ORNL/TM-8949, R-

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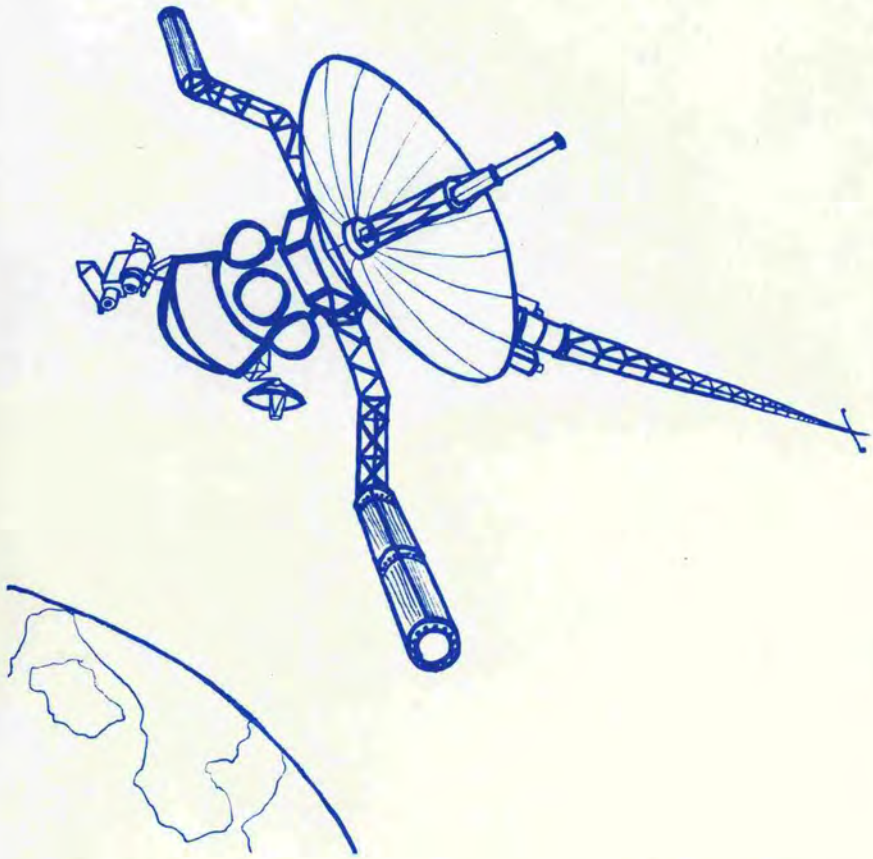
ISOTOPIC SPACE POWER MATERIALS HANDBOOK



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OAK RIDGE NATIONAL LABORATORY
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POST OFFICE BOX Y
OAK RIDGE, TENNESSEE 37831

September 28, 1984

NEW PAGES FOR THE ISOTOPIC SPACE POWER MATERIALS HANDBOOK, ORNL/TM-8949 — UPDATE PACKAGE NO. 4

Enclosed you will find Update Package No. 4 containing new pages of the Isotopic Space Power Materials Handbook (ISPMH), ORNL/TM-8949. Also enclosed is a yellow response card which is to be filled out and returned to us as soon as possible. Return of this card confirms your address and receipt of this update package.

This Update Package contains both new and revised pages. Enclosure 1 is a guideline for proper placement of the pages in the ISPMH. Enclosure 2 is provided as a further aid to updating your Handbook. It contains a listing of each page in this Update Package, a description of the changes or additions, and, in the case of revised pages, indicates the pages to be discarded.

Please remember to notify us of any change in your address, phone number, or custodianship of the ISPMH. If you have any questions, please call me at (615) 574-0714 or FTS 624-0714.

Linda B. Dockery

Linda B. Dockery
Structural Mechanics Section

Enclosures: (1) Insertion Instructions based on ISPMH Page Filing System.
(2) Listing of New and Revised Pages in Update Package No. 4
(3) Update Package No. 4.

Insertion Instructions Based on the ISPMH Page Filing System:

PROPERTY CODE Ⓐ **PAGE** Ⓑ

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Ⓒ	Ⓓ	Ⓔ Ⓕ

Appendix A of the ISPMH contains a detailed description of the ISPMH and should be consulted by those not already familiar with the page filing system. In addition, the following detailed page insertion instruction steps are offered and refer to the circled letters in the above example (same as Fig. A.1 in Appendix A). Note that occasionally there may be exceptions to some of these general rules. In such cases, the insertion procedures to be used will be explained in the accompanying letter and instructions.

1. Check the Red tabs in the binder to find the Part Code coinciding with the Part Code of the page to be inserted. The Part Code is the first character in the Material Code (Ⓔ above).

2. Check the Blue tabs located right after the correct Part tab to find the Group Code coinciding the the Group Code of the Page to be inserted. The Group Code is the second character in both the Material Code (Ⓔ above) and on the blue tab.

3. Check the Yellow Table of Contents/Materials pages immediately after the correct Group tab to find the Section Code coinciding with the Section Code of the page to be inserted. The Section Code is the last 2 characters in the Material Code (Ⓔ above). Note that in some cases the Table of Contents/Materials page itself will be replaced.

4. The Property Codes within each section are organized in ascending order, and the page from the Update should be inserted in sequence.

5. Page Numbers for each Property Code are organized in ascending order starting with 1.0.

6. To determine if individual pages in the Update Package are new or replacement pages: If the Material Code, Property Code, and Page Number coincide with those of a current ISPMH page, then those specific pages are to be discarded. Note that the Update Code on the replacement page will differ from that of the discarded page. CAUTION: DOUBLE CHECK WITH THE LISTINGS IN ENCLOSURE #2. If there is no match between the Material Code, Property Code, and Page Number of any pages in the Update Pckage and current pages, then the Update pages are new, and no current pages are to be discarded. Note that the last two characters in the Update Code will be 0.0 in this case.

Incidentally, if your Update Package accidentally gets shuffled, it may be reassembled using the "Collation Control Code" in the lower right-hand corner of every page. This code indicates Update Number/Volume Number-Sequence Number of the page in this Update Package.

AK RIDGE NATIONAL LABORATORY

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POST OFFICE BOX Y
OAK RIDGE, TENNESSEE 37831

June 15, 1984

NEW PAGES FOR THE ISOTOPIC SPACE POWER MATERIALS HANDBOOK, ORNL/TM-8949/R2 — UPDATE PACKAGE No. 2

Enclosed you will find Update Package No. 2 containing new pages of the Isotopic Space Power Materials Handbook (ISPMH), ORNL/TM-8949/R2. Also enclosed is a yellow response card which is to be filled out and returned to us as soon as possible. Return of this card serves two purposes: (1) confirmation of your address and receipt of this update package and (2) helps us to develop improved methods for updating your ISPMH.

This Update Package contains additional materials and the only pages requiring replacement are the Tables of Contents for the affected sections. Enclosure 1 is a guideline for proper placement of the pages in the ISPMH.

Please remember to notify us of any change in your address, phone number, or custodianship of the ISPMH. If you have any questions, please call me at (615) 574-0714 or FTS 624-0714.

Linda B. Dockery

Linda B. Dockery
Structural Mechanics Section

Enclosures: (1) Insertion Instructions based on ISPMH Page Filing System.
(2) Update Package No. 2.

Insertion Instructions Based on the ISPMH Page Filing System:

PROPERTY CODE Ⓐ **PAGE** Ⓑ

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Ⓒ	Ⓓ	Ⓔ Ⓕ

Appendix A of the ISPMH contains a detailed description of the ISPMH and should be consulted by those not already familiar with the page filing system. In addition, the following detailed page insertion instruction steps are offered and refer to the circled letters in the above example (same as Fig. A.1 in Appendix A). Note that occasionally there may be exceptions to some of these general rules. In such cases, the insertion procedures to be used will be explained in the accompanying letter and instructions.

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Incidentally, if your Update Package accidentally gets shuffled, it may be reassembled using the "Collation Control Code" in the lower right-hand corner of every page. This code indicates Update Number/Volume Number-Sequence Number of the page in this Update Package.

LISTING OF NEW AND REVISED PAGES IN
UPDATE PACKAGE No. 4

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]	
CONTENTS		CONTENTS Tab (Green)	2-v	2-vi	4-v	4-vi	(F/R)	New materials listed.
Revision Control Page		Revision Control Tab	3-vii	Blank	4-vii	Blank	(R)	Current revision No. and date added.
EAXX		EA Graphites Tab	0-95	Blank	4-1	Blank	(R)	New materials listed.
EA03		3-62	**** None ****		4-3	4-4	(N/N)	New pages.
EA03	1000	*	**** None ****		4-5	4-6	(N/N)	New pages.
EA03	1000	*	**** None ****		4-7	Blank	(N)	New page.
EA03	1100	*	**** None ****		4-9	Blank	(N)	New page.
EA03	2100	*	**** None ****		4-11	4-12	(N/N)	New pages.
EA03	2101	*	**** None ****		4-13	4-14	(N/N)	New pages.
EA03	2101	*	**** None ****		4-15	Blank	(N)	New page.

[a]TC/P indicates a yellow-colored Table of Contents/Properties page.

[b]These are the pages or tabs currently in the Handbook that will be used to indicate the location of the page to be inserted. The new or replacement page is to be placed immediately following the page listed here. An asterisk (*) is placed in this column if the preceding page was one you just inserted from the Update Package.

[c]CCC (the number listed in this column) is the Collation Control Code located at the bottom right-hand side of each page.

[d]The letters in parentheses indicate the nature of the page being inserted: "N" indicates a new page, "R" indicates a revised page, and "F" indicates a "flip side," i.e., the unchanged side of a sheet having changes on one side only.

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]	
EA03	2102	*	**** None ****		4-17	Blank	(N)	New page.
EA03	2104	*	**** None ****		4-19	Blank	(N)	New page.
EA03	2105	*	**** None ****		4-21	Blank	(N)	New page.
EA03	2108	*	**** None ****		4-23	Blank	(N)	New page.
EA03	2108	*	**** None ****		4-25	Blank	(N)	New page
EA03	2109	*	**** None ****		4-27	Blank	(N)	New page.
EA03	2110	*	**** None ****		4-29	Blank	(N)	New page.
EA03	2111	*	**** None ****		4-31	Blank	(N)	New page.
EA03	2111	*	**** None ****		4-33	Blank	(N)	New page.
EA03	2117	*	**** None ****		4-35	Blank	(N)	New page.
EA03	2117	*	**** None ****		4-37	Blank	(N)	New page.
EA03	3108	*	**** None ****		4-39	Blank	(N)	New page.
EA03	3112	*	**** None ****		4-41	Blank	(N)	New page.
EA03	3112	*	**** None ****		4-43	Blank	(N)	New page.
EA03	3112	*	**** None ****		4-45	4-46	(N/N)	New pages.

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]	
EA03	3114	*	**** None ****		4-47	Blank	(N)	New page.
EA03	3114	*	**** None ****		4-49	Blank	(N)	New page.
EA03	3201	*	**** None ****		4-51	Blank	(N)	New page.
EA03	4102	*	**** None ****		4-53	Blank	(N)	New page.
EA03	4103	*	**** None ****		4-55	Blank	(N)	New page.
EA03	4107	*	**** None ****		4-57	Blank	(N)	New page.
EA03	5305	*	**** None ****		4-59	4-60	(N/N)	New pages.
EA03	5305	*	**** None ****		4-61	Blank	(N)	New page.
EA03	5305	*	**** None ****		4-63	4-64	(N/N)	New pages.
EA03	5305	*	**** None ****		4-65	4-66	(N/N)	New pages.

2219 ALUMINUM	GENERAL	Material Code AB03 Update Code 2.0.0

Aluminum alloy 2219 is used in the GPHS-RTG in two applications: in the T6 condition as the outer shell assembly and in the T87 condition in the pressure domes. The shell is machined from a hand-forged billet measuring 33-cm outside diam by 20.3-cm inside diam by 122 cm in length. The pressure domes are formed from rolled plate. The mechanical property of most importance is the creep rate under both the preflight standby condition and flight condition.

The results of creep testing at ORNL for conditions expected in the GPHS-RTG are presented from the ORNL report.[3] Comments noted in the report include the observation of creep burst at both testing conditions and that apparently different mechanisms of primary creep are operative at the two temperatures. The higher primary creep rate at 177°C resulted in the unexpected occurrence of the design curve for 0.1% strain for 177°C falling in a lower stress range than for 260°C.

The tensile properties as a function of temperature and the physical properties are from an Alcoa publication.[1]

For further information see refs. 2, 4, and 5.

---

[3]J. P. Hammond, *Creep Properties of Forged 2219 T6 Aluminum Alloy Shell of General Purpose Heat Source — Radioisotope Thermal Generator*, ORNL/TM-8020 (December 1981).

[4]*Aerospace Structural Metals Handbook*, 2, AFML-TR-68-115.

[5]*Military Standardization Handbook*, "Metallic Materials and Elements for Aerospace Vehicle Structures, 1, MIL-HDBK-5C pp. 3—145 (September 15, 1976).

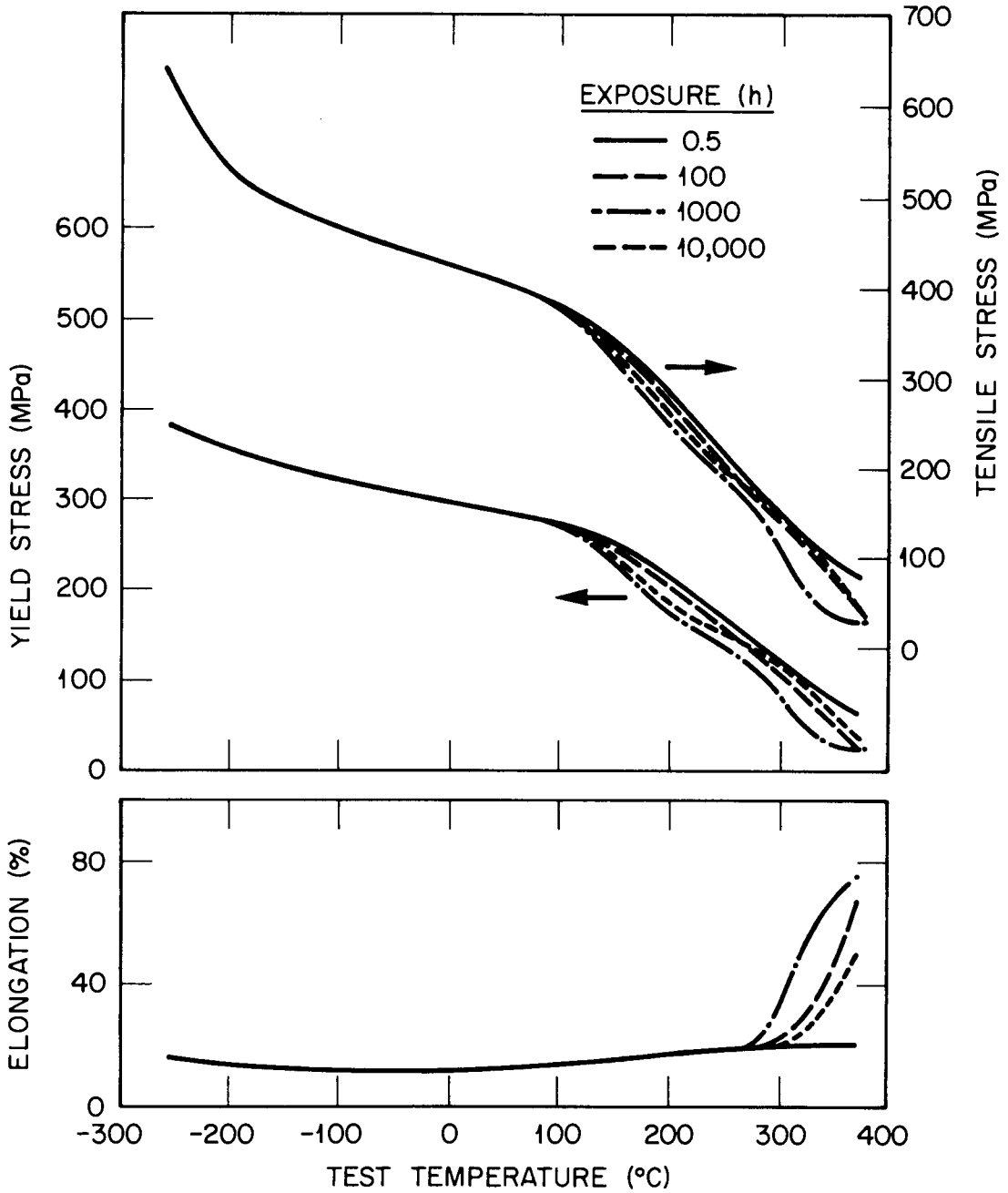
2219 ALUMINUM	CHEMICAL COMPOSITION	Material Code AB03 Update Code 2.0.0

CHEMICAL COMPOSITION
ALLOY 2219

	Nominal %	Specification % (Max. Unless Shown as a Range)
Si	—	0.20
Fe	—	0.30
Cu	6.3	5.8 —6.8
Mn	0.3	0.20—0.40
Mg	—	0.02
Zn	—	0.10
Ti	0.06	0.02—0.10
V	0.10	0.05—0.15
Zr	0.18	0.10—0.25
Others, Each	—	0.05
Others, Total	—	0.15
Aluminum	Remainder	Remainder

2219 T6 ALUMINUM PLATE	TENSILE PROPERTIES	Material Code AB03 Update Code 2.0.0

ORNL-DWG 84-12002

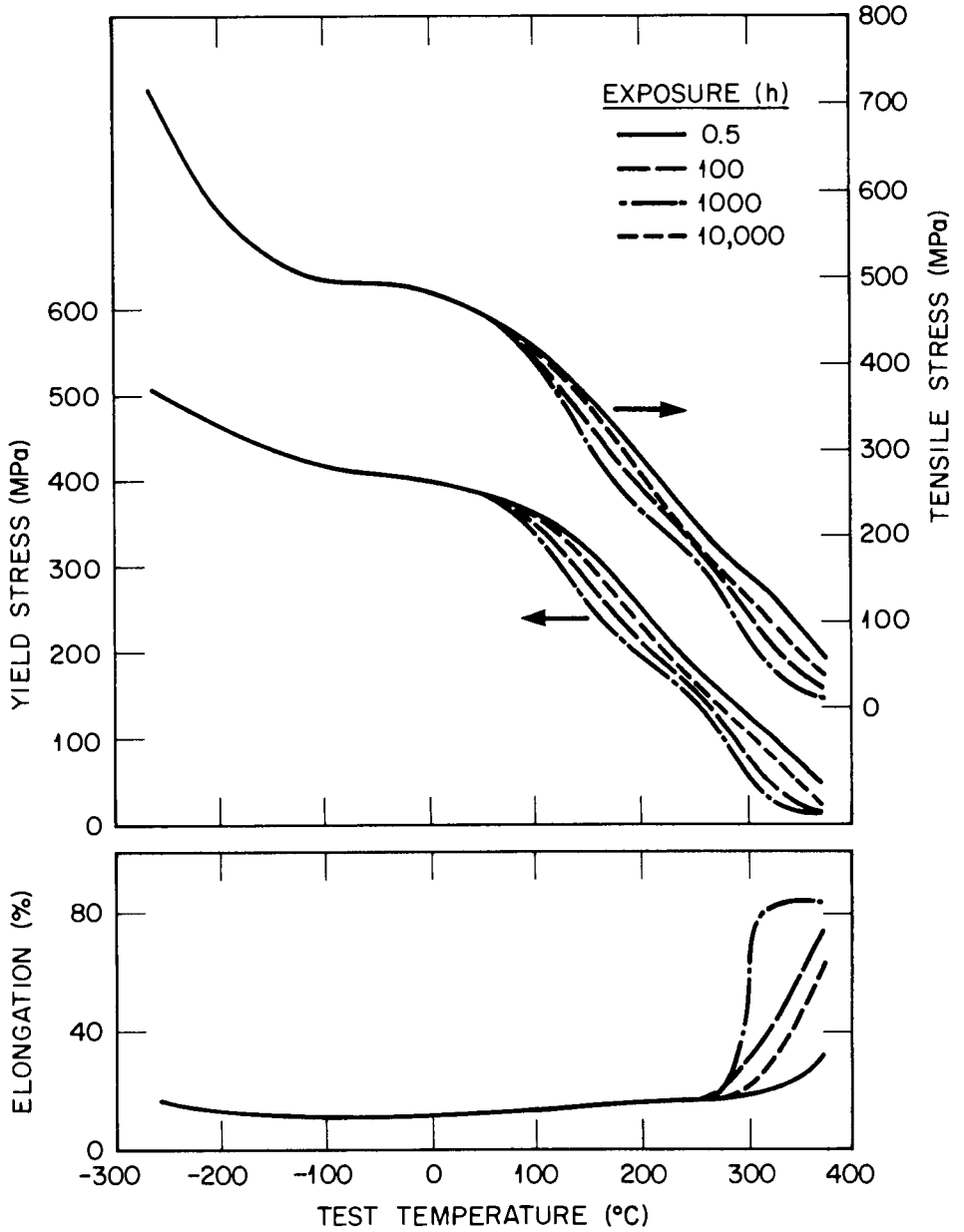


Effect of test temperature and exposure time on tensile properties of plate.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 T87 ALUMINUM PLATE	TENSILE PROPERTIES	Material Code AB03 Update Code 2.0.0

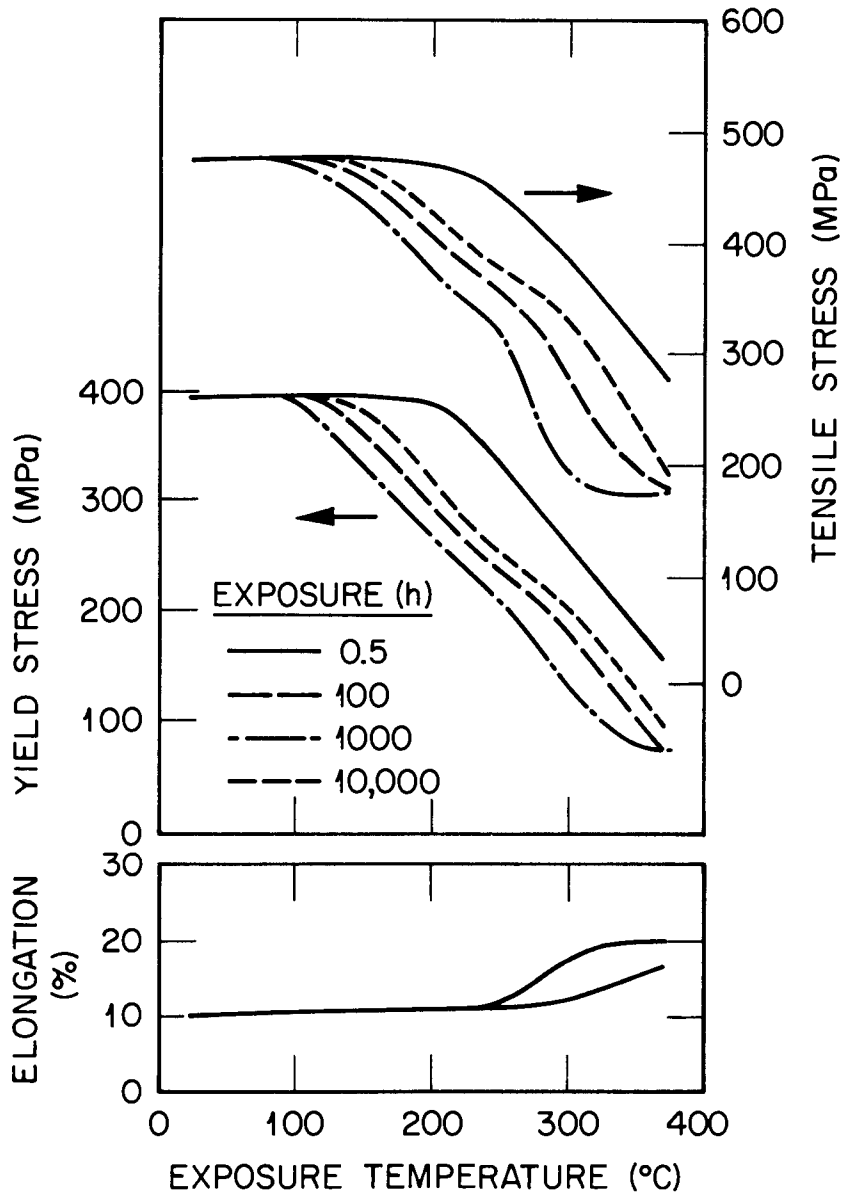
ORNL-DWG 84-12000



Effect of test temperature and exposure time on tensile properties of plate.

2219 T87 ALUMINUM PLATE	TENSILE PROPERTIES	Material Code AB03 Update Code 2.0.0

ORNL-DWG 84-12001



Effect of exposure on room temperature tensile properties of plate.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

CONTENTS	UPDATE CODE 2.1.0

	PAGES
REVISION CONTROL PAGE	1
FOREWORD	1
INTRODUCTION	1
DATA PAGES	

Selected properties are provided for the following materials. For a listing of the properties, see the TABLE OF CONTENTS/PROPERTIES for each material.

Material Code	Material
AA01	Wrought Tungsten
AB0A	Aluminum–Silver Eutectic Alloy
AB01	Aluminum Alloy 1100
AB02	Aluminum Alloy 7075
AB03	Aluminum Alloy 2219
AC01	Titanium
AD01	OFHC Copper
AD02	Dumet
AEA0	Nickel Plating
AE01	Alloy X-750
AF0A	INCUSIL 10
AF0B	NICUSIL 3
AF0C	CUSIL
AF0D	PALCUSIL 15
AG0A	NIORO*

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CONTENTS	UPDATE CODE 4.1.0

Material Code	Material
BA01	N-type Si/Ge/GaP/P
BA02	P-type Si/Ge/GaP/B
BA03	SiMo N-type
BA04	SiMo P-type
BA05	N-type 78Si/22Ge/P
BA06	P-type 78Si/22Ge/B
BA07	N-type 63Si/37Ge/P
BA08	P-type 63Si/37Ge/B
CA01	Silicon Nitride (Si_3N_4) Coating
CB01	Al_2O_3
DA01	Low-temperature Glass
DA02	High-temperature Glass
EA01	Stackpole 2128
EA02	Fineweave Pierced Fabric
EA03	Pyrolytic Graphite
EA04	POCO AXF-5Q
FA01	Multifoil Insulation

		PAGES
APPENDIX A	HANDBOOK FORMAT-ORGANIZATION AND UPDATING	1-4
APPENDIX B	MATERIAL CODES	1-3
APPENDIX C	PROPERTY CODES AND DEFINITIONS	1-13

REVISION CONTROL PAGE	UPDATE CODE 4.0.0

This page will be replaced each time a package of new and/or revised pages is issued. It will provide a cumulative listing of the issue dates associated with consecutive publication packages.

Update Package Number	Issue Date
0	September 30, 1983
1	June 12, 1984
2	June 21, 1984
3	August 15, 1984
4	September 30, 1984

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

GRAPHITES	TABLE OF CONTENTS/MATERIALS	Material Code EAXX Update Code 4.1.0

Material Code	Material
EA01	Stackpole 2128
EA02	Fineweave Pierced Fabric
EA03	Pyrolytic Graphite
EA04	POCO AXF-5Q

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	TABLE OF CONTENTS/PROPERTIES	Material Code: EA03 Update Code: 4.0.0

Property Code	Property	Pages
1000	General	1-3
1100	Chemical Composition	1
2100	Discussion — Static, Short-Term Properties	1-2
2101	Ultimate Tensile Strength — "a" Direction	1.0,1.1
2101	Ultimate Tensile Strength — "c" Direction	2.0
2102	Yield Strength	1.0
2104	Laminar Shear Stress	1.0
2105	Elongation	1.0
2108	Engineering Stress-Strain, Typical Tensile	1.0
2108	Engineering Stress-Strain, Typical Compressive	2.0
2109	Hardness	1.0
2110	Poisson's Ratio	1.0
2111	Young's Modulus, Tension	1.0
2111	Young's Modulus, Bending	2.0
2117	Bend Strength — Load Applied Parallel to Basal Plane	1.0
2117	Bend Strength — Load Applied Normal to Basal Plane	2.0
3103	Melting Point: Graphite does not melt, but sublimes. Sublimation Point: 3650°C	*
3108	Comparative Specific Heat	1.0
3112	Thermal Conductivity — "a" Direction	1.0
3112	Thermal Conductivity — "c" Direction	2.0
3112	Comparative Thermal Conductivity	3.0-3.1
3114	Thermal Expansion — "a" Direction	1.0
3114	Thermal Expansion — "c" Direction	2.0
3119	Latent Heat of Sublimation: 59.75 MJ/kg	*
3201	Electrical Resistivity and Electrical Anisotrophy	1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	TABLE OF CONTENTS/PROPERTIES	Material Code: EA03 Update Code: 4.0.0

Property Code	Property	Pages
4102	Comparative Oxidation in Air	1.0
4103	Reactions with Aqueous Media	1.0
4107	Reactions with Other Substances	1.0
5305	Coefficients of Friction in Air	1.0-1.3
5305	Coefficients of Friction in Air	2.0-2.3

*No separate pages provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	GENERAL	Material Code: EA03 Update Code: 4.0.0

Pyrolytic Graphite (PG) is a unique form of graphite resulting from a pyrolytic deposition process. Pyrolytic deposition takes place in a closely controlled vacuum furnace operating at 1900 to 2500°C. Under prescribed conditions pure carbon atoms are deposited layer by layer on a suitably prepared substrate. These layers are highly ordered and are oriented parallel to the surface of the substrate. Material thus formed is spectroscopically pure carbon, approaches theoretical density, is monolithic, free of voids and exceptionally strong.

PG is generally separated from the substrate to form a free-standing shape, but thin coatings may be bonded to the substrate.

PREFERRED ORIENTATION

The nature of the pyrolytic process builds carbon crystallites atom by atom. This determines the degree of preferred orientation of these crystallites. Up to 1000 crystallites may be oriented perpendicular to the surface for one oriented parallel to the surface. This unique structure results in anisotropic properties (certain properties measured parallel to the surface differ markedly from values perpendicular to the surface).

COMPARISON WITH CONVENTIONAL GRAPHITE

Pyrolytic Graphite crystallites are grown leaving no voids. Conventional graphite, on the other hand, is made by the agglomeration and compaction of discrete particles. Crushed coke mixed with pitch as a binder is extruded or molded to shape and then baked. Since the binder decomposes as the volatiles escape, the material formed is porous. The carbon produced at this stage in this process is baked again at higher temperatures to form graphite. Porosity can be decreased somewhat by reimpregnation with pitch prior to graphitization.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	GENERAL	Material Code: EA03 Update Code: 4.0.0

A certain amount of preferred orientation can be produced by careful handling of coke particles at the beginning of the process. In such cases three or four crystallites may be oriented parallel to the surface for one oriented perpendicular to the surface. However, with respect to both porosity and preferred orientation, the conventional graphite process by its nature presents basic difficulties that are only partially compensated for by refinements.

PG CRYSTALLOGRAPHY

PG is a polycrystallite material in which carbon atoms are arranged in parallel layers of adjacent hexagons. The distance between carbon atoms along the hexagon sides is 1.42 angstroms. The following crystallite properties vary within the range indicated:

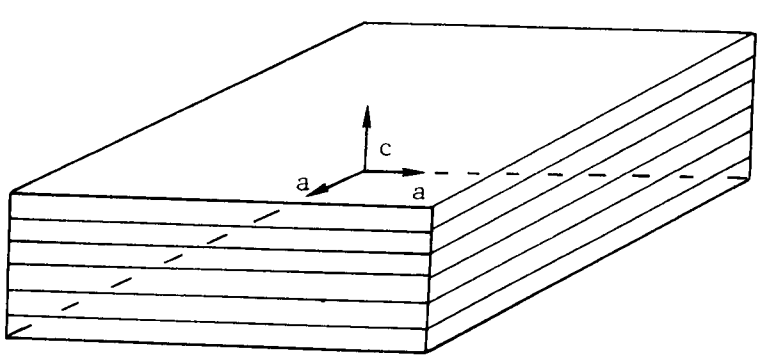
a) The crystallite size varies between 50 to 500 angstroms.

b) The space between layers of basal planes (c/2 spacing) varies between 3.35 to 3.42 angstroms.

c) The ratio of the number of crystallites having basal planes parallel to the deposition surface varies from 100 to 1 to over 1000 to 1.

DIRECTIONAL PROPERTIES

Property data is provided in two directions, wherever appropriate and available, due to the anisotropic properties of PG. The "a" direction is parallel to the deposition surface (and hence the basal planes.) The "c" direction is normal to the deposition surface. (See sketch below).



ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	GENERAL	Material Code: EA03 Update Code: 4.0.0

REFERENCES

4a. High Temperature Materials, Inc.

4b1. Lockheed Missiles and Space Company, Pyrolytic Graphite Data Book, LMSD 288186, April 14, 1961.

4b2. Lockheed Missiles and Space Company, Pyrolytic Graphite Data Book, LMSC 288186 June 26, 1961.

4b3. Lockheed Missile and Space Company, Chemical Study on Pyrolytic Graphite, Monthly Progress Report, E. Dafano to J. Hall, August 16, 1961.

4c. Raytheon Company.

4d. General Electric Company.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	CHEMICAL COMPOSITION	Material Code: EA03 Update Code: 4.0.0

Pyrolytic Graphite is a high purity material. A typical spectrographic analysis is as follows:

B	0.001%
Ca	0.0001
Al	0.0001-0.001
Mg	0.0001
Si	0.0001-0.001
Fe	0.0001
Cu	0.0001
Ti	0.0001
V	ND

The ash content usually ranges between 0.001 and 0.003% weight. A typical spectrogrpahic analysis of the ash content is presented below:

Si	50.0%
Al	6.1
Ca	5.0
Zr	3.3
V	2.7
Fe	2.6
Cb	1.6
Ti	0.7
Mn	0.1
Cu	0.03
Mg	0.003-0.03
Ta, W	1.0
Ni	0.5
B, Co	0.03
O	Bal.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	STATIC, SHORT-TERM PROPERTIES	Material Code: EA03 Update Code: 4.0.0

The tensile testing was carried on by two organizations, Aerojet-General Corporation (AGC) at Azusa, California, and Jet Propulsion Laboratory (JPL) at Pasadena, California. About two-thirds of the test data has been produced by Aerojet-General, and the remaining one-third by Jet Propulsion Laboratory. The majority of the pyrolytic graphite tested to date was made by the General Electric Company (Schenectady) and by High Temperature Materials, Inc., although recently a few specimens produced by the General Electric Company (Detroit) and Raytheon have been received and tested. Properties obtained by both testing agencies have been in the "a-b" plane, i.e., the specimens have been loaded parallel to the laminar structure of the material. In the analysis of the test data received thus far, all results for each temperature have been combined, irrespective of test lab or material producer. In one instance, however, a portion of the data was omitted from the analysis. At 2760°C, the ultimate tensile strength values reported by JPL have been approximately 100% higher than those reported by AGC. Because of this wide difference in the reported values, only AGC data was used in determining the 2760°C properties. (At temperature below 2760°C, the data from the two test laboratories fell within the same scatter-band).

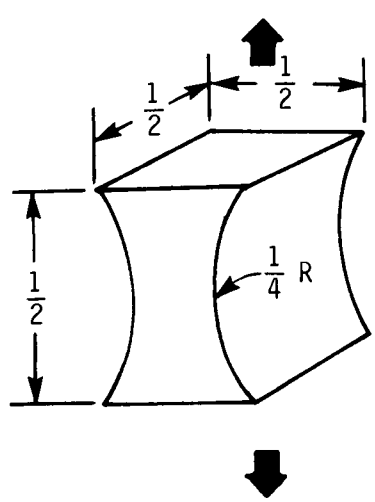
In general, the material exhibits an increase in tensile strength and elongation from room temperature to 2760°C; however, the modulus of elasticity at elevated temperatures shows a decline from the room temperature value. Curves of ultimate tensile strength vs temperature for 50%, 90%, and 99% probability are also given. The number of points at each temperature were taken into account in arriving at the 90% confidence level. Where the Elongation vs Temperature and Modulus of Elasticity vs Temperature are given, the 50% probability curves presented have been corrected for 90% confidence. Typical tensile stress-strain curves are pictured for room temperature, 1650°C, 2205°C, and 2480°C.

Preliminary tests to determine the ultimate tensile strength of pyrolytic graphite in the "c" direction, i.e., perpendicular to the laminations are also given. These data should not be used to obtain allowable values, but may be used to

indicate a trend of temperature effect on tensile stress. In the data presentation, those data points indicated by either a circle or a triangle were obtained from specimens with an "hour glass" shape, see sketch below, while those points marked by a square symbol were obtained using a rectangular shaped specimen.

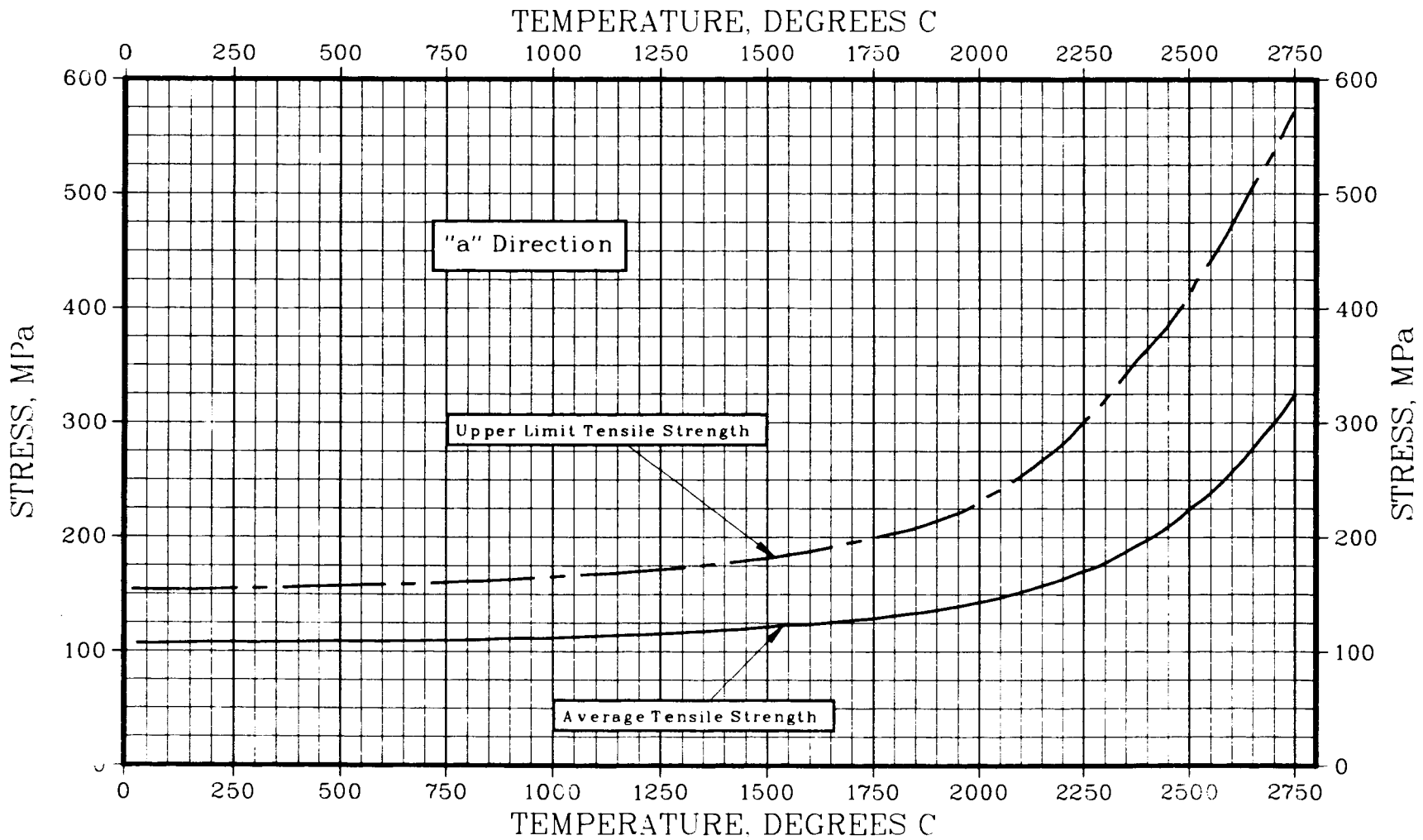
By its nature, the hour glass shape produces a stress concentration, causing the specimen to fail at a computed stress lower than the true tensile strength of the material. By comparing the room temperature experimental data of the notched and un-notched specimens with theoretical calculations, the stress concentration factor for the hour glass specimen was determined to be about 1.25. The lower curve represents an arbitrary "average" of the test data, while the upper curve has been constructed by applying the 1.23 concentration factor to the "average" curve. The 1.25 factor was applied up to 2205°C because the stress-strain relationship is very close to linear at 2205°C and below. However, at temperatures above 2205°C, the material becomes relatively ductile, thereby reducing the stress factor. At 2760°C, the notch effect is considered to exist no longer (Ref. 4b).

Mechanical property measurement data depends upon the test sample size and homogeneity. All of these test data are a result of testing larger bulk pyrolytic specimens and will only reflect the general properties of thin coatings. The coatings should actually have higher values of strength than the bulk material if the substrate has been adequately smoothed.



ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	ULTIMATE TENSILE STRENGTH	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

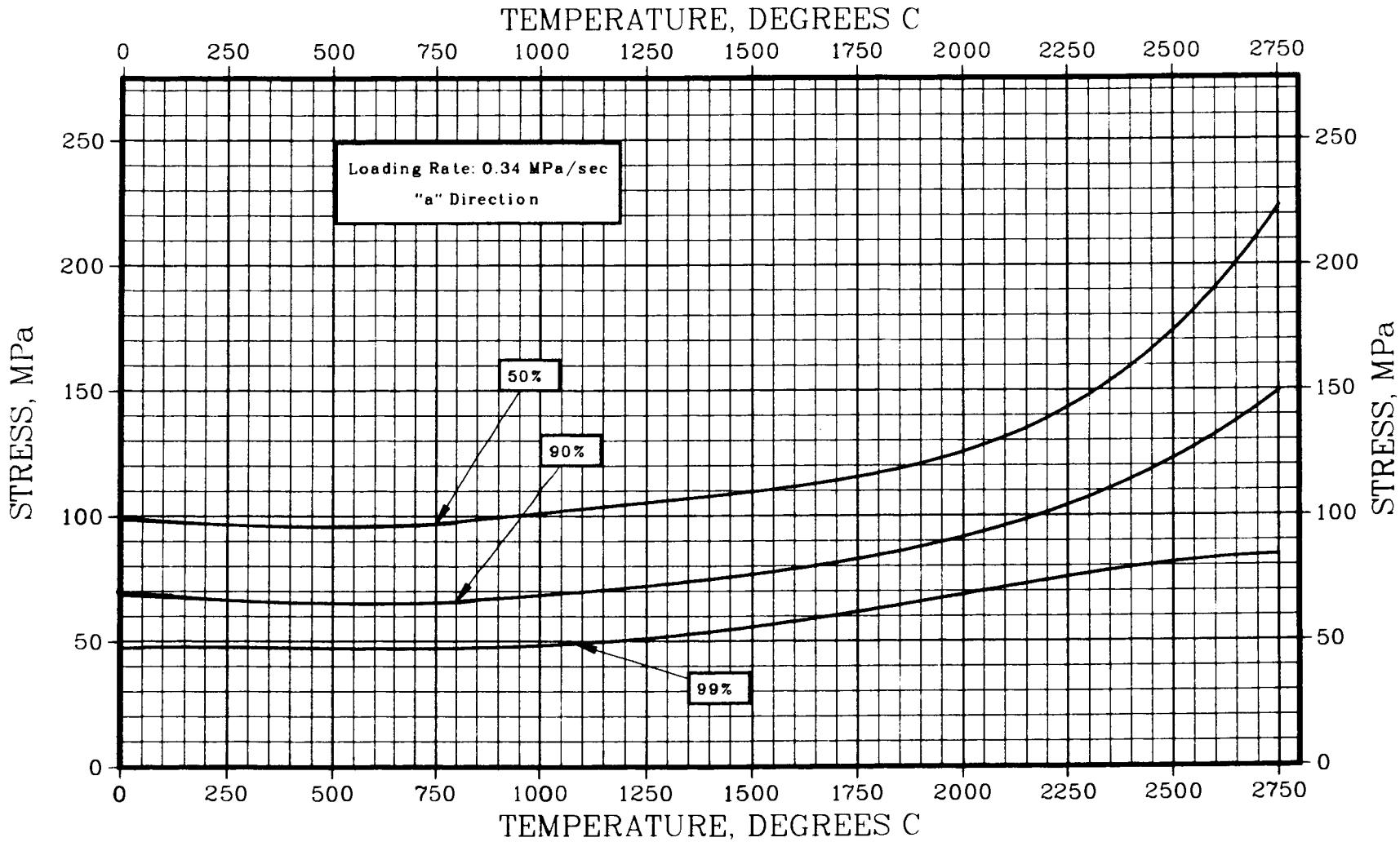


PROPERTY CODE 2101

PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

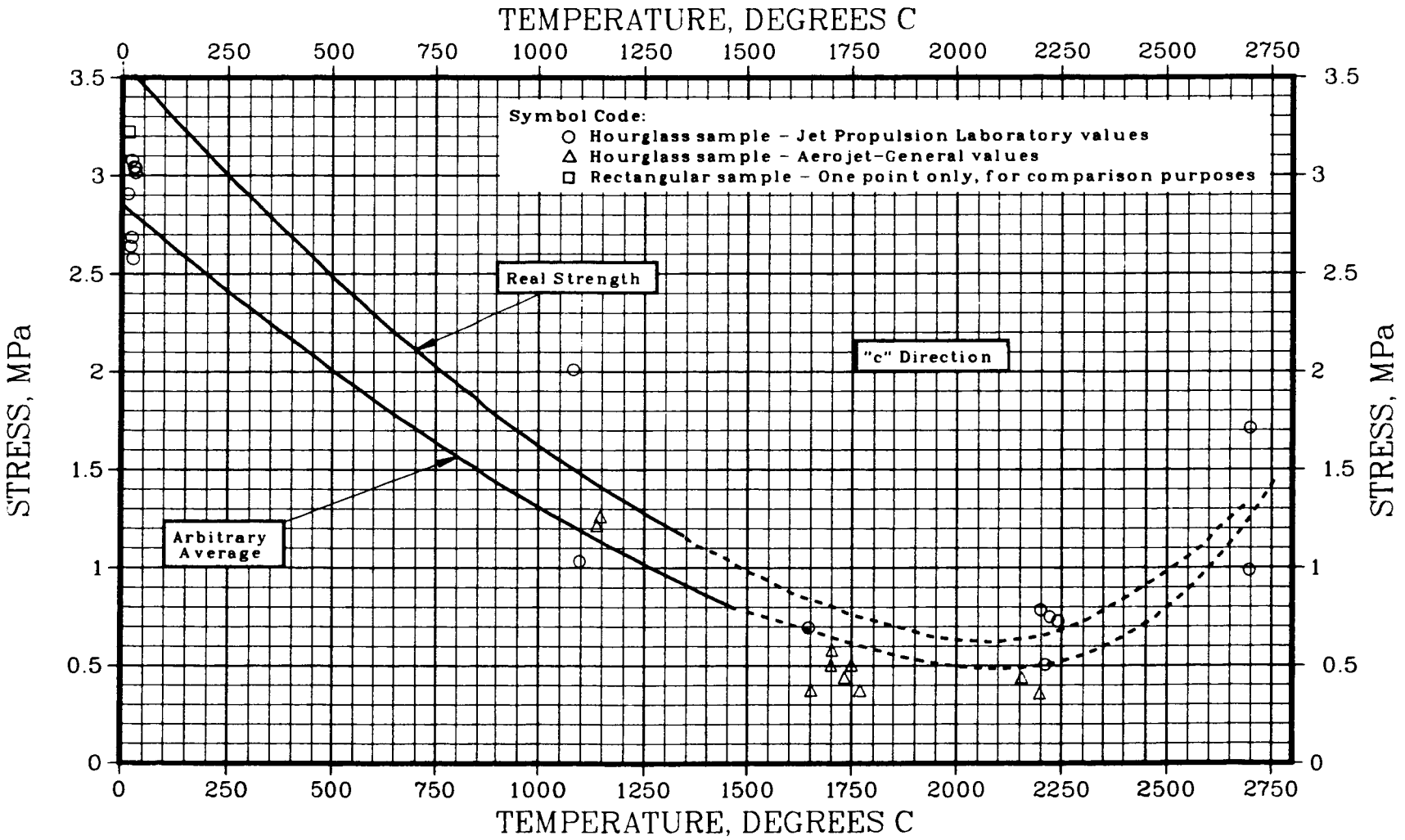
PYROLYTIC GRAPHITE	ULTIMATE TENSILE STRENGTH	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



NOTE: Percentages indicate that a given piece of pyrolytic graphite will have an equal or greater ultimate tensile strength than shown, with 90% confidence.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

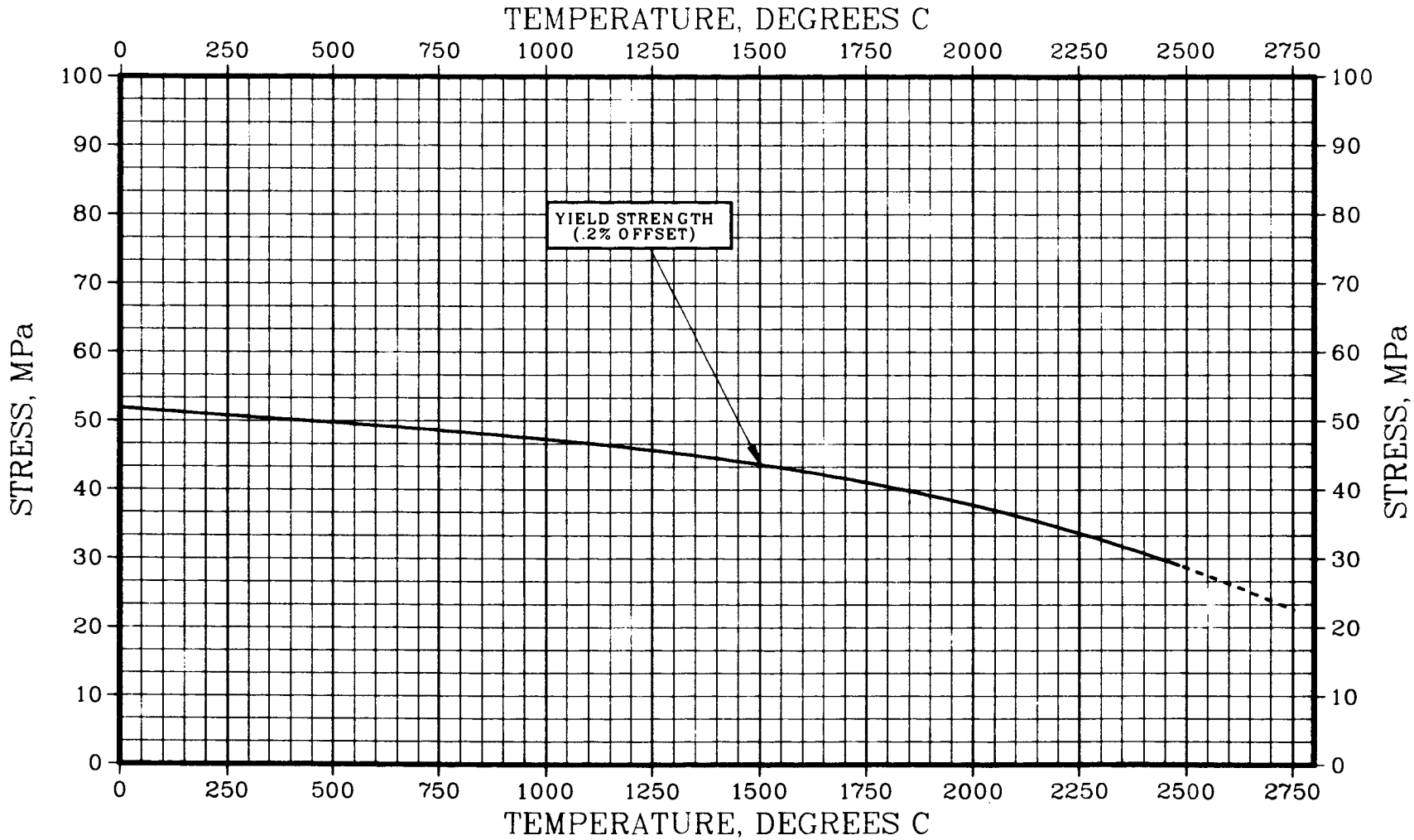
PYROLYTIC GRAPHITE	ULTIMATE TENSILE STRENGTH	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



Note: The Arbitrary Average curve is an estimate (no mathematical curve fitting was done). The Real Strength curve considers the stress concentration factor of the hourglass sample, which was calculated by multiplying the Arbitrary Average by the stress concentration factor of the hourglass sample.

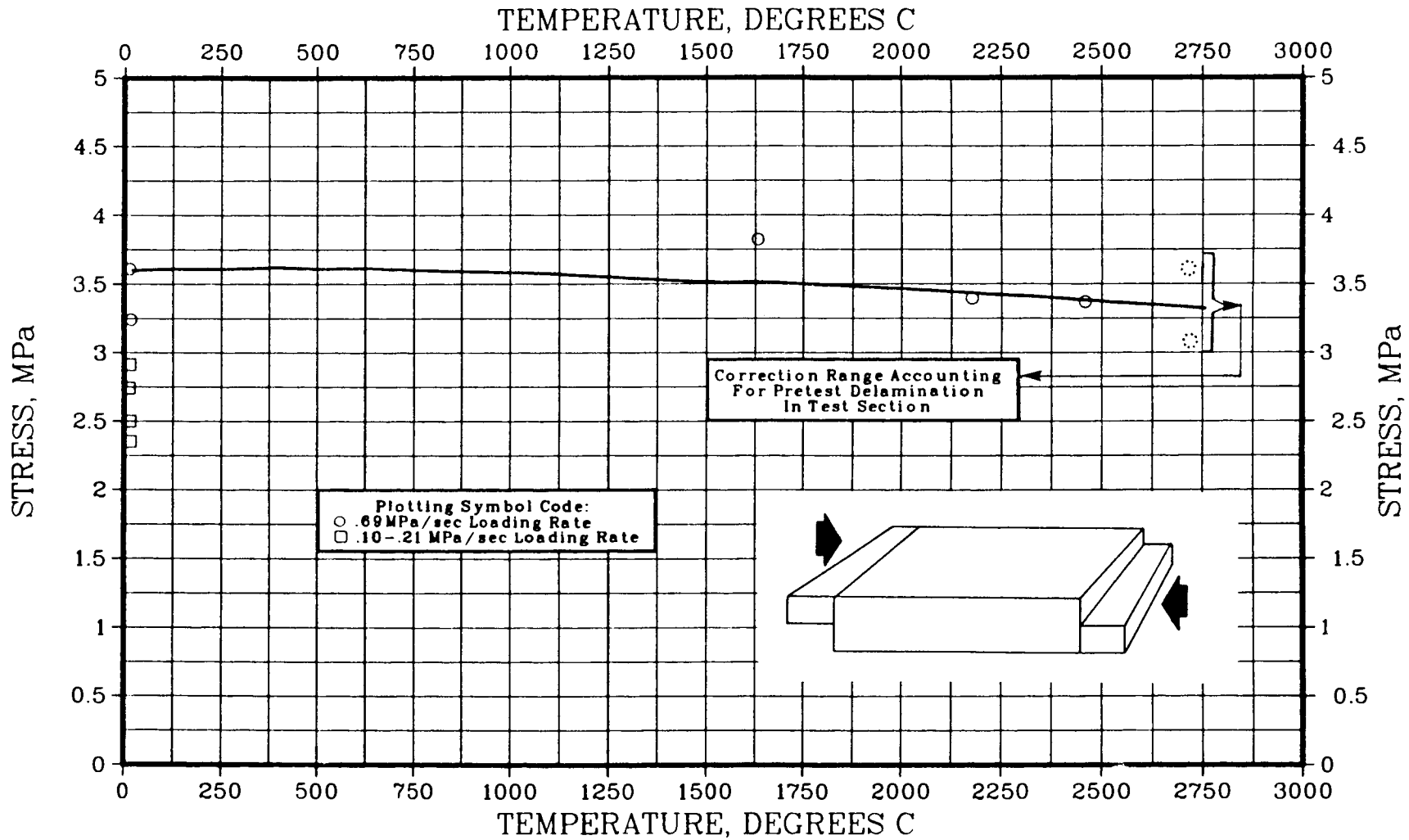
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	YIELD STRENGTH	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	LAMINAR SHEAR STRESS	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0

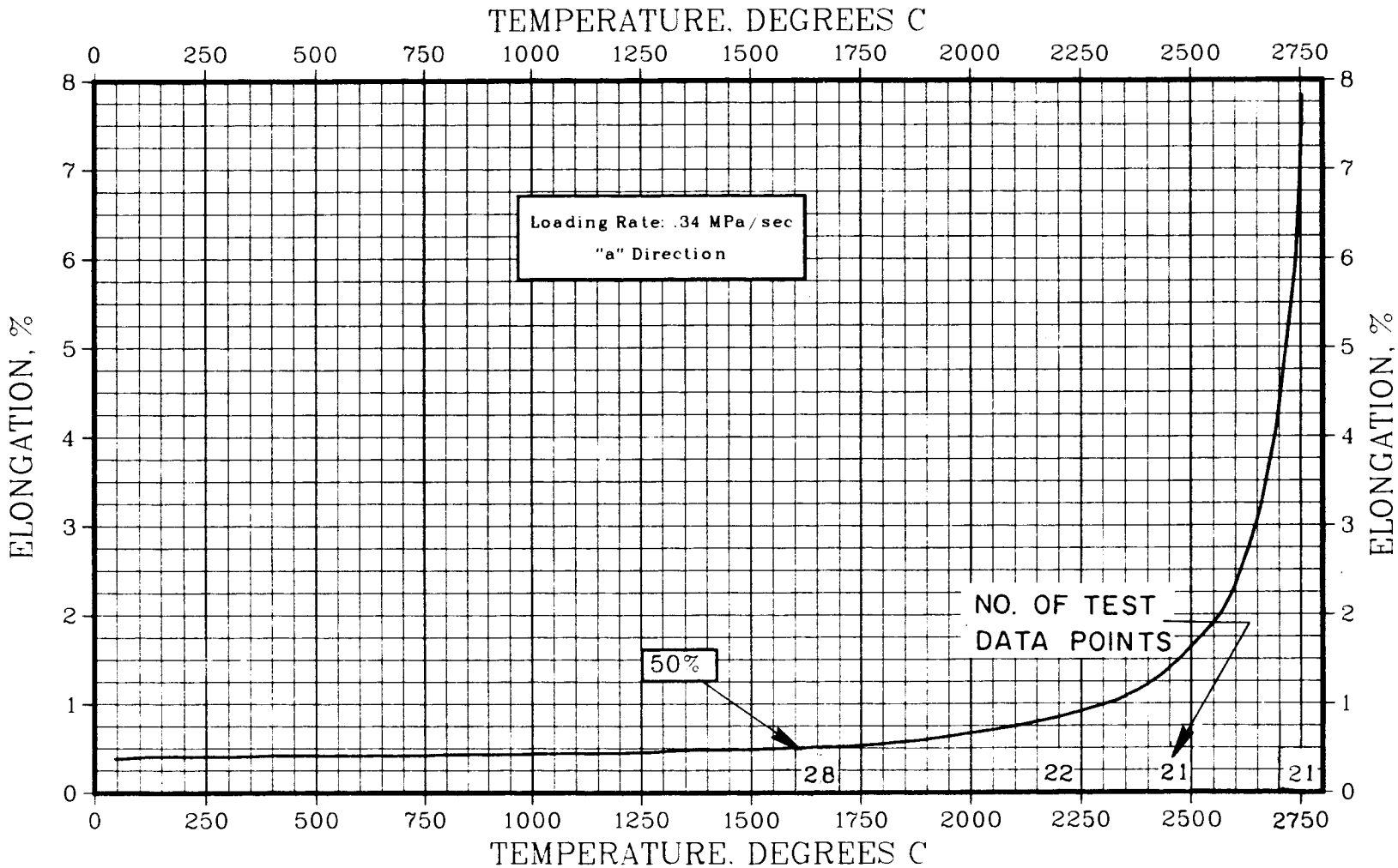


NOTE: This is preliminary data from test run for evaluation of test setup and specimen design. Tests were run at heating rates of 100 to 300°F/sec. Specimens were ultrasonically inspected for delaminations and corrections were made to the test results where applicable.

PROPERTY CODE 2104 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

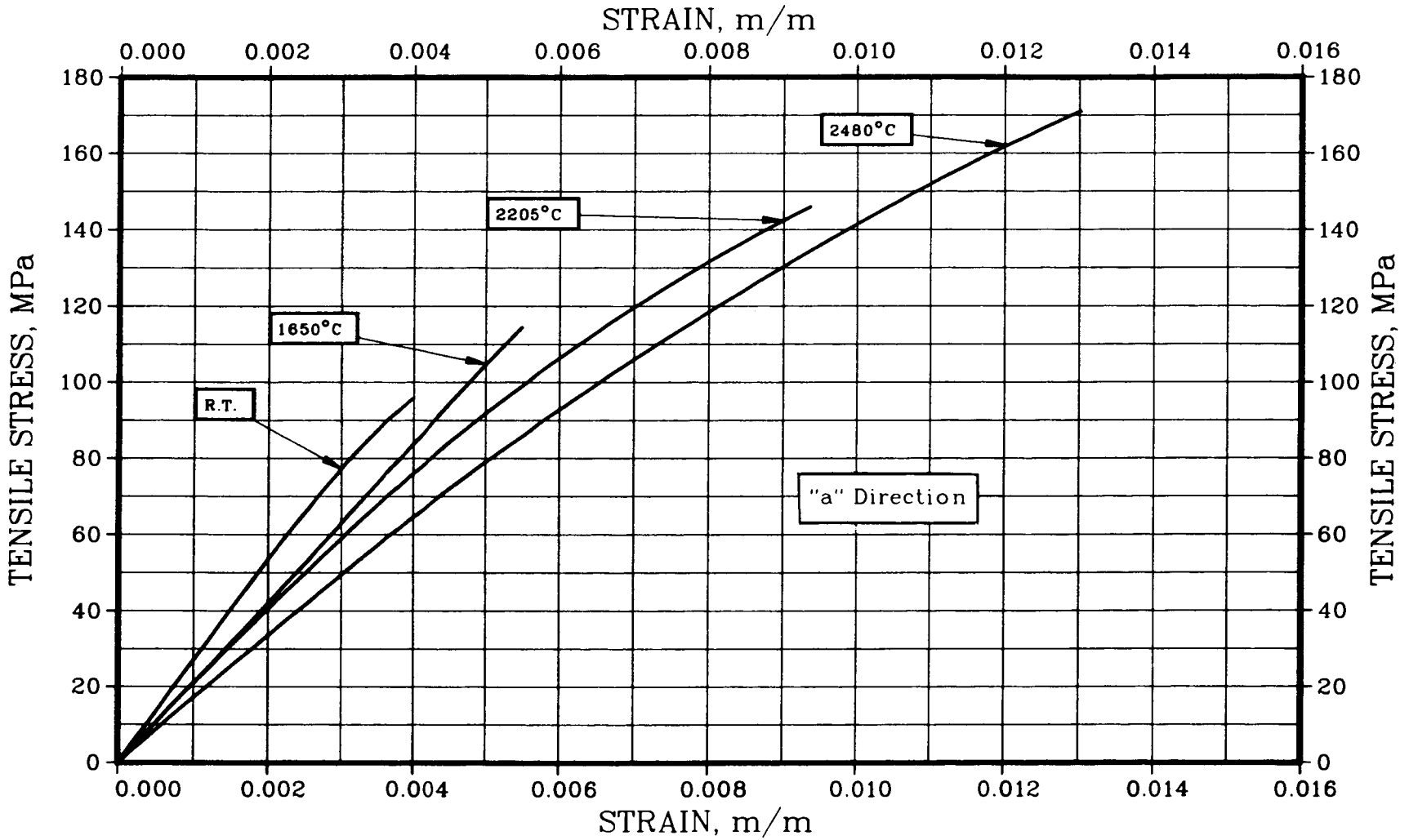
PYROLYTIC GRAPHITE	ELONGATION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



NOTE: Percentage indicates the probability that a given piece of pyrolytic graphite will have an equal or greater elongation than shown, with 90% confidence.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

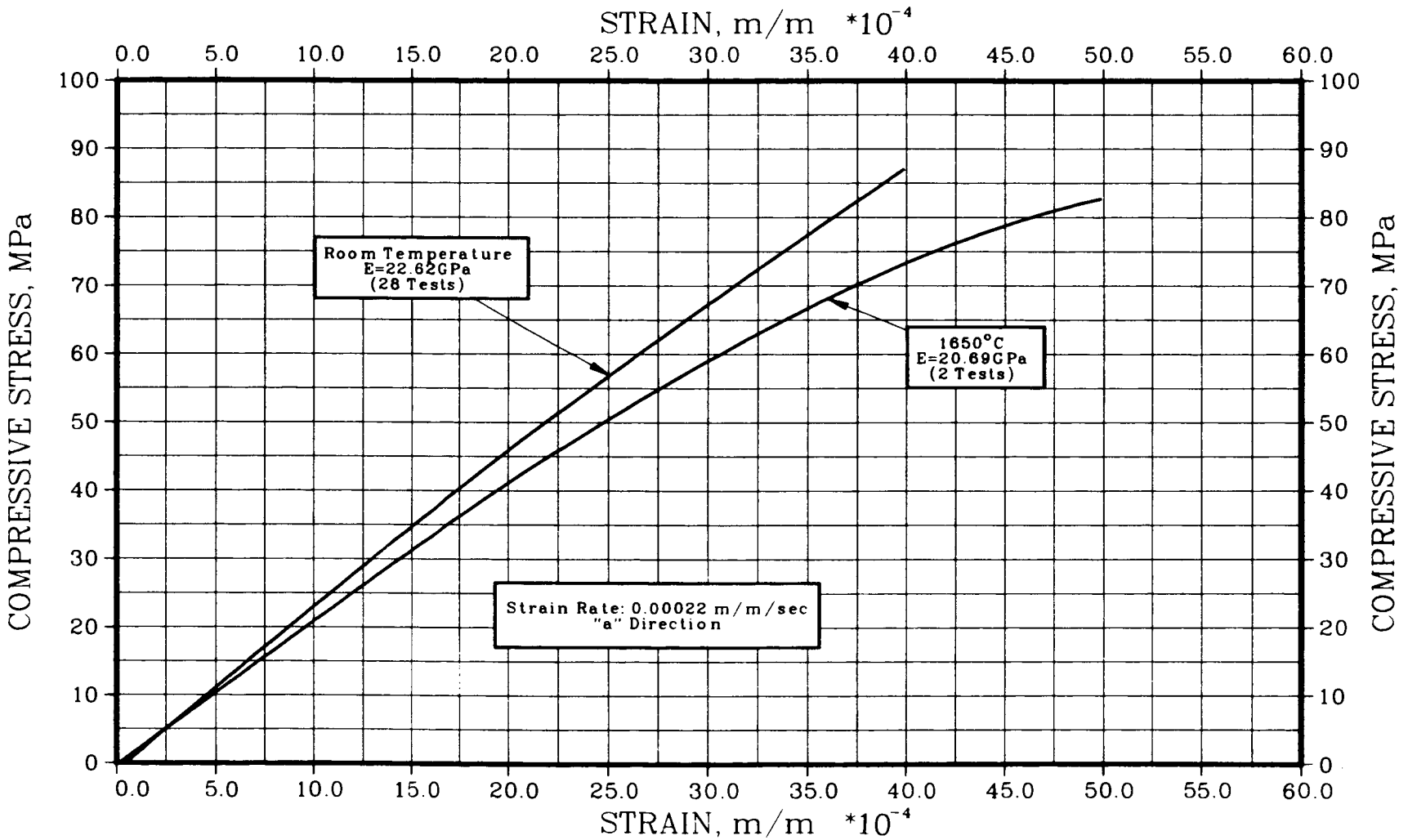
PYROLYTIC GRAPHITE	ENG. STRESS–STRAIN CURVES*	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



*Typical tensile curves.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	ENG. STRESS–STRAIN CURVES *	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

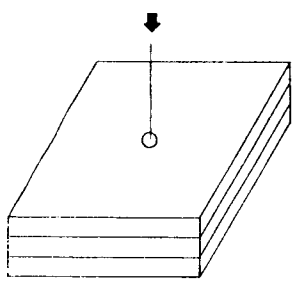


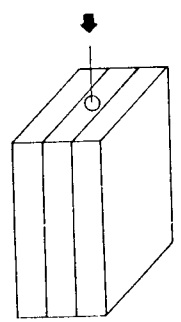
*Typical compressive curves.

