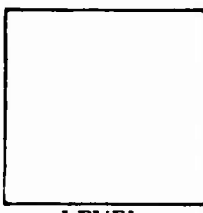


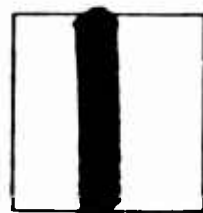
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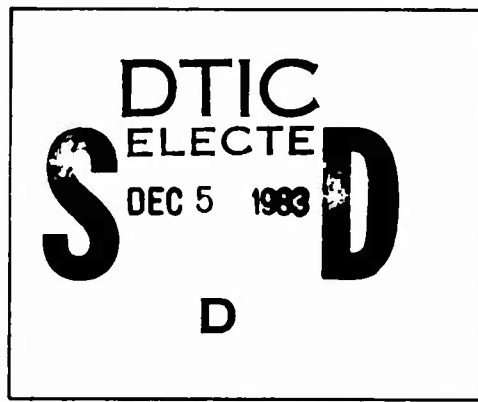
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# THERMOPHYSICAL PROPERTIES RESEARCH CENTER

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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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| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) *Thermal Conductivity---*Emissivity---*Thermal diffusivity---*Specific heat---*Density---*Surface tension---Elements---Aluminum---Beryllium---Chromium---Copper---Iron---Magnesium---Manganese---Nickel---Niobium---Silicon---Tin---Titanium---Zinc---Aluminum alloys---Beryllium alloy---Inconel X---Stainless steels---Titanium alloy---Aluminum oxide---Beryllium oxide---Chromium oxide---Copper oxides---                     |                       |   |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>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 thermophysical properties knowledge. Data are shown for 13 metallic elements, 8 alloys, and 25 different metal oxides. |                       |   |

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19. KEY WORDS (Cont)

Iron oxides---Magnesium oxide---Manganese oxides---Nickel oxide---Niobium oxides---Silicon oxide---Tin oxides---Titanium oxides---Zinc oxide

---

20. ABSTRACT (Cont)

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 studies. 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.

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

Y. S. TOULOUKIAN  
Project Director and Editor

THERMOPHYSICAL PROPERTIES RESEARCH CENTER  
Purdue University  
Lafayette, Indiana

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

February 1966

ERRATA AND CORRIGENDA

in

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

TPRC Report 16

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 "stainless 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 page 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"                                   |
| 21   | 2b       | Change "K = 0.78" to "k = 0.078"  |
| 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   | 1b       | Change "liquid Niobium is" to "liquid niobium are"                                |
| 35   | 6b       | Change "Griineisen" to "Grüneisen"  |
| 37   | 7b       | Change "Sawer" to "Sauer"   |
| 39   | footnote | Change "artificially" to "artificially"   |
| 44   | 19a      | Change 2.18 to 2.28   |
| 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"  |

| Page  | Line       | Correction   |
|-------|------------|--|
| 89    | 16a        | Change "Griineisen" to "Grüneisen"   |
| 90    | 1b         | Change "Reddeman" to "Reddemann"   |
| 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"  |
| 197   |            | Change "M. P. 993 K" to "M. P. 933 K"  |
| 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; change 53* to 42*   |
| 206   | 13a        | Change 18* to 14*  |
| 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"   |
| 230   | 13, 14, 15 | Change 12 to 12.4, 8.6 to 9.0, 6.5 to 6.6  |
| 239   |            | That part of the curve above 1600 K is drawn incorrectly and should be deleted                                     |
| 240   | 16a        | Change 17.5* to 17.7*  |
| 245   | 6a         | Change 26 to 20 (the curve in Figure IV-24 on page 244 should be changed accordingly)                              |
| 257   | 10a        | Change 7000* to 8000*  |
| 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)..."   |

| Page | Line   | Correction  |
|------|--------|---|
| 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"   |
| 319  | 3b     | Change "Ge'ld" to "Gel'd"   |
| 336  |        | Change "M. P. 1650-1930K" to "M. P. 1650-1730K"                               |
| 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 "Komanovski" to "Romanovski"   |
| 357  | 7b     | 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  | 10a    | Change 7. 715 to 7. 775   |
| 443  | 8b     | Change "cahill" to "Cahill"   |
| 455  | 5b     | Should read: "..., Borishanskii, V. M., Novikov, I. I., and Fedinskii, O. S." |
| 478  | 4a     | Change 300 to 900   |
| 500  | 6b     | Change "Schijner" to "Schrijner"  |
| 505  | 15a    | Change "ambiant" to "ambient"   |
| 506  | 13a    | Change "hydrogen ability" to "the ability of hydrogen"                        |

## 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 thermophysical 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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**PAGE INDEX TO MATERIALS AND PROPERTIES**

| MATERIALS  | Thermal<br>Conductivity | Viscosity | Thermal<br>Emissivity | Thermal<br>Diffusivity | Specific<br>Heat | Density | Surface<br>Tension |
|--|-------------------------|-----------|-----------------------|------------------------|------------------|---------|--------------------|
| <b>ELEMENTS:</b>                                     |                         |           |                       |                        |                  |         |                    |
| 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                |
| <b>ALLOYS:</b>                                       |                         |           |                       |                        |                  |         |                    |
| 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 304                                  | 47                      |           | 169                   | 233                    | 335              | 468     |                    |
| Stainless Steel 347                                  | 49                      |           | 170                   | 235                    | 338              | 469     |                    |
| Titanium Alloy A-110AT                               | 51                      |           | 176                   | 237                    | 344              | 473     |                    |
| <b>OXIDES:</b>                                       |                         |           |                       |                        |                  |         |                    |
| Aluminum Oxide Al <sub>2</sub> O <sub>3</sub>        | 53                      | 118       | 178                   | 239                    | 347              | 475     | 531                |
| Beryllium Oxide BeO                                  | 58                      |           | 180                   | 242                    | 351              | 477     |                    |
| Chromium Oxide Cr <sub>2</sub> O <sub>3</sub>        |                         |           | 189                   |                        | 354              | 479     | 532                |
| Cupric Oxide CuO                                     |                         |           | 189                   |                        | 356              |         |                    |
| Cuprous Oxide Cu <sub>2</sub> O                      |                         |           | 189                   |                        | 358              |         |                    |
| Ferrous Oxide FeO                                    |                         | 120       | 189                   |                        | 361              | 481     | 533                |
| Ferric Oxide Fe <sub>2</sub> O <sub>3</sub>          | 63                      |           | 189                   | 246                    | 363              | 483     |                    |
| Iron Oxide Fe <sub>3</sub> O <sub>4</sub>            | 61                      |           |                       | 244                    | 366              |         |                    |
| Magnesium Oxide MgO                                  | 65                      |           | 183                   | 248                    | 368              | 485     | 534                |
| Manganese Monoxide MnO                               | 69                      |           |                       | 250                    | 371              | 487     |                    |
| Manganese Dioxide MnO <sub>2</sub>                   |                         |           |                       |                        | 373              |         |                    |
| Manganese Sesquioxide Mn <sub>2</sub> O <sub>3</sub> |                         |           |                       |                        | 375              |         |                    |
| Manganomanganic Oxide Mn <sub>3</sub> O <sub>4</sub> | 71                      |           |                       | 252                    | 377              |         |                    |
| Nickel Oxide NiO                                     | 73                      |           | 189                   | 254                    | 379              | 489     |                    |
| Niobium Monoxide NbO                                 |                         |           |                       |                        | 381              |         |                    |
| Niobium Dioxide NbO <sub>2</sub>                     |                         |           |                       |                        | 383              |         |                    |
| Niobium Pentoxide Nb <sub>2</sub> O <sub>5</sub>     |                         |           |                       | 190                    | 385              | 491     |                    |
| Silicon Dioxide SiO <sub>2</sub>                     | 75                      | 122       | 185                   | 256                    | 387              | 493     | 535                |
| Tin(ous) Oxide SnO                                   |                         |           |                       |                        | 394              |         |                    |
| Tin(ic) Oxide SnO <sub>2</sub>                       | 80                      |           |                       | 259                    | 396              | 495     |                    |
| Titanium Monoxide TiO                                |                         |           |                       |                        | 398              |         |                    |
| Titanium Dioxide TiO <sub>2</sub>                    | 82                      |           | 187                   | 261                    | 400              | 497     |                    |
| Titanium Sesquioxide Ti <sub>2</sub> O <sub>3</sub>  |                         |           |                       |                        | 405              |         |                    |
| Titanium Tripentoxide Ti <sub>5</sub> O <sub>8</sub> |                         |           |                       |                        | 407              |         |                    |
| Zinc Oxide ZnO                                       | 87                      |           | 190                   | 264                    | 409              |         |                    |

## 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 pas<sup>t</sup> 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\*

|                             | <u>Composition, %</u> |
|-----------------------------|-----------------------|
| 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.

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

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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, polycrystalline 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  $\pm 4$  percent at room and moderate temperatures and within  $\pm 10$  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                |
| $\rho_0$ | residual electrical resistivity |

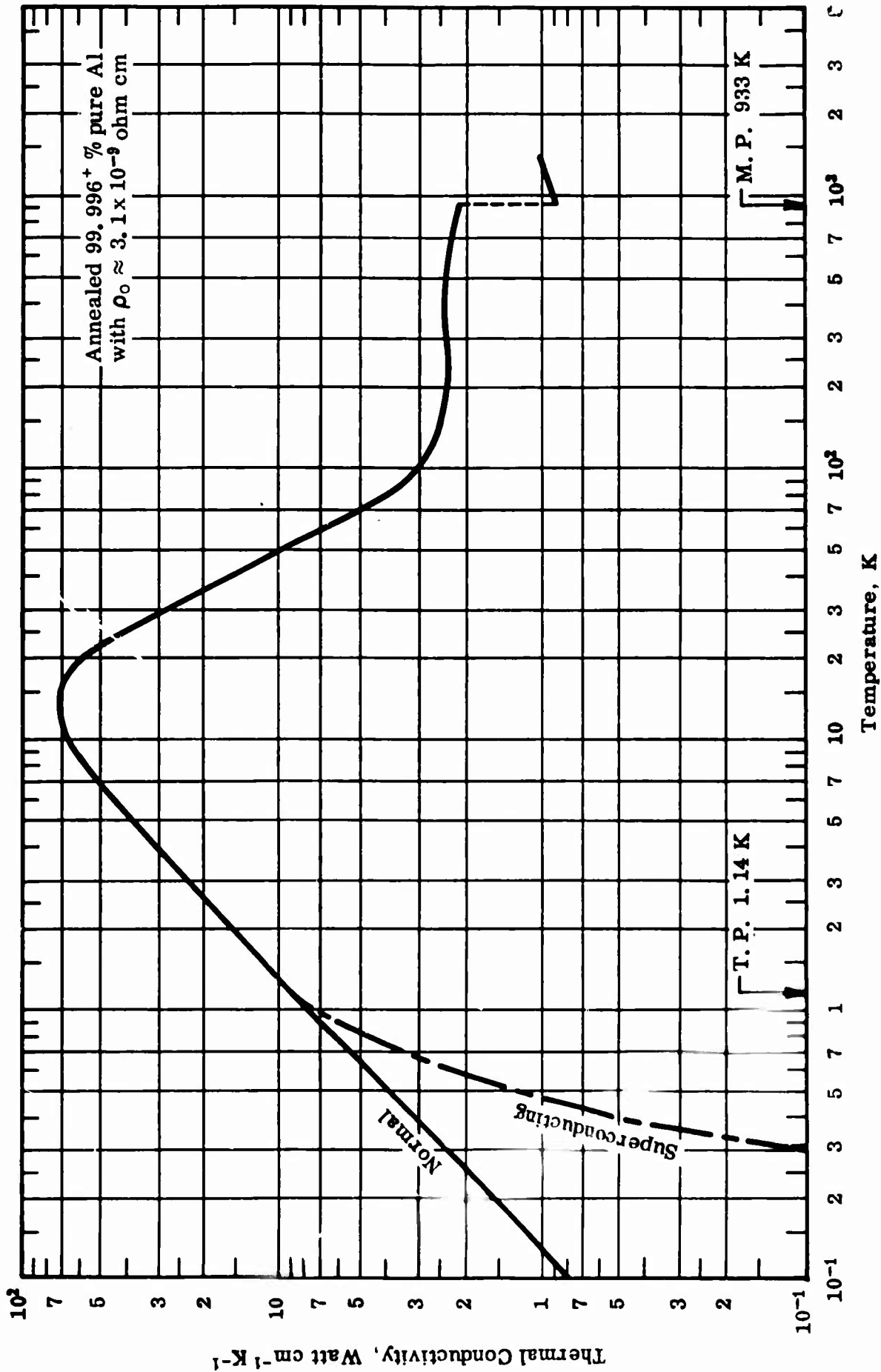


FIG. I-1 THERMAL CONDUCTIVITY OF ALUMINUM

**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 <sup>-1</sup> K <sup>-1</sup> | T, K    | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|---------|--|
| 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    | 1.03*                                    |
| 150  | 2.47                                     |         |  |

In superconducting state:

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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 Sohr (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].

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

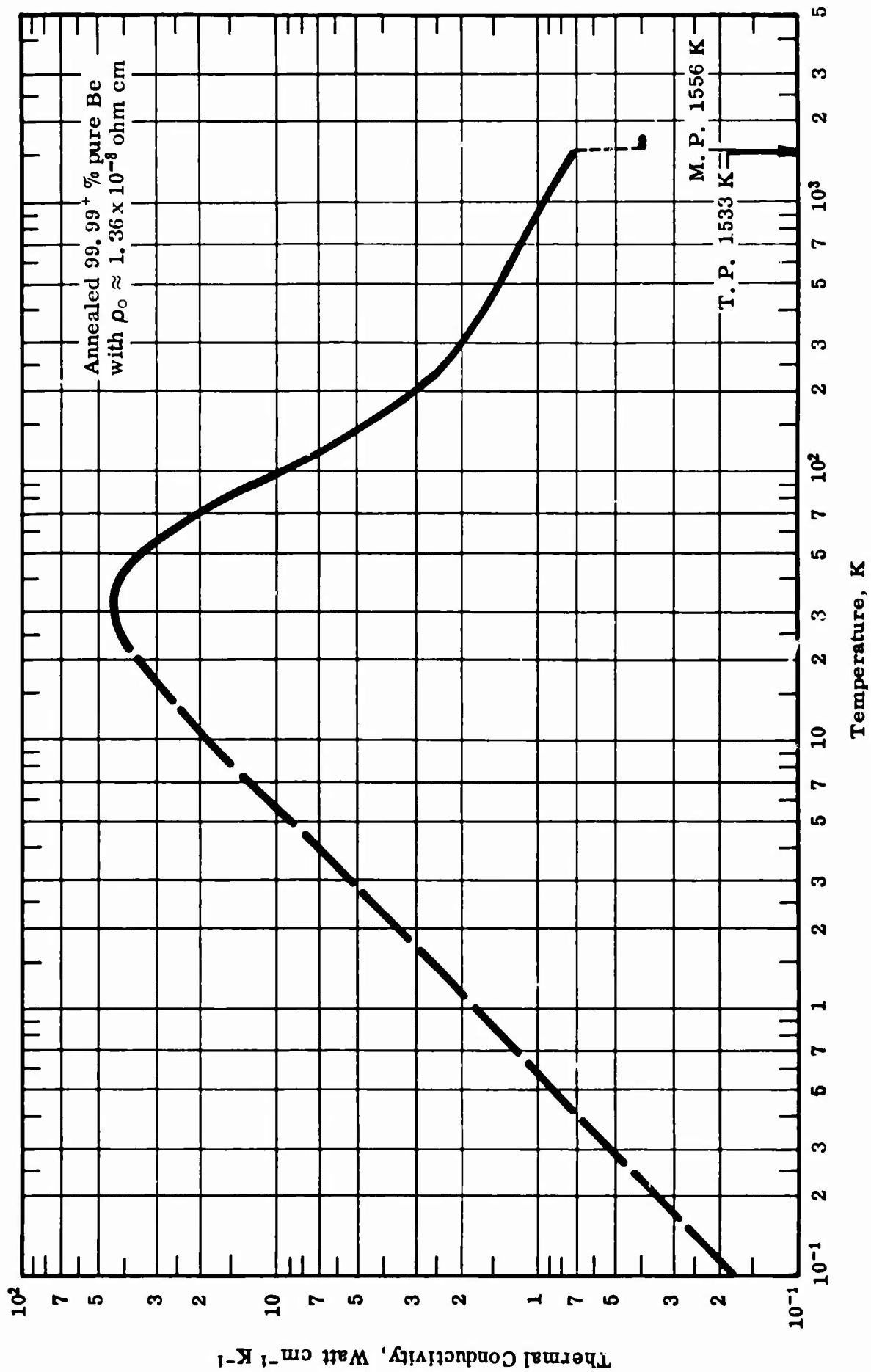


FIG. 1-2 THERMAL CONDUCTIVITY OF BERYLLIUM

**TABLE I-2 THERMAL CONDUCTIVITY OF BERYLLIUM**

Selected Values for Annealed 99.99+ % Pure Beryllium with  $\rho_0 \approx 1.36 \times 10^{-8}$  ohm cm

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K                     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|--------------------------|--|
| 0    | 0  | 250                      | 2.4                                      |
| 0.1  | 0.18*                                    | 273                      | 2.2                                      |
| 1    | <del>1.8</del> 1.8*                      | 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) <del>1556</del> 1550 | 0.72*                                    |
| 150  | 4.4                                      | (l) 1600                 | <del>0.50**</del>                        |
| 200  | 3.0                                      |                          | 0.43**                                   |

**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 Grüneisen 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.

\* Extrapolated.

\*\* Estimated.

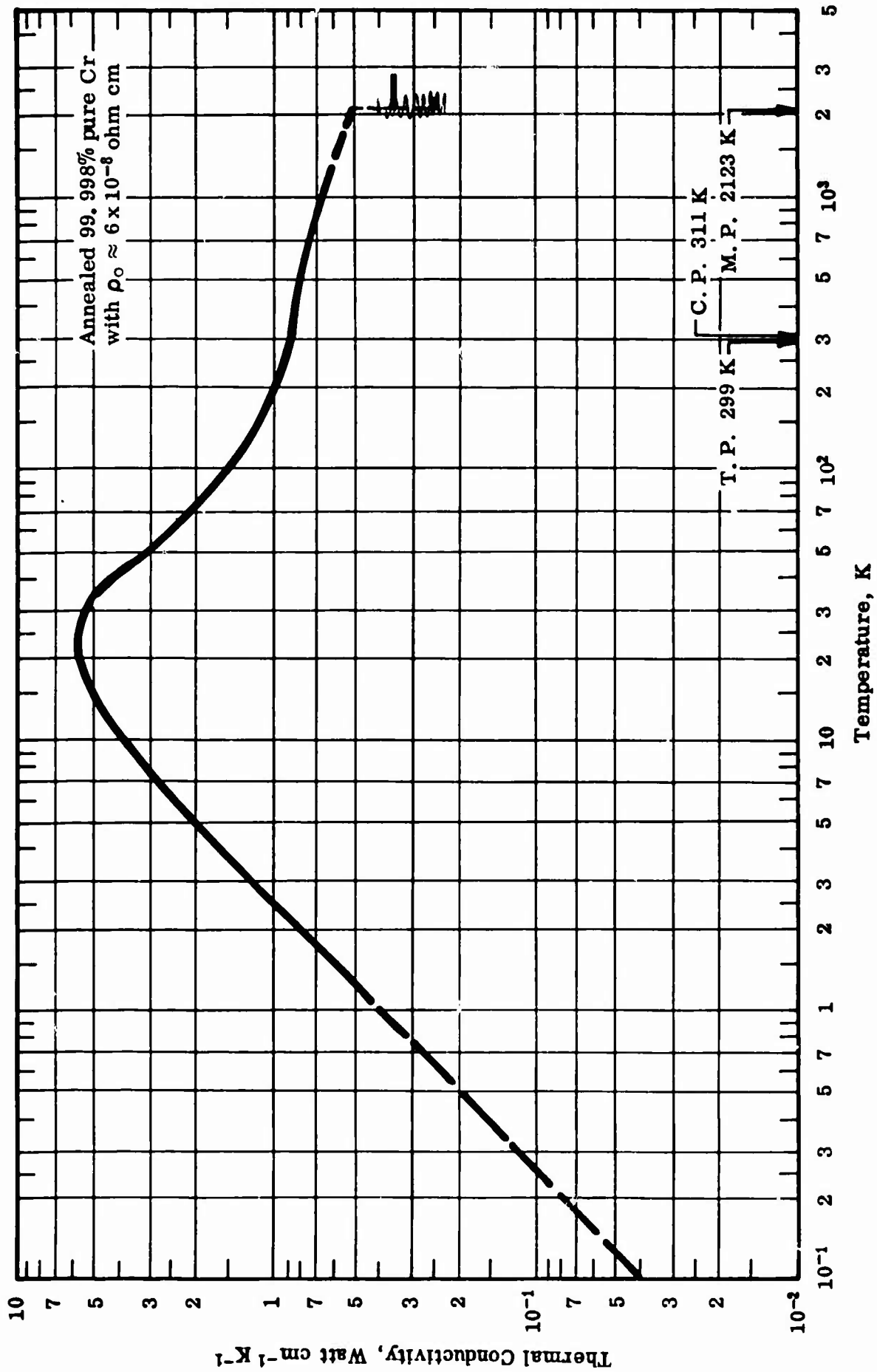


FIG. I-3 THERMAL CONDUCTIVITY OF CHROMIUM

**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 <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.85</del> 0.35**                   |

**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.

\* Extrapolated

\*\* Estimated

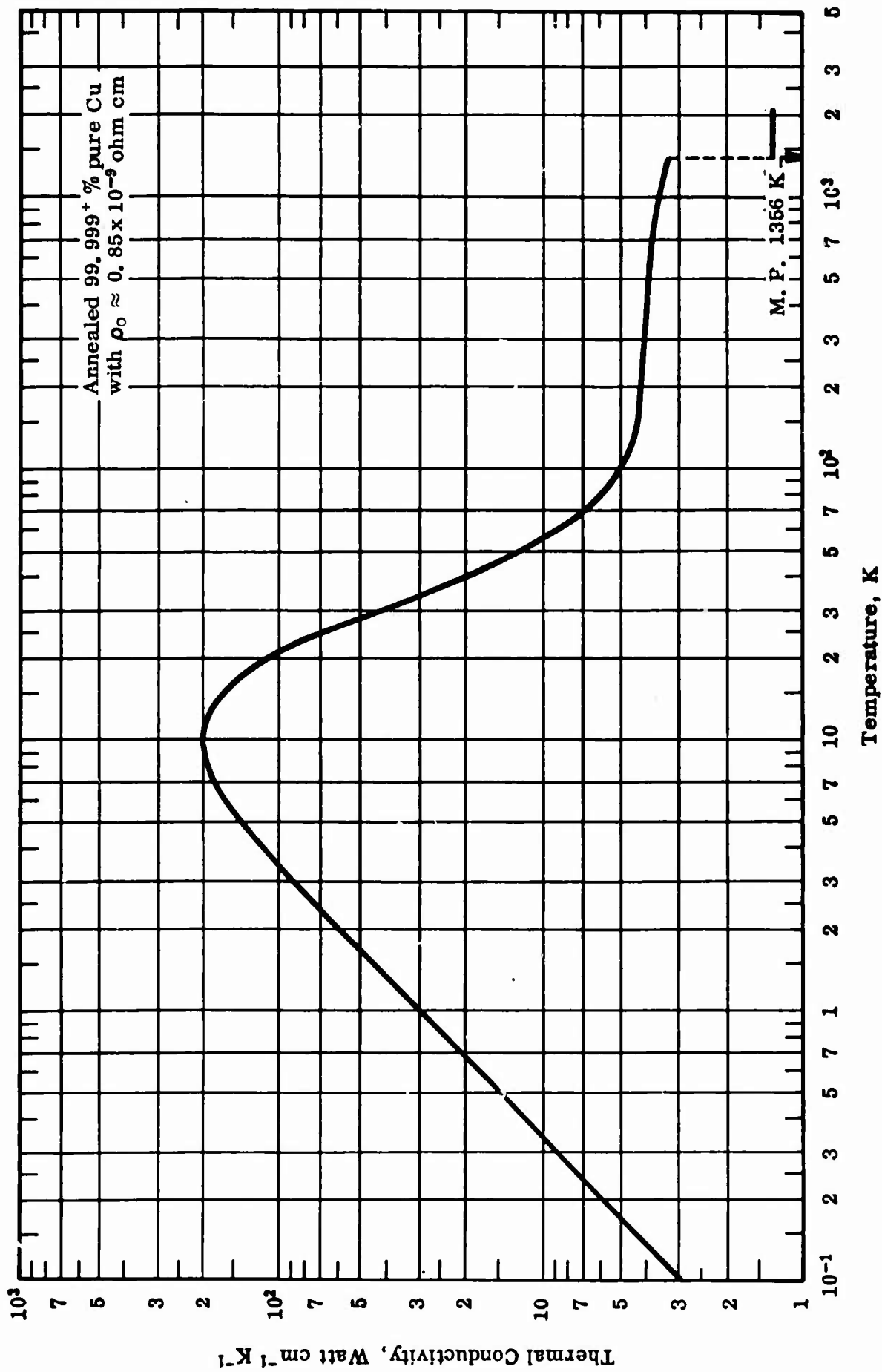


FIG. I-4 THERMAL CONDUCTIVITY OF COPPER

**TABLE I-4 THERMAL CONDUCTIVITY OF COPPER**

Selected Values for Annealed 99.999+ % Pure Copper with  $\rho_0 \approx 0.85 \times 10^{-9}$  ohm cm

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>3.4</del> 1.60                      |
| 90   | 5.1                                      | 1400     | <del>3.4</del> 1.61                      |
| 100  | 4.8                                      | 1600     | <del>3.4</del> 1.68                      |
| 150  | 4.3                                      | 1800     | <del>3.4</del> 1.73                      |
| 200  | 4.1                                      | 2000     | <del>3.4</del> 1.76                      |

**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.

2200 1.77  
2400 1.78  
2600 1.78\*  
2800 1.76\*

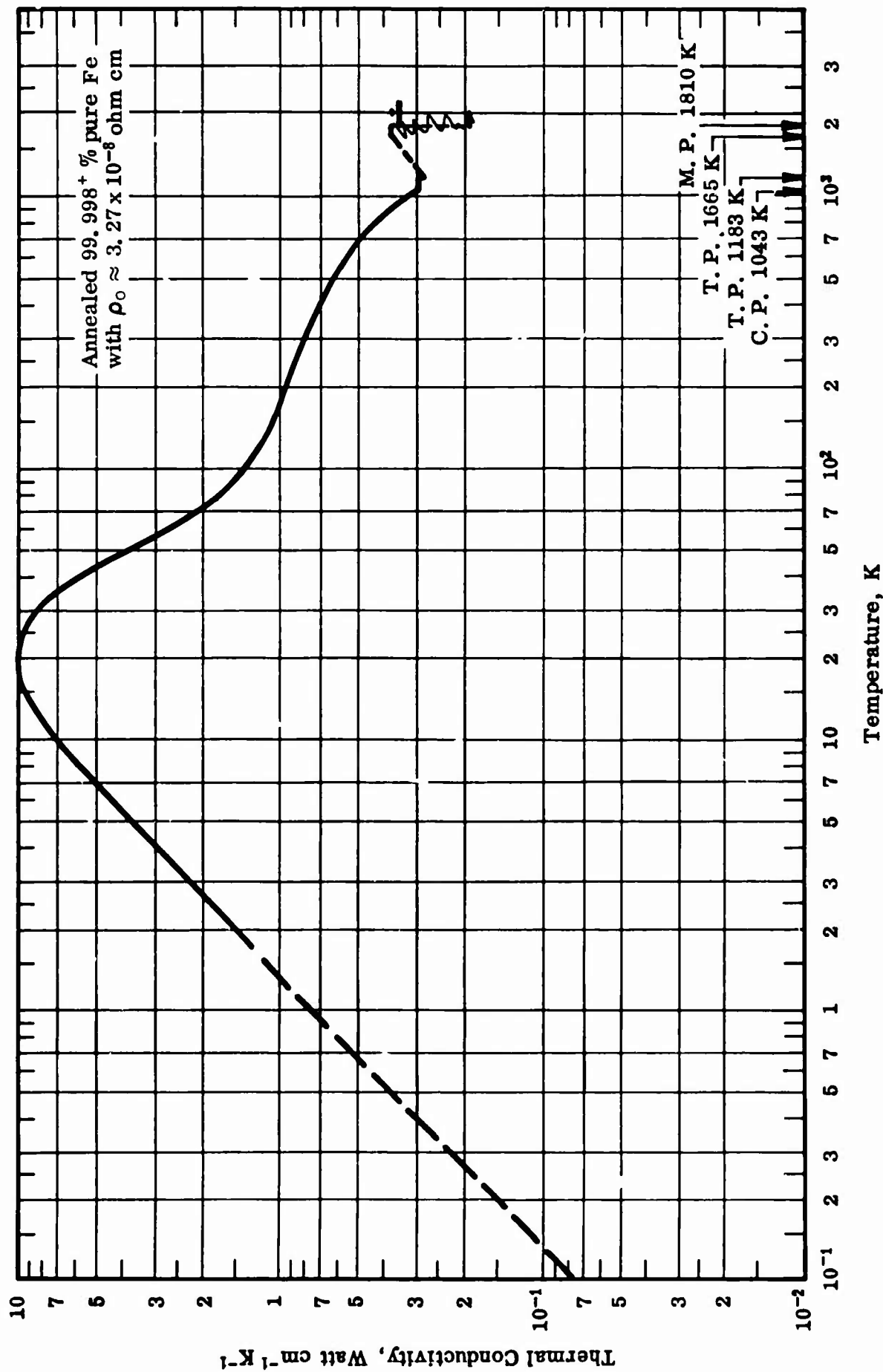


FIG. I-5 THERMAL CONDUCTIVITY OF IRON

TABLE I-5 THERMAL CONDUCTIVITY OF IRON

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

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | i   | T, K                 | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|-----|----------------------|--|
| 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                                      |     | <del>1050</del> 1059 | 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                 | <del>0.38</del><br>0.35                  |

\* 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 Araj's, 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  $\gamma$  - 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  $\delta$  - iron and liquid iron are estimated since no data are available.

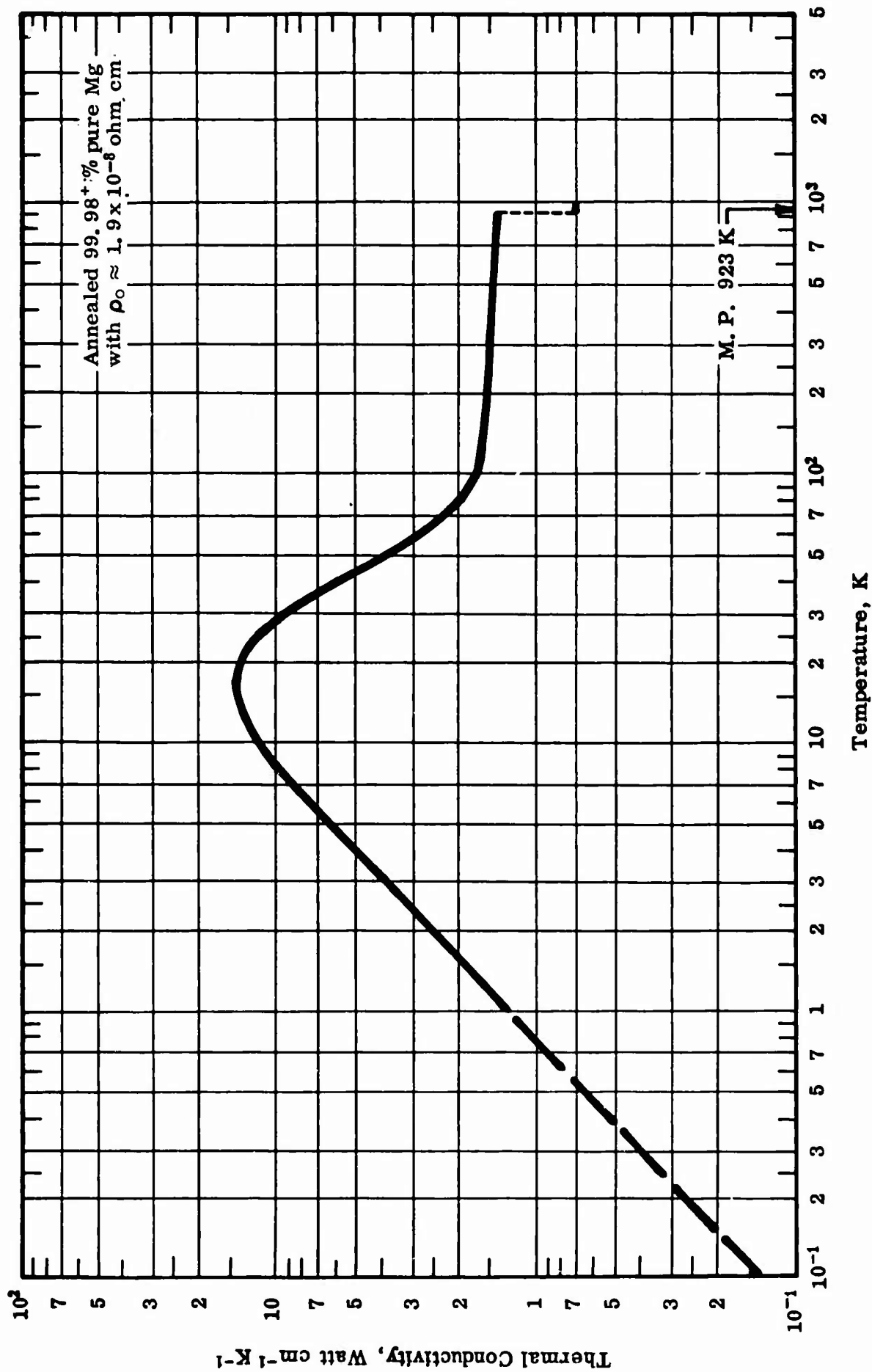


FIG. I-6 THERMAL CONDUCTIVITY OF MAGNESIUM

**TABLE I-6 THERMAL CONDUCTIVITY OF MAGNESIUM**

Selected Values for Annealed 99.98+ % Pure Magnesium with  $\rho_0 \approx 1.9 \times 10^{-8}$  ohm cm

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.7**</del> 0.8**                   |

**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 <sup>liquid</sup> Magnesium and the selected value is from estimation.

\* Extrapolated.

\*\* Estimated

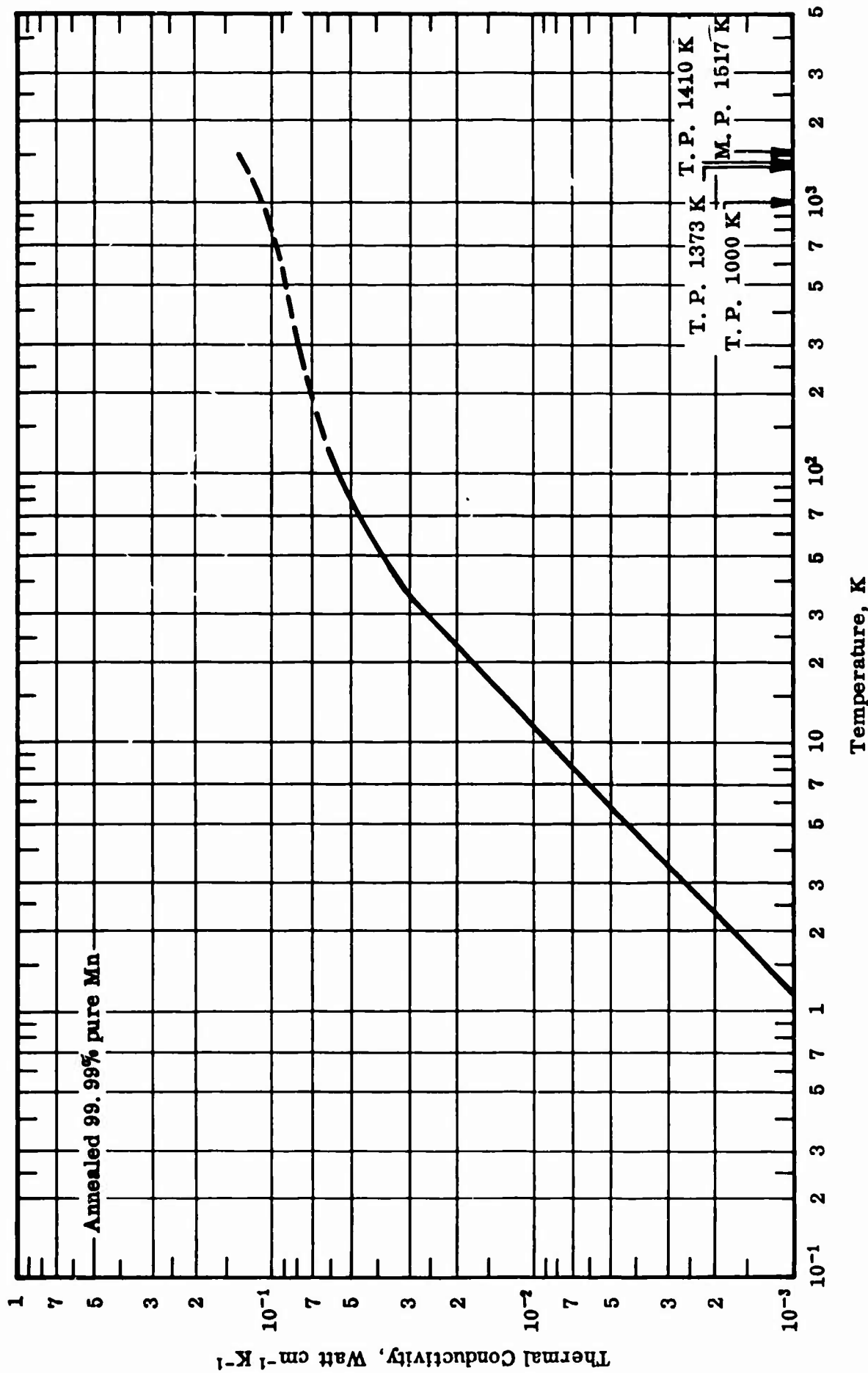


FIG. I-7 THERMAL CONDUCTIVITY OF MANGANESE

**TABLE I-7 THERMAL CONDUCTIVITY OF MANGANESE**  
Selected Values for Annealed 99.99% Pure Manganese

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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,  $k = 0.078$  Watt cm<sup>-1</sup> K<sup>-1</sup> at 293 K, measured recently by Tye (1966) [39].

↑  
 $k = 0.078$

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\* Extrapolated

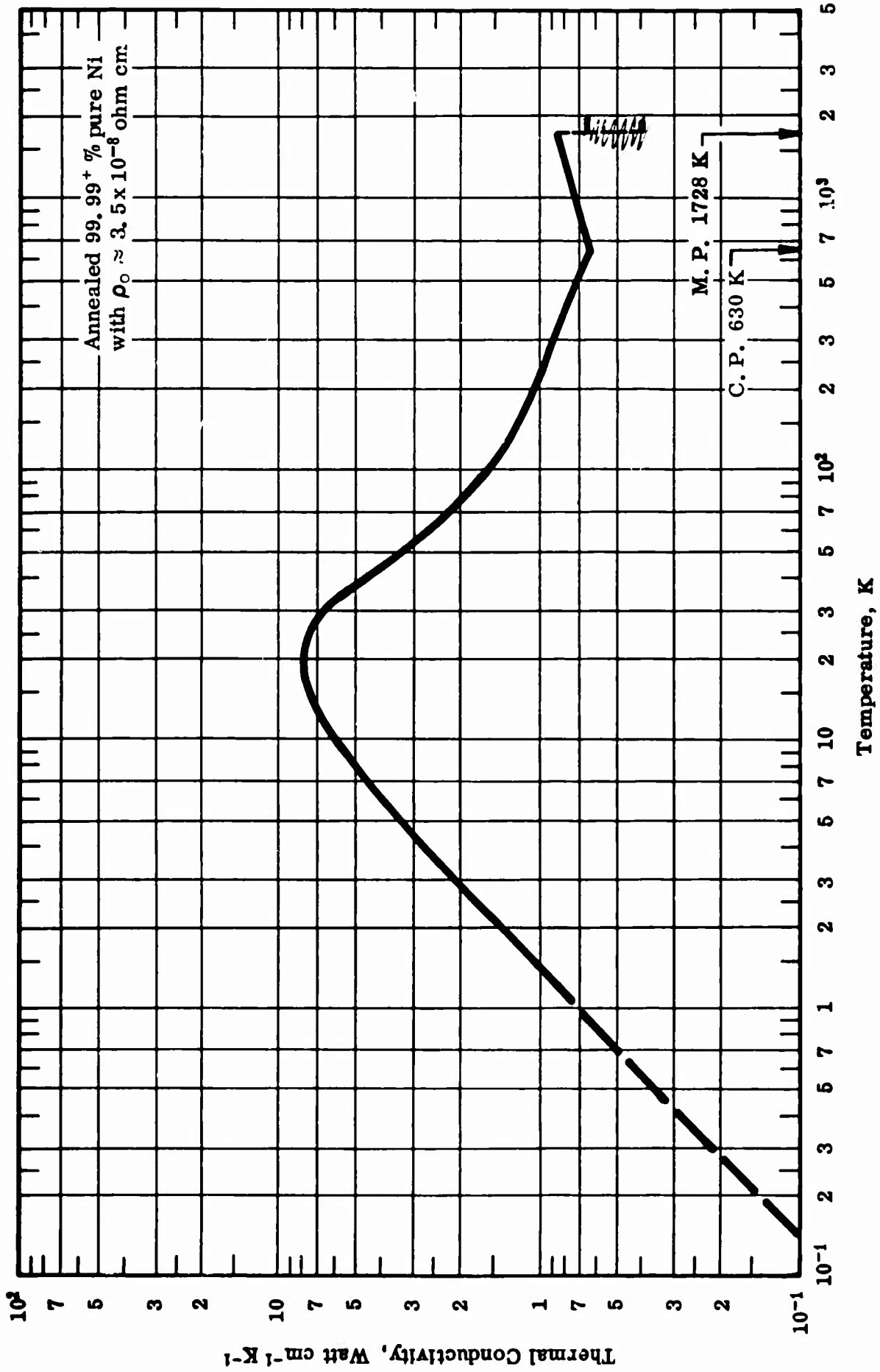


FIG. I-8 THERMAL CONDUCTIVITY OF NICKEL

**TABLE I-8 THERMAL CONDUCTIVITY OF NICKEL**

Selected Values for Annealed 99.99+ % Pure Nickel with  $\rho_0 \approx 3.5 \times 10^{-8}$  ohm cm

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.73</del> ** 0.66**                |
| 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 Hickman (1965) [41]. No data for liquid nickel are available and the selected value is estimated.

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\* Extrapolated.

\*\* Estimated.

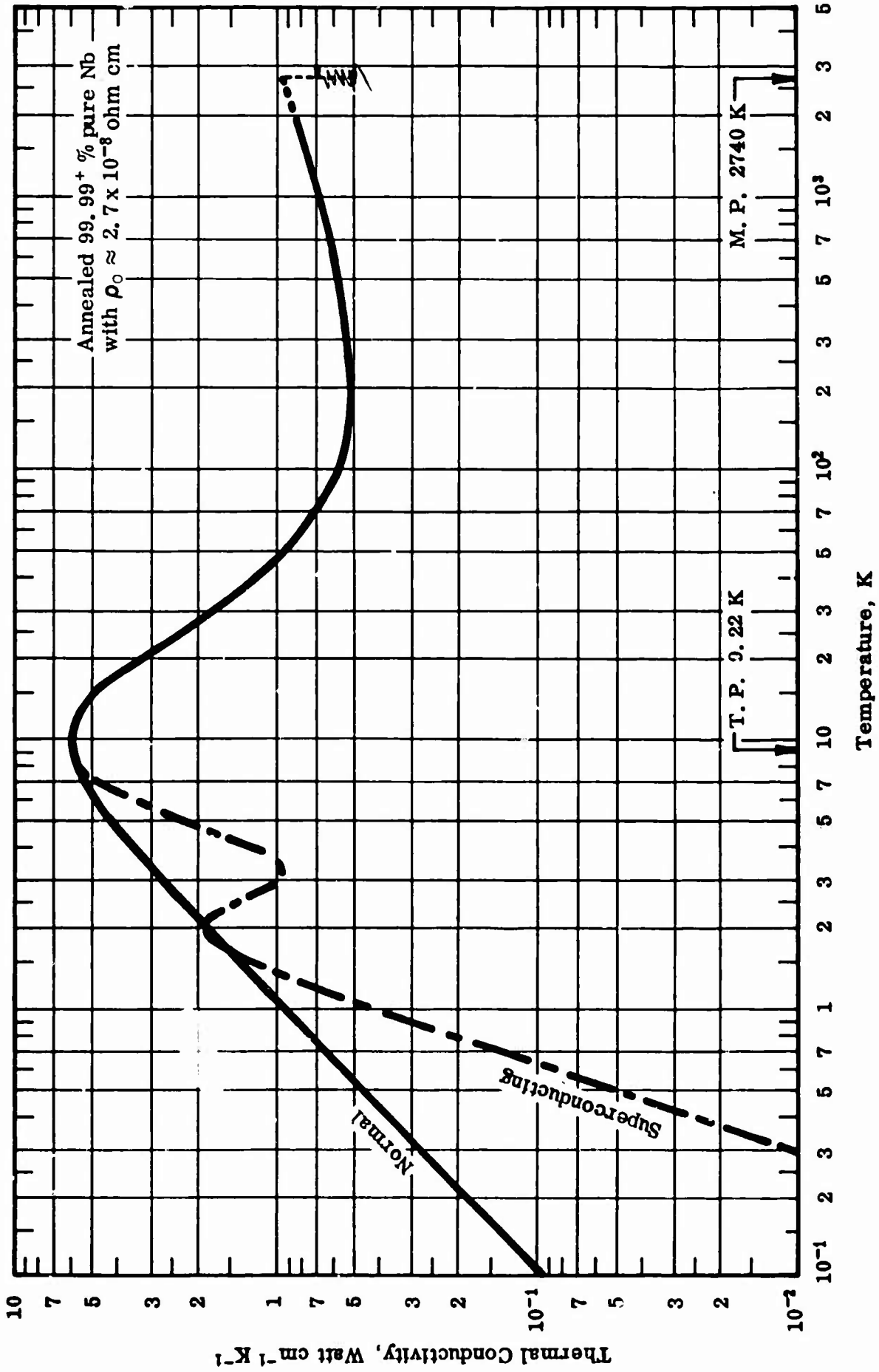


FIG. I-9 THERMAL CONDUCTIVITY OF NIOBIUM

**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 <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.5</del> **                        |
| 350  | 0.54                                     |          | 0.7                                      |

\* Extrapolated

\*\* Estimated

In superconducting state:

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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 <sup>are</sup> available and the value is from estimation.

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\* Extrapolated.

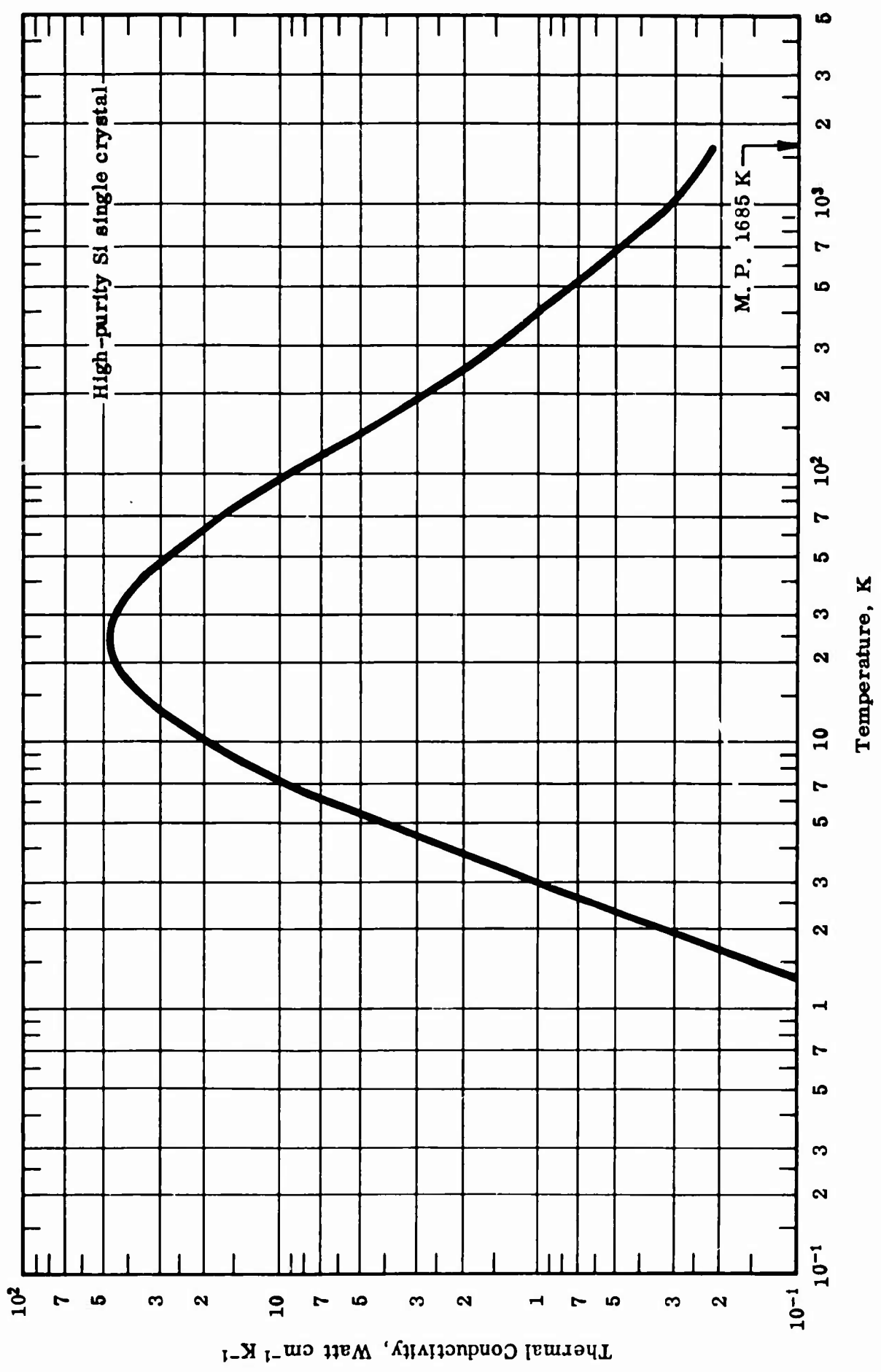


FIG. I-10 THERMAL CONDUCTIVITY OF SILICON

**TABLE I-10 THERMAL CONDUCTIVITY OF SILICON**

**Selected Values for High-Purity Silicon Single Crystal**

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 0    | 0.6                                      | 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].

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\* Extrapolated.

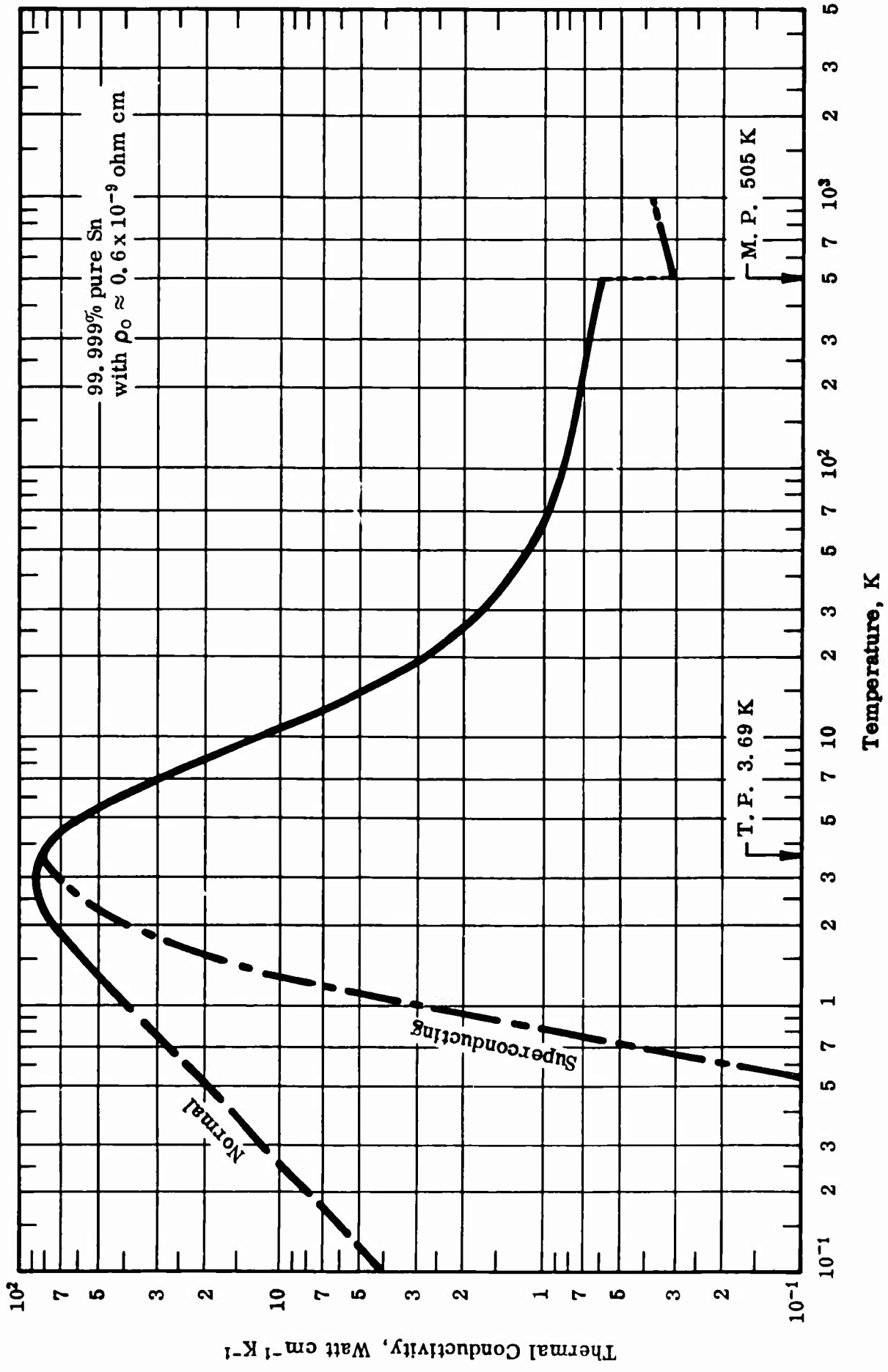


FIG. I-11 THERMAL CONDUCTIVITY OF TIN

**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 <sup>-1</sup> K <sup>-1</sup> |                 | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|-----------------|------|--|
|      | 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*                                   |
| 40   | 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].

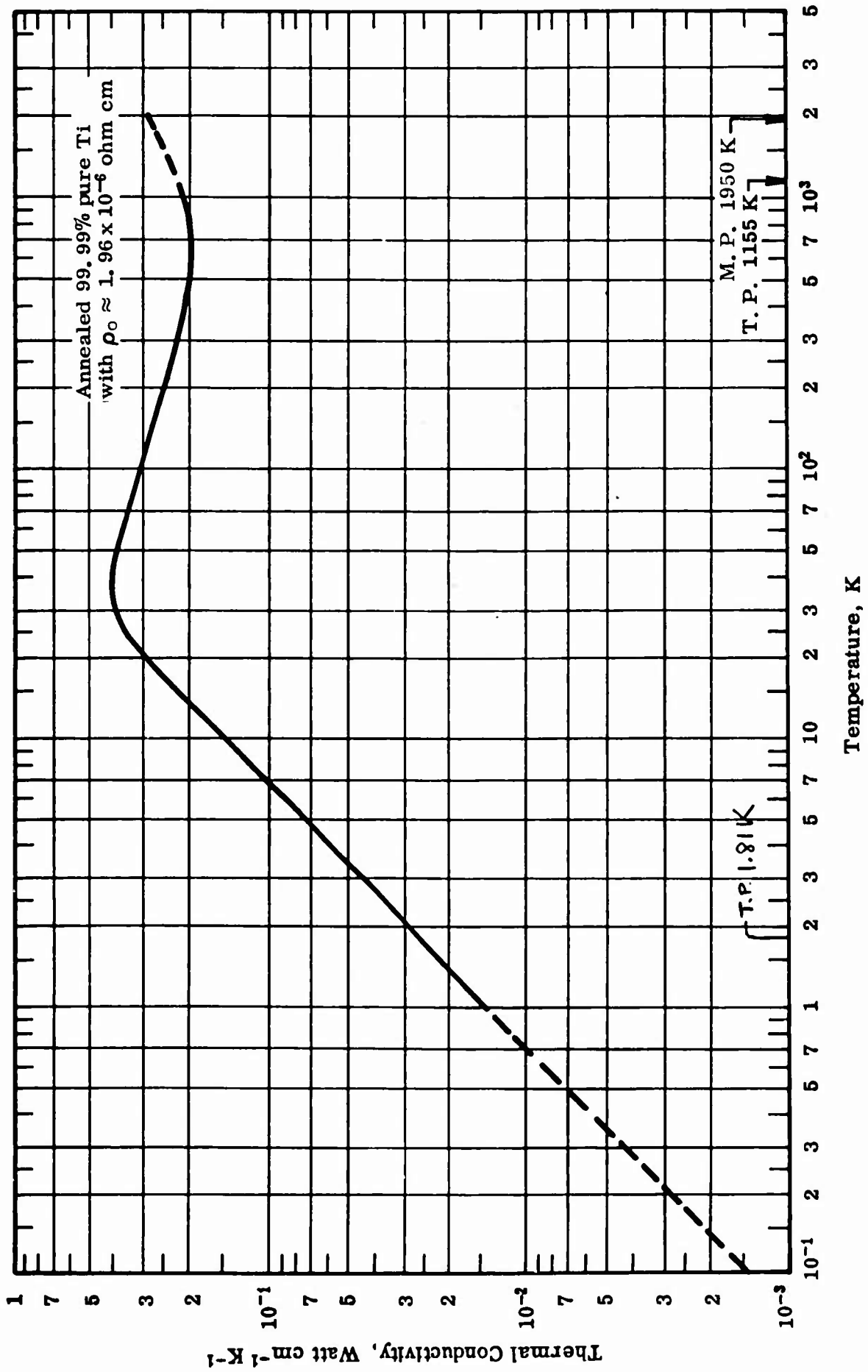


FIG. I-12 THERMAL CONDUCTIVITY OF TITANIUM

**TABLE I-12 THERMAL CONDUCTIVITY OF TITANIUM**

Selected Values for Annealed 99.99% Pure Titanium with  $\rho_0 \approx 1.96 \times 10^{-6}$  ohm cm

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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.

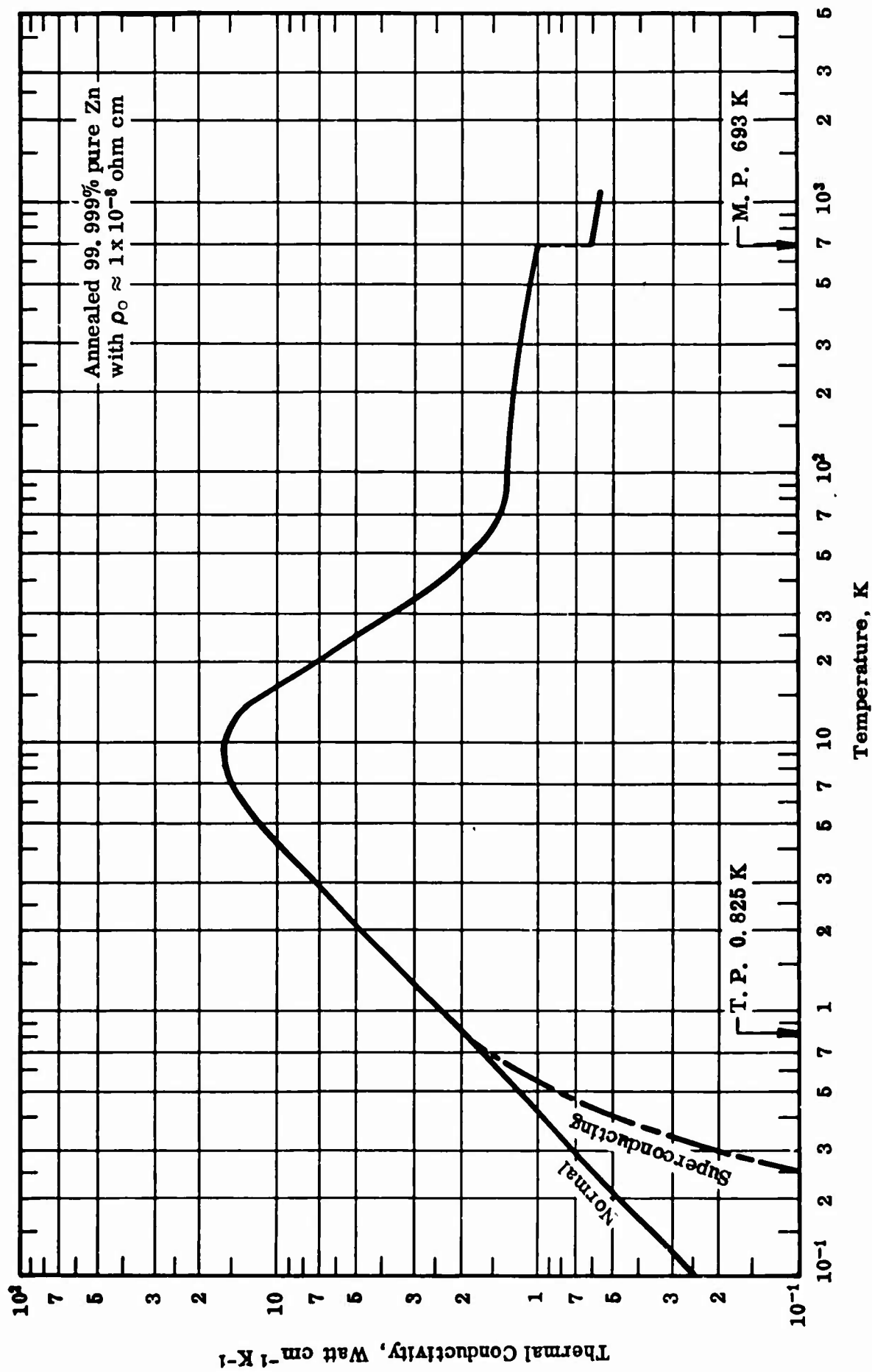


FIG. I-13 THERMAL CONDUCTIVITY OF ZINC

**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 <sup>-1</sup> K <sup>-1</sup> |                 | T, K    | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|-------|--|-----------------|---------|--|
|       | 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    | 0.570                                    |
| 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 Gruneisen (1932) [62], Bidwell and Lewis (1929)[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

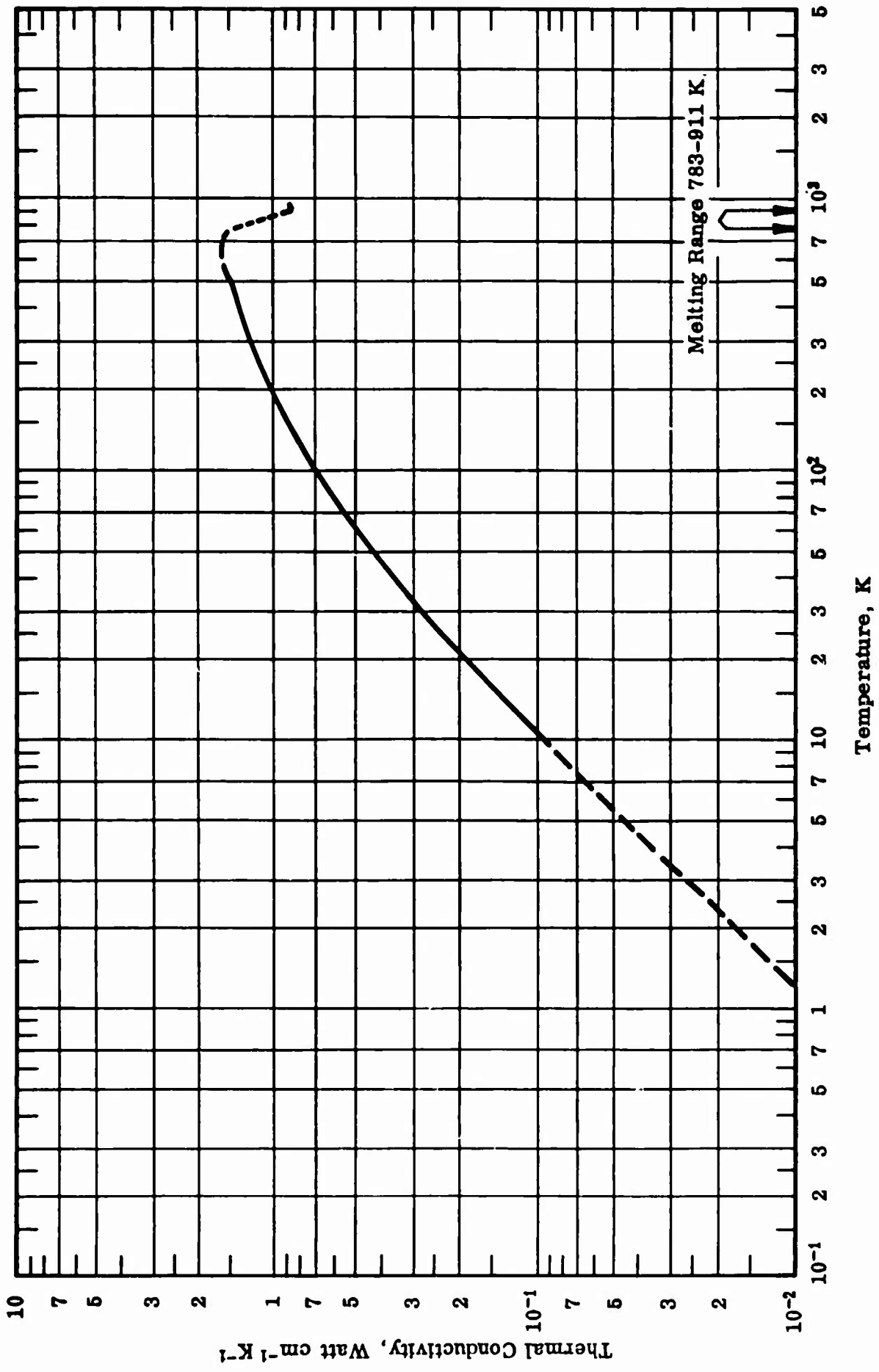


FIG. I-14 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2219-T852

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

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K    | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|---------|--|
| 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<sup>‡</sup>. Rhodes, Moeller, and Sax<sup>u</sup>er (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).

Aluminum alloy 2024-T4  
 T, K                      k, W cm<sup>-1</sup> K<sup>-1</sup>  
 200                          1.01  
 223.2                        1.08  
 250                          1.14  
 273.2                        1.19  
 298.2                        1.245  
 300                          1.25  
 323.2                        1.295

Oct. 27, 1971

\* Extrapolated.

\*\* Estimated.

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

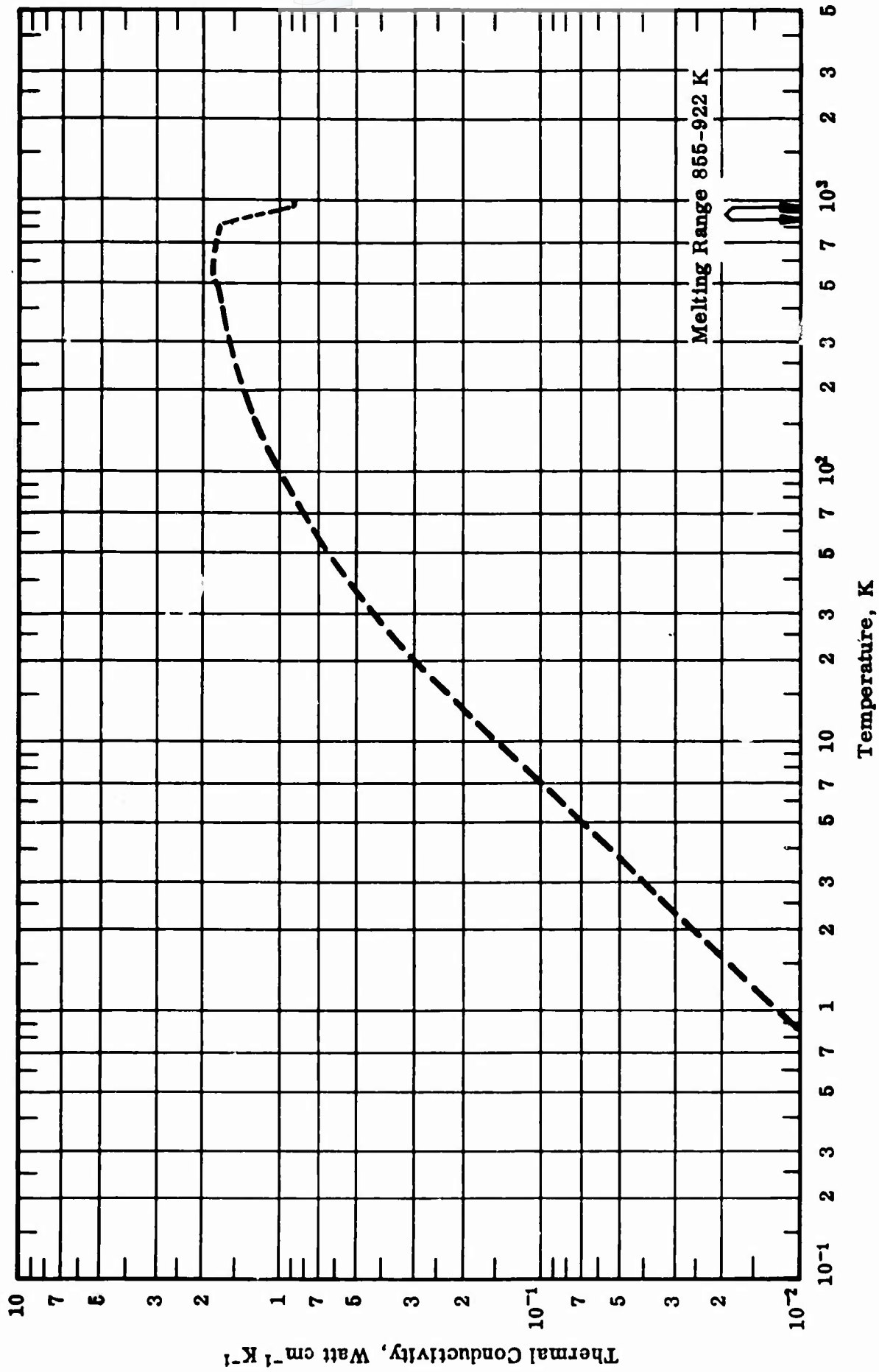


FIG. I-15 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 6061-T6

|         |                    |                     |                     |                     |
|---------|--------------------|---------------------|---------------------|---------------------|
| 6061-T6 | 100F<br>(311K)(38) | 300F<br>(422K)(141) | 500F<br>(533K)(600) | 700F<br>(644K) 371C |
|         | 0.40<br>(1.674)    | 0.414<br>(1.732)    | 0.422<br>(1.766)    | 0.428<br>(1.791)    |
| 6061-O  | 0.428<br>(1.791)   | 0.441<br>(1.845)    | 0.448<br>(1.874)    | 0.450<br>(1.883)    |

1.07      1.065      1.062      1.051

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

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K    | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|---------|--|
| 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<sup>-1</sup> K<sup>-1</sup> 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)‡.

*ALCOA Handbook (1959, 1962) gives a value of 0.40 cal/cm<sup>2</sup> at 25°C (1.674 watt cm<sup>-1</sup> K<sup>-1</sup> at 298 K). Thus the values should all be increased by 8%, i.e. times 1.08. The new recommended values (CINDAS Special Report to IBM Corp., Jan. 1978) are higher by 12% around room temperature. Therefore the tabular values should be increased by multiplying*

\* Estimated. 1.12.

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



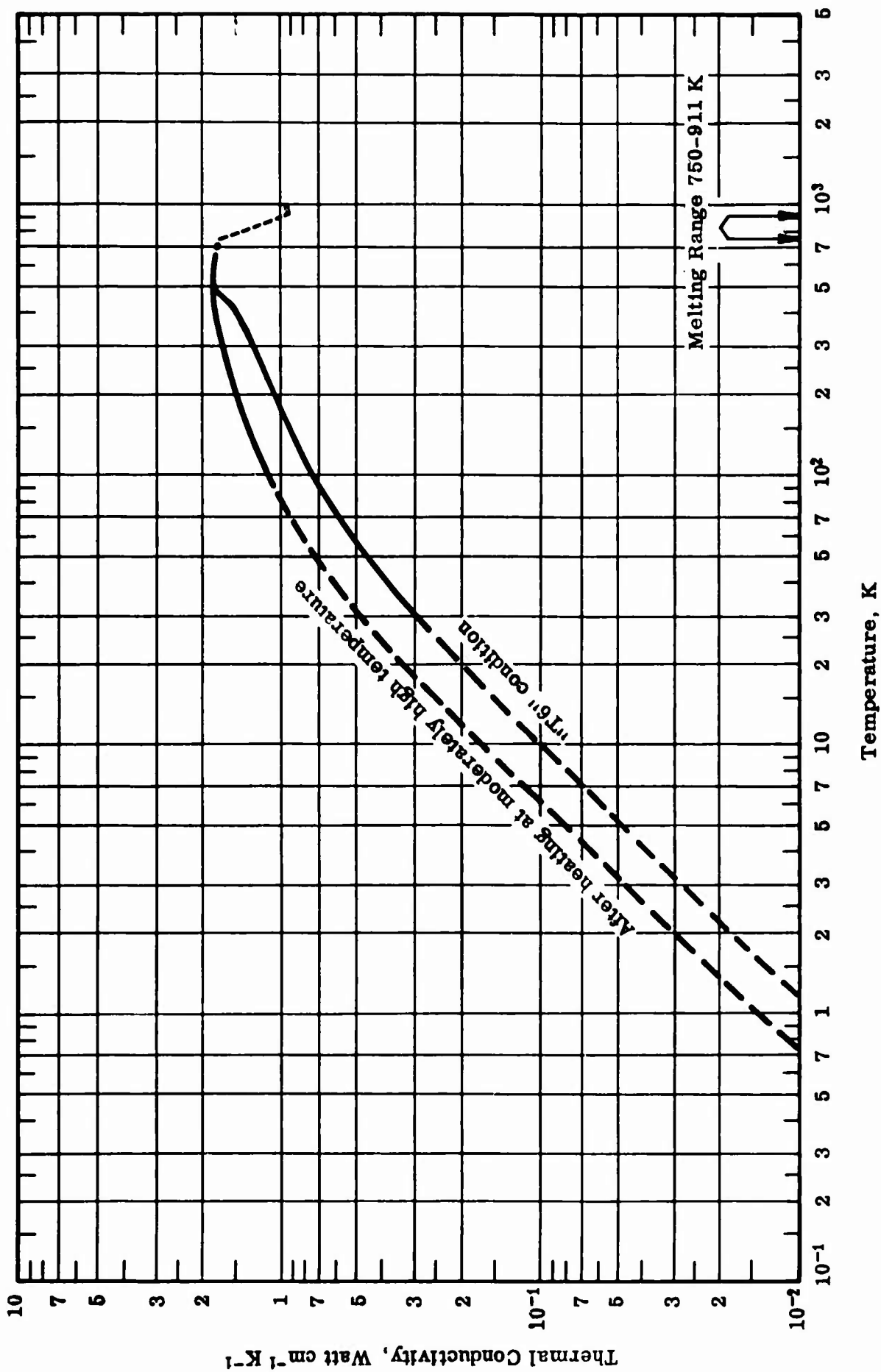


FIG. I-16 THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 7075-T6

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

| T, K    | In Condition "T6"<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> | After Heating at Moderately<br>High Temperature<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|---------|---|---|
| 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.

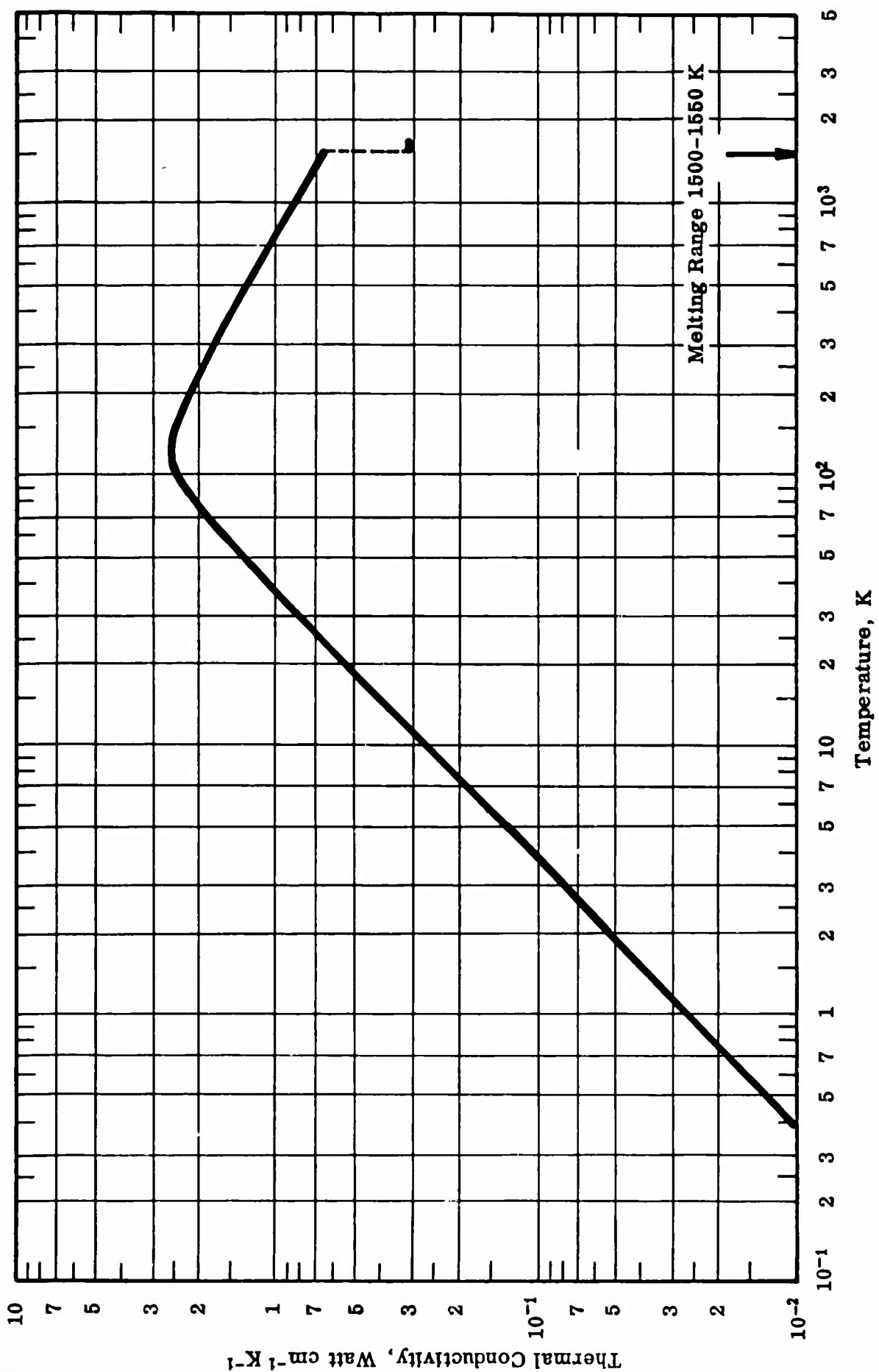


FIG. I-17 THERMAL CONDUCTIVITY OF BERYLLIUM (DILUTE) ALLOY

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

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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   | <del>2.18</del> 2.28                     | 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.

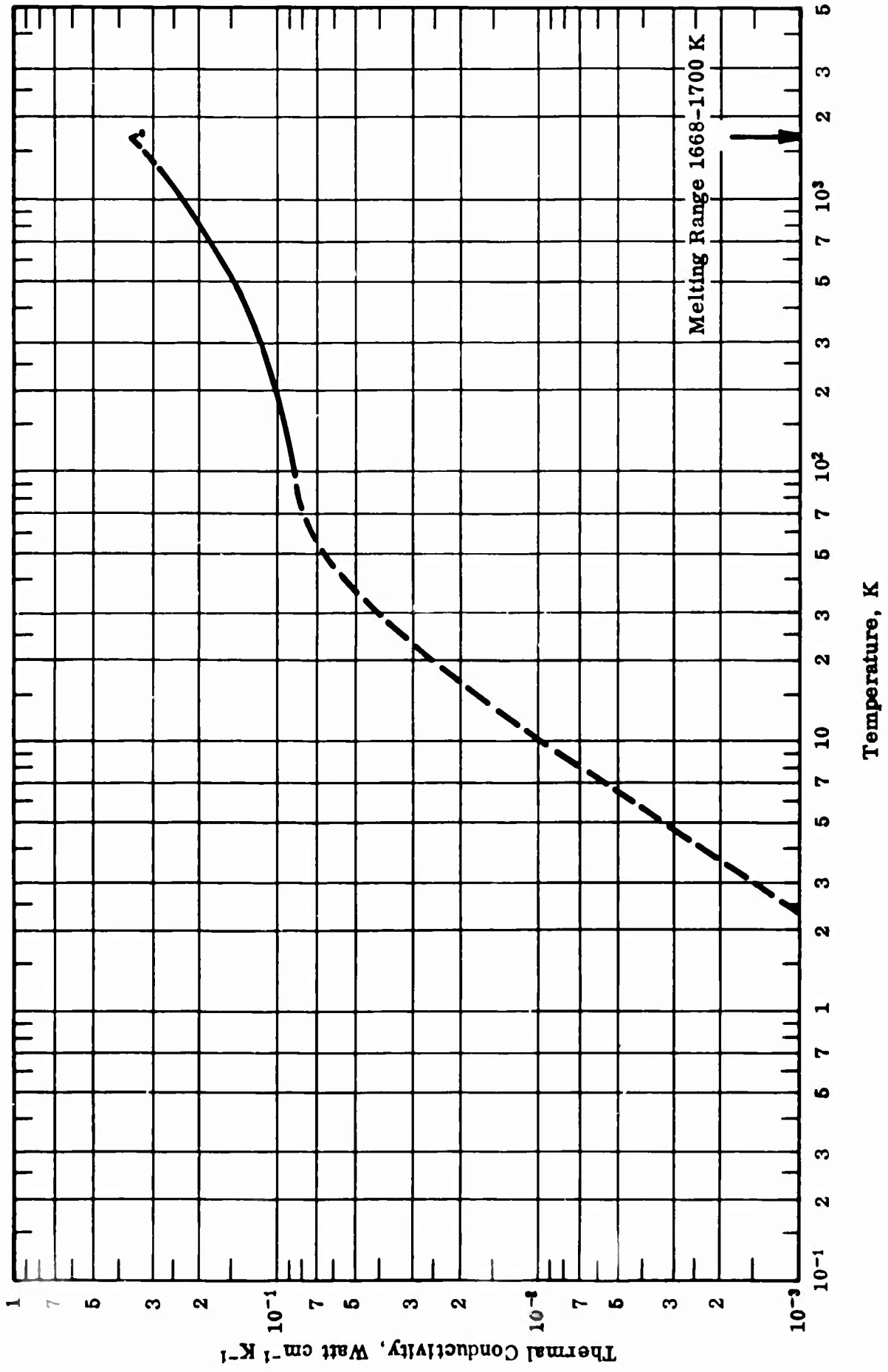


FIG. 1-18 THERMAL CONDUCTIVITY OF INCONEL X-750

TABLE I-18 THERMAL CONDUCTIVITY OF INCONEL X-750

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.33</del> **                       |
| 400  | 0.135                                    |          | 0.38                                     |

**Data Source and Remarks**

Three sets of experimental data are available<sup>‡</sup>. 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.

\* Extrapolated.

\*\* Estimated.

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

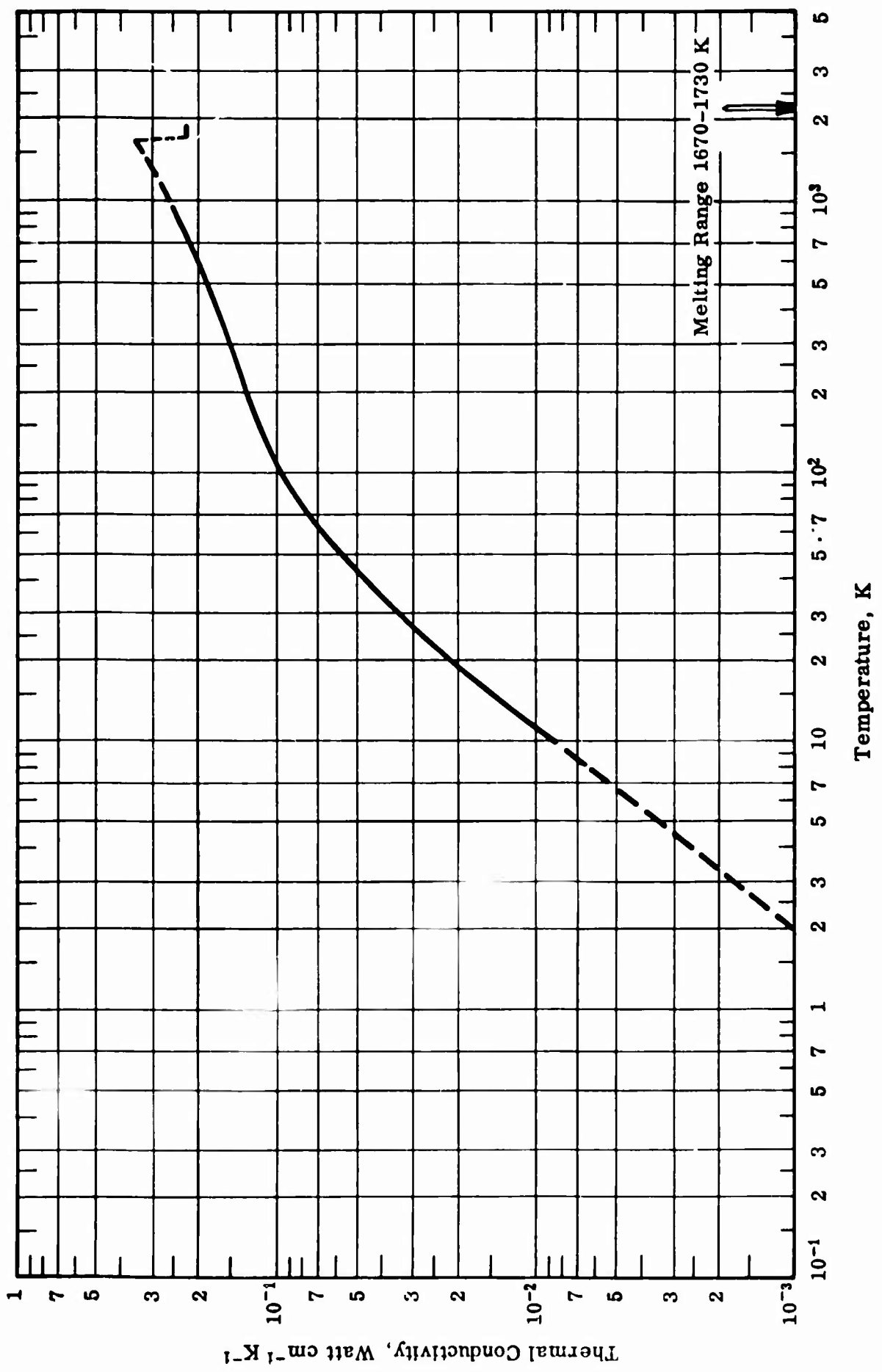


FIG. 1-19 THERMAL CONDUCTIVITY OF STAINLESS STEEL 304A

**TABLE I-19 THERMAL CONDUCTIVITY OF STAINLESS STEEL 304 A**

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.347</del> 0.22**                  |
| 400  | 0.170                                    |          | <del>WAAAX</del>                         |

**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.

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\* Extrapolated.  
 \*\* Estimated

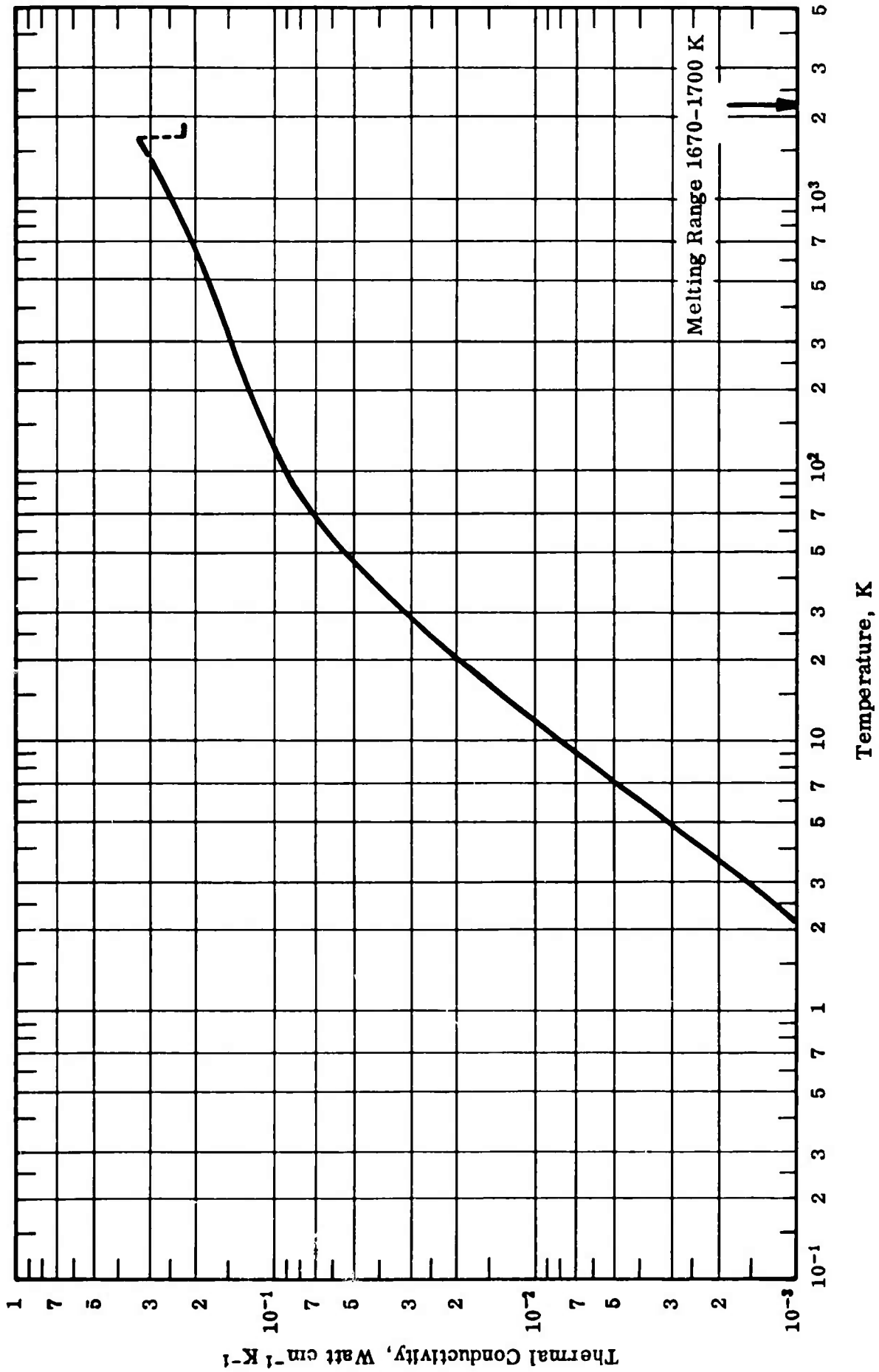


FIG. I-20 THERMAL CONDUCTIVITY OF STAINLESS STEEL 347

TABLE I-20 THERMAL CONDUCTIVITY OF STAINLESS STEEL 347

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K     | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 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 | <del>0.348**</del> 0.22**                |
| 400  | 0.165                                    |          | <del>0.361**</del>                       |

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.

\* Extrapolated.

\*\* Estimated.

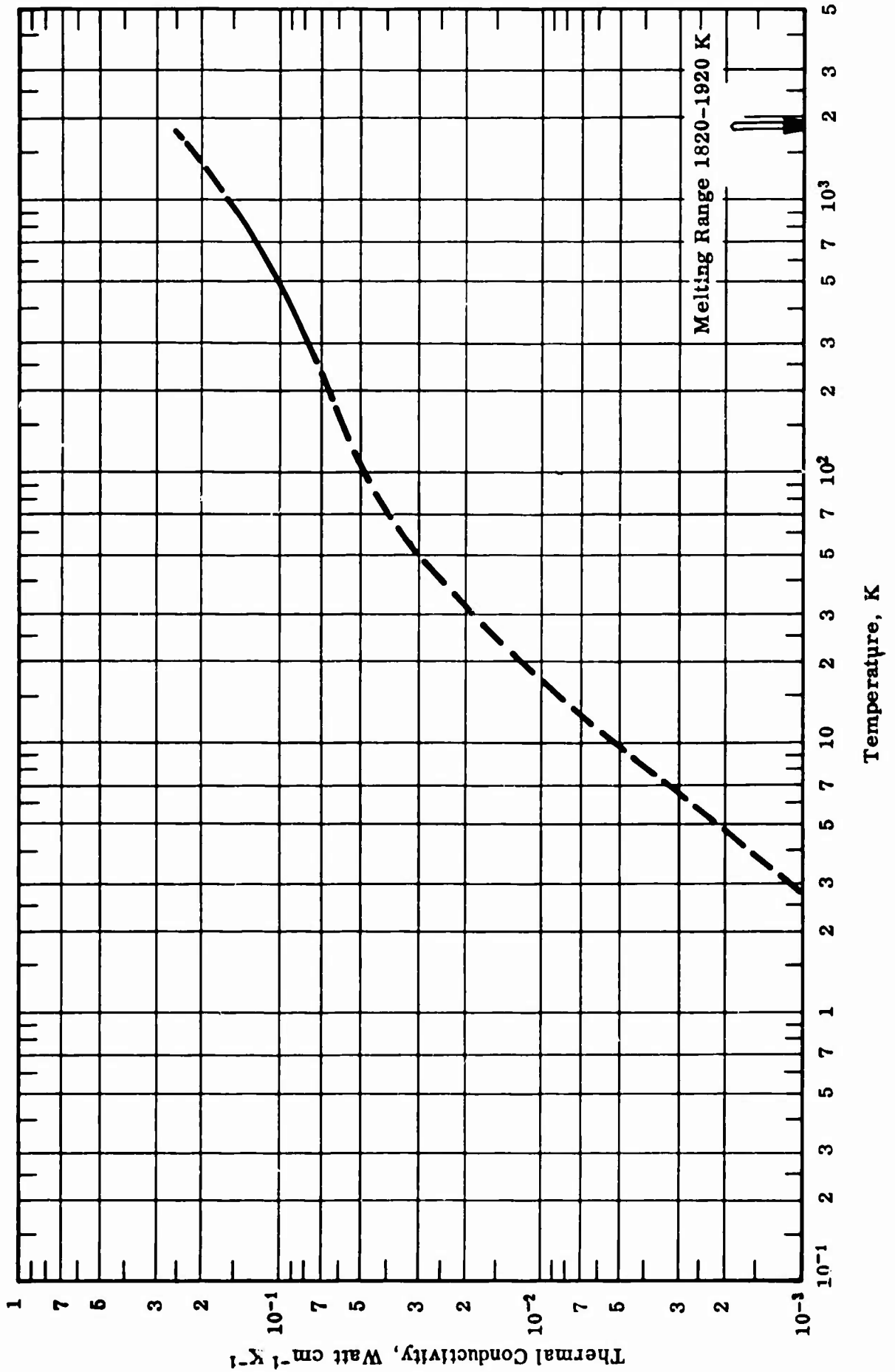


FIG. I-21 THERMAL CONDUCTIVITY OF TITANIUM ALLOY A-110AT

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

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 0    | 0  | 450  | 0.093                                    |
| 0.1  | 0.00015*                                 | 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.

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\* Extrapolated.

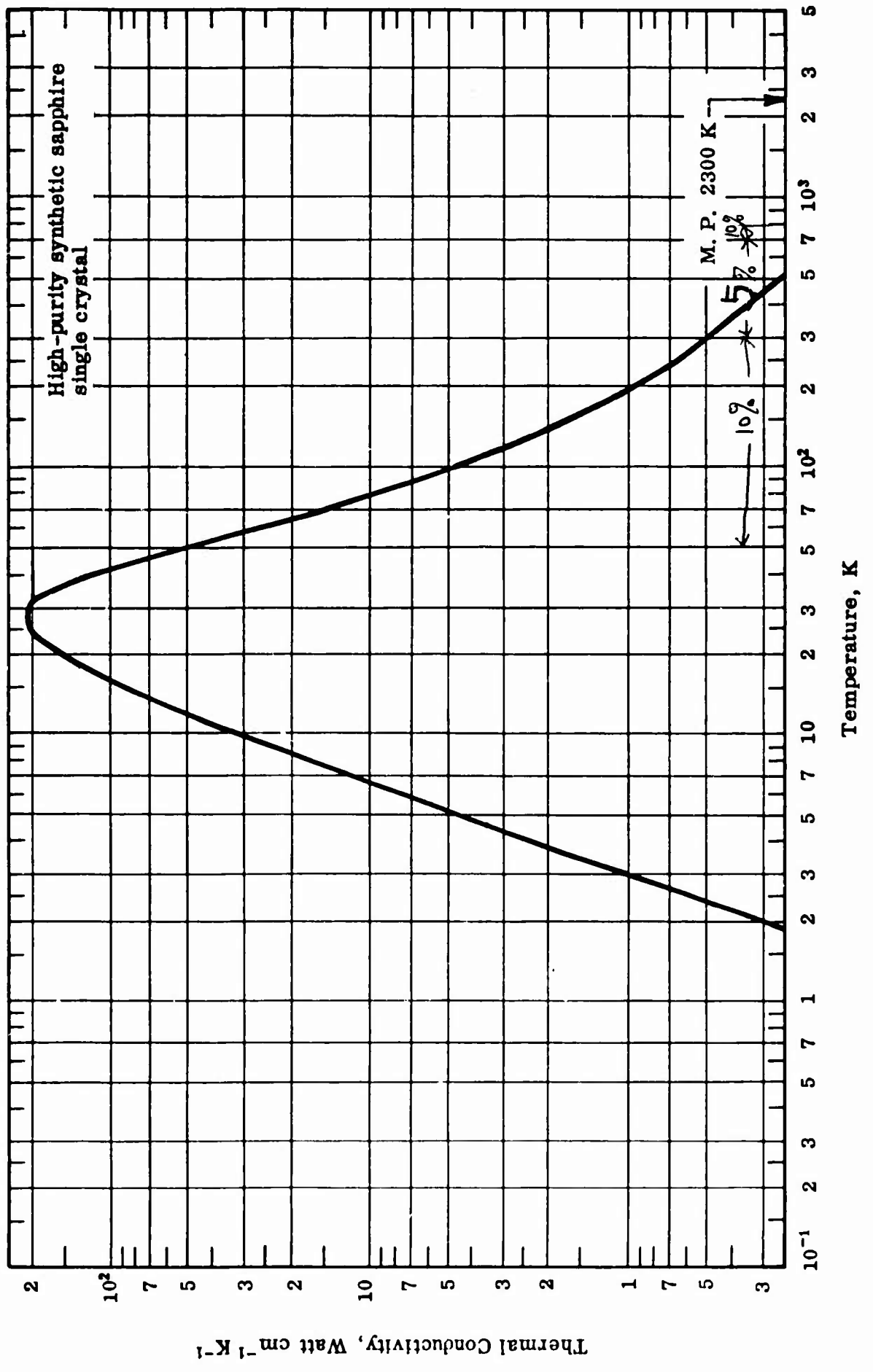


FIG. I-22 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (single crystal) Al<sub>2</sub>O<sub>3</sub>

TABLE I-22 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE  
(single crystal)  $Al_2O_3$   
*Heat flow direction at 60 degrees with the c-axis*  
Selected Values for High-Purity Synthetic Sapphire Single Crystal

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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  | <del>0.85</del> 0.82                     |
| 15   | 87                                       | 250  | <del>0.60</del> 0.58                     |
| 20   | 157                                      | 273  | <del>0.53</del> 0.52                     |
| 25   | 202                                      | 300  | <del>0.47</del> 0.46                     |
| 30   | 207                                      | 350  | <del>0.39</del> 0.38                     |
| 35   | 177                                      | 400  | <del>0.38</del> 0.324                    |
| 40   | 120                                      | 450  | <del>0.28</del> 0.279                    |
| 45   | 77                                       | 500  | <del>0.25</del> 0.242                    |
| 50   | 52                                       | 600  | 0.19 0.189                               |
| 60   | 26.5                                     | 700  | <del>0.16</del> <del>0.152</del> 0.154   |

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].

*Uncertainty ±5% 300 - 700 K*  
*±15% to 50K*  
*no confidence below 50K*

*800 0.130*  
*900 0.115*  
*1100 0.102*  
*1200 0.102*  
*1300 0.107*  
*1400 0.116*  
*1500 0.129*

\*Extrapolated.

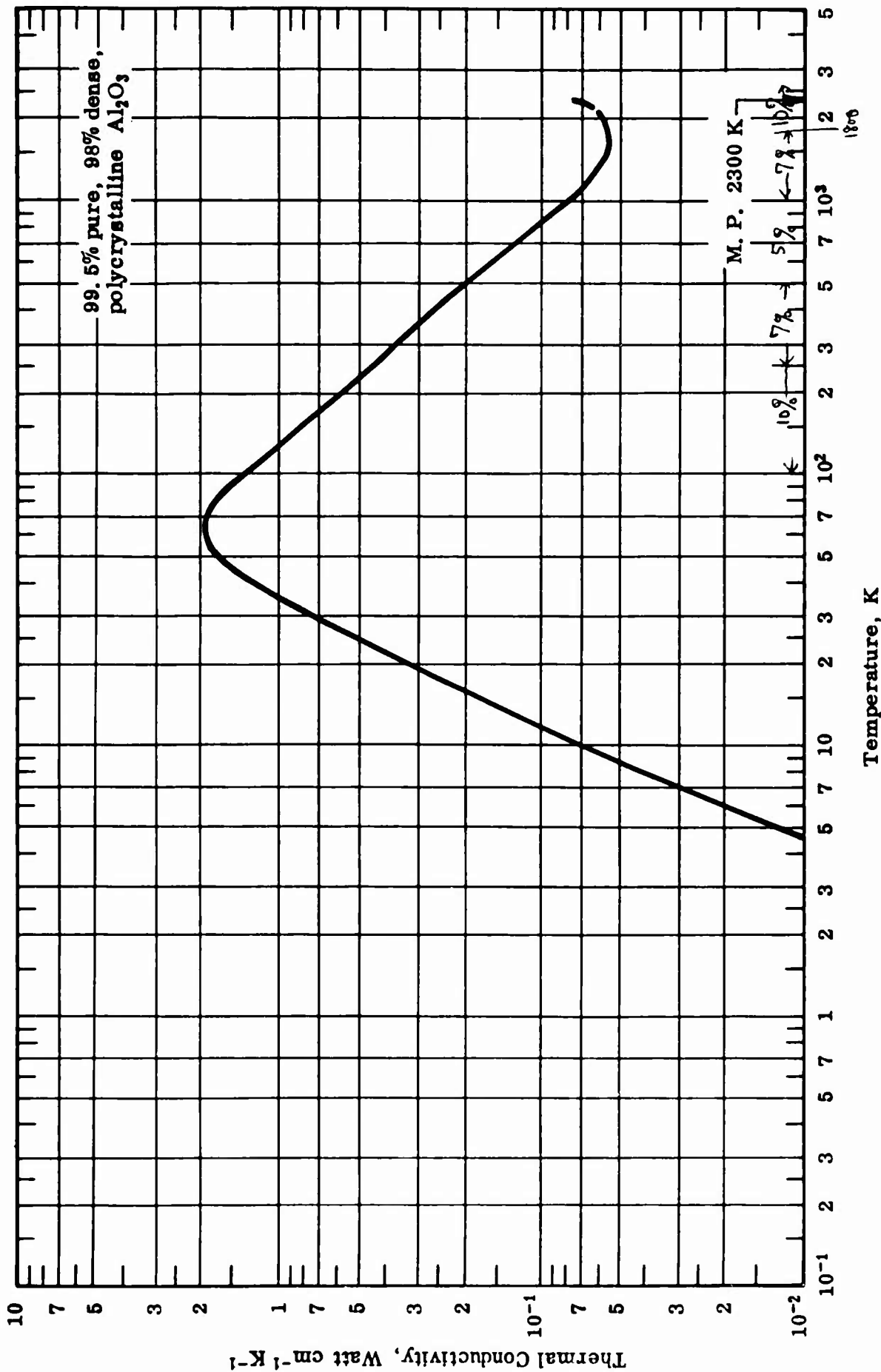


FIG. I-23 THERMAL CONDUCTIVITY OF ALUMINUM OXIDE (polycrystalline)  $Al_2O_3$

**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  | 0.000016*               | 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.

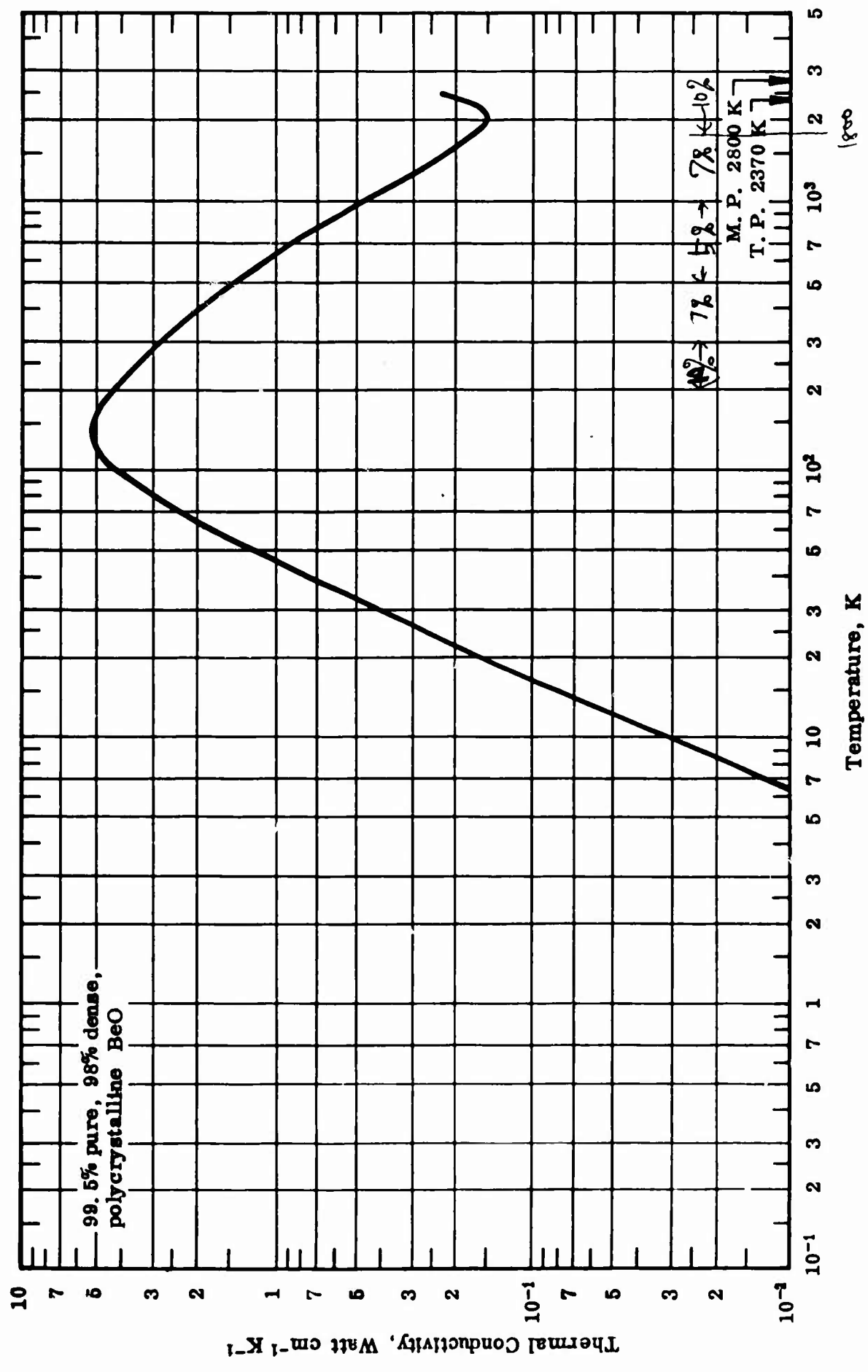


FIG. I-24 THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE BeO

TABLE I-24 THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE BeO

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

| T, K | $k$ , Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | $k$ , Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|---|------|---|
| 0    | 0   | 400  | 1.96  |
| 0.1  | 0.00000063*                                 | 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.

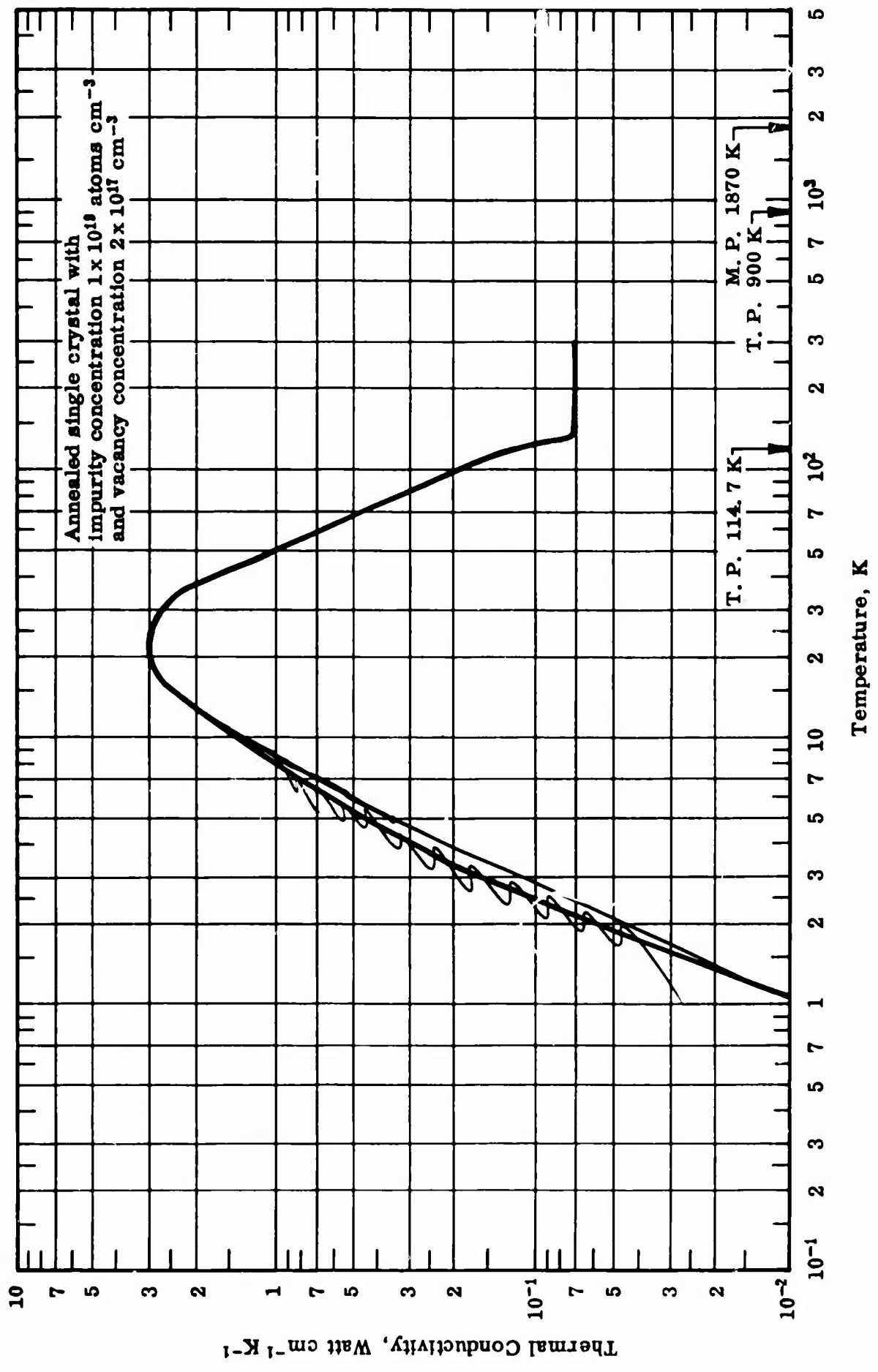


FIG. I-25 THERMAL CONDUCTIVITY OF IRON OXIDE  $\text{Fe}_3\text{O}_4$

**TABLE I-25 THERMAL CONDUCTIVITY OF IRON OXIDE  $Fe_3O_4$**   
 Selected Values for Annealed Single Crystal with Impurity Concentration  $1 \times 10^{19}$   
 atoms  $cm^{-3}$  and Vacancy Concentration  $2 \times 10^{17}$   $cm^{-3}$

| 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    | <del>0.47</del> 0.36     | 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.

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\* Extrapolated.

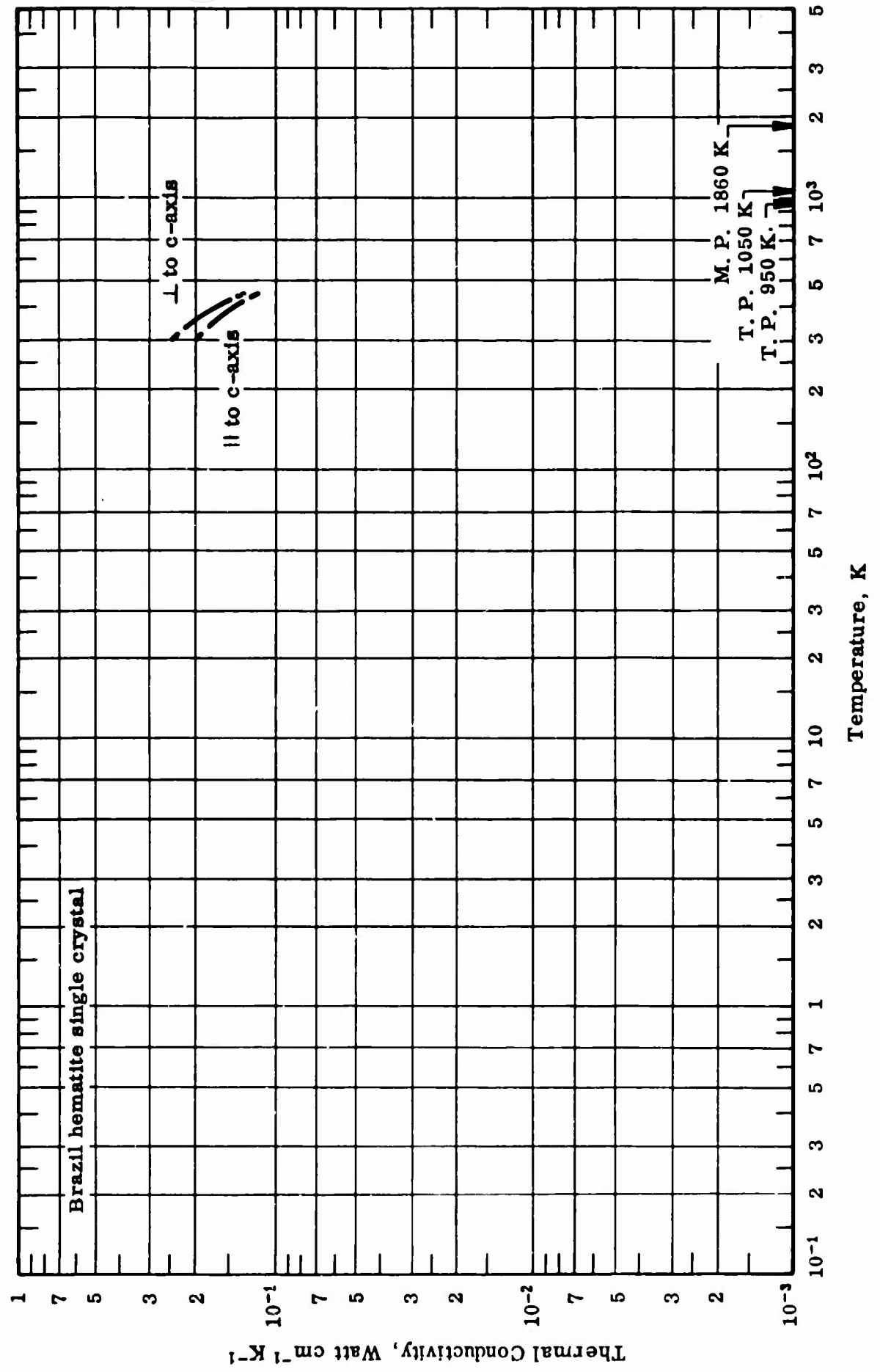


FIG. I-26 THERMAL CONDUCTIVITY OF IRON (IC) OXIDE  $\text{Fe}_2\text{O}_3$

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

**Selected Values for Brazil Hematite Single Crystal**

| T, K | Heat flow parallel<br>to c-axis | Heat flow perpendicular<br>to c-axis |
|------|---------------------------------|--------------------------------------|
|      | k, Watt $cm^{-1}K^{-1}$         | 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, Ilyn, and Eichbaum (1954) [107].

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\* Extrapolated

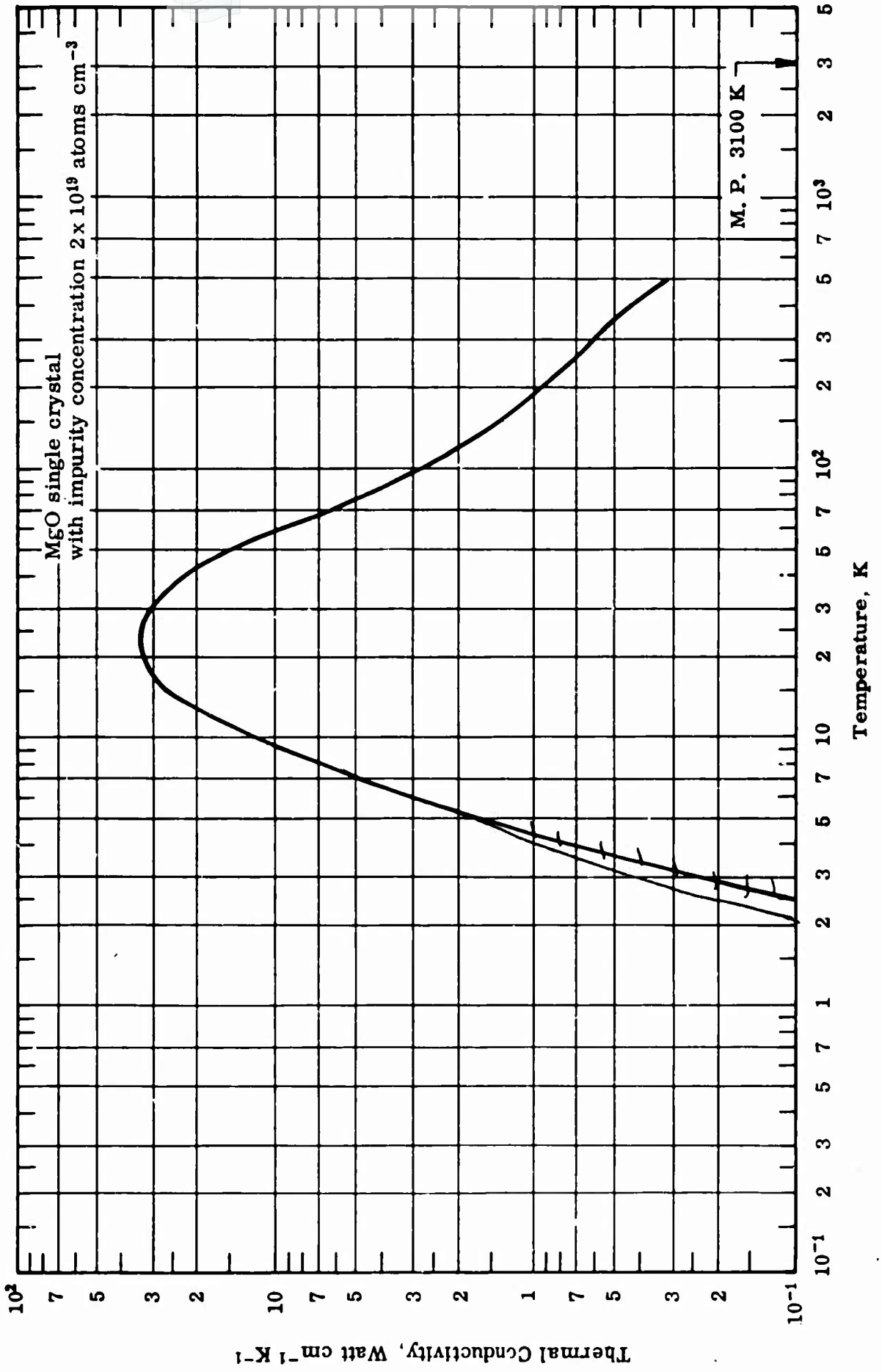


FIG. I-27 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (single crystal) MgO

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

Selected Values for MgO Single Crystal with Impurity Concentration  
 $2 \times 10^{19}$  atoms  $\text{cm}^{-3}$

| T, K | k, Watt $\text{cm}^{-1}\text{K}^{-1}$ | T, K | k, Watt $\text{cm}^{-1}\text{K}^{-1}$ |
|------|---------------------------------------|------|---------------------------------------|
| 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  | <del>0.83</del> 0.94                  |
| 20   | 32.5                                  | 250  | 0.73                                  |
| 25   | 33.1                                  | 273  | 0.665                                 |
| 30   | 30.9                                  | 300  | 0.60                                  |
| 35   | 26.5                                  | 350  | 0.507                                 |
| 40   | 21.6                                  | 400  | 0.431                                 |
| 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 (1962) [108].

\* Extrapolated.

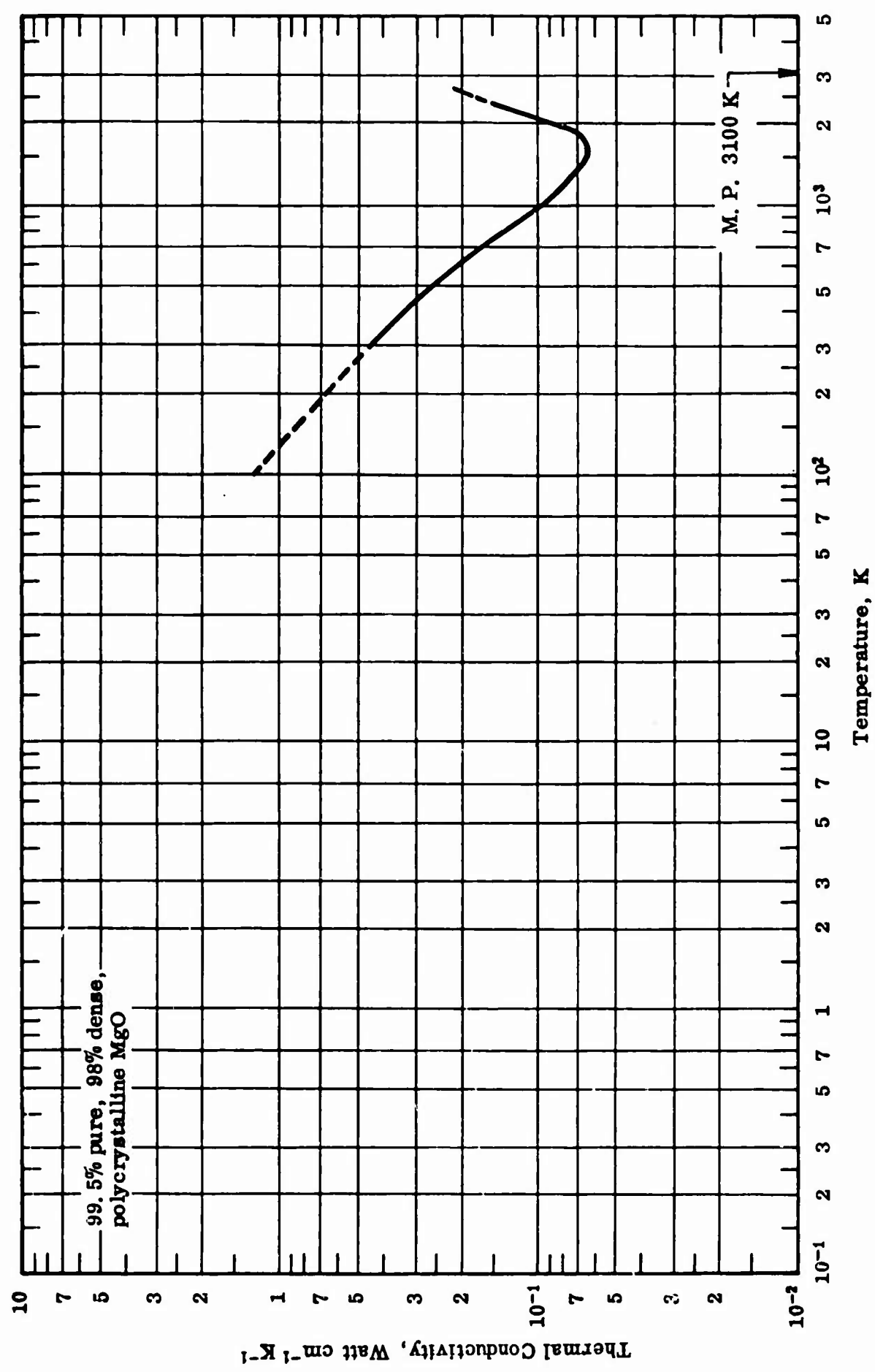


FIG. I-28 THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE (polycrystalline) MgO

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 <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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 | <del>0.155</del> 0.115                   |
| 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.

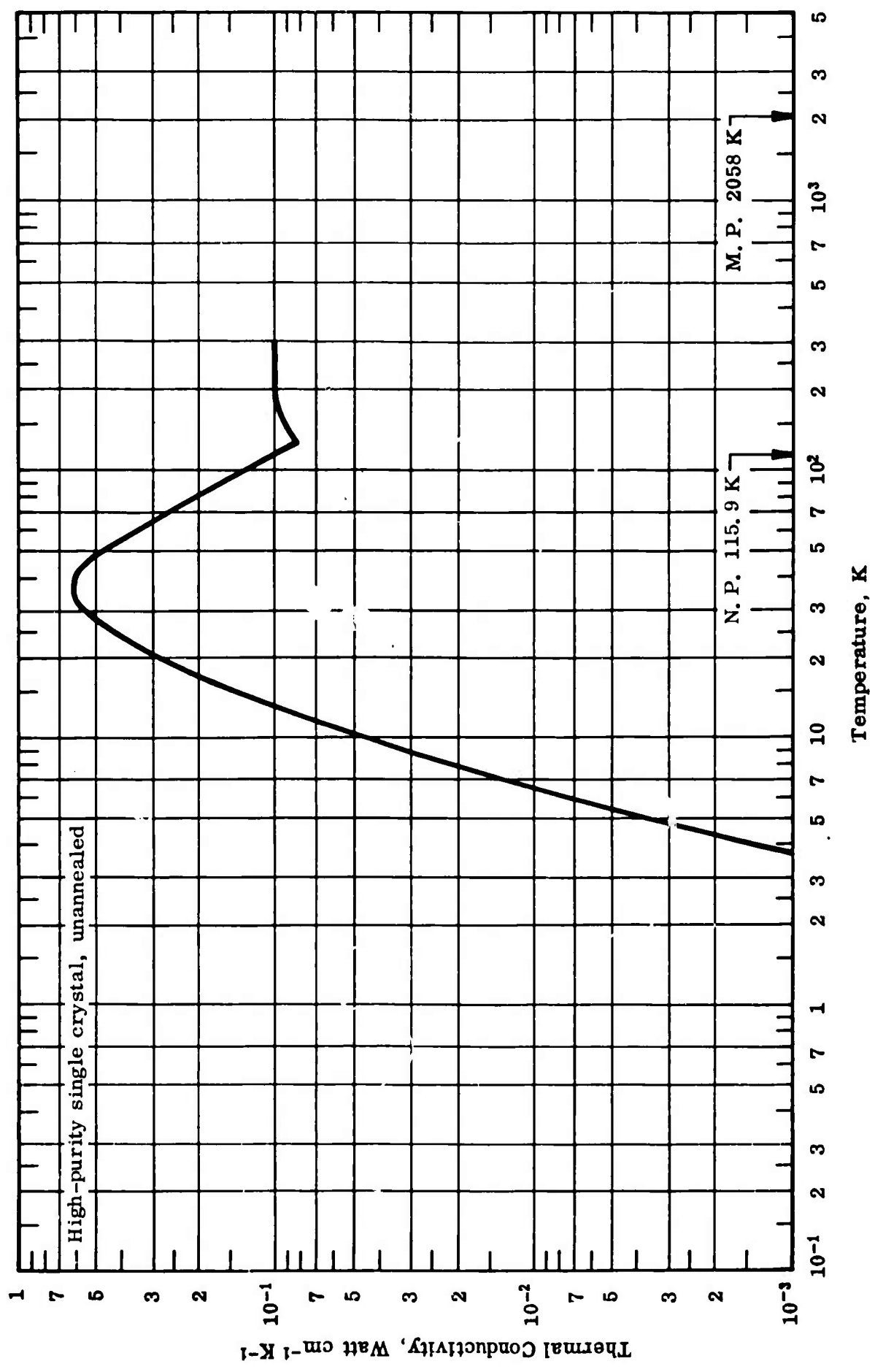


FIG. I-29 THERMAL CONDUCTIVITY OF MANGANESE MONOXIDE MnO

**TABLE I-29 THERMAL CONDUCTIVITY OF MANGANESE MONOXIDE MnO**  
**Selected Values for Unannealed High-Purity Single Crystal**

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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].

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\* Extrapolated

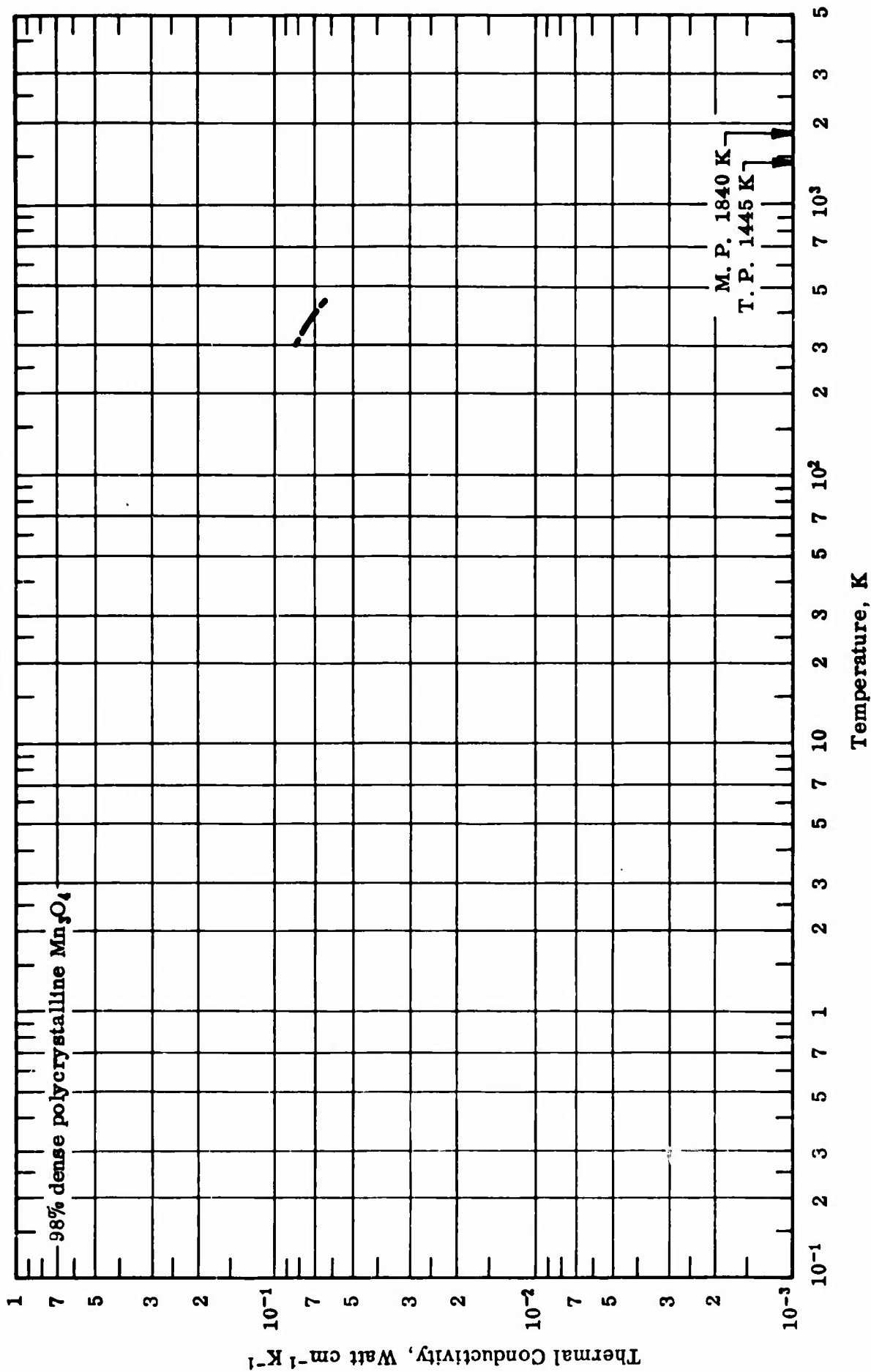


FIG. I-30 THERMAL CONDUCTIVITY OF MANGANOMANGANIC OXIDE  $Mn_2O_4$

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.

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\* Extrapolated.

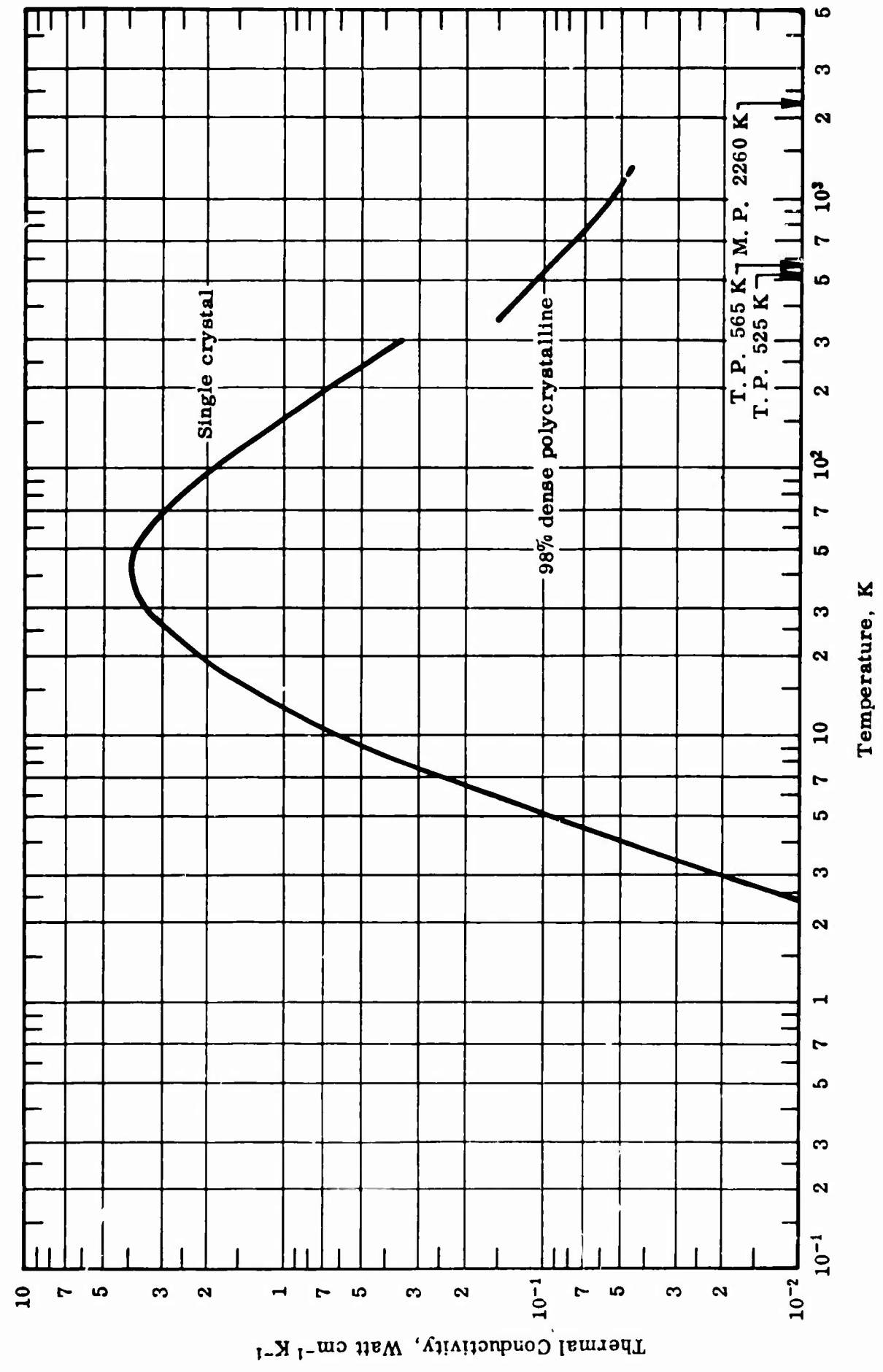


FIG. I-31 THERMAL CONDUCTIVITY OF NICKEL (OUS) OXIDE NiO

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

| NiO Single Crystal |  | 98% Dense Polycrystalline NiO |  |
|--------------------|--|-------------------------------|--|
| T, K               | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K                          | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
| 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.

