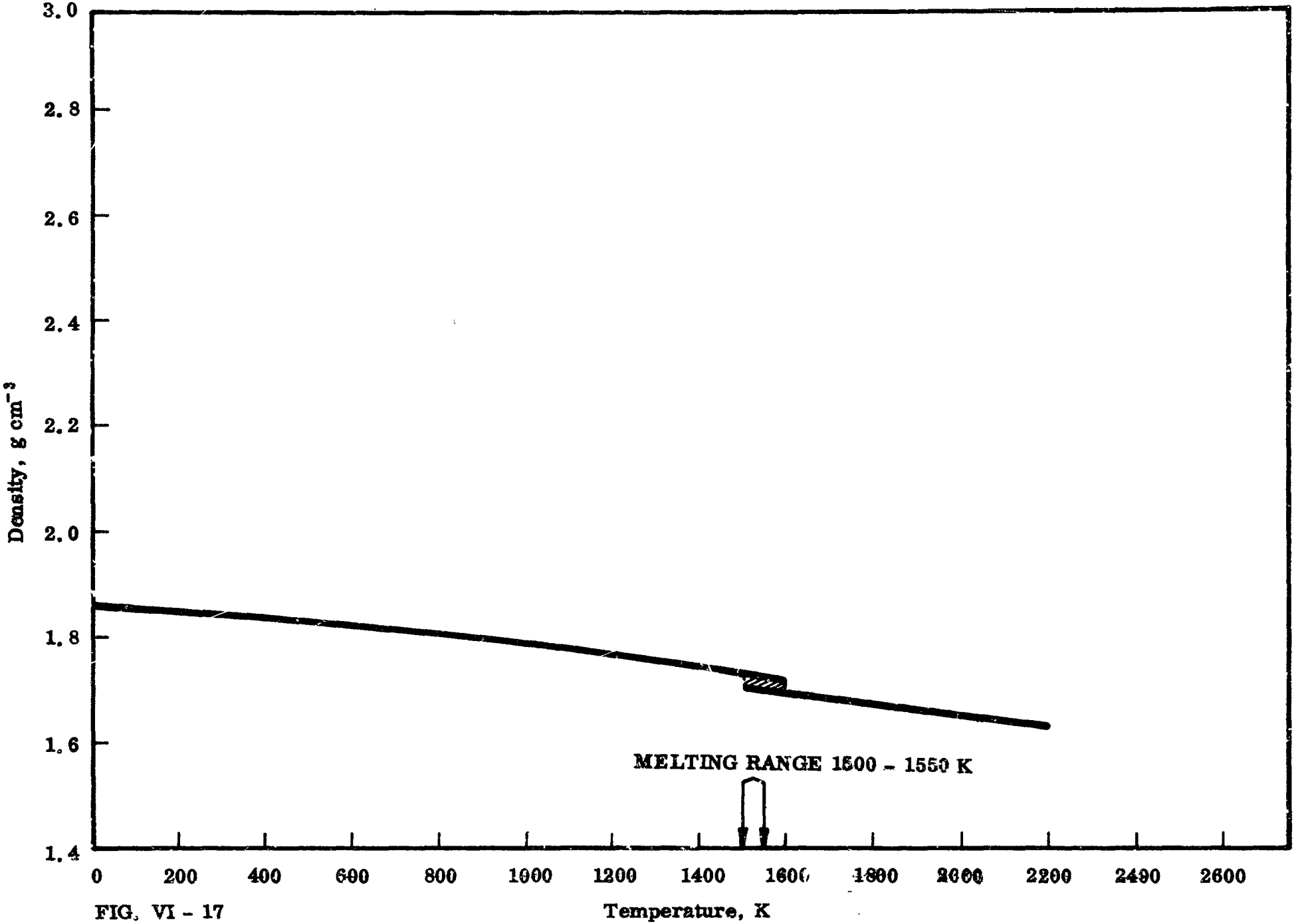

FIG. VI - 17

DENSITY -- BERYLLIUM ALLOY

TABLE VI-17. DENSITY OF BERYLLIUM ALLOY

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 1.857	1200	1.763
100	1.853	1300	1.753
200	1.848	1400	1.742
300	1.842	Melting range 1500-1550°K	
400	1.835	1600	(l) 1.694
500	1.828	1700	1.683
600	1.820	1800	1.672
700	1.812	1900	1.661
800	1.803	2000	1.650
900	1.794	2100	1.639
1000	1.784	2200	1.628
1100	1.774		

SOURCE OF DATA

None

REMARKS: The curve was computed by means of mixing rules.
The recommended curve is only slightly about 0.1% above the curve for pure beryllium.
The accuracy can be estimated the same as for pure beryllium.

TABLE VI-18. DENSITY OF STAINLESS STEEL 304A

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 7.998	900	7.655
100	7.967	1000	7.606
200	7.934	1100	7.555
300	7.899	1200	7.502
400	7.860	1300	7.446
500	7.821	1400	7.387
600	7.780	1500	7.325
700	7.737	1600	7.260
800	7.692		

SOURCE OF DATA

(a) Thornburg, D. L., Thall, E., Brous, J. (65)
(b) Stein, D. B., (63)
(c) Goldsmith, A. et al (III)

REMARKS: Densities between 7.86 (a) and 8.02 (b) have been reported at room temperature. The coefficient of thermal expansion is nearly the same as the coefficient of SS347 (c). More weight is given to information from (a) and this gives for SS 304 the same density as SS 347.

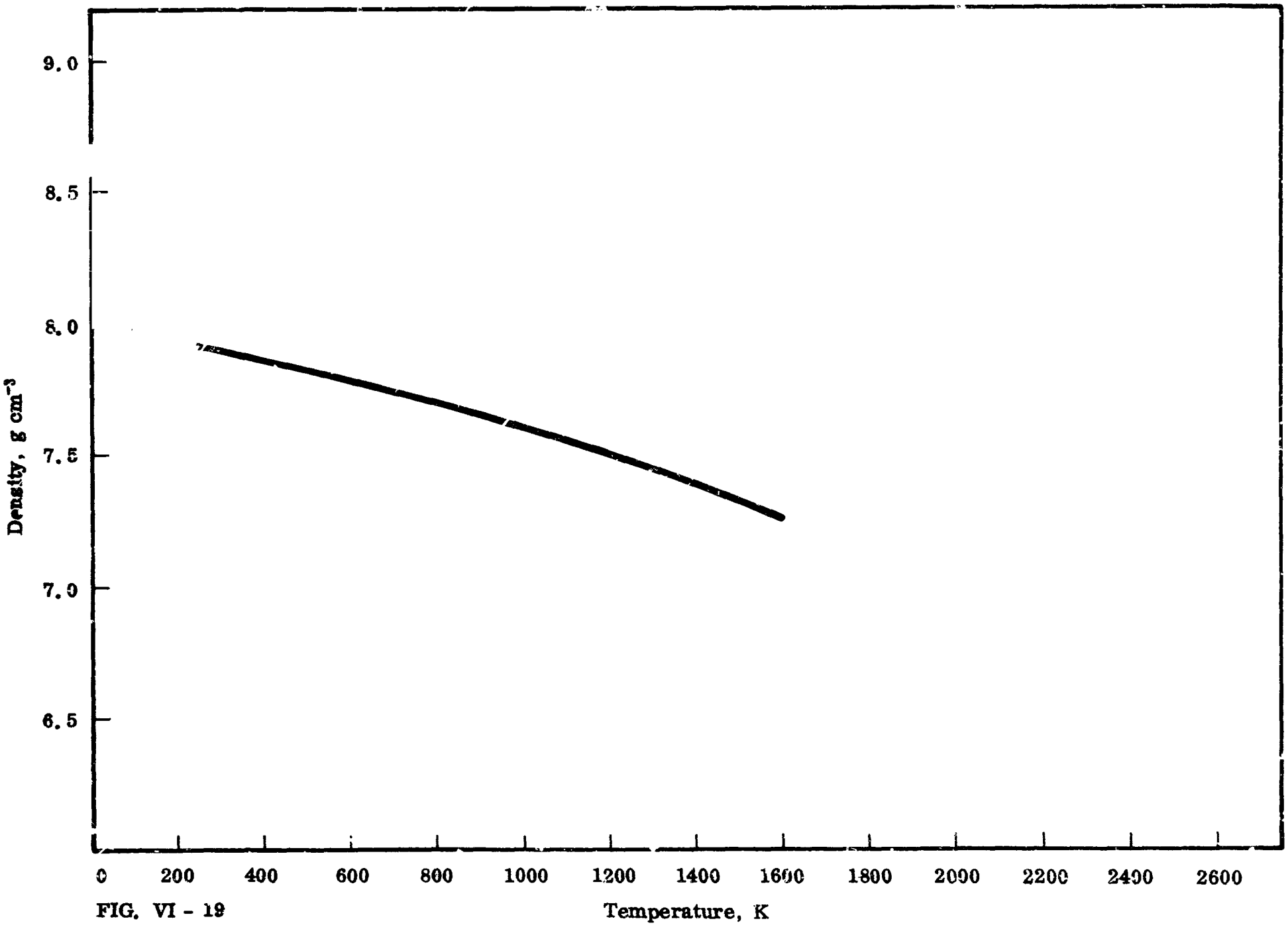

FIG. VI - 19

DENSITY - STAINLESS STEEL 347

TABLE VI-19. DENSITY OF STAINLESS STEEL 347

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) 7.998	900	7.655
100	7.967	1000	7.606
200	7.934	1100	7.555
300	7.899	1200	7.502
400	7.860	1300	7.446
500	7.821	1400	7.387
600	7.780	1500	7.325
700	7.737	1600	7.260
800	7.692		

SOURCE OF DATA

(a) 366-1255°K = Stein, D. B. (63)
(b) 83-1273°K = Lucks, C. F. and Coll. (64)

REMARKS: Accuracy: ±.5% or better.

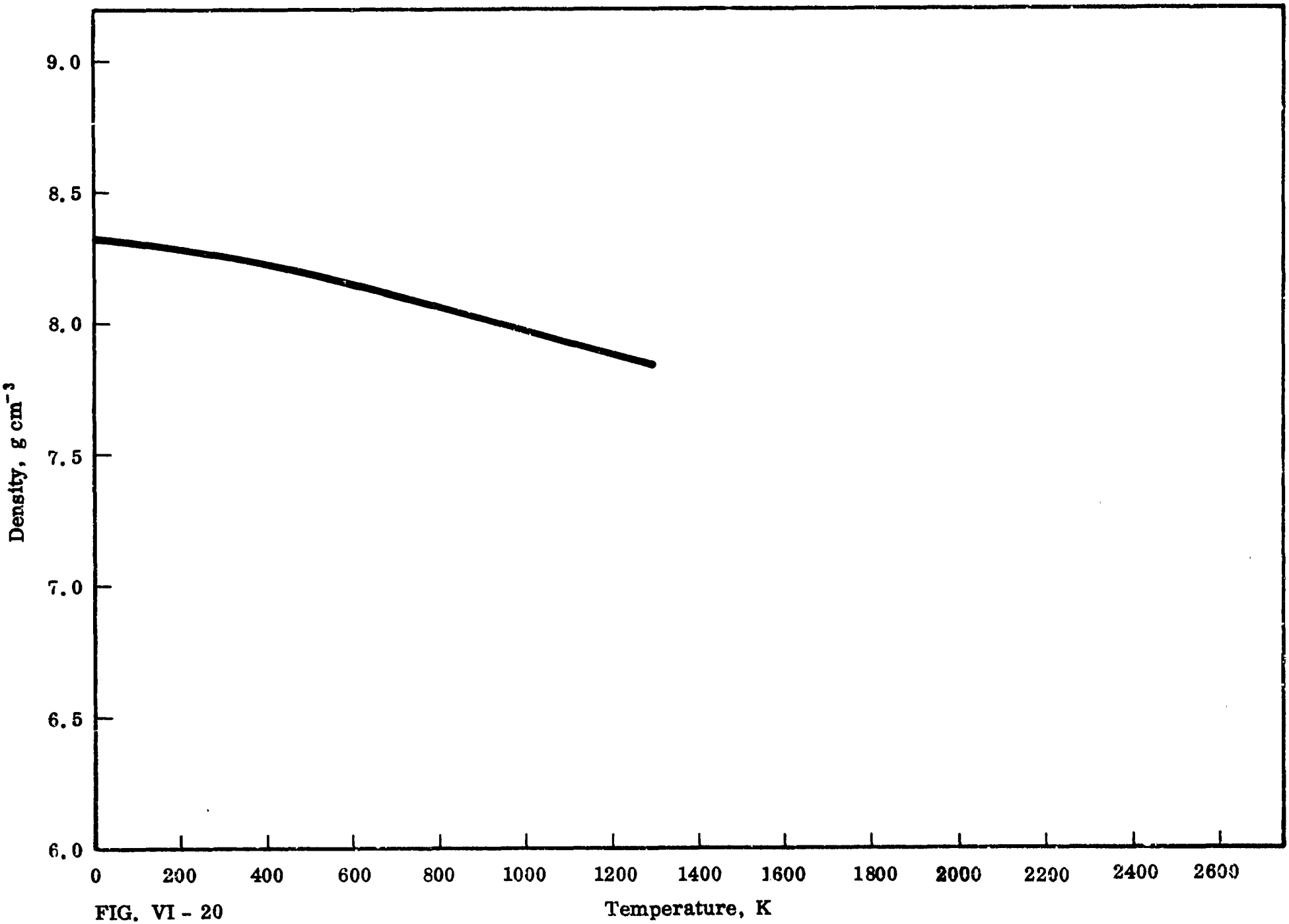

FIG. VI - 20

DENSITY -- INCONEL X-750

TABLE VI-20. DENSITY OF INCONEL X-750

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 8.324	900	8.021
100	8.301	1000	7.977
200	8.276	1100	7.930
300	8.247	1200	7.880
400	8.214	1300	7.828
500	8.179	1400	7.774
600	8.142	1500	7.718
700	8.103	1600	7.660
800	8.063	Melting point at about 1700°K	

SOURCE OF DATA

(a) Stein, D. B. (63) [Note: calculated from thermal expansion data, from unknown source, and a density value of 8.30]
(b) Lucks, C. F. et al (64)

REMARKS: Some value about 3% higher are reported [see Metal Handbook (I)] at room temperature and some 3% lower [see Goldsmith and Coll. (III)]. The values from (b) seems the more reliable values, but the density is expected to be very dependent on composition.

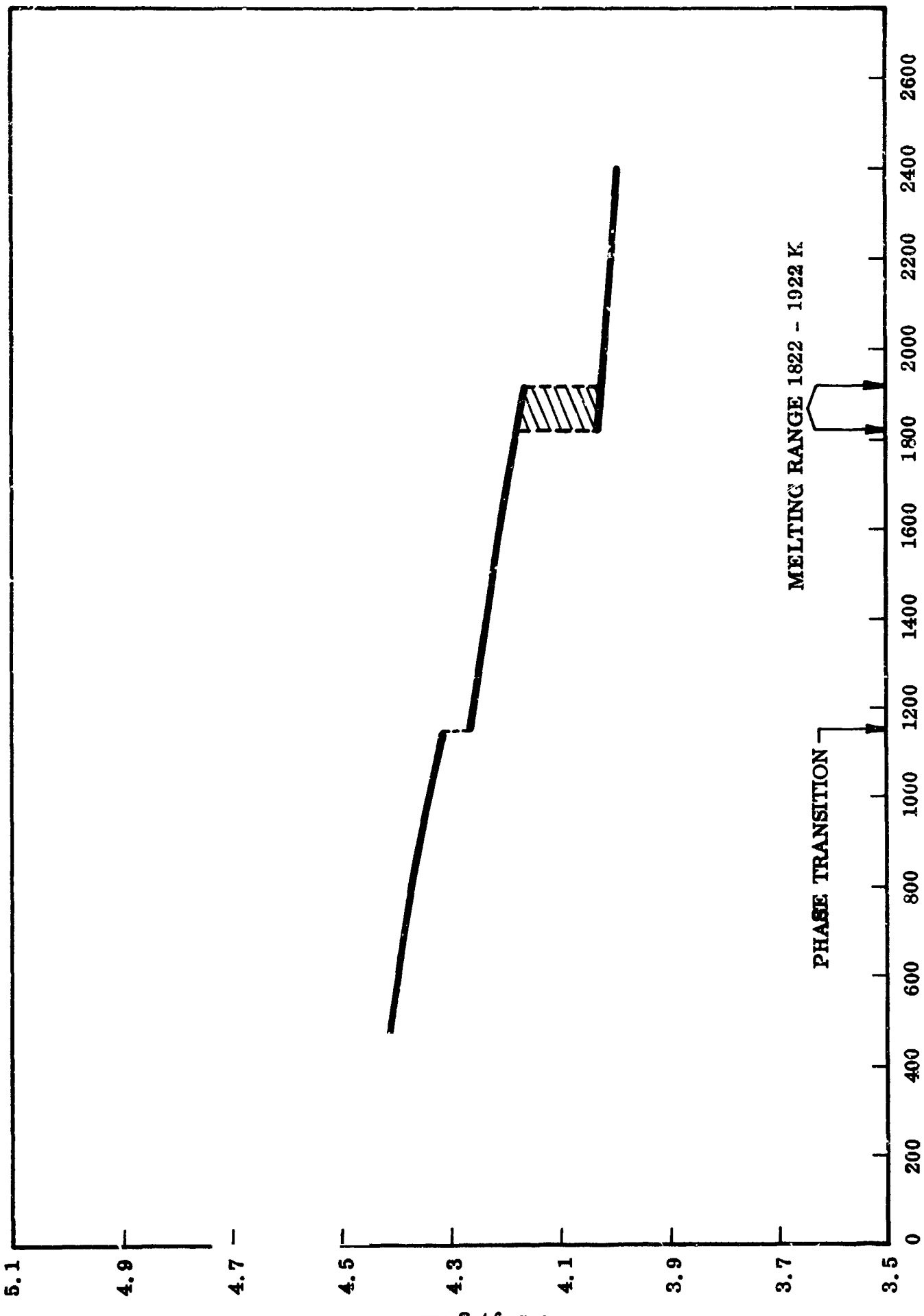

FIG. VI - 21

DENSITY -- TITANIUM ALLOY A-110AT

TABLE VI-21. DENSITY OF TITANIUM ALLOY A-110AT

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 4.454	1200	4.260
100	4.447	1300	4.248
200	4.439	1400	4.235
300	4.430	1500	4.222
400	4.420	1600	4.208
500	4.409	1700	4.194
600	4.397	1800	(s) 4.167
700	4.384	Melting range 1822-1922°K	
800	4.370	2000	(l) 4.013
900	4.355	2100	4.012
1000	4.339	2200	4.005
1100	4.322	2300	3.998
1155 (phase transition of Ti)	4.312	2400	3.991
1155	4.265		

SOURCE OF DATA

1) Solid range: from Metals Handbook (I)

2) Melting range: ibid

3) liquid range: computed from mixing rule

REMARKS: The curve computed by means of mixing rule was found 1 to 2% lower at room temperature than the recommended value of the Metal Handbook. The mean value was chosen. Pure Titanium has a phase transition at 1155°K. Since Ti-alloy is 91% Titanium the phase transition is expected to be noticeable.