HARDNESS

Pyrolytic Graphite — On Edge vs On Planes

Knoop kg/mm^2	Rockwell "L" (1/4" diam ball) 60 kg load	Shore Sclerscope
27–28	Split	70–75
84–91	127	100–105





ISOTOPIC SPACE POWER MATERIALS HANDBOOK

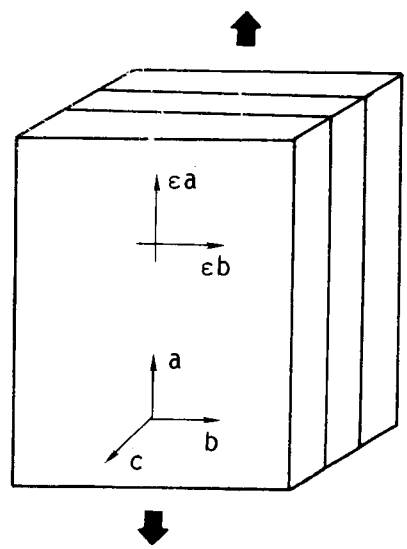
PYROLYTIC GRAPHITE	POISSON'S RATIO	Material Code: EA03 Update Code: 4.0.0

(1) Poisson's ratio in the transverse, isotropic, basal plane direction ("b" direction) as determined by loading the specimen in tension in the "a" direction is:

ν_{ab} = −0.10 to −0.20 at room temperature*

(2) Poisson's ratio in the direction perpendicular to the basal planes ("c" direction) as determined by loading the specimen in tension in the "a" direction is:

ν_{ac} = +0.90 to +0.95 at room temperature*



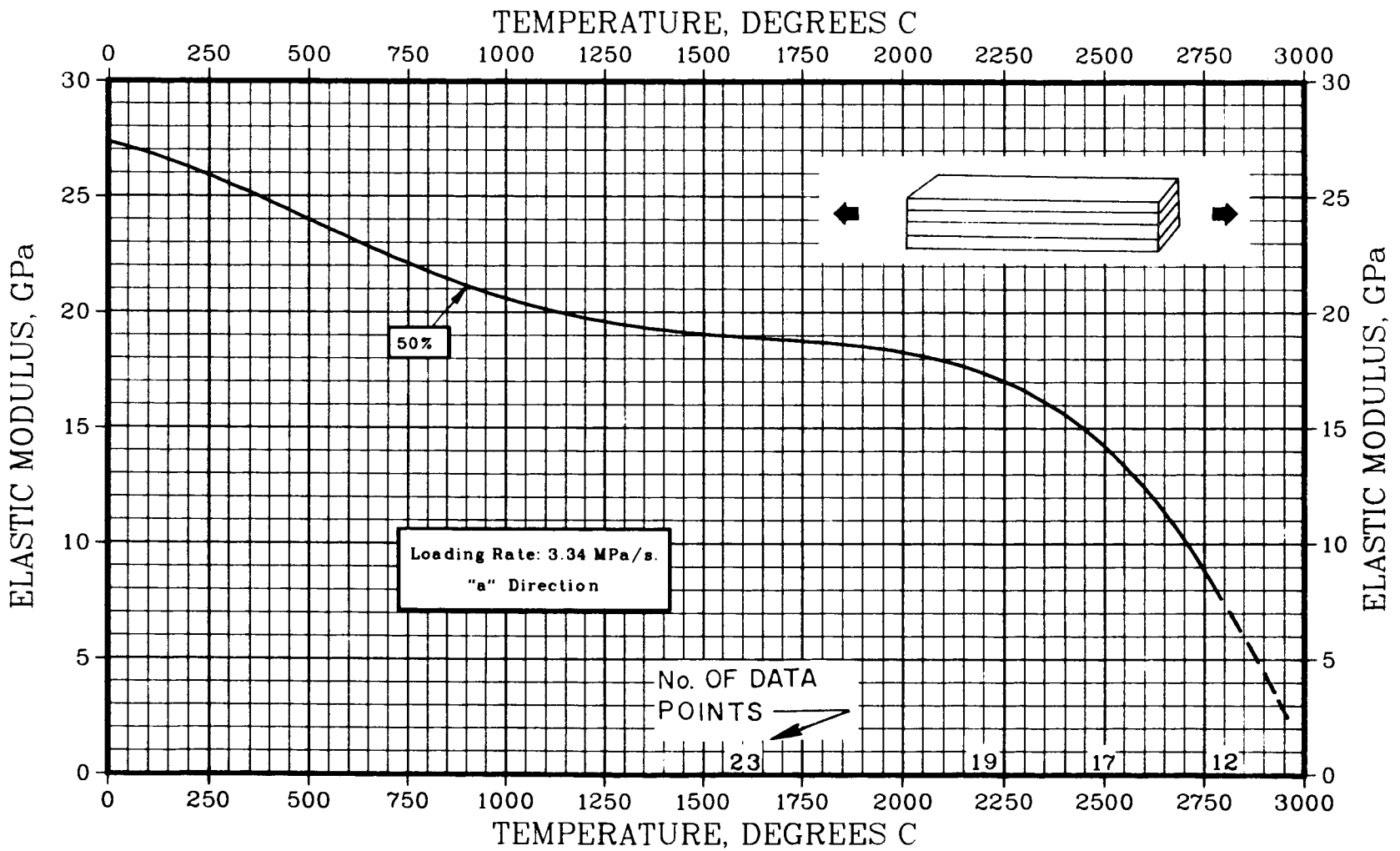
*NOTE:

Minus indicates expansion
Positive indicates contraction

Ref. 4a

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

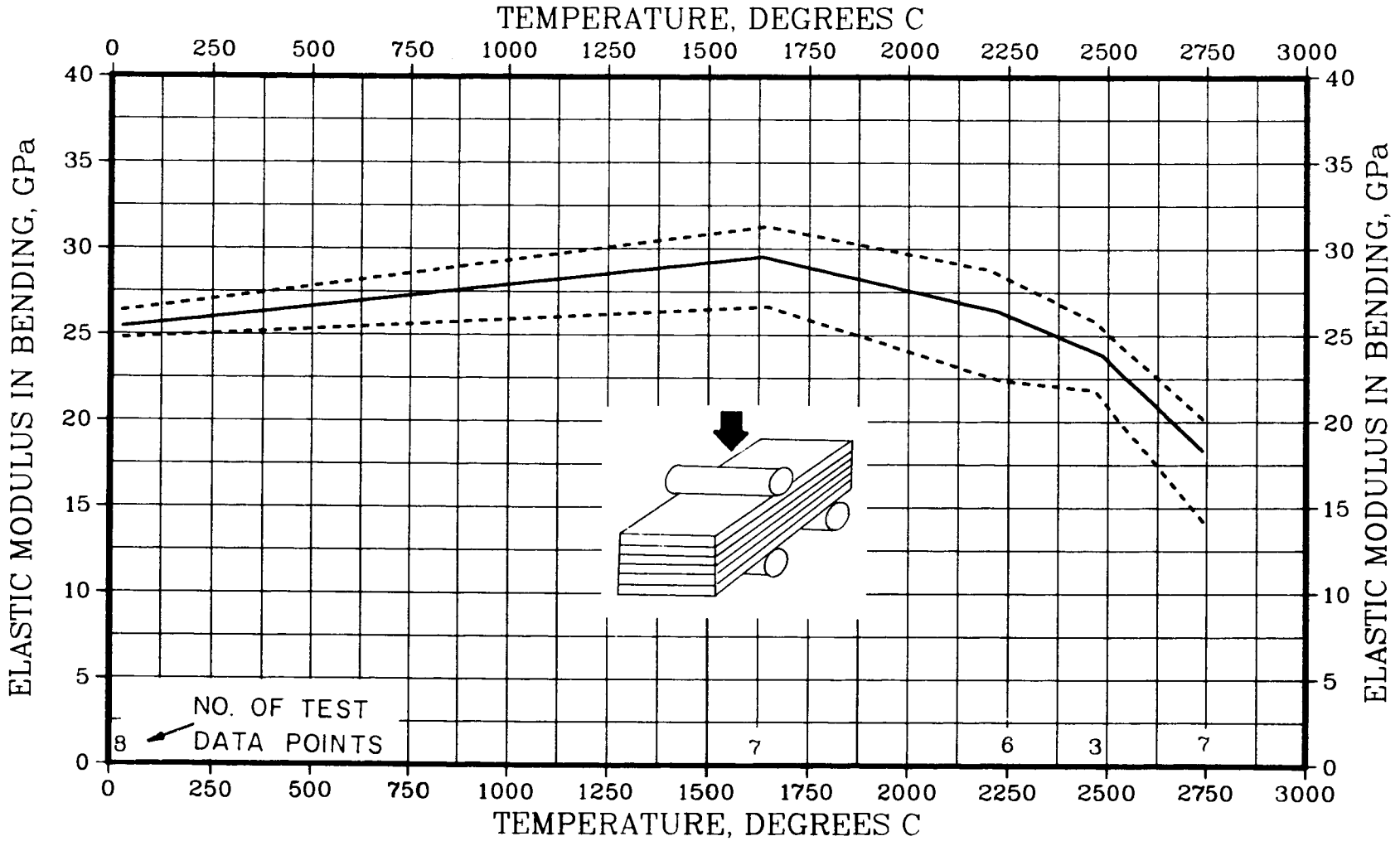
PYROLYTIC GRAPHITE	YOUNG'S MODULUS, TENSION	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



NOTE: Percentage indicates the probability that a given piece of pyrolytic graphite will have an equal or greater modulus than shown with 90% confidence.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	YOUNG'S MODULUS, BENDING	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



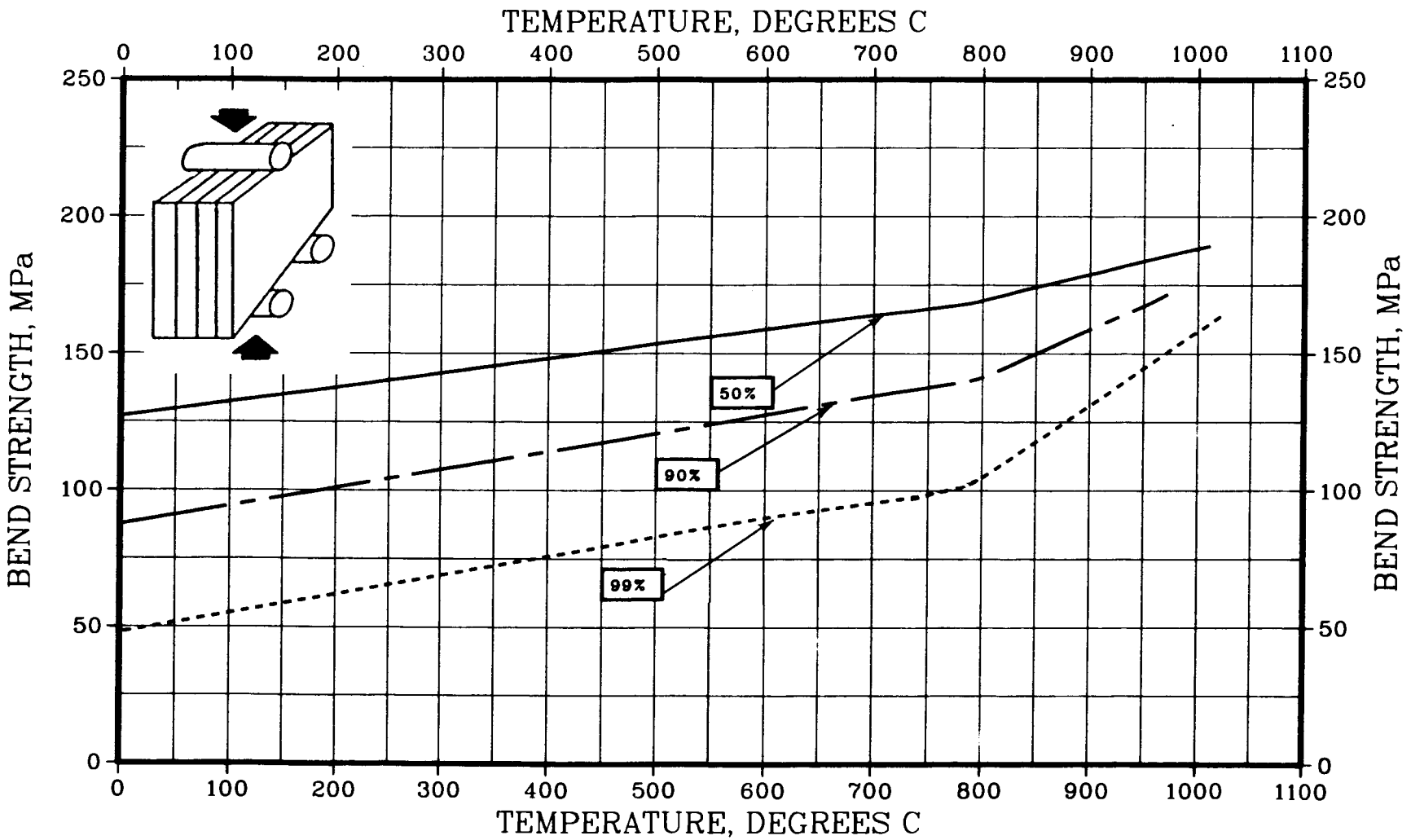
— — — — Limit of data scatter
——— Arithmetic mean

PROPERTY CODE 2111

PAGE 2.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

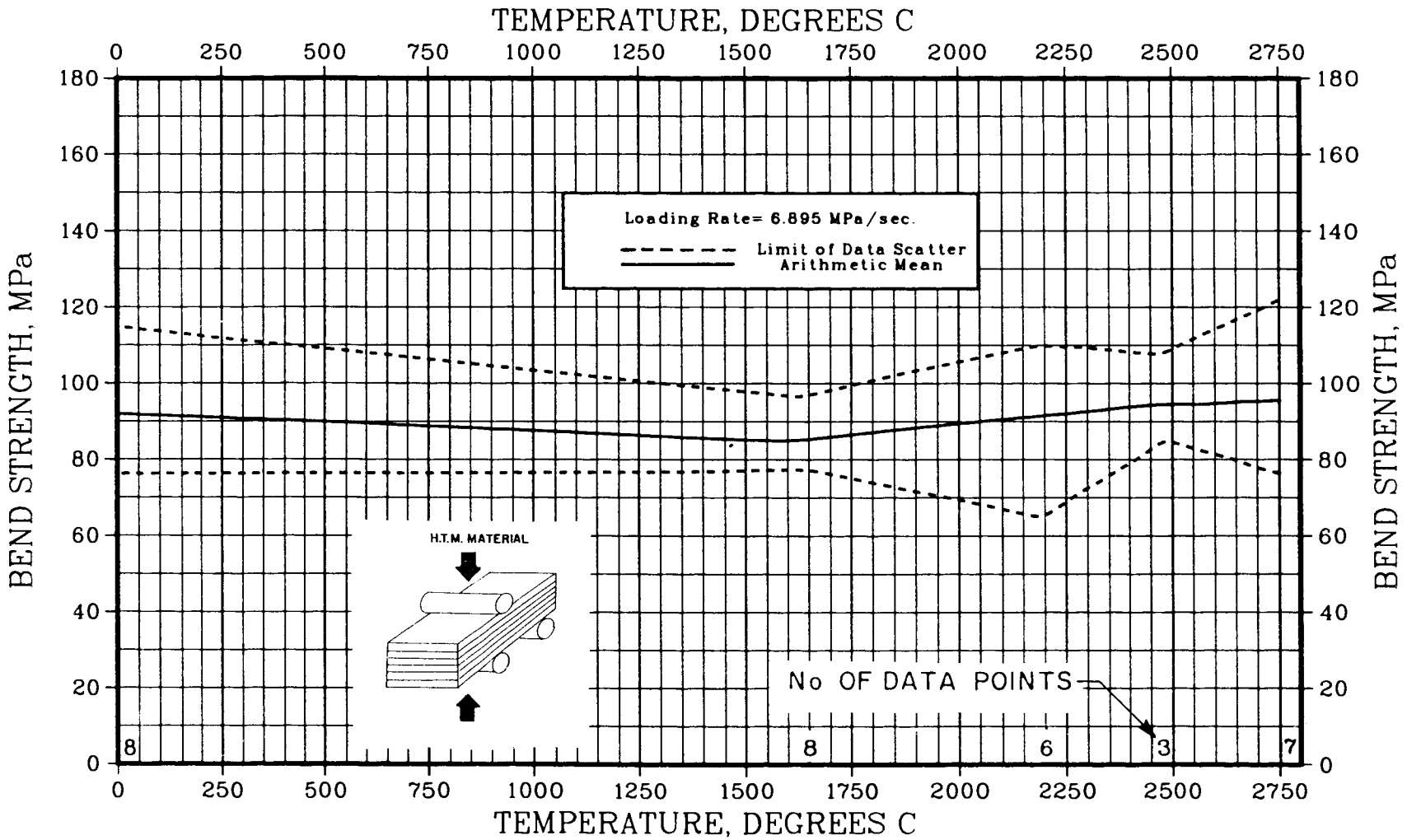
PYROLYTIC GRAPHITE	BENDING STRENGTH	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



Bending strength modulus, with load applied parallel to basal plane.
NOTE: Percentages indicate the probability that a given piece of pyrolytic graphite will have bending strength equal or greater than shown, with confidence <90%.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

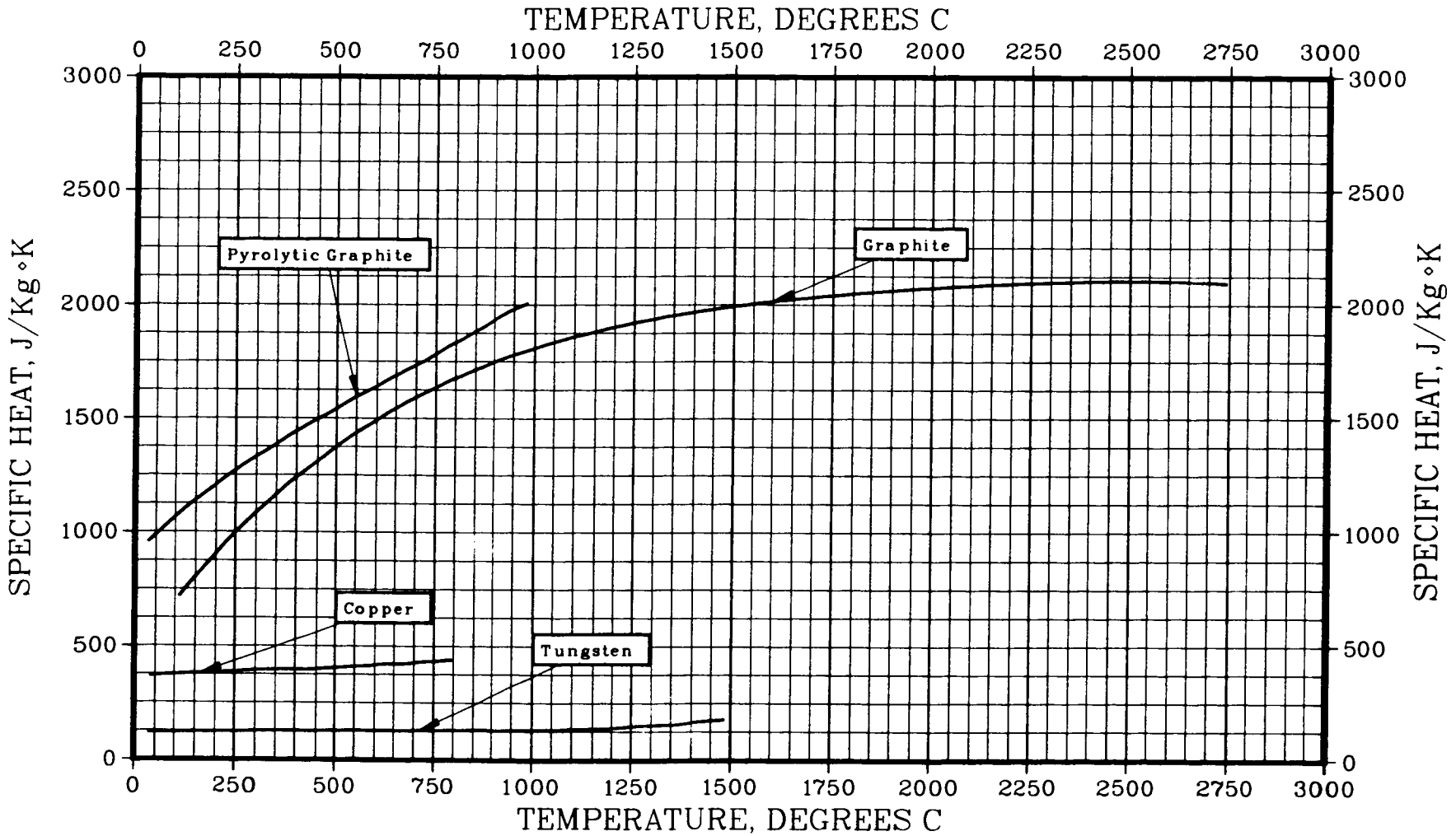
PYROLYTIC GRAPHITE	BEND STRENGTH	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



Bend strength with load applied normal to basal plane.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	COMPARATIVE SPECIFIC HEAT	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

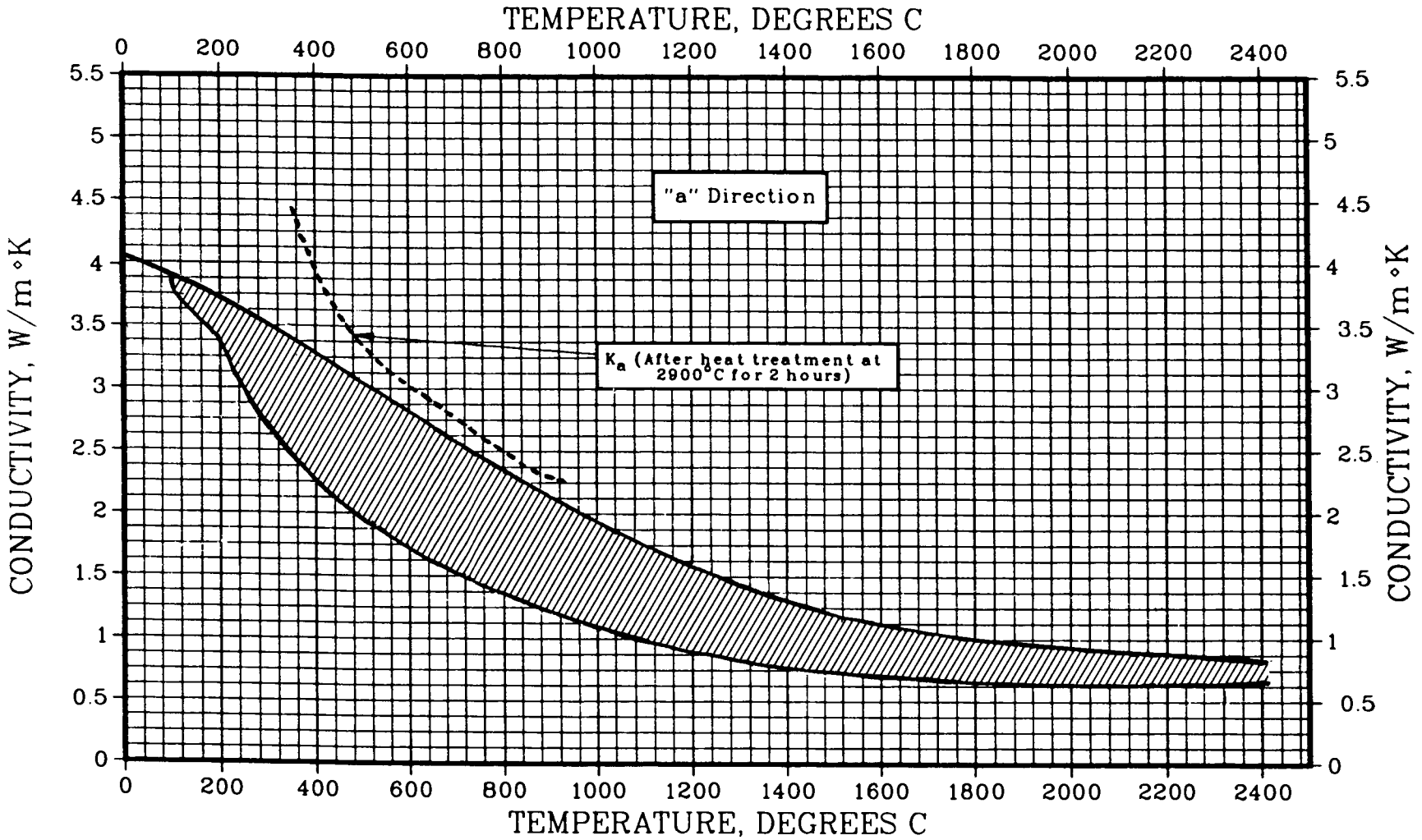


PROPERTY CODE 3108

PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	THERMAL CONDUCTIVITY	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

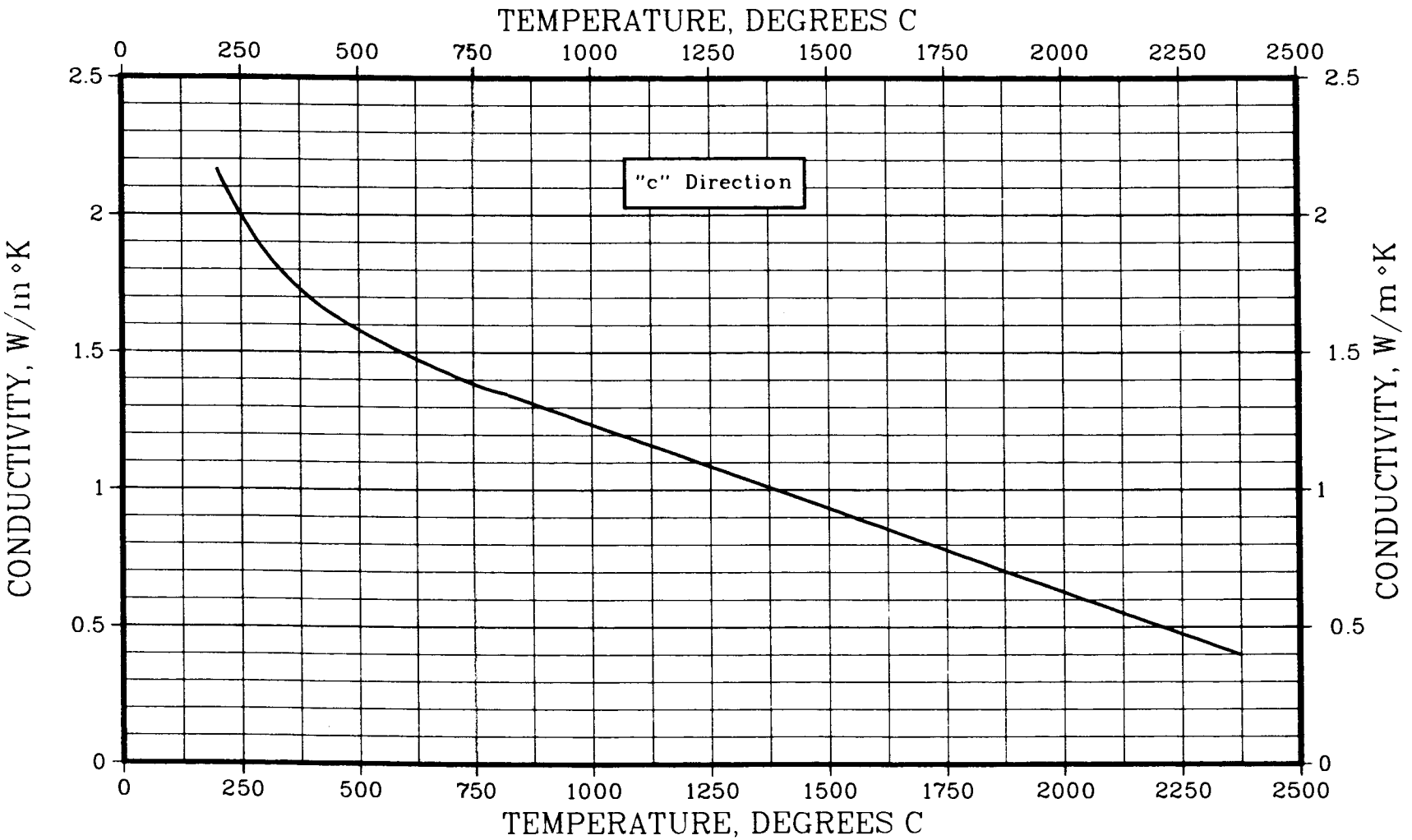


PROPERTY CODE 3112

PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

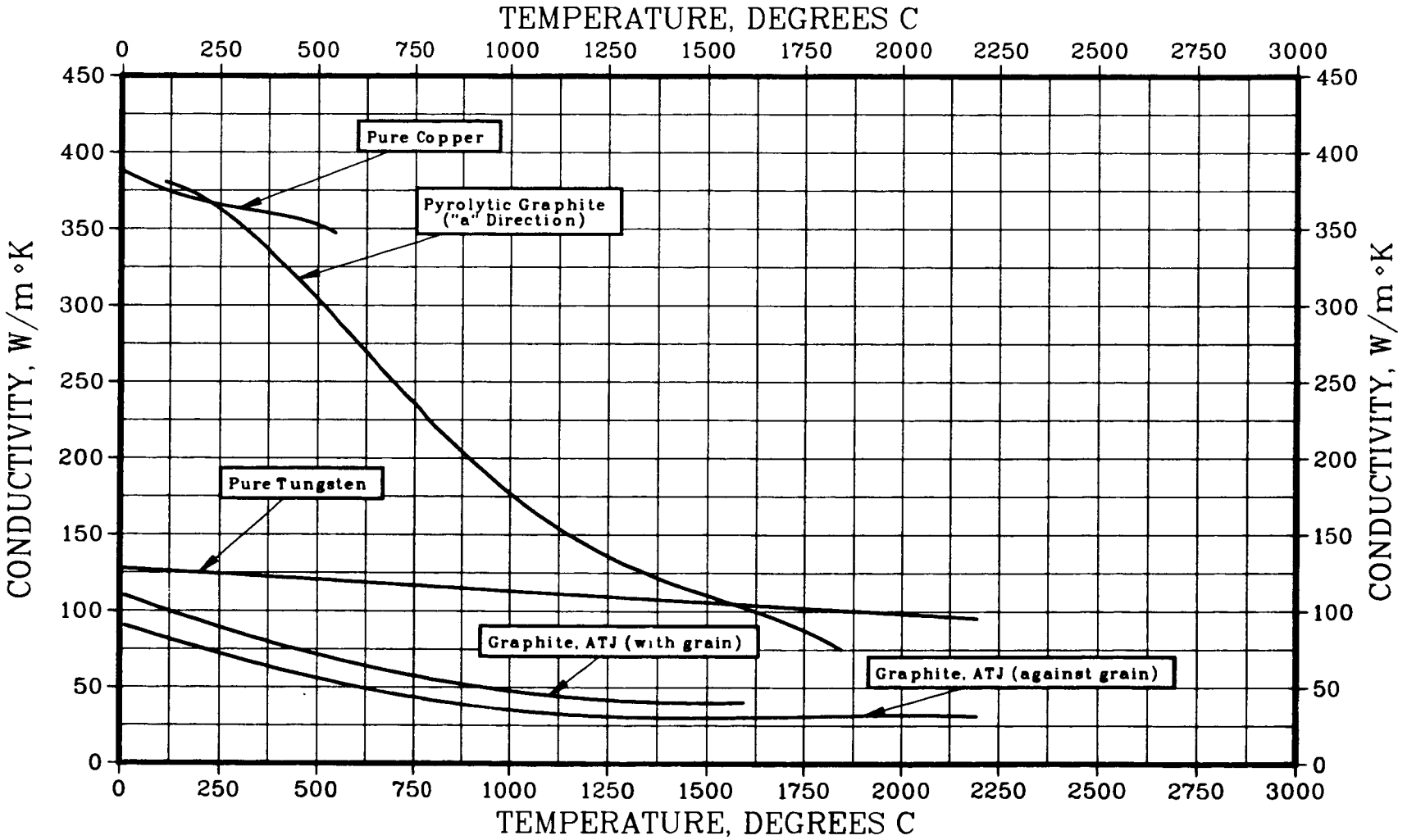
PYROLYTIC GRAPHITE	THERMAL CONDUCTIVITY	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



PROPERTY CODE 3112 PAGE 2.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

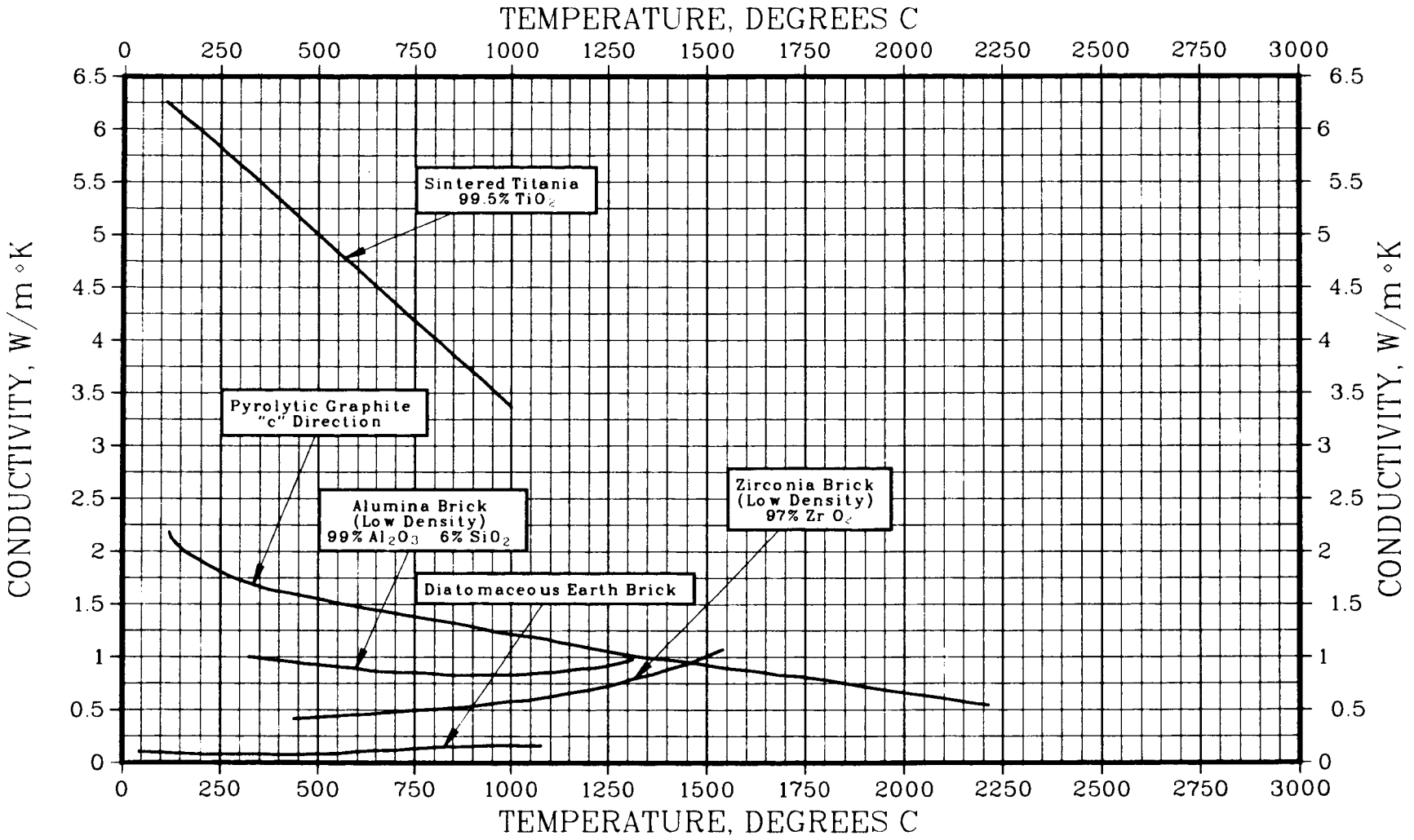
PYROLYTIC GRAPHITE	COMP. THERMAL CONDUCTIVITY	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



Comparative Thermal Conductivity.
NOTE: See Page 3.1 for more comparisons.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

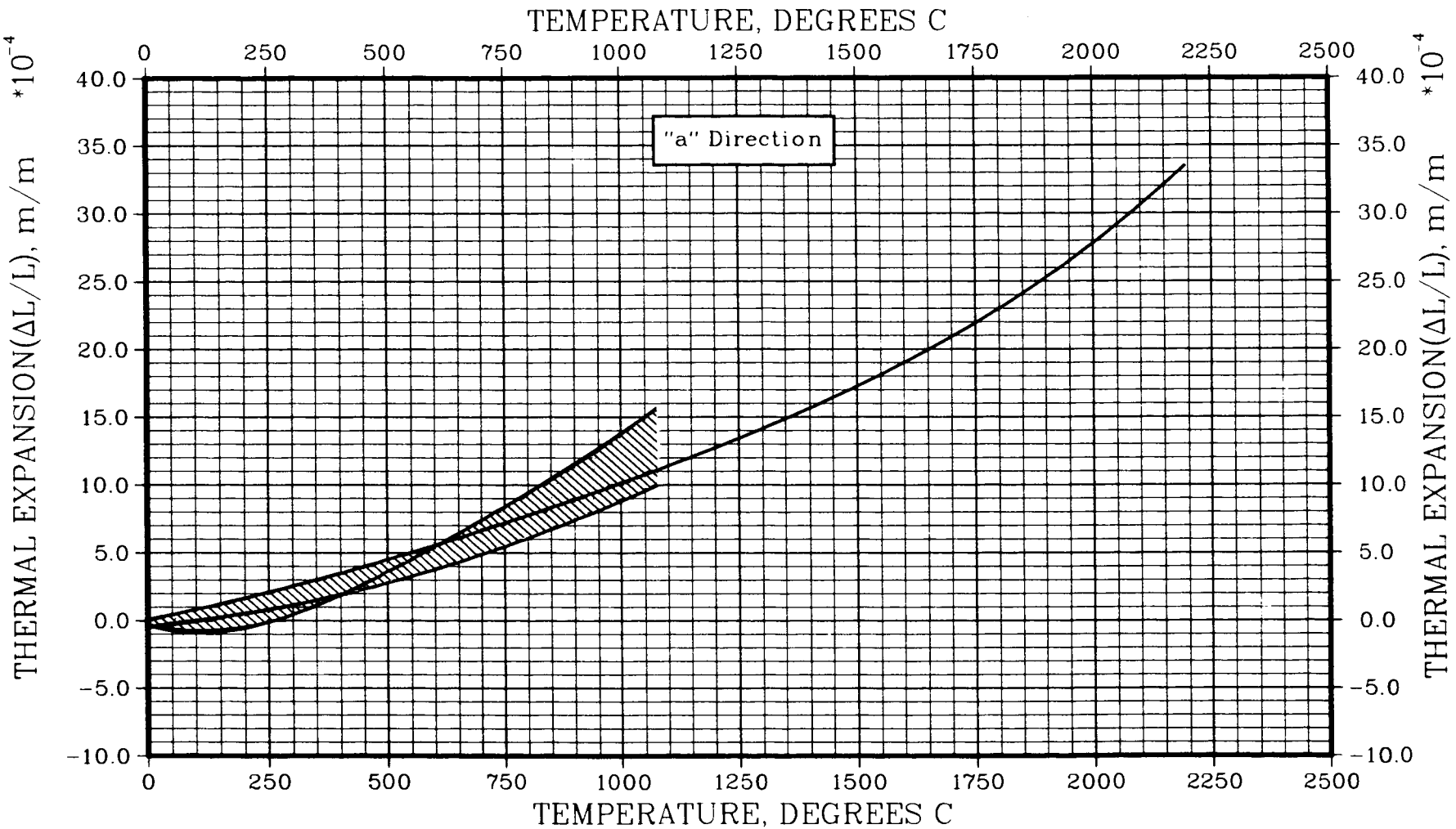
PYROLYTIC GRAPHITE	THERMAL CONDUCTIVITY	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



Reference 4a.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	THERMAL EXPANSION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

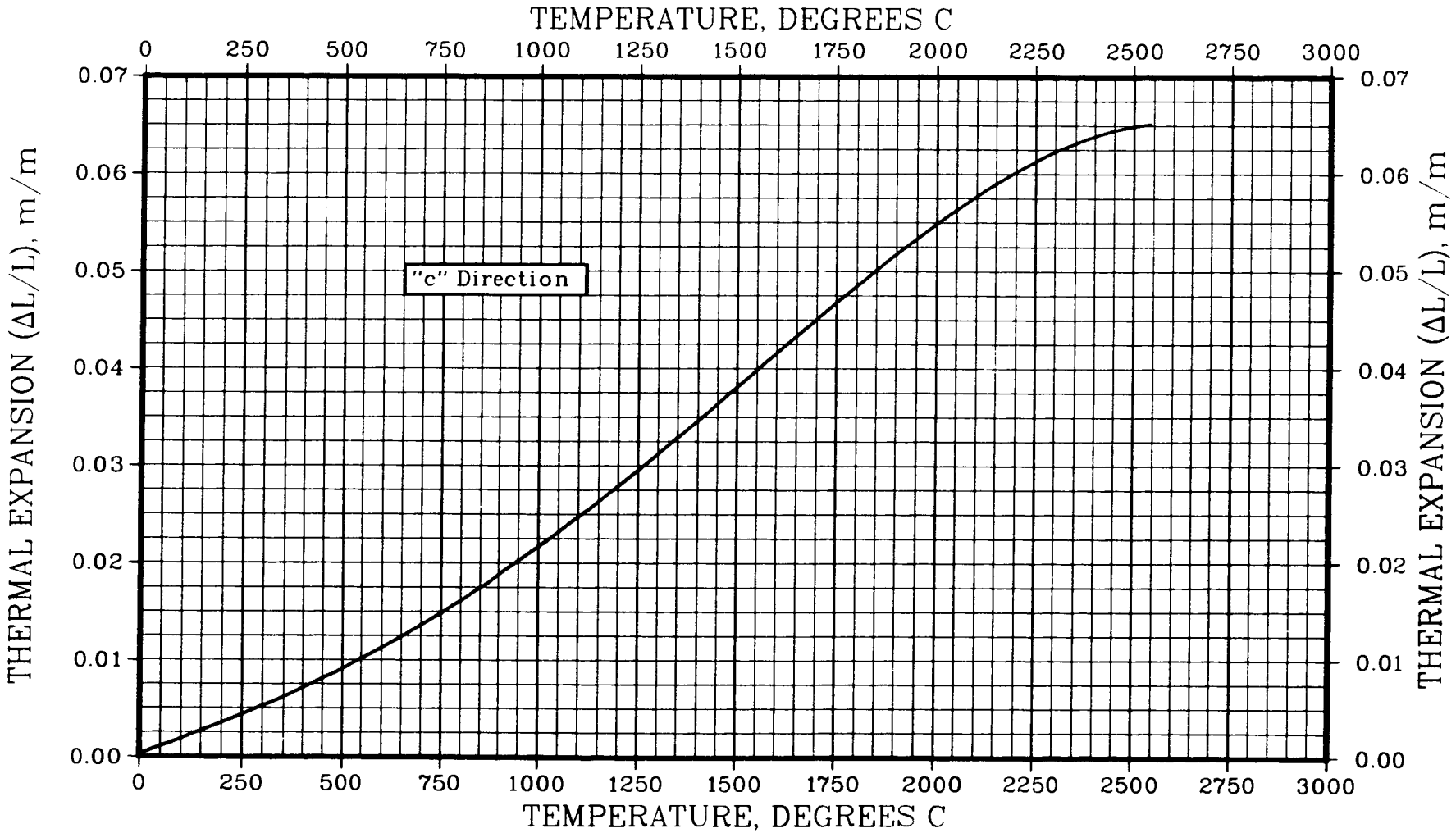


PROPERTY CODE 3114

PAGE 1.0

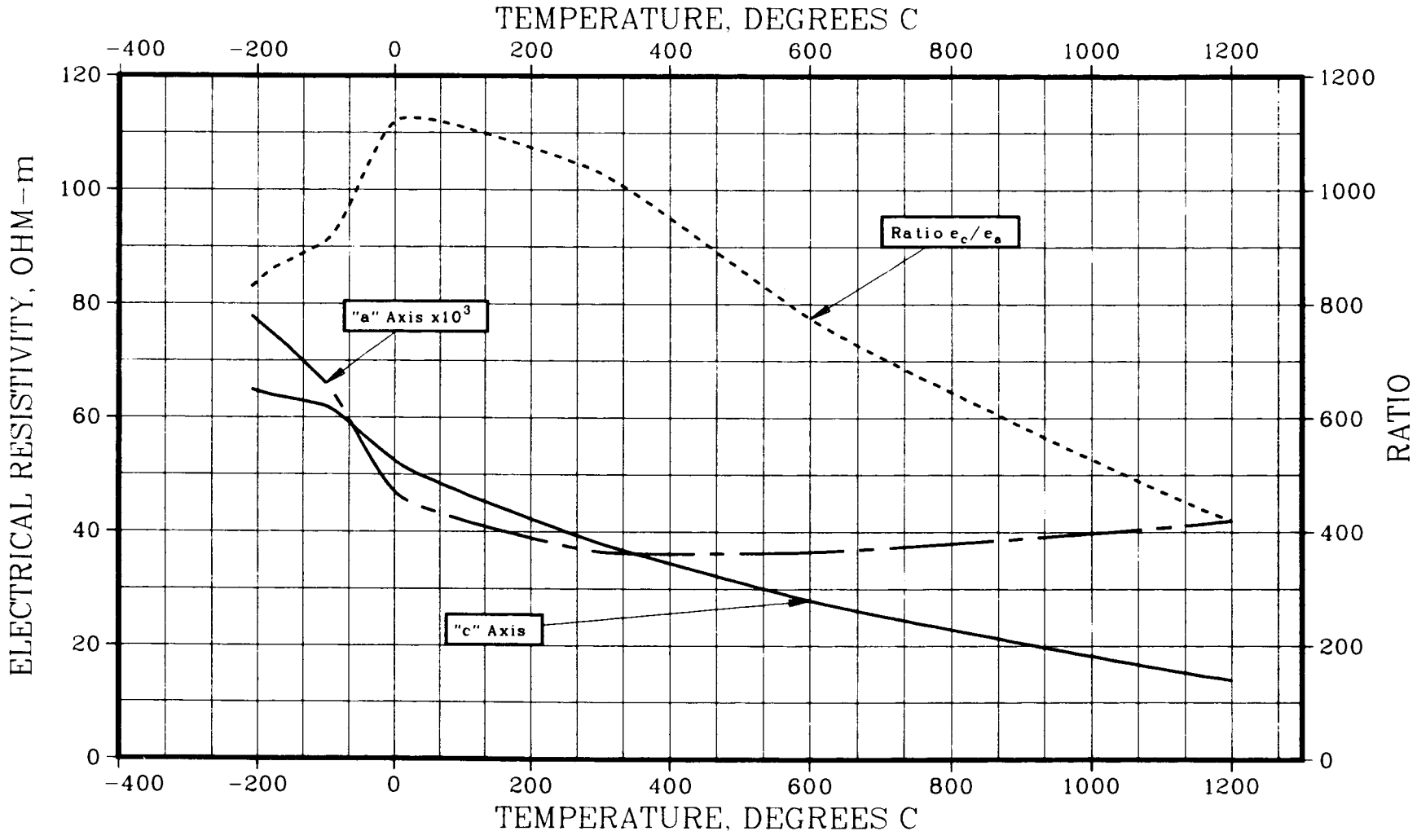
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	THERMAL EXPANSION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	ELECTRICAL RESISTIVITY	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0

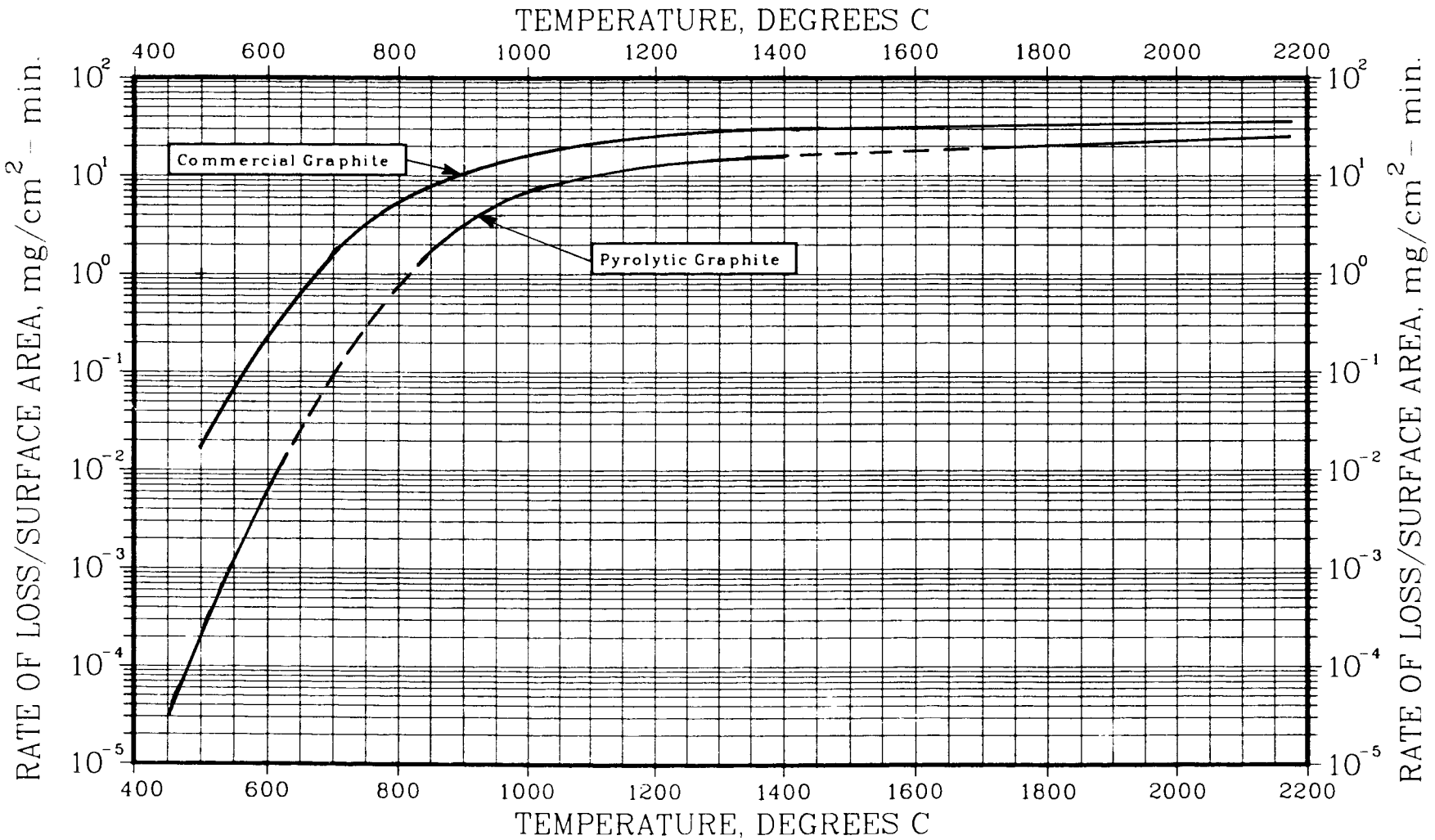


NOTE: Resistivity is dependent on deposition temperature, which was 2100°C for this material.

PROPERTY CODE 3201 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	COMPARATIVE OXIDATION IN AIR	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



Specific gravities: Pyrolytic graphite = 2.2
Commercial graphite = 1.7
Slow moving air, 180 CFM maximum.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	REACTIONS WITH AQUEOUS MEDIA	Material Code: EA03 Update Code: 4.0.0

M = Machined
AD = As-deposited

Graphite	Chemical	Time (hr)	Temperature (°F)	Changes
M	Water	20	RT	None
M	Water vapor	20	RT	None
M	5% diethanol amine in water	20	RT	None
M	5% KOH in water	20	RT	None
M	H_2SO_4, conc.	20	RT	None
M	H_2SO_4, conc.	1	200	None
M	HNO_3, conc.	20	RT	None
M	HNO_3, conc.	1	200	None
M	Chromic soln. A	20	RT	None
M	Chromic soln. B	20	RT	None
M	Chormic soln. B	1	200	Strong attack on all sides. Exfoliation & separation of layers. Formation of black powder on surface. No change in c-layer spacing.
M	Chlorate soln.	20	RT	Immediate action.
AD	Chlorate soln.	20	RT	Exfoliation and separation of layers, opening of gaps and cracks. Action seems stronger on AD samples. Change in c-layer spacing.
M	Hydrogen peroxide 30%	20	RT	None

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

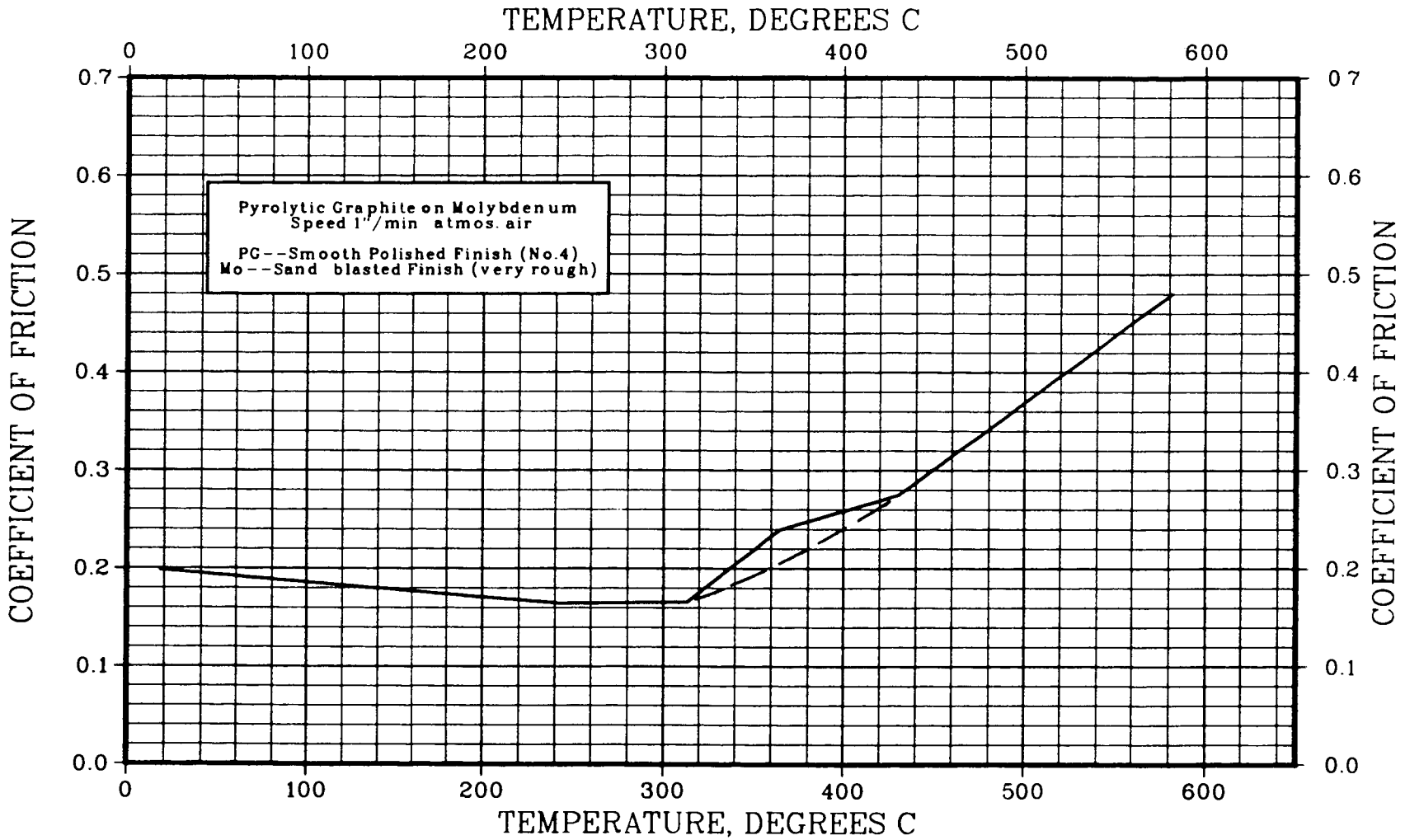
PYROLYTIC GRAPHITE	REACTIONS WITH OTHER SUBSTANCES	Material Code: EA03 Update Code: 4.0.0

Graphite	Chemical	Time (hr)	Temperature (°F)	Changes
M	Trichloroethylene	1	195	None
	Chromic soln. B	40	RT	
M	Isopropyl Alcohol	20	RT	None
M	O-cresol	20	RT	None
M	Carbon tetrachloride	20	RT	None
M	Formaldehyde	20	RT	None
M	Acetone	20	RT	None
M	Formic Acid	20	RT	None
M	Ethyl acetate	20	RT	None
M	Titanium tetra-chloride	20	RT	None
M	2-methyl butane	20	RT	None
M	Benzene	20	RT	None
M	Benzene	20	RT	None
	H_2SO_4, conc.	20	RT	
M	Benzene	20	RT	None
	HNO_3, conc.	20	RT	
M	Benzene	20	RT	None
	Chromic soln. A	20	RT	
M	Xylene	1	285	None
M	Xylene	1	285	None
	Chromic soln. B	40	RT	
M	Trichloroethylene	1	195	None

Ref. 4b3

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

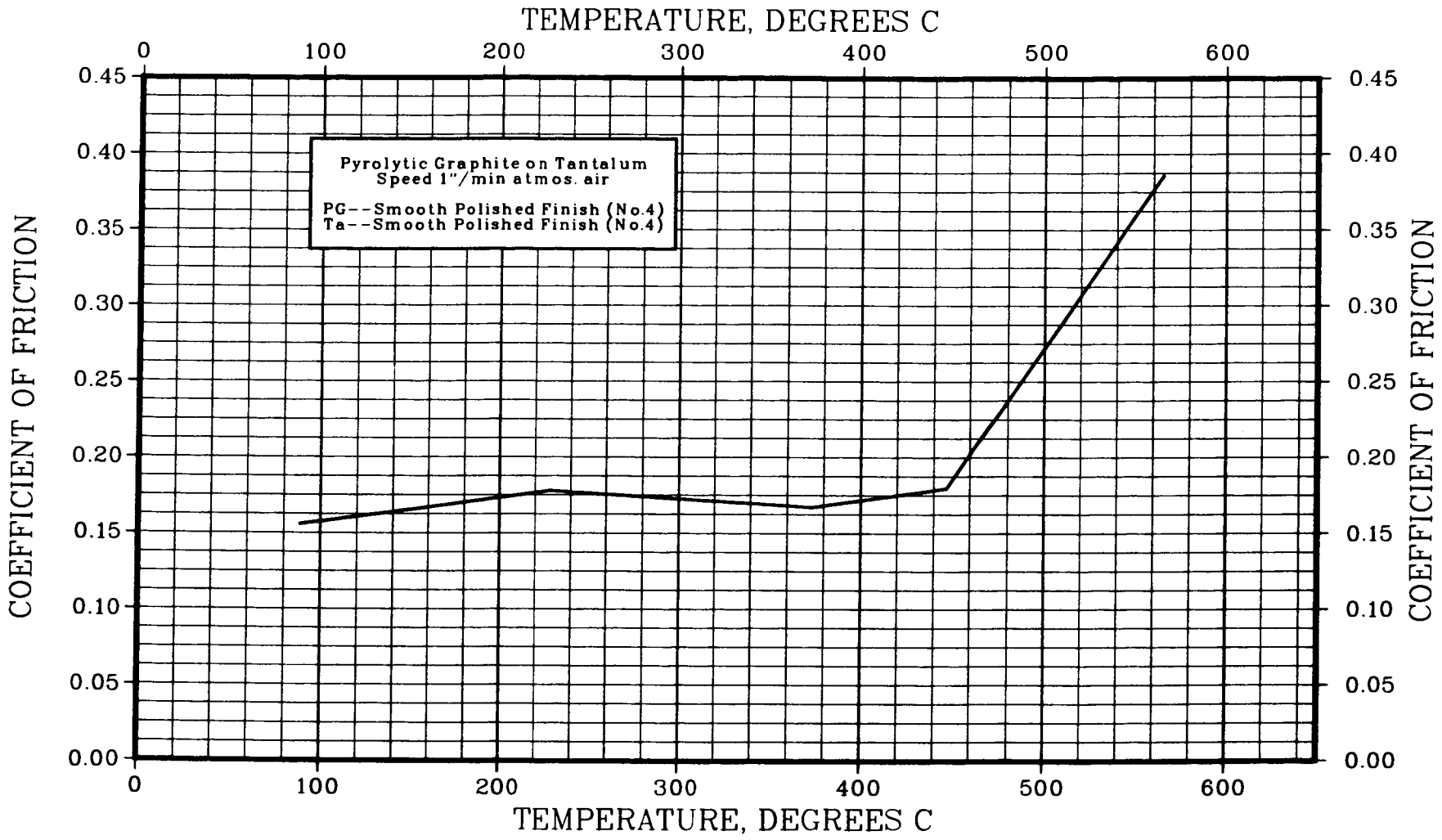
PYROLYTIC GRAPHITE	COEFFICIENTS OF FRICTION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.
See the following pages for more coefficients of friction.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	COEFFICIENT OF FRICTION	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.
See the following pages for more coefficients of friction.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	COEFFICIENTS OF FRICTION IN AIR	Material Code: EA03 Update Code: 4.0.0

Coefficient of Static and Sliding Friction
of Pyrolytic Graphite on Several Materials at Room Temperature

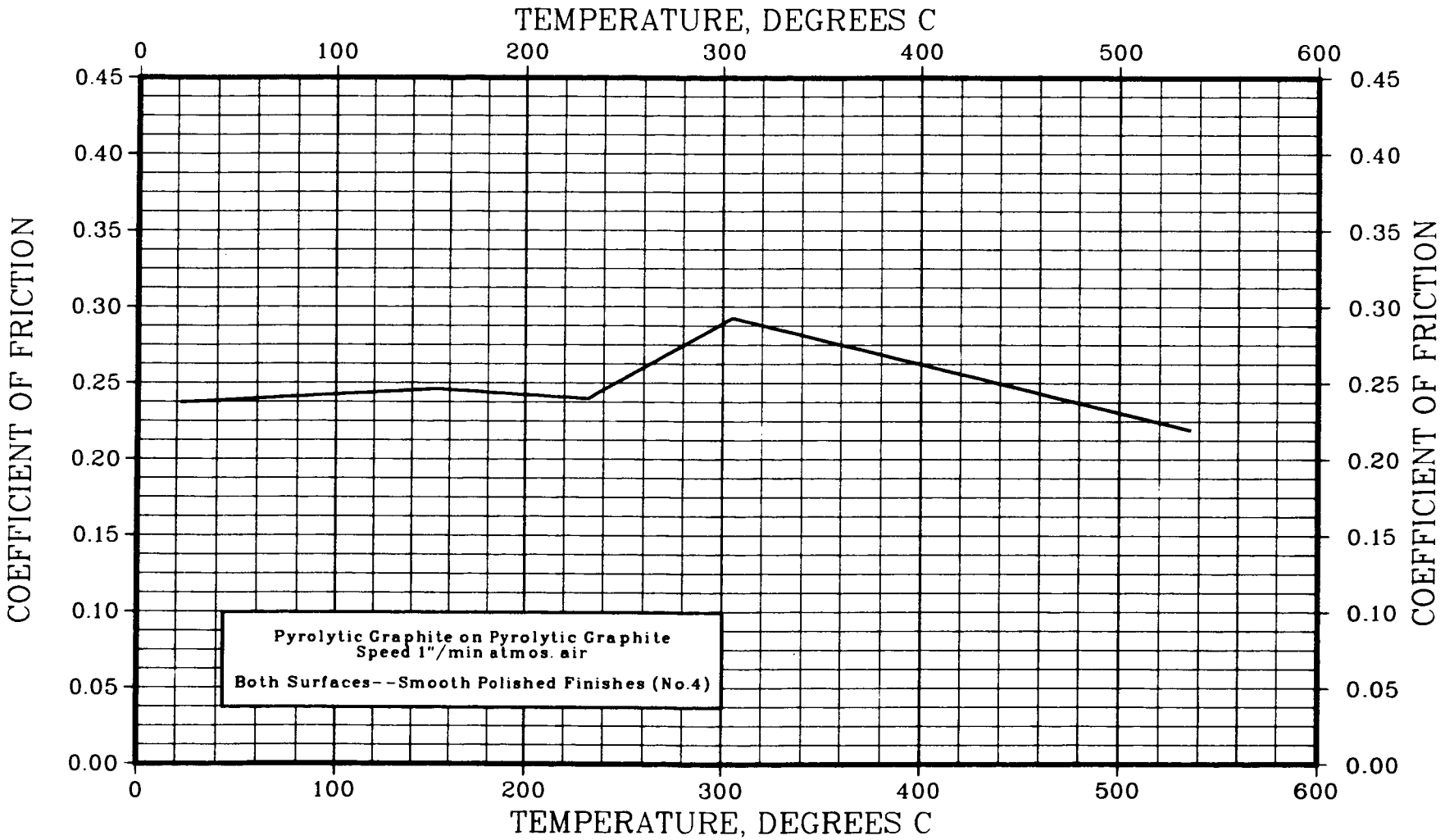
PG on	Surface Roughness (microinches)	Static	Sliding
PG	4	0.23	0.17
Brass	63	0.30	0.25
Tungsten	16	0.18	0.15
Copper	63	0.35	0.31
Molybdenum	Sand Blasted	0.27	0.18
Molybdenum	4	0.25	0.23
Steel (1020 C.R.)	63	0.26	0.21
Stainless (303)	63	0.30	0.25
Graphite (CS)	4	0.28	0.19
Graphite (ATJ)	4	0.25	0.21
Graphite (ATJ)	8	0.28	0.21
Tantalum	4	0.19	0.16

NOTE: Same Pyrolytic Graphite sample used in all tests. After each test the Pyrolytic Graphite sample was repolished. It had a surface roughness of 4 microinches. Load was applied at the rate of 1 in./min. All tests conducted in air.