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\* Extrapolated.

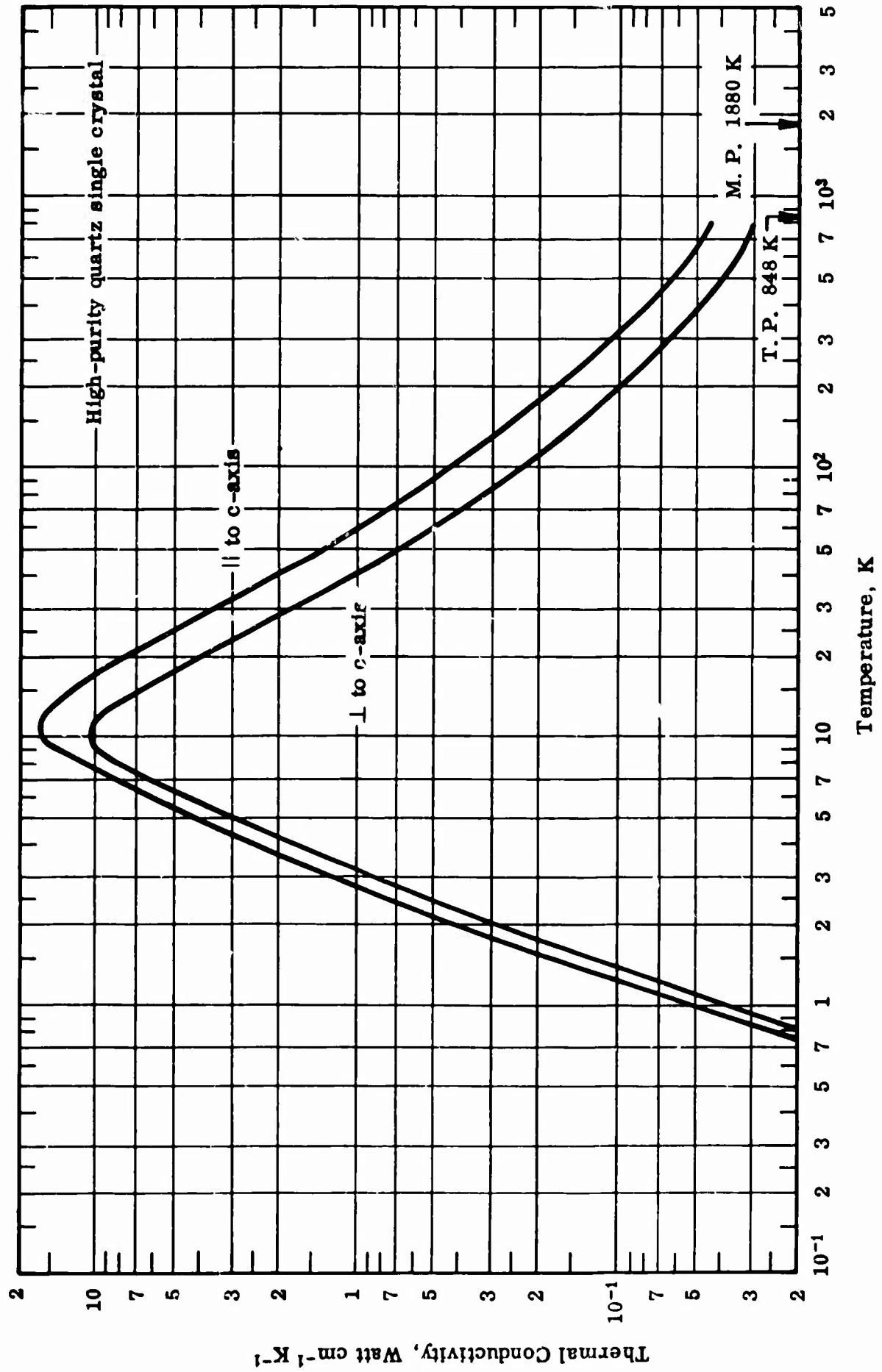


FIG. 1-32 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (quartz single crystal) SiO<sub>2</sub>

**TABLE I-32 THERMAL CONDUCTIVITY OF SILICON DIOXIDE**  
 (quartz single crystal) SiO<sub>2</sub>

Selected Values for High-Purity Quartz Single Crystal

| T, K | $d = 0.134 \text{ cm}$   | $d = 0.216 \text{ cm}$  | $-k_{  }$<br>$k_{\perp}$ |
|------|--|---|--------------------------|
|      | Heat flow parallel to c-axis<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> | Heat flow perpendicular to c-axis<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> |                          |
| 0    | 0  | 0   |                          |
| 0.1  | 0.00005*   | 0.000036*   | 1.389                    |
| 0.5  | 0.0063*  | 0.0045*   | 1.400                    |
| 1    | 0.05*  | 0.036*  | 1.389                    |
| 5    | 4.0  | 3.0   | 1.333                    |
| 8    | <del>16.5</del> 12.1   | 8.6   | 1.407                    |
| 10   | 16.5   | 10.4  | 1.587                    |
| 15   | 12.5   | 6.7   | 1.866                    |
| 20   | 7.5  | 3.9   | 1.923                    |
| 25   | 5.0  | 2.55  | 1.961                    |
| 30   |  | 1.79  | 1.955                    |
| 35   |  | 1.32  | 1.992                    |
| 40   | 2.04   | 1.01  | 2.02                     |
| 45   | 1.64   | 0.82  | 2.00                     |
| 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<br>to c-axis<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> | Heat flow perpendicular<br>to c-axis<br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|---|--|
| 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.

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\* Extrapolated.

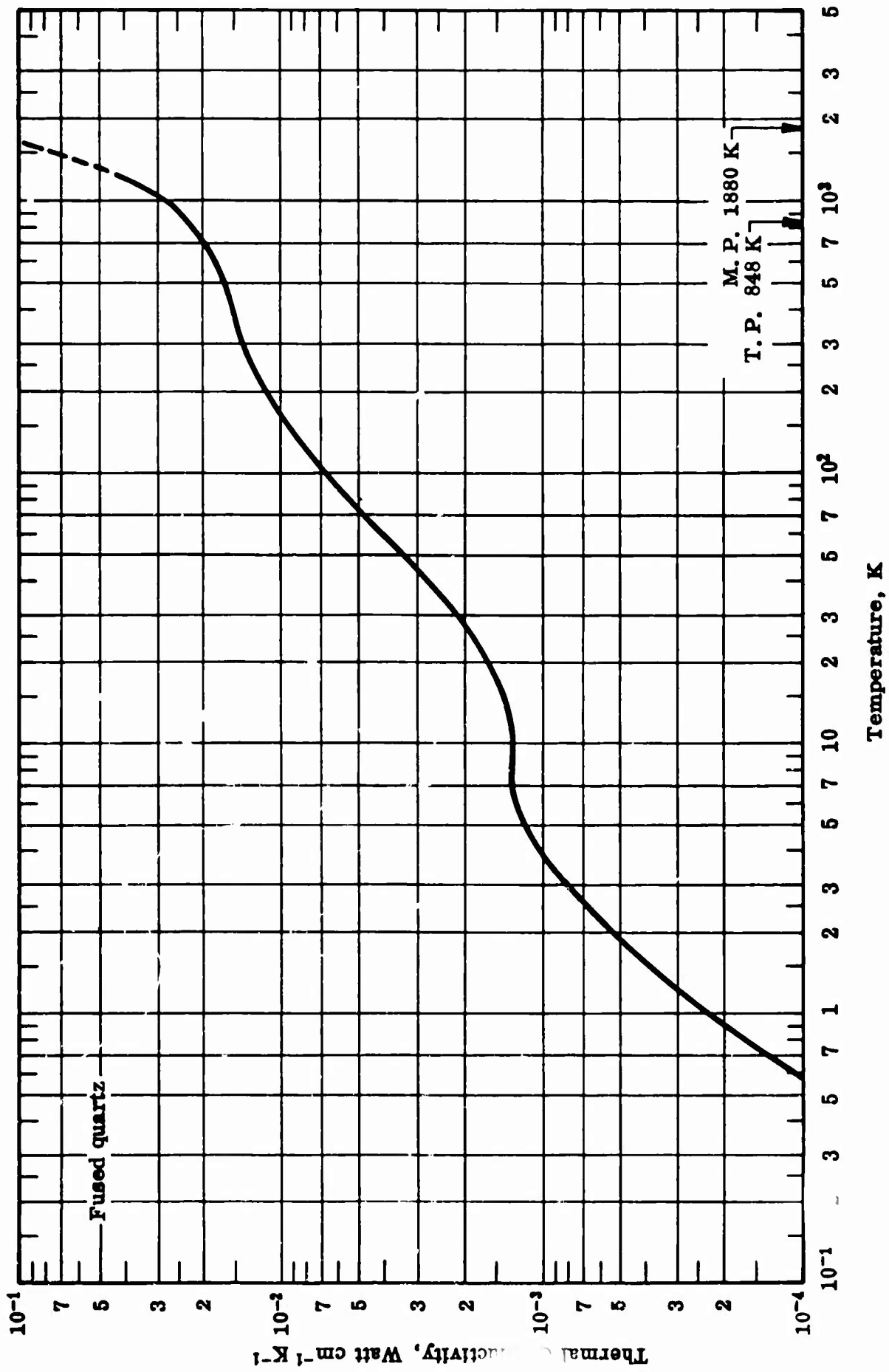


FIG. I-33 THERMAL CONDUCTIVITY OF SILICON DIOXIDE (fused quartz)  $\text{SiO}_2$

TABLE I-33 THERMAL CONDUCTIVITY OF SILICON DIOXIDE  
 (fused quartz) SiO<sub>2</sub>

| T, K | <i>Clear</i><br>k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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 | 0.11*                                    |

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], Ncrton and Kingery (1953) [129], and others.

\* Extrapolated.

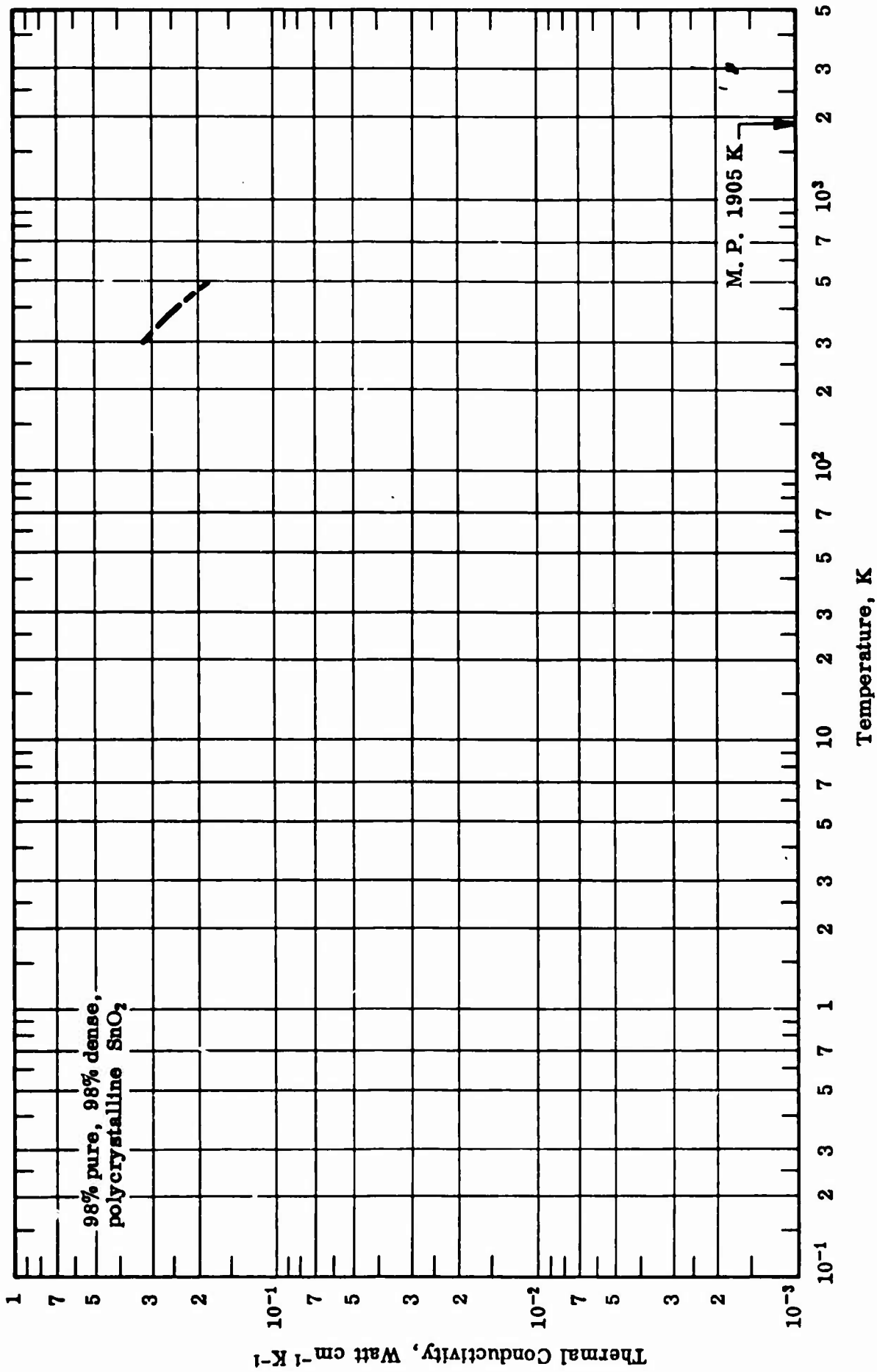


FIG. I-34 THERMAL CONDUCTIVITY OF TIN (IC) OXIDE SnO<sub>2</sub>

TABLE I-34 THERMAL CONDUCTIVITY OF TIN (IC) OXIDE SnO<sub>2</sub>

Selected Values for 98% Pure, 98%Dense, Polycrystalline SnO<sub>2</sub>

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|
| 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].

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\* Extrapolated.

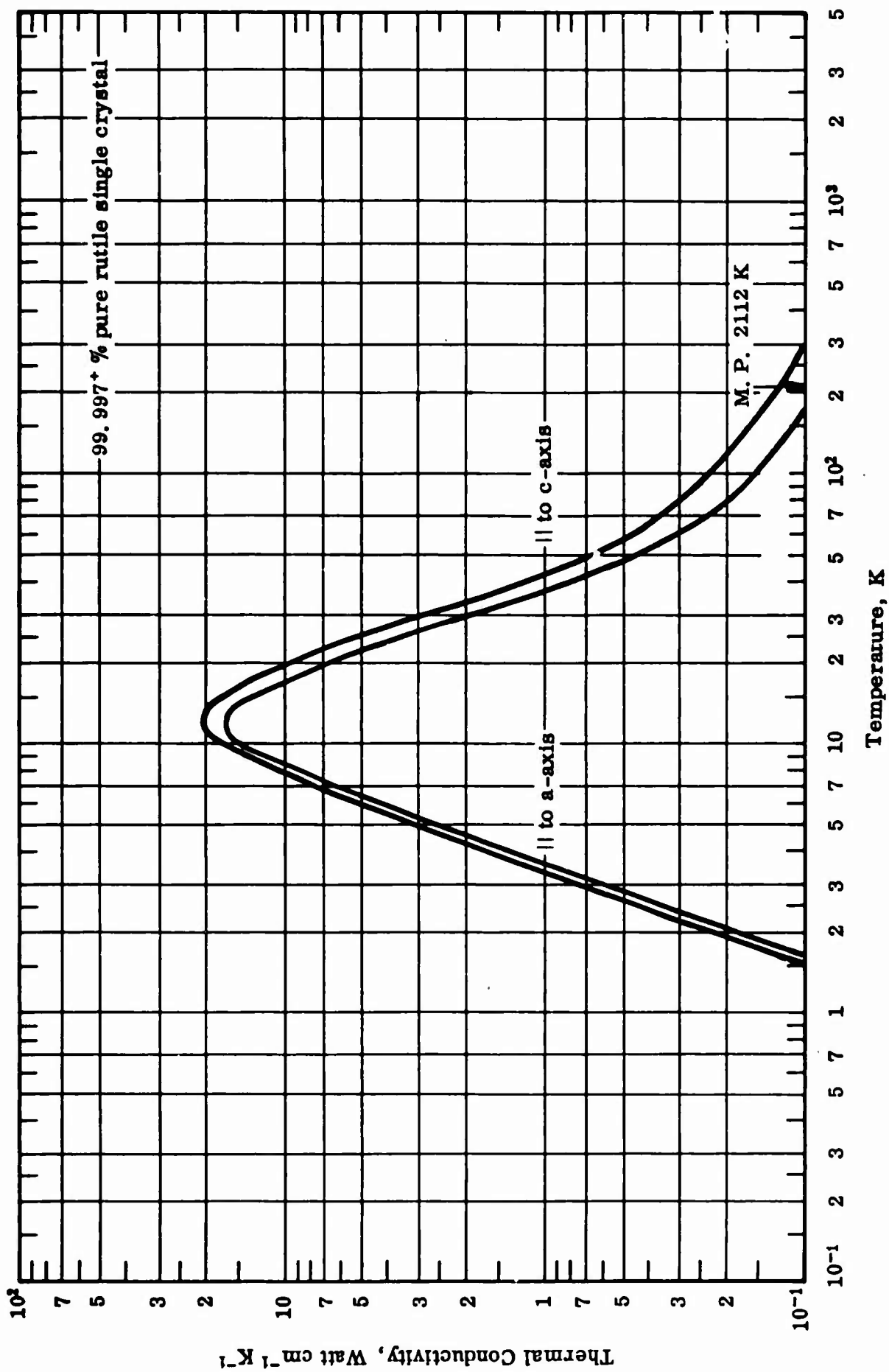


FIG. I-35 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE (single crystal) TiO<sub>2</sub>

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

Selected Values for 99.997% <sup>90</sup> Pure Rutile Single Crystal

| T, K | Heat flow parallel                       | Heat flow parallel                       | $k_{  }/k_{\perp}$ |
|------|--|--|--------------------|
|      | to c-axis                                | to a-axis                                |                    |
|      | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |                    |
| 0    | 0  | 0  |                    |
| 0.1  | 0.000026*                                | 0.000023*                                | 1.1304             |
| 0.5  | 0.0032*                                  | 0.0028*                                  | 1.143              |
| 1    | 0.026*                                   | 0.023*                                   | 1.130              |
| 5    | 3.13                                     | 2.65                                     | 1.181              |
| 10   | 17.9                                     | 14.6                                     | 1.226              |
| 11   | 20.0                                     | 16.3                                     | 1.227              |
| 12   | 20.6                                     | 17.0                                     | 1.212              |
| 13   | 20.2                                     | 16.5                                     | 1.214              |
| 14   | 19.1                                     | 15.4                                     | 1.246              |
| 15   | 17.7                                     | 13.8                                     | 1.283              |
| 20   | 10.0                                     | 6.9                                      | 1.449              |
| 25   | 5.4                                      | 3.6                                      | 1.500              |
| 30   | 2.85                                     | 1.88                                     | 1.516              |
| 35   | 1.75                                     | 1.17                                     | 1.496              |
| 40   | 1.17                                     | 0.80                                     | 1.463              |
| 45   | 0.85                                     | 0.58                                     | 1.466              |
| 50   | 0.66                                     | 0.45                                     | 1.4667             |
| 60   | 0.45                                     | 0.315                                    | 1.429              |
| 70   | 0.35                                     | 0.252                                    | 1.389              |
| 80   | 0.30                                     | 0.213                                    | 1.408              |
| 90   | 0.264                                    | 0.187                                    | 1.412              |
| 100  | 0.235                                    | 0.169                                    | 1.3905             |
| 150  | 0.168                                    | 0.120                                    | 1.400              |
| 200  | 0.137                                    | 0.097                                    | 1.412              |
| 250  | 0.118                                    | 0.083                                    | 1.422              |
| 300  | 0.104                                    | 0.074                                    | 1.405              |
| 350  | 0.094                                    | 0.066                                    | 1.424              |
| 400  | 0.085                                    | 0.060                                    | 1.417              |

\* 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 exist 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].

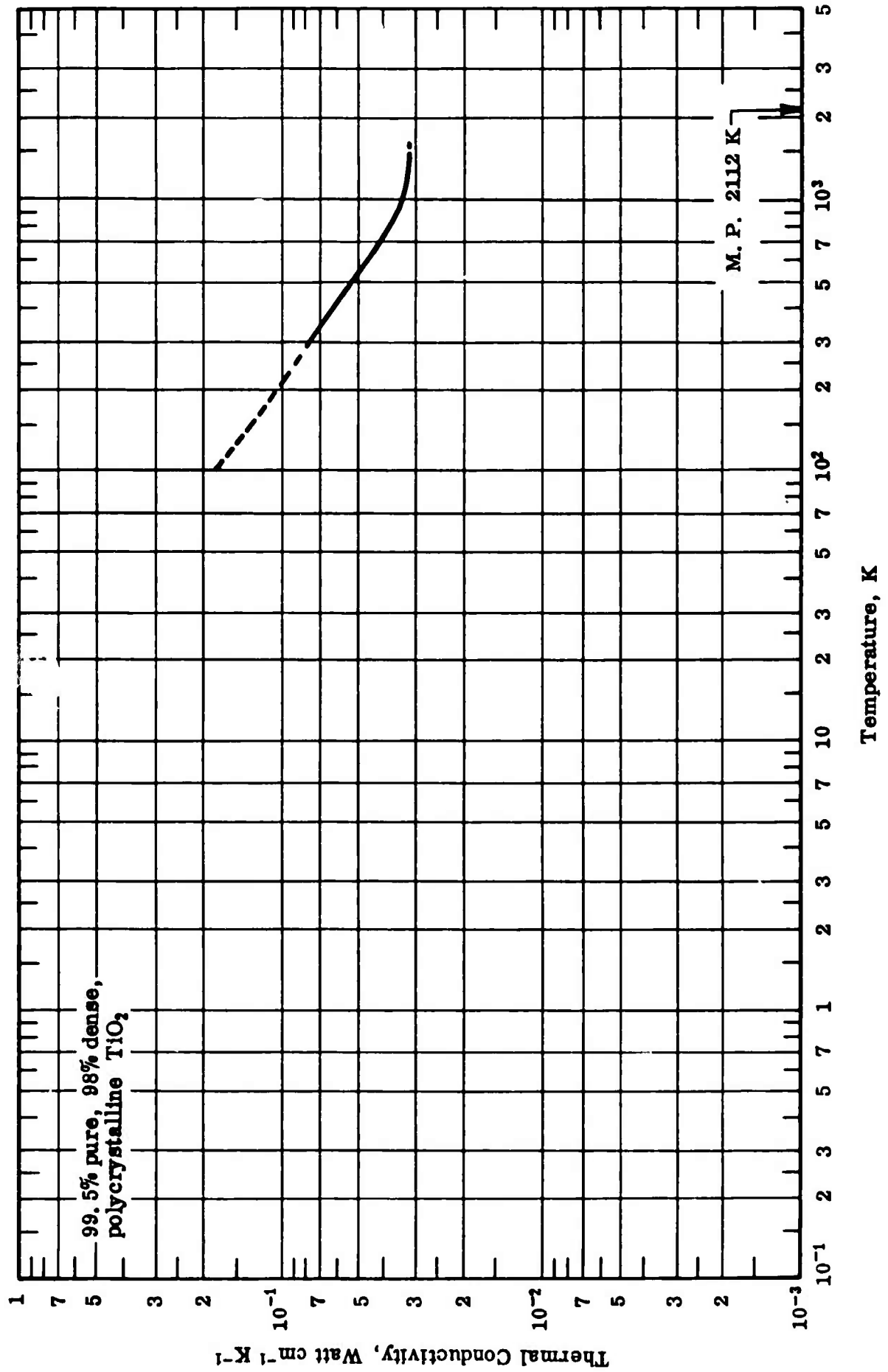


FIG. I-36 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE (polycrystalline)  $TiO_2$

TABLE I-36 THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE  
(polycrystalline)  $\text{TiO}_2$

Selected Values for 99.5% Pure, 98% Dense, Polycrystalline  $\text{TiO}_2$

| T, K | k, Watt $\text{cm}^{-1}\text{K}^{-1}$ | T, K | k, Watt $\text{cm}^{-1}\text{K}^{-1}$ |
|------|---------------------------------------|------|---------------------------------------|
| 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  | 0.053                                 | 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  $\text{TiO}_2$ . 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.

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\* Extrapolated.

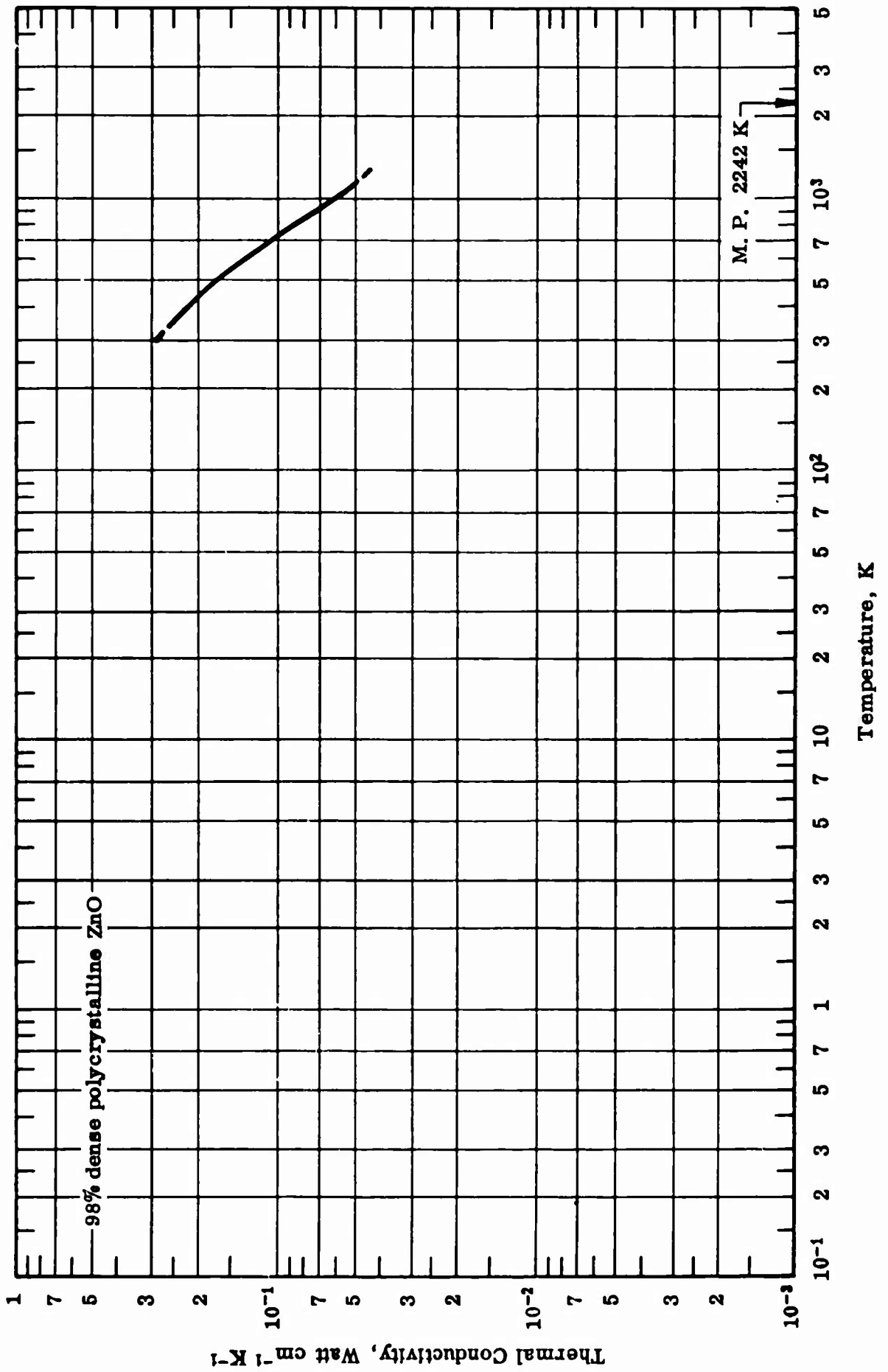


FIG. I-37 THERMAL CONDUCTIVITY OF ZINC OXIDE ZnO

**TABLE I-37 THERMAL CONDUCTIVITY OF ZINC OXIDE ZnO**

**Selected Values for 98% Dense Polycrystalline ZnO**

| T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> | T, K | k, Watt cm <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 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.

D. BIBLIOGRAPHY

| Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 1           | 1971        | Andrews, F.A., Webber, R. T., and Spohr, D. A., Phys. Rev., <u>84</u> , 994-6, 1951.   |
| 2           | 7690        | Powers, R. W., Schwartz, D., and Johnston, H. L., Ohio State Univ. Cryogenic Lab., USAF TR-264-5, 1-19, 1951.  |
| 3.          | 38398       | Powell, R. W., Tye, R. P., and Miss Woodman, M.J., ASME 3rd Symposium on Thermophysical Properties (Gratch S., Editor), 277-88, 1965.                  |
| 4.          | 38399       | Powell, R. W., Tye, R. P., and Metcalf, S. C., ASME 3rd Symposium on Thermophysical Properties (Gratch S., Editor), 289-95, 1965.                      |
| 5.          | 9735        | Zavaritskii, N. V., Zhur. Eksptl. i Teoret. Fiz., <u>34</u> , 1116-24, 1958.   |
| 6.          | 4715        | Grüneisen, E. and Erling, H.D., Ann. Physik, <u>38</u> , 399-420, 1940.  |
| 7.          | 23          | Powell, R. W., Phil. Mag., <u>44</u> , 645-63, 1953.   |
| 8.          | 6970        | Fieldhouse, I.B., Hedge, J.C., Lang, J. I., and Waterman, T.E., Armour Research Foundation, U. S. Office of Technical Services, PB 131718, 1-88, 1958. |
| 9.          | 15793       | Ho, J. and Wright, E.S., Lockheed Aircraft Corp. Missiles and Space Division, Tech. Rept. LMSD-288140, Vol. II, Chapter 2, 1960.                       |
| 10.         | 6662        | Harper, A.F.A., Kemp, W.R.G., Klemens, P.G., Tainsh, R.J., and White, G.K., 8, <u>2</u> , 577-583, 1957.   |
| 11.         | 733         | Powell, R.W. and Tye, R. P., J. Inst. Metals, <u>85</u> , 185-95, 1957.  |
| 12.         | 6560        | Lucks, C.F. and Deem, H. W., WADC TR 55-496, 1-65, 1956. [AD 97185]  |
| 13.         | 17245       | White, G.K. and Tainsh, R.J., Phys. Rev., <u>119</u> , 1869-71, 1960.  |
| 14.         | 15572       | Powell, R. L., Roder, H. M., and Hall, W.J., Phys. Rev., <u>115</u> , (2), 314-23, 1959.   |
| 15.         | 6680        | Powell, R.L., Rogers, W. M., and Coffin, D.O., J. Research NBS, <u>59</u> , 349-55, 1957.  |
| 16.         | 1728        | Berman, R. and MacDonald, D.K.C., Proc. Roy. Soc. (London), <u>A211</u> , 122-8, 1952.   |
| 17.         | 9288        | Lees, C.H., Phil. Trans. Roy. Soc. (London), A208, 381-443, 1908.  |
| 18.         | 1694        | White, G.K., Australian J. Phys., <u>6</u> , 397-404, 1953.  |

BIBLIOGRAPHY (continued)

| Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 19.         | 25469       | Mikryukov, V. E., Vestnik Moskov. Univ. Ser. Mat., Mekh., Astron., Fiz. i Khim., <u>11</u> (2), 53-70, 1956.           |
| 20.         | 6502        | Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E., WADC TR 55-495, I, 1-64, 1956. [AD 110 404]         |
| 21.         | 7003        | Sidles, P. H. and Danielson, G. C., USAEC Rept. ISC-198, 1-24, 1951.   |
| 22.         | 9024        | Pott, F. P., Z. Naturforsch., <u>13a</u> (2), 116-25, 1958.  |
| 23.         | 7184        | Smith, C. S. and Palmer, E. W., AIME Tech. Publ. 648, 1-19, 1935.  |
| 24.         | 6976        | Lucks, C. F. and Deem, H. W., WADC TR 55-496, II, 1-14, 1957. [AD 118 168]   |
| 25.         | 6975        | Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E., WADC TR 55-495, II, 1-18, 1956. [AD 110 526]        |
| 26.         | 6974        | McClelland, J. D., Rasor, N. S., Dahleen, R. C., and Zehms, E. H., WADC TR 56-400, II, 1-6, 1957. [AD 118 243]         |
| 27.         | 36724       | Arajs, S., Oliver, B. F., and Dunmyre, G. R., J. Appl. Phys., <u>36</u> (7), 2210-12, 1965.                            |
| 28.         | 26020       | Cezairliyan, A., Thermophysical Properties Research Center, TPRC Rept. 14, 1-140, 1962.                                |
| 29.         | 38401       | Cezairliyan, A. and Touloukian, Y. S., ASME 3rd Symp. on Thermophysical Properties (Purdue Univ., Ind.), 301-13, 1965. |
| 30.         | 16211       | Kemp, W. R. G., Klemens, P. G., and Tainish, R. J., Ann Physik, <u>5</u> (7), 35-41, 1959.                             |
| 31.         | 24034       | Richter, F., Ph.D. Diss., Cologne Univ. (W. Germany), 1-109, 1964.   |
| 32.         | 7691        | Powers, R. W., Ziegler, J. B., and Johnston, H. L., USAF TR 264-6, 1-14, 1951.   |
| 33.         |             | Moore, J. P., Fulkerson, W., McElroy, D. L., and Kollie, T. G., Unpublished data.                                      |
| 34.         | 6305        | Kemp, W. R. G., Sreedhar, A. K., and White, G. K., Proc. Phys. Soc., <u>A66</u> (11), 1077-8, 1953.                    |
| 35.         | 37865       | Powell, R. W., Hickman, M. J., and Tye, R. P., Metallurgia, <u>70</u> , 159-63, 1964.                                  |
| 36.         | 1732        | Mendelssohn, K. and Rosenberg, H. M., Proc. Phys. Soc. (London), <u>A65</u> (6), 385-94, 1952.                         |
| 37.         | 6470        | Reddemann, H., Ann. Physik, 5, <u>22</u> , 28-30, 1935.  |

BIBLIOGRAPHY (continued)

| Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 38.         | 50          | White, G.K. and Woods, S.B., Can. J. Phys., <u>35</u> , 346-8, 1957.   |
| 39.         |             | Tye, R.P., private communication to R.W. Powell, Jan. 1966.  |
| 40.         | 727         | Kemp, W.R.G., Klemens, P.G., and White, G.K., Australian J. Phys., <u>9</u> , 180-8, 1956.   |
| 41.         | 36264       | Powell, R.W., Tye, R.P., and Hickman, M. J., Intern. J. Heat Mass Transfer, <u>8</u> (5), 679-87, 1965.  |
| 42.         | 15566       | Mendelssohn, K., Physica, <u>24</u> , 553-562, 1958.   |
| 43.         | 15899       | Bell, I.P., UKAEA Rept. R and DB (C) TN-127, 1-10, 1959.   |
| 44.         | 16290       | Powell, R.W., J. Inst. Metals, <u>85</u> , 553-4, 1957.  |
| 45.         | 23587       | Tye, R.P., J. Less-Common Metals, <u>3</u> , 13-18, 1961.  |
| 46.         | 33122       | Glassbrenner, C.J. and Slack, G.A., <u>134</u> (4A), A1058-69, 1964.   |
| 47.         | 26857       | Holland, M.G., Proc. 7th Intern. Conf. Low Temp. Phys., (Toronto, Can.), 280-4, 1961.  |
| 48.         | 1168        | Carruthers, J.A., Geballe, T.H., Rosenberg, H.M., and Ziman, J.M., Proc. Roy. Soc. (London), <u>A238</u> , 502-14, 1957.   |
| 49.         | 29948       | Shanks, H.R., Maycock, P.D., Sidles, P.H., and Danielson, G.C., Phys. Rev., <u>130</u> (5), 1743-8, 1963.  |
| 50.         | 1920        | Rademakers, A., Physica, <u>15</u> , 849-59, 1949.   |
| 51.         | 9941        | Zavaritskii, N.V., Soviet Phys.-JETP, <u>6</u> , 837-47, 1958.   |
| 52.         | 22416       | Zavaritskii, N.V., Soviet Phys.-JETP, <u>11</u> (6), 1207-14, 1960.  |
| 53.         | 1091        | Rosenberg, H.M., Phil. Trans. Roy. Soc. (London), <u>A247</u> , 441-97, 1955.  |
| 54.         | 9288        | Lees, C.H., Phil. Trans. Roy. Soc. (London), <u>A208</u> , 381-443, 1903.  |
| 55.         | 7670        | Konno, S., Sci. Repts-Tohoku Imp. Univ., <u>8</u> , 169-79, 1919.  |
| 56.         | 20699       | Nikol'skii, N.A., Kalakutskaya, N.A., Pchelkin, I. M., Klassen, T. V., and Vel'tishcheva, V.A., Voprosy Teploobmena, Akad. Nauk S.S.S.R. Energet. Ins. im. G.M. Krzhizhanovskago, 11-45, 1959. |
| 57.         | 9866        | Brown, W.B., Phys. Rev., <u>22</u> , 171-9, 1923.  |
| 58.         | 9313        | White, G.K. and Woods, S.B., Phil. trans. Roy Soc. (London), <u>A 251</u> , 273-302, 1959.   |
| 59.         | 23589       | Powell, R.W. and Tye, R.P., J. Less-Common Metals, <u>3</u> , 226-33, 1961.  |
| 60.         | 131         | Loewen, E.G., Trans. Am. Soc. Mec. Engrs., 78, 667-70, 1956.   |

BIBLIOGRAPHY (continued)

- | Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 61          | 9951        | Deem, H.W., Wood, W.D., and Lucks, C. F., Trans. Met. Soc. AIME, <u>212</u> , 520-3, 1958.                                       |
| 62.         | 15512       | Goens, E. and Grüneisen, E., Ann. Physik, <u>14</u> , 164-80, 1932.  |
| 63.         | 7434        | Bidwell, C.C. and Lewis, E.J., Phys. Rev., 2, <u>33</u> , 249-251, 1929.   |
| 64.         | 6250        | Bidwell, C.C., Phys. Rev., 2, <u>56</u> (6), 594-8, 1939.  |
| 65.         | 3452        | Bidwell, C.C., Phys. Rev., <u>58</u> , 561-4, 1940.  |
| 66.         | 9957        | Shelton, S.M. and Swanger, W.H., Trans. Am. Soc. Steel Treating, <u>21</u> , 1061-78, 1933.                                      |
| 67.         | 7272        | Smith, A.W., Ohio State Univ. Eng. Exp. Sta. Bull. 30, 1-61, 1925.   |
| 68.         | 23498       | Zavaritskii, N.V., Soviet Phys-JETP, <u>12</u> (5), 831-3, 1961.   |
| 69.         | 35324       | Rhodes, B.L., Moeller, C.E., and Saver, H.J., Cryogenics. <u>6B</u> , <u>5</u> (1), 17-20, 1965.                                 |
| 70.         |             | ALCOA Aluminum Handbook, Aluminum Co. of America, 1957, p. 30.   |
| 71.         | 8283        | Material Properties Handbook, Vol. I. Aluminum Alloys, Tech. Dept., Royal Aeronautical Soc., London, 1959.                       |
| 72.         | 24780       | Aluminum Data Book, Reynolds Metals Co., 1959, p. 43.  |
| 73.         |             | Metals Handbook, Vol. 1, 8th Ed., Am. Soc. Metals, 1961, p. 946.   |
| 74.         | 10135       | Powers, R.W., Ziegler, J.B., and Johnston, H. L., USAF TR 264-7, 1-10, 1951. [ATI 105 924]                                       |
| 75.         | 6940        | Lucks, C. F., Thompson, H.B., Smith, A.R., Curry, F.P., Deem, H.W., and Bing, G. F., USAF TR 6145, I, 1-127, 1951. [ATI 117 715] |
| 76.         | 1692        | White, G.K. and Woods, S.B., Can. J. Phys., <u>33</u> , 58-73, 1955.   |
| 77.         | 16667       | Powell, R.L., Harden, J.L., and Gibson, E. F., J. Appl. Phys., <u>31</u> , 1221-4, 1960.   |
| 78.         |             | Handbook of Huntington Alloys, 3rd Ed., International Nickel Co., 1965, pp. 4-5.   |
| 79.         | 1079        | Ewing, C.T., Grand, J.A., and Miller, R.R., J. Am. Chem. Soc., <u>74</u> , 11-14, 1952.  |
| 80.         | 9176        | Deverall, J.E., USAEC Rept. LA-2269, 1-62, 1959.   |
| 81.         | 9321        | Zimmerman, J.E., Carnegie Inst. Technol. Doctoral Dissertation, 1-54, 1951.  |

BIBLIOGRAPHY (continued)

- | Ref.<br>No. | TPRC<br>No. |   |
|-------------|-------------|---|
| 82.         | 7689        | Fieldhouse, I. B., Hedge, J. C., and Lang, J. I., WADC TR 58-274, 1-79, 1958.   |
| 83.         | 16756       | Berman, R., Foster, E. L., Schneidmesser, B., and Tirmizi, S. M. A., J. Appl Phys., <u>31</u> (12), 2156-9, 1960.   |
| 84.         | 18644       | Lee, D. W. and Kingery, W. D., J. Am. Ceram. Soc., <u>43</u> (12), 627-33, 1960.  |
| 85.         | 824         | Berman, R., Proc. Phys. Soc. (London), <u>A65</u> , 1029-40, 1952.  |
| 86.         | 10682       | Francis, R. K., Brown, R., McNamara, E. P. and Tinklepaugh, J. R., WADC TR 58-600 (PB 151664), 1-69, 1958. [AD 205 549]                                   |
| 87.         | 10013       | Sutton, W. H., J. Am. Ceram. Soc., <u>43</u> (2), 81-6, 1960.   |
| 88.         | 16036       | Truesdale, R. S., Swica, J. J., and Tinklepaugh, J. R., Alfred Univ., N. Y. State Coll. of Ceramics, WADD Progress Rept. No. 11, 1-67, 1960. [AD 240 278] |
| 89.         | 33767       | Nishigima, T., Kawada, T., and Tshihata, A., J. Am. Ceram. Soc., <u>48</u> (1), 31-34, 1965.  |
| 90.         | 16818       | Norton, F. H., USAEC Rept. NYO-598, 1-10, 1951.   |
| 91.         | 16816       | Norton, F. H. et al., USAEC Rept. NYO-594, 1-22, 1950.  |
| 92.         | 10851       | Norton, F. H. and Kingery, W. D., USAEC Rept. NYO-601, 1-52, 1952.  |
| 93.         | 10083       | Norton, F. H., Kingery, W. D., McQuarrie, M. C., Adams, M., Loeb, A. L., and Francl, J., USAEC Rept. NYO-3643, 1-124, 1953. [AD 13 940]                   |
| 94.         | 2441        | Kingery, W. D., J. Am. Ceram. Soc., <u>37</u> , 88-90, 1954.  |
| 95.         | 10052       | Kingery, W. D., J. Am. Ceram. Soc., <u>42</u> (12), 617-27, 1959.   |
| 96.         | 2429        | Francl, J. and Kingery, W. D., J. Am. Ceram. Soc., <u>37</u> , 99-107, 1954.  |
| 97.         | 2434        | Francl, J. and Kingery, W. D., J. Am. Ceram. Soc., <u>37</u> , 80-4, 1954.  |
| 98.         | 103         | Powell, R. W., Trans. Brit. Ceram. Soc., <u>53</u> , 389-97, 1954.  |
| 99.         | 16022       | Taylor, R. E., USAEC Rept. NAA-SR-4905, 1-19, 1960.   |
| 100.        | 26233       | Feith, A. D., USAEC Rept GEMP-296, 1-25, 1964.  |
| 101.        | 25961       | Hedge, J. C., Kostenko, C., and Lang, J. I., ASD-TDR-63-597, 1-128, 1963. [AD-424 375]  |
| 102.        | 24384       | Rudkin, R. L., ASD-TDR-62-24 (Pt. 2), 1-16, 1963. [AD 413 005]  |

BIBLIOGRAPHY (continued)

- | Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 103.        | 20313       | Burk, M., J. Am. Ceram. Soc., <u>46</u> , 150-1, 1963.   |
| 104.        | 10101       | Kingery, W.D. and Norton, F.H., USAEC Rept. NYO-6447, 1-16, 1955. [AD 55 595]  |
| 105.        | 29253       | Horn, F.H., Slack, G.A., and Engeler, W.E., ASD-TR-61-284 (PB-159966), 1-94, 1961.   |
| 106.        | 10615       | Slack, G.A., Phys. Rev., <u>126</u> (2), 427-41, 1962.   |
| 107.        | 7104        | Smoke, E.J., Ilyn, A.V, and Eichbaum, B.R., Rutgers Univ., N.J. Ceram. Res. Sta., Signal Corps Project Progress Rept. No.5, 1-24, 1954. [AD 308 49]                |
| 108.        | 25901       | Makarounis, O. and Jenkins, R.J., Naval Radiological Dense Lab. (San Francisco, Calif.), NRDL-TR-599, 1-24, 1962. [AD 295 887]                                     |
| 109.        | 24812       | Fieldhouse, I.B. and Lang, J.I., WADD TR 60-904, 1-119, 1961. [AD 268 304]   |
| 110.        | 9404        | Koenig, J.H., Rutgers Univ. N.J. Ceram. Res. Sta., Signal Corps Project Progress Rept. No. 2, 1-117, 1953. [AD 131 54]   |
| 111.        | 16820       | Norton, F.H., Kingery, W.D., Fellows, D.M., Adams, M., McQuarrie, M.C., and Coble, R.L., USAEC Rept. NYO-596, 1-9, 1950.   |
| 112.        | 16821       | Norton, F.H., Kingery, W.D., Fellows, D.M., Adams, M., McQuarrie, M.C., Coble, R.L., Francl, J., Varilos, T., and Anderson, H.H., USAEC Rept. NYO-597, 1-15, 1951. |
| 113.        | 209         | Charvat, F.R. and Kingery, W.D., J. Am. Ceram. Soc., <u>40</u> , 306-15, 1957.   |
| 114.        | 9880        | Slack, G.A. and Newman, R., Phys. Rev. Letters, <u>1</u> (10), 359-60, 1958.   |
| 115.        | 9410        | Koenig, J.H., Rutgers Univ. N.J. Ceram. Res. Sta., Signal Corps Project Progress Rept. No. 6, 1-98, 1952. [ATI 163 519]  |
| 116.        | 6939        | Smoke, E.J. and Koenig, J.H., Rutgers Univ. N.J. Ceram. Res. Sta., Eng. Res. Bull. 40, 1-53, 1958.   |
| 117.        | 7082        | Norton, F.H., Kingery, W.D., Loeb, A.L., Francl, J., Coble, R.L., and Vasilos, T., USAEC Rept. NYO-3647, 1-61, 1953. [AD 23 561]                                   |
| 118.        | 8245        | de Haas, W.J. and Biermasz, T., Communs. Kamerlingh Onnes Lab. Univ. Leiden., Suppl. 82 and 241 to 252, 1-13, 1937.  |
| 119.        | 7648        | Griffiths, E. and Kaye, G.W.C., Proc. Roy. Soc. (London), <u>A 104</u> , 71-98, 1923.  |

BIBLIOGRAPHY (continued)

- | Ref.<br>No. | TPRC<br>No. |   |
|-------------|-------------|---|
| 120.        | 22427       | Kaye, G.W.C. and Higgins, W.F., Proc. Roy. Soc. (London) <u>A113</u> , 335-51, 1926.  |
| 121.        | 20780       | Birch, F. and Clark, H., Am. J. Sci., <u>238</u> , 529-58, 1940.  |
| 122.        | 6708        | Eucken, A., Ann. Physik, <u>34</u> (2), 185-221, 1911.  |
| 123.        | 9289        | de Haas, W.J. and Biermasz, T., Physica, <u>4</u> (8), 752-6, 1937.   |
| 124.        | 1411        | Berman, R., Proc. Roy. Soc. (London), <u>A208</u> , 90-108, 1951.   |
| 125.        | 7013        | Ratcliffe, E.H., Brit. J. Appl. Phys., <u>10</u> , 22-5, 1959.  |
| 126.        | 6200        | Weeks, J.L. and Seifert, R.L., Rev. Sci. Instruments, <u>24</u> (10), 1054-1057, 1953.  |
| 127.        | 26060       | Devyatkova, E.D., Petrov, A.V., Smirnov, I.A., and Moizhes, B. Ya., Soviet Phys.-Solid State, <u>2</u> (4), 681-8, 1960.  |
| 128.        | 20113       | Kamilov, I.K., Soviet Physics-Solid State, <u>4</u> (9), 1693-7, 1963.  |
| 129.        | 10030       | Norton, F.H. and Kingery, W.D., USAEC Rept. NYO-3644, 1-17, 1953. [AD11816]   |
| 130.        | 7067        | Koenig, J.H., Smoke, E.J., Snyder, N.H., Wisely, H.R., Ruh, E., Ilyn, A.V., and Eichbaum, B.R., Rutgers Univ. N.J. Ceram. Res. Sta., Signal Corps Project Progress Rept. No. 3, 1-25, 1953. [AD19833]               |
| 131.        | 35072       | Thurber, W.R. and Mante, A.J.H., Physical Review, <u>139</u> (5A), 1655-65, 1965.   |
| 132.        | 22625       | Yoshida, I., J. Phys. Soc. Japan, <u>15</u> (12), 2211-19, 1960.  |
| 133.        | 7036        | Koenig, J. H., Snyder, N.H., Smoke, E.J., Wisely, H.R., Ruh, E., Bauer, H.L., Ilyn, AV., and Niemczura, S.W., Rutgers Univ. N.J. Ceram. Res. Sta., Signal Corps Project Progress Rept. No. 1, 1-33, 1953. [AD 5552] |
| 134.        | 9316        | Norton, F.H. and Kingery, W.D., et al., USAEC Rept. NYO-602, 1-40, 1952.  |
| 135.        | 2428        | Kingery, W.D., Francl, J., Coble, R.L., and Vasilos, T., J. Am. Ceram. Soc., <u>37</u> , 107-10, 1954.  |

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 ( $\text{Al}_2\text{O}_3$ ), iron oxide ( $\text{FeO}$ ) and silicon oxide ( $\text{SiO}_2$ ).

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. \*\*

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\*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  $\log \mu$  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  $\mu$  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 samples\*.

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\*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  $\pm 10$  percent of the recommended curves, but the other values may diverge as much as  $\pm 20$  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  $\log \mu$  versus  $1/T$ , while the table gives value of  $\mu$  versus  $T$ . For interpolating purposes an equation is given, and should be used.

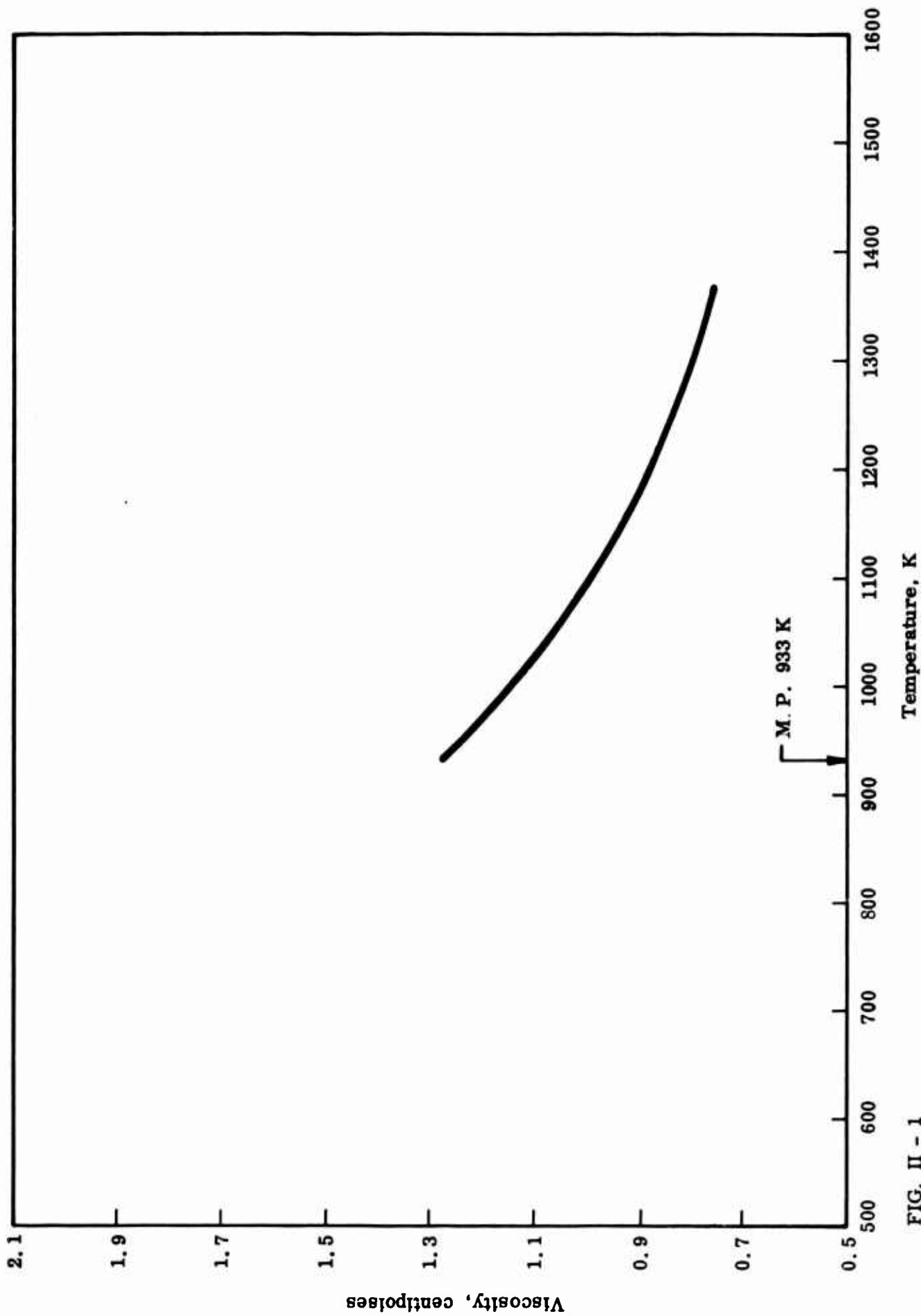


FIG. II - 1

VISCOSITY -- ALUMINUM

TABLE II-1. VISCOSITY OF ALUMINUM

RECOMMENDED VALUES

| T(°K)      | $\mu$ (cp) | T(°K) | $\mu$ (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).

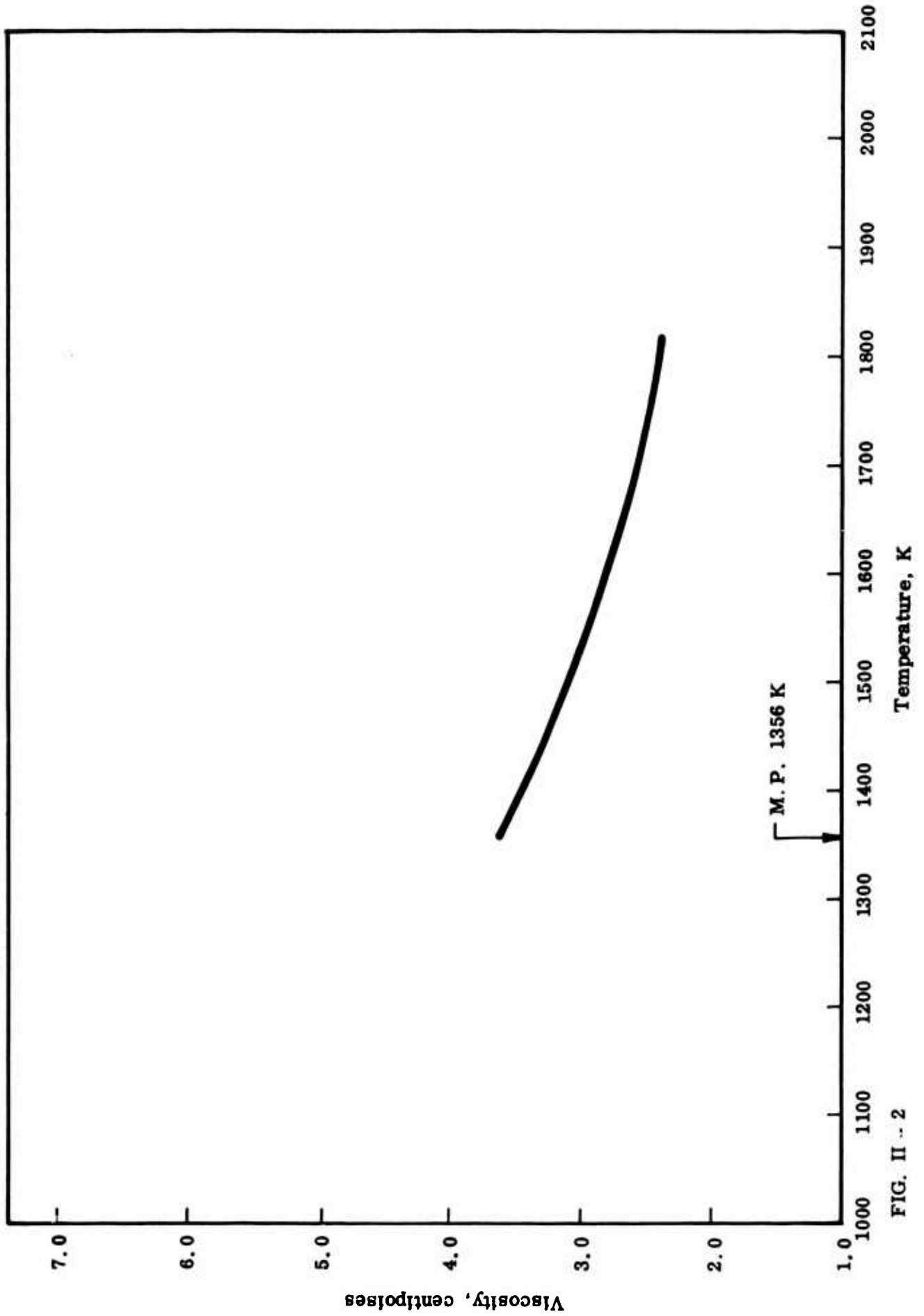


FIG. II -- 2

VISCOSITY -- COPPER

**TABLE II-2. VISCOSITY OF COPPER**

**RECOMMENDED VALUES**

| T(°K)       | $\mu$ (cp) | T(°K) | $\mu$ (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)

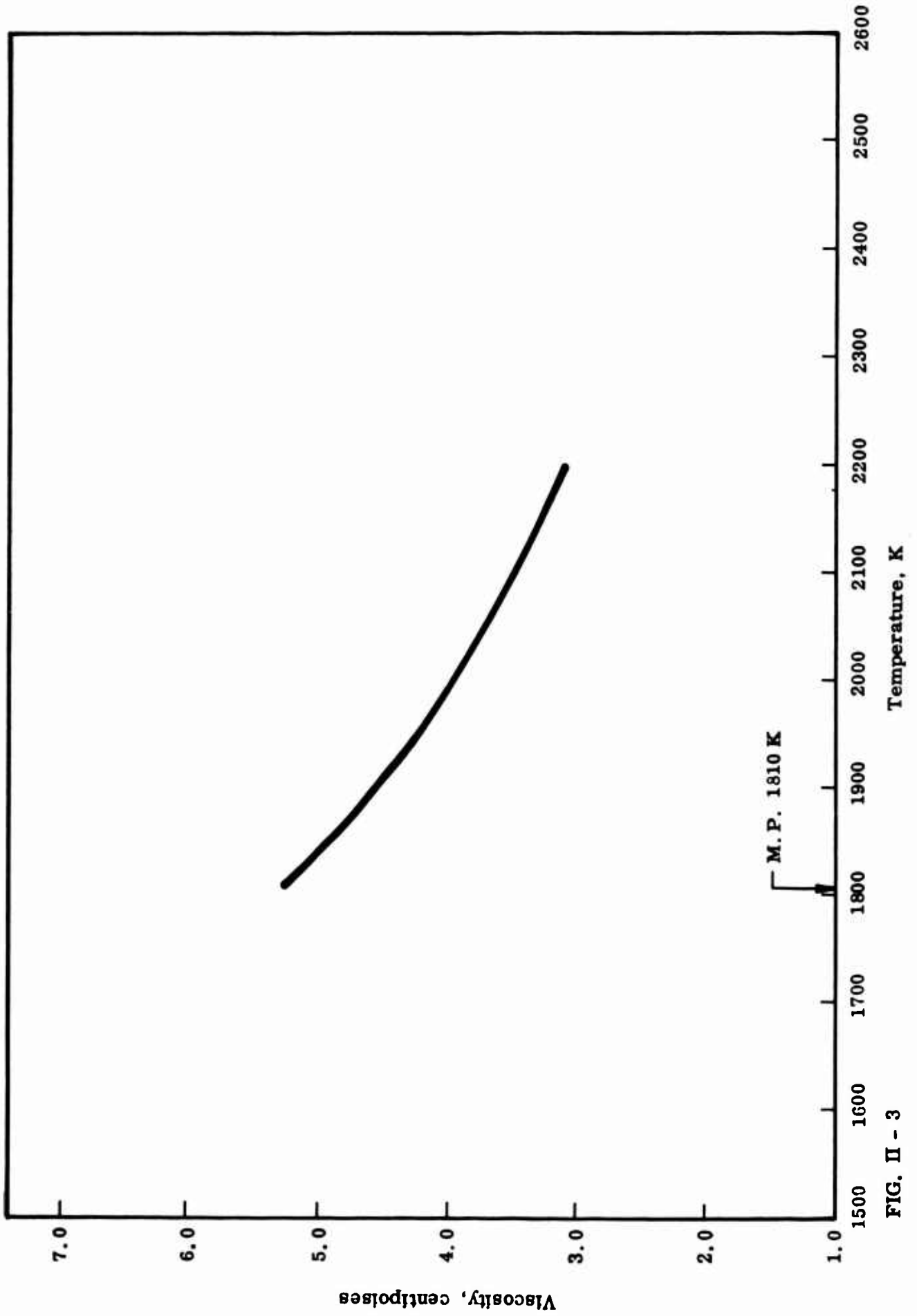


FIG. II - 3  
VISCOSITY -- IRON

TABLE II-3. VISCOSITY OF IRON

RECOMMENDED VALUES

| T(°K)       | $\mu$ (cp) | T(°K) | $\mu$ (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., Froberg, 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)

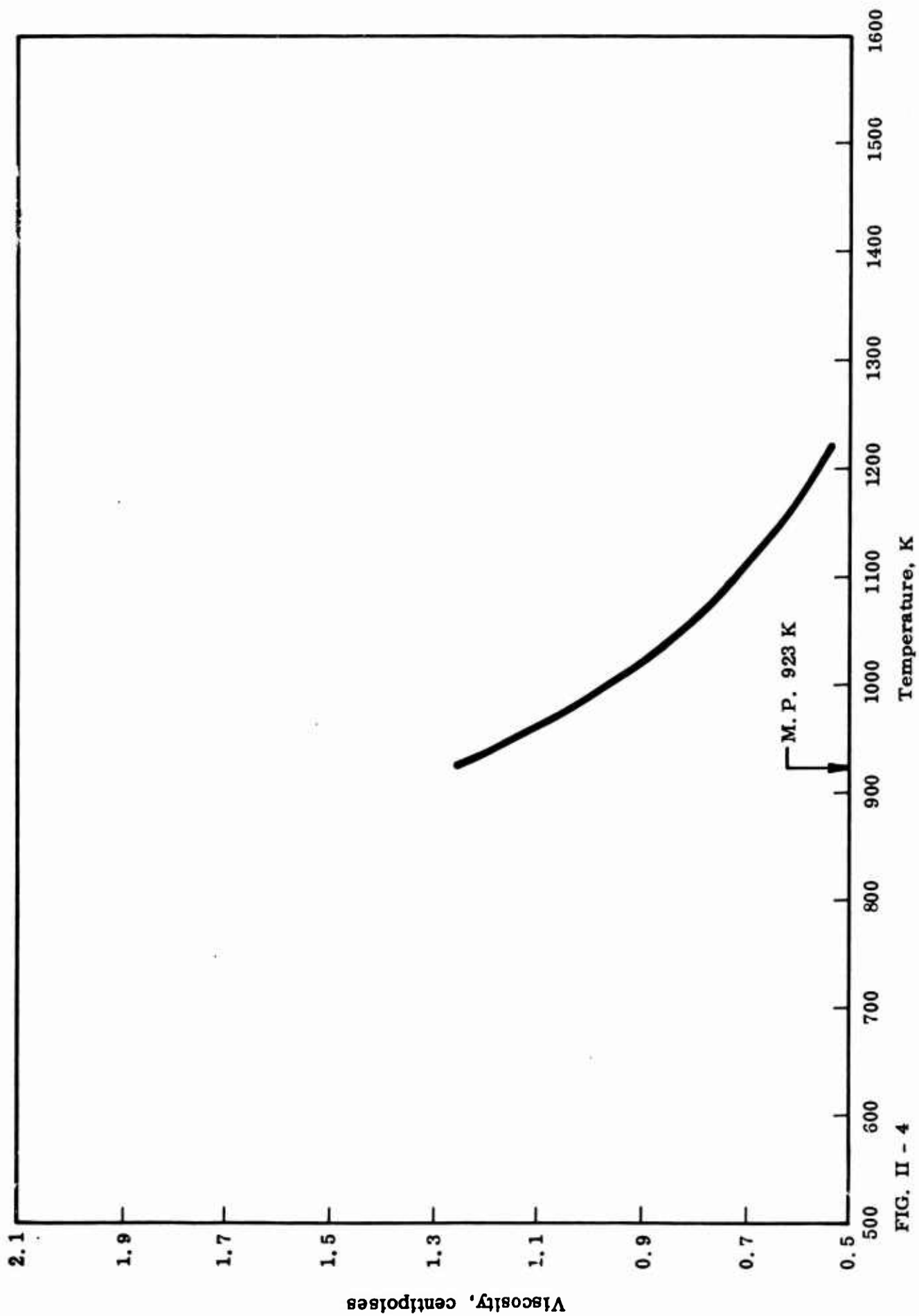


FIG. II - 4

VISCOSITY -- MAGNESIUM

TABLE II-4. VISCOSITY OF MAGNESIUM

RECOMMENDED VALUES

| T(°K)      | $\mu$ (cp) | T(°K) | $\mu$ (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).

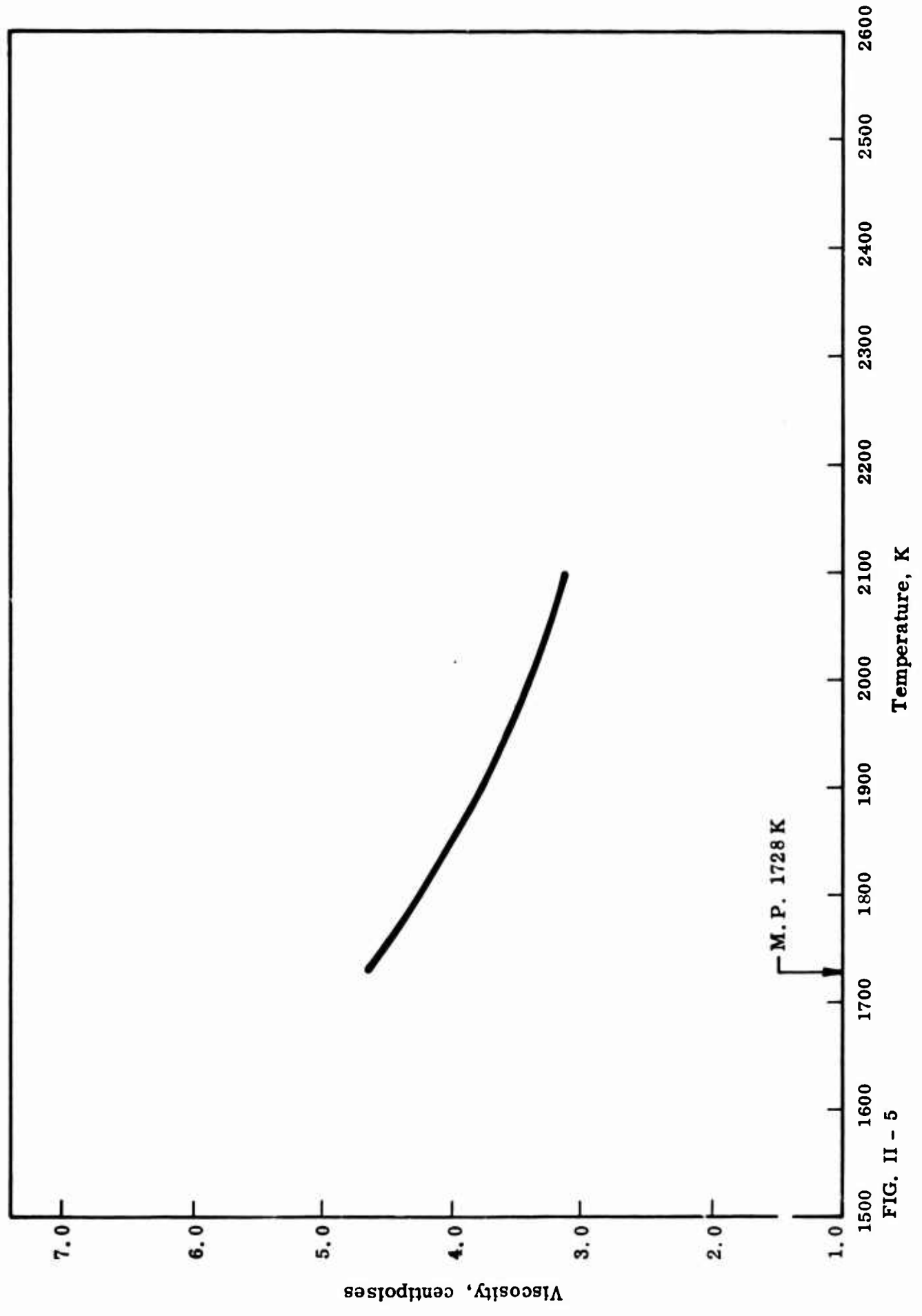


FIG. II - 5

VISCOSITY -- NICKEL

TABLE II-5. VISCOSITY OF NICKEL

RECOMMENDED VALUES

| T(°K)      | $\mu$ (cp) | T(°K) | $\mu$ (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).

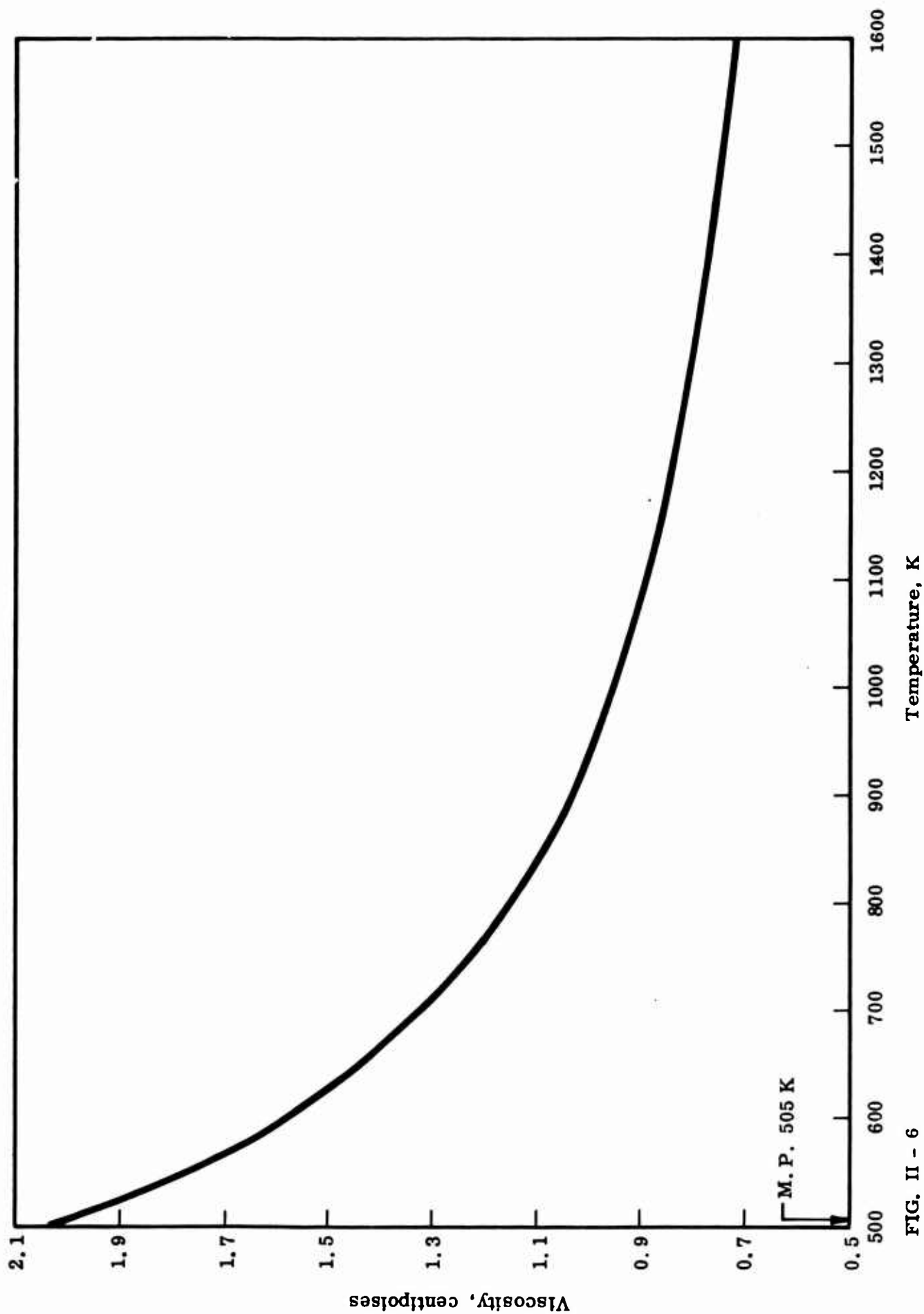


FIG. II - 6  
VISCOSITY -- TIN

TABLE II-6. VISCOSITY OF TIN

RECOMMENDED VALUES

| T(°K)      | $\mu$ (cp) | T(°K) | $\mu$ (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).

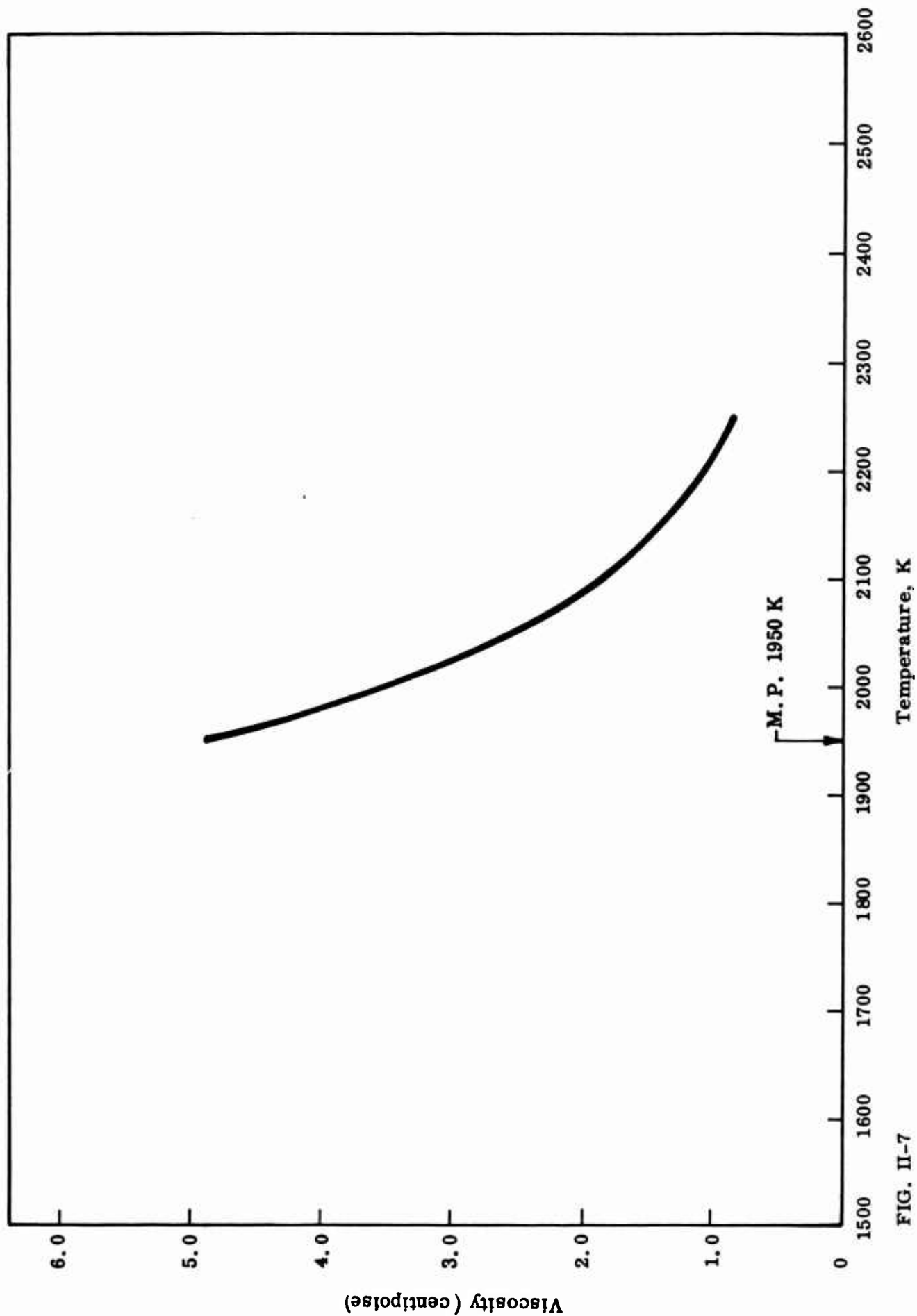


FIG. II-7

VISCOSITY -- TITANIUM

TABLE II-7. VISCOSITY OF TITANIUM

RECOMMENDED VALUES

| T(°K) | $\mu$ (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)

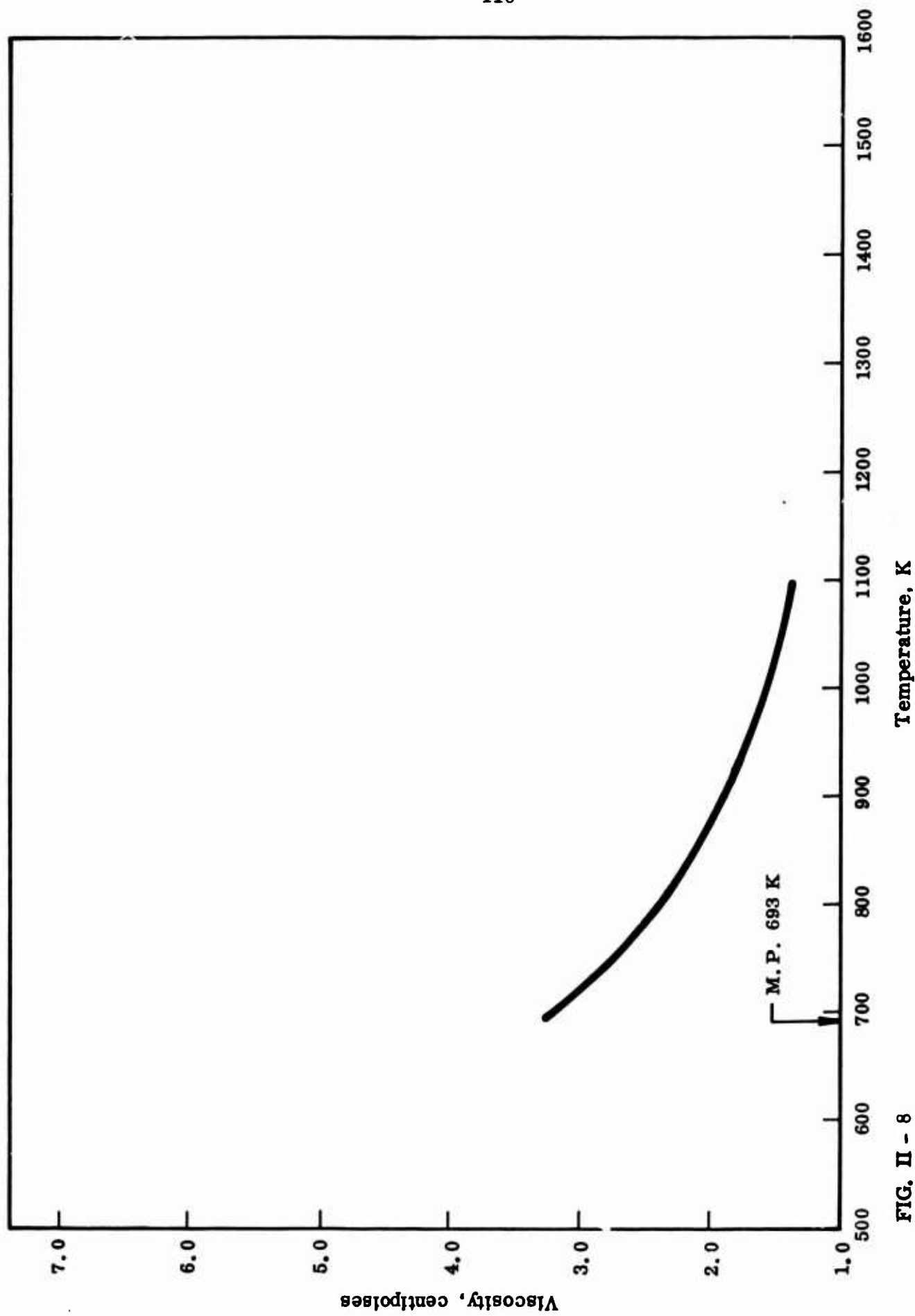


FIG. II - 8

VISCOSITY -- ZINC

TABLE II-8. VISCOSITY OF ZINC

RECOMMENDED VALUES

| T(°K)      | $\mu$ (cp) | T(°K) | $\mu$ (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).

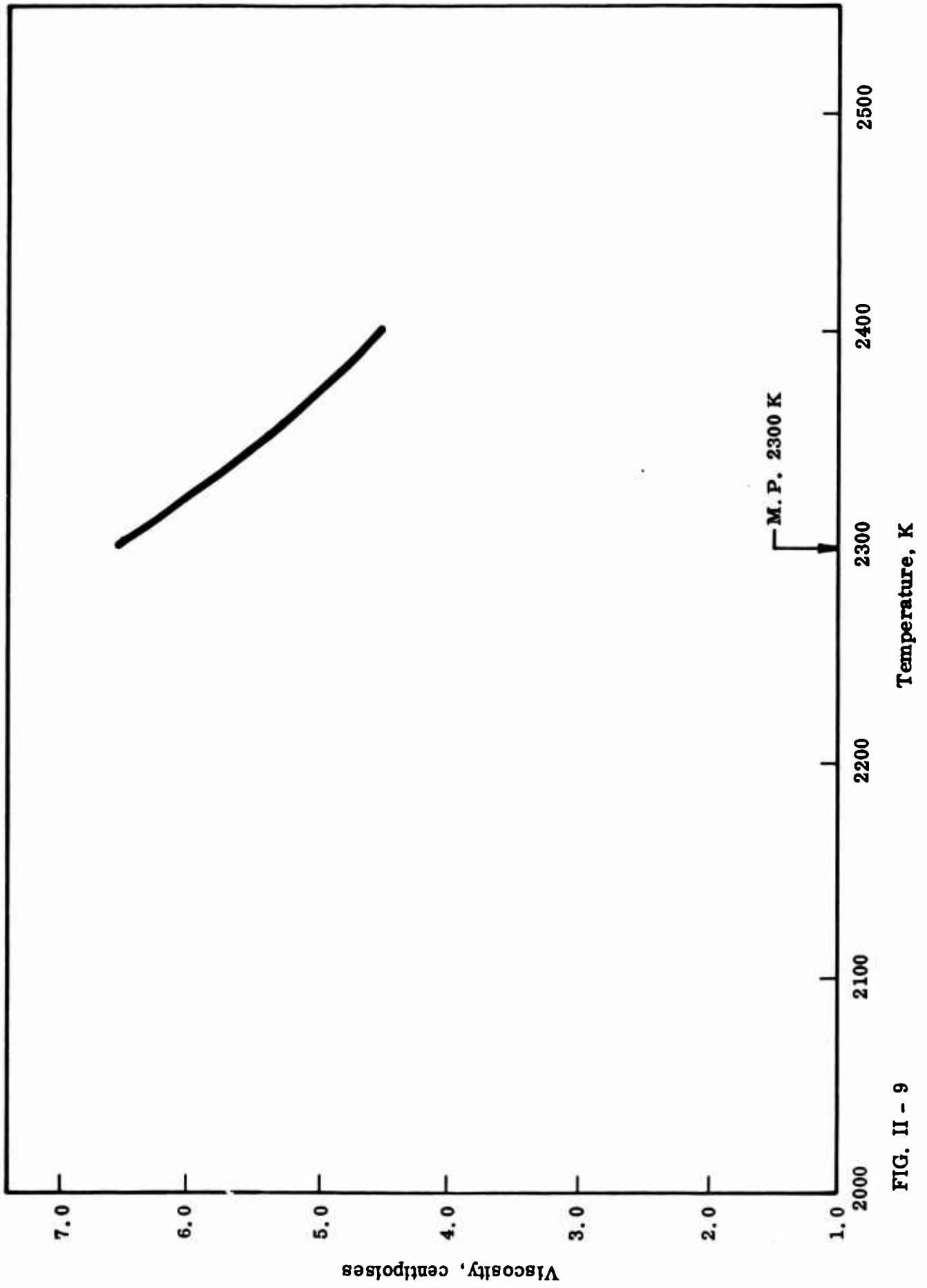


FIG. II - 9

VISCOSITY -- ALUMINUM OXIDE, Al<sub>2</sub>O<sub>3</sub>

TABLE II-9. VISCOSITY OF ALUMINUM OXIDE ( $\text{Al}_2\text{O}_3$ )

RECOMMENDED VALUES

| T( $^{\circ}\text{K}$ ) | $\mu$ (cp) |
|-------------------------|------------|
| 2300(m. p.)             | 65.5       |
| 2350                    | 54.3       |
| 2400                    | 45.4       |

SOURCE OF DATA

(a) Kozakevitch, P. (46)

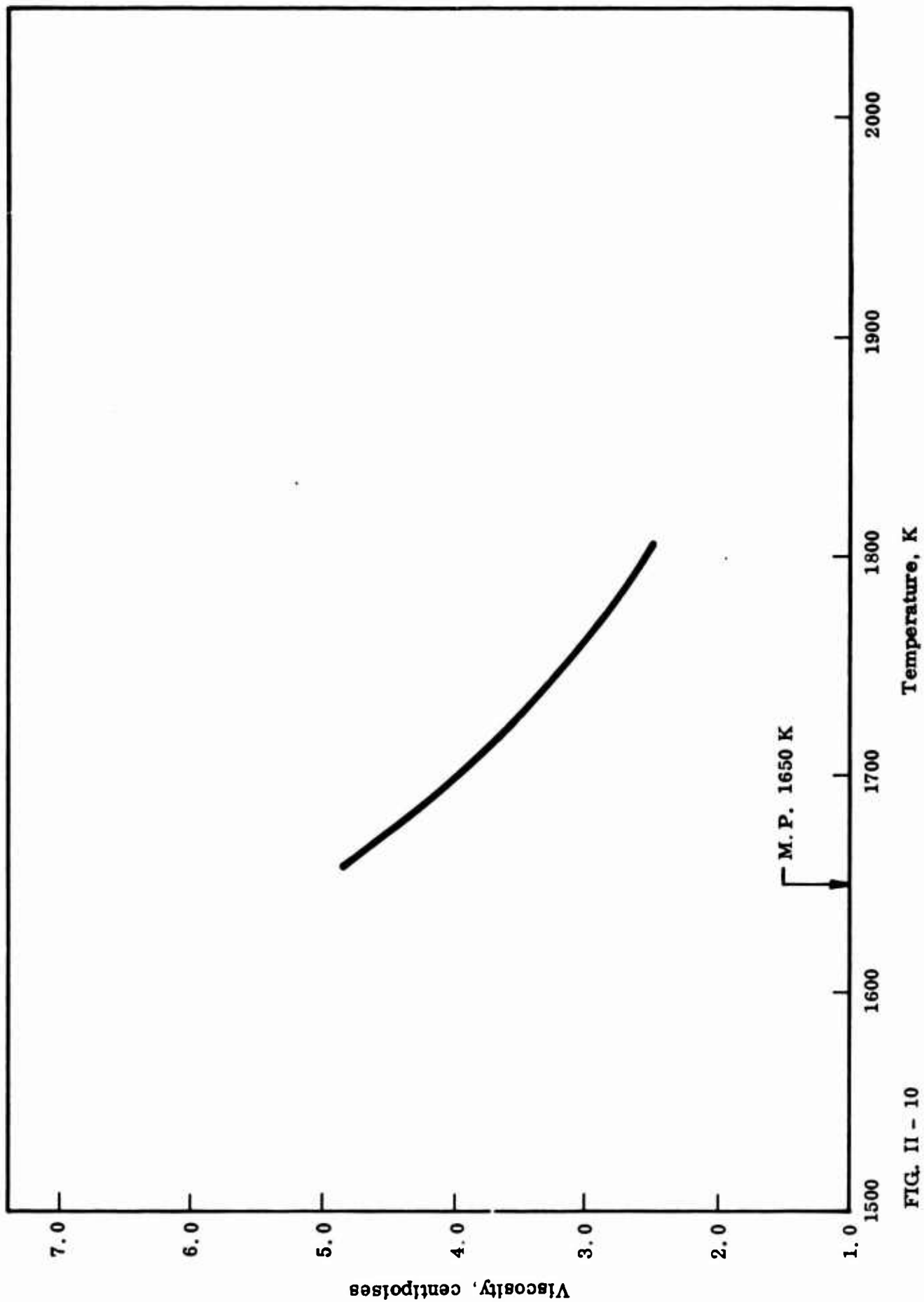


FIG. II - 10

VISCOSITY -- IRON OXIDE, FeO

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

RECOMMENDED VALUES

| T(°K)        | $\mu$ (cp) |
|--------------|------------|
| 1650 (m. p.) | 50.4       |
| 1700         | 39.5       |
| 1750         | 31.5       |
| 1800         | 25.3       |

SOURCE OF DATA

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

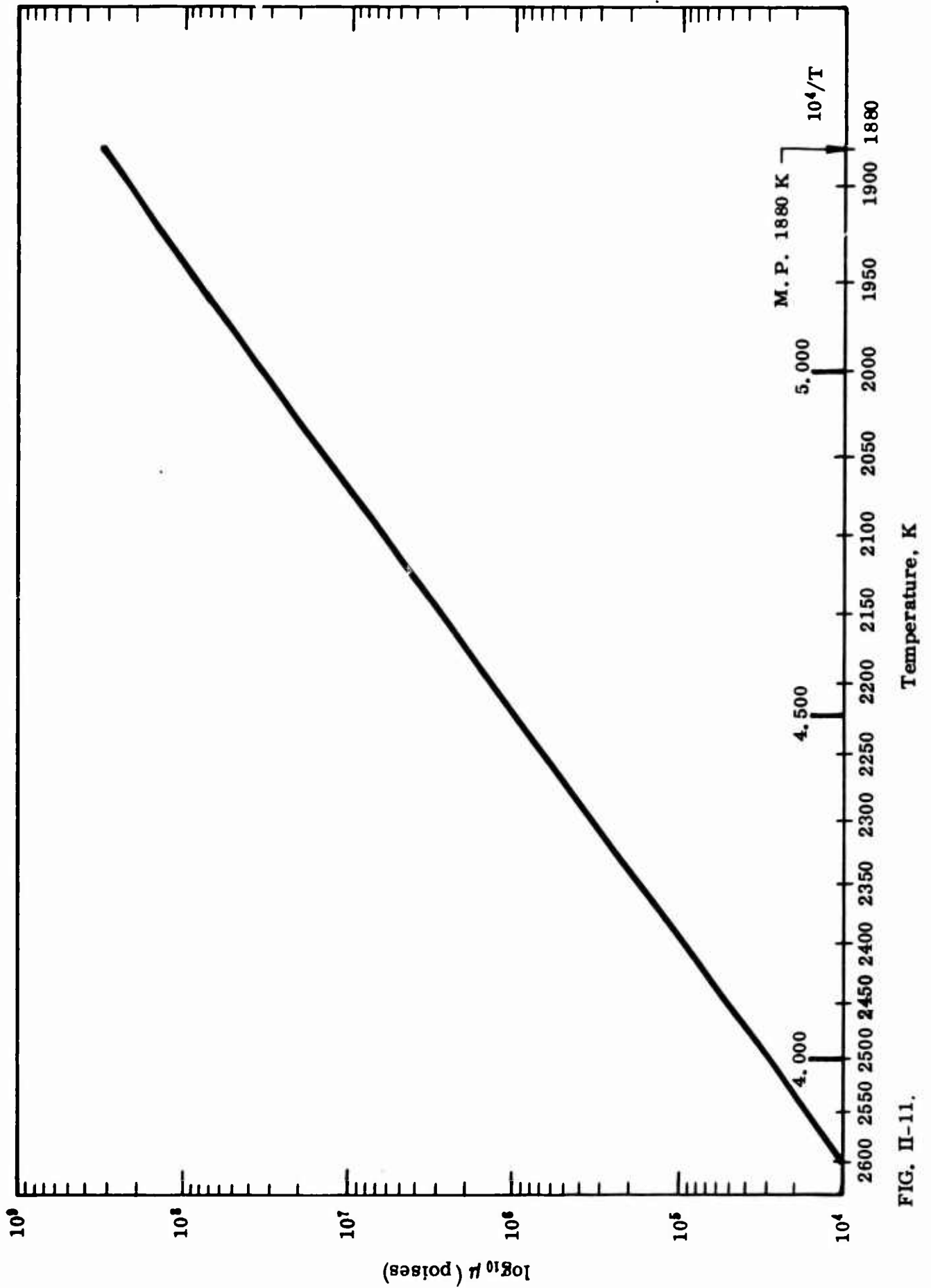


FIG. II-11.

VISCOSITY -- SILICON OXIDE

**TABLE II-11. VISCOSITY OF SILICON OXIDE (SiO<sub>2</sub>)**

**RECOMMENDED VALUES**

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

\* 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.

D. BIBLIOGRAPHY

Ref.  
No.

1. Glazov, V.M., and Chistiakov, Yu. D., *Izv. Akad. Nauk. S.S.S.R. Otdel. Tekhn. Nauk.* 7, 141, (1958).
2. Korolkov, A.M., *Izv. Akad. Nauk S.S.S.R. Otd. Tekhn. Nauk. Met. i Toplivo* 5, 123, (1959).
3. Rothwell, E., *J. Inst. Metals.* 90, 1389, (1962).
4. Gebhardt, E., and Detering, K., *Z. Metallk.* 50, 379, (1953).
5. Gebhardt, E., Becker, M., and Dorner, S., *Aluminium* 31, 315, (1955).
6. Sato, T., and Munahata, S., *Bull. Research Inst. Mineral Dressing and Met. Tokohu Univ.* 11, 183, (1955).
7. Shvidkovskii, E.G., Certain problems related to the viscosity of fused metals. (Engl. Transl.) NASA TT F - 88.
8. Tresh, H.R., Ph.D. Thesis, Univ. of Birmingham (England) (1957).
9. Polyak, E.V., and Sergueiev, S.V., *Dokl. Akad. Nauk. S.S.S.R.* 30, 137, (1941).
10. Sergueiev, S.V., and Polyak, E.V., *Zavodsk. Lab.*, 13, 336, (1947).
11. Yao, T.P., and Kondic, V., *J. Inst. Metals* 81, 17, (1952).
12. Navarro, J.M., and Kondic, V., *Inst. Hierro Y Acero*, 9, 953, (1956).
13. Gebhardt, E., Becker, M., and Schafer, S., *Z. Metallk.* 43, 292, (1952).
14. Gans, W., Pawlek, F., and von Roepenack, A., *Z. Metallk.*, 54, 147, (1963).
15. Lipman, M.S., *Zavodsk. Lab.*, 16, 1349, (1950).
16. Barfield, R.N., and Kitchener, J.A., *J. Iron Steel Inst. (London)* 180, 324, (1955).
17. Vertman, A.A., and Samarin, A.M., *Izv. Akad. Nauk. S.S.S.R. Otd. Tekhn. Nauk. Met. i Toplivo* 4, 95, (1960).
18. F. Bienias, A., and Sauerwald, F., *Z. Anorg. Allgem. Chem.* 161, 51, (1927).
19. Schenck, H., Frohberg, M.G., and Hoffman, K., *Arch. Eisenhutenw*, 34, 93, (1963).
20. Samarin, A.M., *J. Iron Steel Inst. (London)* 200, 95, (1962).
21. Thiele, M., Dr-Ing. Dissertation, Berlin (1958).
22. Cavalier, C. *Compt. Rend.* 244, 2608, (1957).
23. Turovskii, B.M., and Lyubimov, A.D., *Izv. Vysshikh Uchebn. Zavedenii, Metallurgiya* 2, 15, (1960).

BIBLIOGRAPHY (continued) -

- Ref.  
No.
24. Culpin, M.F., Proc. Phys. Soc. (London) B 70, 1079, (1957).
  25. Gebhardt, E., Becker, M., and Tragner, E., Z. Metallk. 46, 90, (1955).
  26. Metals Handbook, A.S.M., Vol. I, 8th Ed., (1961).
  27. Vertman, A.A., and Samarin, A.M., Soviet Phys. Doklady. 5, 598, (1960).
  28. Cavalier, G., Compt. Rend. 256, 1308, (1963).
  29. Lucas, L.D., Compt. Rend. 259, 3760, (1964).
  30. Yao, T.P., and Kondic, V., Nature, 166, 483, (1950).
  31. Jones, W.R.D., and Davies, J. Inst. Metals, 86, 164, (1957).
  32. Lewis, A.J., Proc. Phys. Soc. (London) 48, 299, (1936).
  33. Culpin, M.F., Proc. Phys. Soc. (London) B70, 1069, (1957).
  34. Bastien, P., Ambruster, J.C., and Azou, P. Mod. Castings 41, 72, (1962).
  35. Hedges, E.S., and Homer, C.E., Techn. Publ. Internatl. Tin Res. Develop. Council, Series B n<sup>o</sup> (1) (1937).
  36. Kutateladze, S.S., Borishanskii, V.M., Novikov, I.I., and Fedynskii, O.S., Basic properties of liquid metals, Engl. Transl. Suppl. n 2 of Atomnaya-Energiya (1958) Consultants Bureau Inc. (New York).
  37. (a) Sauerwald, F., and Topler, K. Z. Anorg. Allgem. Chem. 157, 117, (1926).  
 (b) Budde, J., Fischer, K., Monz, W., and Sauerwald, F., Z. Physik. Chem. 218, 100, (1961).
  38. Gebhardt, E., Becker, M., and Tragner, E., Z. Metallk. 44, 379, (1953).
  39. Furth, R., Proc. Cambridge Phil. Soc. 37, 281, (1941).
  40. Sato, T., and Munahata, S., Bull. Research Inst. Mineral Dressing and Met. Tokohu Univ. 10, 173, (1954).
  41. Grigoriev, G.A., Elyutin, V.F., and Maurakh, M.A., Izv. Akad. Nauk. S.S.S.R. Otd. tkhn. Nauk., 8, 95, (1957).
  42. Mound laboratory, Miamisburg (Ohio) MLM - 1108 (1961).
  43. Gering, K., and Sauerwald, F., Z. Anorg. Allgem. Chem. 223, 204, (1935).
  44. Sato, M., Sci. Rep. Tokohu Imp. Univ. 27, 278, (1939).

BIBLIOGRAPHY (continued)

- Ref.  
No.
45. Hopkins, M. R., and Toyne, T. C., Proc. Phys. Soc. (London) 63, 773, (1950).
  46. Kozakevitch, P., Met. Soc. Conf. 7, 97, (1961).
  47. Schenck, H., Froberg, M. G., and Rohde, W., Arch. Eisenhuettenw. 32, 521, (1961).
  48. Bockris, S. D. M., Mackenzie, J. D., and Kitchener, J. A., Trans. Faraday Soc., 51, 1734, (1955).
  49. Hasapis, A. A., Panish, M. B., and Rosen, C., AD 236866.
  50. Bacon, J. F., Hasapis, A. A., and Wholley, J. W. Jr., Phys. Chem. Glasses 1, 90, (1960).
  51. Solomin, N. V., Zh. Fiz. Khim., 14, 235, (1940).
  52. Elyutin, V. P., Maurakh, M. A., and Pech'kov, Izv. Visshykh Uchebn. Zavedenii Tsvetn Met , 7, 128, (1965).

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

**CHAPTER III  
THERMAL EMISSIVITY AND EMITTANCE**

**BY**

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D. G. CHUA  
M. E. PARROTT**

## 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 enough 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,  $\epsilon_{th}$ , can be computed with knowledge of the electrical resistivity ( $\rho$ ) 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<sup>‡</sup> is

$$\begin{aligned} \epsilon_{th} &= 0.75(\rho T)^{1/2} - 0.396(\rho T) & 0 < \rho T < 0.2 \\ \epsilon_{th} &= 0.698(\rho T)^{1/2} - 0.266(\rho T) & 0.2 < \rho T < 0.5 \end{aligned}$$

A similarly styled relation exists for normal total emissivity,  $\epsilon_{tn}$ ; 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  $\epsilon_{tn}$  to 1.05 as  $\epsilon_{tn}$  increases. This ratio as a function of  $\epsilon_{tn}$  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  $\epsilon_{tn}$  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

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<sup>‡</sup>In this relation, the units are:  $\rho$ , 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.

*stainless steel 304*

## 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 composite table. From the meager evidence available, it was not possible to construct recommended curves.

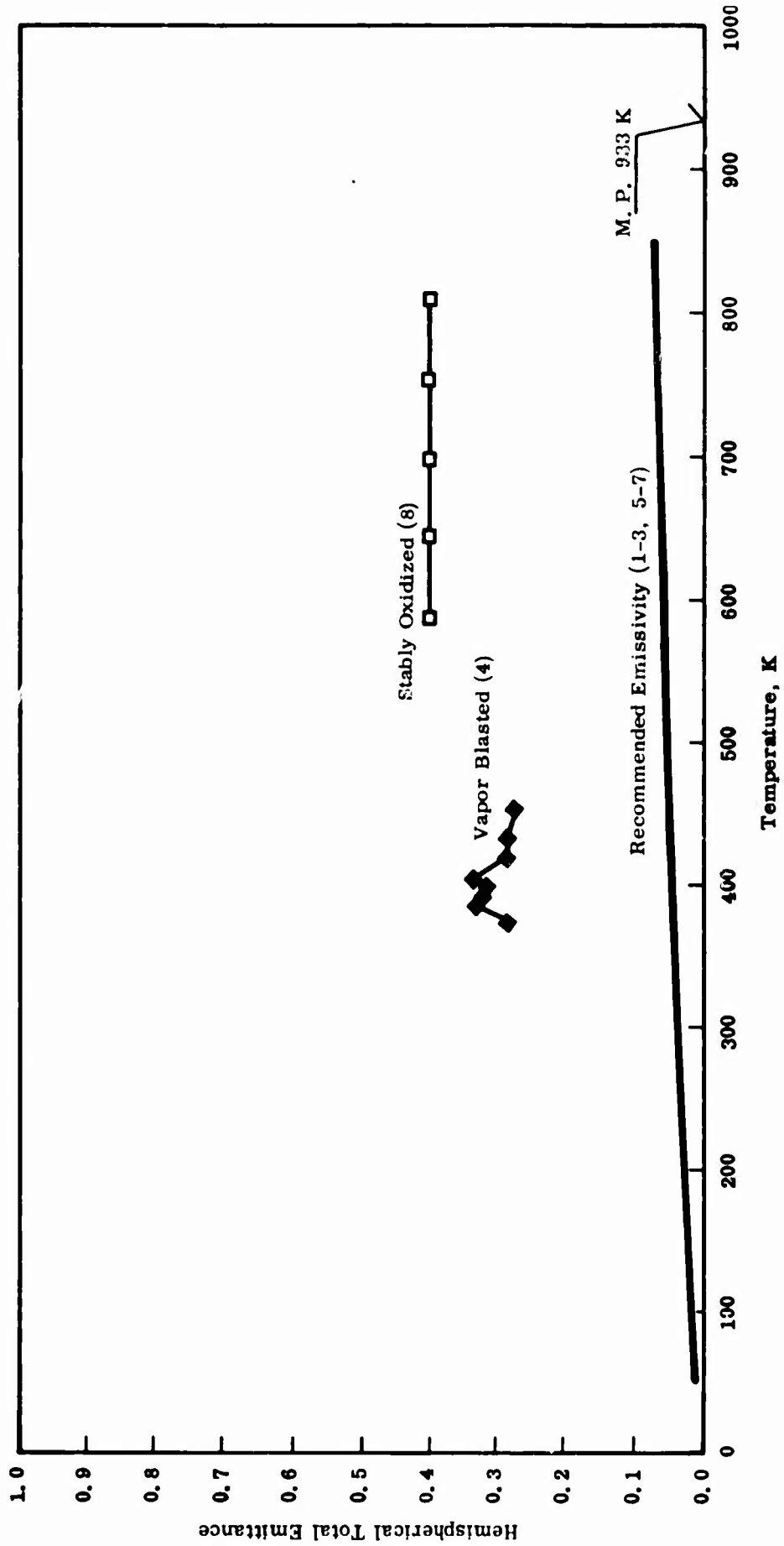


FIG. III-1 HEMISPHERICAL TOTAL EMISSANCE -- ALUMINUM

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)                         | $\epsilon$  | T (K)           | $\epsilon$ | T (K)           | $\epsilon$ |
|-------------------------------|-------------|-----------------|------------|-----------------|------------|
| <u>RECOMMENDED EMISSIVITY</u> |             |                 |            |                 |            |
| 50                            | 0.91 ± 0.02 | 375             | 0.28       | 423             | 0.050      |
| 100                           | 0.02        | 385             | 0.33       | 473             | 0.053      |
| 200                           | 0.03        | 393             | 0.32       | 523             | 0.055      |
| 300                           | 0.04        | 398             | 0.31       | 573             | 0.058      |
| 400                           | 0.045       | 403             | 0.33       | 623             | 0.059      |
| 500                           | 0.055       | 419             | 0.28       | <u>CURVE 7*</u> |            |
| 600                           | 0.06        | 433             | 0.28       | 573             | 0.102      |
| 700                           | 0.06        | 453             | 0.27       | 673             | 0.115      |
| 800                           | 0.07        | <u>CURVE 5*</u> |            | 773             | 0.130      |
| 850                           | 0.075       | 384             | 0.17       | 873             | 0.113      |
| <u>CURVE 1*</u>               |             |                 |            |                 |            |
| 76                            | 0.026       | 395             | 0.18       | <u>CURVE 8</u>  |            |
| <u>CURVE 2*</u>               |             |                 |            |                 |            |
| 76                            | 0.018       | 409             | 0.18       | 588.72          | 0.40       |
| <u>CURVE 3*</u>               |             |                 |            |                 |            |
| 281                           | 0.07        | 420             | 0.18       | 644.27          | 0.40       |
| 266                           | 0.07        | 428             | 0.17       | 699.83          | 0.40       |
| 260                           | 0.07        | 440             | 0.17       | 755.38          | 0.40       |
| 252                           | 0.07        | 452             | 0.16       | 810.94          | 0.40       |
| 244                           | 0.07        | 466             | 0.15       |                 |            |
| 234                           | 0.07        |                 |            |                 |            |
| 227                           | 0.07        |                 |            |                 |            |

\* Not shown on figure.

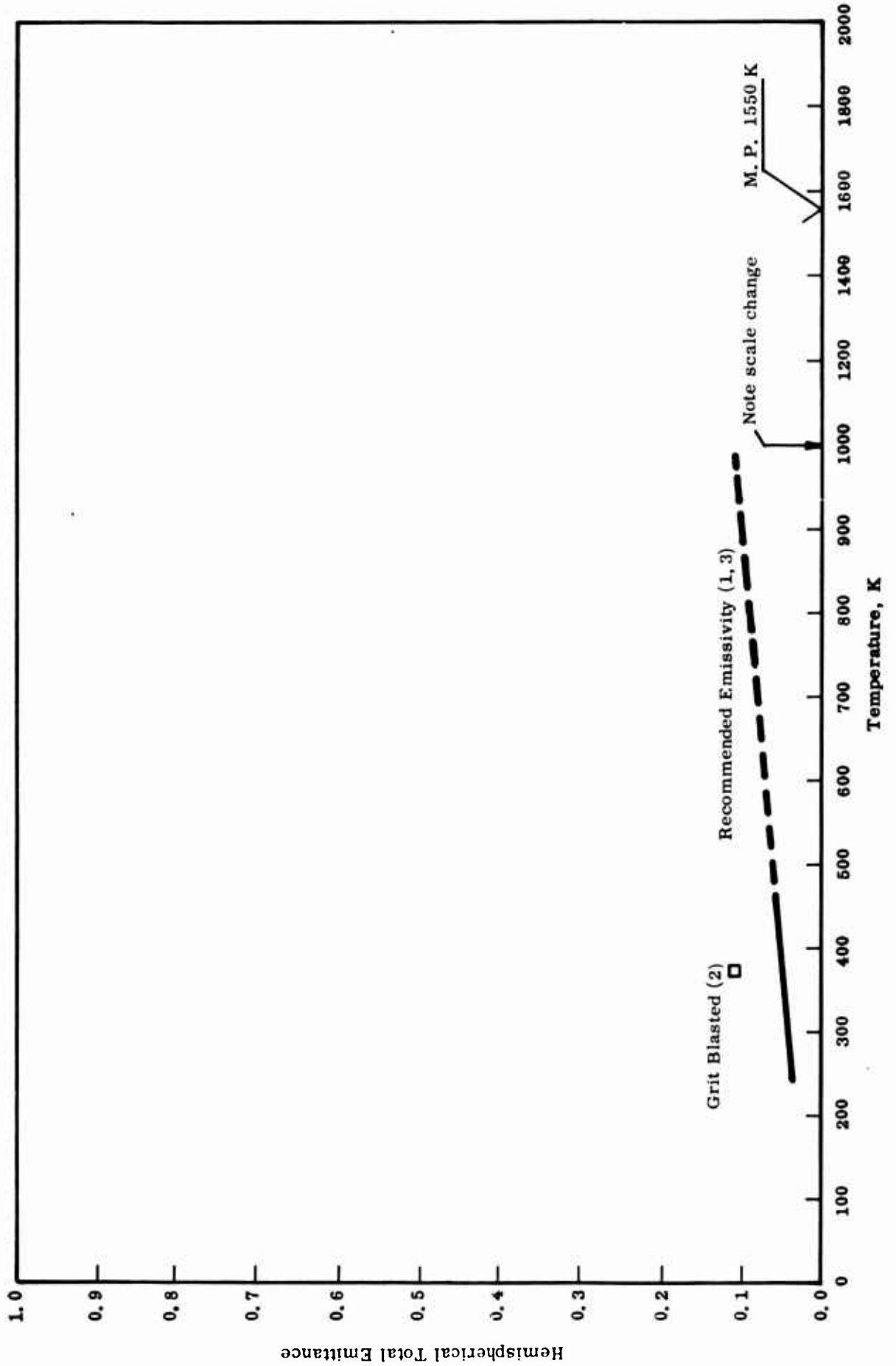


FIG. III-2 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM

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.                             |

| T (K)                         | ε           |
|-------------------------------|-------------|
| <u>RECOMMENDED EMISSIVITY</u> |             |
| 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)      |

| T (K)           | ε     |
|-----------------|-------|
| 277.2           | 0.063 |
| <u>CURVE 1*</u> |       |
| <u>CURVE 2</u>  |       |
| 373             | 0.11  |
| <u>CURVE 3*</u> |       |
| 373             | 0.04  |

\* Not shown on figure

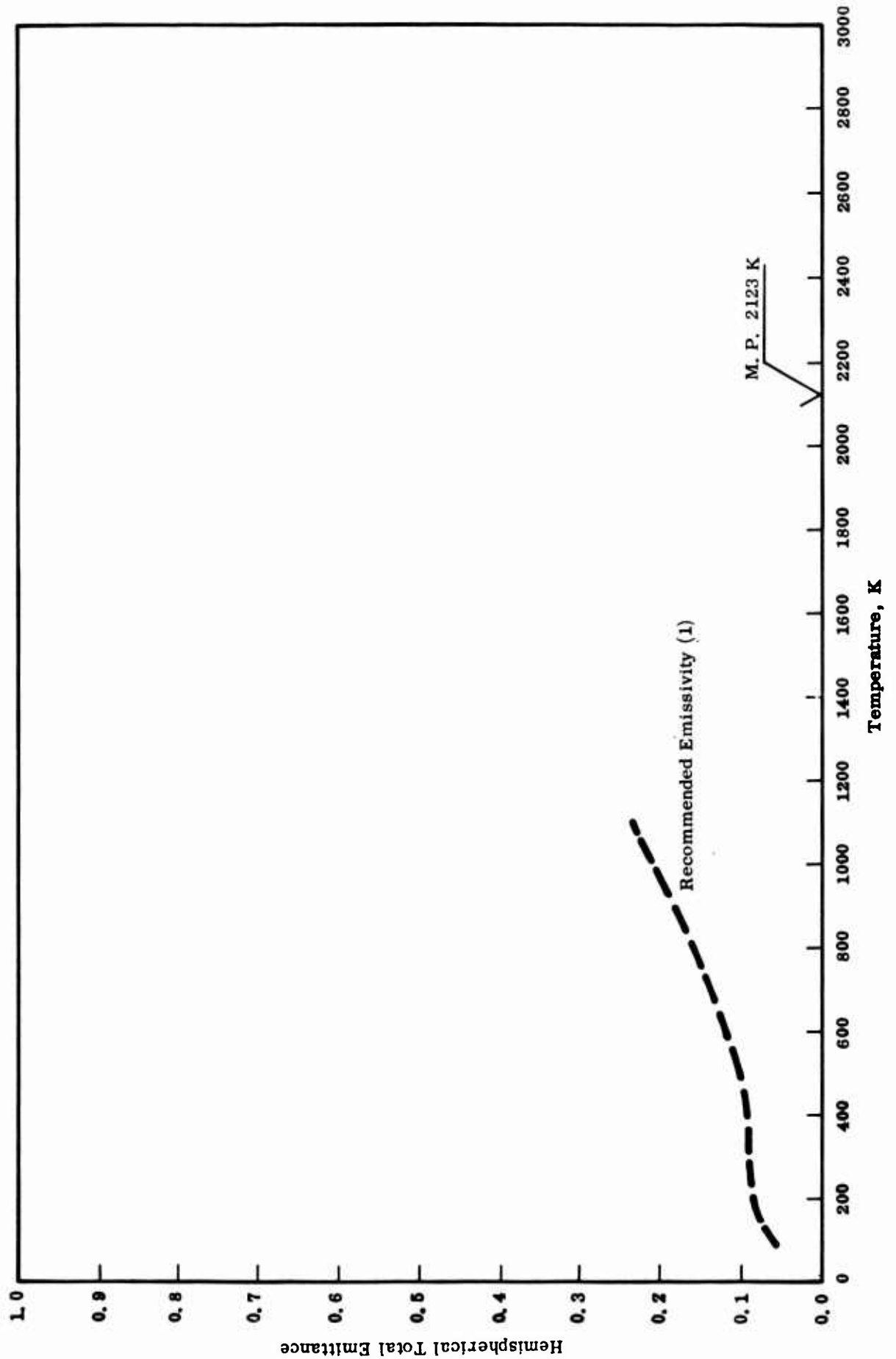


FIG. III-3 HEMISPHERICAL TOTAL EMITTANCE -- CHROMIUM

**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. |

T (K)      €

CURVE 1\*

76      0.08

RECOMMENDED EMISSIVITY

|      |               |
|------|---------------|
| 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)        |

\*Not shown on figure

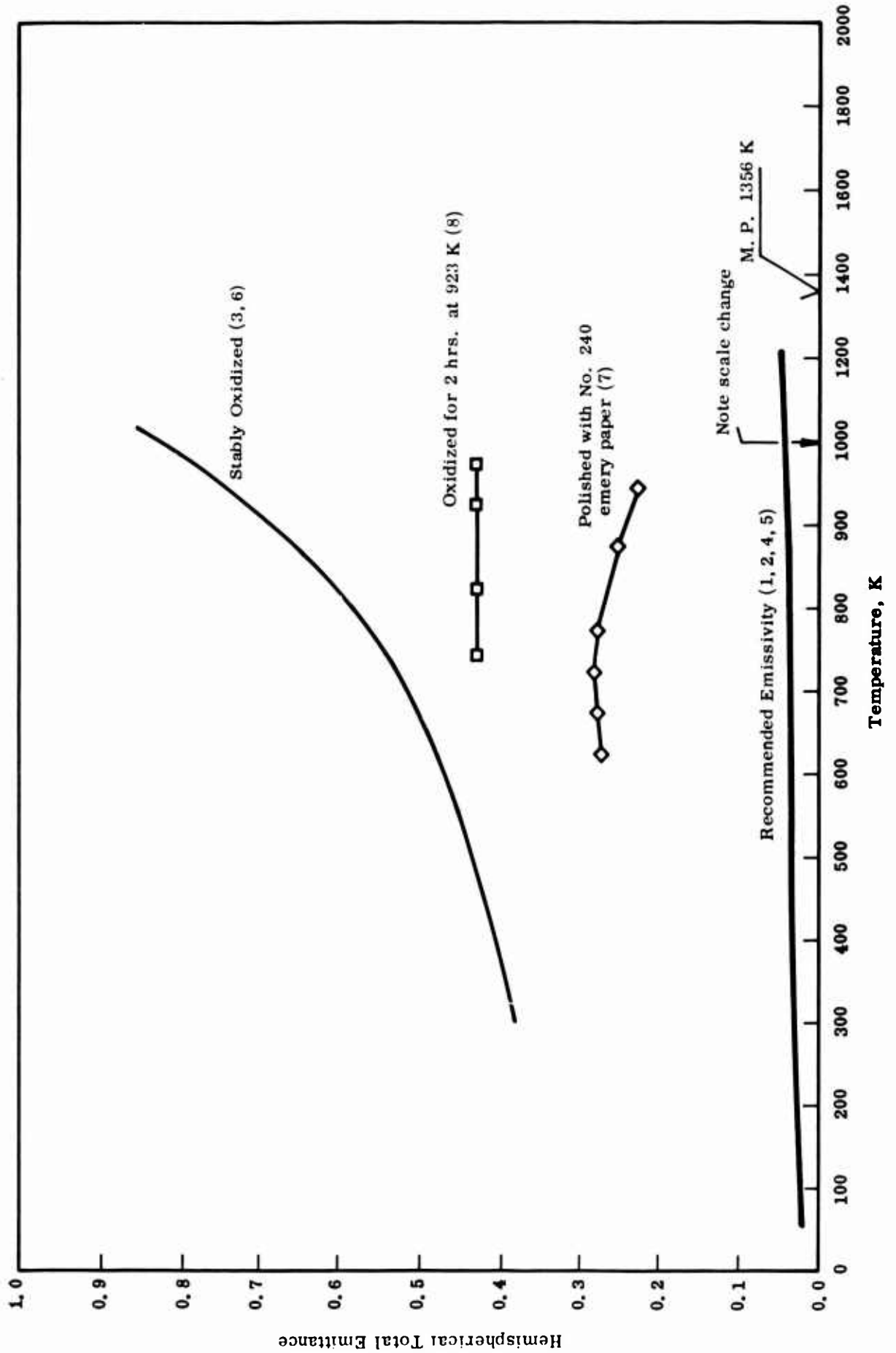


FIG. III-4 HEMISPHERICAL TOTAL EMITTANCE --- COPPER

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)                                | $\epsilon$      | T (K)                  | $\epsilon$ | T (K)                 | $\epsilon$ |
|--------------------------------------|-----------------|------------------------|------------|-----------------------|------------|
| <b><u>RECOMMENDED EMISSIVITY</u></b> |                 |                        |            |                       |            |
| 50                                   | 0.02 $\pm$ 0.01 | 76                     | 0.015      | 588.7                 | 0.495      |
| 100                                  | 0.025           |                        |            | 644.3                 | 0.500      |
| 200                                  | 0.03            | <b><u>CURVE 2*</u></b> |            | 699.8                 | 0.525      |
| 300                                  | 0.03            |                        |            | 755.4                 | 0.545      |
| 400                                  | 0.035           | 76                     | 0.03       | 810.9                 | 0.595      |
| 500                                  | 0.035           | <b><u>CURVE 3*</u></b> |            | 866.5                 | 0.640      |
| 600                                  | 0.04            |                        |            | 922.0                 | 0.710      |
| 700                                  | 0.04            |                        |            | 1033.2                | 0.855      |
| 800                                  | 0.04            | 300                    | 0.38       |                       |            |
| 900                                  | 0.04 $\pm$ 0.02 | <b><u>CURVE 4*</u></b> |            | <b><u>CURVE 7</u></b> |            |
| 1000                                 | 0.04            |                        |            | 623                   | 0.200      |
| 1100                                 | 0.045           | 323                    | 0.040      | 673                   | 0.275      |
| 1200                                 | 0.045           | 473                    | 0.035      | 723                   | 0.280      |
|                                      |                 | 673                    | 0.036      | 773                   | 0.275      |
|                                      |                 | 873                    | 0.038      | 873                   | 0.250      |
|                                      |                 | 1073                   | 0.045      | 943                   | 0.225      |
|                                      |                 | 1173                   | 0.050      |                       |            |
|                                      |                 | <b><u>CURVE 5*</u></b> |            | <b><u>CURVE 8</u></b> |            |
|                                      |                 | 373                    | 0.030      | 743                   | 0.43       |
|                                      |                 | 423                    | 0.030      | 823                   | 0.43       |
|                                      |                 | 473                    | 0.031      | 923                   | 0.43       |
|                                      |                 | 523                    | 0.031      | 973                   | 0.43       |
|                                      |                 | 573                    | 0.032      |                       |            |
|                                      |                 | 623                    | 0.032      |                       |            |

\* Not shown on figure

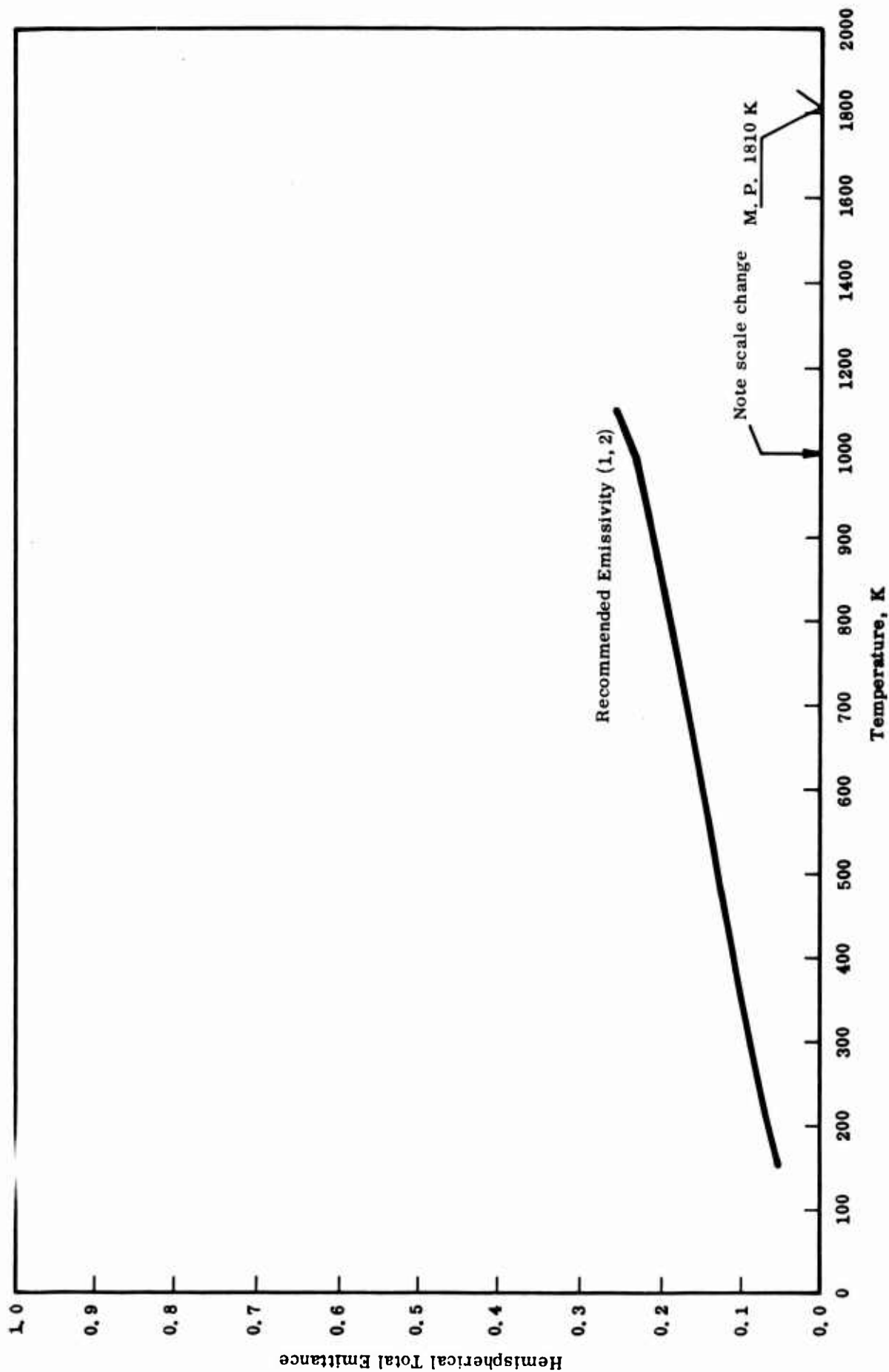


FIG. II-5 HEMISPHERICAL TOTAL EMITTANCE -- IRON

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 <sup>-5</sup> torr. |

| T (K)                         | ε          | T (K)           | ε     |
|-------------------------------|------------|-----------------|-------|
| <u>RECOMMENDED EMISSIVITY</u> |            |                 |       |
| 150                           | 0.05 ±0.01 | 167             | 0.056 |
| 200                           | 0.065      | 195             | 0.064 |
| 300                           | 0.09       | 222             | 0.071 |
| 400                           | 0.11       | 250             | 0.079 |
| 500                           | 0.13       | 278             | 0.086 |
| 600                           | 0.15 ±0.02 | <u>CURVE 2*</u> |       |
| 700                           | 0.17       | 468             | 0.130 |
| 800                           | 0.19       | 668             | 0.160 |
| 900                           | 0.21       | 873             | 0.205 |
| 1000                          | 0.235      | 1093            | 0.255 |
| 1100                          | 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  | T (K)    |          | ε    |      |
|-----------|----------|----------------|-------------------|--|----------|----------|------|------|
|           |          |                |                   |  | CURVE 1* | CURVE 2* |      |      |
| 1*        | 3        | 415-483        | ±3                | Hand polished using fine abrasive papers followed by application of a metal polish; measured in vacuum, 10 <sup>-3</sup> torr. | 415      | 426      | 0.12 | 0.13 |
| 2*        | 3        | 355-478        | ±3                | Hand polished, then vapor blasted; measured in vacuum, 10 <sup>-3</sup> torr.  | 435      | 453      | 0.12 | 0.12 |
|           |          |                |                   |  | 463      | 473      | 0.12 | 0.12 |
|           |          |                |                   |  | 483      |          | 0.12 |      |
|           |          |                |                   |  | 355      | 373      | 0.31 | 0.31 |
|           |          |                |                   |  | 401      | 418      | 0.33 | 0.31 |
|           |          |                |                   |  | 433      | 453      | 0.31 | 0.30 |
|           |          |                |                   |  | 473      | 478      | 0.28 | 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)             $\epsilon$

CURVE 1\*

391.9            0.0480

---

\* No figure presented

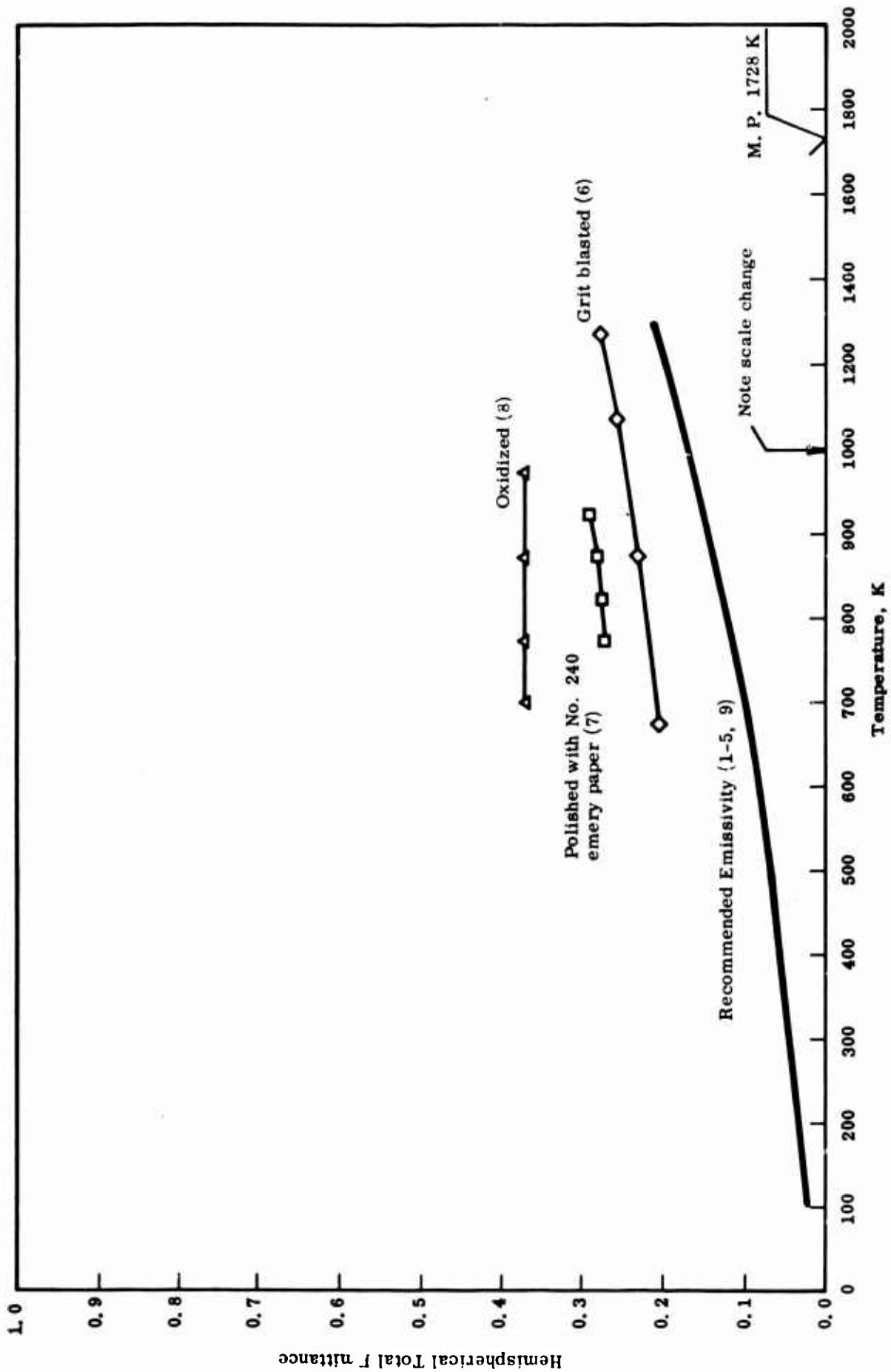


FIG. III-6 HEMISPHERICAL TOTAL EMISSANCE -- NICKEL

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          | $\pm 0.7\%$    | Plating; polished.  |
| 3*        | 14       | 373.6          | $\pm 0.7\%$    | Plating; dull, unpolished.  |
| 4*        | 13       | 463-1093       | < 10%          | Ground with 600 grit carborundum; polished with alumina; measured in vacuum, $10^{-5}$ torr.  |
| 5*        | 15       | 673-1273       | $\pm 2.5\%$    | 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       | $\pm 2.5\%$    | 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       | $\pm 0.01$     | Grade A, polished; average of four specimens, measured in vacuum.   |

\* Not shown on figure

**TABLE III-8B HEMISPHERICAL TOTAL EMITTANCE -- NICKEL**  
**DATA TABLE**

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

\* Not shown on figure

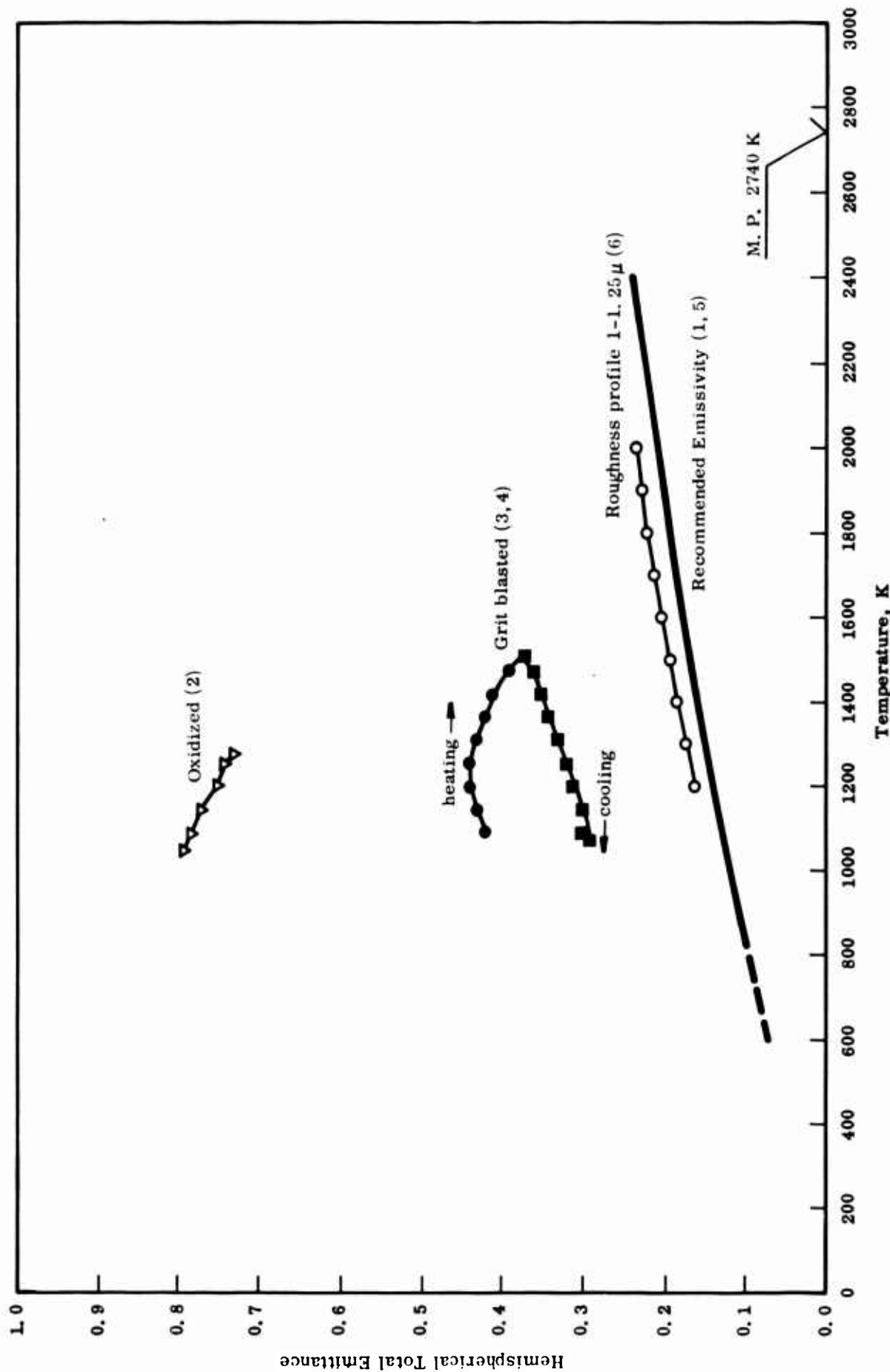


FIG. III-7 HEMISPHERICAL TOTAL EMITTANCE -- NIOBIUM

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 $\mu$ ; height of irregularities, 0.1-0.125 $\mu$ ; measured in vacuum. |
| 6         | 19       | 1200-2000      | < 1.9             | Same composition as above; mean arithmetical profile, 1-1.25 $\mu$ ; height of irregularities 5-6.3 $\mu$ ; measured in vacuum.   |