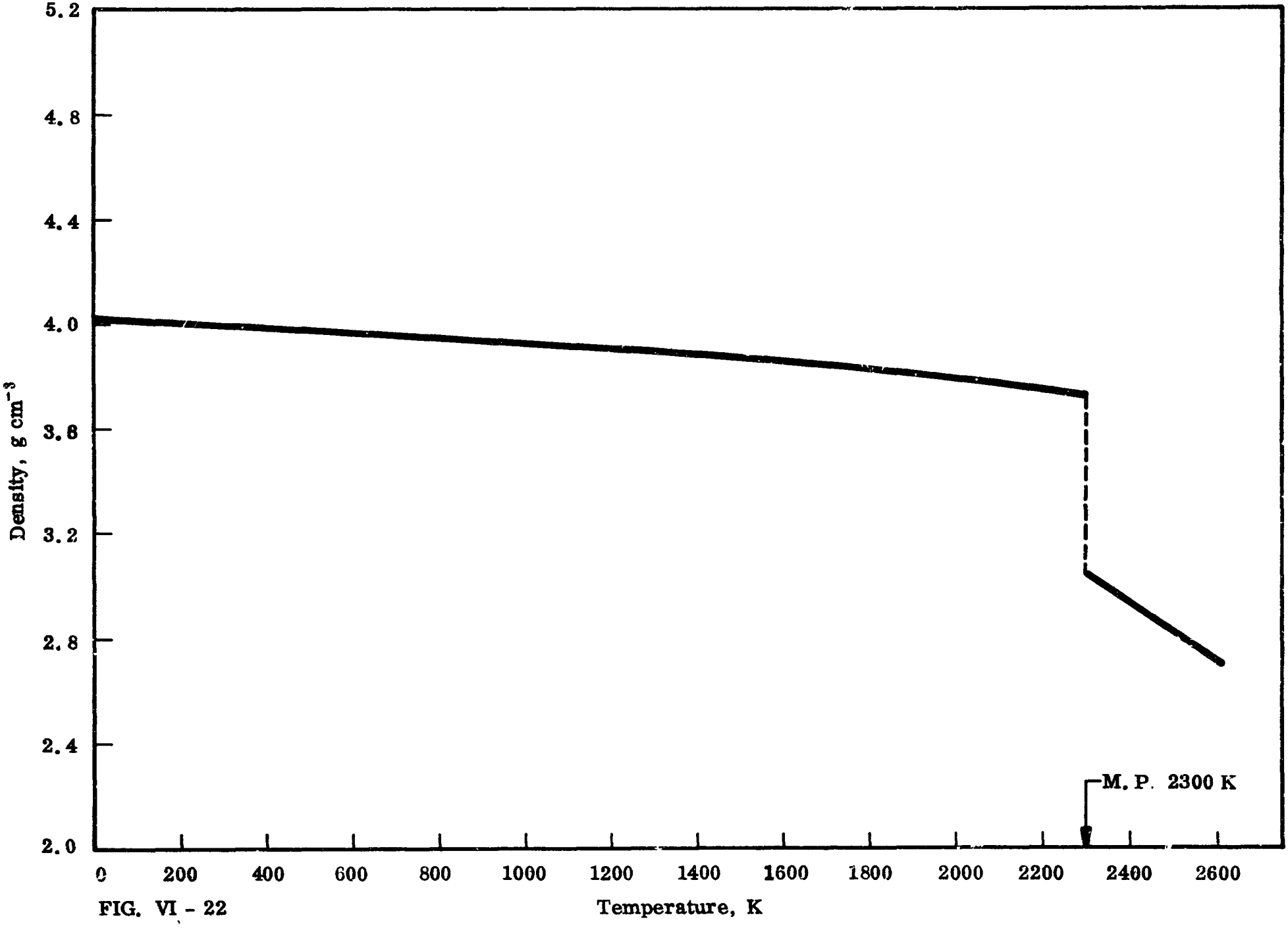

FIG. VI - 22

DENSITY -- ALUMINUM OXIDE, Al_2O_3

TABLE VI-22. DENSITY OF ALUMINUM OXIDE (Al_2O_3)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	(s) 4.03	1400	3.88
100	4.02	1500	3.87
200	4.01	1600	3.85
300	4.00	1700	3.84
400	3.99	1800	3.82
500	3.98	1900	3.81
600	3.97	2000	3.79
700	3.96	2100	3.77
800	3.95	2200	3.75
900	3.94	2300(m.p.) (s)	3.72
1000	3.93	2300(m.p.) (l)	3.04
1100	3.92	2400	2.93
1200	3.91	2500	2.81
1300	3.89	2600	2.70

SOURCE OF DATA

1) Value at room temperature (a) Goldsmith, A. and coll. (III)
2) Solid range (b) thermal expansion coefficient, (ibid.)
3) liquid range (c) Kirshenbaum, A.D. and Cahill, J.A. (66)
   (d) Kingery, W.D. (67)

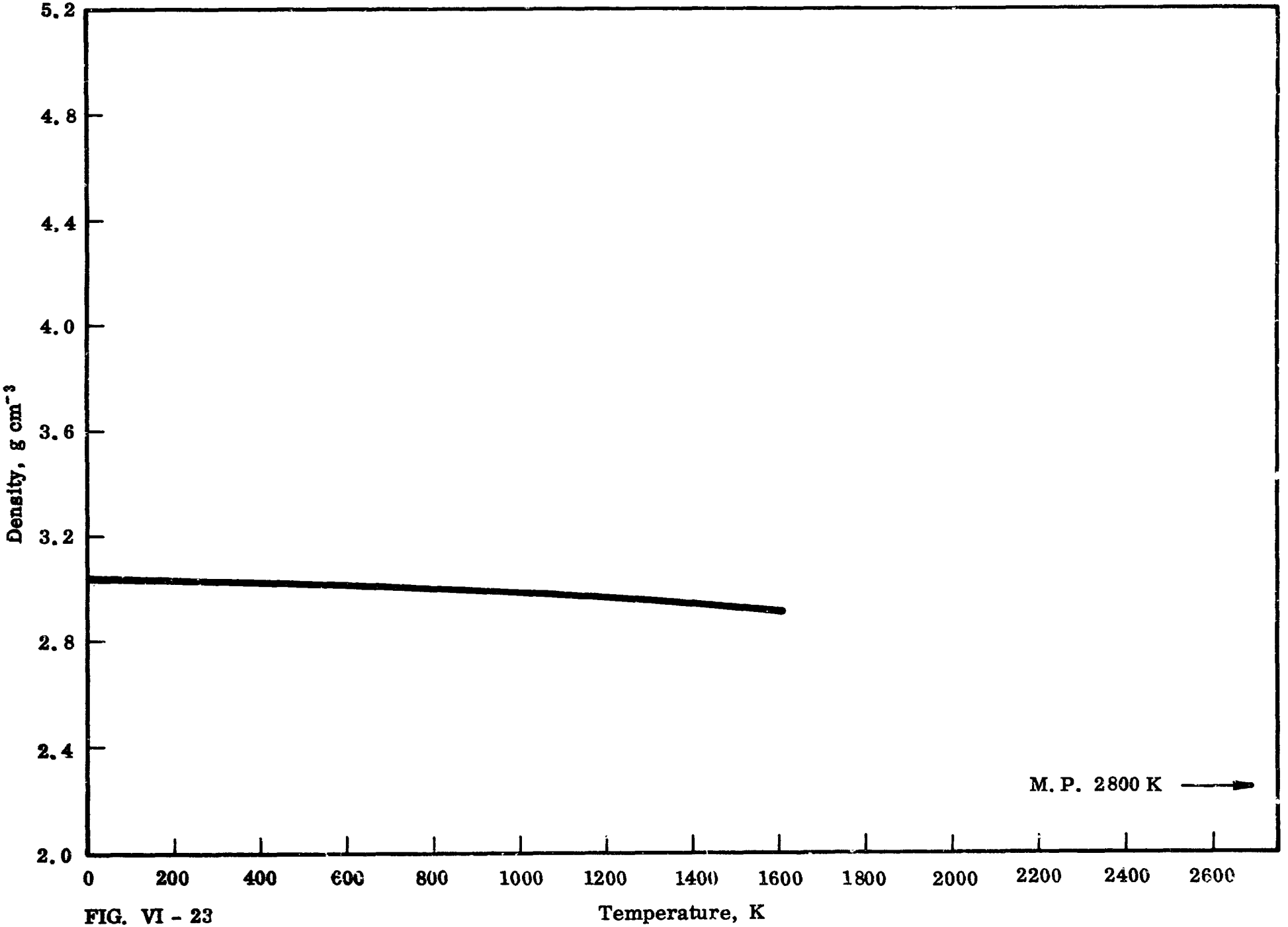

FIG. VI - 23

DENSITY - - BERYLLIUM OXIDE, BeO

TABLE VI-23. DENSITY OF BERYLLIUM OXIDE (BeO)

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) (3.05)	300	2.99
100	(3.04)	1000	2.98
200	(3.04)	1100	2.97
300	3.03	1200	2.96
400	3.02	1300	2.95
500	3.02	1400	2.94
600	3.01	1500	2.93
700	3.00	1600	2.91
800	2.99	2800(m.p.)	

SOURCE OF DATA

1) Value at room temperature:
   (a) Goldsmith, A. and coll. (III)
2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

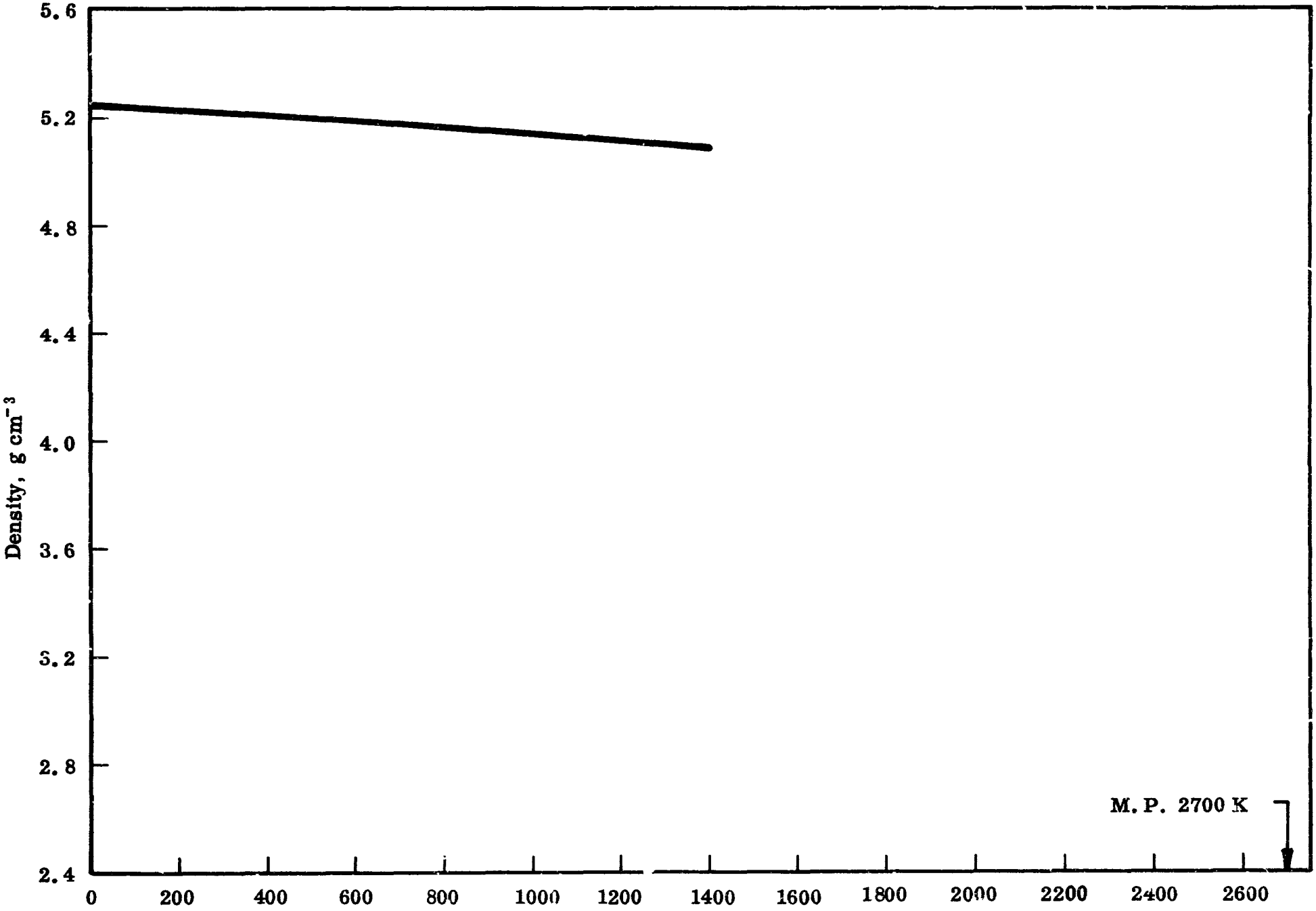

FIG. VI. - 24

DENSITY -- CHROMIUM OXIDE, Cr_2O_3

TABLE VI-24. DENSITY OF CHROMIUM OXIDE (Cr_2O_3)

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) (5.25)	900	5.15
100	(5.24)	1000	5.14
200	(5.23)	1100	5.13
300	5.22	1200	5.11
400	5.21	1300	5.10
500	5.20	1400	5.09
600	5.19		
700	5.17		
800	5.16		

SOURCE OF DATA

1) Value at room temperature: (a) Rigby G.R., Lovell, G.H. and Green A.T. (68)

2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

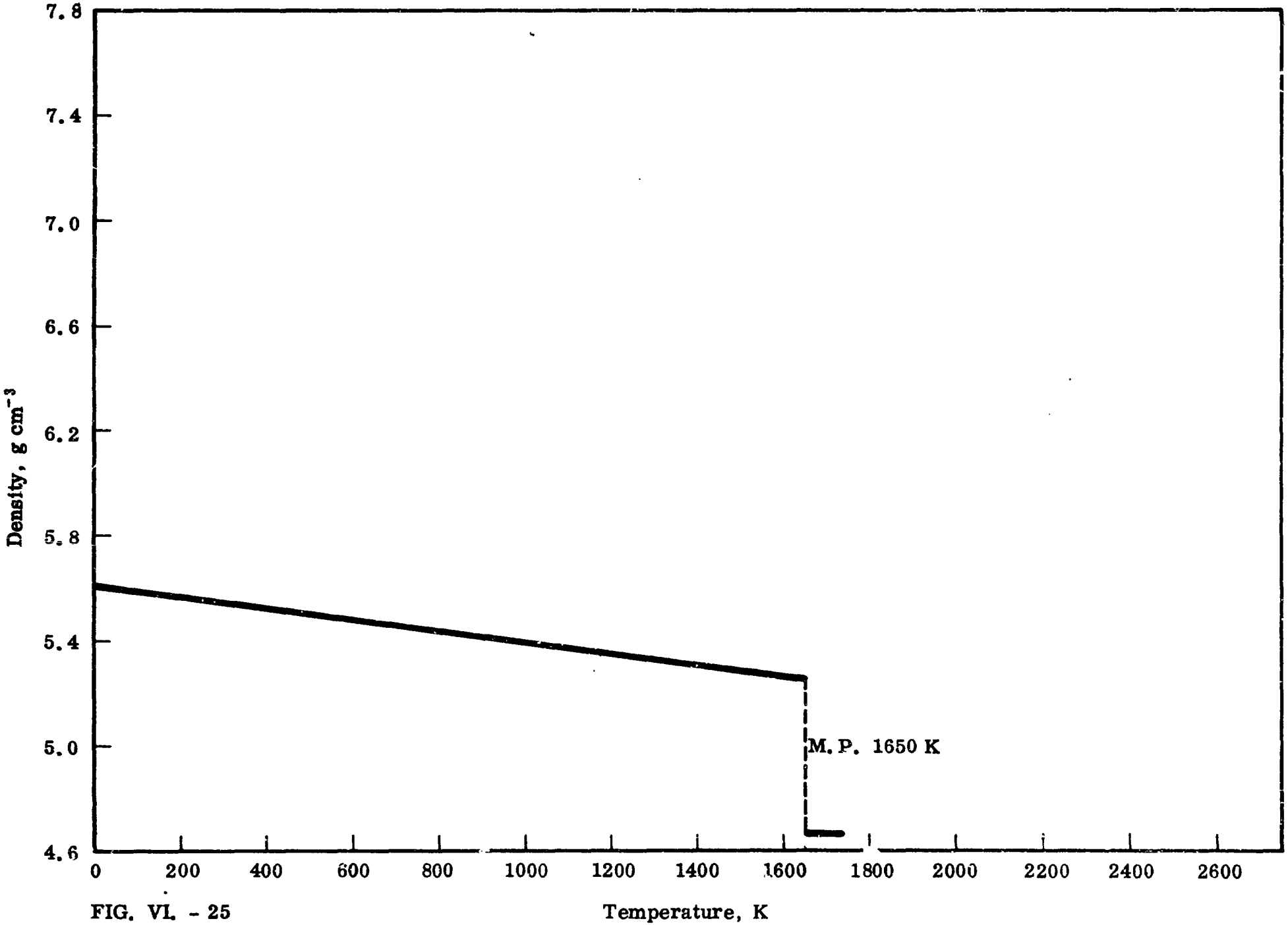

FIG. VI. - 25

DENSITY -- IRON OXIDE, FeO

TABLE VI-25. DENSITY OF IRON OXIDE (FeO)