Ref. 4a

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

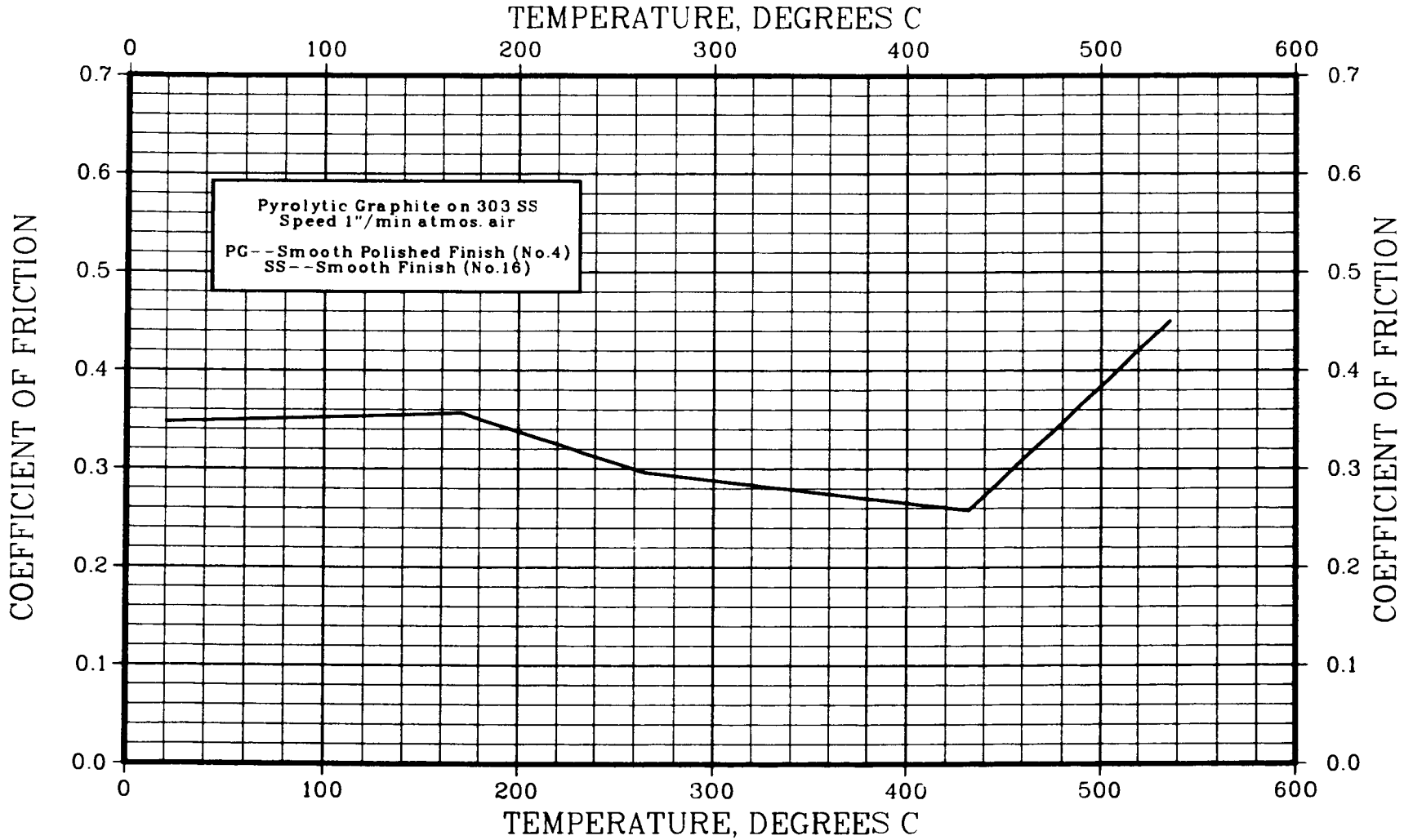
PYROLYTIC GRAPHITE	COEFFICIENT OF FRICTION	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.
See the following pages for more coefficients of friction.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

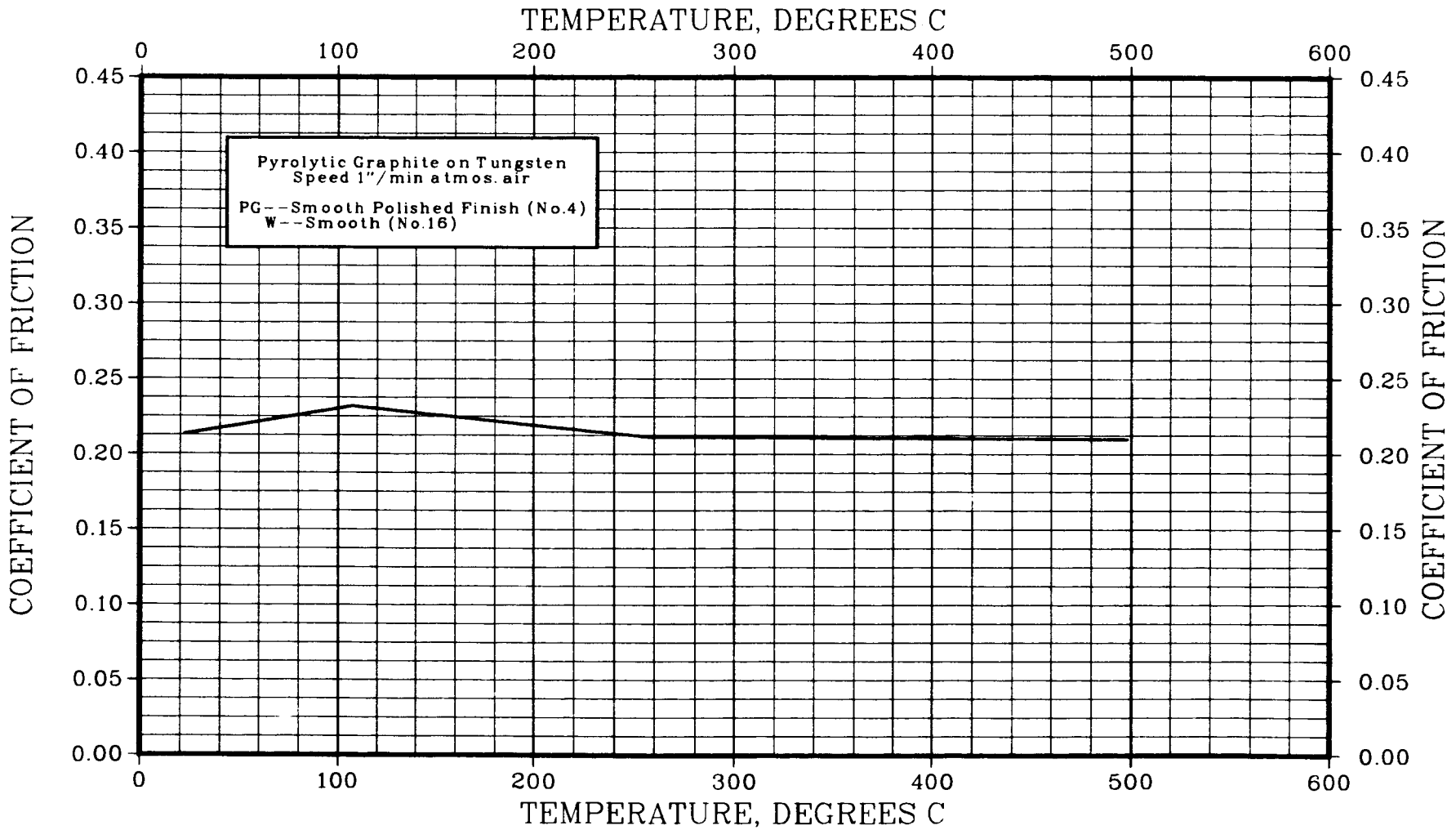
PYROLYTIC GRAPHITE	COEFFICIENTS OF FRICTION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.
See the following pages for more coefficients of friction.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

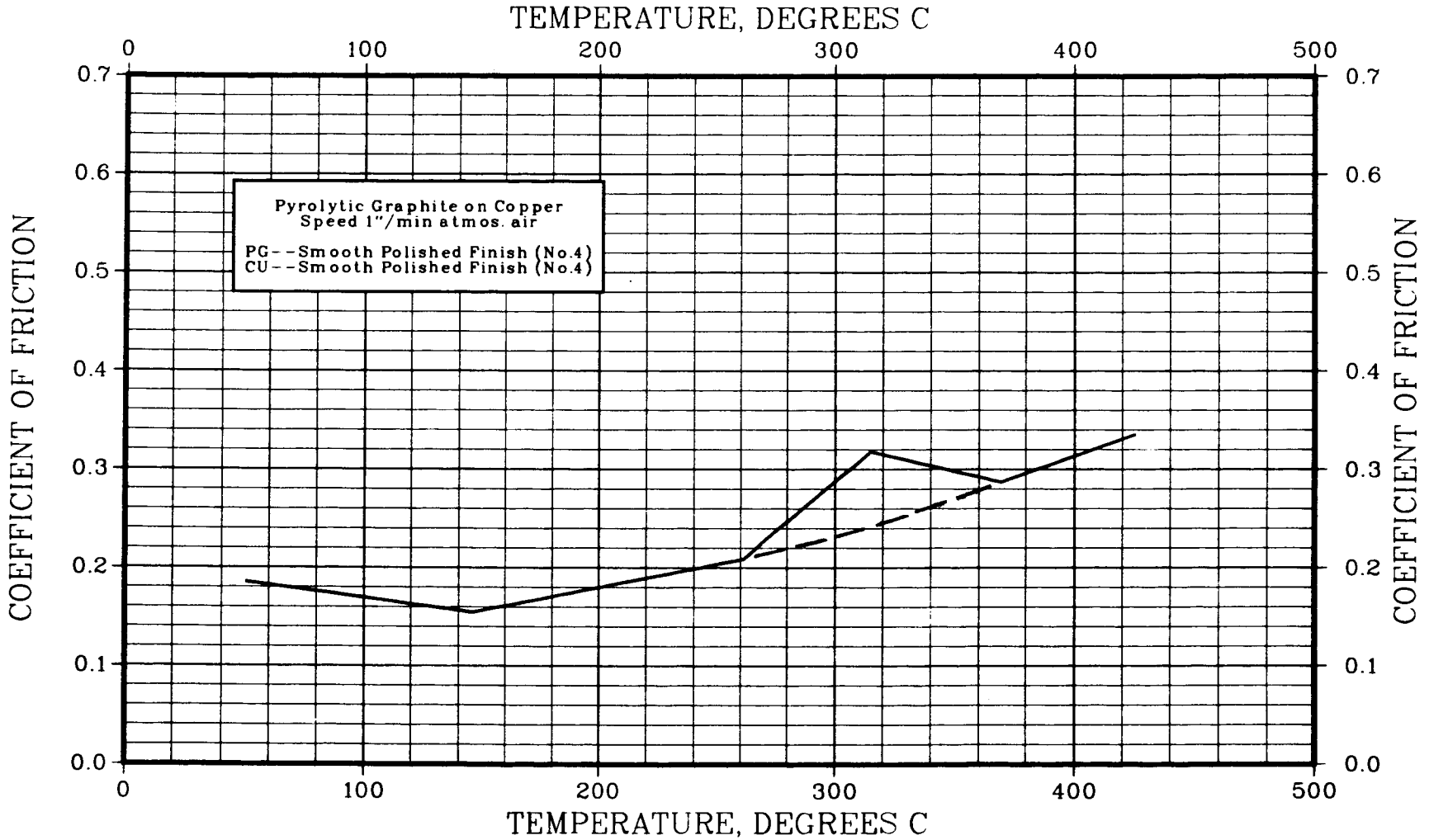
PYROLYTIC GRAPHITE	COEFFICIENT OF FRICTION	MATERIAL CODE: EA03
		UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.
See the following pages for more coefficients of friction.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PYROLYTIC GRAPHITE	COEFFICIENTS OF FRICTION	MATERIAL CODE: EA03 UPDATE CODE: 4.0.0



NOTE: Finish numbers refer to the surface roughness in microinches.
Reference 4a.

ORNL/TM-8949

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION
Radioisotope Thermoelectric
Generator Materals
(FTP/A 01322) Production and
Technology Program

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Compiled by:

G. L. Copeland
R. L. Heestand
C. R. Kennedy
J. F. King
M. F. Marchbanks*
R. K. Williams

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*Engineering Technology Division,
Oak Ridge National Laboratory, Oak Ridge, Tennessee

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Oak Ridge, Tennessee 37830
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ABSTRACT

Properties are compiled for the materials in the Modular Isotopic Thermoelectric Generators (MITG) being developed by General Electric and Thermo Electron for the U.S. Department of Energy's Office of Special Nuclear Projects. Data on properties needed for design, performance review, and safety analysis are included.

Insertion Instructions Based on the ISPMH Page Filing System:

PROPERTY CODE Ⓐ **PAGE** Ⓑ

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Ⓒ	Ⓓ	Ⓔ Ⓕ

Appendix A of the ISPMH contains a detailed description of the ISPMH and should be consulted by those not already familiar with the page filing system. In addition, the following detailed page insertion instruction steps are offered and refer to the circled letters in the above example (same as Fig. A.1 in Appendix A). Note that occasionally there may be exceptions to some of these general rules. In such cases, the insertion procedures to be used will be explained in the accompanying letter and instructions.

1. Check the Red tabs in the binder to find the Part Code coinciding with the Part Code of the page to be inserted. The Part Code is the first character in the Material Code (Ⓔ above).

2. Check the Blue tabs located right after the correct Part tab to find the Group Code coinciding the the Group Code of the Page to be inserted. The Group Code is the second character in both the Material Code (Ⓔ above) and on the blue tab.

3. Check the Yellow Table of Contents/Materials pages immediately after the correct Group tab to find the Section Code coinciding with the Section Code of the page to be inserted. The Section Code is the last 2 characters in the Material Code (Ⓔ above). Note that in some cases the Table of Contents/Materials page itself will be replaced.

4. The Property Codes within each section are organized in ascending order, and the page from the Update should be inserted in sequence.

5. Page Numbers for each Property Code are organized in ascending order starting with 1.0.

6. To determine if individual pages in the Update Package are new or replacement pages: If the Material Code, Property Code, and Page Number coincide with those of a current ISPMH page, then those specific pages are to be discarded. Note that the Update Code on the replacement page will differ from that of the discarded page. CAUTION: DOUBLE CHECK WITH THE LISTINGS IN ENCLOSURE #2. If there is no match between the Material Code, Property Code, and Page Number of any pages in the Update Pckage and current pages, then the Update pages are new, and no current pages are to be discarded. Note that the last two characters in the Update Code will be 0.0 in this case.

Incidentally, if your Update Package accidentally gets shuffled, it may be reassembled using the "Collation Control Code" in the lower right-hand corner of every page. This code indicates Update Number/Volume Number-Sequence Number of the page in this Update Package.

LISTING OF NEW AND REVISED PAGES IN
UPDATE PACKAGE No. 1

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]	
Revision	Control Page	Revision Control Tab	2-vii	Blank	3-vii	Blank	(R)	Current revision No. and date added.
BA05	3112	2-23	*** None ***		3-1	3-2	(N/N)	New pages.
BA05	3112	3-2*	*** None ***		3-3	Blank	(N)	New page.
BA05	3201	3-3*	2-29	Blank	3-5	3-6	(F/N)	Tables were added. No change to curves.
BA05	3201	3-6*	*** None ***		3-7	Blank	(N)	Tables were added. No change to curves.
BA05	3207	3-7*	2-31	Blank	3-9	3-10	(F/N)	Tables were added. No change to curves.
BA05	3207	3-10*	*** None ***		3-11	Blank	(N)	Tables were added. No change to curves.
BA06	3112	2-33	2-35	Blank	3-13	3-14	(F/N)	Tables were added. No change to curves.
BA06	3112	3-14*	*** None ***		3-15	Blank	(N)	Tables were added. No change to curves.
BA07	3112	2-45	2-47	Blank	3-17	3-18	(F/N)	Tables were added. No change to curves.
BA07	3201	3-18*	2-49	Blank	3-19	3-20	(F/N)	Tables were added. No change to curves.
BA07	3201	3-20*	*** None ***		3-21	Blank	(N)	Tables were added. No change to curves.
BA08	3112	2-55	2-57	Blank	3-23	3-24	(F/N)	Tables were added. No change to curves.

[a] TC/P indicates a yellow-colored Table of Contents/Properties page.

[b] These are the pages or tabs currently in the Handbook that will be used to indicate the location of the page to be inserted. The new or replacement page is to be placed immediately following the page listed here. An asterisk (*) is placed by this CCC (see footnote *c*) if the page was one you just inserted from the Update Package.

[c] CCC (the number listed in this column) is the Collation Control Code located at the bottom right-hand side of each page.

[d] The letters in parentheses indicate the nature of the page being inserted: "N" indicates a new page, "R" indicates a revised page, and "F" indicates a "flip side," i.e., the unchanged side of a sheet having changes on one side only.

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]
BA08	3201	3-24*	2-59	Blank	3-25	3-26	(F/N) Tables were added. No change to curves.
BA08	3207	3-26*	2-61	Blank	3-27	3-28	(F/N) Tables were added. No change to curves.
TC/P	—	0-117	*** None ***		3-29	Blank	(N) New page.
EA02	1000	3-29*	*** None ***		3-31	3-32	(N/N) New pages.
EA02	2100	3-32*	*** None ***		3-33	3-34	(N/N) New pages.
EA02	2101	3-34*	*** None ***		3-35	3-36	(N/N) New pages.
EA02	2101	3-36*	*** None ***		3-37	3-38	(N/N) New pages.
EA02	2102	3-38*	*** None ***		3-39	3-40	(N/N) New pages.
EA02	2111	3-40*	*** None ***		3-41	3-42	(N/N) New pages.
EA02	2111	3-42*	*** None ***		3-43	3-44	(N/N) New pages.
EA02	2111	3-44*	*** None ***		3-45	3-46	(N/N) New pages.
EA02	2111	3-46*	*** None ***		3-47	3-48	(N/N) New pages.
EA02	2112	3-48*	*** None ***		3-49	3-50	(N/N) New pages.
EA02	2116	3-50*	*** None ***		3-51	3-52	(N/N) New pages.
EA02	2116	3-52*	*** None ***		3-53	3-54	(N/N) New pages.
EA02	3108	3-54*	*** None ***		3-55	Blank	(N) New page.
EA02	3111	3-55*	*** None ***		3-57	Blank	(N) New page.
EA02	3112	3-57*	*** None ***		3-59	3-60	(N/N) New pages.

Material Code	Property Code[a]	Preceding Page or Tab[b] CCC[c]	Pages to be Discarded: Front Side CCC[c]	Pages to be Discarded: Back Side CCC[c]	New or Revised Pages to be Inserted: Front Side CCC[c]	New or Revised Pages to be Inserted: Back Side CCC[c]	Description of Change or Addition (Front Side/Back Side)[d]
EA02	3114	3-60*	*** None ***		3-61	3-62	(N/N) New pages.
EA04	TC/P	3-62*	*** None ***		3-63	3-64	(N/N) New pages.
EA04	TC/P	3-64*	*** None ***		3-65	Blank	(N) New page.
EA04	1000	3-65*	*** None ***		3-67	Blank	(N) New page.
EA04	1100	3-67*	*** None ***		3-69	Blank	(N) New page.
EA04	1200	3-69*	*** None ***		3-71	Blank	(N) New page.
EA04	2100	3-71*	*** None ***		3-73	Blank	(N) New page.
EA04	2104	3-73*	*** None ***		3-75	Blank	(N) New page.
EA04	2108	3-75*	*** None ***		3-77	Blank	(N) New page.
APPENDIX B		0-130	0-131	0-132	3-79	3-80	(F/R) Shows 4 new metalloids.
APPENDIX C		3-80	0-133	0-134	3-81	3-82	(R/F) Equation for Bulk Modulus was corrected.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

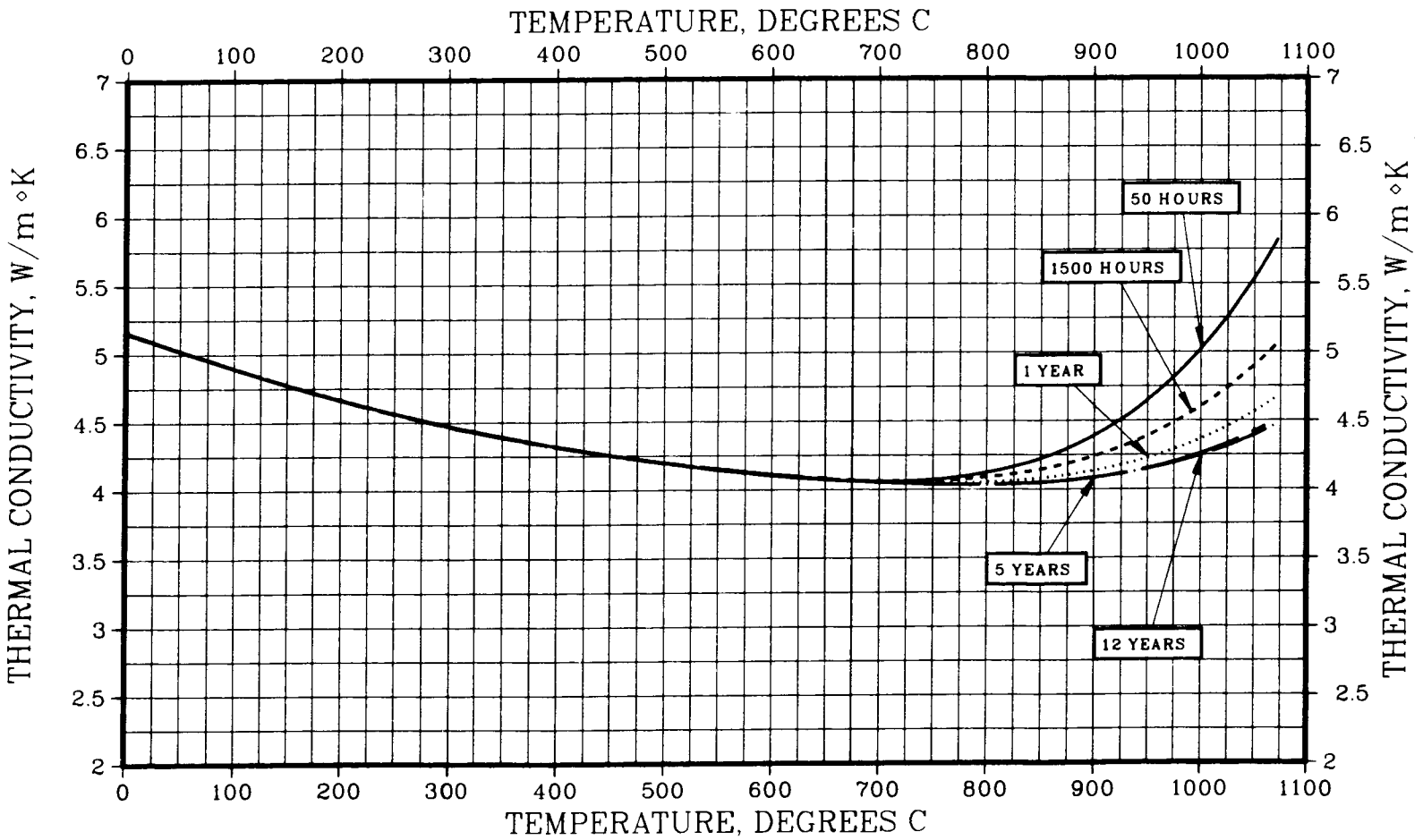
REVISION CONTROL PAGE	UPDATE CODE 3.0.0

This page will be replaced each time a package of new and/or revised pages is issued. It will provide a cumulative listing of the issue dates associated with consecutive publication packages.

Update Package Number	Issue Date
0	September 30, 1983
1	June 12, 1984
2	June 21, 1984
3	August 15, 1984

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 78Si/22Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA05 UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

PROPERTY CODE 3112 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 78Si/22Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA05 UPDATE CODE: 3.0.0

50 HOUR DATA		1500 HOURS DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m°K	DEGREES C	W/m°K	DEGREES C	W/m°K	DEGREES C	W/m°K
0	5.16	0	5.16	0	5.16	0	5.16
50	5.03	50	5.03	50	5.03	50	5.03
100	4.90	100	4.90	100	4.90	100	4.90
150	4.78	150	4.78	150	4.78	150	4.78
200	4.67	200	4.67	200	4.67	200	4.66
250	4.57	250	4.57	250	4.56	250	4.56
300	4.48	300	4.47	300	4.47	300	4.47
350	4.40	350	4.39	350	4.39	350	4.39
400	4.32	400	4.32	400	4.32	400	4.32
450	4.26	450	4.25	450	4.25	450	4.26
500	4.20	500	4.20	500	4.20	500	4.20
550	4.15	550	4.15	550	4.15	550	4.16
600	4.10	600	4.11	600	4.11	600	4.11
650	4.07	650	4.08	650	4.08	650	4.08
700	4.06	700	4.06	700	4.06	700	4.06
750	4.07	750	4.06	750	4.05	750	4.04
800	4.12	800	4.09	800	4.05	800	4.04
850	4.22	850	4.15	850	4.08	850	4.05
900	4.39	900	4.24	900	4.14	900	4.09
950	4.65	950	4.39	950	4.23	950	4.15
1000	5.02	1000	4.60	1000	4.37	1000	4.26
1050	5.54	1050	4.90	1050	4.56	1050	4.42
1075	5.86	1075	5.08	1075	4.69	1075	4.52

The curves on Page 1.0 were generated from the following equations:

50 Hours: $\lambda = 5.1589 - 2.6971\times10^{-3}T + 8.5075\times10^{-9}T^3 - 1.5683\times10^{-11}T^4 + 9.7306\times10^{-15}T^5$,

1500 Hours: $\lambda = 5.1561 - 2.628\times10^{-3}T + 6.5589\times10^{-9}T^3 - 1.0407\times10^{-11}T^4 + 5.9226\times10^{-15}T^5$,

1 Year: $\lambda = 5.1573 - 2.647\times10^{-3}T + 6.5119\times10^{-9}T^3 - 9.6967\times10^{-12}T^4 + 5.0406\times10^{-15}T^5$,

5 Years: $\lambda = 5.1622 - 2.7082\times10^{-3}T + 7.1075\times10^{-9}T^3 - 1.0523\times10^{-11}T^4 + 5.2216\times10^{-15}T^5$, where

λ = Thermal Conductivity, W/m·K, and
T = Temperature, °C.

PROPERTY CODE 3112 PAGE 1.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 78Si/22Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA05 UPDATE CODE: 3.0.0

12 YEAR DATA	
TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m °K
0	5.16
50	5.03
100	4.90
150	4.78
200	4.67
250	4.56
300	4.47
350	4.39
400	4.32
450	4.25
500	4.20
550	4.15
600	4.11
650	4.08
700	4.05
750	4.04
800	4.04
850	4.05
900	4.09
950	4.15
1000	4.25
1050	4.39
1075	4.49

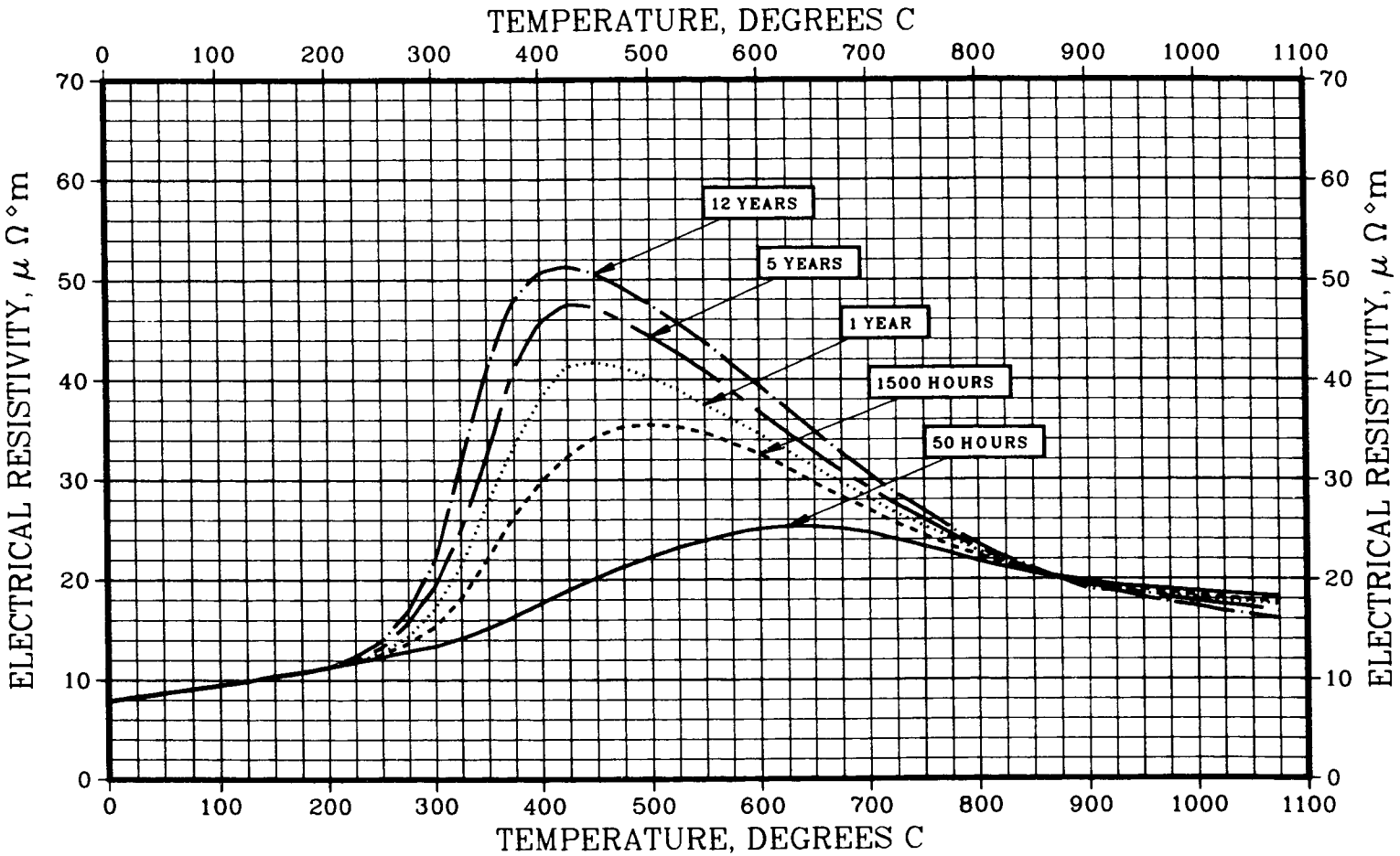
The values above, from the 12 year curve on Page 1.0, were generated from the following equation:

$$\lambda = 5.1579 = 2.6478\times10^{-3}T + 6.3133\times10^{-9}T^3 - 8.9859\times10^{-12}T^4 + 4.4102\times10^{-15}T^5$$

λ = Thermal Conductivity, W/m·K, and
T = Temperature, °C.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA05
		UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA05
		UPDATE CODE: 3.0.0

50 HOUR DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY
DEGREES C	μΩ°m	DEGREES C	μΩ°m	DEGREES C	μΩ°m	DEGREES C	μΩ°m
0	7.9	0	7.9	0	7.9	0	7.9
50	8.7	50	8.7	50	8.7	50	8.7
100	9.5	100	9.5	100	9.5	100	9.5
150	10.4	150	10.4	150	10.4	150	10.4
200	11.3	200	11.3	200	11.3	200	11.3
250	12.3	250	12.6	250	12.8	250	13.3
300	13.4	300	15.4	300	17.2	300	19.4
350	15.2	350	22.2	350	27.7	350	32.6
400	17.7	400	29.8	400	38.1	400	45.7
450	20.2	450	34.3	450	41.7	450	47.2
500	22.3	500	35.5	500	40.2	500	44.3
550	23.9	550	34.7	550	37.5	550	40.9
600	25.1	600	32.6	600	34.6	600	36.8
650	25.3	650	29.7	650	31.3	650	32.8
700	24.7	700	27.0	700	28.2	700	29.2
750	23.3	750	24.4	750	25.3	750	26.0
800	21.8	800	22.4	800	22.8	800	23.1
850	20.6	850	20.7	850	20.9	850	20.9
900	19.8	900	19.6	900	19.5	900	19.4
950	19.2	950	19.0	950	18.6	950	18.6
1000	18.8	1000	18.4	1000	18.2	1000	17.8
1050	18.5	1050	17.9	1050	17.7	1050	17.2
1100	18.3	1100	17.7	1100	17.5	1100	16.8

PROPERTY CODE 3201 PAGE 1.1

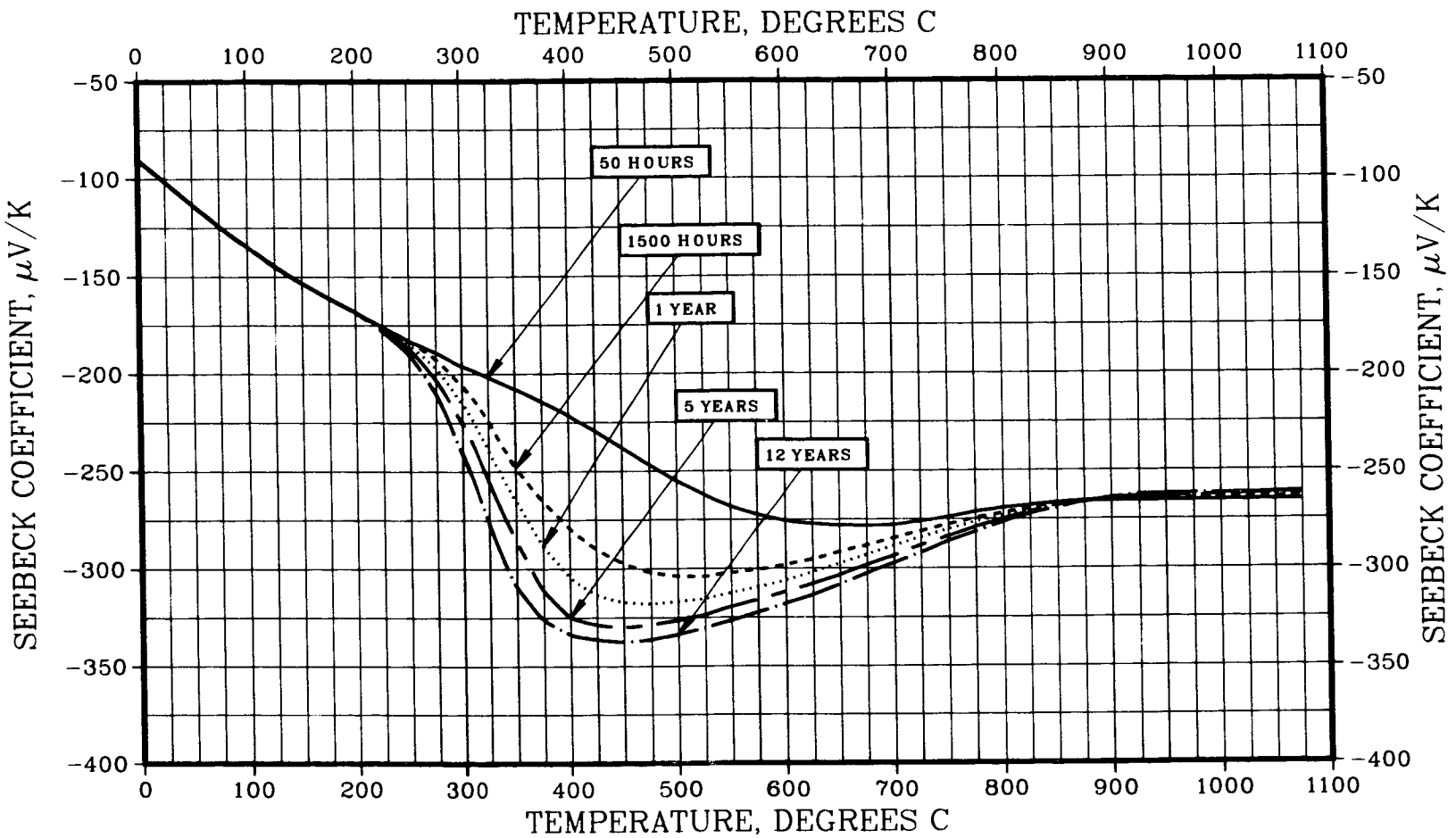
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA05
		UPDATE CODE: 3.0.0

12 YEAR DATA	
TEMPERATURE	RESISTIVITY
DEGREES C	$\mu\Omega^{\circ}m$
0	7.9
50	8.7
100	9.5
150	10.4
200	11.3
250	14.0
300	22.0
350	41.0
400	50.7
450	50.6
500	47.5
550	43.8
600	39.4
650	34.9
700	30.6
750	26.9
800	23.5
850	21.1
900	19.0
950	18.2
1000	17.3
1050	16.5
1100	16.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA05
		UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 78Si/22Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA05 UPDATE CODE: 3.0.0

50 HOUR DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K
0	-90.00	0	-90.00	0	-90.00	0	-90.00
50	-113.01	50	-113.00	50	-113.00	50	-113.00
100	-134.60	100	-134.50	100	-134.60	100	-134.60
150	-153.20	150	-153.20	150	-153.20	150	-153.20
200	-168.20	200	-168.20	200	-168.20	200	-168.20
250	-183.00	250	-183.00	250	-185.00	250	-187.00
300	-196.00	300	-206.00	300	-215.00	300	-225.20
350	-207.70	350	-248.00	350	-265.00	350	-285.60
400	-221.30	400	-279.20	400	-304.20	400	-324.70
450	-237.90	450	-297.20	450	-317.00	450	-329.90
500	-255.00	500	-303.80	500	-316.70	500	-326.40
550	-268.20	550	-302.00	550	-312.30	550	-319.40
600	-275.60	600	-298.00	600	-306.00	600	-311.70
650	-278.00	650	-291.50	650	-297.50	650	-303.30
700	-277.80	700	-284.60	700	-288.50	700	-293.60
750	-273.90	750	-277.70	750	-280.10	750	-283.70
800	-269.30	800	-271.90	800	-273.30	800	-275.00
850	-266.60	850	-267.00	850	-267.90	850	-268.00
900	-265.80	900	-265.20	900	-264.40	900	-264.40
950	-265.60	950	-264.80	950	-263.60	950	-263.30
1000	-265.40	1000	-264.40	1000	-263.20	1000	-262.70
1050	-265.25	1050	-264.10	1050	-262.80	1050	-261.50
1100	-265.23	1100	-263.45	1100	-262.75	1100	-261.25

PROPERTY CODE 3207 PAGE 1.1

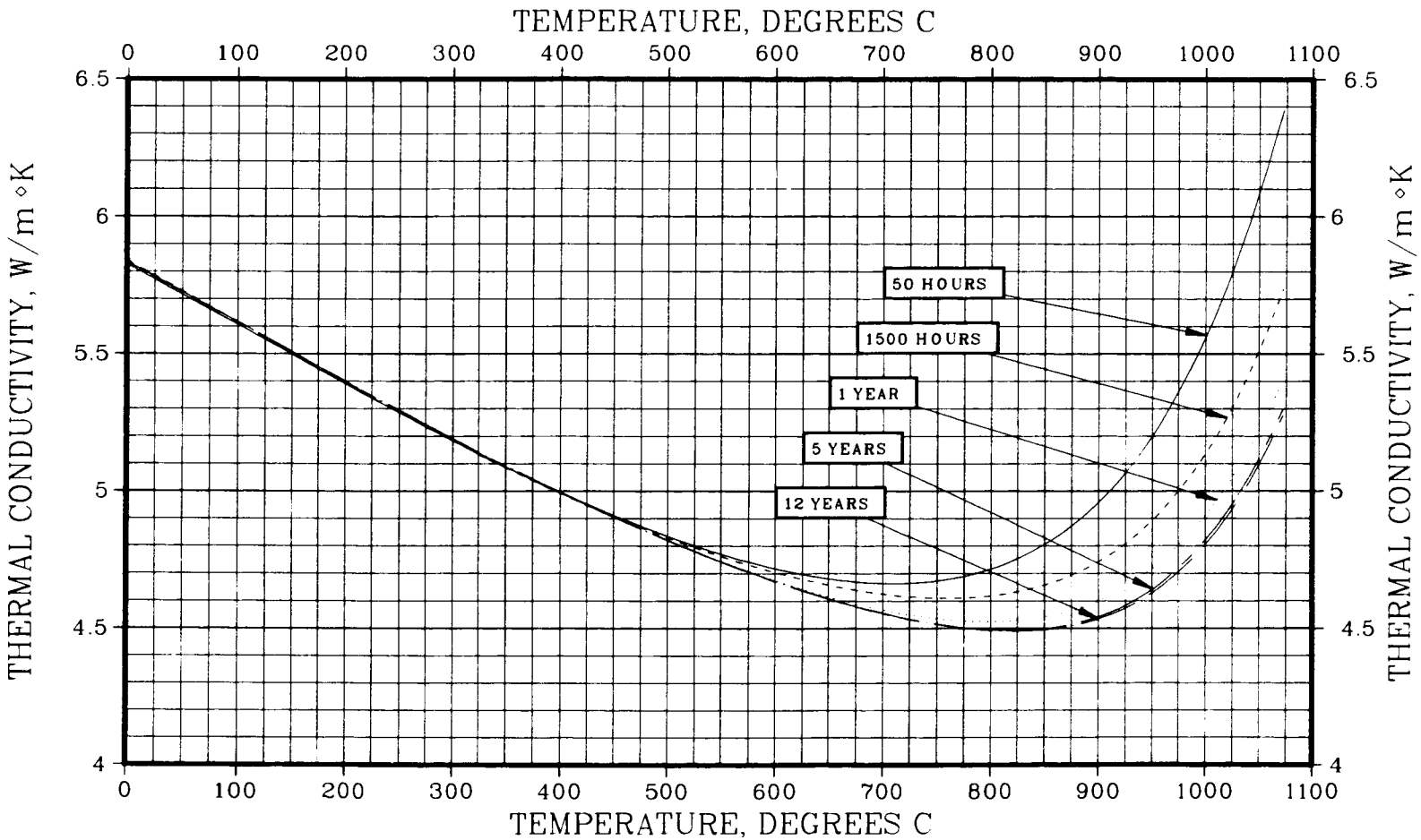
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA05
		UPDATE CODE: 3.0.0

12 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K
0	-90.00
50	-113.00
100	-134.60
150	-153.20
200	-168.20
250	-190.20
300	-241.00
350	-309.20
400	-333.70
450	-337.40
500	-333.60
550	-326.50
600	-317.80
650	-308.10
700	-297.30
750	-286.20
800	-276.50
850	-269.30
900	-264.20
950	-262.20
1000	-262.00
1050	-261.80
1100	-261.70

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA06 UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

PROPERTY CODE 3112 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 78Si/22Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA06
		UPDATE CODE: 3.0.0

50 HOUR DATA		1500 HOURS DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY	TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m °K	DEGREES C	W/m °K	DEGREES C	W/m °K	DEGREES C	W/m °K
0	5.83	0	5.84	0	5.84	0	5.84
50	5.72	50	5.73	50	5.73	50	5.73
100	5.61	100	5.62	100	5.62	100	5.62
150	5.50	150	5.51	150	5.51	150	5.51
200	5.39	200	5.40	200	5.40	200	5.40
250	5.29	250	5.29	250	5.30	250	5.30
300	5.18	300	5.18	300	5.19	300	5.19
350	5.09	350	5.09	350	5.09	350	5.09
400	5.00	400	4.99	400	5.00	400	5.00
450	4.91	450	4.91	450	4.91	450	4.91
500	4.84	500	4.83	500	4.82	500	4.82
550	4.77	550	4.76	550	4.74	550	4.74
600	4.72	600	4.70	600	4.67	600	4.67
650	4.68	650	4.66	650	4.62	650	4.61
700	4.66	700	4.63	700	4.57	700	4.56
750	4.67	750	4.61	750	4.54	750	4.52
800	4.72	800	4.62	800	4.53	800	4.49
850	4.81	850	4.66	850	4.54	850	4.50
900	4.96	900	4.74	900	4.60	900	4.54
950	5.20	950	4.89	950	4.72	950	4.64
1000	5.56	1000	5.14	1000	4.91	1000	4.82
1050	6.08	1050	5.51	1050	5.22	1050	5.12
1075	6.43	1075	5.77	1075	5.43	1075	5.32

The curves on Page 1.0 were generated from the following equations:

50 Hours: $\lambda = 5.8266 - 2.1889\times10^{-3}T + 1.9916\times10^{-12}T^4 - 1.7336\times10^{-18}T^6 + 1.6642\times10^{-24}T^8$,

1500 Hours: $\lambda = 5.8431 - 2.2529\times10^{-3}T + 2.3880\times10^{-12}T^4 - 2.7429\times10^{-18}T^6 + 1.900\times10^{-24}T^8$,

1 Year: $\lambda = 5.8354 - 2.1840\times10^{-3}T + 1.5836\times10^{-12}T^4 - 1.6689\times10^{-18}T^6 + 1.3467\times10^{-24}T^8$,

5 Years: $5.8356 - 2.1868\times10^{-3}T + 1.6965\times10^{-12}T^4 - 2.10\ 74\times10^{-18}T^6 + 1.5838\times10^{-24}T^8$, where

λ = Thermal Conductivity, W/m·K, and
T = Temperature, °C.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA06 UPDATE CODE: 3.0.0

12 YEAR DATA	
TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m°K
0	5.84
50	5.73
100	5.62
150	5.51
200	5.40
250	5.29
300	5.19
350	5.09
400	5.00
450	4.91
500	4.82
550	4.74
600	4.67
650	4.61
700	4.56
750	4.52
800	4.49
850	4.50
900	4.53
950	4.63
1000	4.81
1050	5.10
1075	5.30

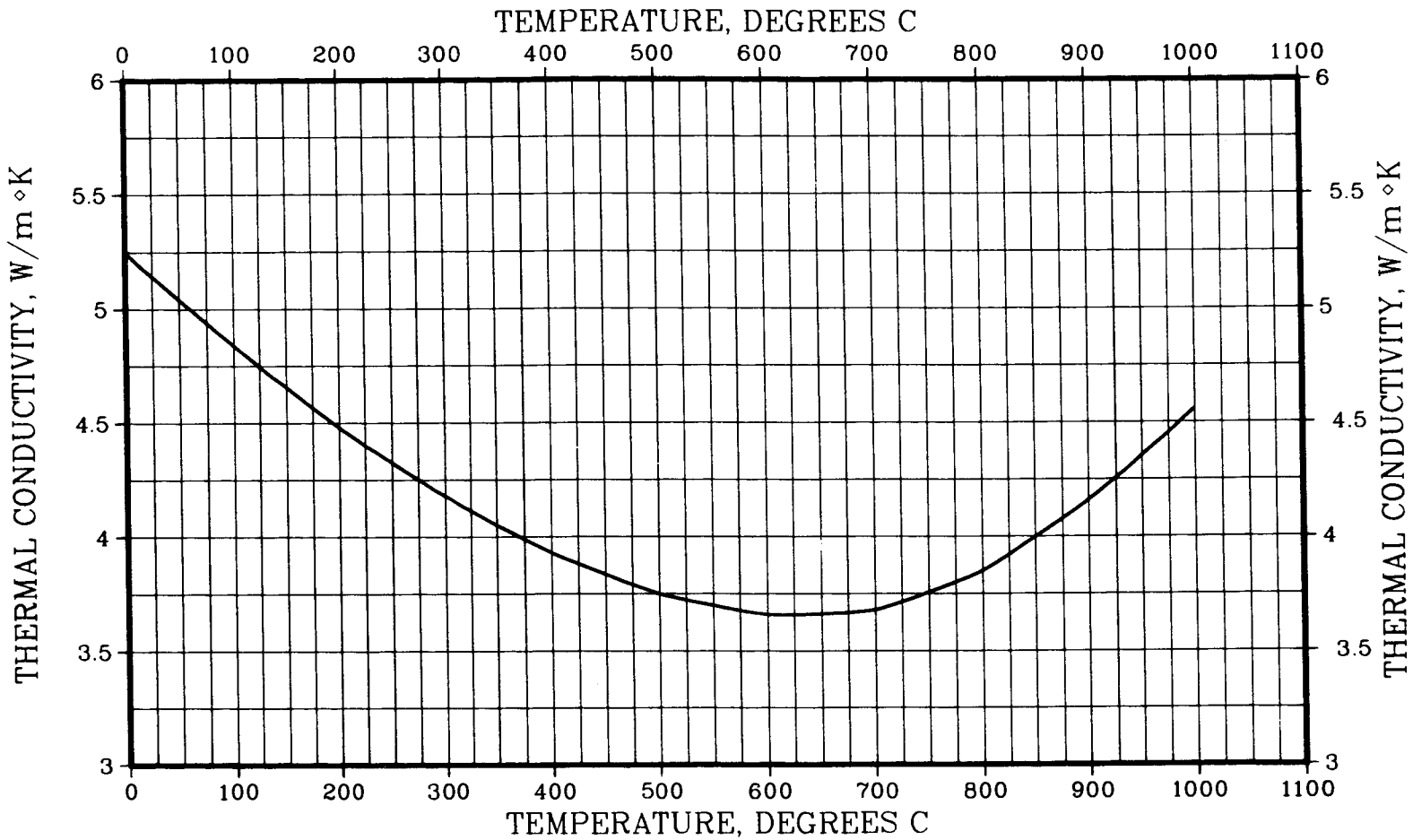
The values above, from the 12 year curve on Page 1.0, were generated from the following equation:

$$\lambda = 5.8370 - 2.1980\times10^{-3}T + 1.8105\times10^{-12}T^4 - 2.3215\times10^{-18}T^6 + 1.6772\times10^{-24}T^8, \text{ where}$$

λ = Thermal Conductivity, W/m·K, and
T = Temperature, °C.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 63Si/37Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 3.0.0



See Page 1.1 for tables of correlation values.

PROPERTY CODE 3112

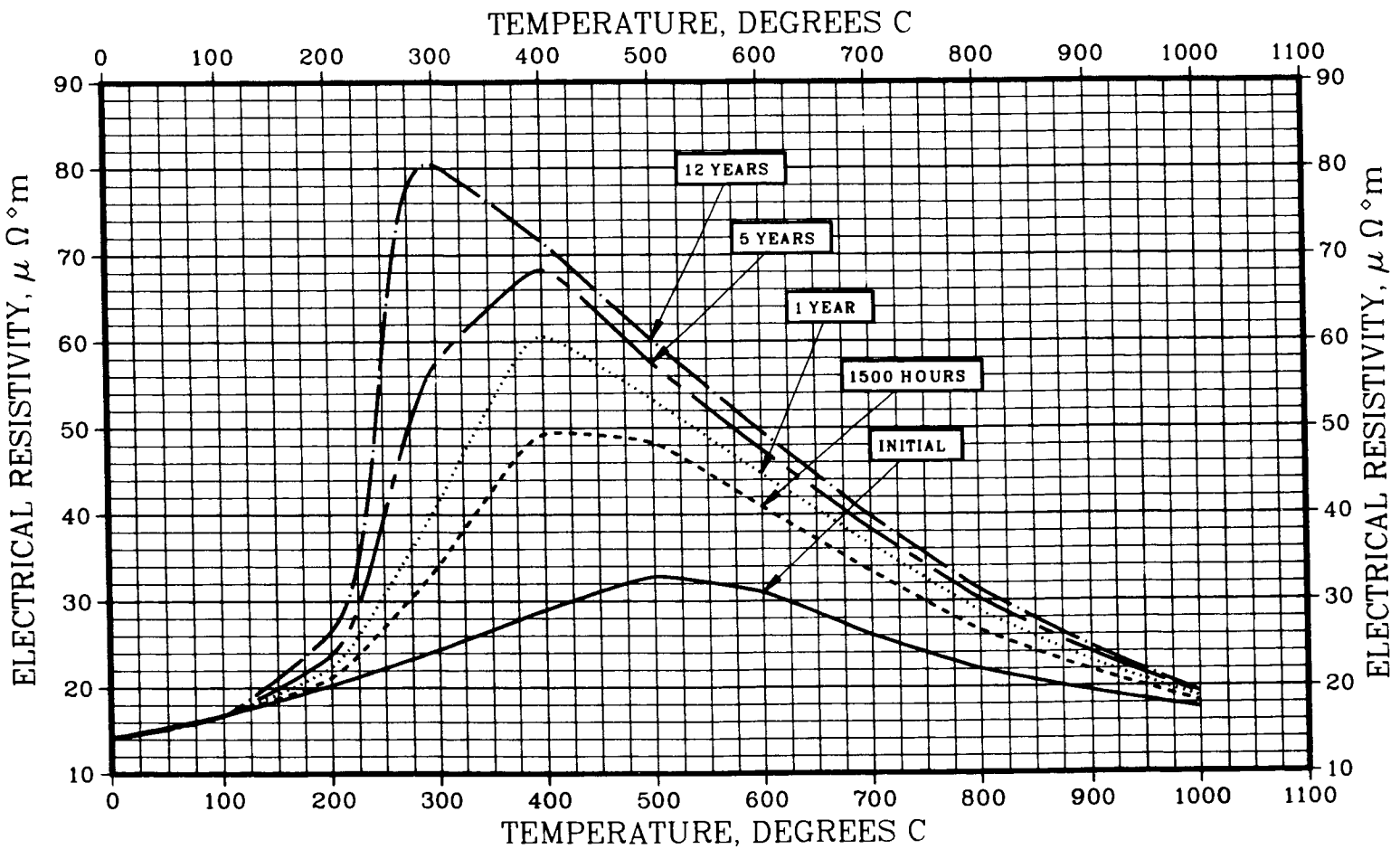
PAGE 1.0

N-TYPE 63Si/37Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 3.0.0

TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m °K
0	5.25
50	5.04
100	4.84
150	4.65
200	4.48
250	4.32
300	4.18
350	4.05
400	3.93
450	3.83
500	3.75
550	3.69
600	3.66
650	3.65
700	3.68
750	3.75
800	3.85
850	3.99
900	4.16
950	4.36
1000	4.56

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 63Si/37Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 3 0 0

INITIAL DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY
DEGREES C	μΩ°m	DEGREES C	μΩ°m	DEGREES C	μΩ°m	DEGREES C	μΩ°m
0	14.2	0	14.2	0	14.2	0	14.2
50	15.4	50	15.3	50	15.1	50	15.0
100	16.8	100	16.8	100	16.8	100	16.8
150	18.5	150	18.0	150	18.0	150	17.0
200	20.3	200	21.2	200	22.4	200	23.8
250	22.3	250	27.3	250	31.7	250	43.5
300	24.4	300	34.0	300	41.2	300	57.5
350	26.8	350	43.7	350	54.2	350	65.6
400	29.0	400	49.3	400	60.6	400	68.3
450	31.6	450	49.6	450	57.1	450	62.8
500	32.8	500	48.3	500	53.3	500	57.5
550	32.3	550	44.6	550	49.0	550	52.4
600	31.0	600	40.9	600	44.7	600	47.5
650	28.4	650	37.1	650	40.5	650	42.8
700	26.1	700	33.4	700	36.5	700	38.3
750	23.9	750	29.7	750	32.4	750	34.0
800	22.1	800	26.6	800	28.8	800	30.2
850	20.7	850	24.1	850	25.7	850	26.9
900	19.5	900	21.9	900	23.0	900	24.0
950	18.6	950	20.2	950	21.0	950	21.7
1000	17.5	1000	18.2	1000	18.7	1000	19.1

PROPERTY CODE 3201 PAGE 1.1

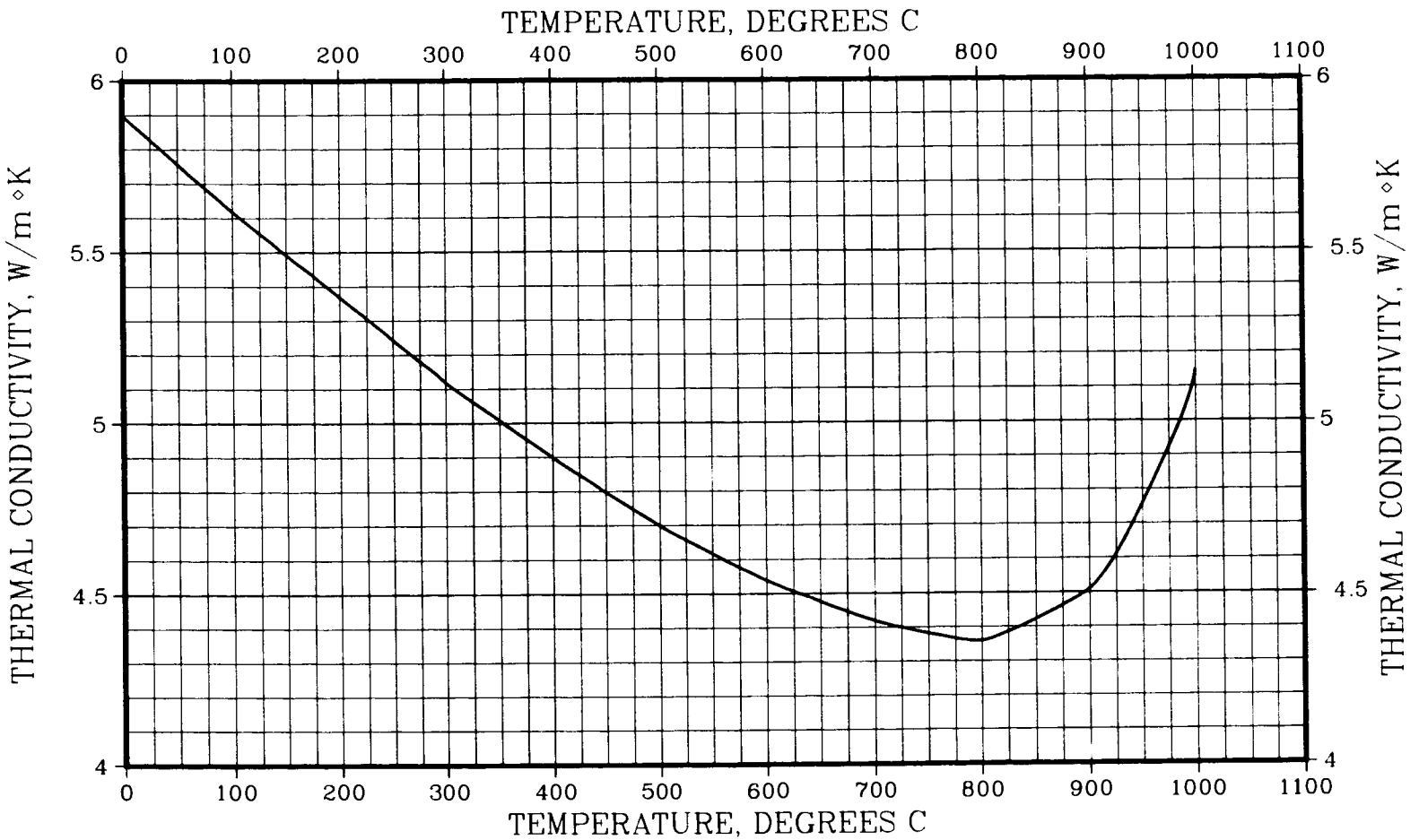
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 3.0.0

12 YEAR DATA	
TEMPERATURE	RESISTIVITY
DEGREES C	$\mu\Omega$ °m
0	14.2
50	14.6
100	16.8
150	16.1
200	26.5
250	61.3
300	80.4
350	76.3
400	71.6
450	65.8
500	60.2
550	54.8
600	49.6
650	44.5
700	39.8
750	35.3
800	31.3
850	27.9
900	24.7
950	22.2
1000	19.3

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 3.0.0



See Page 1.1 for tables of correlation values.