\* Not shown on figure

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

| T (K)                         | $\epsilon$        | T (K)          | $\epsilon$ | T (K)           | $\epsilon$ | T (K) | $\epsilon$ |      |       |
|-------------------------------|-------------------|----------------|------------|-----------------|------------|-------|------------|------|-------|
| <u>RECOMMENDED EMISSIVITY</u> |                   |                |            |                 |            |       |            |      |       |
| 600                           | (0.07) $\pm$ 0.01 | 2040           | 0.242      | 1088.7          | 0.42       | 1200  | 0.163      |      |       |
| 800                           | 0.095             | 2142           | 0.244      | 1144.3          | 0.43       | 1300  | 0.175      |      |       |
| 1000                          | 0.12              | 2234           | 0.248      | 1199.8          | 0.44       | 1400  | 0.186      |      |       |
| 1200                          | 0.14              | 2318           | 0.252      | 1255.4          | 0.44       | 1500  | 0.196      |      |       |
| 1400                          | 0.16              | 2380           | 0.259      | 1310.9          | 0.43       | 1600  | 0.205      |      |       |
| 1600                          | 0.18 $\pm$ 0.02   | <u>CURVE 2</u> |            |                 |            |       |            | 1700 | 0.213 |
| 1800                          | 0.195             |                |            |                 |            |       |            | 1800 | 0.221 |
| 2000                          | 0.21              | 1049.8         | 0.74       | 1477.6          | 0.39*      | 1900  | 0.228      |      |       |
| 2200                          | 0.225             | 1088.7         | 0.73       | 1505.4          | 0.37*      | 2000  | 0.236      |      |       |
| 2400                          | 0.24              | 1144.3         | 0.72       | <u>CURVE 5*</u> |            |       |            |      |       |
| <u>CURVE 1*</u>               |                   |                |            |                 |            |       |            |      |       |
| 1009                          | 0.114             | 1199.8         | 0.70       | 1200            | 0.140      | 1300  | 0.151      |      |       |
| 1132                          | 0.129             | 1255.4         | 0.69       | 1300            | 0.151      | 1400  | 0.161      |      |       |
| 1234                          | 0.143             | 1266.5         | 0.68       | 1400            | 0.161      | 1500  | 0.171      |      |       |
| 1322                          | 0.153             | <u>CURVE 3</u> |            |                 |            |       |            |      |       |
| 1410                          | 0.165             | 1505.4         | 0.37       | 1500            | 0.171      | 1600  | 0.180*     |      |       |
| 1480                          | 0.176             | 1477.6         | 0.36*      | 1600            | 0.180*     | 1700  | 0.188      |      |       |
| 1560                          | 0.184             | 1422.0         | 0.35       | 1700            | 0.188      | 1800  | 0.196      |      |       |
| 1652                          | 0.194             | 1366.5         | 0.34       | 1800            | 0.196      | 1900  | 0.203      |      |       |
| 1763                          | 0.205             | 1310.9         | 0.33       | 1900            | 0.203      | 2000  | 0.209      |      |       |
| 1860                          | 0.218             | 1255.4         | 0.32       | 2000            | 0.209      |       |            |      |       |
| 1952                          | 0.229             | 1199.8         | 0.31       |                 |            |       |            |      |       |
| <u>CURVE 4</u>                |                   |                |            |                 |            |       |            |      |       |
| <u>CURVE 5*</u>               |                   |                |            |                 |            |       |            |      |       |
| <u>CURVE 6</u>                |                   |                |            |                 |            |       |            |      |       |

\*Not shown on figure

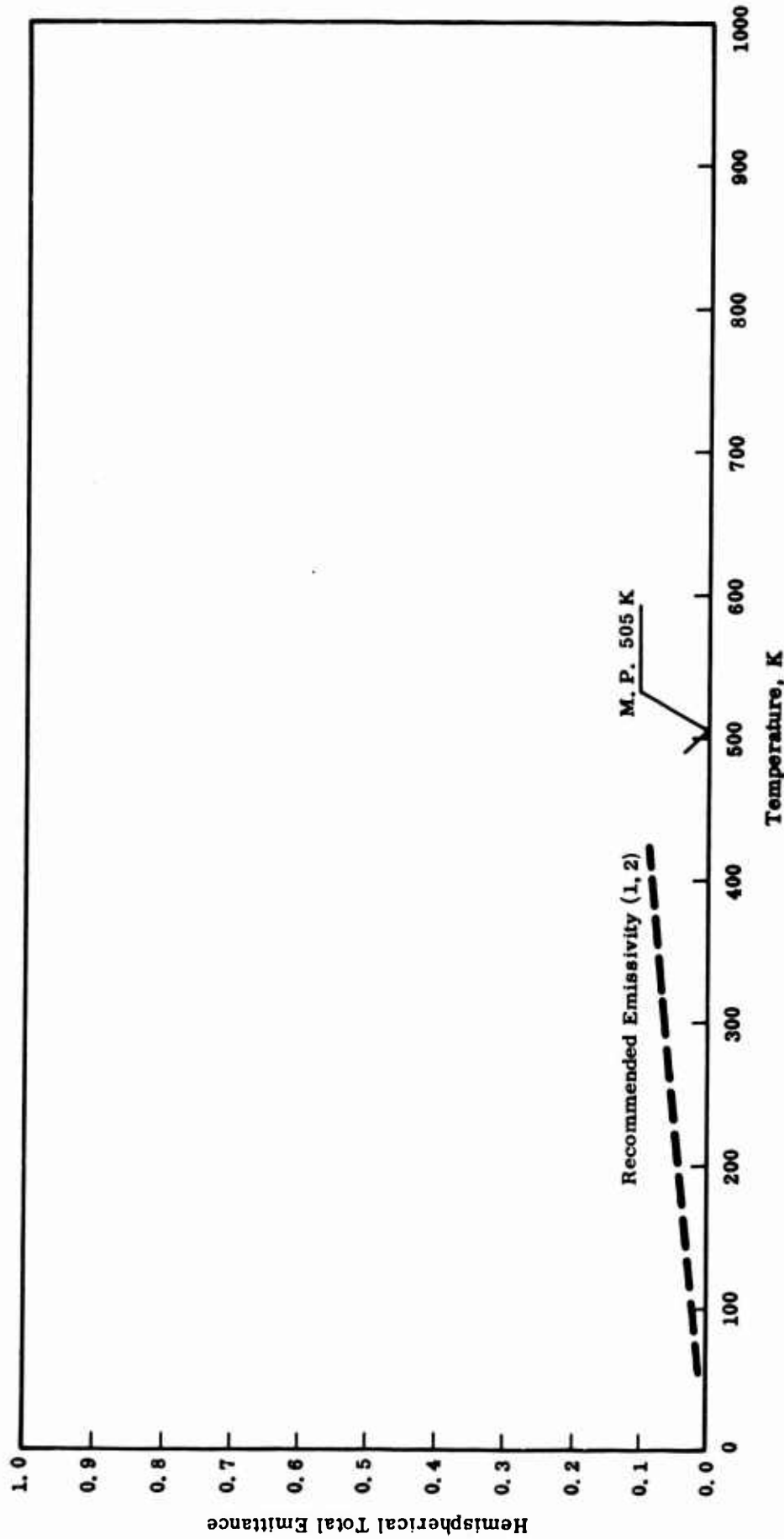


FIG. III-8 HEMISPHERICAL TOTAL EMITTANCE -- TIN

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)                         | ε             | T (K)           | ε     |
|-------------------------------|---------------|-----------------|-------|
| <u>RECOMMENDED EMISSIVITY</u> |               |                 |       |
| 50                            | (0.01) ± 0.02 | <u>CURVE 1*</u> |       |
| 100                           | (0.02)        | 76              | 0.013 |
| 200                           | (0.04)        | <u>CURVE 2*</u> |       |
| 300                           | (0.06)        | 76              | 0.02  |
| 400                           | (0.08)        |                 |       |

\* Not shown on figure

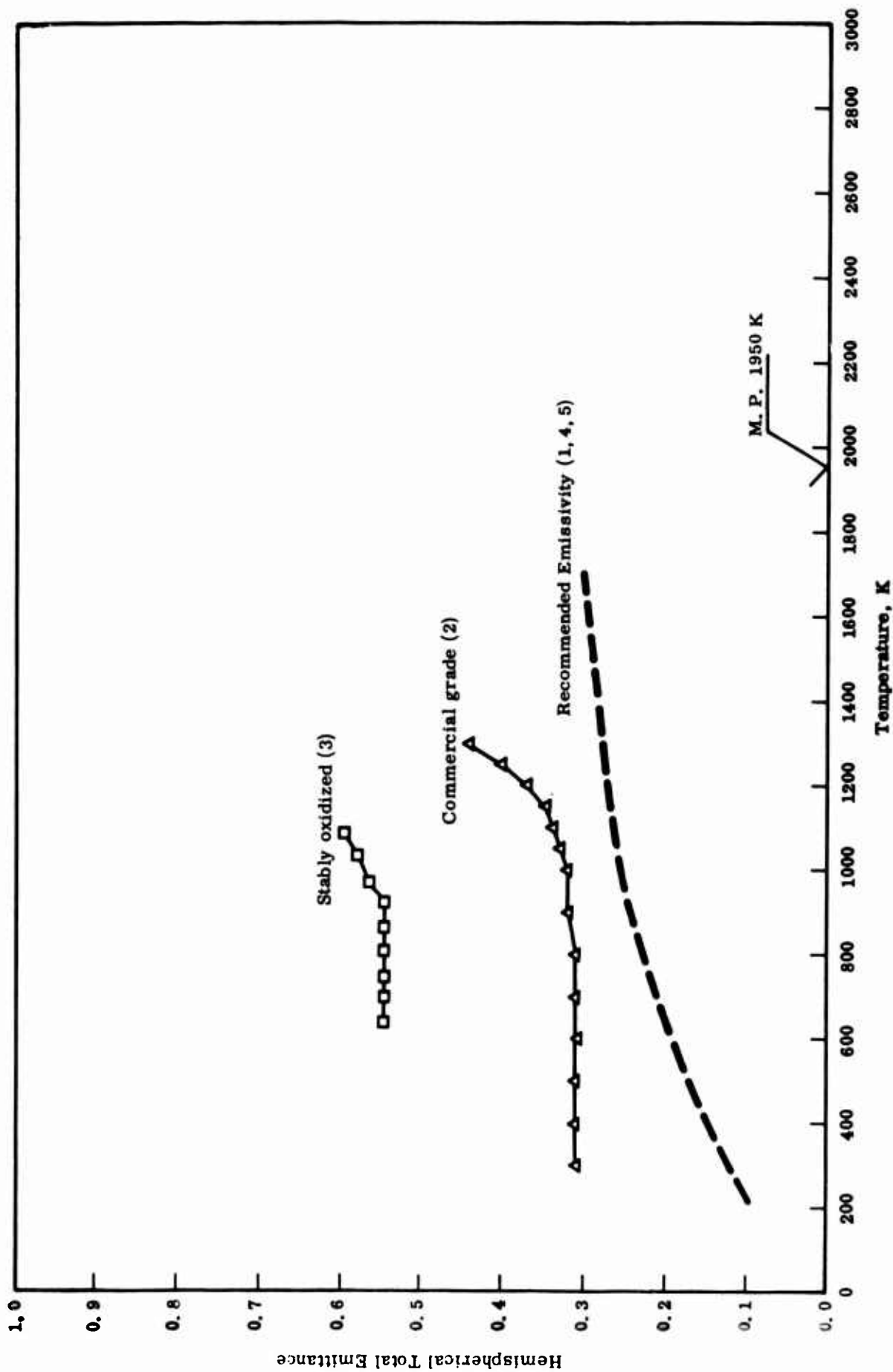


FIG. III-9 HEMISPHERICAL TOTAL EMISSANCE -- TITANIUM

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, $1 \times 10^{-6}$ 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, $1 \times 10^{-5}$ torr.                                    |
| 5*        | 22       | 1700           |                   | Pure; measured in vacuum.  |

| T (K)                         | ε       | T (K) | ε               | T (K) | ε               |
|-------------------------------|---------|-------|-----------------|-------|-----------------|
| <u>RECOMMENDED EMISSIVITY</u> |         |       | <u>CURVE 1*</u> |       |                 |
| 200                           | (0.09)  | 279   | 0.13            | 300   | 0.31            |
| 400                           | (0.15)  | 274   | 0.10            | 400   | 0.31            |
| 600                           | (0.19)  | 267   | 0.10            | 500   | 0.31            |
| 800                           | (0.225) | 262   | 0.10            | 600   | 0.31            |
| 1000                          | (0.255) | 256   | 0.11            | 700   | 0.31            |
| 1200                          | (0.27)  | 252   | 0.11            | 800   | 0.31            |
| 1400                          | (0.28)  | 247   | 0.11            | 900   | 0.32            |
| 1600                          | (0.295) | 241   | 0.12            | 1000  | 0.32            |
| 1700                          | (0.30)  |       |                 | 1050  | 0.33            |
|                               |         |       |                 | 1100  | 0.34            |
|                               |         |       |                 | 1150  | 0.35            |
|                               |         |       |                 | 1200  | 0.37            |
|                               |         |       |                 | 1250  | 0.40            |
|                               |         |       |                 | 1300  | 0.44            |
|                               |         |       |                 |       | <u>CURVE 2</u>  |
|                               |         |       |                 |       | <u>CURVE 3</u>  |
|                               |         |       |                 | 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           |
|                               |         |       |                 |       | <u>CURVE 4*</u> |
|                               |         |       |                 | 891.2 | 0.241           |
|                               |         |       |                 |       | <u>CURVE 5*</u> |
|                               |         |       |                 | 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) | $\epsilon$ |
|-------|------------|
| 76    | 0.02       |

CURVE 1\*

\* No figure presented

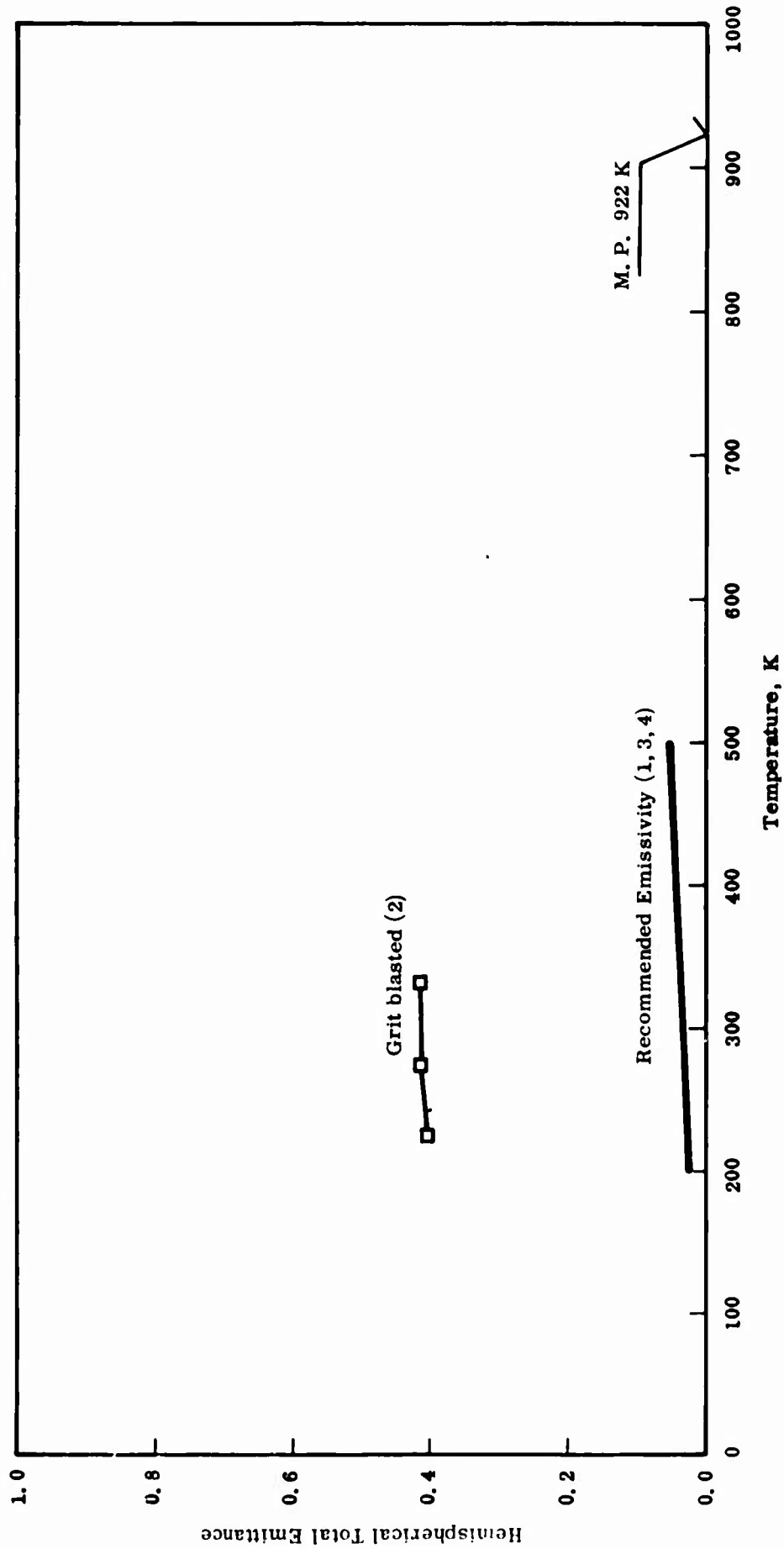


FIG. III-10 HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 6061-T6

**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           | T (K)           | ε    |
|-------------------------------|-------------|-----------------|------|
| <u>RECOMMENDED EMISSIVITY</u> |             |                 |      |
| 200                           | 0.025 ±0.02 | 222             | 0.40 |
| 300                           | 0.035       | 278             | 0.41 |
| 400                           | 0.04        | 333             | 0.41 |
| 500                           | 0.05        | <u>CURVE 3*</u> |      |
| <u>CURVE 1*</u>               |             |                 |      |
| 222                           | 0.04        | 222             | 0.06 |
| 278                           | 0.04        | 278             | 0.06 |
| 333                           | 0.05        | 333             | 0.07 |
| <u>CURVE 4*</u>               |             |                 |      |
| 222                           | 0.09        | 222             | 0.09 |
| 278                           | 0.09        | 278             | 0.09 |
| 333                           | 0.10        | 333             | 0.10 |

\* Not shown on figure

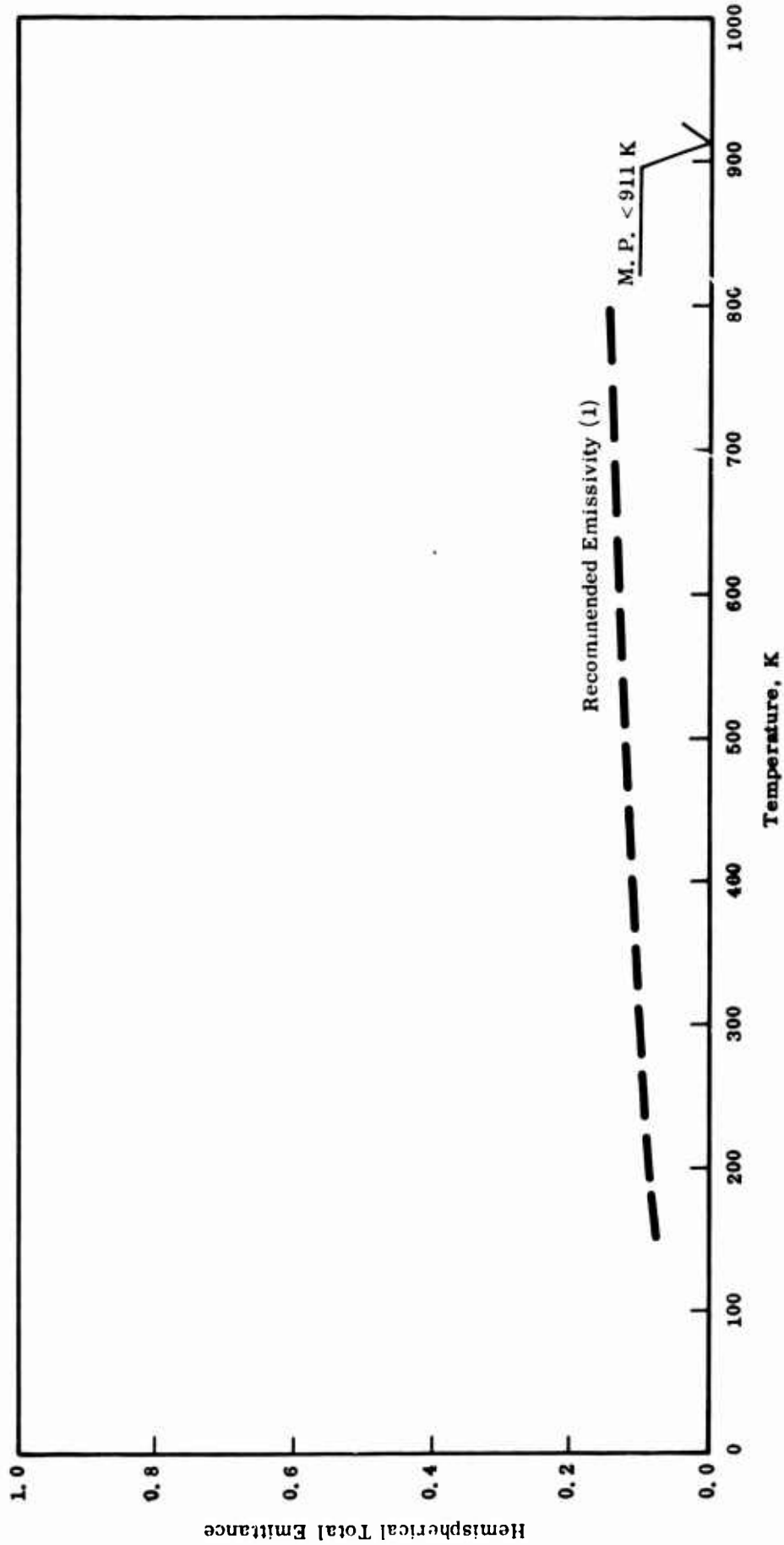


FIG. III-11A HEMISPHERICAL TOTAL EMITTANCE -- ALUMINUM ALLOY 7075-T6

**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)                                | $\epsilon$   |
|--------------------------------------|--------------|
| <b><u>RECOMMENDED EMISSIVITY</u></b> |              |
| 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)       |

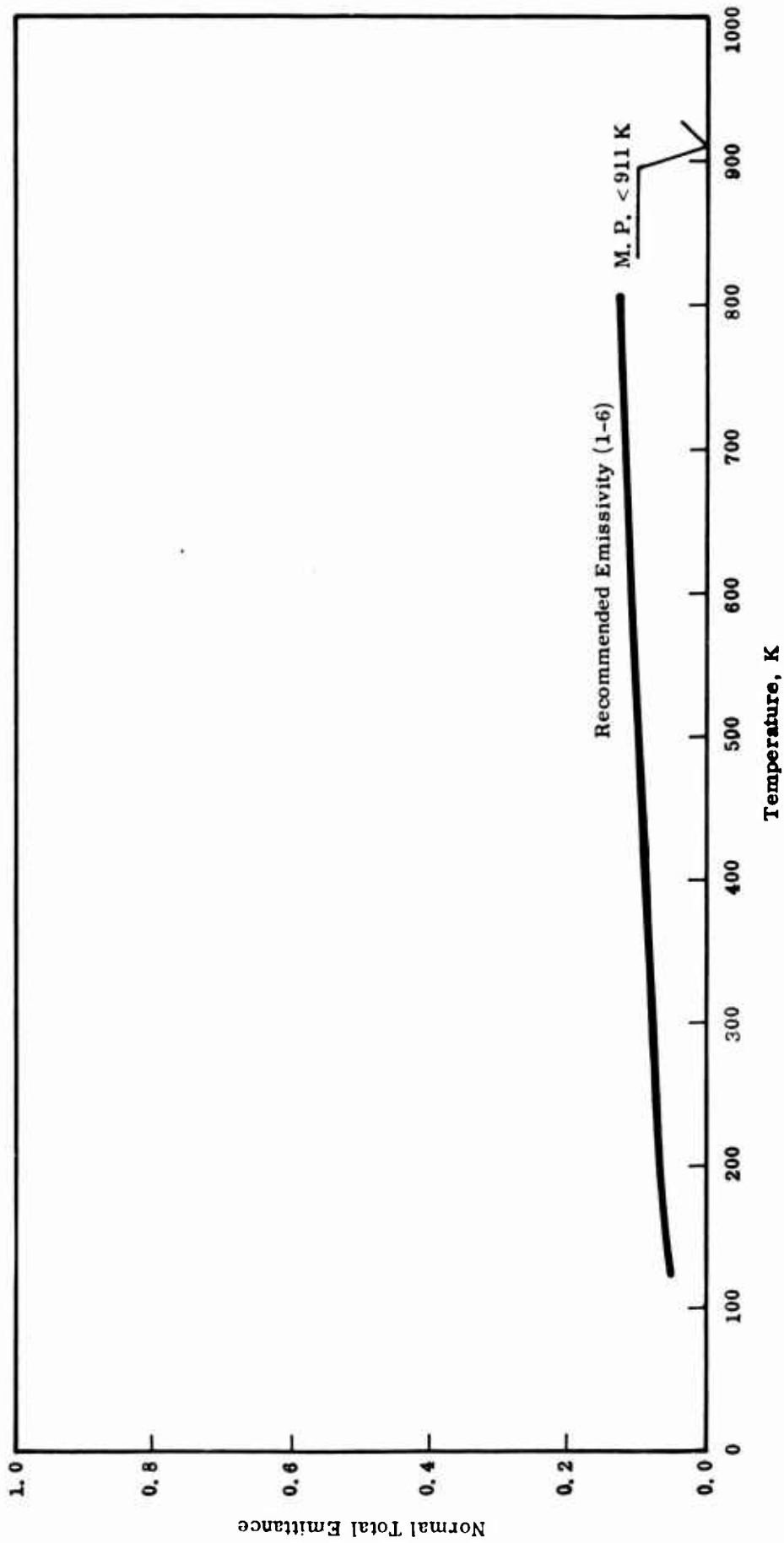


FIG. 100 NORMAL TOTAL EMISSANCE -- ALUMINUM ALLOY 7075-T6

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.  |

| T (K)                         | €           | T (K)           | €    | T (K)           | €     | T (K)           | €     |
|-------------------------------|-------------|-----------------|------|-----------------|-------|-----------------|-------|
| <u>RECOMMENDED EMISSIVITY</u> |             |                 |      |                 |       |                 |       |
| 150                           | 0.06 ± 0.02 | 89              | 0.06 | 303             | 0.02  | 386             | 0.09  |
| 200                           | 0.07        | 255             | 0.08 |                 |       | 433             | 0.095 |
| 300                           | 0.08        | 422             | 0.09 | <u>CURVE 4*</u> |       | 444             | 0.098 |
| 400                           | 0.09        | 589             | 0.10 |                 |       | 505             | 0.12  |
| 500                           | 0.10        | 755             | 0.12 | 383             | 0.13  | 530             | 0.105 |
| 600                           | 0.11        | 805             | 0.12 | 428             | 0.11  | 603             | 0.125 |
| 700                           | 0.115       | <u>CURVE 2*</u> |      | 450             | 0.14  | 650             | 0.13  |
| 800                           | 0.125       |                 |      | 469             | 0.14  | <u>CURVE 6*</u> |       |
|                               |             | 301             | 0.07 | 528             | 0.145 |                 |       |
|                               |             |                 |      | 633             | 0.16  |                 |       |
|                               |             |                 |      | 650             | 0.175 |                 |       |
|                               |             |                 |      | 428             | 0.065 |                 |       |
|                               |             |                 |      | 433             | 0.06  |                 |       |
|                               |             |                 |      |                 |       | 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

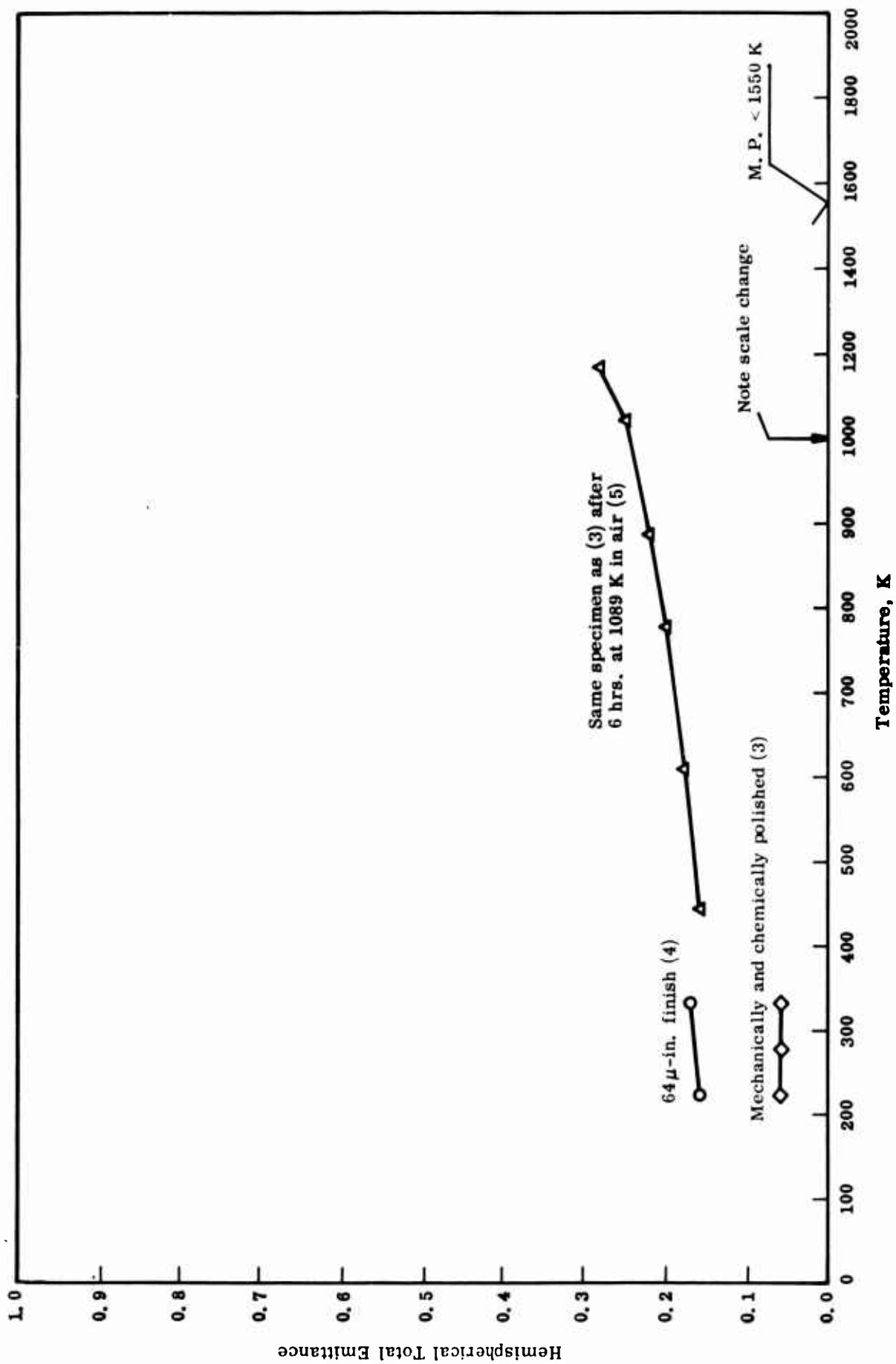


FIG. III-12 HEMISPHERICAL TOTAL EMITTANCE -- BERYLLIUM ALLOY

**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    | T (K) | ε    |
|-----------------|------|-------|------|
| <u>CURVE 1*</u> |      |       |      |
| 222             | 0.11 | 222   | 0.14 |
| 278             | 0.11 | 333   | 0.15 |
| 333             | 0.12 | 445   | 0.16 |
| <u>CURVE 2*</u> |      |       |      |
| 222             | 0.08 | 611   | 0.18 |
| 278             | 0.09 | 778   | 0.20 |
| 333             | 0.10 | 889   | 0.22 |
| <u>CURVE 3</u>  |      |       |      |
| 222             | 0.06 | 1045  | 0.25 |
| 278             | 0.06 | 1167  | 0.28 |
| 333             | 0.06 |       |      |
| <u>CURVE 4</u>  |      |       |      |
| 222             | 0.16 |       |      |
| 333             | 0.17 |       |      |
| <u>CURVE 5</u>  |      |       |      |

\* 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

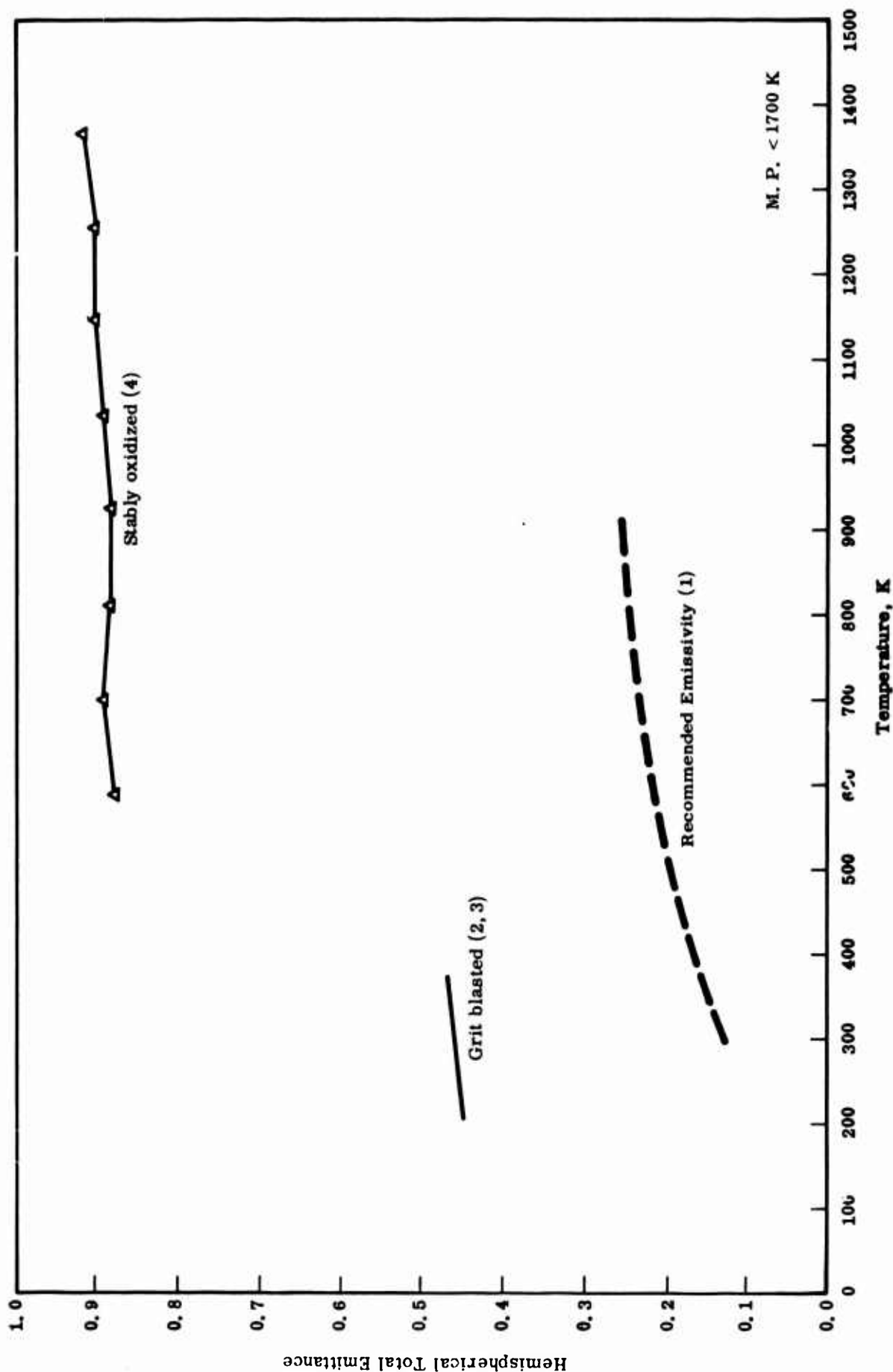


FIG. III-13A HEMISPHERICAL TOTAL EMISSANCE -- STAINLESS STEEL 347

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.  |

| T (K)                         | ε              | T (K)           | ε     |
|-------------------------------|----------------|-----------------|-------|
| <u>RECOMMENDED EMISSIVITY</u> |                |                 |       |
| 300                           | (0.125) ± 0.04 | 222             | 0.46  |
| 400                           | (0.165)        | 278             | 0.46  |
| 500                           | (0.195) ± 0.02 | 333             | 0.47  |
| 600                           | (0.215)        | <u>CURVE 3*</u> |       |
| 700                           | (0.235)        | 222             | 0.44  |
| 800                           | (0.245)        | 278             | 0.45  |
| 900                           | (0.255)        | 333             | 0.46  |
| <u>CURVE 2*</u>               |                |                 |       |
| <u>CURVE 4</u>                |                |                 |       |
|                               |                | 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

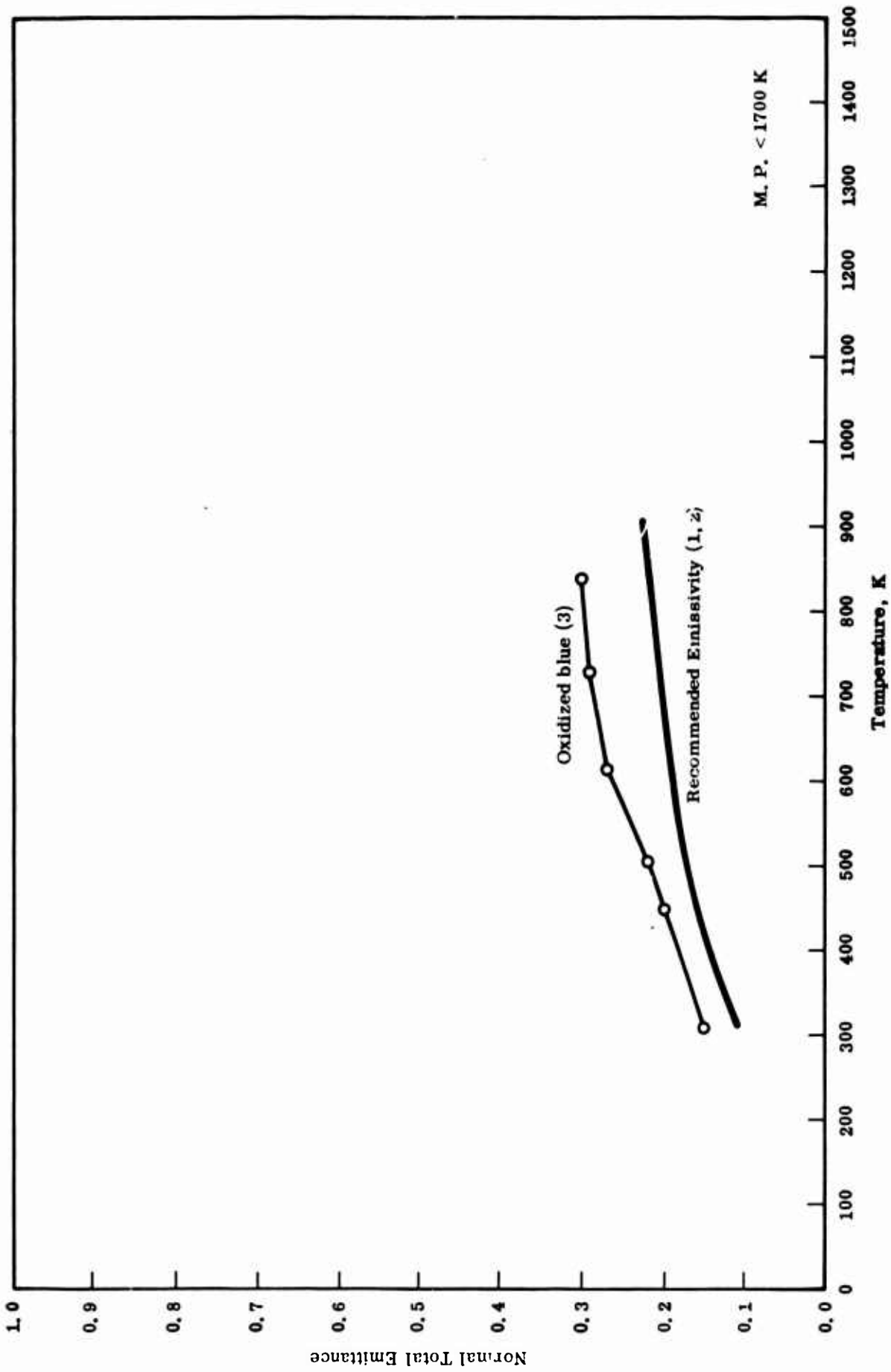


FIG. III-13B NORMAL TOTAL EMITTANCE -- STAINLESS STEEL 347

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.                           |

| T (K)                         | ε           | T (K)                   | ε    | T (K)           | ε    |
|-------------------------------|-------------|-------------------------|------|-----------------|------|
| <b>RECOMMENDED EMISSIVITY</b> |             |                         |      |                 |      |
| 300                           | 0.10 ± 0.04 | 589                     | 0.18 | 311             | 0.15 |
| 400                           | 0.14        | 755                     | 0.20 | 450             | 0.20 |
| 500                           | 0.17 ± 0.02 | 922                     | 0.23 | 505             | 0.22 |
| 600                           | 0.19        | 1089                    | 0.33 | 617             | 0.27 |
| 700                           | 0.205       | 1289                    | 0.66 | 728             | 0.29 |
| 800                           | 0.215       |                         |      | 839             | 0.30 |
| 900                           | 0.225       |                         |      |                 |      |
|                               |             | <b>CURVE 1* (cont.)</b> |      | <b>CURVE 3</b>  |      |
|                               |             | <b>CURVE 1*</b>         |      | <b>CURVE 2*</b> |      |
|                               |             | 311                     | 0.11 | 311             | 0.11 |
|                               |             | 450                     | 0.16 | 450             | 0.16 |
|                               |             | 505                     | 0.18 | 505             | 0.18 |
|                               |             | 617                     | 0.19 | 617             | 0.19 |
|                               |             | 728                     | 0.21 | 728             | 0.21 |
|                               |             | 839                     | 0.23 | 839             | 0.23 |

\* Not shown on figure

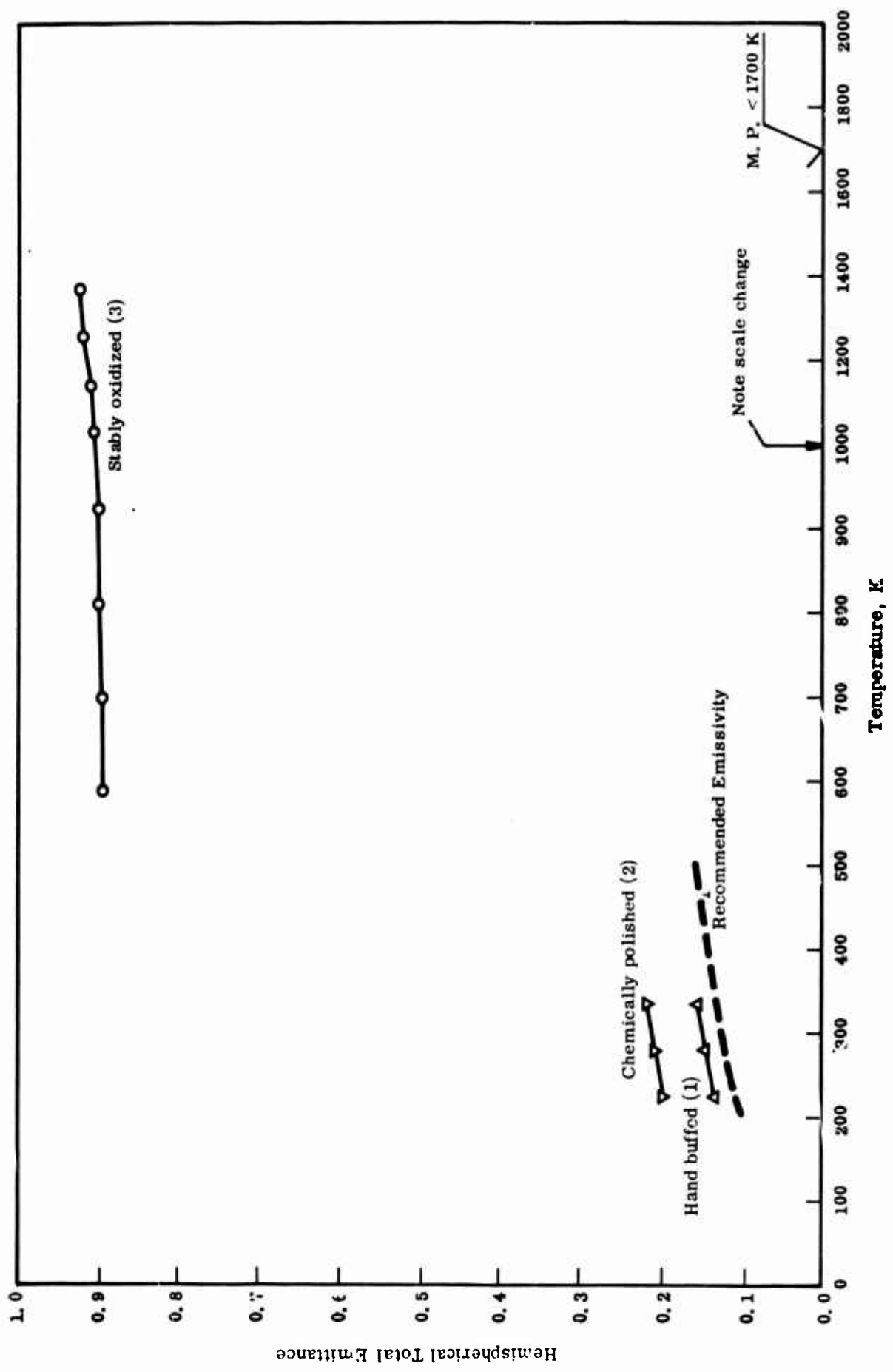


FIG. III-14 HEMISPHERICAL TOTAL EMISSANCE -- INCONEL X-750

**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 polished; computed from spectral reflectance measurements                                     |
| 2         | 22       | 222-333        | ±0.07          | Foil; cleaned and 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)                         | ε            |
|-------------------------------|--------------|
| <u>RECOMMENDED EMISSIVITY</u> |              |
| 200                           | (0.12) ±0.02 |
| 300                           | (0.13)       |
| 400                           | (0.145)      |
| 500                           | (0.16)       |
| <u>CURVE 1</u>                |              |
| 222                           | 0.14         |
| 278                           | 0.15         |
| 333                           | 0.16         |
| <u>CURVE 2</u>                |              |
| 222                           | 0.20         |
| 278                           | 0.21         |
| 333                           | 0.22         |
| <u>CURVE 3</u>                |              |
| 589                           | 0.69         |
| 700                           | 0.705        |
| 811                           | 0.730        |
| 922                           | 0.755        |
| 1033                          | 0.765        |
| 1144                          | 0.795        |
| 1255                          | 0.820        |

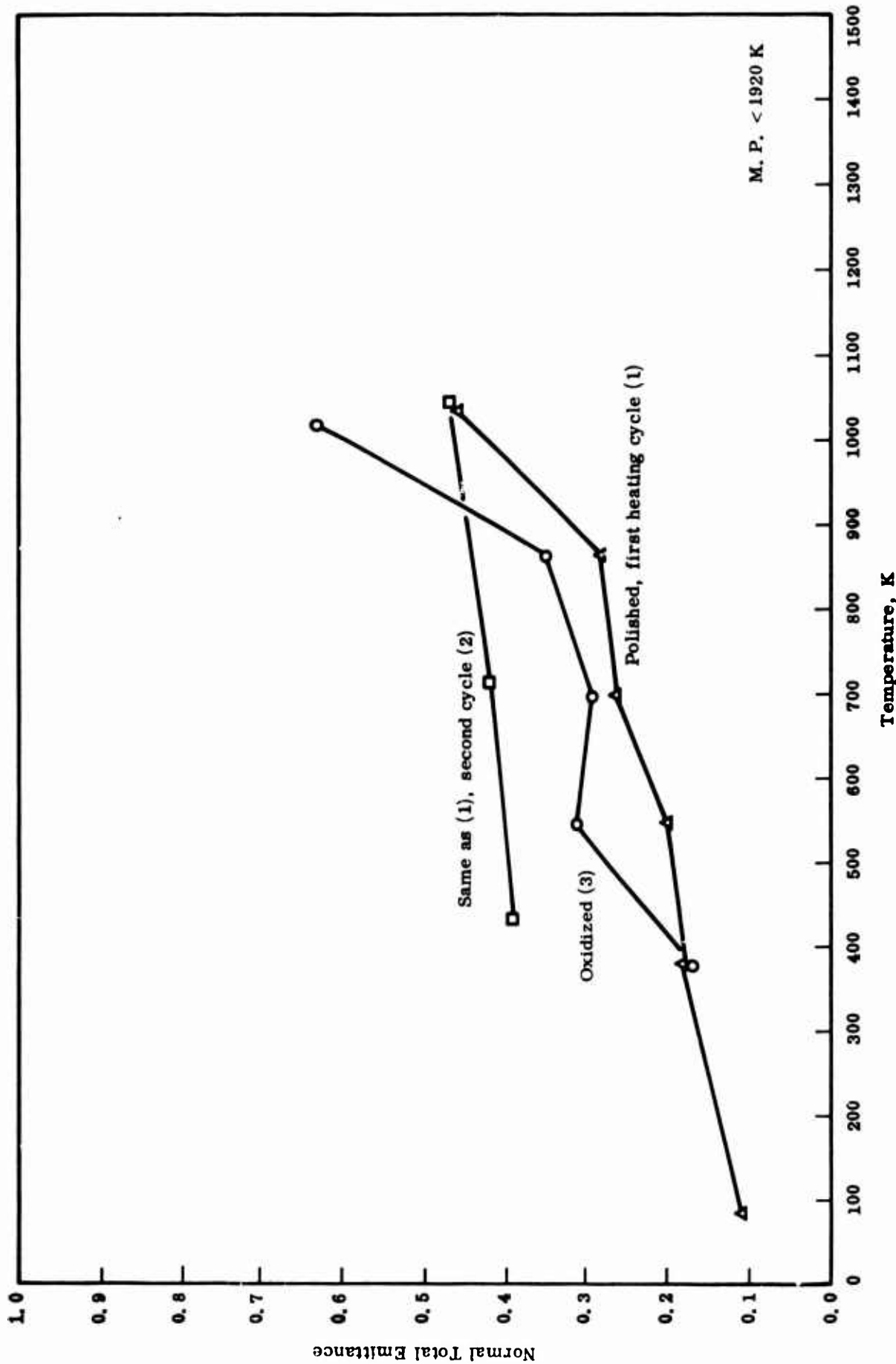


FIG. III-15 NORMAL TOTAL EMITTANCE -- TITANIUM ALLOY A-110AT

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       | 29-1033        |                | 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    | T (K) | ε    |
|----------------|------|-------|------|
| <u>CURVE 1</u> |      |       |      |
| 89             | 0.11 | 380   | 0.17 |
| 380            | 0.18 | 547   | 0.31 |
| 539            | 0.20 | 700   | 0.29 |
| 700            | 0.26 | 867   | 0.35 |
| 867            | 0.28 | 1019  | 0.63 |
| 1033           | 0.46 |       |      |
| <u>CURVE 2</u> |      |       |      |
| 436            | 0.39 |       |      |
| 714            | 0.42 |       |      |
| 1047           | 0.47 |       |      |
| <u>CURVE 3</u> |      |       |      |

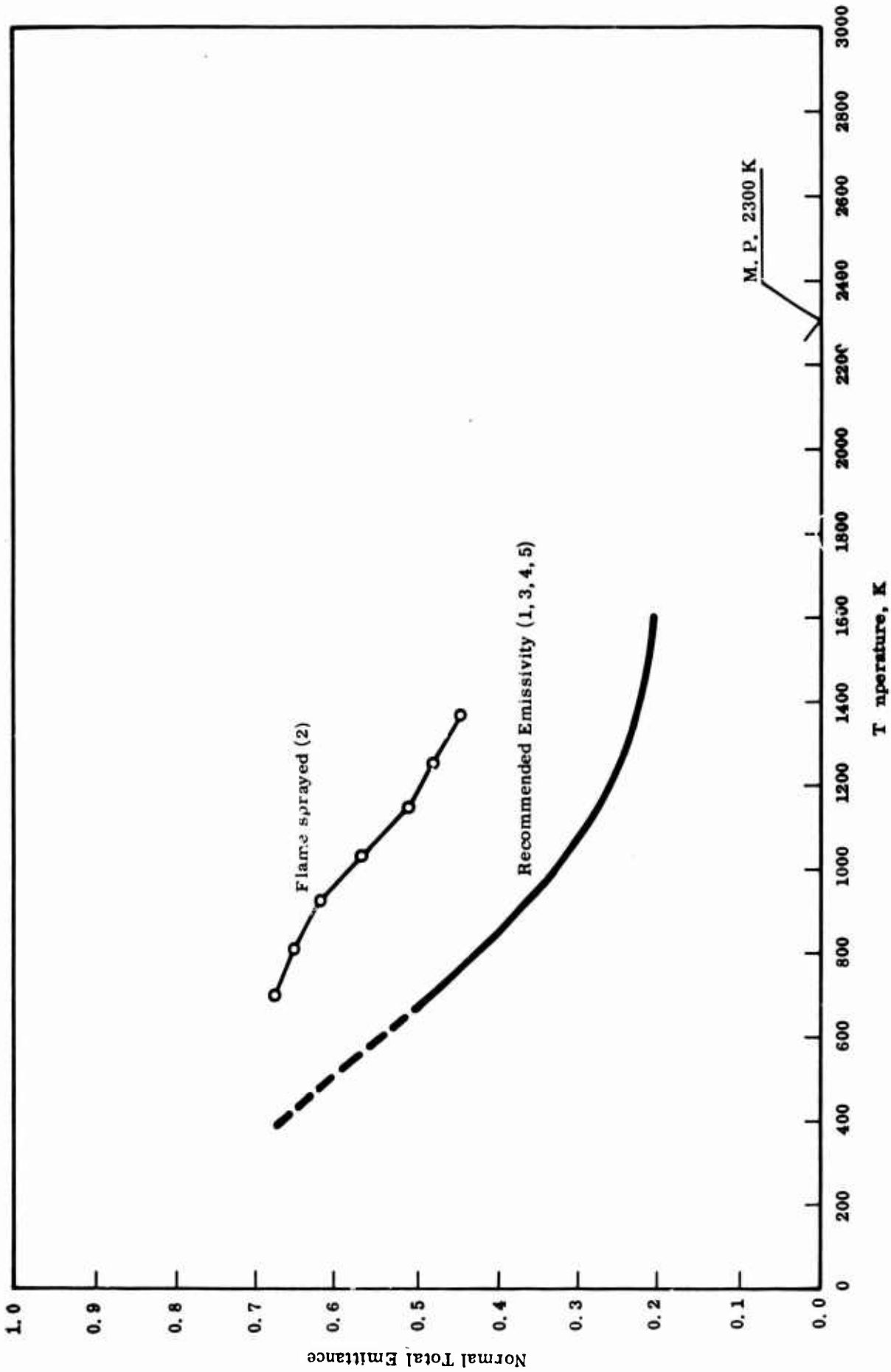


FIG. III-16 NORMAL TOTAL EMITTANCE -- ALUMINUM OXIDE

**TABLE III-20 NORMAL TOTAL EMITTANCE -- ALUMINUM OXIDE  
 SPECIFICATION AND DATA TABLES**

| Curve No. | Rei. 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 <sup>-5</sup> torr) and in air.   |
| 5*        | 34       | 1200-1600      | ±0.02          | 99 <sup>+</sup> Al <sub>2</sub> O <sub>3</sub> , 0.1 SiO <sub>2</sub> , 0.07 CaO, 0.4 FeO; sintered 27 hrs at 1865 K; 30% porosity; computed from spectral emittance measurements. |

| T (K)                         | €            | T (K)          | €    | T (K)           | €     | T (K) | €    |
|-------------------------------|--------------|----------------|------|-----------------|-------|-------|------|
| <u>RECOMMENDED EMISSIVITY</u> |              |                |      |                 |       |       |      |
| 400                           | (0.66) ±0.04 | 673            | 0.48 | 1144            | 0.510 | 1200  | 0.26 |
| 600                           | (0.54)       | 773            | 0.41 | 1255            | 0.480 | 1400  | 0.22 |
| 800                           | 0.43         | 873            | 0.39 | 1366            | 0.445 | 1600  | 0.20 |
| 1000                          | 0.33         | 973            | 0.34 | <u>CURVE 3*</u> |       |       |      |
| 1200                          | 0.26         | 1073           | 0.30 |                 |       |       |      |
| 1400                          | 0.22         | <u>CURVE 2</u> |      |                 |       |       |      |
| 1600                          | 0.20         |                |      | 958             | 0.37  |       |      |
|                               |              |                |      | 1158            | 0.37  |       |      |
|                               |              |                |      | <u>CURVE 4*</u> |       |       |      |
|                               |              |                |      | 1200            | 0.32  |       |      |

\* Not shown on figure

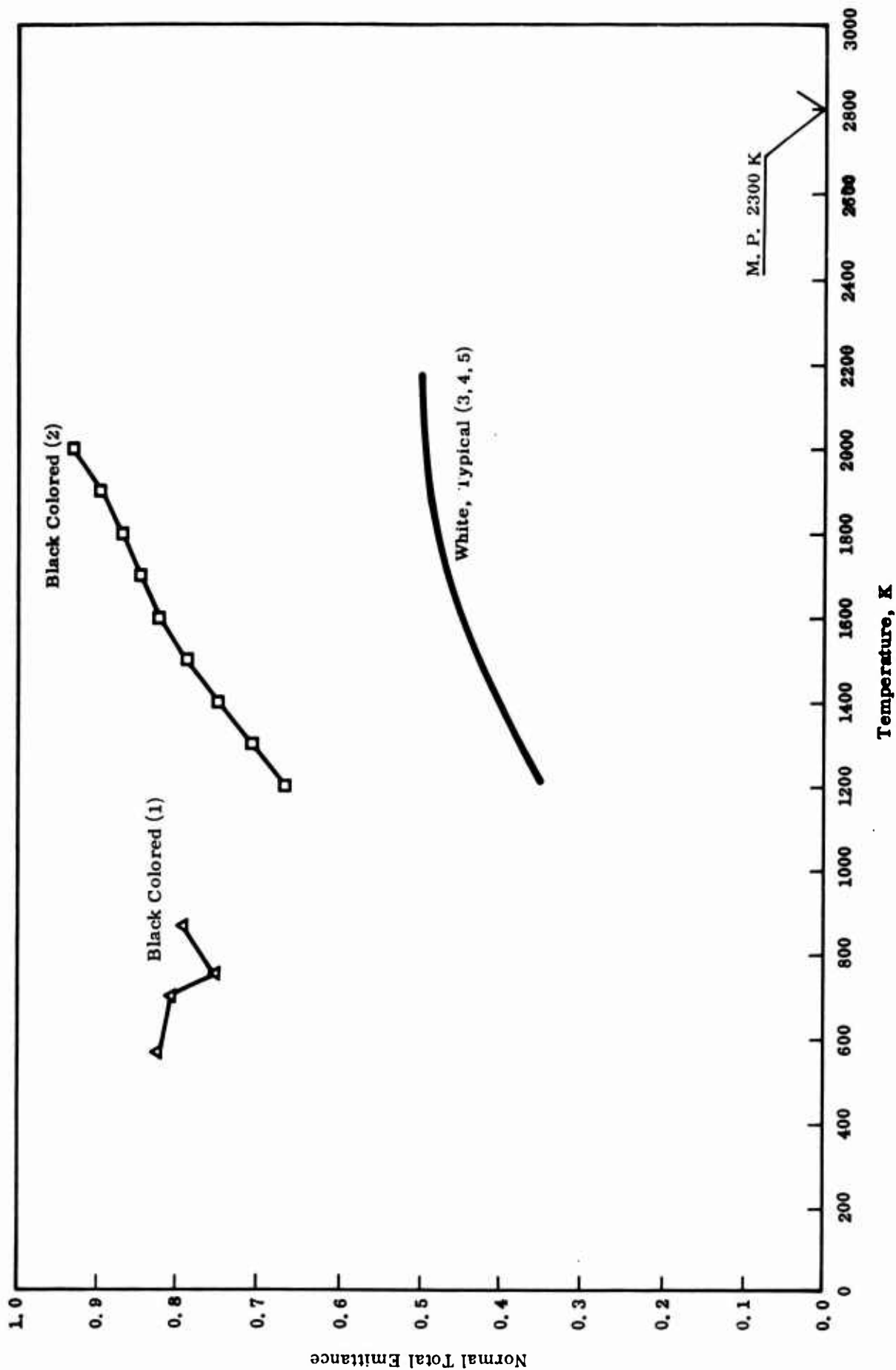


FIG. III-17 NORMAL TOTAL EMITTANCE -- BERYLLIUM OXIDE

**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 $2.85 \text{ gm cm}^{-3}$ ; black colored; measured in vacuum. |
| 3*        | 36       | 1200-2150      | 20                | Same as above; fabricated by hot-pressing Brush S. P. powdered beryllia; density $2.844 \text{ gm cm}^{-3}$ ; white colored.                              |
| 4*        | 36       | 1200-2150      | 20                | Same as No. 3; fabricated as in 3, annealed by ceramic firing; density $2.778 \text{ gm cm}^{-3}$ ; white colored.  |
| 5*        | 37       | 1223           | $\pm 8$           | Sintered at 1973 K for 2 hrs; measured in argon atmosphere.   |

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\* Not shown on figure

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

| T (K)                 | ε          | T (K)           | ε     |
|-----------------------|------------|-----------------|-------|
| <u>WHITE, TYPICAL</u> |            |                 |       |
| 1200                  | 0.35 ±0.02 | 1200            | 0.351 |
| 1400                  | 0.40       | 1300            | 0.383 |
| 1600                  | 0.445      | 1400            | 0.405 |
| 1800                  | 0.48       | 1500            | 0.425 |
| 2000                  | 0.495      | 1600            | 0.447 |
| 2200                  | 0.50       | 1700            | 0.474 |
|                       |            | 1800            | 0.499 |
|                       |            | 1900            | 0.513 |
|                       |            | 2000            | 0.517 |
|                       |            | 2100            | 0.514 |
|                       |            | 2150            | 0.509 |
|                       |            | <u>CURVE 1</u>  |       |
| 561                   | 0.82       |                 |       |
| 700                   | 0.805      |                 |       |
| 755                   | 0.80       |                 |       |
| 867                   | 0.79       |                 |       |
|                       |            | <u>CURVE 2</u>  |       |
| 1200                  | 0.665      | 1200            | 0.336 |
| 1300                  | 0.706      | 1300            | 0.361 |
| 1400                  | 0.746      | 1400            | 0.392 |
| 1500                  | 0.785      | 1500            | 0.420 |
| 1600                  | 0.819      | 1600            | 0.439 |
| 1700                  | 0.843      | 1700            | 0.453 |
| 1800                  | 0.867      | 1800            | 0.463 |
| 1900                  | 0.894      | 1900            | 0.470 |
| 2000                  | 0.931      | 2000            | 0.474 |
|                       |            | 2100            | 0.475 |
|                       |            | 2150            | 0.475 |
|                       |            | <u>CURVE 3*</u> |       |
|                       |            | 1223            | 0.34  |
|                       |            | <u>CURVE 4*</u> |       |
|                       |            | <u>CURVE 5*</u> |       |

\* Not shown on figure

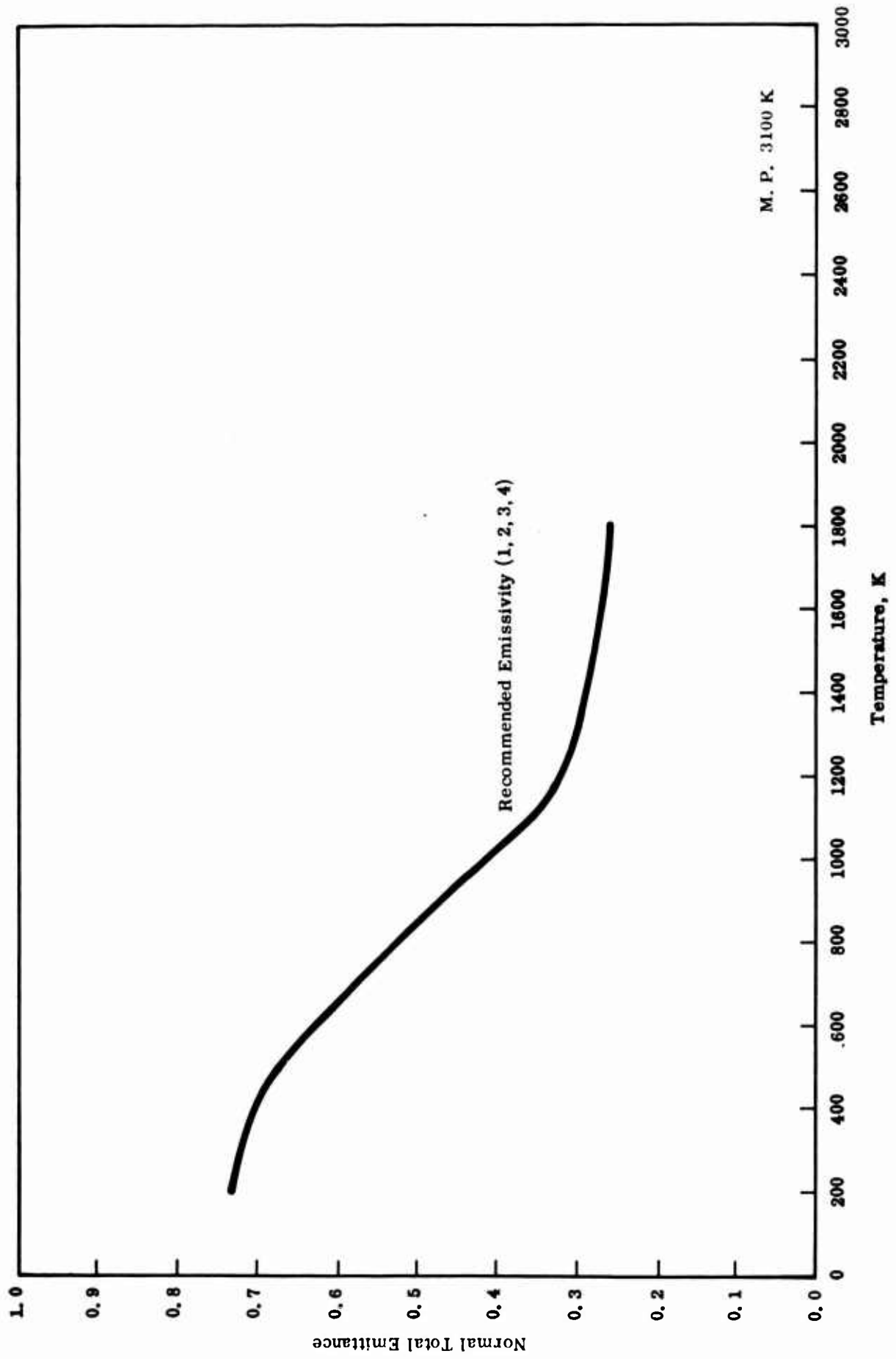


FIG. III-18 NORMAL TOTAL EMITTANCE -- MAGNESIUM OXIDE

**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 nimonoc 75 strip; prepared from super pure Mg.  |
| 4*        | 34       | 1200-1600      | ±0.02          | 99.2 MgO, 0.1 Al <sub>2</sub> O <sub>3</sub> , 0.4 SiO <sub>2</sub> , 0.1 CaO, 0.1 Fe <sub>2</sub> O <sub>3</sub> ; sintered 27 hrs at 1623 K; 30% porosity; computed from spectral emittance measurements. |

| T (K) | ε          | RECOMMENDED EMISSIVITY |       |       |      |
|-------|------------|------------------------|-------|-------|------|
|       |            | T (K)                  | ε     | T (K) | ε    |
| 200   | 0.73 ±0.03 |                        |       |       |      |
| 400   | 0.705      |                        |       |       |      |
| 600   | 0.63       |                        |       |       |      |
| 800   | 0.53       |                        |       |       |      |
| 1000  | 0.41       |                        |       |       |      |
| 1200  | 0.32 ±0.04 |                        |       |       |      |
| 1400  | 0.285      |                        |       |       |      |
| 1600  | 0.27       |                        |       |       |      |
| 1800  | 0.26       |                        |       |       |      |
|       |            | <u>CURVE 1*</u>        |       |       |      |
|       |            | 758                    | 0.700 | 1089  | 0.40 |
|       |            | 378                    | 0.726 | 1255  | 0.36 |
|       |            | 542                    | 0.700 | 1422  | 0.33 |
|       |            | 694                    | 0.555 | 1589  | 0.32 |
|       |            | 866                    | 0.505 | 1755  | 0.31 |
|       |            | 1019                   | 0.490 |       |      |
|       |            | <u>CURVE 2*</u>        |       |       |      |
|       |            | 89                     | 0.74  | 673   | 0.60 |
|       |            | 422                    | 0.70  | 773   | 0.55 |
|       |            | 589                    | 0.63  | 873   | 0.51 |
|       |            | 755                    | 0.55  | 973   | 0.46 |
|       |            | 922                    | 0.47  | 1073  | 0.42 |
|       |            | <u>CURVE 3*</u>        |       |       |      |
|       |            | <u>CURVE 4*</u>        |       |       |      |
|       |            |                        |       | 1200  | 0.26 |
|       |            |                        |       | 1400  | 0.25 |
|       |            |                        |       | 1600  | 0.24 |

\* Not shown on figure

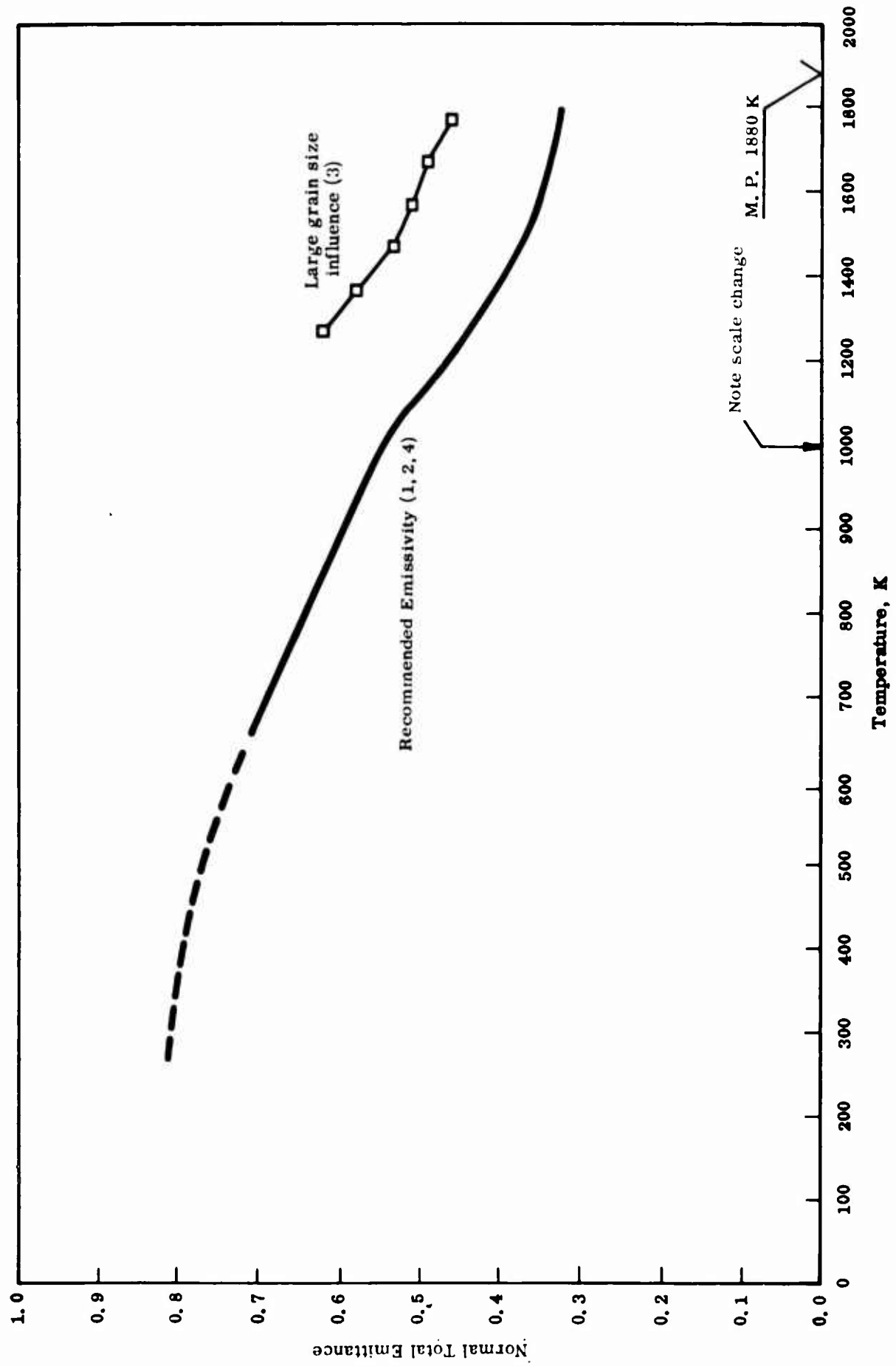


FIG III-19 NORMAL TOTAL EMITTANCE -- SILICON DIOXIDE

**TABLE III-23 NORMAL TOTAL EMITTANCE -- SILICON DIOXIDE  
 SPECIFICATION AND DATA TABLES**

| Curve 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 nimonon 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             | T (K)           | ε    | T (K)          | ε     | T (K)           | ε    |
|-------------------------------|---------------|-----------------|------|----------------|-------|-----------------|------|
| <u>RECOMMENDED EMISSIVITY</u> |               | <u>CURVE 1*</u> |      | <u>CURVE 3</u> |       | <u>CURVE 4*</u> |      |
| 250                           | (0.81) ±0.04  | 673             | 0.69 | 1273           | 0.62  | 1273            | 0.42 |
| 300                           | (0.805)       | 773             | 0.65 | 1373           | 0.58  | 1373            | 0.42 |
| 400                           | (0.79)        | 873             | 0.62 | 1473           | 0.535 | 1473            | 0.41 |
| 500                           | (0.775)       | 973             | 0.57 | 1573           | 0.51  | 1573            | 0.35 |
| 600                           | (0.73)        | 1073            | 0.50 | 1673           | 0.49  | 1673            | 0.34 |
| 700                           | (0.685) ±0.01 | <u>CURVE 2*</u> |      | 1773           | 0.46  | 1773            | 0.33 |
| 800                           | 0.645         |                 |      |                |       |                 |      |
| 900                           | 0.600         |                 |      |                |       |                 |      |
| 1000                          | 0.55          | 1273            | 0.37 |                |       |                 |      |
| 1200                          | 0.465 ±0.03   |                 |      |                |       |                 |      |
| 1400                          | 0.39          |                 |      |                |       |                 |      |
| 1600                          | 0.345         |                 |      |                |       |                 |      |
| 1800                          | 0.315         |                 |      |                |       |                 |      |

\* Not shown on figure

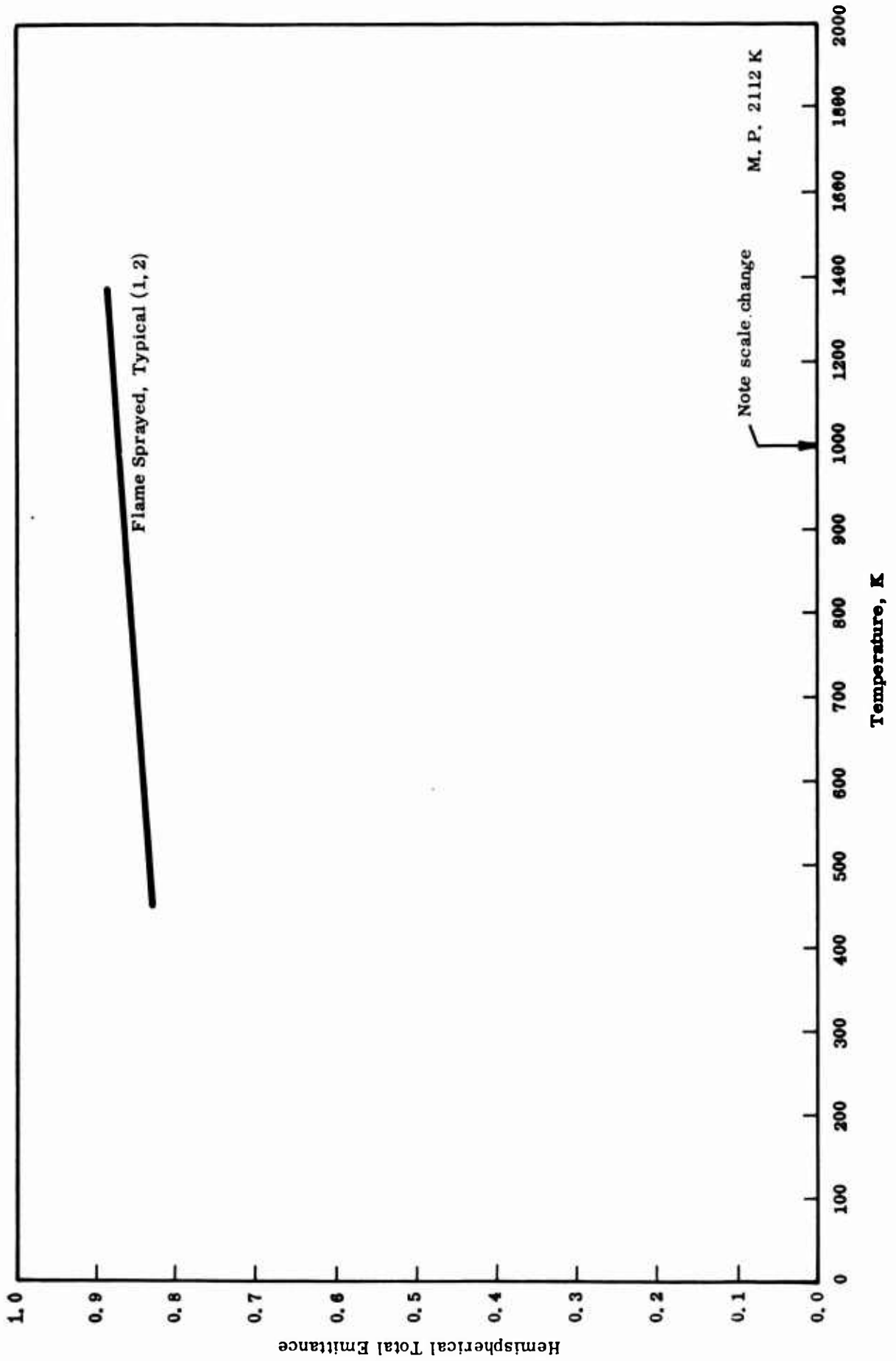


FIG. III-20 HEMISPHERICAL TOTAL EMISSANCE -- TITANIUM DIOXIDE

**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 x 3.4 x 10 <sup>-7</sup> torr); run No. 1A. |
| 2*        | 39       | 1261-649       |                | Same as above; run No. 4B.  |

| T (K)                       | ε            | T (K)           | ε     | T (K)           | ε     |
|-----------------------------|--------------|-----------------|-------|-----------------|-------|
| <u>FLAME SPRAY, TYPICAL</u> |              | <u>CURVE 1*</u> |       | <u>CURVE 2*</u> |       |
| 400                         | 0.825 ± 0.02 | 445             | 0.837 | 1261            | 0.883 |
| 500                         | 0.83         | 493             | 0.844 | 1225            | 0.888 |
| 600                         | 0.84         | 526             | 0.834 | 1187            | 0.897 |
| 700                         | 0.85         | 570             | 0.835 | 1149            | 0.891 |
| 800                         | 0.855        |                 |       | 1121            | 0.875 |
| 900                         | 0.86         |                 |       | 1060            | 0.885 |
| 1000                        | 0.87         |                 |       | 999             | 0.882 |
| 1200                        | 0.88         |                 |       | 999             | 0.882 |
| 1400                        | 0.89         |                 |       | 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) | $\epsilon$ | Reported Error | Specimen Characterization and Remarks  |
|--|-------|------------|----------------|--|
| <u>CHROMIUM OXIDE, Cr<sub>2</sub>O<sub>3</sub></u> |       |            |                |  |
| 40   | 873   | 0.85       |                | Sintered at 2173 K for 2 hrs.  |
|  | 1073  | 0.90       |                |  |
|  | 1273  | 0.80       |                |  |
| <u>CUPRIC OXIDE, CuO</u>                           |       |            |                |  |
| 14   | 406   | 0.759      | 0.7%           | Cu plate with smooth, thick, dark blue oxide layer.  |
| <u>CUPROUS OXIDE, Cu<sub>2</sub>O</u>              |       |            |                |  |
| 41   | 1073  | 0.66       |                | Thin coating on bulk material; computed from total radiation pyrometer measurements.             |
|  | 1173  | 0.60       |                |  |
|  | 1273  | 0.56       |                |  |
|  | 1373  | 0.54       |                |  |
| <u>FERROUS OXIDE, FeO</u>                          |       |            |                |  |
| 42   | 673   | 0.90       |                | Black.   |
| <u>FERRIC OXIDE, Fe<sub>2</sub>O<sub>3</sub></u>   |       |            |                |  |
| 33   | 1200  | 0.67       |                | Sintered 2 hrs at 1273 K<br>Same as above but measured in vacuum, $1 \times 10^{-5}$ torr.       |
| 33   | 1200  | 0.88       |                |  |
| <u>NICKEL OXIDE, NiO</u>                           |       |            |                |  |
| 43   | 873   | 0.53       | $\pm 0.02$     | 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) | $\epsilon$ | Reported Error | Specimen Characterization and Remarks  |
|---|-------|------------|----------------|--|
| <u>NIOBIUM PENTOXIDE, Nb<sub>2</sub>O<sub>5</sub></u> |       |            |                |  |
| 33  | 1200  | 0.36       |                | Sintered 2 hrs at 1573 K.  |
|   | 1200  | 0.52       |                | Same as above but measured in vacuum, $1 \times 10^{-5}$ torr.                                       |
| <u>ZINC OXIDE, ZnO</u>                                |       |            |                |  |
| 44  | 1140  | 0.91       |                | Crystal; measured in vacuum, $1 \times 10^{-4}$ 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 but measured in vacuum, $1.2 \times 10^{-5}$ torr.                                     |

E. BIBLIOGRAPHY

1. Fulk, M. M. , Reynolds, M. M. and Park, O. E. , Advan. Cryog. Eng. , 1, 224-9, 1960, Plenum Press.
2. Carpenter, W. G. D. , and Sewell, J. H. , Royal Aircraft Establishment, Tech. Note CPM 20, AD 418 612, 1963.
3. Carpenter, W. G. D. and Sewell, J. H. , Royal Aircraft Establishment, Rept. No. CHEM. 538, AD 296 648, 1962.
4. Best, G. , J. Opt. Soc. Am. , 39, 1009-11, 1949.
5. Goodman, S. , Natl. Bur. Stds. Report 4239 AD 71 409, 1955.
6. Wade, W. R. , NACA TN 4206, AD 153 191, 1958.
7. Gaumer, Roger E. ; Space/Aeronautics. 36, 60-5, 1961.
8. Merrill, R. , Snoddy, W. and Schocken, K. , NASA TND-1116, 1962.
9. Dunkle, R. V. and Gier, J. T. , Dept. of Engineering, ATI 91560, 1948.
10. Butler, C. P. and Inn, E. C. Y. , USNRDL-TR-327, AD 225 997, 1959.
11. Dorward, J. G. and Reed, D. , UCRL-865, 1949.
12. Birkeback, R. C. , Hartnett, J. P. and Eckert, E. R. G. , Prog. Int. Res. on Measurement of Thermodynamic and Transport Properties, pp. 563-74, 1962.
13. Butler, C. P. , Jenkins, R. J. , Rudkin, R. L. and Laughridge, F. I. , WADD-TR-60-773, AD 267 310, pp. 229-252, 1961.
14. Schmidt, Von E. , and Eckert, E. , Forsch. Gebiete Ingenieurw. , 6, 175-83, 1935.
15. Cade, C. M. , IRE Transactions on Electron Devices ED-8, pp. 56-69, 1961.
16. Moore, G. E. ; Allison, H. W. , J. Appl. Phys. , 12, 431-5, 1941.
17. Parker, W. J. and Abbott, G. L. , Symposium on Thermal Radiation of Solids, NASA SP-55, pp. 11-28, 1965.
18. Wood, W. D. , Deem, H. W. and Lucks, C. F. , DMIC Memo 141, AD 269 784, 1961.
19. Gordon, H. R. and Muchnik, G. F. , High Temp. , 2, 505-7, 1964.
20. Michels, W. C. and Wilford, S. , J. Appl. Phys. , 20, 1223-6, 1949.
21. Cairns, J. H. , J. Sci. Instrum. , 37, 84-7, 1960.
22. Gaumer, R. E. and McKellar, L. A. , LMSD Technical Rept. , 704 014, AD 264 127, 1961.

23. Wilkes, G. B. , ATI 117 901, 1950. .
24. Snyder, N. W. , Gier, J. T. , and Dunkle, R. V. , ASME Transactions, 77, 1011-1019, 1955.
25. Hastings, E. C. , Jr. , Turner, R. E. and Speegle, K. C. , NASA TN D-1001, 1962.
26. Pears, C. D. , Prog. Intern. Research on Measurement of Thermodynamic and Transport Properties, pp. 588-98, 1962.
27. Wade, W. R. , NASA MEMO 1-20-59L, AD 209 192, 1959.
28. Dobbins, J. P. , North American Aviation Report No. NA-49-238, 1949.
29. O'Sullivan, W. J. , Jr. , and Wade, W. R. , NASA TR R-90, 1961.
30. Olson, O. H. and Morris, J. C. , WADC TR 56-222 (Pt. 2, Suppl. 1), AD 202 494, 1958.
31. Sully, A. H. , Brandes, E. A. and Waterhouse, R. B. , Brit. J. Appl. Phys. , 3, 97-101, 1952.
32. Gannon, R. E. and Linder, B. , Amer. Ceram. Soc. , 47, 592-3, 1964.
33. Schatz, E. A. , Counts, III, C. R. , Alvarz, G. H. and Hopcke, M. A. , ML-TDR-64-146 (Pt. 2), AD 468 576, 1965.
34. Unpublished NBS Data, by private communication, D. G. Moore.
35. Olson, O. H. and Morris, J. C. , WADC TR 56-222 (Pt. 3), AD 239 302, 1959.
36. Seifert, R. L. , Phys. Rev. , 73, 1181-7, 1948.
37. Schatz, E. A. , Goldberg, D. M. , Pearson, E. G. , and Burks, T. L. , ASD-TDR-63-657 (Pt. 1), AD 423 743, 1963.
38. Michaud, M. , Silicates Ind. , 19, 243-50, 1954.
39. Pratt and Whitney Aircraft Div. , PWA-1877 NASA N62-10783, 1960.
40. Schatz, E. A. , Counts, III, C. R. , and Burks, T. L. , ML TDR 64-146, AD 442 286, 1964.
41. Burgess, G. K. , Natl. Bur. Stds. Bull, 6, 111-9, 1909.
42. Stevenson, J. A. and Grafton, J. C. , ASD TR-61-119 (Pt. 1), AD 271 917, 1961.
43. Burgess, G. K. and Foote, P. D. , Natl. Bur. Stds. Bull, 11, 41-64, 1915.
44. Mollino, E. , Z. Angew. Phys. , 6, 257-60, 1954.
45. Jakob, M. , Heat Transfer, Volume I, Wiley and Sons, 1949.
46. Edwards, D. K. and Roddick, R. D. , UCLA Dept. of Engineering Rept. 62-27, NSF G9505, 1961.
47. Richmond, J. C. , DeWitt, D. P. and Hayes, W. D. , ML TDR 64-257, AD 612 812, 1965.

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

CHAPTER IV  
THERMAL DIFFUSIVITY

BY

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M. NALBANTYAN

## 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  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{Mn}_3\text{O}_4$ ,  $\text{NiO}$ ,  $\text{SnO}_2$ ,  $\text{TiO}_2$ , and  $\text{ZnO}$ . 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  $\pm 5$  percent at room and moderate temperatures and within  $\pm 10$  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.    | Curie 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                           |
| $\alpha$ | thermal diffusivity                        |
| $\rho_0$ | residual electrical resistivity            |

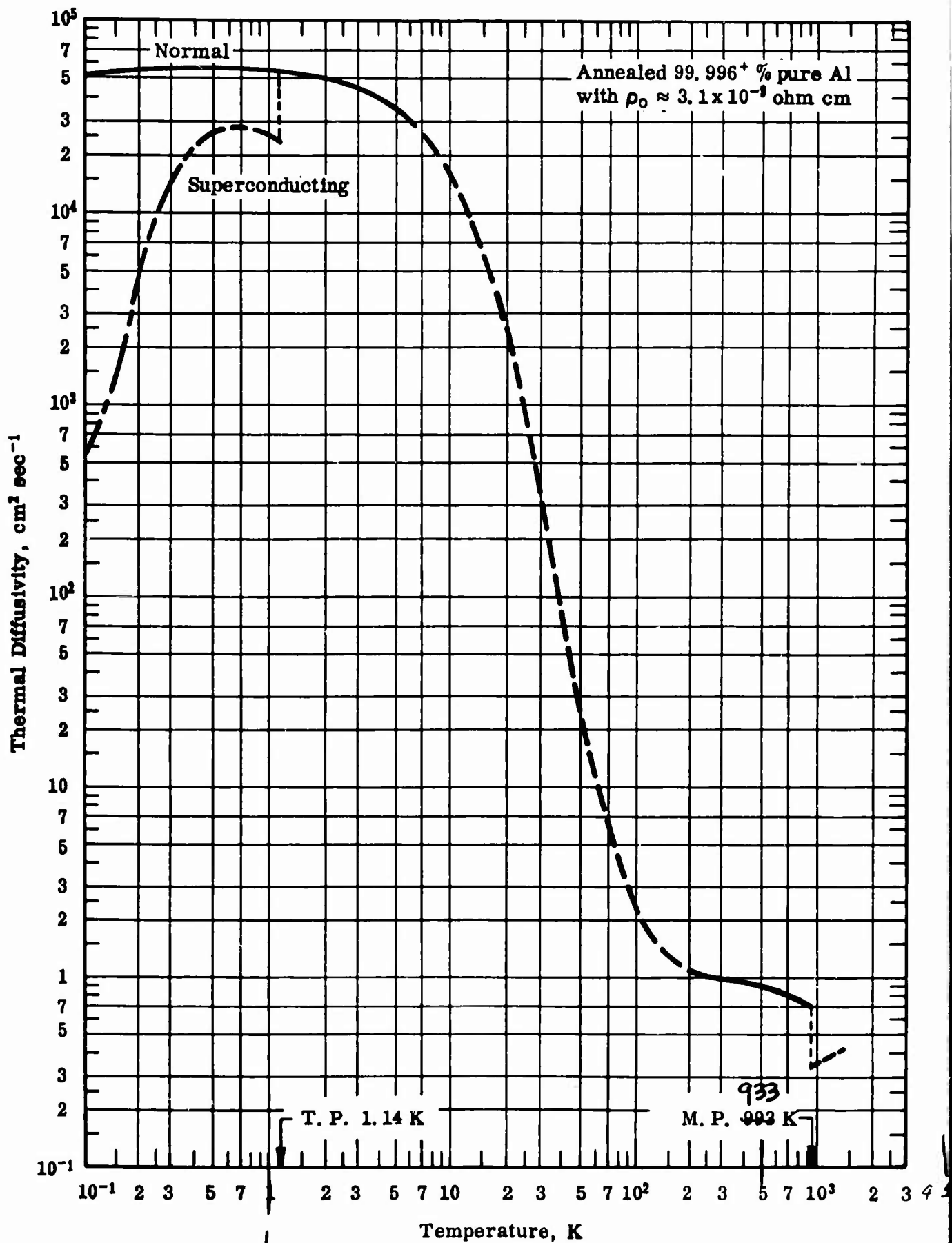


FIG. IV-1 THERMAL DIFFUSIVITY OF ALUMINUM

**TABLE IV-1 THERMAL DIFFUSIVITY OF ALUMINUM**

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

| T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |                 | T, K      | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
|------|---------------------------------------|-----------------|-----------|---------------------------------------|
|      | 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 aluminum than those measured by these authors.

\* Calculated or estimated.

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

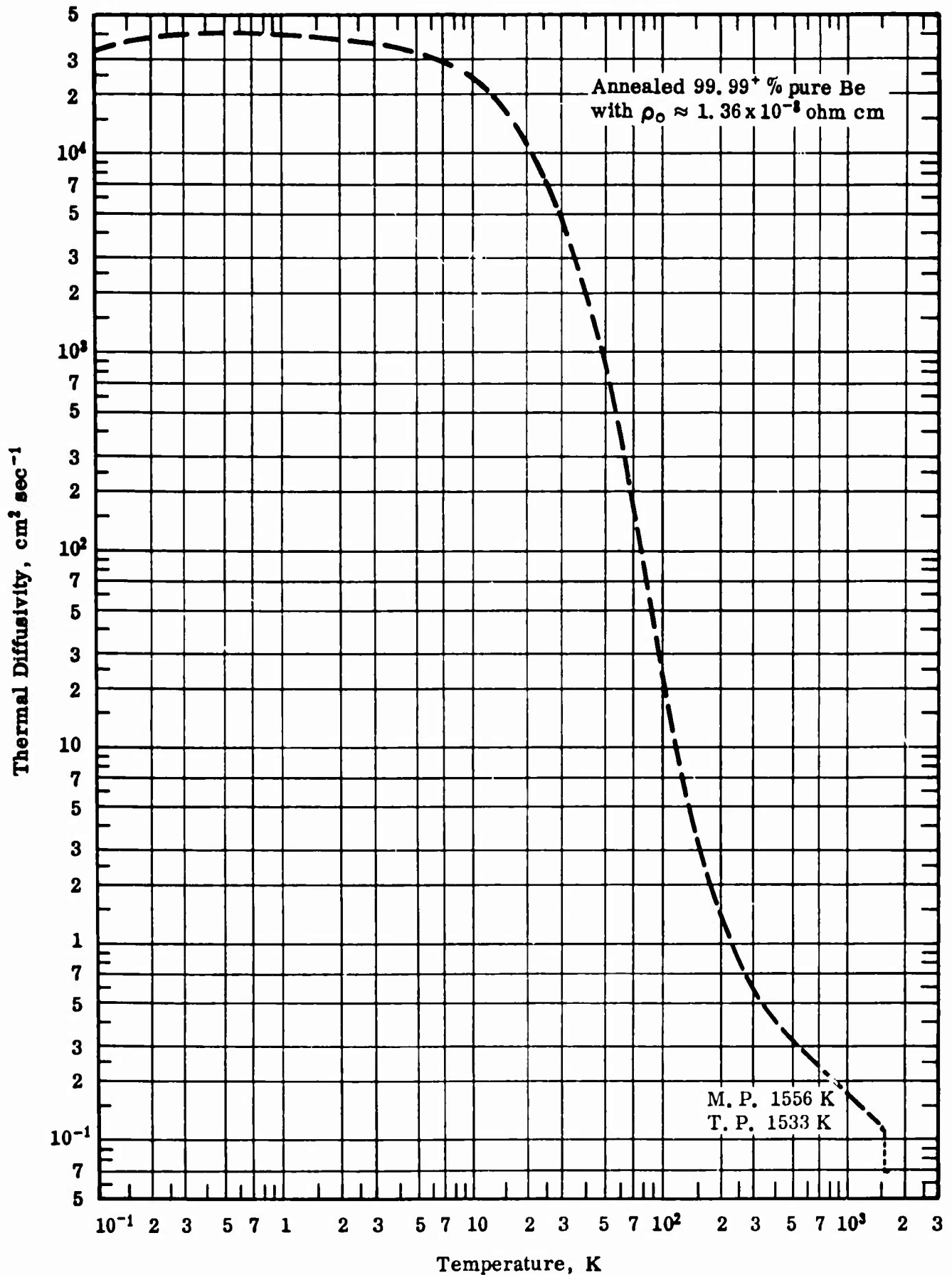


FIG. IV-2 THERMAL DIFFUSIVITY OF BERYLLIUM

**TABLE IV-2 THERMAL DIFFUSIVITY OF BERYLLIUM**

Selected Values for Annealed 99.99% Pure Beryllium with  $\rho_0 \approx 1.36 \times 10^{-8}$  ohm cm\*

| T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | T, K      | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
|------|---------------------------------------|-----------|---------------------------------------|
| 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.

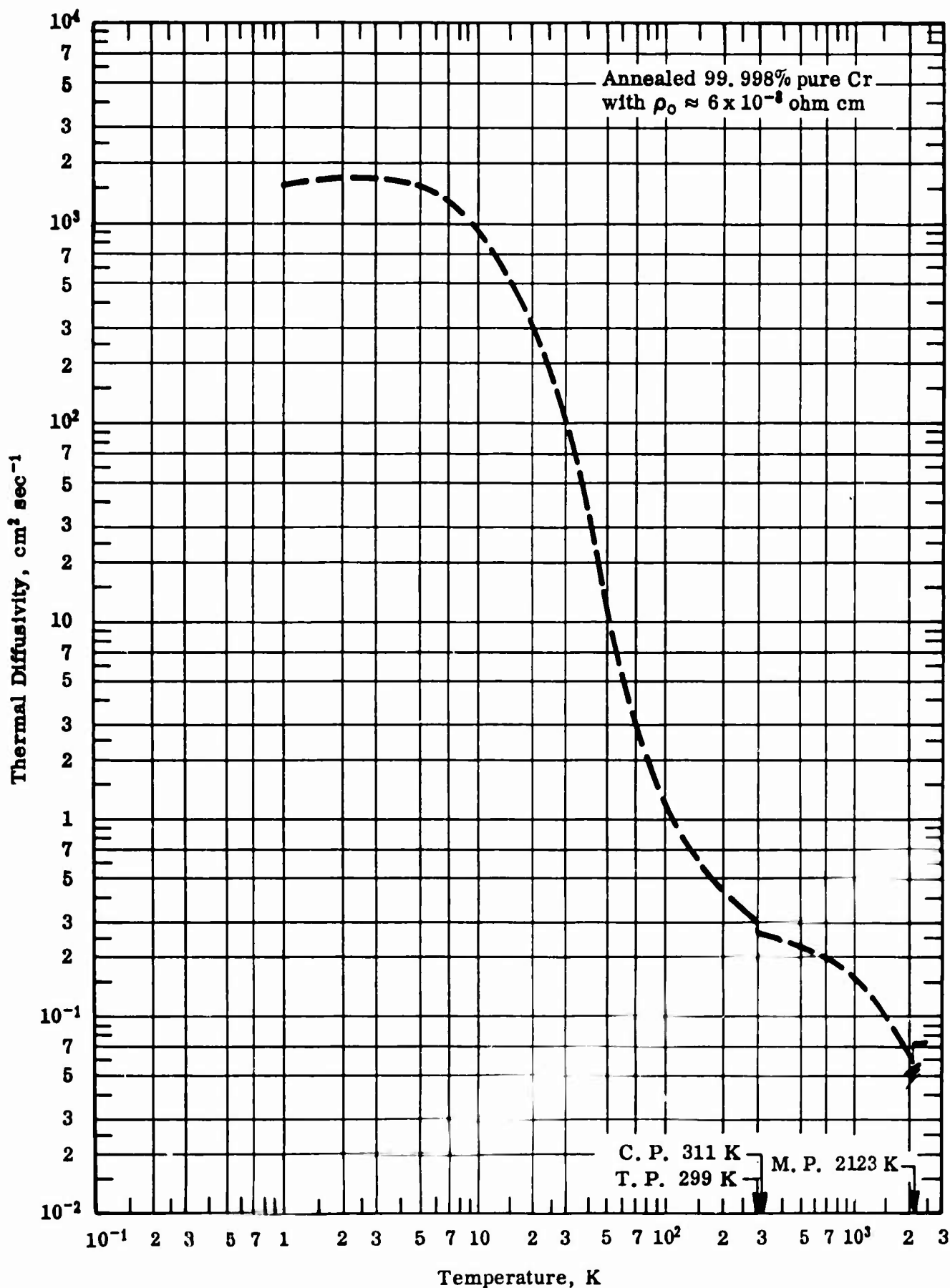


FIG. IV-3 THERMAL DIFFUSIVITY OF CHROMIUM

TABLE IV-3 THERMAL DIFFUSIVITY OF CHROMIUM

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

| T, K      | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K       | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|-----------|--|------------|--|
| 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  |
| (cph) 290 | 0.33   | (bcc) 2100 | 0.060  |
| (bcc) 300 | 0.27   | (l) 2200   | <del>0.054</del> 0.075                       |
| 400       | 0.24   |            |  |

**Data Source and Remarks**

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

\* All values are calculated or estimated.

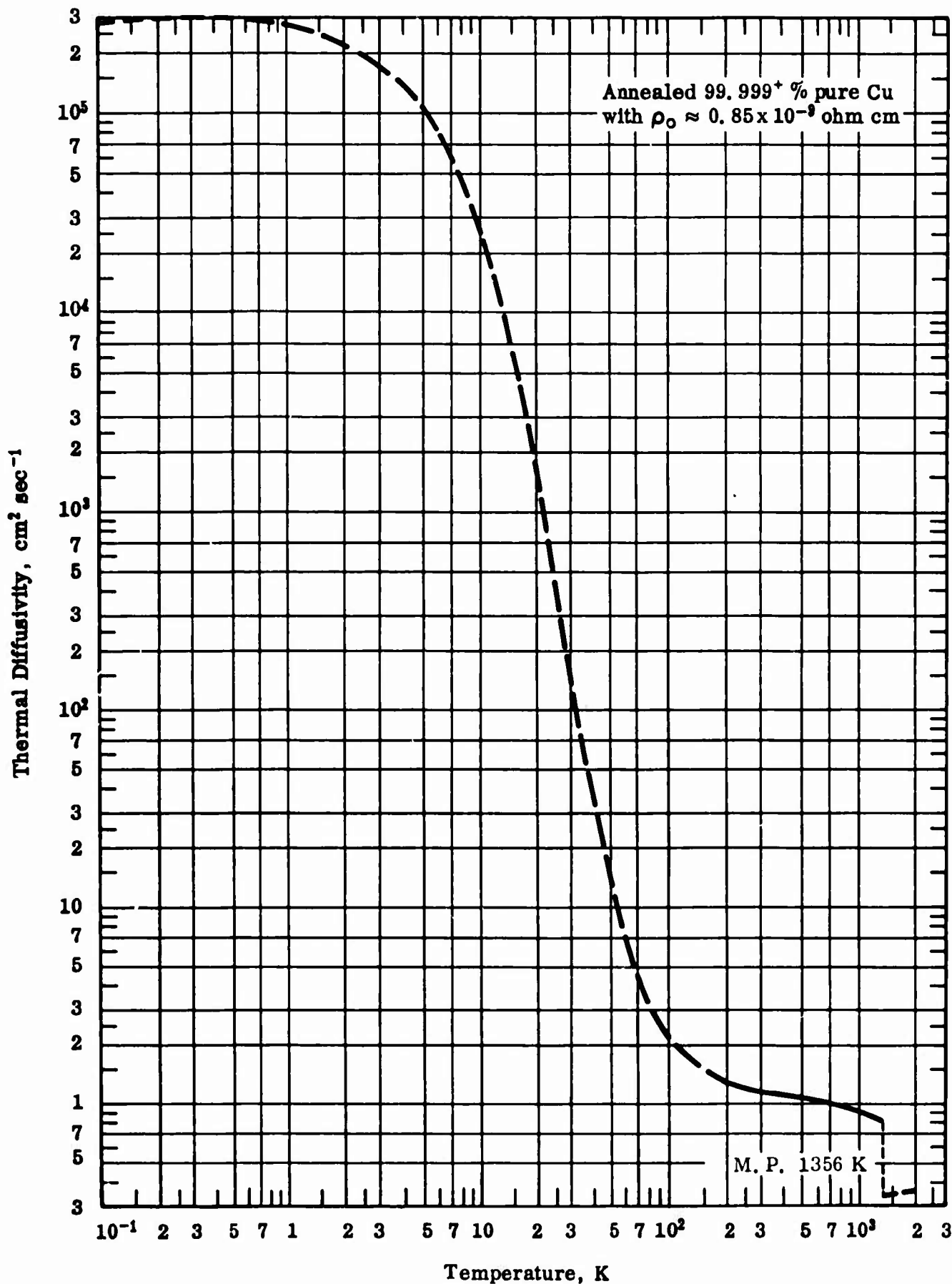


FIG. IV-4 THERMAL DIFFUSIVITY OF COPPER

**TABLE IV-4 THERMAL DIFFUSIVITY OF COPPER**

Selected Values for Annealed 99.999<sup>+</sup> % Pure Copper with  $\rho_0 \approx 0.85 \times 10^{-9}$  ohm cm

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K      | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|-----------|--|
| 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], Mrozowski, Andrew, Juul, 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.

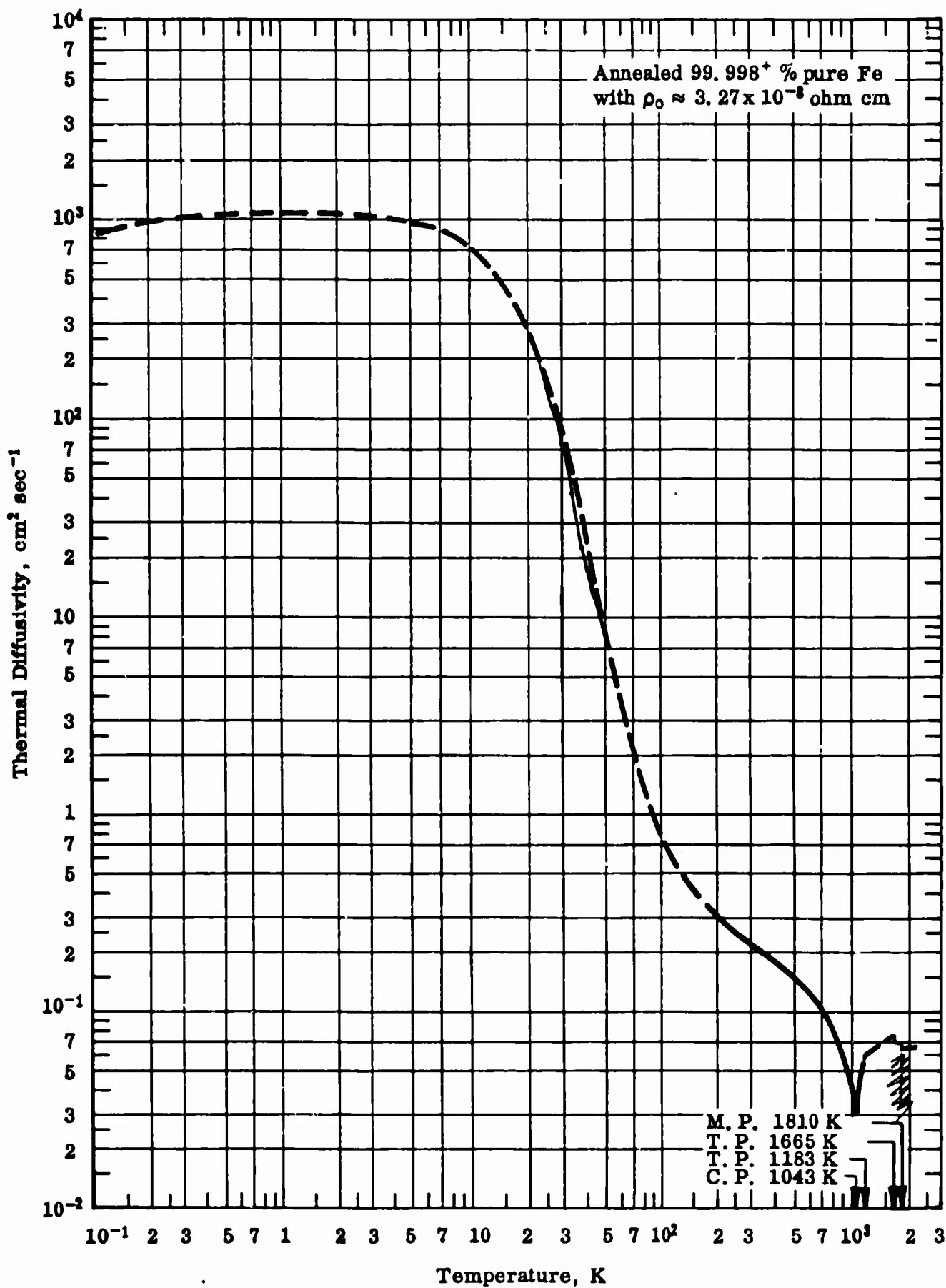


FIG. IV-5 THERMAL DIFFUSIVITY OF IRON

TABLE IV-5 THERMAL DIFFUSIVITY OF IRON

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K                 | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|----------------------|--|
| 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   | <del>58*</del> 42*                           | <del>1053</del> 1059 | 0.037  |
| 40   | 24*  | 1100                 | 0.051  |
| 45   | <del>18*</del> 14*                           | (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  | (1) 1900             | <del>0.085*</del><br>0.065                   |

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.

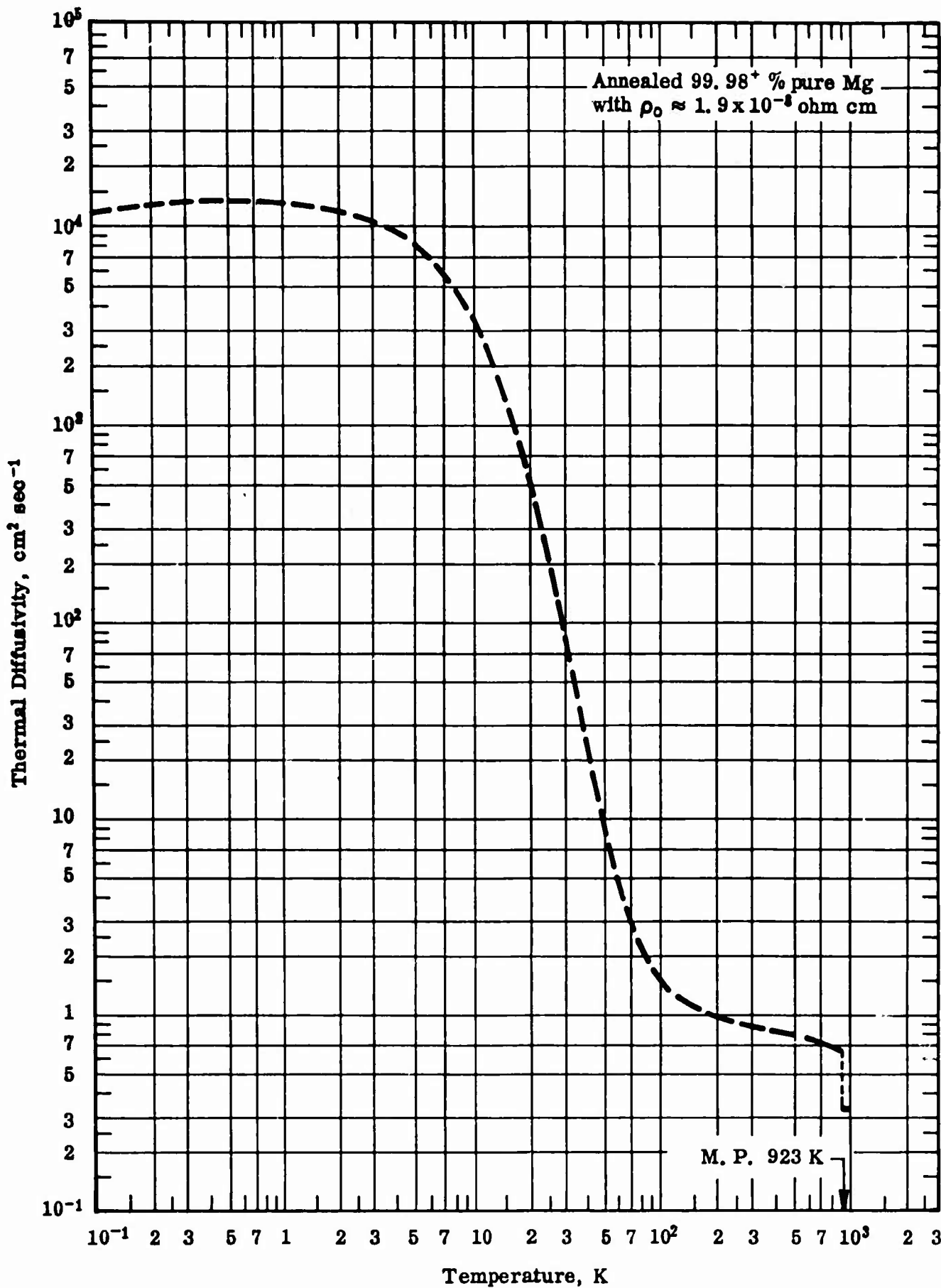


FIG. IV-6 THERMAL DIFFUSIVITY OF MAGNESIUM

**TABLE IV-6 THERMAL DIFFUSIVITY OF MAGNESIUM**

Selected Values for Annealed 99.98<sup>+</sup> % Pure Magnesium with  $\rho_0 \approx 1.9 \times 10^{-8}$  ohm cm \*

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K      | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|-----------|--|
| 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.

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\* All values are calculated or estimated.

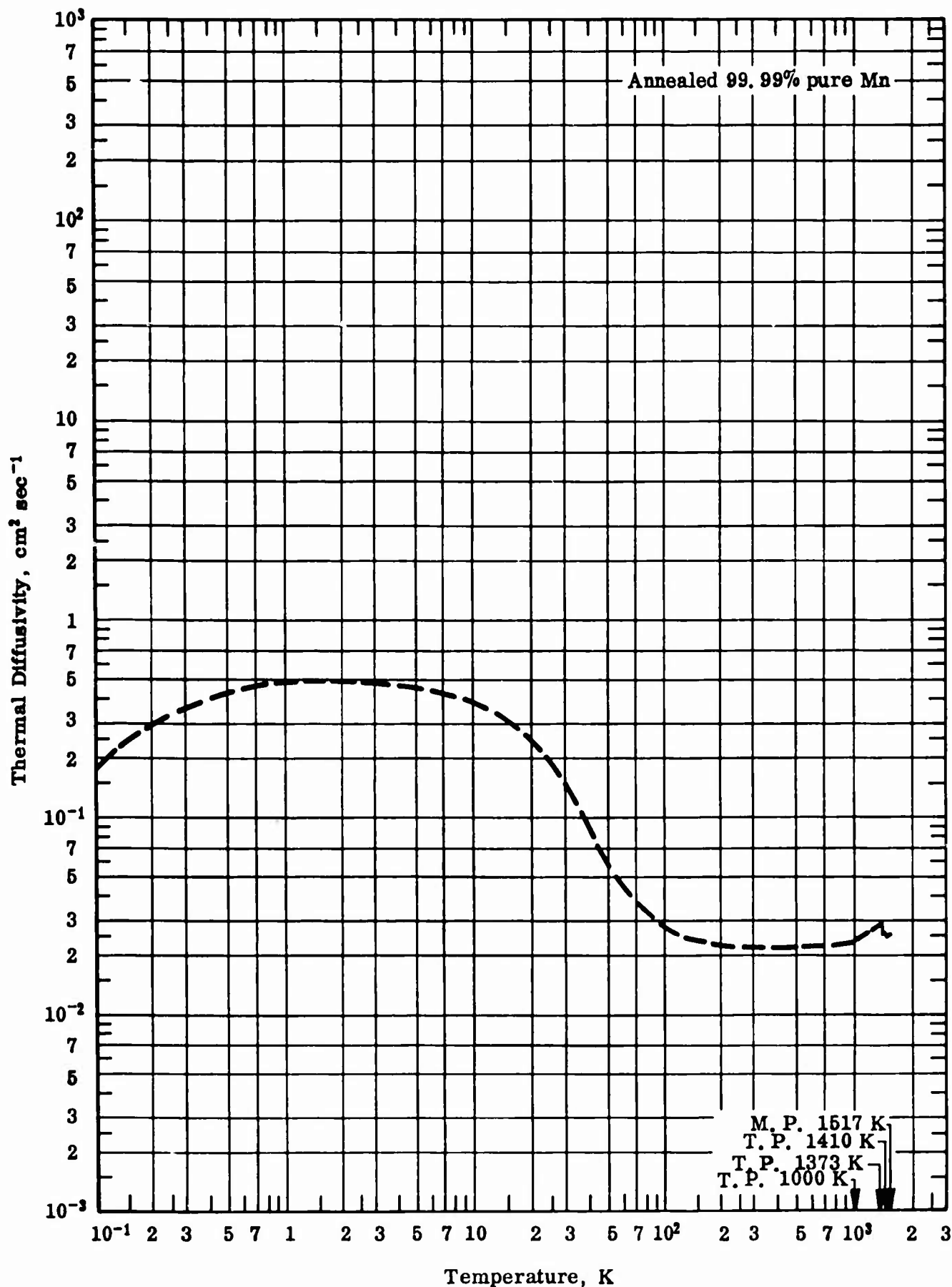


FIG. IV-7 THERMAL DIFFUSIVITY OF MANGANESE

**TABLE IV-7 THERMAL DIFFUSIVITY OF MANGANESE**

Selected Values for Annealed 99.99% Pure Manganese\*

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K       | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------------|--|
| 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.

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\* All values are calculated or estimated.

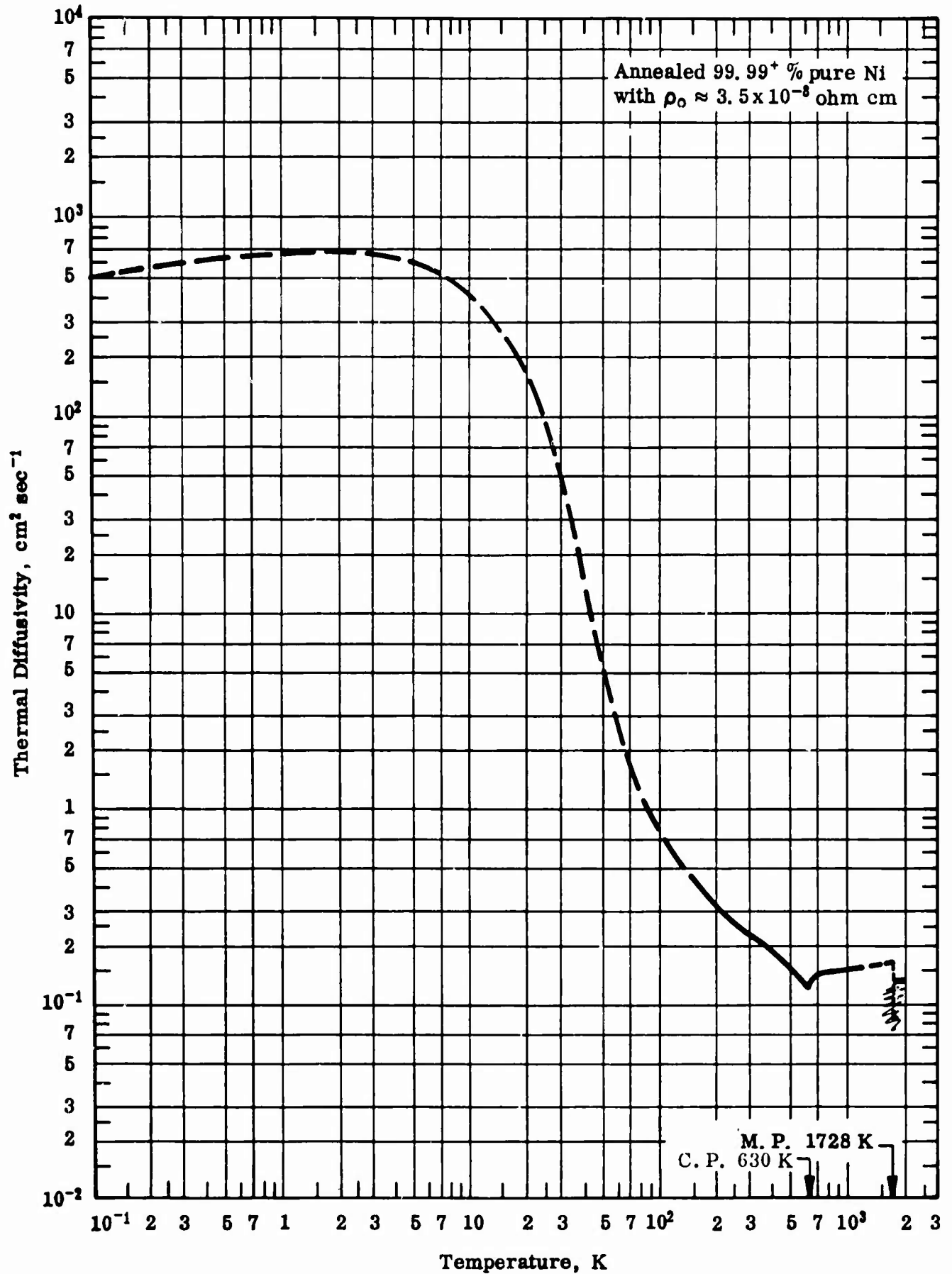


FIG. IV-8 THERMAL DIFFUSIVITY OF NICKEL

TABLE IV-8 THERMAL DIFFUSIVITY OF NICKEL

Selected Values for Annealed 99.99+ % Pure Nickel with  $\rho_0 \approx 3.5 \times 10^{-8}$  ohm cm

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K       | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------------|--|
| 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   | <del>0.084</del> * 0.129*                    |

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 (1960) [6].

\* Calculated or estimated.

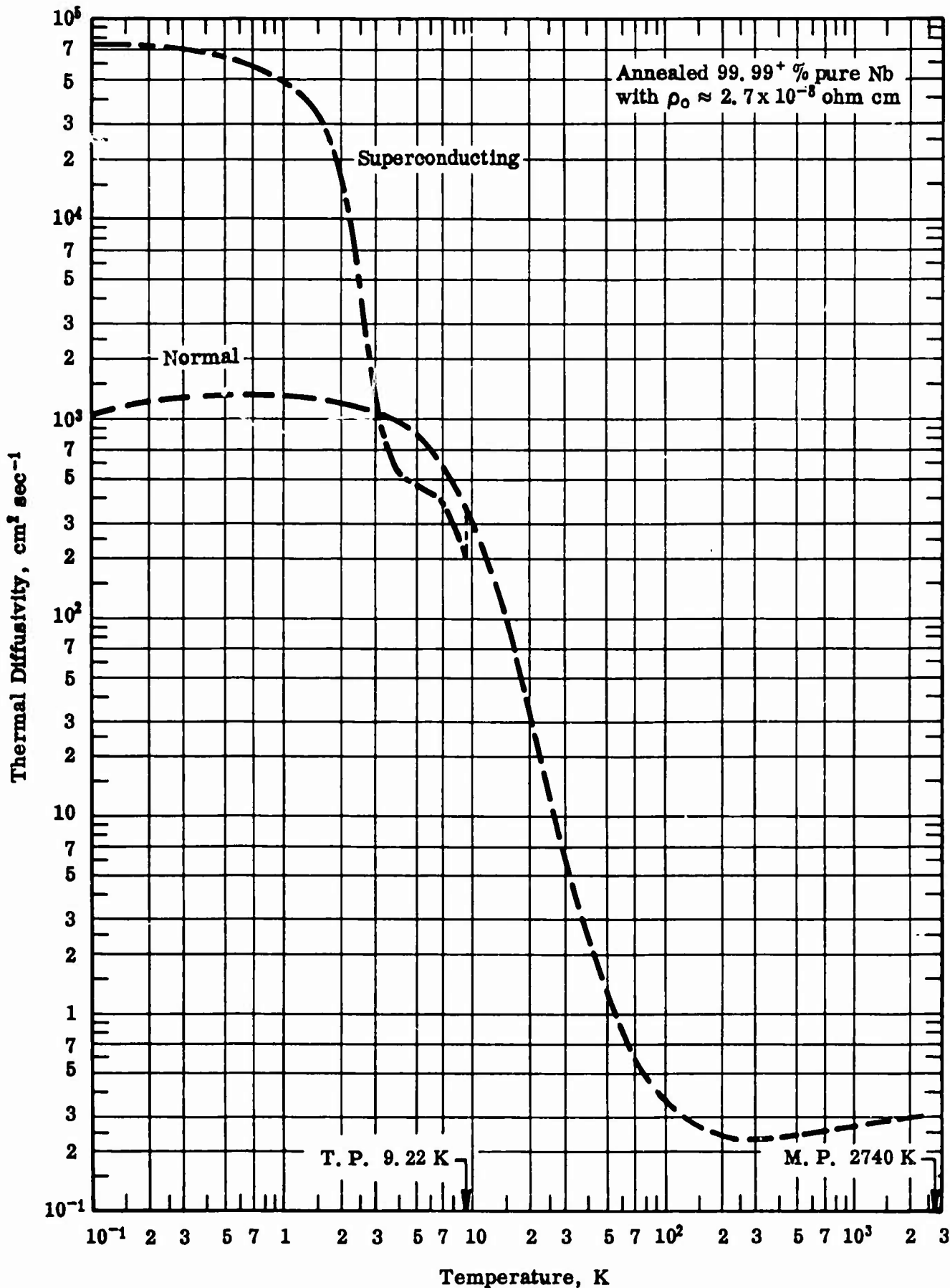


FIG. IV-9 THERMAL DIFFUSIVITY OF NIOBIUM

**TABLE IV-9 THERMAL DIFFUSIVITY OF NIOBIUM**

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |                 | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|-----------------|------|--|
|      | Normal                                       | Superconducting |      |  |
| 0.1  | 1020 <sup>*</sup>                            | 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.

<sup>\*</sup> All values are calculated or estimated.

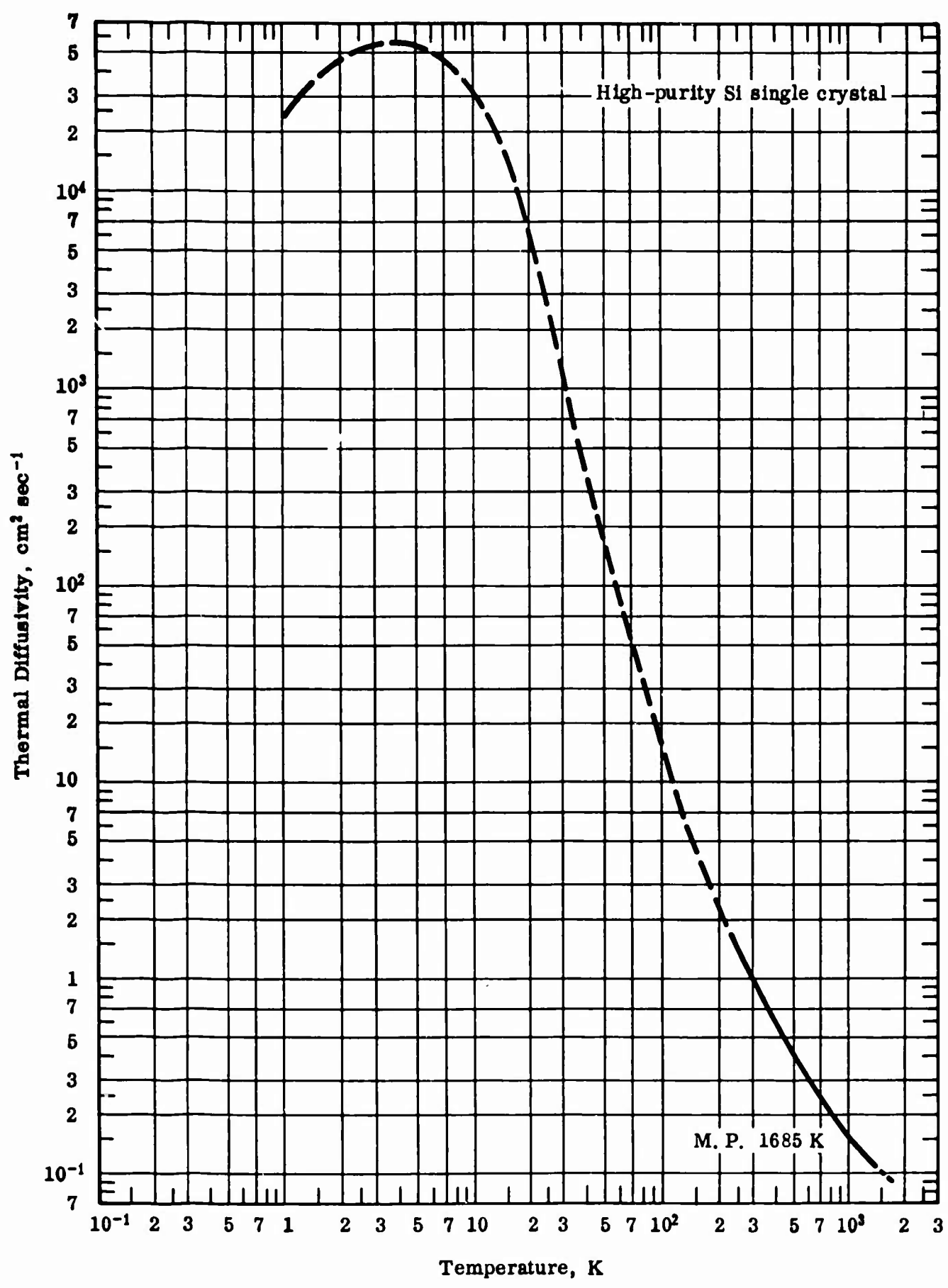


FIG. IV-10 THERMAL DIFFUSIVITY OF SILICON

**TABLE IV-10 THERMAL DIFFUSIVITY OF SILICON**

**Selected Values for High-Purity Silicon Single Crystal**

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 1    | 24000*                                       | 200  | 2.08*  |
| 2    | 46000*                                       | 300  | 0.88   |
| 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].

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\* Calculated or estimated.

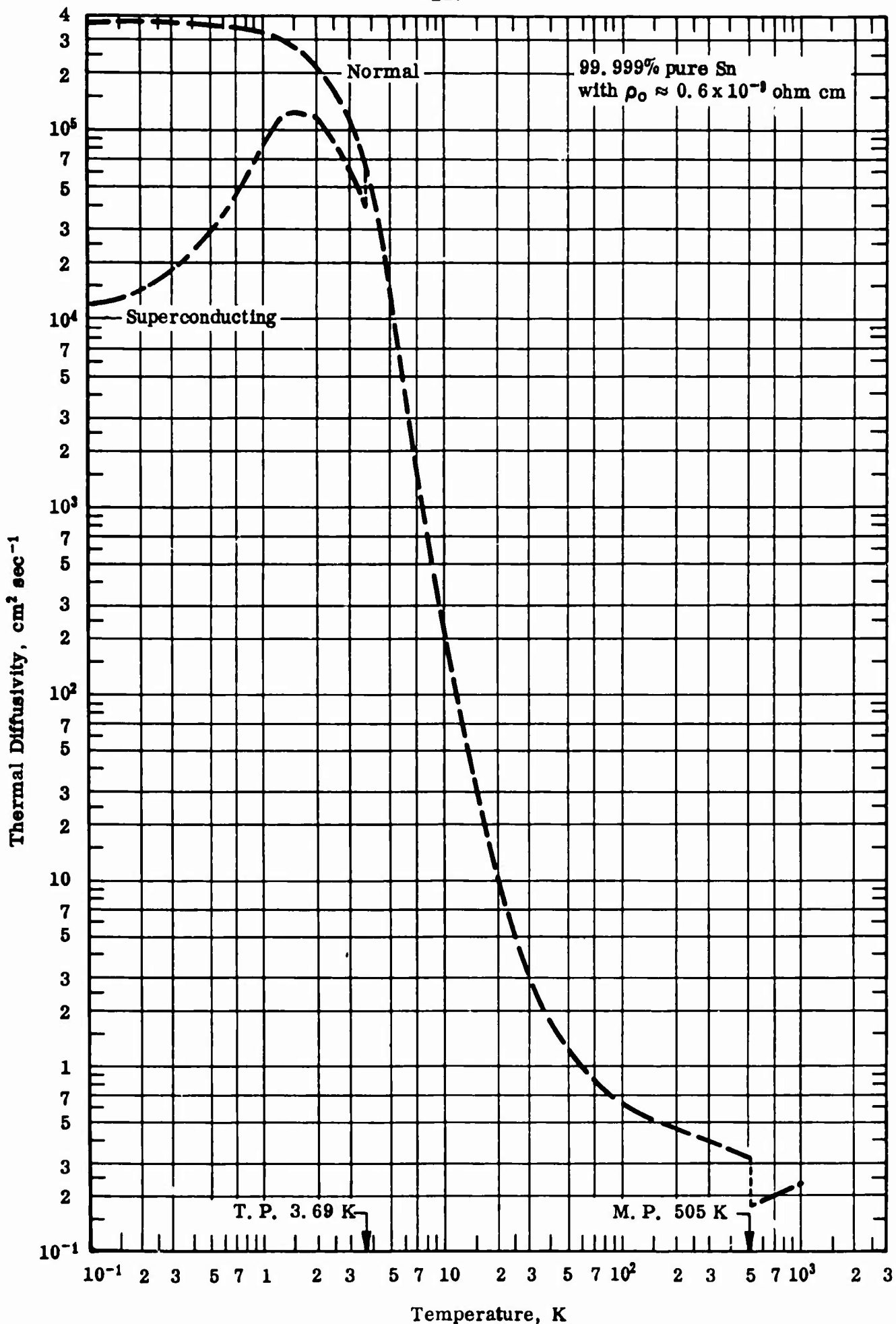


FIG. IV-11 THERMAL DIFFUSIVITY OF TIN

TABLE IV-11 THERMAL DIFFUSIVITY OF TIN

Selected Values for 99.999% Pure Tin with  $\rho_0 \approx 0.6 \times 10^{-9}$  ohm cm\*

| T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |                   | T, K      | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
|------|---------------------------------------|-------------------|-----------|---------------------------------------|
|      | 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.