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})	T(°K)	ρ(g.cm^{-3})
0	(s) (5.60)	1000	5.40
100	(5.58)	1100	5.38
200	(5.56)	1200	5.36
300	5.54	1300	5.34
400	5.52	1400	5.32
500	5.50	1500	5.30
600	5.48	(1600)	5.28
700	5.46	1650	(s) 5.27
800	5.44	1650	(l) 4.65 ± 0.10
900	5.42		

SOURCE OF DATA

1) Value at room temperature: (a) Rigby, G.R., Lovell G.H., and Green, A.T. (68)

2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

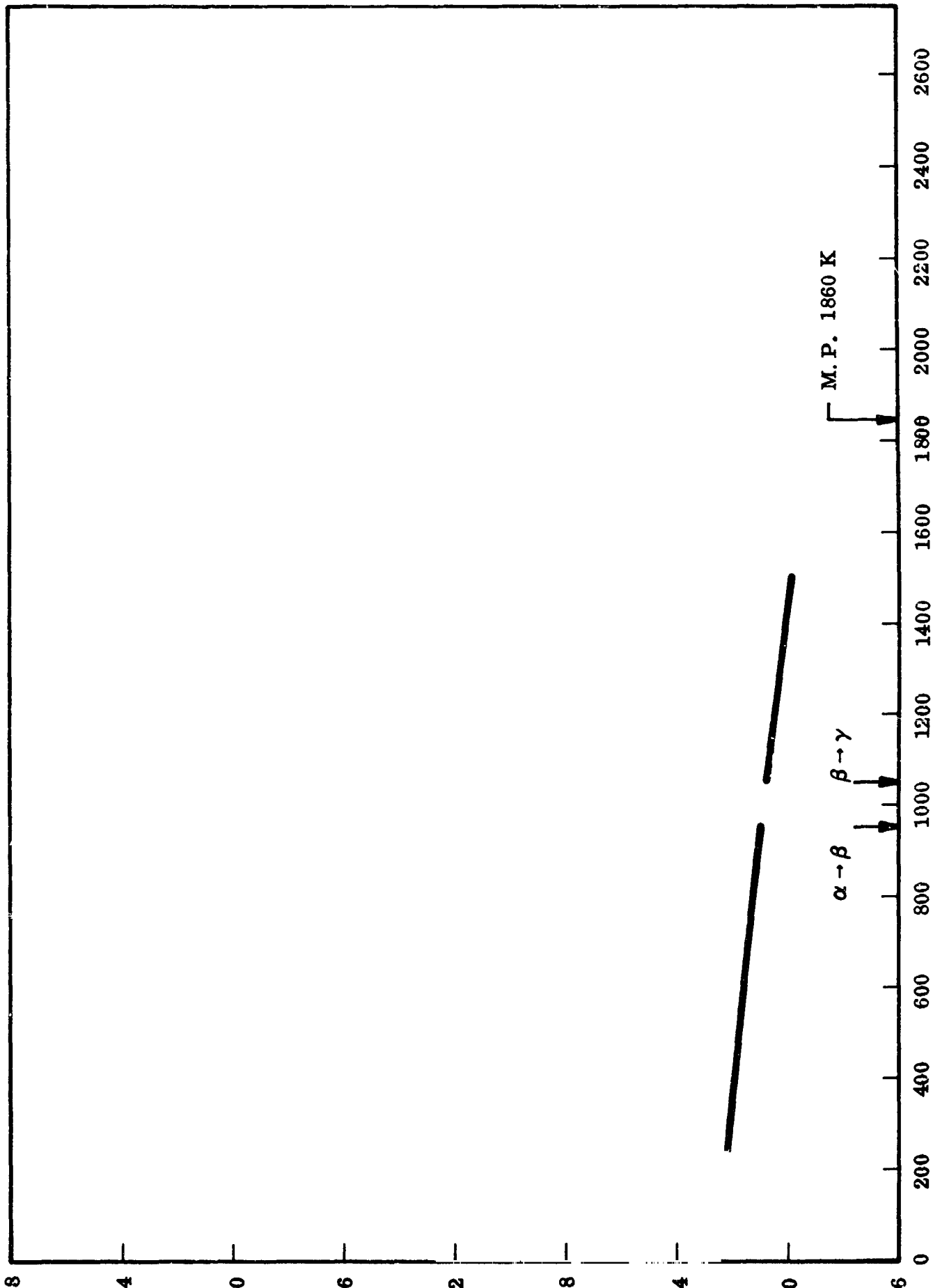

FIG. VI. - 26

DENSITY -- IRON OXIDE, Fe_2O_3

TABLE VI-26. DENSITY OF IRON OXIDE (Fe_2O_3)

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3})
0	(s) (5.28)
100	(5.26)
200	(5.24)
300	5.22
400	5.20
500	5.18
600	5.16
700	5.14
800	5.12
900	5.10
transformation point $\alpha - \beta$	
1000	(5.08)
transformation point $\beta - \gamma$	
1100	5.06
1200	5.04
1300	5.02
1400	5.00
1500	4.98

SOURCE OF DATA

1) Value at room temperature: Rigby, G.R., Lovell, G.H., and Green A.T. (68)

2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

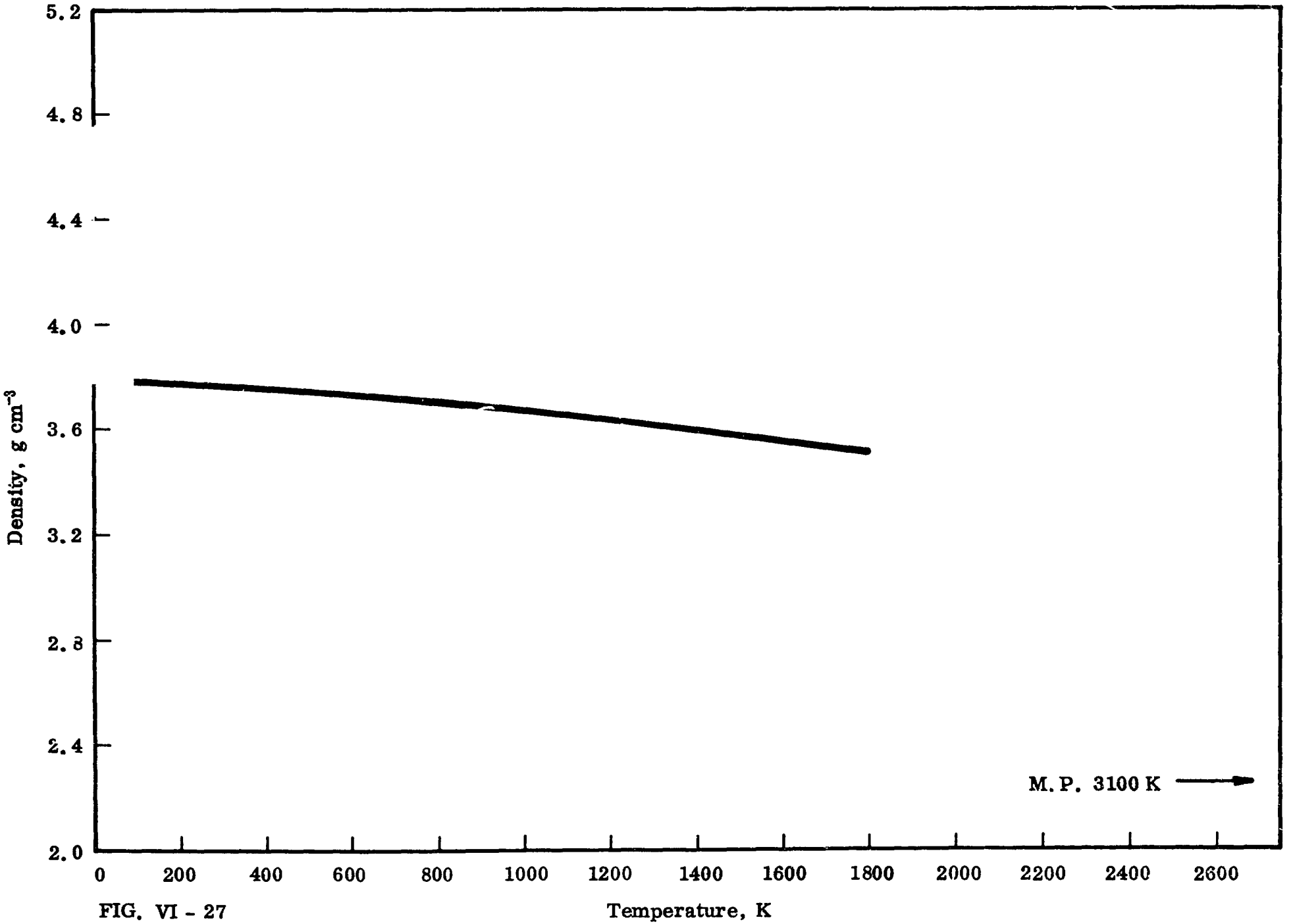

FIG. VI - 27

DENSITY -- MAGNESIUM OXIDE, MgO

TABLE VI-27. DENSITY OF MAGNESIUM OXIDE (MgO)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	3.81	1000	3.67
100	3.80	1100	3.65
200	3.78	1200	3.63
300	3.77	1300	3.61
400	3.76	1400	3.59
500	3.74	1500	3.57
600	3.73	1600	3.55
700	3.71	1700	3.53
800	3.70	1800	3.51
900	3.68	3100 m.p.	

SOURCE OF DATA

1) Value at room temperature: (from lattice constants) Johnson, P.D. (69)

2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

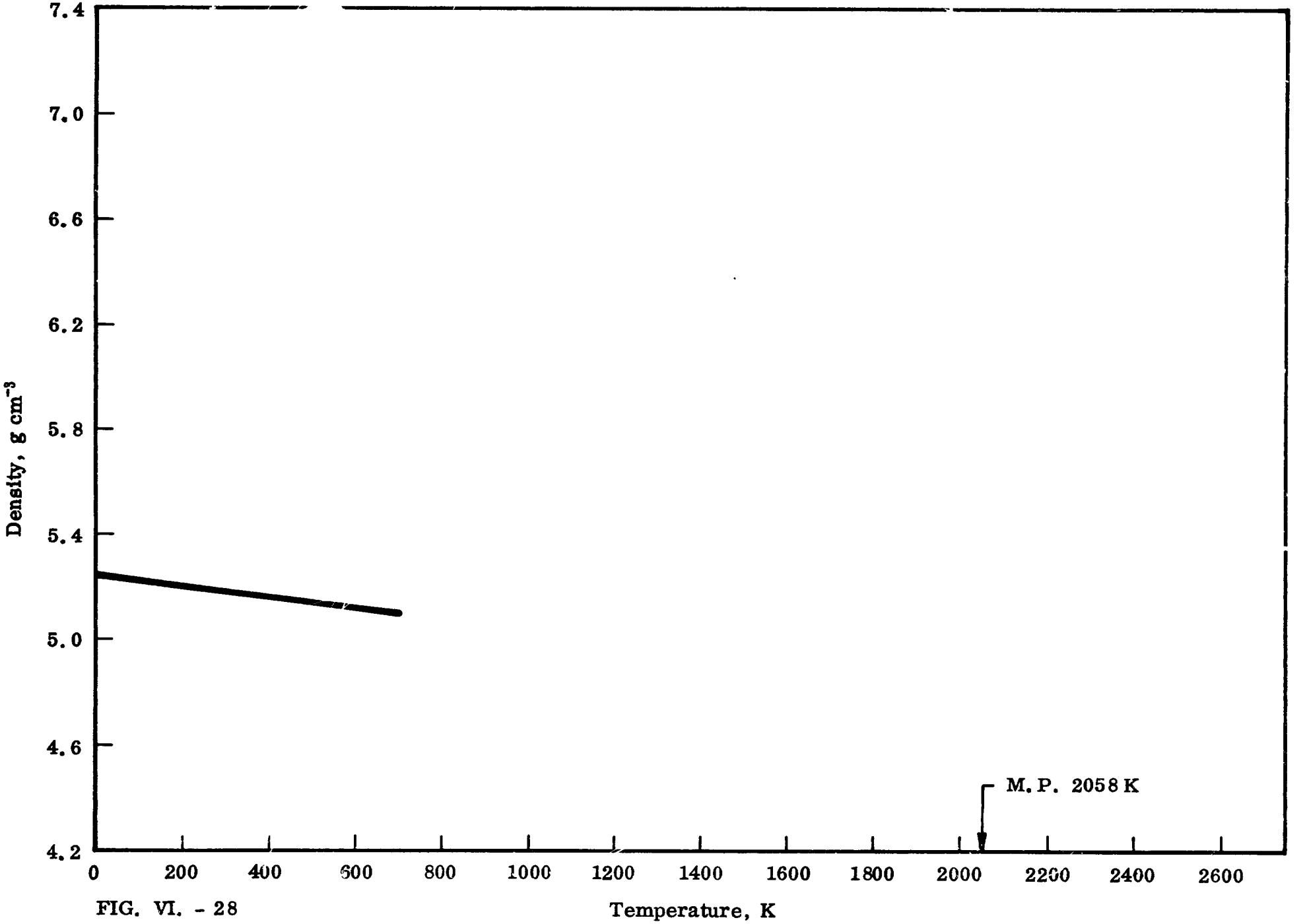

FIG. VI. - 28

DENSITY -- MANGANESE OXIDE, MnO

TABLE VI-28. DENSITY OF MANGANESE OXIDE (MnO)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	5.24	500	5.14
100	5.22	600	5.12
200	5.20	700	5.10
300	5.18		
400	5.16		

SOURCE OF DATA

1) Value at room temperature: Handbook of Chemistry and Physics (IV)
2) Solid range: from thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

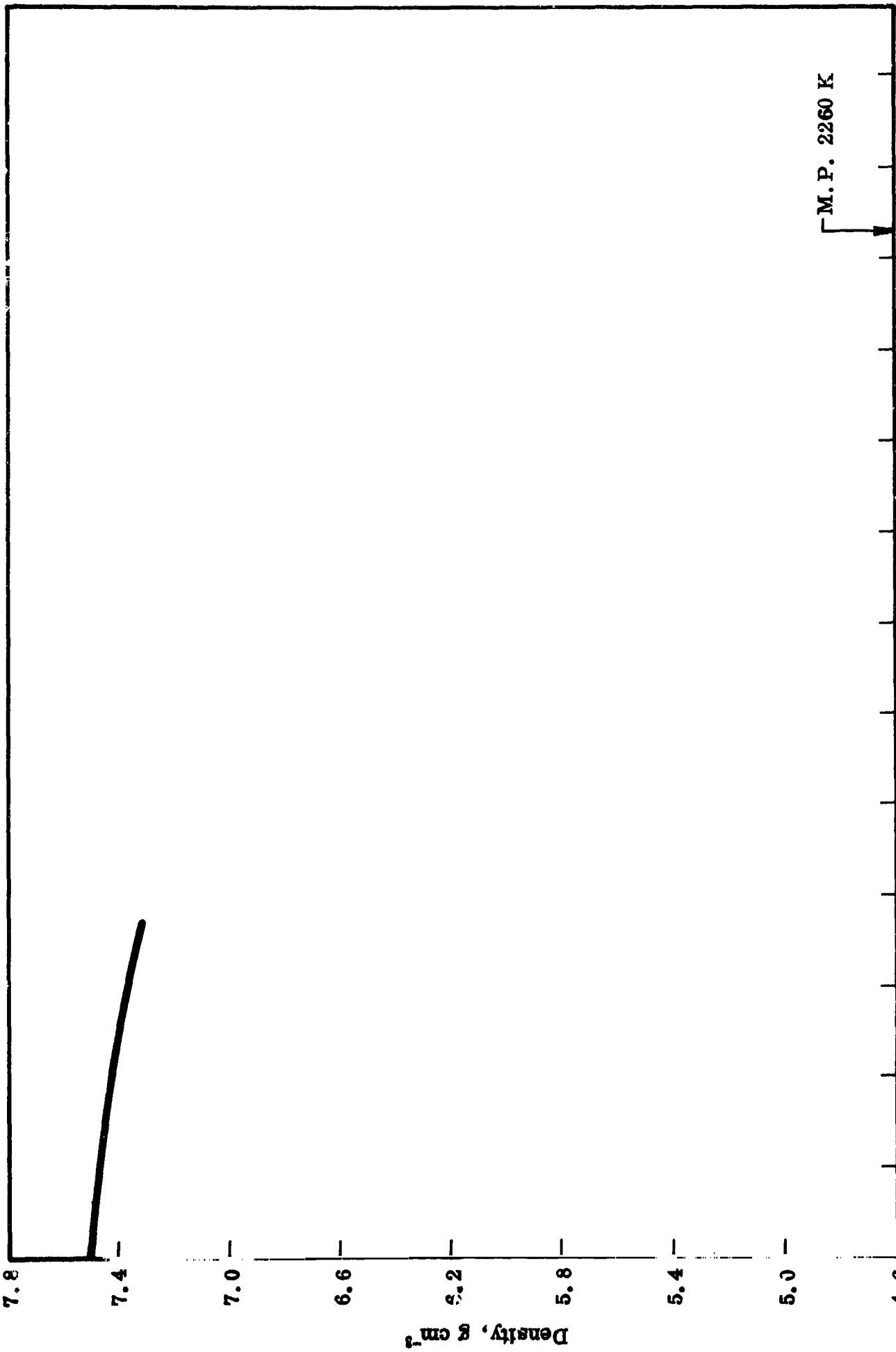

FIG. VI. - 29

DENSITY -- NICKEL OXIDE, NiO

TABLE VI-29. DENSITY OF NICKEL OXIDE (NiO)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	7.50	500	7.39
100	7.48	600	7.36
200	7.46	700	7.33
300	7.45		
400	7.42		