PROPERTY CODE 3112 PAGE 1.0

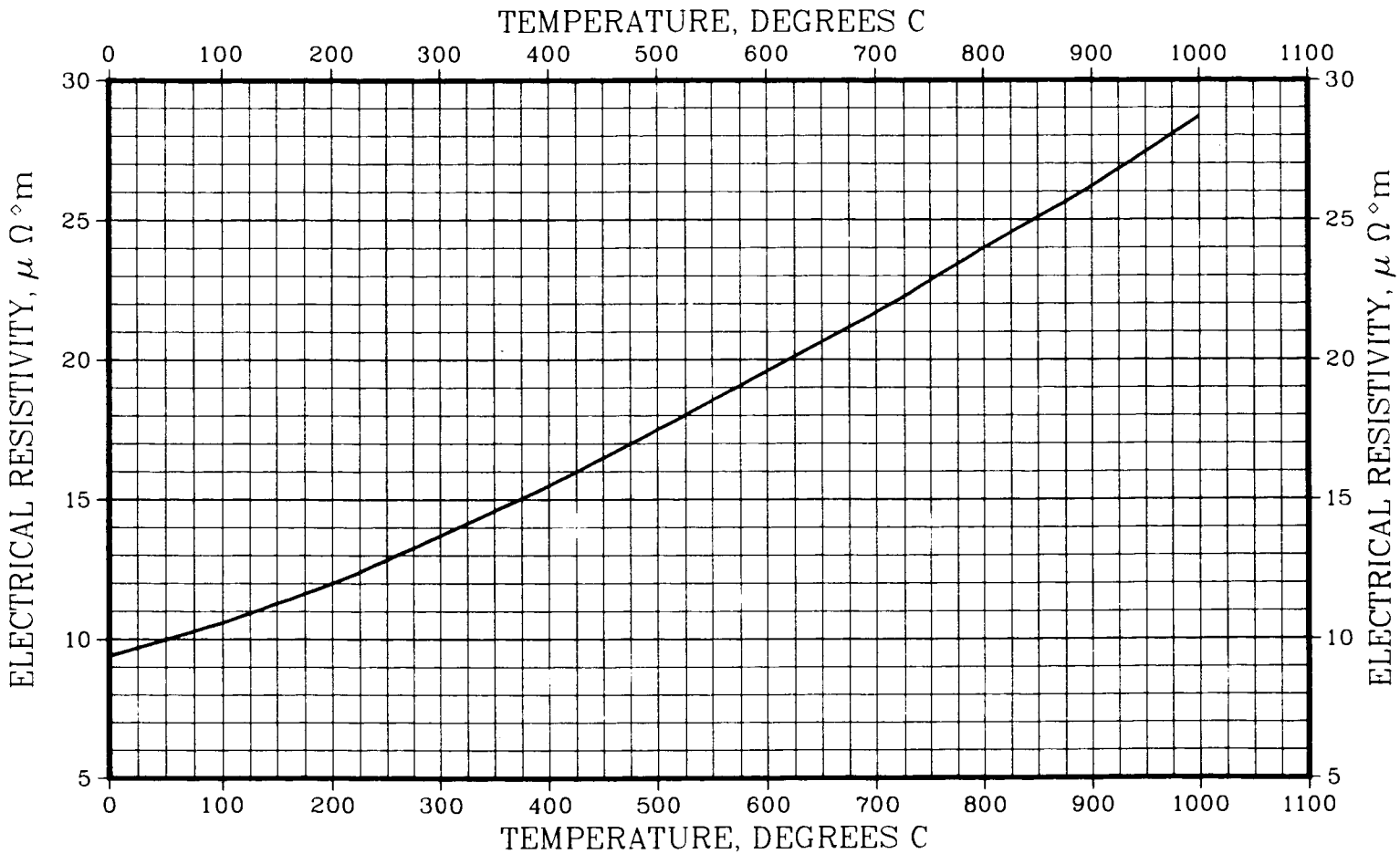
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 63Si/37Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 3.0.0

TEMPERATURE	CONDUCTIVITY
DEGREES C	W/m◇K
0	5.90
50	5.76
100	5.62
150	5.50
200	5.37
250	5.24
300	5.12
350	5.01
400	4.90
450	4.80
500	4.70
550	4.62
600	4.54
650	4.47
700	4.42
750	4.36
800	4.36
850	4.37
900	4.51
950	4.83
1000	5.15

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

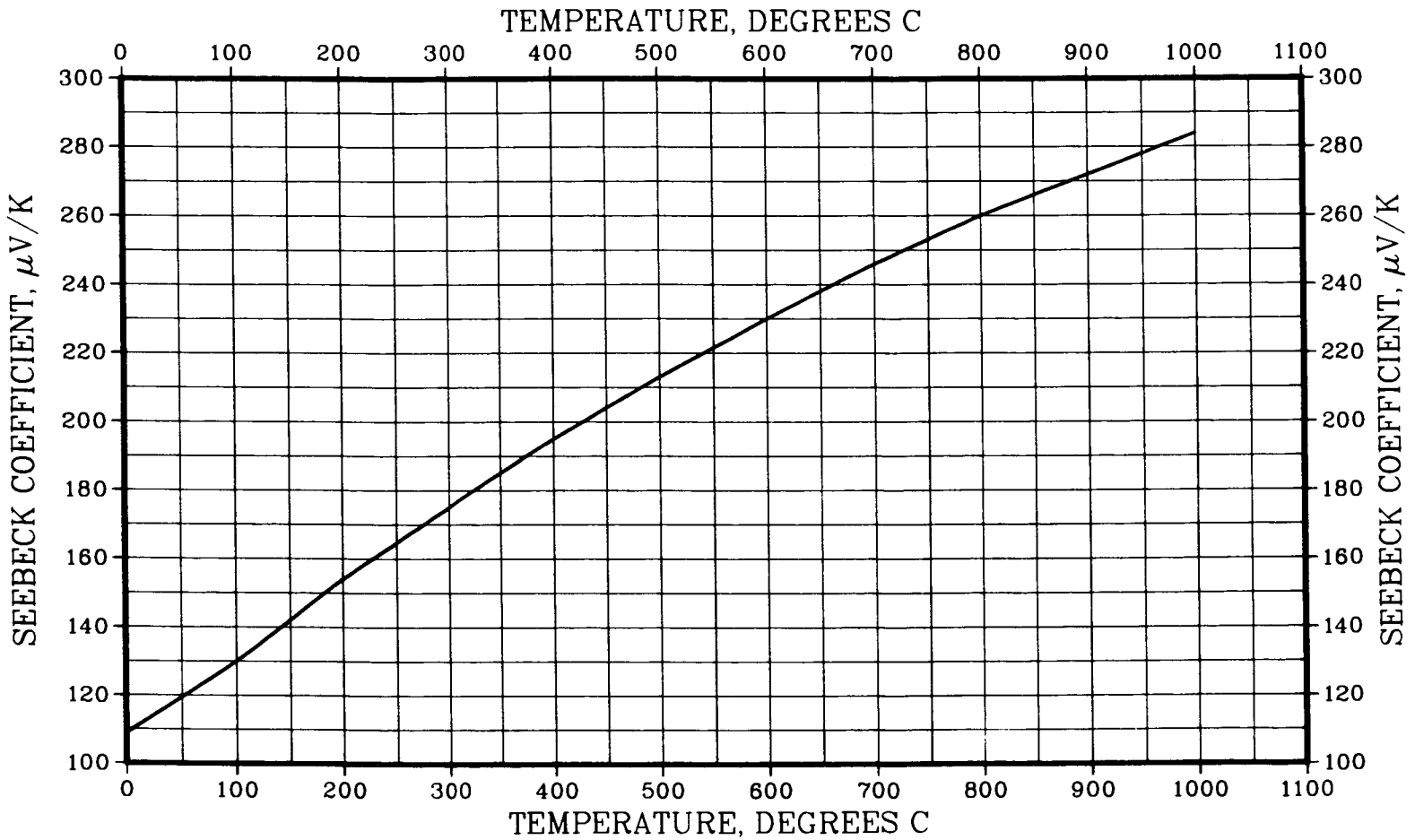
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 63Si/37Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 3.0.1

TEMPERATURE	RESISTIVITY
DEGREES C	$\mu\Omega$ °m
0	9.4
50	10.0
100	10.6
150	11.3
200	12.0
250	12.8
300	13.7
350	14.6
400	15.5
450	16.5
500	17.5
550	18.5
600	19.6
650	20.6
700	21.7
750	22.9
800	24.0
850	25.1
900	26.2
950	27.5
1000	28.7

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA08 UPDATE CODE: 3.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA08 UPDATE CODE: 3.0 1

TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K
0	109.0
50	119.5
100	130.0
150	142.0
200	154.0
250	164.5
300	175.0
350	185.0
400	195.0
450	204.0
500	213.0
550	221.5
600	230.0
650	238.0
700	246.0
750	253.0
800	260.0
850	266.0
900	272.0
950	278.0
1000	284.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

FINEWEAVE PIERCED FABRIC	TABLE OF CONTENTS/PROPERTIES	Material Code: EA02 Update Code: 3.0.0

Property Code	Property	Pages
1000	GENERAL INFORMATION	1.0–1.1
2100	STATIC, SHORT-TERM PROPERTIES	1.0–1.1
2101	ULTIMATE TENSILE STRENGTH	1.0–1.3
2102	YIELD STRENGTH (SHEAR)	1.0–1.1
2111	YOUNG'S MODULUS, TENSILE	1.0–1.1
2111	YOUNG'S MODULUS, COMPRESSIVE	2.0–2.1
2111	SECANT MODULUS, TENSILE	1.0–1.1
2111	SECANT MODULUS, COMPRESSIVE	2.0–2.1
2112	SHEAR MODULUS, XY	1.0
2112	SHEAR MODULUS, XZ	1.0
2116	COMPRESSIVE STRENGTH	1.0–1.1
2116	COMPRESSIVE STRENGTH	2.0–2.1
3108	SPECIFIC HEAT	1.0
3111	EMISSIVITY	1.0
3112	THERMAL CONDUCTIVITY	1.0–1.1
3114	THERMAL EXPANSION	1.0–1.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

FINEWEAVE PIERCED FABRIC	GENERAL INFORMATION	Material Code: EA02 Update Code: 3.0.0

The primary concern in the use of the Fineweave Pierced Fabric® (FWPF) is its ability to resist an inadvertant reentry into the earth's atmosphere. The data needed, therefore, must be relevant to the reentry problem and include the mechanical and thermal properties as a function of temperature.

The FWPF consists of carbon fibers layed up in a three-dimensional orthogonal weave which has been infiltrated and impregnated with organic precursors, pyrolyzed under pressure, and graphitized. The eventual structure is a carbon-carbon composite of reasonable density and reduced porosity. The orthogonal weave, however, produces a block with anisotropic physical properties which are characteristic of the weave. The tensile strengths in the orthogonal directions are fairly high; however, the off-axis strengths are reduced with a minimum at 45°. The flexural and shear strengths are also relatively low in contrast to the tensile strengths. The thermal stress is reduced in this type of composite due to the low coefficients of thermal expansion. Ablation and erosion resistance are generally less than the better graphites used in reentry vehicles.

The data presented is all from Southern Research Institute (SoRI), sponsored by the Air Force and DOE. The information has been summarized by K. R. Waeber, John Hopkins University, Applied Physical Laboratory (JHU/APL), from the following reports. The Mound procurement specification is: SPA 790053.

REFERENCES:

1. H. S. Starrett, S. J. Causey, H. E. Littleton, and G. W. Driggers, Evaluation of Carbon Carbon Composites for the Pan Pilot Production Program (P^4), Air Force Materials Laboratory (MXE) Report AFML-TR-78-2, Vol. II, May 1979.

2. Letter dated August 24, 1978, from G. F. Fornaro, Southern Research Institute, to F. Schumann, Teledyne Energy Systems (TES), Subject: "Preliminary Data Package for P^4 FWPF Material Properties."

3. Letter dated April 24, 1979, form F. G. Fornaro, Southern Research Institute, to F. Schumann, TES, Subject: "Mechanical Test Data on GE 3 DCC and FWPF."

4. Letter dated May 10, 1979, from F. G. Fornaro, Southern Research Institute, to F. Schumann, TES, Subject: "Thermal Expansion Test Data on GE 3 DCC and FWPF."

5. Letter dated June 14, 1979, from G. F. Fornaro, Southern Research Institute, to F. Schumann, TES, Subject: "Thermal Expansion Test Data on GE 3 DCC and FWPF."

6. F. A. Schumann, R. H. Anderson, and D. W. Stoffell, Improved Multi-Hundred Watt Heat Source, Galileo Program — Task 12, Teledyne Energy Systems Report TES-33009-43, May 1979.

7. Letter dated March 18, 1980, from H. S. Starrett, Southern Research Institute, to K. R. Waeber, JHU/APL, Subject: "FWPF, 45° Off-Axis, Mechanical Data."

8. K. R. Waeber, Comparison of DOE Sponsored FWPF Data With That From the Air Force P^4 Program, JHU/APL Memo ANSP-167, September 1979.

TENSILE AND COMPRESSIVE STRENGTH

The X and Z tensile and compressive strengths are shown in the following figures. Criteria established for compressive failures are:

(1) 20°C > t > 2205°C, initial failure evidenced by sudden increases in strain accompanied by a loss in load, and

(2) 2760°C > t > 3320°C, no classic compressive failure occurs. A 1% strain was used instead to set a strength value.

The test specimens were found to exhibit extensive plastic yielding and deformation under compressive loading. For temperatures between 0° and 2205°C, failure is taken as initial yarn bundle buckle, evidenced on a stress-strain plot as a sudden loss in load accompanied by an increase in strain. For temperatures greater than 2205°C, the specimens did not demonstrate a distinct initial failure; rather, barreling occurred for strains up to 3% without loss of material integrity. Stress at 1% strain is arbitrarily chosen by Southern Research Institute in reporting the ultimate compressive strength. For strains greater than 1% at temperatures greater than 2205°C, the stress-strain curve slope is such that large increases in strain result in smaller increases in stress. This slope, coupled with the inaccuracy of strain gage readings at large strain values, dictates the 1% value. The stress at 1% strain should therefore be considered a lower-bound compressive strength, indicating no catastrophic failure but a point of increased plastic deformation.

The P^4 Z-direction tensile specimens did not fail properly; instead the Z yarn bundles pulled through the grip section of the specimen before their ultimate tensile strength was reached. The Z-direction tensile strengths reported can also be considered only as lower bounds.

The 45° off-axis mechanical data are also illustrated. All tensile and compressive 45XY and 45XZ elastic moduli are taken as 1000 psi secant values. The dashed curves shown on these figures are a straight-line interpolation between the average data values. Ultimate tensile strengths are taken to be the maximum stress

measured. The compressive strengths for 0° > t > 2760°C were recorded at 1% strain and are subject to the interpretation established above for the X and Z compressive strengths at 1% strain.

TENSILE AND COMPRESSIVE MODULUS

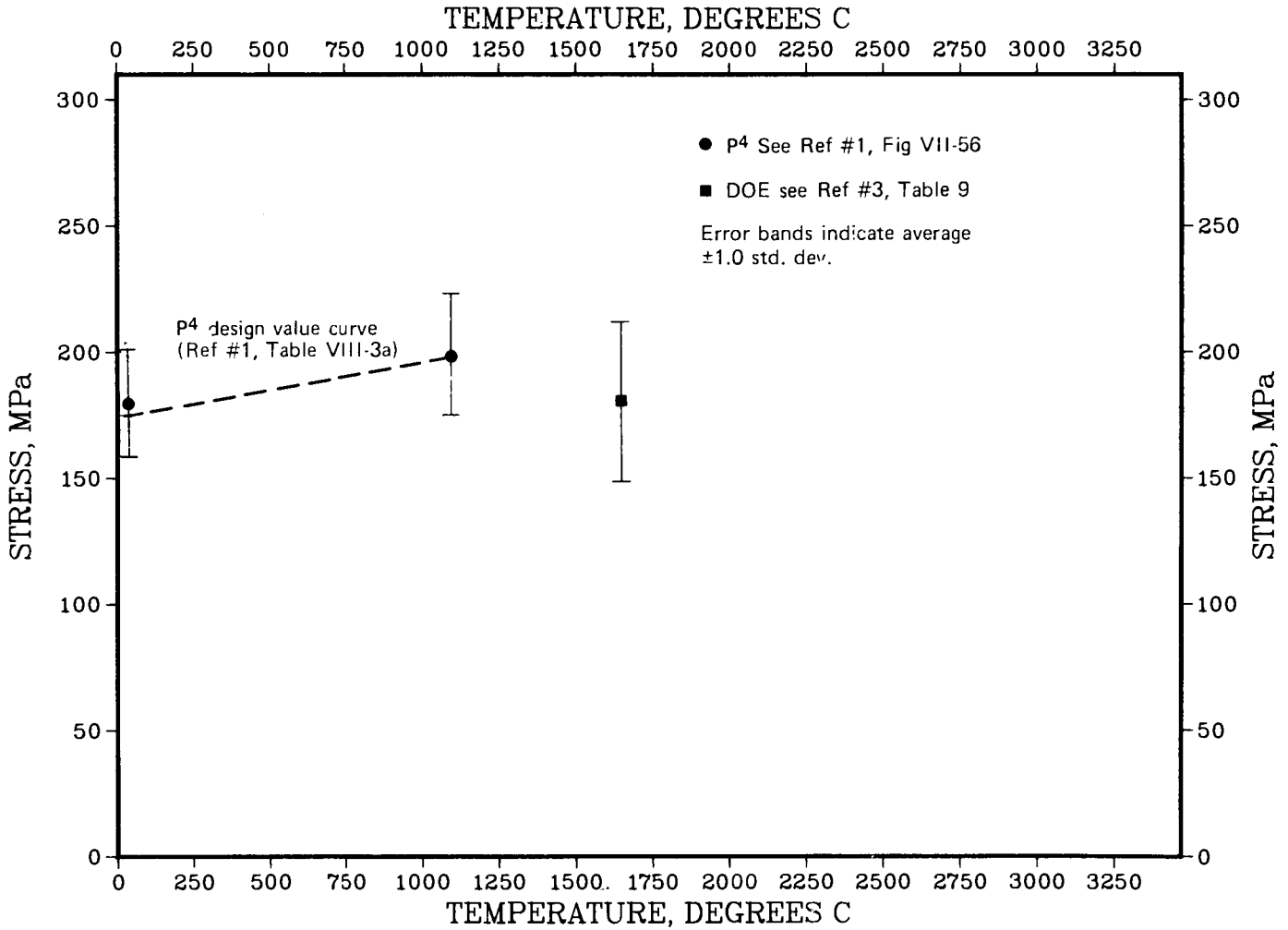
Plots of tensile and compressive elastic moduli versus temperature for the X- and Z-directions are given. The X and Z tensile and the X compressive elastic-moduli nominal-design value curves suggested in the P^4 package are taken to be equal. Compressive X and Z moduli are approximated by initial tangent slopes of the stress-strain curves. Compressive moduli averages from the P^4 program are not shown, as only maximum and minimum curves are included in Ref. 1.

SHEAR STRENGTH AND MODULUS

Plots of shear strength and moduli versus temperature are also given with all shear moduli data taken from Ref. 1. The moduli data are based on torsion, off-axis tension, and off-axis compression data. All of the P^4 shear strength data are for 0.2% yield, where DOE shear strength data are to specimen failure.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

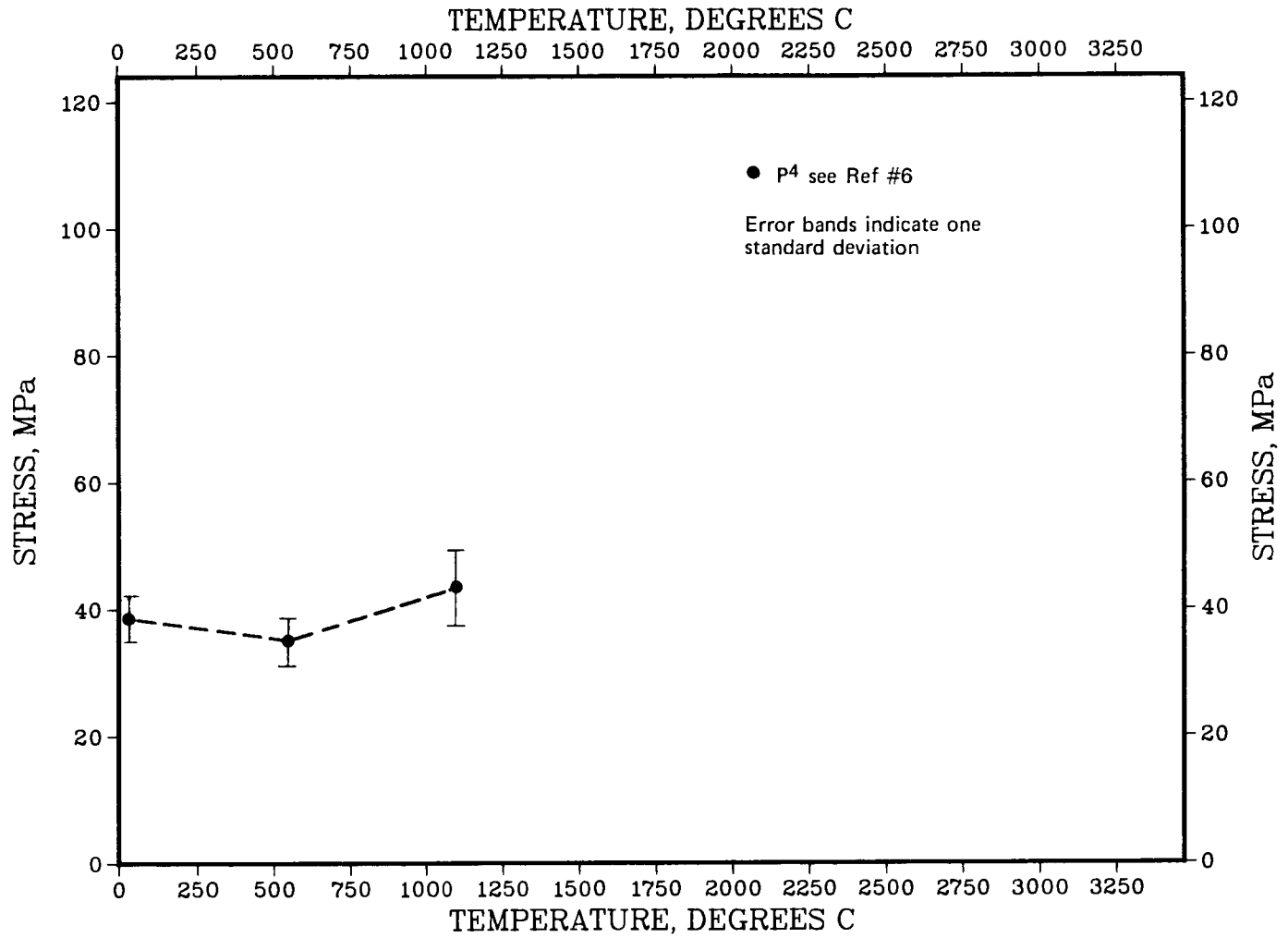
Fine Weave Pierced Fabric	ULTIMATE TENSILE STRENGTH (X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	ULTIMATE TENSILE STRENGTH (45XZ)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

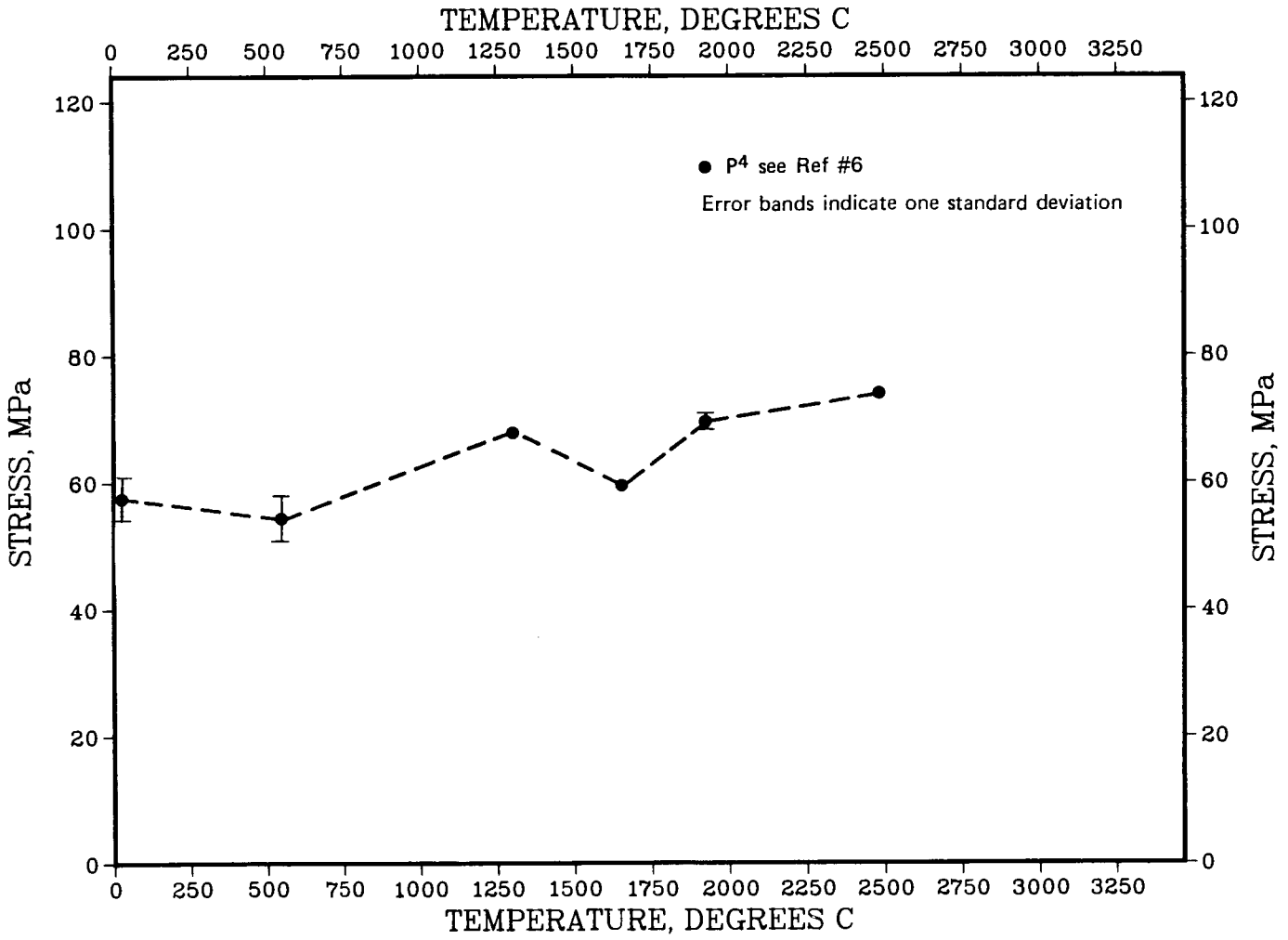


NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2101 PAGE 11

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	ULTIMATE TENSILE STRENGTH (45XY)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

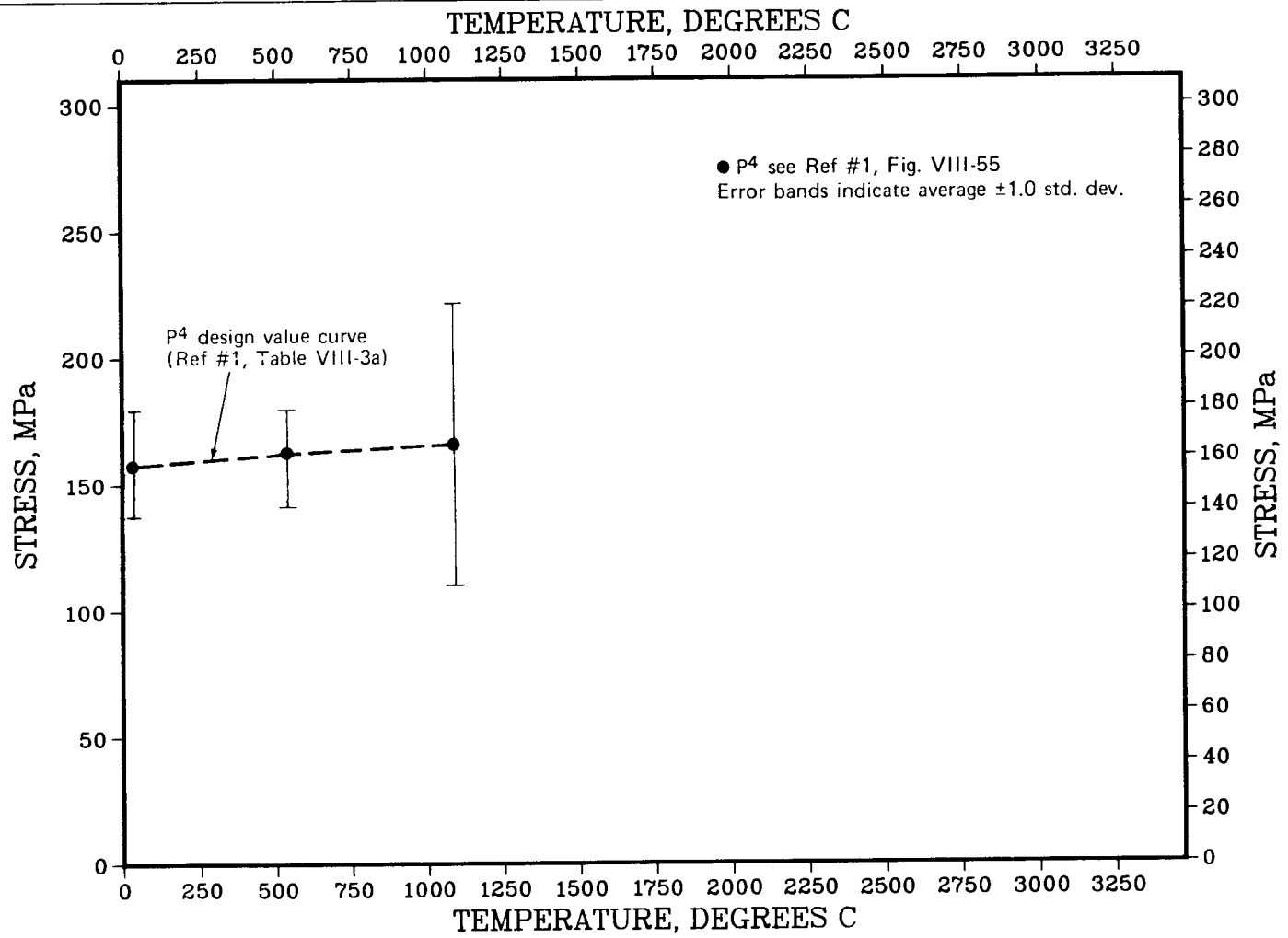


NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2101 PAGE 1.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	ULTIMATE TENSILE STRENGTH (Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

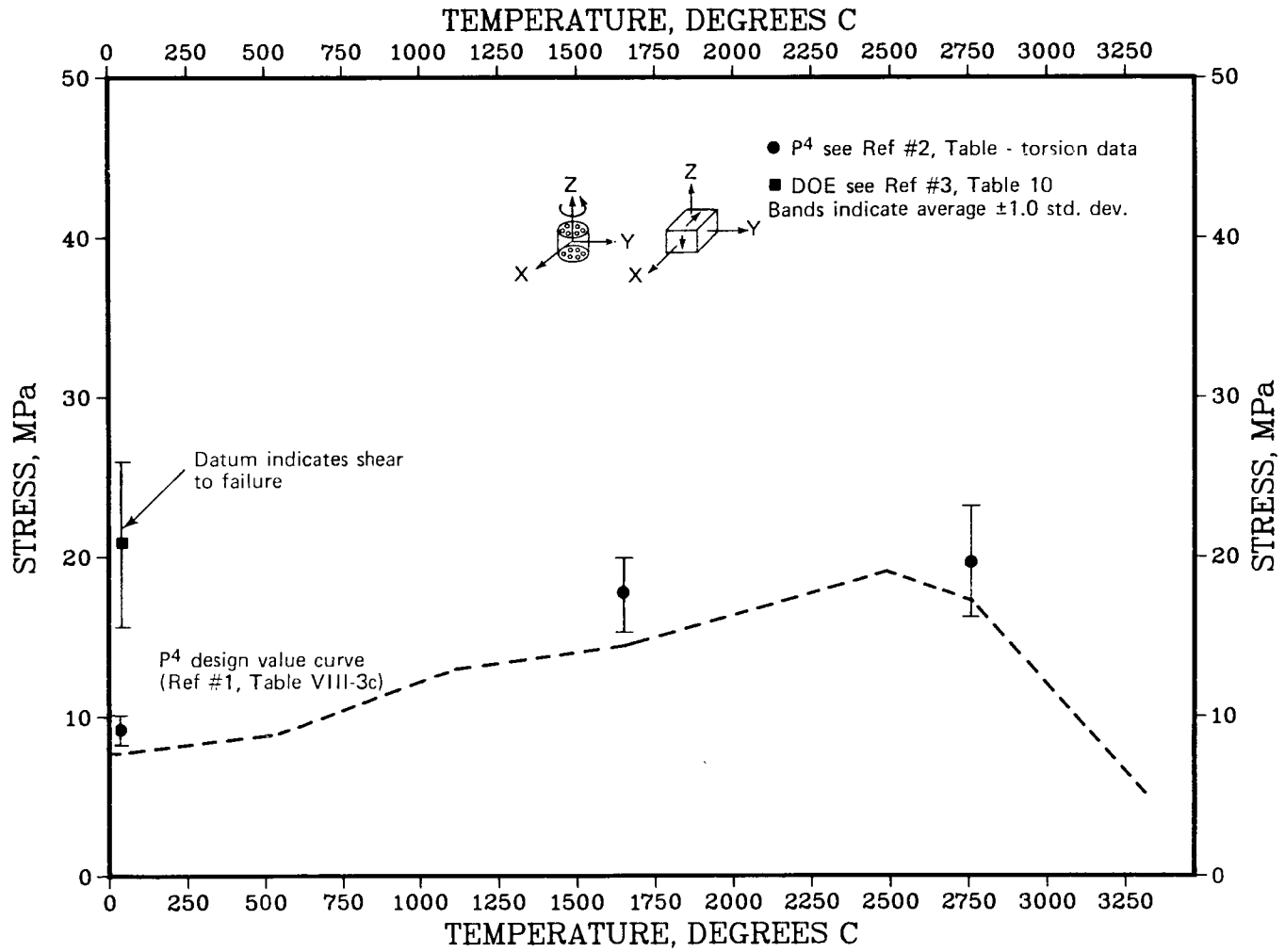


NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2101 PAGE 1.3

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	YIELD STRENGTH (XZ SHEAR)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

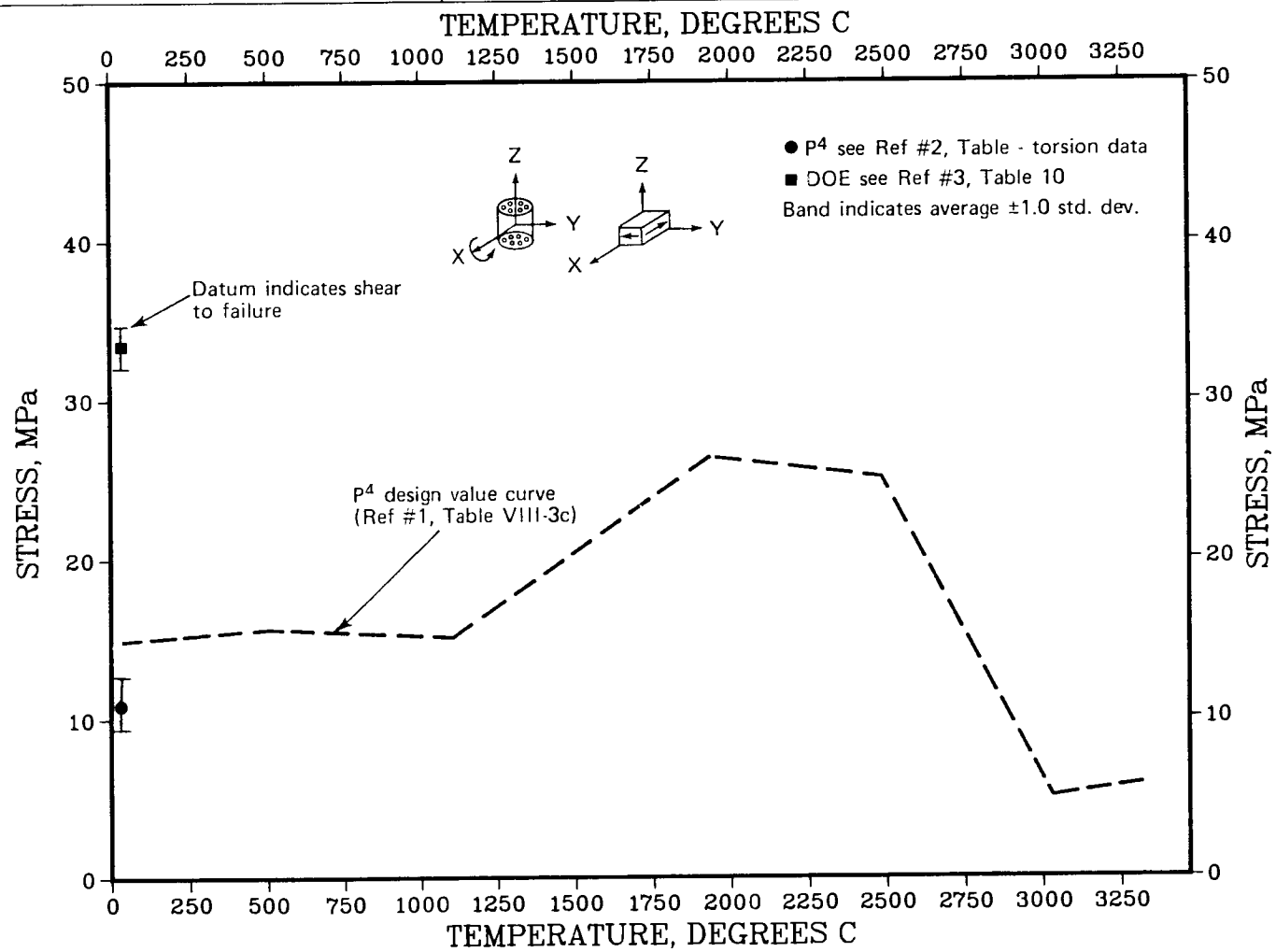


Shear Z fibers, failure occurs in XY plane.

NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	YIELD STRENGTH (XY SHEAR)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

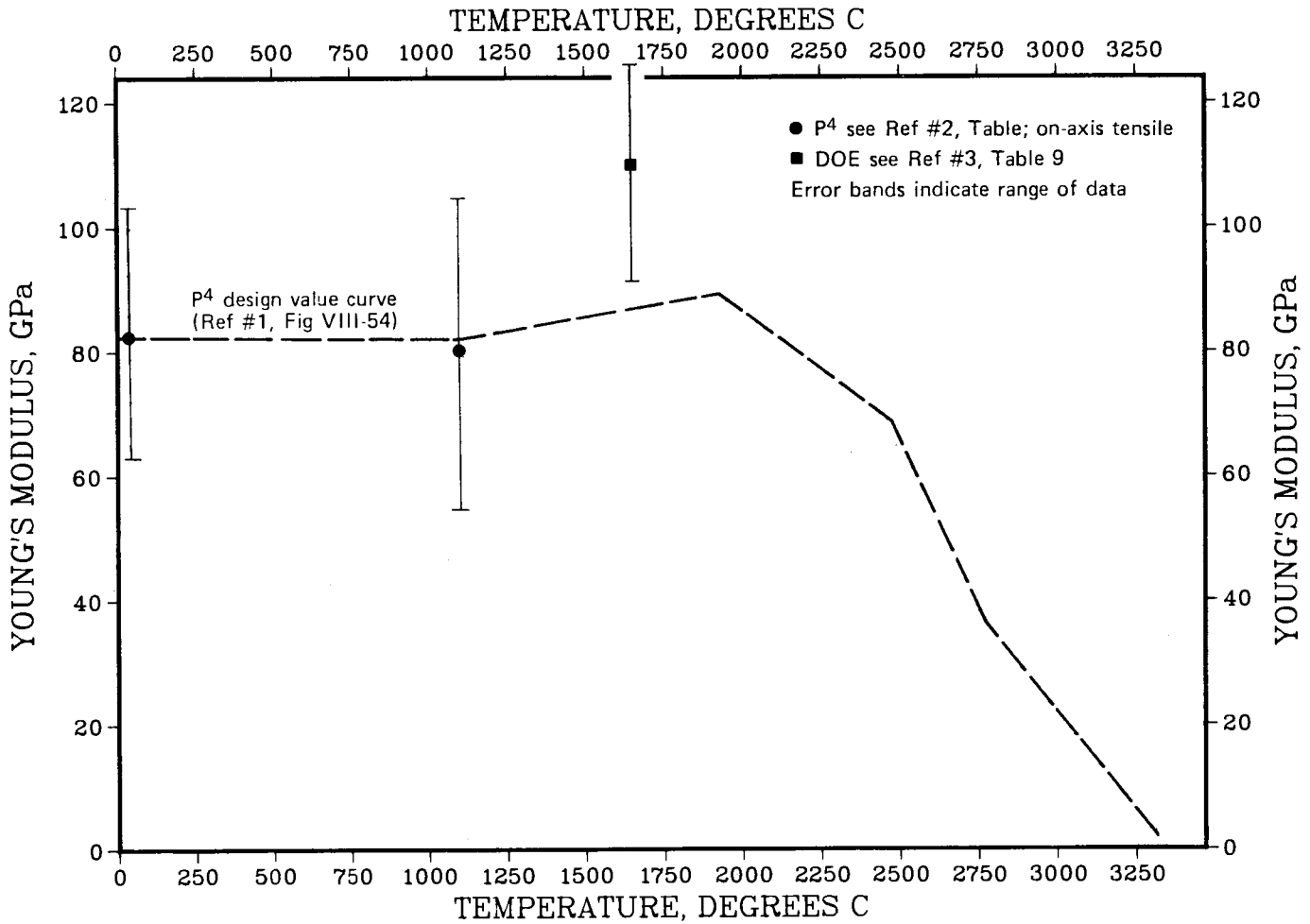


Shear X fibers, failure occurs in the YZ plane. NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2102 PAGE 1.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

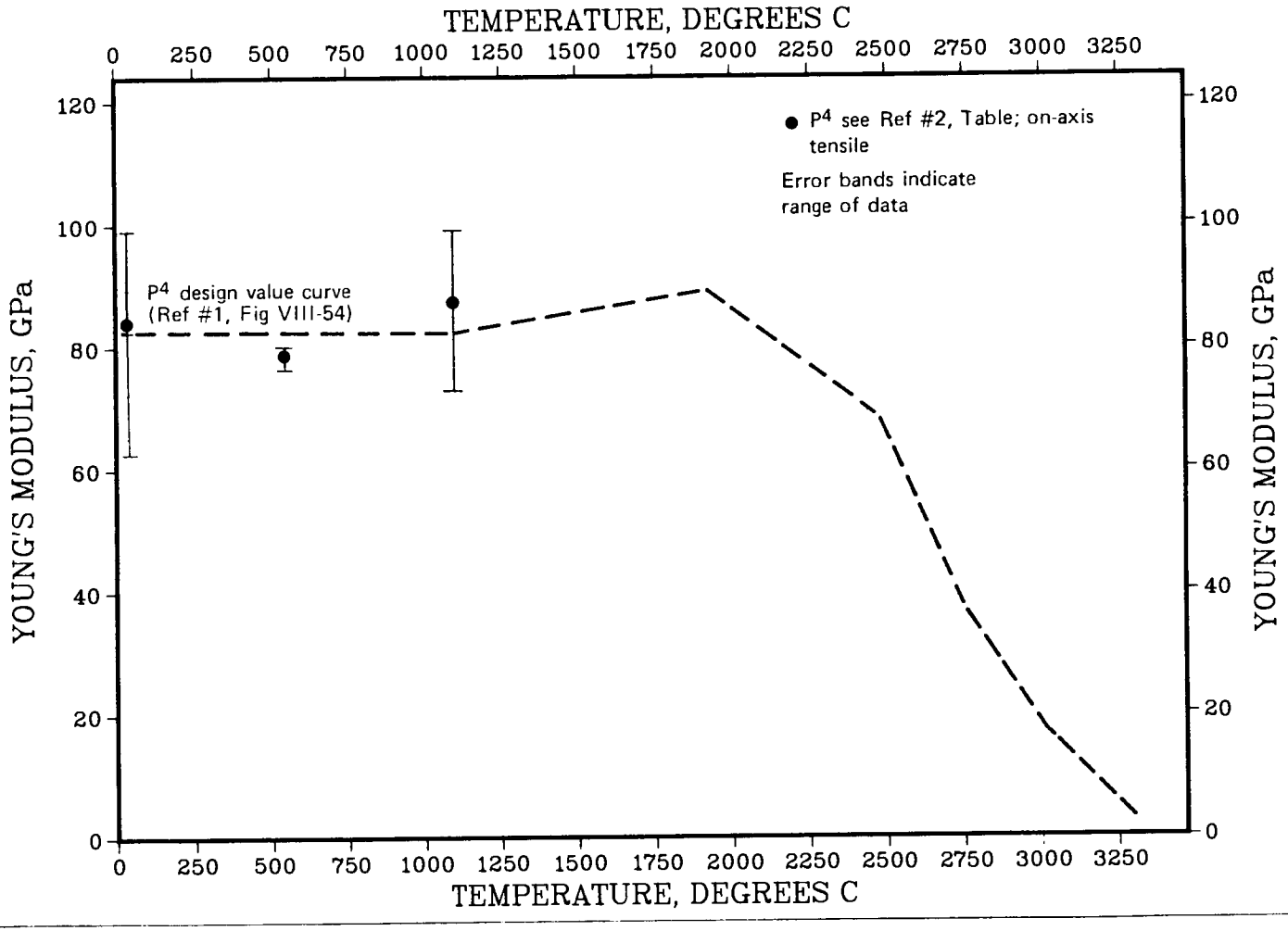
Fine Weave Pierced Fabric	YOUNG'S MODULUS, TENSILE (X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2111 PAGE 1.0

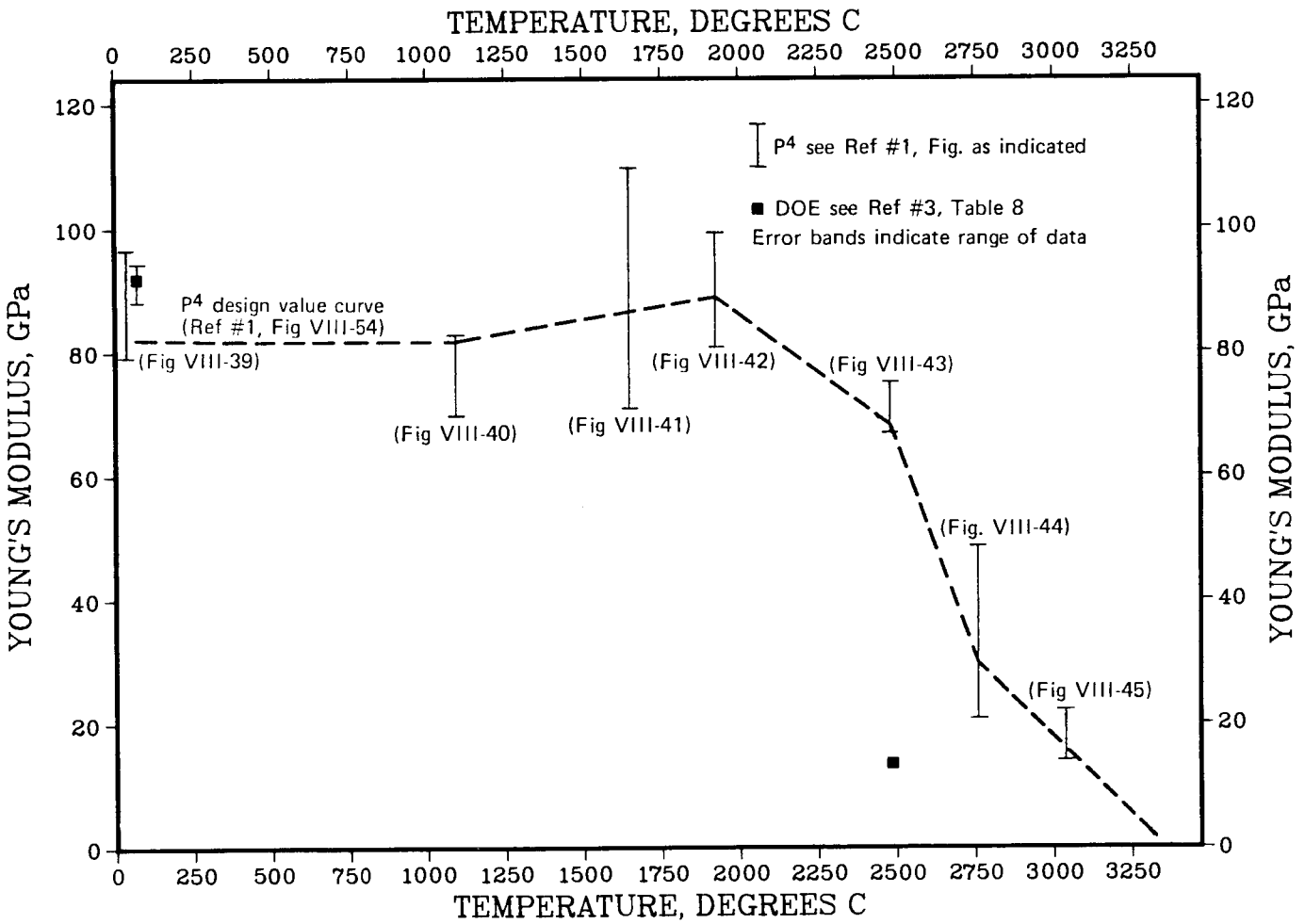
Fine Weave Pierced Fabric	YOUNG'S MODULUS, TENSILE (Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

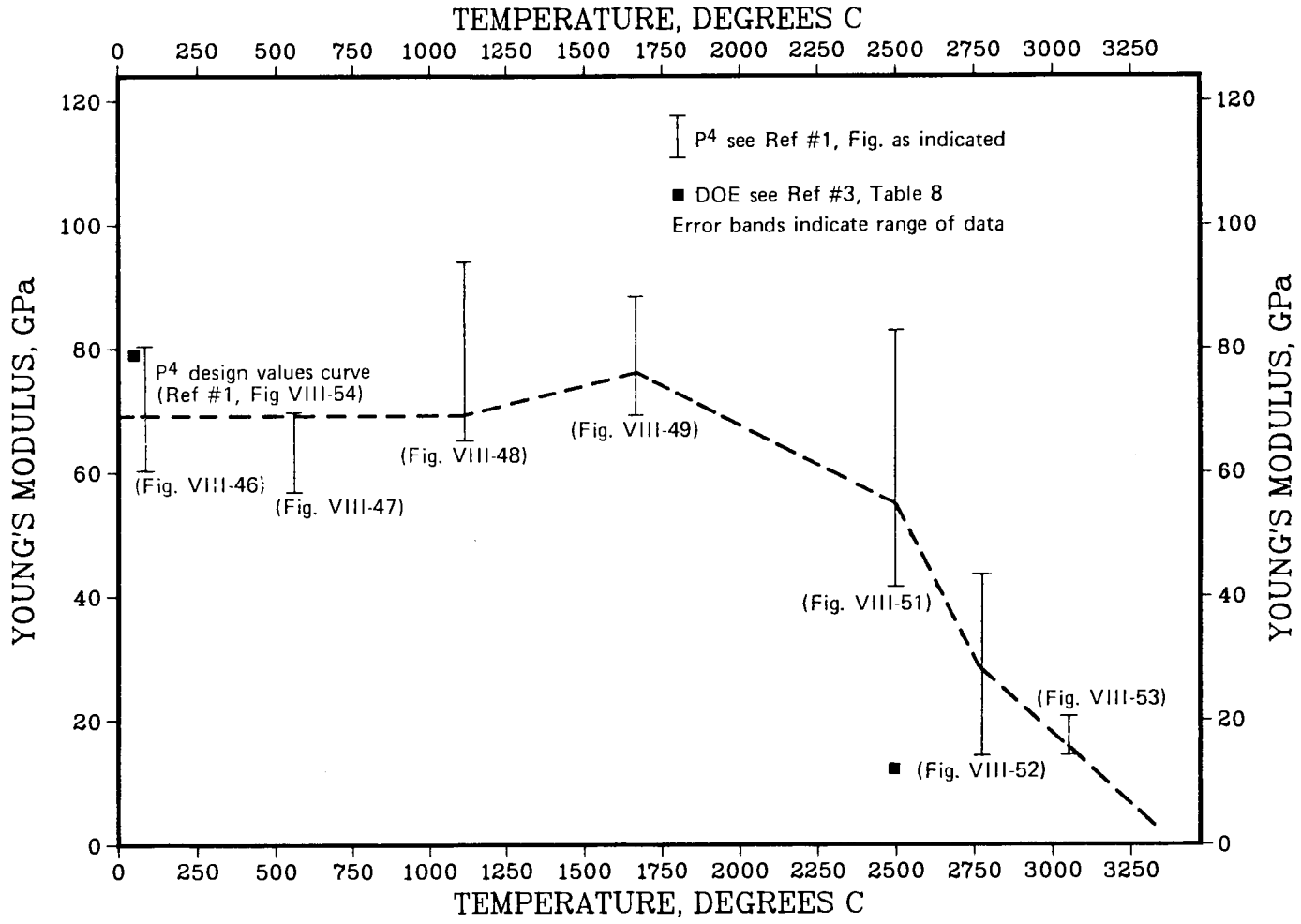
Fine Weave Pierced Fabric	YOUNG'S MODULUS, COMPRESSIVE(X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

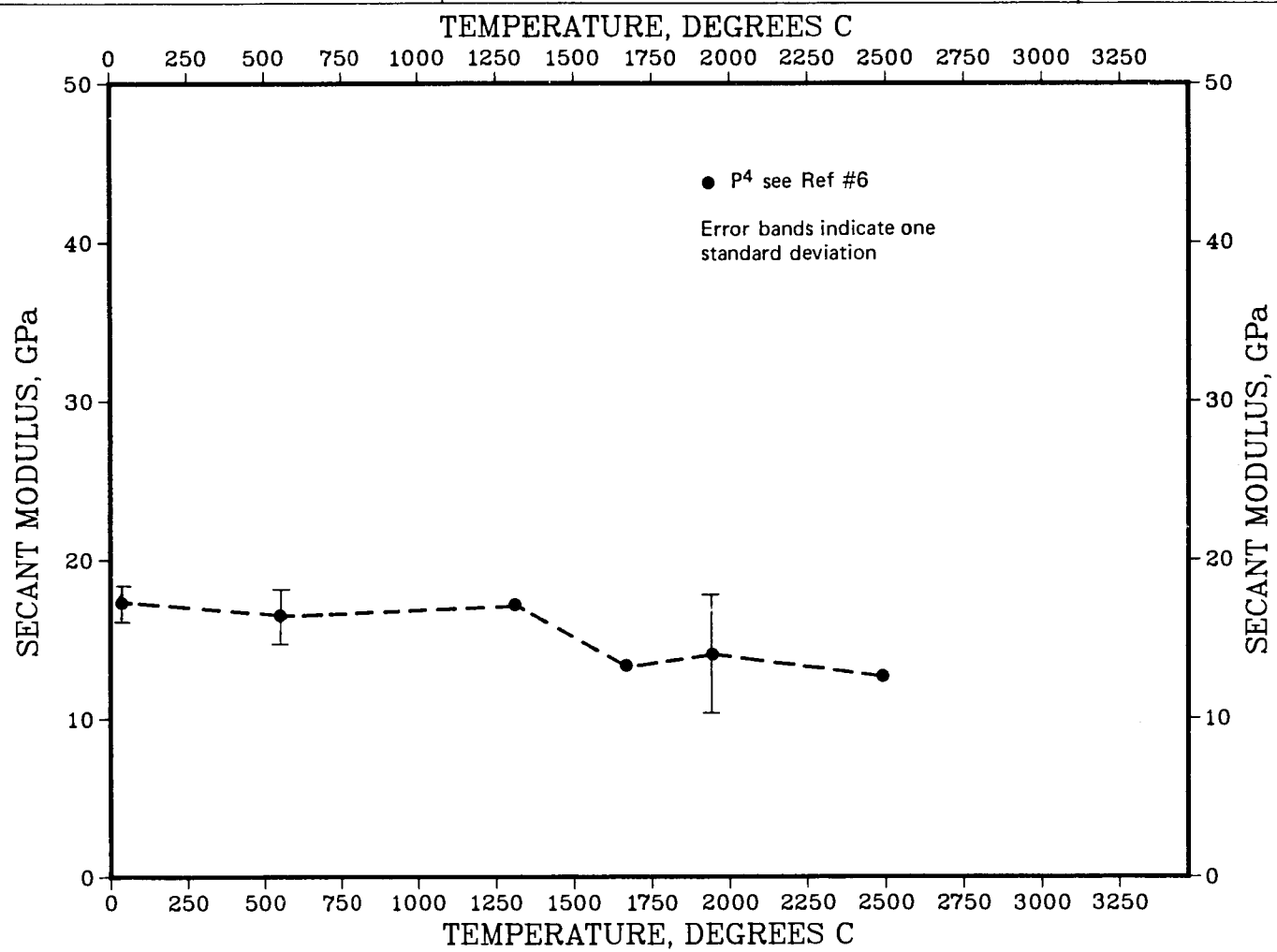
Fine Weave Pierced Fabric	YOUNG'S MODULUS, COMPRESSIVE(Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	6.9MPa TEN. SEC. MOD. (45XY)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



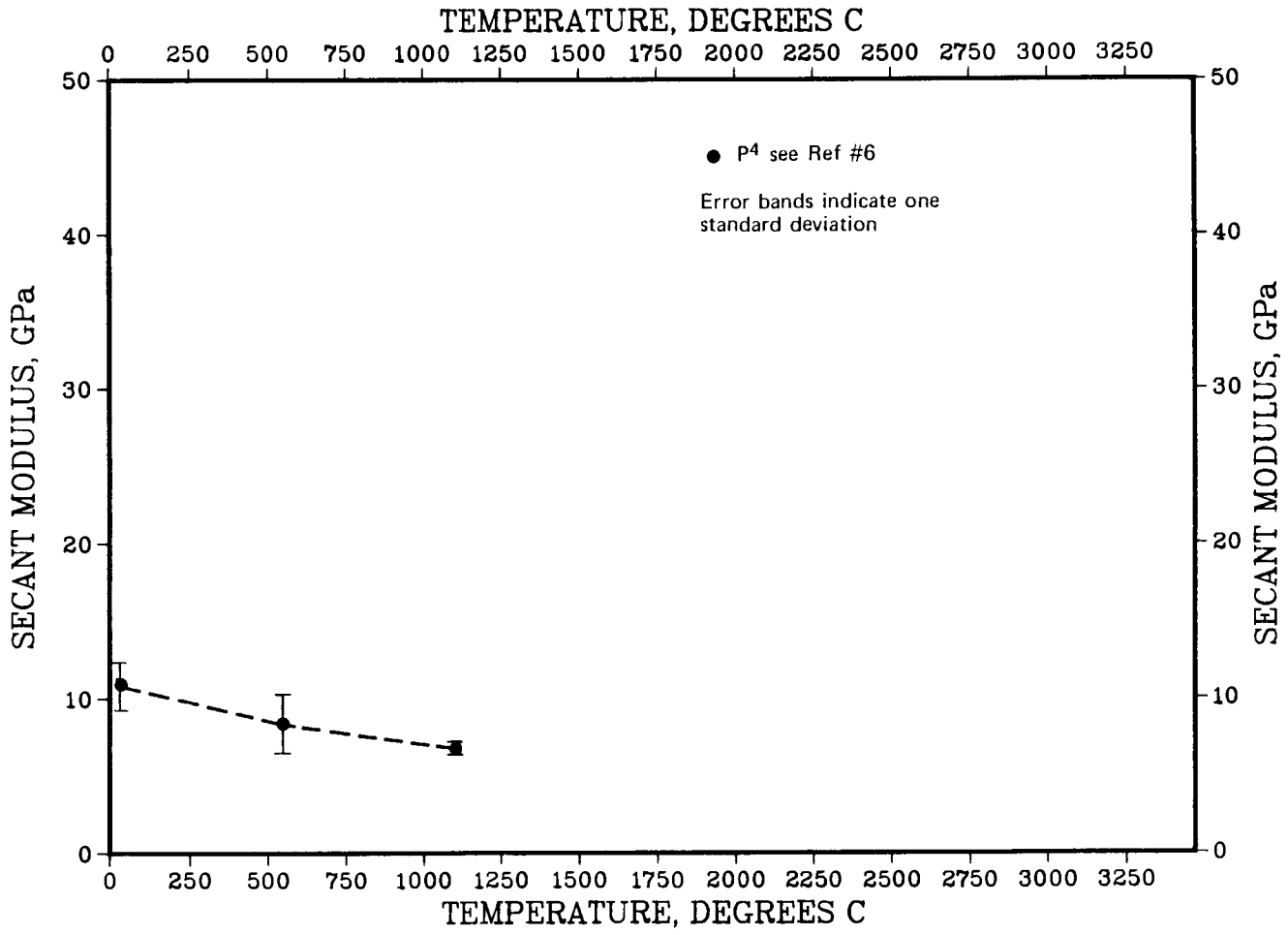
6.9 MPa (1 KSI) Secant Elastic Modulus, Tensile (45XY)

NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2111 PAGE 3.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	6.9MPa TEN. SEC. MOD. (45XZ)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

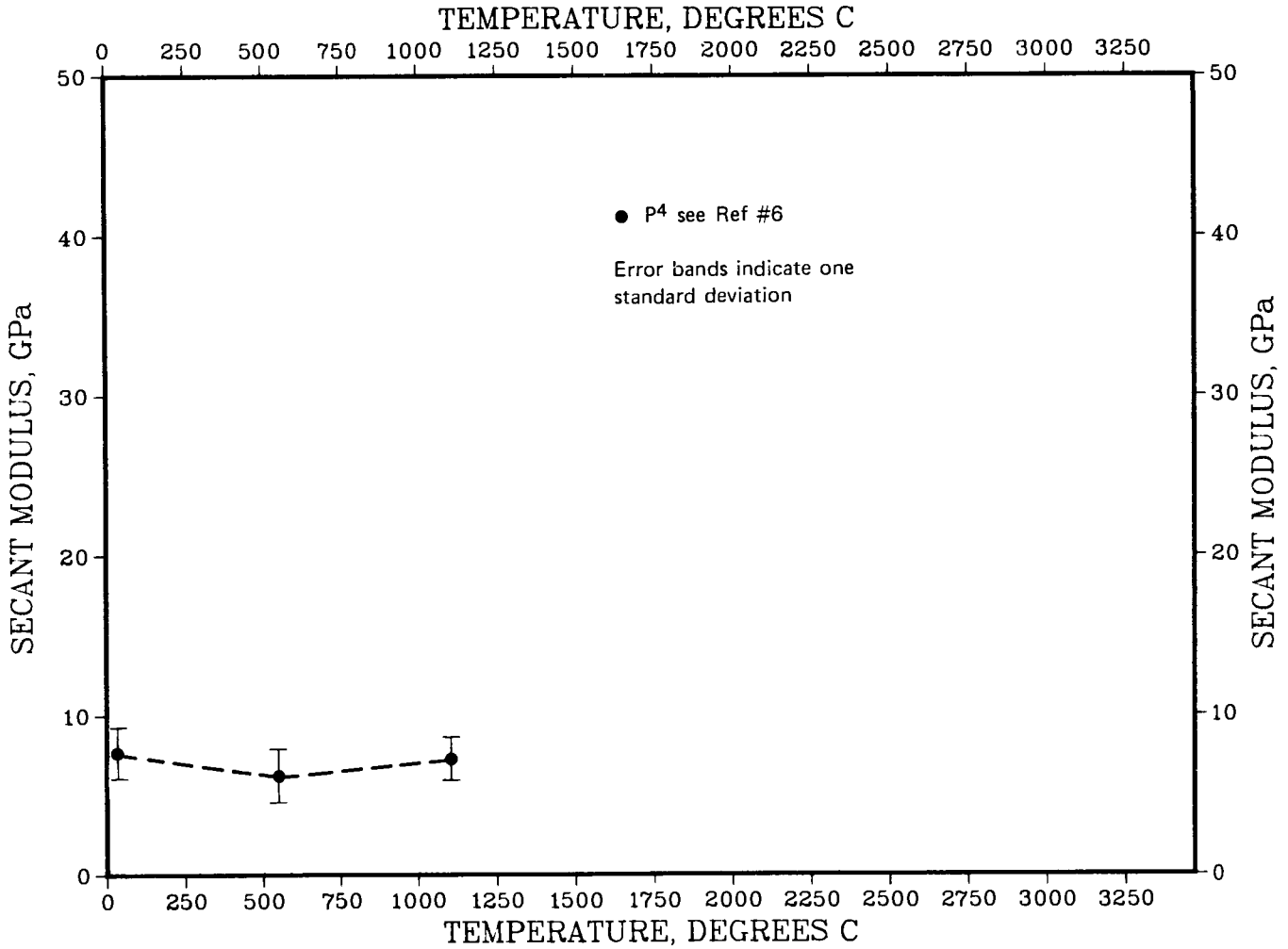


6.9 MPa (1 KSI) Secant Elastic Modulus, Tensile (45XZ) NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2111 PAGE 31

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	6.9MPa COM. SEC. MOD. (45XY)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