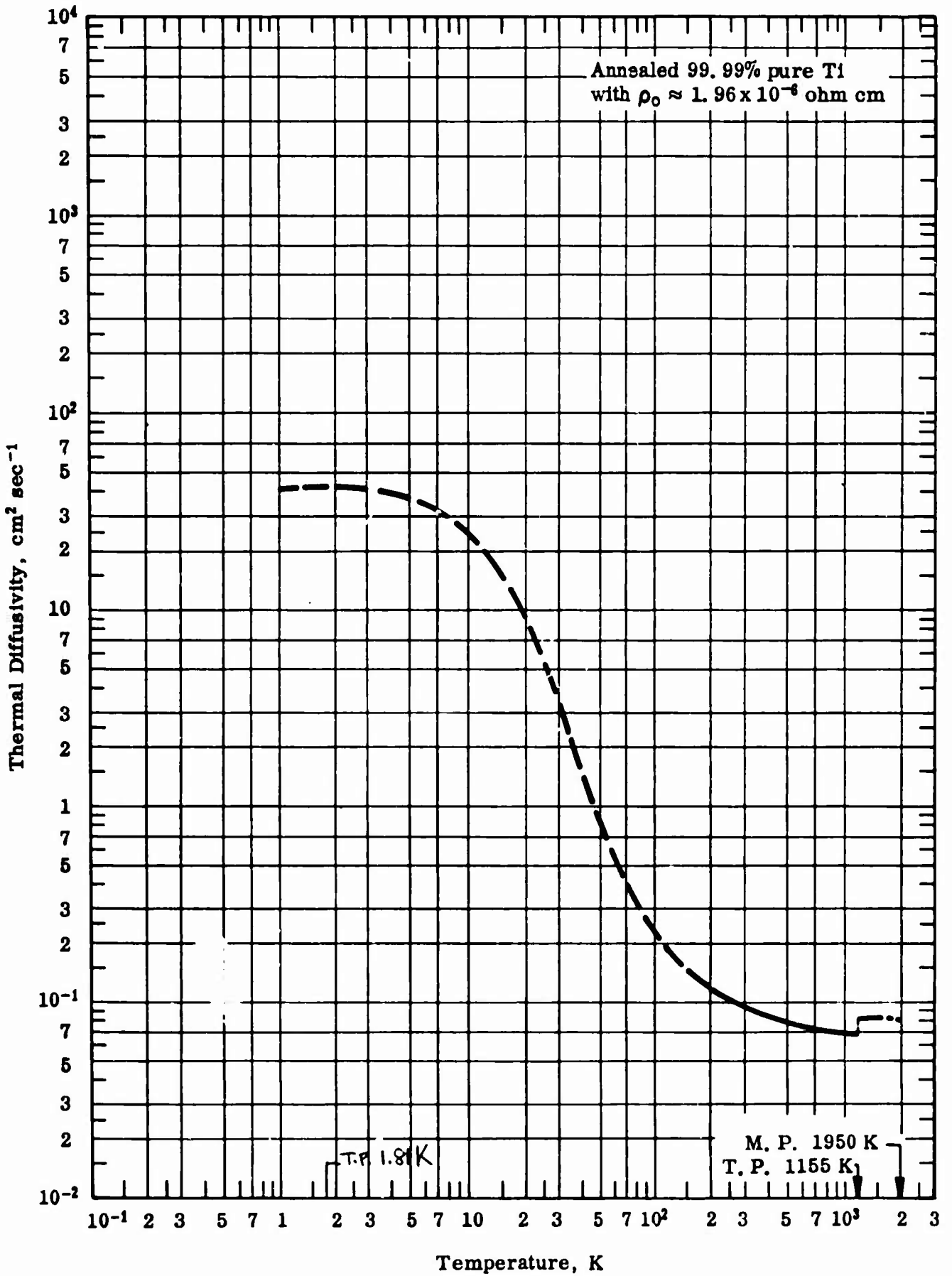


FIG. IV-12 THERMAL DIFFUSIVITY OF TITANIUM

TABLE IV-12 THERMAL DIFFUSIVITY OF TITANIUM

Selected Values for Annealed 99.99% Pure Titanium with  $\rho_0 \approx 1.96 \times 10^{-6}$  ohm cm

| T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | T, K       | $\alpha, \text{cm}^2 \text{Sec}^{-1}$ |
|------|---------------------------------------|------------|---------------------------------------|
| 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.

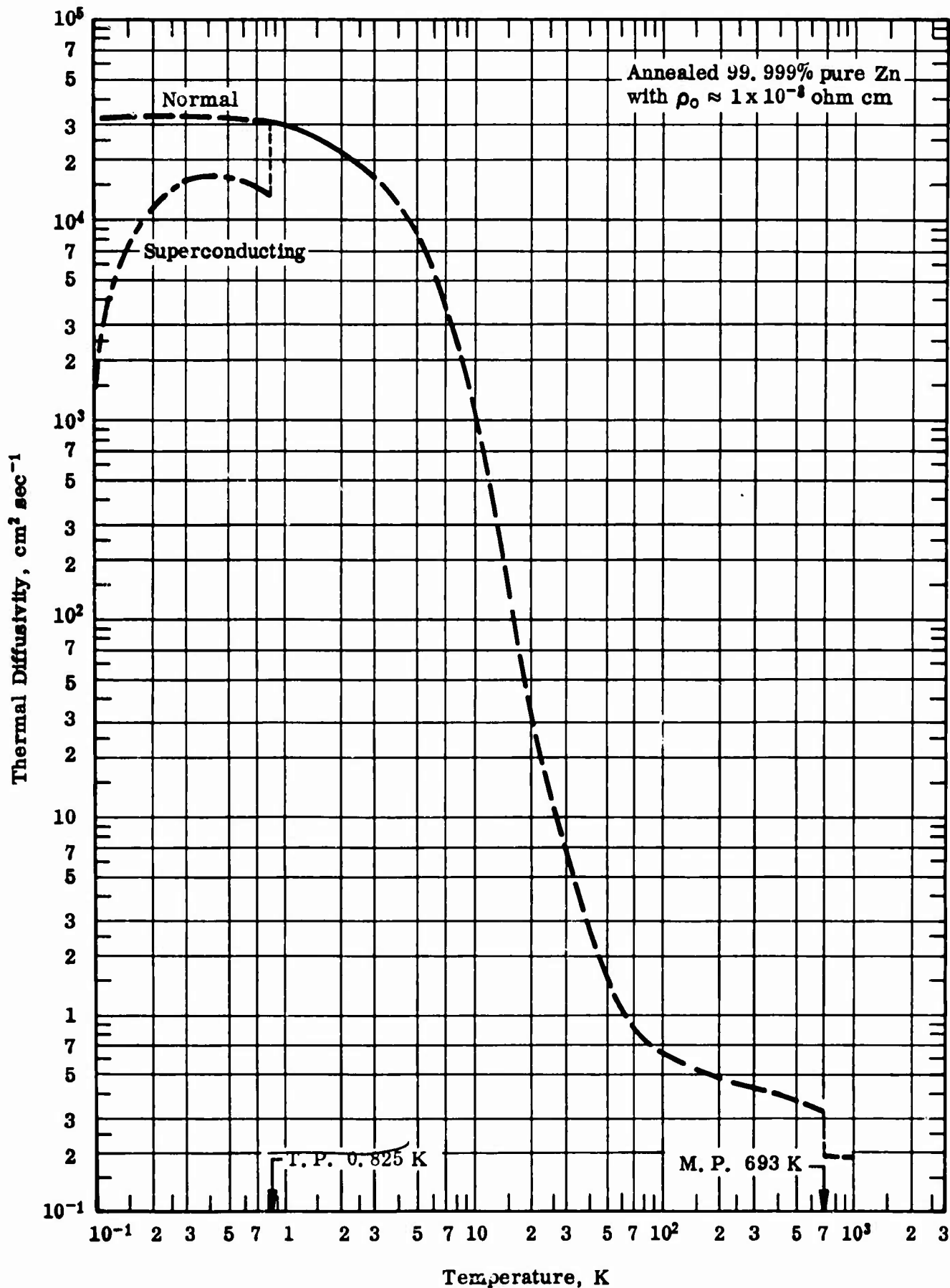


FIG. IV-13 THERMAL DIFFUSIVITY OF ZINC

**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  | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |                 | T, K      | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|-------|--|-----------------|-----------|--|
|       | 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.

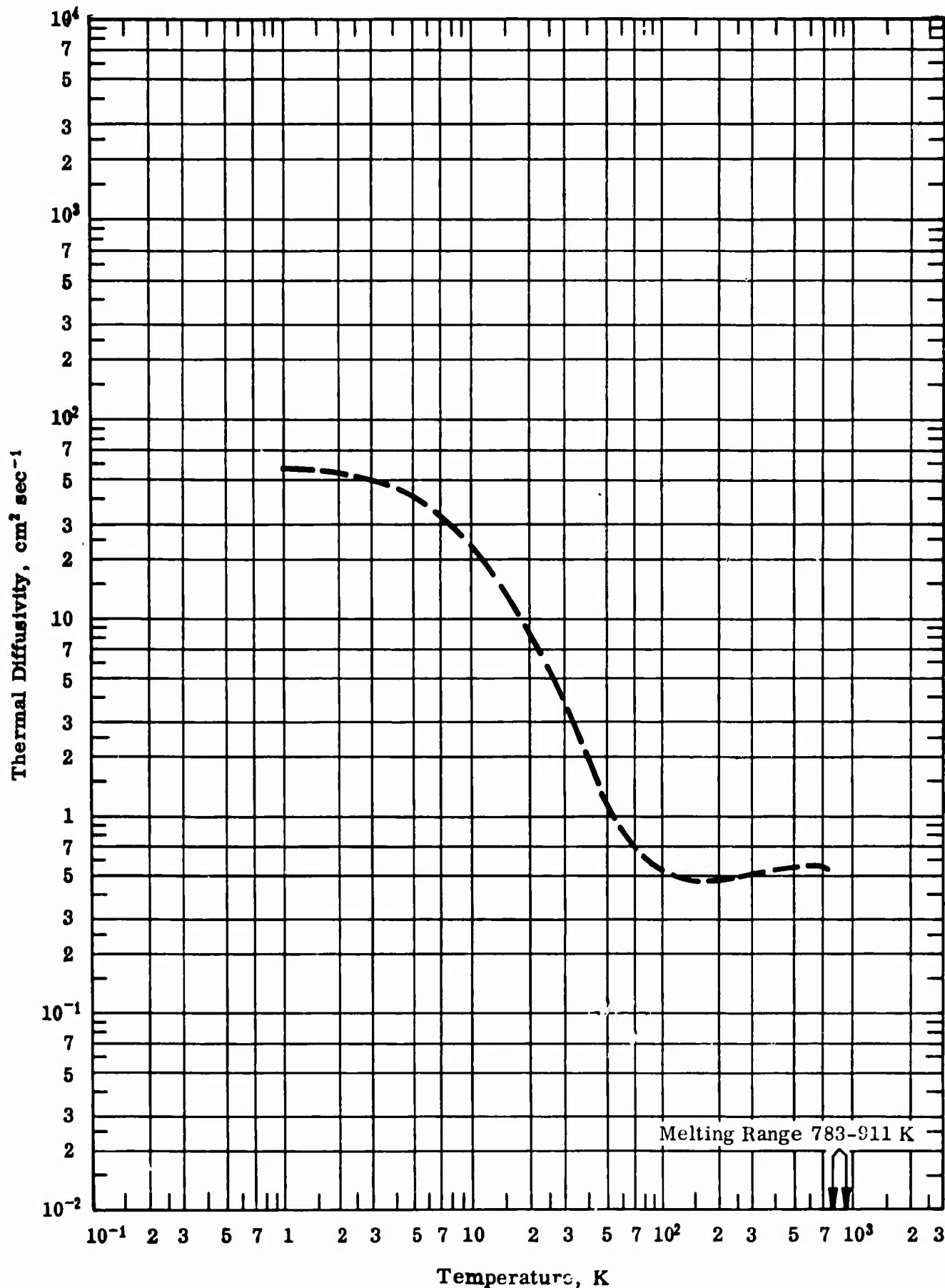


FIG. IV-14 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2219-T852

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|
| 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~~ <sup>diffusivity</sup> will consequently become higher (see Fig. IV-16 for aluminum alloy 7075-T6 for comparison).

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\* All values are calculated or estimated.

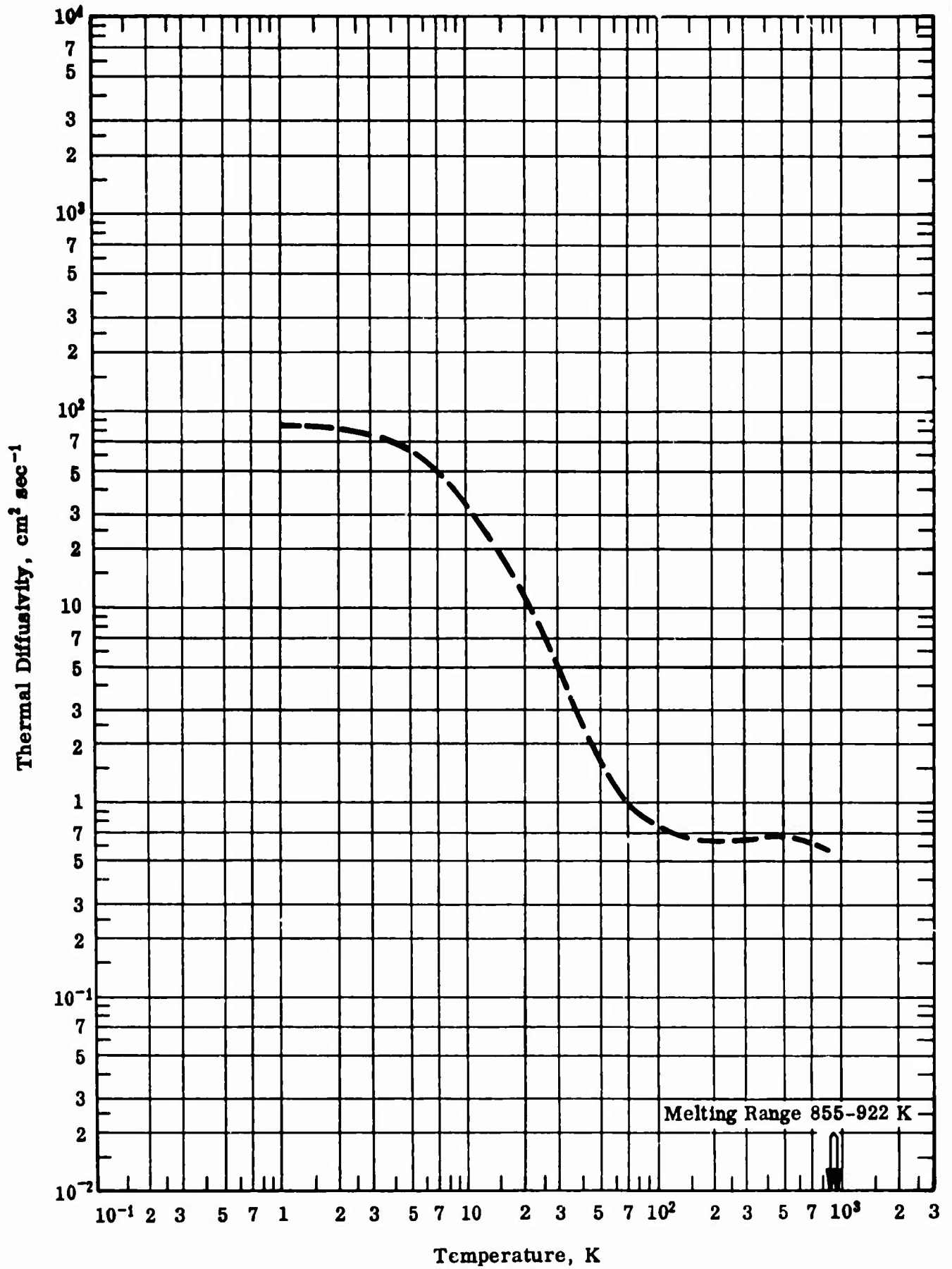


FIG. IV-15 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 6061-T6

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|
| 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~~ <sup>diffusivity</sup> will consequently become higher (see Fig. IV-16 for aluminum alloy 7075-T6 for comparison).

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\* All values calculated or estimated.

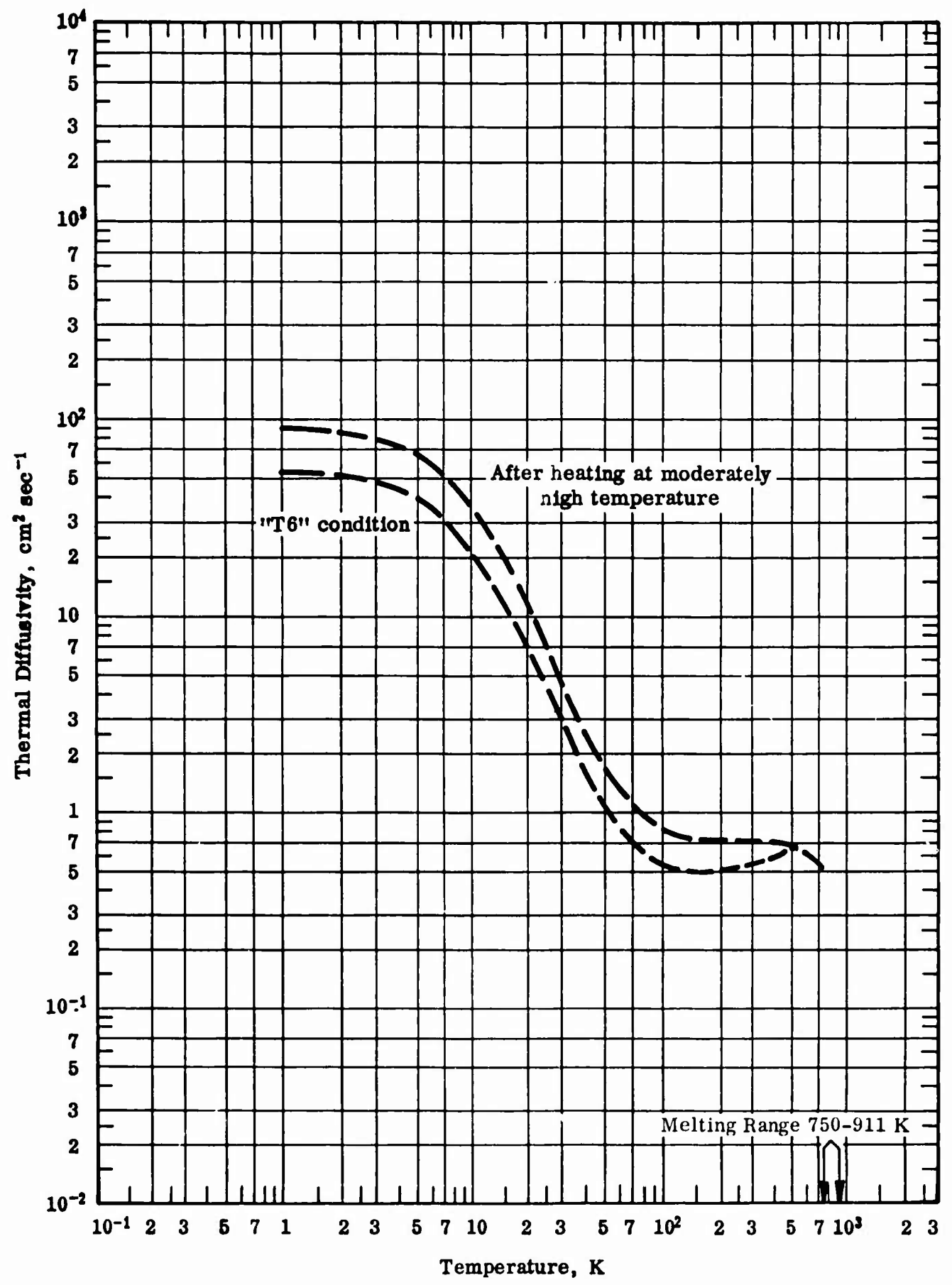


FIG. IV-16 THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 7075-T6

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

| "T6" Condition |                                       | After Heating at Moderately High temperature |                                       |
|----------------|---------------------------------------|--|---------------------------------------|
| T, K           | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | T, K   | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
| 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.

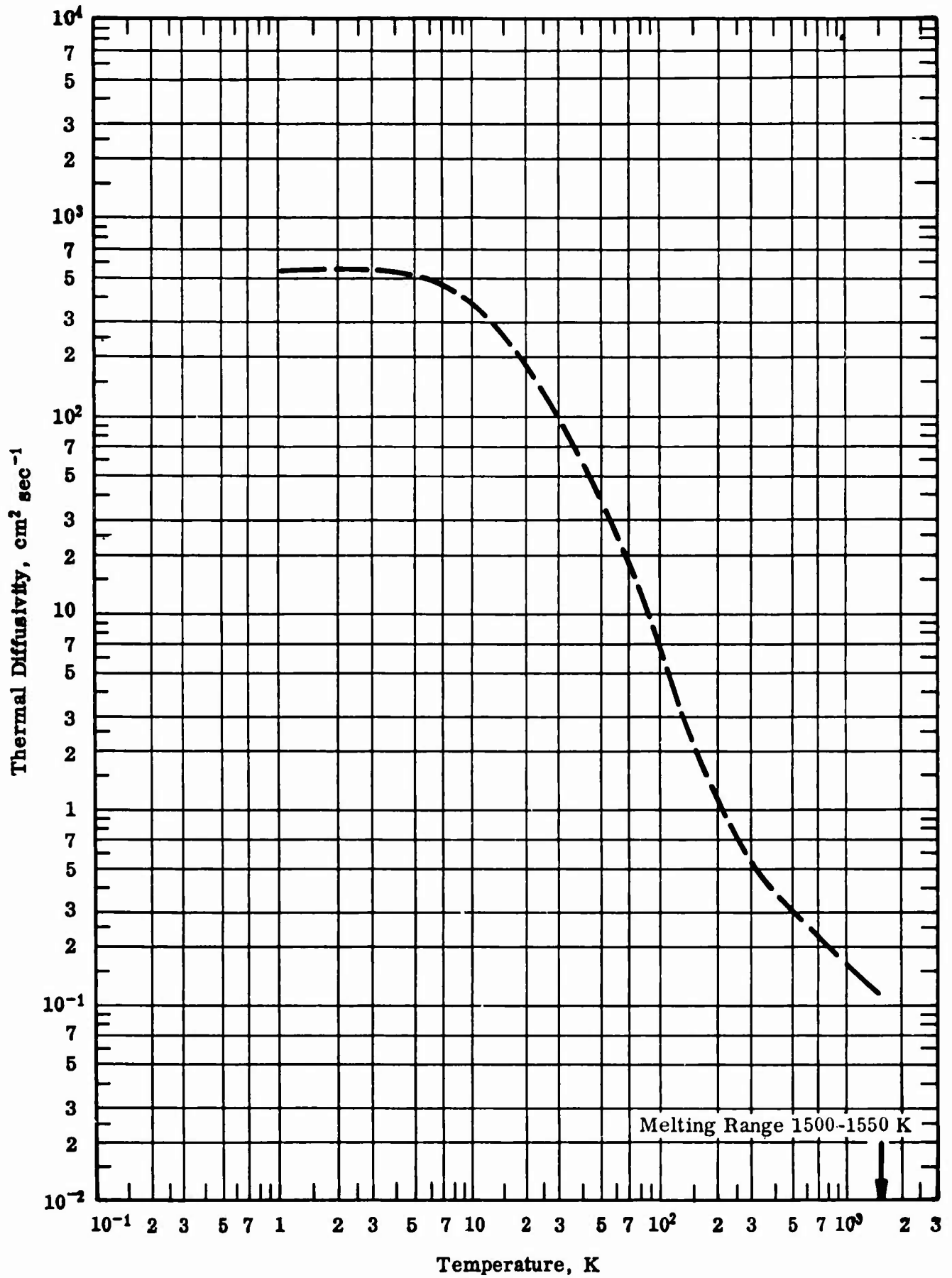


FIG. IV-17 THERMAL DIFFUSIVITY OF BERYLLIUM (DILUTE) ALLOY

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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   | 12.4   | 1200 | 0.133  |
| 90   | <del>8.6</del> 9.0                           | 1300 | 0.123  |
| 100  | 6.6  | 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.

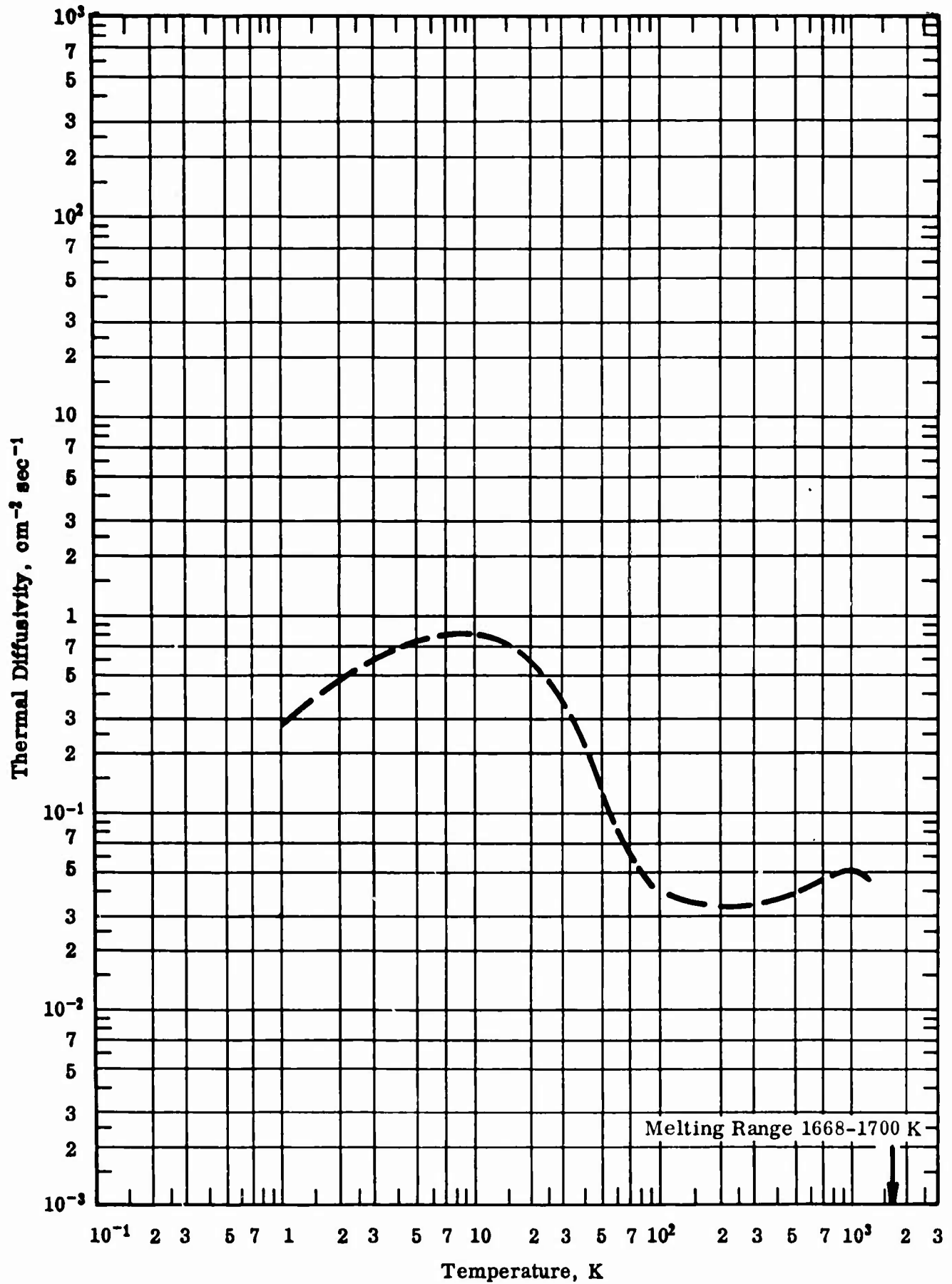


FIG. IV-18 THERMAL DIFFUSIVITY OF INCONEL X-750

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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.

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\* All values are calculated or estimated.

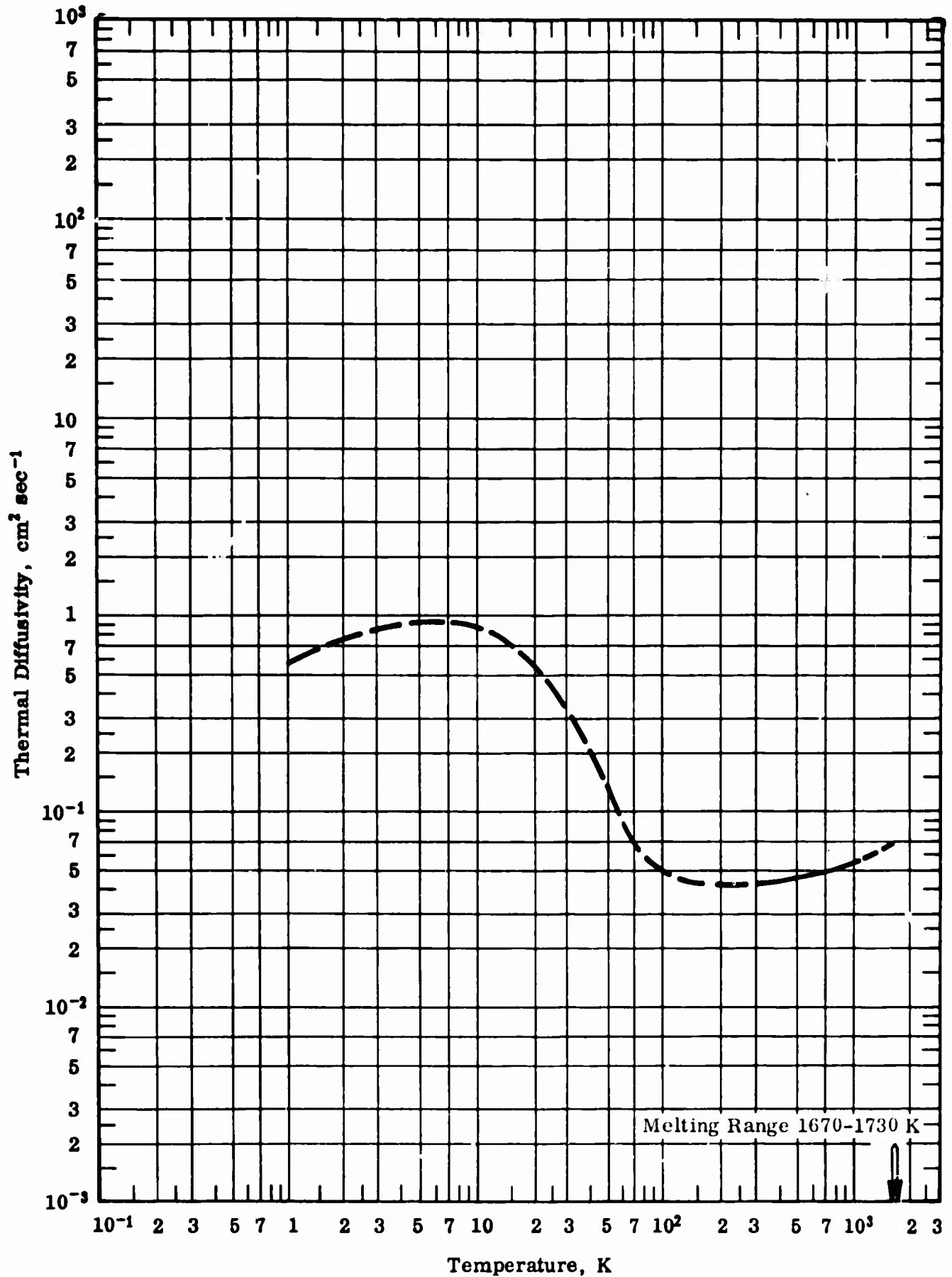


FIG. IV-19 THERMAL DIFFUSIVITY OF STAINLESS STEEL 304A

TABLE IV-19 THERMAL DIFFUSIVITY OF STAINLESS STEEL 304 A

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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.

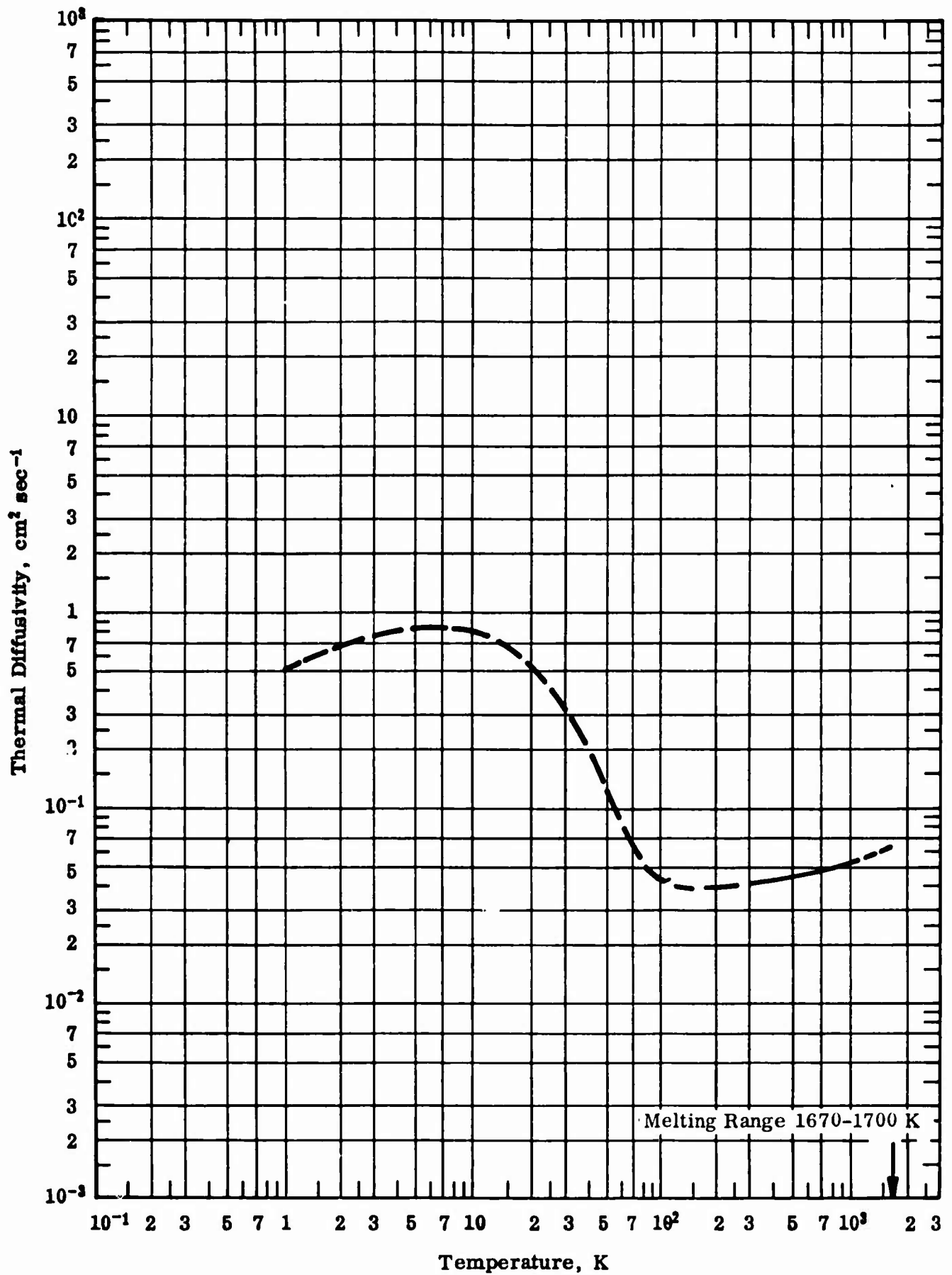


FIG. IV-20 THERMAL DIFFUSIVITY OF STAINLESS STEEL 347

**TABLE IV-20 THERMAL DIFFUSIVITY OF STAINLESS STEEL 347**

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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.

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\* Calculated or estimated.

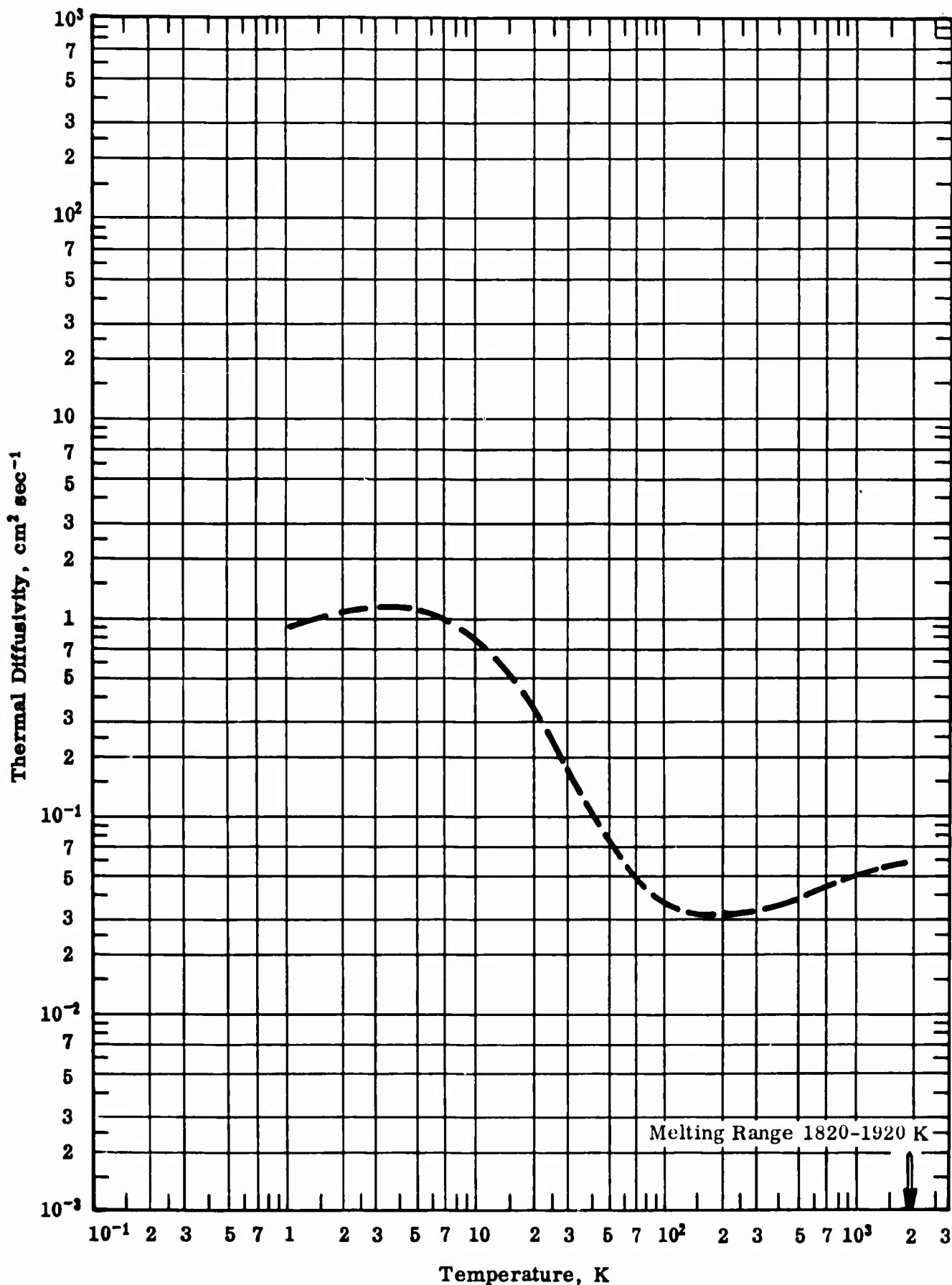


FIG. IV-21 THERMAL DIFFUSIVITY OF TITANIUM ALLOY A-110AT

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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.

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\* All values are calculated or estimated.

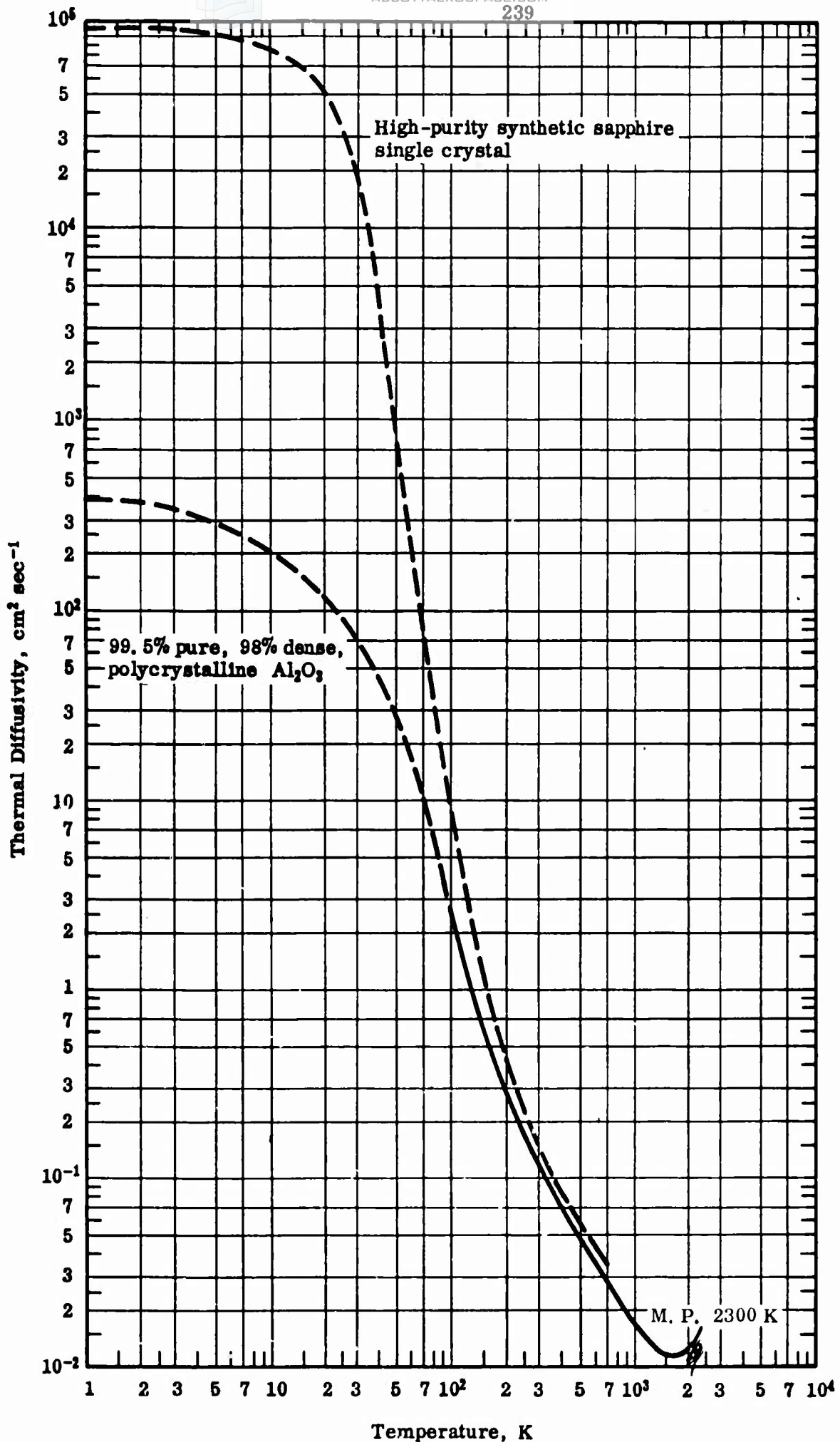


FIG. IV-22 THERMAL DIFFUSIVITY OF ALUMINUM OXIDE Al<sub>2</sub>O<sub>3</sub>

**TABLE IV-22 THERMAL DIFFUSIVITY OF ALUMINUM OXIDE  $Al_2O_3$**

| T, K | 99.5% Pure, 98% Dense,<br>Polycrystalline $Al_2O_3$ | High-Purity Synthetic<br>Sapphire Single Crystal |
|------|---|--|
|      | $\alpha, cm^2 sec^{-1}$                             | $\alpha, cm^2 sec^{-1}$                          |
| 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   | <del>17.5*</del> 17.7*                              | 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,<br>Polycrystalline Al <sub>2</sub> O <sub>3</sub><br>$\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | High-Purity Synthetic<br>Sapphire Single Crystal<br>$\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|--|
| 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.

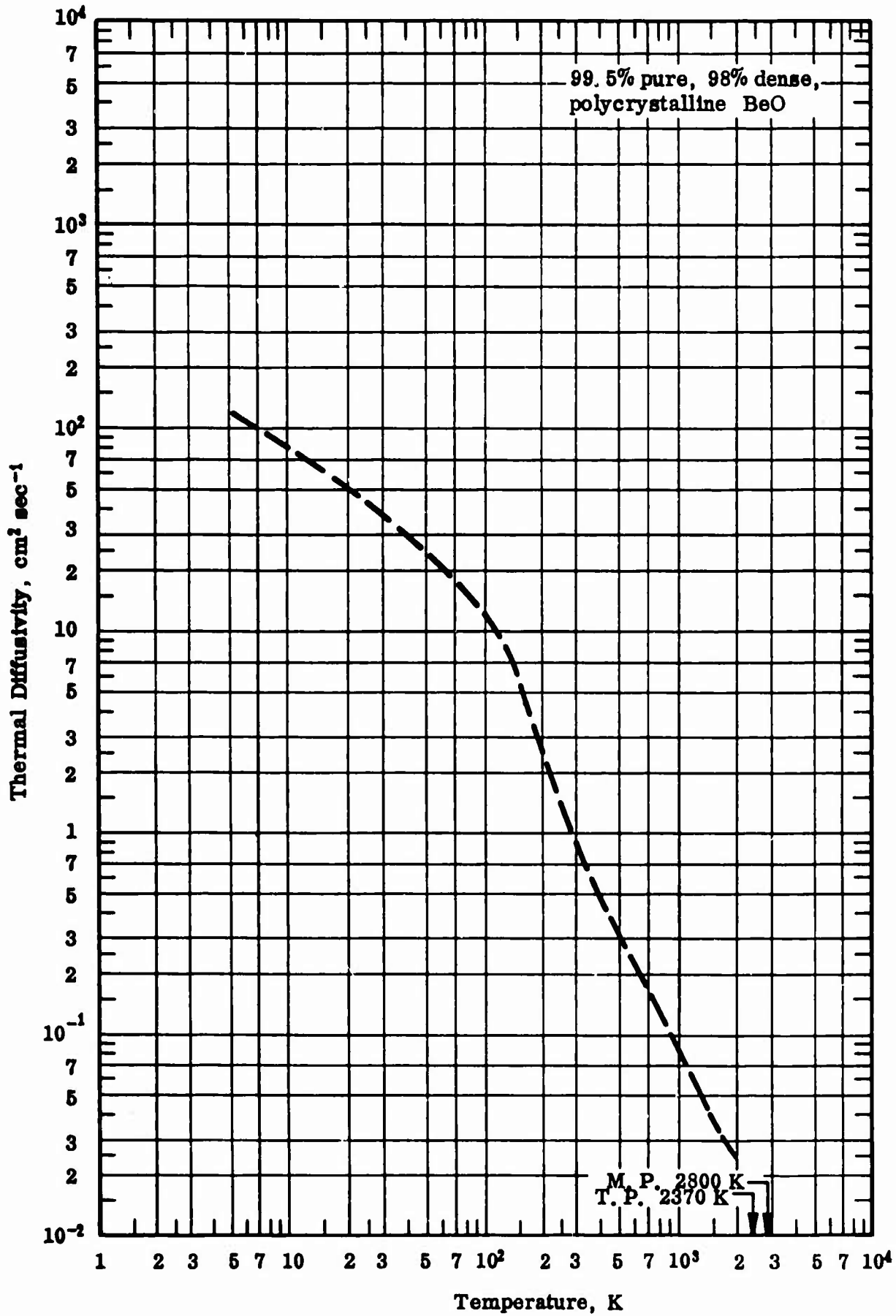


FIG. IV-23 THERMAL DIFFUSIVITY OF BERYLLIUM OXIDE BeO

TABLE IV-23 THERMAL DIFFUSIVITY OF BERYLLIUM OXIDE BeO

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

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 1    | 170*   | 400  | 0.50   |
| 5    | 120*   | 450  | 0.39   |
| 10   | 83*  | 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.

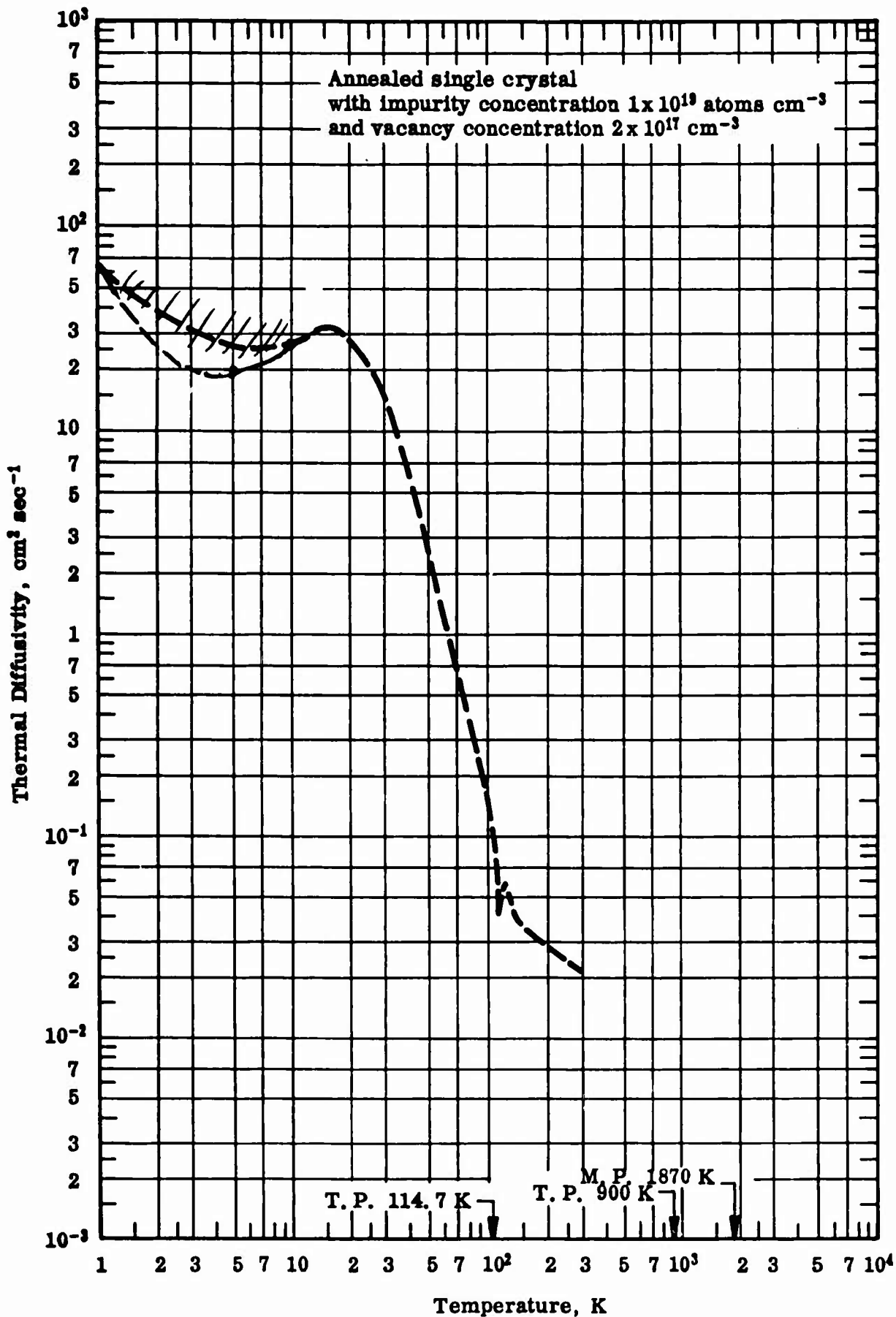


FIG. IV-24 THERMAL DIFFUSIVITY OF IRON OXIDE  $\text{Fe}_3\text{O}_4$

TABLE IV-24 THERMAL DIFFUSIVITY OF IRON OXIDE  $\text{Fe}_3\text{O}_4$

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

| T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ | T, K  | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ |
|------|--|-------|--|
| 1    | 65*                                      | 100   | 0.15                                     |
| 5    | <del>26</del> 20                         | 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.

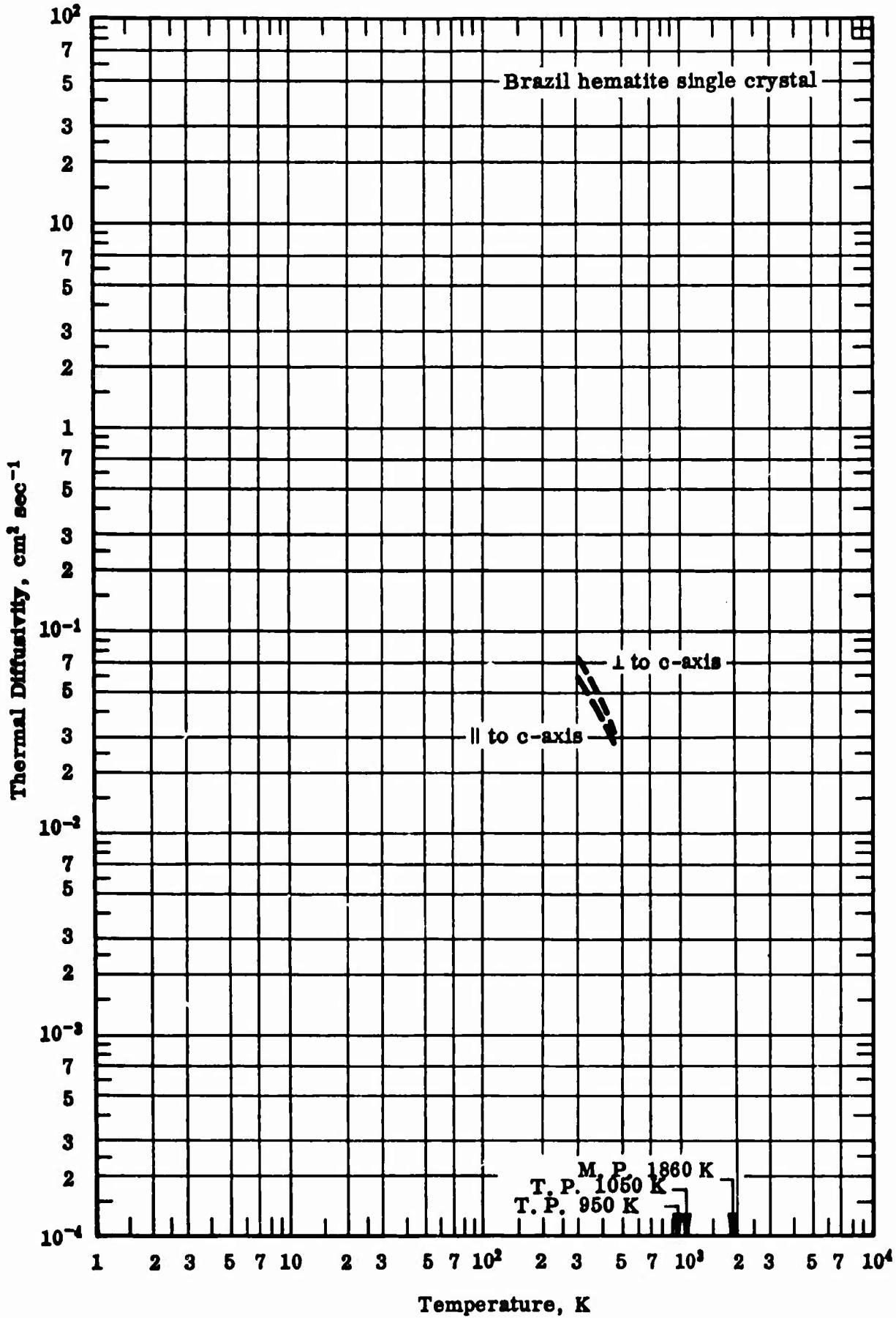


Fig. IV-25 THERMAL DIFFUSIVITY OF IRON (IC) OXIDE  $\text{Fe}_2\text{O}_3$

TABLE IV-25 THERMAL DIFFUSIVITY OF IRON (IC) OXIDE  $\text{Fe}_2\text{O}_3$

Selected Values for Brazil Hematite Single Crystal

| T,K | Heat flow parallel<br>to c-axis       | Heat flow perpendicular<br>to c-axis  |
|-----|---------------------------------------|---------------------------------------|
|     | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
| 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.

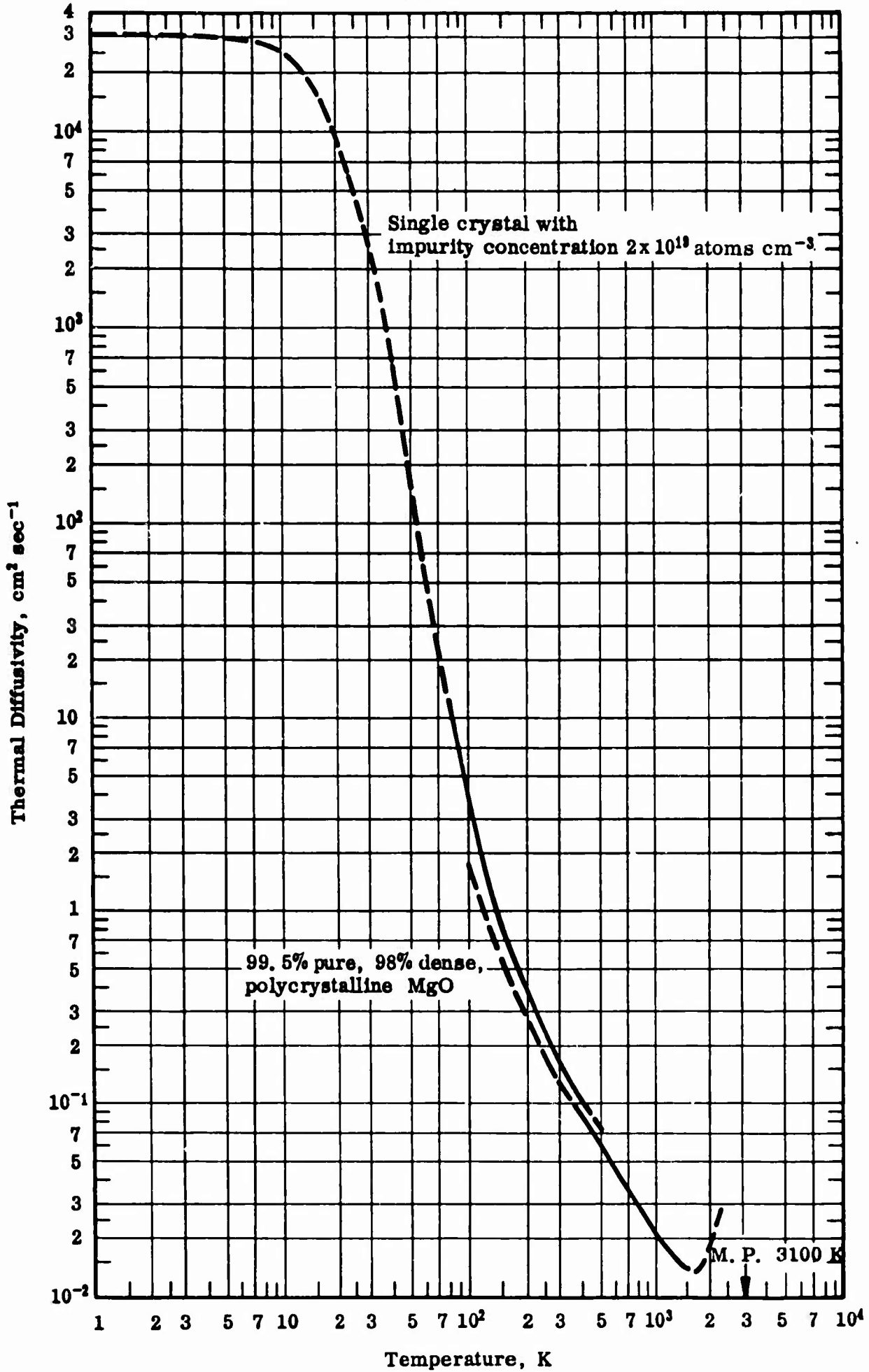


FIG. IV-26 THERMAL DIFFUSIVITY OF MAGNESIUM OXIDE MgO

TABLE IV-26 THERMAL DIFFUSIVITY OF MAGNESIUM OXIDE MgO

Selected Values for MgO Single Crystal with Impurity Concentration  
 $2 \times 10^{19}$  atoms  $\text{cm}^{-3}$

| T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ | T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ |
|------|--|------|--|
| 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 | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ | T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ |
|------|--|------|--|
| 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.

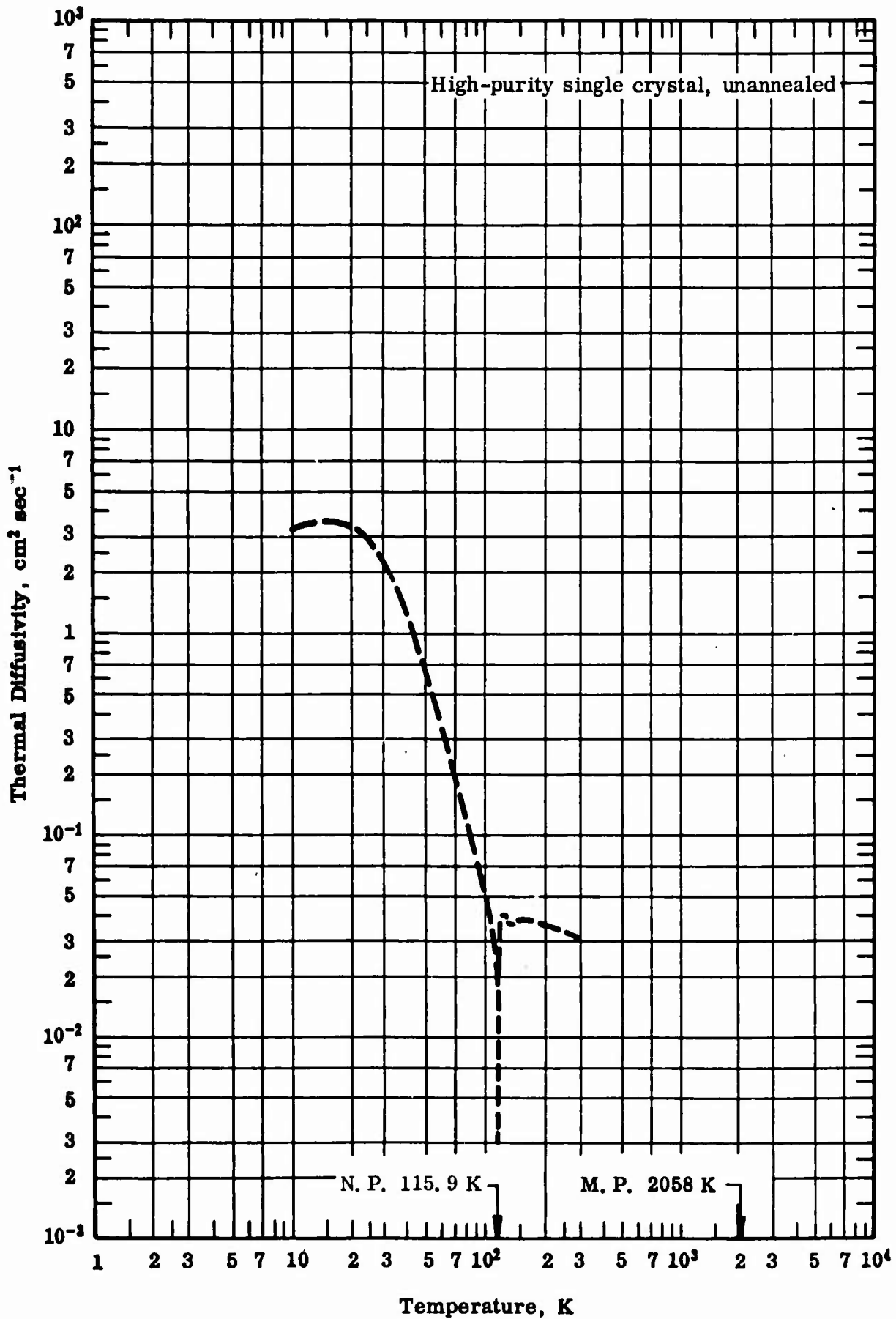


FIG. IV-27 THERMAL DIFFUSIVITY OF MANGANESE MONOXIDE MnO

**TABLE IV-27 THERMAL DIFFUSIVITY OF MANGANESE MONOXIDE MnO**  
**Selected Values for Unannealed High-Purity Single Crystal\***

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K  | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|-------|--|
| 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.

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\*All values are calculated or estimated.

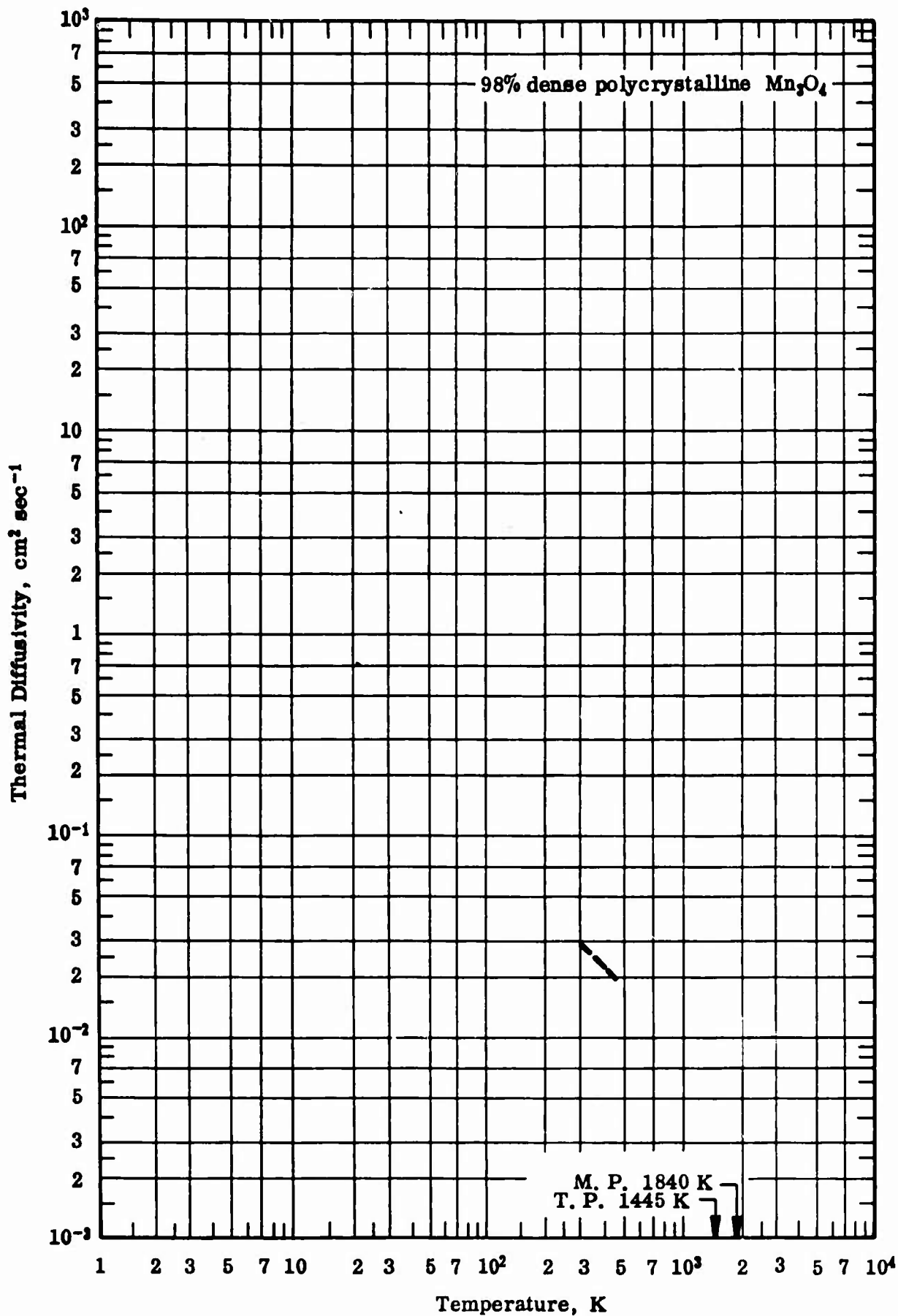


FIG. IV-28 THERMAL DIFFUSIVITY OF MANGANOMANGANIC OXIDE  $Mn_3O_4$

TABLE IV-28 THERMAL DIFFUSIVITY OF MANGANOMANGANIC OXIDE  
 $Mn_3O_4$

Selected Values for 98% Dense Polycrystalline  $Mn_3O_4$

| T, K | $\alpha$ , $cm^2 sec^{-1}$ |
|------|----------------------------|
| 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.

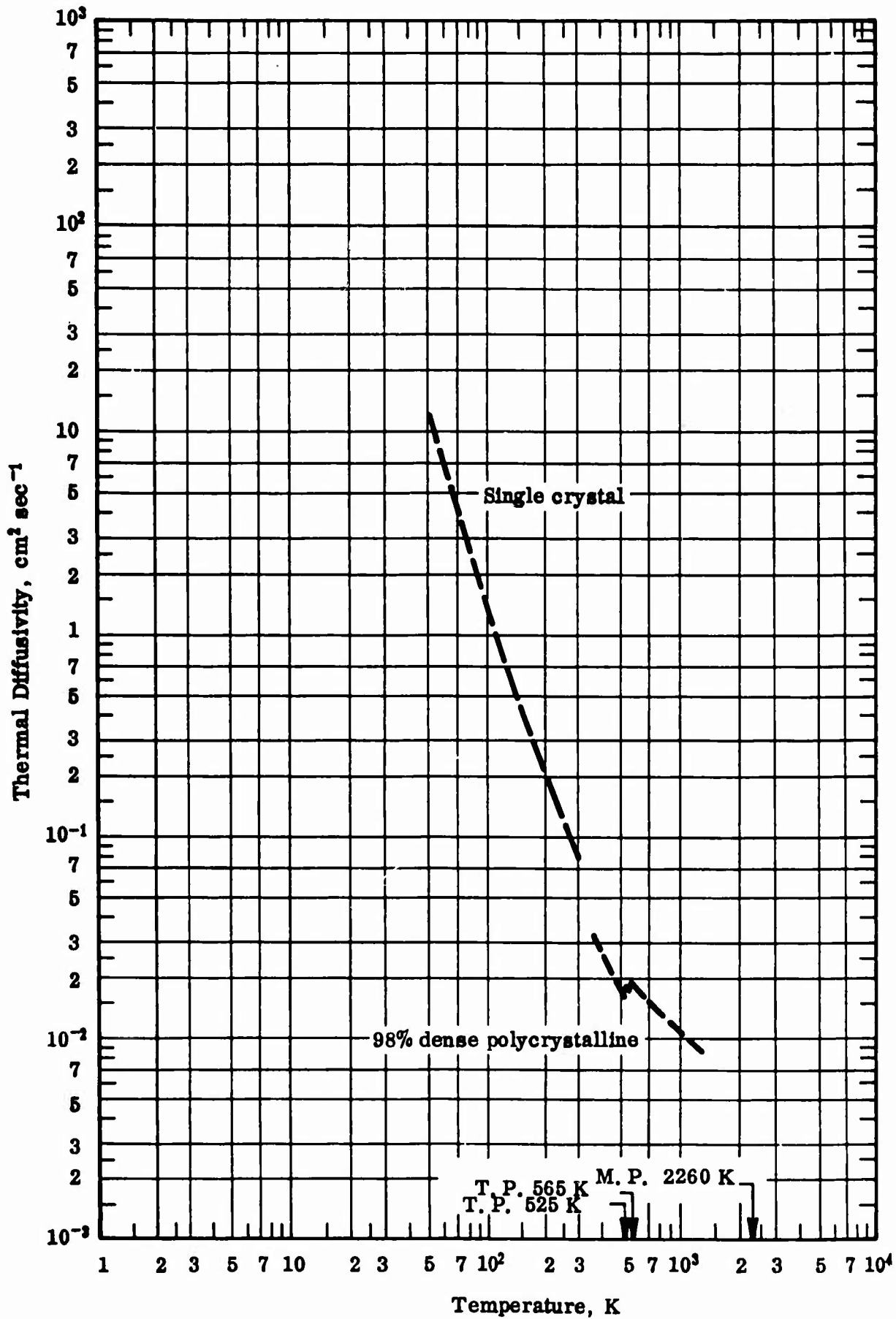


FIG. IV-29 THERMAL DIFFUSIVITY OF NICKEL (OUS) OXIDE NiO

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

**Selected Values for High-Purity NiO Single Crystal\***

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|------|--|
| 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             | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> | T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------------------|--|------|--|
| 350              | 0.032*                                       | 600  | 0.0178                                       |
| 400              | 0.026  | 700  | 0.0151                                       |
| 450              | 0.021  | 800  | 0.0132                                       |
| 500              | 0.017  | 900  | 0.0117                                       |
| ( $\alpha$ ) 524 | 0.0156                                       | 1000 | 0.0103                                       |
| ( $\beta$ ) 526  | 0.0132                                       | 1100 | 0.0095                                       |
| 550              | 0.0173                                       | 1200 | 0.0088                                       |
| ( $\beta$ ) 564  | 0.0169                                       | 1300 | 0.0084                                       |
| ( $\gamma$ ) 566 | 0.0192                                       |      |  |

**Data Source and Remarks**

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

\* All values are calculated or estimated.

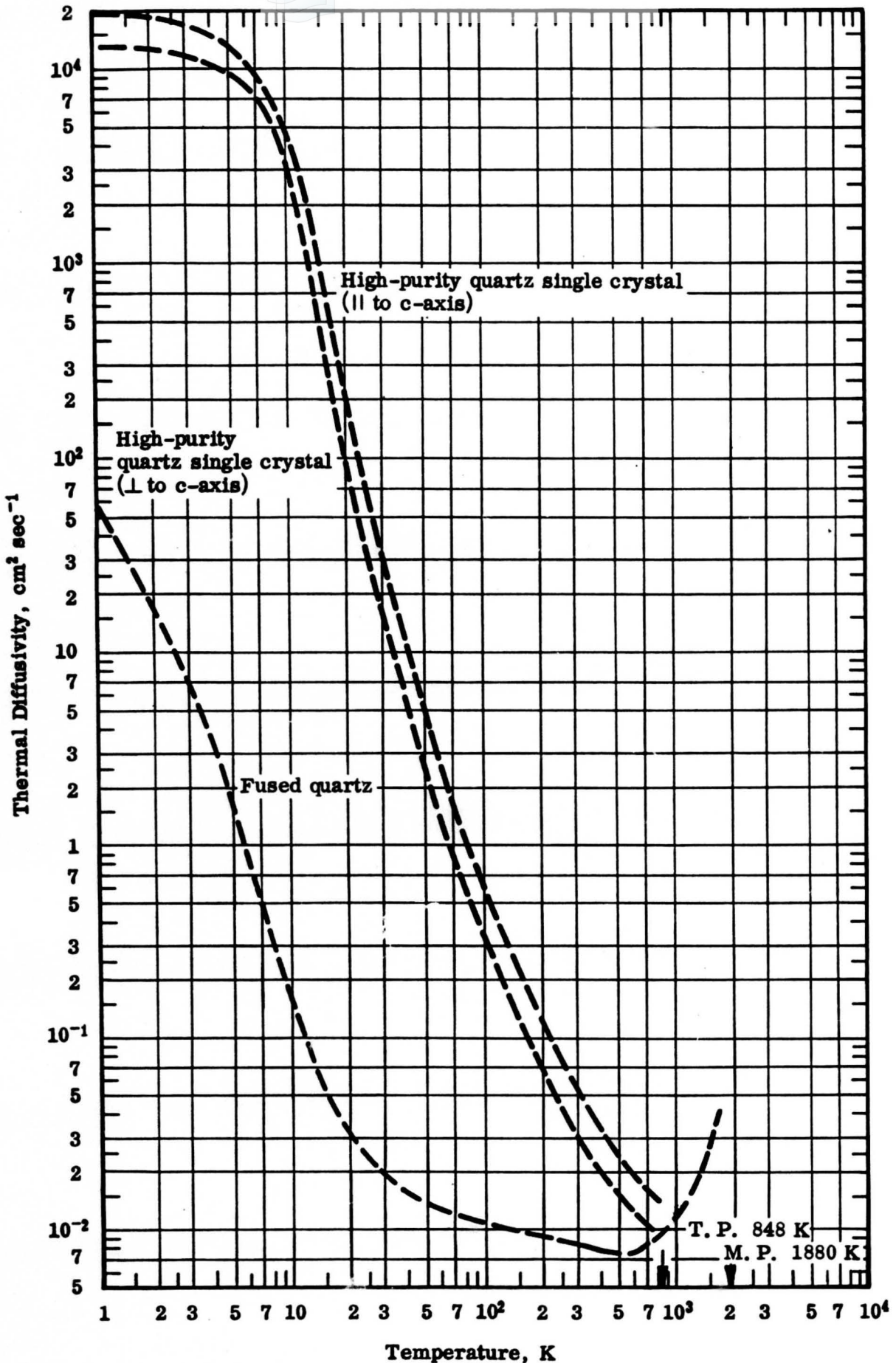


FIG. IV-30 THERMAL DIFFUSIVITY OF SILICON DIOXIDE  $\text{SiO}_2$

TABLE IV-30 THERMAL DIFFUSIVITY OF SILICON DIOXIDE SiO<sub>2</sub>

| T, K | Fused Quartz                          | High-Purity Quartz<br>parallel to<br>c-axis | Single Crystal<br>perpendicular to<br>c-axis |
|------|---------------------------------------|---|--|
|      | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | $\alpha, \text{cm}^2 \text{sec}^{-1}$       | $\alpha, \text{cm}^2 \text{sec}^{-1}$        |
| 1    | 59*                                   | 19000*                                      | 13000*                                       |
| 2    | 15.8                                  |   |  |
| 3    | 7.1*                                  |   |  |
| 5    | 1.55*                                 | 13000*                                      | 9400*  |
| 8    |                                       | <del>1000*</del> 8000*                      | 5700*  |
| 10   | 0.146*                                | 4300*                                       | 2700*  |
| 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*                                       | 0.068*                                       |
| 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.

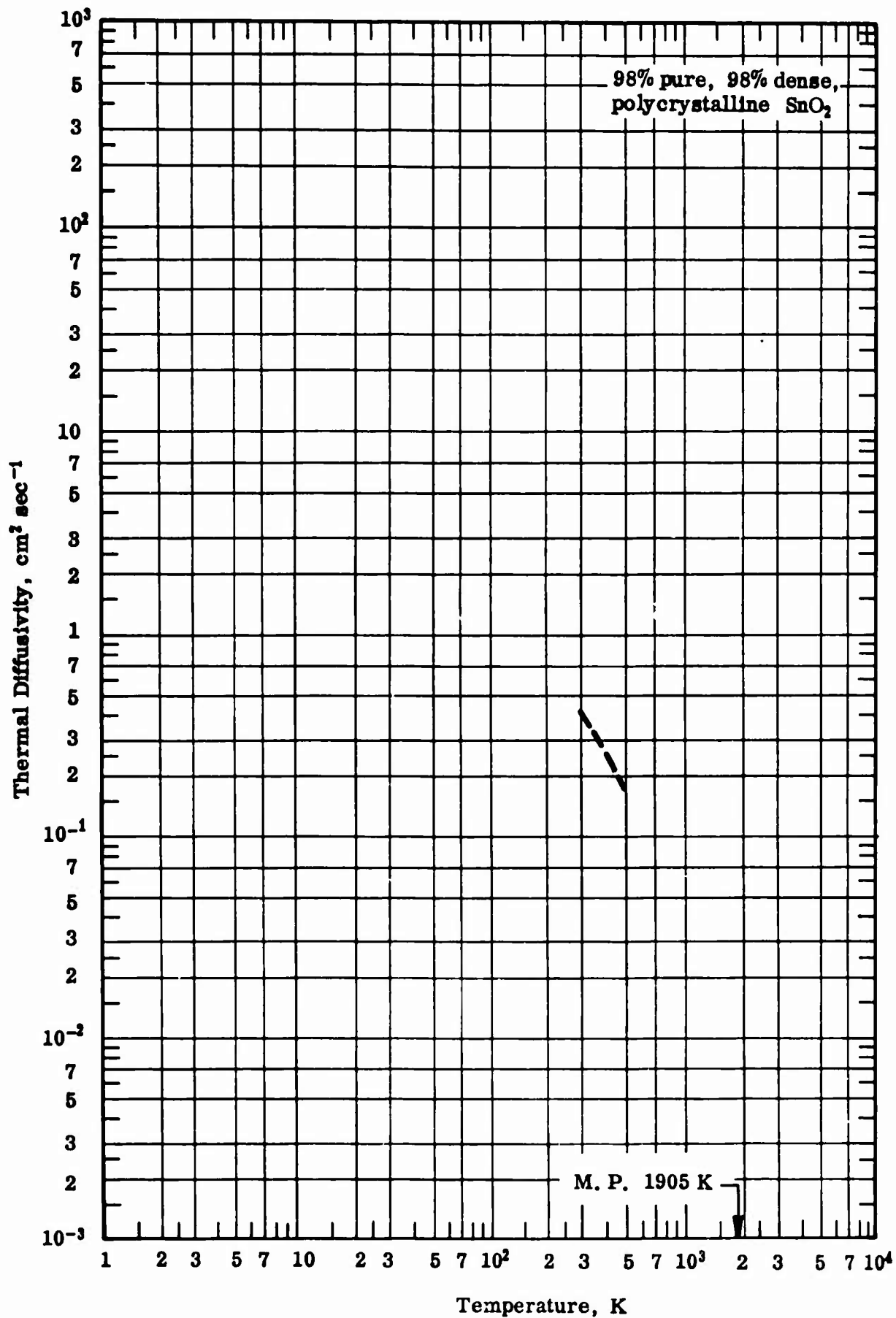


FIG. IV-31 THERMAL DIFFUSIVITY OF TIN (IC) OXIDE SnO<sub>2</sub>

TABLE IV-31 THERMAL DIFFUSIVITY OF TIN (IC) OXIDE SnO<sub>2</sub>

Selected Values for 98% Pure, 98% Dense, Polycrystalline SnO<sub>2</sub>

| T, K | $\alpha$ , cm <sup>2</sup> sec <sup>-1</sup> |
|------|--|
| 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.

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\* Calculated or estimated.

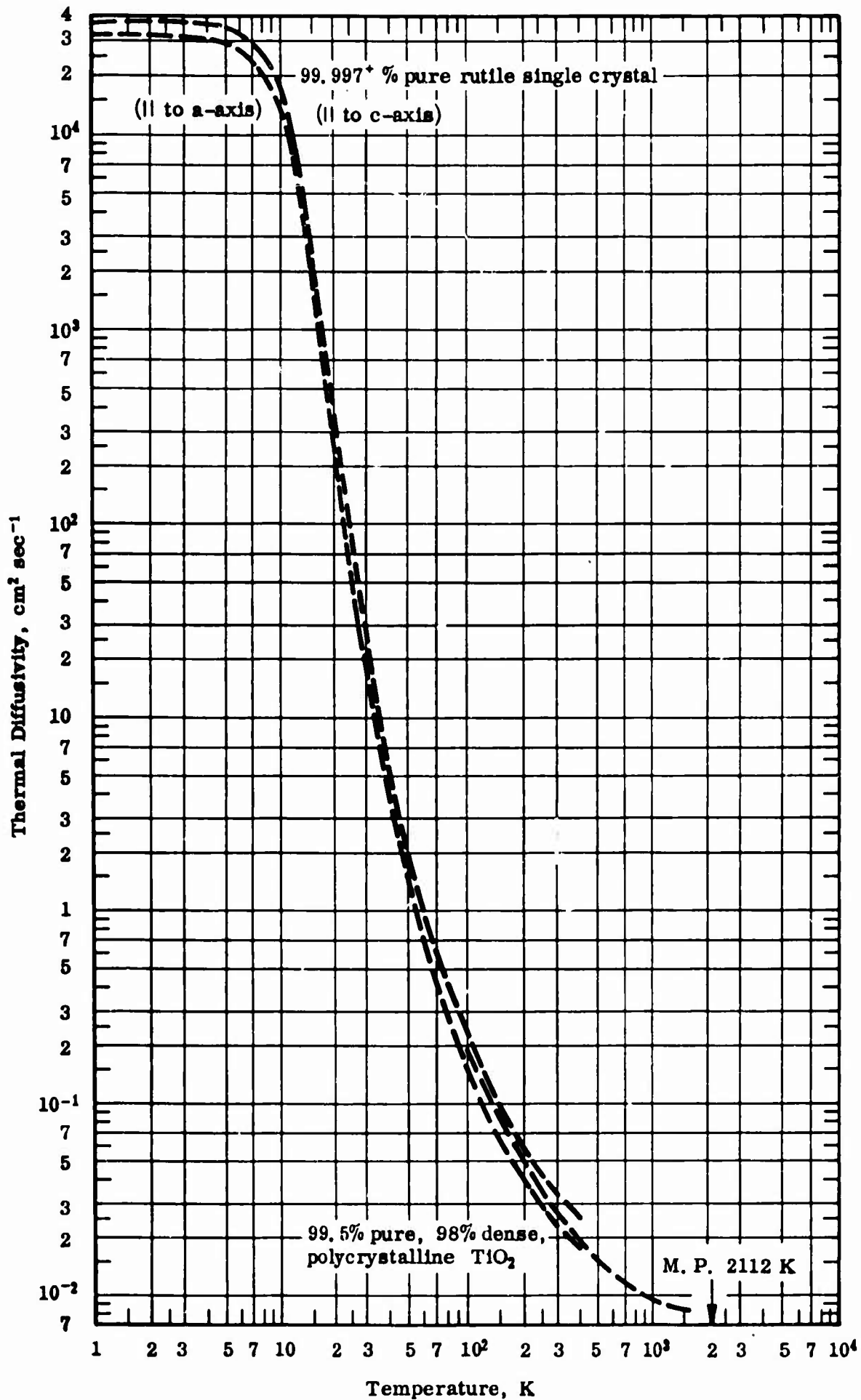


FIG. IV-32 THERMAL DIFFUSIVITY OF TITANIUM DIOXIDE  $\text{TiO}_2$

TABLE IV-32 THERMAL DIFFUSIVITY OF TITANIUM DIOXIDE  $\text{TiO}_2$

Selected Values for 99.997+ % Pure Rutile Single Crystal\*

| T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ |                    |
|------|--|--------------------|
|      | 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  $\text{TiO}_2$ \*

| T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ | T, K | $\alpha$ , $\text{cm}^2 \text{sec}^{-1}$ |
|------|--|------|--|
| 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.

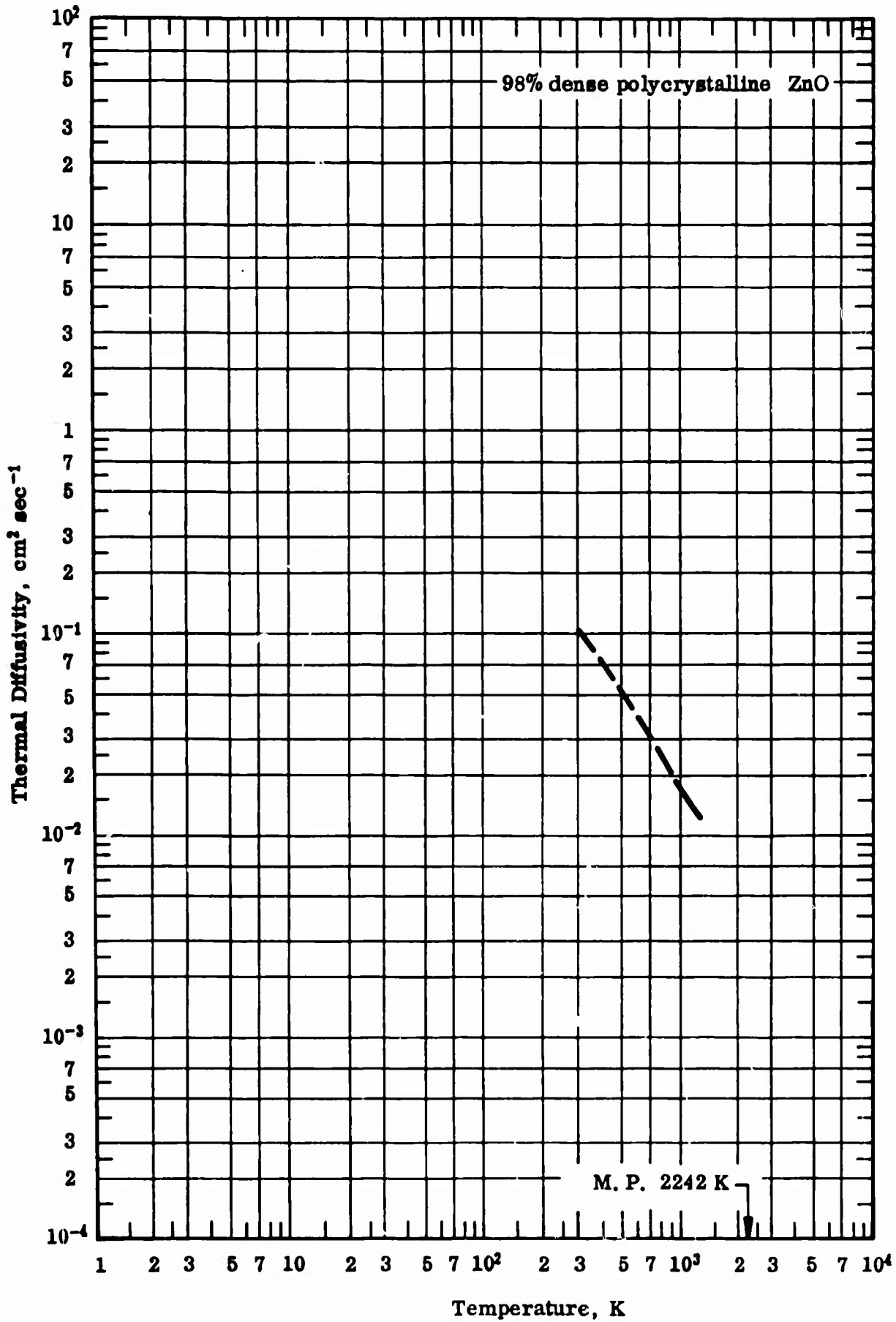


FIG. IV-33 THERMAL DIFFUSIVITY OF ZINC OXIDE ZnO

**TABLE IV-33 THERMAL DIFFUSIVITY OF ZINC OXIDE ZnO**

Selected Values for 98% Dense Polycrystalline ZnO\*

| T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ | T, K | $\alpha, \text{cm}^2 \text{sec}^{-1}$ |
|------|---------------------------------------|------|---------------------------------------|
| 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.

D. BIBLIOGRAPHY

- | Ref.<br>No. | TPRC<br>No. |   |
|-------------|-------------|---|
| 1.          | 9735        | Zavaritskii, N.V., Zhur. Eksptl. i Teoret. Fiz., <u>34</u> , 1116-24, 1958.   |
| 2.          | 1553        | Howling, D. H., Mendoza, E., and Zimmerman, J.E., Proc. Roy. Soc. (London), <u>A229</u> , 86-109, 1955.                   |
| 3.          | 15663       | Sonnenschein, G and Winn, R. A., WADC TR 59-273, 1-65, 1960. [AD 236 660]   |
| 4.          | 24813       | Jenkins, R.J. and Parker, W.J., WADD TR 61-95, 1-27, 1961. [AD 268 752]   |
| 5.          | 24921       | Schmidt, D. L., WADD TR 60-862, 1-85, 1961. [AD 268 078]  |
| 6.          | 19742       | Sidles, P.H. and Danielson, G.C., Proc. Conf. Thermo-electricity (1958), 270-87, 1960.                                    |
| 7.          | 7053        | Sidles, P.H. and Danielson, G.C., USAEC Rept. ISC-311, 1-33, 1953. [AD 16 202]  |
| 8.          | 7003        | Sidles, P.H. and Danielson, G.C., USAEC Rept. ISC-198, 1-24, 1951.  |
| 9.          | 6693        | Butler, C.P. and Inn, E.C.Y., USNRDL TR 177, 1-27, 1957. [AD 143 863]   |
| 10.         | 22836       | Mrozowski, S., Andrew, J.F., Juul, N., Sato, S., Strauss, H.E., and Tsuzuku, T., WADC TR 58-360, 1-68, 1963. [AD 427 104] |
| 11.         | 22004       | Moser, J.B. and Kruger, O.L., Argonne Nat. Lab. Rept. ANL 6868, 1-447, 1963.  |
| 12.         | 3916        | El-hifini, M.A. and Chao, B.A., Trans. Am. Soc. Mech. Engrs., <u>78</u> , 813-21, 1956.                                   |
| 13.         | 16699       | Abeles, B., Beers, D., Cody, G., Novak, R., and Rosi, F., WADD TR 60-266, 1-51, 1960. [AD 246 620]                        |
| 14.         | 10758       | Abeles, B., Cody, G.D., and Novak, R., WADC Progr. Rept. No. 1, 1-33, 1959. [AD 225 854]                                  |
| 15.         | 9975        | Chiotti, P. and Carlson, O.N. (Comp.), USAEC Rept. ISC-709, 1-23, 1956.   |
| 16.         | 15925       | Kennedy, W.L., USAEC Rept. IS-137, 1-59, 1960.  |
| 17.         | 16899       | Dennis, J.F., Hirschman, A., Derksen, W.L., and Monahan, T.I. Naval Mat. Lab. Rept. DASA-1187, 1-14, 1960. [AD 242 669]   |
| 18.         | 29948       | Shanks, H.R., Maycock, P.D., Sidles, P.H., and Danielson, G.C., Phys. Rev., <u>130</u> (5), 1743-8, 1963.                 |
| 19.         | 27679       | Karagezyan, A.G., Phys. Metals and Metallog. (USSR), <u>12</u> (4), 39-44, 1962.  |
| 20.         | 24367       | Rudkin, R.L., Parker, W.J., and Jenkins, R.J., ASD TDR 62-24, 1-20, 1963. [AD 297 836]                                    |

BIBLIOGRAPHY (continued)

- | Ref. No. | TPRC No. |  |
|----------|----------|--|
| 21.      | 16443    | Frazier, R. H., Phys. Rev., <u>43</u> , 135-6, 1933.   |
| 22.      | 6941     | Soxlian, E. J., Alfred Univ. ONR, Proj. Rept., 1-36, 1955.   |
| 23.      | 24384    | Rudkin, R. L., ASD TDR 62-24 (Pt 2), 1-16, 1963.<br>[AD 413 005]   |
| 24.      | 6930     | Crandall, W. B. and Ging, J., J. Am. Ceram. Soc., <u>38</u><br>(1), 44-54, 1955.                                     |
| 25.      | 5155     | Fitzsimmons, E. S., J. Am. Ceram. Soc., <u>33</u> , 327-32, 1950.  |
| 26.      | 19418    | Elston, J. & Caillat, R., Proc. U N 2nd Intern. Conf.<br>Peaceful Uses At. Energy (Geneva), <u>5</u> , 345-66, 1958. |
| 27.      | 25901    | Makarounis, O. & Jenkins, R. J., USNRDL-TR-599,<br>1-16, 1962. [AD 295 887]  |
| 28.      | 27922    | Plummer, W. A., Campbell, D. E., and Comstock, A. A.,<br>J. Am. Ceram. Soc., <u>45</u> (7), 310-16, 1962.            |
| 29.      | 26684    | Hartunian, R. A. and Varwig, R. L., Phys. Fluids, <u>5</u> (2),<br>169-174, 1962.                                    |

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

**CHAPTER V  
SPECIFIC HEAT**

**BY**

**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 Eldridge, 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  $\text{cal g}^{-1} \text{K}^{-1}$  ( $1 \text{ cal} = 4.1840$  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  $\pm 5$  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

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

$$C_v = \frac{234R}{M} \left( \frac{T}{\theta} \right)^3$$

may be used for metals and oxides respectively, where,

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

$T$  = temperature, K,

$\beta, \gamma$  = constants,

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

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

$\theta$  = Debye temperature.

The expression  $\beta T^3$  represents the lattice specific heat and obeys a cube law while the terms  $\gamma T$ , 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 ( $T > 300 \text{ K}$ ), the specific heat levels off to almost a constant value. This value varies for various substances but for some metals it is approximately  $6.5 \text{ cal mol}^{-1} \text{K}^{-1}$ .

The Kopp-<sup>Neumann</sup>~~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:

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

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  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$ , and the solid and liquid phases by the letters "s" and "l" respectively. Extrapolated and interpolated values are indicated by parenthesis 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 superconducting 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-Neuman<sup>v</sup> 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. J., 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,  $\theta$ , 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.

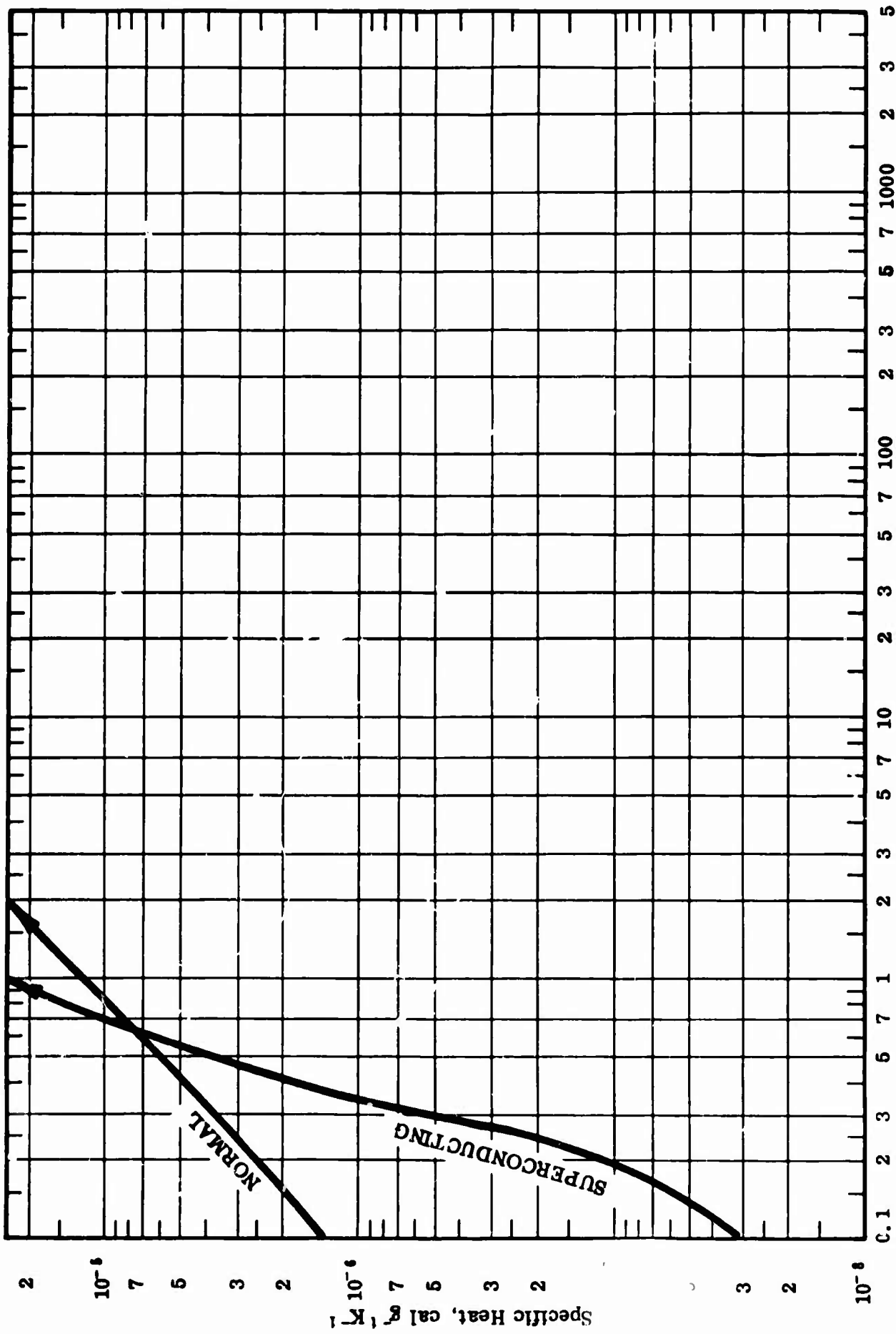


FIG. V - 1 (a)

SPECIFIC HEAT -- ALUMINUM

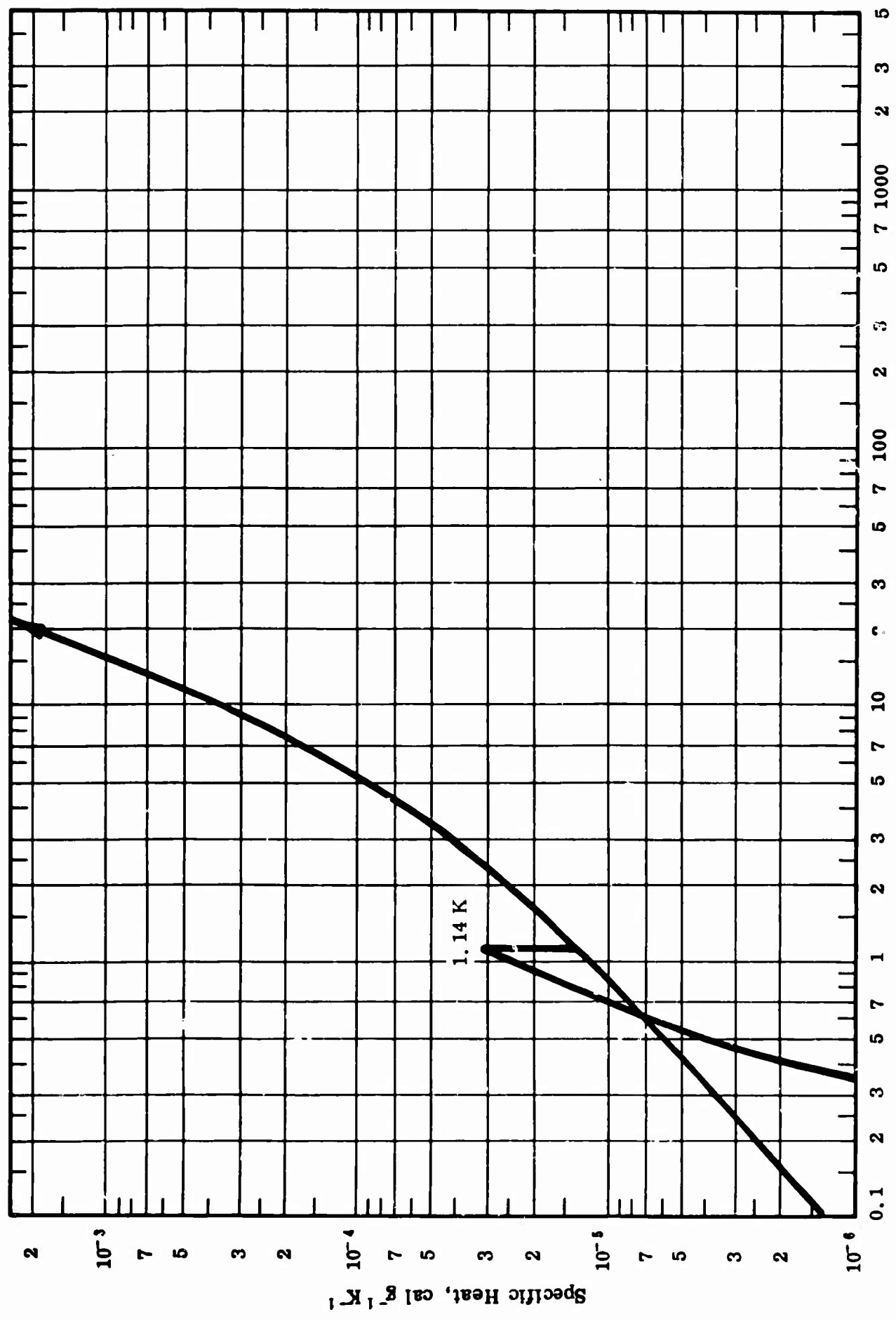


FIG. V - 1 (b)

SPECIFIC HEAT -- ALUMINUM

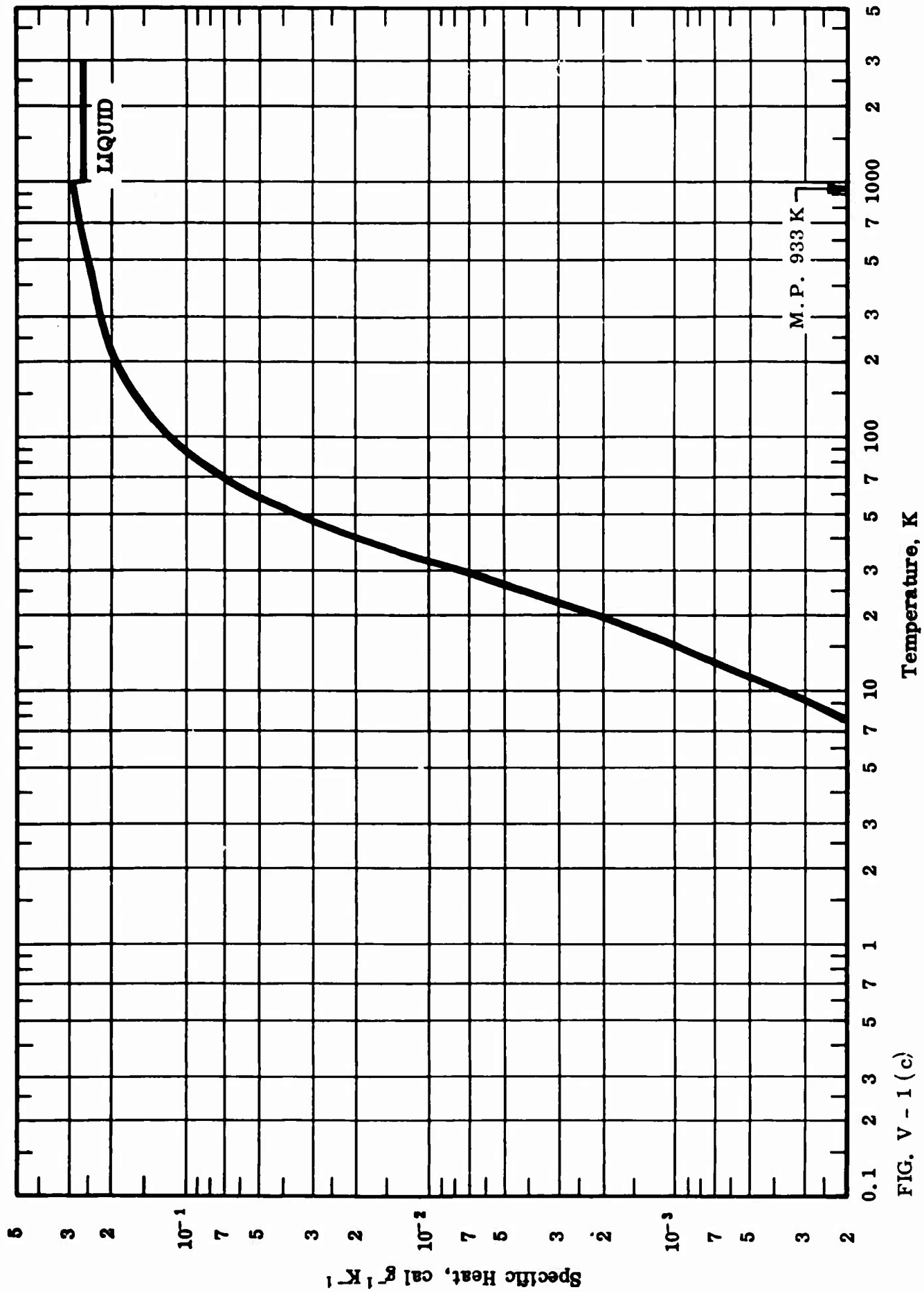


FIG. V - 1 (c)

SPECIFIC HEAT -- ALUMINUM

TABLE V-1. SPECIFIC HEAT OF ALUMINUM

| NORMAL |  | SUPERCONDUCTING                                      |         |  |
|--------|--|--|---------|--|
| T °K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 0.1    | (1.32 x 10 <sup>-9</sup> ) <sup>†</sup>              | (3.02 x 10 <sup>-8</sup> ) <sup>†</sup>              | 300     | 2.17 x 10 <sup>-1</sup>                              |
| 0.2    | 2.50   | 1.00 x 10 <sup>-7</sup>                              | 400     | 2.27   |
| 0.3    | 3.68   | 5.10 x 10 <sup>-7</sup>                              | 500     | 2.38   |
| 0.4    | 4.85   | 1.83 x 10 <sup>-6</sup>                              | 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 x 10 <sup>-5</sup>                              | 900     | 2.82   |
| 0.8    | 9.70   | 1.47   | (s) 933 | 2.85   |
| 0.9    | 1.10 x 10 <sup>-5</sup>                              | 1.95   | (l) 933 | (2.59 x 10 <sup>-1</sup> ) <sup>‡</sup>              |
| 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 x 10 <sup>-4</sup>                              |  | 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 x 10 <sup>-3</sup>                              |  | 2200    | (2.59 )  |
| 30     | 7.50   |  | 2300    | (2.59 )  |
| 40     | 1.85 x 10 <sup>-2</sup>                              |  | 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 x 10 <sup>-1</sup>                              |  | 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 Lvoviskaya, L. A., (18) [323-573 K].

<sup>†</sup> Extrapolated

<sup>‡</sup> Estimated (5)

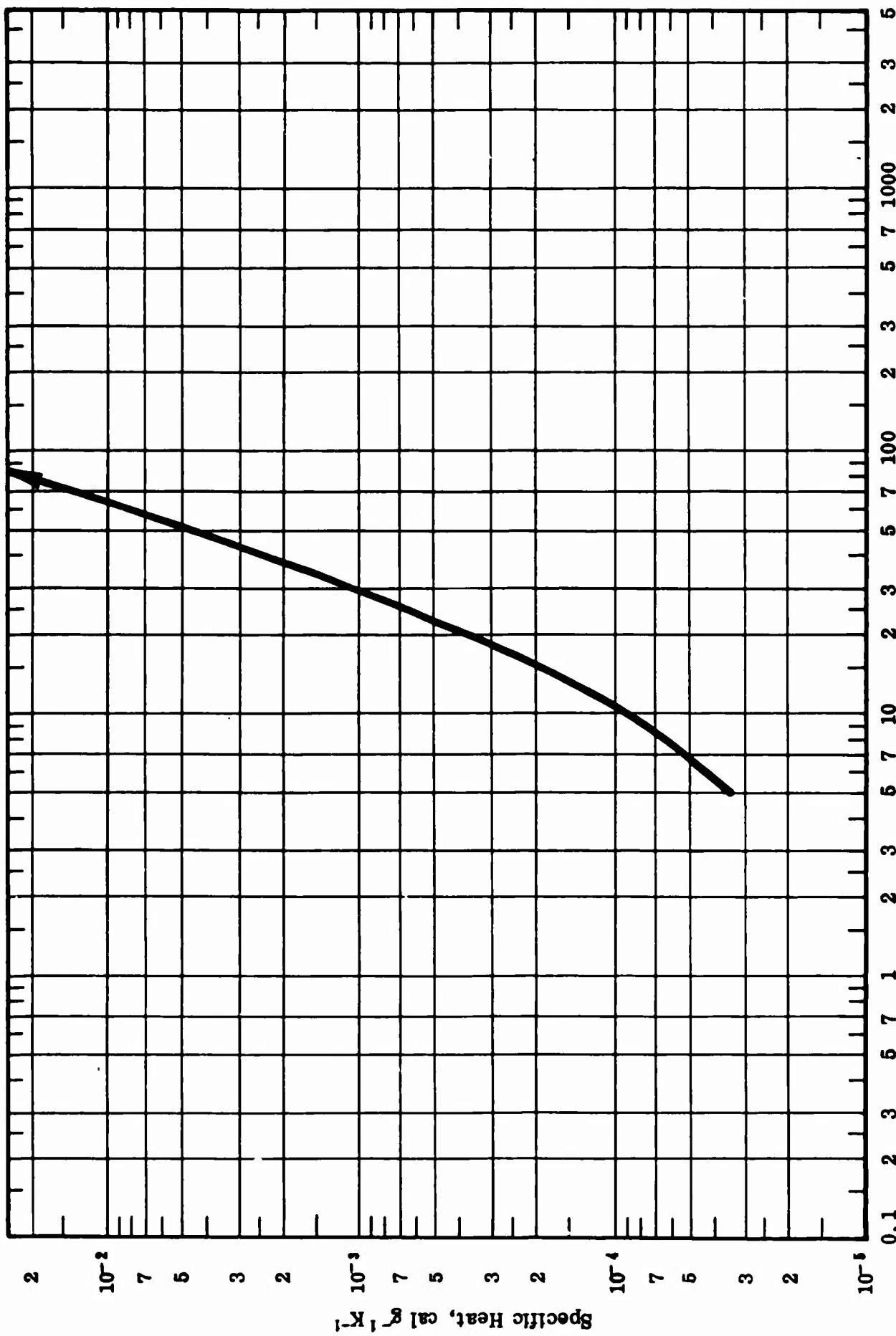


FIG. V - 2 (a)

Temperature, K

SPECIFIC HEAT-- BERYLLIUM

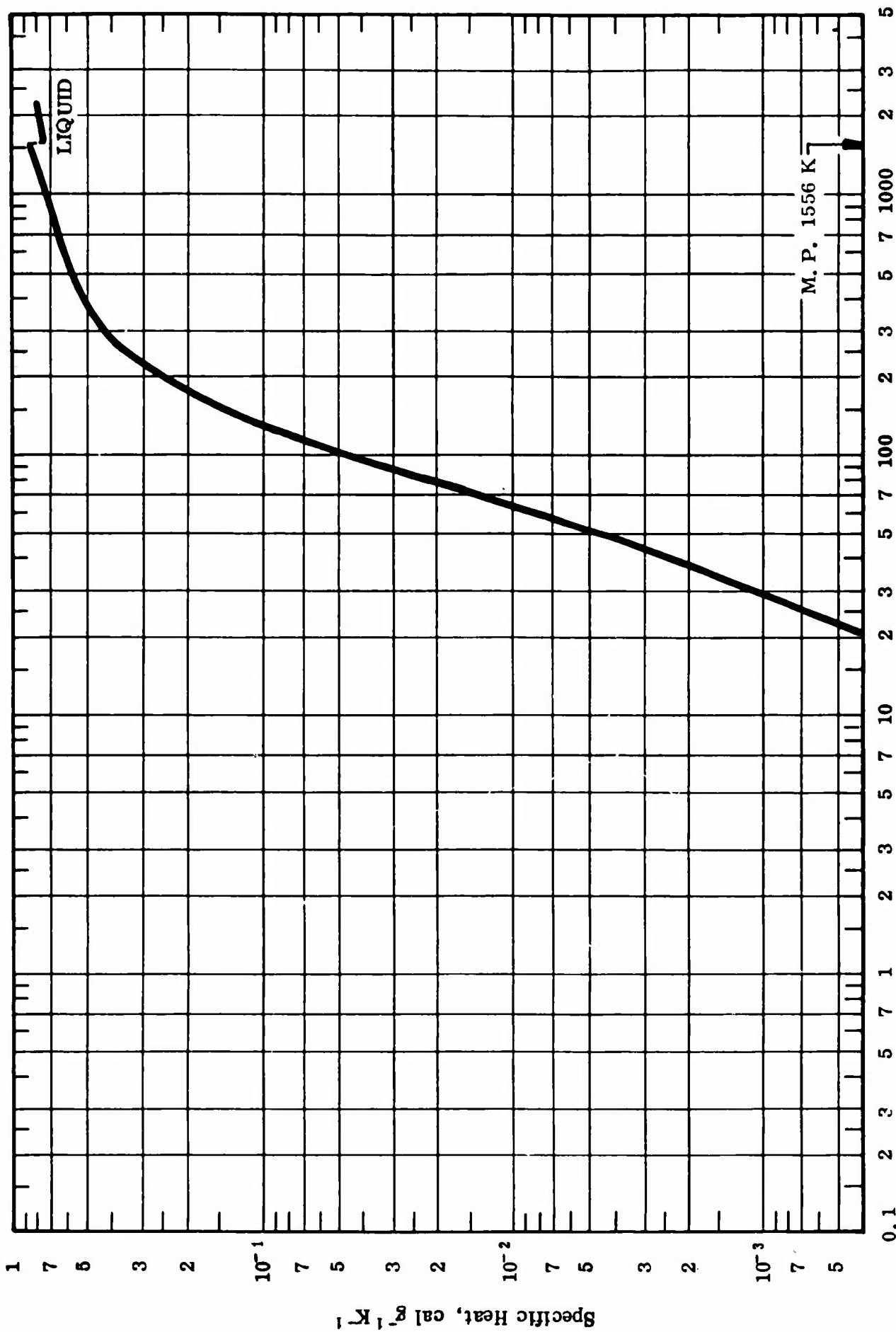


FIG. V - 2 (b)

SPECIFIC HEAT --- BERYLLIUM

TABLE V-2. SPECIFIC HEAT OF BERYLLIUM

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 5    | 3.4 x 10 <sup>-5</sup>                               | 700      | 6.49 x 10 <sup>-1</sup>                              |
| 10   | 9.2  | 800      | 6.73   |
| 20   | 3.83 x 10 <sup>-4</sup>                              | 900      | 6.97   |
| 30   | 1.13 x 10 <sup>-3</sup>                              | 1000     | 7.22   |
| 40   | 2.40   | 1100     | 7.46   |
| 50   | 4.45   | 1200     | 7.70   |
| 60   | 8.14   | 1300     | 7.94   |
| 70   | 1.37 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup>                              | 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]; Mitina, E.A. (23) [323-773K].

*AR*

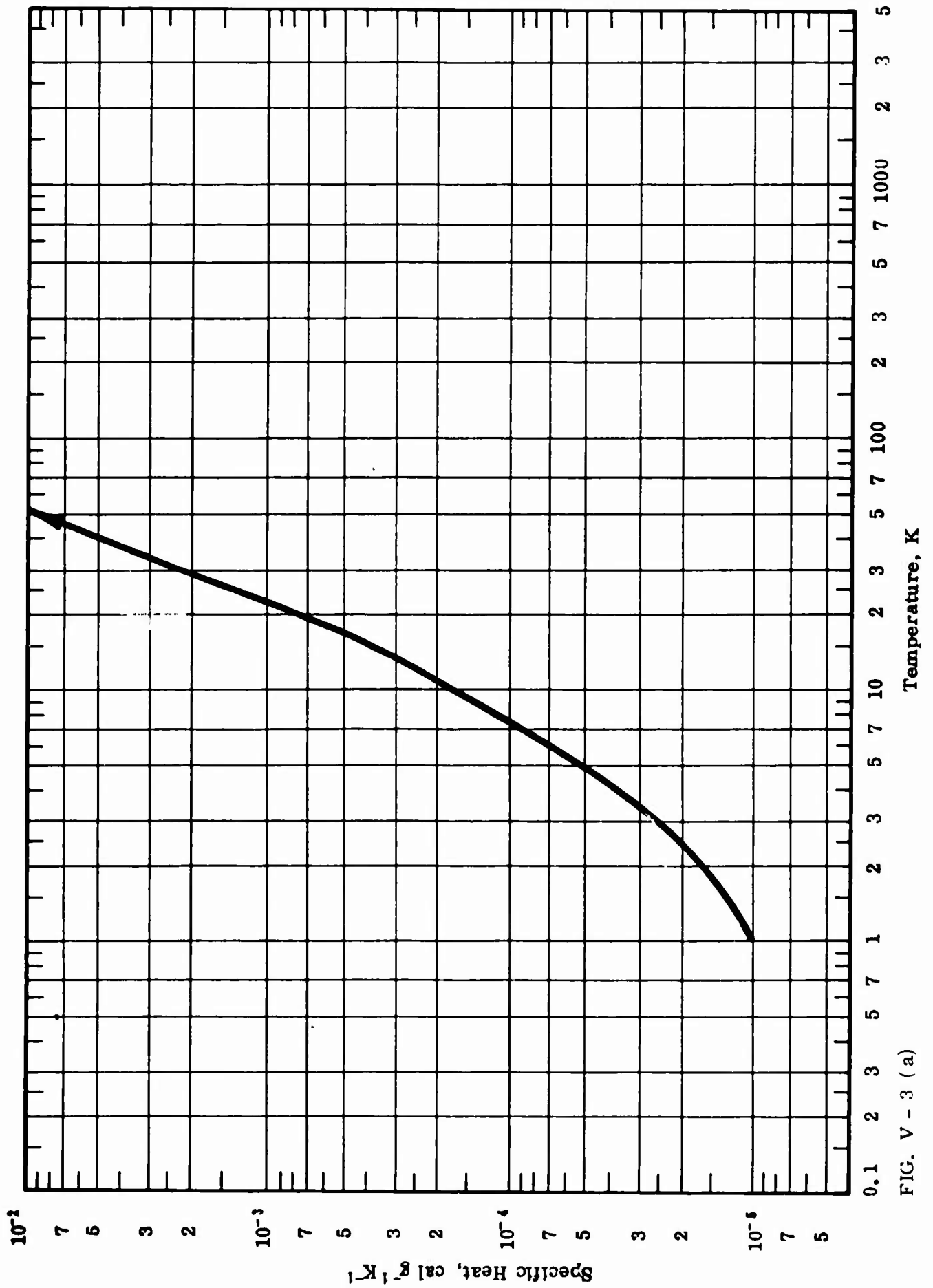


FIG. V - 3 (a)

SPECIFIC HEAT -- CHROMIUM

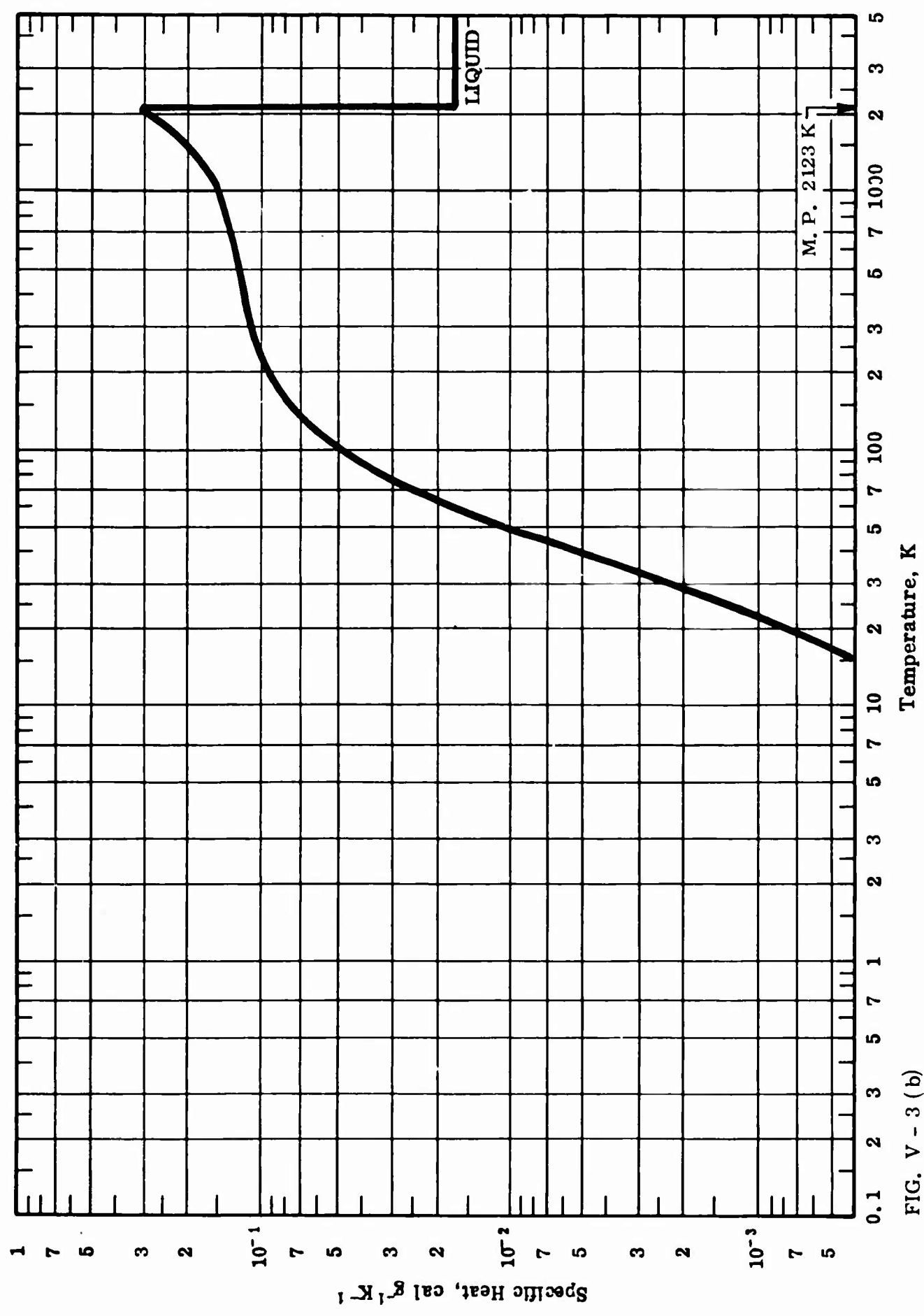


FIG. V - 3 (b)

SPECIFIC HEAT -- CHROMIUM

TABLE V-3. SPECIFIC HEAT OF CHROMIUM

| T°K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T°K      | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|-----|--|----------|--|
| 1   | (1 x 10 <sup>-5</sup> ) <sup>†</sup>                 | 800      | 1.31 x 10 <sup>-1</sup>                              |
| 2   | 1.58   | 900      | 1.38   |
| 3   | 2.50   | 1000     | 1.45   |
| 4   | 3.70   | 1100     | 1.53   |
| 5   | (5.10) <sup>‡</sup>                                  | 1200     | 1.63   |
| 6   | (6.90)   | 1300     | 1.72   |
| 7   | (8.90)   | 1400     | 1.84   |
| 8   | (1.12 x 10 <sup>-4</sup> )                           | 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  | 1.99 x 10 <sup>-3</sup>                              | 2000     | (2.82) <sup>†</sup>                                  |
| 40  | 4.72   | 2100     | (3.03)   |
| 50  | 9.37   | (s) 2123 | (3.18)   |
| 60  | 1.64 x 10 <sup>-2</sup>                              | (l) 2123 | (1.81) <sup>††</sup>                                 |
| 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 x 10 <sup>-1</sup>                              | 2800     | (1.81)   |
| 400 | 1.17   | 2900     | (1.81)   |
| 500 | 1.23   | 3000     | (1.81)   |
| 600 | 1.27   |          |  |
| 700 | 1.28   |          |  |

Investigators: Armstrong, 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].

<sup>†</sup> Extrapolated

<sup>‡</sup> Interpolated

<sup>††</sup> Estimated (5)

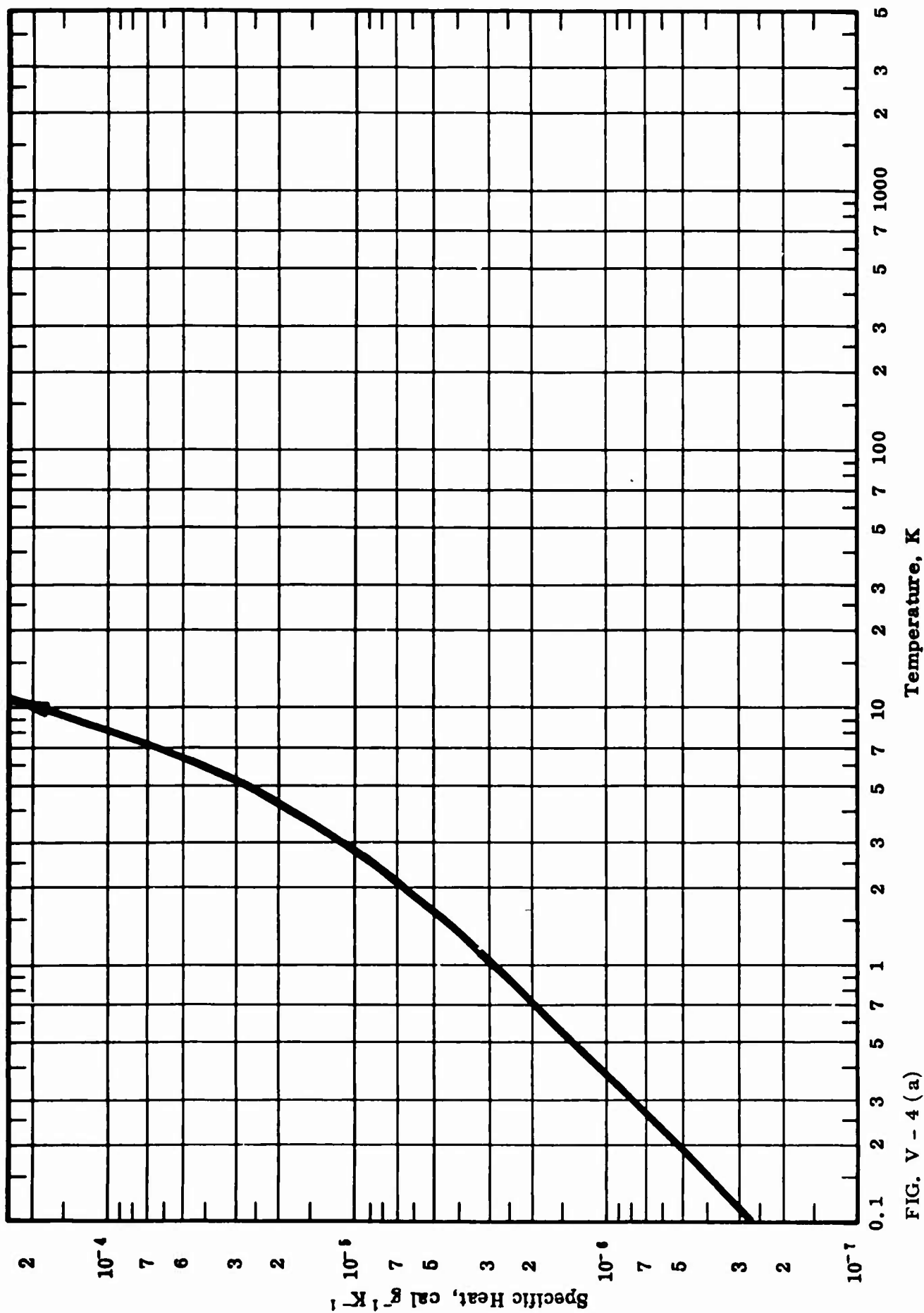


FIG. V - 4 (a)

SPECIFIC HEAT -- COPPER

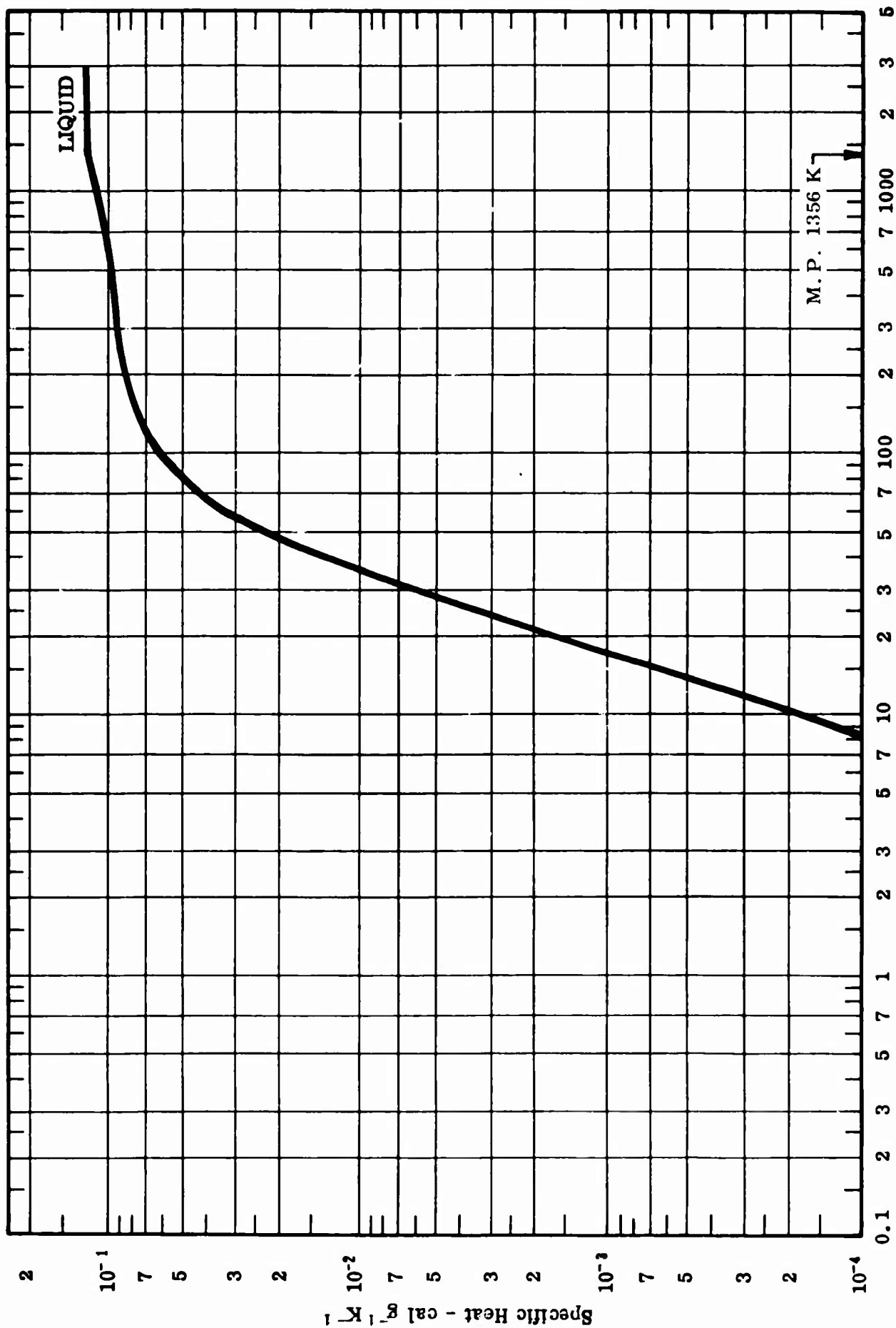


FIG. V - 4 (b)

SPECIFIC HEAT -- COPPER

TABLE V-4. SPECIFIC HEAT OF COPPER

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 0.1  | 2.70 x 10 <sup>-7</sup>                              | 300      | 9.23 x 10 <sup>-2</sup>                              |
| 0.2  | 5.30   | 400      | 9.46   |
| 0.3  | 7.95   | 500      | 9.71   |
| 0.4  | 1.05 x 10 <sup>-6</sup>                              | 600      | 9.95   |
| 0.5  | 1.32   | 700      | 1.02 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-5</sup>                              | (s) 1356 | 1.18   |
| 4    | 2.17   | (l) 1356 | (1.18) <sup>†</sup>                                  |
| 5    | 3.45   | 1400     | (1.18)   |
| 6    | 5.45   | 1500     | (1.18)   |
| 7    | 8.00   | 1600     | (1.18)   |
| 8    | 1.14 x 10 <sup>-4</sup>                              | 1700     | (1.18)   |
| 9    | 1.56   | 1800     | (1.18)   |
| 10   | 2.05   | 1900     | (1.18)   |
| 15   | 6.63   | 2000     | (1.18)   |
| 20   | 1.76 x 10 <sup>-3</sup>                              | 2100     | (1.18)   |
| 30   | 6.53   | 2200     | (1.18)   |
| 40   | 1.42 x 10 <sup>-2</sup>                              | 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]; Giaque, 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];

<sup>†</sup>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].