SOURCE OF DATA

1) Value at room temperature: Handbook of Chemistry and Physics (IV)
2) Solid range: Thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

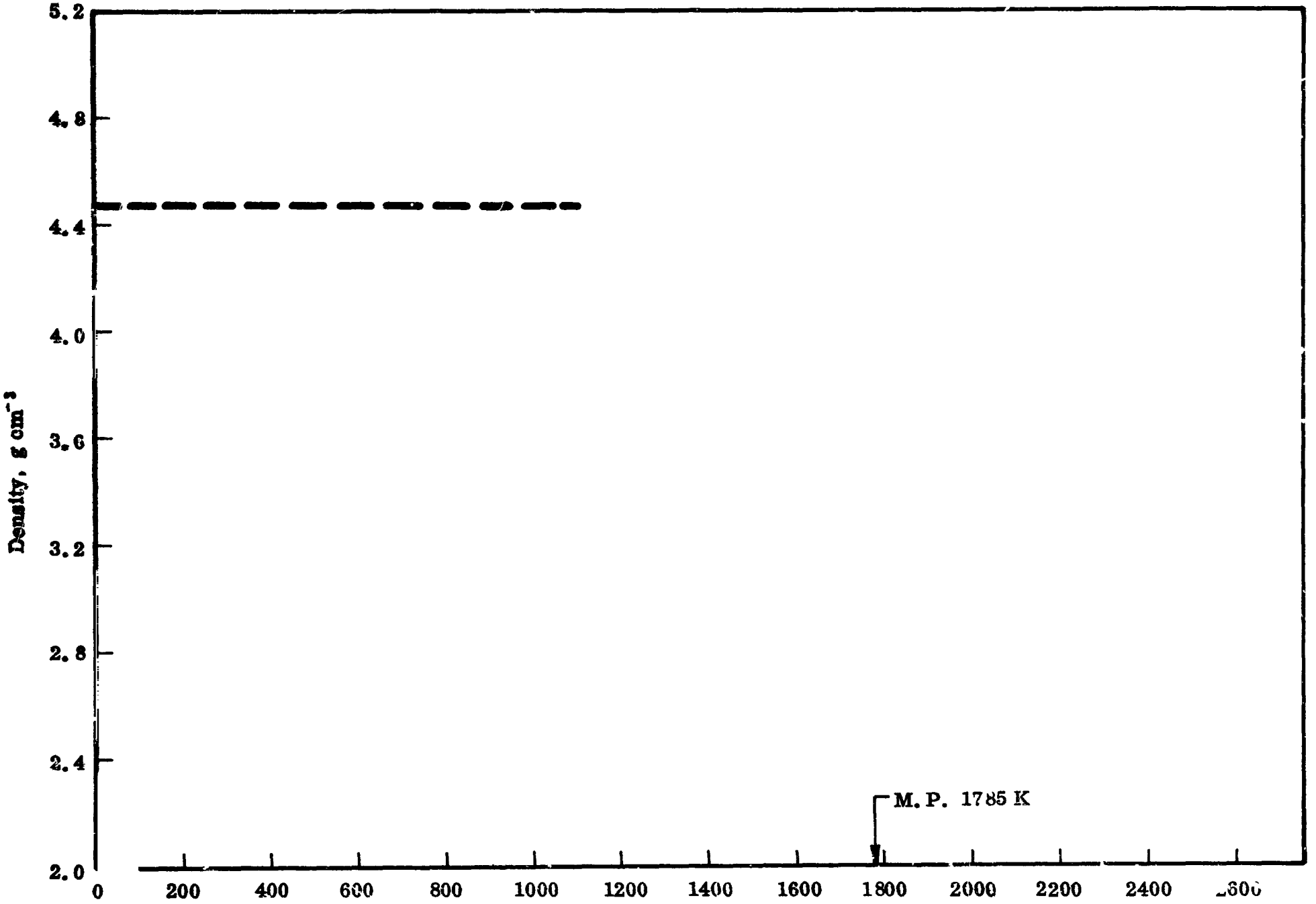

FIG. VI. - 30

DENSITY -- NIOBIUM OXIDE, Nb_2O_5

TABLE VI-30. DENSITY OF NIOBIUM OXIDE (Nb_2O_5)

RECOMMENDED VALUE

Value at room temperature = 7.45 g. cm^{-3} (a)

At other temperature, up to 1100°K one should accept the same value, the coefficient of linear expansion being particularly small. (b)

SOURCE OF DATA

1) Value at room temperature: (a) Handbook of Chemistry and Physics (IV)
2) Solid range: (b) thermal expansion coefficient recommended by Goldsmith, A. and coll. (III)

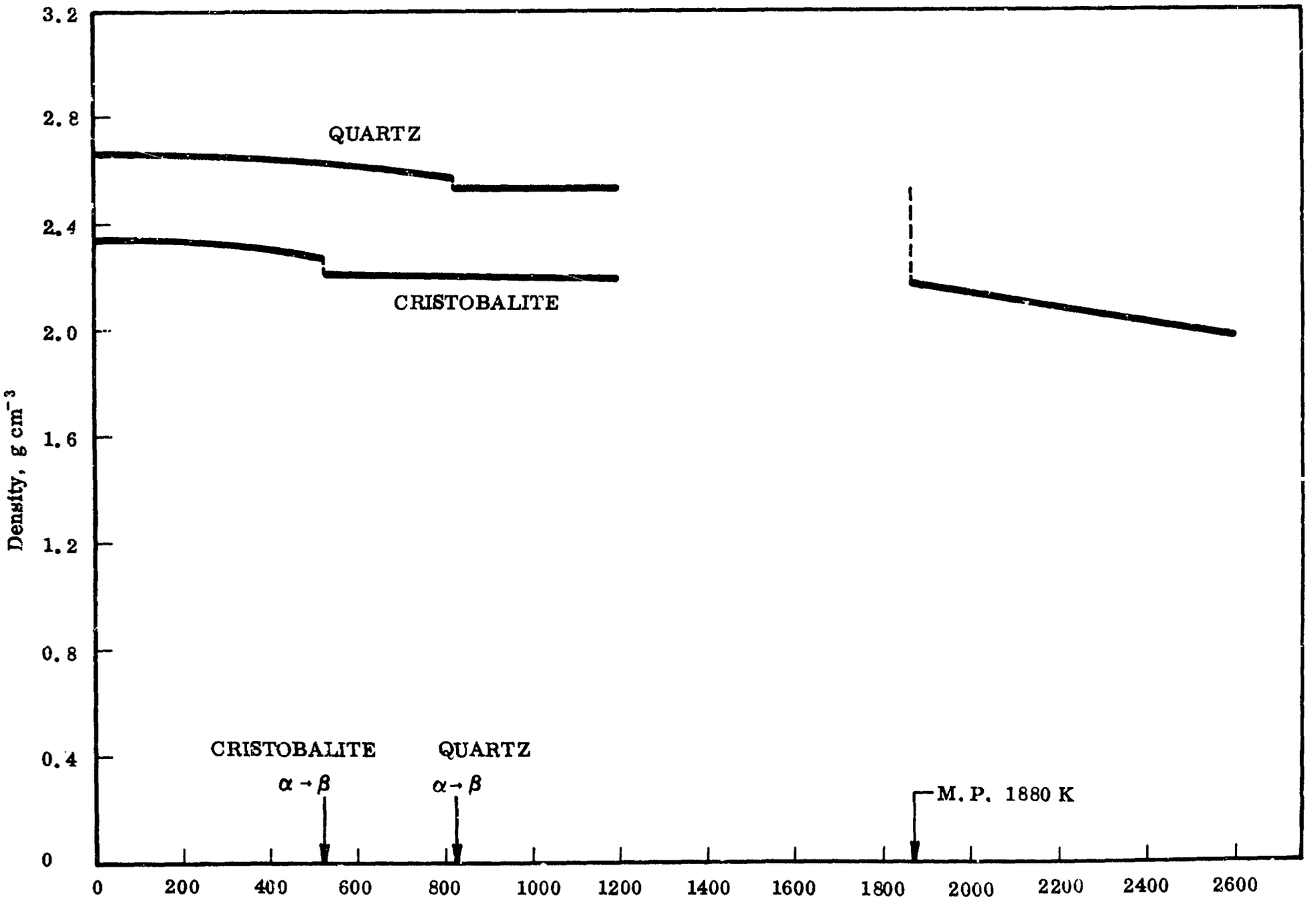

FIG. VI. - 31

DENSITY -- SILICON OXIDE, SiO_2

TABLE VI-31. DENSITY OF SILICON OXIDE (SiO_2)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3}) (Quartz)	(Cristobalite)	T(°K)	ρ(g. cm^{-3})
0	(s) 2.668	(s) 2.34	1880(m.p.)	(l) 2.17
100	2.664	2.34	1900	2.16
200	2.658	2.33	2000	2.13
300	2.650	2.320	2100	2.11
400	2.640	2.31	2200	2.08
500	2.628	2.27	2300	2.05
523		p.t. $\alpha \rightarrow \beta$	2400	2.03
600	2.614	2.20	2500	2.00
700	2.598	2.20	2600	1.97
800	2.570	2.20		
848	p.t. $\alpha \rightarrow \beta$			
900	2.531	2.19		
1000	2.531	2.19		
1100	2.531	2.19		
1200	2.531	2.19		

SOURCE OF DATA

1) Value at room temperature: i-Quartz (a) Batuecas, T. and Gutierrez, L. (70), (b) Smakula A. and Sils, V. (2) (c) Miller, P.H., and Dumond, J.W.M. (3). ii-Cristobalite (d) Handbook of Chemistry and Physics (IV)

2) Thermal expansion coefficient: i-Quartz; (e) Rosenholtz, S.L. and Smith, D.T. (71); ii-Cristobalite (f) Hummel, F.A. (72).

3) Liquid range: (g) Bacon, J.F., Hasapis, A.A., and Wholley, J. W. Jr. (73).

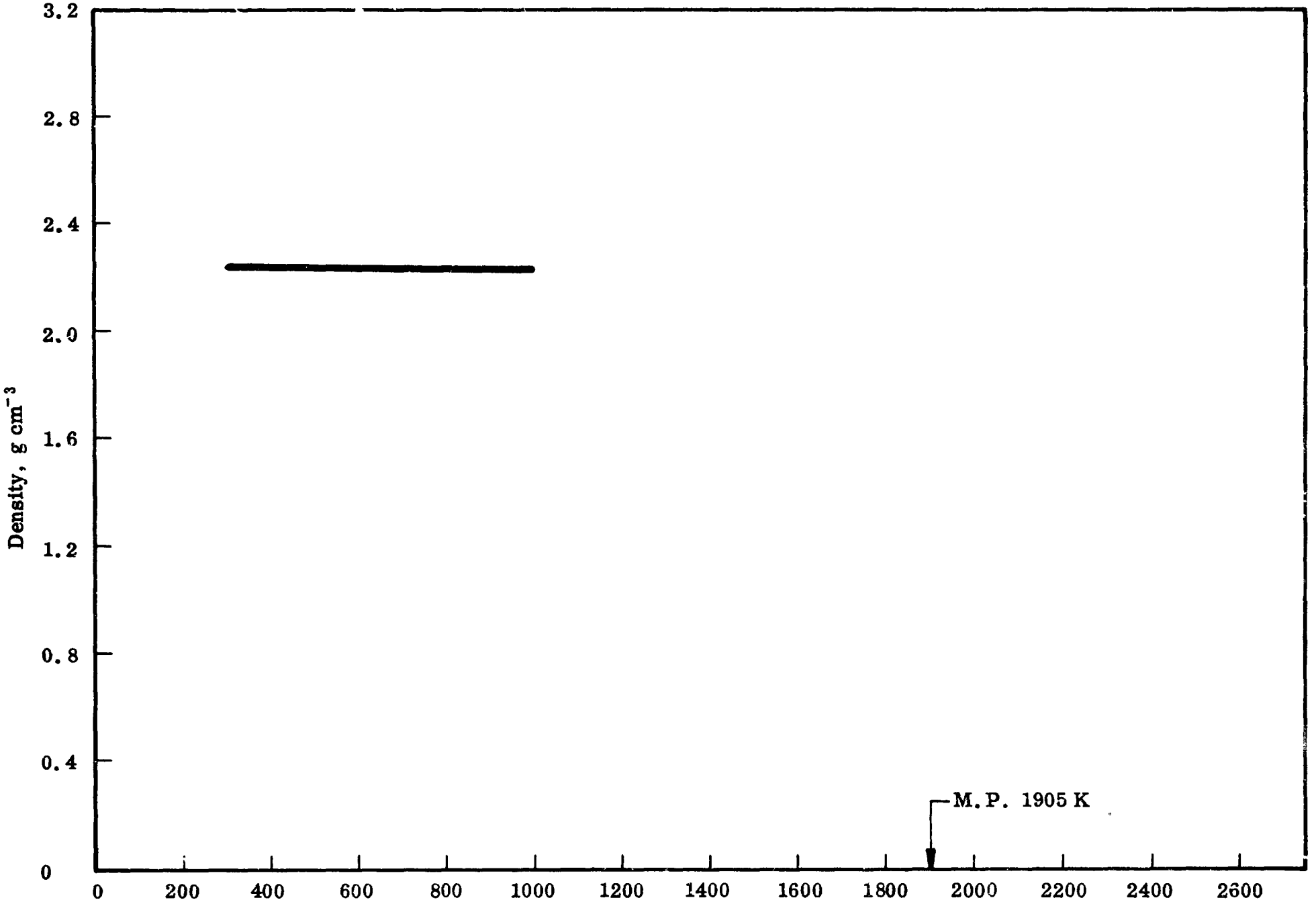

FIG. VI. - 32

DENSITY -- TIN OXIDE, SnO_2

TABLE VI-32. DENSITY OF TIN OXIDE (SnO_2)

RECOMMENDED VALUES

T(°K)	ρ(g. cm^{-3})	T(°K)	ρ(g. cm^{-3})
0	2.25	600	2.23
100	2.25	700	2.23
200	2.25	800	2.23
300	2.24	900	2.23
400	2.24	1000	2.23
500	2.24		

SOURCE OF DATA

1) Value at room temperature: (a) Goldsmith, A. and coll. (III)
2) Solid range: (b) from thermal expansion coefficient (ibid)

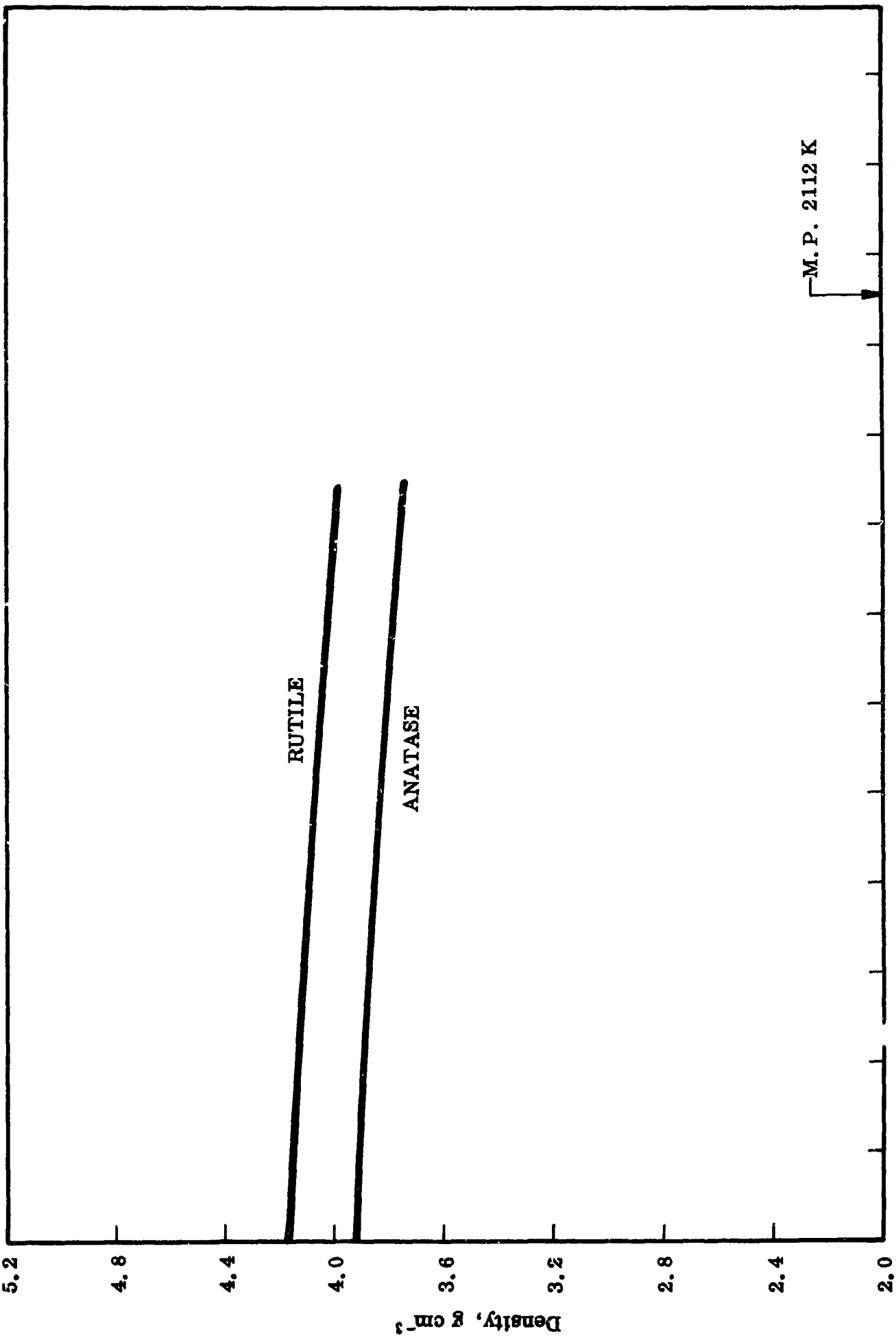

FIG. VI. - 33

DENSITY -- TITANIUM OXIDE, TiO_2

TABLE VI-33. DENSITY OF TITANIUM OXIDE (TiO_2)

RECOMMENDED VALUES

T(°K)	ρ(g.cm^{-3}) (a)	ρ(g.cm^{-3}) (b)	T(°K)	ρ(g.cm^{-3}) (a)	ρ(g.cm^{-3}) (b)
0	(s) 3.930	4.176	900	3.844	4.088
100	3.922	4.168	1000	3.833	4.076
200	3.913	4.159	1100	3.822	4.064
300	3.904	4.150	1200	3.810	4.051
400	3.894	4.140	1300	3.798	4.038
500	3.884	4.130	1400	3.785	4.025
600	3.874	4.120	1500	3.772	4.011
700	3.864	4.110	1600	3.758	3.997
800	3.855	4.099	1700	3.744	3.983

(a) anatase (b) rutile

SOURCE OF DATA

1) Value at room temperature: (a) Rietz, J. (74)

2) Solid range: (b) from thermal expansion coefficient recommended by Goldsmith, A., et al (III)

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RECOMMENDED VALUES OF THE THERMOPHYSICAL PROPERTIES OF EIGHT ALLOYS, MAJOR CONSTITUENTS AND THEIR OXIDES

CHAPTER VII
SURFACE TENSION

BY

P. HESTERMANS
T. D. STORM

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CHAPTER VII
SURFACE TENSION

A. INTRODUCTION

As a result of an extensive survey of the literature, it was found that reliable values for surface tension of the metallic elements, oxides and alloys were very limited. For the majority of the elements considered, a substantial amount of information was discovered, but data were scanty, discordant, and were restricted to a small temperature range. Few data were found on oxides, while data on the alloys considered in this work were nonexistent.