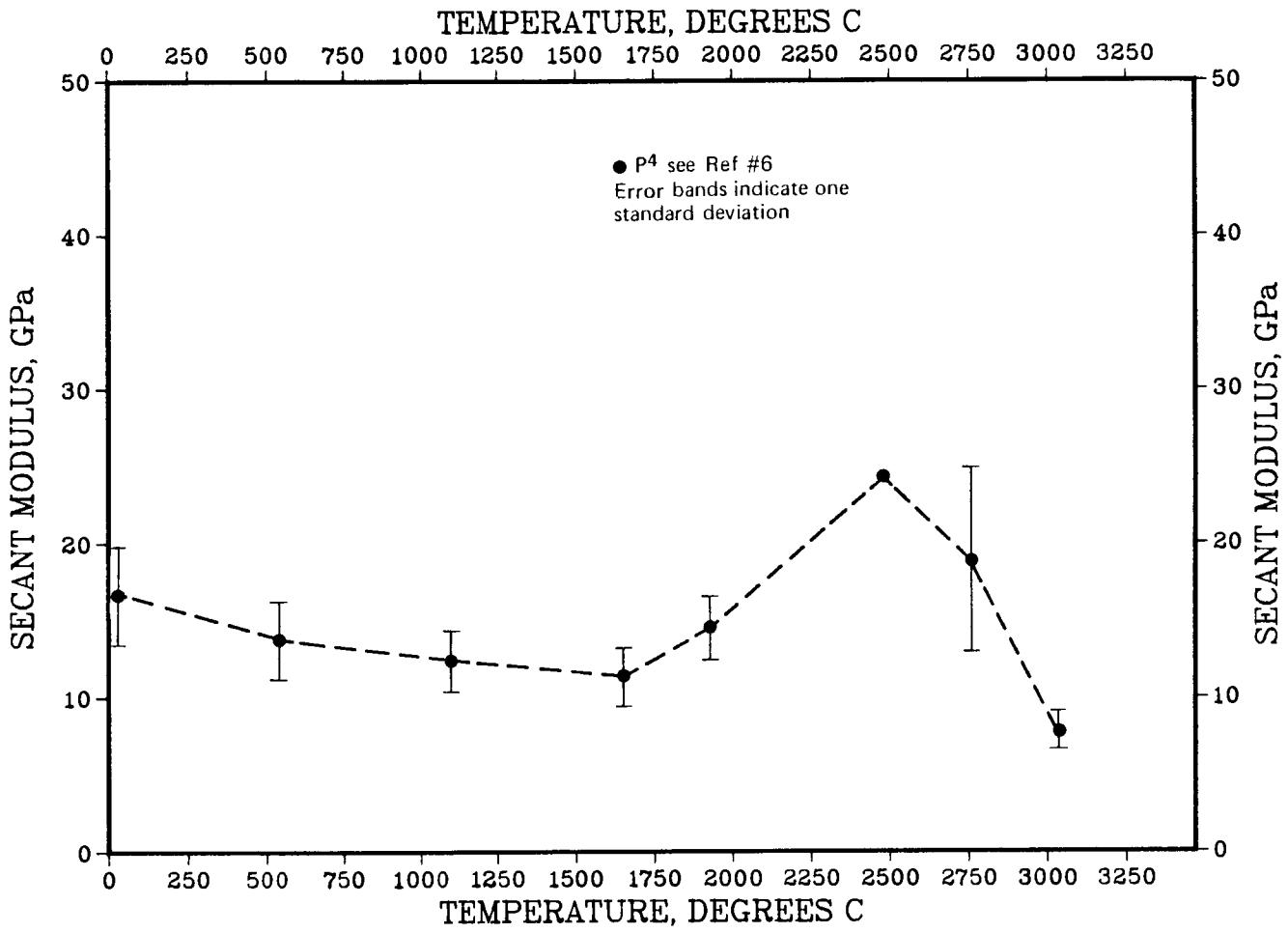
6.9 MPa (1 KSI) Secant Elastic Modulus, Compressive (45XY)

NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2111 PAGE 4.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	6.9MPa COM. SEC. MOD. (45XZ)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



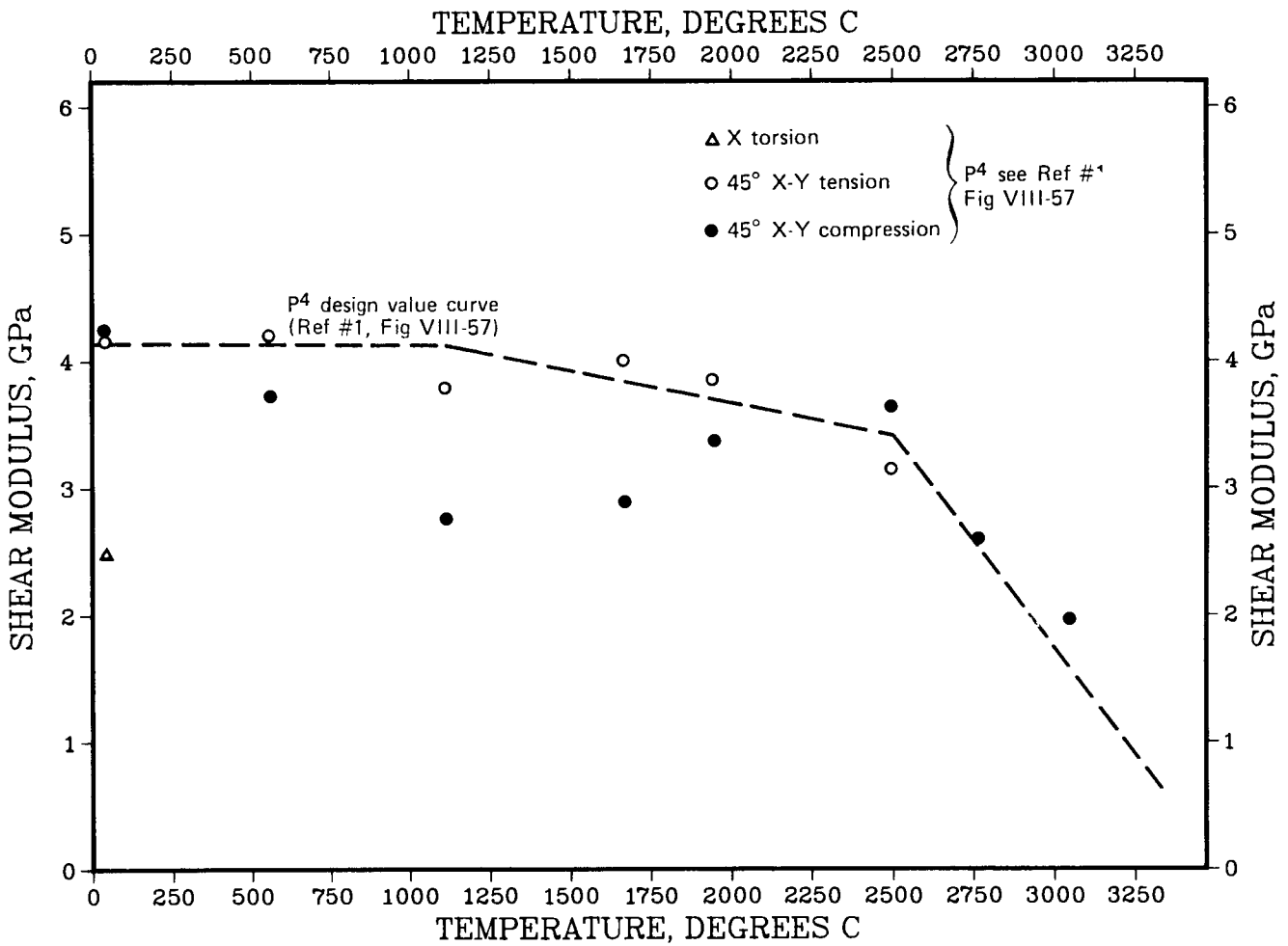
6.9 MPa (1 KSI) Secant Elastic Modulus, Compressive (45XZ)

NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2111 PAGE 4.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

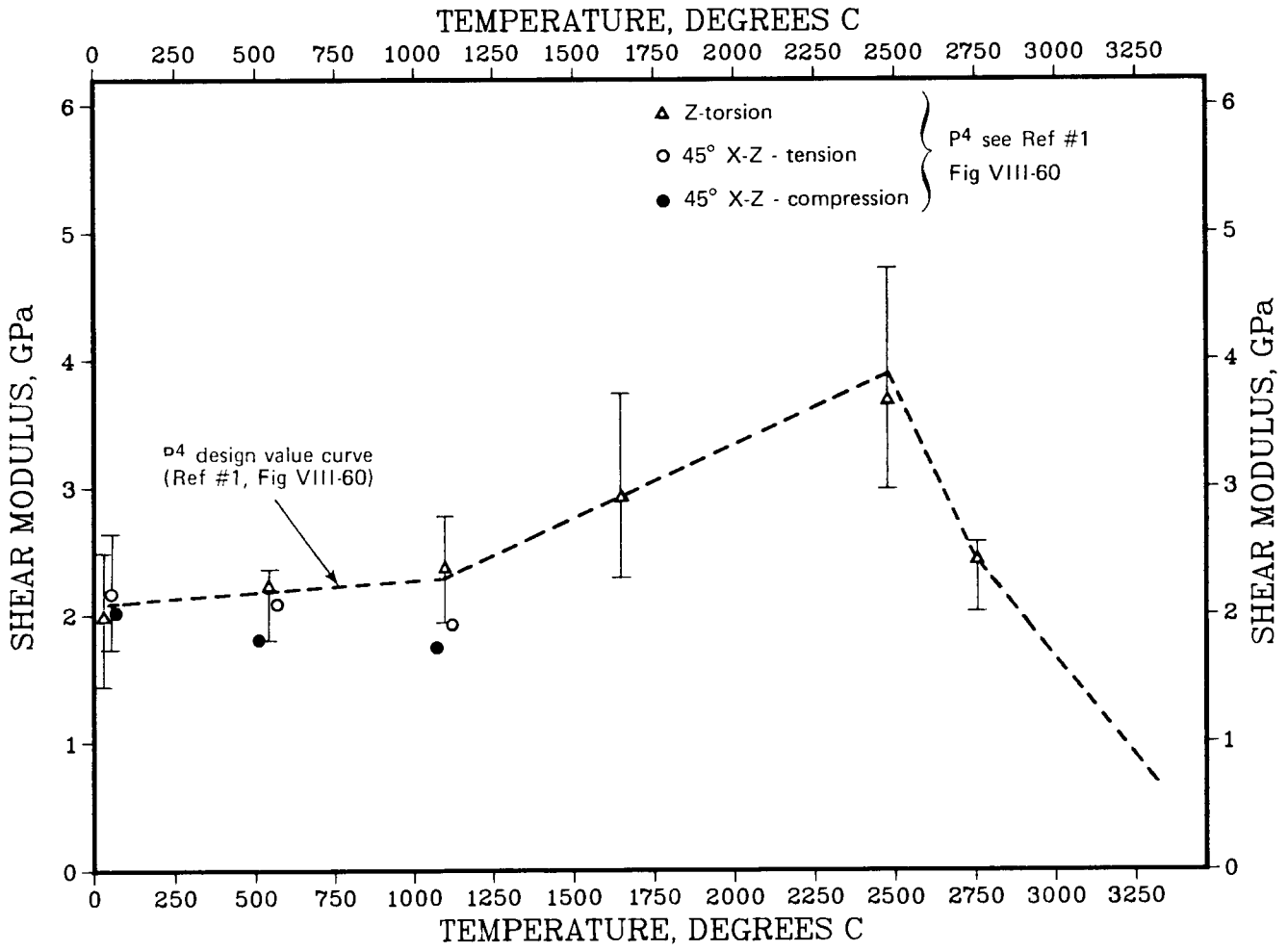
Fine Weave Pierced Fabric	SHEAR MODULUS (XY)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2112 PAGE 1.0

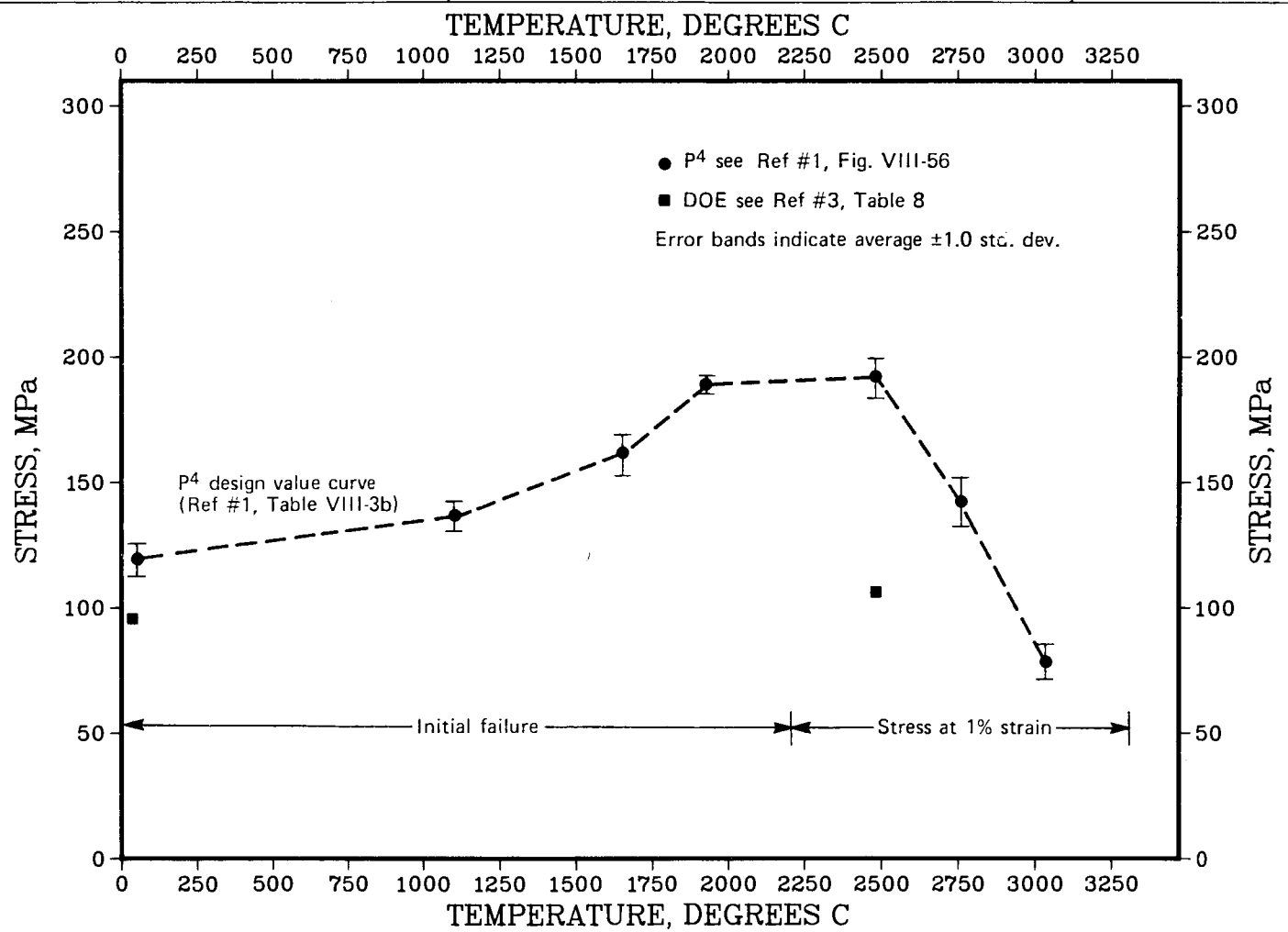
Fine Weave Pierced Fabric	SHEAR MODULUS (XZ)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	COMPRESSIVE STRENGTH (X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

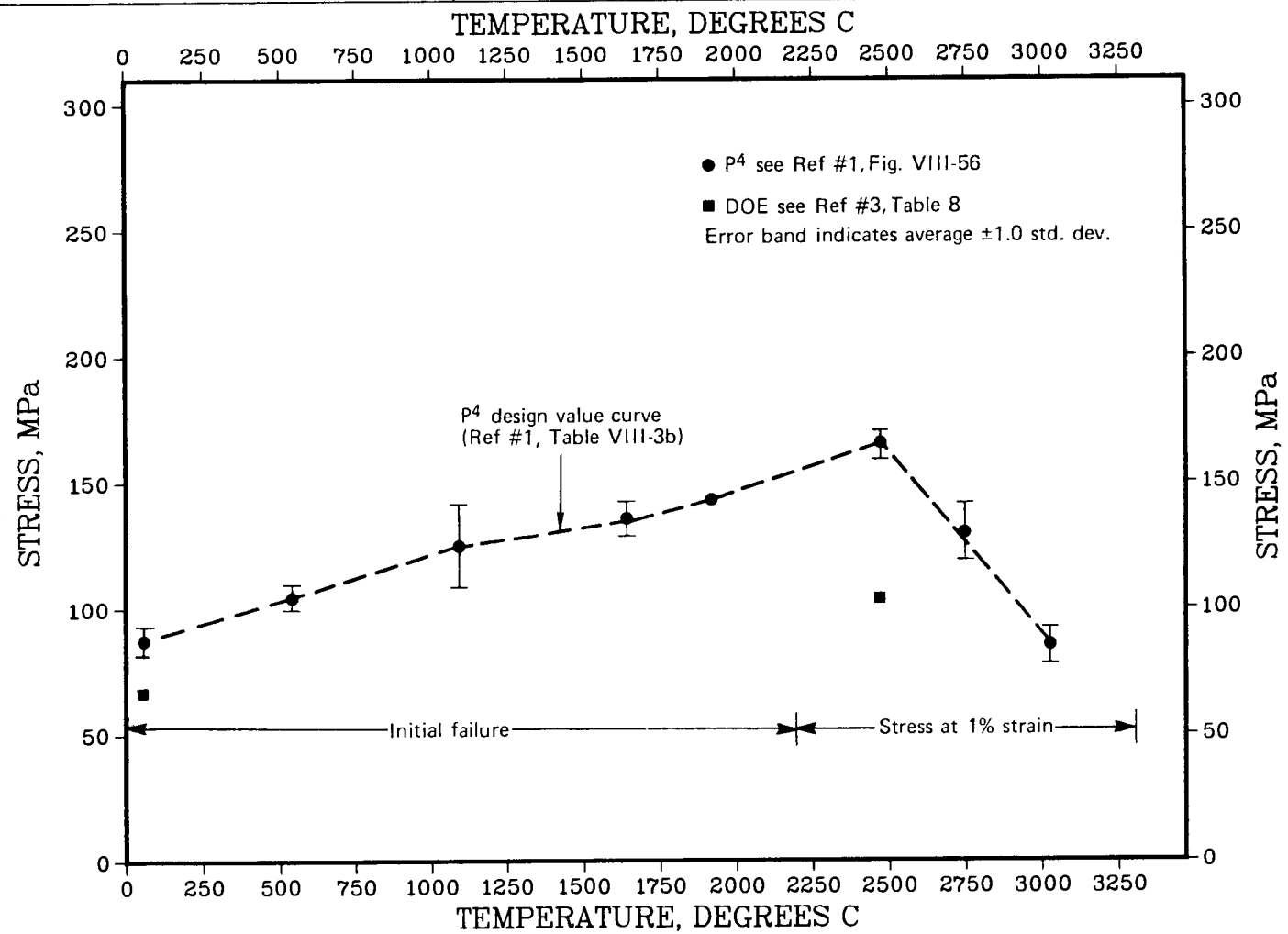


NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2116 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	COMPRESSIVE STRENGTH (Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0

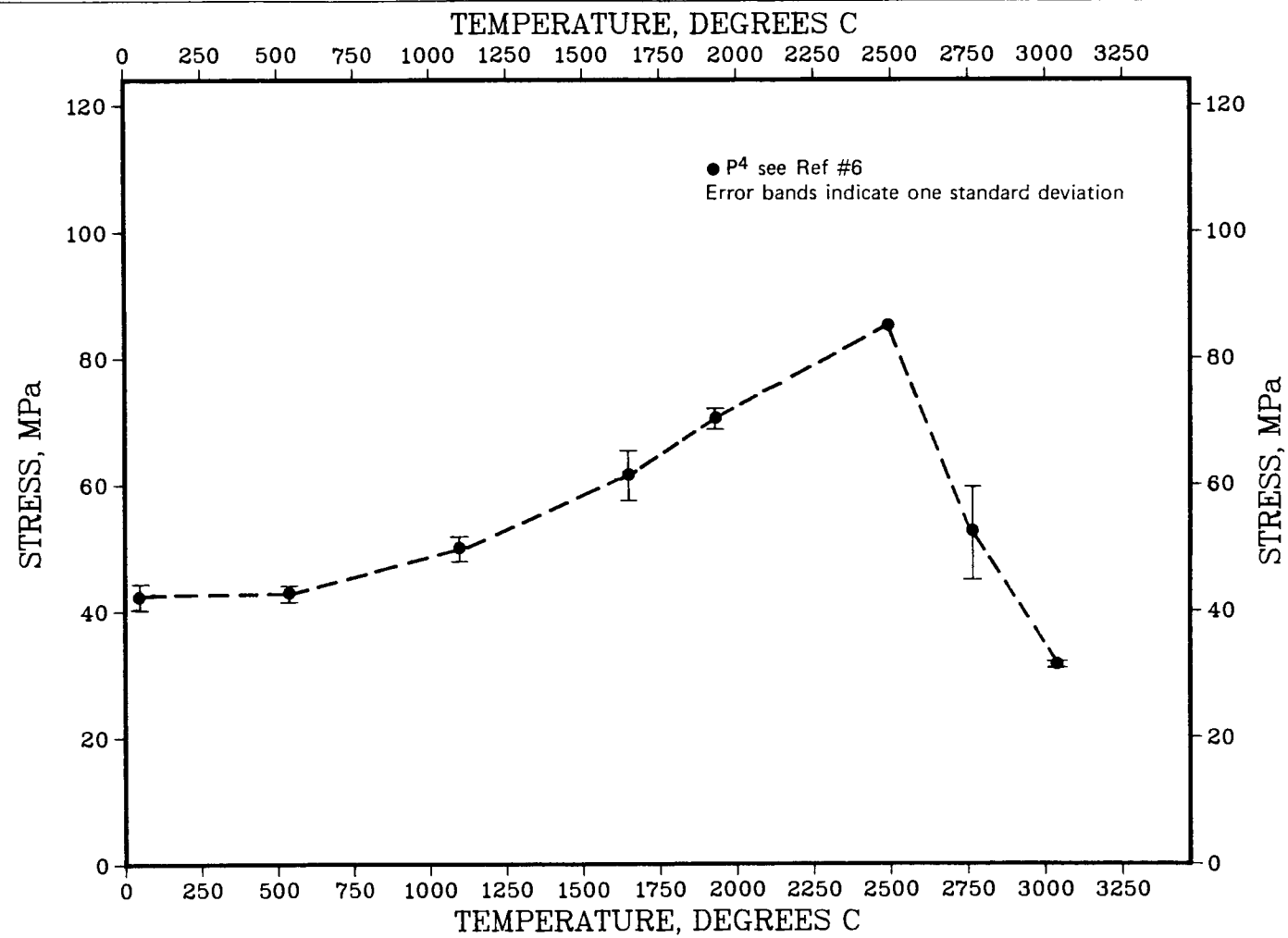


NOTE: See Property Codes 1000 and 2100.

PROPERTY CODE 2116 PAGE 1.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

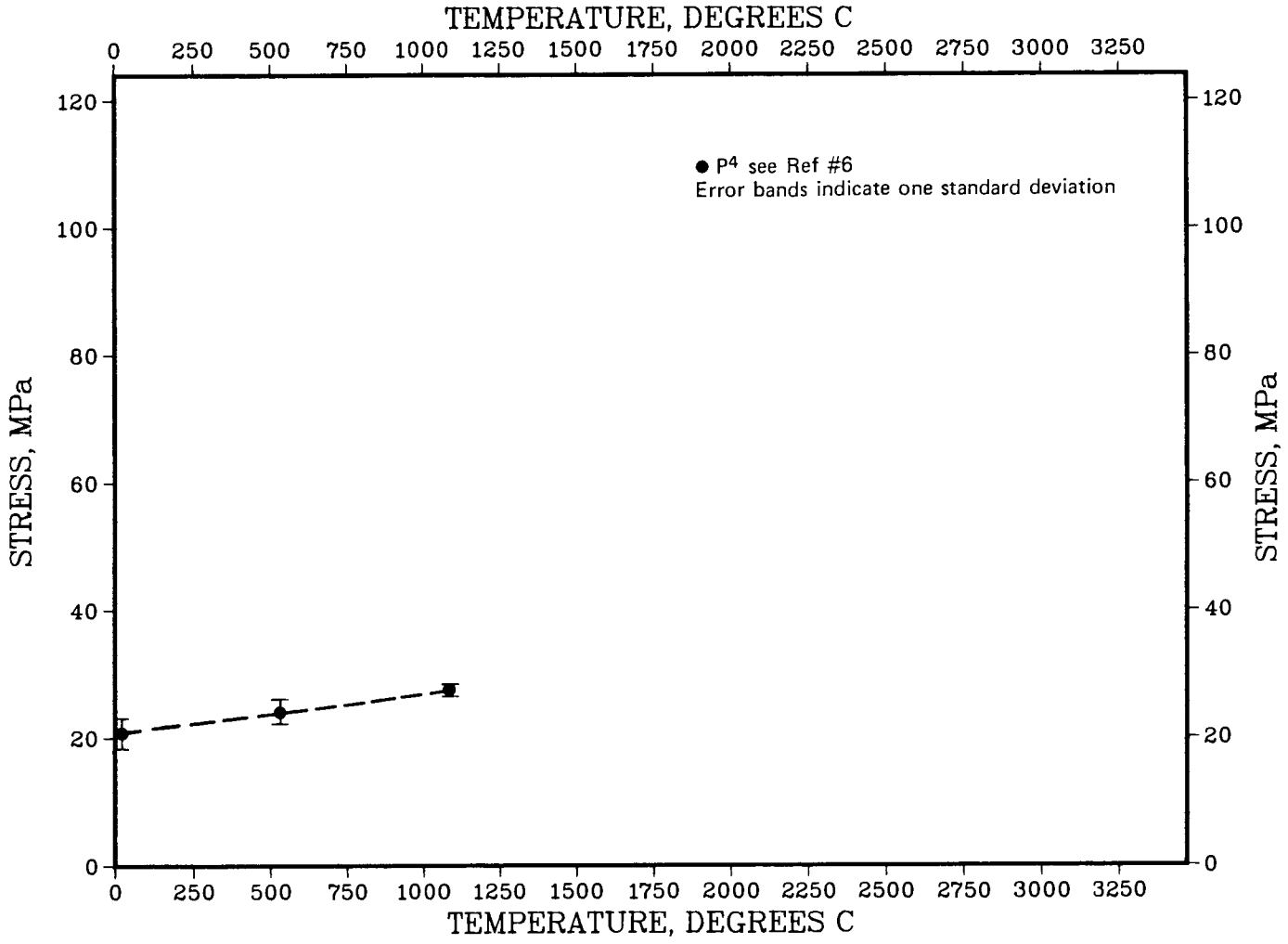
Fine Weave Pierced Fabric	COMPRESSIVE STRENGTH (45XZ)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

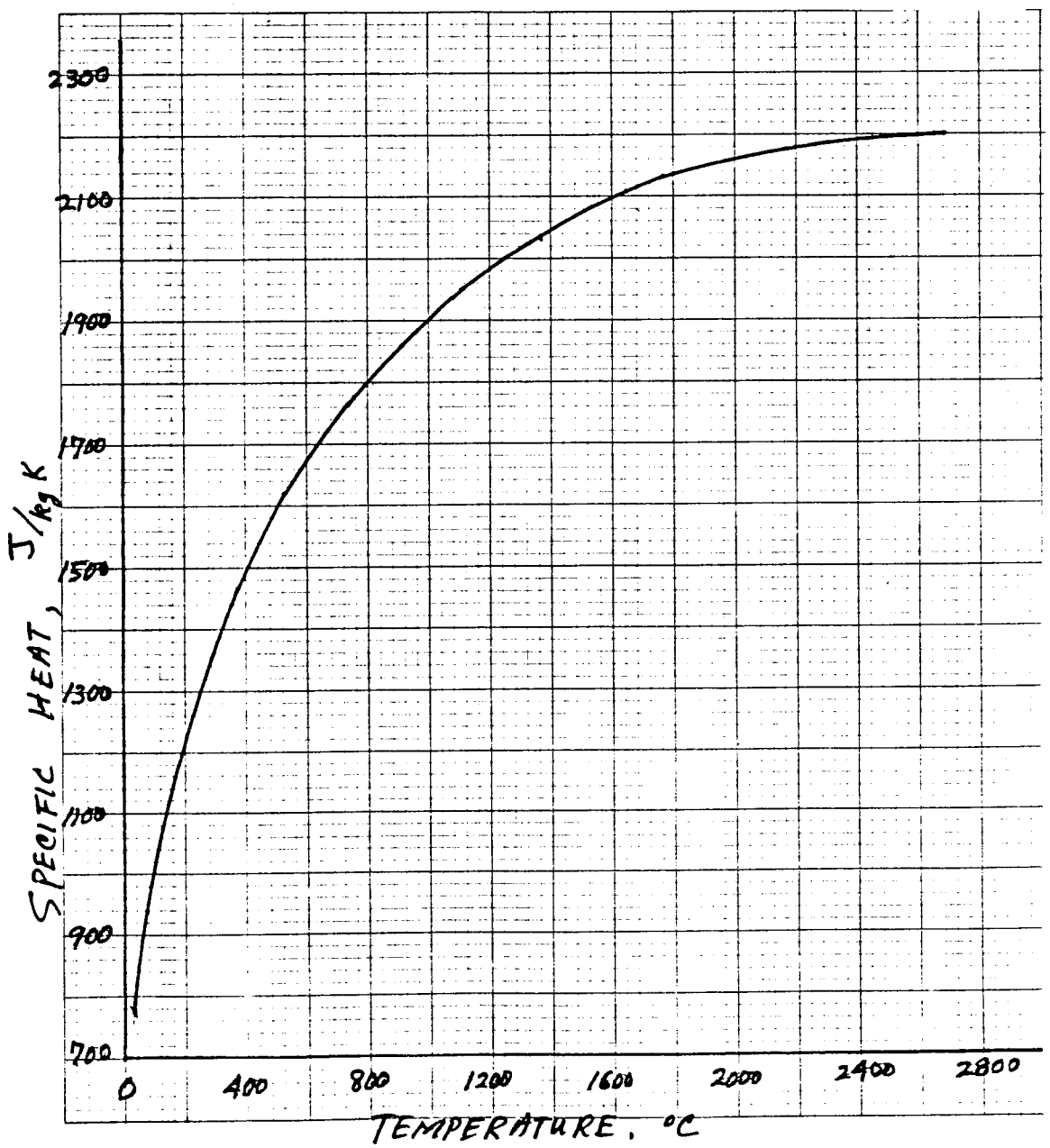
Fine Weave Pierced Fabric	COMPRESSIVE STRENGTH (45XY)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Codes 1000 and 2100.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

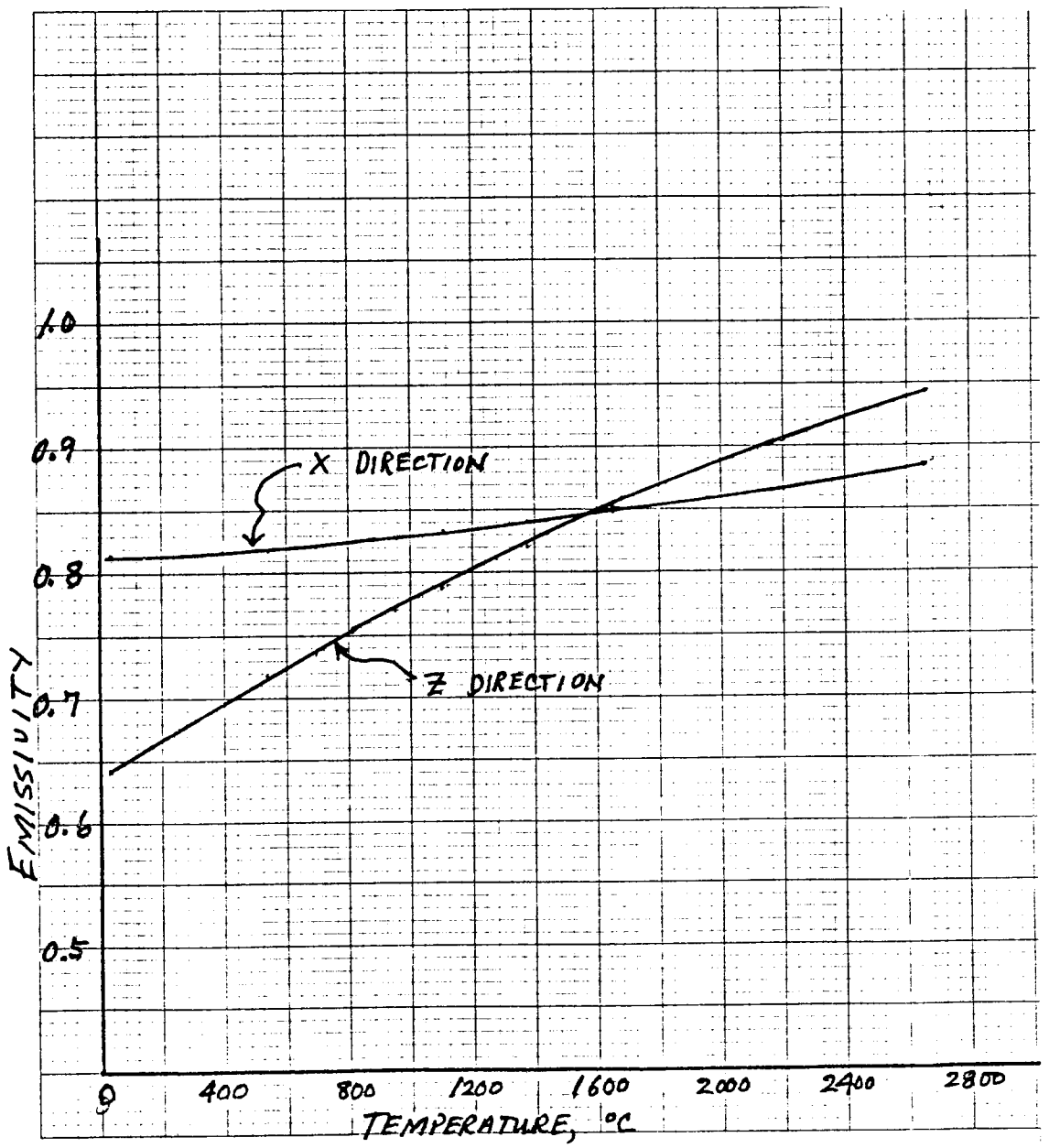
FINE WEAVE PIERCED FABRIC	SPECIFIC HEAT	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

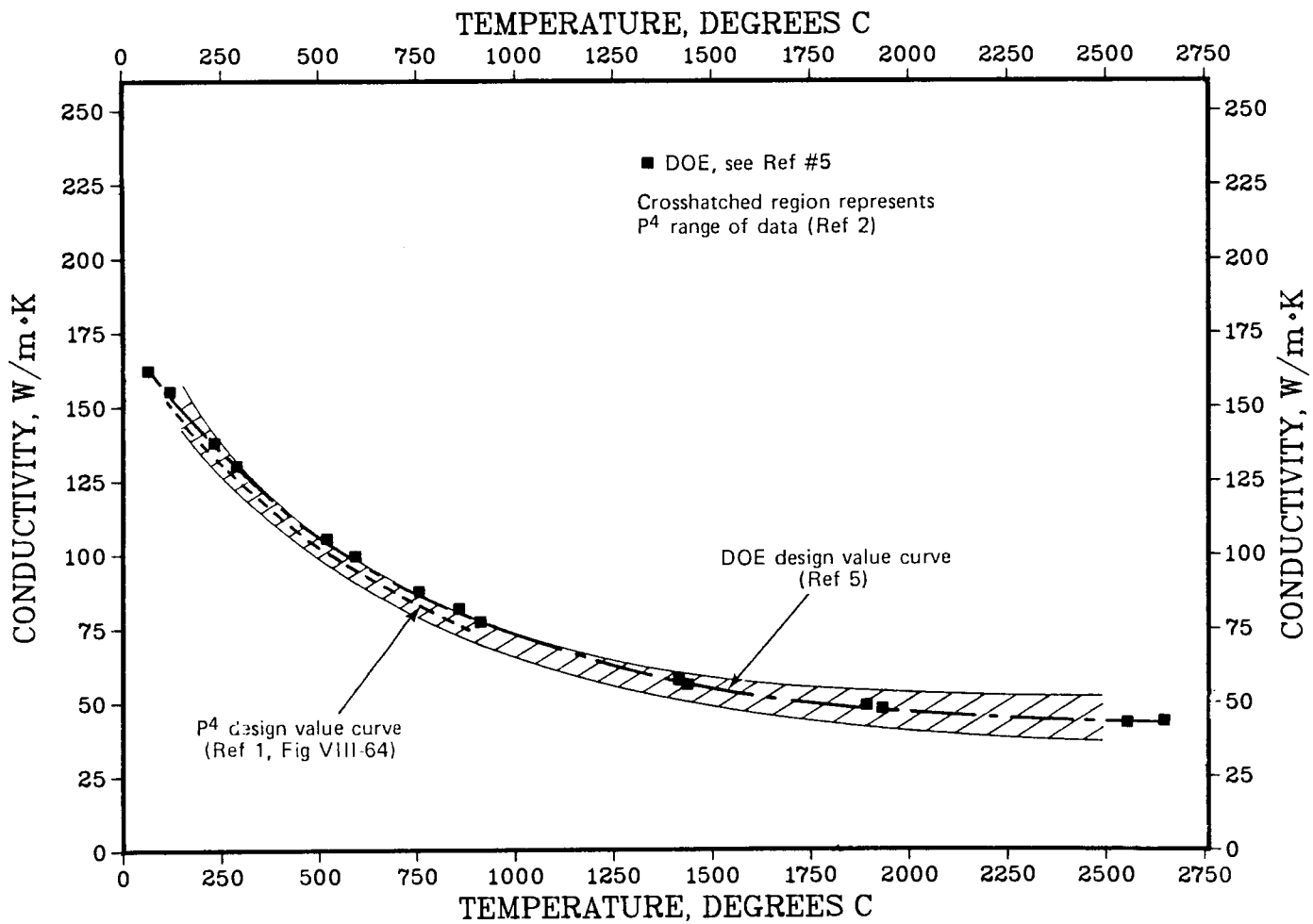
FINE WEAVE PIERCED FABRIC	EMISSIVITY	MATERIAL CODE: EA02
		UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

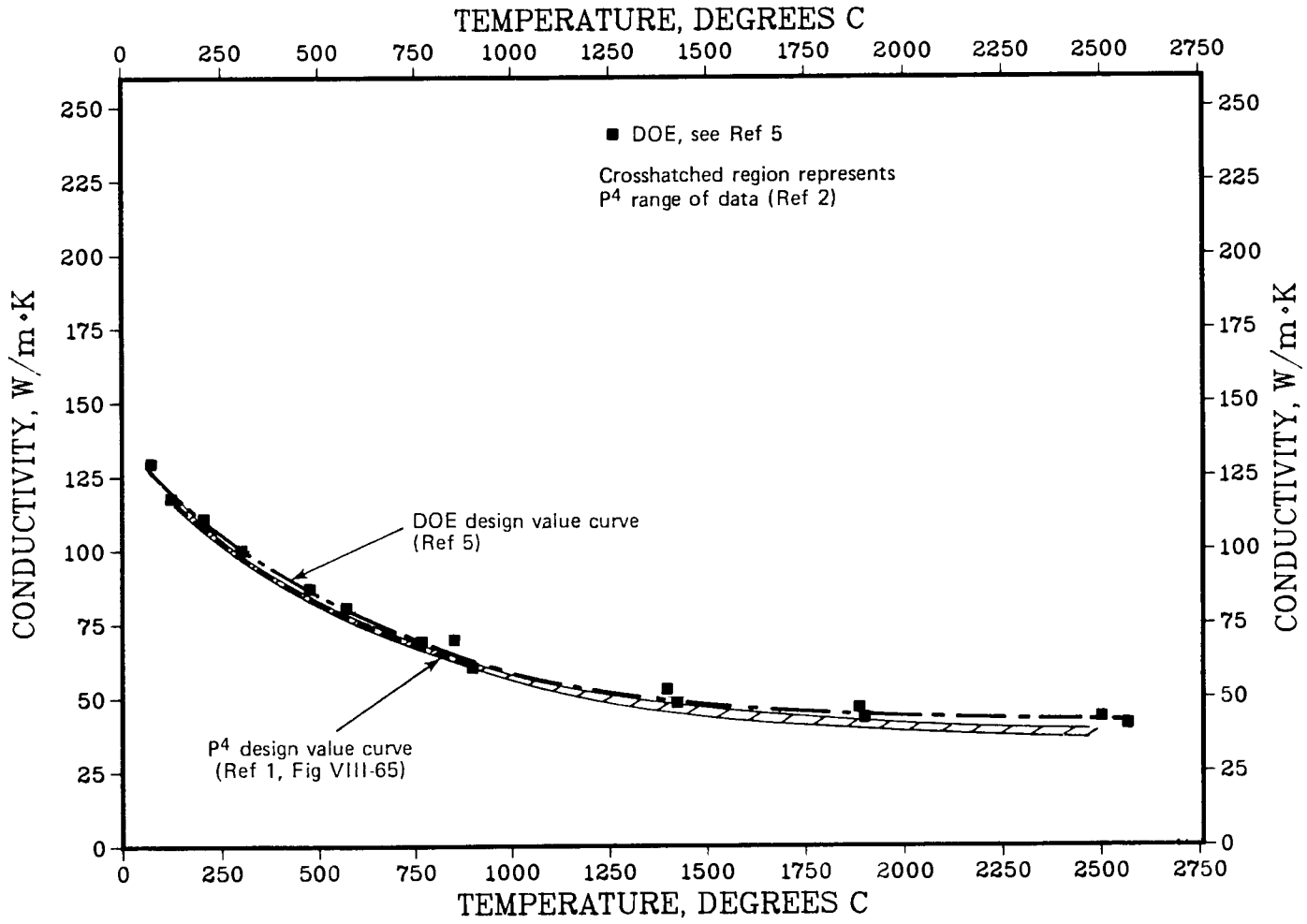
Fine Weave Pierced Fabric	THERMAL CONDUCTIVITY (X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

PROPERTY CODE 3112 PAGE 1.0

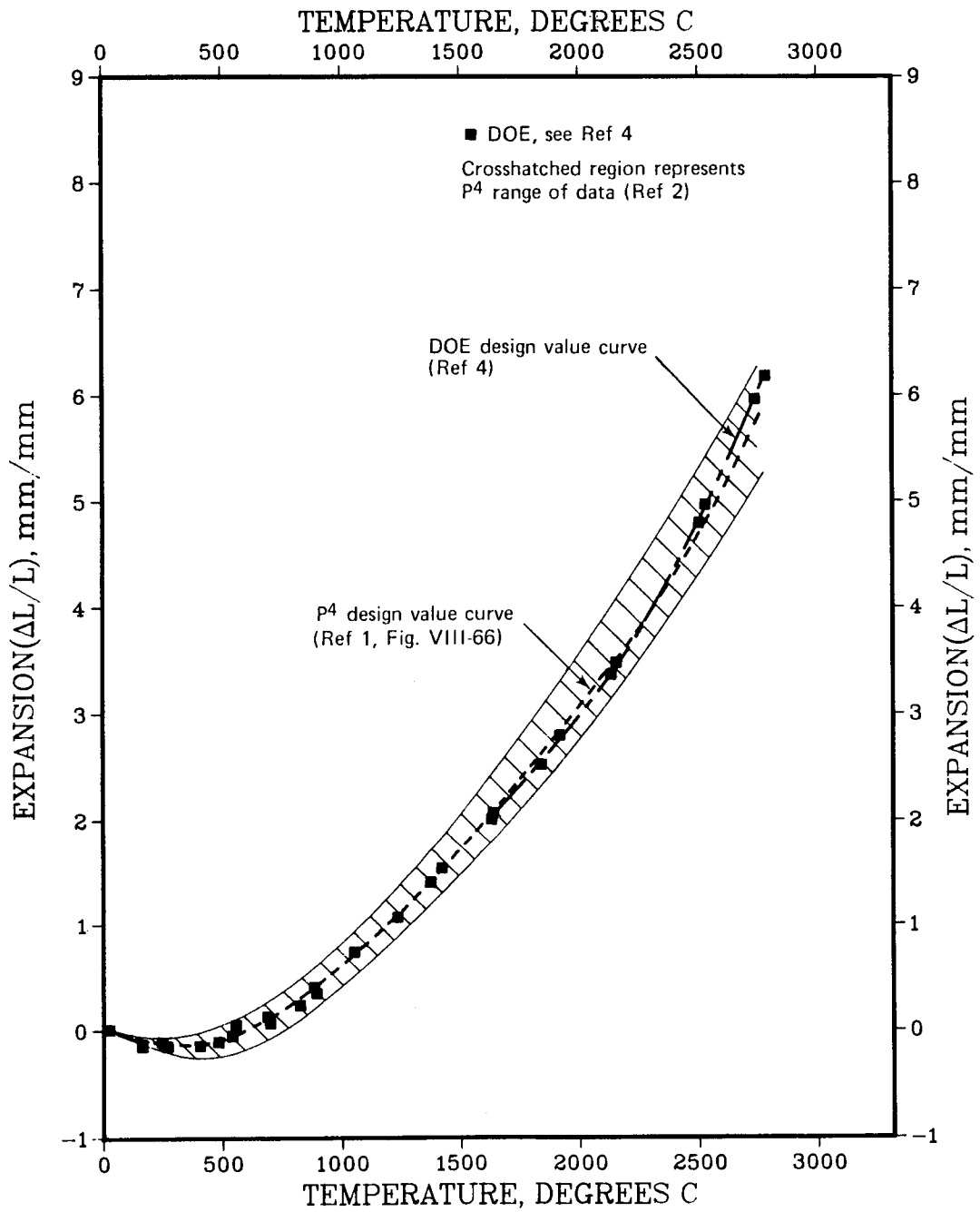
Fine Weave Pierced Fabric	THERMAL CONDUCTIVITY (Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

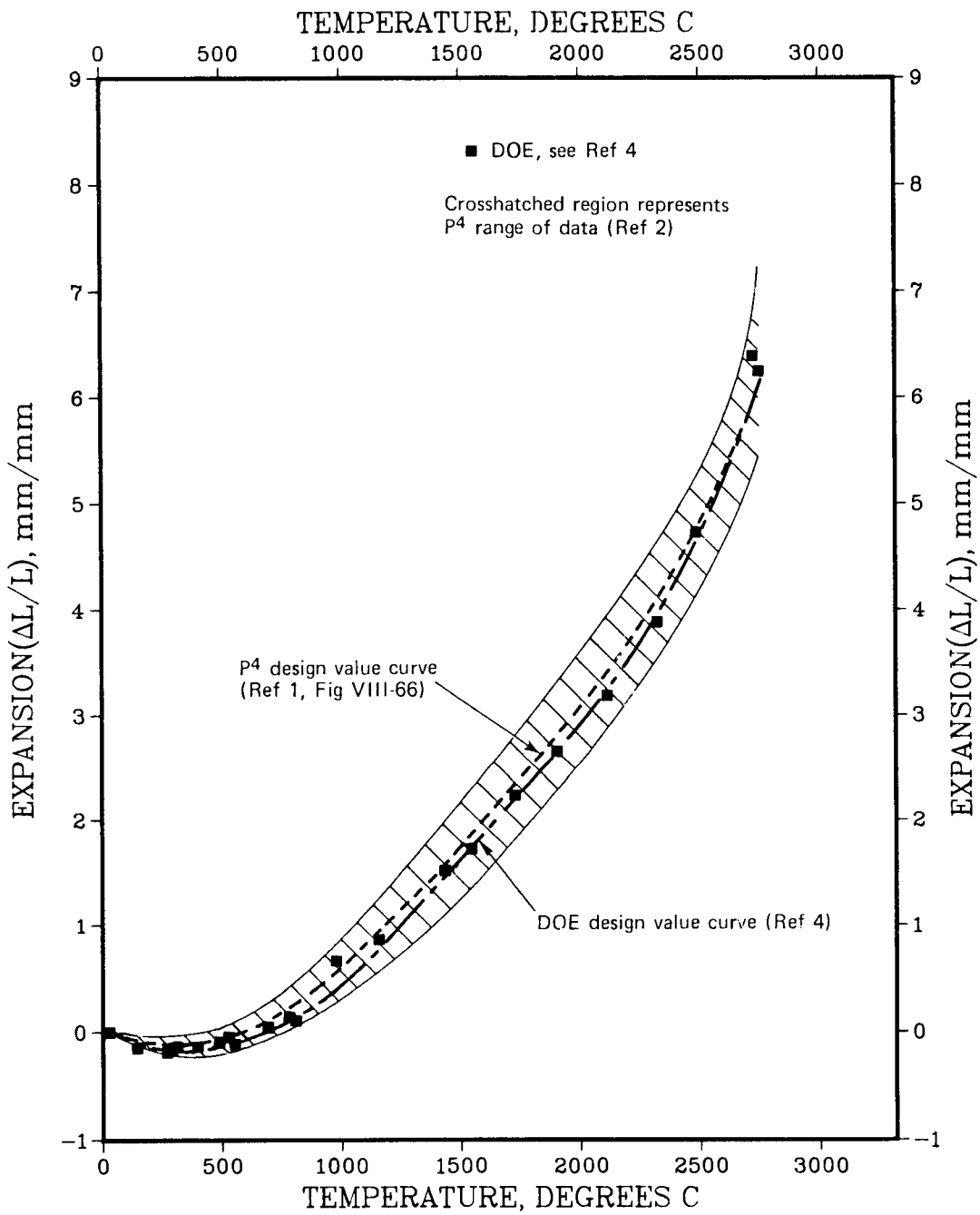
Fine Weave Pierced Fabric	THERMAL EXPANSION (X)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Fine Weave Pierced Fabric	THERMAL EXPANSION (Z)	MATERIAL CODE: EA02 UPDATE CODE: 3.0.0



NOTE: See Property Code 1000.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	TABLE OF CONTENTS/PROPERTIES	Material Code: EA04 Update Code: 3.0.0

Property Code	Property	Pages
1000	General Information	1.0
1100	Crystal Structure	1.0
1200	Product Forms	1.0
2100	Static, Short-Term Mechanical Properties — General Notes	1.0
2101	Ultimate Tensile Strength:	*

POCO AXF-5Q is essentially isotropic so there is no preferred orientation.

The tensile strengths are as follows:

Temperature (°C)	Tensile strength (MPa) 50% probability	Tensile strength (MPa) 98% probability
20	62	54
1085	69	56
1650	85	—

2104	Shear Strength	1.0
2105	Elongation:	*

Nominal values of elongation from tensile testing are as follows:

Temperature (°C)	Fracture Elongation (%)
20	0.82
1085	0.75
1650	0.88

2108	Engineering Stress-Strain Curves	1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	TABLE OF CONTENTS/PROPERTIES	Material Code: EA04 Update Code: 3.0.0

Property Code	Property	Pages
2109	Hardness:	
	Shore Scleroscope — 70	*
2110	Poisson's Ratio:	*
	0.15 from tensile tests	
	0.25 from sonic testing	
2111	Young's Modulus:	*

Temperature (°C)	Young's Modulus (GPa)
20	13.7
1085	15.0
1650	17.0

2112	Shear Modulus:	*
	at room temperature = 5.5 GPa	
2114	Bulk Modulus:	*
	at room temperature = 9.13 GPa	
2115	Modulus of Rupture:	*
	at room temperature = 82.7 MPa	
2116	Compressive strength:	*
	at room temperature = 130 MPa	
2122	Isothermal Compressibility:	*
	$1/K = 1.10 \times 10^{-10}$	
2432	Fracture Toughness:	*
	at room temperature = 1.65 $MPa\sqrt{m}$	
3112	Thermal Conductivity:	*
	at room temperature = 121 W/mK	

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	TABLE OF CONTENTS/PROPERTIES	Material Code: EA04 Update Code: 3.0.0

Property Code	Property	Pages
3114	Coefficient of Thermal Expansion: from room temperature to 1000°C = $7.7 \times 10^{-6}/°C$	*
3201	Electrical Resistivity: at room temperature = 13 μΩ-m	*
3304	Bulk Density: 1.80–1.88 g/cm^3	*
3305	Porosity: 15–20%	*
3306	Speed of Sound: at room temperature: longitudinal wave = 3.10 Km/s shear wave = 1.78 Km/s	*
3311	Gas Permeability: He permeability is 0.001 Darcies	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	GENERAL INFORMATION	Material Code: EA04 Update Code: 3.0.0

The small locking screw that keeps the cap holding the isotopic heating units in place are made of graphite grade POCO AXF-5Q. This graphite is isostatically molded using a very fine particle size filler to obtain an isotropic graphite with fairly high mechanical properties. The final heat treatment temperature is a nominal 2500°C. It is classified as a very fine grained, isotropic, very high strength material with a fairly small, open pore size. The graphite has a very high coefficient of thermal expansion for graphites. The electrical and thermal conductivity are fairly low compared to most electrode grades.

The physical properties of concern would be the coefficient of thermal expansion and the strength of the material. The Mound procurement specification number is: SPA 780523.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	CRYSTAL STRUCTURE	Material Code: EA04 Update Code: 3.0.0

Graphite has a hexagonal crystal structure with ABAB stacking. The crystal is highly anisotropic with strong chemical bonding in the hexagonal plane and with Van der Wall bonding between planes. Fabrication techniques that allow a preferred orientation of the crystals to exist will produce strongly anisotropic physical properties. Graphite grade POCO AXF-5Q is isostatically molded to reduce the tendency for preferred orientation.

This grade of graphite will have a total ash content of less than 600 ppm with the major impurities listed as follows:

Element	Range (ppm)
Iron	50–200
Silicon	25–200
Aluminum	10–50
Vanadium	50–100
Titanium	1–5

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	PRODUCT FORMS	Material Code: EA04 Update Code: 3.0.0

Grade AXF-5Q can be obtained in plate form in numerous sizes from 38.1 × 101.6 × 152.4 mm to 50.8 × 101.6 × 457.2 mm or 101.6 × 127 × 203.2 mm. Solid cylinders up to 101.6 mm diam × 457.2 mm and 203.2 mm diam × 304.8 mm can also be obtained.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	STATIC, SHORT-TERM MECHANICAL PROPERTIES	Material Code: EA04 Update Code: 3.0.0

GENERAL NOTES

The mechanical properties of graphite are stress volume dependent. Because of the increased probability of finding a critical flaw, the fracture strength is lower in larger specimens. The greater the variability in strength, the greater the effect of increased stress volume in reducing strength. Also, tensile bars generally fail as a result of surface flaws. If the internal stress concentration component peaked internally at a value greater than twice that for the critical flaw size from a surface, the resistance to fracture would be greater. The increased stress volume of the tensile specimen mainly accounts for the reduced tensile strength compared to flexural strength. There is always about a 10% correction needed to correct the modulus of rupture fracture stress calculation to actual fracture stress resulting from redistribution of stress in flexure. This is caused by the nonlinear stress-strain relationship. In the case of components where the stress volume is small, the stress resistance will probably be higher than measured values; however, the failures would all be related to surface flaws. In the small locking screw, the major stresses of concern would be either shear or flexural stresses which would be fairly minor under normal operation. The large mismatch in the coefficient of thermal expansions between the fine weave pierced fabric carbon-carbon composite and the POCO AXF-5Q screws will generate a significant compressive stress on the locking screw. However, the compressive strength of this grade is quite high.

The static, short-term mechanical properties of graphite are not time dependent until operational temperatures exceed 1600°C. There is some increased strength in extraordinarily high strain rates (impact); however, the increase is very grade dependent and cannot be approximated without test data.

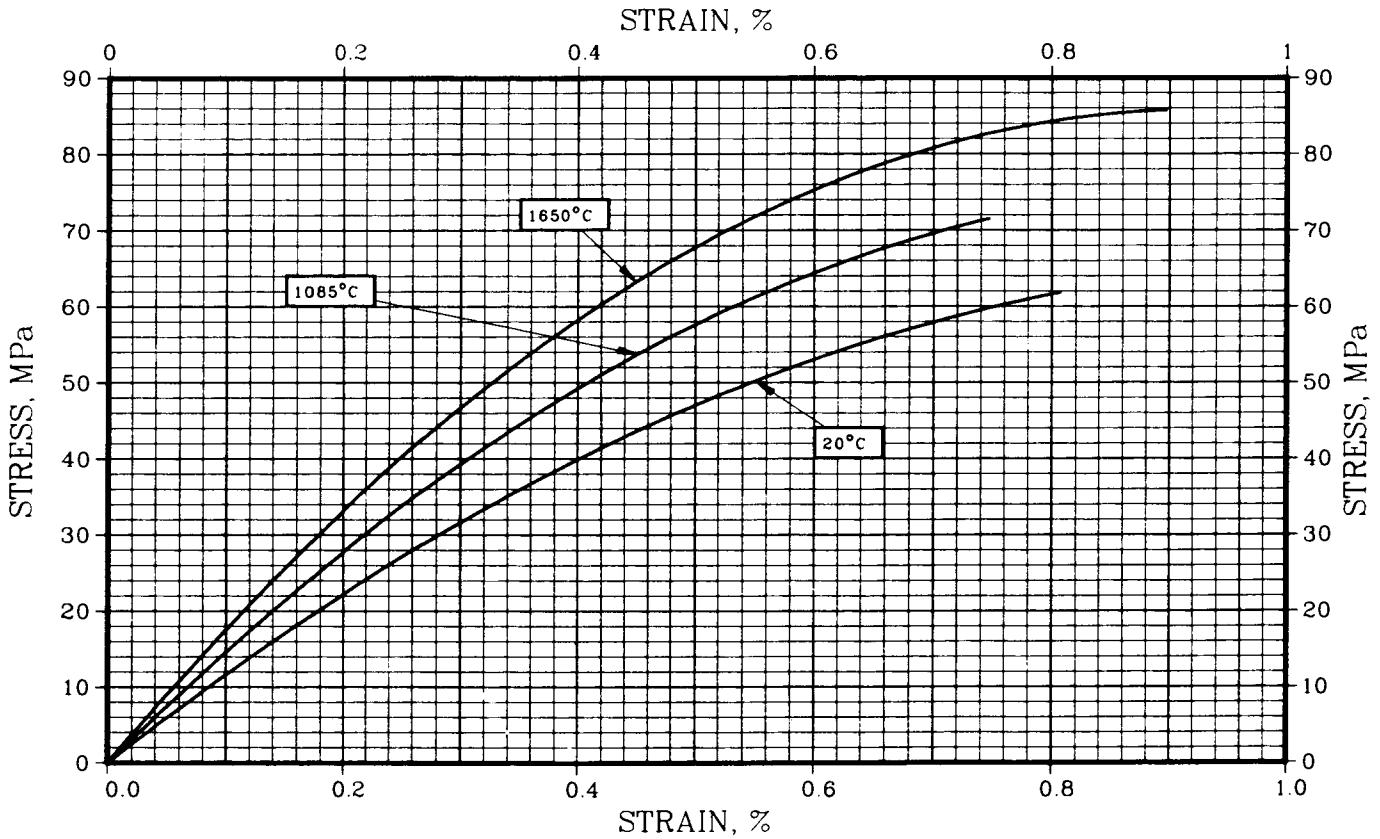
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	SHEAR STRENGTH	Material Code: EA04 Update Code: 3.0.0

Shear strength values are not available. However, they may be inferred from tensile and compressive strength values. Graphite fails by the principal stress criterion or a maximum shear stress criterion. The tensile properties define the maximum principal stress and the compressive strength defines the maximum shear strength. Thus, for pure shear or torsion the maximum value would either be equal to the tensile strength or one-half of the compressive strength, whichever is less. Generally, the tensile strength equals the shear strength.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

POCO AXF-5Q	ENG. STRESS-STRAIN CURVES	MATERIAL CODE: EA04
		UPDATE CODE: 3.0.0



PROPERTY CODE 2108

PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	MATERIAL CODES	Update Code 0.0.0

The following list shows how the materials to be covered in this handbook are placed in the various divisions (Part, Group, and Section) of the Material Code. The Material Code of each specific alloy or material is also listed.

Part–Group–Section Divisions

Part A — Metals	**Material Code**
Group A—Tungsten Alloys	
Section 0A—Brazing Alloys	AA0A
01—Wrought Tungsten	AA01
02—Sputtered Tungsten	AA02
03—CVD Tungsten	AA03
Group B—Aluminum Alloys	
Section 0A—Al-Ag Eutectic	AB0A
01—Alloy 1100	AB01
02—Alloy 7075	AB02
Group C—Titanium Alloys	
Section 0A—	
01—Titanium	AC01
Group D—Copper Alloys	
Section 0A—	
01—OFHC Copper	AD01
02—Dumet	AD02
Group E—Nickel Alloys	
Section A0—Nickel Plating	AEA0
Section 01—Alloy X-750	AE01
Group F—Silver Alloys	
Section 0A—INCUSIL 10	AF0A
0B—NICUSIL 3	AF0B
0C—CUSIL	AF0C
0D—PALCUSIL 15	AF0D
Group G—Gold Alloys	
Section 0A—NIORO*	AG0A

*Registered trademark of Western Gold and Platinum Company, 477 Harbor Blvd., Belmont, Calif., 94002.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	MATERIAL CODES	Update Code: 3.1.0

Part B — Metalloids

Group A — High-Silicon Metalloids
Section 0A —

01—N-type Si/Ge/GaP/P	BA01
02—P-type Si/Ge/GaP/B	BA02
03—SiMo N-type	BA03
04—SiMo P-type	BA04
05—N-type 78Si/22Ge/P	BA05
06—P-type 78Si/22Ge/B	BA06
07—N-type 63Se/37Ge/P	BA07
08—P-type 63Si/37Ge/B	BA08

Part C — Crystalline Ceramics

Group A — Nitrides
Section 01—Si_3N_4 CA01

Group B — Oxides
Section 01—Al_2O_3 CB01
Section 02—Astroquartz CB02

Part D — Amorphous Ceramics and Glasses

Group A — Silicate glasses
Section 01—Low-temperature Glass DA01
02—High-temperature Glass DA02

Part E — Nonmetals

Group A — Graphites
Section 01—Stackpole 2128 EA01
Section 02—Fineweave Pierced Fabric EA02
Section 03—Pyrolytic Graphite EA03
Section 04—POCO AXF-5Q EA04

Part F — Composites

Group A — Metal/Ceramic composites
Section 01—Multifoil (Mo/ZrO_2) FA01

Group B — Metalloid Composites
Section 01—SiMo/Ge Diffusion Bond FB01

2112 **Shear Modulus (Modulus of Rigidity)**—The ratio of stress to corresponding strain below the proportional limit. (Ref. ASTM E-6) This value is obtained in shear or torsion tests.

2113 **Tangent Modulus**—The slope of the engineering stress-strain curve at any specified stress or strain. (Ref. ASTM E-6)

2114 **Bulk Modulus**—Ratio of stress to change in volume of a material subjected to axial loading. Related to Young's modulus (E) and Poisson's ratio (ν) by the following equation:

$$K = \frac{E}{3(1 - 2\nu)} .$$

2115 **Rupture Modulus**—Nominal elastically calculated maximum stress at fracture in a bend test or torsion test. In bending, it is the bending moment at fracture divided by the section modulus. In torsion, it is the torque at fracture divided by the polar section modulus. See ASTM E-6 for further notes on modulus of rupture in bending and modulus of rupture in torsion.

2116 **Compressive Strength**—The maximum compressive stress that a material is capable of sustaining. It is calculated from the maximum load during a compression test and the undeformed cross-sectional area of the specimen. (Ref. ASTM E-6)

2117 **Bending Strength**—Also called flexural strength. Maximum fiber stress developed in a specimen just before it cracks or breaks in a flexure test.

2118 **Fracture Stress**—True stress generated in a material at fracture.

2119 **Vicat Softening Point (ASTM D1525)**—A test of the heat softening characteristics of a material.

2120 **Taber Abrasion (ASTM D1044)**—Resistance of a material to abrasion.

2121 **Elastic Stiffness**—A measure of the dimensional change of a material along crystallographic planes, generally a change in length.

2122 **Isothermal Compressibility**—Reciprocal of Bulk Modulus.

2200 **Static, Long-term Properties**—Properties that exhibit a time dependence effect under nonimpact conditions.

2201 **Effects of Prior Creep on Tensile Ductility**—Total elongation measured in a tensile test on materials subjected to some specified amount of prior creep service.

2202 **Stress-Rupture Strength**—The stress that will cause fracture in a creep test in a specified time and environment. (Ref. ASTM E-6)

2203 **Burst Pressure (Biaxial)**—The pressure at which a tube material bursts or allows gas leakage when subjected to internal pressurization.

2204 **Uniform ΔD/D (Biaxial)**—The net increase in tube diameter per unit length of the undeformed diameter under burst pressure testing, measured away from the failure area (far enough so that effects of rupture are not included).

2205 **Time to Tertiary Creep**—For a given stress and environment, the time measured from the initiation of the loading to the onset of the departure from secondary creep. Methods used to determine the onset of departure must be defined with the relationship because there are no universally accepted methods at this time.

2206 **Creep**—Strain occurring under given constant load expressed as a function of time and environment. This Property Code generally includes a creep equation depicting the strain–time–temperature–stress relationship; however, expressions for minimum creep rate may also be included.

2207 **Stress Relaxation**—The time-dependent decrease in stress in a constrained specimen at a constant temperature. (Ref. ASTM E-6)

2208 **Strain at Fracture**—The strain at failure for constant load-temperature conditions, expressed as reduction of area and/or percent elongation.

2209 **Isochronous Stress-Strain Curve**—A curve of applied stress versus total strain for fixed times, for example, the locus of total strains accumulated when different constant stresses are applied for a fixed time. These curves may be generated through use of the stress-strain relationship (2108) and the creep equation (2206), or by other graphical means.

CONTENTS

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

CONTENTS	Update Code 0.0.0

	PAGES
REVISION CONTROL PAGE	1
FOREWORD	1
INTRODUCTION	1
DATA PAGES	

Selected properties are provided for the following materials. For a listing of the properties, see the TABLE OF CONTENTS/PROPERTIES for each material.