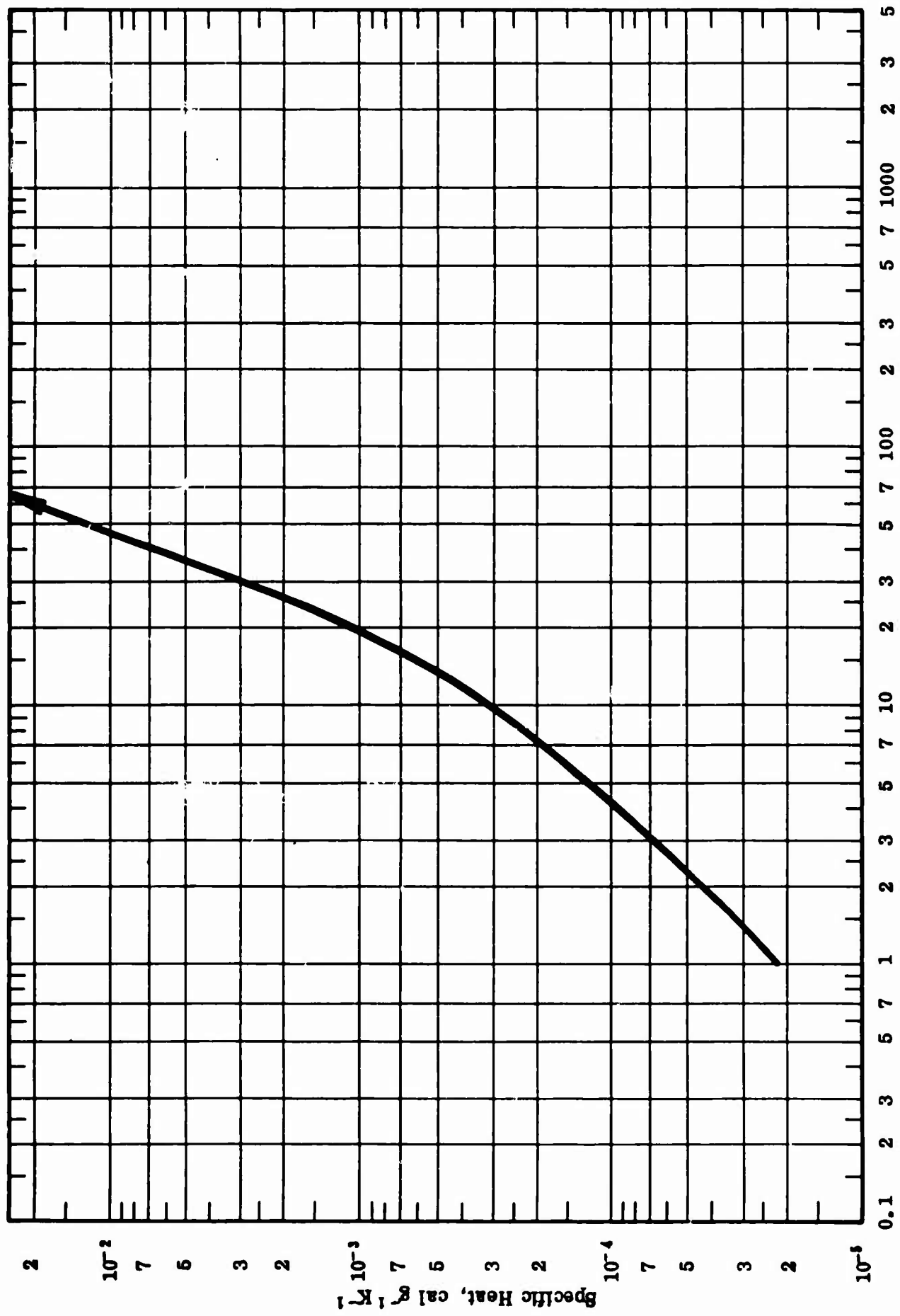


FIG V. - 5 (a)

SPECIFIC HEAT -- IRON

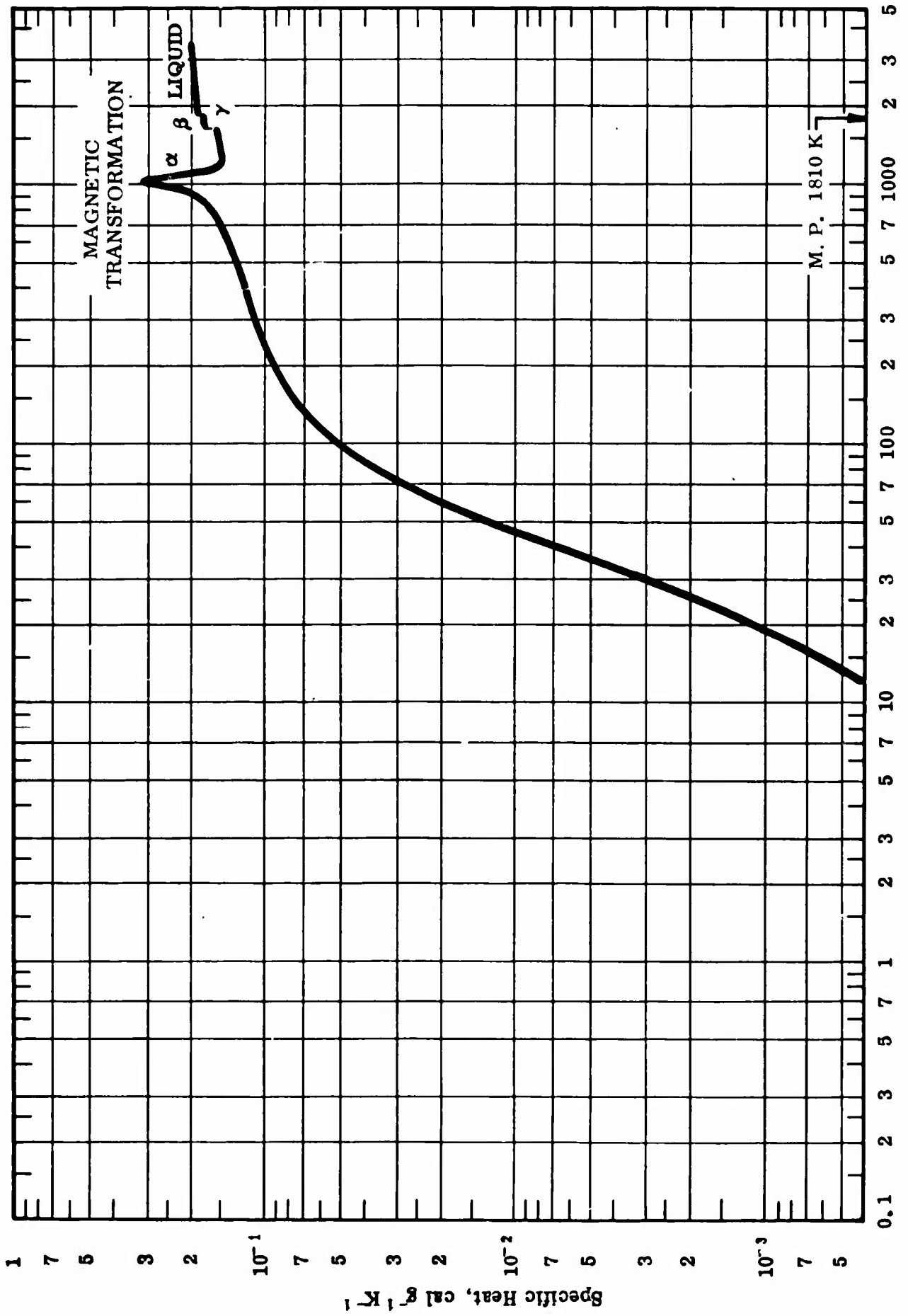


FIG. V - 5 (b)

Temperature, K

SPECIFIC HEAT -- IRON

TABLE V-5. SPECIFIC HEAT OF IRON

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 1    | (2.18 x 10 <sup>-5</sup> ) <sup>†</sup>              | 900      | 1.88 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-4</sup>                              | 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 x 10 <sup>-3</sup>                              | (γ) 1188 | 1.46   |
| 30   | 3.19   | 1200     | 1.46   |
| 40   | 7.09   | 1300     | 1.49   |
| 50   | 1.27 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup>                              | 1900     | 1.89   |
| 300  | 1.08   | 2000     | 1.89   |
| 400  | 1.16   | 2300     | (1.92) <sup>‡</sup>                                  |
| 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.,

<sup>†</sup>Extrapolated

<sup>‡</sup>Estimated (5)

Investigators(continued) (IRON)

(79) [901-923 K]; Picklesimer, M. L. (80) [70-935 K];  
Quinney, H., and Taylor, G. I. (81) [773-973 K]; Rodebush,  
W. H., and Mickalek, J. C. (82) [73-200 K]; Schroder, K.  
(83) [173-623 K]; Trefyakov, 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].

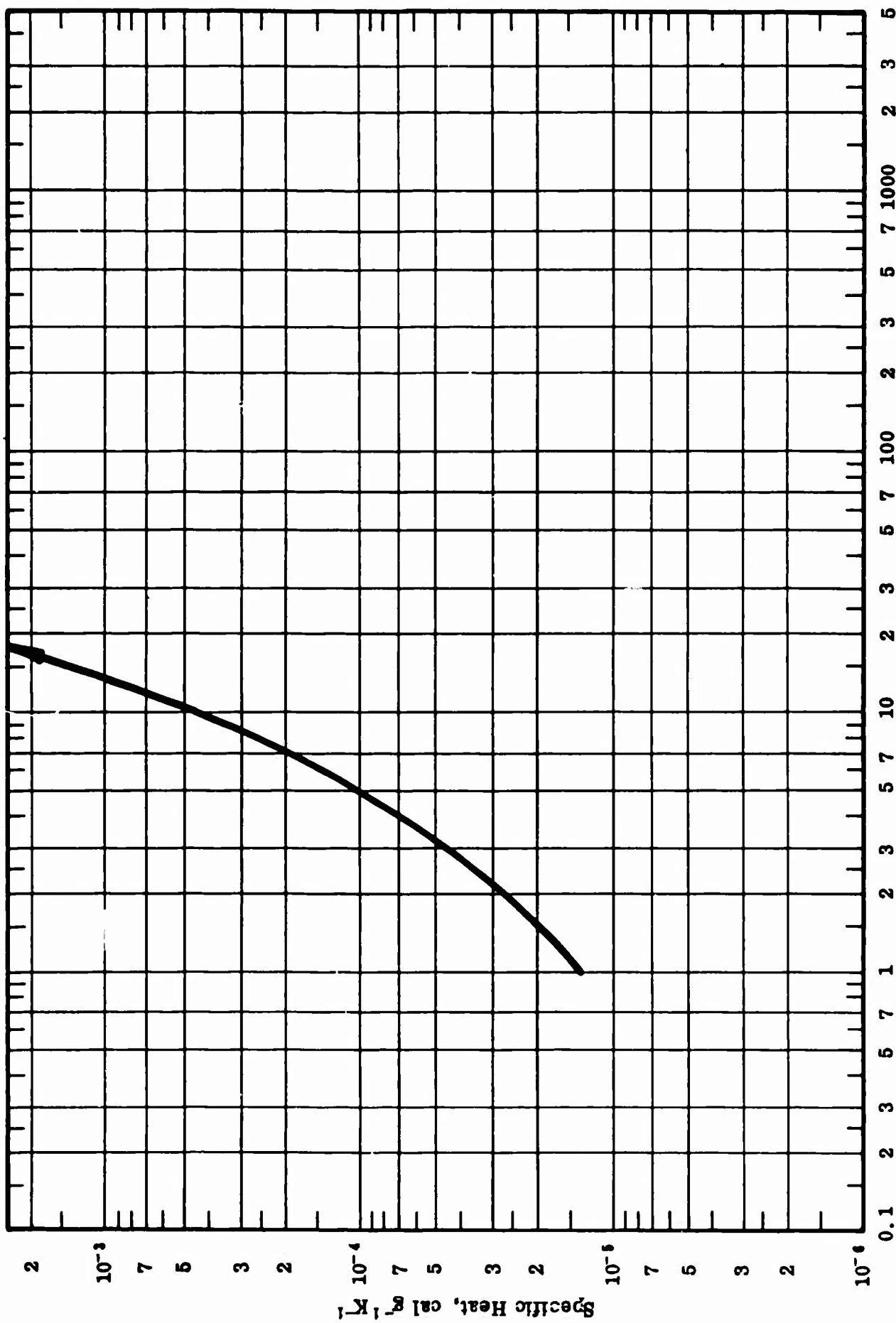


FIG. V - 6 (a)

Temperature, K

SPECIFIC HEAT -- MAGNESIUM

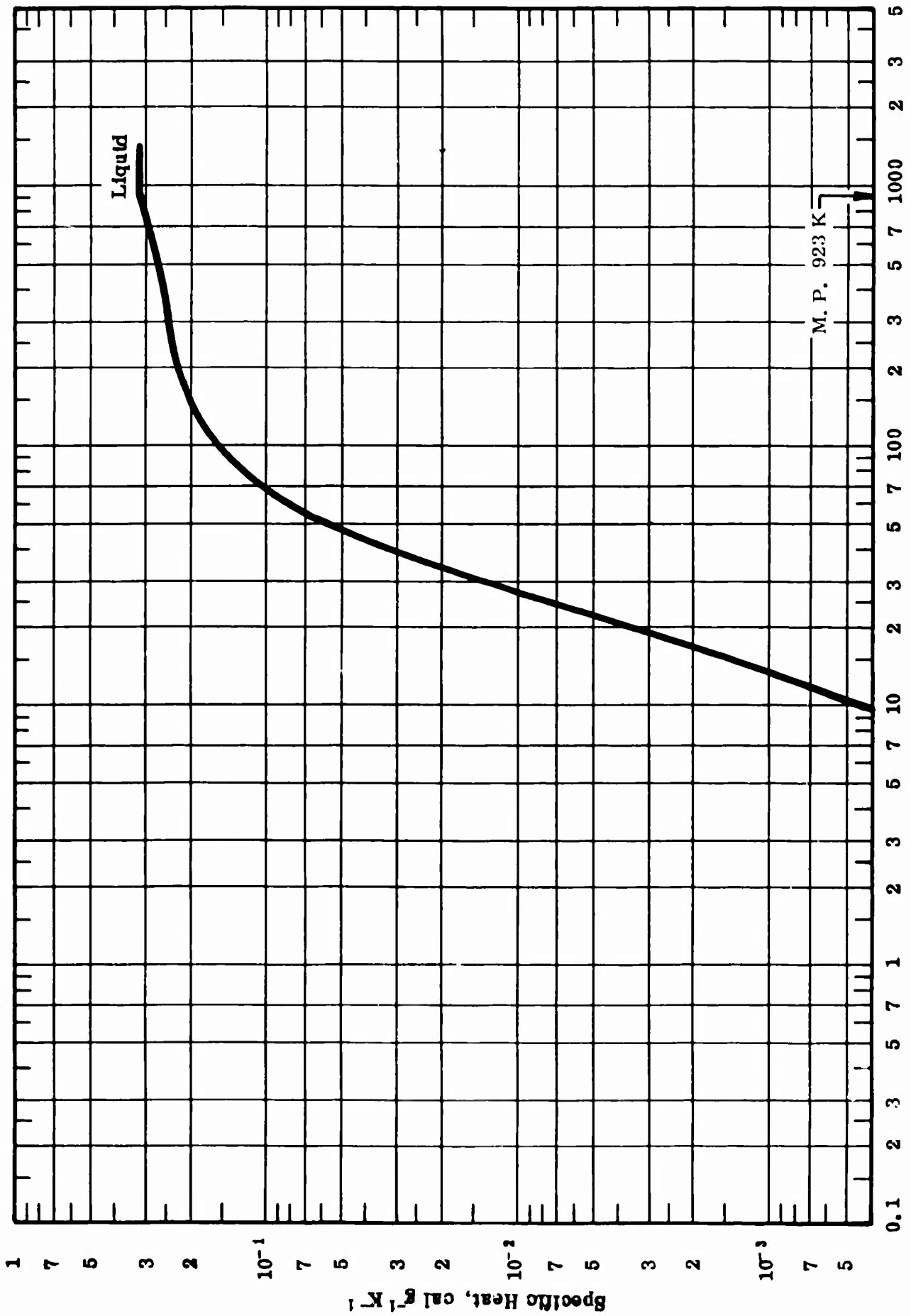


FIG. V - 6 (b)  
Temperature, K  
SPECIFIC HEAT -- MAGNESIUM

TABLE V-6. SPECIFIC HEAT OF MAGNESIUM

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|---------|--|
| 1    | 1.33 x 10 <sup>-5</sup>                              | 200     | 2.23 x 10 <sup>-1</sup>                              |
| 2    | 2.85   | 300     | 2.44   |
| 3    | 4.77   | 400     | 2.57   |
| 4    | 7.32   | 500     | 2.66   |
| 5    | 1.07 x 10 <sup>-4</sup>                              | 600     | 2.78   |
| 10   | 4.52   | 700     | 2.91   |
| 20   | 3.55 x 10 <sup>-3</sup>                              | 800     | 3.05   |
| 30   | 1.40 x 10 <sup>-2</sup>                              | 900     | 3.21   |
| 40   | 3.31   | (s) 923 | 3.23   |
| 50   | 5.67   | (l) 923 | (3.20) <sup>†</sup>                                  |
| 60   | 8.03   | 1000    | (3.20)   |
| 70   | 1.03 x 10 <sup>-1</sup>                              | 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) [11-222K]; 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) [273-873K]; 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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<sup>†</sup>Estimated (5)

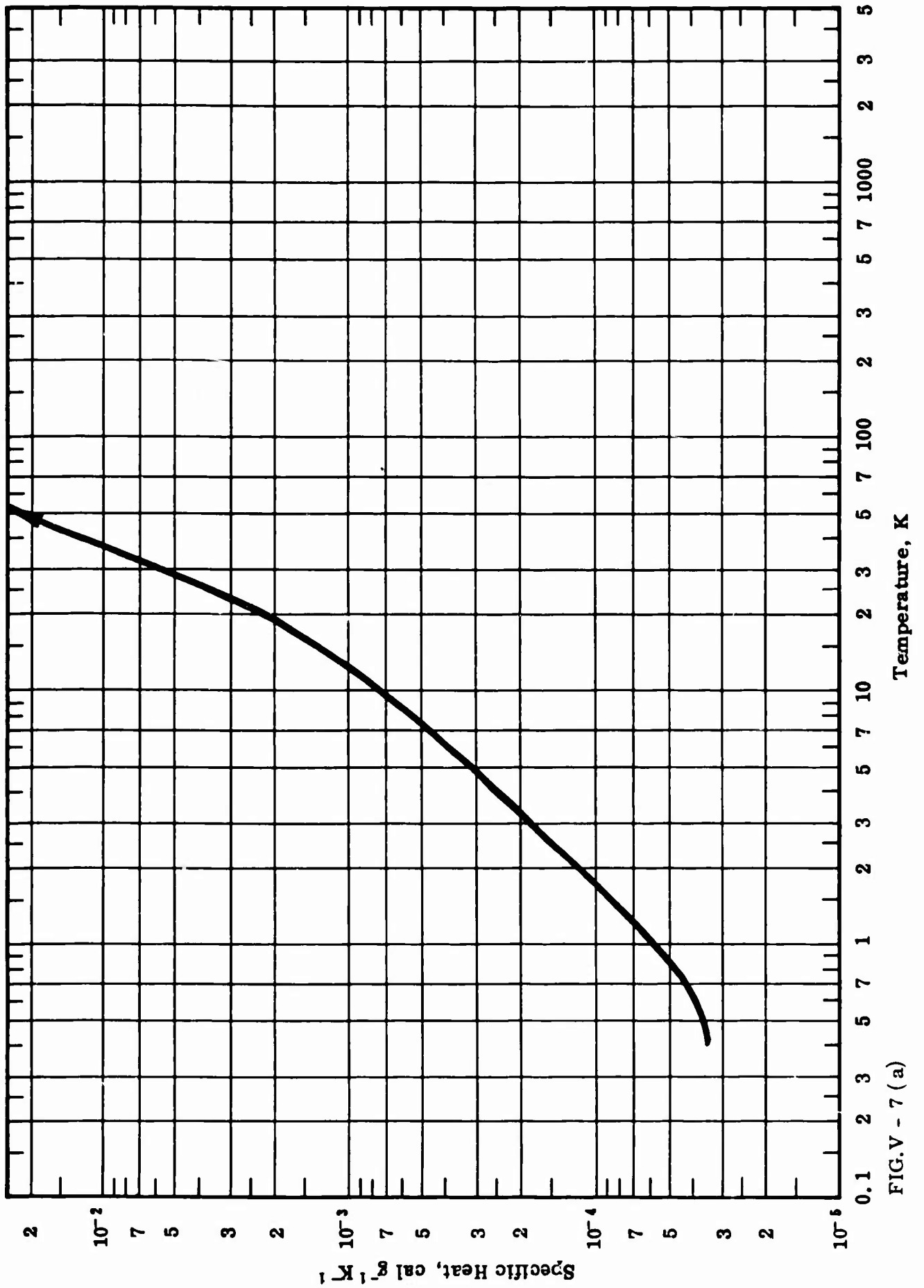


FIG.V - 7 (a)

SPECIFIC HEAT -- MANGANESE

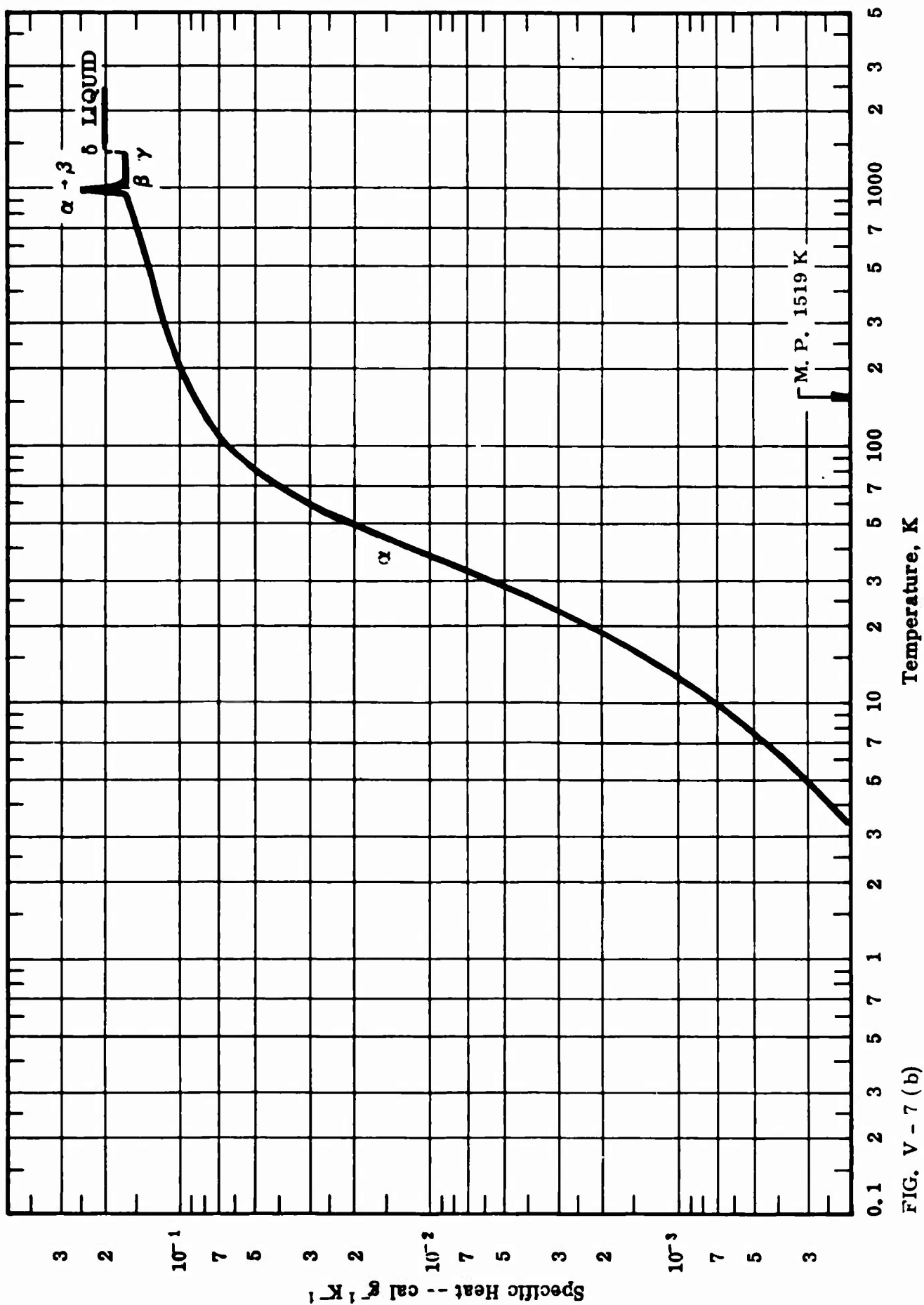


FIG. V - 7 (b)

SPECIFIC HEAT -- MANGANESE

TABLE V-7. SPECIFIC HEAT OF MANGANESE

| T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|----------|--|--------|--|
| (α) 0.4  | 3.48 x 10 <sup>-5</sup>                              |        |  |
| 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 x 10 <sup>-4</sup>                              |        |  |
| 2.0      | 1.20   |        |  |
| 3.0      | (1.82) <sup>††</sup>                                 |        |  |
| 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 x 10 <sup>-4</sup>                              |
| 15       | 1.31 x 10 <sup>-3</sup>                              | 15     | 1.22 x 10 <sup>-3</sup>                              |
| 20       | 2.13   | 20     | 2.22   |
| 30       | 5.72   | 30     | 6.30   |
| 40       | 1.21 x 10 <sup>-2</sup>                              | 40     | 1.35 x 10 <sup>-2</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 200    | 1.03 x 10 <sup>-1</sup>                              |
| 300      | 1.15   | 300    | 1.21   |
| 400      | 1.24   | 400    | (1.31) <sup>‡</sup>                                  |
| 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 x 10 <sup>-1</sup>                              |        |  |
| 1100     | 1.65   | 1100   | (1.80)   |

† Extrapolated  
‡ Estimated (5)  
†† Interpolated

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

| T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|----------|--|----------|--|
| (β) 1200 | 1.66 x 10 <sup>-1</sup>                              | (γ) 1200 | (1.87 x 10 <sup>-1</sup> )                           |
| 1300     | 1.67   | 1300     | (1.94)   |
| (β) 1374 | 1.68   |          |  |
| (γ) 1374 | 1.95 x 10 <sup>-1</sup>                              |          |  |
| 1400     | 1.95   |          |  |
| (γ) 1410 | 1.95   |          |  |
| (δ) 1410 | 2.06 x 10 <sup>-1</sup>                              |          |  |
| 1500     | 2.06   |          |  |
| (δ) 1517 | 2.06   |          |  |
| (l) 1517 | (2.00 x 10 <sup>-1</sup> ) <sup>‡</sup>              |          |  |
| 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: <sup>✓</sup>Armstrong, L. D., and Grayson-Smith, H. (100) [273-1073K];  
<sup>✓</sup>Armstrong, 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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<sup>‡</sup>Estimated (5)

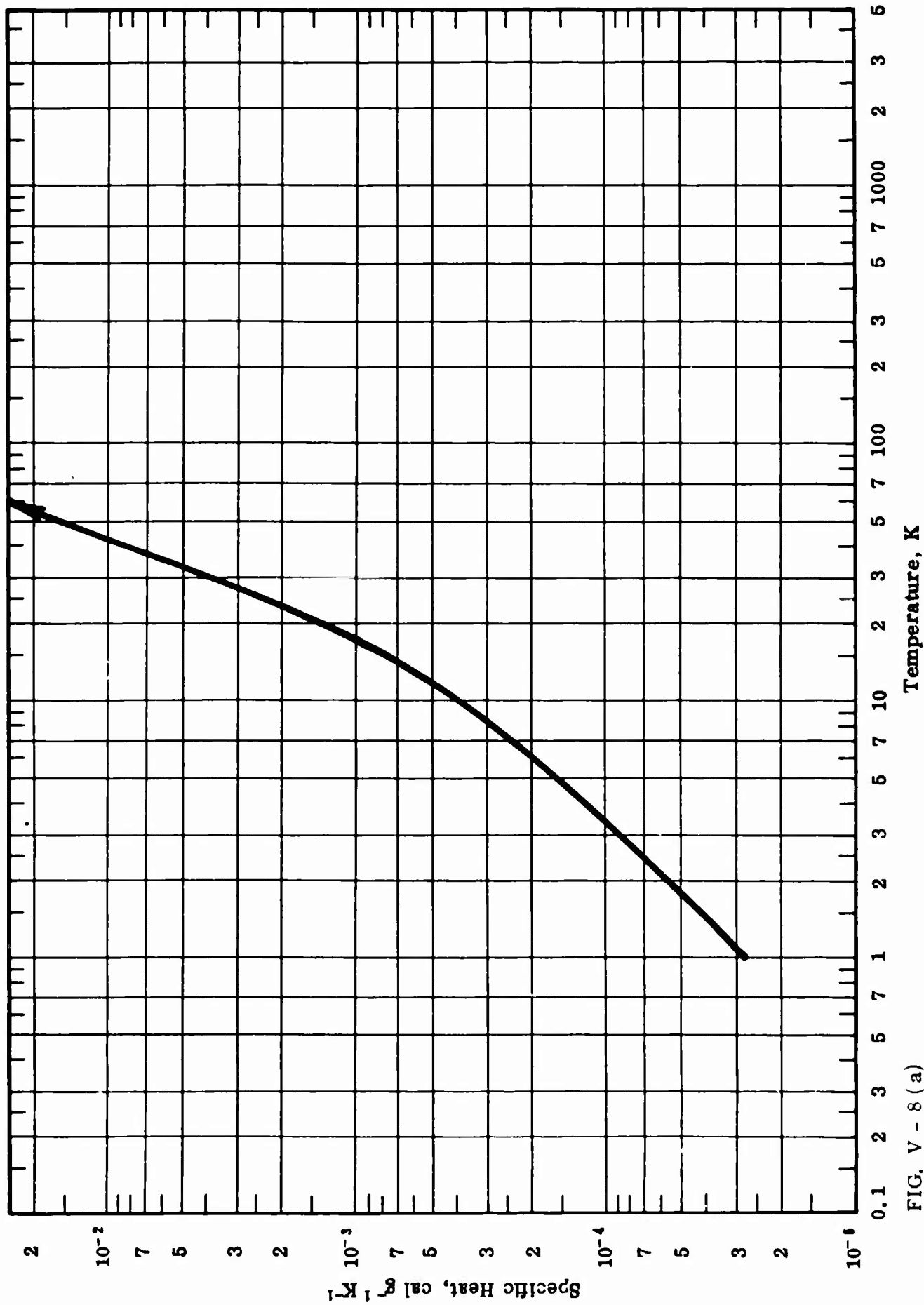


FIG. V - 8 (a)

SPECIFIC HEAT --- NICKEL

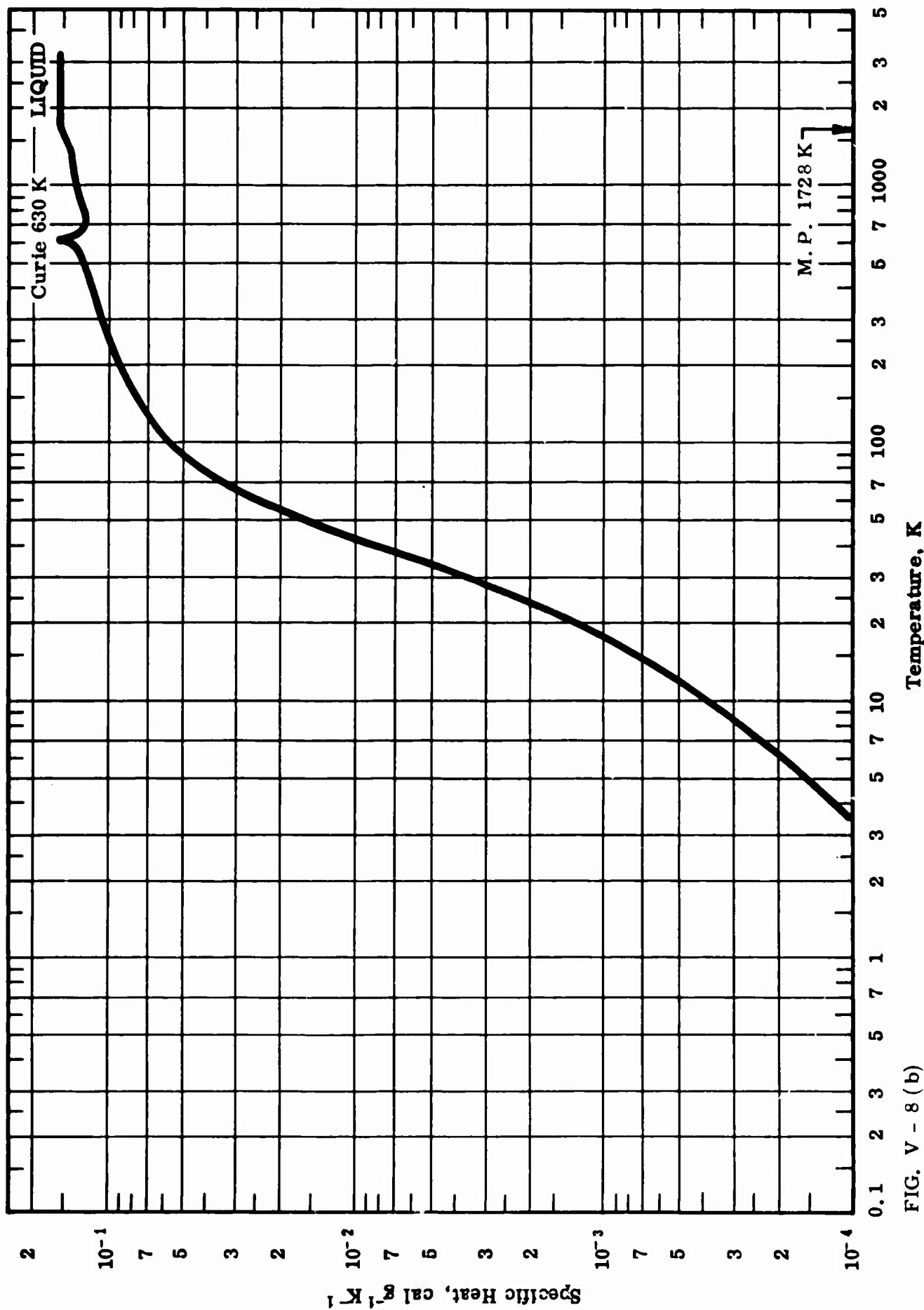


FIG. V - 8 (b)

SPECIFIC HEAT -- NICKEL

TABLE V-8. SPECIFIC HEAT OF NICKEL

| T ° K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T ° K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|-------|--|----------|--|
| 1     | 2.88 x 10 <sup>-5</sup>                              | 640      | 1.34 x 10 <sup>-1</sup>                              |
| 2     | 5.79   | 650      | 1.30   |
| 3     | 8.84   | 700      | 1.26   |
| 4     | 1.20 x 10 <sup>-4</sup>                              | 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) <sup>†</sup>                                  |
| 20    | 1.31 x 10 <sup>-3</sup>                              | 1600     | (1.51)   |
| 30    | 3.93   | 1700     | (1.54)   |
| 40    | 9.04   | (s) 1728 | (1.54)   |
| 50    | 1.63 x 10 <sup>-2</sup>                              | (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 x 10 <sup>-1</sup>                              | 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]; Hultgren, 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];

<sup>†</sup>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].

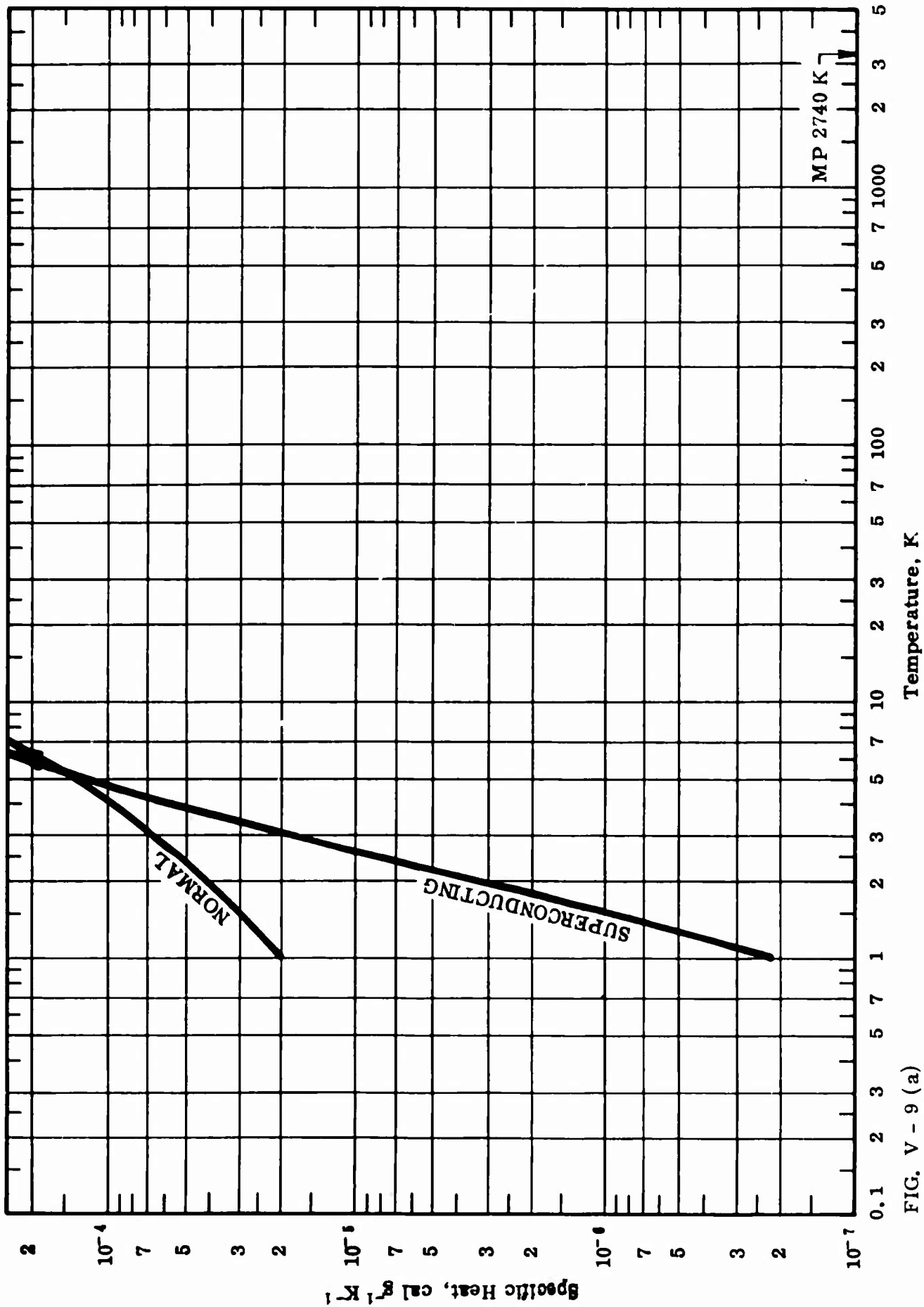


FIG. V - 9 (a)

SPECIFIC HEAT --- NIOBIUM

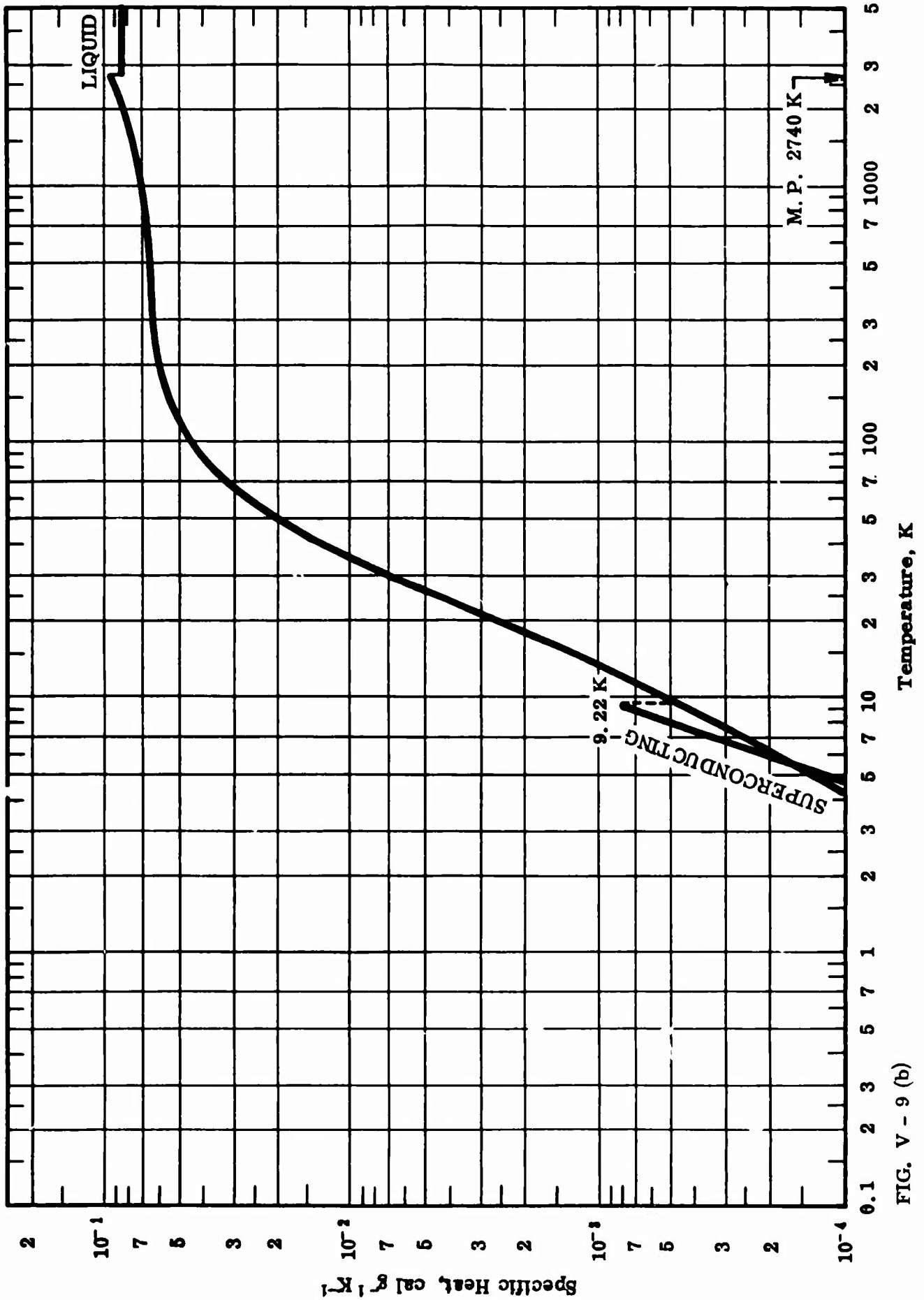


FIG. V - 9 (b)

SPECIFIC HEAT -- NIOBIUM

TABLE V-9. SPECIFIC HEAT OF NIOBIUM

| NORMAL |  | SUPERCONDUCTING                                      |          |  |
|--------|--|--|----------|--|
| T °K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 1      | 1.97 x 10 <sup>-5</sup>                              | 2.2 x 10 <sup>-7</sup>                               | 800      | 6.93 x 10 <sup>-2</sup>                              |
| 2      | 4.13   | 3.6 x 10 <sup>-6</sup>                               | 900      | 7.03   |
| 3      | 6.72   | 2.1 x 10 <sup>-5</sup>                               | 1000     | 7.14   |
| 4      | 9.90   | 6.29   | 1100     | 7.23   |
| 5      | 1.39 x 10 <sup>-4</sup>                              | 1.32 x 10 <sup>-4</sup>                              | 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 x 10 <sup>-3</sup>                              |  | 1900     | (8.30) <sup>†</sup>                                  |
| 20     | 2.52   |  | 2000     | (8.40)   |
| 30     | 6.96   |  | 2100     | (8.50)   |
| 40     | 1.33 x 10 <sup>-2</sup>                              |  | 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 x 10 <sup>-2</sup> ) <sup>‡</sup>              |
| 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]; ~~Wagner~~, F.H., and Veenstra, W.A. (137) [273-1873K]. *Taeger*

<sup>†</sup> Extrapolated

<sup>‡</sup> Estimated (5)

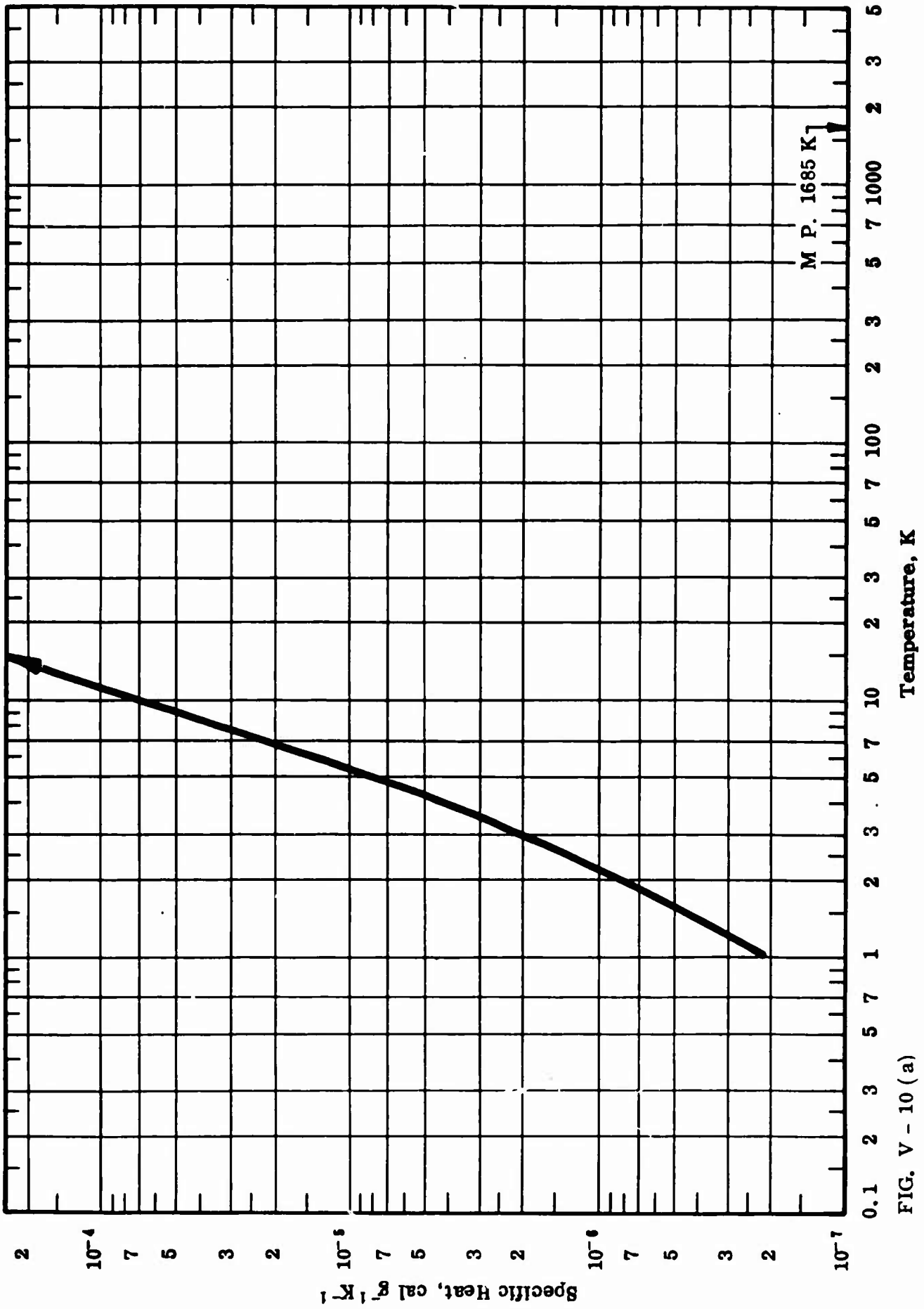


FIG. V - 10 (a)

SPECIFIC HEAT -- SILICON

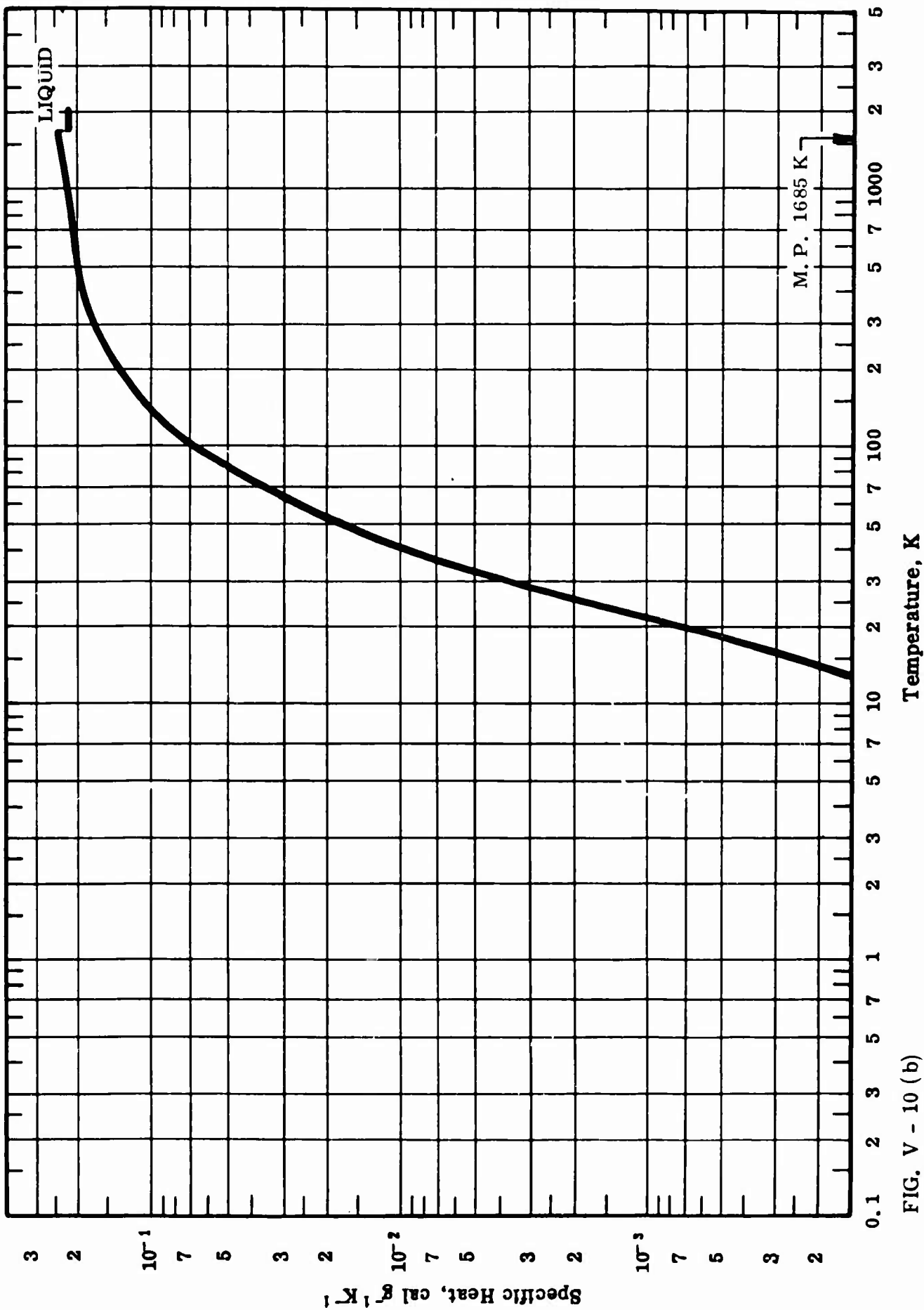


FIG. V - 10 (b)

SPECIFIC HEAT -- SILICON

TABLE V- 10. SPECIFIC HEAT OF SILICON

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 1    | (2.18 x 10 <sup>-7</sup> ) <sup>†</sup>              | 200      | 1.33 x 10 <sup>-1</sup>                              |
| 1.5  | (4.58)   | 300      | 1.72   |
| 2    | 8.07   | 400      | 1.88   |
| 3    | 2.08 x 10 <sup>-6</sup>                              | 500      | 1.97   |
| 4    | 4.40   | 600      | 2.04   |
| 5    | 8.10   | 700      | 2.08   |
| 6    | 1.38 x 10 <sup>-5</sup>                              | 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 x 10 <sup>-4</sup>                              | 1300     | 2.30   |
| 20   | 8.00   | 1400     | 2.35   |
| 30   | 4.08 x 10 <sup>-3</sup>                              | 1500     | 2.38   |
| 40   | 1.05 x 10 <sup>-2</sup>                              | 1600     | 2.42   |
| 50   | 1.86   | (s) 1885 | 2.46   |
| 60   | 2.75   | (l) 1685 | (2.17 x 10 <sup>-1</sup> ) <sup>‡</sup>              |
| 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 x 10 <sup>-1</sup>                              |          |  |

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

<sup>†</sup> Extrapolated

<sup>‡</sup> Estimated (5)

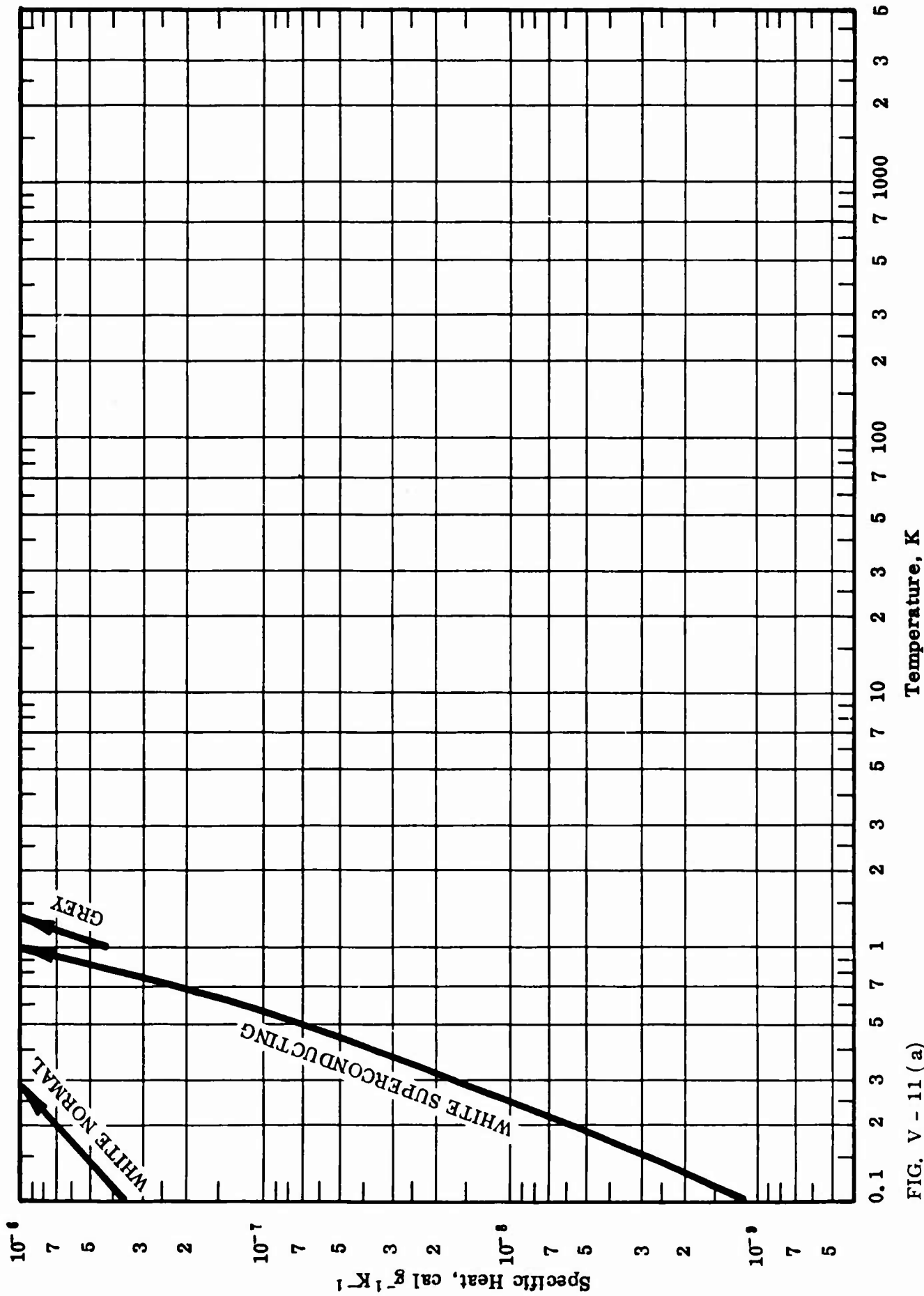


FIG. V - 11 (a)

SPECIFIC HEAT -- TIN

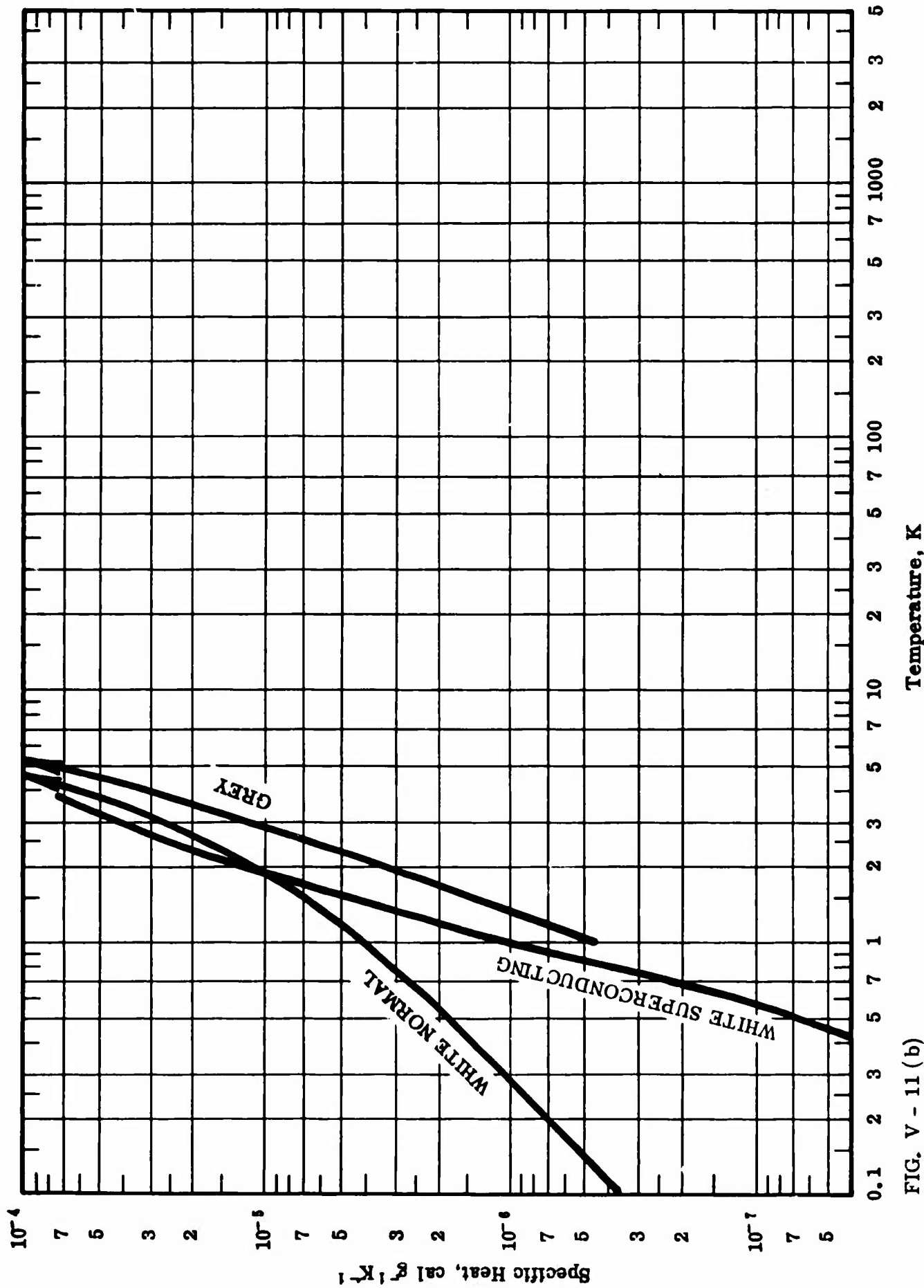
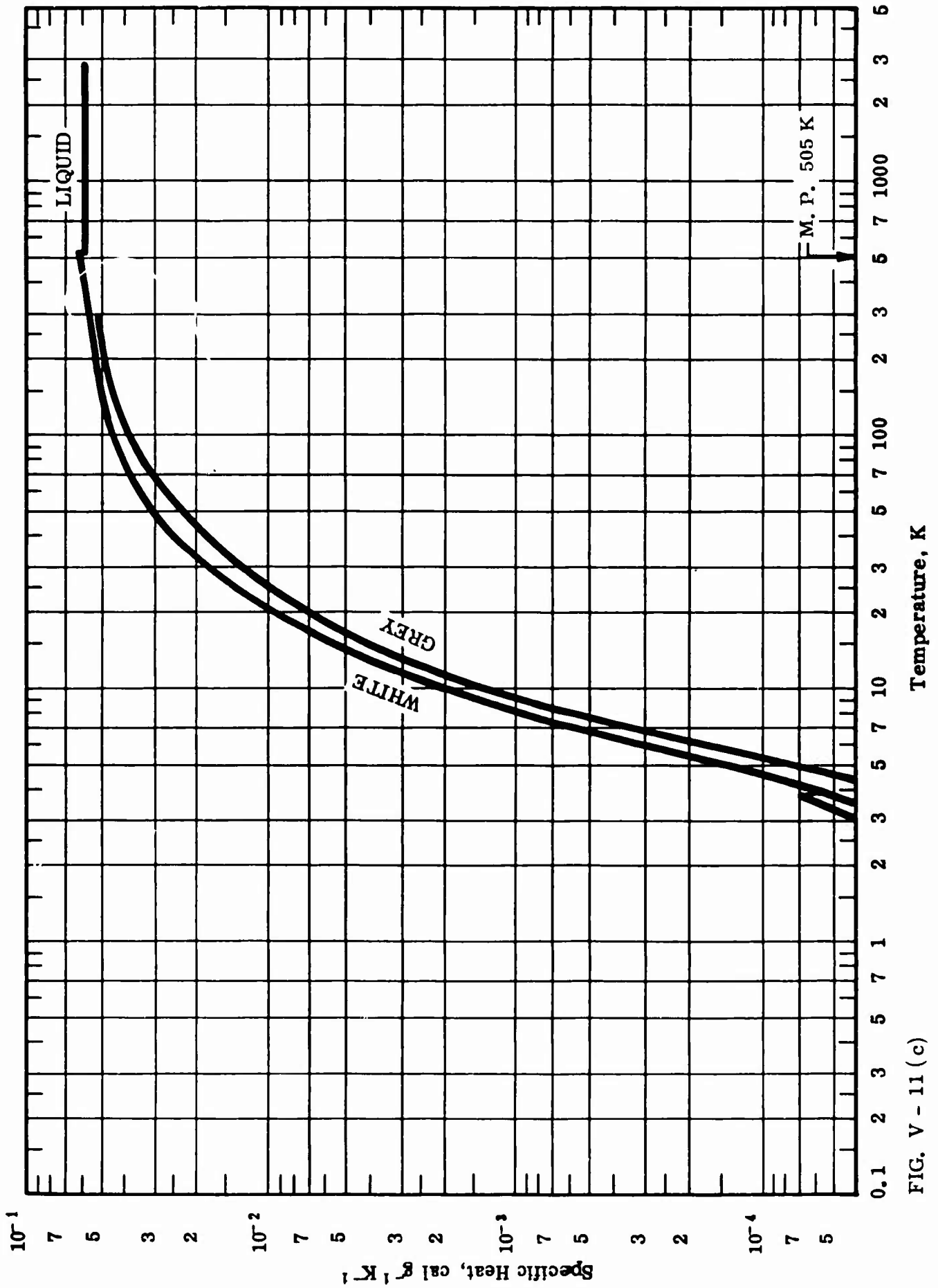


FIG. V - 11 (b)

SPECIFIC HEAT --- TIN



Temperature, K

FIG. V - 11 (c)

SPECIFIC HEAT -- TIN

**TABLE V-11. SPECIFIC HEAT OF TIN**

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

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

| T °K    | WHITE NORMAL<br>C <sub>p</sub> cal g <sup>-1</sup> K <sup>-1</sup> | WHITE SUPERCONDUCTING<br>C <sub>p</sub> cal g <sup>-1</sup> K <sup>-1</sup> | GREY<br>C <sub>p</sub> cal g <sup>-1</sup> K <sup>-1</sup> |
|---------|--|---|--|
| 50      | 3.10 x 10 <sup>-2</sup>  |   | 2.25 x 10 <sup>-2</sup>                                    |
| 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   |   |  |
| (1) 505 | (6.00 x 10 <sup>-2</sup> ) <sup>†</sup>                            |   |  |
| 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)   |   |  |

<sup>†</sup> 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].

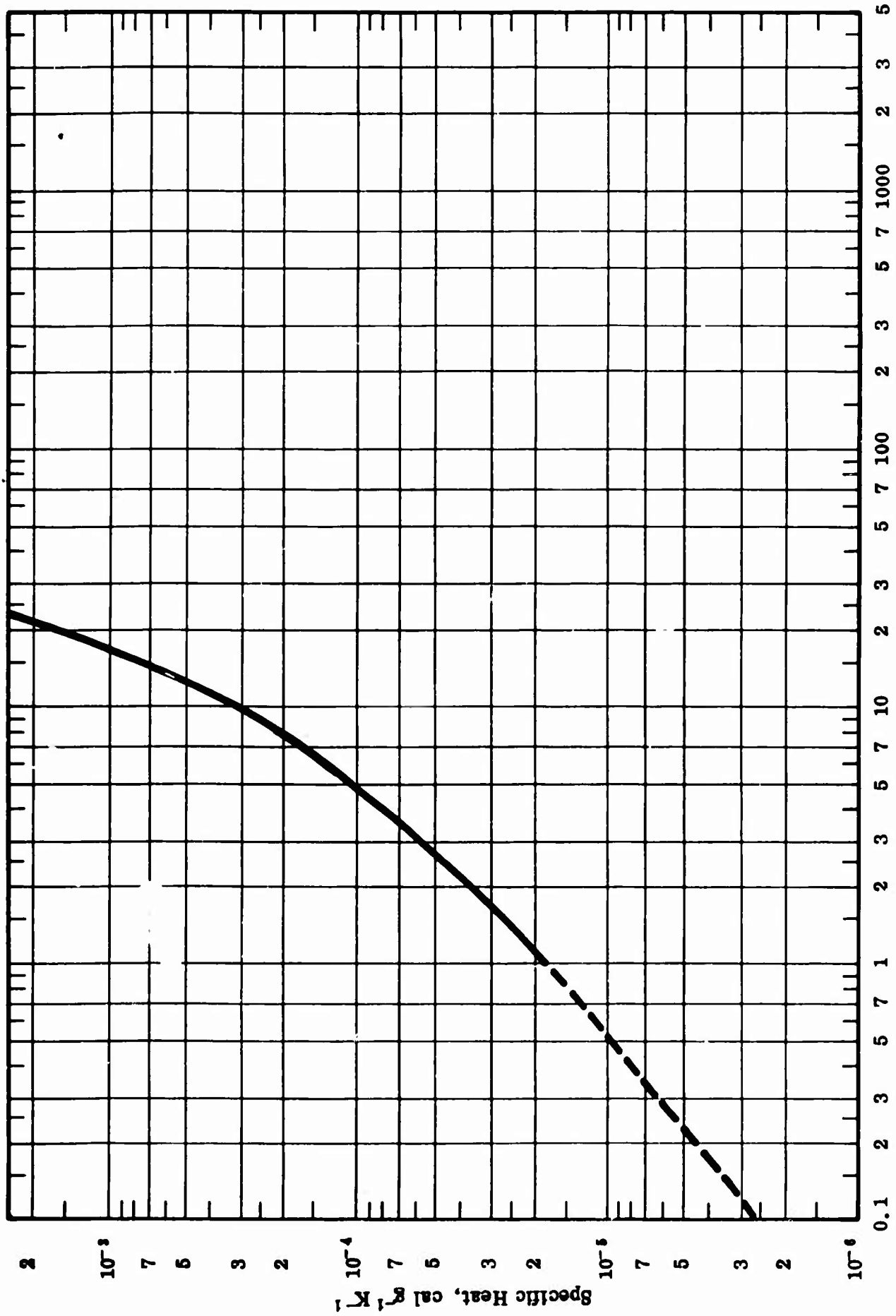


FIG. V - 12 (a)

SPECIFIC HEAT -- TITANIUM

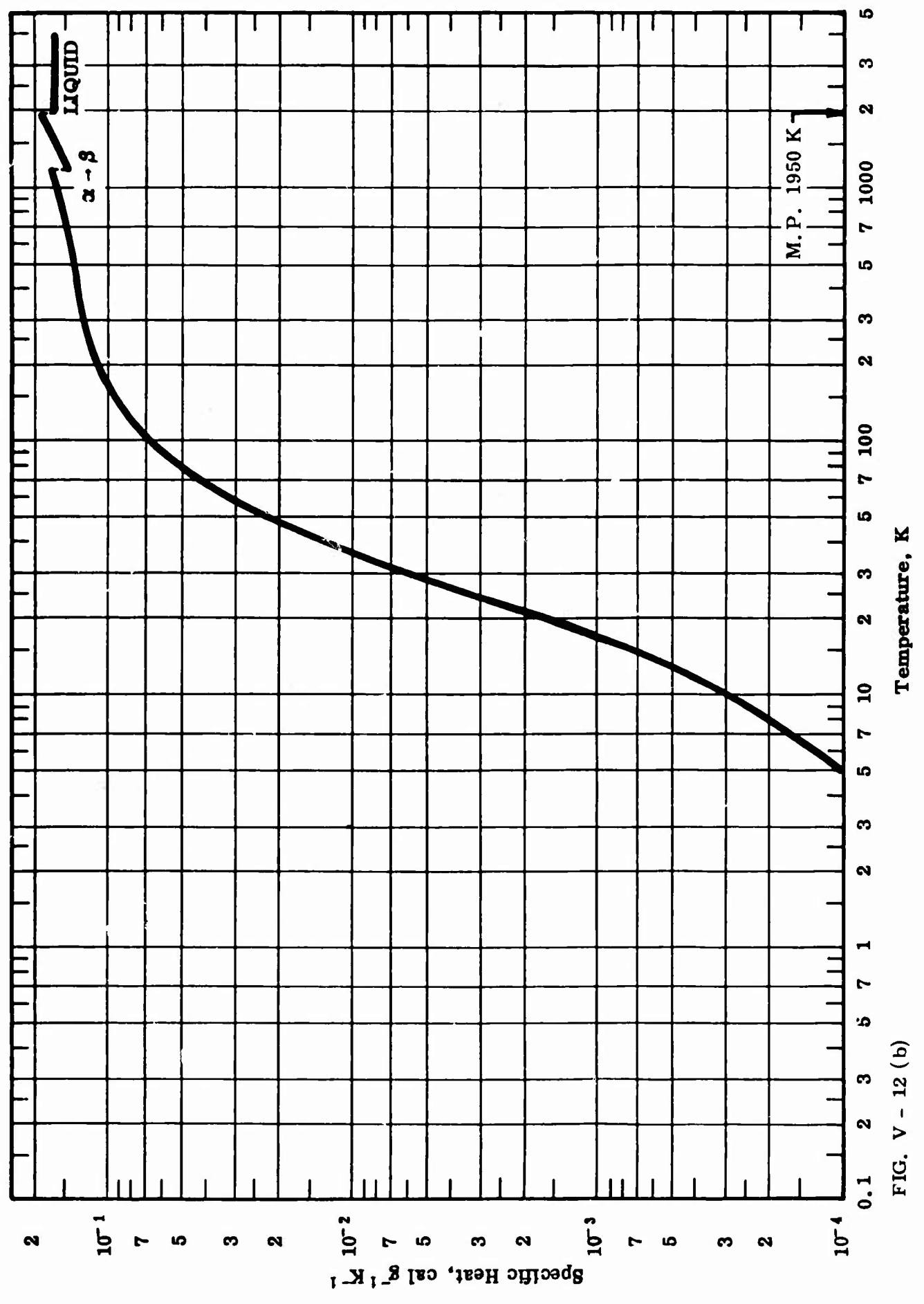


FIG. V - 12 (b)

SPECIFIC HEAT -- TITANIUM

TABLE V-12. SPECIFIC HEAT OF TITANIUM

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|----------|--|
| 1    | 1.78 x 10 <sup>-5</sup>                              | 600      | 1.42 x 10 <sup>-1</sup>                              |
| 2    | 3.63   | 700      | 1.47   |
| 3    | 5.63   | 800      | 1.52   |
| 4    | 7.85   | 900      | 1.57   |
| 5    | 1.03 x 10 <sup>-4</sup>                              | 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 x 10 <sup>-3</sup>                              | 1500     | 1.63   |
| 30   | 5.85   | 1600     | 1.68   |
| 40   | 1.34 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup> )†                          |
| 90   | 6.50   | 2000     | (1.67)   |
| 100  | 7.12   | 2200     | (1.67)   |
| 150  | 9.71   | 2400     | (1.67)   |
| 200  | 1.11 x 10 <sup>-1</sup>                              | 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) [343-1603K]; Rea, J. A. (169) [422-977K]; Serebryannikov, N. N., and ~~Gard~~ P. V. (170) [294-1923K]; Scott, J. L. (171) [323-1273K]; Wolcott, N. M. (172) [1.2-21K].

† Estimated (5)

*field*

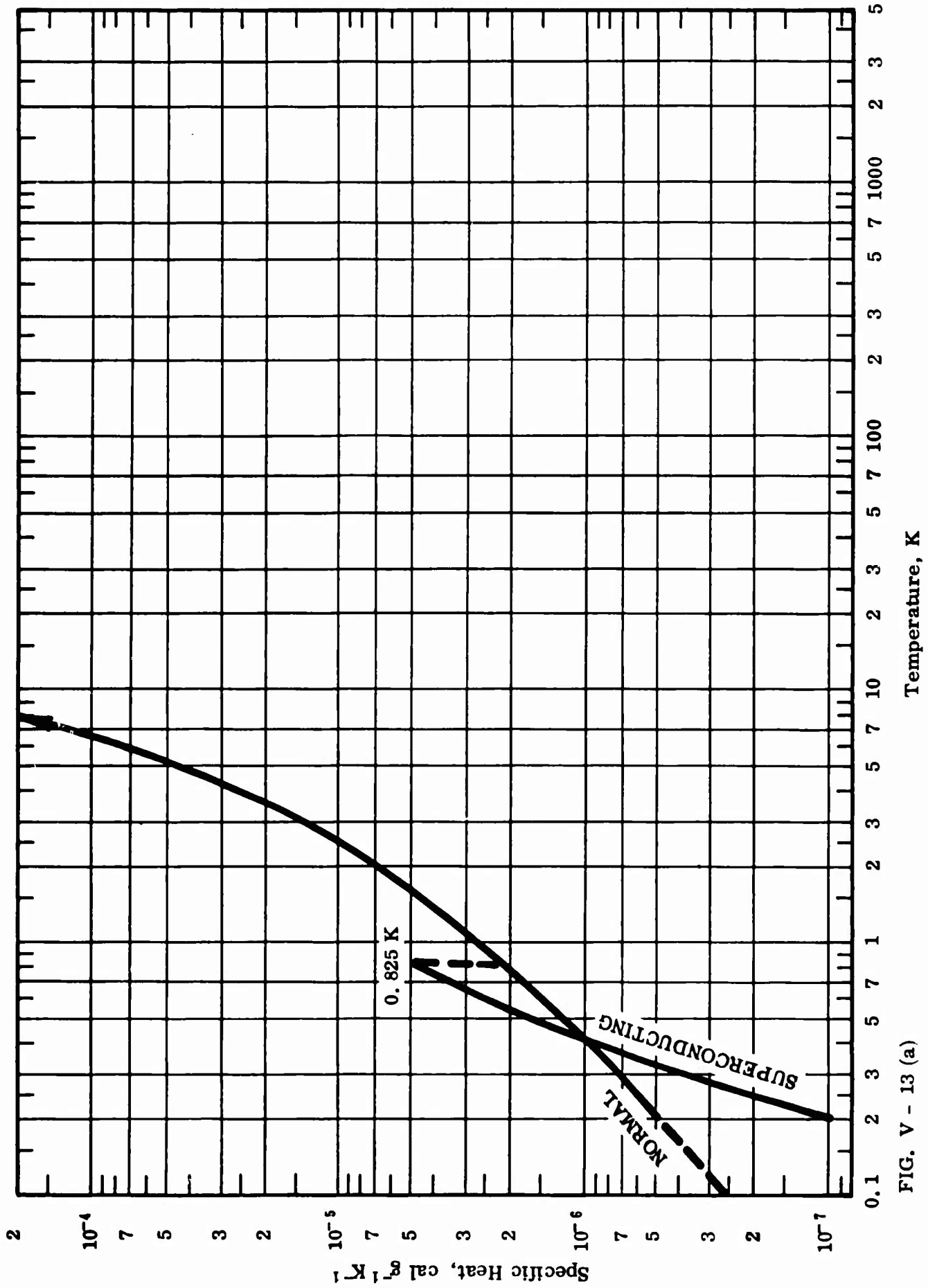


FIG. V - 13 (a)  
SPECIFIC HEAT -- ZINC

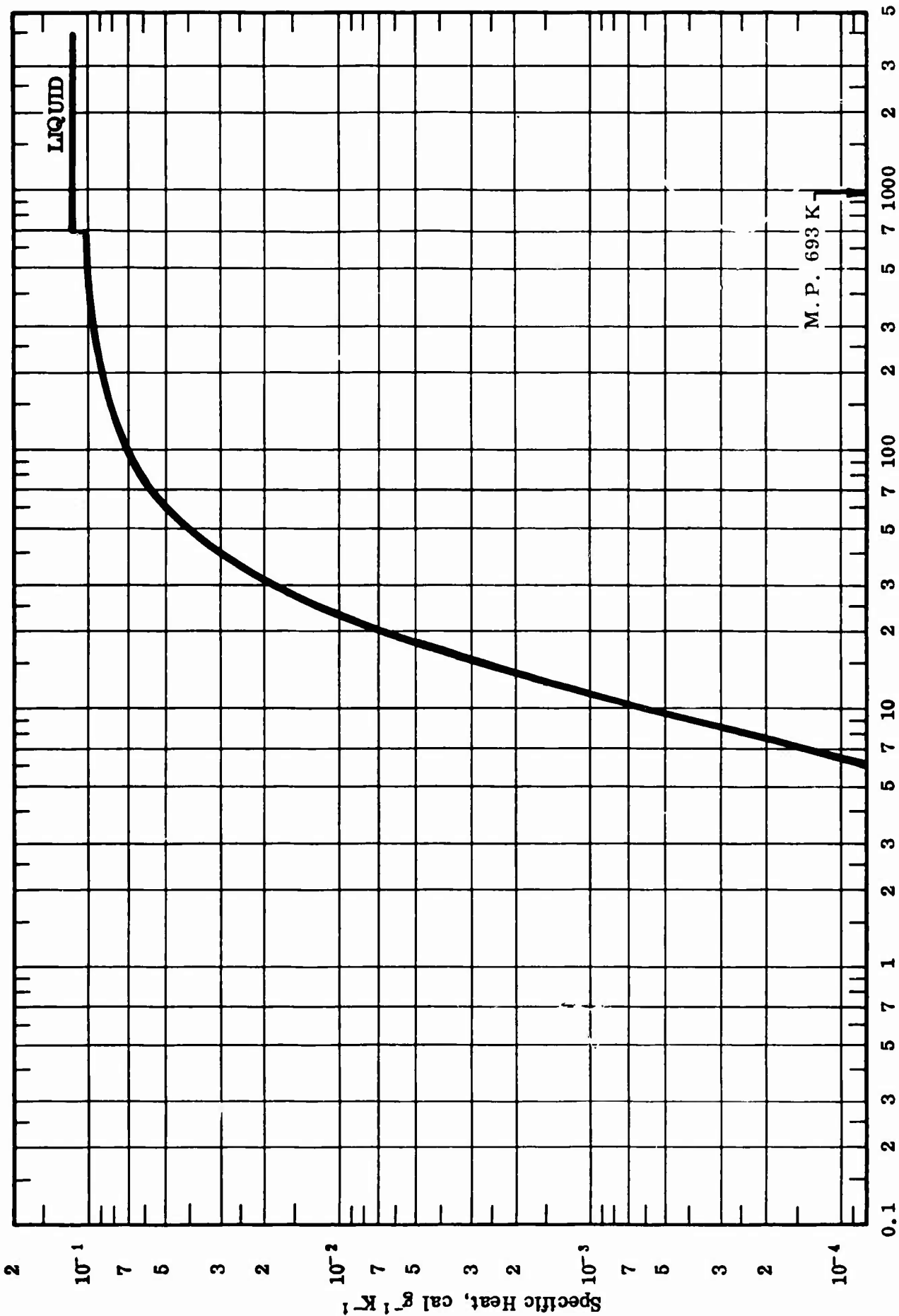


FIG. V - 13 (b)

SPECIFIC HEAT -- ZINC

TABLE V-12. SPECIFIC HEAT OF ZINC

| NORMAL |  | SUPERCONDUCTING                                      |         |  |
|--------|--|--|---------|--|
| T °K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 0.1    | 2.46 x 10 <sup>-7</sup>                              |  | 40      | 2.98 x 10 <sup>-2</sup>                              |
| 0.2    | 4.85   | 9.5 x 10 <sup>-8</sup>                               | 50      | 4.05   |
| 0.3    | 7.30   | 4.2 x 10 <sup>-7</sup>                               | 60      | 4.90   |
| 0.4    | 9.82   | 9.78 x 10 <sup>-7</sup>                              | 70      | 5.60   |
| 0.5    | 1.25 x 10 <sup>-6</sup>                              | 1.74 x 10 <sup>-6</sup>                              | 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 x 10 <sup>-5</sup>                              |  | 500     | 1.00 x 10 <sup>-1</sup>                              |
| 4      | 2.71   |  | 600     | 1.04   |
| 5      | 4.67   |  | (s) 693 | 1.07   |
| 6      | 7.60   |  | (l) 693 | (1.15) <sup>†</sup>                                  |
| 7      | 1.23 x 10 <sup>-4</sup>                              |  | 700     | (1.15)   |
| 8      | 2.34   |  | 800     | (1.15)   |
| 9      | 3.85   |  | 900     | (1.15)   |
| 10     | 5.54   |  | 1000    | (1.15)   |
| 15     | 2.72 x 10 <sup>-3</sup>                              |  | 1100    | (1.15)   |
| 20     | 6.64   |  | 1200    | (1.15)   |
| 30     | 1.79 x 10 <sup>-2</sup>                              |  |         |  |

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]; Eichenauer, 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)

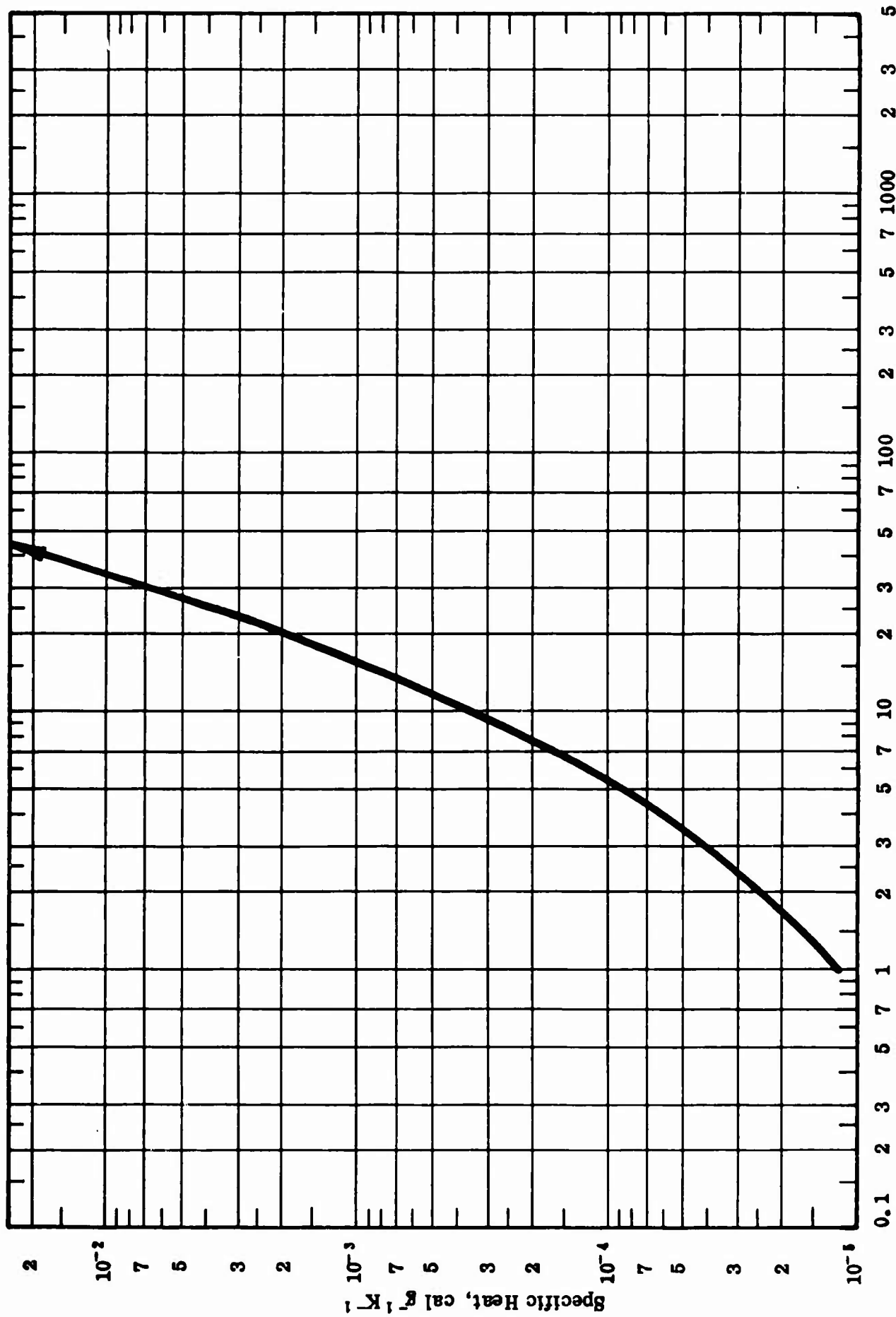


FIG. V - 14 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 2219 - T852

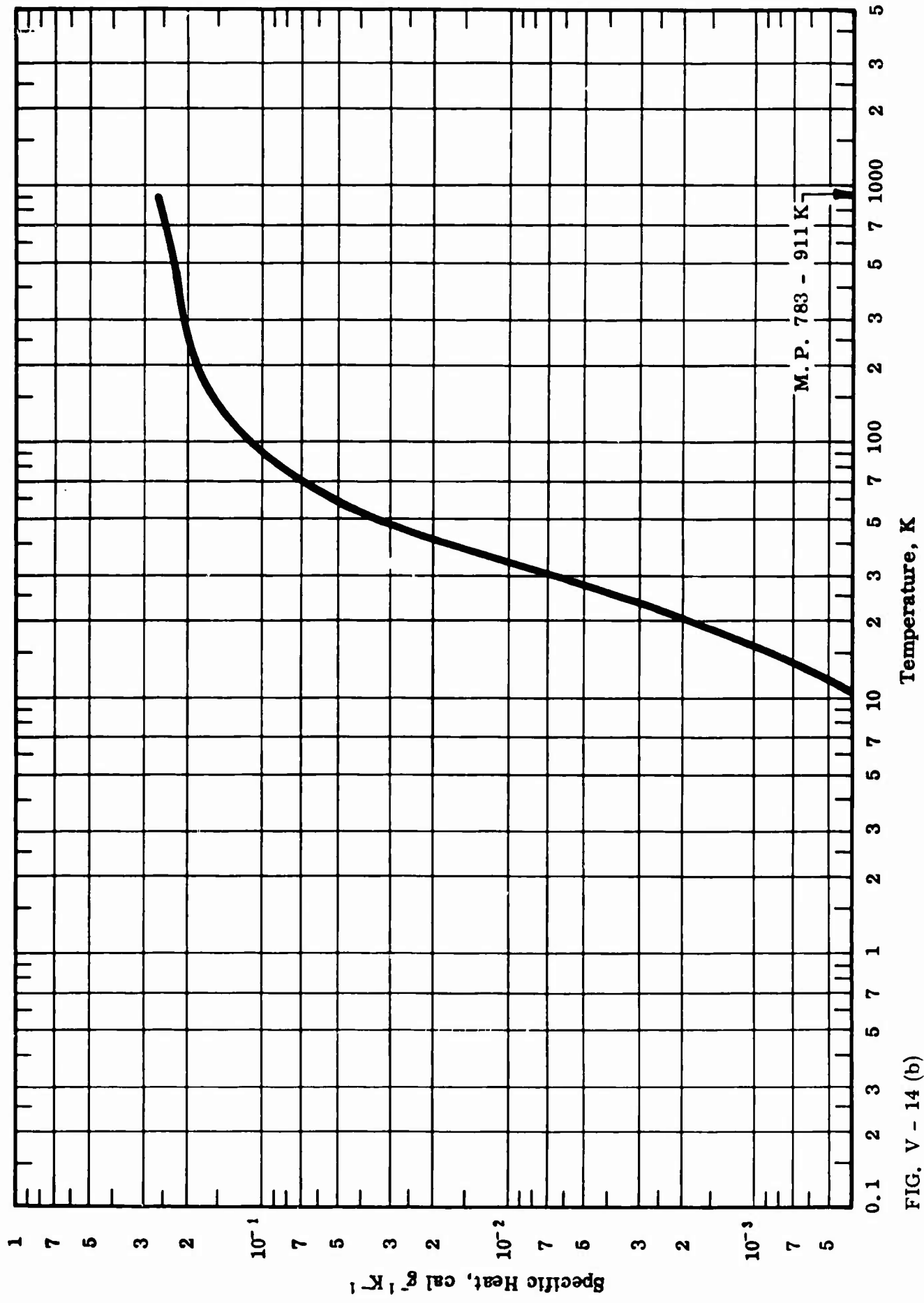


FIG. V - 14 (b)

SPECIFIC HEAT -- ALUMINUM ALLOY 2219 - T852

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 1.19 x 10 <sup>-5</sup> *                            | 60   | 5.13 x 10 <sup>-2</sup> *                            |
| 2    | 2.42*  | 70   | 6.92*  |
| 3    | 3.97*  | 80   | 8.37*  |
| 4    | 5.92*  | 90   | 9.94*  |
| 5    | 9.07*  | 100  | 1.12 x 10 <sup>-1</sup> *                            |
| 6    | 1.23 x 10 <sup>-4</sup> *                            | 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 x 10 <sup>-3</sup> *                            | 700  | 2.48*  |
| 30   | 7.41*  | 800  | 2.59*  |
| 40   | 1.81 x 10 <sup>-2</sup> *                            | 900  | 2.69*  |
| 50   | 3.30*  |      |  |

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

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\* Calculated using Kopp-Newman Law

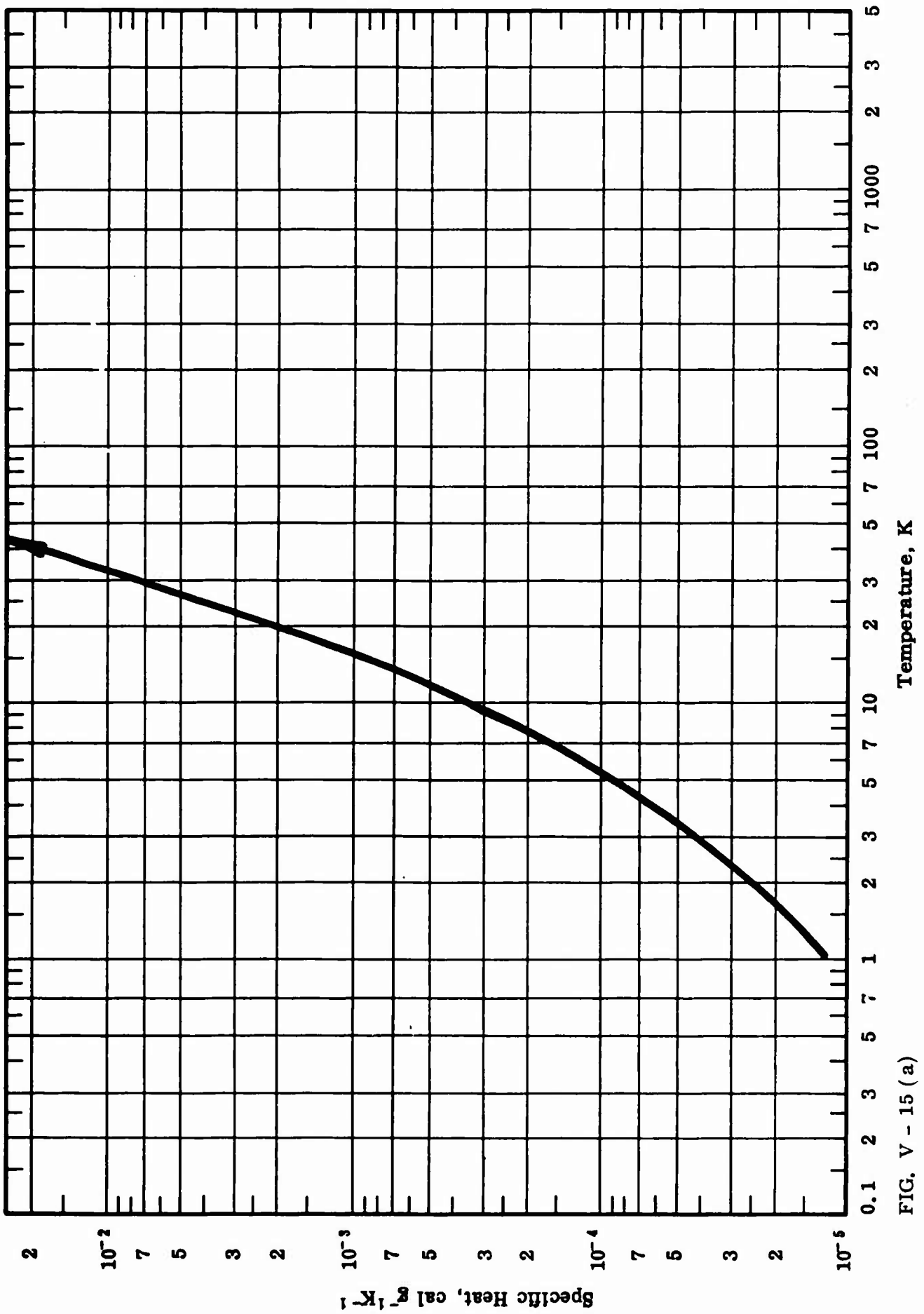


FIG. V - 15 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 6061 - T6

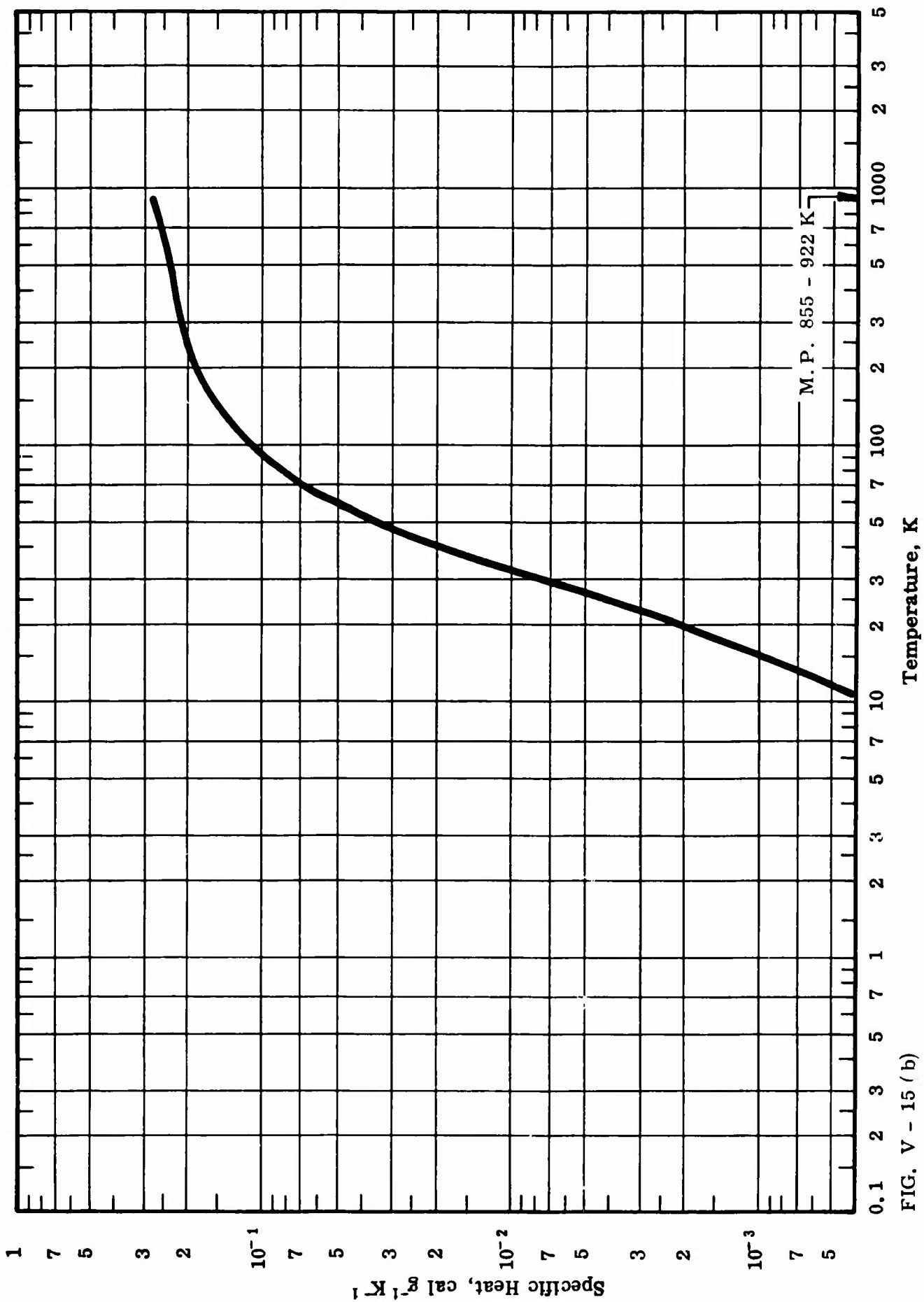


FIG. V - 15 (b)

SPECIFIC HEAT -- ALUMINUM ALLOY 6061 - T6

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 1.23 x 10 <sup>-5</sup> *                            | 60   | 5.14 x 10 <sup>-2</sup> *                            |
| 2    | 2.49 *   | 70   | 6.97 *   |
| 3    | 4.08 *   | 80   | 8.65 *   |
| 4    | 6.07 *   | 90   | 1.02 x 10 <sup>-1</sup> *                            |
| 5    | 9.31 *   | 100  | 1.15 *   |
| 6    | 1.26 x 10 <sup>-4</sup> *                            | 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 x 10 <sup>-3</sup> *                            | 700  | 2.58 *   |
| 30   | 7.54 *   | 800  | 2.69 *   |
| 40   | 1.85 x 10 <sup>-2</sup> *                            | 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

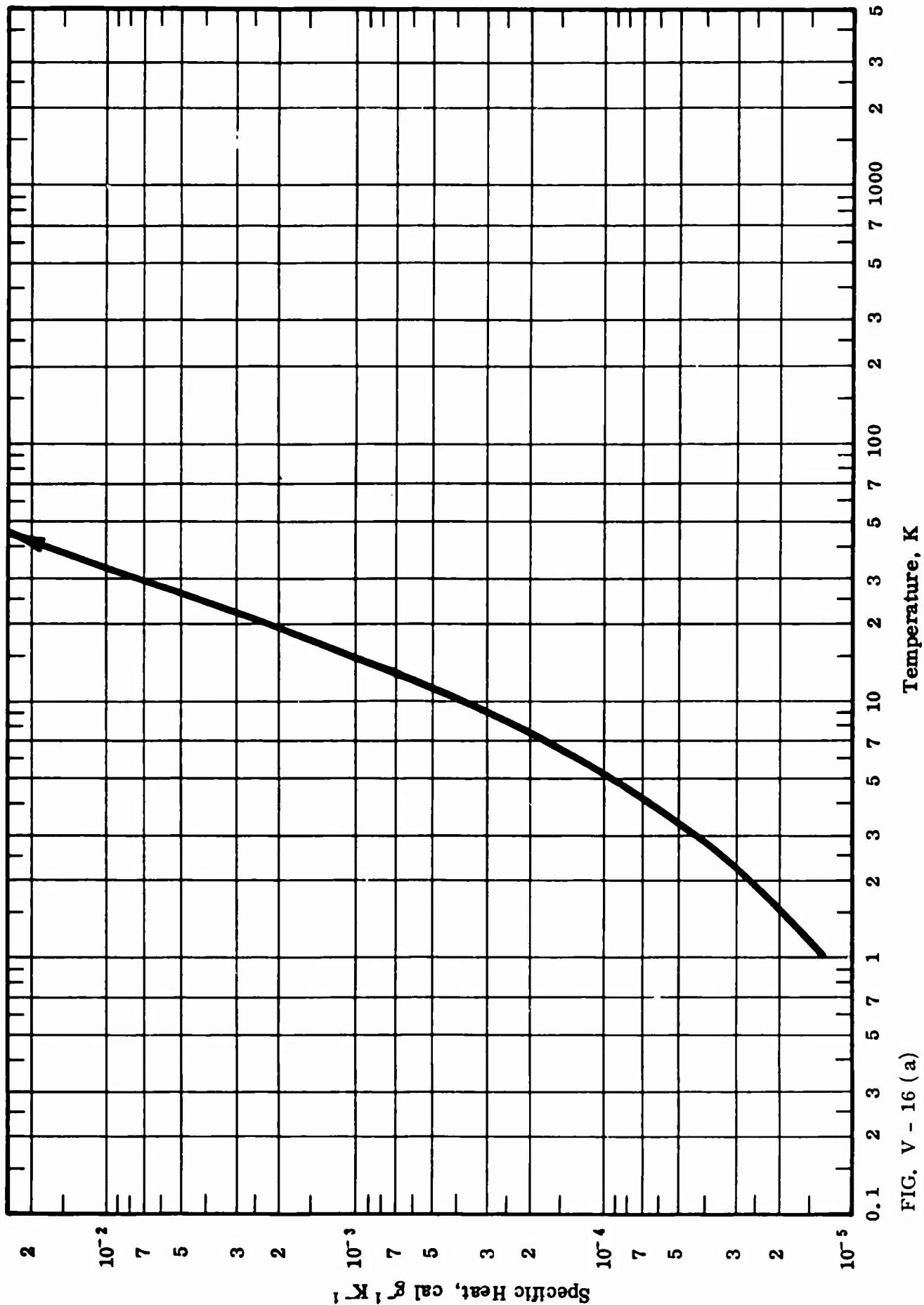


FIG. V - 16 (a)

SPECIFIC HEAT -- ALUMINUM ALLOY 7075 - T6

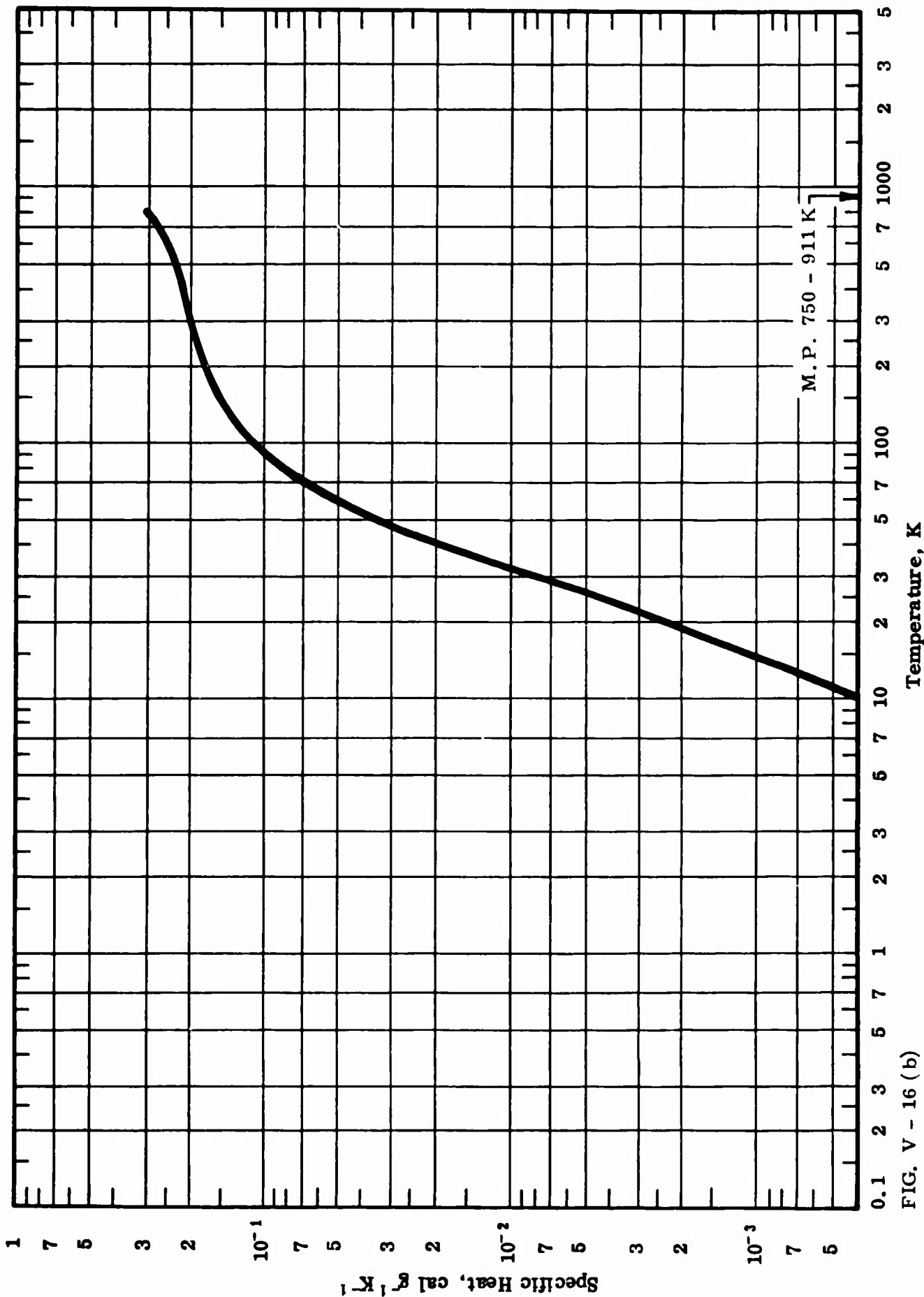


FIG. V - 16 (b)

SPECIFIC HEAT -- ALUMINUM ALLOY 7075 - T6

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 1.33 x 10 <sup>-5*</sup>                             | 50   | 3.44 x 10 <sup>-2*</sup>                             |
| 2    | 2.71*  | 60   | 5.40*  |
| 3    | 4.42*  | 70   | 7.10*  |
| 4    | 6.54*  | 80   | 8.56*  |
| 5    | 9.87*  | 90   | 1.01 x 10 <sup>-1*</sup>                             |
| 6    | 1.34 x 10 <sup>-4*</sup>                             | 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 x 10 <sup>-3*</sup>                             | 500  | 2.29   |
| 20   | 2.33*  | 600  | 2.50   |
| 30   | 8.24*  | 700  | 2.78   |
| 40   | 1.93 x 10 <sup>-2*</sup>                             | 800  | (3.10 x 10 <sup>-1</sup> )†                          |

Investigators: Lucks, C. F. and Deem, H. W. (190) [73-723 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

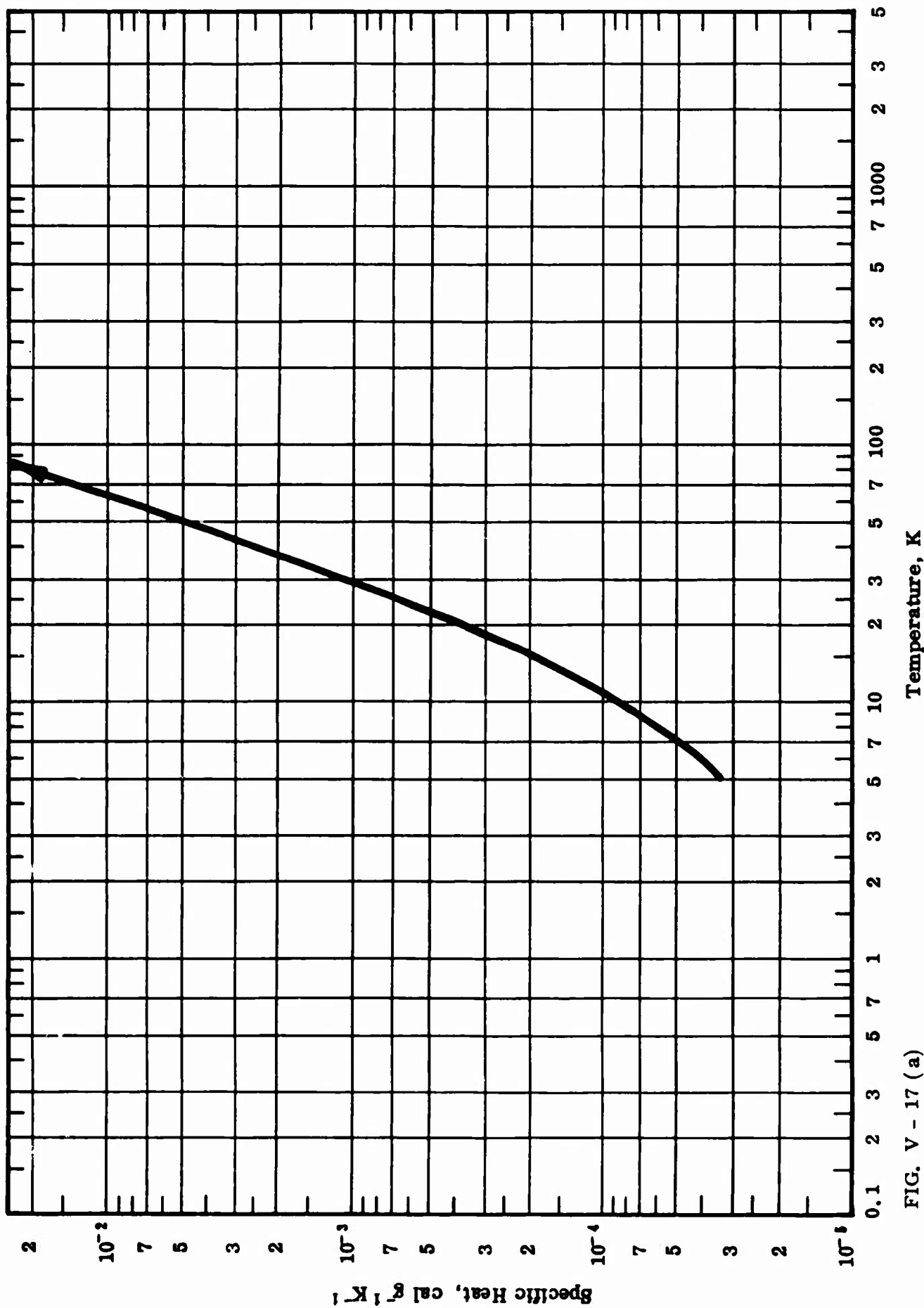


FIG. V - 17 (a)

SPECIFIC HEAT -- BERYLLIUM ALLOY

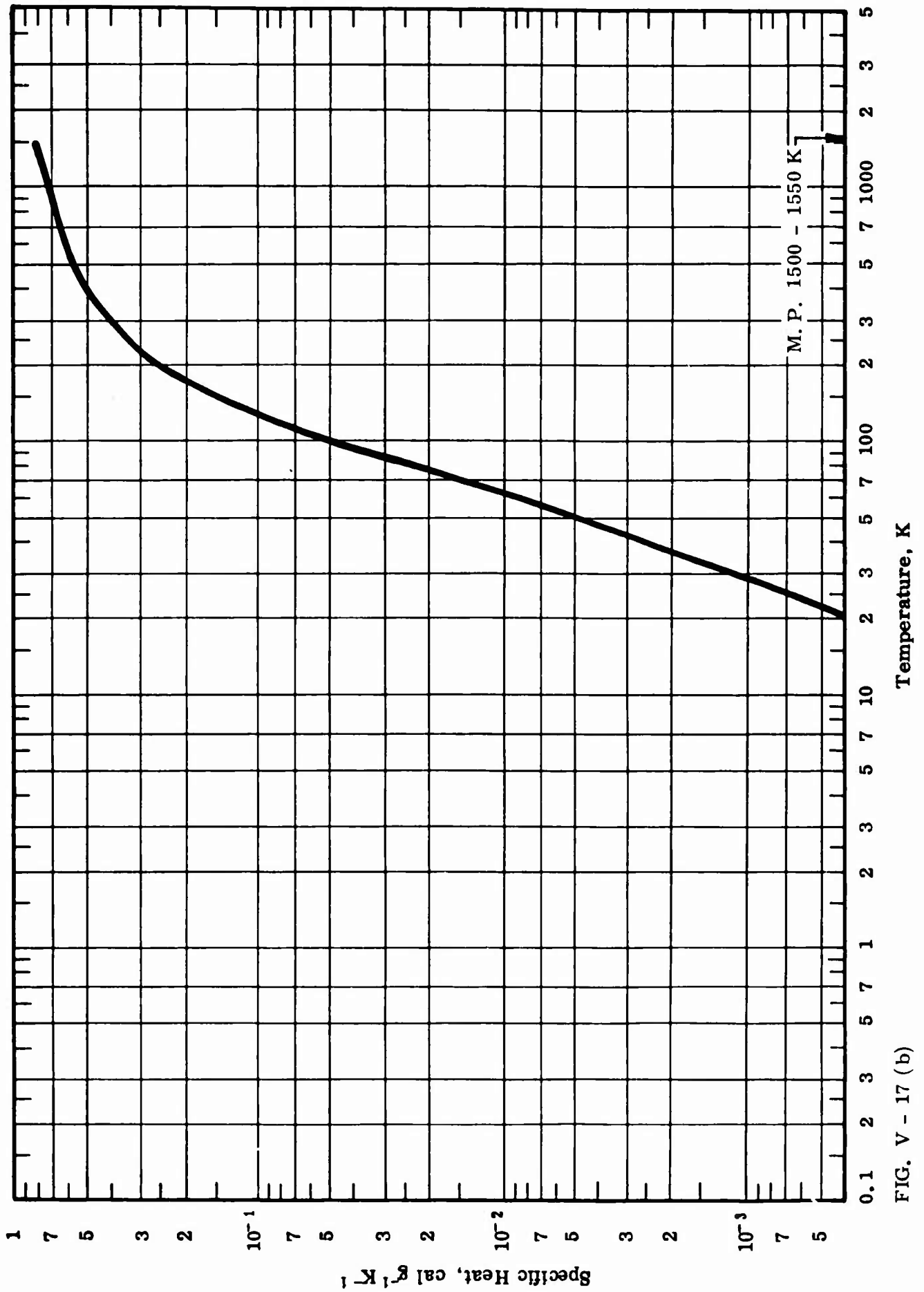


FIG. V - 17 (b)

SPECIFIC HEAT -- BERYLLIUM ALLOY

TABLE V-17. SPECIFIC HEAT OF BERYLLIUM ALLOY

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 5    | 3.35 x 10 <sup>-5*</sup>                             | 150  | 1.45 x 10 <sup>-1*</sup>                             |
| 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 x 10 <sup>-4*</sup>                             | 700  | 6.45   |
| 20   | 3.80*  | 800  | 6.68   |
| 30   | 1.12 x 10 <sup>-3*</sup>                             | 900  | 6.92   |
| 40   | 2.34*  | 1000 | 7.17   |
| 50   | 4.44*  | 1100 | 7.41   |
| 60   | 8.11*  | 1200 | 7.64   |
| 70   | 1.36 x 10 <sup>-2*</sup>                             | 1300 | 7.88   |
| 80   | 2.14*  | 1400 | 8.00   |
| 90   | 3.27*  | 1500 | (8.20 x 10 <sup>-1</sup> ) <sup>†</sup>              |
| 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].

\* Calculated from Kopp-Newman Law

† Extrapolated

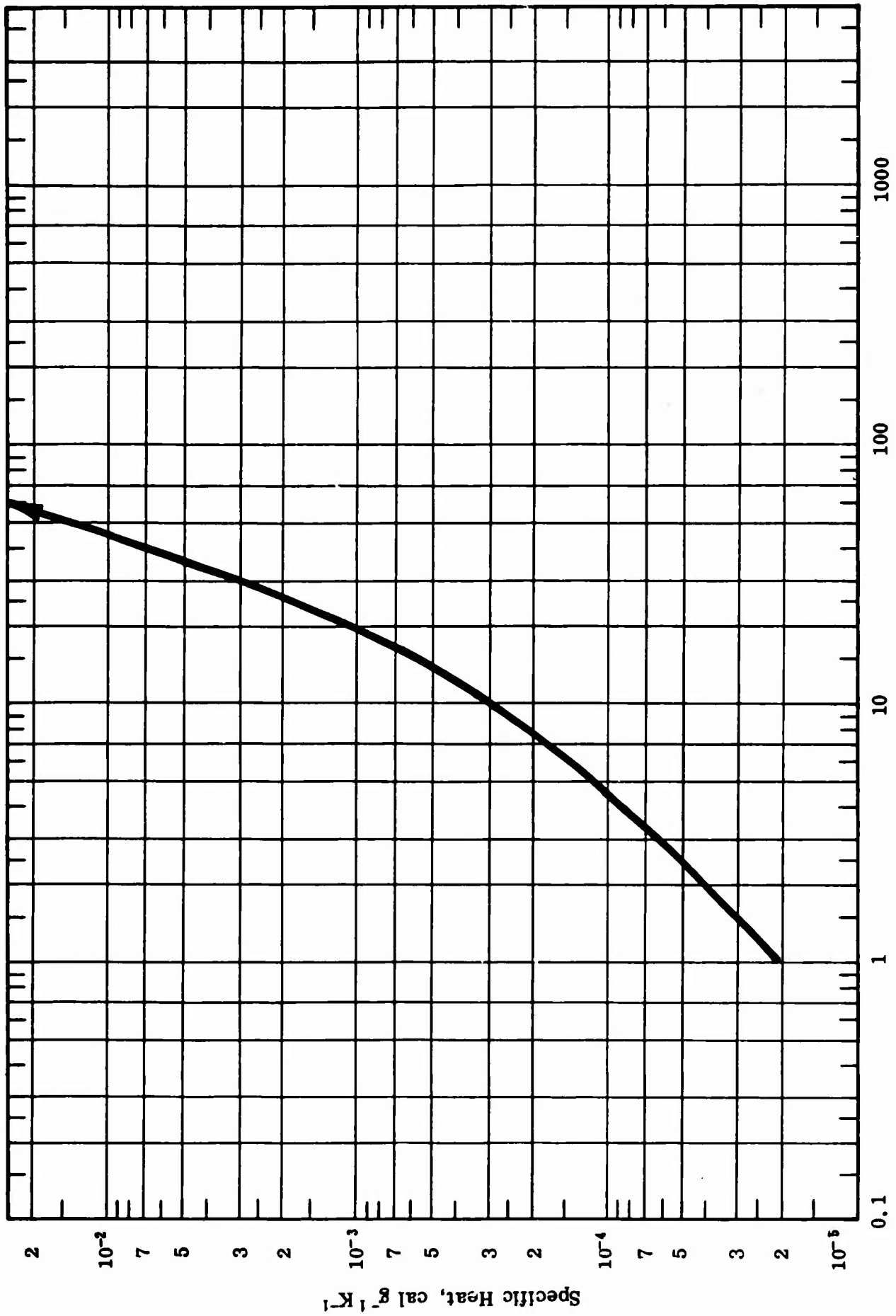


FIG. V - 18 (a)

SPECIFIC HEAT -- STAINLESS STEEL AISI 304A

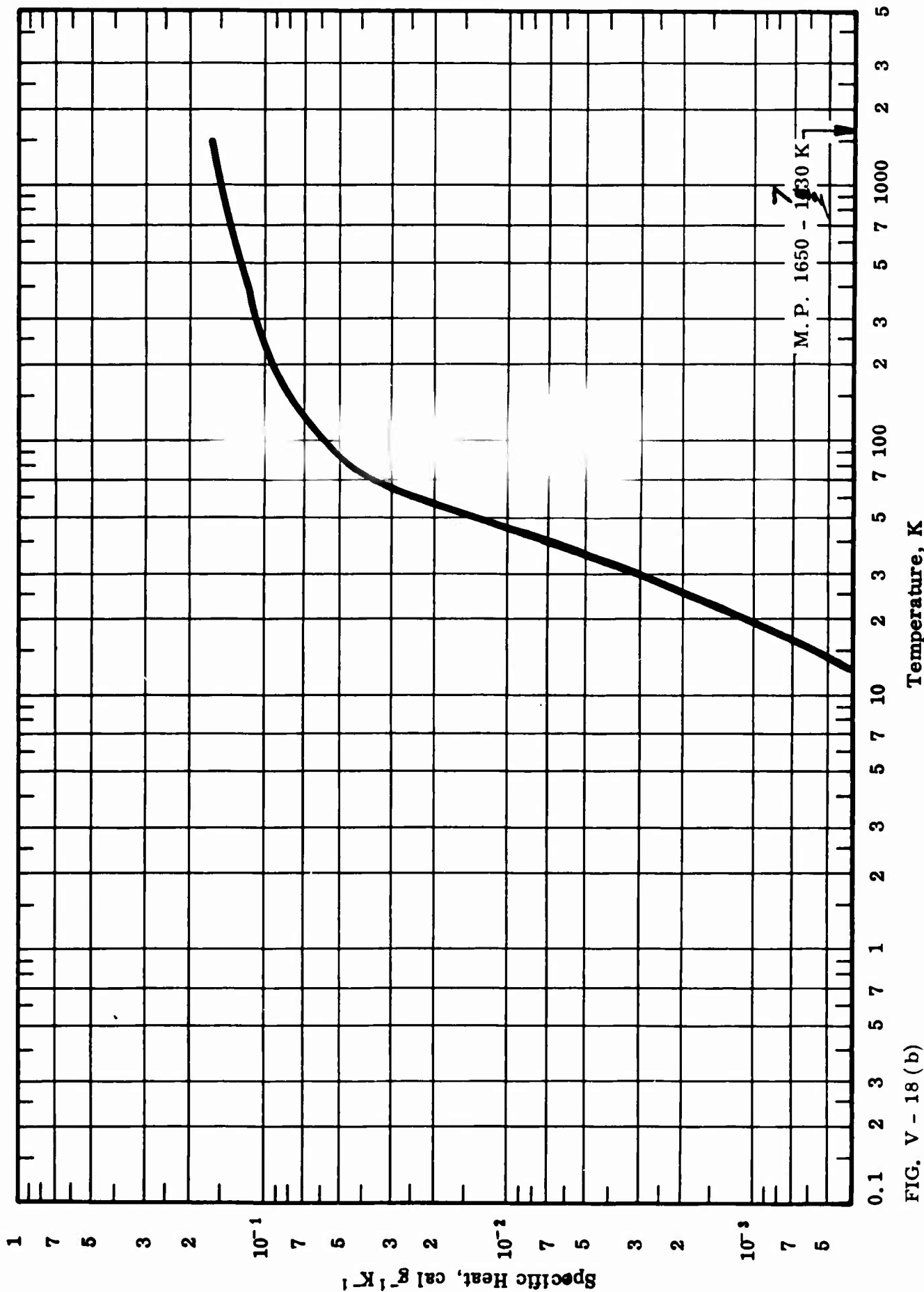


FIG. V - 18 (b)

SPECIFIC HEAT -- STAINLESS STEEL AISI 304A

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K  | C <sub>p</sub> , cal <sup>-1</sup> K <sup>-1</sup> |
|------|--|-------|--|
| 1    | 2.07 x 10 <sup>-5*</sup>                             | 90    | 5.17 x 10 <sup>-2*</sup>                           |
| 2    | 4.09*  | 100   | 5.85*  |
| 3    | 6.26*  | 150   | 8.10*  |
| 4    | 8.60*  | 200   | 9.30*  |
| 5    | 1.12 x 10 <sup>-4*</sup>                             | 300   | 1.08 x 10 <sup>-1*</sup>                           |
| 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 x 10 <sup>-3*</sup>                             | 1000  | 1.50   |
| 30   | 3.09*  | 1100  | 1.52   |
| 40   | 6.96*  | 1200  | 1.54   |
| 50   | 1.26 x 10 <sup>-2*</sup>                             | 1300  | 1.57   |
| 60   | 2.58*  | 1400  | 1.60   |
| 70   | 3.57*  | (1500 | 1.62 x 10 <sup>-1</sup> †                          |
| 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].

\* Calculated using Kopp-Newman Law

† Extrapolated

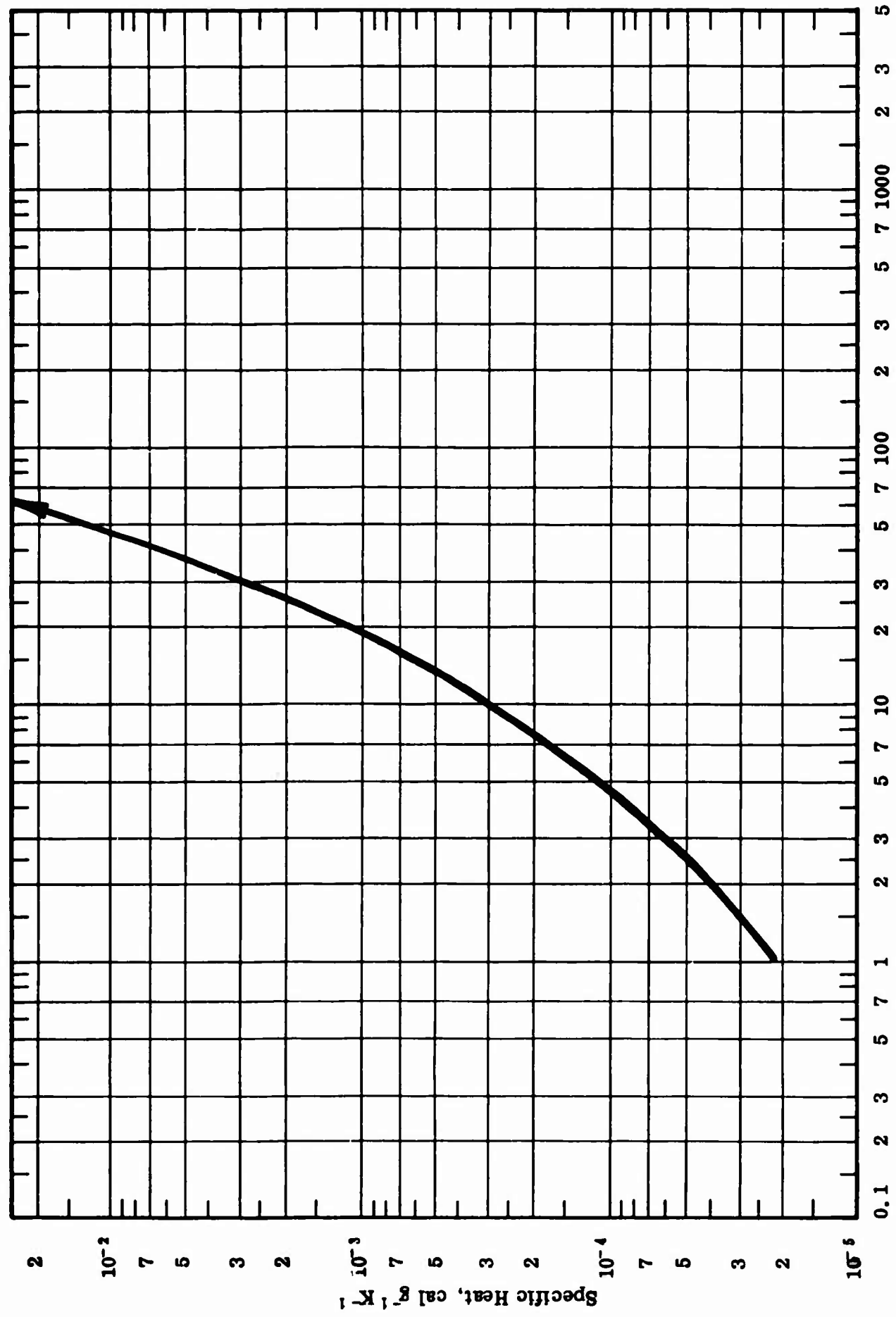


FIG. V - 19 (a)

SPECIFIC HEAT -- STAINLESS STEEL AISI 347

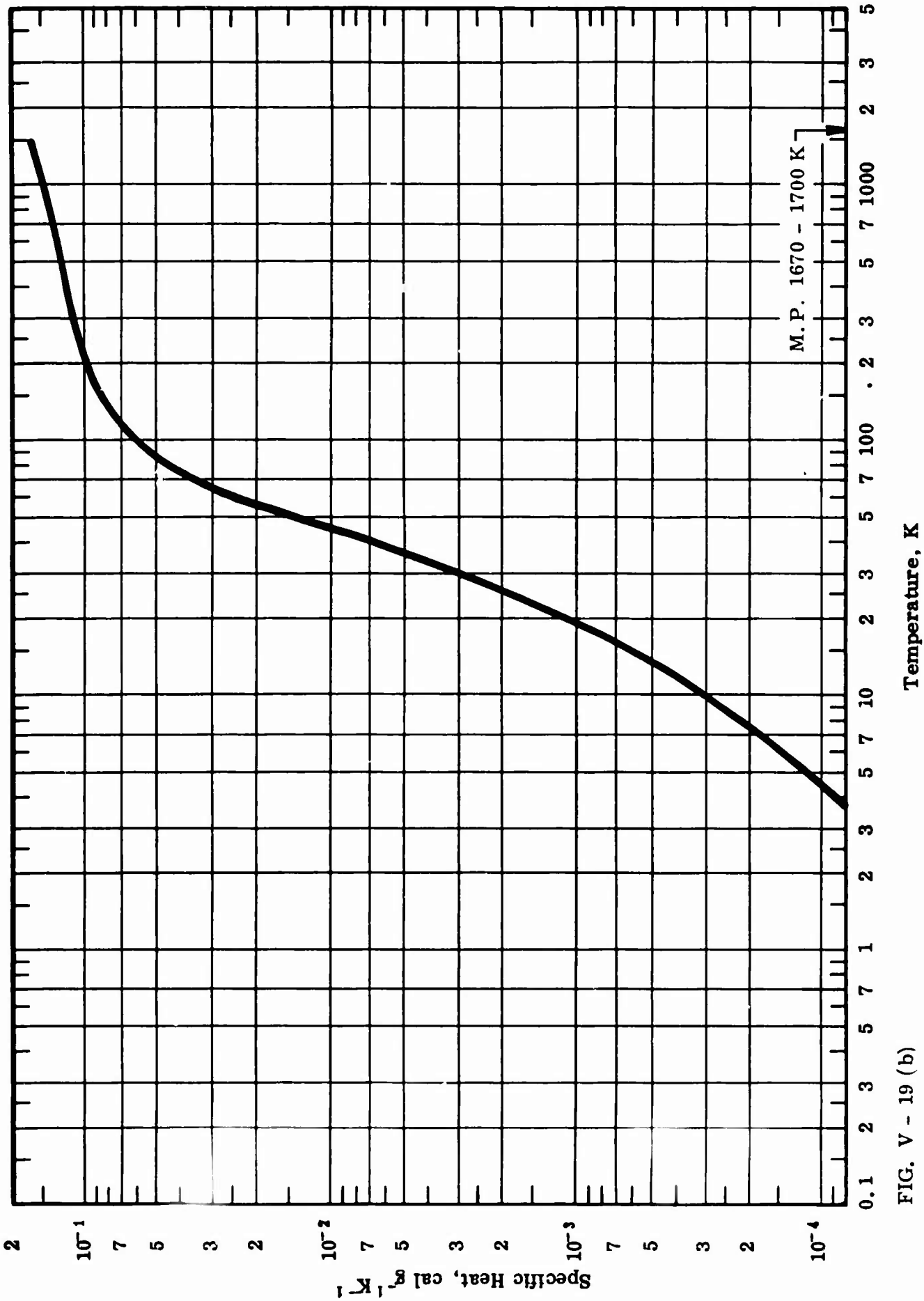


FIG. V - 19 (b)

SPECIFIC HEAT -- STAINLESS STEEL AISI 347

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 2.09 x 10 <sup>-5*</sup>                             | 90   | 5.40 x 10 <sup>-2*</sup>                             |
| 2    | 4.13*  | 100  | 6.30*  |
| 3    | 6.33*  | 150  | 8.70   |
| 4    | 8.70*  | 200  | 9.70   |
| 5    | 1.13 x 10 <sup>-4*</sup>                             | 300  | 1.08 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-3*</sup>                             | 1000 | 1.49   |
| 30   | 3.15*  | 1100 | 1.52   |
| 40   | 7.08*  | 1200 | 1.56   |
| 50   | 1.28 x 10 <sup>-2*</sup>                             | 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

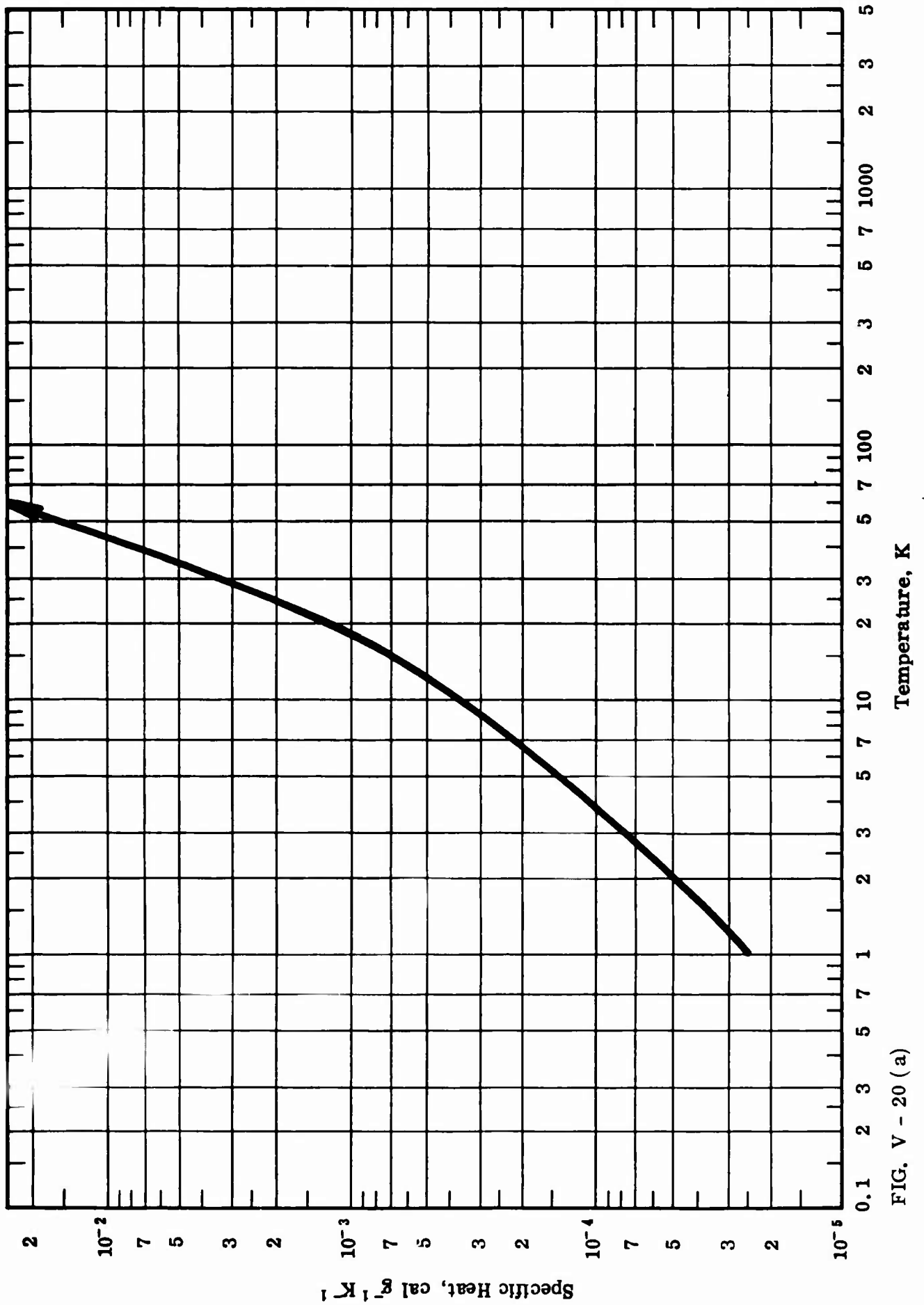


FIG. V - 20 (a)

SPECIFIC HEAT -- INCONEL X - 750

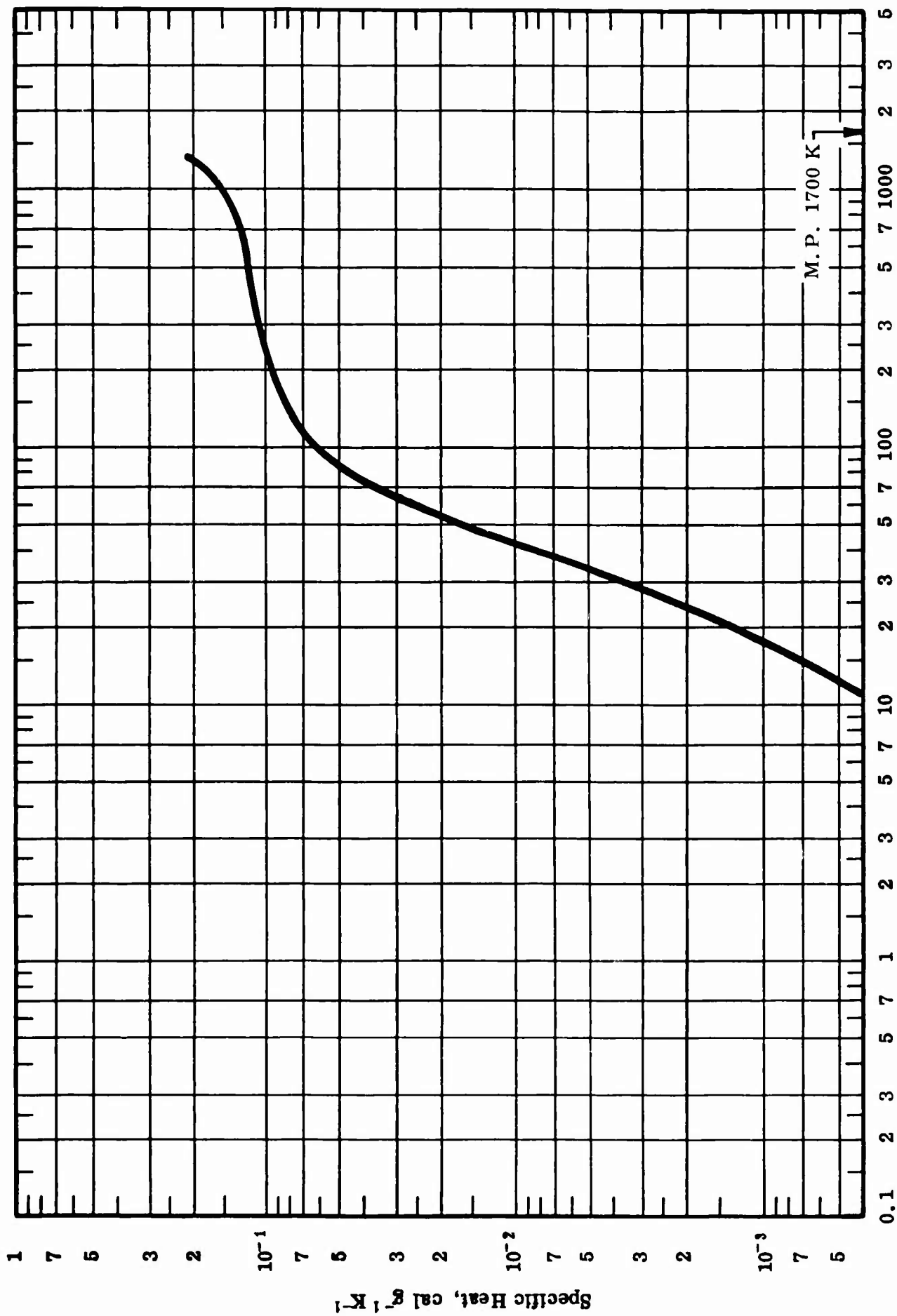


FIG. V - 20 (b)

SPECIFIC HEAT --- INCONEL X - 750

Temperature, K

M. P. 1700 K

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 2.47 x 10 <sup>-5*</sup>                             | 80   | 4.70 x 10 <sup>-2*</sup>                             |
| 2    | 4.91*  | 90   | 5.65*  |
| 3    | 7.52*  | 100  | 6.55   |
| 4    | 1.03 x 10 <sup>-4*</sup>                             | 150  | 8.20   |
| 5    | 1.34*  | 200  | 9.10   |
| 6    | 1.76*  | 300  | 1.04 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-3*</sup>                             | 900  | 1.40   |
| 30   | 3.68*  | 1000 | 1.49   |
| 40   | 8.43*  | 1100 | 1.60   |
| 50   | 1.53 x 10 <sup>-2*</sup>                             | 1200 | 1.80   |
| 60   | 2.67*  | 1300 | (2.15 x 10 <sup>-1</sup> )†                          |
| 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].