Although there has been a large amount of work on surface tension of molten metals, there is considerable doubt about their reliability. The main source of discrepancy lies in the purity of the metals used, and in the risk of contamination during experiment. Methodological difficulties associated with the environmental condition are also involved as a consequence of the high chemical reactivity of molten metals. The ambiant gas may easily combine or diffuse into the liquid metal forming layers or compound on the surface, with a resultant lowering of the surface tension.

No prediction of the surface tension of alloys can be made since the values would not only depend on concentration, but also on the surface activity of the components which tend to concentrate in the surface layer.

The elements and oxides for which data are presented are listed in the Page Index to Materials and Properties. The recommended values are presented in both tabular and graphical form when the temperature dependence has been evaluated. In those cases where values are restricted to only one temperature (i. e., the melting point) no graph is presented.

B. DATA ANALYSIS

To obtain a recommended curve for surface tension, first, all experimental data available were plotted. Then, each set of data was classified according to purity, environment and method of determination. Based on the above three criteria decisions were made determining the most reliable data.

The purity of the metal was considered of the utmost importance since substances such as sulfur and oxygen are very surface active, even in minute quantities.

The effect of environment was found to be dependent on the element's position in the periodic table. The elements in group II, III and IV (Mg, Al, Si, Sn, Zn, Ti) appeared to be independent of the type of atmosphere used. The elements in group VIII (Fe, Ni) and copper appeared to be extremely sensitive to the type of atmosphere used. For these three elements, even when the data of the purest metals were used, the results were still widely scattered. Experimental work using hydrogen as an experimental gas were discarded. The experiments using helium as the environmental gas were viewed with caution. Both of these gases have a high tendency to diffuse in metals, and it seemed likely that hydrogen ability to diffuse overshadows its ability to avoid oxidation. Although experiments using argon and nitrogen as environment appeared more reliable, preference was given to those experiments made in vacuum.

Concerning theoretical calculations (4, 9, 10, 31, 32, 52, 68)* or empirical correlations (12), none seems to be able to predict surface tension correctly. However, the work of Zadumkin and Pugachevich (5) concerning the temperature coefficient of surface tension was felt to give values of the correct order of magnitude. Therefore, these values were used to check or supplement the experimental values.

C. PRESENTATION OF DATA ON THE SURFACE TENSION OF SELECTED MATERIALS

The recommended values are presented in graphical form, each graph being accompanied by a table of values at 50 K intervals. With each table a list of references is given. The experimental values closer to the recommended curve are given as selected values, they fall generally within 5 or 10 percent of the recommended curve.

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*Number in parentheses refer to the Bibliography at the end of this chapter.

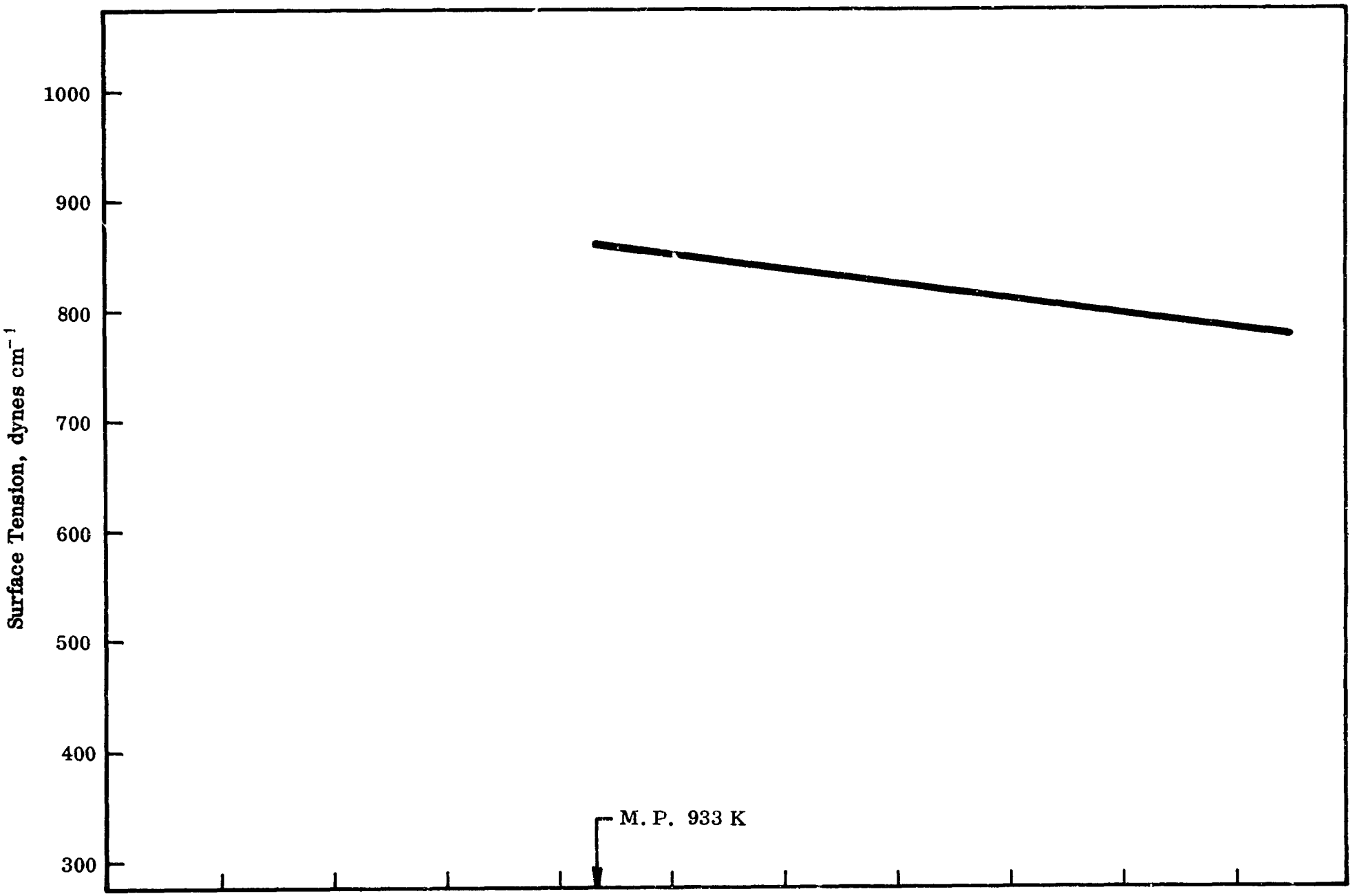

FIG. VII - 1

SURFACE TENSION -- ALUMINUM

TABLE VII-1. SURFACE TENSION OF ALUMINUM

RECOMMENDED VALUES

From equation: $\sigma = 860 - 0.134\,(T - 933)$

T(°K)	σ(dynes cm^{-1})	T(°K)	σ(dynes cm^{-1})
933(m.p.)	860	1260	817
950	857	1300	811
1000	851	1350	804
1050	844	1400	797
1100	838	1450	791
1150	831	1500	784
1200	824	1550	777

SOURCE OF DATA

Selected Values:

Experimental: (a) Naidich, Yu. V. and Eremenko, V.N. (1) (b) Eremenko, V.N., Nizhenko, V.I. and Ivashchenko Yu. N. (2) (c) Pelzel, E. (3)
Theoretical: (d) Zadumkin, S.N. (4)
Temperature coefficient (theoretical) (e) Zadumkin, S.N., and Pugachevich, P.P. (5)

Other Values:

Experimental: (f) Monma, K. and Suto, H. (6) (g) Powers, R.M. and Wilhelm, H.A. (7) (h) Smith, S.W. (8)
Theoretical or empirical evaluation: (h) Mayer, S.W. (9) (i) McLachlan, D. (10)

REMARKS: Estimated accuracy: 5%.

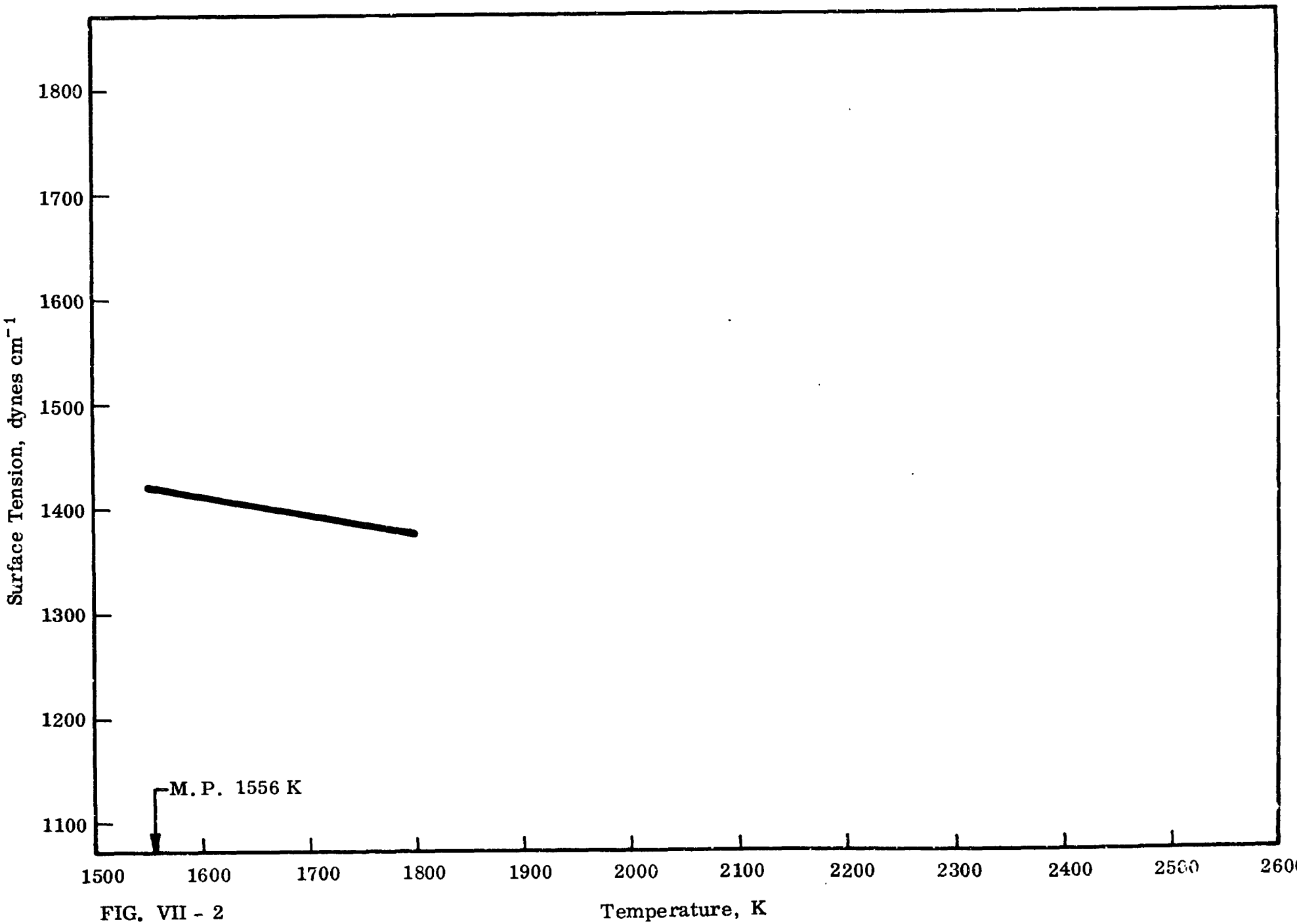

FIG. VII - 2

SURFACE TENSION -- BERYLLIUM

TABLE VII-2. SURFACE TENSION OF BERYLLIUM

RECOMMENDED VALUES

From equation: $\sigma = 1420 - 0.184\,(T - 1556)$

T (°K)	σ(dynes cm^{-1})
1556(m.p.)	1420
1660	1411
1650	1402
1700	1392
1750	1383
1800	1374

SOURCE OF DATA

Selected Values:

Experimental: (a) Eremenko, V.N., Nizhenko, V.I., and Tai Shou Vei (11) (after correction for density)
From empirical correlation: (b) Taylor, J.W. (12)
Temperature coefficient (theoretical): (c) Zadumkin, S.N., and Pugachevich, P.P. (5)

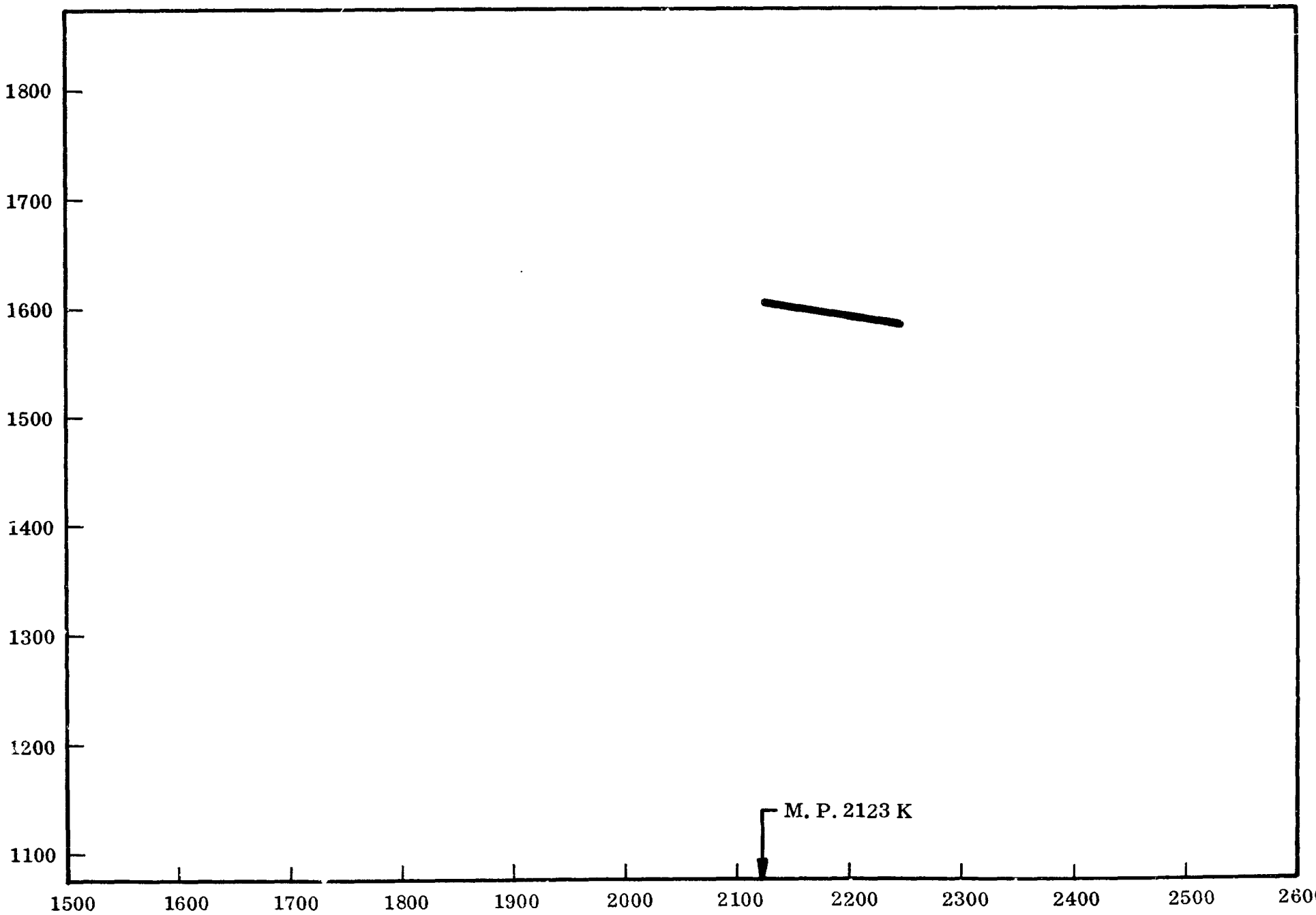

FIG. VII - 3

SURFACE TENSION -- CHROMIUM

TABLE VII-3. SURFACE TENSION OF CHROMIUM

RECOMMENDED VALUES

From equation: $\sigma = 1604 - 0.166\,(T - 2123)$

T(°K)	σ(dynes cm^{-1})
2123(m.p.)	1604
2150	1600
2200	1591
2250	1583

SOURCE OF DATA

Selected Values:

-Experimental: (a) Eremenko, V.N., and Naidich, Yu. V. (13)
-Temperature coefficient (theoretical): (b) Zadumkin, S.N., and Pugachevich, P.P. (5)

Other Values:

-From empirical correlation: (c) Taylor, J. W. (12)

REMARKS: Estimated accuracy: 5%

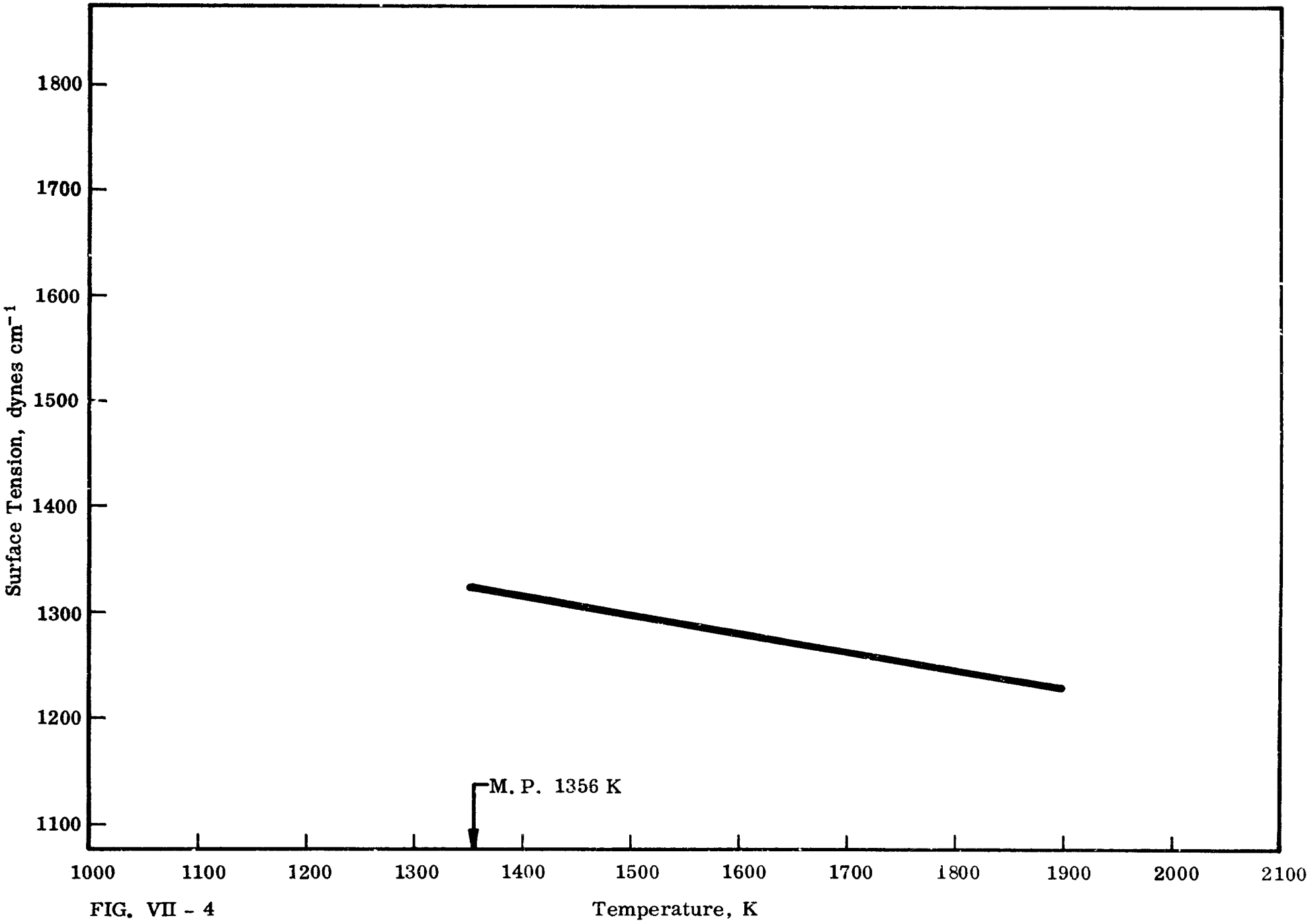

FIG. VII - 4

SURFACE TENSION -- COPPER

TABLE VII-4. SURFACE TENSION OF COPPER

RECOMMENDED VALUES

From equation: $\sigma = 1325 - 0.180\ (T - 1356)$

T(°K)	σ(dynes cm^{-1})	T(°K)	σ(dynes cm^{-1})
1356(m.p.)	1325	1650	1272
1400	1317	1700	1263
1450	1308	1750	1254
1500	1299	1800	1245
1550	1290	1850	1236
1600	1281	1900	1227

SOURCE OF DATA

Selected Values:

-Experimental: (a) Kozakevitch, P., and Urbain, G. (14) (b) Yashkichev, V.I., and Lazarev, V.B. (15) (c) Fezenko, V.V. and Eremenko, V.N. (16) (d) Lauermann, I., and Sauerwald, F. (17) (e) Allen, B.C. (18) (f) Metzger, G. (19) (g) Baes, C.F., and Kellog, H.H. (20) (h) Allen, B.C., and Kingery, W.D. (21) (i) Gans, W., Pawlek, F., and von Ropenack, A. (22) (j) Belforti, D.A., and Lepie, M.P. (23) (k) Monma, K., and Suto, H. (6)
-Temperature coefficient (theoretical): (l) Zadumkin, S.N., and Pugachevich, P.P. (5).

Other Values:

-Experimental: (m) Hoage, Y.H. (24); (n) Pugachevich, P.P., and Yashkichev, V.I. (25); (o) Becker, G., Harders, F., and Kornfeld, H. (26); (p) Smirnova, V.I., and Ormont, B.F. (27); (q) Whalen, T.Y. and Humenik, J.R.M. (28); (r) Smith, S.W. (8); (s) Drath, G., and Sauerwald, F. (29); (t) Krause, W., and Sauerwald, F.C. (30)
-Theoretical or empirical evaluation: (u) Mayer, S.W. (9); (v) Skapski, A.S. (31); (w) Pavlov, V.V., Popel, S.I., and Esin, O.A. (32) (x) McLachlan, D. (10)

REMARKS: Estimated accuracy: ± 10%

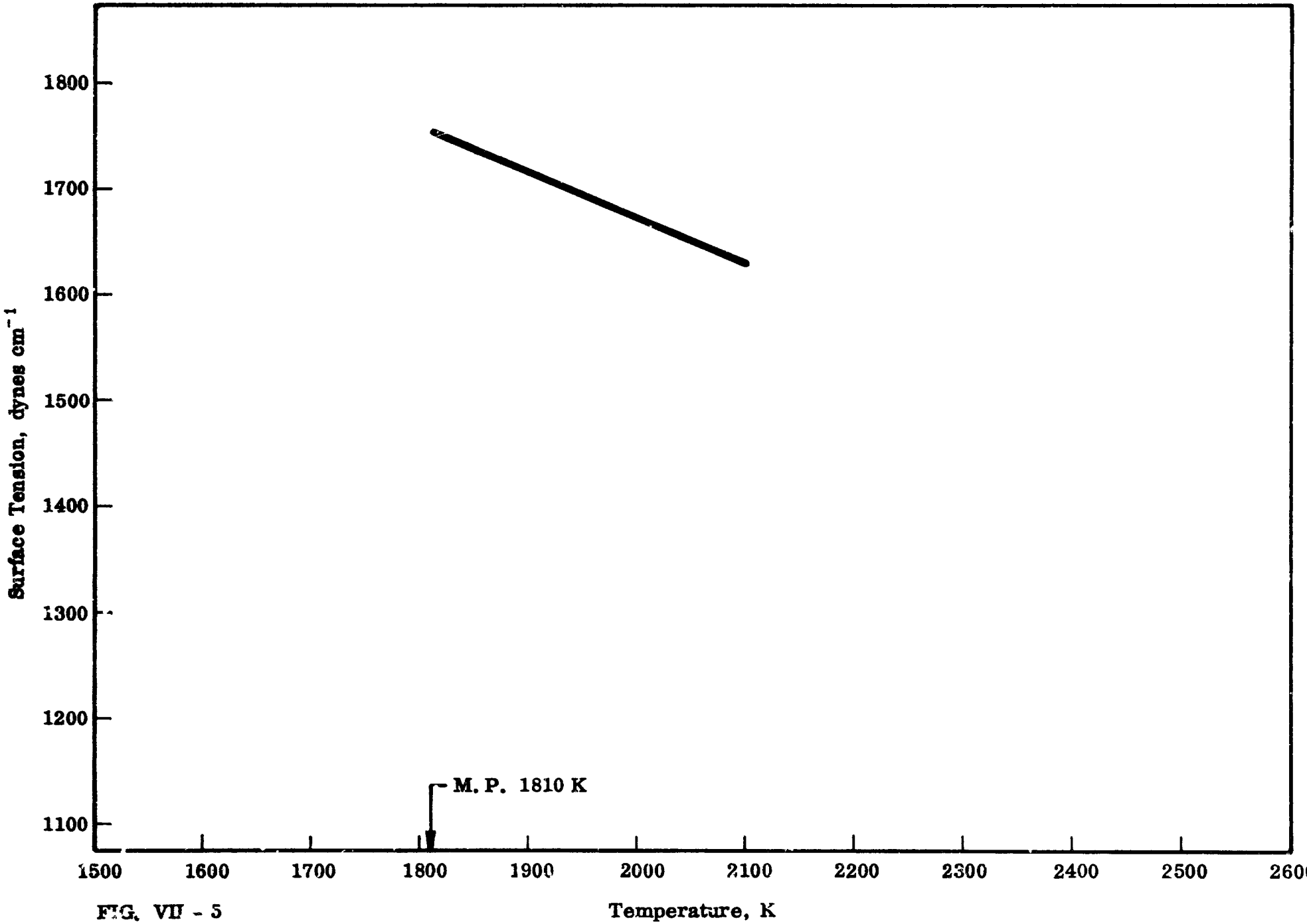

FIG. VII - 5

SURFACE TENSION -- IRON

TABLE VII-5. SURFACE TENSION OF IRON

RECOMMENDED VALUES

From equation: $\sigma = 1754 - 0.430\,(T - 1810)$

T(°K)	σ(dynes cm^{-1})
1810(m.p.)	1750
1850	1736
1900	1714
1950	1693
2000	1671
2050	1650
2100	1628

SOURCE OF DATA

Selected Values:

-Experimental: (a) Kozakevitch, P., and Urbain, G. (33)(34)(35) (b) Monma, K., and Suto, H. (6) (c) Dyson, B.F. (36) (d) Allen, B.C., and Kingery, W.D. (21) (e) Halden, F.A., and Kingery, W.D. (37) (f) Allen, B.C. (18) (g) Eremenko, V.N., Nizhenko, V.I., and Ivashchenko, (2)

-Theoretical or empirical evaluation: (h) Mayer, S.W. (9)

Other Values:

-Experimental: (i) Kingery, W.D., and Humenik, M. Jr. (38) (j) Eremenko, V.N., Ivashchenko, Yu. N., Nizhenko, V.I., and Fesenko, V.V. (39) (k) Becker, G., Harders, F., and Kornfeld, H. (26) (l) Fesenko, V.V., and Eremenko, V.N. (16) (40) (m) Smirnova, V.F., and Ormont, B.F. (27) (n) Von den Esche, W., and Peter, O. (41)

-Theoretical or empirical evaluation: (o) McLachlan, D. (10) (p) Pavlov, V.V., Popel, S.I., and Esin, O.A. (32)

REMARKS: Estimated accuracy: The selected values are within ± 6% of the recommended curve.

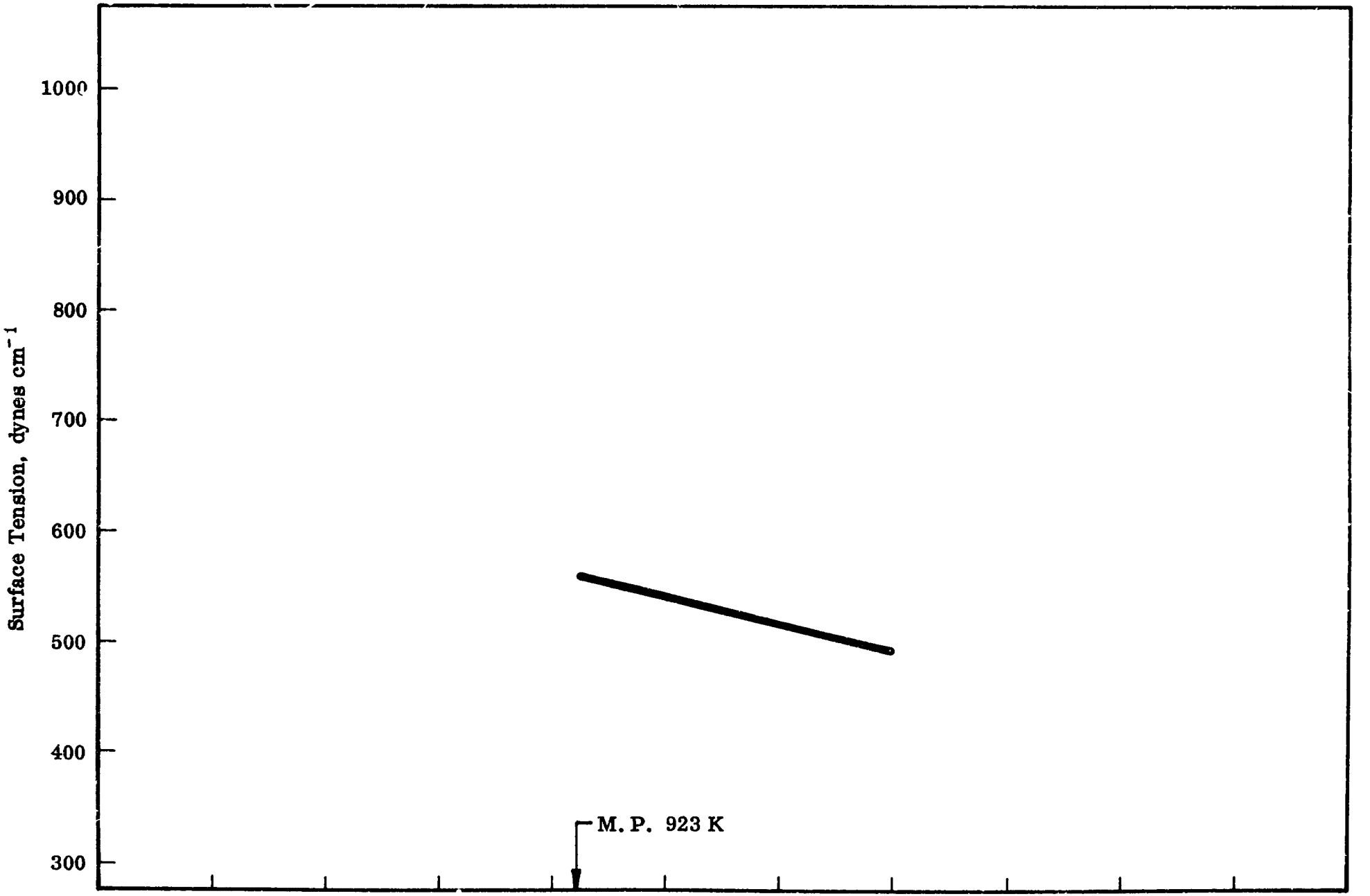

FIG. VII - 6

SURFACE TENSION -- MAGNESIUM

TABLE VII-6. SURFACE TENSION OF MAGNESIUM

RECOMMENDED VALUES

From equation: $\sigma = 560 - 0.240\ (T - 923)$

T(°K)	σ(dynes cm^{-1})
923 (m.p.)	560
950	554
1000	542
1050	530
1100	518
1150	506
1200	494

SOURCE OF DATA

Selected Values:

-Experimental: (a) Zhivov, N.G. (42) (b) Pelzel, E. (43)

Other Values:

-Experimental: (c) Powers, R.M., and Wilhelm, H.A. (7)
-Theoretical: (d) Mayer, S.W. (9)

REMARKS: Estimated accuracy: ± 6%.