Material Code	Material
AA01	Wrought Tungsten
AB0A	Aluminum-Silver Eutectic Alloy
AB01	Alloy 1100
AB02	Alloy 7075
AC01	Titanium
AD01	OFHC Copper
AD02	Dumet
AEA0	Nickel Plating
AE01	Alloy X-750
AF0A	INCUSIL 10
AF0B	NICUSIL 3
AF0C	CUSIL
AF0D	PALCUSIL 15
AG0A	NIORO*

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ISOTOPIC SPACE POWER MATERIALS HANDBOOK

CONTENTS	Update Code 0.0.0

Material Code	Material
BA01	N-type Si/Ge/GaP/P
BA02	P-type Si/Ge/GaP/B
BA03	SiMo N-type
BA04	SiMo P-type
CA01	Silicon Nitride (Si_3N_4) Coating
CB01	Al_2O_3
DA01	Low-temperature Glass
DA02	High-temperature Glass
EA01	Stackpole 2128
FA01	Multifoil Insulation

		PAGES
APPENDIX A	HANDBOOK FORMAT-ORGANIZATION AND UPDATING	1–4
APPENDIX B	MATERIAL CODES	1–3
APPENDIX C	PROPERTY CODES AND DEFINITIONS	1–13

REVISION CONTROL

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

REVISION CONTROL PAGE	Update Code 0.0.0

This page will be replaced each time a package of new and/or revised pages is issued. It will provide a cumulative listing of the issue dates associated with consecutive publication packages.

Update Package Number	Issue Date
0	September 30, 1983

FOREWARD

FOREWORD	Update Code 0.0.0

The *Isotopic Space Power Materials Handbook* (ISPMH) is being compiled to provide a single source of evaluated and reviewed properties data for materials used in the Modular Isotopic Thermoelectric Generator (MITG) and the General Purpose Heat Source (GPHS). The intent is to include those material properties required for design, performance evaluation, and safety evaluations.

The ISPMH is sponsored by the Office of Special Nuclear Projects, U.S. Department of Energy (DOE). Oak Ridge National Laboratory (ORNL) is the publisher. Contributions to the data for the MITG portion have been provided by ORNL staff and by the contractors responsible for the bicouple (General Electric Company, Advanced Energy Program Department) and the multicouple (Thermo Electron Corporation) thermoelectric modules. The distribution of the handbook is limited to DOE, their contractors, and subcontractors. Requests for copies of the handbook as well as comments on content, additions, corrections, etc., should be addressed to:

M. F. Marchbanks
Oak Ridge National Laboratory
Bldg. 9240-1, MS-11
P. O. Box Y
Oak Ridge, TN 37830

INTRODUCTION

INTRODUCTION	Update Code 0.0.0

PURPOSE

New versions of the Radioisotope Thermoelectric Generator (RTG) based on the Modular Isotopic Thermoelectric Generator (MITG) and the General Purpose Heat Source (GPHS) that utilize both improved materials and advanced design concepts are currently being developed. The resulting new system promises significant gains in output voltage-to-weight ratio, the advantages of modular assembly, and increased versatility of application.

This handbook is being developed to provide a single source of evaluated and reviewed materials properties data for the MITG and GPHS. A single data base will allow the designer, fabricator, safety analyst, and performance analyst to make their calculations and judgments from a common source.

SCOPE

This initial release of the handbook attempts to include the needed data for all the materials in the MITG. The materials for the GPHS will be added at a later date (in FY 1984).

REVISIONS AND ADDITIONS

It is recognized that the initial issue of the handbook will not include all the data needed for all materials and conditions. Suggestions for additions, conditions, etc., should be sent to ORNL to help develop the handbook as a useful tool. The proper materials data to be added to the handbook will be reviewed by the appropriate member of the handbook committee at ORNL and, if deemed appropriate, will be sent to GE, TECO, Fairchild, and others as needed for review and approval.

A METALS

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

TUNGSTEN ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code AAXX Update Code 0.0.0

Material Code	Material
AA01	Wrought Tungsten

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

WROUGHT TUNGSTEN[a]	TABLE OF CONTENTS/PROPERTIES	Material Code AA01 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information: Structure—Swaged tungsten rod or bar stock, elongated grains parallel to the long axis not to exceed 0.010 in. in width.	*
1100	Chemical Composition (wt %): W 99.90 min Mo 0.02 max Impurities: 0.08 max	*
1200	Applicable Specification: GE 23991-M2A1	*
3304	Density: 18.94 Mg/m^3, minimum	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.
[a]Sylvania Electric Products, Towanda, Pa.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

ALUMINUM ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code ABXX Update Code 0.0.0

Material Code	Material
AB0A	Aluminum-Silver Eutectic Alloy
AB01	Alloy 1100
AB02	Alloy 7075

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

ALUMINUM SILVER EUTECTIC ALLOY	TABLE OF CONTENTS/PROPERTIES	Material Code AB0A Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Al 70 Ag 30	*
3103	This brazing alloy is the eutectic composition and has a solidus and liquidus temperature of 566°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

ALUMINUM ALLOY 1100	TABLE OF CONTENTS/PROPERTIES	Material Code AB01 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Al 99.0 min	*
3103	Melting Point: 643 to 657 °C	*
3112	Thermal Conductivity (room temperature, annealed): 222 W/(m·K)	*
3114	Coefficient of Thermal Expansion (20 to 300 °C): 25.5×10^{-6} °C^{-1}	*
3201	Electrical Resistivity (room temperature, annealed): 2.92 $\mu\Omega$-cm	*
3304	Density: 2.71 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

ALUMINUM ALLOY 7075	TABLE OF CONTENTS/PROPERTIES	Material Code AB02 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Zn 5.1 to 6.1 Mg 2.1 to 2.9 Cu 1.2 to 2.0 Cr 0.18 to 0.28 Al Remainder	*
3103	Melting Point: 477 to 638 °C	*
3112	Thermal Conductivity: Room Temperature, T6: 130 W/(m·K) 315°C: 123 W/m·K	
3114	Coefficient of Thermal Expansion (20 to 300 °C): 25.2×10^{-6} °C^{-1}	*
3201	Electrical Resistivity (room temperature, T6): 5.7 $\mu\Omega$-cm	*
3304	Density: 2.80 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 ALUMINUM	TABLE OF CONTENTS/PROPERTIES	Material Code AB03 Update Code 2.0.0

Property Code	Property	Pages
1000	General	1.0
1100	Chemical Composition	1.0
1200	Product Forms: Two forms are used in the GPHS-RTG. The shell is made from a hand-forged billet measuring 33-cm outside diam by 20.3-cm inside diam by 122 cm in length and is in the T6 condition. The pressure domes and fins are formed from rolled plate in the T87 condition. Applicable Specifications: GE specification N50060-01-19, QQ-A-367F, MIL-A-8920A.	*
2100	Short Term Mechanical Properties	1.0–1.2
2111	Young's Modulus (Modulus of Elasticity):[1] T62, T87	*

Temperature, °C	–253	–80	24	100	204	288	371
Modulus of Elasticity, GPa (compression 2% greater)	86	76	72	70	63	55	43

2200	Static, Long Term Properties	1.0–1.5
3103	Melting Point: 543–643°C	*
3108	Specific Heat Capacity at 100°C:[1]	*

$$963 \frac{J}{kgK} \left(0.23 \frac{Btu}{lb\text{-}F}\right)$$

[1]L. W. Mayer, "Alcoa Aluminum Alloy 2219," Aluminum Company of America, Application Engineering Division, New Kensington, PA, rev. June 1967.

*No separate pages provided. The values are listed in the "Property" column of this Table of Contents.

2219 ALUMINUM	TABLE OF CONTENTS/PROPERTIES	Material Code AB03 Update Code 2.0.0

Property Code	Property	Pages
3112	Thermal Conductivity at 25°C, T6 and T87 conditions:[1]	*

$$125 \frac{W}{mK} \left(72 \frac{Btu \cdot ft}{h \cdot ft^2\ F}\right)$$

3114	Thermal Expansion Coefficient:[2]	*

0 Temper (Heat treated condition ~1.5% higher)

Temperature, °C	−100	−50	0	50	100	200	300	400
Coefficient at t, per °C × 10^6	17.7	19.9	21.3	22.3	23.4	25.1	27.0	28.4

Average coefficient:[1]

20–100°C	22.3 × 10^{-6} per °C
20–200°C	23.6
20–300°C	24.5

3201	Electrical Resistivity, room temperature:[1]	*

0 Temper 3.91 μΩ-cm

T62,T87, 5.38 μΩ-cm

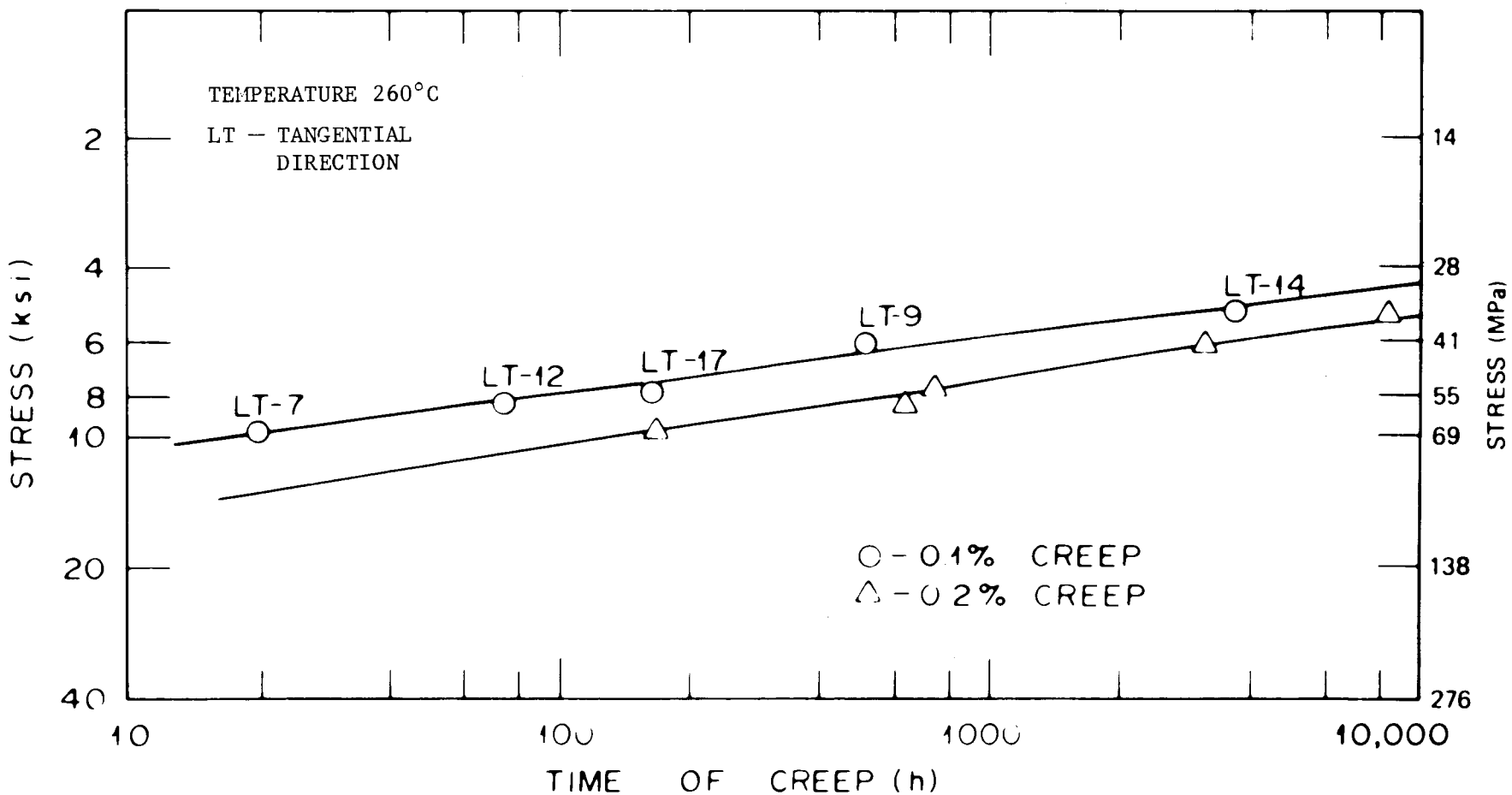
3304	Density $2.832 \frac{Mg}{m^3}$	*

[2] *Alcoa Aluminum Handbook*, Aluminum Company of America, New Kensington, PA.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 T6 ALUMINUM FORGING	CREEP DESIGN CURVE	Material Code: AB03 Update Code: 2.0.0

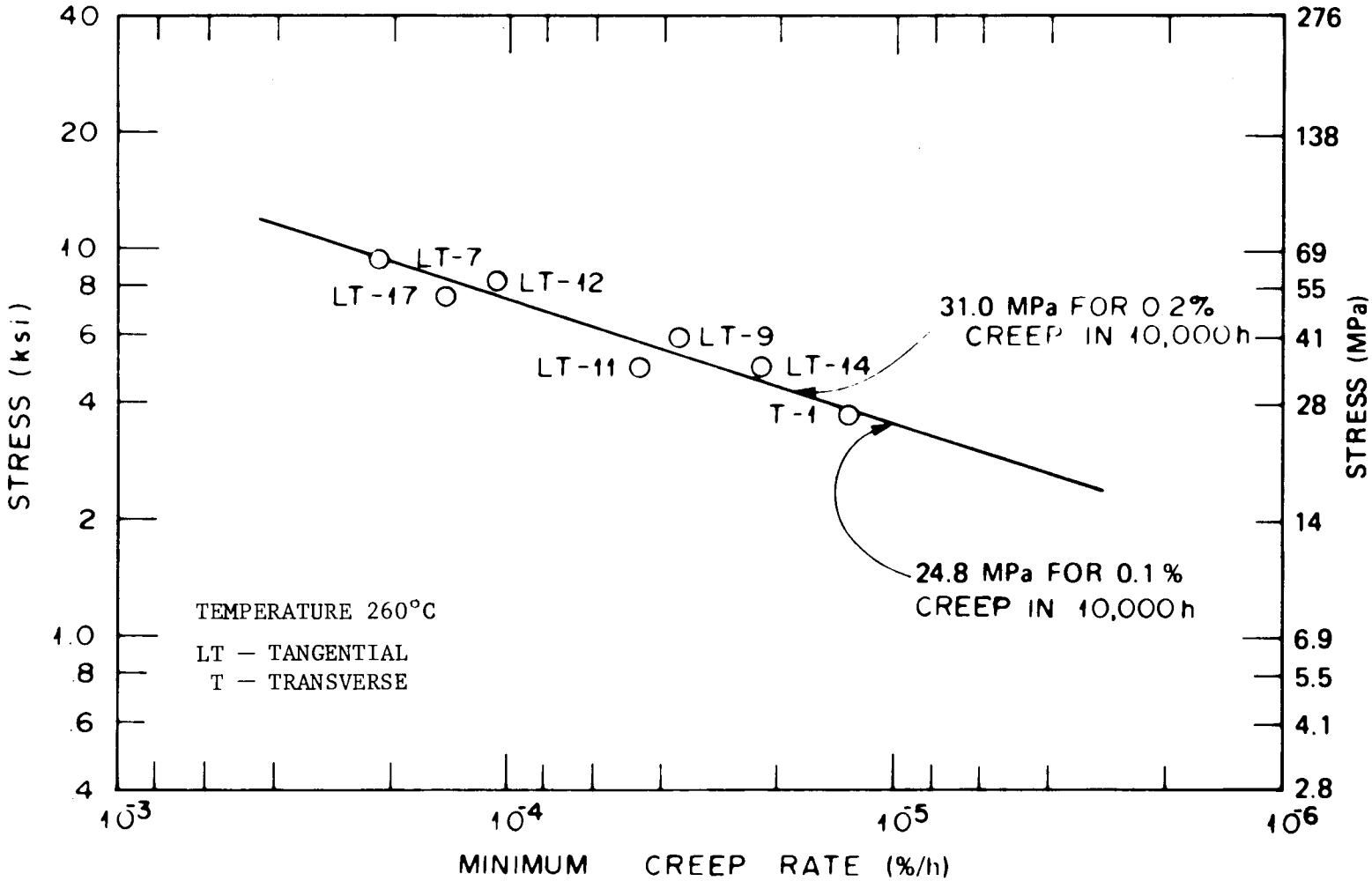
ORNL-DWG 81-14059R



PROPERTY CODE 2200 PAGE 1.0

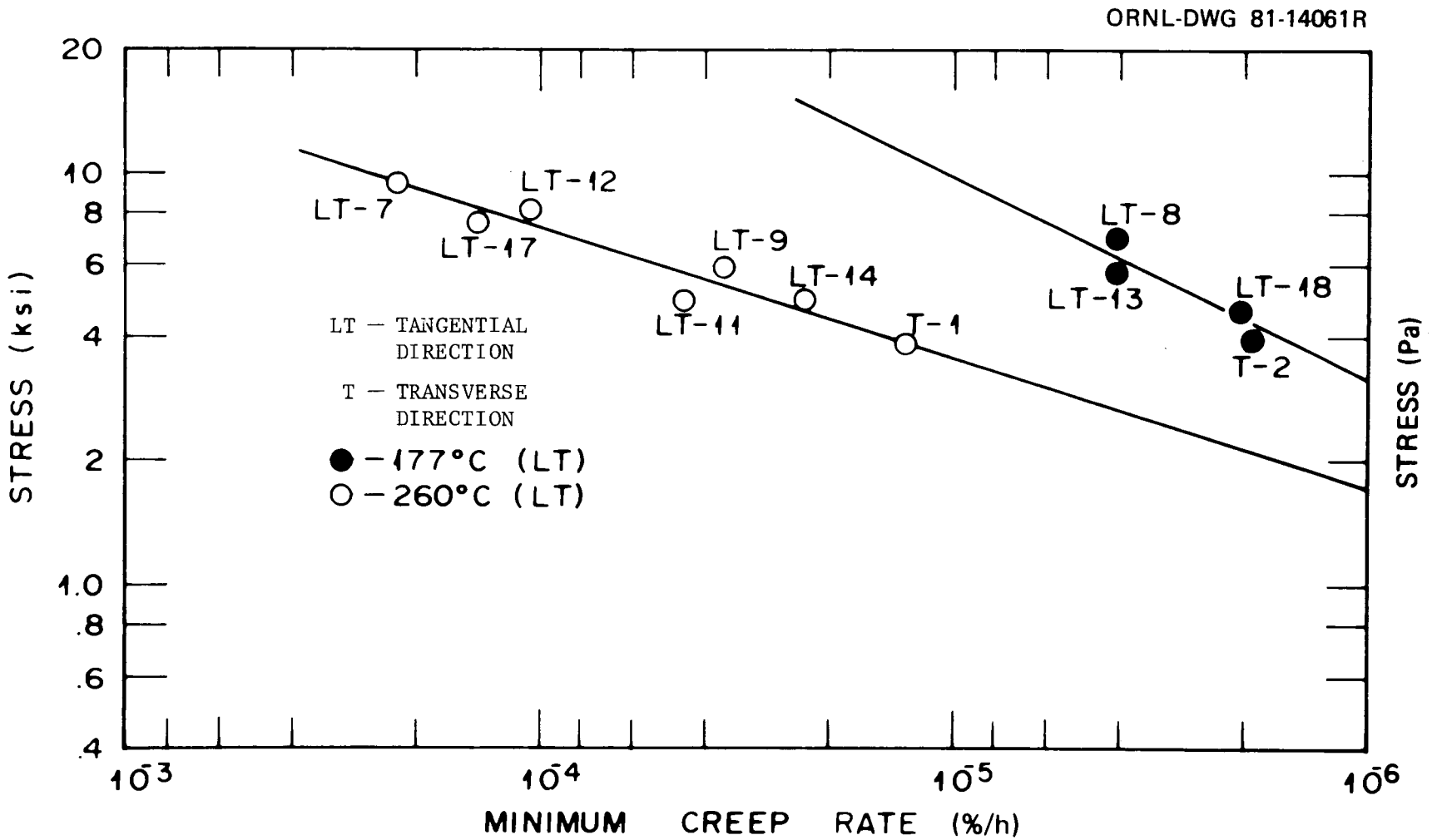
2219 T6 ALUMINUM FORGING	MINIMUM CREEP RATE	Material Code: AB03 Update Code: 2.0.0

ORNL-DWG 81-14058R



ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 T6 ALUMINUM FORGING	MINIMUM CREEP RATE	Material Code: AB03 Update Code: 2.0.0

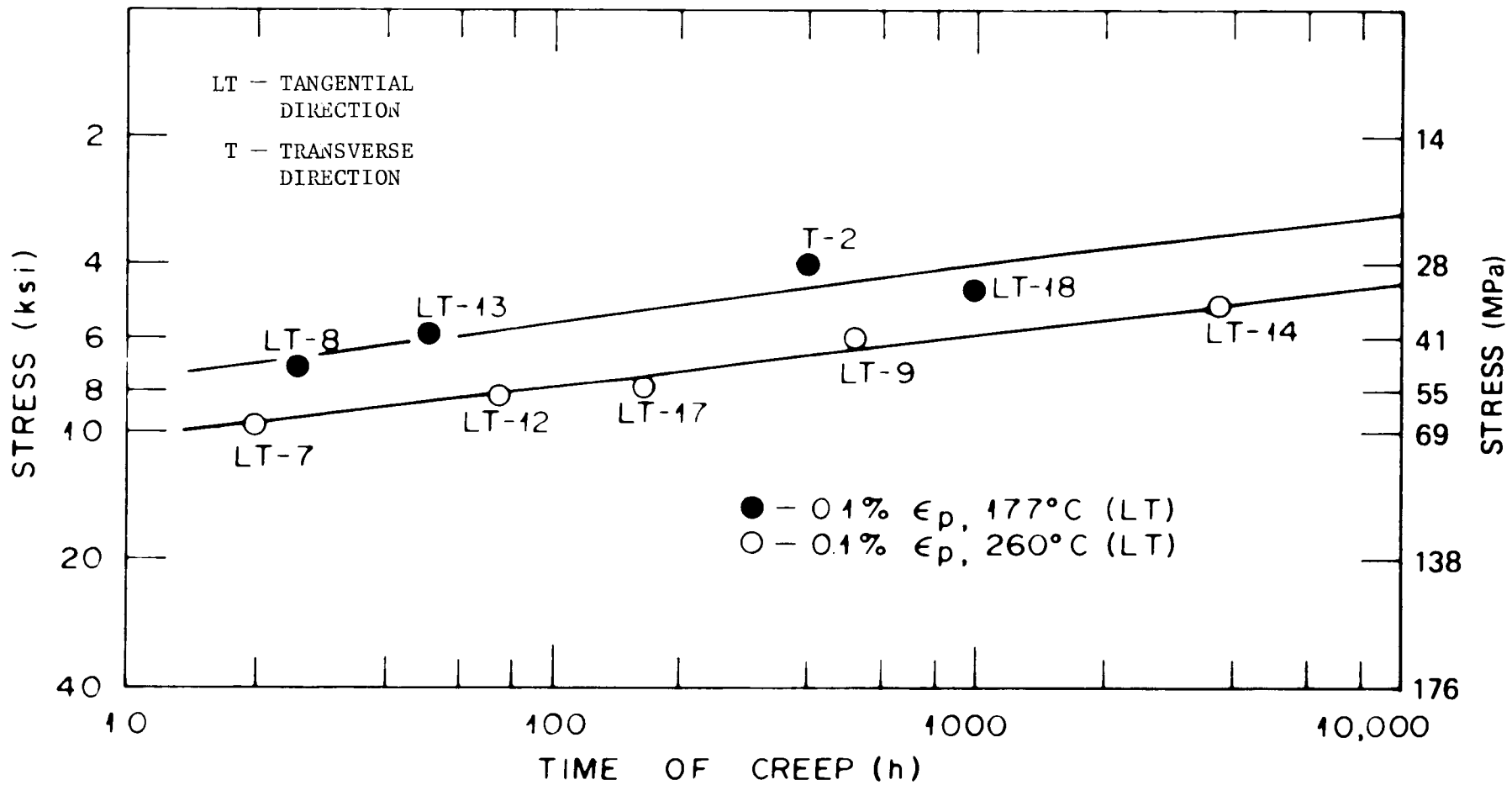


PROPERTY CODE 2200 PAGE 1.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 T6 ALUMINUM FORGING	CREEP DESIGN CURVE	Material Code: AB03 Update Code: 2.0.0

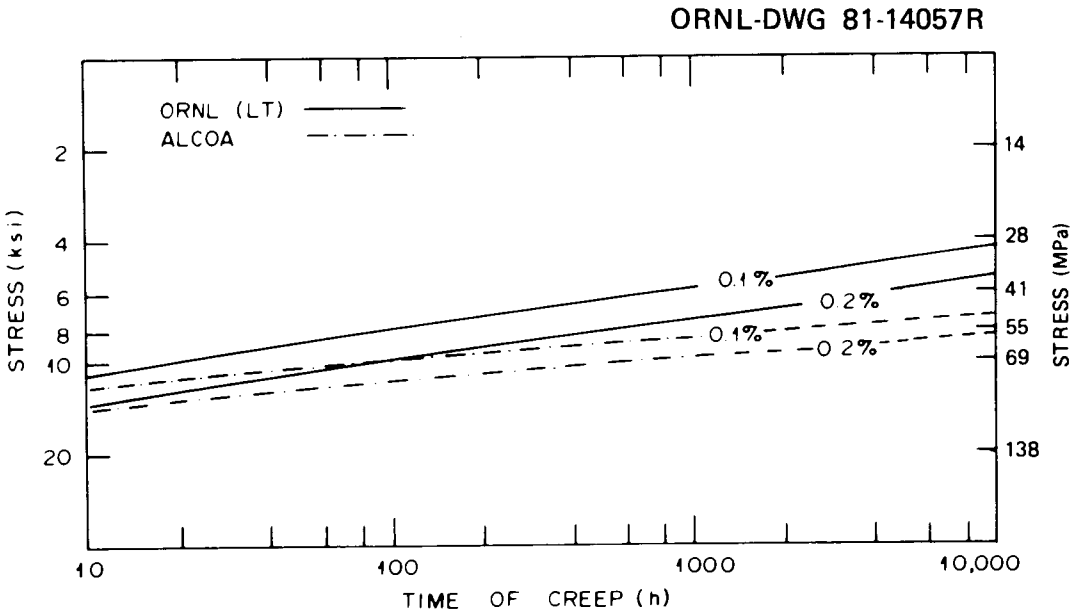
ORNL-DWG 81-14060R



PROPERTY CODE 2200 PAGE 1.3

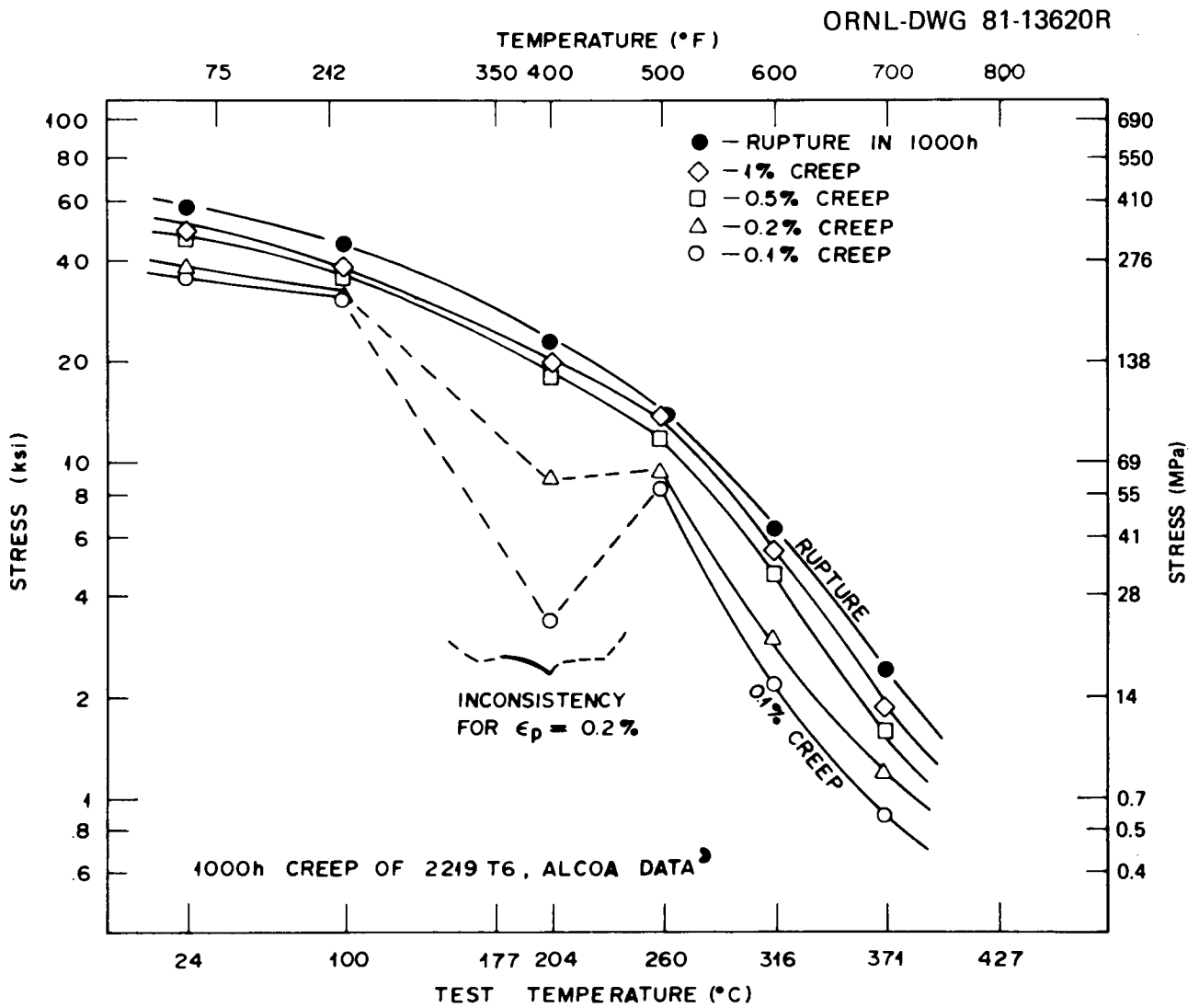
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

2219 T6 ALUMINUM FORGING	CREEP DESIGN CURVE	Material Code: AB03 Update Code: 2.0.0



Comparison of ORNL design curves at 260°C (stress-time for 0.1 and 0.2% creep) of 2219 T6 forging with Alcoa data.

2219 T6 ALUMINUM FORGING	CREEP	Material Code: AB03 Update Code: 2.0.0



Stress-temperature relationship for increasing amounts of creep of 2219 T6 forging.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

TITANIUM ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code ACXX Update Code 0.0.0

Material Code	Material
AC01	Titanium

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

TITANIUM	TABLE OF CONTENTS/PROPERTIES	Material Code AC01 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %):	*
	Fe 0.50	
	O 0.30	
	C 0.08	
	H 0.015	
	N 0.05	
	Ti Remainder	
	Total other elements 0.60	
1200	Applicable Specifications: AMS -4900C, GE 23991 – M14B1	*
3103	Melting Point: 1649 to 1671 °C	*
3304	Density: 4.54 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

COPPER ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code ADXX Update Code 0.0.0

Material Code	Material
AD01	Oxygen-Free, High-Conductivity Copper (OFHC)
AD02	Dumet

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

OFHC COPPER	TABLE OF CONTENTS/PROPERTIES	Material Code AD01 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Cu 99.99 (Difference of impurity level from 100%) P 0.0003 S 0.0018 Zn 0.0001 Hg 0.0001 Pb 0.0010	*
1200	Applicable Specifications: Copper Development Association C-10200, GE-23991-M1A1	*
2109	Hardness: Soft temper, maximum grain size 0.050 mm	*
3201	Electrical Resistivity (room temperature): 1.7 $\mu\Omega$-cm	
3304	Density: 20°C 8.95 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

DUMET	TABLE OF CONTENTS/PROPERTIES	Material Code AD02 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Fe 58 Ni 42 (Copper coated)	*
3114	Thermal Expansion: Approximately $9 \times 10^{-6}\,°C^{-1}$	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

NICKEL ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code AEXX Update Code 0.0.0

Material Code	Material
AEA0	Nickel Plating
AE01	Alloy X-750

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

NICKEL PLATING	TABLE OF CONTENTS/PROPERTIES	Material Code AEA0 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information: Evaluation of the coating is by visual inspection and metallographic analysis of coating thickness.	*
1200	Applicable Specifications: QQN-290A Class 1 Grade G, GE23991-RG3F1, GE23991-RG3A	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

ALLOY X-750	TABLE OF CONTENTS/PROPERTIES	Material Code AE01 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %):	*
	C 0.08	
	Mn 1	
	Ni 70 min	
	Cr 14 to 17	
	Fe 5 to 9	
	Ti 2.25 to 2.75	
	Cb + Ta 0.7 to 1.2	
	Al 0.4 to 1	
	Cu 0.5	
	Si 0.5	
	S 0.01	
3103	Melting Point: 1343 to 1427 °C	*
3112	Thermal Conductivity (room temperature): 8.3 W/(m·K)	*
3114	Coefficient of Thermal Expansion:	*
	(21 to 871 °C): 16.4×10^{-6} °C^{-1}	
3304	Density: 8.25 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SILVER ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code AFXX Update Code 0.0.0

Material Code	Material
AF0A	INCUSIL 10
AF0B	NICUSIL 3
AF0C	CUSIL
AF0D	PALCUSIL 15

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

INCUSIL 10	TABLE OF CONTENTS/PROPERTIES	Material Code AF0A Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Ag 62 to 64 Cu 26 to 28 In 9.5 to 10.5 Cd 0.001 max Pb 0.002 max P 0.002 max Sn 0.001 max Zn 0.001 max C 0.005 max	*
3103	This brazing alloy has a solidus temperature at 685°C and liquidus temperature at 730°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

NICUSIL 3	TABLE OF CONTENTS/PROPERTIES	Material Code AF0B Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Ag 70 to 72 Cu 27 to 29 Ni 0.5 to 1 Cd 0.001 max Pb 0.002 max P 0.002 max Sn 0.001 max Zn 0.001 max C 0.005 max	*
3103	This brazing alloy has a solidus temperature at 780°C and a liquidus temperature at 795°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

CUSIL	TABLE OF CONTENTS/PROPERTIES	Material Code AF0C Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Ag 71.0 to 73 Cu Remainder Total other elements 0.15	*
1200	Specification: AWS A5.8 Classification BAg-8	*
3103	This brazing alloy is a eutectic composition with a solidus and liquidus temperature of 780°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

PALCUSIL 15	TABLE OF CONTENTS/PROPERTIES	Material Code AF0D Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Ag 64 to 66 Cu 19 to 21 Pd 14.5 to 15.5	*
3103	This brazing alloy has a solidus temperature of 850°C and a liquidus temperature of 900°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

GOLD ALLOYS	TABLE OF CONTENTS/MATERIALS	Material Code AGXX Update Code 0.0.0

Material Code	Material
AG0A	NIORO[a]

[a]Registered trademark of Western Gold and Platinum Company, 477 Harbor Blvd., Belmont, Calif., 94002.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

NIORO[a]	TABLE OF CONTENTS/PROPERTIES	Material Code AG0A Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Au 81.5 to 82.5 Ni Remainder Total other elements 0.15%	*
1200	Applicable Specifications: AWS A5.8 Classification BAu-4, AMS 4787	*
3103	This brazing alloy is the eutectic composition and has a solidus and liquidus temperature of 949°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents
[a]Registered trademark of Western Gold and Platinum Company, 477 Harbor Blvd., Belmont, Calif., 94002.

BA High Silicon
Metalloids

HIGH-SILICON METALLOIDS	TABLE OF CONTENTS/MATERIALS	Material Code BAXX Update Code 2.1.0

Material Code	Material
BA01	N-type Si/Ge/GaP/P
BA02	P-type Si/Ge/GaP/B
BA03	SiMo N-type
BA04	SiMo P-type
BA05	N-type 78Si/22Ge/P
BA06	P-type 78Si/22Ge/B
BA07	N-type 63Si/37Ge/P
BA08	P-type 63Si/37Ge/B

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE Si/Ge/GaP/B	TABLE OF CONTENTS/PROPERTIES	Material Code BA02 Update Code 2.0.1

Property Code	Property	Pages
1000	General Information — Special Notes — NOTE THAT THIS SECTION CONTAINS IMPORTANT BACKGROUND INFORMATION CONCERNING THE FOLLOWING PROPERTIES	1.0-1.1
1100	Nominal Chemical Composition (at. %):	*
	B 2	
	Ga 2.5	
	P 2.5	
	Ge 74.4	
	Si 18.6	
	Note: See Property Code 1000 for information concerning the individual materials used in manufacturing P-type Si/Ge/GaP/B	
2101	Tensile Strength: 134 MPa	*
3112	Thermal Conductivity	1.0-1.1
3114	Coefficient of Thermal Expansion: 3.8×10^{-6} K^{-1}	*
3201	Electrical Resistivity	1.0-1.1
3207	Absolute Seebeck Coefficient	1.0-1.1
3304	Density: 2.88 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

N-type Si/Ge/GaP/P	GENERAL INFORMATION— SPECIAL NOTES	Material Code BA01 Update Code 0.0.0

The GaP-modified Si-Ge thermoelectric materials are currently being developed and the property values shown are therefore tentative. These notes present background material and indicate areas of uncertainty.

The density given is from General Electric (GE) data on six 1982 compacts supplied by TECO. Atomic sizes yield a theoretical density at 3.14 Mg/m^3 for this composition. The tensile strength was obtained from GE and probably applies to N-type material. This value is significantly higher than the value for binary Si-Ge material, and the factors responsible are not understood. The thermal expansion value, from GE data, is 15% greater than the value reported for 80Si-20Ge. It is also 36% greater than an earlier value (3.39×10^{-6}) reported for GaP-modified material. This value is an important parameter for calculating hot junction thermal stresses, and these discrepancies should be resolved.

The transport properties are largely based on the "agreed upon" values quoted by Schock.[a] The resistivity and Seebeck coefficient values seem to be consistent with GE data for 1982 material. The reported thermal conductivity values have a range of about $\pm 15\%$, and the table values exceed the agreed upon values. The new values, which follow the Purdue data for dense ($\sim$ 3.07 Mg/cm^3) material, were obtained by averaging the total spread in reported values. This procedure was adopted because the results are probably affected by both experimental errors and sample variations. Resistivity measurements on the thermal conductivity samples might help to resolve those differences.

The following information is provided for the gallium phosphide[b] used in manufacturing N-type and P-type Si/Ge/GaP/P metalloid compounds.

Chemical Composition (wt %):

P	99.999 min (semiconductor grade)
Fe, Zn, Pb, Ca	0.0001 max

Applicable Specification: GE 23991-M32A1, RM1B1, RG16A1

The following information is provided for the gallium phosphide[a] used in manufacturing N-type and P-type Si/Ge/GaP/P metalloid compounds.

Chemical Composition (wt %):

GaP 99.999 semiconductor grade

The following information is provided for the germanium[c] used in manufacturing N-type and P-type Si/Ge/GaP/P metalloid compounds.

Chemical Composition (wt %):

Ge	99.99 as reduced ingots
Ag, Al, Cu, Mg,	1 ppm
Ca, Fe, Si	10 ppm

Resistivity: 2.0 Ω-m, min

Applicable Specification: GE 23991-M30A1, RQ18A1

[a] A. Schock, "Modular Isotopic Thermoelectric Generator," 1981 IECEC, vol. 1, Paper 819174, August 1981, p. 327.
[b] Alpha Ventron Corp., P.O. Box 299, 152 Andover St., Danvers, MA 01923
[c] Source: GTE Sylvania Electric, 1000 Huyler St., Teterboro, NJ 07602

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-type Si/Ge/GaP/P	GENERAL INFORMATION— SPECIAL NOTES	Material Code BA01 Update Code 0.0.0

The following information is provided for the semiconductor-grade silicon used in manufacturing N-type and P-type Si/Ge/GaP/P metalloid compounds.

Chemical Composition (wt %, except where noted):

Si	99.99 polycrystalline silicon nuggets
Ca - Cr - Cu	0.0005
Mg - Mn	0.001
Ge - Al - Sb	0.005
Pb - Fe - Ni - Mo	0.005

Total metallic impurities: 0.01

B $\leqslant$ 0.3 ppba (parts per billion atomic)

Donor content $\leqslant$ 1.5 ppba

Net impurity calculated by $C_D - C_B = C_{Net}$

where

C_D = concentration of donor impurities,

C_B = concentration of boron impurities,

C_{Net} = net impurity concentration after one argon pass.

Electrical Resistivity: 1.00 Ω-m, min

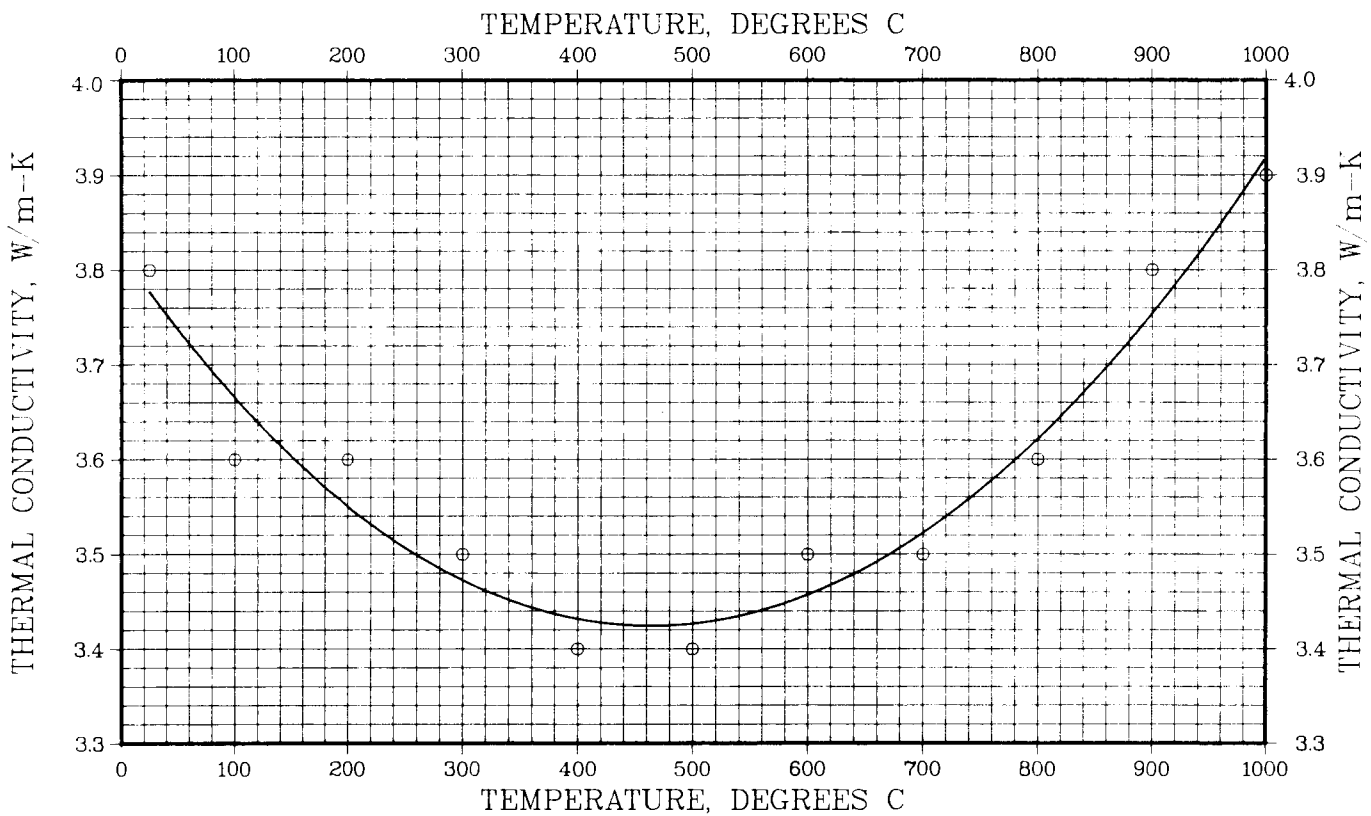
Applicable Specification: GE23991 - M29A1, RQ18A1

ORNL–DWG 83-17533

PLOT 1 08.15.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA01 UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3112 PAGE 1.0

PLOT 2 08.17.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	THERMAL CONDUCTIVITY
DEGREES C	W/m–K	DEGREES C	W/m–K
75	3.7	100	3.6
125	3.6	200	3.6
175	3.6	300	3.5
225	3.5	400	3.4
275	3.5	500	3.4
325	3.5	600	3.5
375	3.4	700	3.5
425	3.4	800	3.6
475	3.4	900	3.8
525	3.4	1000	3.9
575	3.4		
625	3.5		
675	3.5		
725	3.5		
775	3.6		
825	3.7		
875	3.7		
925	3.8		
975	3.9		
1000	3.9		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$\lambda = 3.81892 - 1.72657\times10^{-3}T + 1.94378\times10^{-6}T^2 - 1.16902\times10^{-10}T^3,$$ where

λ = Thermal Conductivity, W/m–K, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 4.6343×10^{-2} and the coefficient of determination was 0.97278.

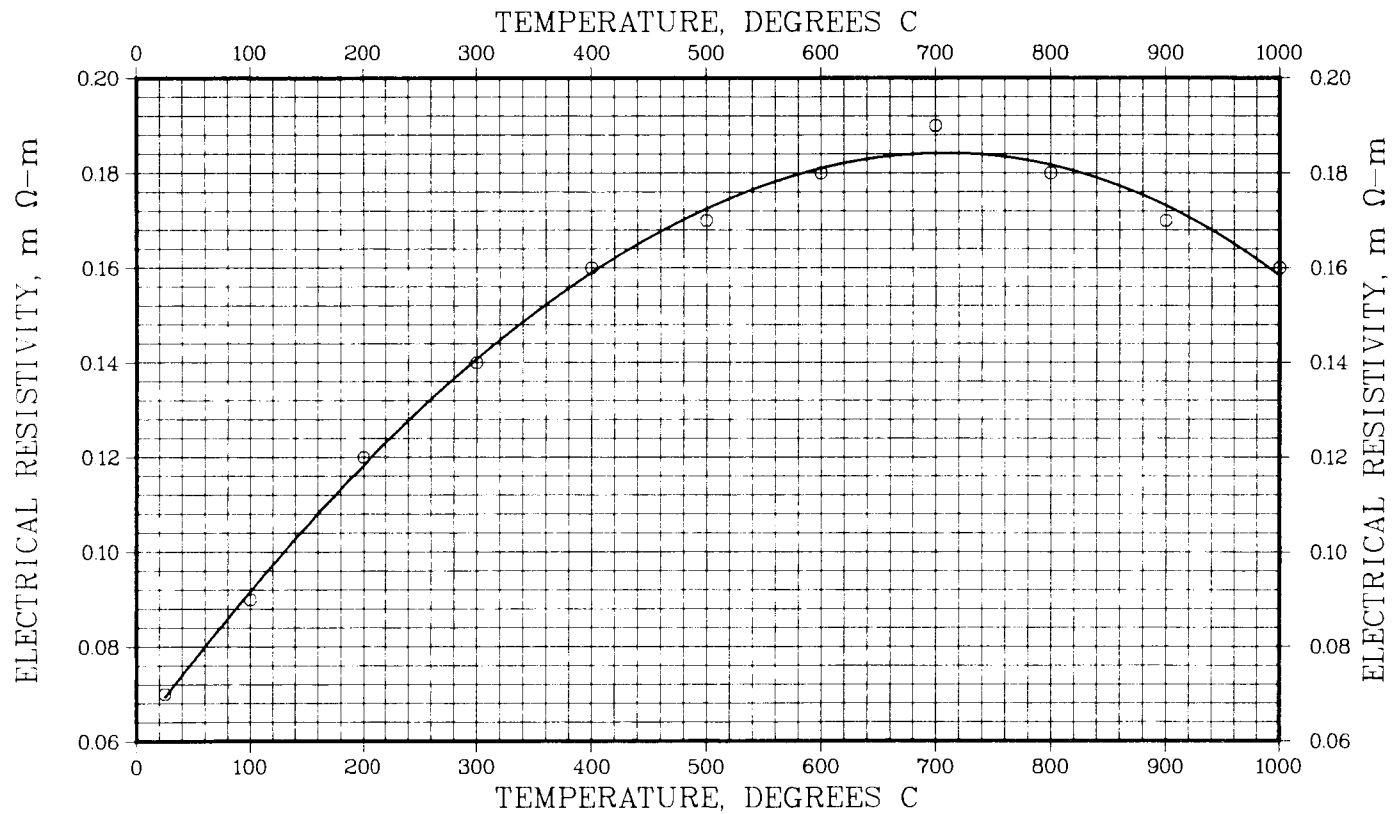
See Property Code 1000 for Special Notes.

ORNL–DWG 83-17531

PLOT 1 07.11.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA01 UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3201 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	ELECT. RESISTIVITY	TEMPERATURE	ELECT. RESISTIVITY
DEGREES C	mΩ–m	DEGREES C	mΩ–m
100	0.09	100	0.09
150	0.11	200	0.12
200	0.12	300	0.14
250	0.13	400	0.16
300	0.14	500	0.17
350	0.15	600	0.18
400	0.16	700	0.19
450	0.17	800	0.18
500	0.17	900	0.17
550	0.18	1000	0.16
600	0.18		
650	0.18		
700	0.18		
750	0.18		
800	0.18		
850	0.18		
900	0.17		
950	0.17		
1000	0.16		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$T = 6.14415X10^{-2} + 3.19680X10^{-4}T - 1.67268X10^{-7}T^2 - 5.55384X10^{-11}T^3,$$ where

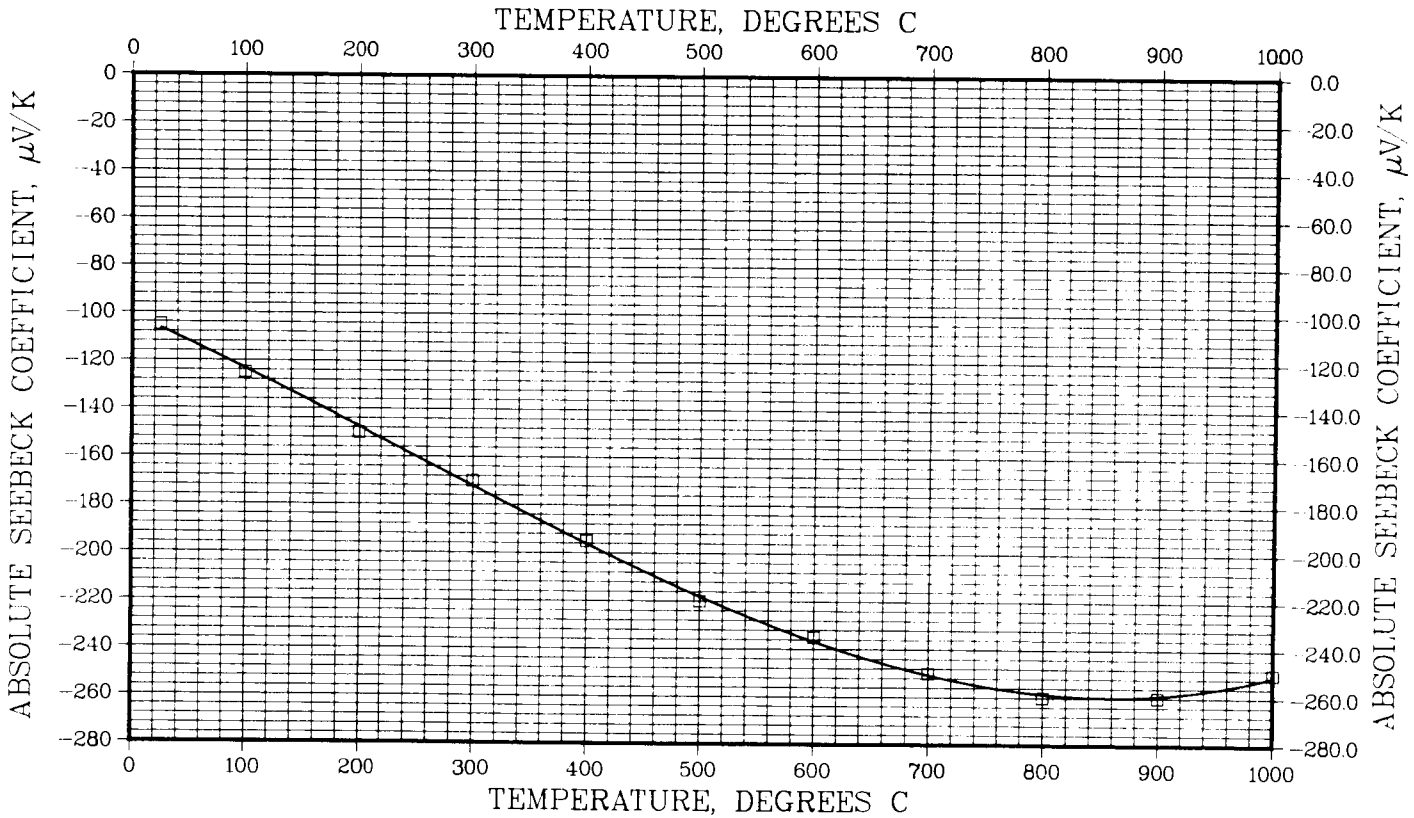
T = Electrical Resistivity, m Ω–m, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 5.8516 and the coefficient of determination was 0.99284.

See Property Code 1000 for Special Notes.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA01 UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PLOT 2 10.35.00 FRI 2 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–Type Si/Ge/GaP/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	SEEBECK COEFFICIENT	TEMPERATURE	SEEBECK COEFFICIENT
DEGREES C	μV/K	DEGREES C	μV/K
50	−112.	100	−125.
100	−123.	200	−150.
150	−135.	300	−170.
200	−148.	400	−195.
250	−160.	500	−220.
300	−172.	600	−235.
350	−184.	700	−250.
400	−196.	800	−260.
450	−207.	900	−260.
500	−218.	1000	−250.
550	−228.		
600	−237.		
650	−244.		
700	−251.		
750	−255.		
800	−259.		
850	−260.		
900	−259.		
950	−256.		
1000	−251.		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$E = -101.369 - 0.206678T - 1.64406\times10^{-4}T^2 + 2.21492\times10^{-7}T^3,$$ where

E = Absolute Seebeck Coefficient, μv/k, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 2.0081 and the coefficient of determination was 0.99956.

See Property Code 1000 for Special Notes.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-type Si/Ge/GaP/P	TABLE OF CONTENTS/PROPERTIES	Material Code BA03 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information—Special Notes...NOTE THAT THIS SECTION CONTAINS IMPORTANT BACKGROUND INFORMATION CONCERNING THE FOLLOWING PROPERTIES	1.0–1.1
1100	Nominal Chemical Composition (at. %): B 2 Ga 2.5 P 2.5 Ge 74.4 Si 18.6 Note: See Property Code 1000 for information concerning the individual materials used in manufacturing P-type Si/Ge/GaP/P.	*
2101	Tensile Strength: 134 MPa	*
3112	Thermal Conductivity	1.0–1.1
3114	Coefficient of Thermal Expansion: $3.8 \times 10^{-6}\ K^{-1}$	*
3201	Electrical Resistivity	1.0–1.1
3207	Absolute Seebeck Coefficient	1.0–1.1
3304	Density: 2.88 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

P-type Si/Ge/GaP/B	GENERAL INFORMATION— SPECIAL NOTES	Material Code BA03 Update Code 0.0.0

The GaP-modified Si-Ge thermoelectric materials are currently being developed and the property values shown are therefore tentative. These notes present background material and point out areas of uncertainty.

The composition of this material apparently has not been fixed, and the samples usually have higher porosity than N-type material. The density data are from four 1982 compacts supplied to GE by TECO. Atomic radii yield a theoretical density of 3.08 Mg/m^3 for this composition. The tensile strength shown probably applies to denser, N-type material; this point should be checked. The expansion coefficient is 96% of the value for the binary alloy, and this seems more reasonable than the results reported for the N-type material. It is, however, surprising that the expansion coefficients of these materials do not appear to depend on temperature. Careful experiments have shown that the expansion coefficient of Si varies from 2.62×10^{-6} at room temperature to 4.63 at 1000 K.

The transport properties are similar to Schock's "agreed upon" values,[a] but they differ in some details. The resistivities, which are higher, are based on the 1982 GE room temperature values for four samples and they merge with the Schock values at 700°C. The room temperature values show more scatter than for N-type material—about ±25%. The thermal conductivity values were obtained by the method used for N-type material and generally follow the Purdue data for samples that are about 91% dense. Refining these values and determining the factors that control the conductivity would probably lead to further improvements in this material.

Information on the gallium phosphide, germanium, and silicon used in the manufacture of P-type Si/Ge/GaP/B is given in Material Code BA01, Property Code 1000.

The following information is provided for the crystalline boron powder used in the manufacture of P-type Si/Ge/GaP/B:

Chemical Composition (wt %):

B	98.0 min
Fe, Al, Cu, Mg, Mn, Mo	0.5 max
C	1.5 max
Total all metallic impurities	1.0 max

Applicable Specification: GE 23991-M31A1

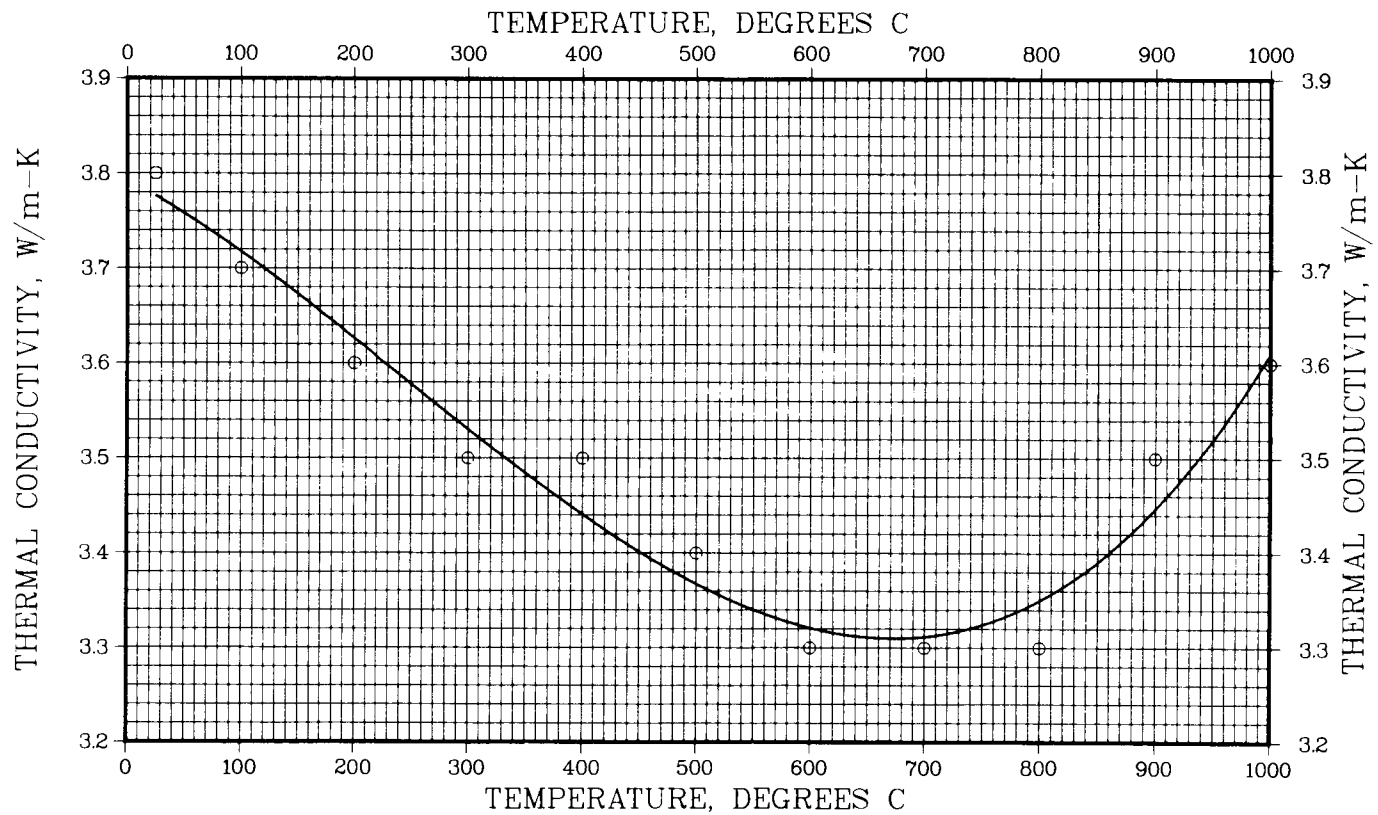
[a] A. Schock, "Modular Isotopic Thermoelectric Generator," 1981 IECEC, vol. 1, Paper 819174, August 1981, p. 327.

ORNL–DWG 83-17527

PLOT 1 13.17.00 WED 7 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–Type Si/Ge/GaP/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA02 UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3112 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–Type Si/Ge/GaP/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA02
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	THERMAL CONDUCTIVITY
DEGREES C	W/m–K	DEGREES C	W/m–K
50	3.8	100	3.7
100	3.7	200	3.6
150	3.7	300	3.5
200	3.6	400	3.5
250	3.6	500	3.4
300	3.5	600	3.3
350	3.5	700	3.3
400	3.4	800	3.3
450	3.4	900	3.5
500	3.4	1000	3.6
550	3.3		
600	3.3		
650	3.3		
700	3.3		
750	3.3		
800	3.4		
850	3.4		
900	3.4		
950	3.5		
1000	3.6		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$\lambda = 3.79363 - 6.53162\times10^{-4}T - 1.26722\times10^{-6}T^2 + 1.73830\times10^{-9}T^3,$$ where

λ = Thermal Conductivity, W/m–K, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 4.3264×10^{-2}, and the coefficient of determination was 0.97632.

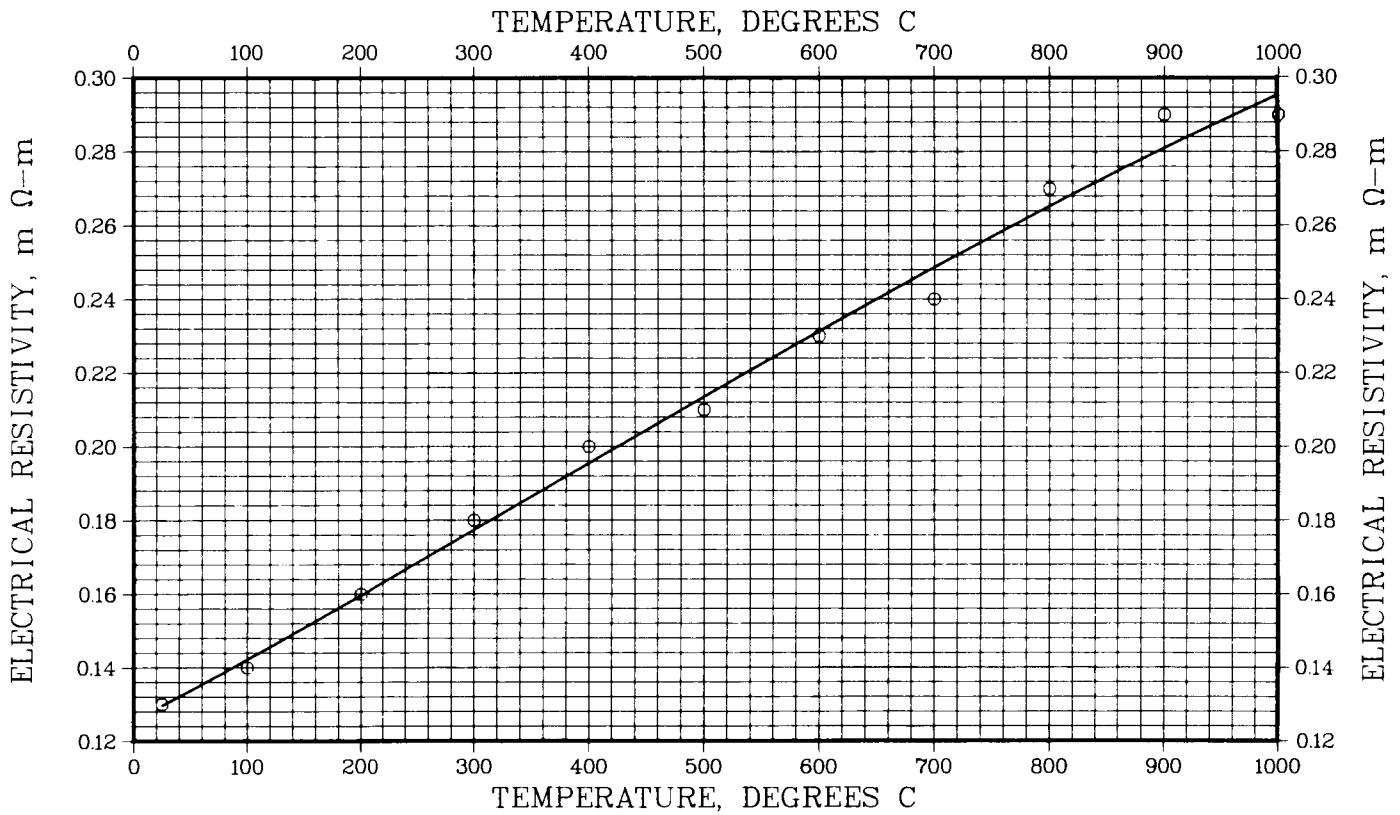
See Property Code 1000 for Special Notes.