\* Calculated from Kopp-Newman Law

† Extrapolated

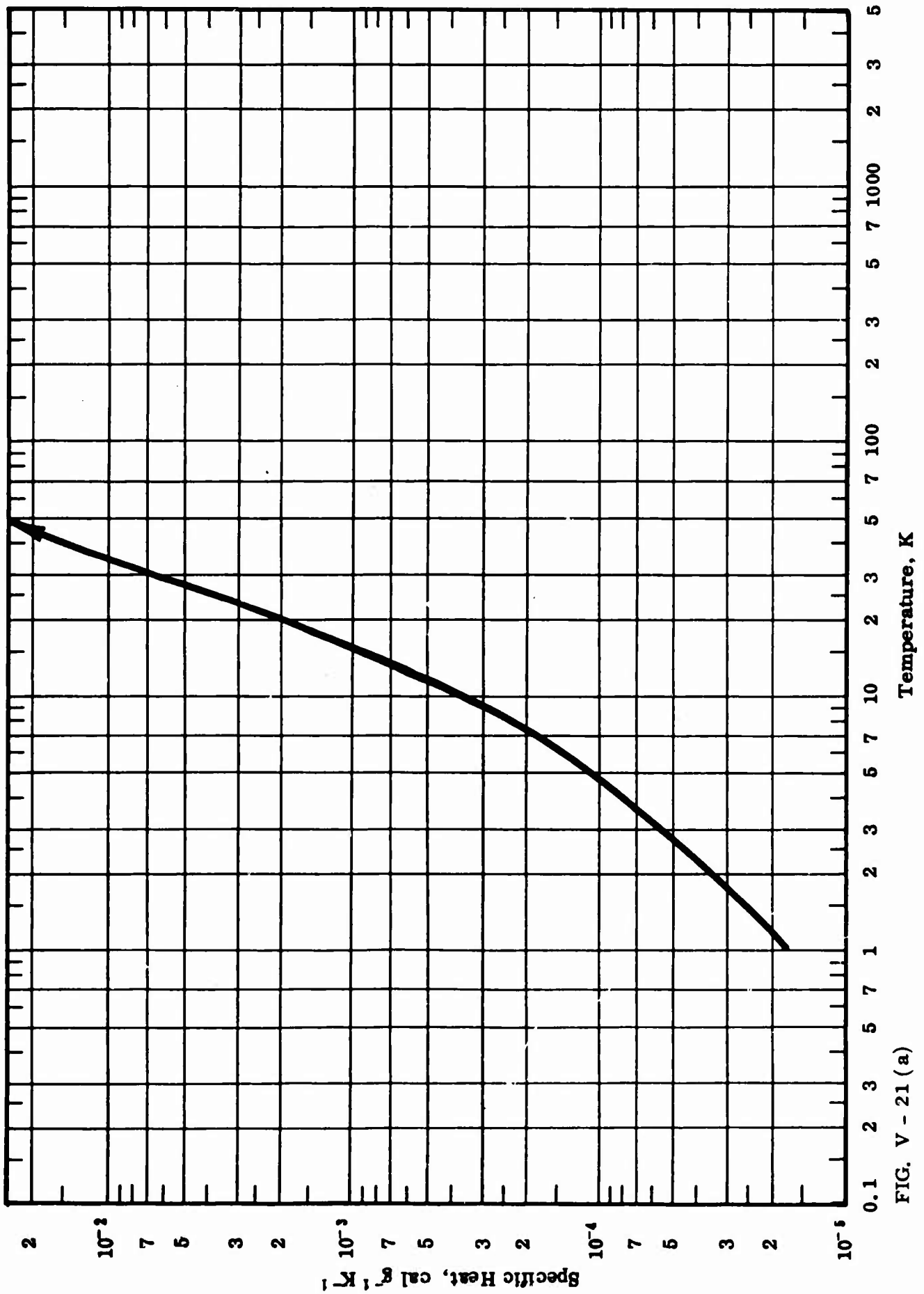


FIG. V - 21 (a)

SPECIFIC HEAT -- TITANIUM ALLOY A-110AT

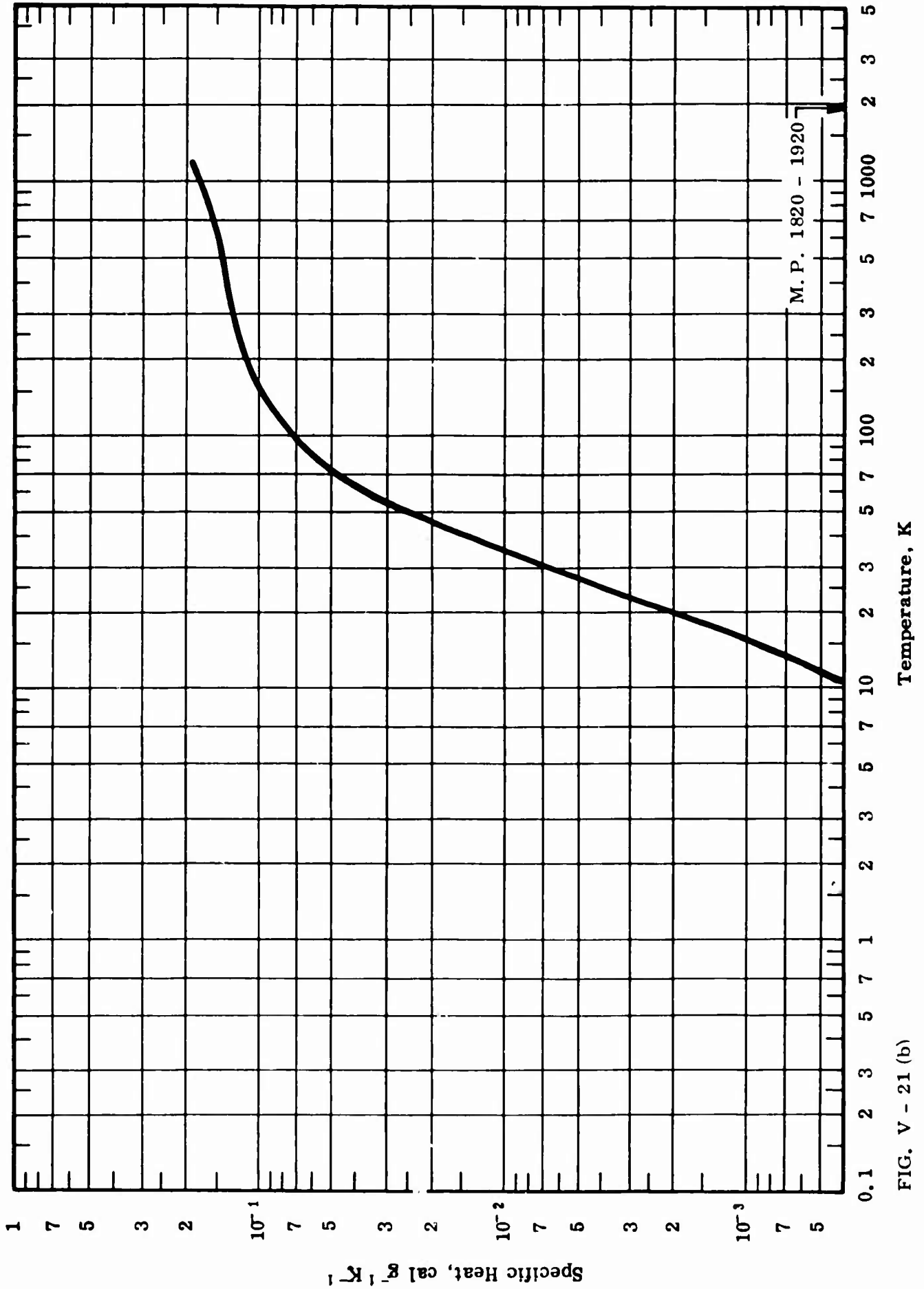


FIG. V - 21 (b)

SPECIFIC HEAT -- TITANIUM ALLOY A-110AT

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 1    | 1.71 x 10 <sup>-5*</sup>                             | 70   | 4.64 x 10 <sup>-2</sup>                              |
| 2    | 3.50*  | 80   | 5.66*  |
| 3    | 5.46*  | 90   | 6.65*  |
| 4    | 7.69*  | 100  | 7.30*  |
| 5    | 1.04 x 10 <sup>-4</sup>                              | 150  | 1.00 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-3*</sup>                             | 800  | 1.60   |
| 30   | 6.28*  | 900  | 1.68   |
| 40   | 1.40 x 10 <sup>-2*</sup>                             | 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

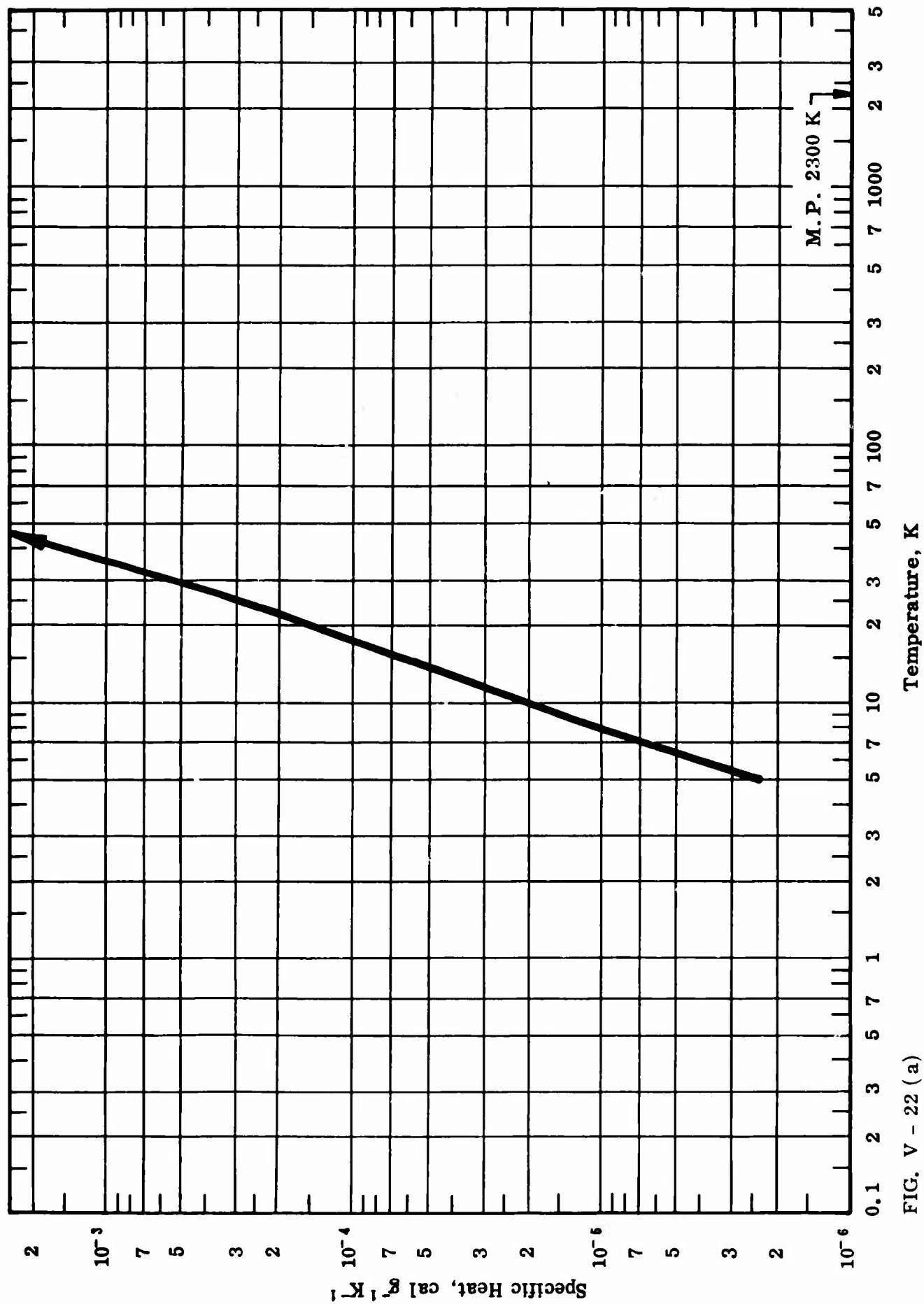


FIG. V - 22 (a)

SPECIFIC HEAT -- ALUMINUM OXIDE, Al<sub>2</sub>O<sub>3</sub>

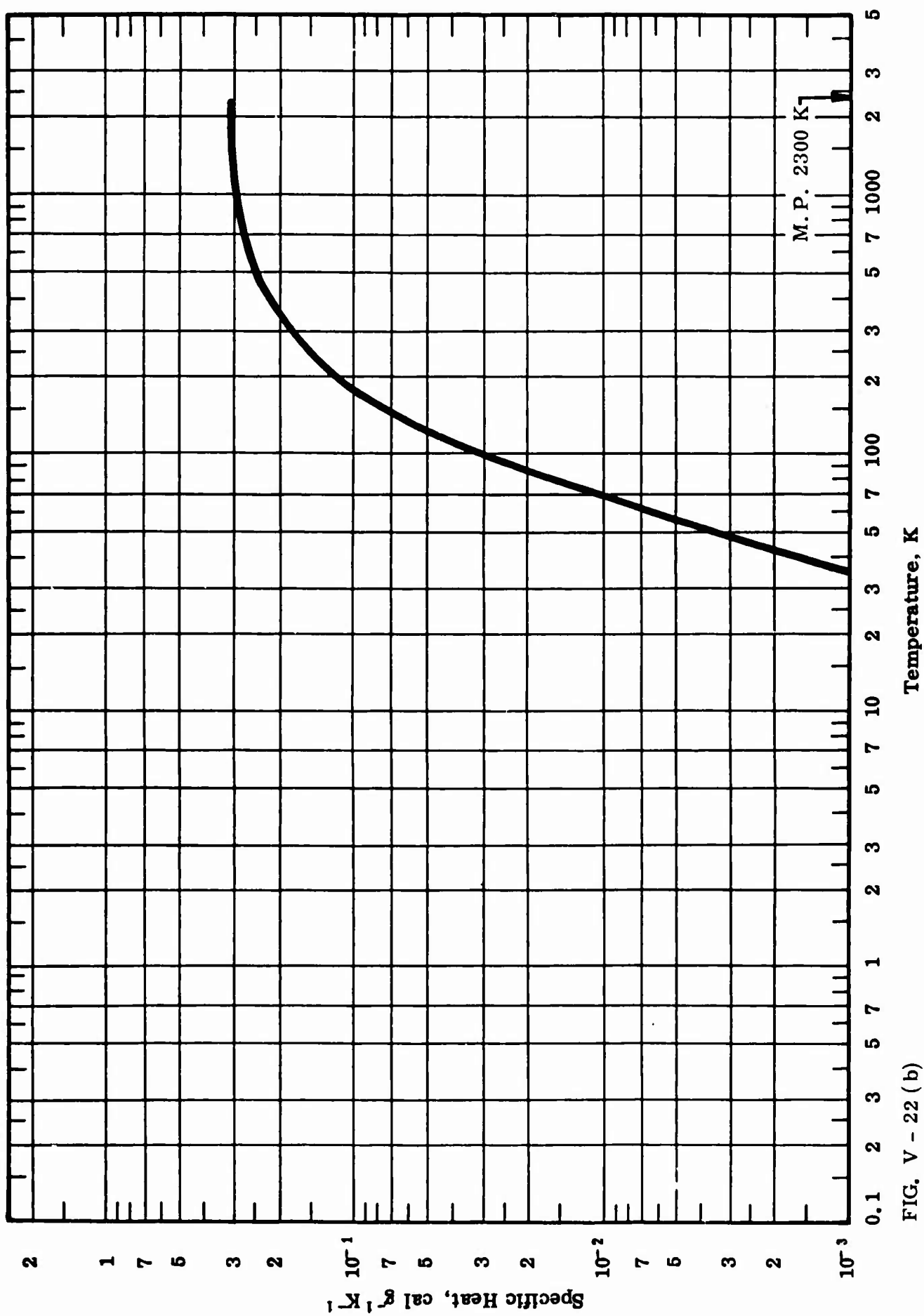


FIG. V - 22 (b)

SPECIFIC HEAT -- ALUMINUM OXIDE, Al<sub>2</sub>O<sub>3</sub>

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

| $T^{\circ}K$ | $C_p, cal\ g^{-1}\ K^{-1}$ | $T^{\circ}K$ | $C_p, cal\ g^{-1}\ K^{-1}$ |
|--------------|----------------------------|--------------|----------------------------|
| 5            | $2.35 \times 10^{-6}$      | 300          | $1.86 \times 10^{-1}$      |
| 10           | $2.11 \times 10^{-5}$      | 310          | 1.91                       |
| 15           | 7.03                       | 320          | 1.96                       |
| 20           | $1.78 \times 10^{-4}$      | 330          | 2.00                       |
| 25           | 3.33                       | 340          | 2.04                       |
| 30           | 6.16                       | 350          | 2.08                       |
| 35           | $1.03 \times 10^{-3}$      | 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           | $1.07 \times 10^{-2}$      | 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          | $1.03 \times 10^{-1}$      | 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<sub>2</sub>O<sub>3</sub>)

Anthony, F. M., et al (213) [533-1228K]; Boggs, 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) [20-395K]; Romanovskii, 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. J. (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. E., et al  
 (235) [337-923K]; Walker, B. E., et al (236) [337-923K];  
 West, E. D., and Ginnings, D. C. (237) [311-689K]; Wiebelt,  
 J. A. (238) [1089-1700K].

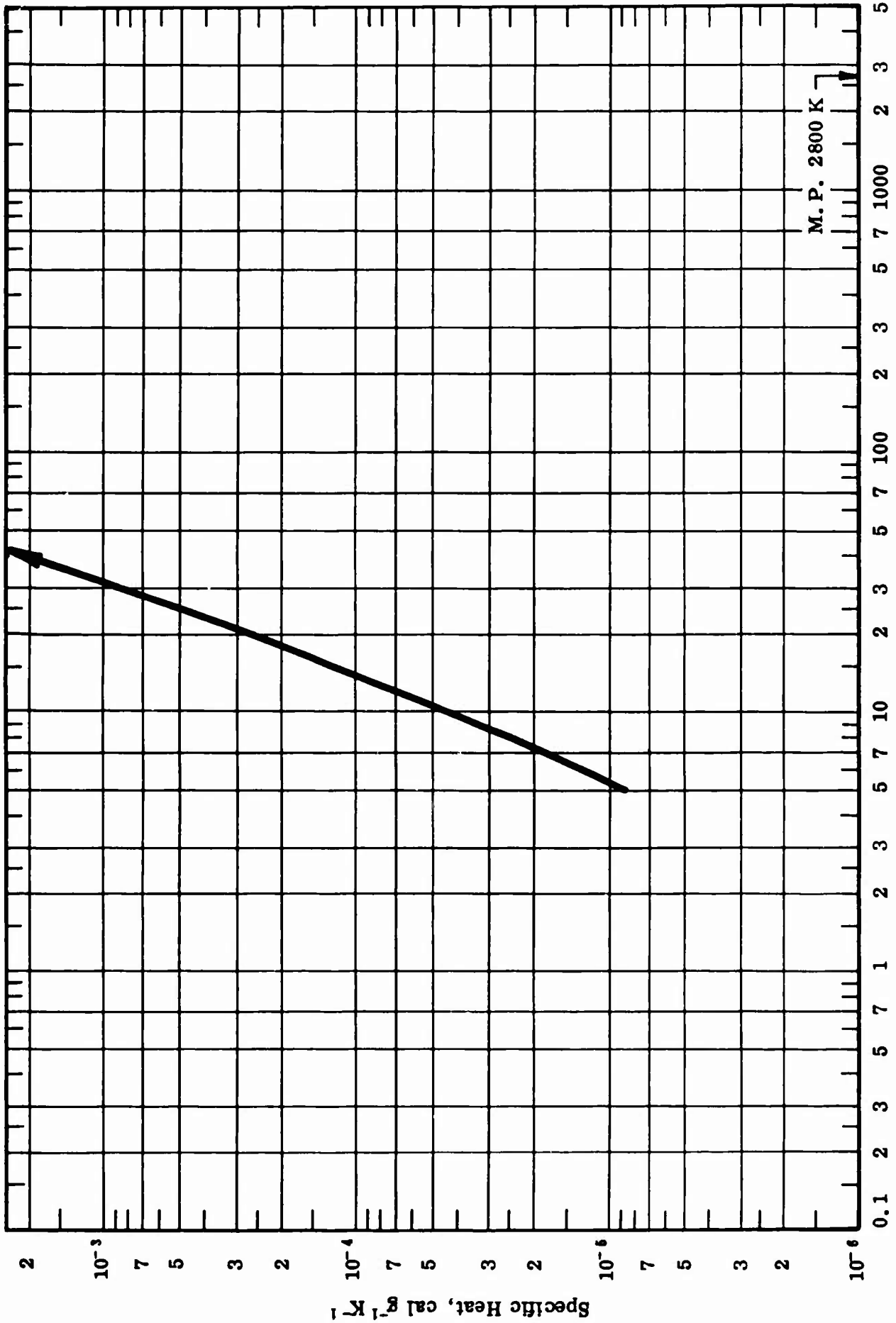


FIG. V - 23 (a)  
SPECIFIC HEAT -- BERYLLIUM OXIDE, BeO

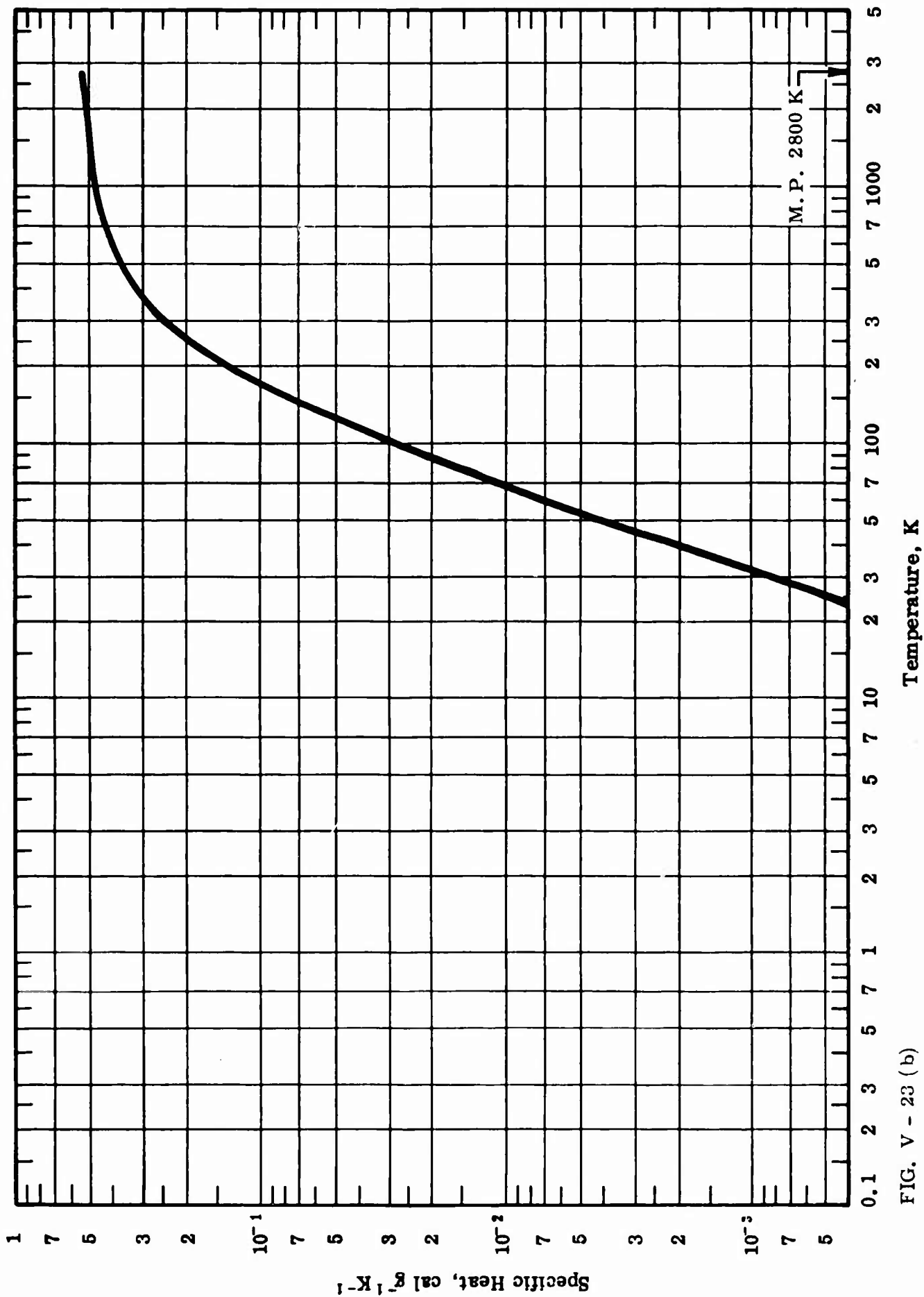


FIG. V - 23 (b)

SPECIFIC HEAT -- BERYLLIUM OXIDE, BeO

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 5    | (8.40 x 10 <sup>-6</sup> ) <sup>†</sup>              | 750  | 4.38 x 10 <sup>-1</sup>                              |
| 10   | 4.00 x 10 <sup>-5</sup>                              | 800  | 4.46   |
| 15   | 1.20 x 10 <sup>-4</sup>                              | 850  | 4.53   |
| 20   | 2.40   | 900  | 4.60   |
| 30   | 8.40   | 950  | 4.66   |
| 40   | 2.00 x 10 <sup>-3</sup>                              | 1000 | 4.71   |
| 50   | 3.90   | 1100 | 4.80   |
| 60   | 6.67   | 1200 | 4.88   |
| 70   | 1.03 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup>                              | 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) [303-1073K].

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<sup>†</sup> Extrapolated

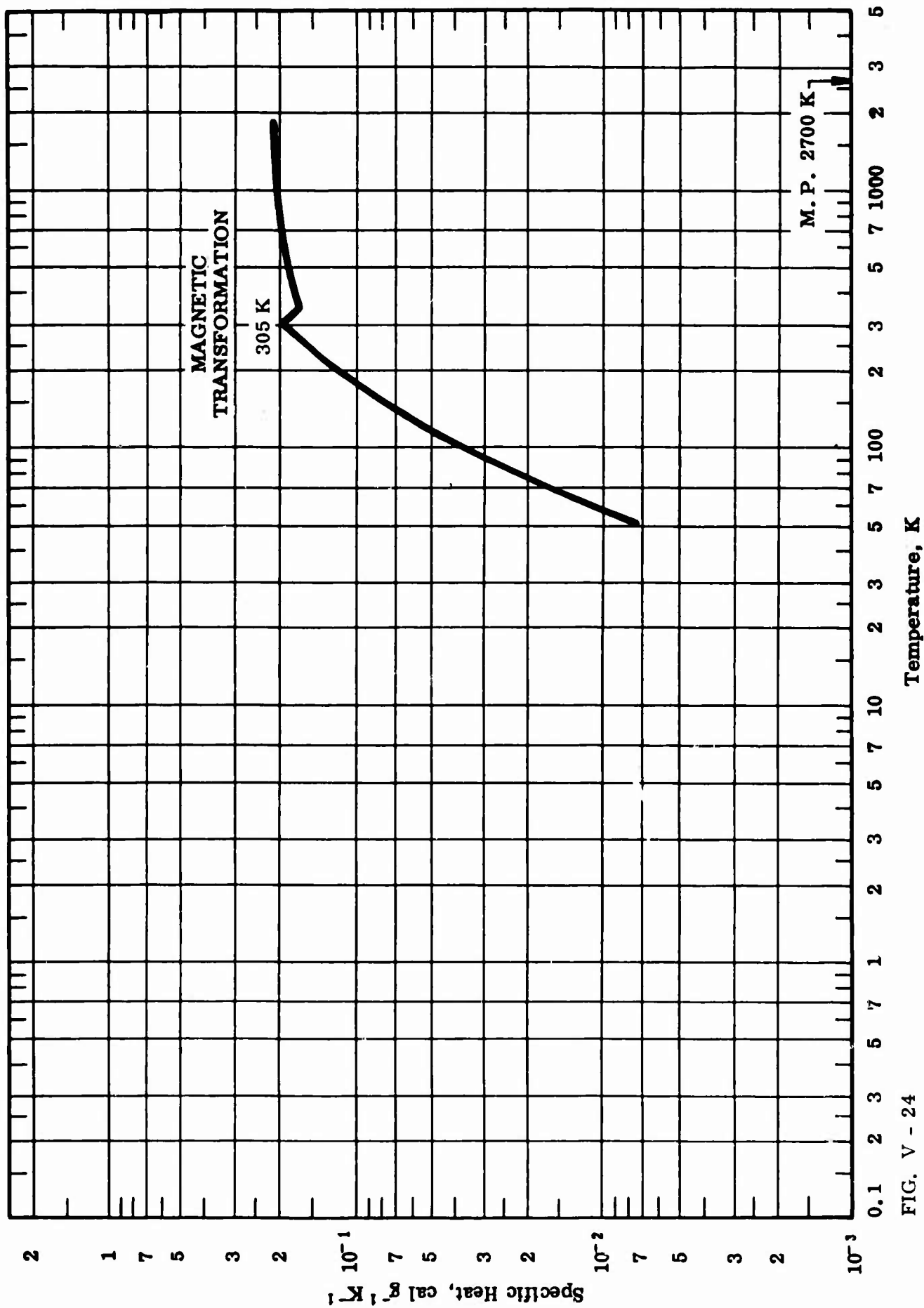


FIG. V - 24

SPECIFIC HEAT --- CHROMIUM OXIDE, Cr<sub>2</sub>O<sub>3</sub>

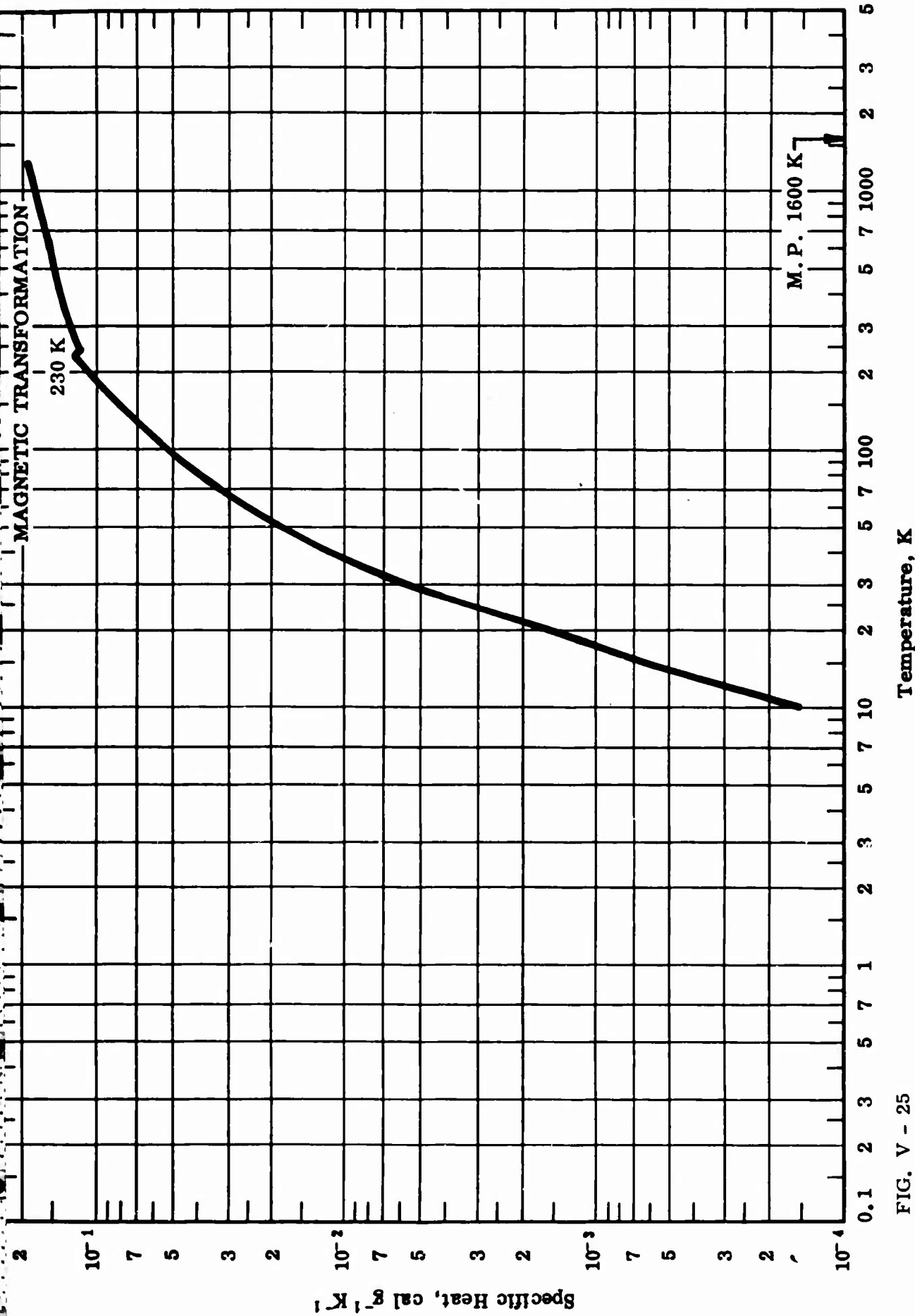
TABLE V-24. SPECIFIC HEAT OF CHROMIUM OXIDE, Cr<sub>2</sub>O<sub>3</sub>

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 50   | (7.30 x 10 <sup>-3</sup> ) <sup>†</sup>              | 330  | 1.68 x 10 <sup>-1</sup>                              |
| 60   | 1.08 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup>                              | 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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<sup>†</sup> Extrapolated



Temperature, K

SPECIFIC HEAT -- CUPRIC OXIDE, CuO

FIG. V - 25

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

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 10   | (1.5 x 10 <sup>-4</sup> ) <sup>†</sup>               | 240  | 1.17 x 10 <sup>-2</sup>                              |
| 15   | 6.29 x 10 <sup>-4</sup>                              | 250  | 1.19   |
| 20   | 1.55 x 10 <sup>-3</sup>                              | 260  | 1.21   |
| 25   | 3.12   | 270  | 1.22   |
| 30   | 5.80   | 280  | 1.24   |
| 40   | 1.20 x 10 <sup>-2</sup>                              | 290  | 1.26   |
| 50   | 1.85   | 300  | 1.28   |
| 60   | 2.59   | 400  | 1.41 x 10 <sup>-1</sup>                              |
| 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 Harteck, 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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<sup>†</sup> Extrapolated

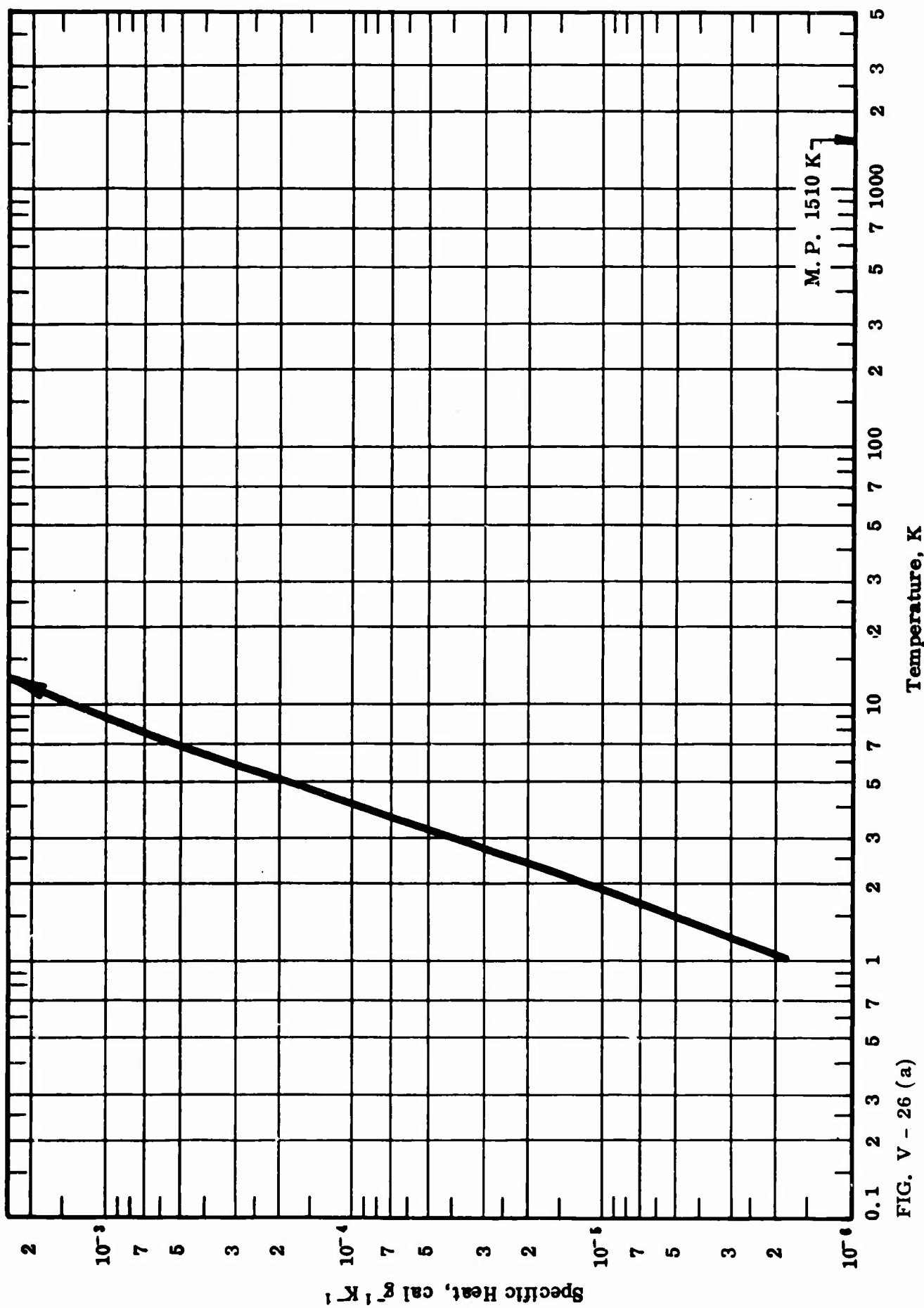


FIG. V - 26 (a)

SPECIFIC HEAT -- CUPROUS OXIDE, Cu<sub>2</sub>O

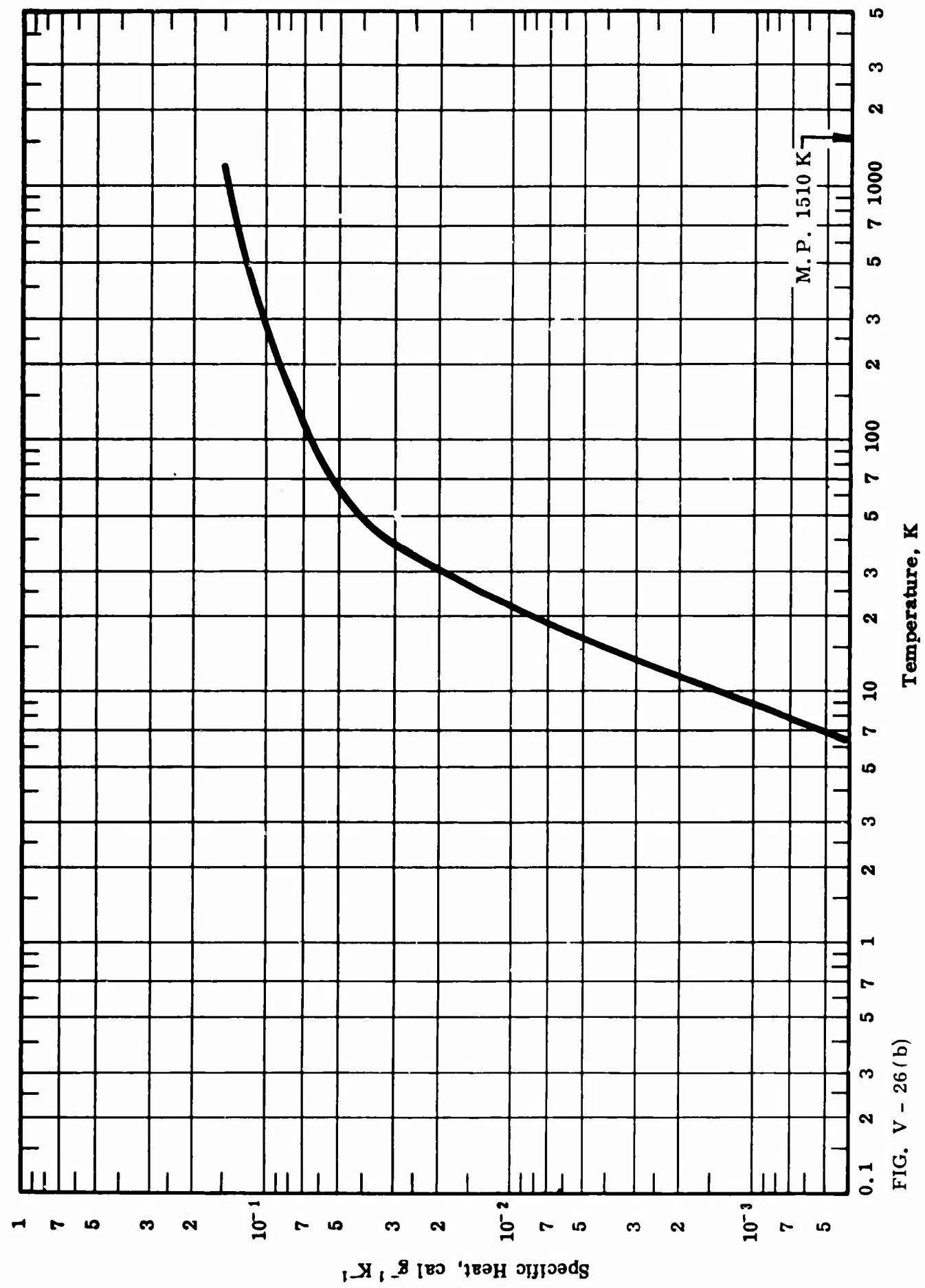


FIG. V - 26 (b)

SPECIFIC HEAT -- CUPROUS OXIDE, Cu<sub>2</sub>O

TABLE V-26. SPECIFIC HEAT OF CUPROUS OXIDE,  $\text{Cu}_2\text{O}$

| $T$ , °K | $C_p$ , $\text{cal}^{-1} \text{K}^{-1}$ | $T$ , °K | $C_p$ , $\text{cal g}^{-1} \text{K}^{-1}$ |
|----------|---|----------|---|
| 1        | $(1.80 \times 10^{-6})^\dagger$         | 100      | $6.70 \times 10^{-2}$                     |
| 1.5      | $(5.20 \times 10^{-6})$                 | 120      | 7.20                                      |
| 2        | $(1.17 \times 10^{-5})$                 | 140      | 7.70                                      |
| 3        | 3.90                                    | 160      | 8.10                                      |
| 4        | 9.50                                    | 180      | 8.60                                      |
| 5        | $1.92 \times 10^{-4}$                   | 200      | 8.95                                      |
| 6        | 3.34                                    | 220      | 9.40                                      |
| 7        | 5.40                                    | 240      | 9.75                                      |
| 8        | 7.60                                    | 260      | $1.00 \times 10^{-1}$                     |
| 9        | $1.02 \times 10^{-3}$                   | 280      | 1.02                                      |
| 10       | 1.32                                    | 300      | 1.06                                      |
| 15       | 4.00                                    | 400      | 1.19                                      |
| 20       | 8.40                                    | 500      | 1.23                                      |
| 30       | $2.05 \times 10^{-2}$                   | 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].

<sup>†</sup> Extrapolated

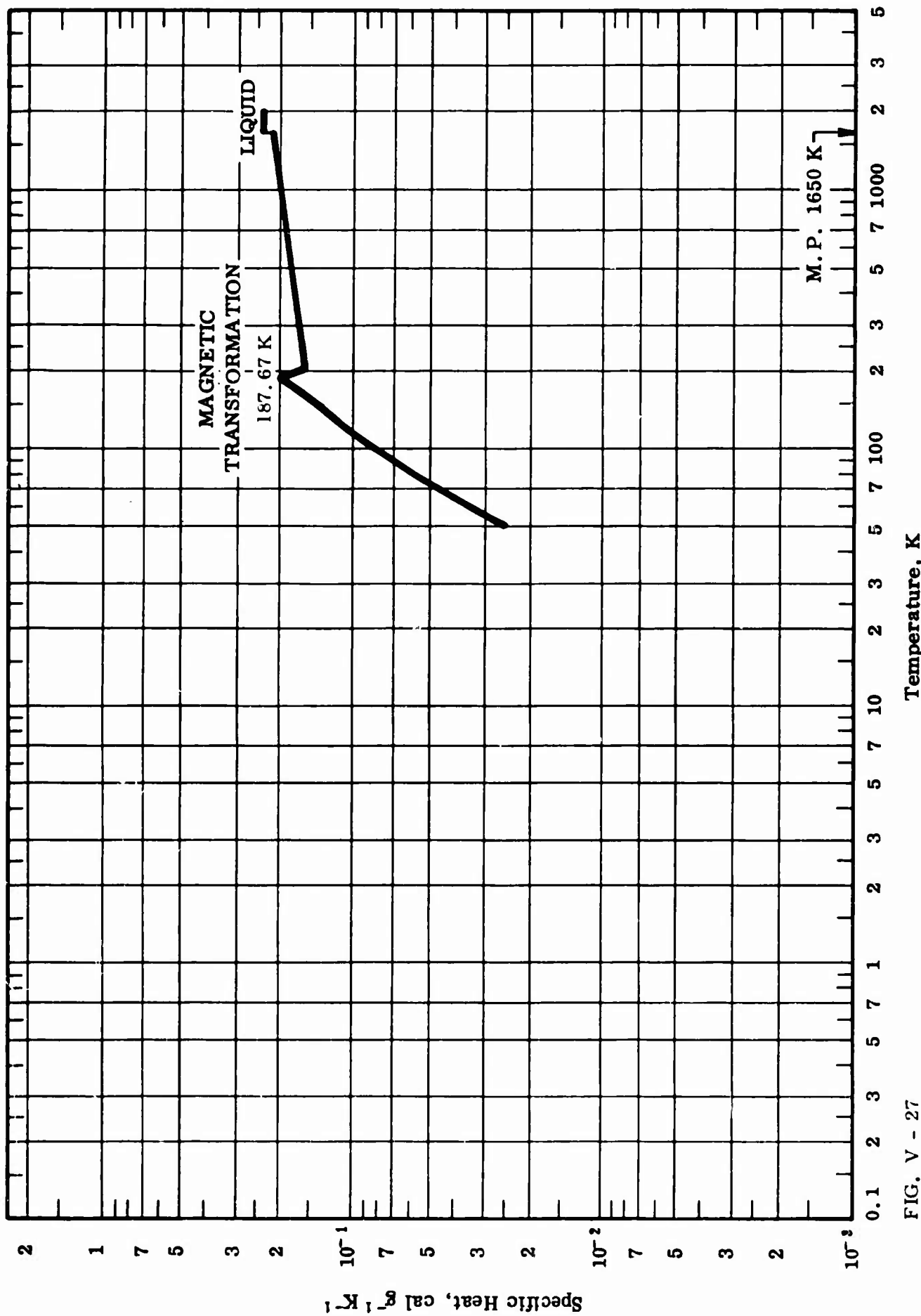


FIG. V - 27

SPECIFIC HEAT -- FERROUS OXIDE, Fe<sub>0.94</sub>O

Temperature, K

**TABLE V-27. SPECIFIC HEAT OF FERROUS OXIDE, Fe<sub>0.947</sub>O**

| T °K   | C <sub>p</sub> cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> cal g <sup>-1</sup> K <sup>-1</sup> |
|--------|--|----------|--|
| 50     | 2.45 x 10 <sup>-2</sup>                            | 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 x 10 <sup>-1</sup>                            | 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 x 10 <sup>-1</sup> ) <sup>†</sup>            |
| 600    | 1.84   | 2000     | (2.37 x 10 <sup>-1</sup> )                         |

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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<sup>†</sup> Extrapolated

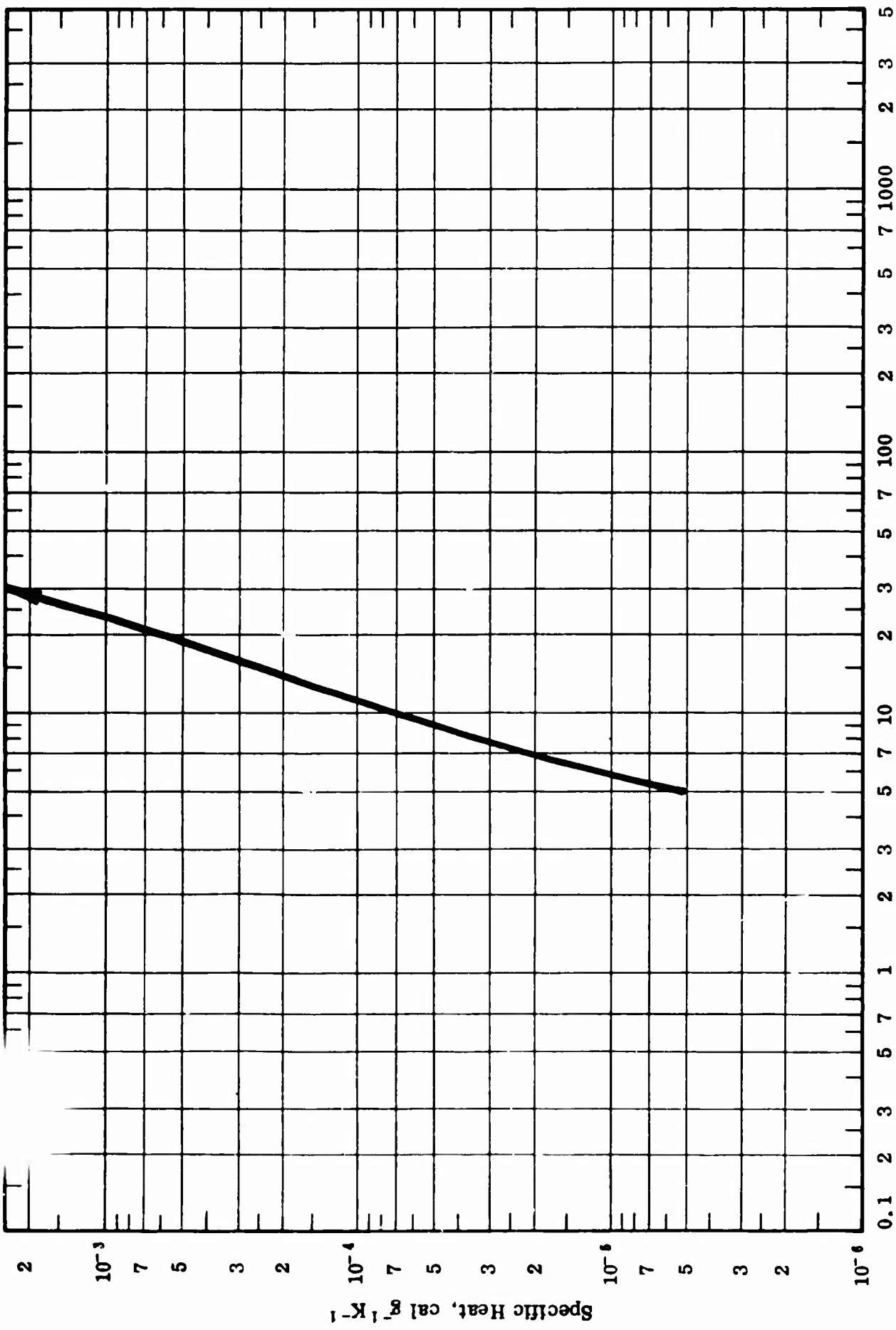


FIG. V - 25 (a)

Temperature, K

SPECIFIC HEAT -- FERRIC OXIDE, Fe<sub>2</sub>O<sub>3</sub>

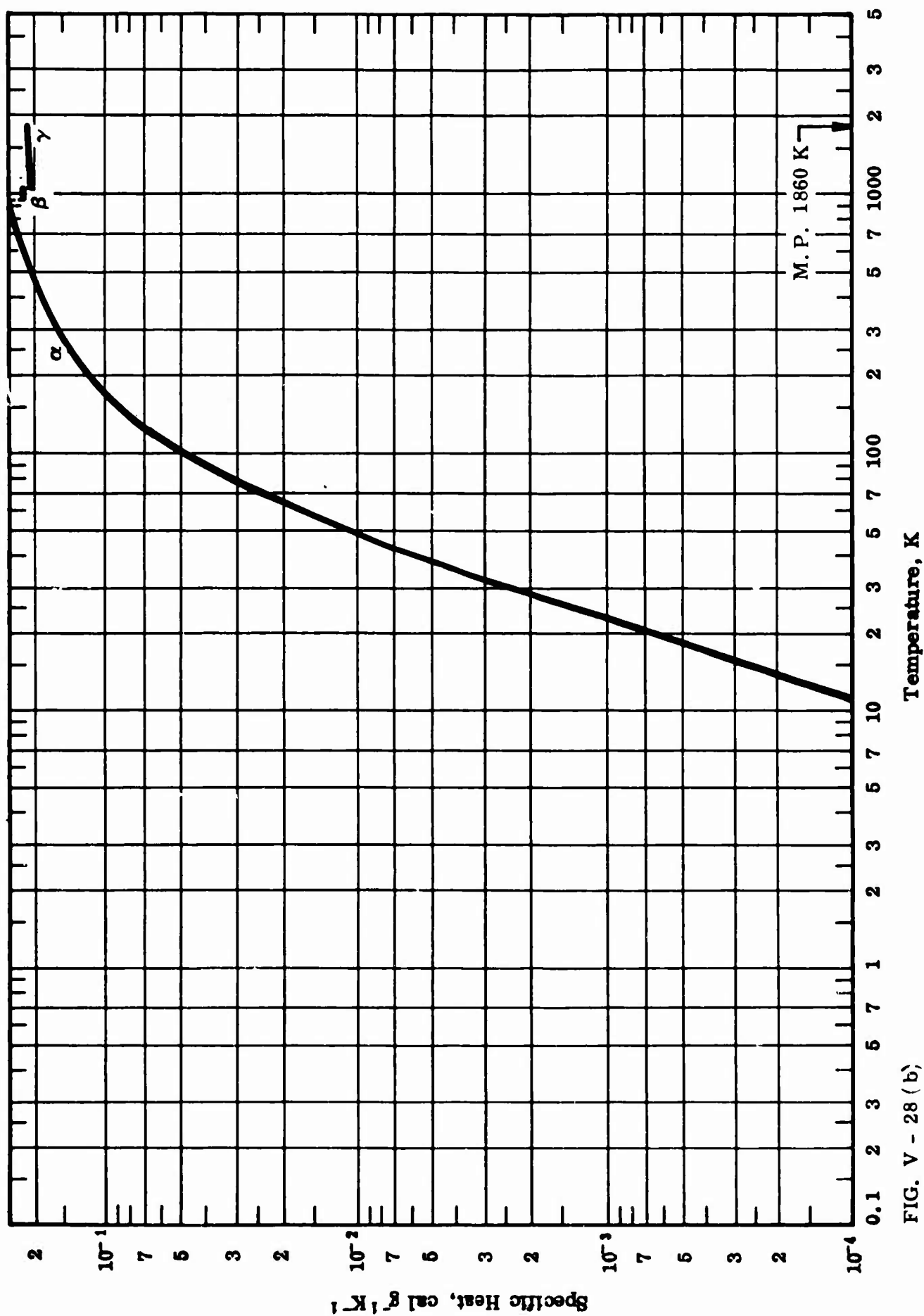


FIG. V - 28 (b)

SPECIFIC HEAT -- FERRIC OXIDE, Fe<sub>2</sub>O<sub>3</sub>

TABLE NO. V-28. SPECIFIC HEAT OF FERRIC OXIDE  $\text{Fe}_2\text{O}_3$

| $T$ °K           | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> | $T$ °K            | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> |
|------------------|---|-------------------|---|
| 5                | $5.00 \times 10^{-6}$                       | ( $\alpha$ ) 700  | $2.28 \times 10^{-1}$                       |
| 10               | $7.51 \times 10^{-5}$                       | 800               | 2.40  |
| 15               | $2.67 \times 10^{-4}$                       | 900               | 2.52  |
| 20               | 5.70  | ( $\alpha$ ) 950  | 2.58  |
| 30               | $2.36 \times 10^{-3}$                       | ( $\beta$ ) 950   | 2.25  |
| 40               | 5.96  | 1000              | 2.25  |
| 50               | $1.10 \times 10^{-2}$                       | ( $\beta$ ) 1050  | 2.25  |
| 60               | 1.72  | ( $\gamma$ ) 1050 | 2.10  |
| 70               | 2.42  | 1100              | 2.11  |
| 80               | 3.17  | 1200              | 2.12  |
| 90               | 3.95  | 1300              | 2.13  |
| ( $\alpha$ ) 100 | 4.71  | 1400              | 2.14  |
| 150              | 8.42  | 1500              | 2.15  |
| 200              | $1.14 \times 10^{-1}$                       | 1600              | 2.16  |
| 300              | 1.56  | 1700              | 2.17  |
| 400              | 1.85  | ( $\gamma$ ) 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].

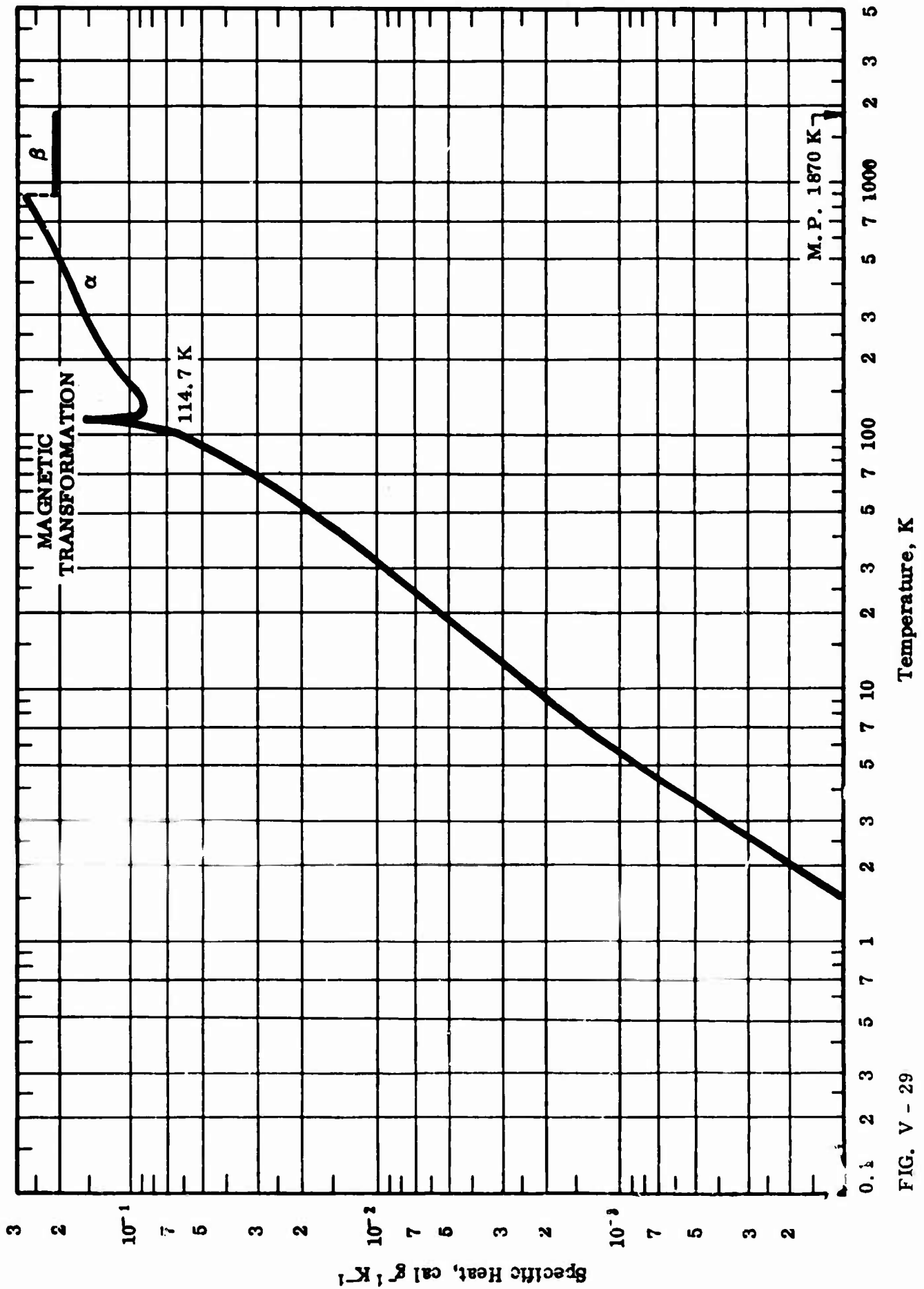


FIG. V - 29

SPECIFIC HEAT -- IRON OXIDE (MAGNETITE) Fe<sub>3</sub>O<sub>4</sub>

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

| T °K | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> | T °K             | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|---|------------------|---|
| 1.0  | (5.80 x 10 <sup>-5</sup> ) <sup>†</sup>     | 114.7            | 1.57 x 10 <sup>-1</sup>                     |
| 1.5  | (1.19 x 10 <sup>-4</sup> ) <sup>†</sup>     | 116              | 1.27  |
| 2    | 1.95  | 119              | 9.29 x 10 <sup>-2</sup>                     |
| 3    | 3.90  | 120              | 9.25  |
| 4    | 6.20  | 130              | 8.50  |
| 5    | 8.50  | 140              | 9.00  |
| 6    | (1.10 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 150              | 9.60  |
| 7    | (1.36 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 200              | 1.20 x 10 <sup>-1</sup>                     |
| 8    | (1.65 x 10 <sup>-3</sup> ) <sup>‡</sup>     | ( $\alpha$ ) 300 | 1.57  |
| 9    | (1.92 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 400              | 1.78  |
| 10   | (2.40 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 500              | 1.99  |
| 15   | (3.60 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 600              | 2.19  |
| 20   | (5.20 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 700              | 2.40  |
| 30   | (8.90 x 10 <sup>-3</sup> ) <sup>‡</sup>     | 800              | 2.61  |
| 40   | (1.34 x 10 <sup>-2</sup> ) <sup>‡</sup>     | ( $\alpha$ ) 900 | 2.82  |
| 50   | (1.85 x 10 <sup>-2</sup> ) <sup>‡</sup>     | ( $\beta$ ) 900  | 2.07  |
| 60   | 2.37 x 10 <sup>-2</sup>                     | 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 x 10 <sup>-1</sup>                     | 1700             | 2.07  |
| 114  | 1.42  | ( $\beta$ )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 Bertram, W. W. (272) [293-1056 K].

<sup>†</sup>Extrapolated

<sup>‡</sup>Interpolated

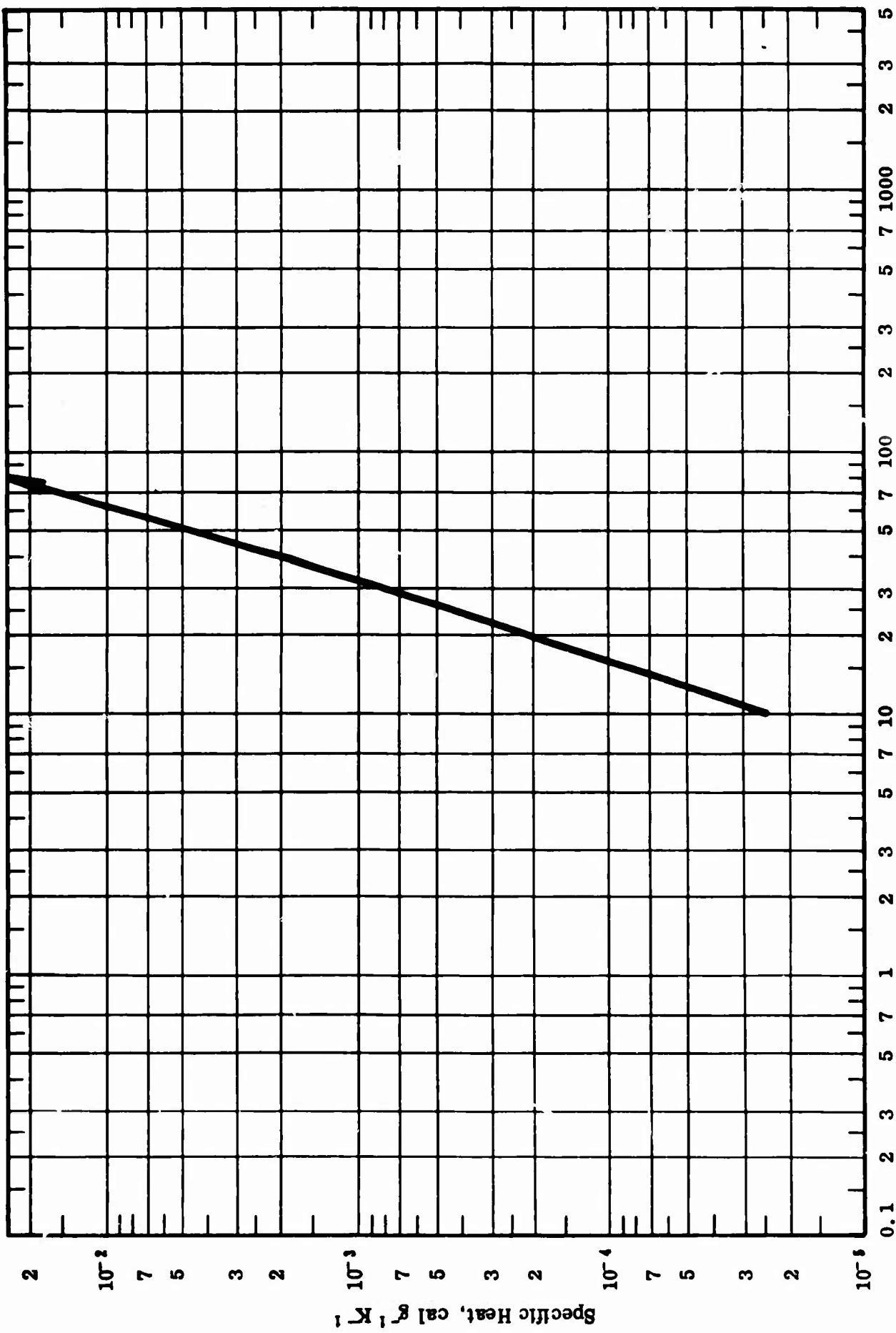


FIG. V - 30 (a)  
SPECIFIC HEAT -- MAGNESIUM OXIDE, MgO  
Temperature, K

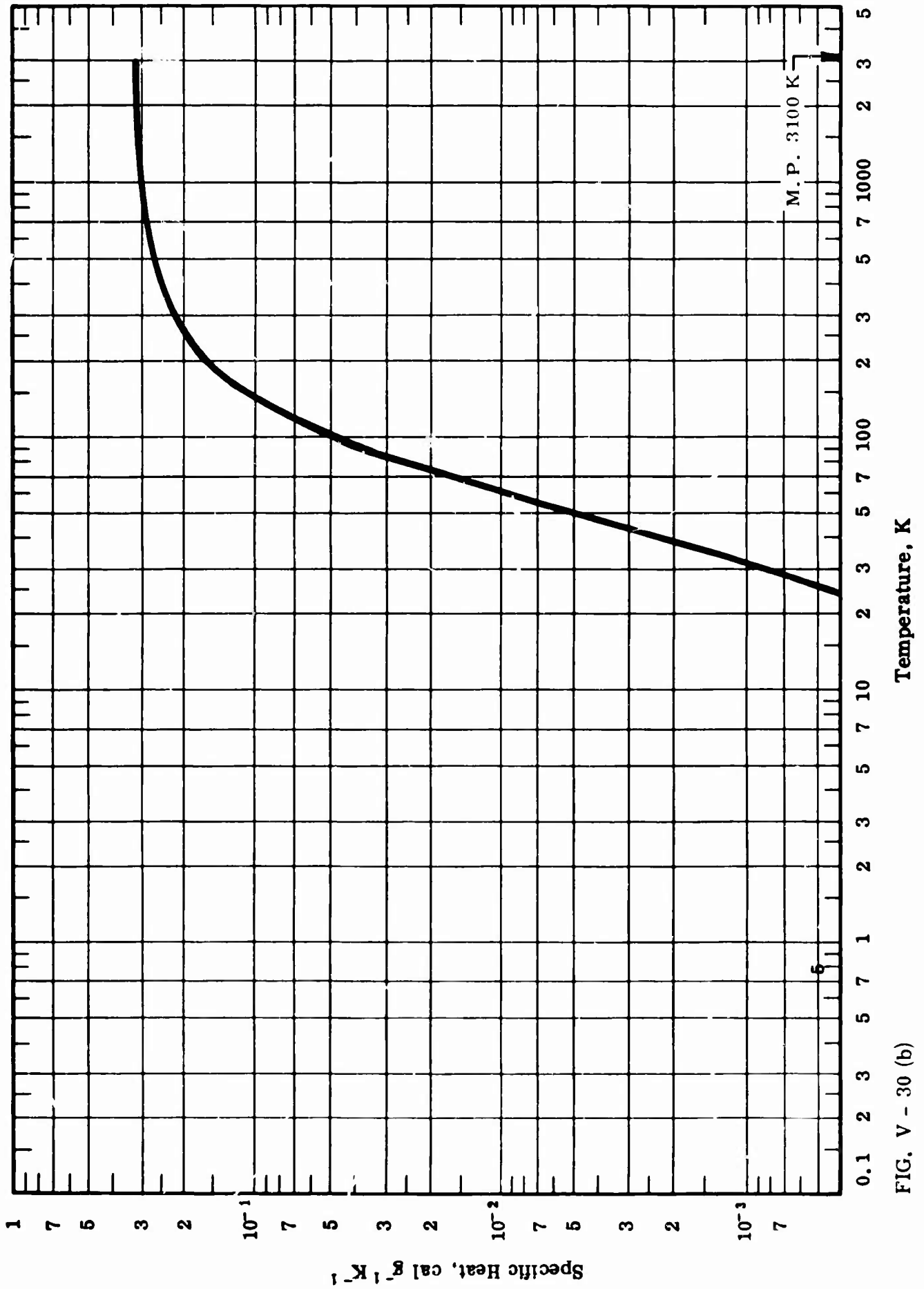


FIG. V - 30 (b)

SPECIFIC HEAT -- MAGNESIUM OXIDE, MgO

TABLE V-30. SPECIFIC HEAT OF MAGNESIUM OXIDE MgO

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 10   | 2.50 x 10 <sup>-5</sup>                              | 1100 | 3.07 x 10 <sup>-1</sup>                              |
| 15   | 9.90   | 1200 | 3.10   |
| 20   | 2.20 x 10 <sup>-4</sup>                              | 1300 | 3.12   |
| 30   | 8.20   | 1400 | 3.13   |
| 40   | 2.20 x 10 <sup>-3</sup>                              | 1500 | 3.15   |
| 50   | 4.94   | 1600 | 3.16   |
| 60   | 9.52   | 1700 | 3.18   |
| 70   | 1.62 x 10 <sup>-2</sup>                              | 1800 | 3.19   |
| 80   | 2.48   | 1900 | 3.19   |
| 90   | 3.49   | 2000 | 3.20   |
| 100  | 4.62   | 2100 | 3.21   |
| 150  | 1.02 x 10 <sup>-1</sup>                              | 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]; Giaque, 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) [298-1800 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].

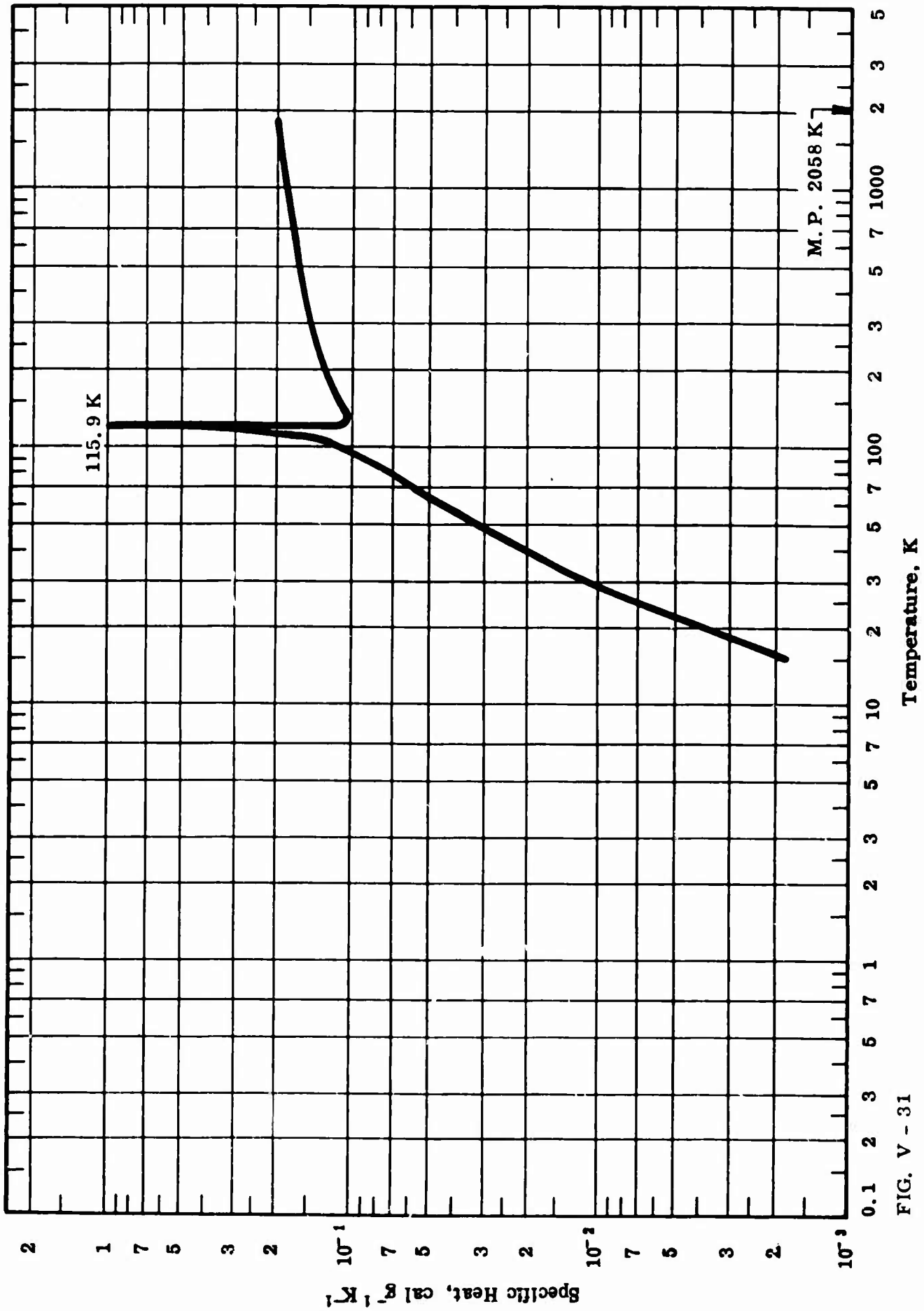


FIG. V - 31

SPECIFIC HEAT -- MANGANOUS OXIDE, MnO

TABLE V-31. . SPECIFIC HEAT OF MANGANESE MONOXIDE MnO

| T °K  | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|-------|--|------|--|
| 10    | (5.64 x 10 <sup>-4</sup> )                           | 150  | 1.12 x 10 <sup>-1</sup>                              |
| 15    | (1.75 x 10 <sup>-3</sup> )                           | 200  | 1.28   |
| 20    | (3.95 x 10 <sup>-3</sup> )                           | 250  | 1.40   |
| 30    | (1.09 x 10 <sup>-2</sup> )                           | 300  | 1.49   |
| 40    | (2.05 x 10 <sup>-2</sup> )                           | 400  | 1.60   |
| 50    | (3.20 x 10 <sup>-2</sup> )                           | 500  | 1.65   |
| 60    | 4.50 x 10 <sup>-2</sup>                              | 600  | 1.70   |
| 70    | 5.90   | 700  | 1.73   |
| 80    | 7.50   | 800  | 1.76   |
| 90    | 8.80   | 900  | 1.80   |
| 100   | 1.09 x 10 <sup>-1</sup>                              | 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 x 10 <sup>0</sup>                               | 1500 | 1.97   |
| 116   | 3.37 x 10 <sup>-1</sup>                              | 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) [ $\Delta H$ , 298-1800 K]; Todd, S. S. and Bonnicksen, K. R. (286) [55-298 K].

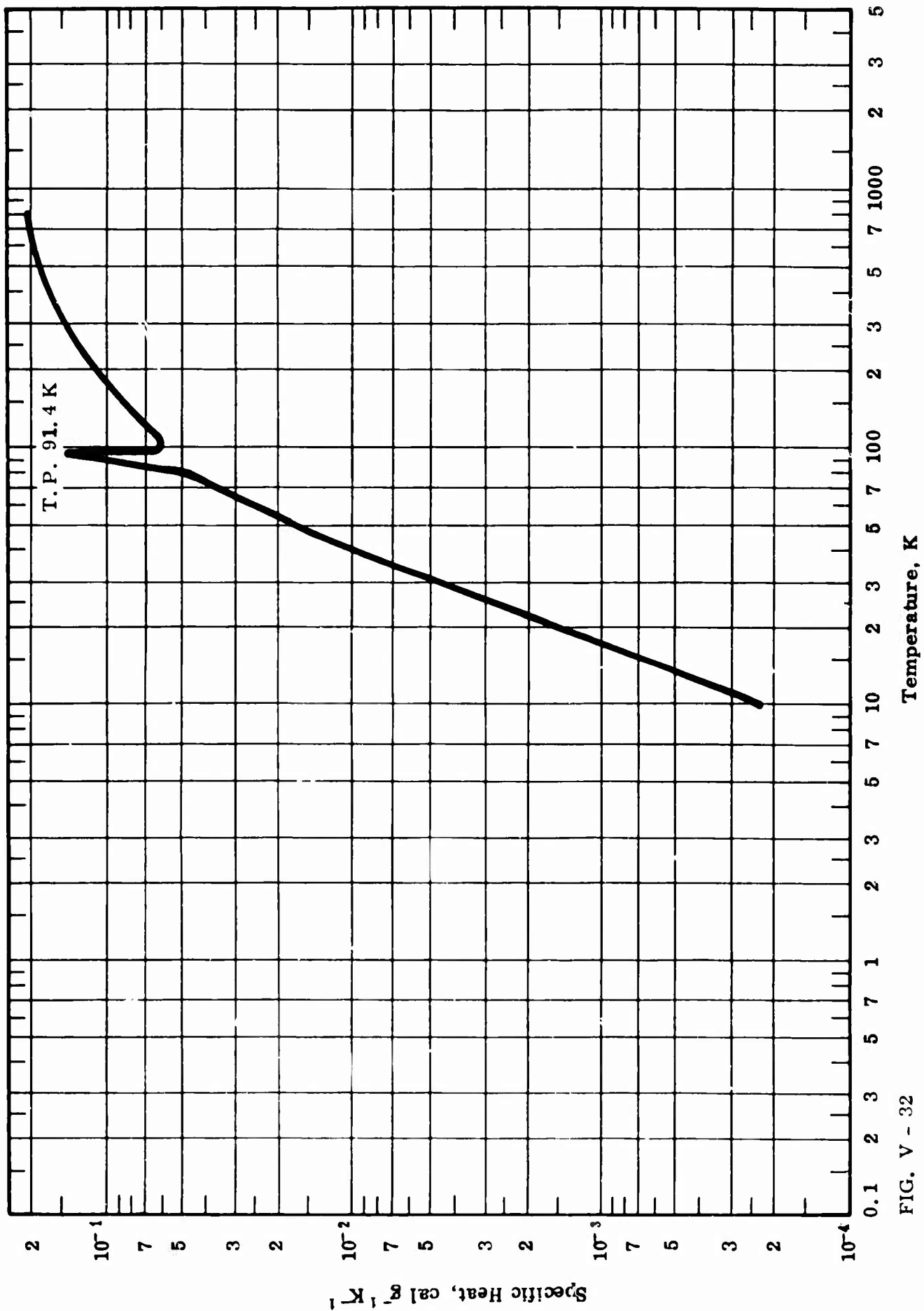


FIG. V - 32

SPECIFIC HEAT -- MANGANESE DIOXIDE, MnO<sub>2</sub>

TABLE V-32. SPECIFIC HEAT OF MANGANESE DIOXIDE MnO<sub>2</sub>

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 10   | (2.30 x 10 <sup>-4</sup> ) <sup>†</sup>              | 92.1 | 1.26 x 10 <sup>-1</sup>                              |
| 15   | (7.20 x 10 <sup>-4</sup> ) <sup>†</sup>              | 97.4 | 6.06 x 10 <sup>-2</sup>                              |
| 20   | (1.55 x 10 <sup>-3</sup> ) <sup>†</sup>              | 100  | 5.95   |
| 30   | (4.70 x 10 <sup>-3</sup> ) <sup>†</sup>              | 150  | 8.50   |
| 40   | (1.02 x 10 <sup>-2</sup> ) <sup>†</sup>              | 200  | 1.10 x 10 <sup>-1</sup>                              |
| 50   | 1.76 x 10 <sup>-2</sup>                              | 300  | 1.50   |
| 60   | 2.70   | 400  | 1.74   |
| 70   | 3.90   | 500  | 1.87   |
| 80   | 5.28   | 600  | 1.95   |
| 90   | 1.01 x 10 <sup>-1</sup>                              | 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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<sup>†</sup>Extrapolated

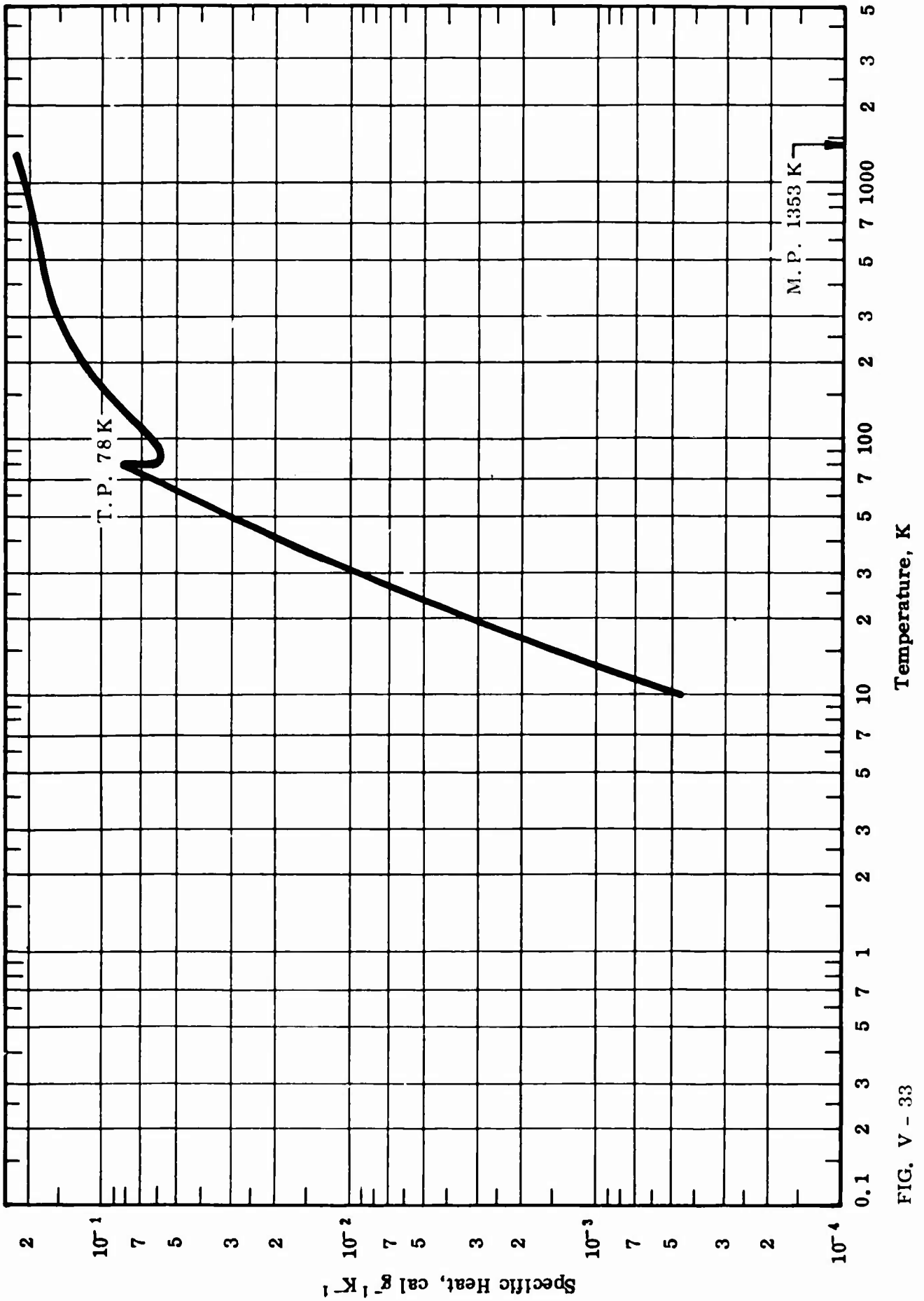


FIG. V - 33

SPECIFIC HEAT -- MANGANESE SESQUIOXIDE, Mn<sub>2</sub>O<sub>3</sub>

TABLE V-33. SPECIFIC HEAT OF MANGANESE SESQUIOXIDE  $Mn_2O_3$

| T °K | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|---|------|---|
| 10   | (4.43 x 10 <sup>-4</sup> ) <sup>†</sup>     | 90   | 5.90 x 10 <sup>-2</sup>                     |
| 15   | (1.50 x 10 <sup>-3</sup> )                  | 100  | 6.30  |
| 20   | (3.15 x 10 <sup>-3</sup> )                  | 150  | 9.30  |
| 30   | (9.10 x 10 <sup>-3</sup> )                  | 200  | 1.19 x 10 <sup>-1</sup>                     |
| 40   | (1.84 x 10 <sup>-2</sup> )                  | 300  | 1.50  |
| 50   | 3.00 x 10 <sup>-2</sup>                     | 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].

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<sup>†</sup>Extrapolated

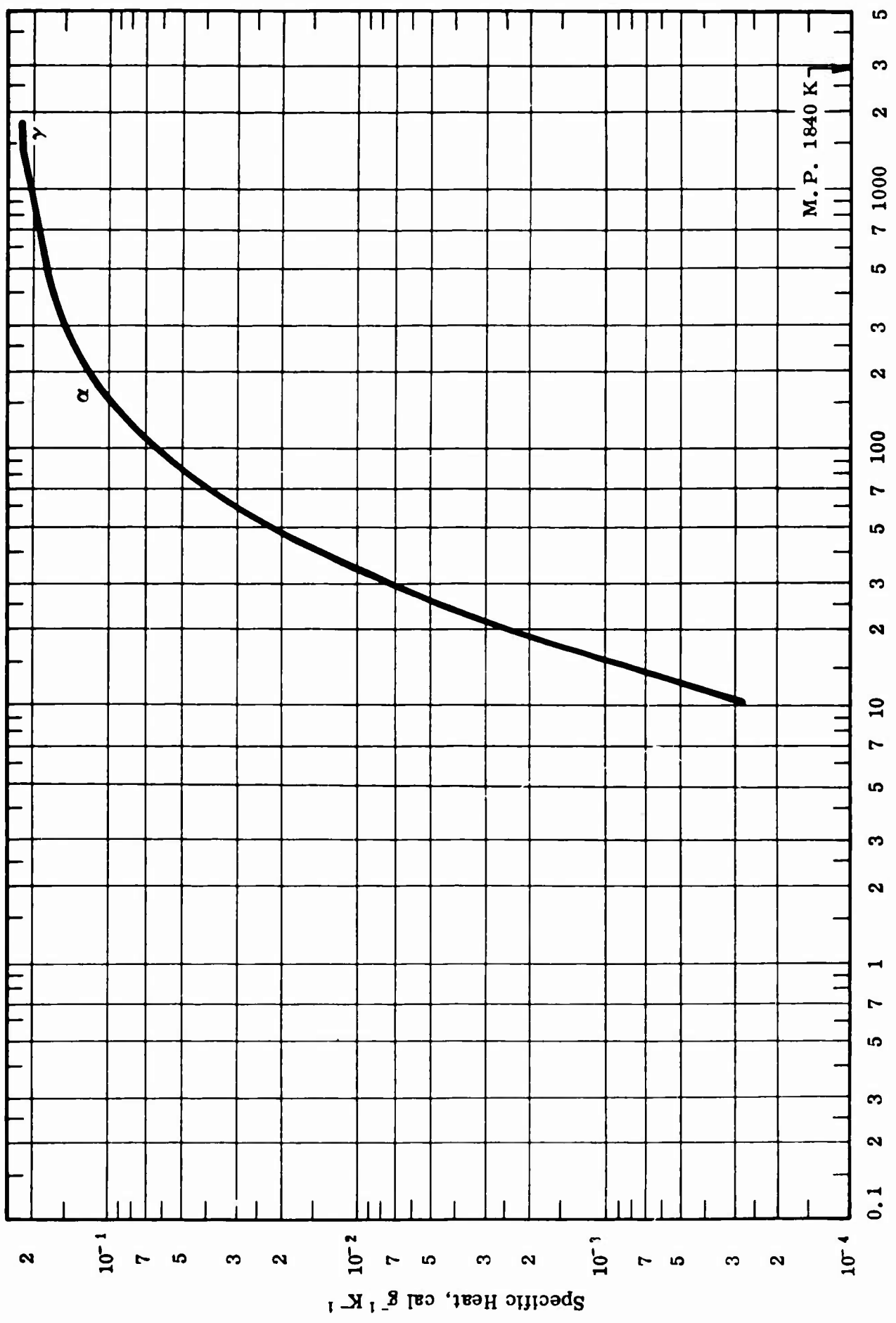


FIG. V - 34

SPECIFIC HEAT -- MANGANOMANGANIC OXIDE, Mn<sub>3</sub>O<sub>4</sub>

TABLE V-34. SPECIFIC HEAT OF MANGANOMANGANIC OXIDE  $Mn_3O_4$

| T °K             | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> | T °K              | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> |
|------------------|---|-------------------|---|
| 10               | $2.62 \times 10^{-4}$                       | ( $\alpha$ ) 600  | $1.77 \times 10^{-1}$                       |
| 15               | 9.20  | 700               | 1.82  |
| 20               | $2.40 \times 10^{-3}$                       | 800               | 1.88  |
| 30               | 7.10  | 900               | 1.93  |
| 40               | $1.44 \times 10^{-2}$                       | 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  | ( $\alpha$ ) 1445 | 2.19  |
| ( $\alpha$ ) 100 | 6.40  | ( $\beta$ ) 1145  | $2.20 \times 10^{-1}$                       |
| 150              | 9.60  | 1500              | 2.20  |
| 200              | $1.19 \times 10^{-1}$                       | 1600              | 2.20  |
| 300              | 1.46  | 1700              | 2.20  |
| 400              | 1.64  | ( $\beta$ ) 1800  | 2.20  |
| 500              | 1.71  |                   |   |

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

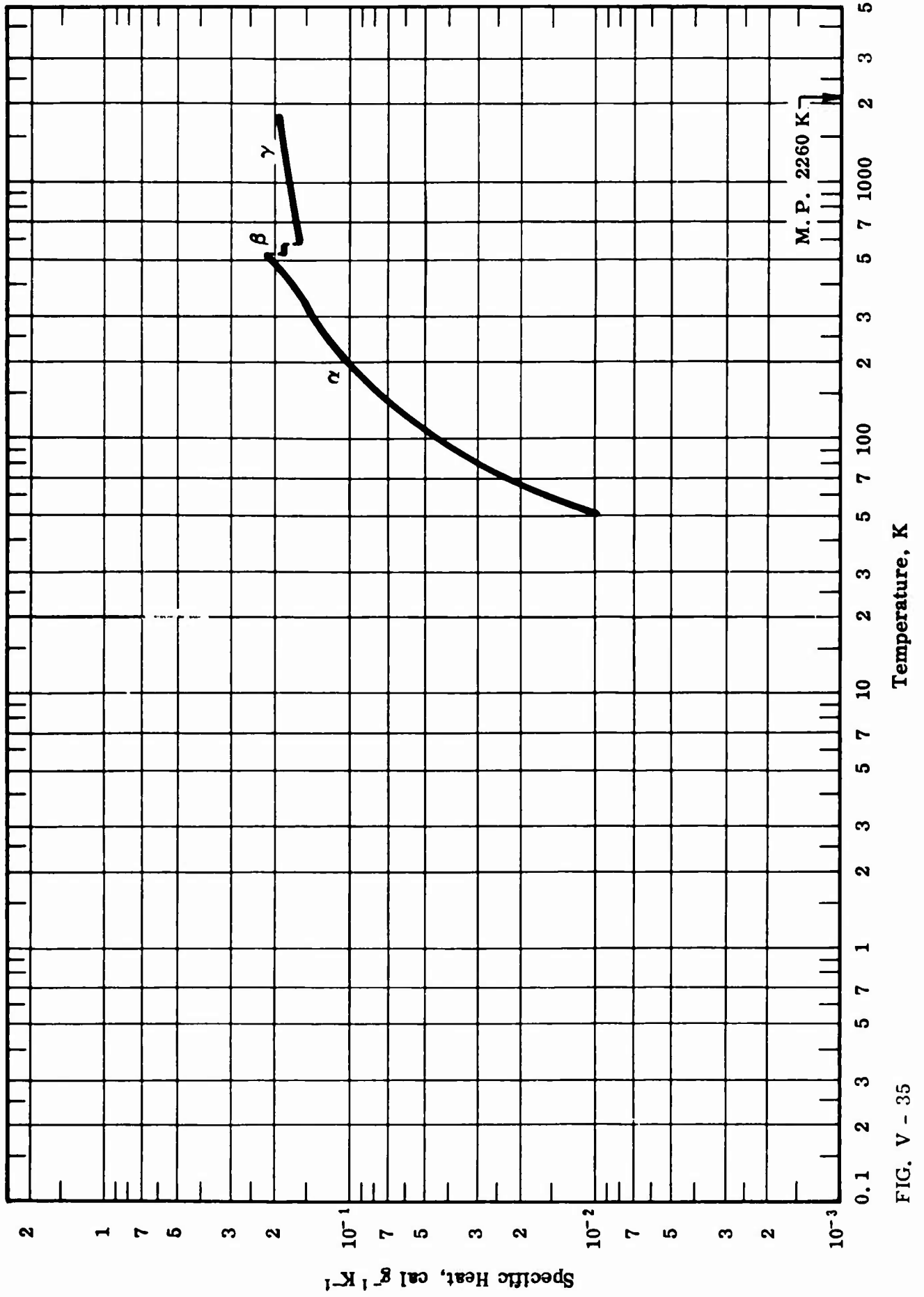


FIG. V - 35

SPECIFIC HEAT -- NICKEL OXIDE, NiO

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

| T °K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|---------|--|----------|--|
| (α) 50  | 9.90 x 10 <sup>-3</sup>                              | (γ) 565  | 1.64 x 10 <sup>-1</sup>                              |
| 60      | 1.65 x 10 <sup>-2</sup>                              | 600      | 1.65   |
| 70      | 2.40   | 700      | 1.68   |
| 80      | 3.01   | 800      | 1.70   |
| 90      | 3.80   | 900      | 1.73   |
| 100     | 4.60   | 1000     | 1.76   |
| 150     | 7.80   | 1100     | 1.78   |
| 200     | 1.06 x 10 <sup>-1</sup>                              | 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 x 10 <sup>-1</sup>                              | 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].

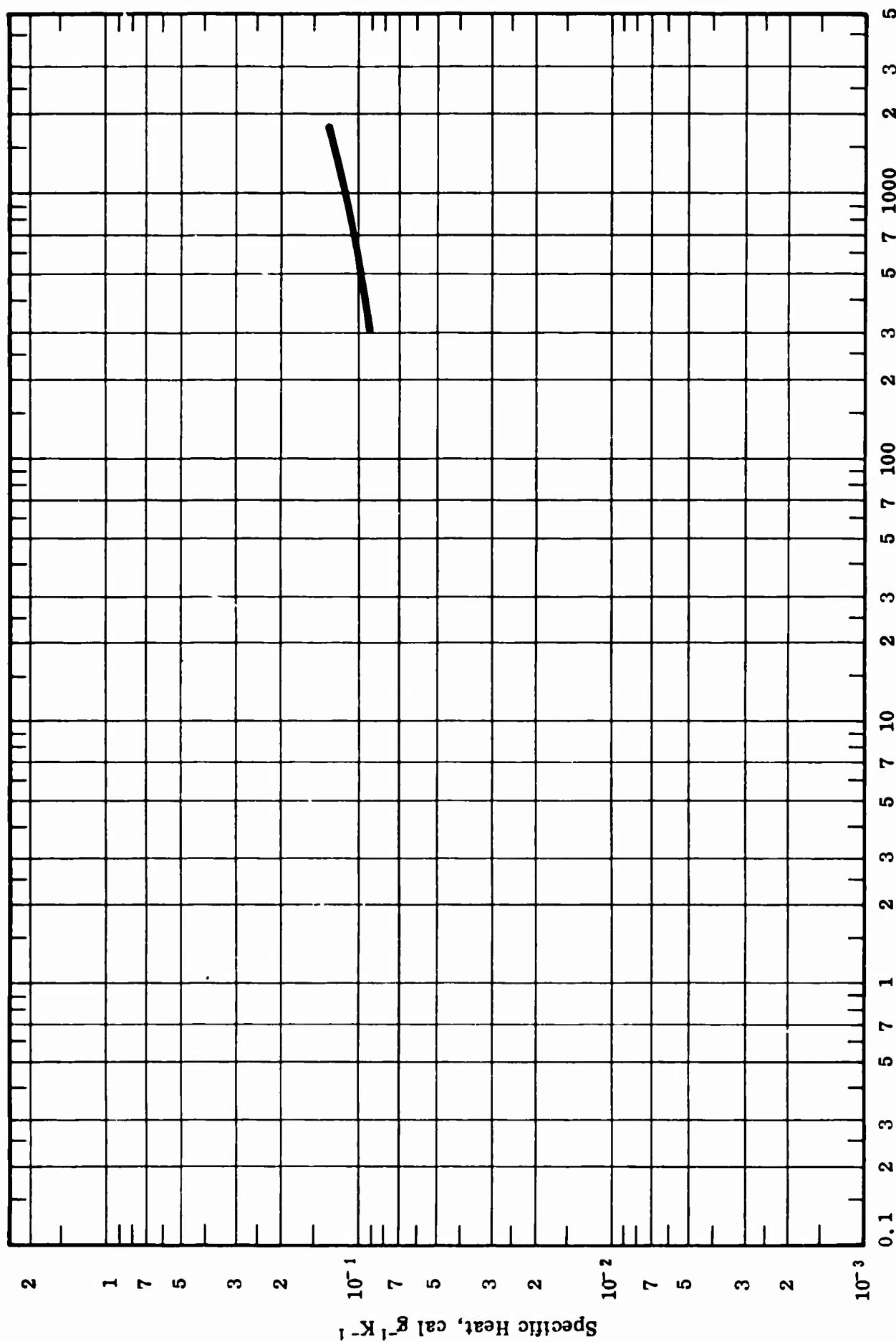


FIG. V - 36

Temperature, K

SPECIFIC HEAT -- NIOBIUM MONOXIDE, NbO

TABLE V-36. . SPECIFIC HEAT OF NIOBIUM MONOXIDE NbO

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 300  | 9.06 x 10 <sup>-2</sup>                              | 1100 | 1.15 x 10 <sup>-1</sup>                              |
| 400  | 9.63   | 1200 | 1.18   |
| 500  | 1.00 x 10 <sup>-1</sup>                              | 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].

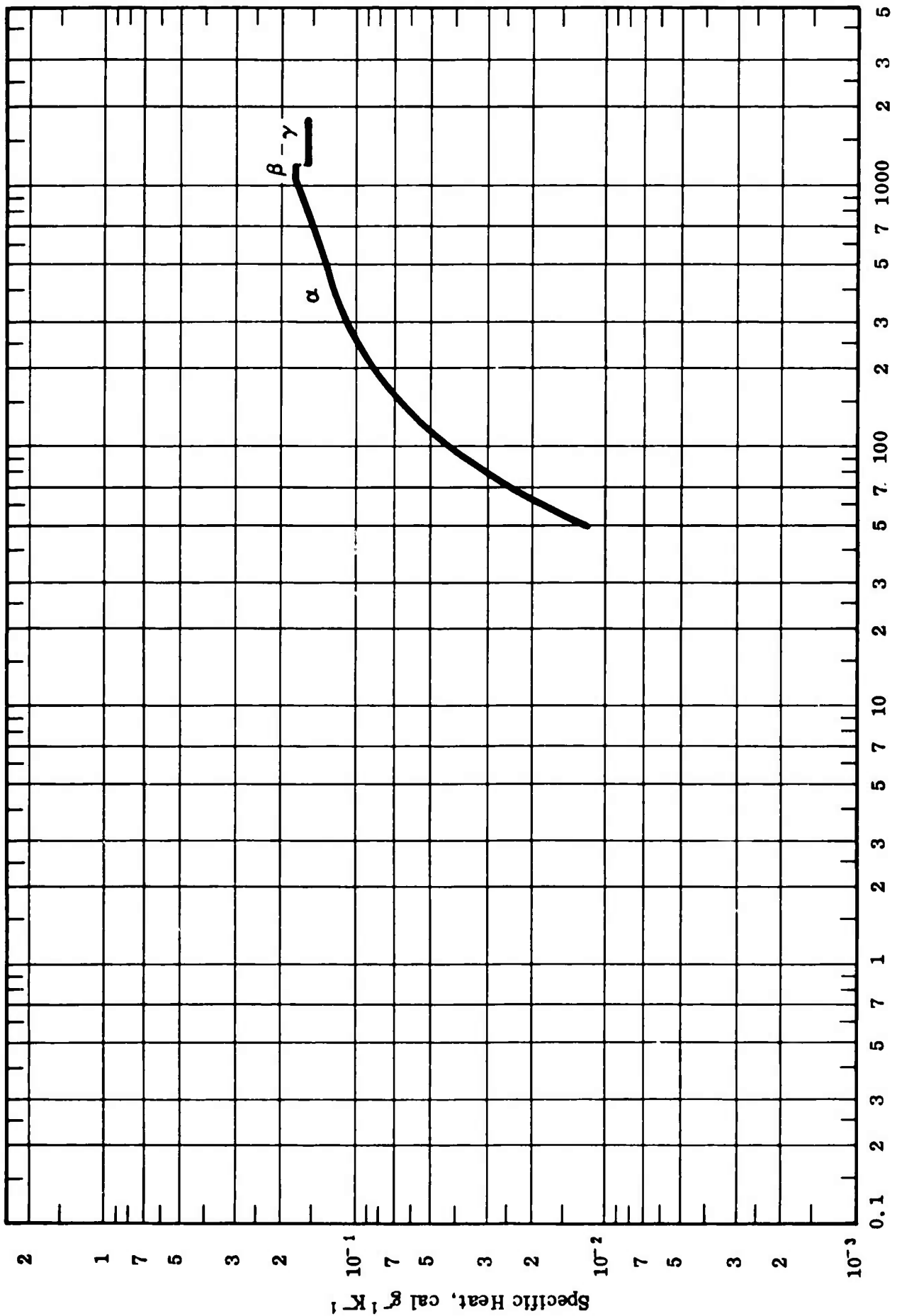


FIG. V - 37

Temperature, K

SPECIFIC HEAT -- NIOBIUM DIOXIDE, NbO<sub>2</sub>

TABLE V-37. . SPECIFIC HEAT OF NIOBIUM DIOXIDE NbO<sub>2</sub>

| T °K    | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|---------|--|----------|--|
| (α) 50  | 1.19 x 10 <sup>-2</sup>                              | (α) 900  | 1.62 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 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].

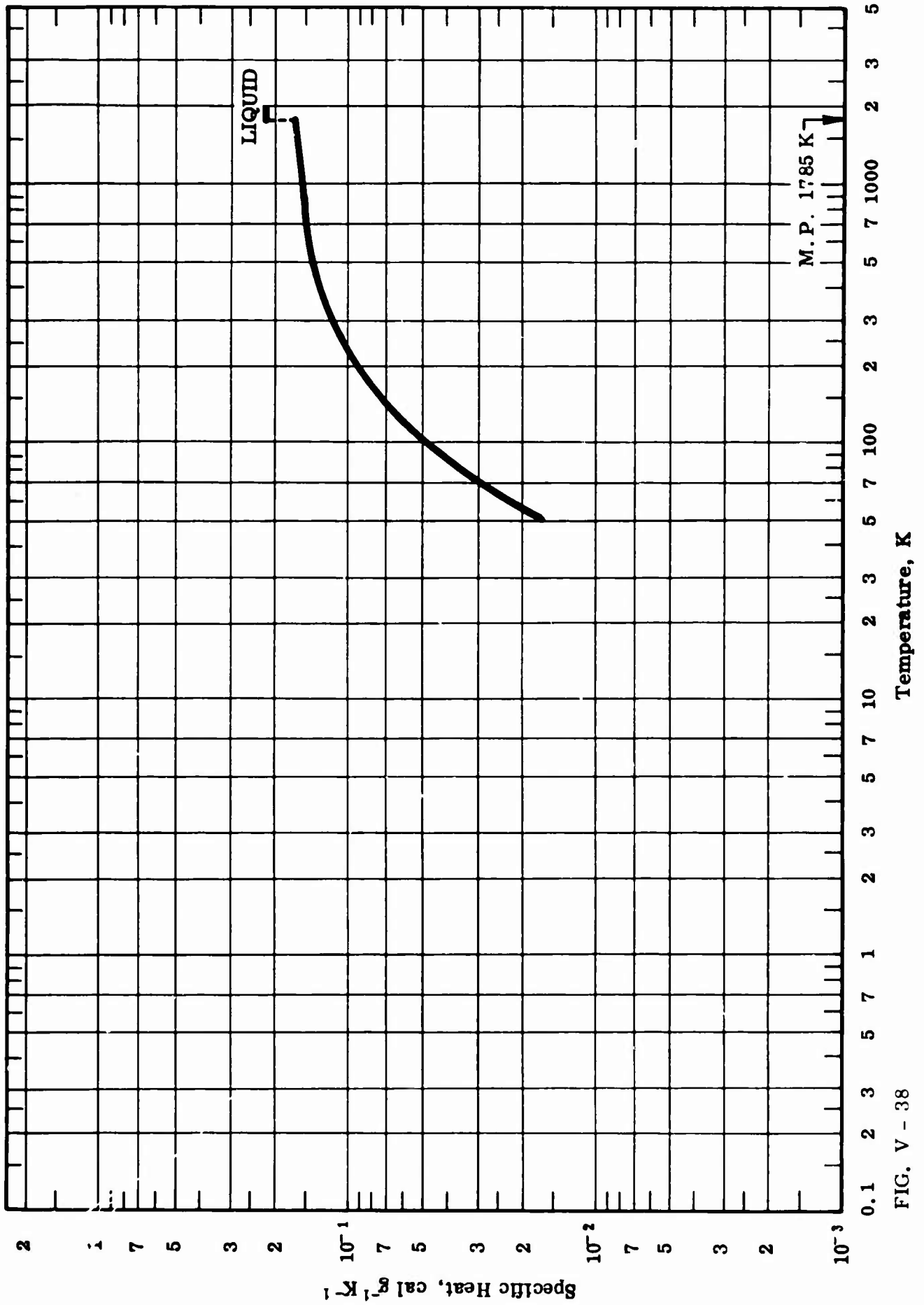


FIG. V - 38

SPECIFIC HEAT -- NIOBIUM PENTOXIDE, Nb<sub>2</sub>O<sub>5</sub>

TABLE V-38. . . SPECIFIC HEAT OF NIOBIUM PENTOXIDE  $Nb_2O_5$

| T °K   | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | $C_p$ , cal g <sup>-1</sup> K <sup>-1</sup> |
|--------|---|----------|---|
| (s) 50 | (1.65 x 10 <sup>-2</sup> ) <sup>†</sup>     | (s) 900  | 1.54 x 10 <sup>-1</sup>                     |
| 60     | 2.35 x 10 <sup>-2</sup>                     | 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 x 10 <sup>-1</sup>                     | 1700     | 1.68  |
| 400    | 1.34  | (s) 1785 | 1.68  |
| 500    | 1.42  | (l) 1785 | 2.18 x 10 <sup>-1</sup>                     |
| 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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<sup>†</sup>Extrapolated

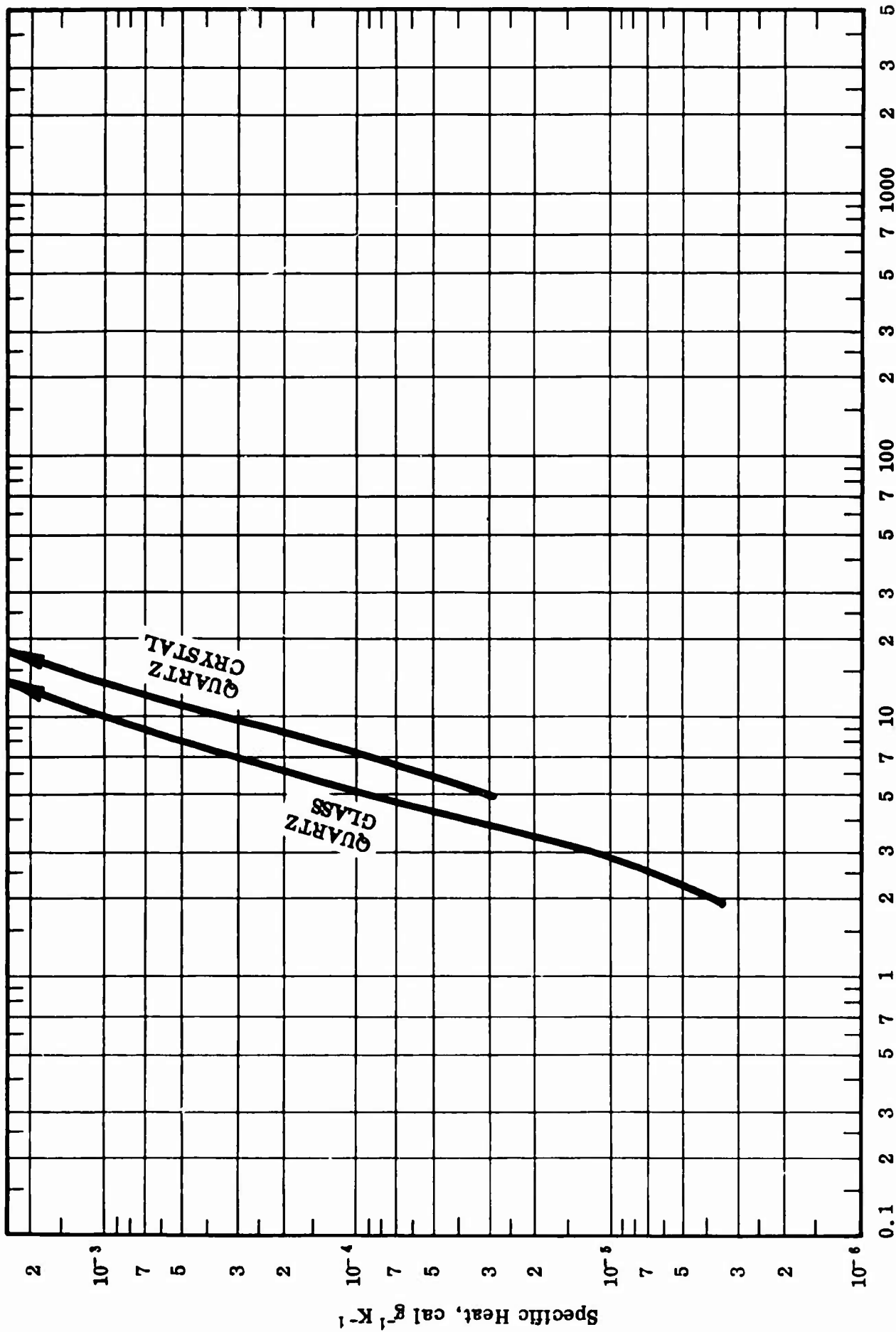


FIG. V - 39 (a)

SPECIFIC HEAT -- SILICON DIOXIDE

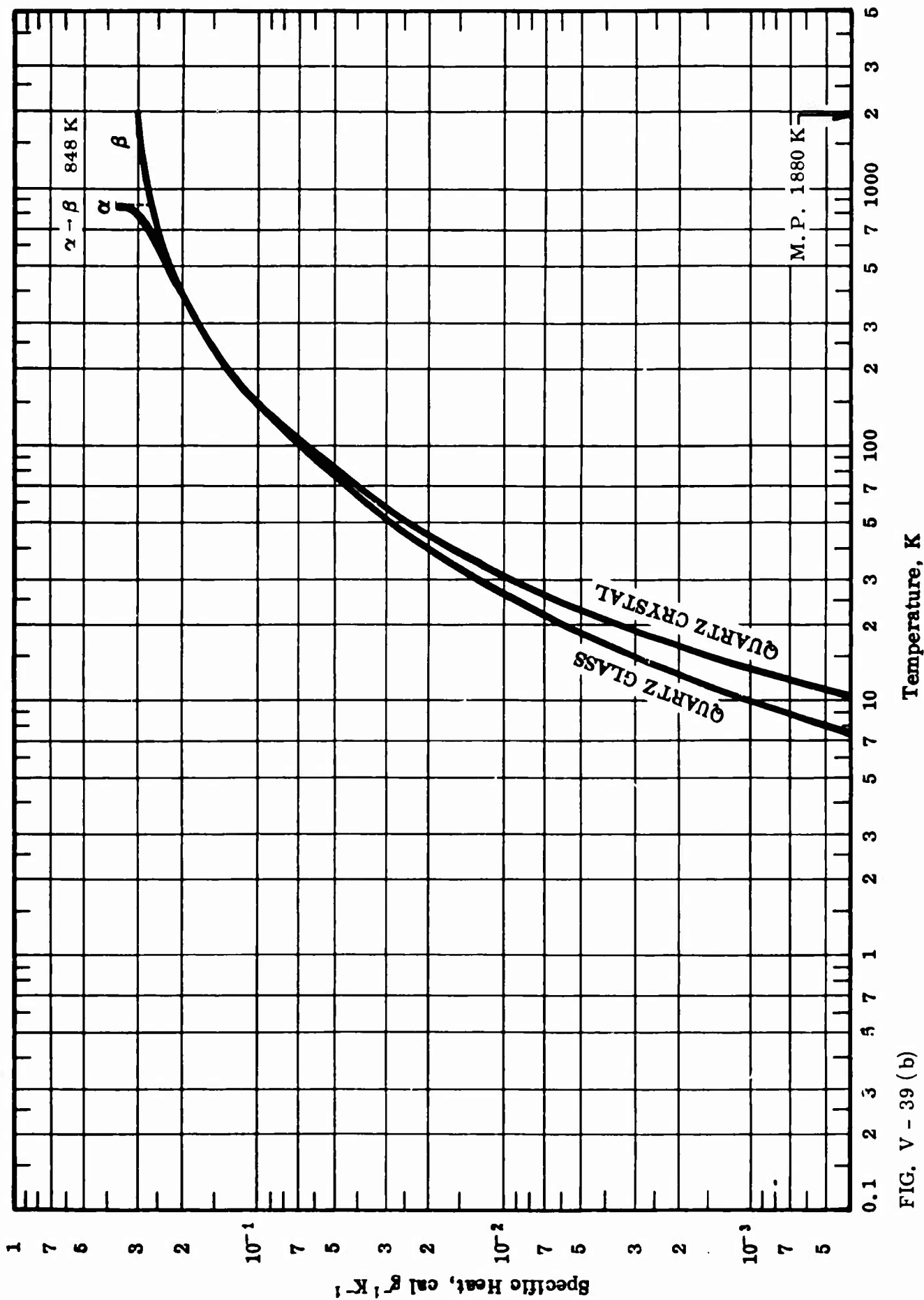


FIG. V - 39 (b)

SPECIFIC HEAT -- SILICON DIOXIDE

TABLE V-39. SPECIFIC HEAT OF SILICON DIOXIDE SiO<sub>2</sub>

| T °K | QUARTZ GLASS   | QUARTZ CRYSTAL                                       |
|------|--|--|
|      | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 2    | (3.55 x 10 <sup>-6</sup> ) <sup>†</sup>              |  |
| 3    | 1.22 x 10 <sup>-5</sup>                              |  |
| 4    | 3.40   |  |
| 5    | 8.40   | 2.85 x 10 <sup>-5</sup>                              |
| 6    | 1.65 x 10 <sup>-4</sup>                              | 4.90   |
| 7    | 2.90   | 7.95   |
| 8    | 4.64   | 1.35 x 10 <sup>-4</sup>                              |
| 9    | 6.90   | 2.25   |
| 10   | 9.70   | 3.42   |
| 15   | 2.98 x 10 <sup>-3</sup>                              | 1.48 x 10 <sup>-3</sup>                              |
| 20   | 5.95   | 3.65   |
| 30   | 1.30 x 10 <sup>-2</sup>                              | 9.60   |
| 40   | 2.02   | 1.68 x 10 <sup>-2</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 1.00 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 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 x 10 <sup>-1</sup> ) <sup>†</sup>              |
| 1700 |  | (2.95 x 10 <sup>-1</sup> )                           |
| 1800 |  | (2.98 x 10 <sup>-1</sup> )                           |
| 1900 |  | (3.01 x 10 <sup>-1</sup> )                           |
| 2000 |  | (3.045 x 10 <sup>-1</sup> )                          |

<sup>†</sup> Extrapolated

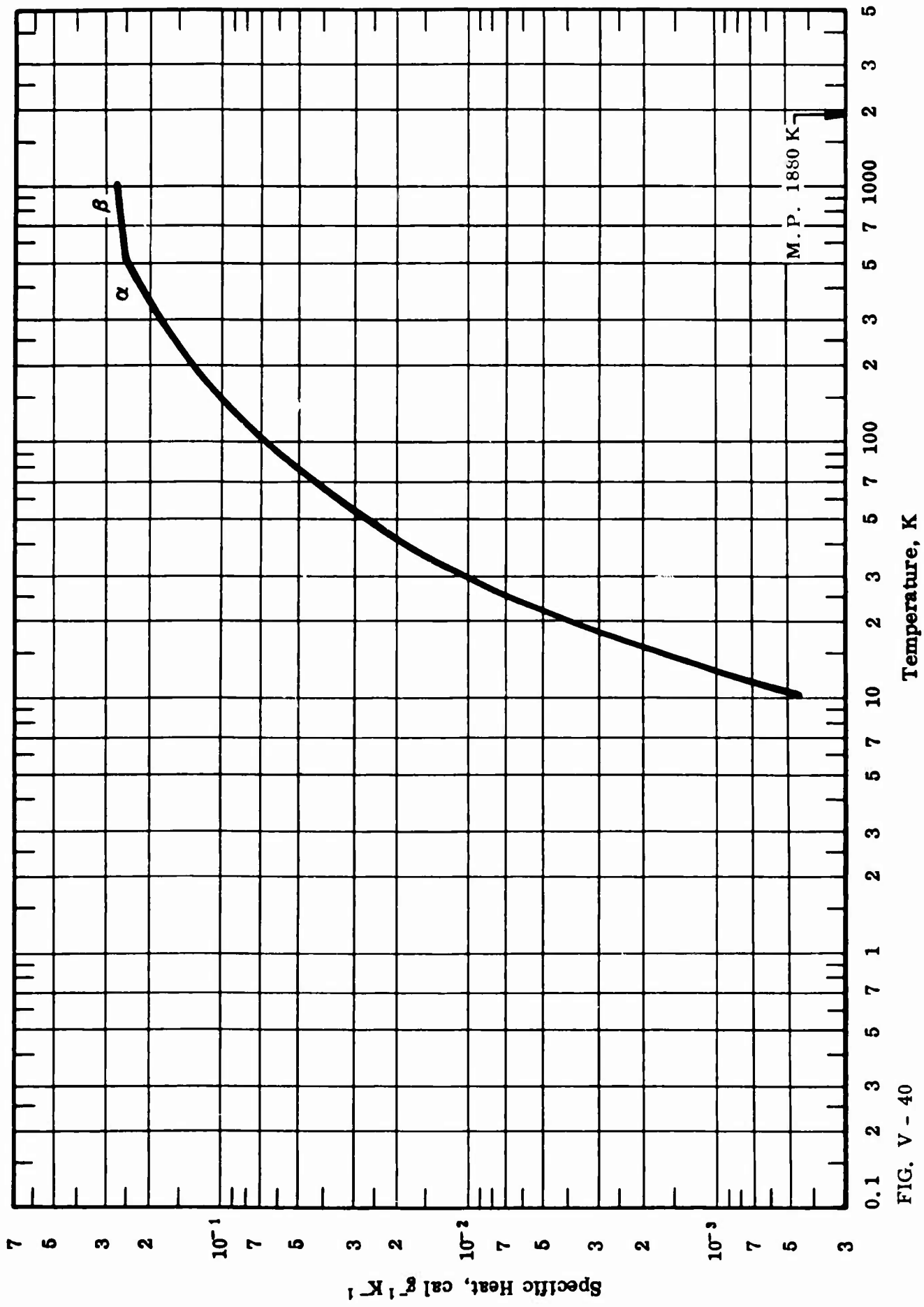


FIG. V - 40  
SPECIFIC HEAT -- SILICON DIOXIDE (CRISTOBALITE)

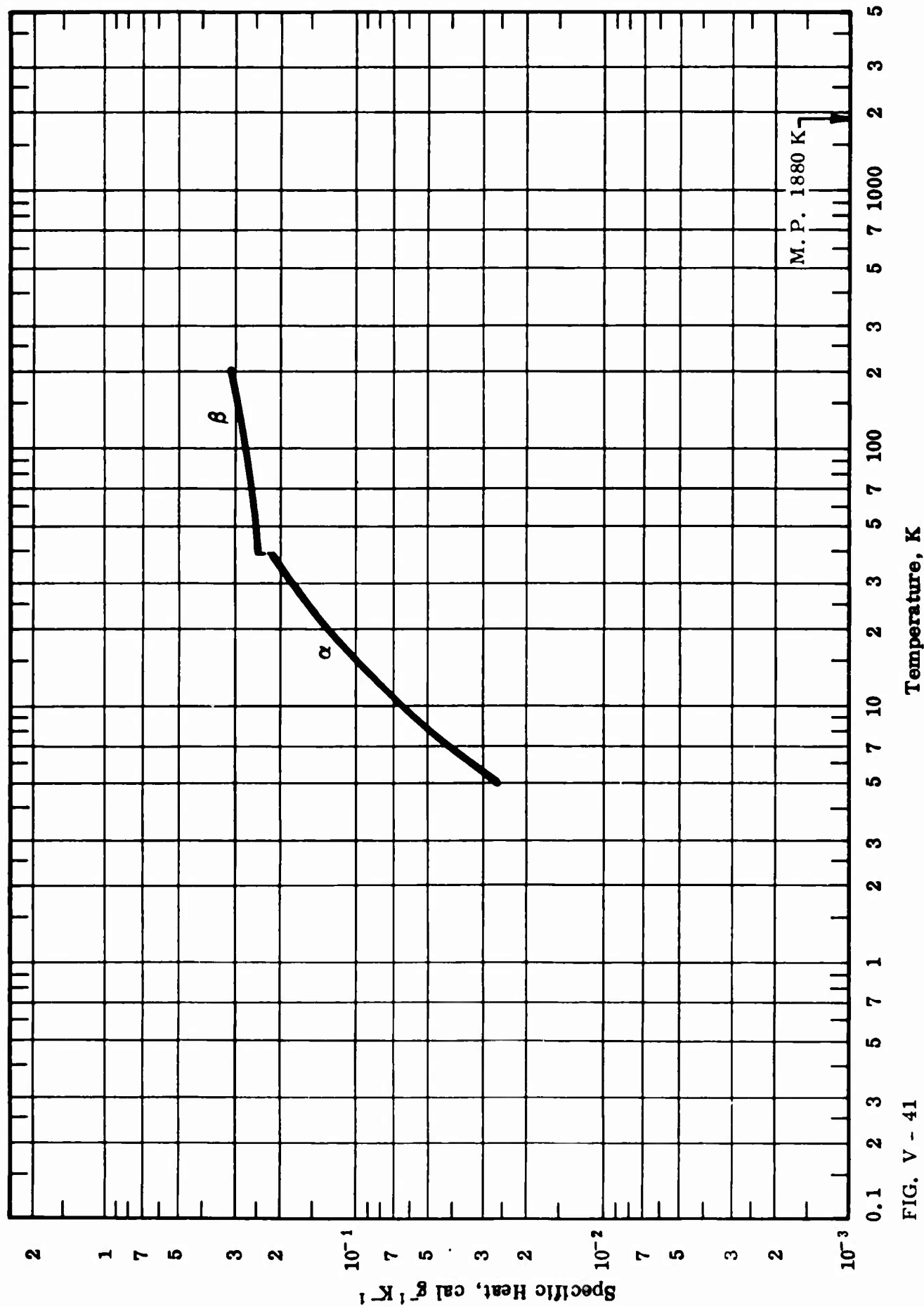


FIG. V - 41

SPECIFIC HEAT -- SILICON DIOXIDE (TRIDYMITE)

TABLE V-39. SPECIFIC HEAT OF SILICON DIOXIDE SiO<sub>2</sub> (continued)

| T °K | CRISTOBALITE   | TRIDYMITE  |
|------|--|--|
|      | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 10   | 4.50 x 10 <sup>-4</sup>                              |  |
| 15   | 1.70 x 10 <sup>-3</sup>                              |  |
| 20   | 3.70   |  |
| 30   | 1.10 x 10 <sup>-2</sup>                              |  |
| 40   | 1.85   |  |
| 50   | 2.57   | 2.60 x 10 <sup>-2</sup>                              |
| 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 x 10 <sup>-1</sup>                              |
| 160  | 1.08 x 10 <sup>-1</sup>                              |  |
| 180  | 1.21   |  |
| 200  | 1.34   | 1.32 x 10 <sup>-1</sup>                              |
| 220  | 1.44   |  |
| 240  | 1.54   |  |
| 260  | 1.64   |  |
| 300  | 1.76   | 1.78 x 10 <sup>-1</sup>                              |
| 390  |  | (α) 2.15   |
| 390  |  | (β) 2.44   |
| 400  | 2.11 x 10 <sup>-1</sup>                              | 2.45   |
| 500  | 2.46   | 2.49   |
| 523  | (α) 2.54   |  |
| 523  | (β) 2.57   |  |
| 600  | 2.60   | 2.53 x 10 <sup>-1</sup>                              |
| 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  $\text{SiO}_2$ )

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, cristobalite, 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, cristobalite, 10-273 K].