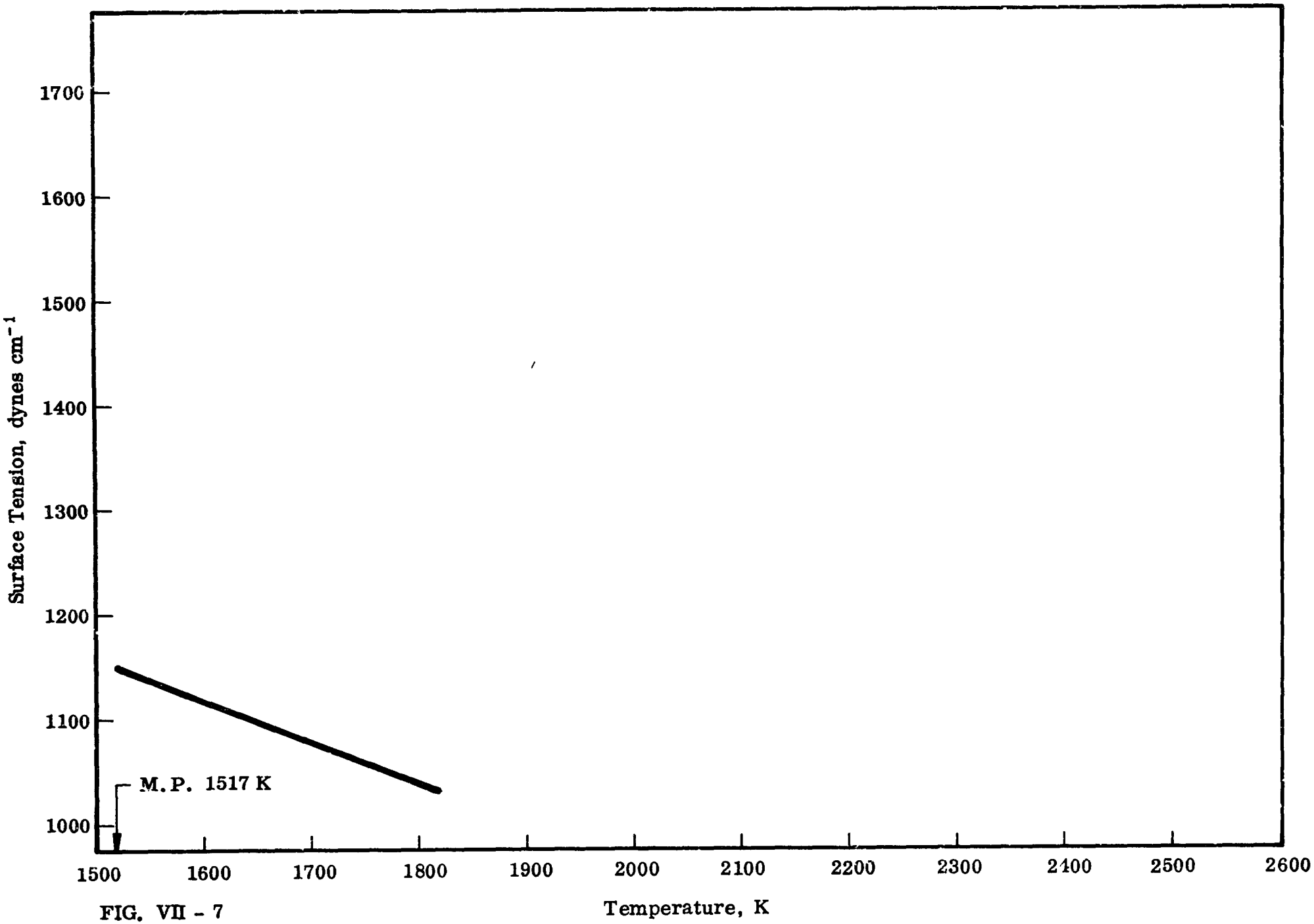

FIG. VII - 7

SURFACE TENSION -- MANGANESE

TABLE VII-7. SURFACE TENSION OF MANGANESE

RECOMMENDED VALUES

From equation: $\sigma = 1150 - 0.39\ (T - 1517)$

T(°K)	σ(dynes cm^{-1})
1517(m.p.)	1150
1550	1138
1600	1118
1650	1099
1700	1079
1750	1060
1800	1040
1850	1021
1900	1001

SOURCE OF DATA

Selected Values:

-Experimental: (a) Popel, S.I., Tsarevskii, B.V., and Dzhenilev, N.K. (44) (b) Elliott, J.F., and Gleiser, M. (45) (corrected for density)

Other Values:

-Experimental: (c) Kiyora, R., and Sata, T. (46) (d) Powers, R.M., and Wilhelm, H.A. (7)
-From empirical correlation: (e) Taylor, J. W. (12)

REMARKS: Estimated accuracy: ± 5%.

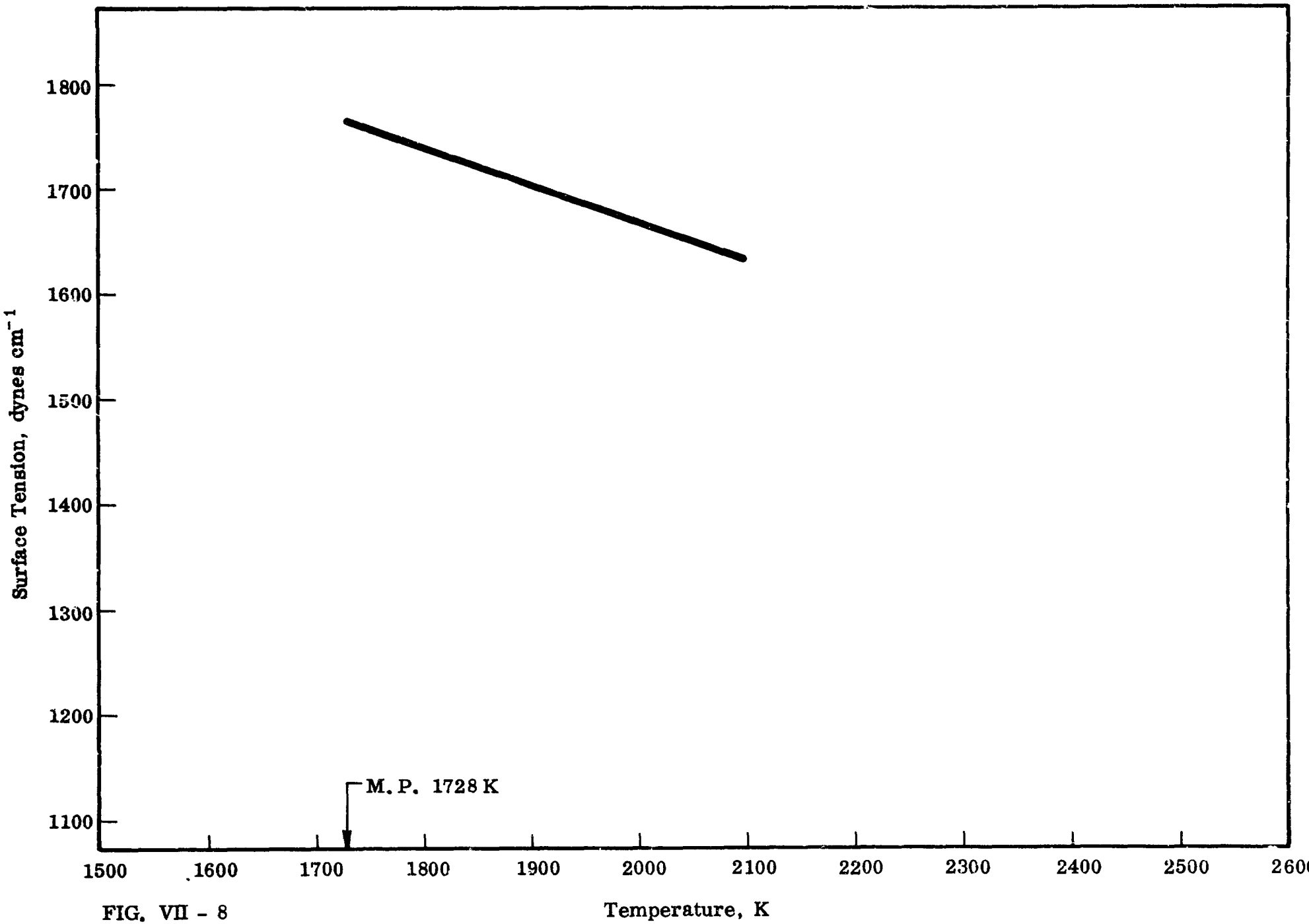

FIG. VII - 8

SURFACE TENSION -- NICKEL

TABLE VII-8. SURFACE TENSION OF NICKEL

RECOMMENDED VALUES

From equation: $\sigma = 1765 - 0.36\,(T - 1728)$

T(°K)	σ(dynes cm^{-1})
1728(m.p.)	1765
1750	1756
1800	1738
1850	1720
1900	1702
1950	1684
2000	1666
2050	1648
2100	1630

SOURCE OF DATA

Selected Values:

-Experimental: (a) Kingery, W.O., and Humenik, M. Jr. (38) (b) Eremenko, V.N., Ivashchenko, Yu N., Nizhenko, V.I., and Fesenko, V.V. (39) (c) Monma, K., and Suto, H. (6) (d) Allen, B.C. (18) (e) Smirnova, V.I., and Ormont, B.F. (27) (f) Whalen, T.Y., and Humenik, M. Jr. (28) (g) Eremenko, V.N., and Nizhenko, V.I. (47) (h) Allen, B.C., and Kingery, W.D. (21) (i) Kurkjian, C.R., and Kingery, W.D. (48)

-From theoretical calculation: (j) Pavlov, V.V. Popel, S.I., and Esin, O.A. (32)

Other Values:

-Experimental: (k) Powers, R.M., and Wilhelm, H. A. (7) (l) Kozakevitch, P., and Urbain, G. (33) (34) (m) Fesenko, V.V. and Eremenko, V.N. (16) (40) (n) Norton, F.H., and Kingery, W.D. (49)

REMARKS: Estimated accuracy: ± 9%.

TABLE VII-9. SURFACE TENSION OF NIOBIUM

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
2740	1900 ± 100

SOURCE OF DATA

Experimental: (a) Allen, B.C. (18)

[Note: From an estimation of the critical temperature the author suggests a temperature coefficient of 0.24 degrees $cm^{-1} K^{-1}$]

From empirical correlation: (b) Taylor, J.W. (12)

REMARKS: Estimated accuracy: ± 5%.

TABLE VII-10. SURFACE TENSION OF SILICON

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
1625	725

SOURCE OF DATA

Selected Values:

Experimental: (a) Kingery, W.D., and Humenik, M. Jr. (38) (b) Keck, P.H., and Van Horn, W. (50) (c) Shashkov, Yu. M., and Kolesnikova, T.P. (51)
Theoretical calculation: (d) Zadumkin, S.N. (52)

REMARKS: Estimated accuracy: ± 5%.

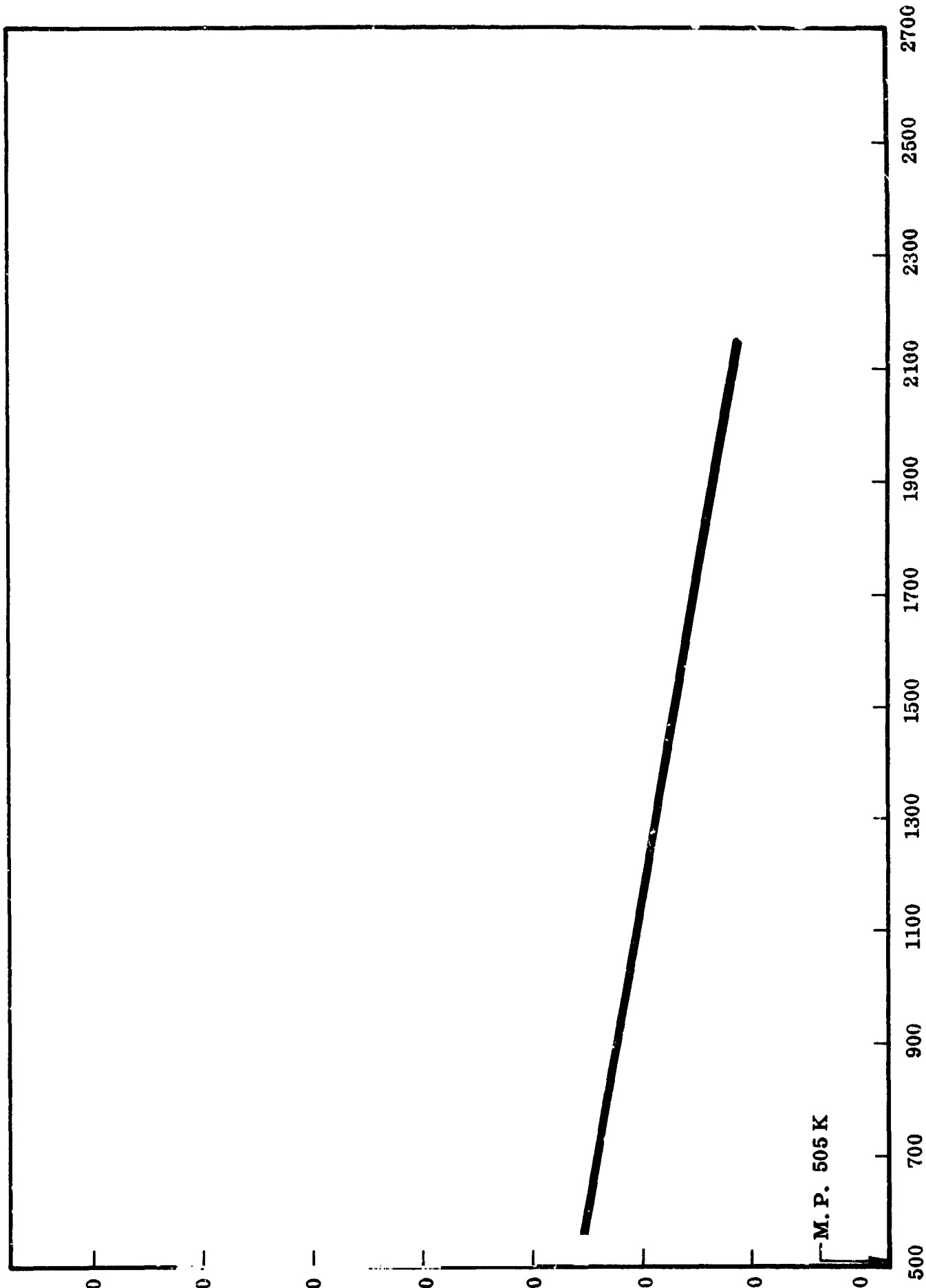

FIG. VII - 11

SURFACE TENSION -- TIN

TABLE VII-11. SURFACE TENSION OF TIN

RECOMMENDED VALUES

From equation: $\sigma = 559 - 0.089\ (T - 505)$

T(°K)	σ(dynes cm^{-1})	T(°K)	σ(dynes cm^{-1})
505 (m.p.)	559	1400	479
600	551	1500	470
700	542	1600	462
800	533	1700	453
900	524	1800	444
1000	515	1900	435
1100	506	2000	426
1200	497	2100	417
1300	488	2200	408

SOURCE OF DATA

Selected Values:

-Experimental: (a) Kirshenbaum, A.D., and Grosse, A.V. (53); (b) Pokrovskii, N.L. and Galanina, N.D. (54) (c) Fesenko, V.V. and Eremenko, V.N. (16) (d) Melford, D.H. and Hoar, T.P. (55) (e) Eremenko, V.N., and Nizhenko, V.I. (47) (f) Lauermann, I., Metzger, G., and Sauerwald, F. (56) (g) Atterton, D.V., and Hoar, T.P. (57) (h) Coffman, A.W., and Parr, S.W., (58) (i) Ziv, D.M., and Shestakov, B.I. (59) (j) Hogness, T.R. (60) (k) Drath, G., and Sauerwald, F. (29) (l) Bircumshaw, L.L. (61)
-Theoretical calculation or empirical relations: (m) Zadumkin, S.N. (52) (n) McLachlan, D. (10)

Other Values:

-Experimental: (o) Monma, K., and Suto, H. (6) (p) Smirnova, V.I. and Ormont, B.F. (27) (q) Krause, W., and Sauerwald, F. (30) (r) Allen, B.C., and Kingery, W.D. (21) (s) Smith, S.W. (8)
-Theoretical: (t) Mayer, S.W. (9)
-Temperature coefficient (theoretical): (u) Zadumkin, S.N., and Pugachevich, P.P. (5)

REMARKS: Estimated accuracy: ± 6%.