ORNL–DWG 83-17525

PLOT 1 13.34.00 WED 7 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–Type Si/Ge/GaP/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA02 UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3201 PAGE 1.0

PLOT 2 13.35.00 WED 7 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–Type Si/Ge/GaP/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA02 UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	ELECT. RESISTIVITY	TEMPERATURE	ELECT. RESISTIVITY
DEGREES C	m Ω–m	DEGREES C	m Ω–m
50	0.13	100	0.14
150	0.15	200	0.16
250	0.17	300	0.18
350	0.19	400	0.20
450	0.20	500	0.21
550	0.22	600	0.23
650	0.24	700	0.24
750	0.26	800	0.27
850	0.27	900	0.29
950	0.29	1000	0.29
1000	0.30		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$T = 0.125513 + 1.63355\times10^{-4}T + 4.41289\times10^{-8}T^2 - 3.73897\times10^{-11}T^3, \text{ where}$$

T = Electrical Resistivity, m Ω–m, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 5.8493 and the coefficient of determination was 0.99630.

See Property Code 1000 for Special Notes.

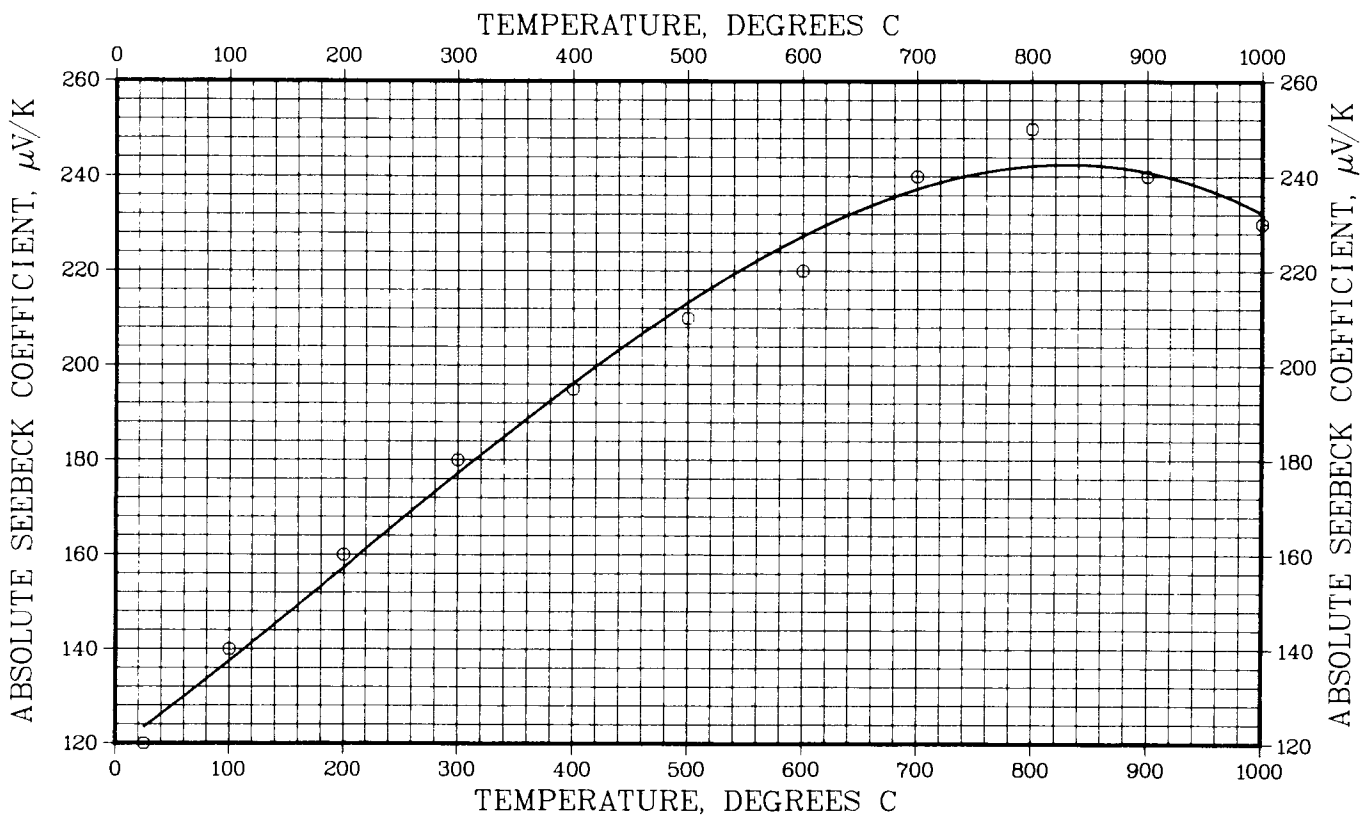
PROPERTY CODE 3201 PAGE 1.1

ORNL–DWG 83-17523

PLOT 1 12.57.00 WED 7 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–Type Si/Ge/GaP/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA02
		UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3207 PAGE 1.0

PLOT 2 12.59.00 WED 7 SEP, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P--Type Si/Ge/GaP/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA02
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL DATA	
TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K	DEGREES C	μV/K
50	128.	100	140.
100	137.	200	160.
150	147.	300	180.
200	157.	400	195.
250	167.	500	210.
300	177.	600	220.
350	187.	700	240.
400	196.	800	250.
450	205.	900	240.
500	213.	1000	230.
550	221.		
600	227.		
650	233.		
700	237.		
750	241.		
800	242.		
850	242.		
900	241.		
950	238.		
1000	232.		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$E = 119.004 + 0.175093T + 1.15894X10^{-4}T^2 - 1.77752X10^{-7}T^3, \text{ where}$$

E = Absolute Seebeck Coefficient, and
T = Temperature, Degrees C.

The standard error of estimate of the fit was 4.9804 and the coefficient of the determination was 0.99545.

See Property Code 1000 for Special Notes.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SiMo N-type	TABLE OF CONTENTS/PROPERTIES	Material Code BA08 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information	1.0
1100	Chemical Composition (wt %): Si 85 Mo 15 Note: See Property Code 1000 for composition of Mo powder used in manufacture of SiMo.	*
1200	Applicable Specifications: Applicable specifications for Mo powder are provided in Property Code 1200	*
3114	Coefficient of Thermal Expansion (measured value): $3.96 \times 10^{-6}\,K^{-1}$	*
3201	Electrical Resistivity	1.0–1.1
3207	Seebeck Coefficient (room temperature): -29 to $-70\ \mu V\ K^{-1}$	*
3304	Density: 2.59 to 2.87 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SiMo N-type	GENERAL INFORMATION	Material Code BA03 Update Code 0.0.0

The following information is provided for the Mo powder[a] used in manufacturing SiMo metalloid compounds.

Chemical Composition (wt %):

Mo	99.8 min
Al, Fe, Sn	0.01 max
Ca, Ni, Cu, Cr, Mg	0.005 max
Pb, Mn, Ti	0.001 max
Total metallic impurities	0.2 max

Particle size: 100%—80 mesh, 85%—325 mesh

Applicable Specification: ASTM E300-70

The manufacturer of Mo powder for which those data are applicable is Fisher Scientific Co., 52 Fadem Rd, Springfield NJ 07081.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SiMo P-type	TABLE OF CONTENTS/PROPERTIES	Material Code BA04 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information: See Material Code BA03, Property Code 1000 for information on the Mo powder used in manufacturing this SiMo.	*
1100	Chemical Composition (wt %): Si 85 Mo 15 Note: See Material Code BA03 Property Code 1000 for composition of Mo powder used in manufacture of SiMo.	*
1200	Applicable Specifications for Mo powder are provided in Material Code BA03, Property Code 1000.	*
3114	Coefficient of Thermal Expansion (assumed value): $3.96 \times 10^{-6}\ K^{-1}$	*
3207	Seebeck Coefficient (room temperature): +60 to +96 $\mu V\ K^{-1}$	*
3304	Density: 2.63 to 2.80 Mg/m^3	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

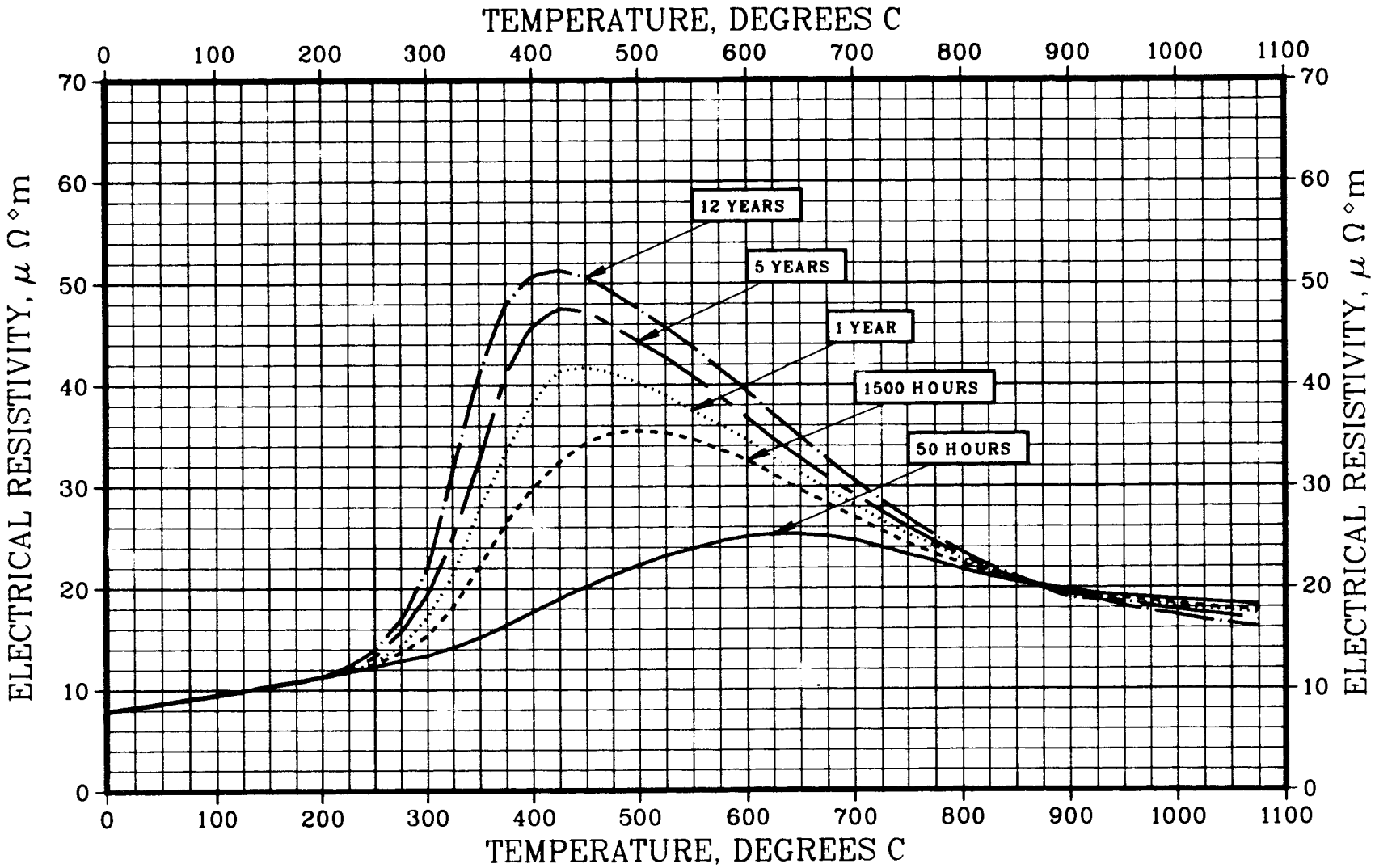
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 78Si/22Ge/P	TABLE OF CONTENTS/PROPERTIES	Material Code BA05 Update Code 2.0.0

Property Code	Property	Pages
3112	Thermal Conductivity	1.0-1.2
3201	Electrical Resistivity	1.0-1.2
3207	Absolute Seebeck Coefficient	1.0-1.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA05 UPDATE CODE 2.0.0

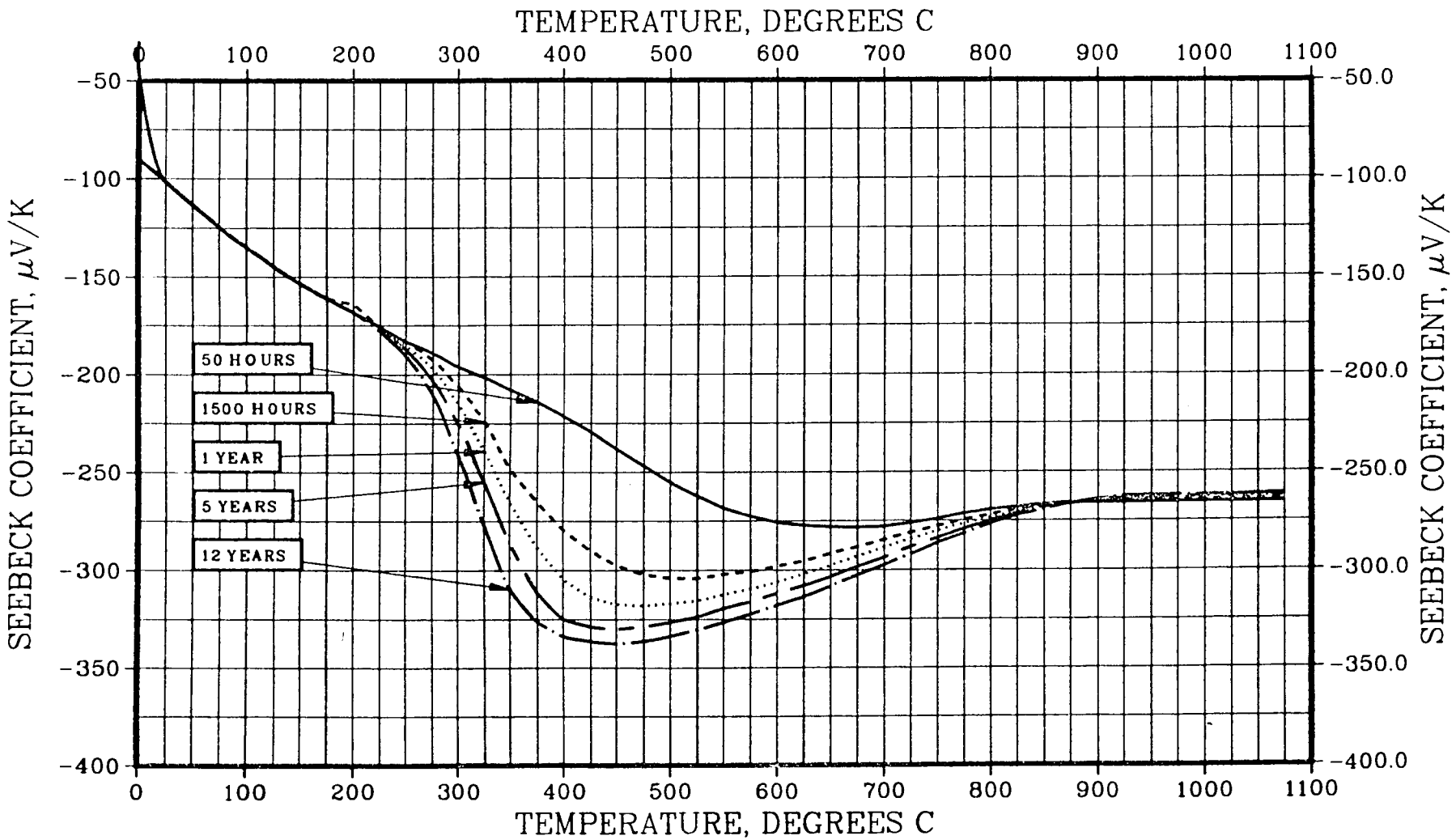


See Pages 1.1–1.2 for tables of correlation values.

PROPERTY CODE 3201 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 78Si/22Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA05
		UPDATE CODE: 2.0.0



See Pages 1.1–1.2 for tables of correlation values.

PROPERTY CODE 3207 PAGE 1.0

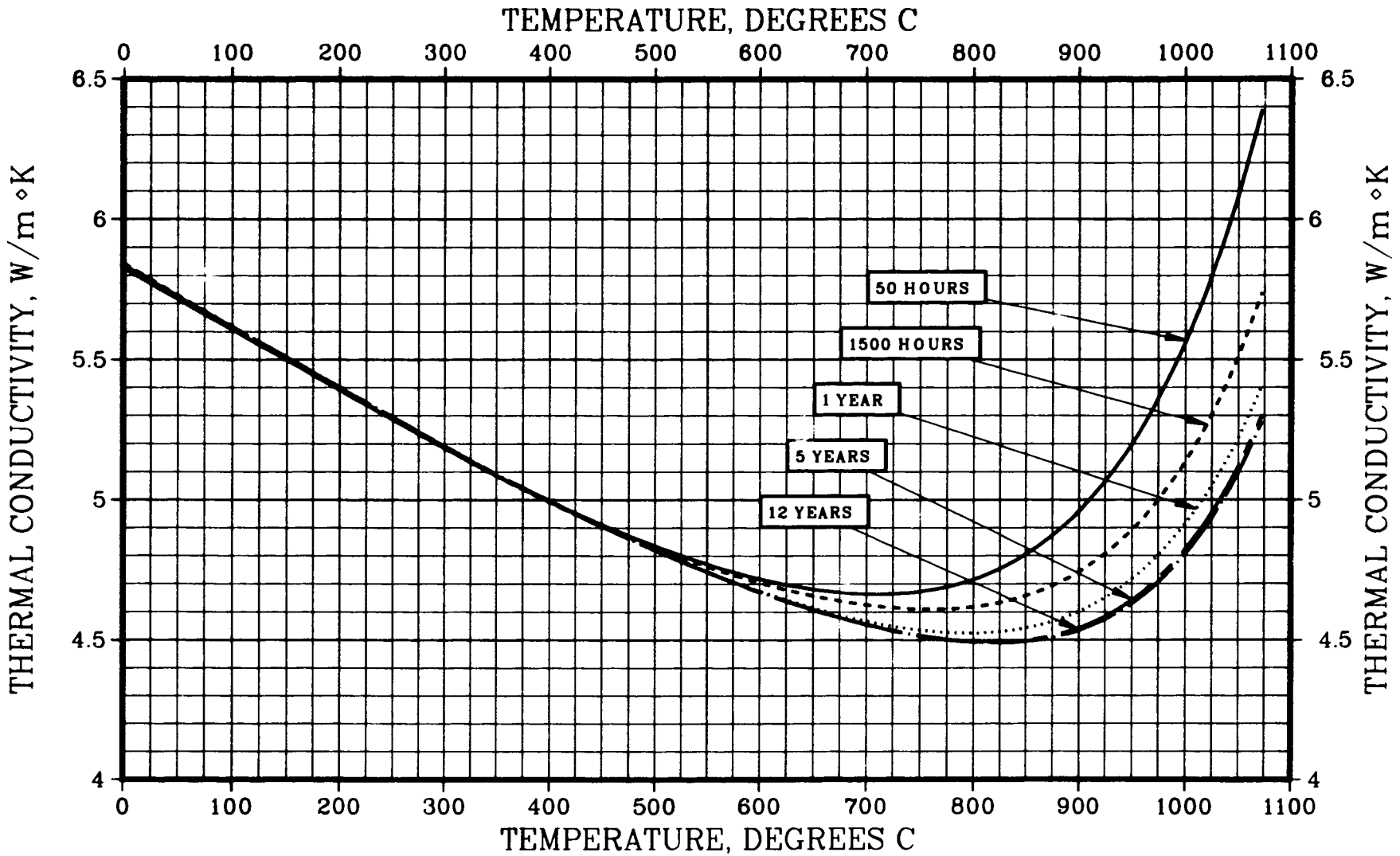
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 78Si/22Ge/B	TABLE OF CONTENTS/PROPERTIES	Material Code BA06 Update Code 2.0.0

Property Code	Property	Pages
3112	Thermal Conductivity	1.0-1.2
3201	Electrical Resistivity	1.0-1.2
3207	Absolute Seebeck Coefficient	1.0-1.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

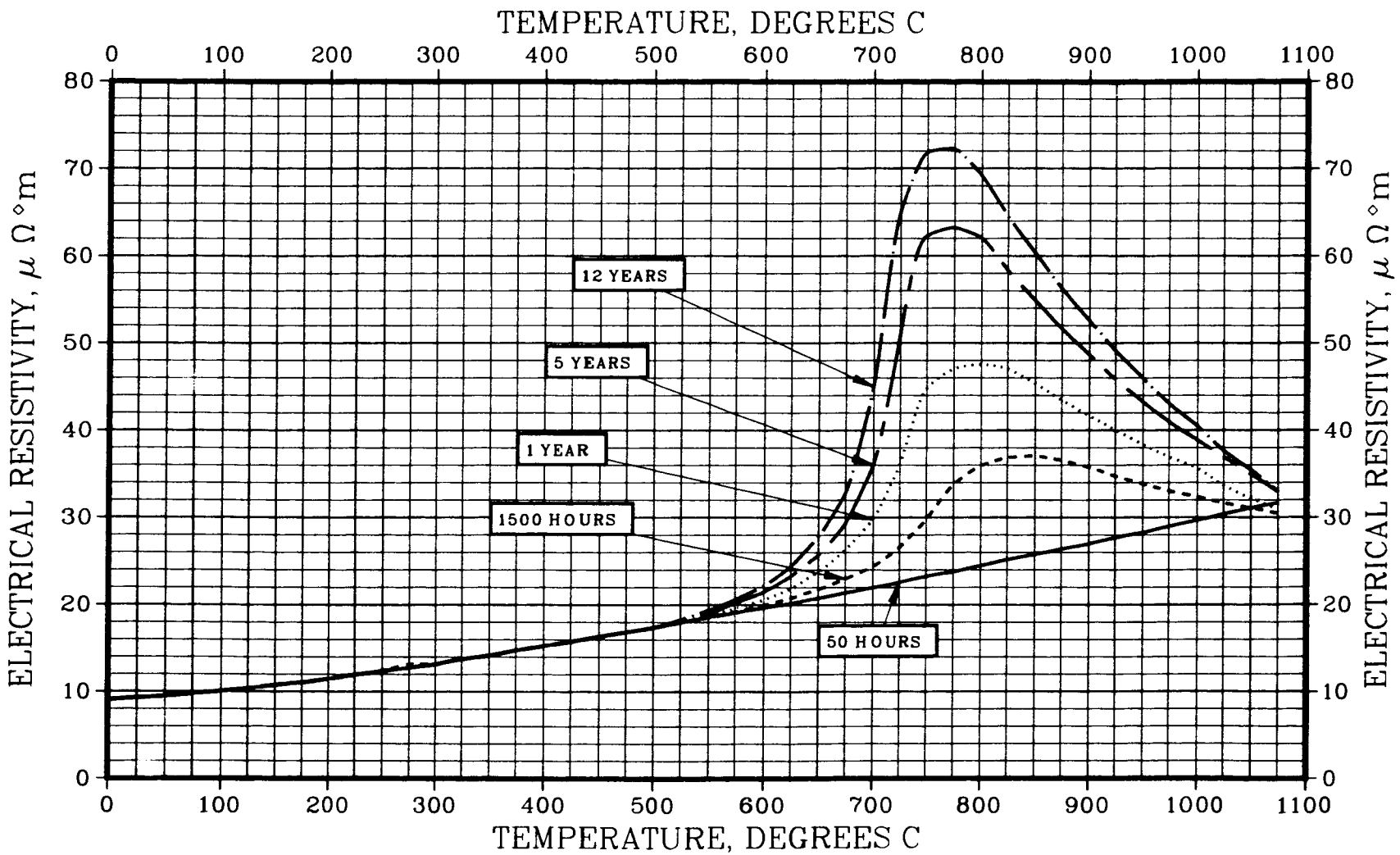
P–TYPE 78Si/22Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA06 UPDATE CODE: 0.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA06 UPDATE CODE: 2.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA06
		UPDATE CODE: [illegible]

50 HOUR DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY	TEMPERATURE	RESISTIVITY
DEGREES C	μ Ω◇m	DEGREES C	μ Ω◇m	DEGREES C	μ Ω◇m	DEGREES C	μ Ω◇m
0	9.1	0	9.1	0	9.1	0	9.1
50	9.5	50	9.5	50	9.5	50	9.5
100	10.1	100	10.1	100	10.1	100	10.1
150	10.8	150	10.8	150	10.8	150	10.8
200	11.5	200	11.5	200	11.5	200	11.5
250	12.4	250	12.4	250	12.4	250	12.4
300	13.2	300	13.2	300	13.2	300	13.2
350	14.2	350	14.2	350	14.2	350	14.2
400	15.3	400	15.3	400	15.3	400	15.3
450	16.4	450	16.3	450	16.4	450	16.4
500	17.4	500	17.4	500	17.4	500	17.4
550	18.6	550	18.6	550	18.7	550	19.0
600	19.7	600	20.0	600	20.6	600	21.5
650	20.8	650	21.8	650	23.8	650	25.7
700	22.0	700	24.4	700	29.8	700	36.0
750	23.3	750	29.8	750	44.9	750	62.4
800	24.5	800	36.0	800	47.6	800	62.1
850	25.8	850	37.1	850	45.4	850	54.9
900	27.0	900	35.8	900	41.7	900	48.7
950	28.3	950	33.9	950	38.4	950	43.3
1000	29.7	1000	32.4	1000	35.7	1000	38.9
1050	31.1	1050	31.1	1050	32.2	1050	35.0
1100	31.7	1100	30.5	1100	31.0	1100	33.0

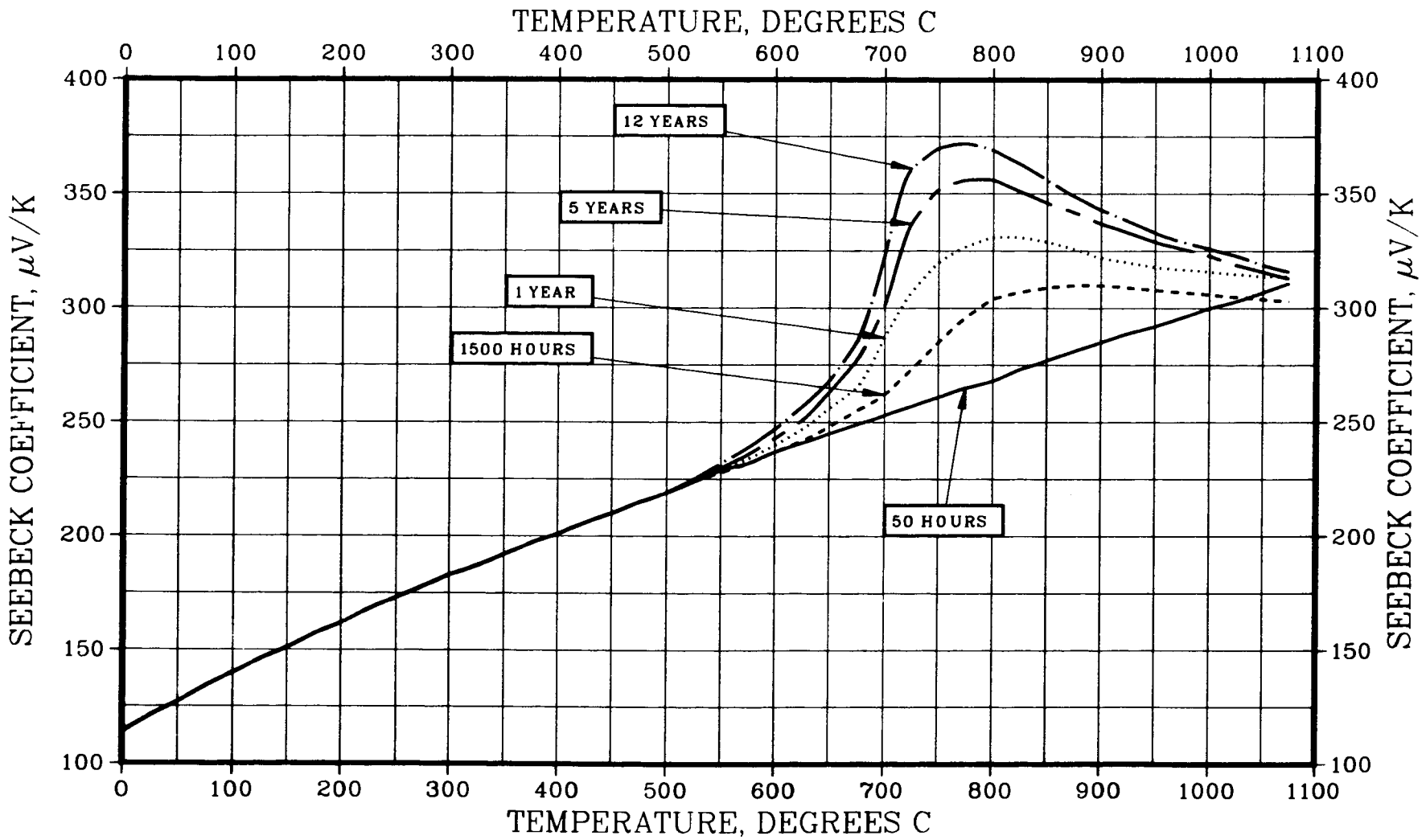
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA06
		UPDATE CODE: 2.0.0

12 YEAR DATA	
TEMPERATURE	RESISTIVITY
DEGREES C	$\mu\Omega^{\circ}m$
0	9.1
50	9.5
100	10.1
150	10.8
200	11.5
250	12.4
300	13.2
350	14.2
400	15.3
450	16.4
500	17.4
550	19.4
600	22.2
650	27.8
700	45.0
750	71.9
800	69.2
850	60.3
900	52.6
950	46.0
1000	40.5
1050	35.5
1100	33.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA06
		UPDATE CODE: 2.0.0



See Pages 1.1–1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 78Si/22Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA06
		UPDATE CODE: 2.0.0

50 HOUR DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K
0	114.	0	114.	0	114.	0	114.
50	127.	50	127.	50	127.	50	127.
100	140.	100	140.	100	140.	100	140.
150	151.	150	151.	150	151.	150	151.
200	162.	200	162.	200	162.	200	162.
250	173.	250	173.	250	173.	250	173.
300	183.	300	183.	300	183.	300	183.
350	192.	350	192.	350	192.	350	192.
400	201.	400	201.	400	201.	400	201.
450	210.	450	210.	450	210.	450	210.
500	219.	500	219.	500	219.	500	219.
550	229.	550	228.	550	229.	550	230.
600	237.	600	237.	600	240.	600	243.
650	245.	650	248.	650	256.	650	263.
700	253.	700	262.	700	287.	700	301.
750	261.	750	285.	750	320.	750	352.
800	268.	800	304.	800	331.	800	356.
850	277.	850	309.	850	329.	850	346.
900	285.	900	310.	900	322.	900	337.
950	292.	950	308.	950	318.	950	329.
1000	300.	1000	306.	1000	316.	1000	323.
1050	307.	1050	304.	1050	314.	1050	316.
1100	311.	1100	303.	1100	314.	1100	313.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 78Si/22Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA06
		UPDATE CODE: 2.0.0

12 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K
0	114.
50	127.
100	140.
150	151.
200	162.
250	173.
300	183.
350	192.
400	201.
450	210.
500	219.
550	232.
600	247.
650	268.
700	323.
750	370.
800	369.
850	356.
900	343.
950	333.
1000	326.
1050	319.
1100	316.

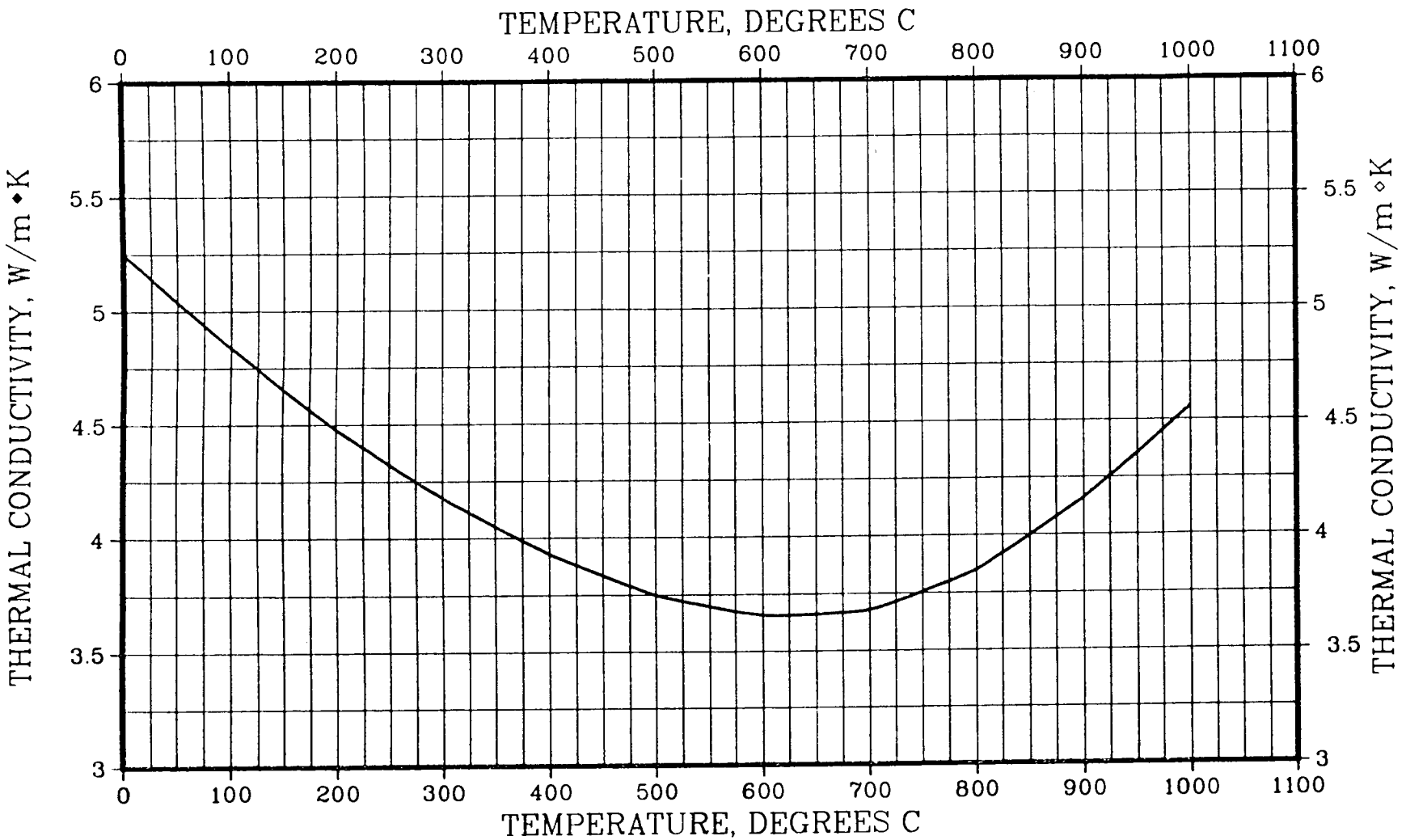
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	TABLE OF CONTENTS/PROPERTIES	Material Code BA07 Update Code 2.0.0

Property Code	Property	Pages
3112	Thermal Conductivity	1.0-1.1
3201	Electrical Resistivity	1.0-1.2
3207	Absolute Seebeck Coefficient	1.0-1.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 63Si/37Ge/P	THERMAL CONDUCTIVITY	MATERIAL CODE: BA07 UPDATE CODE: 0.0.0

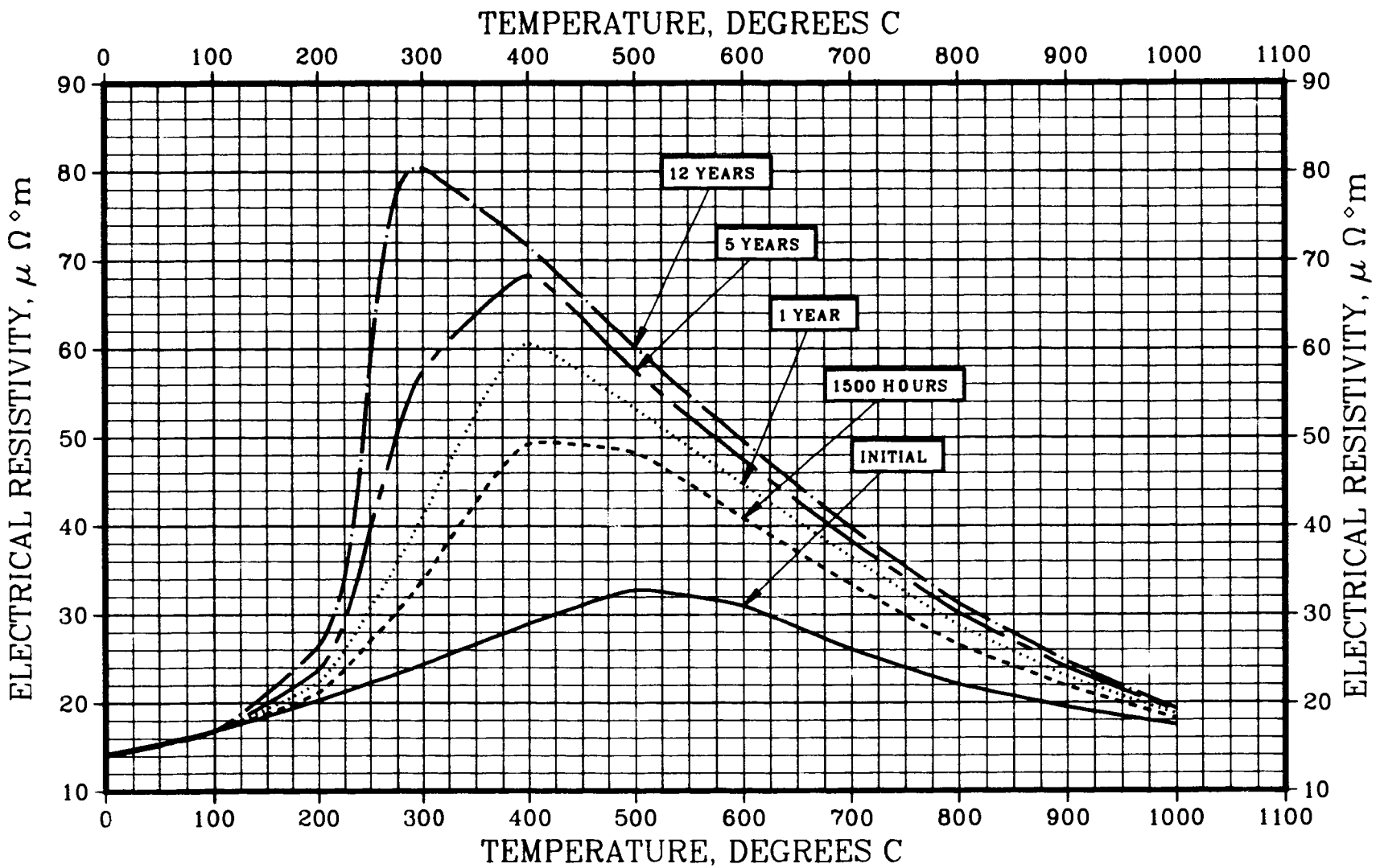


See Page 1.1 for tables of correlation values.

PROPERTY CODE 3112 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N–TYPE 63Si/37Ge/P	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA07
		UPDATE CODE: 0.0.0



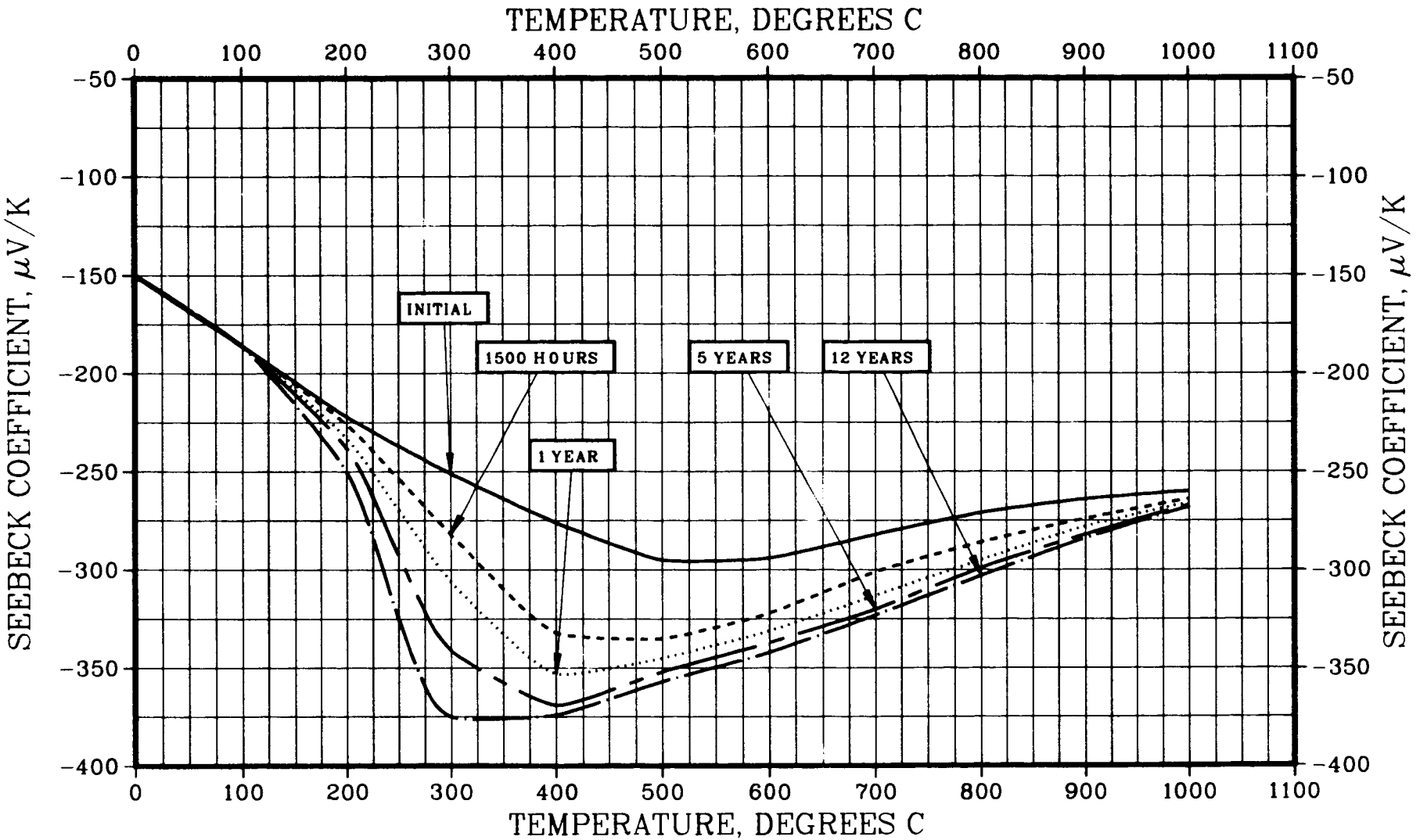
See Pages 1.1–1.2 for tables of correlation values.

PROPERTY CODE 3201

PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA07 UPDATE CODE: 0.0.0



See Pages 1.1-1.2 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA07
		UPDATE CODE: 0.0.0

INITIAL DATA		1500 HOUR DATA		1 YEAR DATA		5 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.	TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K	DEGREES C	μV/K
0	-150.00	0	-150.00	0	-150.00	0	-150.00
50	-168.00	50	-168.00	50	-168.00	50	-168.00
100	-186.00	100	-186.00	100	-186.00	100	-186.00
150	-204.00	150	-206.00	150	-209.50	150	-212.00
200	-222.00	200	-226.00	200	-233.00	200	-238.00
250	-236.50	250	-254.00	250	-269.50	250	-289.50
300	-251.00	300	-282.00	300	-306.00	300	-341.00
350	-263.50	350	-307.00	350	-329.50	350	-355.00
400	-276.00	400	-332.00	400	-353.00	400	-369.00
450	-285.50	450	-333.50	450	-349.00	450	-360.50
500	-295.00	500	-335.00	500	-345.00	500	-352.00
550	-294.50	550	-328.50	550	-338.00	550	-344.50
600	-294.00	600	-322.00	600	-331.00	600	-337.00
650	-288.00	650	-311.50	650	-322.00	650	-328.50
700	-282.00	700	-301.00	700	-313.00	700	-320.00
750	-276.50	750	-293.50	750	-304.00	750	-309.50
800	-271.00	800	-286.00	800	-295.00	800	-299.00
850	-267.50	850	-280.00	850	-286.50	850	-290.50
900	-264.00	900	-274.00	900	-278.00	900	-282.00
950	-262.00	950	-269.00	950	-272.00	950	-274.50
1000	-260.00	1000	-264.00	1000	-266.00	1000	-267.00

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

N-TYPE 63Si/37Ge/P	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA07
		UPDATE CODE: 0.0.0

12 YEAR DATA	
TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K
0	-150.00
50	-168.00
100	-186.00
150	-218.00
200	-250.00
250	-312.50
300	-375.00
350	-374.50
400	-374.00
450	-365.50
500	-357.00
550	-349.50
600	-342.00
650	-332.50
700	-323.00
750	-313.00
800	-303.00
850	-293.50
900	-284.00
950	-276.00
1000	-268.00

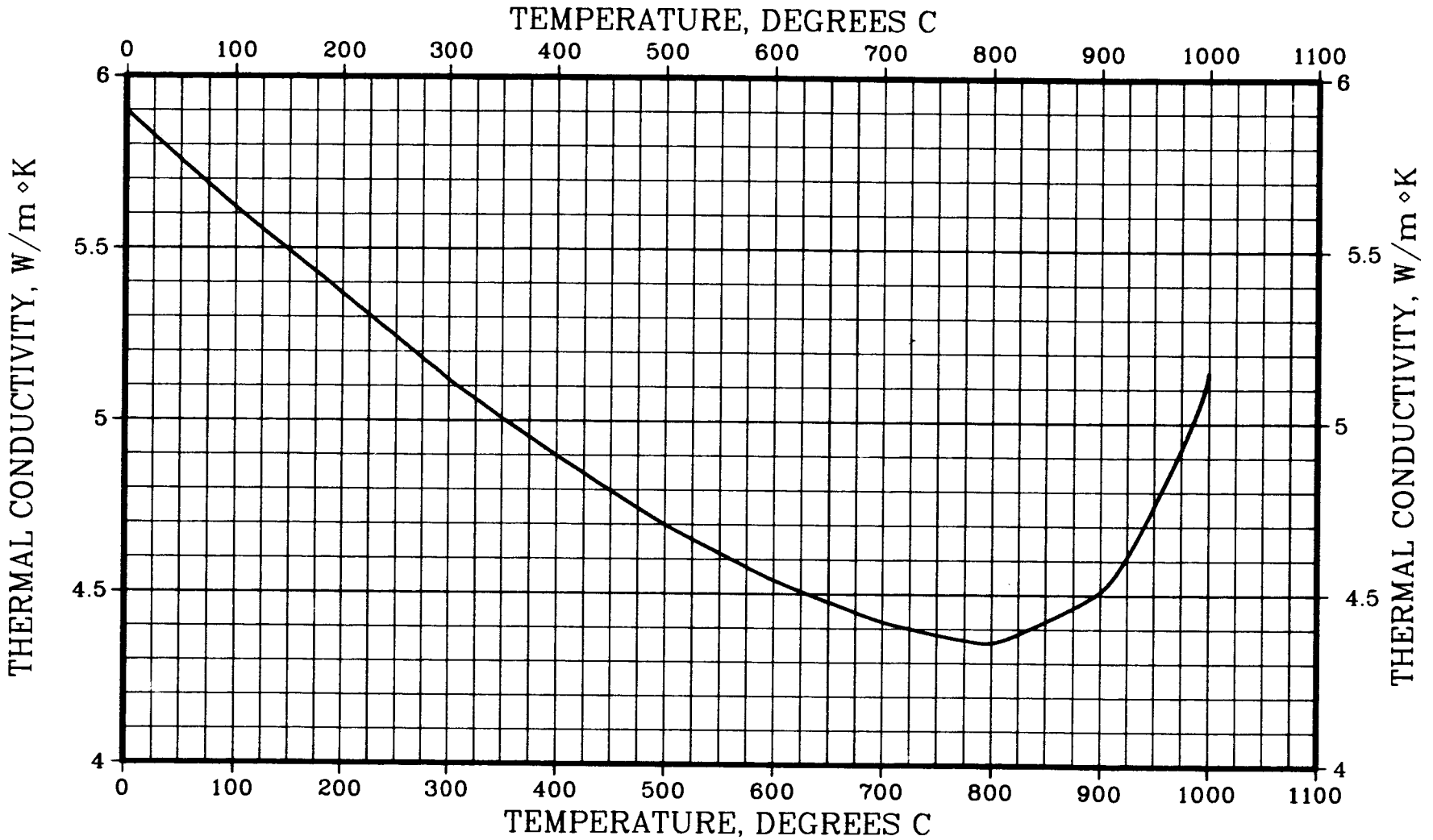
ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P-TYPE 63Si/37Ge/B	TABLE OF CONTENTS/PROPERTIES	Material Code BA08 Update Code 2.0.0

Property Code	Property	Pages
3112	Thermal Conductivity	1.0-1.1
3201	Electrical Resistivity	1.0-1.1
3207	Absolute Seebeck Coefficient	1.0-1.1

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

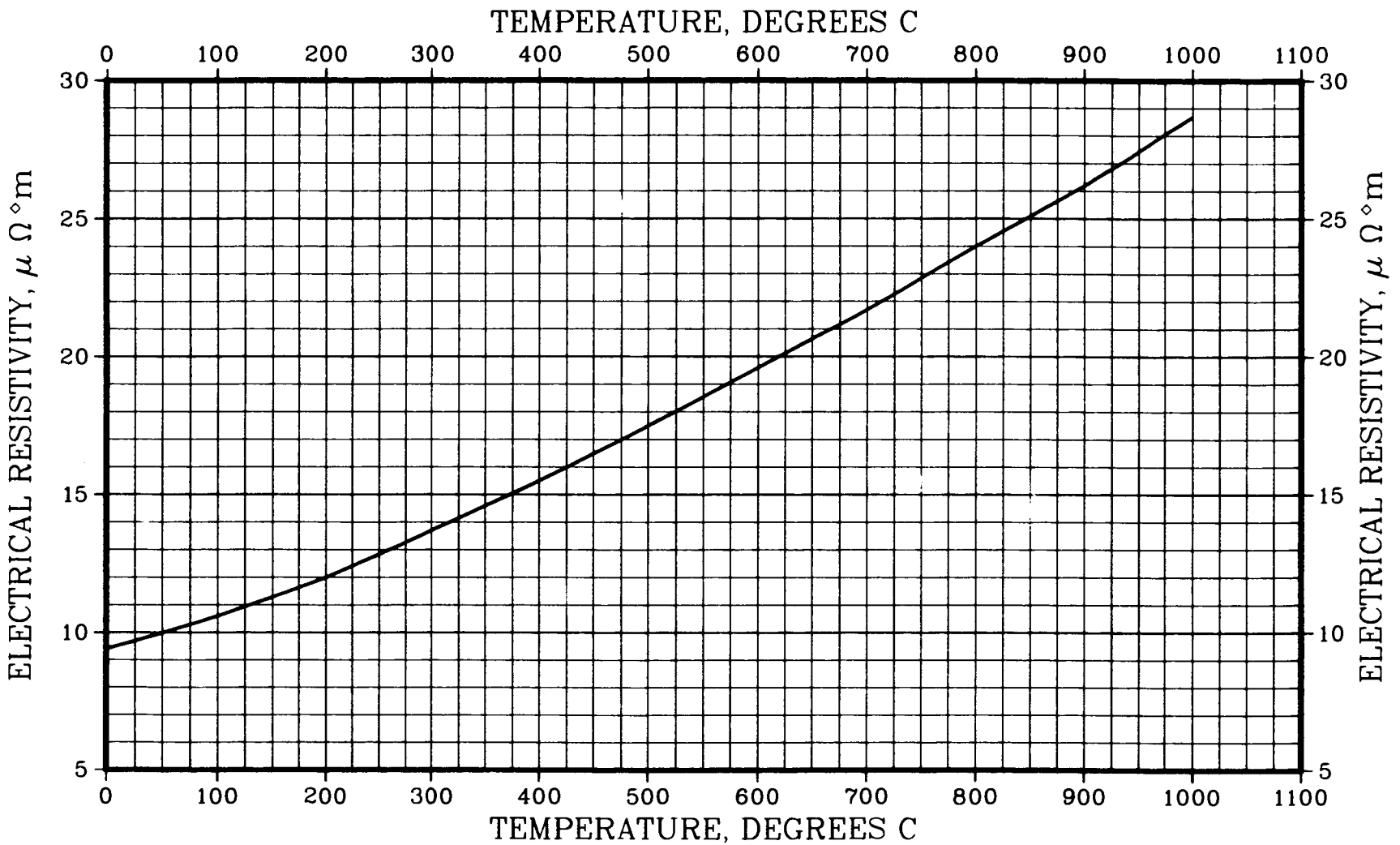
P–TYPE 63Si/37Ge/B	THERMAL CONDUCTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 0.0.0



See Page 1.1 for tables of correlation values.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 0.0.0



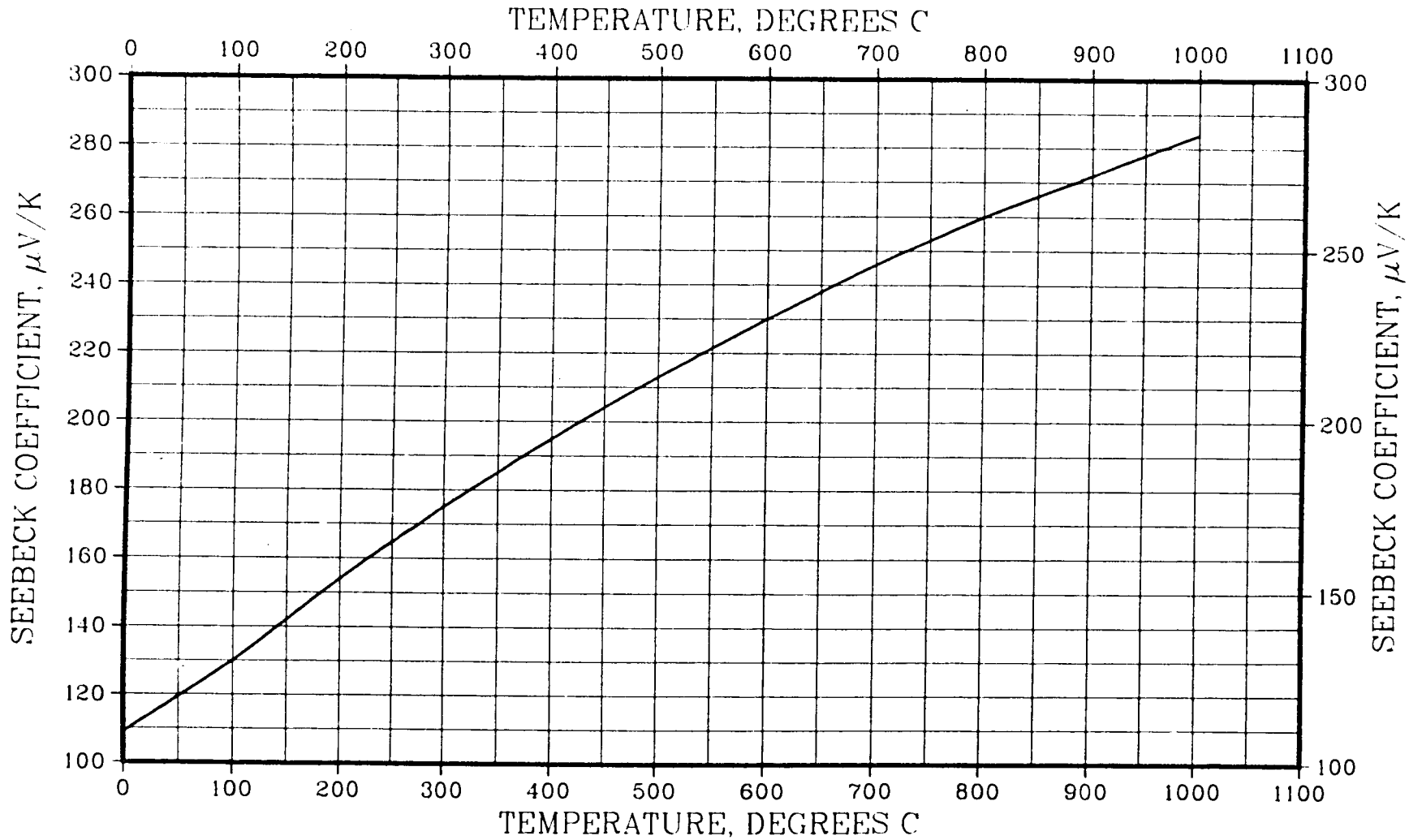
See Pages 1.1–1.2 for tables of correlation values.

P–TYPE 63Si/37Ge/B	ELECTRICAL RESISTIVITY	MATERIAL CODE: BA08 UPDATE CODE: 0.0.0

TEMPERATURE	RESISTIVITY
DEGREES C	$\mu\Omega\,°m$
0	9.40
50	9.98
100	10.60
150	11.26
200	12.00
250	12.84
300	13.70
350	14.58
400	15.50
450	16.49
500	17.50
550	18.55
600	19.60
650	20.63
700	21.70
750	22.86
800	24.00
850	25.06
900	26.20
950	27.46
1000	28.70

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

P–TYPE 63Si/37Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA08
		UPDATE CODE: 0.0.0



See Pages 1.1 - 1.2 for tables of correlation values.

PROPERTY CODE 3207

PAGE 1.0

P–TYPE 63Si/37Ge/B	ABSOLUTE SEEBECK COEFFICIENT	MATERIAL CODE: BA08 UPDATE CODE: 0.0.0

TEMPERATURE	SEEBECK COEFF.
DEGREES C	μV/K
0	109.00
50	119.50
100	130.00
150	142.00
200	154.00
250	164.50
300	175.00
350	185.00
400	195.00
450	204.00
500	213.00
550	221.50
600	230.00
650	238.00
700	246.00
750	253.00
800	260.00
850	266.00
900	272.00
950	278.00
1000	284.00

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

CRYSTALLINE CERAMICS	TABLE OF CONTENTS/MATERIALS	Material Code CAXX Update Code 0.0.0

Material Code	Material
CA01	Silicon Nitride (Si_3N_4) Coating

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SILICON NITRIDE (Si_3N_4) COATING	TABLE OF CONTENTS/PROPERTIES	Material Code CA01 Update Code 0.0.0

Property Code	Property	Pages
1100	Chemical Composition (wt %): Si 60.06 N 39.94	*
1200	Applicable Specifications: GE23991-CP3A1, GE23991-CP4A1. Note: Coating composition and thickness by chemical vapor deposition process control.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

OXIDES	TABLE OF CONTENTS/MATERIALS	Material Code CBXX Update Code 0.0.0

Material Code	Material
CB01	Al_2O_3

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Al_2O_3	TABLE OF CONTENTS/PROPERTIES	Material Code CB01 Update Code 0.0.0

Property Code	Property	Pages
2101	Tensile Strength[a]:	*
	Average >34.5 MPa	
	Minimum 27.6 MPa	
2115	Rupture Modulus[b]:	
	Average ≥345 MPa	
	Minimum 207 MPa	
3305	Porosity[a]: 7% maximum	*
	Pore Size[a] (μm):	
	Rounded / Elongated	
	Maximum 100 / 200	
	Average ≤40 / ≥60	
4207	Grain Size[a] (μm):	*
	Maximum 240	
	Minimum 5	
	Average 10 to 50	

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.
[a]Data for Alumina Hot Shoe Spacer including metallized material.
[b]Data for Alumina Hot Shoe Spacer, metallized only.

D. AMORPHOUS CERAMICS AND GLASSES

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

SILICATE GLASSES	TABLE OF CONTENTS/MATERIALS	Material Code DAXX Update Code 0.0.0

Material Code	Material
DA01	Low-temperature Glass
DA02	High-temperature Glass

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

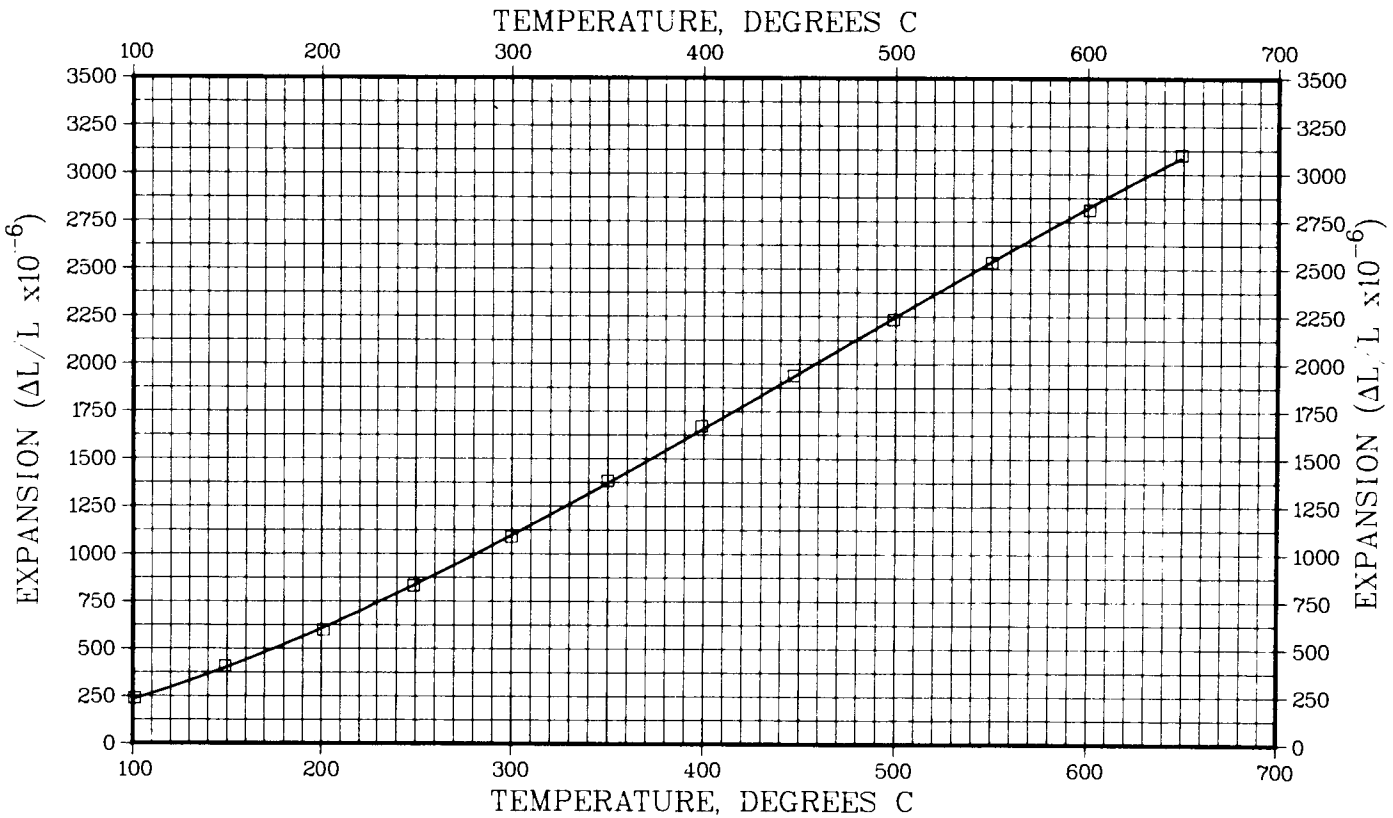
LOW-TEMPERATURE GLASS[a]	TABLE OF CONTENTS/PROPERTIES	Material Code DA01 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information: Kimball CV-635 low-temperature glass is recommended for sealing glasses and metals of thermal expansion (0 to 300°C) from 40 to 45 $\times$ 10^{-7} °C^{-1}. The sealing range is 680 to 700°C for 1 h.	*
1100	Nominal Chemical Composition (wt %):	*
	ZnO 60 SiO_2 15 CuO 2 B_2O_3 19 PbO_2 4	
3114	Thermal Expansion	1.0-1.1
3201	Volume Resistivity, (ρ) ohm-cm (devitrified solder glass): log ρ at 250°C 12.8 350°C 11.0	*
3203	Dielectric Constant (ASTM D150-54T) (devitrified solder glass): one megacycle, K 7.0	*
3301	Viscosity: Fiber Softening Point (vitreous material, before maturing): 632°C Annealing Point (vitreous material, before maturing): 530°C	*
3304	Density (vitreous material, before maturing): 3.90 Mg/m^3	

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.
[a]Kimball CV-635.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

LOW TEMPERATURE GLASS	THERMAL EXPANSION	MATERIAL CODE: DA01
		UPDATE CODE: 0.0.0



See Page 1.1 for a table of values and a correlation.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

LOW TEMPERATURE GLASS	THERMAL EXPANSION	MATERIAL CODE: DA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	EXPANSION	TEMPERATURE	EXPANSION
DEGREES C	$\Delta L/L \times 10^{-6}$	DEGREES C	$\Delta L/L \times 10^{-6}$
100	234.	101	240.
150	404.	149	409.
200	609.	201	600.
250	842.	249	834.
300	1098.	300	1090.
350	1373.	350	1384.
400	1659.	399	1673.
450	1953.	447	1940.
500	2249.	499	2235.
550	2541.	550	2535.
600	2824.	601	2813.
650	3092.	649	3102.