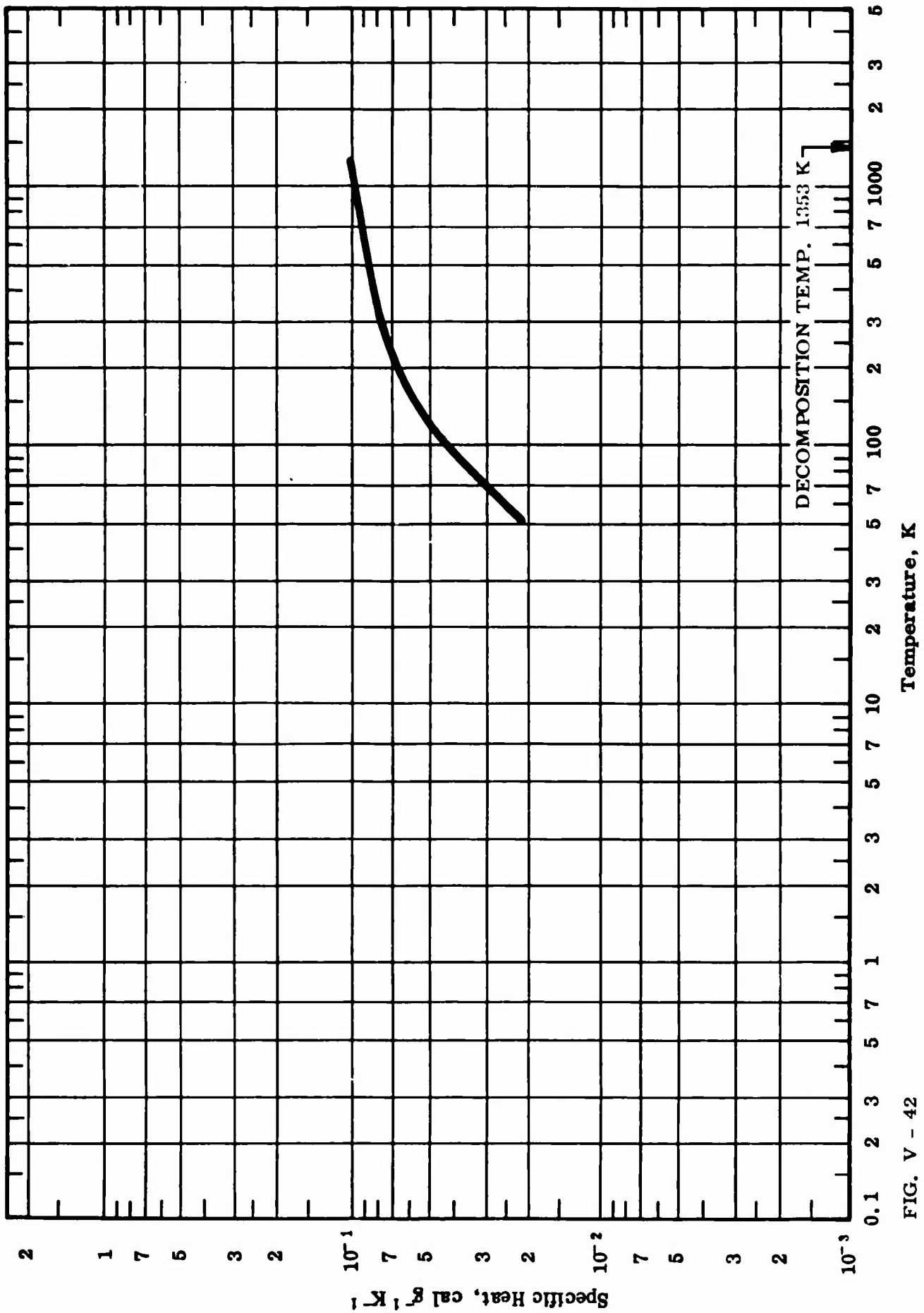


FIG. V - 42

SPECIFIC HEAT -- TIN OXIDE, SnO

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

| T°K  | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T°K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|-------|--|
| 50   | 2.09 x 10 <sup>-2</sup>                              | *500  | (8.39x 10 <sup>-2</sup> )                            |
| 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 x 10 <sup>-1</sup>                              |
| 300  | 7.80   | *1273 | 1.04   |
| *400 | 8.13 x 10 <sup>-2</sup>                              |       |  |

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

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\* Calculated (5)

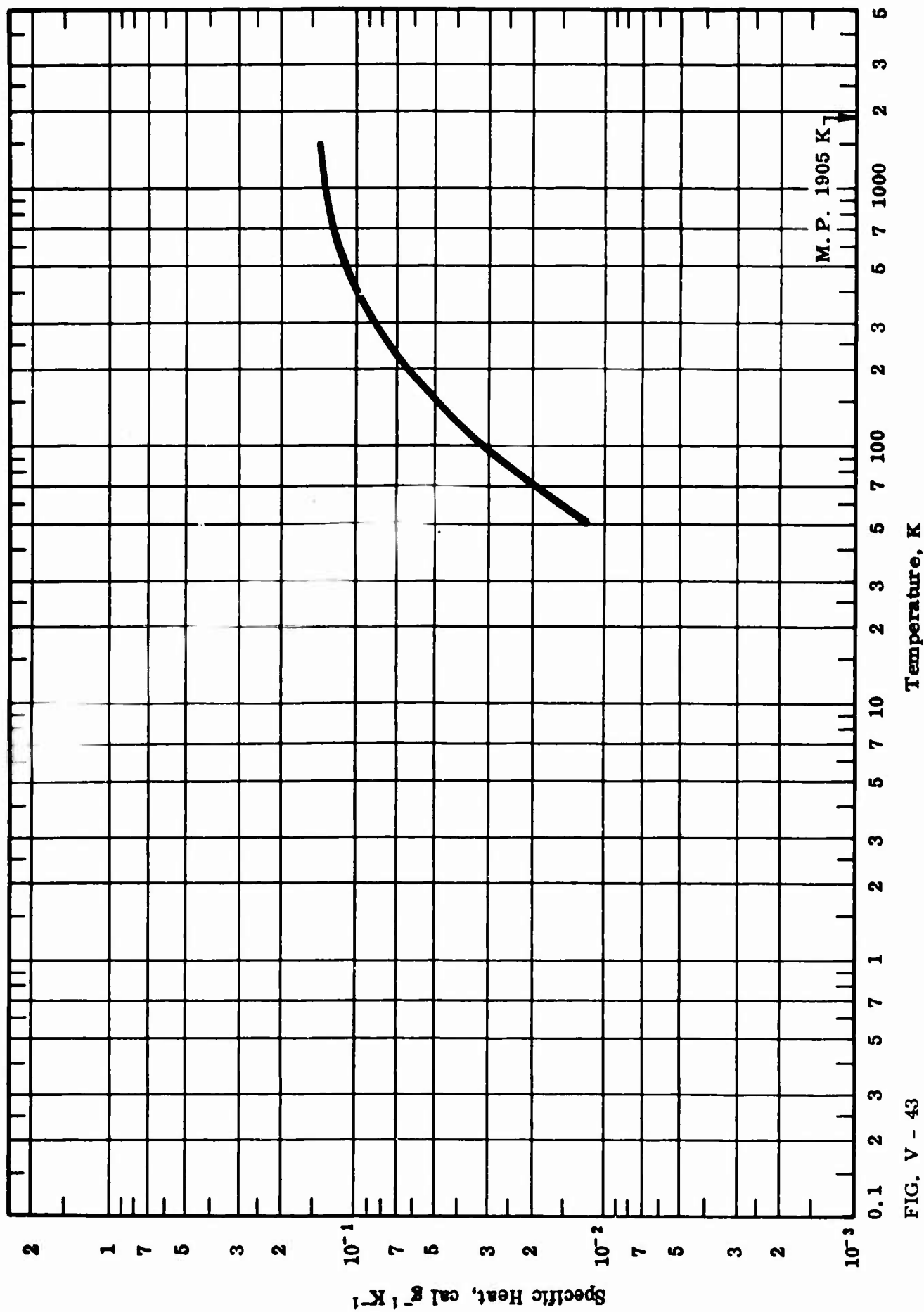


FIG. V - 43  
SPECIFIC HEAT --- TIN DIOXIDE, SnO<sub>2</sub>

TABLE V-41. SPECIFIC HEAT OF TIN(STANNIC) OXIDE, SnO<sub>2</sub>

| T°K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T°K  | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|-----|--|------|--|
| 50  | (1.17 x 10 <sup>-2</sup> ) <sup>†</sup>              | 600  | 1.17 x 10 <sup>-1</sup>                              |
| 60  | 1.58 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup>                              | 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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<sup>†</sup> Extrapolated

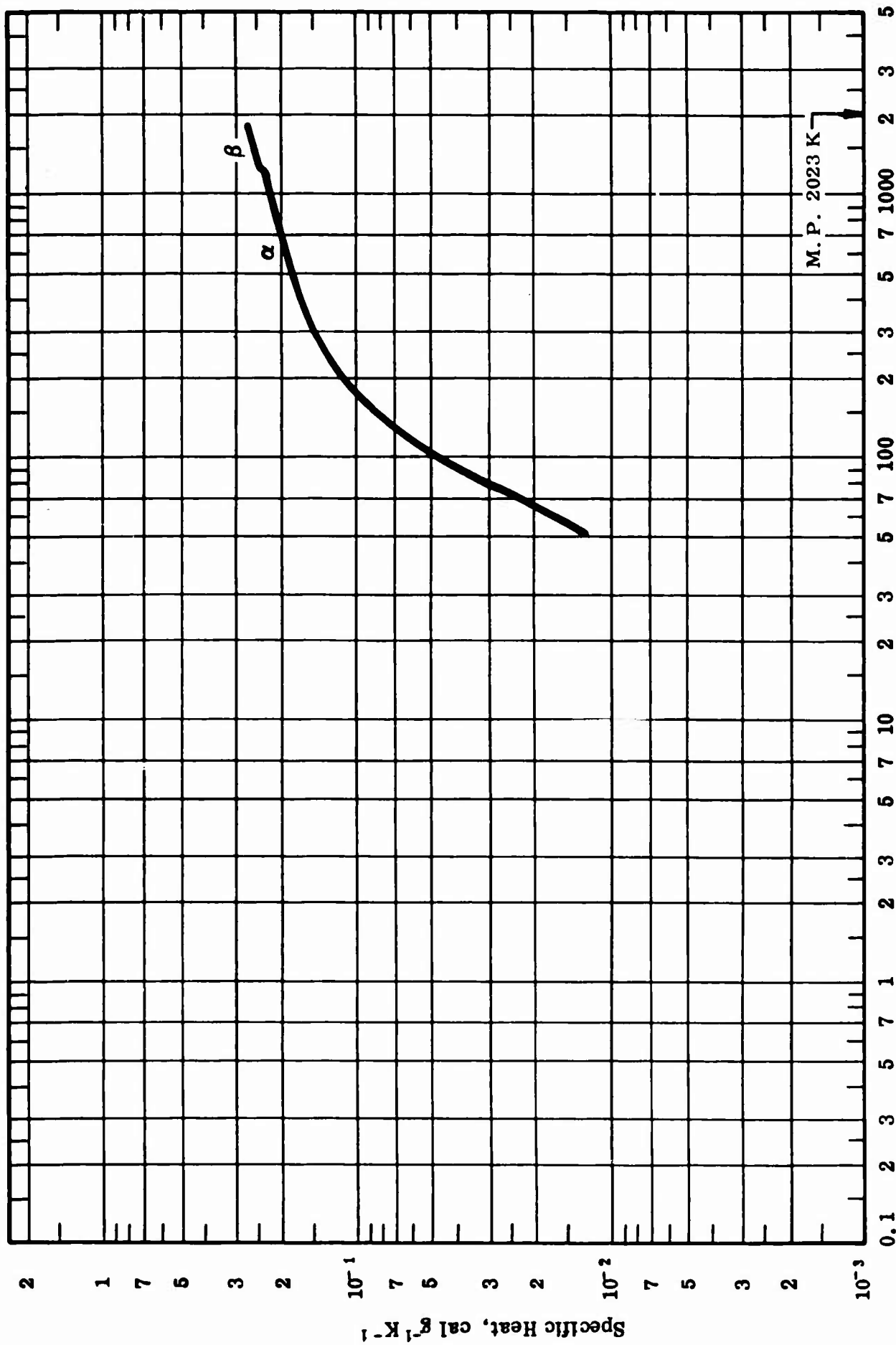


FIG. V - 44

Temperature, K

SPECIFIC HEAT -- TITANIUM MONOXIDE, TiO

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

| T °K   | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K     | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|--------|--|----------|--|
| (α) 50 | 1.02 x 10 <sup>-2</sup>                              | 800      | 2.06 x 10 <sup>-1</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 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) [52-298 K].

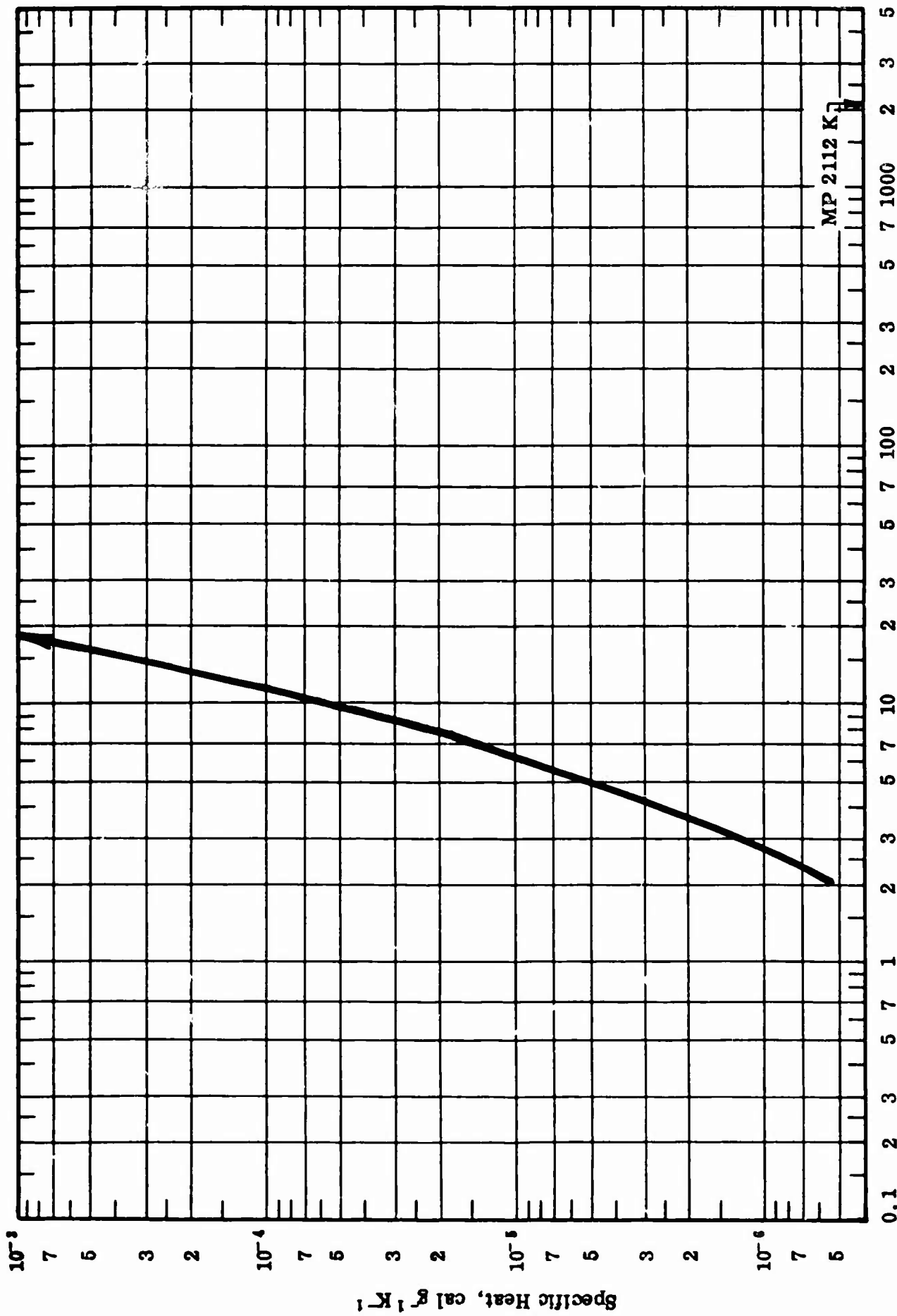


FIG. V - 45 (a)  
SPECIFIC HEAT -- TITANIUM DIOXIDE (RUTILE) TiO<sub>2</sub>  
Temperature, K

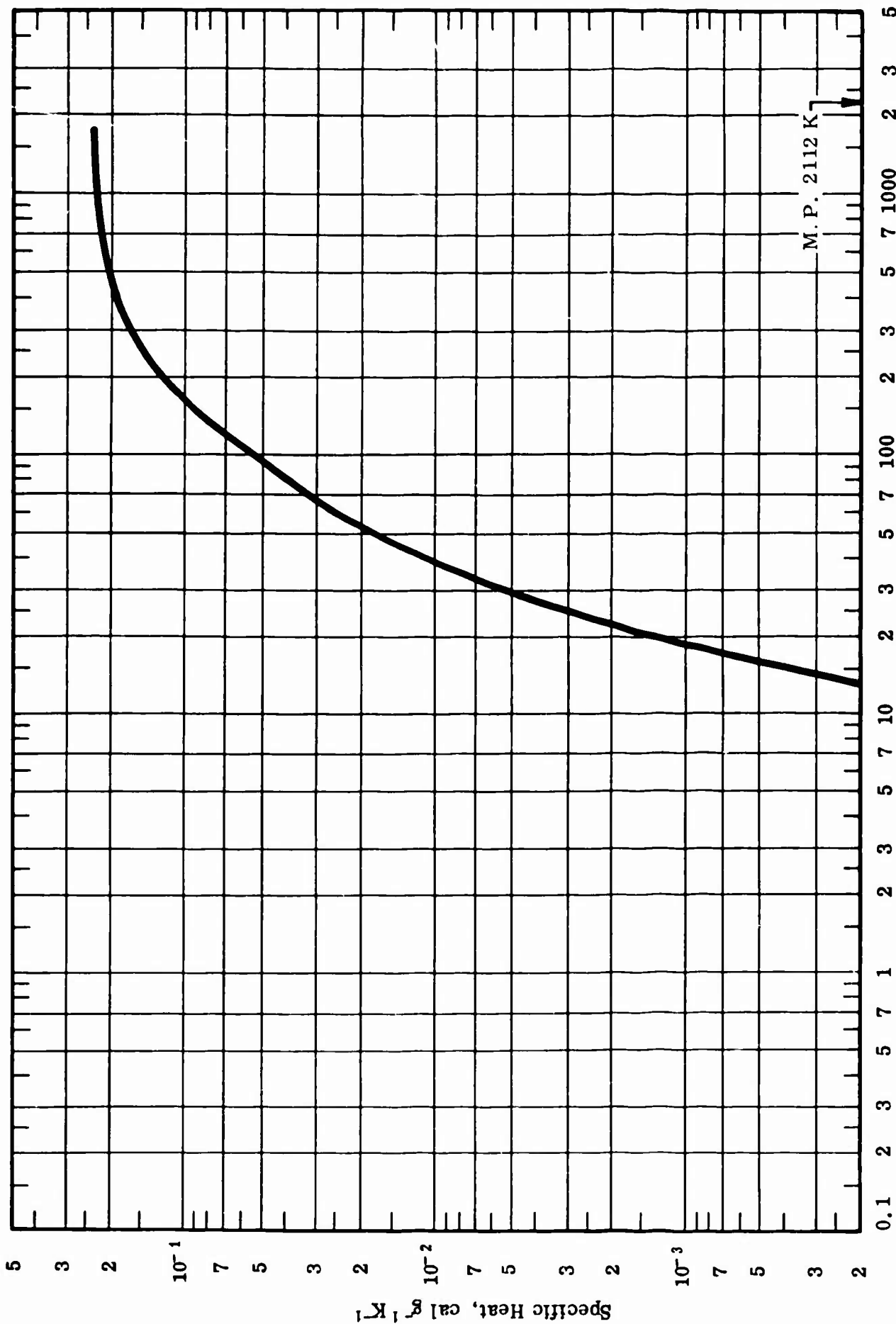


FIG. V - 45 (b)

SPECIFIC HEAT -- TITANIUM DIOXIDE (RUTILE) TiO<sub>2</sub>

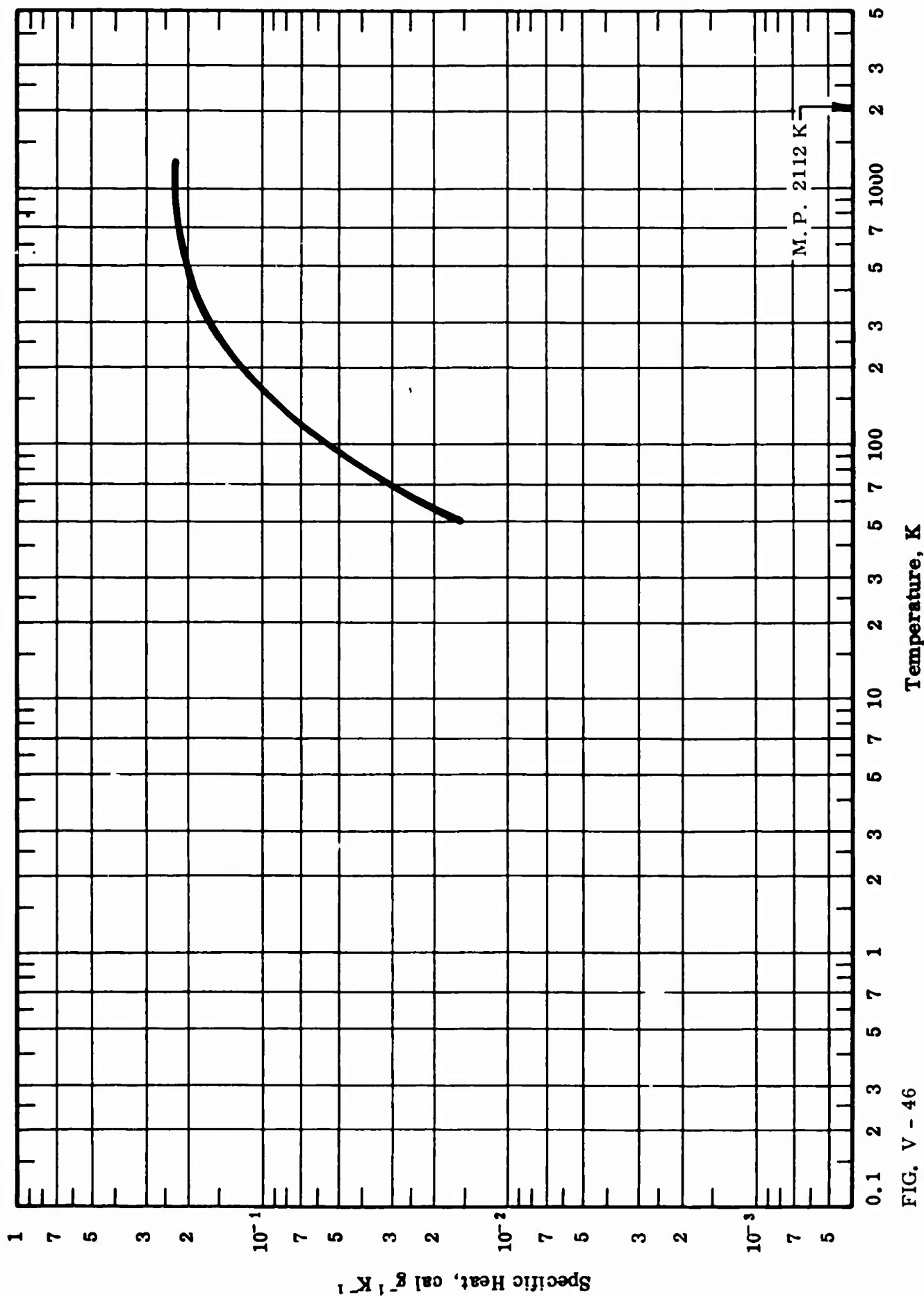


FIG. V - 46

SPECIFIC HEAT -- TITANIUM DIOXIDE (ANATASE)

TABLE V-43. SPECIFIC HEAT OF TITANIUM DIOXIDE, TiO<sub>2</sub>

| T °K | RUTILE   | ANATASE  |
|------|--|--|
|      | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
| 2    | 5.30 x 10 <sup>-7</sup>                              |  |
| 3    | 1.20 x 10 <sup>-6</sup>                              |  |
| 4    | 2.70   |  |
| 5    | 5.00   |  |
| 6    | 8.80   |  |
| 7    | 1.45 x 10 <sup>-5</sup>                              |  |
| 8    | 2.35   |  |
| 9    | 3.55   |  |
| 10   | 5.25   |  |
| 15   | 3.90 x 10 <sup>-4</sup>                              |  |
| 20   | 1.30 x 10 <sup>-3</sup>                              |  |
| 30   | 5.20   |  |
| 40   | 1.12 x 10 <sup>-2</sup>                              |  |
| 50   | 1.82   | 1.52 x 10 <sup>-2</sup>                              |
| 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 x 10 <sup>-1</sup>                              | 1.23 x 10 <sup>-1</sup>                              |
| 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  $\Delta H$ , 298-1300K; rutile  $\Delta H$ , 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].

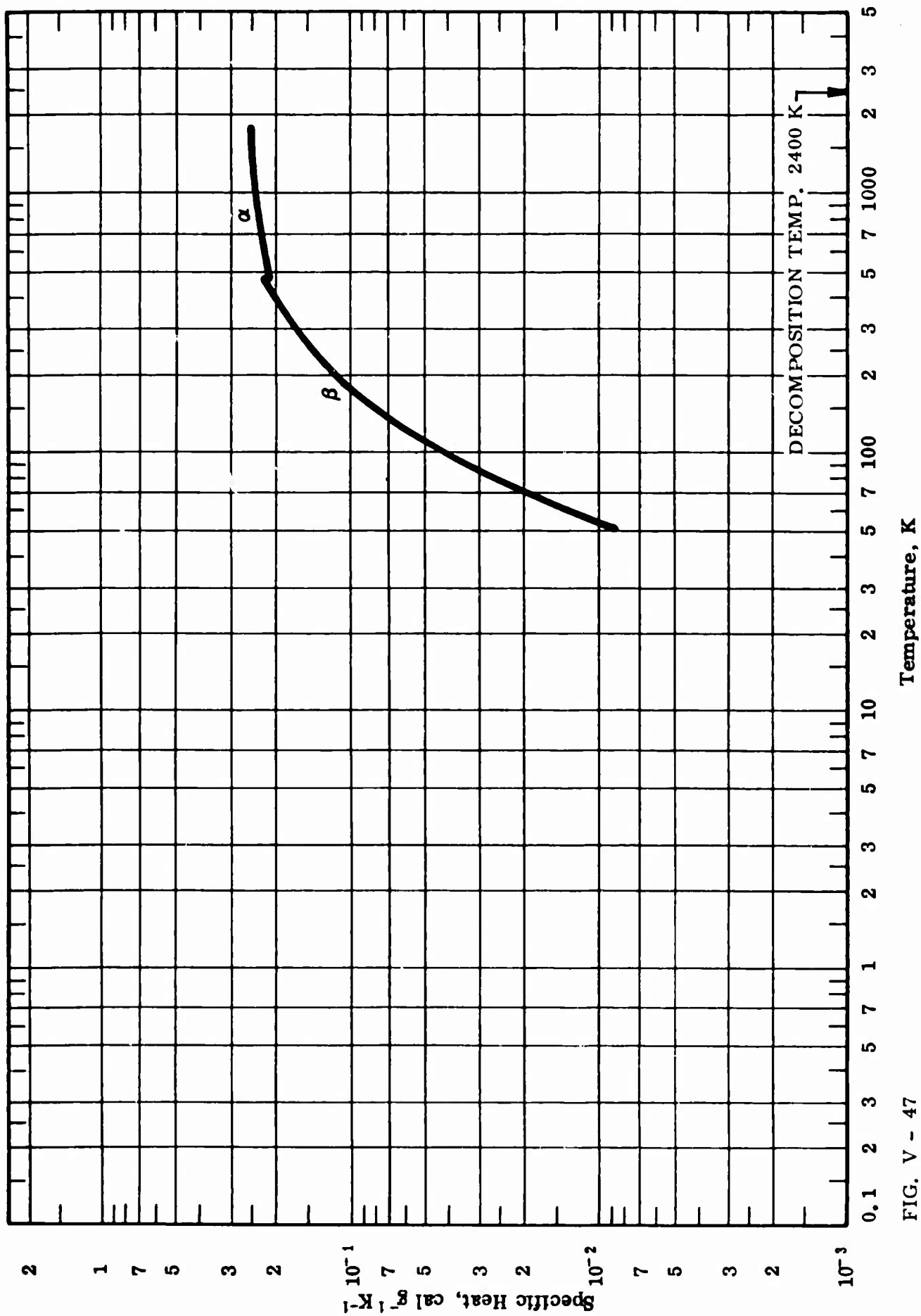


FIG. V - 47

SPECIFIC HEAT -- TITANIUM SESQUOXIDE, Ti<sub>2</sub>O<sub>3</sub>

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

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

Investigators: Kelley, K. K. and Mah, A. D. (336) [ $\Delta H$ , 298-2000 K];  
 Naylor, B. F. (337) [298-1800 K]; Shomate, C. H. (338)  
 [53-298 K].

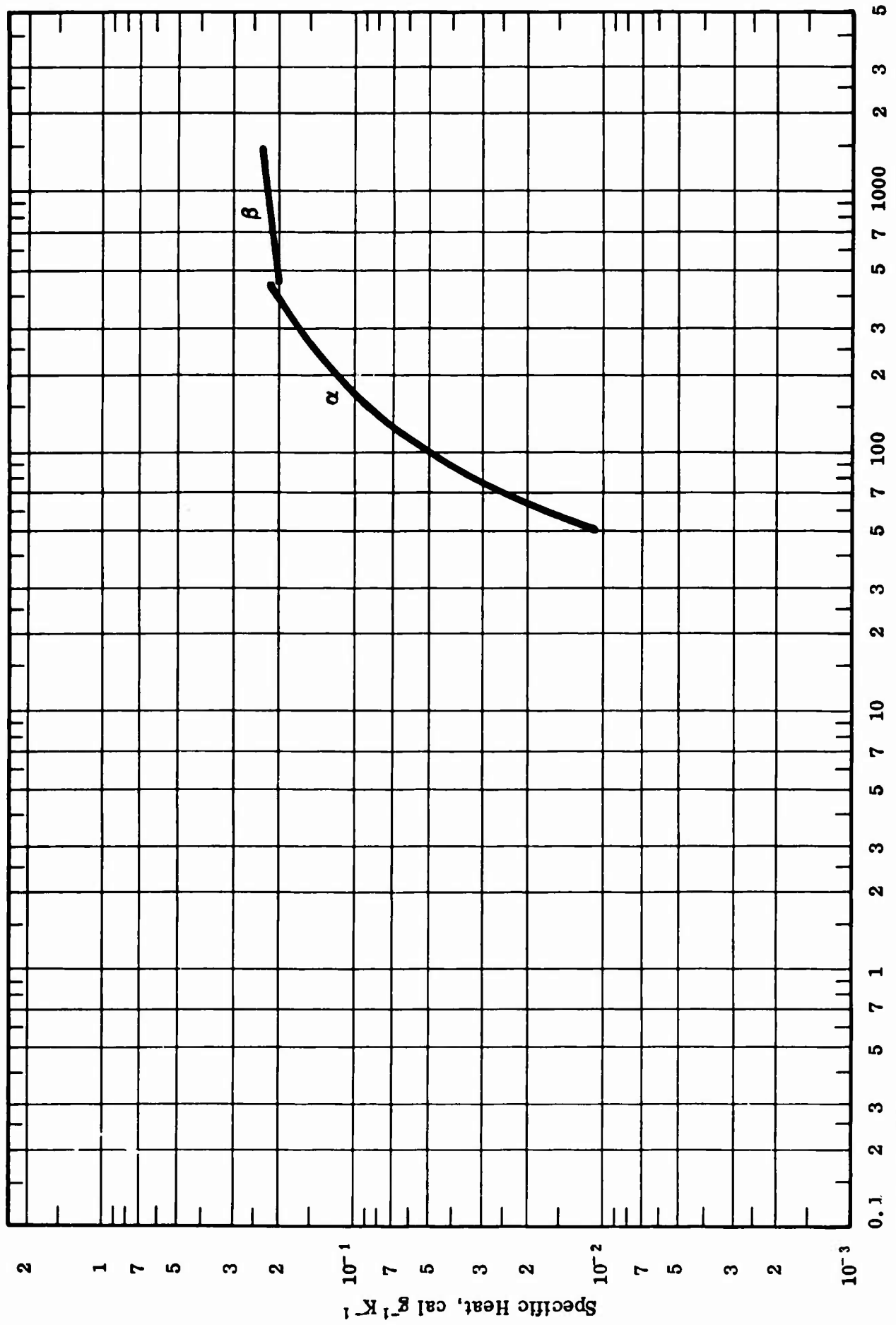


FIG. V - 48

SPECIFIC HEAT -- TITANIUM TRIPENTOXIDE, Ti<sub>3</sub>O<sub>5</sub>

TABLE V-45. SPECIFIC HEAT OF TITANIUM TRIPENTOXIDE  $Ti_3O_5$

| T °K             | $C_p, \text{ cal g}^{-1} \text{ K}^{-1}$ | T °K             | $C_p, \text{ cal g}^{-1} \text{ K}^{-1}$ |
|------------------|--|------------------|--|
| ( $\alpha$ ) 50  | $1.05 \times 10^{-2}$                    | ( $\beta$ ) 450  | $2.02 \times 10^{-1}$                    |
| 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              | $1.22 \times 10^{-1}$                    | 1100             | 2.25                                     |
| 300              | 1.66                                     | 1200             | 2.29                                     |
| 400              | 2.08                                     | 1300             | 2.32                                     |
| ( $\alpha$ ) 450 | 2.18                                     | 1400             | 2.36                                     |
|                  |  | ( $\beta$ ) 1500 | $(2.39 \times 10^{-1})$                  |

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

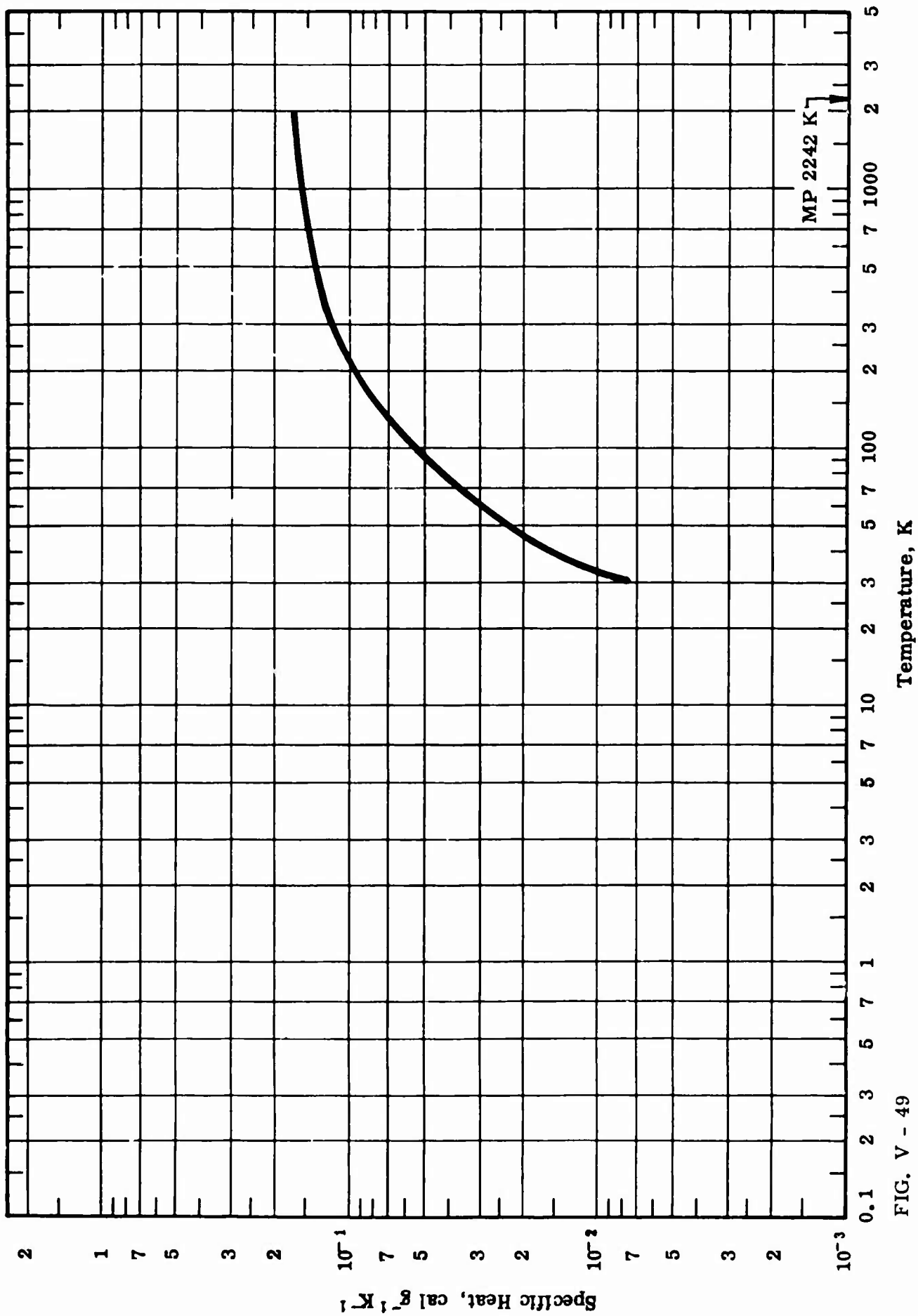


FIG. V - 49

SPECIFIC HEAT -- ZINC OXIDE, ZnO

**TABLE V-46. SPECIFIC HEAT OF ZINC OXIDE ZnO**

| T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> | T °K | C <sub>p</sub> , cal g <sup>-1</sup> K <sup>-1</sup> |
|------|--|------|--|
| 30   | 7.40 x 10 <sup>-3</sup>                              | 700  | 1.49 x 10 <sup>-1</sup>                              |
| 40   | 1.62 x 10 <sup>-2</sup>                              | 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 x 10 <sup>-1</sup> †                            |
| 200  | 9.95   | 1600 | 1.67 †   |
| 300  | 1.19 x 10 <sup>-1</sup>                              | 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

D. BIBLIOGRAPHY

GENERAL

- | Ref.<br>No. | TPRC<br>No. |  |
|-------------|-------------|--|
| 1.          | 13701       | Eldridge, E. A. and Deem, H. W., Am. Soc. Testing Mater., Spec. Tech. Publ. (296). 1-206, 1960.  |
| 2.          | 17036       | Furukawa, G. T., Reilly, M. L., Henning, J. M., Douglas, T. B., Victor, A. C. and Beaudoin, A. R., Natl. Bur. Std., Rept. 6484, 17-35, 1959. [AD 235429] |
| 3.          | 16704       | Goldsmith, A., Waterman, T. E., and Hirschhoen, H. J., WADC TR 58-476, <u>1</u> , 1-798, 1960. [AD 247193]   |
| 4.          | 31642       | Hultgren, R., Orr, R. L., Anderson, P. D., and Kelley, K. K., John Wiley and Sons, Inc., 1-963, 1963.  |
| 5.          | 28478       | Kelley, K. K., U. S. Bur. Mines, Bull. 584, 1-232, 1960.   |
| 6.          | 29577       | Loser, J. B., Moeller, C. E., and Tompson, M. B., ML-TDR-64-5, 1-356, 1964. [AD 601535]  |
| 7.          | 16701       | Johnson, V. J., WADD TR 60-56, (Phase 1) Pt. 2, 1-200, 1960. [AD 249786]   |
| 8.          | 33746       | Wood, W. D. and Deem, H. W., RSIC-202, 1-399, 1964. [AD 455069]  |

ALUMINUM

- |     |       |  |
|-----|-------|--|
| 9.  | 6448  | Avramescu, A., Z. Tech. Phys., <u>20</u> (7), 213-7, 1939.                                       |
| 10. | 21779 | Eastman, E. D., Williams, A. M., and Young, T. F., J. Am. Chem. Soc., <u>46</u> , 1178-83, 1924. |
| 11. | 7827  | Giauque, W. F. and Meads, P. F., J. Am. Chem. Soc., <u>63</u> , 1897-1901, 1941.                 |
| 12. | 23058 | Hopkins, D. C., PhD. Thesis, Univ. Illinois, AROD 2771:9, 1-80, 1960. [AD 282758]                |
| 13. | 7595  | Kok, J. A. and Keesom, W. H., Physica, <u>4</u> (9), 835-42, 1937.                               |
| 14. | 19230 | Phillips, N. E., Phys. Rev., <u>114</u> (3), 676-85, 1959.                                       |
| 15. | 7514  | Pochapsky, T. E., Acta. Met., <u>1</u> (6), 747-51, 1953.  |
| 16. | 6795  | Quinney, H. and Taylor, G. I., Proc. Roy. Soc. (London), <u>A163</u> (913), 157-81, 1937.        |
| 17. | 27682 | Rorer, D. C., Meyer, H. and Richardson, R. C., 1-29, 1962. [AD 293874]                           |
| 18. | 27596 | Yurkov, V. A. and Ivoninskaya, L. A., Izv. Vysshikh Uchebn. Zavedenii, Fiz., (1), 138-43, 1962.  |

BERYLLIUM

- |     |       |   |
|-----|-------|---|
| 19. | 936   | Ginnings, D. C., Douglas, T. B., and Ball, A. F., J. Am. Chem. Soc., <u>73</u> , 1236-40, 1951. |
| 20. | 1004  | Hill, R. W. and Smith, P. L., Phil. Mag., <u>44</u> , 636-44, 1953.                             |
| 21. | 10323 | Jaeger, F. M. and Rosenbohm, E., Rec. Trav. Chim., <u>53</u> , 451-63, 1934.                    |

Ref. TPRC  
 No. No.

**BERYLLIUM (continued)**

22. 22591 Kantor, P. B., Krasovitskaya, R. M. and Kisil, O. M., (English Transl., Fiz. Metal. i Metalloved. USSR, 10 (6), 835-7, 1960), MCL-950/1, 1-6, 1961. [AD 261792]
23. 20106 Mit'kina, E. A., At. Energ. (USSR), 7 (2), 163-5, 1959.

**CHROMIUM**

24. 6320 <sup>r</sup>Amstrong, L. D. and Grayson-Smith, H., Can. J. Res., A28 (1), 51-9, 1950.
25. 12111 Anderson, C. T., J. Am. Chem. Soc., 59, 488-91, 1937.
26. 20721 Beaumont, R. H., Chihara, H. and Morrison, J. A., Phil. Mag., 5 (50), 188-91, 1960.
27. 26103 Clusius, K. and Franzosini, P., Z. Naturforsch., A17 (6), 522-5, 1962.
28. 37902 Conway, J. B. and Hein, R. A., Advances Thermophys. Properties Extreme Temp. Pres., 3rd ASME Symp., Lafayette, Indiana, 131-37, 1965.
29. 1886 Estermann, I., Friedberg, S. A. and Goldman, J. E., Phys. Rev., 87 (4), 582-8, 1952.
30. 6715 Friedberg, S. A., U. S. At. Energy Comm., ND-5668, 1-32, 1954. [AD 63407]
31. 10730 Hultgren, R. and Land, C., Trans. Met. Soc. AIME, 215 (1), 165-6, 1959. [AD 216259]
32. 9161 Krauss, F., Z. Metallk., 49 (7), 386-92, 1958.
33. 9736 Lucks, C. F. and Deem, H. W., Am. Soc. Testing Materials, Spec. Tech. Publ. (227), 1-29, 1958.

**COPPER**

34. 6448 Avramescu, A., Z. Tech. Phys., 20 (7), 213-7, 1939.
35. 15899 Bell, I. P., U. K. At. Energy Authority, Ind. Group, R & DB (C) TN-127, FRDC/P-112, FRFEWP/P-32, 1-2, 1959.
36. 24810 Booker, J., Paine, R. M. and Stonehouse, A. J., WADD TR 60-889, 1-133, 1961. [AD 265625]
37. 31341 Butler, C. P. and Inn, E. C. Y., USNRDL-TR-235, 1-30, 1958. [AD 200857]
38. 6379 Dockerty, S. M., Can. J. Res., 9, 84-93, 1933.
39. 6240 Dockerty, S. M., Can. J. Res., A15 (4), 59-66, 1937.
40. 17559 Eder, F. X., Bull. Inst. Intern. Froid. Annexe, 2, 137-41, 1955.
41. 1883 Esterman, I., Friedberg, S. A. and Goldman, J. E., Phys. Rev., 87 (4), 582-8, 1952.

| Ref. No. | TPRC No. | COPPER (continued)  |
|----------|----------|---|
| 42.      | 22751    | Eucken, A and Werth, H. , Z. Anorg. Allgem. Chem. , <u>188</u> , 152-72, 1930.  |
| 43.      | 6502     | Fieldhouse, I. B. , Hedge, J. C. , Lang, J. I. , Takata, A. N. and Waterman, T. E. , WADC TR 55-495, Pt. I, 1-64, 1956. [AD 110404] |
| 44.      | 6975     | Fieldhouse, I. B. , Hedge, J. C. , Lang, J. I. and Waterman, T. E. , WADC TR 55-495, Pt. II, 1-18, 1956. [AD 110510]                |
| 45.      | 7827     | Giauque, W. F. and Meads, P. F. , J. Am. Chem. Soc. , <u>63</u> , 1897-1901, 1941.  |
| 46.      | 18235    | Howse, P. T. , Jr. , Pears, C. D. , and Oglesby, S. , Jr. , WADD TR 60-657, 1-137, 1961. [AD 260065]                                |
| 47.      | 14596    | Jaeger, F. M. , Rosenbohm, E. , and Bottema, J. A. , Proc. Acad. Sci. (Amsterdam) , <u>35</u> , 772-9, 1932.                        |
| 48.      | 6323     | Kok, J. A. and Keesom, W. H. , Physica , <u>3</u> (9) , 1035-45, 1936.  |
| 49.      | 21420    | Klinkhardt, H. , Ann. Physik , <u>84</u> , 167-200, 1927.   |
| 50.      | 9736     | Lucks, C. F. and Deem, H. W. , Am. Soc. Testing Mater. , Spec. Tech. Publ. (227) , 1-29, 1958.                                      |
| 51.      | 6560     | Lucks, C. F. and Deem, H. W. , WADC TR 55-496, 1-65, 1956. [AD 97185]   |
| 52.      | 19328    | Lyusternik, V. E. , Pribery i Tekhn. Eksperim. , <u>4</u> , 127-9, 1959.  |
| 53.      | 26581    | Masuda, Y. , Sci. Rept. Res. Inst. , Tohoku Univ. , <u>A</u> (3) , 156-64, 1962.  |
| 54.      | 16061    | Martin, D. L. , Can. J. Phys. , <u>38</u> (1) , 17-24, 1960.  |
| 55.      | 28756    | Martin, D. L. , Can. J. Phys. , <u>40</u> , 1166-73, 1962.  |
| 56.      | 26074    | Neel, D. S. , Pears, C. D. and Oglesby, S. , Jr. , WADD TR 60-924, 1-216, 1962. [AD 275-536]  |
| 57.      | 28986    | O'Neal, H. R. , PhD. Thesis, Univ. Calif. , UCRL-10426, 1-66, 1963.   |
| 58.      | 33569    | Pawel, R. E. , PhD Thesis, Univ. Tennessee, 1-143, 1956.  |
| 59.      | 29349    | Picklesimer, M. L. , PhD Thesis, Univ. Tennessee, 1-106, 1954.  |
| 60.      | 6795     | Quinney, H. and Taylor, G. I. , Proc. Roy. Soc. (London) , <u>163A</u> (913) , 157-81, 1937.  |
| 61.      | 182      | Sandenaw, T. A. , U. S. At. Energy Comm. , LA-2307, 1-19, 1959.   |
| 62.      | 601      | Trice, J. B. , Neely, J. J. and Teeter, C. E. , Jr. , U. S. At. Energy Comm. , AECU-19, NEPA 816-SCR-28, 1-12, 1948.                |

- | Ref.<br>No. | TPRC<br>No. | IRON   |
|-------------|-------------|--|
| 63.         | 27879       | Anderson, P. D. and Hultgren, R., Trans. Met. Soc. AIME, <u>224</u> (4), 842-5, 1962.                  |
| 64.         | 9350        | Awbery, J.H. and Challoner, A.R., J. Iron Steel Inst. (London), <u>154</u> (2), 83-111, 1946.          |
| 65.         | 4677        | Awbery, J.H. and Griffiths, E., Proc. Roy. Soc. (London), <u>A174</u> , 1-15, 1940.                    |
| 66.         | 29865       | Dench, W.A. and Kubaschewski, O., J. Iron Steel Inst. (London), <u>201</u> (2), 140-3, 1963.           |
| 67.         | 1903        | Duyckaerts, G., Memo. Soc. Roy. Sci. Liege, <u>6</u> , 193-329, 1945.                                  |
| 68.         | 11924       | Duyckaerts, G., Physica, <u>6</u> , 401-8, 1939.   |
| 69.         | 22751       | Eucken, A. and Werth, H., Z. Anorg. Allgem. Chem., <u>188</u> , 152-72, 1930.                          |
| 70.         | 7668        | Jaeger, F.M., Rosenbohm, E. and Zuithoff, A.J., Rec. Trav. Chim., <u>57</u> , 1313-40, 1938.           |
| 71.         | 28696       | Keesom, W.H. and Kurrelmeyer, B., Physica, <u>6</u> (7), 633-46, 1939.                                 |
| 72.         | 1149        | Kelley, K.K., J. Chem. Phys., <u>11</u> , 16-8, 1943.  |
| 73.         | 21420       | Klinkhardt, H., Ann. Physik, <u>84</u> , 167-200, 1927.  |
| 74.         | 24279       | McElroy, D.L., PhD Thesis, Univ. Tennessee, 1-157, 1957.   |
| 75.         | 27987       | Kohlhaas, R. and Braun, M., Forschungsber. Landes Nordrhein-Westfalen (1104), 1-109, 1962.             |
| 76.         | 30108       | Kohlhaas, R. and Braun, M., Arch. Eisenhüttenw., <u>34</u> (5), 391-9, 1963.                           |
| 77.         | 20619       | Lyubimov, A.P. and Belashchenko, D.K., Mosk. Inst. Stali. Sb., (33), 3-11, 1955.                       |
| 78.         | 7468        | Pallister, P.R., J. Iron Steel Inst. (London), <u>161</u> , 87-90, 1949.                               |
| 79.         | 1234        | Pallister, P.R., J. Iron Steel Inst. (London), <u>178</u> , 346-53, 1954.                              |
| 80.         | 29349       | Picklesimer, M.L., PhD Thesis, Univ. Tennessee, 1-106, 1954.   |
| 81.         | 6795        | Quinney, H. and Taylor, G.I., Proc. Roy. Soc. (London), <u>163A</u> (913), 157-81, 1937.               |
| 82.         | 21789       | Rodebush, W.H. and Mickalek, J.C., J. Am. Chem. Soc., <u>47</u> , 2117-21, 1925.                       |
| 83.         | 25622       | Schroder, K., Phys. Rev., <u>125</u> (4), 1209-12, 1962.   |
| 84.         | 17940       | Tret'yakov, Yu D., Troshkina, V.A., and Khomyakov, K.G., Zh. Neorgan. Khim., <u>4</u> (1), 5-12, 1959. |
| 85.         | 9938        | Umino, S., Sci. Repts. Tohoku Univ., <u>18</u> , 91-107, 1929.   |
| 86.         | 10062       | Wallace, D.C., Sidles, P.H., and Danielson, G.C., J. Appl. Phys., <u>31</u> (1), 168-76, 1960.         |
| 87.         | 13491       | Zuithoff, A.J., Proc. Acad. Sci. (Amsterdam), <u>41</u> , 264-74, 1938.                                |

Ref. TPRC  
No. No.

MAGNESIUM

88. 10537 Baker, H., WADC TR 57-194, Pt. II, 1-24, 1957. [AD 131034], [PB 131436]
89. 21823 Clusius, K. and Vaughen, J. V., J. Am. Chem. Soc., 52, 4686-99, 1930.
90. 8495 Craig, R. S., Krier, C. A., Coffey, L. W., Bates, E. A. and Wallace, W. E., U. S. At. Energy Comm., NYO-6161, 1-10, 1953.
91. 1886 Esterman, I., Friedberg, S. A., and Goldman, J. E., Phys. Rev., 87, 582-8, 1952.
92. 21779 Eastman, E. D., Williams, A. M. and Young, T. F., J. Am. Chem. Soc., 46, 1178-83, 1924.
93. 6251 Jaeger, F. M. and Poppema, T. J., Rec. Trav. Chim., 55 (6), 492-517, 1936.
94. 298 Logan, J. K., Clement, J. R. and Jeffers, H. R., Phys. Rev., 105, 1435-7, 1957.
95. 23142 Mannchen, W. and Bornkessel, K., Z. Metallk., 51, 482-5, 1960.
96. 6329 Poppema, T. J. and Jaeger, F. M., Proc. K. Akad. Wet. Amsterdam, 38, 510-20, 1935.
97. 1705 Smith, P. L., Phil. Mag., 46 (378), 744-50, 1955.
98. 30903 Stull, D. R. and McDonald, R. A., J. Am. Chem. Soc., 77, 5293, 1955.
99. 422 Wallace, W. E., Craig, R. S., Saba, W. G. and Sterrett, K. F., U. S. At. Energy Comm., NYO-6334, 1-8, 1957.

MANGANESE

100. 6320 Armstrong, L. D. and Grayson-Smith, H., Can. J. Res., A28 (1), 51-9, 1950.
101. 197 Armstrong, L. D. and Grayson-Smith, H., Can. J. Res., A27, 9-16, 1949.
102. 1309 Booth, G. L., Hoare, F. E. and Murphy, B. T., Proc. Phys. Soc. (London), B68, 830-2, 1955.
103. 7879 Elson, R. G., Grayson-Smith, H. and Wilhelm, J. O., Can. J. Res., A18, 83-9, 1940.
104. 36200 Franzosini, P., Losa, C. G. and Clusius, K., Z. Naturforsch., A19, 1348-53, 1964.
105. 16871 Heer, C. V., AFOSR-TR-59-198, 1-6, 1959. [PB 161461]
106. 31499 Kelley, K. K., J. Am. Chem. Soc., 61, 203-7, 1939.
107. 11413 Kelley, K. K., Naylor, B. F., and Shomate, C. H., U. S. Bur. Mines, Tech. Paper 686, 1-34, 1946.

| Ref.<br>No. | TPRC<br>No. | NICKEL   |
|-------------|-------------|--|
| 108.        | 24810       | Booker, J., Paine, R. M. and Stonehouse, A. J., WADD TR 60-889, 1-133, 1961. [AD 265625]   |
| 109.        | 6246        | Bronson, H. L., Hewson, E. W. and Wilson, A. J. C., Can. J. Res., <u>A14</u> (10), 194-9, 1936.                                  |
| 110.        | 6245        | Bronson, H. L. and Wilson, A. J. C., Can. J. Res., <u>A14</u> (10), 181-93, 1936.  |
| 111.        | 1884        | Busey, R. H. and Giaouque, W. F., J. Am. Chem. Soc., <u>74</u> , 3157-8, 1952.   |
| 112.        | 31341       | Butler, C. P. and Inn, E. C. Y., USNRDL TR-235, 1-30, 1958. [AD 200857]  |
| 113.        | 22751       | Eucken, A. and Werth, H., Z. Anorg. Allgem. Chem., <u>188</u> , 152-72, 1930.  |
| 114.        | 6238        | Ewert, M., Proc. K. Akad. Wet. (Amsterdam), <u>39</u> (7), 833-8, 1936.  |
| 115.        | 6502        | Fieldhouse, I. B., Hedge, J. C., Lang, J. I., Takata, A. N., and Waterman, T. E., WADC TR 55-495, Pt. I, 1-64, 1956. [AD 110404] |
| 116.        | 7373        | Grew, K. E., Proc. Roy. Soc. (London), <u>A145</u> , 509-22, 1934.   |
| 117.        | 7115        | Hagel, W. C., Pound, G. M. and Mehl, R. F., Carnegie Inst. Tech., 1-103, 1954. [AD 39272]  |
| 118.        | 10730       | Hultgren, R. and Land, C., Trans. Met. Soc. AIME, <u>215</u> (1), 165-6, 1959. [AD 216259]                                       |
| 119.        | 6212        | Keesom, W. H. and Clark, C. W., Physica, <u>2</u> , 513-20, 1935.  |
| 120.        | 7596        | Keesom, W. H. and Kok, J. A., Congr. Intern. Froid, 7 <sup>e</sup> , Compt. Rend. Trav. Comm. I et II, 156-68, 1936.             |
| 121.        | 510         | Krauss, F. and Warncke, H., Z. Metallk., <u>46</u> , 61-9, 1955.   |
| 122.        | 19090       | Lapp, C., Compt. Rend., <u>186</u> , 1104-6, 1928.   |
| 123.        | 6314        | Moser, H., Physik. Z., <u>37</u> (21), 737-53, 1936.   |
| 124.        | 6390        | Neel, L., Compt. Rend., <u>207</u> , 1384-6, 1938.   |
| 125.        | 33569       | Pawel, R. E., PhD Thesis, Univ. Tennessee, 1-143, 1956.  |
| 126.        | 6434        | Persoz, B., Compt. Rend., <u>208</u> (21), 1632-4, 1939.   |
| 127.        | 316         | Rayne, J. A. and Kemp, W. R. G., Phil. Mag., <u>1</u> , 918-25, 1956.  |
| 128.        | 22424       | Sucksmith, W. and Potter, H. H., Proc. Roy. Soc. (London), <u>112</u> , 157-76, 1926.  |
| 129.        | 6405        | Sykes, C. and Wilkinson, H., Proc. Roy. Soc., (London), <u>50</u> (5), 834-51, 1938.   |

Ref. TPRC  
 No. No.

NIOBIUM

130. 1525 Brown, A., Zemansky, M.W. and Boorse, H. A., Phys. Rev., 86 (1), 134-5, 1952.
131. 911 Brown, A., Zemansky, M.W. and Boorse, H. A., Phys. Rev., 92, 52-8, 1953.
132. 7239 Chou, C., White, D. and Johnston, H. L., Phys. Rev., 109 (3), 788-96, 1958.
133. 27635 Clusius, K., Franzosini, P. and Piesbergen, U., Z. Naturforsch., A15, 728-34, 1960.
134. 37902 Conway, J. B. and Hein, R. A., Advances Thermophys. Properties Extreme Temp. Pres., 3rd ASME Symp., Lafayette, Indiana, 131-7, 1965.
135. 7689 Fieldhouse, I. B., Hedge, J. C. and Lang, J. I., WADC TR 58-274, 1-79, 1958. [AD 206892], [PB 151583]
136. 27207 Lowenthal, G. C., Australian J. Phys., 16 (1), 47-67, 1963.
137. 7602 <sup>Jaeger</sup>~~Jaeger~~, F. H. and Veenstra, W. A., Rec. Trav. Chim., 53, 677-87, 1934.

SILICON

138. 21831 Anderson, C. T., J. Am. Chem. Soc., 52, 2301-4, 1930.
139. 37419 Dismukes, J. P., Ekstrom, L., Hockings, E. F., Kudman, I., Lindenbald, N. E., Miller, R. E., Rosi, E. D., and Steigmeier, E. F., 1-103, 1964. [AD 441794]
140. 9182 Flubacher, P., Leadbetter, A. J. and Morrison, J. A., Phil. Mag., 4 (39), 273-94, 1959.
141. 17357 Gul'tyaev, P. V. and Petrov, A. V., Soviet Phys., Solid State (English Transl.) 1, 330-4, 1959.
142. 21087 Kantor, P. B., Kisel, O. M., and Fomichev, E. M., Ukrain. Fiz. Zhur., 5, 358-62, 1960.
143. 635 Pearlman, N. and Keesom, P. H., Phys. Rev., 88, 398-405, 1952.
144. 29948 Shanks, H. R., Maycock, P. D., Sidles, P. H. and Danielson, G. C., Phys. Rev., 130, 1743-8, 1963.

TIN

145. 490 Corak, W. S. and Satterthwaite, C. B., Phys. Rev., 102, 662-6, 1956.
146. 22849 Fritz, L., Z. Physik. Chem., 110, 343-62, 1924.
147. 29573 Heffan, H., M.S. Thesis, Univ. California, 1-17, 1958.
148. 2122 Hill, R. W. and Parkinson, D. H., Phil. Mag, 43, 309-16, 1952.
149. 22375 Jaeger, F. M. and Bottema, J. A., Proc. Acad. Sci. Amsterdam, 35, 352-62, 1932.

| Ref.<br>No. | TPRC<br>No. | TIN (continued)   |
|-------------|-------------|---|
| 150.        | 22378       | Keesom, W. H. and Ende, Van den J. N. , Proc. Roy. Acad. Sci. Amsterdam, <u>35</u> , 143-55, 1932.  |
| 151.        | 6415        | Keesom, W. H. and Laer, Van, P. H. , Physica, <u>5</u> (3), 193-201, 1938.  |
| 152.        | 23215       | Kutateladze, S. S. , Borishanskii, V. M. , Novikov, I. I. , and Fedynskii, O. S. , (English Transl. ) , Zhidkometallicheskie Teplonosileti, 1-12, 1959. |
| 153.        | 28986       | O' Neal, H. R. , Univ. Calif. Radiation Lab. , U. S. At. Energy Comm. UCRL-10426, 1-66, 1963.   |
| 154.        | 38436       | O' Neal, H. R. and Phillips, N. E. , Phys. Rev. , <u>137</u> (3A), 748-59, 1965.  |
| 155.        | 21774       | Rodebush, W. H. , J. Am. Chem. Soc. , <u>45</u> , 1413-6, 1923.   |
| 156.        | 1190        | Webb, F. J. and Wilkes, J. , Proc. Roy. Soc. (London), <u>A230</u> , 549-59, 1955.  |
| 157.        | 24027       | Yaqub, M. , Cryogenics, <u>1</u> (3), 166-70, 1961.   |

TITANIUM

|      |       |   |
|------|-------|---|
| 158. | 1271  | Aven, M. H. , Craig, R. S. , Waite, T. R. and Wallace, W. E. , Phys. Rev. , <u>102</u> , 1263-4, 1956.                  |
| 159. | 7170  | Backhurst, I. , J. Iron Steel Inst. (London), <u>189</u> , 124-34, 1958.  |
| 160. | 21224 | Clusius, K. and Franzosini, P. , Z. Physik. Chem. (Frankfurt), <u>16</u> (3/6), 194-202, 1958.                          |
| 161. | 23764 | Golutrin, Y. M. , Russian J. Phys. Chem. , <u>33</u> (8), 164-8, 1959.  |
| 162. | 24340 | Holland, L. R. , J. Appl. Phys. , <u>34</u> (8), 2350-7, 1963.  |
| 163. | 6797  | Jaeger, F. M. , Rosenbohm, E. , and Fonteyne, R. , Rec. Trav. Chim. , <u>55</u> (7/8), 615-54, 1936.                    |
| 164. | 1877  | Kelley, K. K. , Ind. Eng. Chem. , <u>36</u> , 865-6, 1944.  |
| 165. | 29598 | Kothen, C. W. , Univ. Microfilms (Ann Arbor, Mich.) Publ. No. 23697, 1-93, 1957.  |
| 166. | 532   | Kothen, C. W. and Johnston, H. L. , J. Am. Chem. Soc. , <u>75</u> , 3101-2, 1953.                                       |
| 167. | 131   | Loewen, E. G. , Trans. Am. Soc. Mech. Engrs. , <u>78</u> , 667-70, 1956.  |
| 168. | 36669 | Parker, R. , Trans. Met. Soc. , AIME, <u>233</u> , 1545-9, 1965.  |
| 169. | 10139 | Rea, J. A. , M. S. Thesis, Oklahoma Agricultural and Mech. College, 1-52, 1956.   |
| 170. | 27610 | Serebryannikov, N. N. and Gel'd, P. V. , Izvest. Vysshikh. Ucheb. Zavedenii, Isvetnaya Met. , <u>4</u> (4), 80-6, 1961. |

| Ref. No. | TPRC No. | TITANIUM (continued)                                    |
|----------|----------|---|
| 171.     | 250      | Scott, J. L., ORNL-2328, 1-122, 1957. [AD 138838]       |
| 172.     | 7242     | Wolcott, N.M., Phil. Mag., 8, <u>2</u> , 1246-54, 1957. |

ZINC

|      |       |   |
|------|-------|---|
| 173. | 6245  | Bronson, H. L. and Wilson, A. J. C., Can. J. Res., <u>A14</u> (10), 181-93, 1936.                 |
| 174. | 7025  | Clusius, K. and Harteck, P., Z. Physik. Chem., <u>134</u> , 243-63, 1928.                         |
| 175. | 21779 | Eastman, E. D., Williams, A. M. and Young, T. F., J. Am. Chem. Soc., <u>46</u> , 1178-83, 1924.   |
| 176. | 23965 | Eichonuer, W. and Schulze, M., Z. Naturforsch., <u>A14</u> (1), 28-32, 1959.                      |
| 177. | 6251  | Jaeger, F.M. and Poppema, T. J., Rec. Trav. Chem., <u>55</u> (6), 492-517, 1936.                  |
| 178. | 22378 | Keesom, W.H. and Ende, Van den, J. N., Proc. Roy. Acad. Sci. Amsterdam, <u>35</u> , 143-55, 1932. |
| 179. | 6330  | Keesom, W.H. and Kok, J. A., Physica, <u>1</u> , 770-8, 1934.                                     |
| 180. | 9206  | Phillips, N. E., Phys. Rev. Letters, <u>1</u> (10), 363-5, 1958.                                  |
| 181. | 6329  | Poppema, T. J. and Jaeger, F. M., Proc. K. Akad., Wet. Amsterdam, <u>38</u> , 510-20, 1935.       |
| 182. | 1813  | Silvidi, A. A. and Daunt, J. G., Phys. Rev., <u>77</u> , 125-9, 1950.                             |
| 183. | 1705  | Smith, P. L., Phil. Mag., 7, <u>46</u> (378), 744-50, 1955.                                       |
| 184. | 9136  | Srinivasan, T. M., Proc. Indian Acad. Sci., <u>A49</u> (2), 61-5, 1959.                           |
| 185. | 9735  | Zavaritsky, N. V., Zhur. Eksptl. i. Theoret. Fiz., <u>34</u> (5), 1116-24, 1958.                  |

ALUMINUM ALLOY 2219-T 852

|      |      |   |
|------|------|---|
| 186. | 6206 | Honda, K. and Tokunaga, M., Sci. Repts. Tohoku Imp. Univ., 1, <u>23</u> , 816-34, 1935. |
|------|------|---|

ALUMINUM ALLOY 6061-T6

|      |       |  |
|------|-------|--|
| 187. | 16837 | Johnson, E. W., Chem. Eng., <u>67</u> (16), 133-6, 1960. |
| 188. | 24108 | Materials Design Eng., <u>50</u> , 98-141, 1959.         |
| 189. | 8283  | Materials Properties Handbook, <u>1</u> , N-68112, 1958. |

| Ref. No. | TPRC No. |   |
|----------|----------|---|
|          |          | <b>ALUMINUM ALLOY 7075-T6</b>   |
| 190.     | 9736     | Lucks, C. F. and Deem, H. W. , ASTM Spec. Tech. Publ. 227, 1-29, 1958.                |
| 191.     | 6565     | Lucks, C. F. , Matolich, J. and VanValzor, J. A. , AF TR 6145, 1-71, 1954. [AD 95406] |
| 192.     | 24108    | Materials Design Eng. , <u>50</u> , 98-141, 1959.                                     |
| 193.     | 8283     | Materials Properties Handbook, <u>1</u> , N-68112, 1958.                              |

**BERYLLIUM ALLOY**

|      |       |   |
|------|-------|---|
| 194. | 6970  | Fieldhouse, I. B. , Hedge, J. C. , Lang, J. I. and Waterman, T. E. , WADC TR 57-487, 1958. [AD 150954], [PB 131718] |
| 195. | 15793 | Kanazawa, E. , and Packer, C. M. , LMSD-288140, <u>2</u> , 1-28, 1960. [AD 241410]                                  |
| 196. | 29978 | Walker, B. E. , Jr. , Ewing, C. T. and Miller, R. R. , J. Chem. Eng. Data, <u>7</u> , 595-7, 1962.                  |

**STAINLESS STEEL AISI 304A**

|      |       |   |
|------|-------|---|
| 197. | 26074 | Neel, D. S. , Pears, C. D. and Oglesby, S. , Jr. , WADD TR 60-924, 1-201, 1962. [AD 275536] |
| 198. | 28864 | Thornburg, D. L. , Thall, E. S. and Brous, J. , WADD TR 60-325, 1-238, 1961. [AD 267 327]   |
| 199. | 16743 | Venturi, R. and Seibel, R. D. , Denver Univ. , Denver Res. Inst. , DRI-1023, 1-31, 1959.    |

**STAINLESS STEEL AISI 347**

|      |       |   |
|------|-------|---|
| 200. | 7412  | Douglas, T. B. and Dever, J. L. , Natl. Bur. Std. Rept. 2302, 1-18, 1953.                               |
| 201. | 677   | Douglas, T. B. and Dever, J. L. , J. Res. Natl. Bur. Std. , <u>54</u> , (1), 15-19, 1955.               |
| 202. | 20286 | Douglas, T. B. and Victor, A. C. , J. Res. Natl. Bur. Std. , <u>65C</u> (1), 65-9, 1961.                |
| 203. | 35093 | DuChatenier, F. J. , Boerstael, B. M. and DeNobel, J. , Physica, <u>31</u> (7), 1061-2, 1965.           |
| 204. | 7689  | Fieldhouse, I. B. , Hedge, J. C. and Lang, J. I. , WADC TR 58-274, 1-79, 1958. [AD 206892], [PB 151583] |
| 205. | 6453  | Lang, J. I. , ASME Symp. Thermal Prop. , Lafayette, Indiana, 405-14, 1959.                              |
| 206. | 9736  | Lucks, C. F. and Deem, H. W. , ASTM Spec. Tech. Publ. 227, 1-29, 1958.                                  |
| 207. | 6565  | Lucks, C. F. , Matolich, J. and Van Valzor, J. A. , AF TR 6145, 1-71, 1954. [AD 95406]                  |

- | Ref. No.                | TPRC No. |  |
|-------------------------|----------|--|
|                         |          | INCONEL X 750  |
| 208.                    | 9736     | Lucks, C. F. and Deem, H. W. , ASTM Spec. Tech. Publ. 227, 1-29, 1958.   |
| 209.                    | 6565     | Lucks, C. F. , Matolich, J. and Van Valzor, J. A. , AF TR 6145, 1-71, 1954. [AD 95406]   |
| 210.                    | 16743    | Venturi, R. and Seibel, R. D. , Denver Univ. , Denver Res. Inst. , DRI-1023, 1-31, 1959.   |
| TITANIUM ALLOY A-110 AT |          |  |
| 211.                    | 10938    | Crucible Steel Company of America (Corporate Author, Crucible Steel Co. Data Sheet A-110 AT, 1-8, 1958.  |
| 212.                    | 6580     | Deem, H. W. and Lucks, C. F. , TML Rept. 39, 1-34, 1956. [AD 90949]  |
| ALUMINUM OXIDE          |          |  |
| 213.                    | 19559    | Anthony, F. M. , Merrihew, F. A. , Mistretta, A. L. and Dukes, W. H. , WADC TR 59-744, <u>1</u> , 1-263, 1961. [AD 264861]   |
| 214.                    | 28530    | Boggs, J. H. and Wiebelt, J. A. , U. S. At. Energy Comm. , TID-5734, 1-91, 1960.   |
| 215.                    | 26393    | Edwards, J. W. and Kington, G. L. , Trans. Faraday Soc. , <u>58</u> , Pt. 7, 1313-22, 1962.  |
| 216.                    | 25229    | Ewing, C. T. , Stone, J. P. , Spann, J. R. , Kovachina, T. A. and Miller, R. R. , 9th Progr. Rept. , U. S. Naval Res. Lab. , NRL Rept. 5964, 1-13, 1963. [AD 405673] |
| 217.                    | 7689     | Fieldhouse, I. B. , Hedge, J. C. , and Lang, J. I. , WADC TR 58-274, 1-79, 1958. [AD 206892], [PB 151583]  |
| 218.                    | 16590    | Fieldhouse, I. B. , Lang, J. I. , and Blau, H. H. , WADC TR 59-744, <u>4</u> , 1-78, 1960. [AD 249166]   |
| 219.                    | 452      | Furukawa, G. T. , Douglas, T. B. , McCoskey, R. E. and Ginnings, D. C. , J. Res. Natl. Bur. Std. , <u>57</u> , 67-82, 1956.  |
| 220.                    | 33992    | Ginnings, D. C. and Corruccini, R. J. , Natl. Bur. Std. , Res. Paper RP 1797, <u>38</u> (6), 593-600, 1947.  |
| 221.                    | 1699     | Ginnings, D. C. and Furukawa, G. T. , J. Am. Chem. Soc. , <u>75</u> , 522-7, 1953.   |
| 222.                    | 23817    | Hoch, M. and Johnston, H. L. , J. Phys. Chem. , <u>65</u> , 1184-5, 1961.  |
| 223.                    | 20017    | Kerr, E. C. , Johnston, H. L. and Hallett, N. C. , J. Am. Chem. Soc. , <u>72</u> , 4740-2, 1950.   |
| 224.                    | 28756    | Martin, D. L. , Can. J. Phys. , <u>40</u> , 1166-73, 1962.   |
| 225.                    | 26074    | Neel, D. S. , Pears, C. D. and Oglesby, S. , Jr. , WADD TR 60-924, 1-20, 1962. [AD 275536]   |
| 226.                    | 21364    | Oetting, F. L. , Univ. Microfilms, L. C. , Card No. Mic. 60-5976, 1-74, 1961.  |
| 227.                    | 21864    | Parks, G. S. and Kelley, K. K. , J. Phys. Chem. , <u>30</u> , 47-55, 1926.   |

| Ref. No. | TPRC No. |  |
|----------|----------|--|
|          |          | <b>ALUMINUM OXIDE (continued)</b>  |
| 228.     | 28672    | Pears, C. D. and Neel, D. S., <i>Ceram. Age</i> , <u>76</u> (5), 30-5, 1960.   |
| 229.     | 29980    | Prophet, H. and Stull, D. R., <i>J. Chem. Eng. Data</i> , <u>8</u> (1), 78-81, 1963.   |
| 230.     | 26503    | Romanovskii, V. A. and Tarasov, V. V., <i>Soviet Phys. Solid State</i> , <u>2</u> (6), 1176-8, 1960.   |
| 231.     | 22766    | Roth, W. A. and Bertram, W. W., <i>Z. Elektrochem.</i> , <u>35</u> , 297-308, 1929.  |
| 232.     | 20084    | Schmidt, N. E. and Sokolov, V. A., <i>Russ. J. Inorg. Chem.</i> , <u>5</u> , 797-802, 1960.  |
| 233.     | 1895     | Shomate, C. H. and Naylor, B. F., <i>J. Am. Chem. Soc.</i> , <u>67</u> (1), 72-5, 1945.  |
| 234.     | 33982    | Sterrett, K. F., Blackburn, D. H., Bestul, A. B., Chang, S. S. and Horman, J., <i>J. Res. Natl. Bur. Std.</i> , <u>69C</u> (1), 19-26, 1965. |
| 235.     | 24900    | Walker, B. E., Ewing, C. T. and Williams, D. D., <i>NRL Memo. Rept.</i> 312, 1-6, 1954.  |
| 236.     | 276      | Walker, B. E., Grand, J. A. and Miller, R. R., <i>J. Phys. Chem.</i> , <u>60</u> , 231-3, 1956.  |
| 237.     | 18576    | West, E. D. and Ginnings, D. C., <i>J. Res. Natl. Bur. Std.</i> , <u>60</u> , 309-16, 1958.  |
| 238.     | 29885    | Wiebelt, J. A., <i>PhD Thesis, Oklahoma State Univ.</i> , 1-91, 1960.  |

**BERYLLIUM OXIDE**

|      |       |   |
|------|-------|---|
| 239. | 25961 | Hedge, J. C., Kostenko, C. and Lang, J. I., <i>ASD-TDR-63-597</i> , 1-128, 1963. [AD 424375]  |
| 240. | 15021 | Kandyba, V. V., Kantor, P. B., Krasovitskaya, R. M., and Fomichev, E. N., <i>AEC-TR-4310 (English Transl. Doklady Akad. Nauk., SSSR)</i> , <u>131</u> (3), 566-7, 1960), 1-4, 1960. |
| 241. | 11861 | Kelley, K. K., <i>J. Am. Chem. Soc.</i> , <u>61</u> , 1217-8, 1939.   |
| 242. | 21405 | Magnus, A. and Danz, H., <i>Ann Physik</i> , <u>81</u> , 407-24, 1926.  |
| 243. | 26008 | Pears, C. D., <i>ASD-TDR-62-765</i> , 1-420, 1962. [AD 298061]  |
| 244. | 30541 | Victor, A. C. and Douglas, T. B., <i>J. Res. Natl. Bur. Std.</i> , <u>67A</u> (4), 325-9, 1963.   |
| 245. | 29978 | Walker, B. E., Jr., Ewing, C. T. and Miller, R. R., <i>J. Chem. Eng. Data</i> , <u>7</u> , 595-7, 1962.   |

| Ref. No. | TPRC No. | CHROMIUM OXIDE  |
|----------|----------|---|
| 246.     | 12111    | Anderson, C. T. , J. Am. Chem. Soc. , <u>59</u> , 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, <u>170</u> , 1027, 1952.   |

#### CUPRIC OXIDE

|      |       |  |
|------|-------|--|
| 249. | 1213  | Assayag, G. and Bizette, H. , Compt. Rend. , <u>239</u> , 238-40, 1954.                |
| 250. | 7025  | Clusius, K. and Harteck, P. , Z. Physik. Chem. , <u>134</u> , 243-63, 1928.            |
| 251. | 932   | Hu, J. H. and Johnston, H. L. , J. Am. Chem. Soc. , <u>75</u> , 2471-3, 1953.          |
| 252. | 21814 | Millar, R. W. , J. Am. Chem. Soc. , <u>51</u> , 215-22, 1929.                          |
| 253. | 20978 | Wohler, L. and Jochum, N. , Z. Physik. Chem. (Leipzig), <u>A167</u> (3), 169-79, 1933. |

#### CUPROUS OXIDE

|      |       |   |
|------|-------|---|
| 254. | 27444 | Gregor, L. V. , J. Phys. Chem. , <u>66</u> , 1645-7, 1962.                    |
| 255. | 7768  | Hu, J. H. and Johnston, H. L. , J. Am. Chem. Soc. , <u>73</u> , 4450-1, 1951. |
| 256. | 21814 | Millar, R. W. , J. Am. Chem. Soc. , <u>51</u> , 215-22, 1929.                 |
| 257. | 20978 | Wohler, L. and Jochum, N. , Z. Physik. Chem. , <u>167A</u> , 169-, 1933.      |

#### FERROUS OXIDE

|      |       |   |
|------|-------|---|
| 258. | 1296  | Coughlin, J. P. , King, E. G. and Bonnicksen, K. R. , J. Am. Chem. Soc. , <u>73</u> , 3891-3, 1951. |
| 259. | 21814 | Millar, R. W. , J. Am. Chem. Soc. , <u>51</u> , 215-22, 1929.                                       |
| 260. | 1295  | Todd, S. S. and Bonnicksen, K. R. , J. Am. Chem. Soc. , <u>73</u> , 3894-5, 1951.                   |
| 261. | 14383 | White, W. P. , J. Am. Chem. Soc. , <u>55</u> , 1047-53, 1933.                                       |

#### FERRIC OXIDE

|      |       |   |
|------|-------|---|
| 262. | 19866 | Brown, G. G. and Furnas, C. C. , Trans. Am. Inst. Chem. Eng. , <u>18</u> , 309-46, 1926.            |
| 263. | 1296  | Coughlin, J. P. , King, E. G. and Bonnicksen, K. R. , J. Am. Chem. Soc. , <u>73</u> , 3891-3, 1951. |

Ref. TPRC  
No. No.

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 Giaugue, 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. TPRC  
No. 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. |   |
|----------|----------|---|
| 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, <u>2</u> (2), 43-5, 1960. |
| 301.     | 18112    | King, E. G. , J. Am. Chem. Soc. , <u>80</u> (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. , <u>3</u> (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, <u>2</u> (2), 43-5, 1960. |
| 305. | 386   | King, E. G. , J. Am. Chem. Soc. , <u>76</u> , 3289-91, 1954.  |
| 306. | 529   | Orr, R. L. , J. Am. Chem. Soc. , <u>75</u> , 2808-9, 1953.  |

#### SILICON DIOXIDE

- |      |       |   |
|------|-------|---|
| 307. | 15366 | Anderson, C. T. , J. Am. Chem. Soc. , <u>58</u> , 568-70, 1936.   |
| 308. | 26662 | Clark, A. E. and Starkna, R. E. , Phys. Chem. Glasses, <u>3</u> (4), 121-6, 1962.   |
| 309. | 23932 | Flubacher, P. , Leadbetter, A. J. , Morrison, J. A. and Stoicheff, B. P. , J. Phys. Chem. Solids, <u>12</u> (1), 53-65, 1959. |
| 310. | 296   | Lord, R. C. and Morrow, J. C. , J. Chem. Phys. , <u>26</u> (2), 230-2, 1957.  |
| 311. | 10947 | Lucks, C. F. , Deem, H. W. and Wood, W. D. , Am. Ceram. Soc. Bull. , <u>39</u> (6), 313-9, 1960.                              |
| 312. | 6314  | Moser, H. , Phys. Z. , <u>37</u> (21), 737-53, 1936.  |
| 313. | 30160 | Mosesman, M. A. and Pitzer, K. S. , J. Am. Chem. Soc. , <u>63</u> , 2348-56, 1941.  |
| 314. | 29642 | Nernst, W. , Ann. Physik, <u>36</u> (4), 395-439, 1911.   |
| 315. | 21397 | Simon, F. , Ann. Physik, <u>68</u> , 241-80, 1922.  |
| 316. | 619   | Sinel'nikov, N. N. , Doklady Akad. Nauk. SSSR, <u>92</u> , 369-72, 1953.  |
| 317. | 25447 | Southard, J. C. , J. Am. Chem. Soc. , <u>63</u> , 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 <sup>e</sup> Congr. Intern. du Verre, Paris, 396-9, 1956.   |
| 320. | 30241 | Wietzel, R. , Z. Anorg. Chem. , <u>116</u> , 71-95, 1921.   |

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), 800-4, 1958.  
 331. Kelley, K. K. and Mah, A. D. , U. S. Bur. Mines Rept. Invest. 5490, 1-20, 1959.  
 332. 987 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. TPRC  
No. 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

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C. E. VOLK

## 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 <sup>were</sup> ~~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 reveal 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  $\rho$  = density of the alloy

$\rho_i$  = 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.

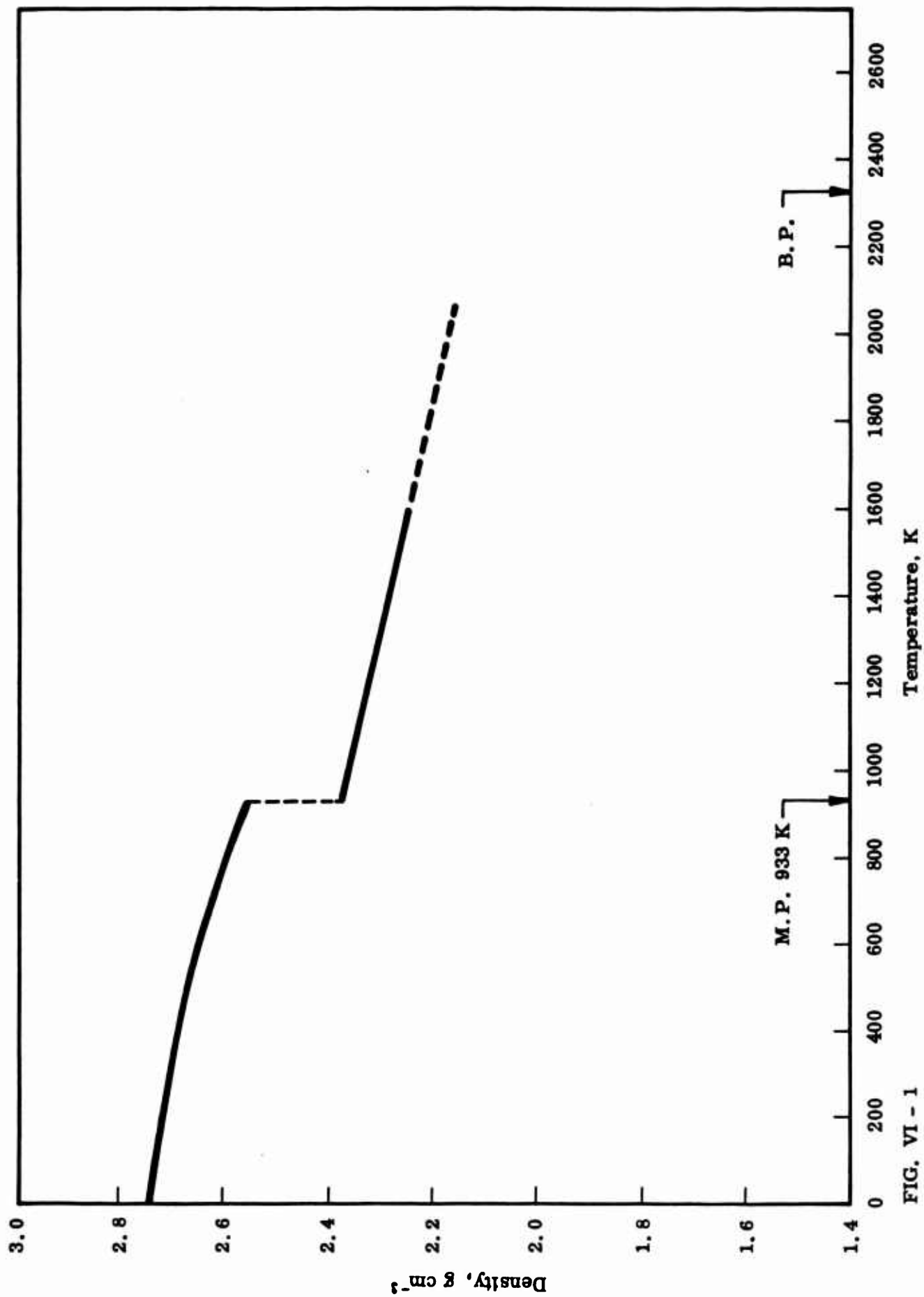


FIG. VI - 1

DENSITY -- ALUMINUM

TABLE VI-1. DENSITY OF ALUMINUM

RECOMMENDED VALUES

| T(°K)      | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)          | $\rho$ (g. cm <sup>-3</sup> ) |
|------------|-------------------------------|----------------|-------------------------------|
| 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  $\pm .5\%$  or better.  
 liquid range  $\pm .1\%$  or better.

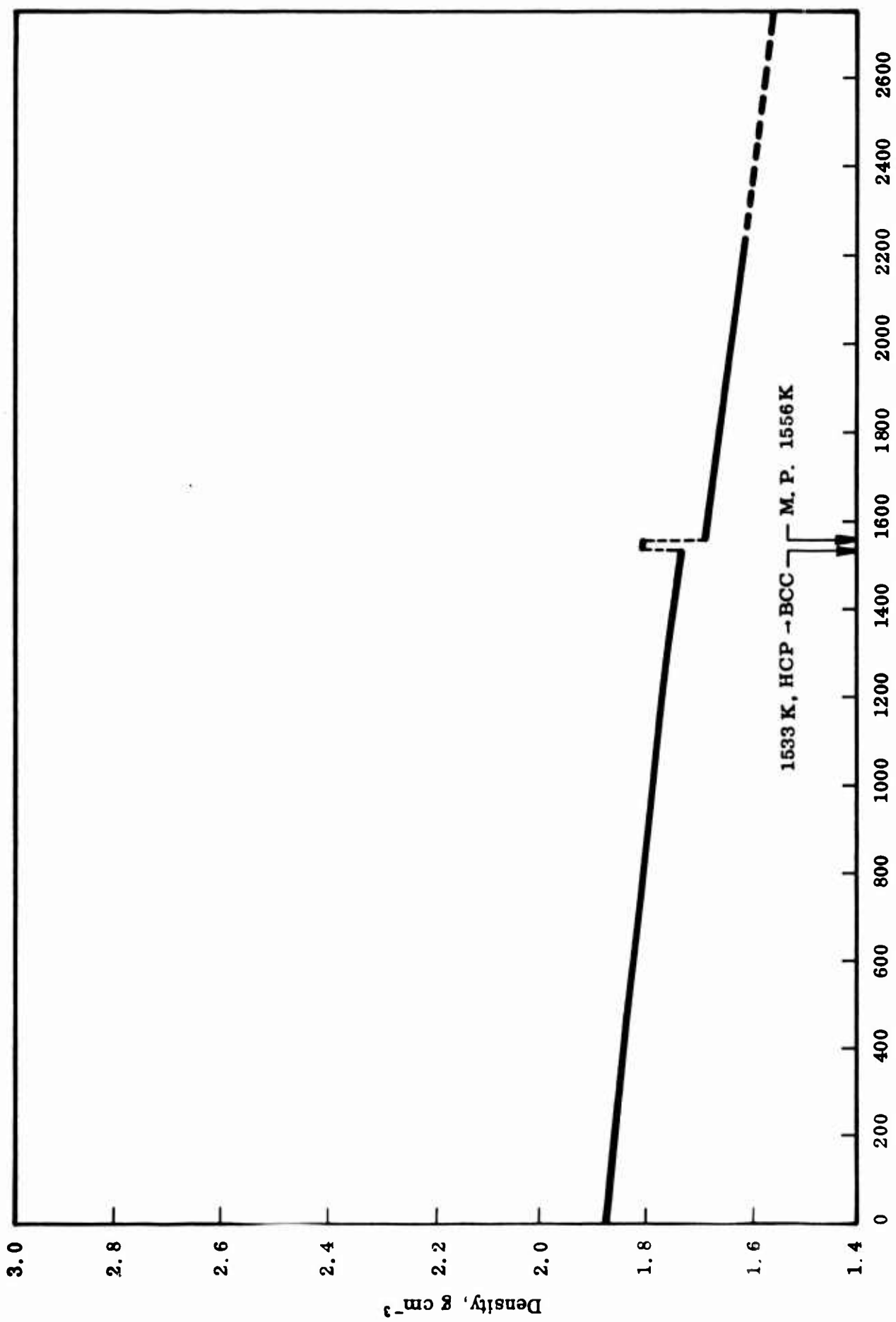


FIG. VI - 2

DENSITY -- BERYLLIUM

**TABLE VI-2. DENSITY OF BERYLLIUM**

**RECOMMENDED VALUES**

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)        | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|--------------|-------------------------------|
| 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) 1.808                |
| 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  $\pm$  .5%  
 liquid range  $\pm$  4%

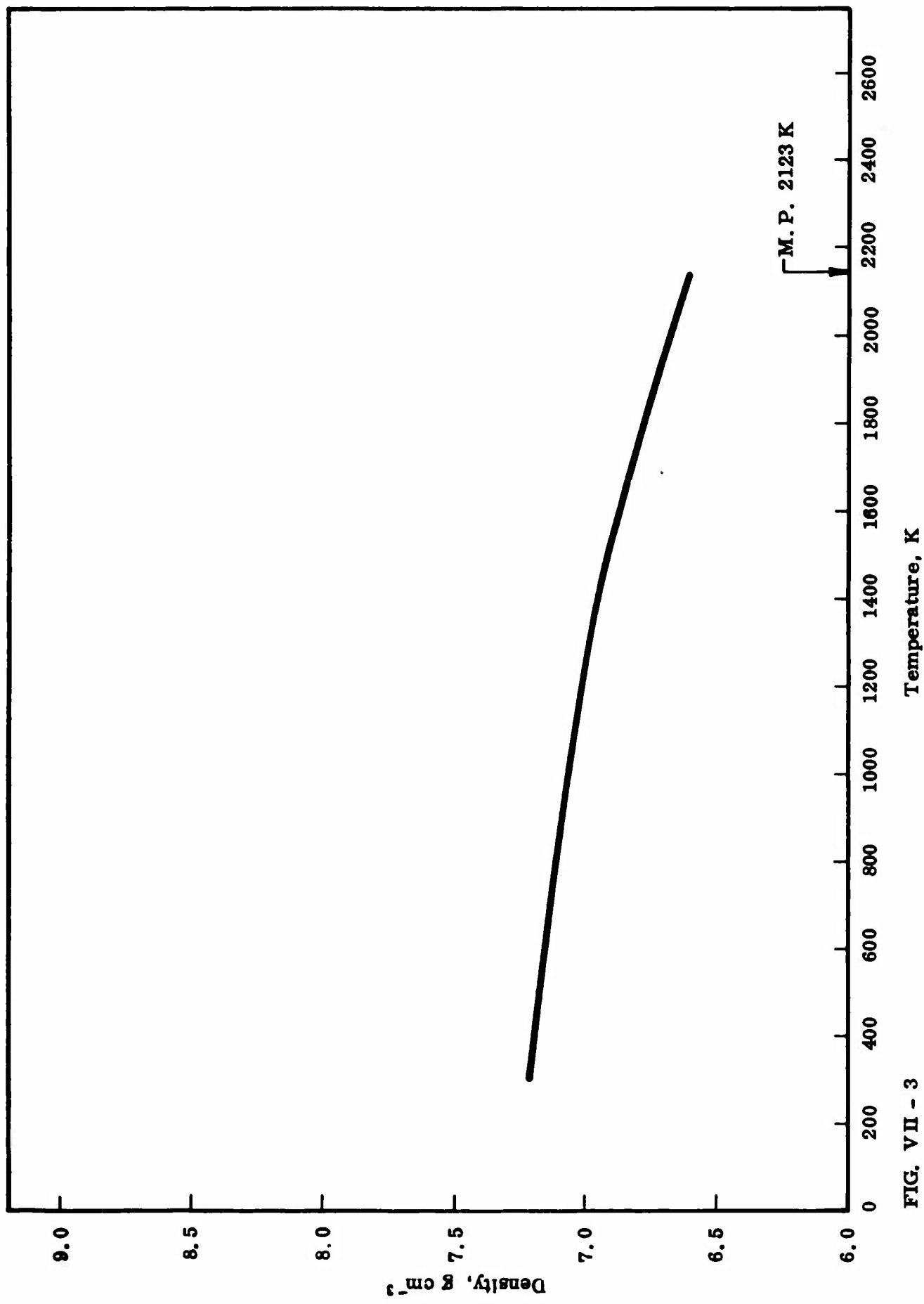


FIG. VI - 3

DENSITY -- CHROMIUM

TABLE VI-3. DENSITY OF CHROMIUM

| T(°K) | $\rho$ (g. cm <sup>-3</sup> )  | T(°K)       | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|--------------------------------|-------------|-------------------------------|
| 299   | (s, HCP) <del>6.08</del> 7.215 | 1300        | 6.98                          |
| 299   | (s, BCC) <del>7.21</del> 7.215 | 1400        | 6.94                          |
| 300   | <del>7.21</del> 7.215          | 1500        | 6.91                          |
| 400   | 7.20                           | 1600        | 6.87                          |
| 500   | 7.18                           | 1700        | 6.83                          |
| 600   | 7.16                           | 1800        | 6.78                          |
| 800   | 7.11 <sup>7.14</sup>           | 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        | (1) 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.

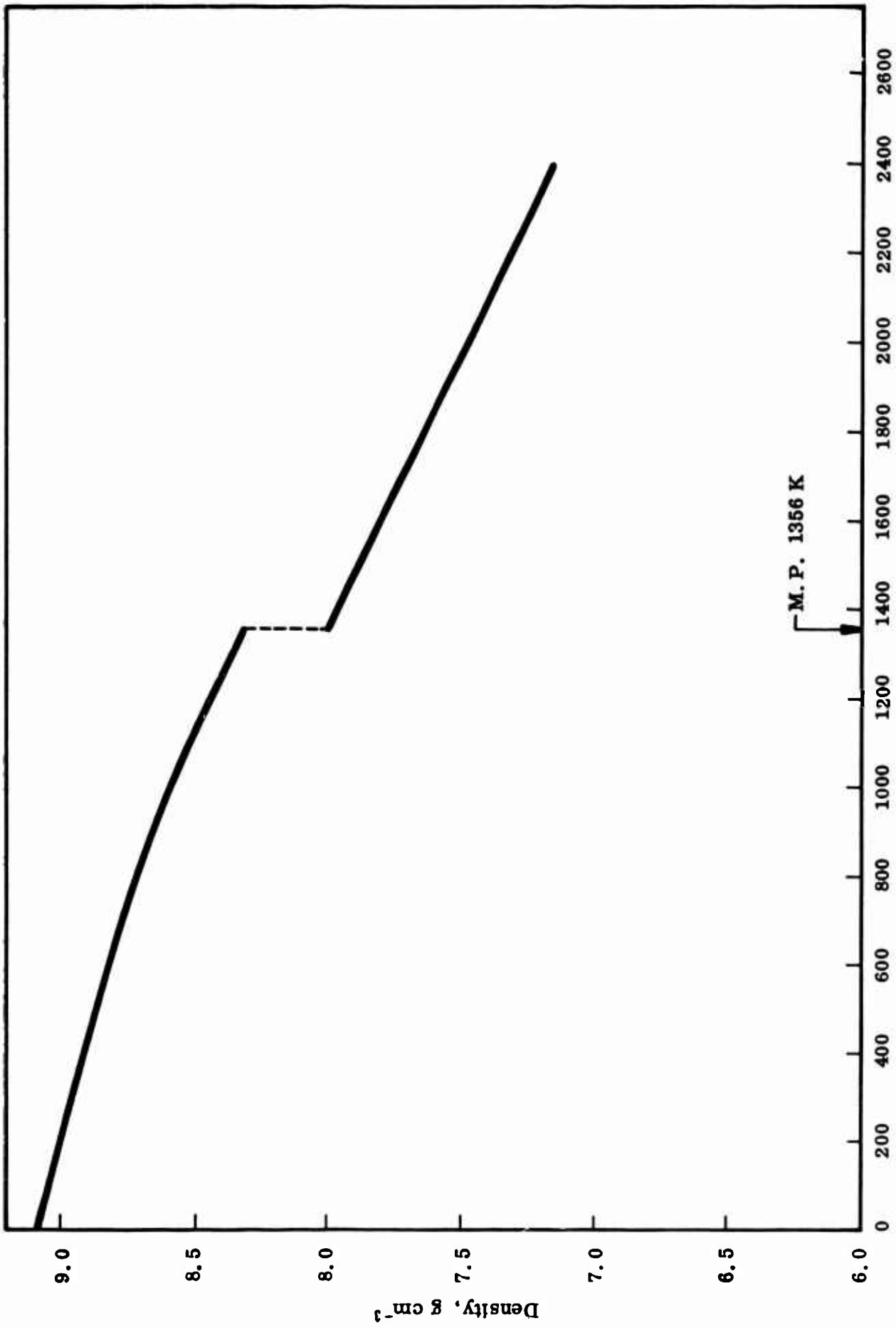


FIG. VI - 4

DENSITY -- COPPER

**TABLE VI-4. DENSITY OF COPPER**

**RECOMMENDED VALUES**

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)        | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|--------------|-------------------------------|
| 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         | 7.32                          |
| 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.

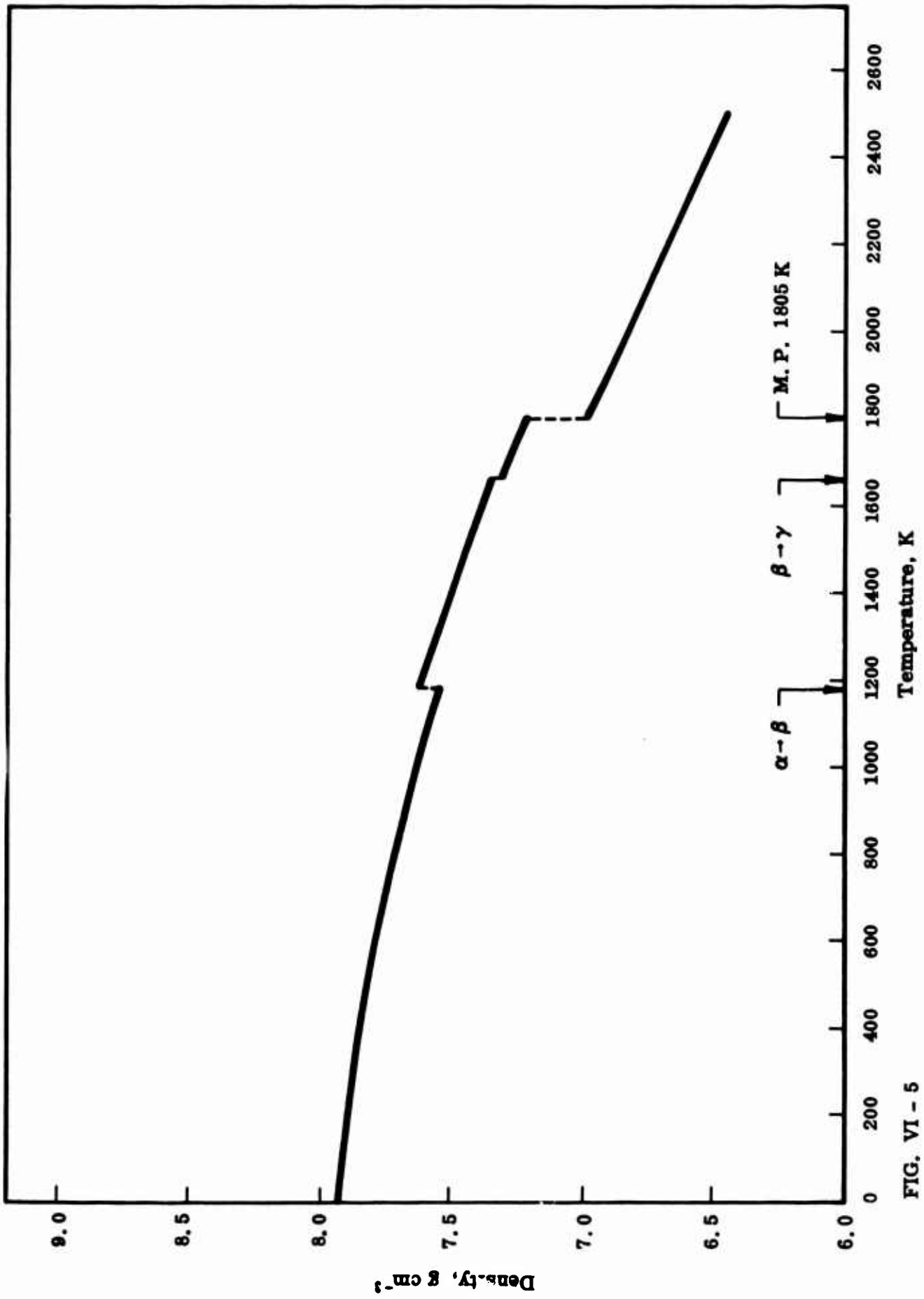


FIG. VI - 5  
DENSITY -- IRON

TABLE VI-5. DENSITY OF IRON

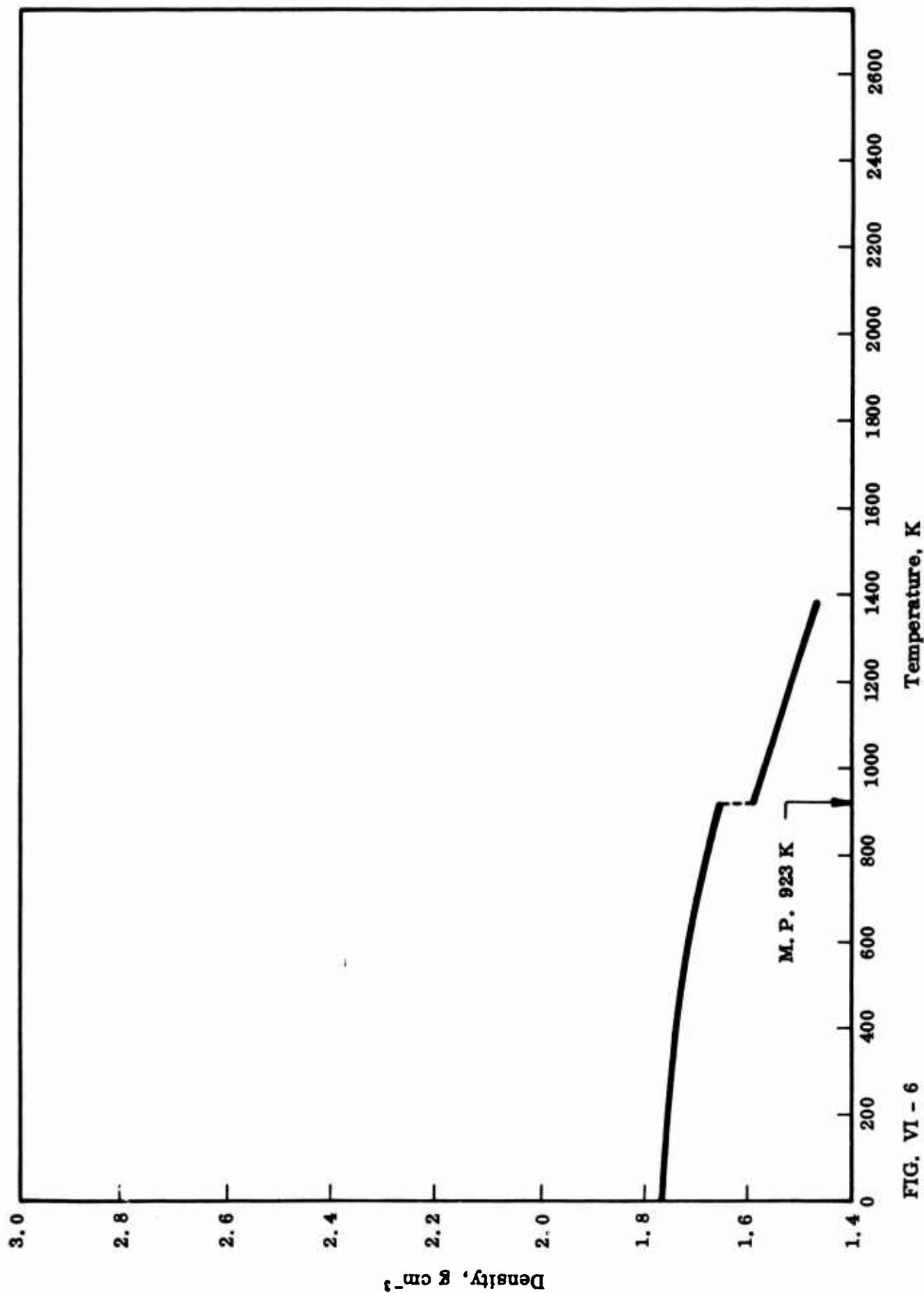
RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)             | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------------------|-------------------------------|
| 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   | 7.775                         | 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



DENSITY -- MAGNESIUM

FIG. VI - 6

TABLE VI-6. DENSITY OF MAGNESIUM

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)           | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-----------------|-------------------------------|
| 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:  $\pm .5\%$  or better  
liquid range:  $\pm .5\%$  or better  
Values above boiling point are from (h) and are extrapolated values.

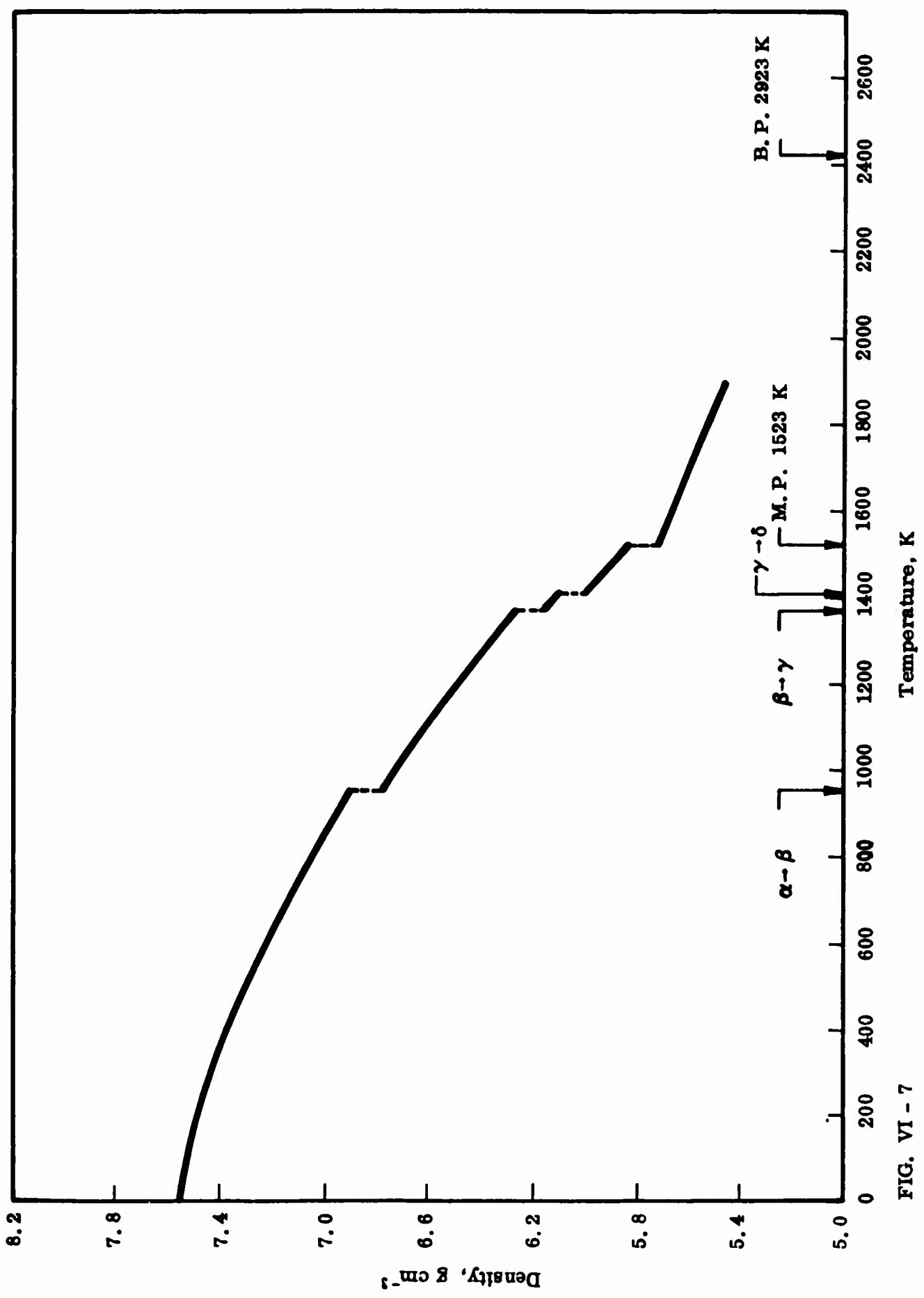


FIG. VI - 7

DENSITY -- MANGANESE

TABLE VI-7. DENSITY OF MANGANESE

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | $\bar{T}$ (°K) | $\bar{\rho}$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|----------------|-------------------------------------|
| 0     | (s, $\alpha$ ) 7.55           | 1200           | 6.49                                |
| 100   | 7.52                          | 1300           | 6.36                                |
| 200   | 7.48                          | 1373           | (s, $\beta$ ) 6.27                  |
| 300   | 7.43                          | 1373           | (s, $\gamma$ ) 6.17                 |
| 400   | 7.37                          | 1400           | 6.12                                |
| 500   | 7.30                          | 1411           | (s, $\gamma$ ) 6.10                 |
| 600   | 7.23                          | 1411           | (s, $\delta$ ) 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, $\alpha$ ) 6.90           | 1600           | 5.67                                |
| 951   | (s, $\beta$ ) 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  $\alpha$ ,  $\beta$ ,  $\gamma$ , 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 Dzhenelev, N. K. (33)

REMARKS: Up to 951°K the curve was constructed using the value of  $\alpha$ -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  $\beta$ ,  $\gamma$ , and  $\delta$  phases, behavior similar to the  $\alpha$  phase. No accuracy can be evaluated in this case. The values should be considered as tentative values and used with caution.

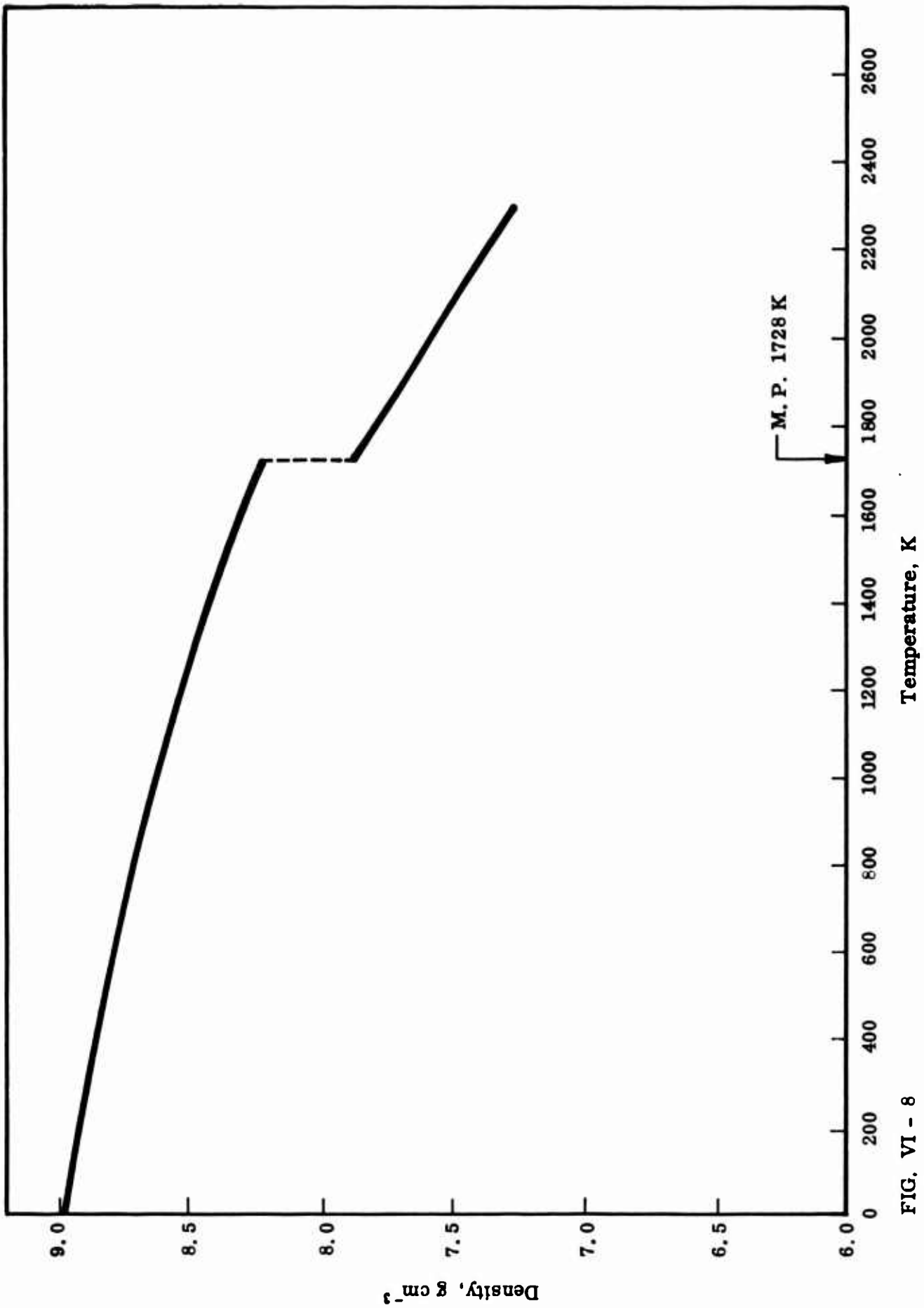


FIG. VI - 8

DENSITY -- NICKEL

TABLE VI-8. DENSITY OF NICKEL

RECOMMENDED VALUES

| T(°K) | $\rho$ (g.cm <sup>-3</sup> ) | T(°K)        | $\rho$ (g.cm <sup>-3</sup> ) |
|-------|------------------------------|--------------|------------------------------|
| 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:  $\pm .5\%$   
 liquid range:  $\pm 1.0\%$

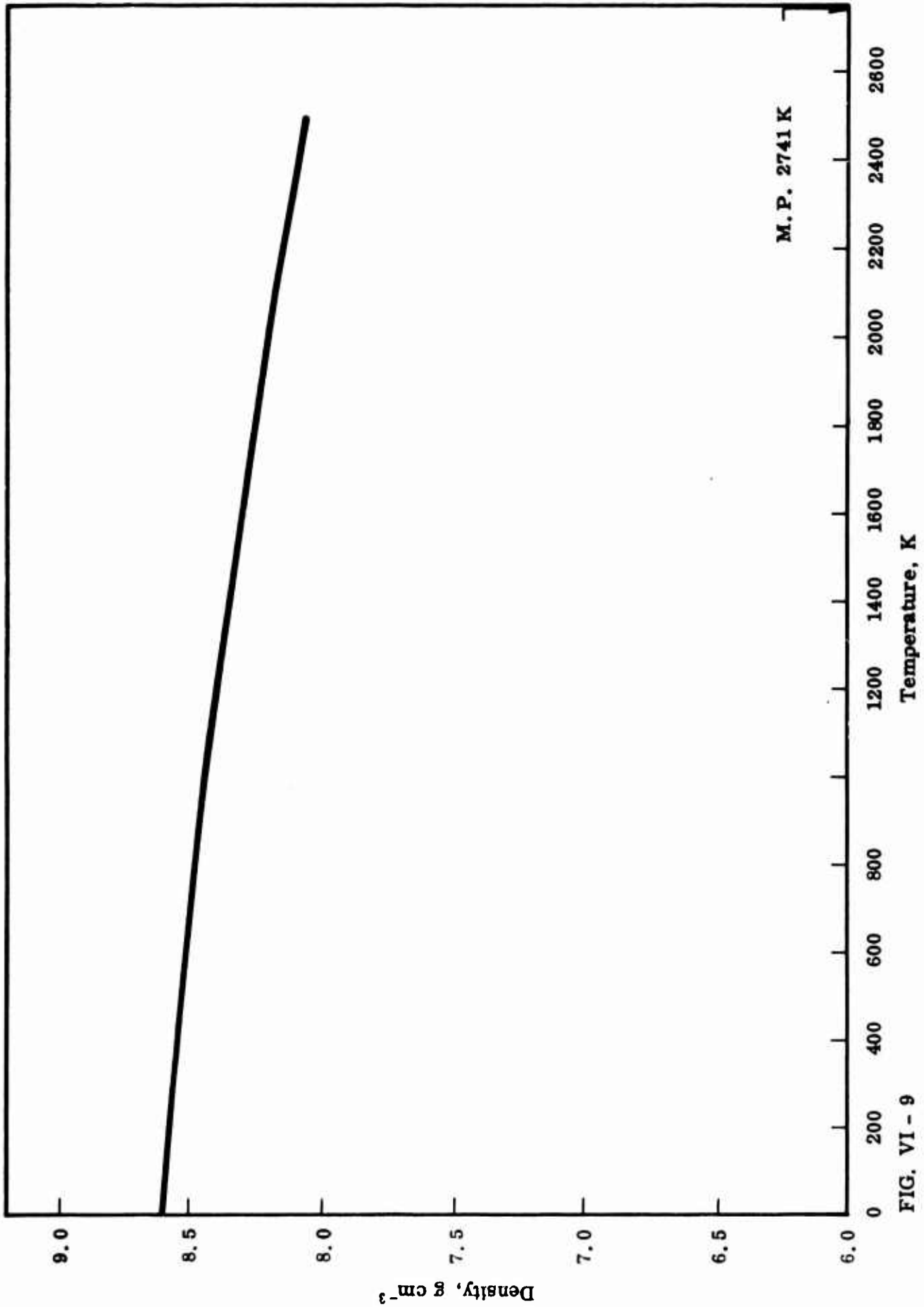


FIG. VI - 9

DENSITY -- NIOBIUM

TABLE VI-9. DENSITY OF NIOBIUM

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------|-------------------------------|
| 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:  $\pm .5\%$

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

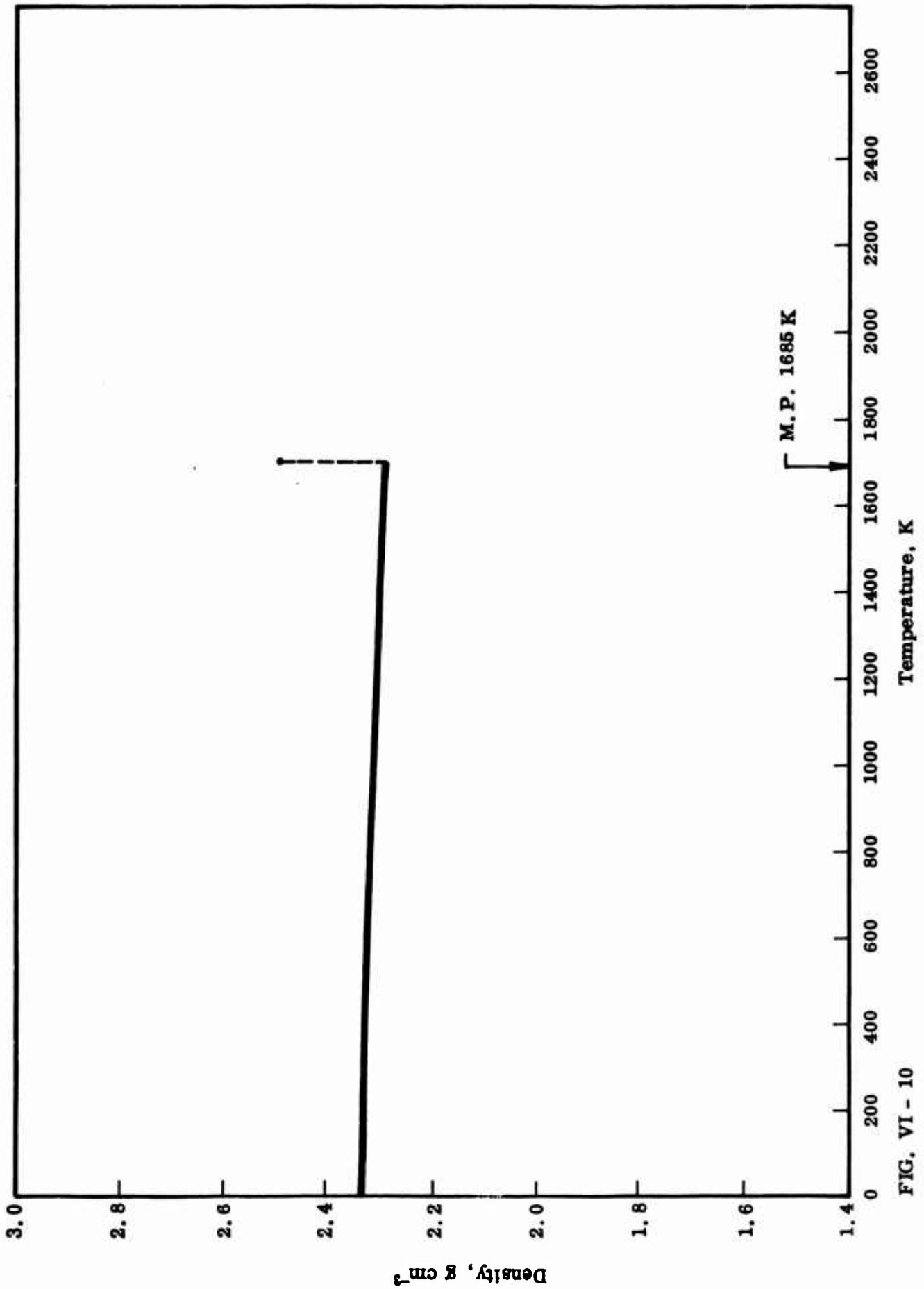


FIG. VI - 10

DENSITY -- SILICON

TABLE VI - 10. DENSITY OF SILICON

RECOMMENDED VALUES

| T(°K) | $\rho$ (g, cm <sup>-3</sup> ) | T(°K)        | $\rho$ (g, cm <sup>-3</sup> ) |
|-------|-------------------------------|--------------|-------------------------------|
| 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.

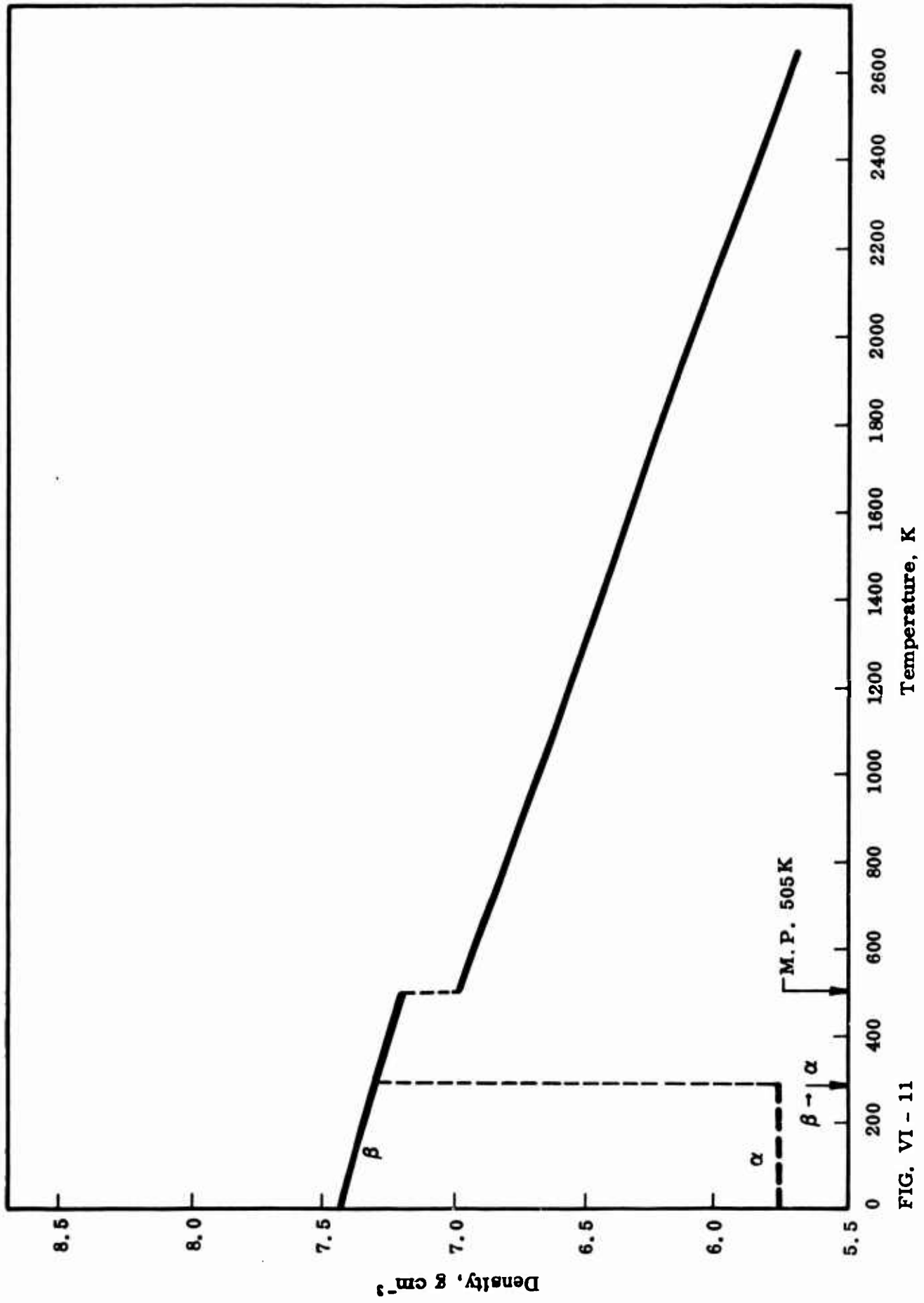


FIG. VI - 11

DENSITY -- TIN

**TABLE VI-11. DENSITY OF TIN**

**RECOMMENDED VALUES**

| T(°K)       | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)           | $\rho$ (g. cm <sup>-3</sup> ) |
|-------------|-------------------------------|-----------------|-------------------------------|
| 0           | (s, $\alpha$ ) 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 ( $\alpha$  - tin) transforms to gray tin ( $\beta$  - tin) but the transformation is slow. The density of  $\beta$  - tin at 286.36 is 5.765 g cm<sup>-3</sup>

**SOURCE OF DATA**

- 1) Value near room temperature:  
 $\beta$ -tin (tetragonal) and  $\alpha$ -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. (49); (l) Gebhardt, E. Becker, M. and Schafer, S. (15); (m) Kutateladze, S. S., Borishanskii, V. M., and Novikov, I. I. (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:  $\pm .5\%$  or better

*(and Fedinskii, O. S.)*

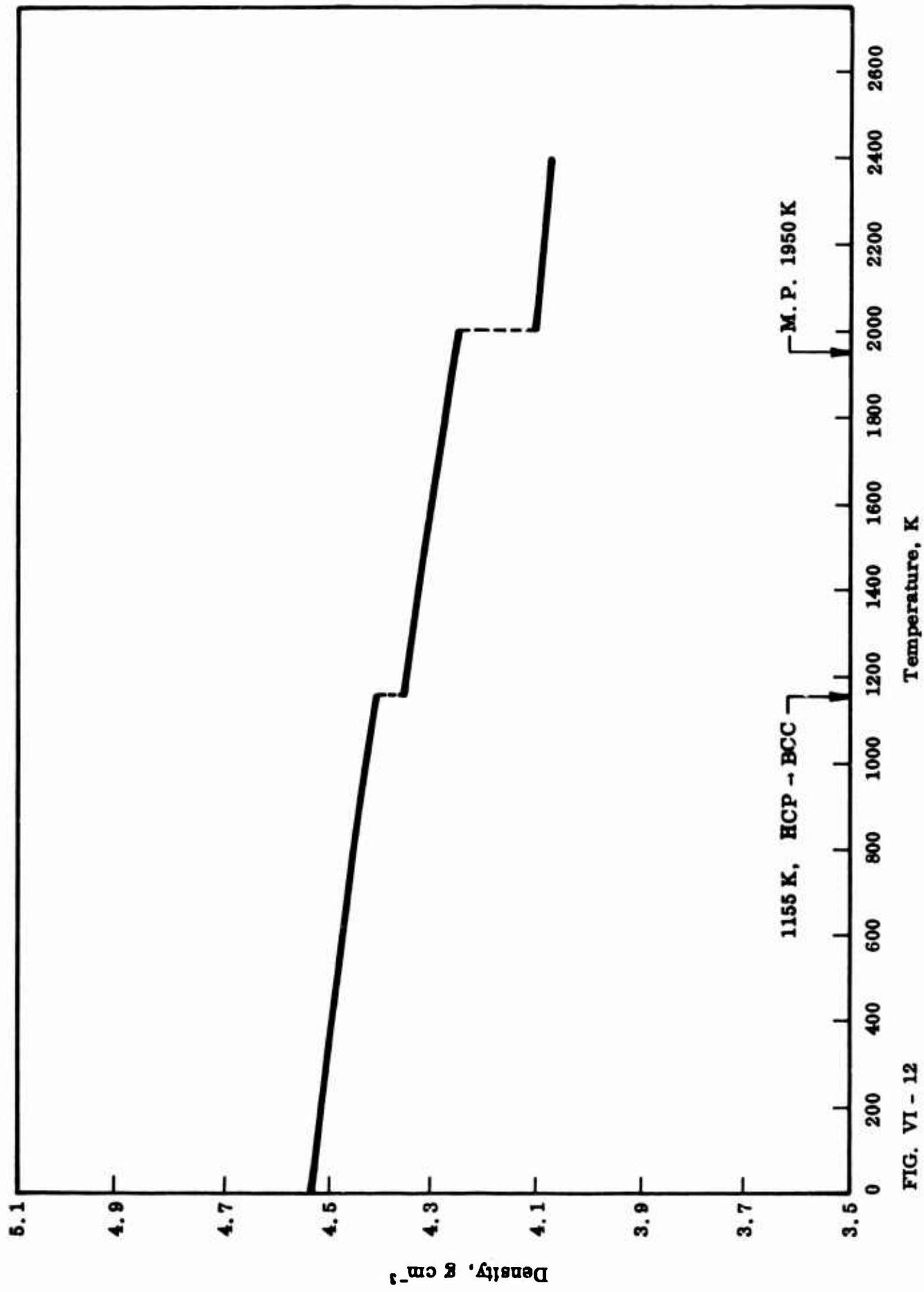


FIG. VI - 12

DENSITY -- TITANIUM

TABLE VI-12. DENSITY OF TITANIUM

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)       | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------------|-------------------------------|
| 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):  $\pm .5\%$   
(BCC): non evaluable  
liquid range: non evaluable

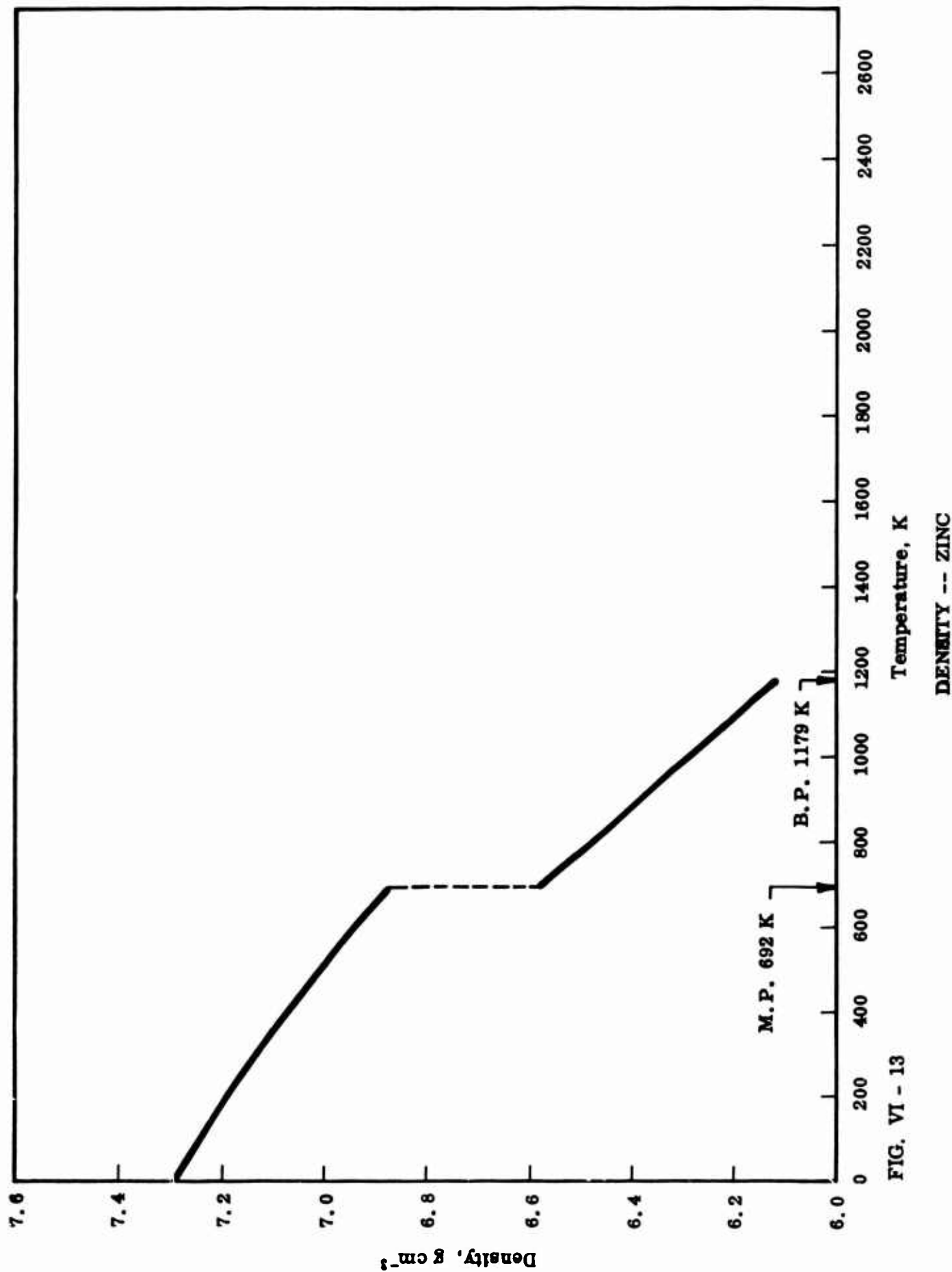


FIG. VI - 13

TABLE VI-13. DENSITY OF ZINC

RECOMMENDED VALUES

| T(°K)      | ρ(g. cm <sup>-3</sup> ) | T(°K)          | ρ(g. cm <sup>-3</sup> ) |
|------------|-------------------------|----------------|-------------------------|
| 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%

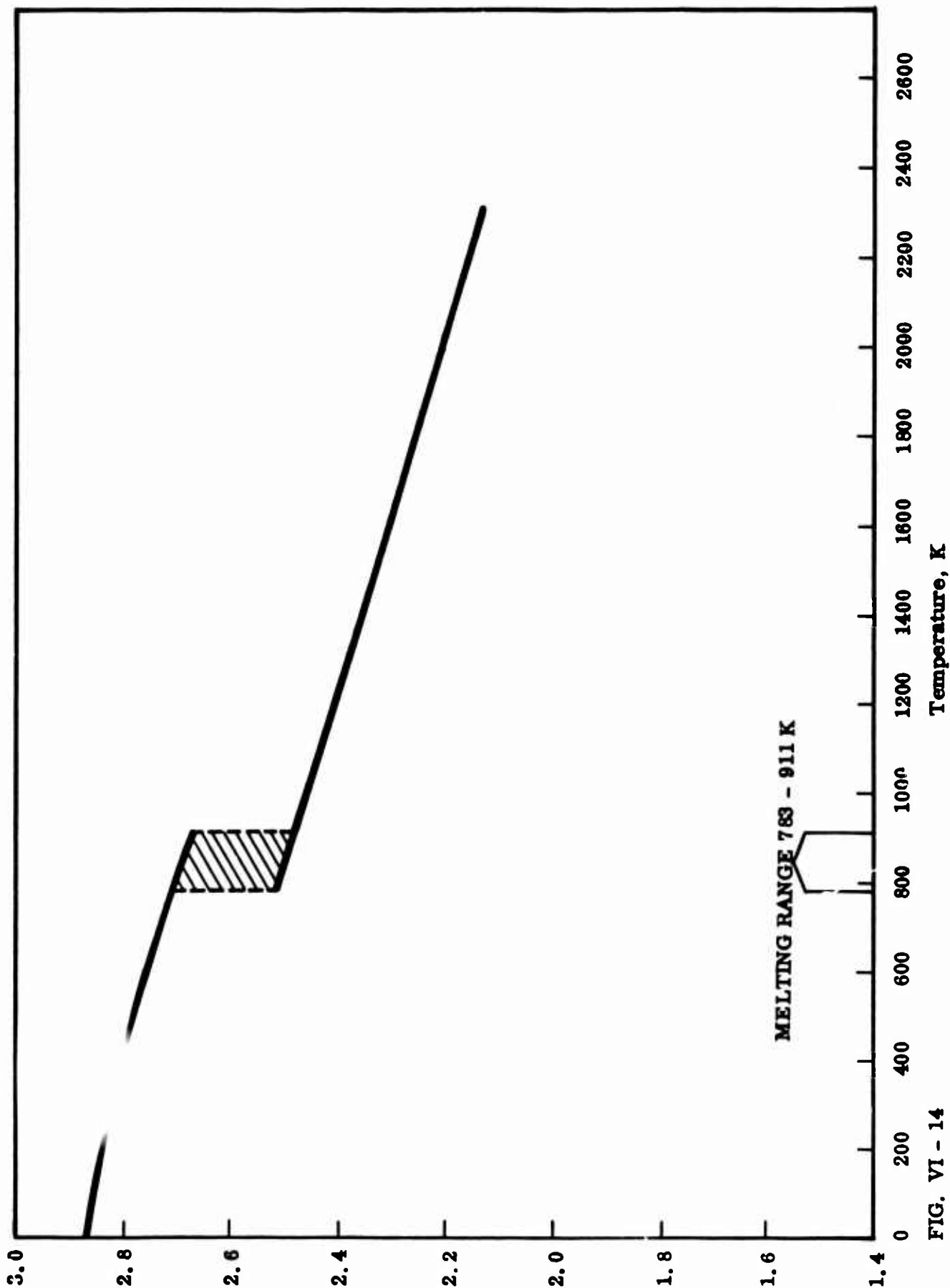


FIG. VI - 14

DENSITY -- ALUMINUM ALLOY 2219-T852

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

**RECOMMENDED VALUES**

| $T(^{\circ}\text{K})$                | $\rho(\text{g. cm}^{-3})$ | $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ |
|--------------------------------------|---------------------------|-----------------------|---------------------------|
| 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 <sup>o</sup> 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.