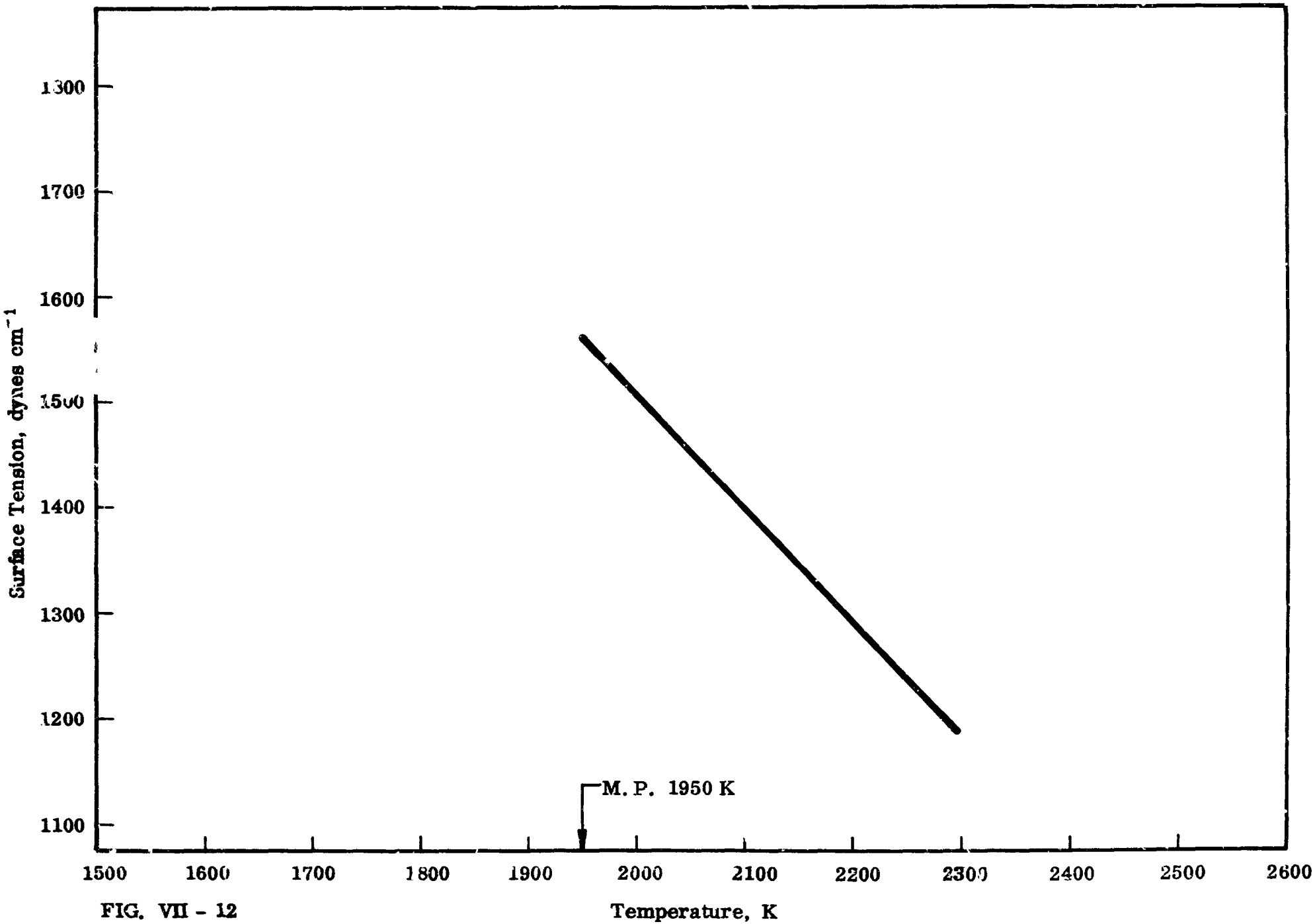

FIG. VII - 12

SURFACE TENSION -- TITANIUM

TABLE VII-12. SURFACE TENSION OF TITANIUM

RECOMMENDED VALUES

From equation: $\sigma = 1563 - 1.075\,(T - 1950)$

T(°K)	σ(dynes cm^{-1})
1950(m.p.)	1563
2000	1509
2050	1456
2100	1402
2150	1348
2200	1294
2250	1241
2300	1187

SOURCE OF DATA

Selected Values:

-Experimental: (a) Tille, J., and Kelly, J.C. (62) (b) Allen, B.C. (18) (c) Yelyutin, V.P., and Maurakh, M.A. (63)
-Temperature coefficient (experimental) (d) from Maurakh, M.A. (64)

Other Values:

-Experimental: (e) Peterson, A.W., Kedesdy, H., Keck, P.H., and Schwarz, E. (65) (f) Powers, R.M., and Wilhelm, H.A. (7)
-Theoretical calculation or empirical relation: (g) Taylor, J W. (12) (h. McLachlan, D. (10)

REMARKS: Estimated accuracy at melting point: ± 10%
The values above the melting point should be taken with caution the temperature coefficient being abnormally high.

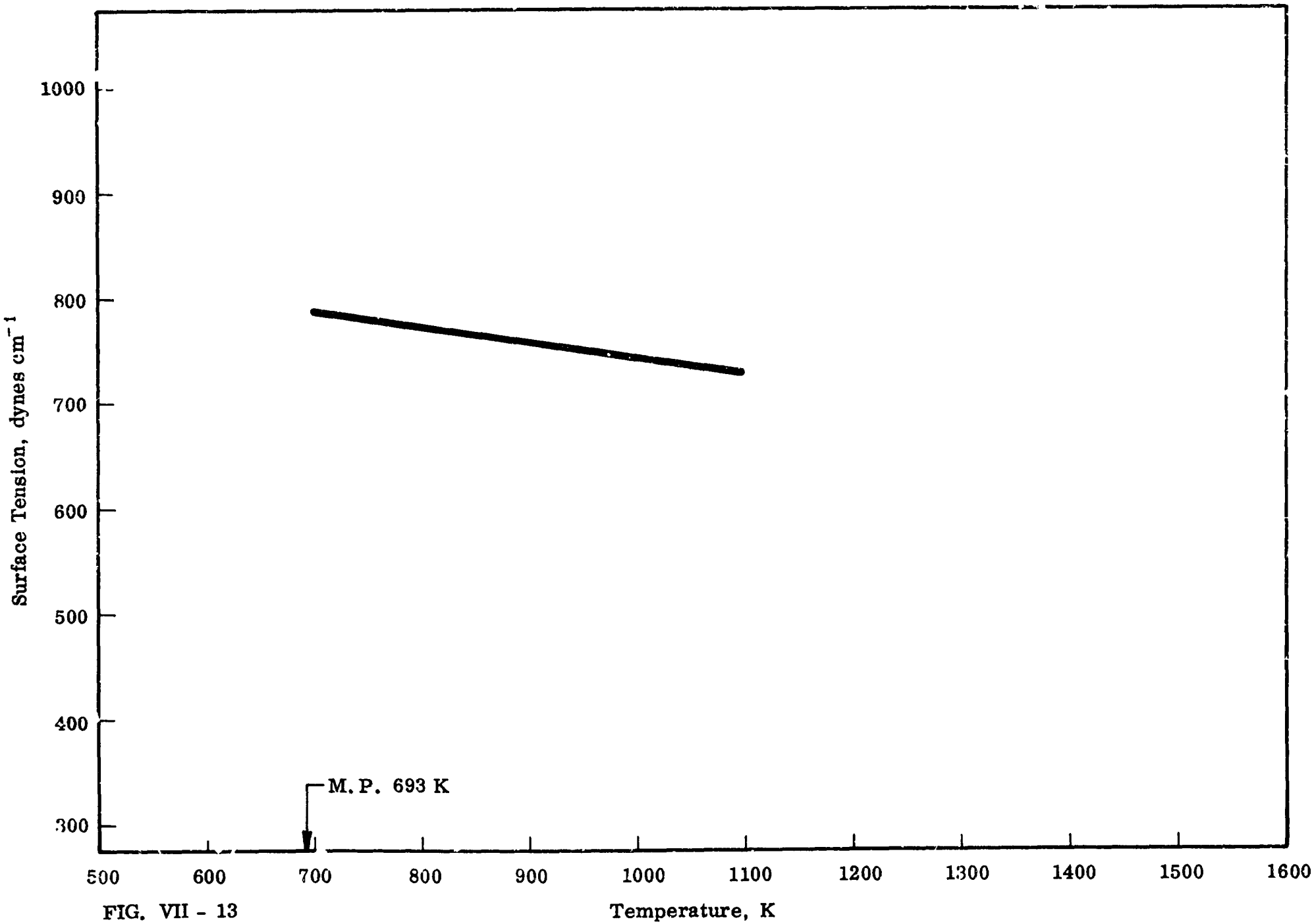

FIG. VII - 13

SURFACE TENSION -- ZINC

TABLE VII-13. SURFACE TENSION OF ZINC

RECOMMENDED VALUES

From equation: $\sigma = 789 - 0.146\ (T - 693)$

T(°K)	σ(dynes cm^{-1})
693(m.p.)	789
700	788
750	781
800	773
850	766
900	759
950	751
1000	744
1050	737
1100	730

SOURCE OF DATA

Selected Values:

-Experimental: (a) Hogness, T.R. (60) (b) Bircumshaw, L.L. (61) (c) Matuyama, Y. (66) (d) Klyachko, Yu A. (67) (e) Krause, W., Sauerwald, F., Michalke, M. (30) (f) Pelzel, E. (43)
-Theoretical: (g) Zadumkin, S.N. (68)
-Temperature coefficient (theoretical): Zadumkin, S.N., and Pugachevich, P.P. (5)

Other Values:

-Experimental (h) Monma, K. and Suto, H. (6) Powers, R.M., and Wilhelm, H.A. (7) (i) Smith, S.W. (8)
-Theoretical calculation: (j) Mayer, S.W. (9)

REMARKS: Estimated accuracy: ± 5%.

TABLE VII-14. SURFACE TENSION OF ALUMINUM OXIDE (Al_2O_3)

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
2300 (m.p.)	706 ± 30

SOURCE OF DATA

Selected Values:

-Experimental: (a) Kingery, W.D. (69) (b) Margrave, J.L., et al (70) (c) von Wartenberg, H., Wehner, G., and Saran, E. (71)

Other Values: (d) Hasapis, A.A., et al (72)

REMARKS: Estimated accuracy: ± 6%.

TABLE VII-15. SURFACE TENSION OF CHROMIUM OXIDE (Cr_2O_3)

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
above m.p.	462 ± 40

SOURCE OF DATA

Hasapis, A.A., et al (72)

TABLE VII-16. SURFACE TENSION OF IRON OXIDE (FeO)

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
1843	585

SOURCE OF DATA

Kingery, W.D. (69)

TABLE VII-17. SURFACE TENSION OF MAGNESIUM OXIDE (MgO)

RECOMMENDED VALUE

T(°K)	σ(dynes cm^{-1})
above m.p.	590

SOURCE OF DATA

Hasapis, A.A., et al (72)

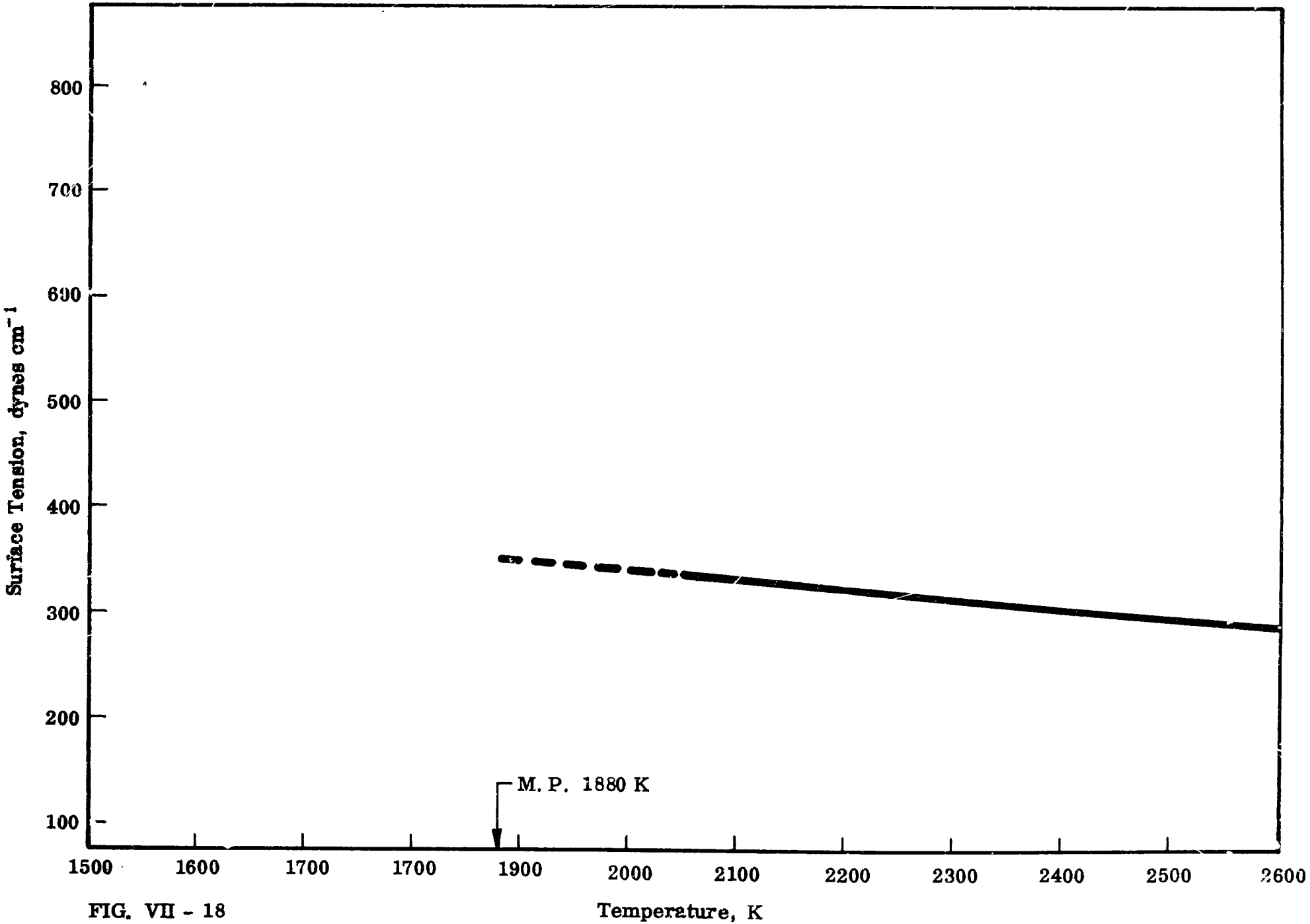

FIG. VII - 18

SURFACE TENSION -- SILICON OXIDE

TABLE VII-18. SURFACE TENSION OF SILICON OXIDE (SiO_2)

RECOMMENDED VALUES

From equation: $\sigma = 352 - 0.089\ (T - 1880)$

T(°K)	σ(dynes cm^{-1})	T(°K)	σ(dynes cm^{-1})
1880(m.p.)	352	2250	319
1900	350	2300	315
1950	346	2350	311
2000	341	2400	306
2050	337	2450	302
2100	333	2500	297
2150	328	2550	293
2200	324	2600	288

SOURCE OF DATA

-Experimental: (a) Kingery, W.D. (69) (b) Hasapis, A.A., et al (72)

REMARKS: Estimated accuracy: ± 10%.

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ERRATA:

THROUGHOUT THIS REPORT, THE DESIGNATION "STAINLESS STEEL 304-A" SHOULD READ "STAINLESS STEEL 304".

ERRATA AND CORRIGENDA

in

TPRC Report on

NBS Sub-Contract No. CST-7590, NASA Order R-45

(February 1966)

NOTE: Referring to lines on a given page, "a" means "from above", "b" means "from below".

Page	Line	Correction
		Throughout this Report, "stainless steel 304A" should read "s ainless steel 304"
ix	13b	Change "pass" to "past"
8	3a	Change "Sophr" to "Spohr"
10	6a	Change 1.18* to 1.8*
10	5b	Change "Griineisen" to "Grüneisen"
12	25a	Change 0.25** to 0 35** (the same change should be made in Figure I-3 on 11)
14	9b	Change "Powell Rogers" to "Powell, Rogers"
16	14a	Change 1053 to 1059
16	1b	Change 0.19** to 0.35** (the same change should be made in Figure I-5 on page 15)
19	2b	Change "liquid Magnesium" to "liquid magnesium"
23	23a	Change 0.43** to 0.66** (the same change should be made in Figure I-8 on page 22)
23	3b	Change "Hickmen" to "Hickman"
25	2b	Change 0.5** to 0.7** (the same change should be made in Figure I-9 on page 24)
26	1c	Change "liquid Niobium is" to "liquid niobium are"
35	6b	Change "Griineisen" to "Grüneisen"
37	7b	Change "Sawer" to "Sauer"
62	7a	Change 0.47 to 0.36
68	14a	Change 0.155 to 0.115
76	12a	Change 10.5 to 12.1
84	3a	Change "exists" to "exist"
89	16a	Change "Griineisen" to "Grüneisen"
90	1b	Change "Reddeman" to "Reddemann"

Page	Line	Correction
100	1b	Change "sample" to "samples"
129	10b	Change "enought" to "enough"
130	5a	Change "homogenous" to "homogeneous"
134	15a	Should read: ".....There were insufficient data for the beryllium alloy, stainless steel 304 and titanium alloy...."
135	2b	Change "composit" to "composite"
196	12b	Change "Curic point" to "Curie point"
202	5b	Change 0.054 to 0.075 (the same change should be made in Figure IV-3 on page 201)
204	5b	Change "Mrozawski, Andrew, Fuul", to "Mrozowski, Andrew, Juul,"
206	11a	Change 1053 to 1059
206	9b	Change 0.035* to 0.065* (the same change should be made in Figure IV-5 on page 205)
212	5b	Change 0.084* to 0.129* (the same change should be made in Figure IV-8 on page 211)
224	2b	Change "thermal conductivity" to "thermal diffusivity"
226	2b	Change "thermal conductivity" to "thermal diffusivity"
239		That part of the curve above 1600 K is drawn incorrectly and should be deleted
245	6a	Change 26 to 20 (the curve in Figure IV-24 on page 244 should be changed accordingly)
271	12a	Change "Eldgridge" to "Eldridge"
273ff		Throughout Chapter V, "Kopp-Newman" should read "Kopp-Neumann"
274	10b	Change "super conducting" to "superconducting"
274	14b	Change "rulite" to "rutile"
274	15a	Change "paranthesis" to "parenthesis"
275	11a	Should read: "...heat measurement of DuChatenier, F.J. et al. (203)..."
279	2b	Change "Invoniskaya" to "Ivoninskaya"
285	8b	Change "Amstrong" to "Armstrong"
300	5b, 6b	Change "Amstrong" to "Armstrong"
307	2b	Change "Yeager" to "Jaeger"

Page	Line	Correction
319	3b	Change "Ge'ld" to "Gel'd"
336		Change "M. P. 1650-1930 K" to "M. P. 1650-1730 K"
350	3b, 4b	Change "Walker, B. F." to "Walker, B. E."
350	7b	Change (230) to (229)
350	8b	Change (229) to (228)
350	9b	Change (228) to (227)
350	10b	Change (227) to (226)
350	10b	Change (226) to (225)
350	11b	Change (224) to (230)
350	12b	Change "Komanovskii" to "Romanovskii"
357	3b	Change "Hasteck" to "Harteck"
412	8a	Change "Amstrong" to "Armstrong"
415	14b	Change "Amstrong" to "Armstrong"
417	17a	Change "Yaeger" to "Jaeger"
431	13b	Change "...data was..." to "...data were..."
439	2b	Eliminate comma
443	8b	Change "cahill" to "Cahill"
455	5b	Should read: "..., Borishanskii, V. M., Novikov, I. I., and Fedinskii, O. S."
500	6b	Change "Schijner" to "Schrijner"
505	15a	Change "ambiant" to "ambient"
506	13a	Change "hydrogen ability" to "ability of hydrogen"