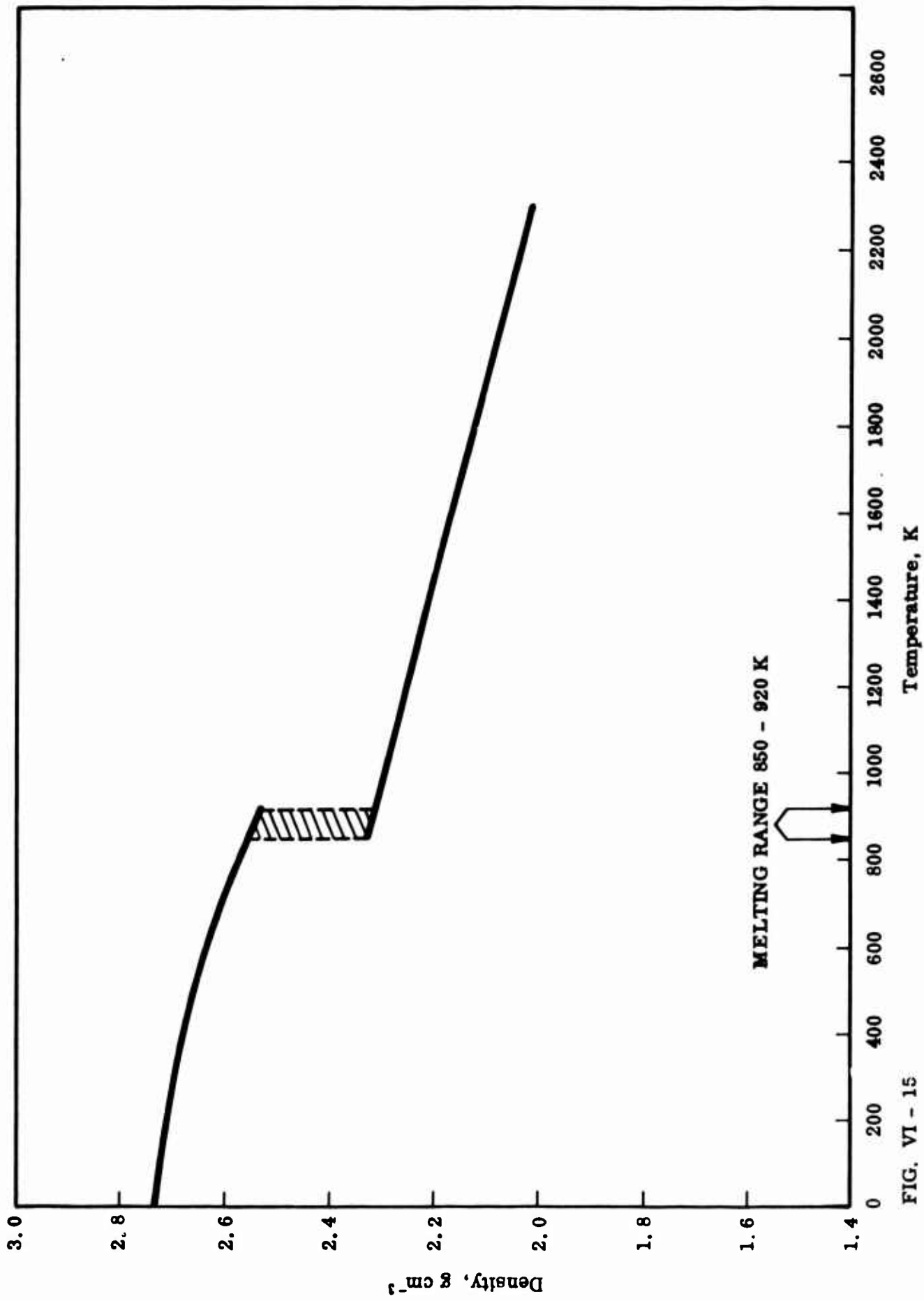


FIG. VI - 15

DENSITY -- ALUMINUM ALLOY 6061-T6

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

**RECOMMENDED VALUES**

| T(°K)                     | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|---------------------------|-------------------------------|-------|-------------------------------|
| 0                         | (s) 2.73                      | 1200  | 2.26                          |
| 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.

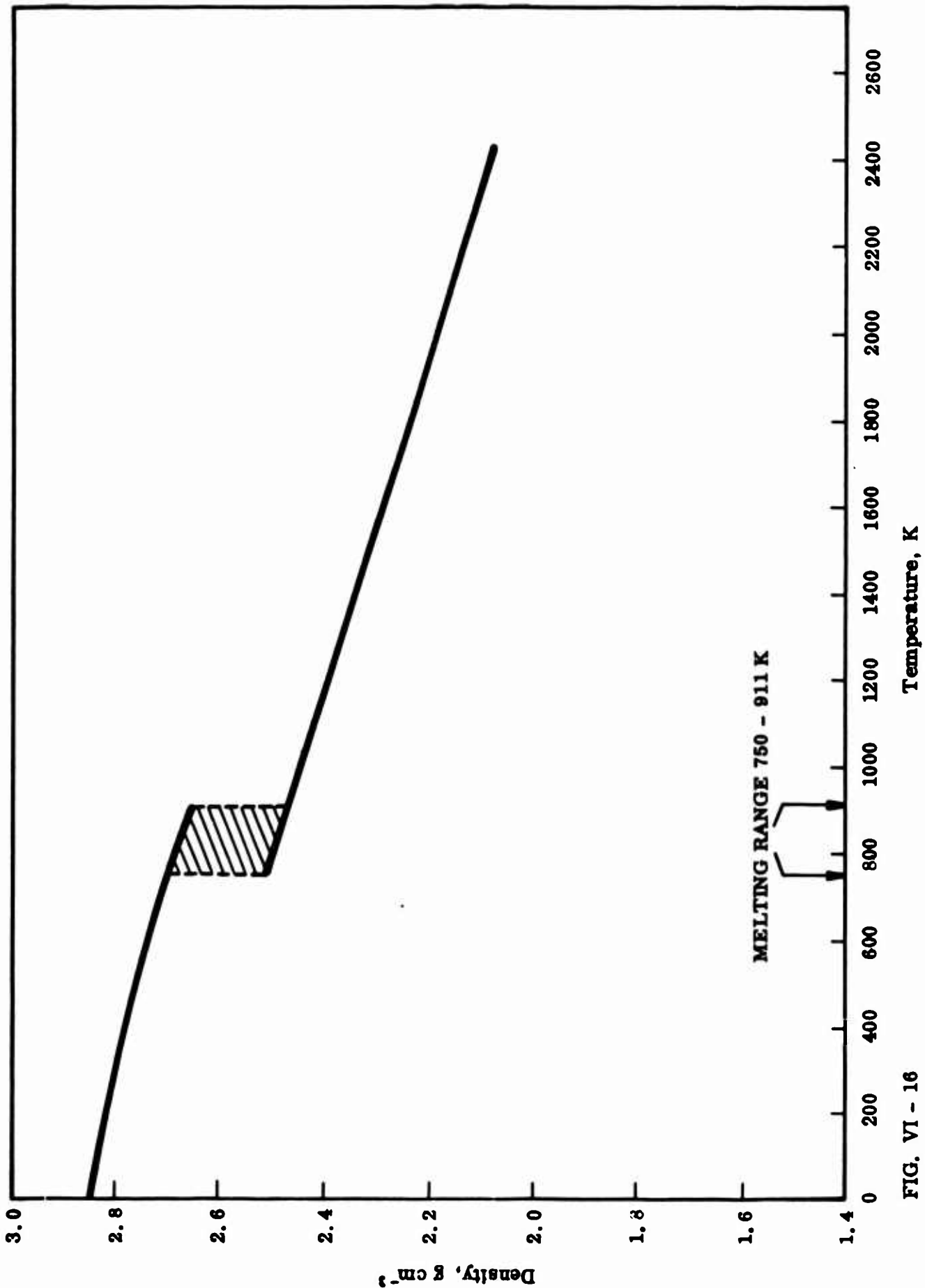


FIG. VI - 16

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

**RECOMMENDED VALUES**

| T(°K)                    | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|--------------------------|-------------------------------|-------|-------------------------------|
| 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                     | (l) 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.

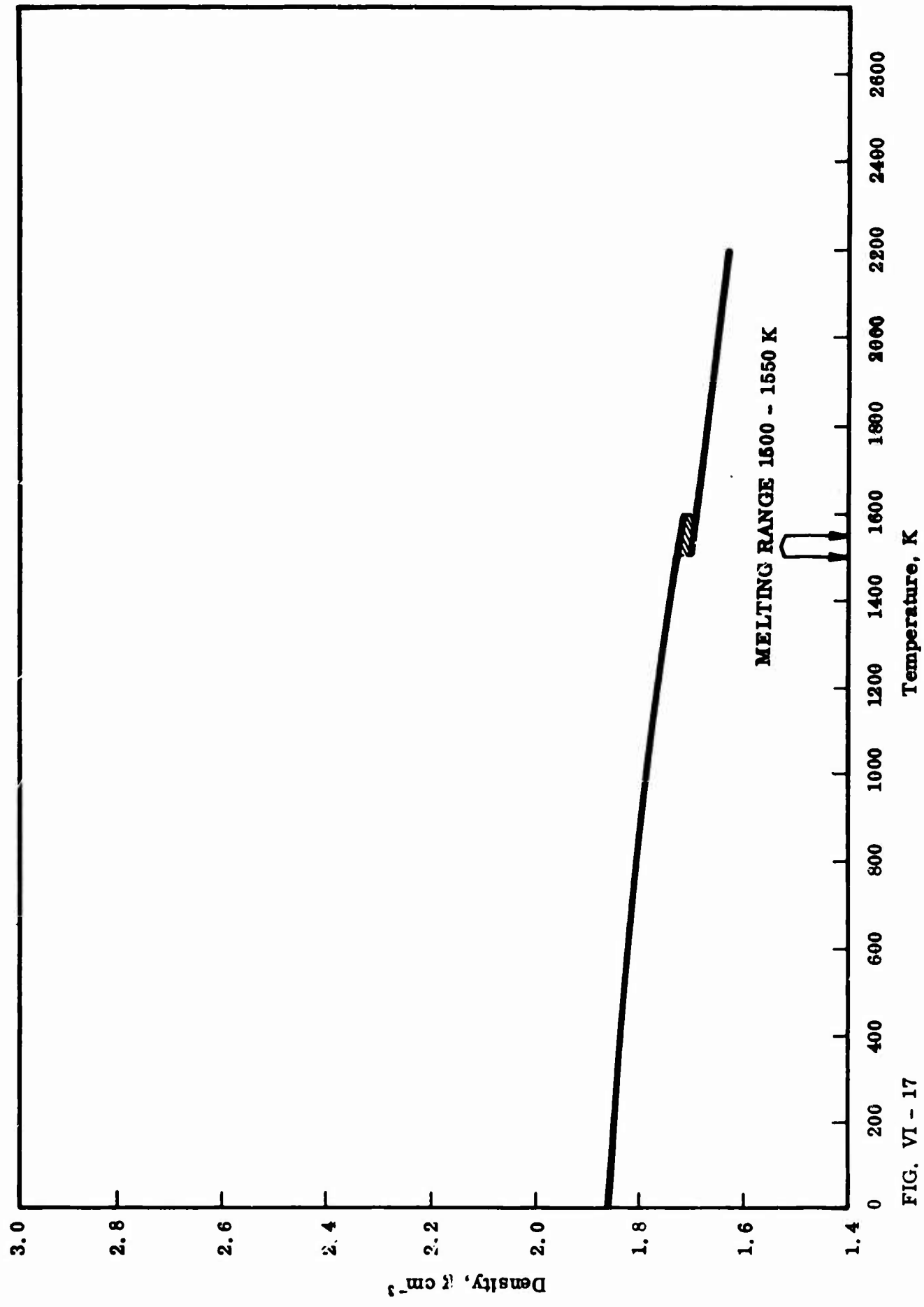


FIG. VI - 17

DENSITY -- BERYLLIUM ALLOY

TABLE VI-17. DENSITY OF BERYLLIUM ALLOY

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)                      | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|----------------------------|-------------------------------|
| 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 304 A**

**RECOMMENDED VALUES**

| $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ | $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ |
|-----------------------|---------------------------|-----------------------|---------------------------|
| 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.

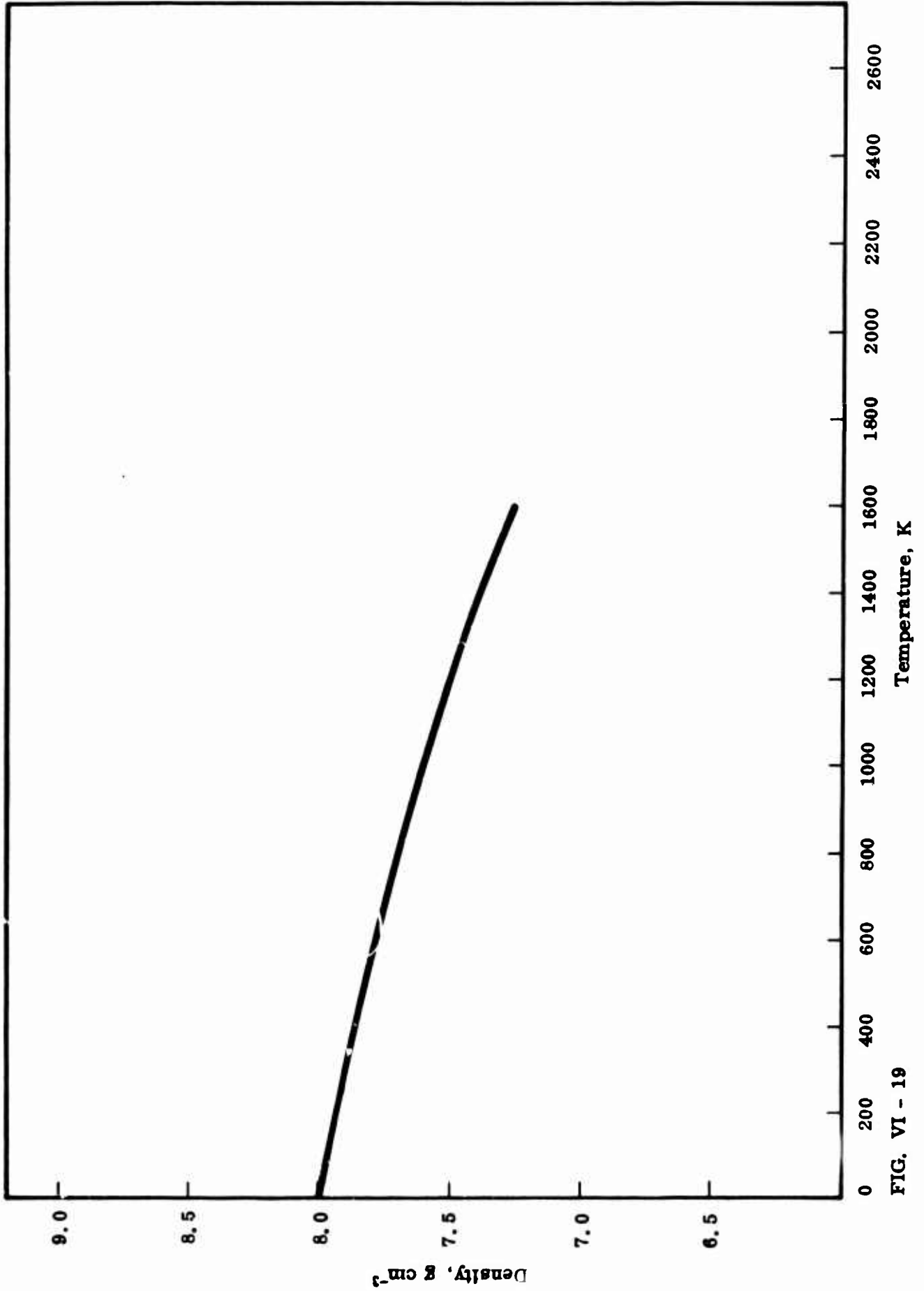


FIG. VI - 19

DENSITY -- STAINLESS STEEL 347

TABLE VI-19. DENSITY OF STAINLESS STEEL 347

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------|-------------------------------|
| 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:  $\pm 0.5\%$  or better.

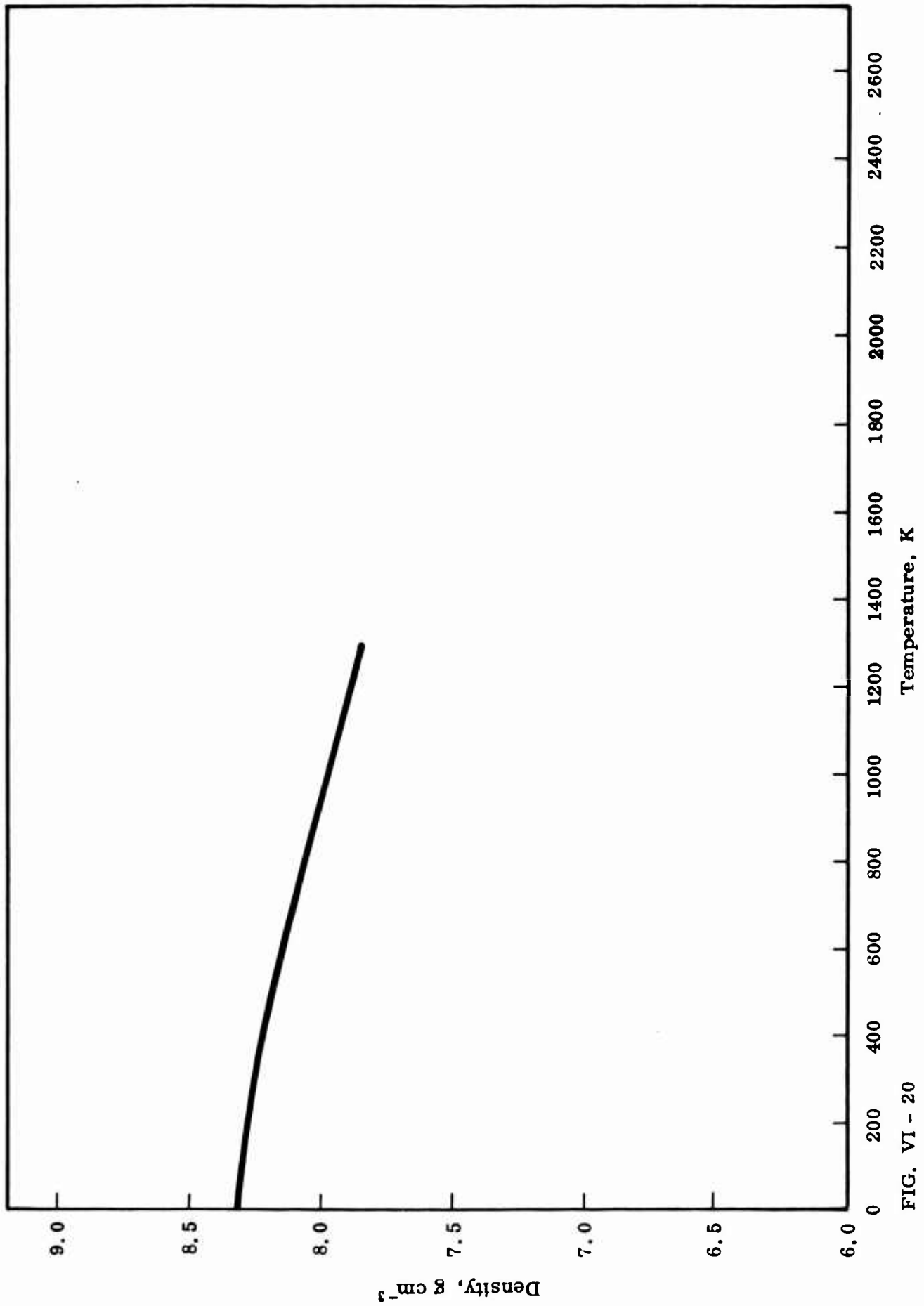


FIG. VI - 20

DENSITY -- INCONEL X - 750

TABLE VI-20. DENSITY OF INCONEL X-750

RECOMMENDED VALUES

| $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ | $T(^{\circ}\text{K})$                      | $\rho(\text{g. cm}^{-3})$ |
|-----------------------|---------------------------|--|---------------------------|
| 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 <sup>o</sup> 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. (II)]. The values from (b) seems the more reliable values, but the density is expected to be very dependent on composition.

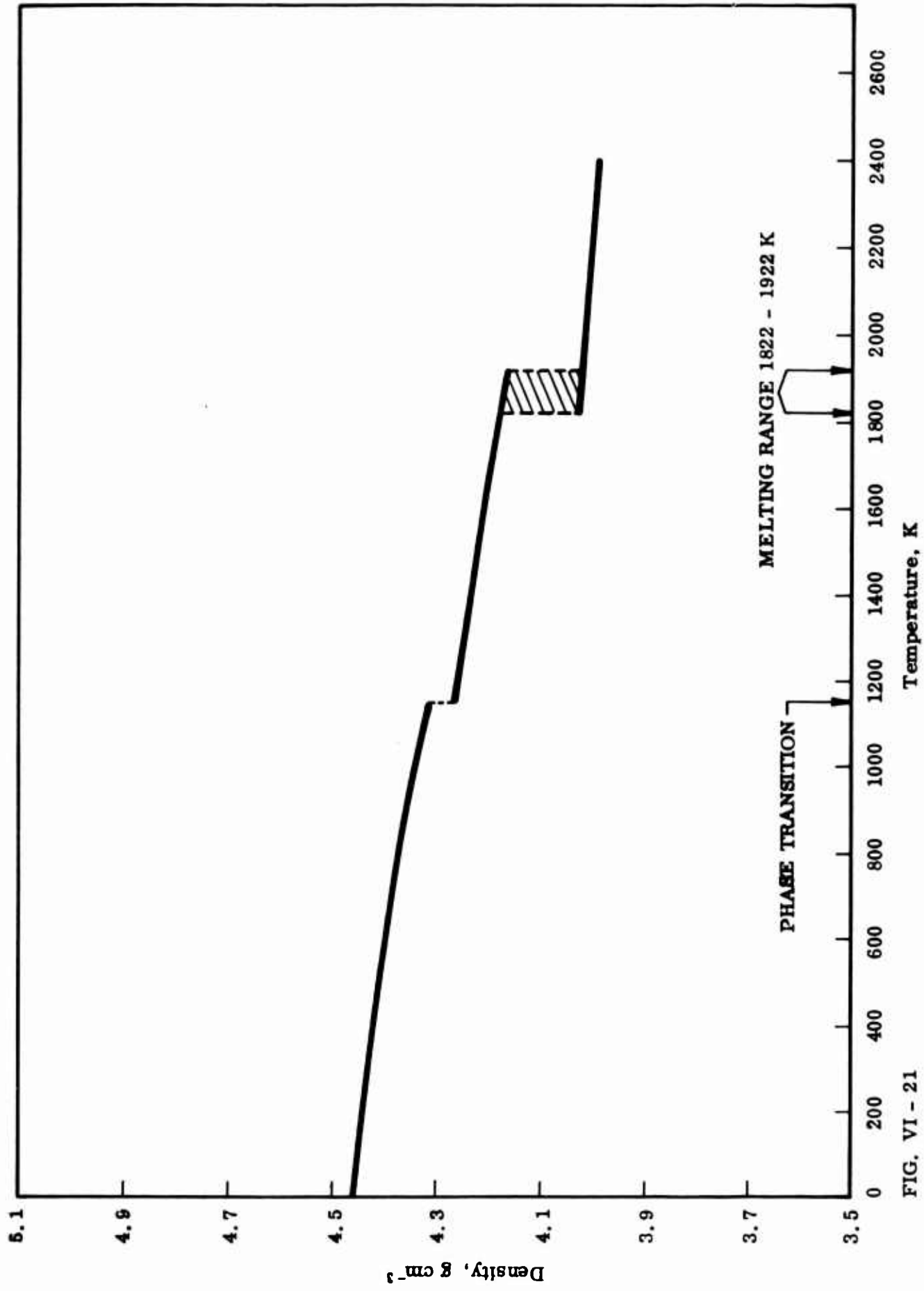


FIG. VI - 21

DENSITY -- TITANIUM ALLOY A-110AT

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

RECOMMENDED VALUES

| T(°K)                         | ρ(g. cm <sup>-3</sup> ) | T(°K)                     | ρ(g. cm <sup>-3</sup> ) |
|-------------------------------|-------------------------|---------------------------|-------------------------|
| 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.

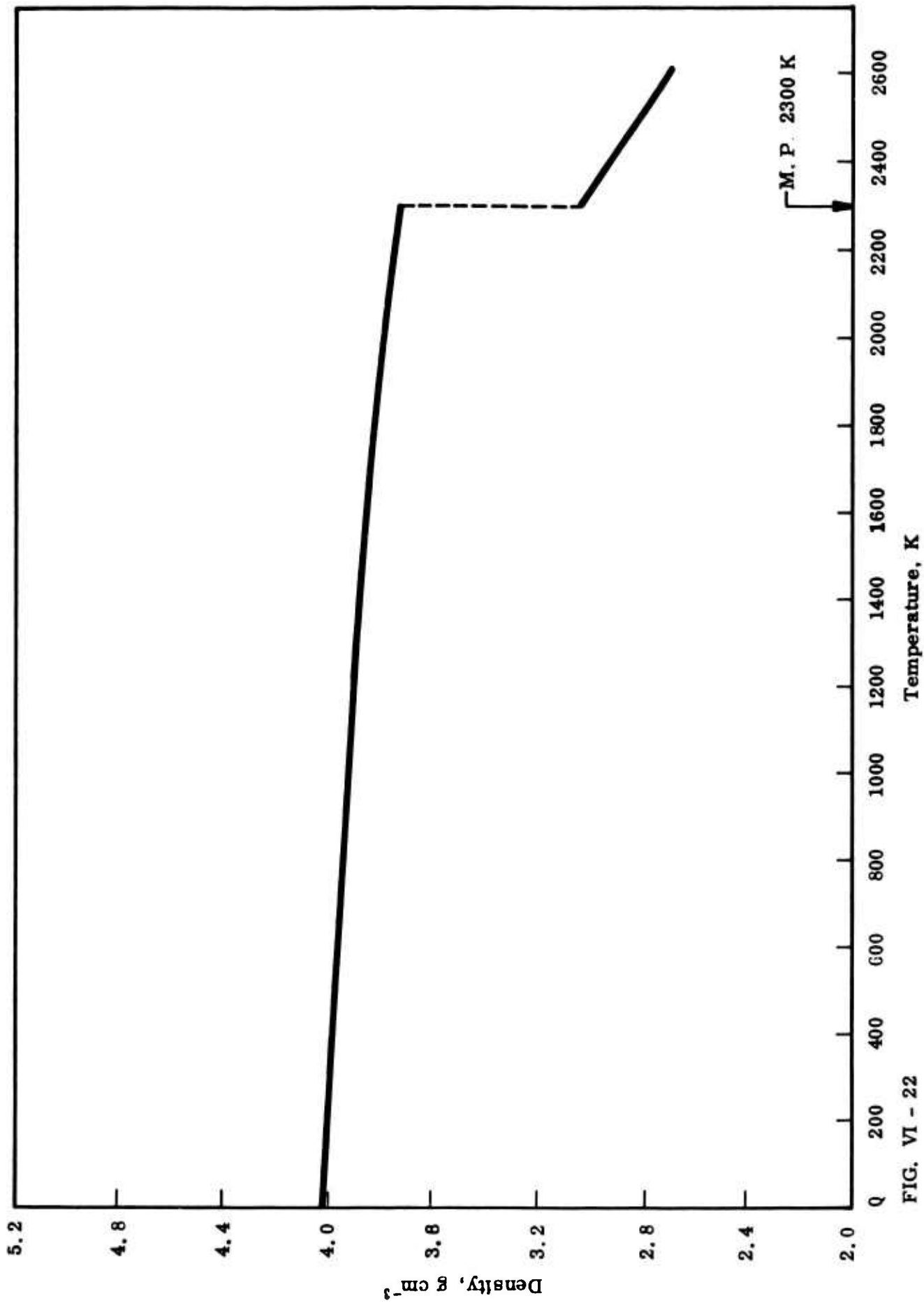


FIG. VI - 22

DENSITY -- ALUMINUM OXIDE,  $Al_2O_3$

**TABLE VI-22. DENSITY OF ALUMINUM OXIDE (Al<sub>2</sub>O<sub>3</sub>)**

**RECOMMENDED VALUES**

| T(°K) | ρ(g. cm <sup>-3</sup> ) | T(°K)                | ρ(g. cm <sup>-3</sup> ) |
|-------|-------------------------|----------------------|-------------------------|
| 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)

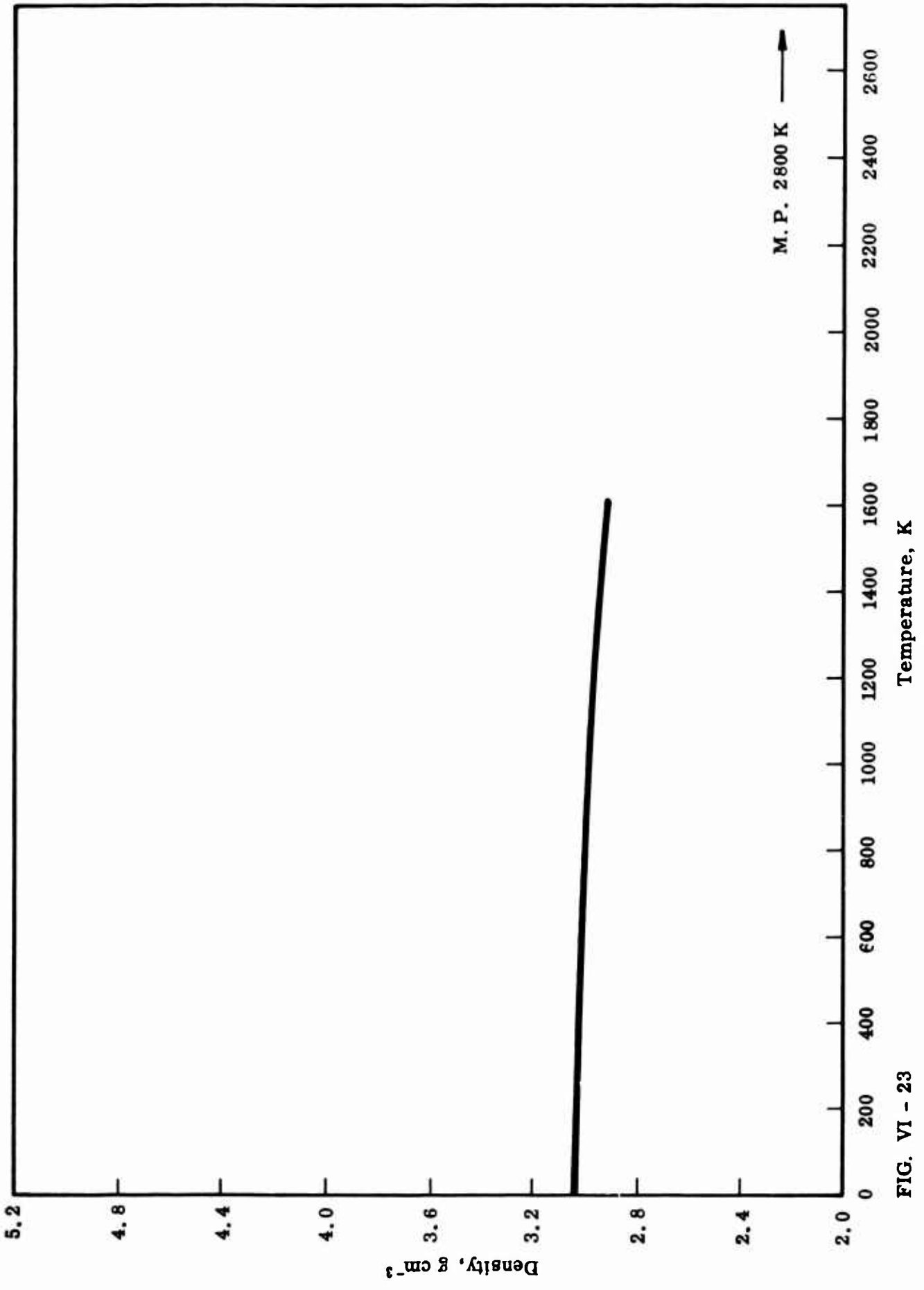


FIG. VI - 23

DENSITY -- BERYLLIUM OXIDE, BeO

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

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)       | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------------|-------------------------------|
| 0     | (s) (3.05)                    | 900         | 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)

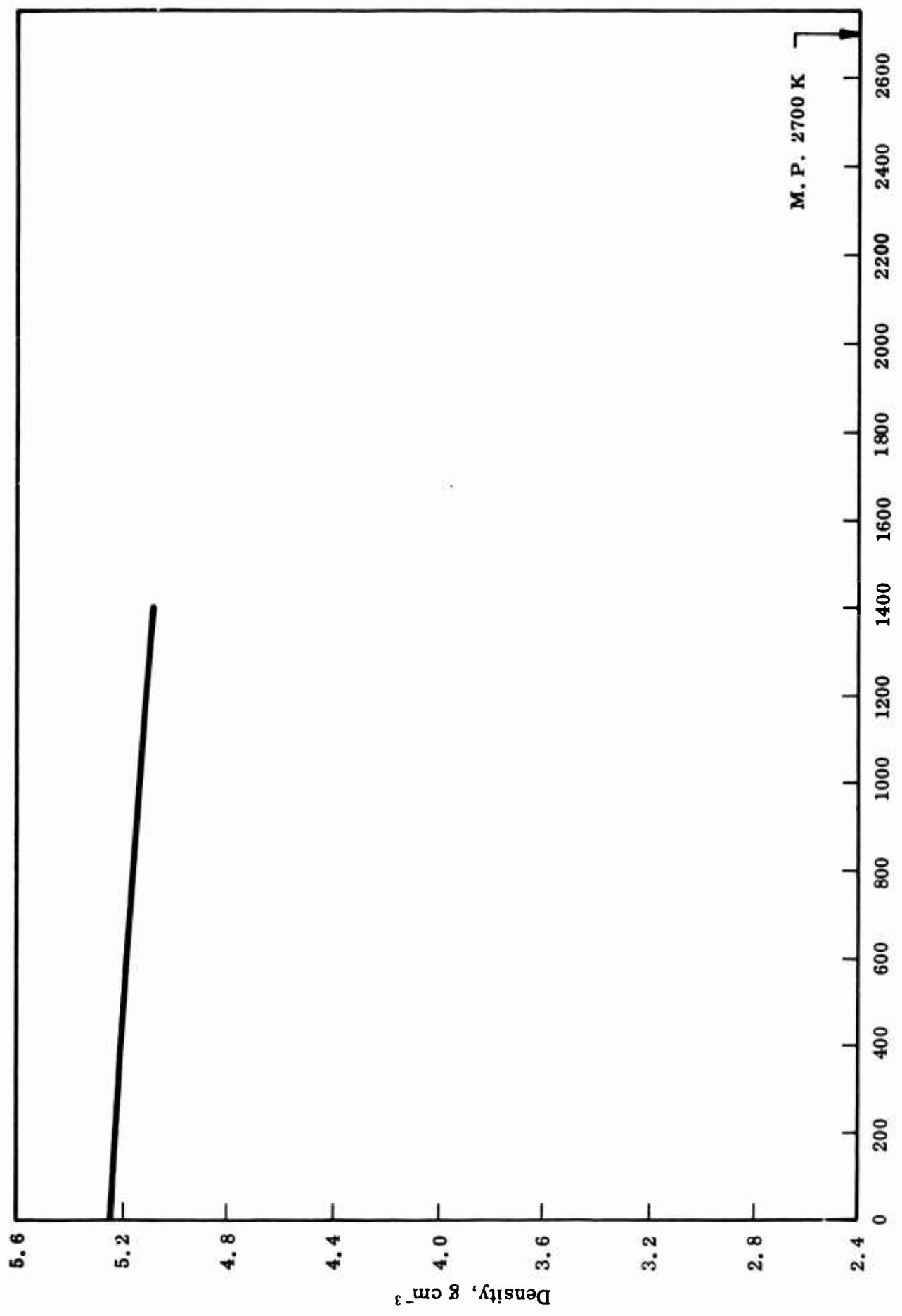


FIG. VI - 24

DENSITY -- CHROMIUM OXIDE, Cr<sub>2</sub>O<sub>3</sub>

TABLE VI-24. DENSITY OF CHROMIUM OXIDE ( $\text{Cr}_2\text{O}_3$ )

RECOMMENDED VALUES

| T( $^{\circ}$ K) | $\rho$ (g. $\text{cm}^{-3}$ ) | T( $^{\circ}$ K) | $\rho$ (g. $\text{cm}^{-3}$ ) |
|------------------|-------------------------------|------------------|-------------------------------|
| 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. (II)



FIG. VI - 25

DENSITY -- IRON OXIDE, FeO

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

**RECOMMENDED VALUES**

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)  | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|--------|-------------------------------|
| 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)

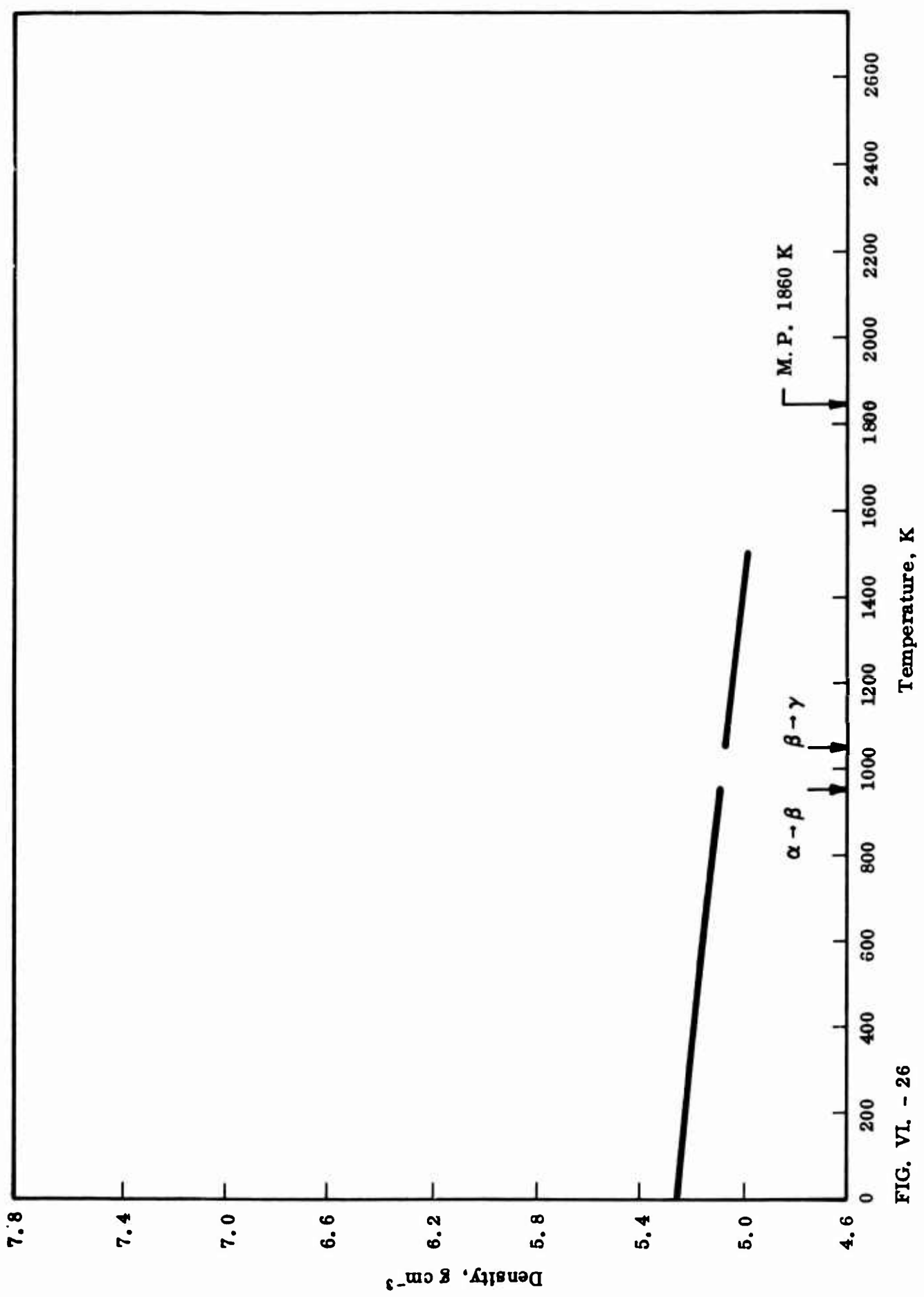


FIG. VI. - 26

DENSITY -- IRON OXIDE, Fe<sub>2</sub>O<sub>3</sub>

**TABLE VI-26. DENSITY OF IRON OXIDE ( $\text{Fe}_2\text{O}_3$ )**

**RECOMMENDED VALUES**

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

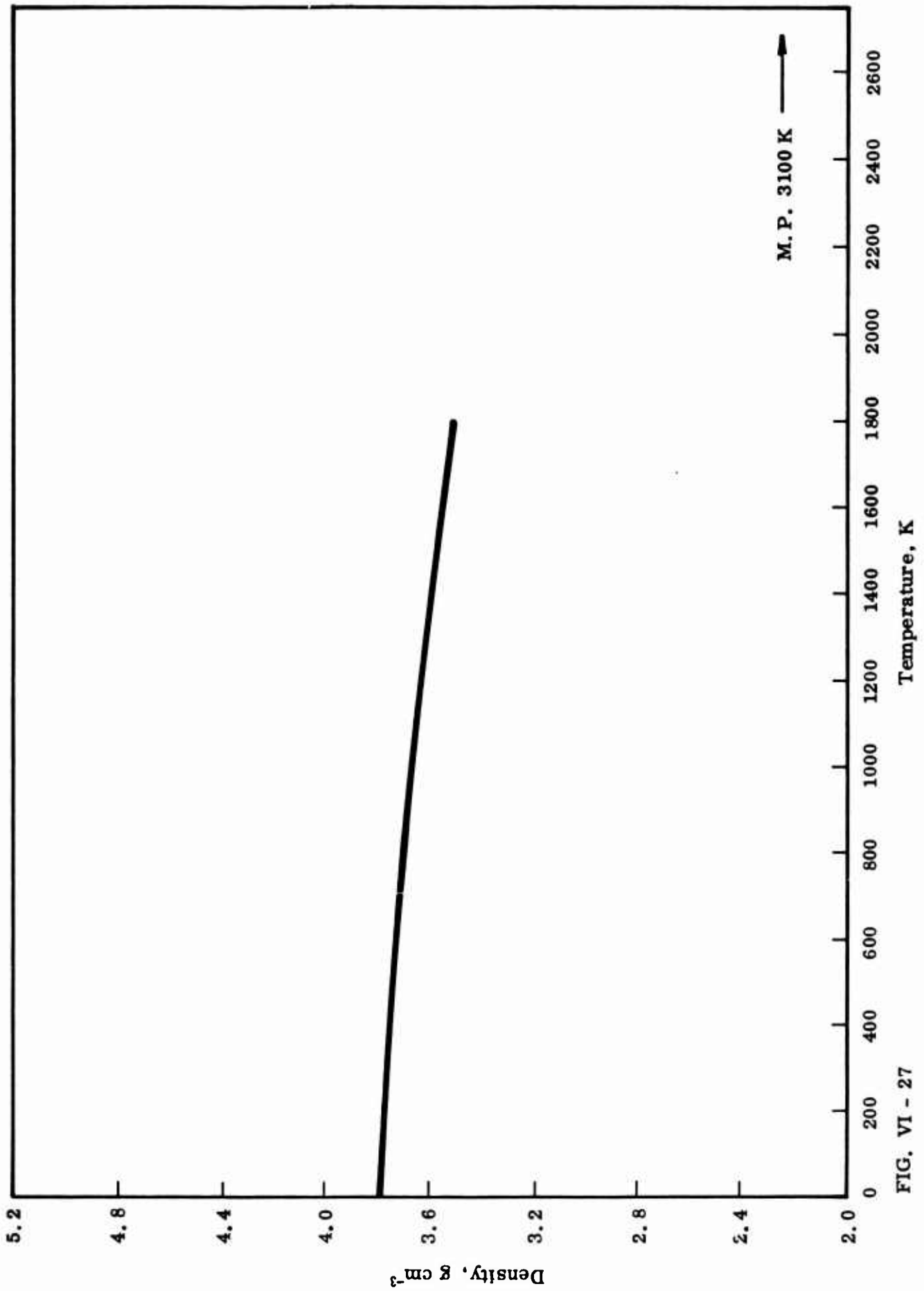


FIG. VI - 27  
DENSITY -- MAGNESIUM OXIDE, MgO

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

**RECOMMENDED VALUES**

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K)      | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|------------|-------------------------------|
| 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)

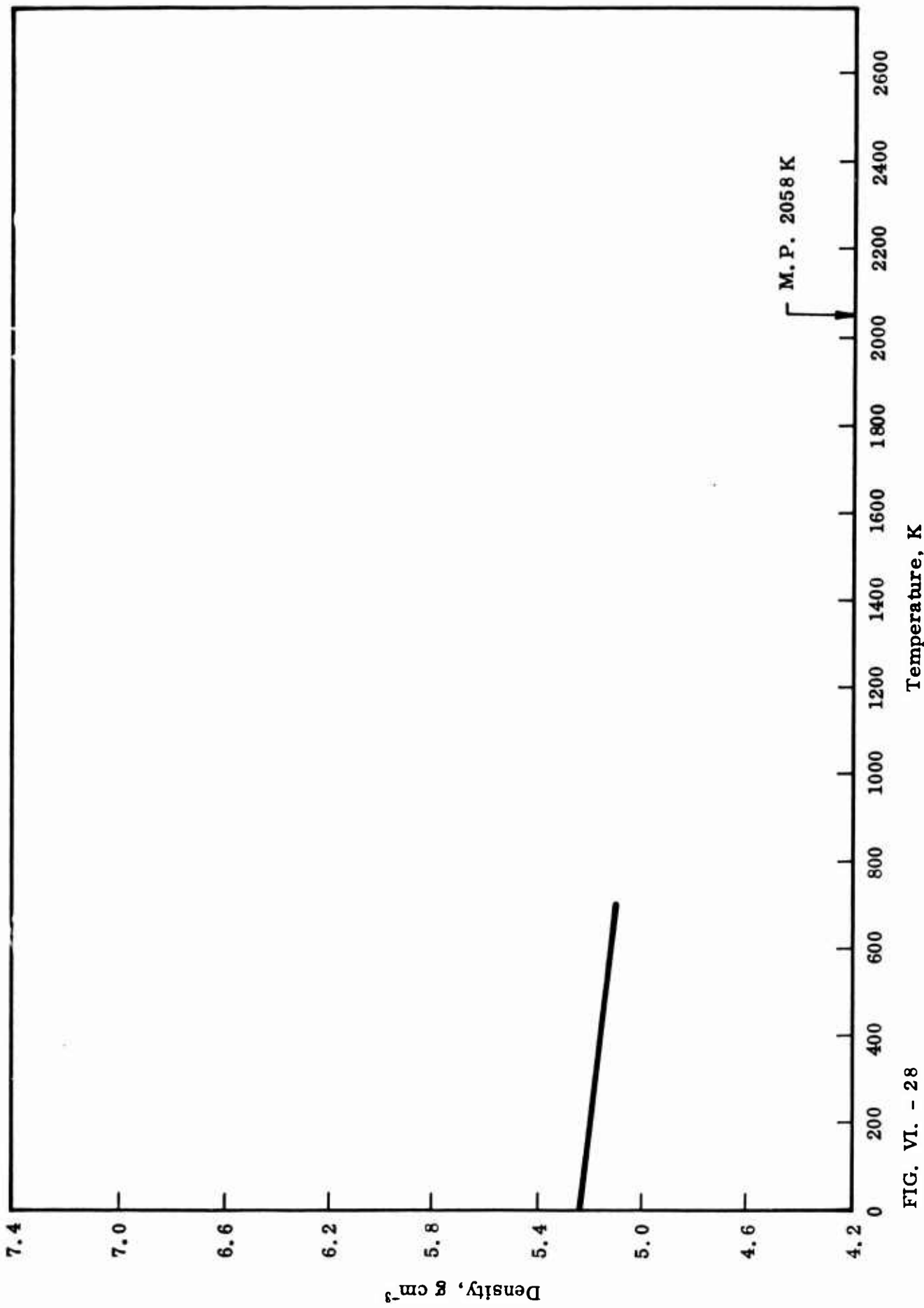


FIG. VI. - 28

DENSITY -- MANGANESE OXIDE, MnO

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

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------|-------------------------------|
| 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)

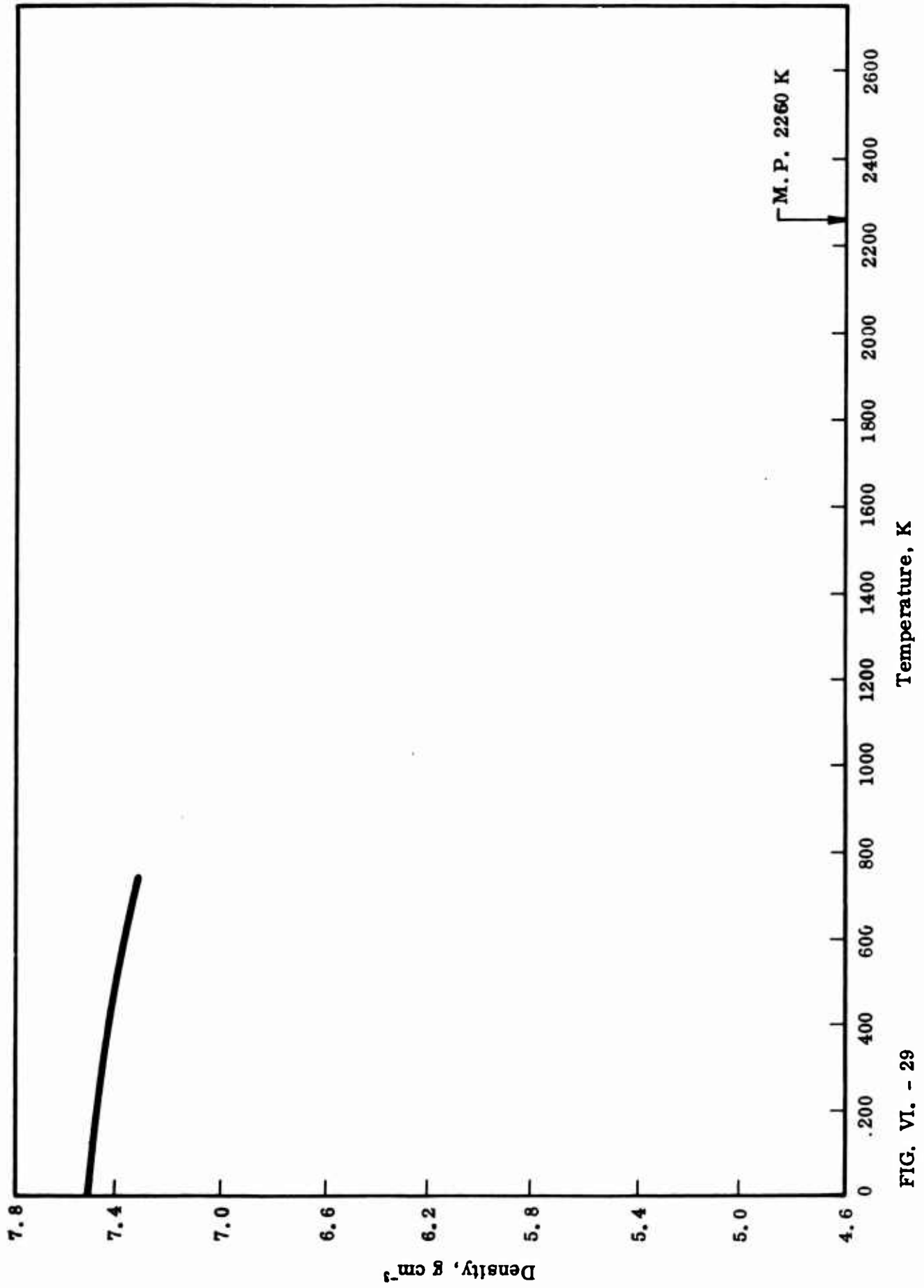


FIG. VI. - 29

DENSITY -- NICKEL OXIDE, NiO

TABLE VI-29. DENSITY OF NICKEL OXIDE (NiO)

RECOMMENDED VALUES

| T(°K) | $\rho$ (g. cm <sup>-3</sup> ) | T(°K) | $\rho$ (g. cm <sup>-3</sup> ) |
|-------|-------------------------------|-------|-------------------------------|
| 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)

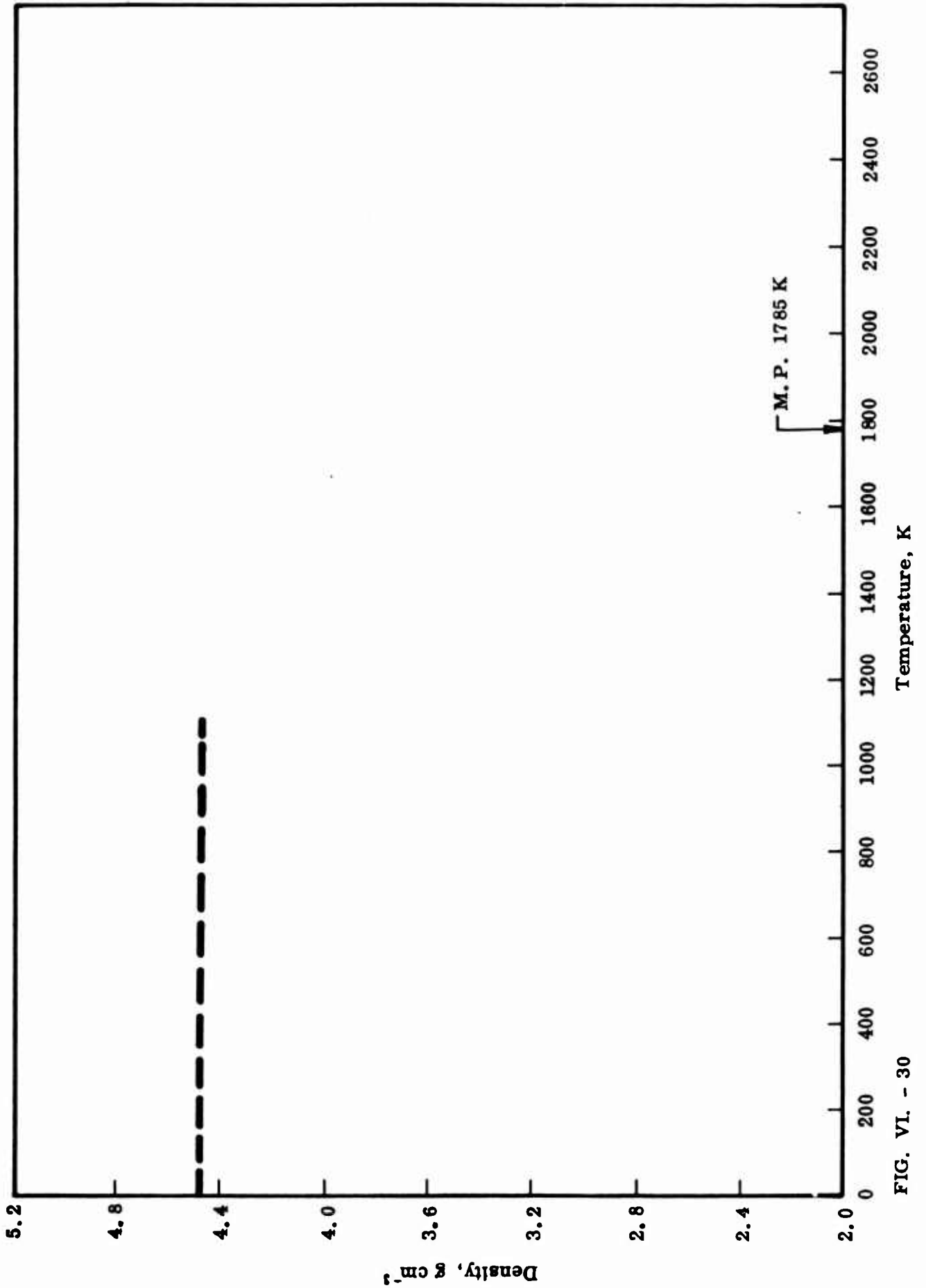


FIG. VI. - 30

DENSITY -- NIOBIUM OXIDE, Nb<sub>2</sub>O<sub>5</sub>

TABLE VI-30. DENSITY OF NIOBIUM OXIDE ( $\text{Nb}_2\text{O}_5$ )

**RECOMMENDED VALUE**

Value at room temperature =  $7.45 \text{ g. cm}^{-3}$  (a)

At other temperature, up to  $1100^\circ\text{K}$  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)

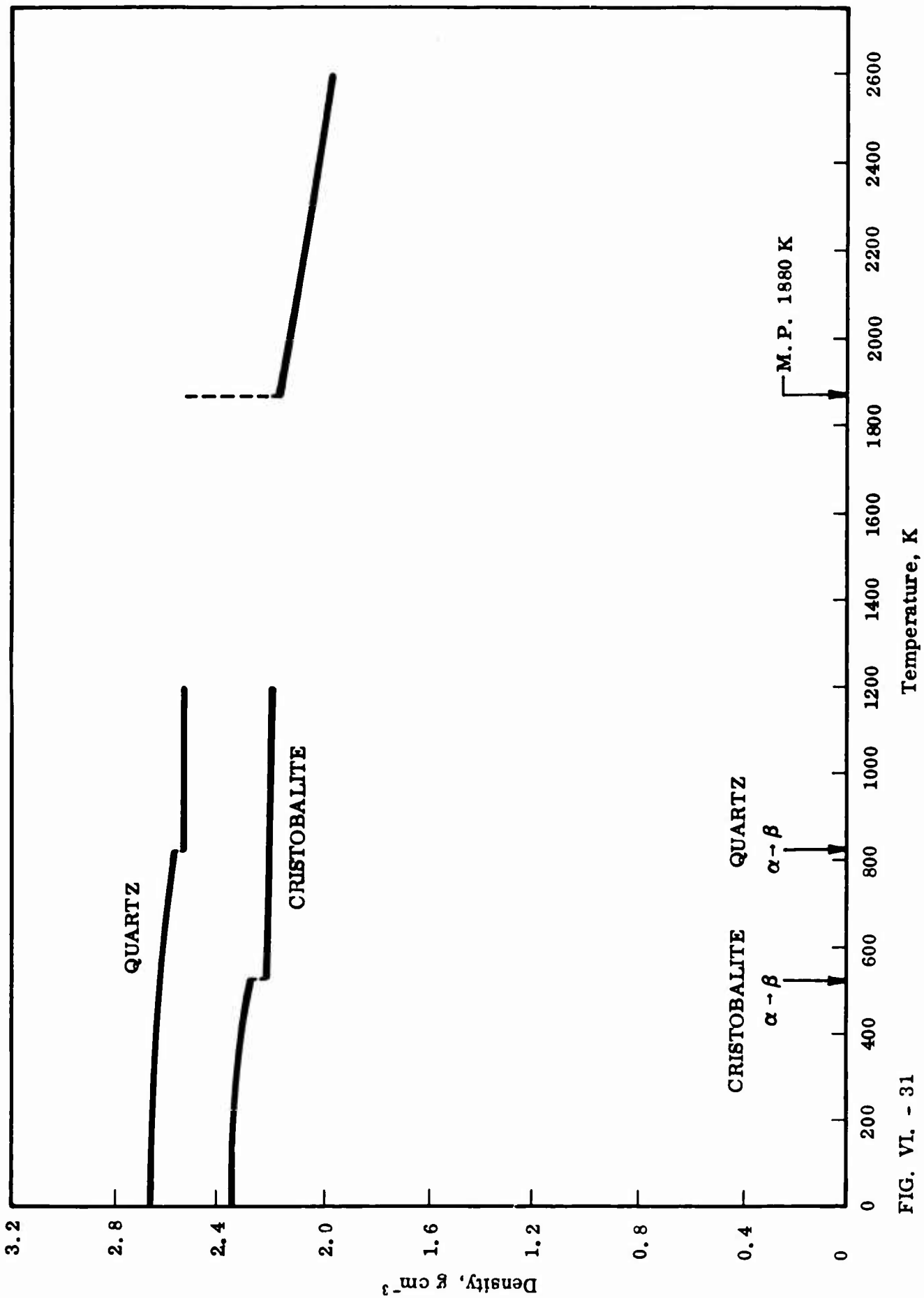


FIG. VI. - 31

DENSITY -- SILICON OXIDE,  $\text{SiO}_2$

TABLE VI-31. DENSITY OF SILICON OXIDE (SiO<sub>2</sub>)

RECOMMENDED VALUES

| T(°K) | ρ(g. cm <sup>-3</sup> ) |                | T(°K)       | ρ(g. cm <sup>-3</sup> ) |
|-------|-------------------------|----------------|-------------|-------------------------|
|       | (Quartz)                | (Cristobalite) |             |                         |
| 0     | (s) 2.668               | (s) 2.34       | 1880(m. p.) | (1) 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. α → β    | 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. α → β    |             |                         |
| 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).

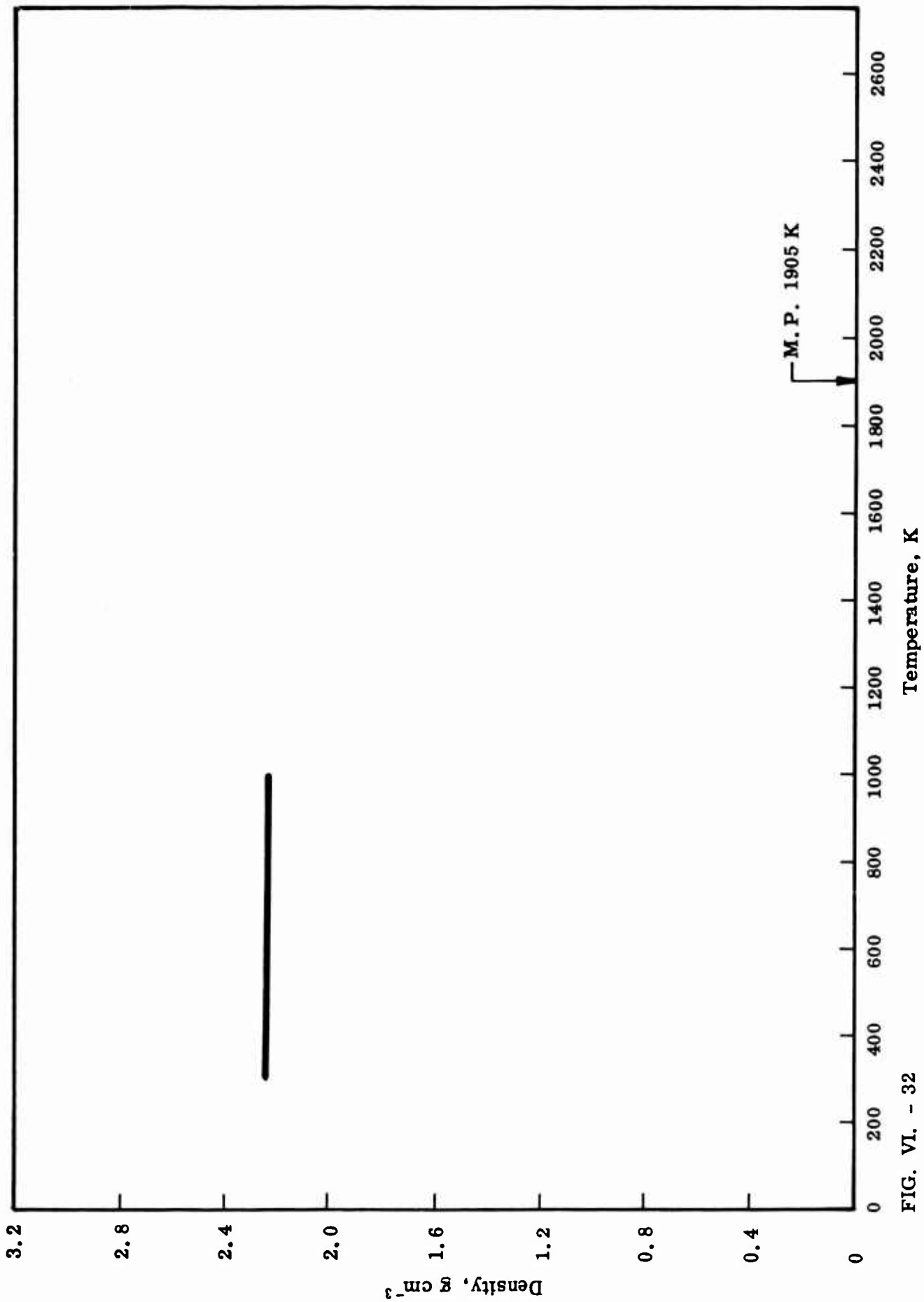


FIG. VI. - 32

DENSITY -- TIN OXIDE, SnO<sub>2</sub>

TABLE VI-32. DENSITY OF TIN OXIDE ( $\text{SnO}_2$ )

RECOMMENDED VALUES

| $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ | $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ |
|-----------------------|---------------------------|-----------------------|---------------------------|
| 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)

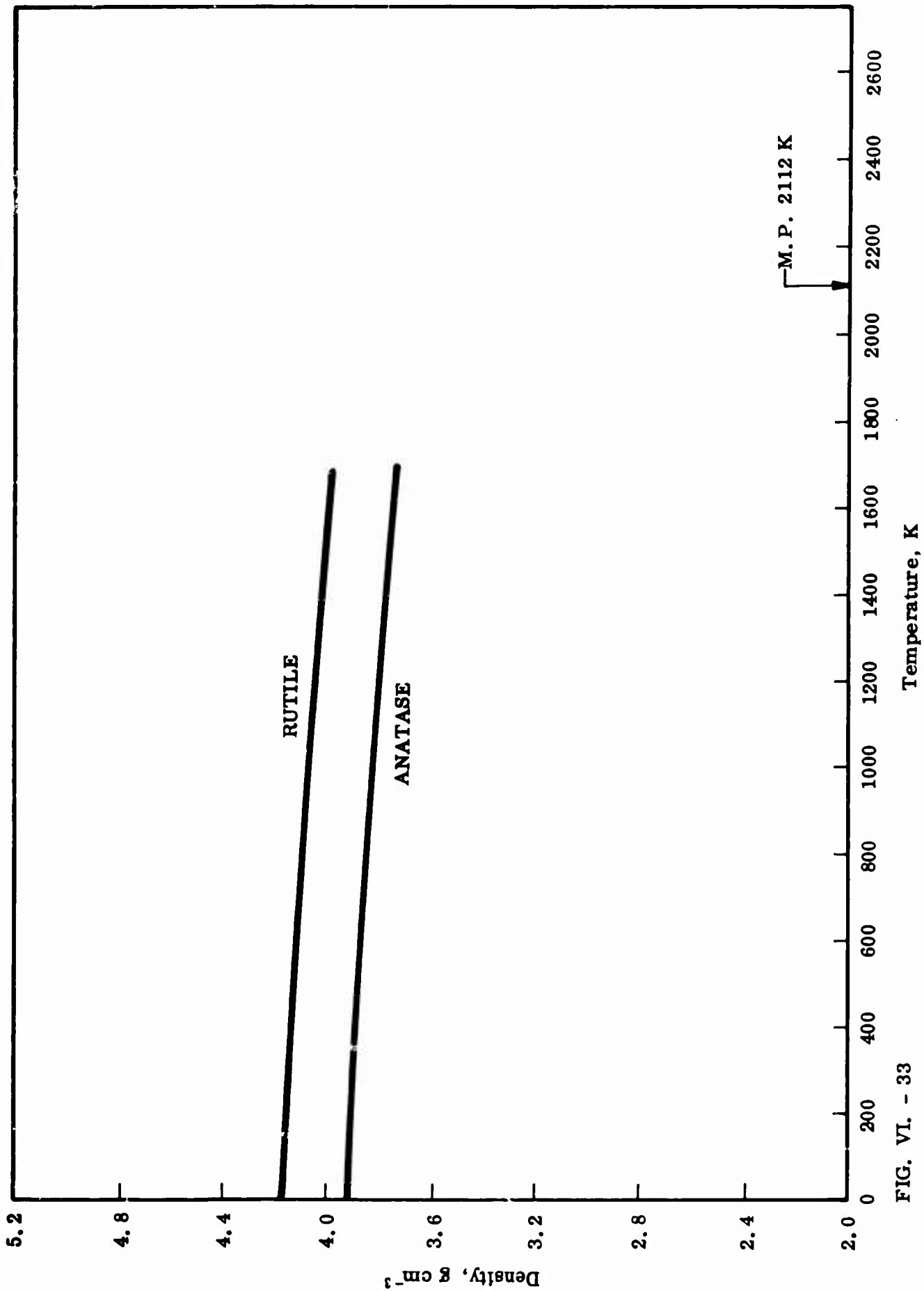


FIG. VI. - 33

DENSITY -- TITANIUM OXIDE, TiO<sub>2</sub>

**TABLE VI-33. DENSITY OF TITANIUM OXIDE (TiO<sub>2</sub>)**

**RECOMMENDED VALUES**

| $-T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ (a) | $\rho(\text{g. cm}^{-3})$ (b) | $T(^{\circ}\text{K})$ | $\rho(\text{g. cm}^{-3})$ (a) | $\rho(\text{g. cm}^{-3})$ (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)

D. BIBLIOGRAPHY

GENERAL

Ref.  
No.

- I. Metals Handbook, ASM, Vol I, 8th Ed. (1961).
- II. Liquid-Metals Handbook, NAVEXOS-P-733, TID 5277,(1955).
- III. Goldsmith, A., Hirschhorn, H.J., and Waterman, G. "Thermophysical properties of materials," WADC Technical Report 58-476.
- IV. Handbook of Chemistry and Physics, 40th Ed., Chemical Rubber Publ. Co., Cleveland (Ohio).
- V. American Institute of Physics Handbook, McGraw-Hill, New York, 1957.

ORIGINAL PAPERS

1. Snoek, J. L., Phil. Mag. 41, 1188, (1950).
2. Smakula, A., and Sils, V., Phys. Rev. 99, 1744, (1955).
3. Miller, P.N., and Dumond, J.N.M., Phys. Rev. 57, 198, (1940).
4. Foote, F., and Jette, E.F., Phys. Rev. 58, 81, (1940).
5. Edwards, J.D., and Moorman, J.A., Chem. Met. Engg. 24, 61, (1921).
6. Kanda, K.A., and Keller, D.V., U.S. At. Energy Comm. Rep. TID - 15836, (1961).
7. Gebhardt, E., Becker, M., and Dorner, S., Aluminium 31, 315, (1955).
8. Solet, I.S., and St Clair, H.W., U.S. Bur. Mines, Rep. Invest. 4553, (1949).
9. Naidich, Yu V., and Eremenko, V.N., Fiz. Metal i Metalloved. 11, 62, (1961).
10. Bornemann, K., and Sauerwald, F., Z. Metallk. 14, 145, (1922).
11. Martin, A.J., and Moore, A., J. Less-Common Metals, 1, 85, (1959).
12. Grosse, A.V., and Cahill, J.A., Am. Soc. Metals, Trans. Quart. 57, 739, (1964).
13. Smart, J.S., Smith, A.A., and Phillips, A.J., Am. Inst. Mining Met. Engrs. 143, 272, (1941).
14. Lucas, L.D., Compt. Rend. 253, 2526, (1961).
15. Gebhardt, E., Becker, M., and Schafer, S., Z. Metallk. 43, 292, (1952).
16. Cahill, J.A., and Kirshenbaum, A.D., J. Phys. Chem. 66, 1080, (1963).
17. Allen, B.C., and Kingery, W.D., Trans. AIME 215, 30, (1959).

ORIGINAL PAPERS (continued)

18. Keeler, J.H., and Davis, A.M., J. Metals, Trans. 5, 44,(1958).
19. Kirshenbaum, A.D., and Cahill, J.A., Trans. AIME 224, 816,(1962).
20. Stott, V.H., and Rendall, J. H., J. Iron Steel Inst. (London) 175, 374,(1953).
21. Kozakevitch, P., and Urbain, G., Compt. Rend. 244, 335,(1957).
22. Lucas, L.D., Compt. Rend. 250, 1850,(1960).
23. Benedicks, C., Berlin, D.W., Phragmen, G., Carnegie Schol. Mem. Iron Steel Inst. (London) 13, 129,(1924).
24. Desch, C.H., and Smith, B.S., J. Iron Steel Inst. (London) 119, 358,(1929).
25. Seddon, B.J., and Francis, E.L., U.K. At. Energy Authority Develop. Eng. Group, DEG. Rep. 90(R), (1960).
26. Pelzel, E., and Sauerwald, F., Z. Metallk. 33,229,(1941).
27. Edwards, J.D., and Taylor, C.S., Trans. Am. Inst. Mining Met. Engrs 69, 1070,(1923).
28. Batuecas, T., and Casado, J.L., ZPhysik. Chem. 181A, 197,(1937).
29. McGonigal, P.J., Kirshenbaum, A.D., and Grosse, A.V., J. Phys. Chem. 66, 737,(1962).
30. Arndt, K., and Ploetz, G., Z. Physik. Chem. 130, 184,(1927).
31. Gebhardt, E., Becker, M., and Tragner, E., Z. Metallk. 46, 90,(1955).
32. Grothe, H., and Mangelsdorf, C., Z. Metallk. 29, 352,(1937).
33. Papel, S. I., Tsarevskiy, B.V., and Dzhenilev, N.K. Phys. Metals Metallog. (U.S.S.R.) 18, (3), 158,(1964).
34. Jordan, L., and Swanger, W.H., J. Res. Nat. Bur. Std. 5, 1291,(1930).
35. Grosse, A.V., and Kirshenbaum, A.D., J. Inorg. Nucl. Chem. 25, 331,(1963).
36. Eremenko, V.N., and Nizhenko, V.I., Ukr. Khim. Zh. 30, 125,(1964).
37. Schijner, A.J., and Middelhoek, A., J. Electrochem. Soc. 111, 1167,(1964).
38. Tietz, J.E., and Wilson, J.W., AD 266824,(1961).
39. Prener, J.S., and Williams, F.E., J. Chem. Phys. 35, 1803,(1961).
40. Horn, F.H., Phys. Rev. 97, 1521,(1955).

ORIGINAL PAPERS (continued)

41. Smakula, A., Kalnass, J., and Sils, V., Phys. Rev. 99, 1747,(1955).
42. Logan, R.A., and Bond, W.L., J. Appl. Phys. 30, 322,(1959).
43. Hedges, E.S., and Homer, C.E., Techn. Publ. Internatl. Tin Res. Develop. Council, Series B(1) (1937).
44. Kirshenbaum, A.D., and Cahill, J.A., Am. Soc. Metals Trans. Quart. 55, 844,(1963).
45. Matuyama, Y., Sci. Rep. Tokohu Univ. First Ser. 18, 19,(1929).
46. Bornemann, K., and Siebe, P., Z. Metallk. 14, 339,(1922).
47. Hogness, T.R., J. Am. Chem. Soc. 43, 1621,(1921).
48. Eremenko, V.N., and Naidich, Yu. V., Izv. Akad. Nauk S.S.S.R. Otd. Tekhn. Nauk, Met i Toplivo 2, 111,(1959).
49. Ubelacker, E., and Lucas, L.D., Compt. Rend. 254, 1622,(1962).
50. Kutateladze, S.S., Borishanskii, V.M., Novikov, I.I., and Fedinskii, O.S., Basic properties of liquid metals, Engl. Transl. of Suppl. n 2 to Atomnaya Energiia (1958). (Consultants Bureau Inc., New York).
51. Atterton, D.V., and Hoar, T.P., J. Inst. Metals 81, 541,(1952-3).
52. Pascal, P., and Jouniaux, A., Compt. Rend. 158, 414,(1914).
53. Herezynska, E., Naturwiss, 47, 200,(1960).
54. Gamertsfelder, C., J. Chem. Phys. 9, 450,(1941).
55. Majima, M., Bull. Inst. Phys. Chem. Res., (Tokyo) 3, 51,(1924).
56. Pluss, M., J. Inorg. Chem. 93, 1,(1915).
57. Sosman, R.B., Day, A.J., and Hostetter, J.C., Am. J. Sci. 37, 1,(1914).
58. Yelyutin, V.P., and Maurakh, M.A., Izv. Akad. Nauk S.S.S.R., Otd. Tekhn. Nauk. Met. i Toplivo, 4,139,(1956).
59. Maurakh, M.A., Trans. Indian Inst. Metals 14, 209,(1961).
60. Mound laboratory, Miamisburg, (Ohio) MLM-1108,(1961).
61. Levy, A.V., NP-9028 MP595,(1952).
62. Material Properties Handbook, Vol. I Aluminum Alloys, NATO, N68112.(1958).
63. Stein, D.B., NAA-SR-Memo-8499,(1963).
64. Lucks, C.F., Thompson, H.B., Smith, A.R., Curry, F.P., Deem, H.W., and Bing, G.F., AF-TR-6145. (ATI 117715)(1951).

ORIGINAL PAPERS (continued)

65. Thornburg, D. L., Thall, E.S., Brous, J., WADD TR 60-325 (AD 267327), (1961).
66. Kirshenbaum, A.D., and Cahill, J.A., J. Inorg. Nucl. Chem. 14, 283,(1960).
67. Kingery, W.D., J. Am. Ceram. Soc. 42, 6,(1959).
68. Rigby, G.R., Lovell, G.H.B., and Green, A.T., Brit. Ceram. Soc. 45, 137,(1946).
69. Johnson, P.D., J. Am. Ceram. Soc. 33, 168,(1950).
70. Batuecas, T., and Gutierrez, L., Anales Real Soc. Espan. Fiz. Quim. 47B, 5,(1951).
71. Rosenholtz, J.L., and Smith, D.T., Am. Mineralogist 26, 103,(1941).
72. Hummel, F.A., J. Am. Ceram. Soc. 32 320,(1949).
73. Bacon, J.F., Hasapis, A.A., and Wholley, J.W., Jr., Phys. Chem. Glasses 1, 30, (1960).
74. Lietz, J., Hamburger Beitr. Angew. Mineral-und Kristallphys. 1, 229, (1956).

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

CHAPTER VII  
SURFACE TENSION

BY

P. HESTERMANS  
T. D. STORM

## 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 ambient 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 <sup>the</sup>hydrogen <sup>of hydrogen</sup>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.

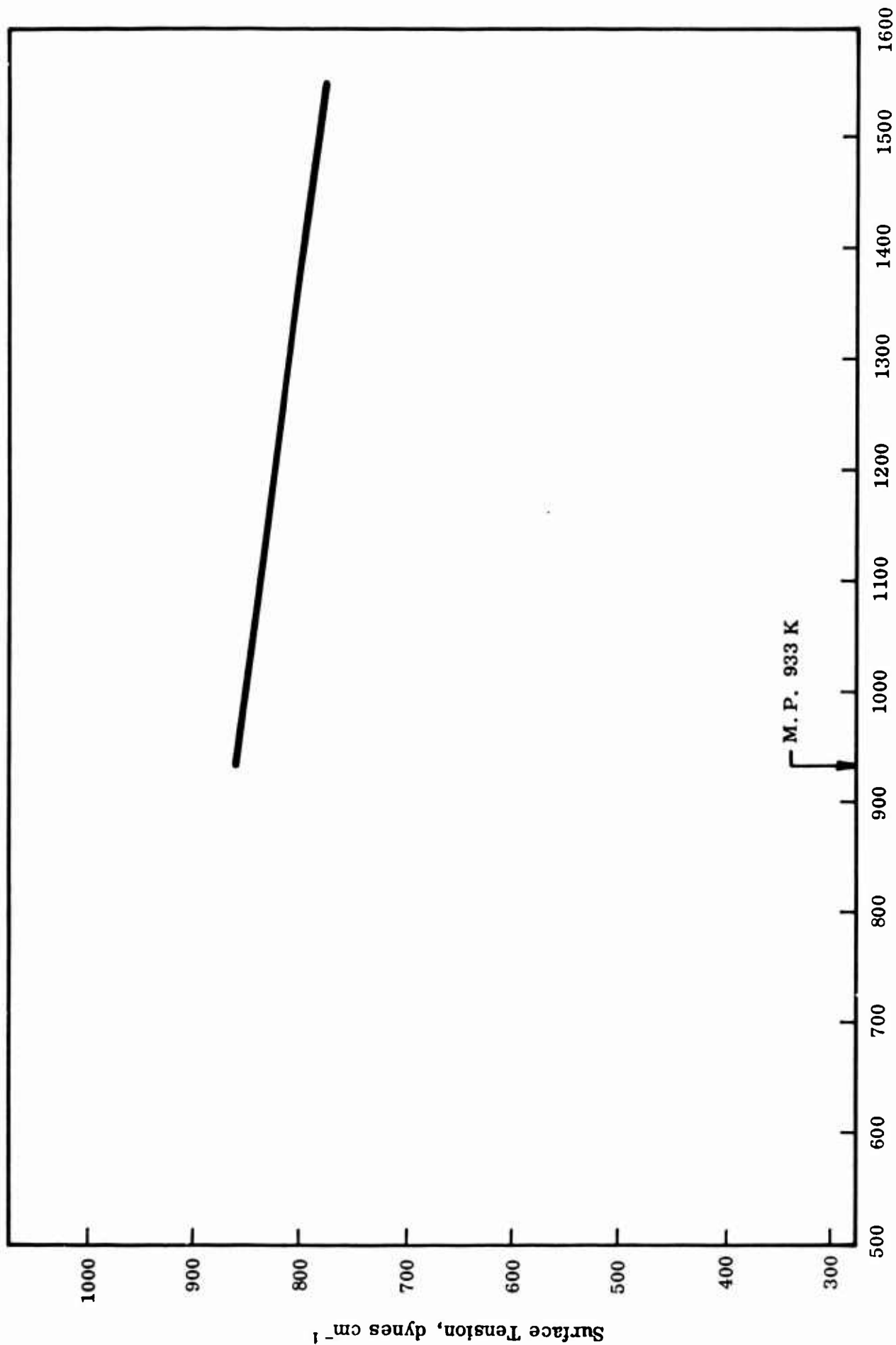


FIG. VII - 1

SURFACE TENSION -- ALUMINUM

TABLE VII-1. SURFACE TENSION OF ALUMINUM

RECOMMENDED VALUES

From equation:  $\sigma = 860 - 0.134 (T - 933)$

| T(°K)      | $\sigma$ (dynes cm <sup>-1</sup> ) | T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|------------|------------------------------------|-------|------------------------------------|
| 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%.

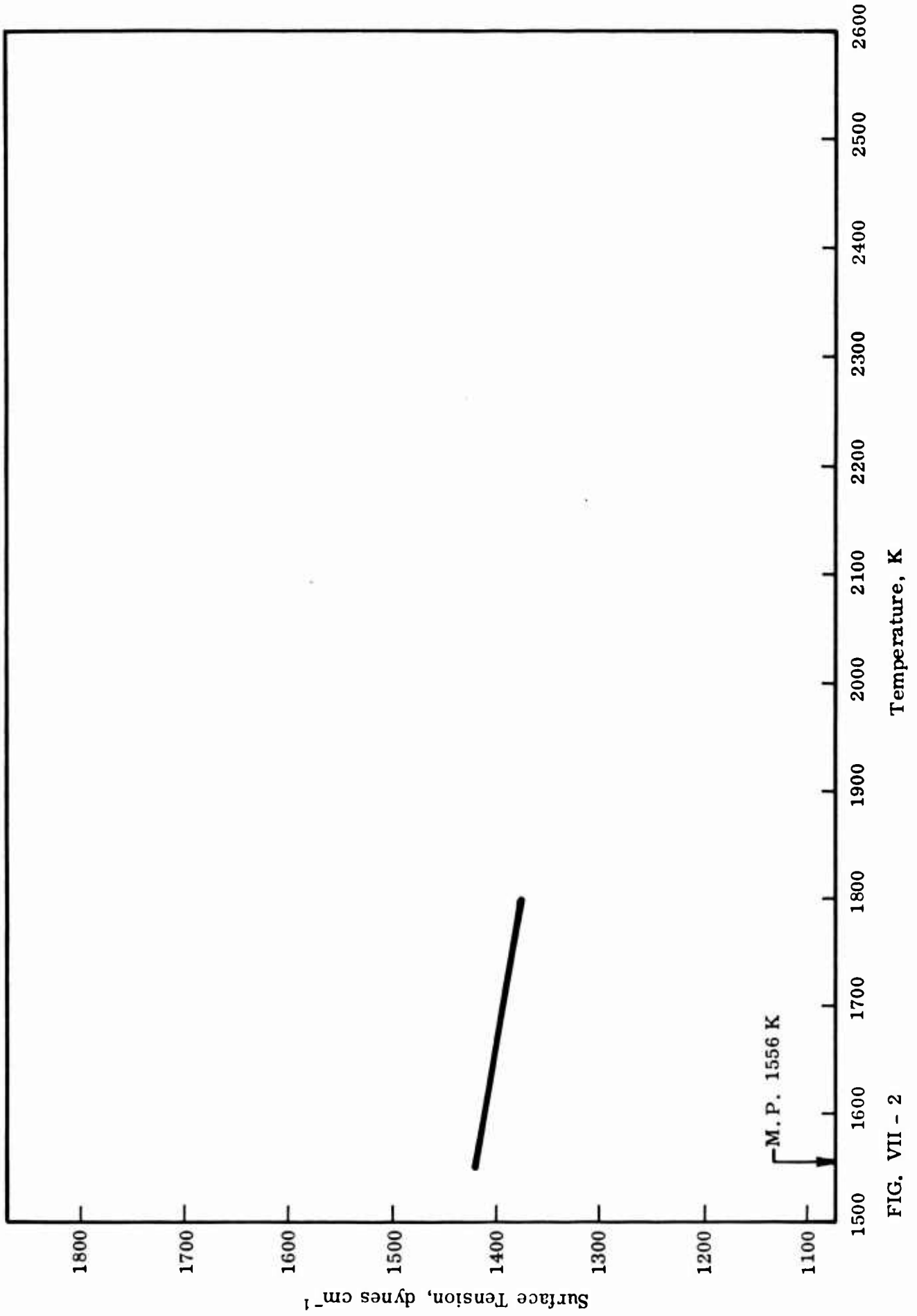


FIG. VII - 2

SURFACE TENSION --- BERYLLIUM

TABLE VII-2. SURFACE TENSION OF BERYLLIUM

RECOMMENDED VALUES

From equation:  $\sigma = 1420 - 0.184 (T - 1556)$

| T (°K)      | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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)

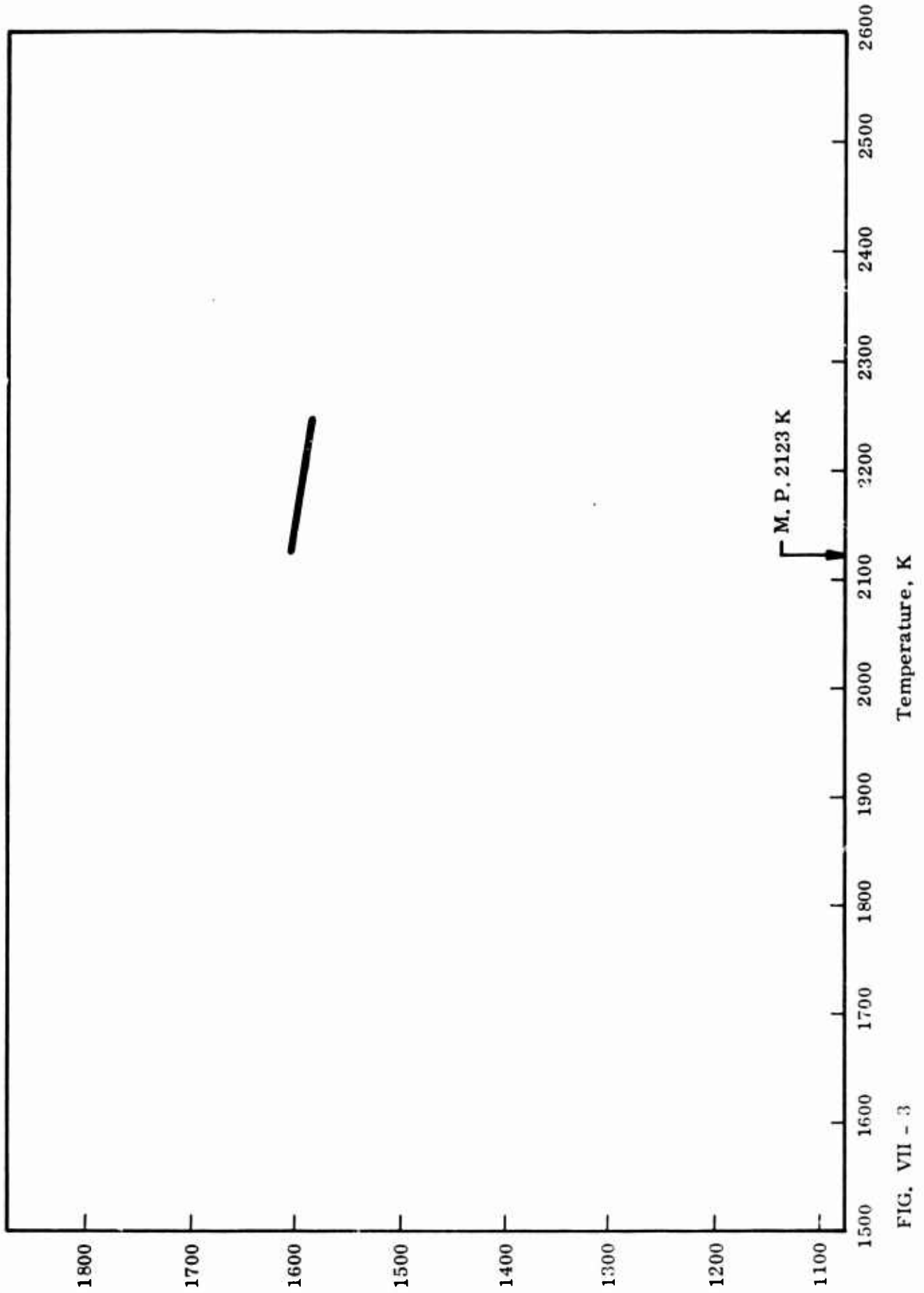


FIG. VII - 3

SURFACE TENSION -- CHROMIUM

TABLE VII-3. SURFACE TENSION OF CHROMIUM

RECOMMENDED VALUES

From equation:  $\sigma = 1604 - 0.166 (T - 2123)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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%

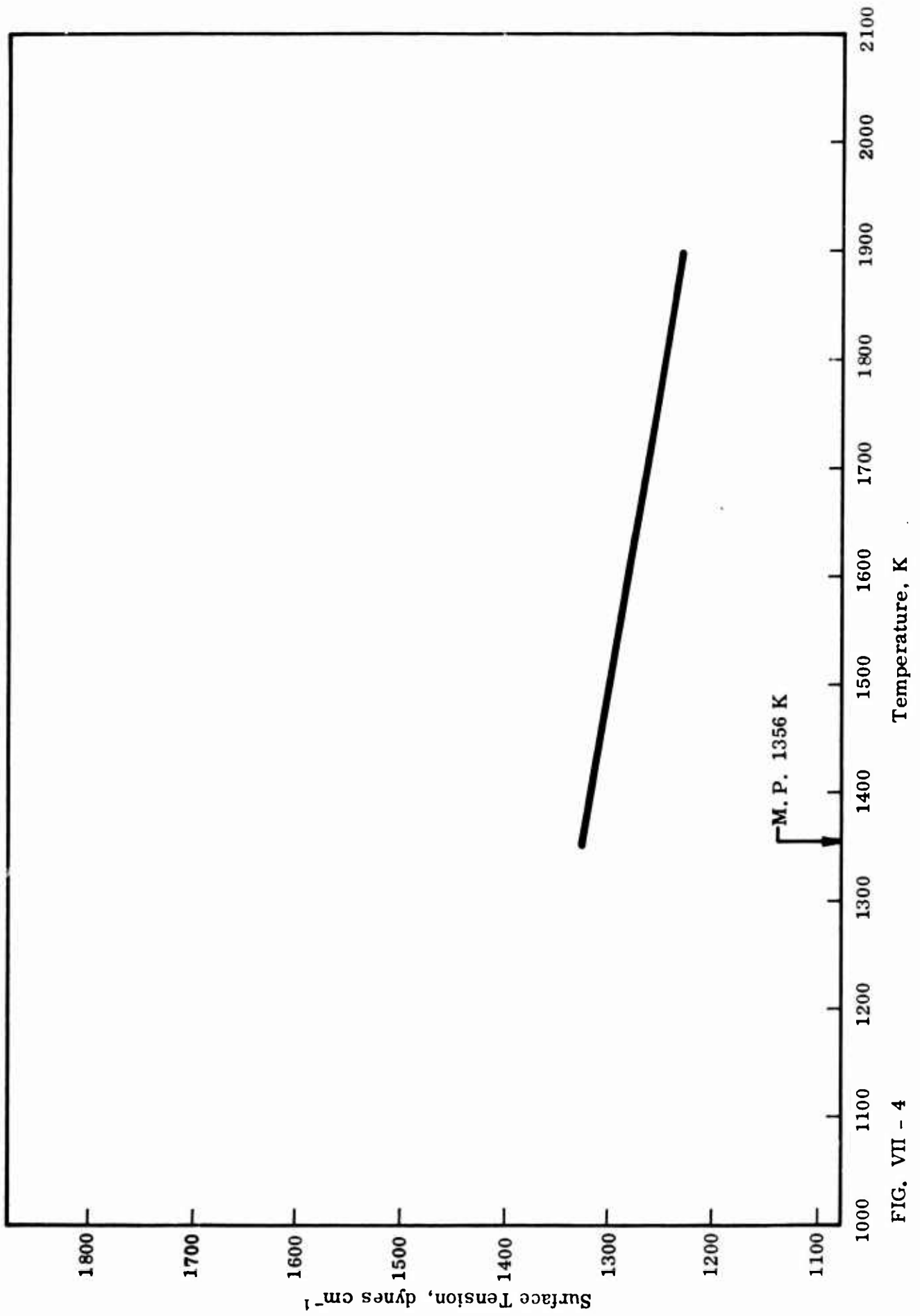


FIG. VII - 4

SURFACE TENSION -- COPPER

TABLE VII-4. SURFACE TENSION OF COPPER

RECOMMENDED VALUES

From equation:  $\sigma = 1325 - 0.180 (T - 1356)$

| $\bar{T} (^{\circ}\text{K})$ | $\sigma (\text{dynes cm}^{-1})$ | $T (^{\circ}\text{K})$ | $\sigma (\text{dynes cm}^{-1})$ |
|------------------------------|---------------------------------|------------------------|---------------------------------|
| 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) Lauer mann, 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): (1) 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:  $\pm 10\%$

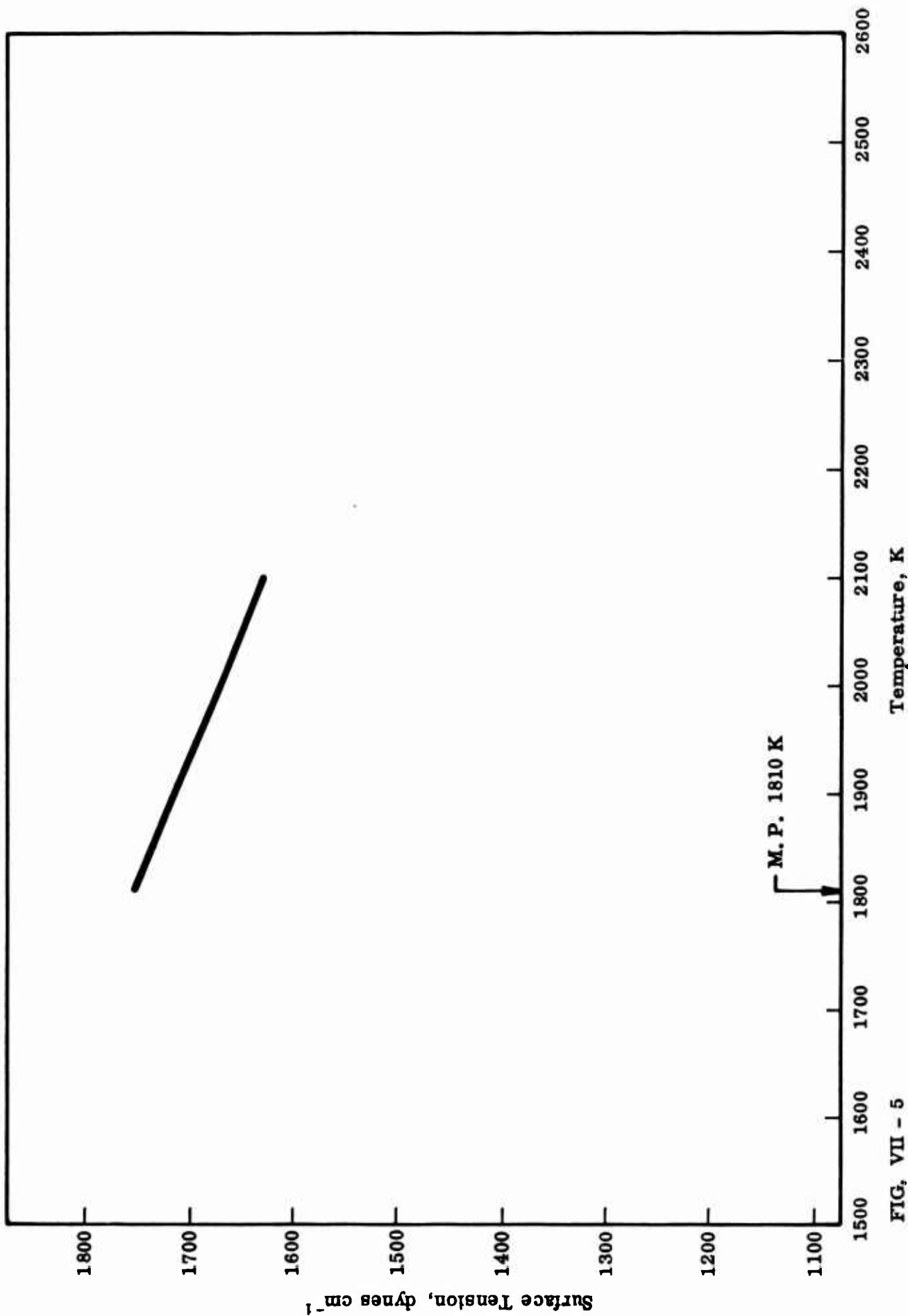


FIG. VII - 5

SURFACE TENSION -- IRON

TABLE VII-5. SURFACE TENSION OF IRON

RECOMMENDED VALUES

From equation:  $\sigma = 1754 - 0.430 (T - 1810)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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  $\pm 6\%$  of the recommended curve.

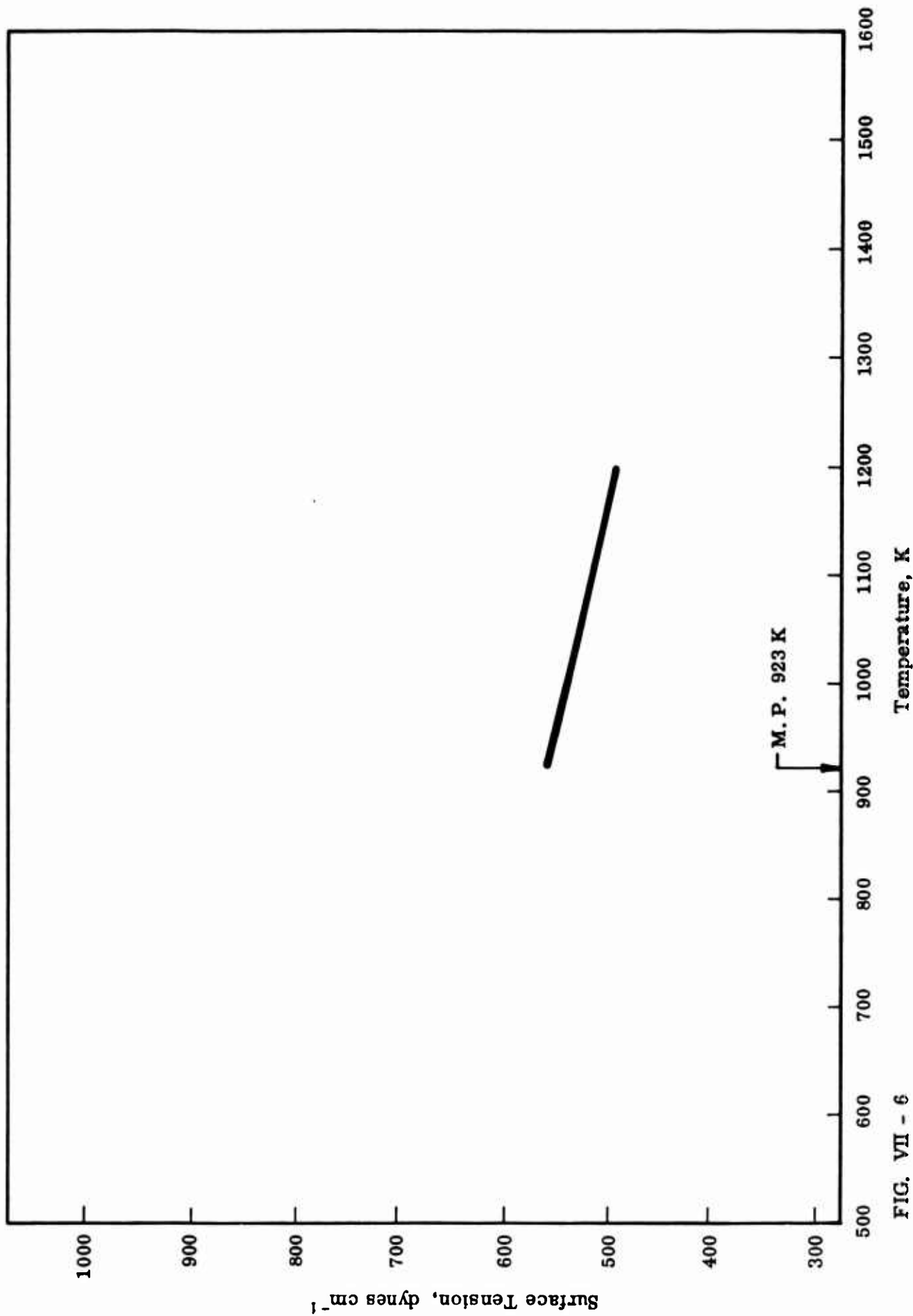


FIG. VII - 6

SURFACE TENSION -- MAGNESIUM

TABLE VII-6. SURFACE TENSION OF MAGNESIUM

RECOMMENDED VALUES

From equation:  $\sigma = 560 - 0.240 (T - 923)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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:  $\pm 6\%$ .

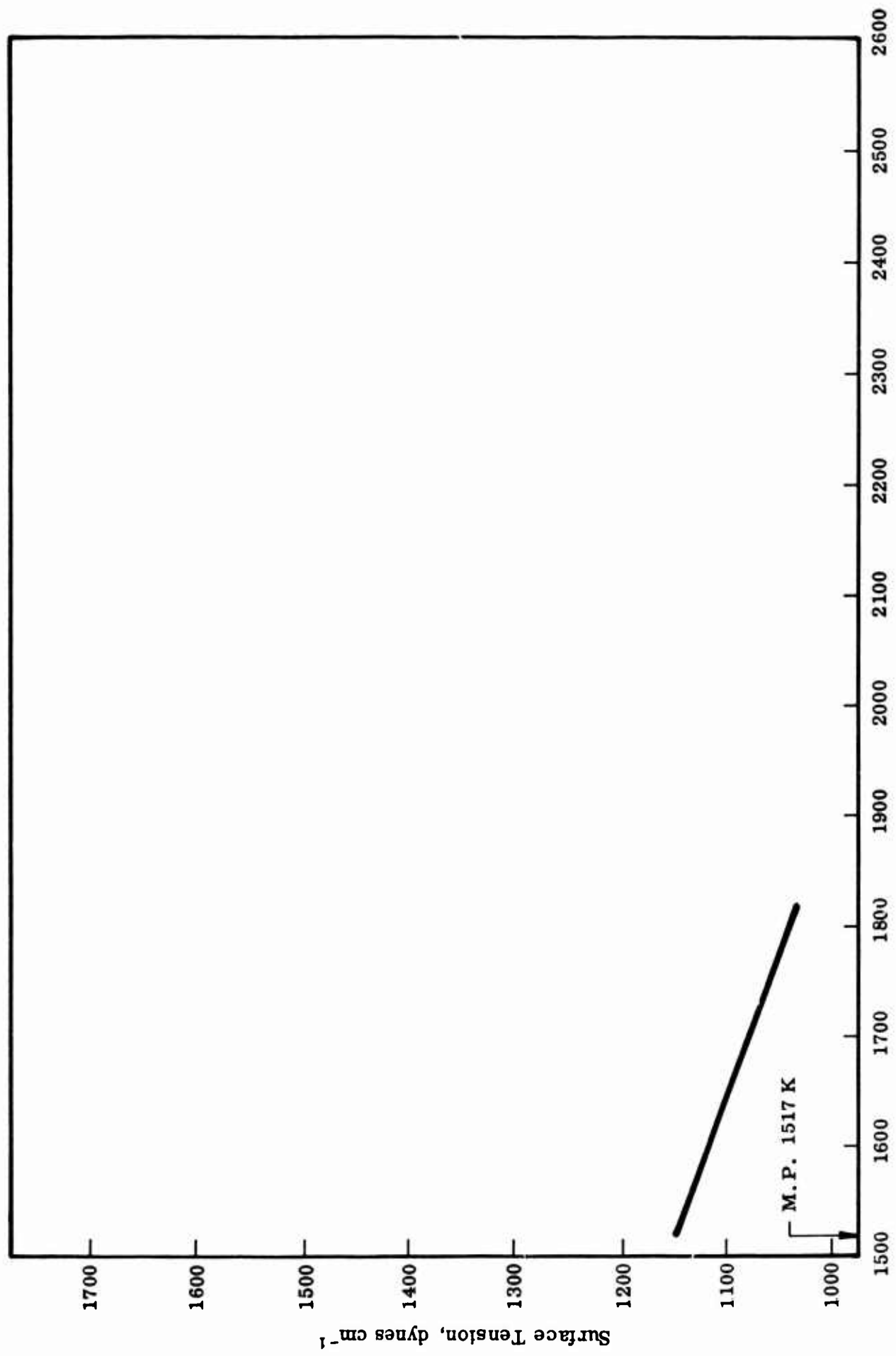


FIG. VII - 7

SURFACE TENSION -- MANGANESE

TABLE VII-7. SURFACE TENSION OF MANGANESE

RECOMMENDED VALUES

From equation:  $\sigma = 1150 - 0.39 (T - 1517)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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:  $\pm 5\%$ .

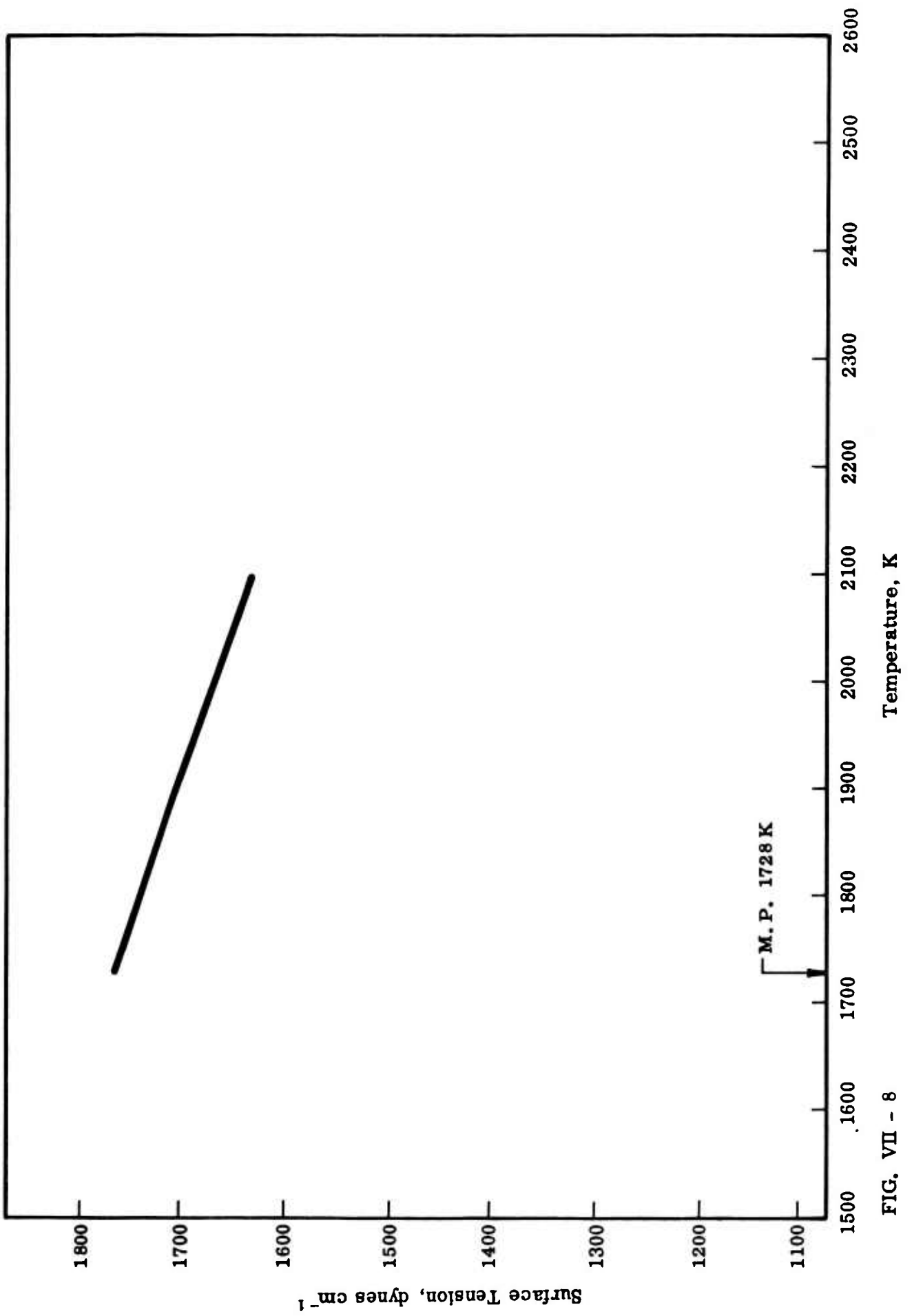


FIG. VII - 8  
SURFACE TENSION -- NICKEL

**TABLE VII-8. SURFACE TENSION OF NICKEL**

**RECOMMENDED VALUES**

From equation:  $\sigma = 1765 - 0.36 (T - 1728)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 1728(m. p.) | 1765                               |
| 1760        | 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:  $\pm 9\%$ .

TABLE VII-9. SURFACE TENSION OF NIOBIUM

RECOMMENDED VALUE

| T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------|------------------------------------|
| 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<sup>-1</sup> K<sup>-1</sup>]

From empirical correlation: (b) Taylor, J. W. (12)

REMARKS: Estimated accuracy: ± 5%.

TABLE VII-10. SURFACE TENSION OF SILICON

RECOMMENDED VALUE

| T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------|------------------------------------|
| 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:  $\pm 5\%$ .

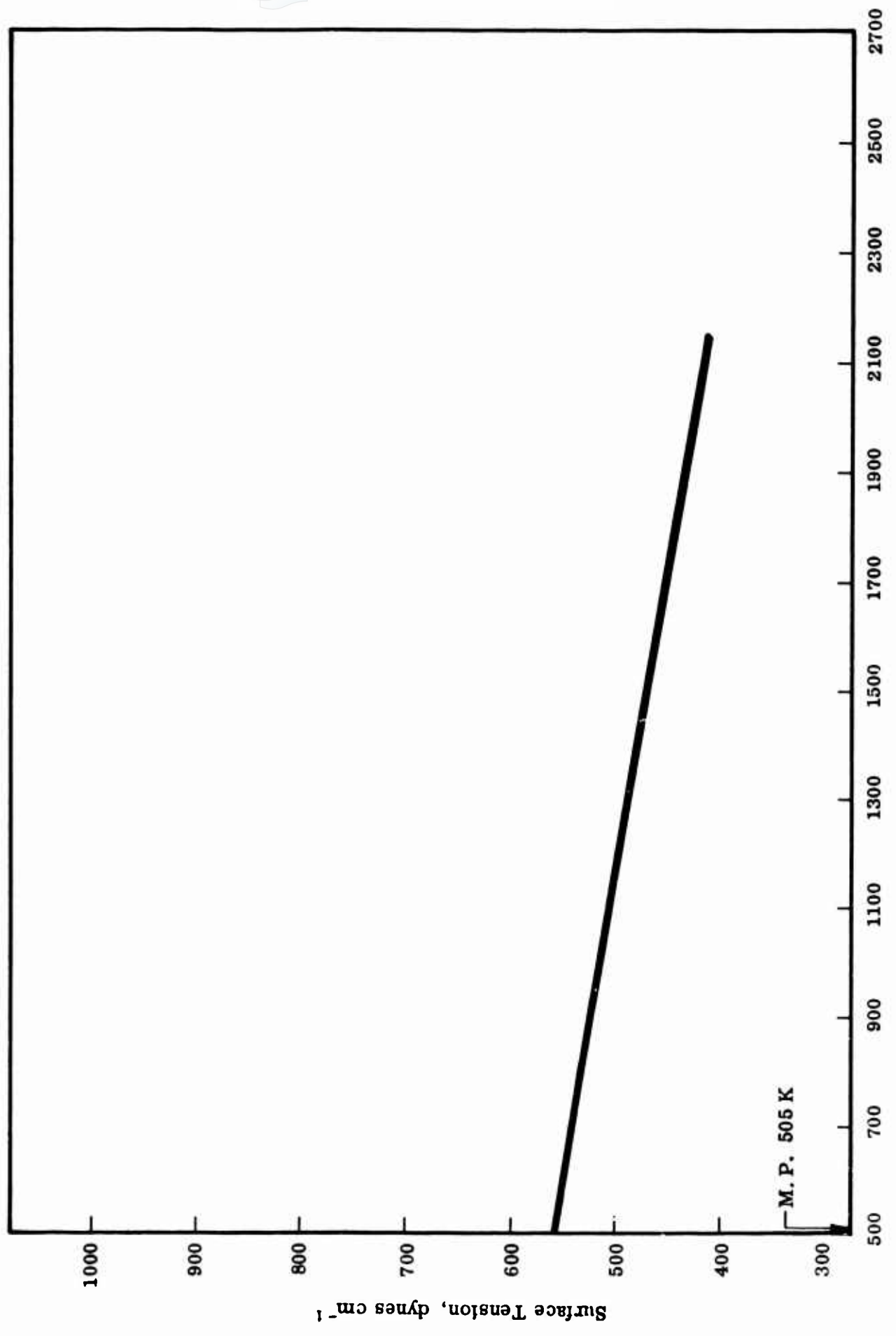


FIG. VII - 11

SURFACE TENSION -- TIN

TABLE VII-11. SURFACE TENSION OF TIN

RECOMMENDED VALUES

From equation:  $\sigma = 559 - 0.089 (T - 505)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) | T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|-------|------------------------------------|
| 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) Rokrovskii, 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:  $\pm 6\%$ .

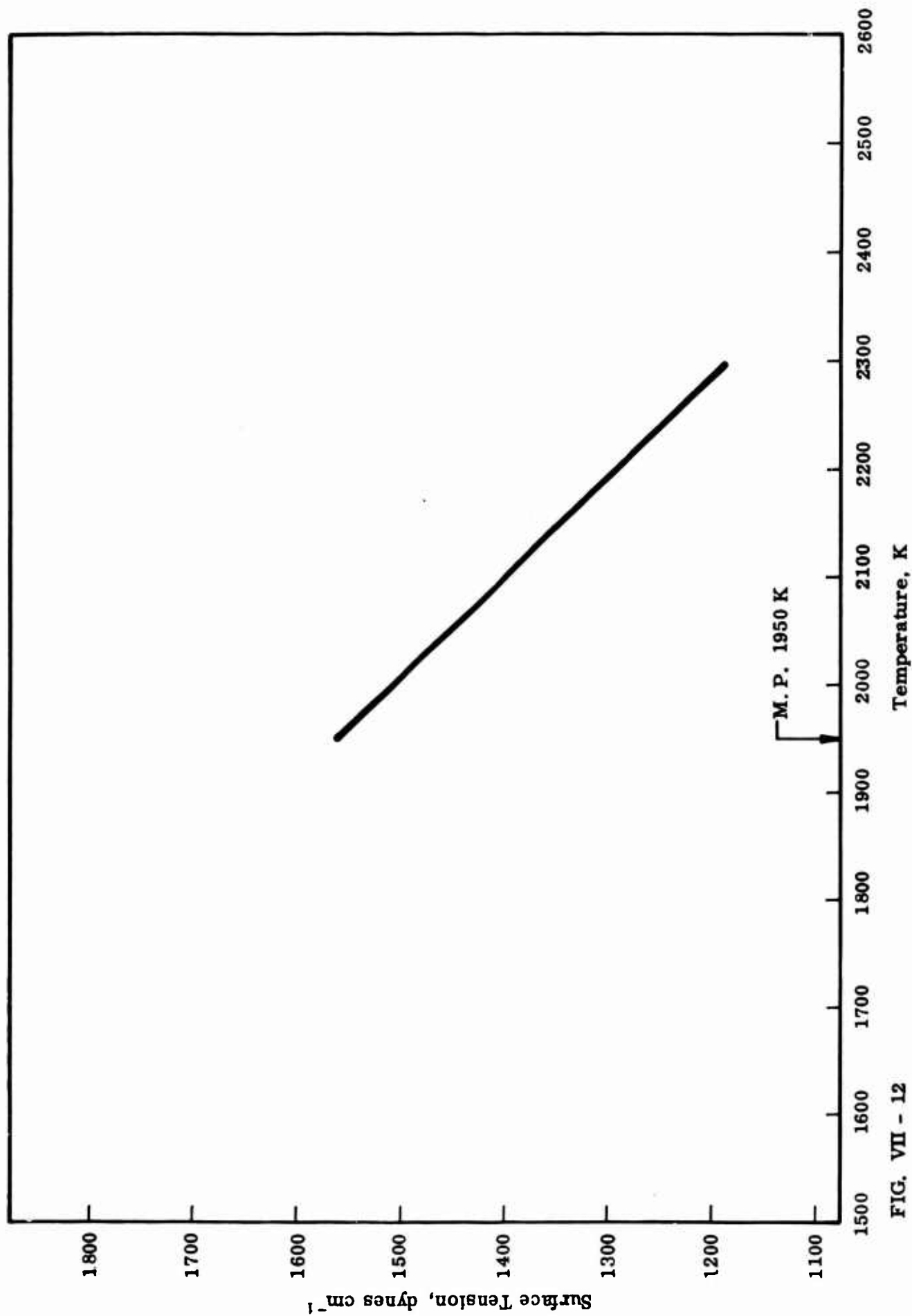


FIG. VII - 12

SURFACE TENSION -- TITANIUM

**TABLE VII-12. SURFACE TENSION OF TITANIUM**

**RECOMMENDED VALUES**

From equation:  $\sigma = 1563 - 1.075 (T - 1950)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|
| 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:  $\pm 10\%$   
 The values above the melting point should be taken with caution the temperature coefficient being abnormally high.

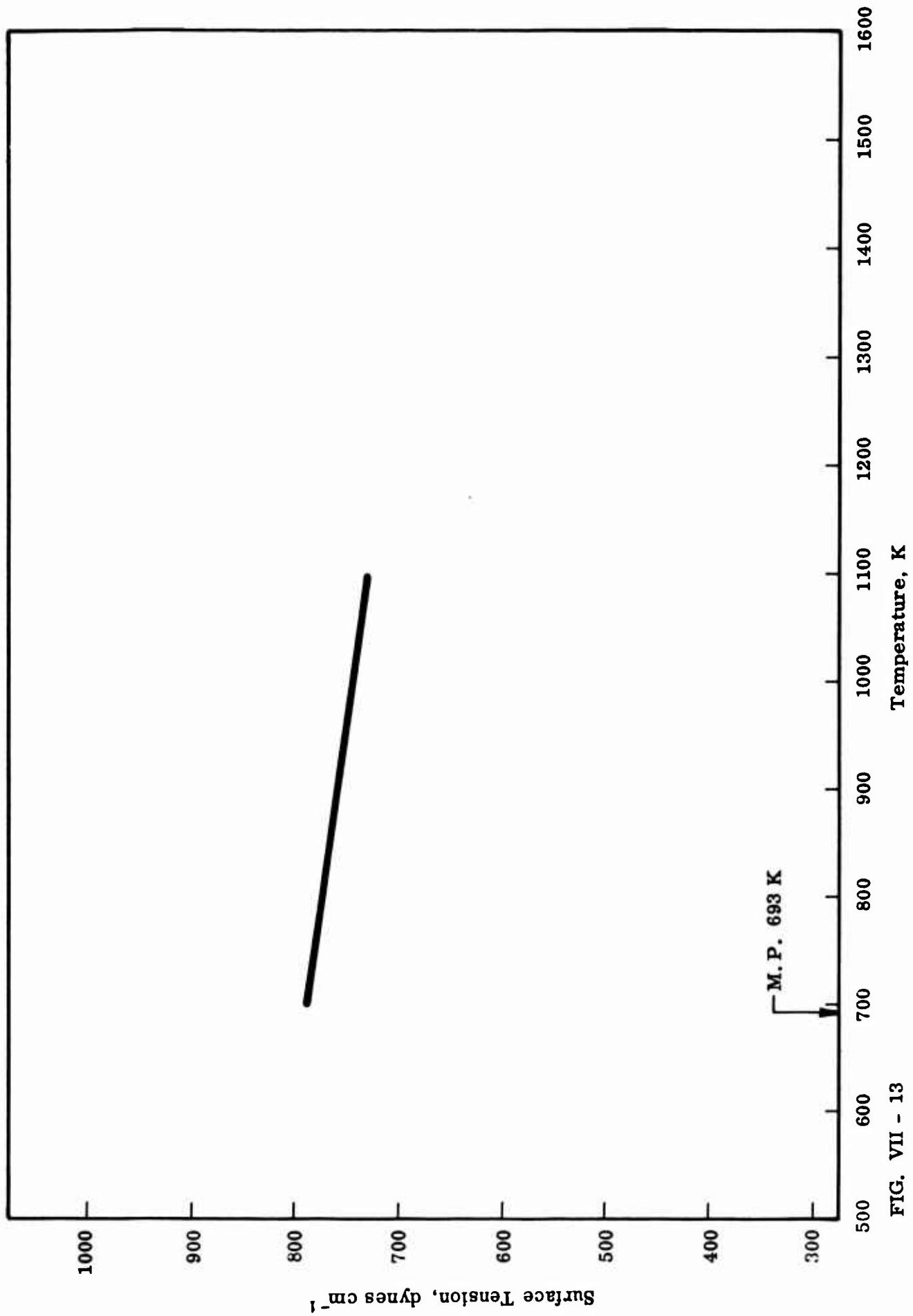


FIG. VII - 13

SURFACE TENSION -- ZINC

**TABLE VII-13. SURFACE TENSION OF ZINC**

**RECOMMENDED VALUES**

From equation:  $\sigma = 789 - 0.146 (T - 693)$

| T(°K)      | $\sigma$ (dynes cm <sup>-1</sup> ) |
|------------|------------------------------------|
| 693(m. p.) | 789                                |
| 700        | 788                                |
| 750        | 781                                |
| 800        | 773                                |
| 850        | 766                                |
| 900        | 759                                |
| 950        | 751                                |
| 1000       | 743                                |
| 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:  $\pm 5\%$ .

TABLE VII-14. SURFACE TENSION OF ALUMINUM OXIDE ( $\text{Al}_2\text{O}_3$ )

RECOMMENDED VALUE

| T( $^{\circ}\text{K}$ ) | $\sigma$ (dynes $\text{cm}^{-1}$ ) |
|-------------------------|------------------------------------|
| 2300 (m. p.)            | $706 \pm 30$                       |

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:  $\pm 6\%$ .

TABLE VII-15. SURFACE TENSION OF CHROMIUM OXIDE ( $\text{Cr}_2\text{O}_3$ )

RECOMMENDED VALUE

| T( $^{\circ}\text{K}$ ) | $\sigma$ (dynes $\text{cm}^{-1}$ ) |
|-------------------------|------------------------------------|
| above m. p.             | $462 \pm 40$                       |

SOURCE OF DATA

Hasapis, A. A. , et al (72)

TABLE VII-16. SURFACE TENSION OF IRON OXIDE (FeO)

RECOMMENDED VALUE

| T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------|------------------------------------|
| 1843  | 585                                |

SOURCE OF DATA

Kingery, W.D. (69)

-TABLE VII-17. SURFACE TENSION OF MAGNESIUM OXIDE (MgO)

RECOMMENDED VALUE

| T(°K)      | $\sigma$ (dynes cm <sup>-1</sup> ) |
|------------|------------------------------------|
| above m.p. | 590                                |

SOURCE OF DATA

Hasapis, A. A. , et al (72)

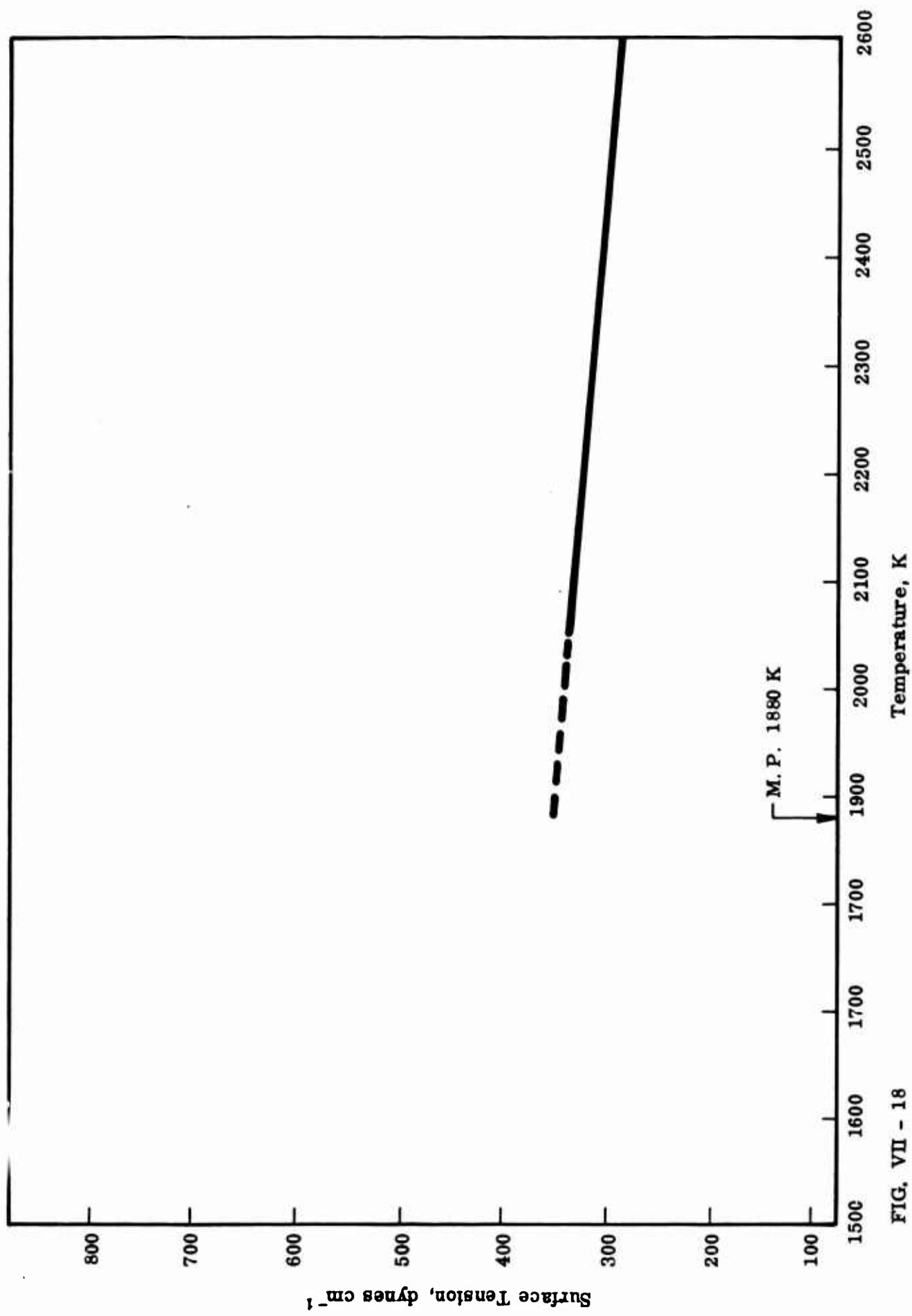


FIG. VII - 18

SURFACE TENSION -- SILICON OXIDE

TABLE VII-18. SURFACE TENSION OF SILICON OXIDE (SiO<sub>2</sub>)

RECOMMENDED VALUES

From equation:  $\sigma = 352 - 0.089 (T - 1880)$

| T(°K)       | $\sigma$ (dynes cm <sup>-1</sup> ) | T(°K) | $\sigma$ (dynes cm <sup>-1</sup> ) |
|-------------|------------------------------------|-------|------------------------------------|
| 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:  $\pm 10\%$ .

D. BIBLIOGRAPHY

Ref.  
No.

1. Naidich, Yu. V., and Eremenko, V.N., Phys. Metals Metallog. (USSR) 11, 62, (1961).
2. Eremenko, V.N., Nizhenko, V.I., and Ivashchenko Yu. N., Byul. Inst. Metallokeram. i Spets. Splavov. A.N. Ukr. SSR (4), 65, (1959).
3. Pelzel, E., Berg-u. Huttenman. Monatsh. Montan. Hochschule Leoben, 93, 248, (1948).
4. Zadumkin, S.N., Zh. Fiz. Khim. 27, 502, (1953).
5. Zadumkin, S.N., and Pugachevich, P.P., Soviet Phys. Doklady, 7, 743, (1962).
6. Monma, K., and Suto, H., Trans. Japan Inst. Metals, 1, 69, (1960).
7. Powers, R.M., and Wilhelm, H.A., U.S. At. Energy Comm. ISC - 228, (1952).
8. Smith, S.W., J. Inst. Metals (London) 12, 168, (1914).
9. Mayer, S.W., J. Chem. Phys. 35, 1513, (1961).
10. McLachlan, D., Acta Met. 5, 111, (1957).
11. Eremenko, V.N., Nizhenko, V.I., and Tai Shou Vei, Russ. Met. Fuels. (3) 100, (1960).
12. Taylor, J.W., Metallurgia, 50, 161, (1961).
13. Eremenko, V.N., and Naidich, Yu. V., Izv. Akad. Nauk. SSSR Otdel. Tekhn. Nauk. Met. i Toplivo 2, 111, (1959).
14. Kozakevitch, P., and Urbain, G., Mem. Sci. Rev. Met. 58, 401, (1961).
15. Yashkichev, V.I., and Lazarev, V.B., Izv. Akad. Nauk. SSSR Ser. Khim. (1), 170, (1964).
16. Fezenko, V.V., and Eremenko, V.N., Ukr. Khim. Zh. 26, 198, (1960).
17. Lauermann, I., and Sauerwald, F., Z. Metallk. 55, 605, (1964).
18. Allen, B.C., Trans. AIME 227, 1175, (1963).
19. Metzger, G., Z. Physik. Chem. 211, 1, (1959).
20. Baes, C.F., and Kellog, H.H., J. Metals, 5, 643, (1953).

BIBLIOGRAPHY (continued)

- Ref.  
No.
21. Allen, B. C., and Kingery, W. D., Trans. AIME 215, 30, (1959).
  22. Gans, W., Pawlek, F., and von Ropenack, A., Z. Metallk 54, 147, (1953).
  23. Belforti, D. A., and Lepie, M. P., Trans. AIME, 227, 80, (1963).
  24. Hoage, J. H., U.S. At. Energy Comm. HW - 78132 (1963).
  25. Pugachevich, P. P., and Yashkichev, V. I., Bull. Acad. Sci. USSR Div. Chem. Sci. (English Transl.) 1, 782, (1960).
  26. Becker, G., Harders, F., and Kornfeld, H., Arch. Eisenhüttenw, 20, 363, (1949).
  27. Smirnova, V. I., and Ormont, B. F., Dokl. Akad. Nauk. SSSR 82, 751, (1952).
  28. Whalen, T. J., and Humenik, J. R. M., Trans. AIME 218, 352, (1960).
  29. Drath, G., and Sauerwald, F., Z. Anorg. Allgem. Chem. 162, 301, (1927).
  30. Krause, W., Sauerwald, F., and Michalke, M., Z. Anorg. Allgem. Chem. 181, 353, (1929).
  31. Skapski, A. S., Acta Met. 4, 576, (1956).
  32. Pavlov, V. V., Popel', S. I., and Esin, O. A., Zh. Fiz. Khim. 37, 797, (1963).
  33. Kozakevitch, P., and Urbain, P., Compt. Rend. 244, 335, (1957).
  34. Kozakevitch, P., and Urbain, P., Compt. Rend. 253, 2229, (1961).
  35. Kozakevitch, P., and Urbain, P., J. Iron Steel Inst. (London) 186, 167, (1957).
  36. Dyson, B. F., Trans. AIME 227, 1098, (1955).
  37. Halden, F. A., and Kingery, W. D., J. Phys. Chem. 59, 557, (1955).
  38. Kingery, W. D., and Humenik, M. Jr., J. Phys. Chem. 57, 353, (1953).
  39. Eremenko, V. N., Ivashchenko, Yu. N., Nizhenko, V. I., and Fezenko, V. V., Izv. Akad. Nauk. SSSR, Otdel. Tekhn. Nauk. (7), 144, (1958).

BIBLIOGRAPHY (continued)

- Ref.  
No.
40. Fezenko, V. V., and Eremenko, V. N., Byul. Inst. Metallokeram. i Spets. Splavov. A. N. UKR. SSR (4), 52, (1959).
  41. Von den Esche, W., and Peter, O., Arch. Eisenhüttenw 27, 355, (1956).
  42. Zhivov, N. G., Trans. Al-Mg Institute (USSR) 14, 99, (1937).
  43. Pelzel, E., Metal Progr. 58, 252, (1950).
  44. Popel, S. I., Tsarevskii, B. V., and Dzhenelev, N. K., Phys. Metals, Metallograph. [English Transl.] 18, (3), 158, (1964).
  45. Elliott, J. F., and Gleiser, M., in "Thermochemistry for Steel Making," Addison-Wesley Publ. Co. London (1960).
  46. Kiyora, R., and Sata, T., J. Ceram. Assoc. Japan 66, 747, (1958).
  47. Eremenko, V. N., and Nizhenko, V. I., Ukr. Khim. Zh. 30, 125, (1964).
  48. Kurkjian, C. R., and Kingery, W. D., J. Phys. Chem. 60, 961, (1956).
  49. Norton, F. H., and Kingery, W. D., AEC Progress Report NYO-4632, (1955).
  50. Keck, P. H., and Van Horn, W., Phys. Rev. 91, 512, (1953).
  51. Shashkov, Yu. M., and Kolesnikova, T. P., Zh. Fiz. Khim. 37, 1397, (1963).
  52. Zadumkin, S. N., Sov. Phys-Solid State 1, 516, (1959).
  53. (a) Kirshenbaum, A. D., and Grosse, A. V., U. S. At. Energy Comm. TID-1895 (1963).
  - (b) Cahill, J. A., and Kirshenbaum, A. D., J. Inorg. Nucl. Chem. 26, 206, (1964).
  54. Pokrovskii, N. L., and Galanina, N. D., Zh. Fiz. Khim. 23, 324, (1949).
  55. Melford, D. A., and Hoar, T. P., J. Inst. Metals (London) 85, 197, (1957).
  56. Lauer mann, I., Metzger, G., and Sauerwald, F., Z. Physik. Chem. 216, 42, (1961).
  57. Atterton, D. V., and Hoar, T. P., J. Inst. Metals (London) 81, 541, (1952).
  58. Coffmann, A. W., and Parr, S. W., Ind. Eng. Chem. 19, 1308, (1927).
  59. Ziv, D. M., and Shestakov, B. I., Zh. Prikl. Khim. 32, 1767, (1959).

BIBLIOGRAPHY (continued)

- Ref. No.
60. Hogness, T.R., J. Am. Chem. Soc. 43, 1621, (1921).
  61. Bircumshaw, L.L., Phil. Mag. 2, 341, (1926), Phil. Mag. 3, 1286, (1927).
  62. Tille, J., and Kelly, J.C., Brit. J. Appl. Phys. 14, 717, (1963).
  63. Yelyutin, V.P., and Maurakh, M.A., Izv. Akad. Nauk. SSSR. Otdel Tekhn. Nauk. 4, 129, (1956).
  64. Maurakh, M.A., Trans. Indian Inst. Metals 14, 209, (1961).
  65. Peterson, A.W., Kedesdy, H., Keck, P.H., and Schwartz, E., J. Appl. Phys. 29, 213, (1958).
  66. Matuyama, Y., Sci. Rep. Tokoku Imp. Univ. 16, 555, (1927).
  67. Klyachko, Yu. A., Zavodsk. lab. 6, 1376, (1937).
  68. Zadumkin, S.N., Dokl. Akad. Nauk. SSSR 92, 115, (1953).
  69. Kingery, W.D., J. Am. Ceram. Soc. 42, 6, (1959).
  70. Margrave, J.L., et al. U.S. At. Energy Comm. TID-13678, (1961).
  71. von Wartenberg, H., Wehner, G., and Saran, E., Nach. Akad. Wiss. Goettingen, 2, 65, (1936).
  72. Hasapis, A.A., Melveger, A.J., Panish, M.B., Reif, L., and Rosen, C.L., AD 255758.

Further corrections

Page Correction

206 ~~53~~\* → 42\* , ~~18~~\* → 14\*

77 \*

62 Grüneisen

282 Mit'kina

415 Naturforsch.,

24-26 Low-temperature Absorber  
 are based on Mendelsohn (1958) [42]'s  
 data which are uncorrected presented  
 in their original paper by 10 times too high.