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$\Delta L/L = 15.6595 + 1.25232T + 1.00010\times10^{-2}T^{2} - 7.14738\times10^{-6}T^{3}, \text{ where}$$

$\Delta L/L$ = Elongation, $\Delta L/L \times 10^{-6}$, and
T = Temperature, 100 , T ≤ 650 Degrees C.

The standard error of estimate of the fit was 12.436 and the coefficient of determination was 0.99994.

The "Original Values" were obtained by reading values from the graph in Reference DA01, 2105-1, through the use of a graphics tablet.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH-TEMPERATURE GLASS[a]	TABLE OF CONTENTS/PROPERTIES	Material Code DA02 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information	1.0
1100	Nominal Chemical Composition (wt %):	*
	SiO_2 76	
	Al_2O_3 12	
	MgO 6	
	CaO 6	
2119	Softening Point:	*
	Component — Degrees C	
	EE2 — 955	
	EE5 — 1070	
3108	Specific Heat	1.0-1.1
3112	Thermal Conductivity	1.0-1.1
3114	Thermal Expansion:	*
	Component — Expansion Coefficient, $\times 10^7$ °C^{-1} (0 to 300 °C)	
	EE2 — 43	
	EE5 — 31	
	Contraction Coefficient:	*
	Component — Contraction Coefficient A.P. 25°C $\times 10^7$ °C^{-1}	
	EE2	
	EE5 — 40	
3201	Electricity Resistivity:	*
	Component — Volume Resistivity (ρ) Ω-cm (Expressed as Logarithm of ρ)	
	EE2 — 13.2	
	EE5	

[a]Owens Corning glass, 30 wt % EE2, 70 wt % EE9. The values given here are for the individual components EE2 and EE5 (which is approximately equivalent to EE9), not for the EE2/EE9 compound.

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH-TEMPERATURE GLASS[a]	TABLE OF CONTENTS/PROPERTIES	Material Code DA02 Update Code 0.0.0

Property Code	Property	Pages
3301	Viscosity:	*
	Annealing Point:	*
	Component / Degrees C EE2 761 EE5 819	
	Softening Point: See Property Code 2119	*
	Strain Point:	*
	Component / Degrees C EE2 714 EE5 772	
	Working Point:	*
	Component / Degrees C EE2 1210 EE5 1395	
3304	Density (23 to 1200 °C): 2.542 Mg/m^3	*
4202	Thermal Diffusivity	1.0-1.1

[a]Owens Corning glass, 30 wt % EE2, 70 wt % EE9. The values given here are for the individual components EE2 and EE5 (which is approximately equivalent to EE9), not for the EE2/EE9 compound.

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

HIGH-TEMPERATURE GLASS[a]	GENERAL PROPERTIES	Material Code DA03 Update Code 0.0.0

The high-temperature glass used in multicouple thermopile and hot shoe bonding is formed from a mixture of 30 wt % EE2 and 70 wt % EE9 Owens Corning glass. The following information is for the EE 2 component only.

Processing or Handling EE 2 Glass

Lampworking

Rapid heating with sharp fires will cause reboil[b] in the glass. Use soft, somewhat reducing oxygen-gas flames, or preferably hydrogen flames, bringing the glass to red heat uniformly. Heating may then be increased with sharper or hotter flame conditions. Bubbling the gas through a solution of ethyl orthosilicate has been found beneficial.

Reboil may also be minimized by cleaning or washing to remove surface contaminants.

In stem-sealing bulb envelopes it may be necessary to neck-down larger tubes to match smaller sizes or exert control so that the seal edges are not heated unevenly or too rapidly.

Sealing Techniques

The thermal expansion of EE 2 (0 to 300°C) lies close to that of tungsten and below that of molybdenum and is similar to other "hard" glasses. Seals to these metals will require temperature levels generally above 1000°C, at which over-oxidation of the metals tends to occur, so that best results are obtained by sealing in an inert atmosphere.

Careful thermal processing or annealing of seals may be necessary. Seals to tungsten may require graded seal techniques employing other hard glasses, clad metal forms, or foil-type seals. Annealing bake levels should be at about 790°C (1450°F).

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[a]Owens Corning Glass, 30 wt % EE2, 70 wt % EE9.

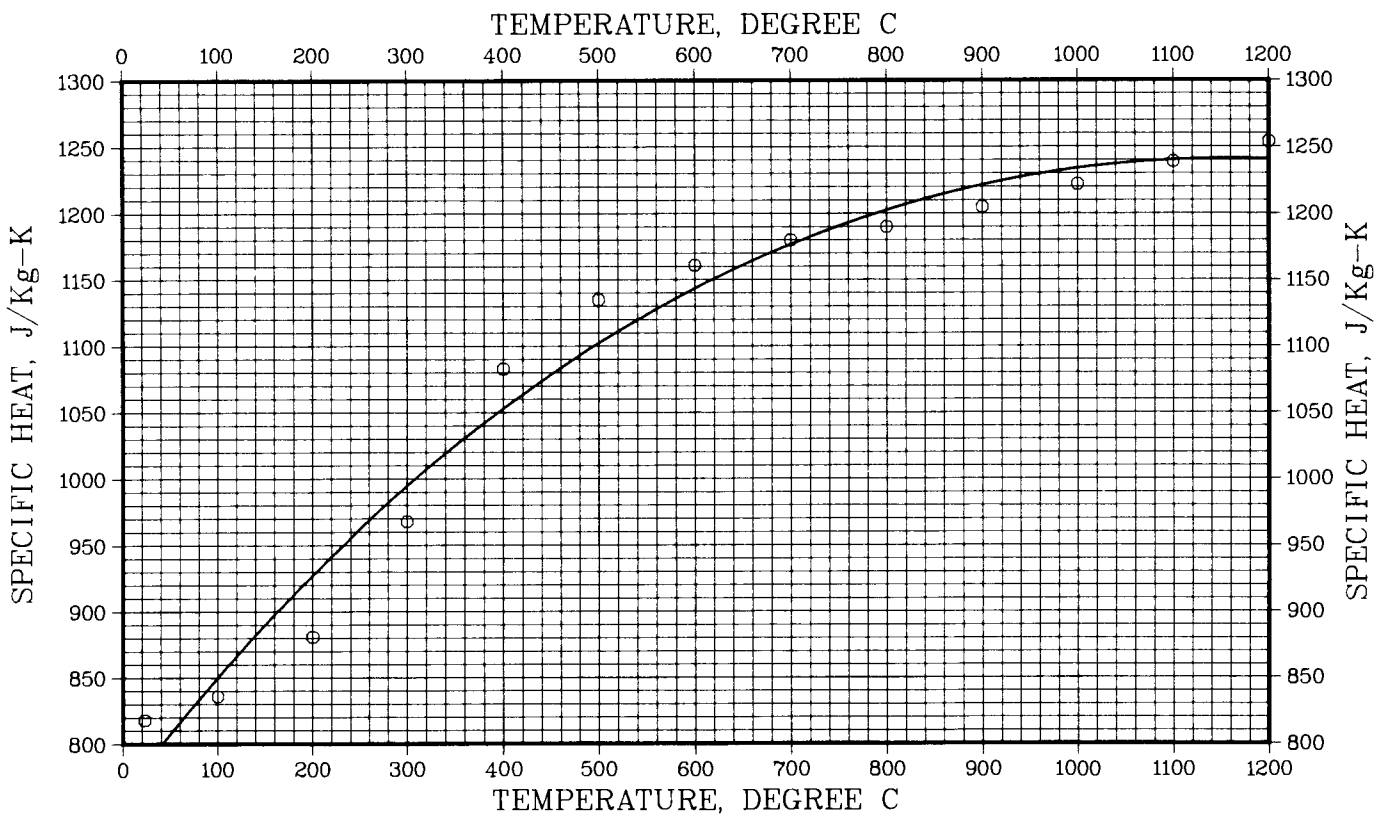
[b]Reboil is the reappearance or formation of gases that may remain in the glass as bubbles or seeds when a glass is reheated to temperatures suitable for lampworking or sealing after the glass had previously appeared clean and free of bubbles. A method of reboil testing has been published in the *Proceedings of the Fifth Annual Symposium of the American Scientific Glassblowers Society* June, 1960, pp. 16–20.

ORNL—DWG 83-17519

PLOT 1 13.09.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	SPECIFIC HEAT	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0



Owens Corning glass, 30 wt% EE-2, 70 wt% EE-9.
See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3108 PAGE 1.0

PLOT 2 13.13.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	SPECIFIC HEAT	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	SPECIFIC HEAT	TEMPERATURE	SPECIFIC HEAT
DEGREES C	J/Kg-K	DEGREES C	J/Kg-K
100	850.	100	836.
150	890.	200	881.
200	927.	300	968.
250	962.	400	1083.
300	995.	500	1135.
350	1025.	600	1161.
400	1053.	700	1180.
450	1079.	800	1190.
500	1103.	900	1205.
550	1124.	1000	1222.
600	1144.	1100	1239.
650	1161.	1200	1254.
700	1177.		
750	1191.		
800	1203.		
850	1213.		
900	1222.		
950	1229.		
1000	1234.		
1050	1238.		
1100	1240.		
1150	1241.		
1200	1241.		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$C_p = 762.896 + 9.25256\times10^{-1}T - 5.29706\times10^{-4}T^2 + 7.55180\times10^{-8}T^3, \text{ where}$$

C_p = Specific Heat, J/Kg-K, and
T = Temperature, $23 < T < 1200$ Degrees C.

The standard error of estimate of the fit was 28.378 and the coefficient of determination was 0.98793.

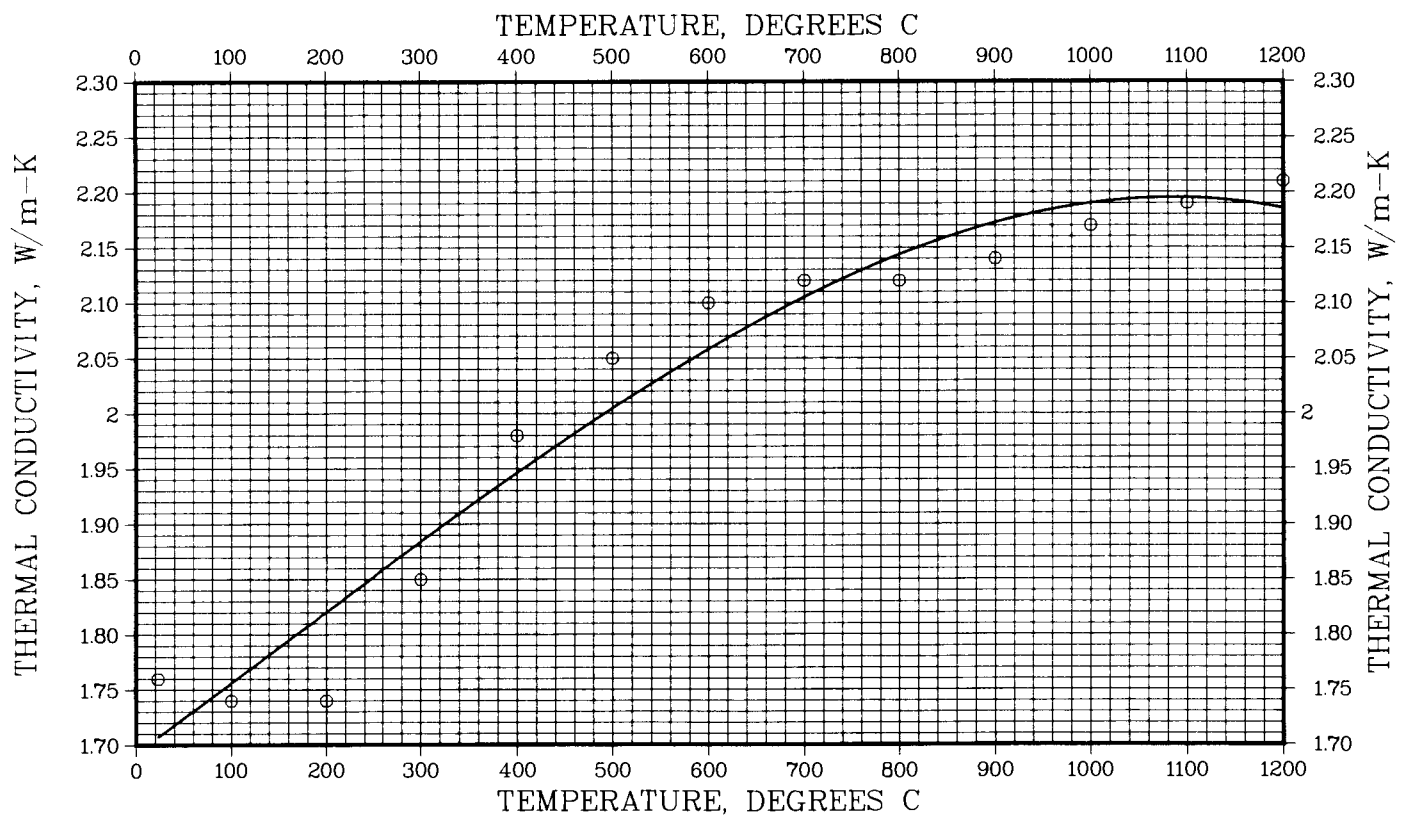
See Property Code 1000 for Special Notes.

ORNL–DWG 83-17517

PLOT 1 11.09.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	THERMAL CONDUCTIVITY	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0



Owens Corning glass, 30 wt% EE–2, 70 wt% EE–9.
See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3112 PAGE 1.0

PLOT 2 11.15.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	THERMAL CONDUCTIVITY	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	THERMAL CONDUCTIVITY
DEGREES C	W/m-K	DEGREES C	W/m-K
50	1.72	100	1.74
100	1.76	200	1.74
150	1.79	300	1.85
200	1.82	400	1.98
250	1.85	500	2.05
300	1.88	600	2.10
350	1.92	700	2.12
400	1.95	800	2.12
450	1.98	900	2.14
500	2.00	1000	2.17
550	2.03	1100	2.19
600	2.06	1200	2.21
650	2.08		
700	2.11		
750	2.13		
800	2.14		
850	2.16		
900	2.17		
950	2.18		
1000	2.19		
1050	2.19		
1100	2.20		
1150	2.19		
1200	2.19		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$\lambda = 1.69296 + 6.20255\times10^{-4}\,T + 1.37230\times10^{-7}T^2 - 2.60167\times10^{-10}T^3,$$ where

λ = Thermal Conductivity, W/m–K, and
T = Temperature, $23 < T < 1200$ Degrees C.

The standard error of estimate of the fit was 4.5326×10^{-2} and the coefficient of determination was 0.97559.

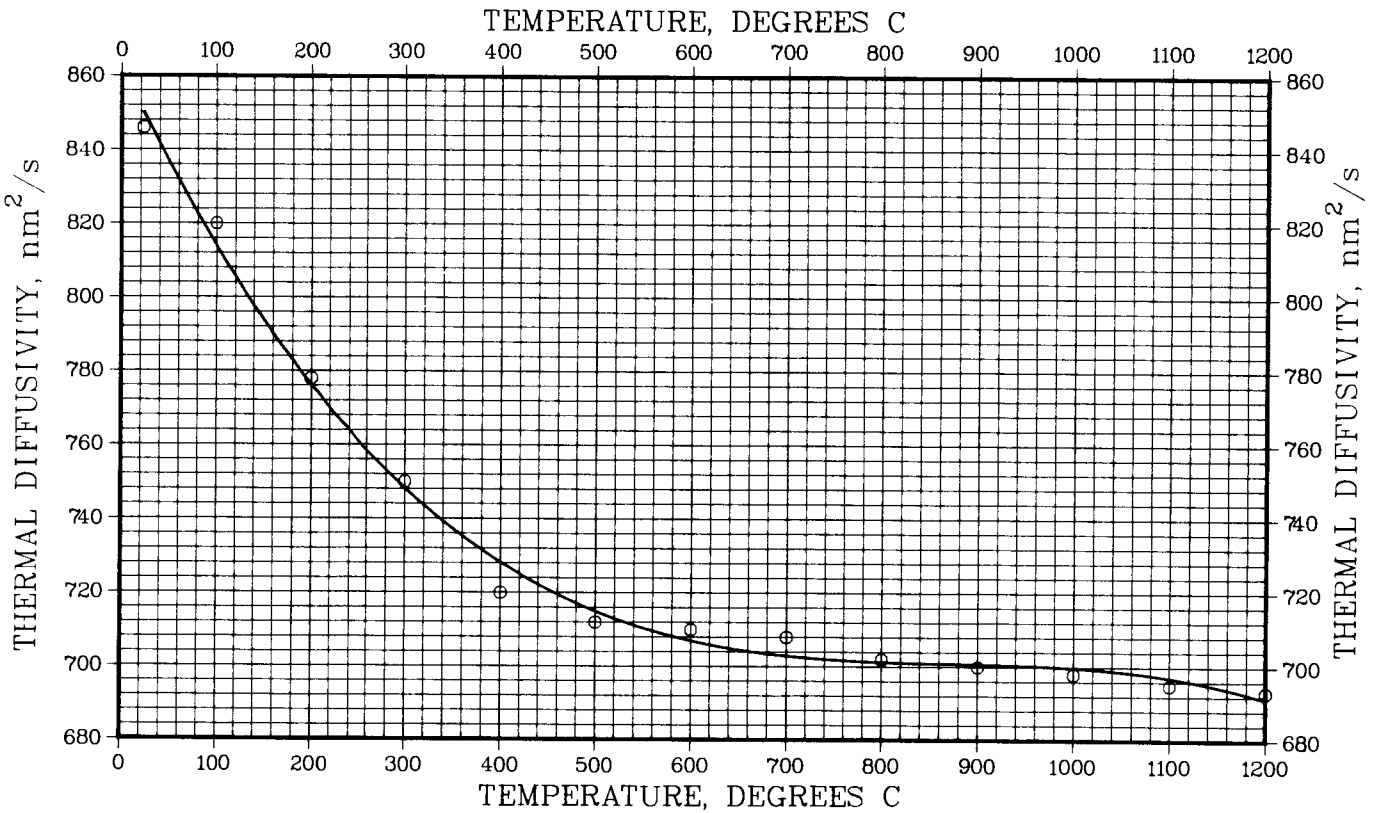
See Property Code 1000 for Special Notes.

ORNL–DWG 83-17515

PLOT 1 12.41.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	THERMAL DIFFUSIVITY	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0



Owens Corning glass, 30 wt% EE–2, 70 wt% EE–9.
See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 4202 PAGE 1.0

PLOT 2 12.42.00 FRI 26 AUG, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HIGH TEMPERATURE GLASS	THERMAL DIFFUSIVITY	MATERIAL CODE: DA02
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	THERMAL DIFFUSIVITY	TEMPERATURE	THERMAL DIFFUSIVITY
DEGREES C	nm^2/s	DEGREES C	nm^2/s
100	814.	100	820.
150	794.	200	778.
200	776.	300	750.
250	761.	400	720.
300	748.	500	712.
350	737.	600	710.
400	728.	700	708.
450	721.	800	702.
500	715.	900	700.
550	710.	1000	698.
600	707.	1100	695.
650	705.	1200	693.
700	703.		
750	702.		
800	701.		
850	701.		
900	701.		
950	700.		
1000	700.		
1050	699.		
1100	697.		
1150	695.		
1200	691.		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$D = 862.547 - 5.45311\times10^{-1}T + 6.18118\times10^{-4}T^2 - 2.35575\times10^{-7}T^3, \text{ where}$$

D = Thermal Diffusivity, nm^2/s
T = Temperature, $23 < T < 1200$ Degrees C.

The standard error of estimate of the fit was 4.5305 and the coefficient of determination was 0.99699.

See Property Code 1000 for Special Notes.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

GRAPHITES	TABLE OF CONTENTS/MATERIALS	Material Code EAXX Update Code 0.0.0

Material Code	Material
EA01	Stackpole 2128

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	TABLE OF CONTENTS/PROPERTIES	Material Code EA01 Update Code 0.0.0

Property Code	Property	Pages
1000	General	1.0
1100	Crystal Structure	1.0
1200	Product Forms: Grade 2128 can be obtained in 330 × 330 × 915 mm blocks and 318-mm-diam by 915-mm-long rounds.	*
2000	Mechanical Properties—General Notes	1.0
2101	Tensile Strength: Typical tensile strength provided by Stackpole, with grain: 14.2 MPa. (Against grain, as inferred by flexural test data: 11.6 MPa)	*
2104	Shear Strength	1.0
2109	Hardness: Scleroscope Hardness = 40, independent of orientation	*
2110	Poisson's Ratio	1.0
2111	Young's Modulus as measured by sonic methods:	*

	Sample 1	Sample 2
$1/S_{11}$	9.04 GPa	9.25 GPa
$1/S_{33}$	7.76 GPa	7.90 GPa

$1/S_{11}$ = Young's Modulus in the with-grain direction

$1/S_{33}$ = Young's Modulus in the against-grain direction

2112	Shear Modulus as measured by sonic methods:	*

	Sample 1	Sample 2
C_{44}	3.73 GPa	3.81 GPa
C_{66}	3.81 GPa	3.88 GPa

C_{44} and C_{66} are the two shear moduli for graphite.

2114	Bulk Modulus (K):	*

$K = 1/S$

S = Bulk compressibility

$S = 2S_{11} + S_{33} + 2S_{12} + 4S_{13}$

	Sample 1	Sample 2
S	$2.55 \times 10^{-10}\ Pa^{-1}$	$2.46 \times 10^{-10}\ Pa^{-1}$
K	3.92 GPa	4.07 GPa

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

STACKPOLE 2128	TABLE OF CONTENTS/PROPERTIES	Material Code EA01 Update Code 0.0.0

Property Code	Property	Pages
2115	The Rupture Modulus has only been measured for bending. The bending modulus of rupture is: With grain, 26.9 MPa Against grain, 22.1 MPa (This modulus of rupture is specimen size dependent and the specimen sizes of this test are not available.)	*
2116	Compressive Strength: With grain 55.2 MPa Against grain 45.5 MPa (The compressive strength is virtually independent of specimen size and has low variability.)	*
2117	Bending Strength or Flexural Strength is generally given as the modulus of rupture for graphite: With grain, 26.9 MPa Against grain, 22.1 MPa	*
2118	Fracture Strength: The fracture strength of graphite is generally taken as the tensile strength. However, the mode of loading should be taken into consideration.	*
2121	Elastic Stiffness	1.0
2200	Static, Long-term Properties: Graphite does not exhibit time-dependent properties of any magnitude until temperature exceeds 1600°C. These data do not exist for graphite 2128.	*
2300	Dynamic, Short-term Properties: These data do not exist. While most of the properties probably are not rate sensitive, there are no data to justify this assumption. The impact strength and thermal shock resistance of the graphite are of relevant concern to the use of 2128 graphite.	*
2400	Cyclic loading properties of 2128 graphite have not been measured. Generally, graphite has a very high fatigue strength to tensile strength ratio (>0.90) and is generally not a design consideration. However, while the discontinuities in the graphite hot shoe may reduce long-range stresses, highly localized stress intensities around the milled-in notches may result. Therefore, the fracture mechanics parameters should be evaluated.	*
3101	Maximum Service Temperature: The maximum service temperature is controlled by the compatibility of adjacent materials as long as the environment is nonoxidizing. Graphite is compatible with WC virtually up to the melting point of WC at 2800°C.	*

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	TABLE OF CONTENTS/PROPERTIES	Material Code EA01 Update Code 0.0.0

Property Code	Property	Pages
3108	Specific Heat Capacity	1.0–1.1
3109	Enthalpy	1.0–1.1
3110	Thermal Diffusivity: Thermal diffusivity data are not available but can be obtained from the thermal conductivity, density, and heat capacity.	*
3112	Thermal Conductivity: Thermal conductivity at room temperature was calculated from the electrical resistance using the Wiedemann-Franz Ratio. With grain 99 W/m·K Against grain 83 W/m·K The conductivity will decrease as temperature increases. The conductivity at 1000°C will be about one-half of the room temperature conductivity.	*
3114	Thermal Expansion: Thermal expansion of graphite increases with increasing temperature. The coeficient of thermal expansion defined by $\Delta l/l \cdot \Delta T$ for 600°C is With grain $2.3 \times 10^{-6}\,°F^{-1}$ ($4.2 \times 10^{-6}\,°C^{-1}$) Against grain $2.4 \times 10^{-6}\,°F^{-1}$ ($4.3 \times 10^{-6}\,°C^{-1}$)	*
3115	Entropy	1.0–1.1
3201	Electrical Resistivity: Electrical resistivity at room temperature is With grain 0.0008 Ω in. (20.3 μΩ-m) Against grain 0.0001 Ω in. (22.9 μΩ-m)	*
3304	Density: 1.70 Mg/m^3	*
3305	Porosity: Total porosity approximately 22.5%	*
3306	Speed of Sound	1.0
3314	Permeability:	*

Direction	Hydrogen	Nitrogen
With grain	0.12 darcies	0.05 darcies
Against grain	0.10 darcies	0.04 darcies

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	GENERAL	Material Code EA01 Update Code 0.0.0

The graphite for use in the multicouple must first be fine grained because of (1) the small component sizes and (2) the need for precision machining. The physical properties of most importance are the coefficients of thermal expansion (CTE) and compliances because of thermal stress problems. Minimum values of thermal conductivity and strength are also required but can be easily obtained for materials having the above prerequisite properties.

The graphite chosen for the components in the multicouple is Stackpole 2128.

Graphite Grade Stackpole 2128 is a molded graphite grade using an electrographite filler. The molding is done isostatically and has received a nominal 2500°C final graphitization heat treatment. It can be classified as a fine-grained graphite with low to medium density and with properties that are reasonably isotropic. A relatively high electrical resistivity coupled with a relatively low thermal conductivity imply a lack of crystallinity in the structure in either the filler or binder carbon. The modulus is high for its density, which also implies a lack of crystallinity in its structure. The graphite does appear to have good strength; however, the high modulus and possible low crystallinity may mean that it might have a low fracture toughness.

The physical properties needed are mainly those related to the thermal stress problem and heat flow problems.

STACKPOLE 2128	CRYSTAL STRUCTURE	Material Code EA01 Update Code 0.0.0

Graphite has a hexagonal crystal structure with ABAB stacking. The crystal is highly anisotropic with strong chemical bonding in the hexagonal plane and weak Van der Wall bonding between planes. Fabrication techniques that allow a preferred orientation of the crystals to exist will produce strongly anisotropic physical properties. Grade 2128 is isostatically molded to reduce the tendency for preferred orientation.

STACKPOLE 2128	MECHANICA PROPERTIES— GENERAL NOTES	Material Code EA01 Update Code 0.0.0

The mechanical properties of graphite are stress volume dependent. Because of the increased probability of finding a critical flaw, the fracture strength is lower in larger specimens. The greater the variability in strength, the greater the effect of increased stress volume in reducing strength. Also, tensile bars generally fail as a result of surface flaws. If the internal stress concentration component peaked internally at a value greater than twice that for the critical flaw size from a surface, the resistance to fracture would be greater. The increased stress volume of the tensile specimen mainly accounts for the reduced tensile strength compared to flexural strength. There is always about a 10% correction needed to correct the modulus of rupture fracture stress calculation to actual fracture stress resulting from redistribution of stress in flexure. This is caused by the nonlinear stress-strain relationship. In the case of multicouple components where the stress volume is small, the stress resistance will probably be higher than measured values; however, the failures would all be related to surface flaws. In the hot shoe, the major stresses are a result of restrained bending; therefore it would be more appropriate to consider the flexural properties as the more relevant values.

Graphite grade Stackpole 2128 is a molded grade with some degree of anisotropy. Therefore, the strength will be weaker in the molding direction than in a plane normal to the molding direction. The with-grain direction will be stronger and have rotational symmetry about the weaker against-grain direction (molding direction). The elastic constants will also have similar relationships.

The static, short-term mechanical properties of graphite are not time dependent until operational temperatures exceed 1600°C. There is some increased strength in extraordinarily high strain rates (impact); however, the increase is very grade dependent and cannot be approximated without test data.

STACKPOLE 2128	SHEAR STRENGTH	Material Code EA01 Update Code 0.0.0

Shear strength values are not available. However, they may be inferred from tensile and compressive strength values. Graphite fails by the principal stress criterion or a maximum shear stress criterion. The tensile properties define the maximum principal stress and the compressive strength defines the maximum shear strength. Thus, for pure shear or torsion the maximum value would either be equal to the tensile strength or one-half of the compressive strength, whichever is less. Generally, the tensile strength equals the shear strength.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	POISSON'S RATIO	Material Code EA01 Update Code 0.0.0

Poisson's Ratios were calculated from sonic measurements. The values are:

Ratio	Sample 1	Sample 2
$-S_{12}/S_{11}$	0.18	0.19
$-S_{13}/S_{11}$	0.13	0.13
$-S_{13}/S_{33}$	0.11	0.11

$-S_{12}/S_{11}$ The ratio of the against-grain direction strain to the with-grain direction strain of a specimen loaded in the with-grain direction.

$-S_{13}/S_{11}$ The ratio of the with-grain direction strain to the with-grain direction strain of a specimen loaded in the with-grain direction.

$-S_{13}/S_{33}$ The ratio of with-grain direction strain to the against-grain direction strain of a specimen loaded in the against-grain direction.

STACKPOLE 2128	ELASTIC STIFFNESS	Material Code EA01 Update Code 0.0.0

The single crystal values for graphite are generally not applicable for bulk graphites. The anisotropic elastic constants for graphite 2128 are as follows:

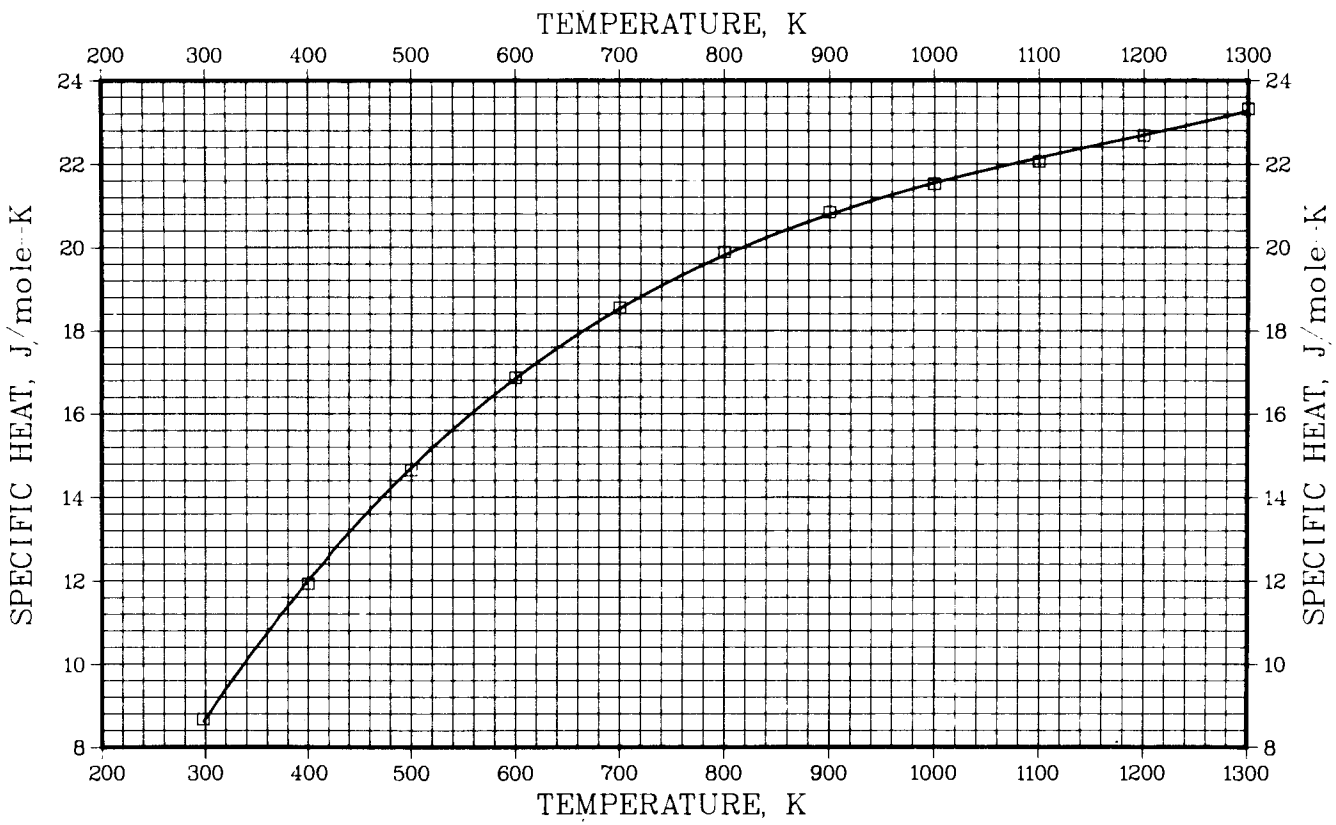
	Sample 1	Sample 2
S_{11}	$1.11 \times 10^{-10}\,Pa^{-1}$	$1.09 \times 10^{-10}\,Pa^{-1}$
S_{33}	$1.29 \times 10^{-10}\,Pa^{-1}$	$1.27 \times 10^{-10}\,Pa^{-1}$
S_{12}	$-2.00 \times 10^{-11}\,Pa^{-1}$	$-2.05 \times 10^{-11}\,Pa^{-1}$
S_{13}	$-1.65 \times 10^{-11}\,Pa^{-1}$	$-1.41 \times 10^{-11}\,Pa^{-1}$
S_{44}	$-2.68 \times 10^{-10}\,Pa^{-1}$	$-2.62 \times 10^{-10}\,Pa^{-1}$

ORNL-DWG 83-17513

PLOT 1 14.56.00 FRI 9 DEC, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	SPECIFIC HEAT	MATERIAL CODE: EA01
		UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3108 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	SPECIFIC HEAT	MATERIAL CODE: EA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	SPECIFIC HEAT	TEMPERATURE	SPECIFIC HEAT
KELVINS	J/mole–K	KELVINS	J/mole–K
298	8.50	298	8.50
300	8.67	400	11.93
350	10.43	500	14.65
400	12.01	600	16.87
450	13.43	700	18.55
500	14.71	800	19.89
550	15.85	900	20.85
600	16.86	1000	21.52
650	17.75	1100	22.06
700	18.53	1200	22.69
750	19.22	1300	23.32
800	19.82		
850	20.34		
900	20.79		
950	21.19		
1000	21.55		
1050	21.86		
1100	22.16		
1150	22.43		
1200	22.70		
1250	22.98		
1300	23.27		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$C_p = -5.97116 + 6.20556\times10^{-2}T - 4.82309\times10^{-5}T^2 + 1.36928\times10^{-8}T^3, \text{ where}$$

C_p = Specific Heat, J/mole–K, and
T = Temperature, $298 < T < 1300$ Kelvins.

The standard error of estimate of the fit was 7.1948×10^{-2} and the coefficient of determination was 0.9992.

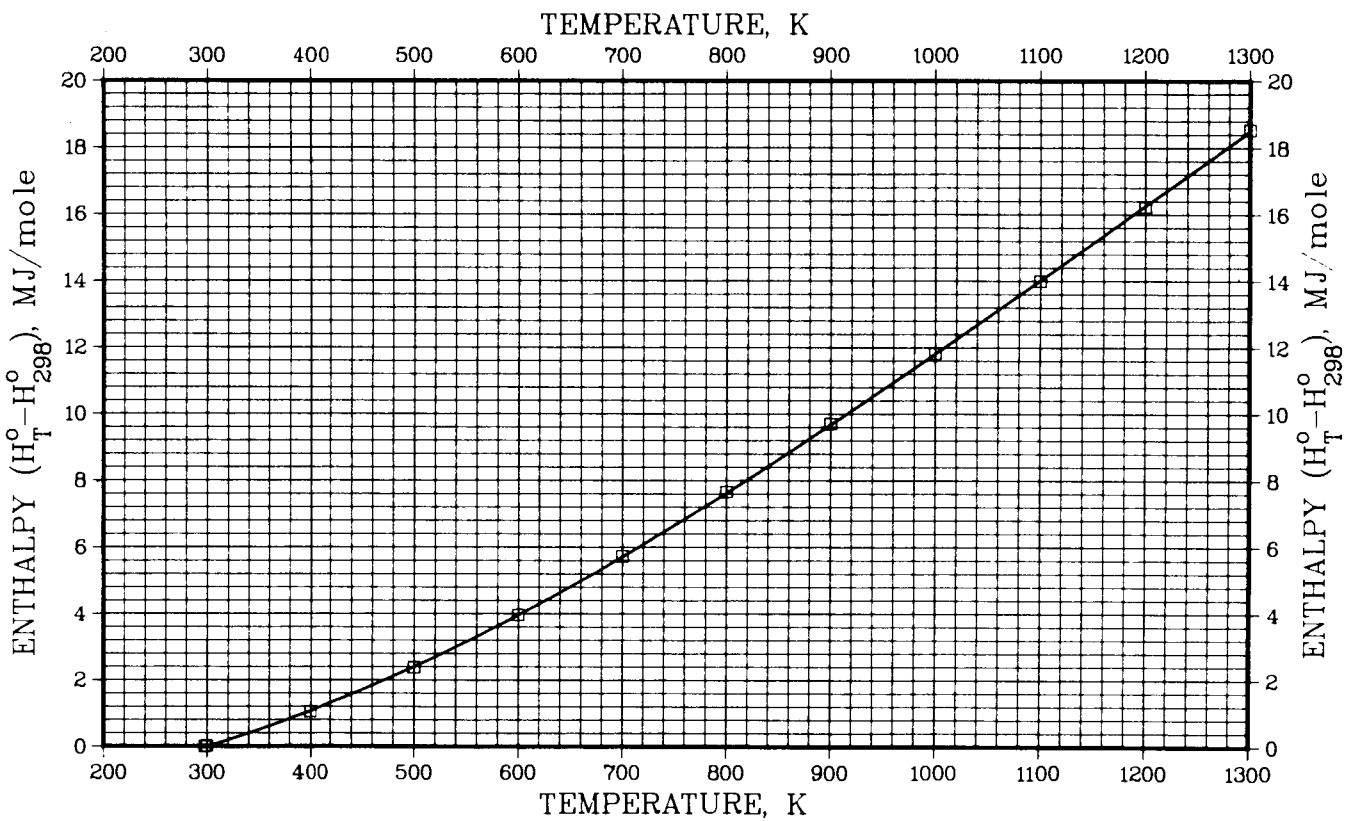
See Property Code 1000 for Special Notes.

ORNL-DWG 83-17511

PLOT 1 15.05.00 FRI 9 DEC, 1983 , ORNL DISSPLA VER 8.2

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	ENTHALPY	MATERIAL CODE: EA01
		UPDATE CODE: 0.0.0



See Property Code 1000 for Special Notes.
See Page 1.1 for a table of values and a correlation.

PROPERTY CODE 3109 PAGE 1.0

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	ENTHALPY	MATERIAL CODE: EA01
		UPDATE CODE: 0.0.0

CORRELATION VALUES		ORIGINAL VALUES	
TEMPERATURE	ENTHALPY	TEMPERATURE	ENTHALPY
K	MJ/mole	K	MJ/mole
298	-0.015	298	0.000
50	-1.341	300	0.017
100	-1.241	400	1.051
150	-1.053	500	2.382
200	-0.780	600	3.965
250	-0.426	700	5.736
300	0.004	800	7.662
350	0.507	900	9.705
400	1.078	1000	11.819
450	1.714	1100	14.001
500	2.411	1200	16.220
550	3.164	1300	18.539
600	3.969		
650	4.823		
700	5.722		
750	6.661		
800	7.636		
850	8.643		
900	9.679		
950	10.740		
1000	11.820		
1050	12.917		
1100	14.026		
1150	15.143		
1200	16.264		
1250	17.386		
1300	18.503		

The curve on Page 1.0 and the above "Correlation Values" were generated from a least squares fit of the "Original Values" shown above. The result of the fit was the following equation:

$$H^o = -1.34743 - 8.1963\times10^{-4}T + 1.93562\times10^{-5}T^2 - 5.36909\times10^{-9}T^3, \text{ where}$$

H^o = Enthalpy ($H^o_T - H^o_{298}$) MJ/mole, and

T = Temperature, K

The standard error of estimate of the fit was 3.0334×10^{-2} and the coefficient of determination was 0.99999.

See Property Code 1000 for Special Notes.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

STACKPOLE 2128	SPEED OF SOUND	Material Code EA01 Update Code 0.0.0

Longitudinal wave

	Sample 1	Sample 2
With grain	−2.38 km/s	2.41 km/s
Against grain	−2.18 km/s	2.20 km/s

Shear wave

	Sample 1	Sample 2
v_{66}	1.50 km/s	1.52 km/s
v_{44}	1.47 km/s	1.50 km/s

F. COMPOSITES

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

METAL/CERAMIC COMPOSITES	TABLE OF CONTENTS/MATERIALS	Material Code FAXX Update Code 0.0.0

Material Code	Material
FA01	Multifoil Insulation

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

MULTIFOIL[a] INSULATION	TABLE OF CONTENTS/PROPERTIES	Material Code FA01 Update Code 0.0.0

Property Code	Property	Pages
1000	General Information	1.0–1.1
1100	Composition:	*
	7.6 μm-thick Mo foil coated with ~0.1 gm/cm^2 particulate ZrO_2	
3112	Heat Transfer Characteristics: See Property Code 1000 for notes on the heat flow through this material.	*

[a]Trademark of the Thermo Electron Corp., Waltham, Mass.

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

MULTIFOIL[a] INSULATION	GENERAL INFORMATION	Material Code FA01 Update Code 0.0.0

Figure 1 gives a schematic representation of the Multifoil insulation and the heat transfer mechanisms involved. The insulating effect of various layers of this materials is represented in Fig. 2.

ORNL-DWG 83-17251

- CONVECTION–ZERO
- RADIATION–REDUCED BY MULTIPLE REFLECTING FOILS
- CONDUCTION–MINIMIZED DUE TO:
  1. SMALL FRACTION OF PARTICLES BRIDGE FOILS
  2. LOW THERMAL CONDUCTIVITY OF OXIDE PARTICLES
  3. HIGH PARTICLE-TO-FOIL CONTACT RESISTANCE
  4. OPTIMIZED PARTICLE SIZE AND AREAL DENSITY
  5. LOW THERMAL CONDUCTANCE IN PLANE OF FOIL

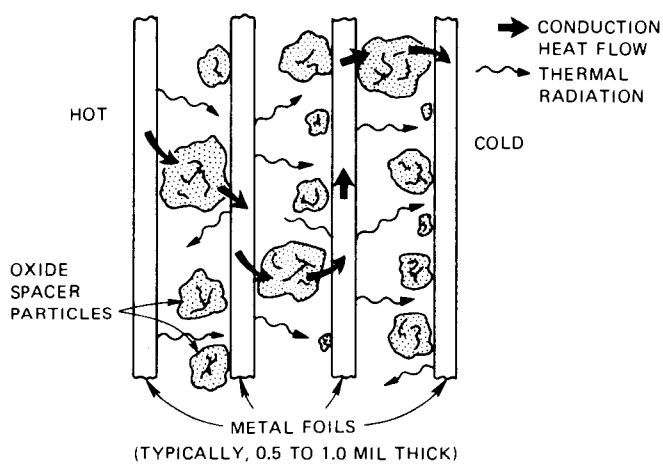


Fig. 1. Multifoil Heat Tranfer Mechanisms.

Trademark of the Thermo Electron Corp., Waltham, Mass.

*No separate pages are provided. The values are listed in the "Property" column of this Table of Contents.

MULTIFOIL[a] INSULATION	GENERAL INFORMATION	Material Code FA01 Update Code 0.0.0

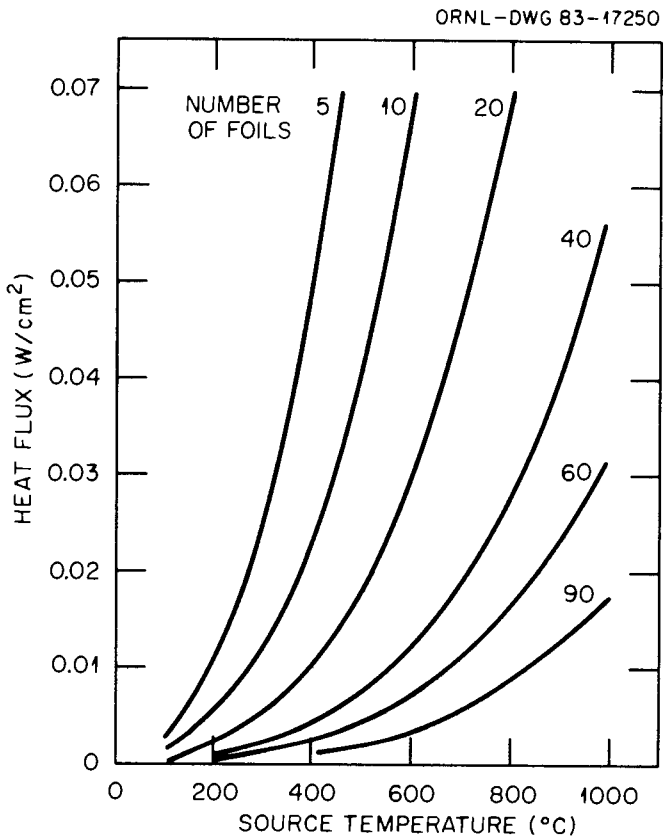


Fig. 2. Multifoil Heat Flux Calculated from Function Fit Expression.

[a]Trademark of the Thermo Electron Corp., Waltham, Mass.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

APPENDIX-CONTENTS	Update Code 0.0.0

		PAGES
APPENDIX A	HANDBOOK FORMAT-ORGANIZATION AND UPDATING	1–4
APPENDIX B	MATERIAL CODES	1–2
APPENDIX C	PROPERTY CODES AND DEFINITIONS	1–13

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	ORGANIZATION AND UPDATING	Update Code 0.0.0

PAGE FILING SYSTEM

The *Isotopic Space Power Materials Handbook* (ISPMH) is organized by material type. The ISPMH, a continuously revised document, currently contains data on only a fraction of the materials for which information will eventually be compiled. As new or revised information is obtained, it will be provided to all ISPMH recipients. Details on organization, procedures for revision and additions, and current contents follow.

Each page of materials properties information contains a uniform heading format at the top of the page identical to that shown in Fig. A.1. Figure A.1 is labeled with encircled letters to indicate the use of the various boxes and lines as explained.

PROPERTY CODE Ⓐ Page Ⓑ

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

Ⓒ	Ⓓ	Material Code Ⓔ Update Code Ⓕ

Fig. A.1. Illustration of page heading for ISPMH.

The ISPMH is organized by material type beginning with metals progressing through metalloids, ceramics, glasses, and nonmetals, and ending with composite materials. The indexing is "open ended," which allows for insertion of new pages without the necessity of renumbering current pages. This arrangement also makes it possible to keep grouped together pages treating identical or related materials. Materials are indexed by a Material Code that identifies Parts, Groups, and Sections; Parts and Groups are identified by tabbed dividers. To maintain a reasonable balance between the number of tabs and pages, tabs for the various Sections will not be provided initially. When the contents grow sufficiently in variety and size, Section tabs will be added to aid in locating specific materials. In the interim, each Section will be separated by the use of a colored (yellow) Table of Properties page (see Table of Contents below).

The Material Code contains both letters and numbers. Arrangement of pages by Material Code uses letters alphabetically as the primary ordering element and numbers as the secondary element. This scheme is shown in Appendix B, which lists all materials considered for inclusion in the ISPMH. In each materials Section, properties are placed in numerical order according to a "Property Code" number. A detailed explanation of the organization of the materials and properties follows:

Material Code ("E" in Fig. A.1)

Each material (to be spelled out in "C" of Fig. A.1) is cataloged by a four-character Material Code consisting of three identifying parameters as follows.

Parts—"Parts" refer to the first and most general material division, which is primarily by material type. Parts are divided in the ISPMH by a red tab. The Part Code is the first character of the Materials Code, for example:

Part A—Metals [red tab],
Part B—Metalloids [red tab],
Part F—Composites [red tab].

Groups—The second material division is by material "family," and is characterized by a common compositional trait. Groups are identified by a blue tab. The Group Code is the second character of the Material Code, for example:

Part A—Metals [red tab],
Group A—Tungsten Alloys [blue tab],
Group B—Aluminum Alloys [blue tab].

Sections—The last material division is by specific material or alloy. The last two characters of the Material Code are reserved for the Section Code, for example:

Part A—Metals [red tab],
Group A—Tungsten Alloys [blue tab],
Section 0A—Brazing Alloys,
Section 02—Sputtered Tungsten.

Thus the complete Material Code for sputtered Tungsten would be AA02 ("E" in Fig. A.1). Note that in the Section Code, letters are used to designate bonding materials, platings and coatings, while numbers designate structural and other materials.

Property Code ("A" in Fig. A.1)

The pages in each Section are arranged according to the property (to be spelled out in "D" of Fig. A.1) described on each page. Each property is identified in numerical order by a four-digit Property Code Number according to three parameters.

- **Property Type**—This is the most general division of properties, and the Property Code Number designation is by whole one-thousands, for example:
  2000—Mechanical Properties
  3000—Physical Properties

- **Property Family**—The second property subdivides the general division, and the Property Code Number designation is by whole one-hundreds, for example:
  2000—Mechanical Properties,
  2100—Static, Short-term Properties,
  2200—Static, Long-term Properties.

- **Specific Property**—The last property division is by specific property, which is identified by the last two digits of the Property Code Number, for example:
  2101—Ultimate Tensile Strength,
  2102—Yield Strength.

A tabulation of Property Codes and their definitions is found in Appendix C. It will be obvious that not all entries are true properties but rather terms that describe the behavior of a certain geometric shape.

Page Numbering ("B" in Fig. A.1)

The page numbering of pages containing technical information runs consecutively from 1.0–1.X or 2.0–2.X, etc., for each specific Property Code. The integer portion of the page number designates differences under the same Property Code. For example, the Property Code for elongation is 2105. Both *total* and *uniform* elongation may be covered. The first page for *total* elongation would be 1.0, the second page 1.1, etc. The first page for *uniform* elongation would be 2.0, the second page 2.1, etc. The page numbering of nontechnical pages such as Tables of Contents, Introductions, etc. generally follows the conventional style.

Update Packages

As previously mentioned, this handbook will be continuously updated with new or revised information. Each update package will be assigned a unique "Update Package Number" beginning at zero (0) with the initial issue and will increment consecutively (1, 2, . . .) thereafter.

Revision Control

A Revision Control page is located behind the green Revision Control tab in the front of this handbook. The Revision Control page will be replaced each time that a package of new and/or revised pages is issued. It will provide a cumulative listing of the Update Package Number and issue date associated with each Update Package.

Update Code ("F" in Fig. A.1)

The Update Code is a bi-decimal number in the form a.b.c and contains three specific items of information concerning the revision status of each page. The first number (a) is the Update Package Number for the package in which the page was issued. The second number (b) indicates the Revision Number or Version Number of the information contained for each property. This number will begin at zero (0) with the *first issue* of each *property,* regardless of the Update Package Number, and will be incremented only in cases where actual data or information changes have occured (that is, not for typographical corrections). The third number (c) indicates only typographical corrections or format changes. It will begin at zero and be incremented only in cases where typographical corrections or format changes are involved. It will be reset to zero each time the Revision Number (b) is incremented, i.e., each time there is an actual change in the data base.

Correlation Control Code

Each page in the Update Packages will contain a Code number on the lower right-hand corner. This number gives the Update Package number and the page sequence number of each page within that Update Package. This number will be used as guide for inserting each page of the Update Package in the correct location in the ISPMH.

Table of Contents

A Table of Contents listing all materials currently covered in the ISPMH is located behind the green tab labeled CONTENTS.

Table of Contents/Materials

A short Table of Contents is provided behind each blue tab at the beginning of each material Group listing all materials currently covered in that group.

Table of Contents/Properties

A table listing all properties currently covered is located at the beginning of each Materials Section. This page will be colored yellow as an aid in locating the various sections.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	MATERIAL CODES	Update Code 0.0.0

The following list shows how the materials to be covered in this handbook are placed in the various divisions (Part, Group, and Section) of the Material Code. The Material Code of each specific alloy or material is also listed.

Part–Group–Section Divisions

Part A — Metals	**Material Code**
Group A—Tungsten Alloys	
Section 0A—Brazing Alloys	AA0A
01—Wrought Tungsten	AA01
02—Sputtered Tungsten	AA02
03—CVD Tungsten	AA03
Group B—Aluminum Alloys	
Section 0A—Al-Ag Eutectic	AB0A
01—Alloy 1100	AB01
02—Alloy 7075	AB02
Group C—Titanium Alloys	
Section 0A—	
01—Titanium	AC01
Group D—Copper Alloys	
Section 0A—	
01—OFHC Copper	AD01
02—Dumet	AD02
Group E—Nickel Alloys	
Section A0—Nickel Plating	AEA0
Section 01—Alloy X-750	AE01
Group F—Silver Alloys	
Section 0A—INCUSIL 10	AF0A
0B—NICUSIL 3	AF0B
0C—CUSIL	AF0C
0D—PALCUSIL 15	AF0D
Group G—Gold Alloys	
Section 0A—NIORO*	AG0A

*Registered trademark of Western Gold and Platinum Company, 477 Harbor Blvd., Belmont, Calif., 94002.

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	MATERIAL CODES	Update Code 0.0.0

Part B—Metalloids

Group A—High-Silicon Metalloids

Section 0A—

01—N-type Si/Ge/GaP/P	BA01
02—P-type Si/Ge/GaP/B	BA02
03—SiMo N-type	BA03
04—SiMo P-type	BA04

Part C—Crystalline Ceramics

Group A—Nitrides

Section 01—Si_3N_4	CA01

Group B—Oxides

Section 01—Al_2O_3	CB01
Section 02—Astroquartz	CB02

Part D—Amorphous Ceramics and Glasses

Group A—Silicate glasses

Section 01—Low-temperature Glass	DA01
02—High-temperature Glass	DA02

Part E—Nonmetals

Group A—Graphites

Section 01—Stackpole 2128	EA01

Part F—Composites

Group A—Metal/Ceramic Composites

Section 01—Multifoil (Mo/ZrO_2)	FA01

Group B—Metalloid Composites

Section 01—SiMo/Ge Diffusion Bond	FB01

PROPERTY DESCRIPTIONS

The following pages describe the properties that may be addressed within the ISPMH. Property Codes are organized as follows.

1xxx — General Information
2xxx — Mechanical Properties
3xxx — Physical Properties
4xxx — Chemical/Nuclear Properties
5xxx — Friction/Wear/Self-Welding Behavior

1000 **GENERAL INFORMATION**—Information/data/characteristics that apply to all forms of the material and are not a function of property. Special notes may also be added here.

1100 **Chemical Composition/Stoichiometry/Crystal Structure**—These items are listed as needed, with primary emphasis on compositional ranges.

1200 **Product Forms/Applicable Specification**—A list of product forms of interest and the applicable specifications (ASTM, ASME, RDT, others).

1300 **Minimum Specified Properties**—The room temperature minimum properties as specified by the applicable specifications per product form (if minimum properties vary with product form).

2000 **MECHANICAL PROPERTIES**

2100 **Static, Short-term Properties**—Properties that do not exhibit a time dependence under nonimpact conditions. All properties listed as 21XX are obtained from uniaxial, monotonic loading.

2101 **Ultimate Tensile Strength**—The maximum tensile stress that a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the *original* cross-sectional area of the specimen. (Ref. ASTM E-6).

2102 **Yield Strength**—The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain. (Ref. ASTM E-6).

2103 **Proportional Elastic Limit**—The greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law). (Ref. ASTM E-6)

2104 **Shear Strength**—The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original dimensions of the cross section of the specimen. (Ref. ASTM E-6)

2105 **Elongation**—Total elongation is the increase in the gage length per unit length of the undeformed gage length, measured after fracture of the specimen within the gage length. Uniform elongation is the maximum increase in gage length that occurs before necking of the specimen begins. (See also ASTM E-6)

2106 **Reduction of Area**—The difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross section (measured at or after fracture) divided by the original cross-sectional area of the specimen. (Ref. ASTM E-6)

2107 **True Stress-Strain**—A curve or expression of true stress versus true strain. True strain is the natural logarithm of the ratio of the deformed length to the undeformed gage length. True stress is the applied force per unit of the deformed cross-sectional area at the moment of the force measurement.

2108 **Engineering Stress-Strain**—A curve or expression of engineering stress versus engineering strain. Engineering strain is the change per unit length of a linear dimension referred to the undeformed gage length. Engineering stress is the applied force per unit area of the undeformed cross section.

2109 **Hardness**—The resistance of a material to deformation, particularly permanent deformation, indentation, or scratching. There is no absolute scale for hardness; therefore, to express hardness quantitatively, each type of test has its own scale of arbitrarily defined hardness. See also the definition of indentation hardness defined in ASTM E-6.

2110 **Poisson's Ratio**—The ratio of transverse contraction of a strained specimen to its longitudinal elongation. See also ASTM E-6.

2111 **Young's Modulus (Modulus of Elasticity)**—The ratio of stress to corresponding strain below the proportional limit. (Ref. ASTM E-6) This value is obtained in tension or compression tests.

2112 **Shear Modulus (Modulus of Rigidity)**—The ratio of stress to corresponding strain below the proportional limit. (Ref. ASTM E-6) This value is obtained in shear or torsion tests.

2113 **Tangent Modulus**—The slope of the engineering stress-strain curve at any specified stress or strain. (Ref. ASTM E-6)

2114 **Bulk Modulus**—Ratio of stress to change in volume of a material subjected to axial loading. Related to Young's modulus (E) and Poisson's ratio (ν) by the following equation:

$$K = \frac{E\nu}{3(1 - 2\nu)} .$$

2115 **Rupture Modulus**—Nominal elastically calculated maximum stress at fracture in a bend test or torsion test. In bending, it is the bending moment at fracture divided by the section modulus. In torsion, it is the torque at fracture divided by the polar section modulus. See ASTM E-6 for further notes on modulus of rupture in bending and modulus of rupture in torsion.

2116 **Compressive Strength**—The maximum compressive stress that a material is capable of sustaining. It is calculated from the maximum load during a compression test and the undeformed cross-sectional area of the specimen. (Ref. ASTM E-6)

2117 **Bending Strength**—Also called flexural strength. Maximum fiber stress developed in a specimen just before it cracks or breaks in a flexure test.

2118 **Fracture Stress**—True stress generated in a material at fracture.

2119 **Vicat Softening Point (ASTM D1525)**—A test of the heat softening characteristics of a material.

2120 **Taber Abrasion (ASTM D1044)**—Resistance of a material to abrasion.

2121 **Elastic Stiffness**—A measure of the dimensional change of a material along crystallographic planes, generally a change in length.

2122 **Isothermal Compressibility**—Reciprocal of Bulk Modulus.

2200 **Static, Long-term Properties**—Properties that exhibit a time dependence effect under nonimpact conditions.

2201 **Effects of Prior Creep on Tensile Ductility**—Total elongation measured in a tensile test on materials subjected to some specified amount of prior creep service.

2202 **Stress-Rupture Strength**—The stress that will cause fracture in a creep test in a specified time and environment. (Ref. ASTM E-6)

2203 **Burst Pressure (Biaxial)**—The pressure at which a tube material bursts or allows gas leakage when subjected to internal pressurization.

2204 **Uniform ΔD/D (Biaxial)**—The net increase in tube diameter per unit length of the undeformed diameter under burst pressure testing, measured away from the failure area (far enough so that effects of rupture are not included).

2205 **Time to Tertiary Creep**—For a given stress and environment, the time measured from the initiation of the loading to the onset of the departure from secondary creep. Methods used to determine the onset of departure must be defined with the relationship because there are no universally accepted methods at this time.

2206 **Creep**—Strain occurring under given constant load expressed as a function of time and environment. This Property Code generally includes a creep equation depicting the strain–time–temperature–stress relationship; however, expressions for minimum creep rate may also be included.

2207 **Stress Relaxation**—The time-dependent decrease in stress in a constrained specimen at a constant temperature. (Ref. ASTM E-6)

2208 **Strain at Fracture**—The strain at failure for constant load-temperature conditions, expressed as reduction of area and/or percent elongation.

2209 **Isochronous Stress-Strain Curve**—A curve of applied stress versus total strain for fixed times, for example, the locus of total strains accumulated when different constant stresses are applied for a fixed time. These curves may be generated through use of the stress-strain relationship (2108) and the creep equation (2206), or by other graphical means.

HANDBOOK FORMAT	PROPERTY CODES	Update Code 0.0.0

2300 **Dynamic, Short-term Properties**—Properties characteristic of high-rate loading conditions.

2301 **Strain Rate Effects**—The effects of controlled strain rate in loading on the stress-strain characteristics. Strain rate effects may be depicted for a number of tensile properties within this single Property Code Number.

2302 **Impact Strength**—Energy required to fracture a specimen subjected to shock loading, as in an impact test. It is an indication of the toughness of the material and is reported as energy absorbed or lateral expansion versus test temperature.

2303 **Ductile-to-Brittle Transition Temperature**—The temperature, determined in a series of impact tests at decreasing temperatures, at which metals undergo a transition from ductile to brittle behavior.

2304 **Thermal Shock Resistance**—The ability of a material to withstand high stresses resulting from the development of a steep temperature gradient in the material. Conditions under which the property is measured must be specified.

2305 **Coefficient of Restitution**—A coefficient that expresses the degree to which a pair of colliding bodies approach perfect elasticity. It is the negative ratio of the relative velocity after collision to the relative velocity before collision.

2306 **Toughness for Tensile Instability**—The area under an engineering stress-strain curve out to the departure from uniform elongation, from a uniaxial tensile test.

2307 **Transient Burst Strength**—The strength exhibited by a tubular product subjected to rapid application of internal pressure.

2308 **Transient Burst Ductility**—The relative increase in tube diameter during rapid burst pressure testing, measured away from the failure area (far enough away so that effects of rupture are not included).

2400 Cyclic Loading Properties

2401 **Strain-Controlled Fatigue for T < 427°C**—Included within this category will be expressions of cycles to failure as a function of axial strain range. Cycles to failure may be the total cycles to specimen separation, N_f; or cycles at which the load carrying capacity drops 5%, N_5; or that point of initiation, a crack of a given length, N_0. Strain range may be expressed as total or plastic strain.

2402 **Strain-Controlled Fatigue for T > 427°C**—See description above for 2401.

2403–2410 **Other Strain-Controlled Fatigue Properties**—These Property Codes and Definitions are provided as needed and currently include the following.

2405 **Creep-Fatigue**—Materials behavior under combined creep and fatigue loading conditions that involve complex interactions among stress, time, temperature, and environment.

2411–2420 **Stress-Controlled Fatigue**—Data presented within this category describe the behavior of materials cycled between two load levels or stress levels. This is typically referred to as high cycle fatigue. The most common representation is a plot of cycles to failure versus applied load. (Individual Property Codes and Definitions within this general category will be provided at a later date.)

2421–2430 **Cyclic Stress-Strain Properties**—Mechanical properties associated with representing the stress-strain response of the material as it is cycled between fixed strain limits. The independent variables include the strain range, temperature, and material. The properties data are those required to implement inelastic analysis guidelines. The properties and their physical interpretation differ for various materials. These differences result from characteristic trends of cyclic hardening and softening and are identified within recommended inelastic analysis equations or specific materials.

2421 **Cyclic Yield Strengths**—Discrete monotonic and cyclic yield strengths, σ_0, σ_1, σ_2, versus strain range from bilinear σ-ϵ representations.

2422 **Cyclic Yield Parameters**—Discrete monotonic and cyclic yield parameter κ_0, κ_1, κ_2, versus strain range from bilinear representations of cyclic stress-strain curves.

2423 **Plastic Modulus and Slope Parameter**—Plastic modulus E_p and slope parameter C versus strain range from bilinear stress-strain representations.

2424 **Cyclic Stress-Strain Curves**—Plots of and equations for nonlinear cyclic stress-strain curves.

2431–2440 **Fracture Mechanics Parameters**—Parameters that consider noncontinuity and nonhomogeneity and provide a quantitative method for estimating the effects of minute cracks in materials. The parameters are: (1) a toughness (energy-absorption) factor, (2) applied stress, (3) size of crack, (4) operating temperature, (5) crack growth rate data and the "state of stress," and (6) hold time.

2431 **Fatigue Crack Growth Rate (ASTM E616), da/dN, [L]**—The rate of crack extension caused by constant-amplitude fatigue loading, expressed in terms of crack extension per cycle of fatigue.

2432 **Fracture Toughness (ASTM E616)**—The measurement of the resistance of a material to crack extension.

2500 **Viscoelastic Properties**—Properties of elastic materials having time-dependent viscous effects. The following Property Codes are limited to plastics or polymers.

2501 **Flexural Strength (ASTM D790)**—The loading (bending) at failure of a stressed beam, or stress at 5% strain.

2502 **Flexural Modulus (ASTM D747)**—"Stiffness in flexure," a measure of the relative stiffness.

2503 **Breaking Elongation (ASTM D638)**—Elongation at fracture in tensile loading.

2504 **Deformation Under Load (ASTM D621)**—Ability of a material to withstand continuous short-term compression without yielding and loosening at temperature.

2505 **Axial Fatigue Endurance Limit (ASTM E466-76)**—Relative endurance of a material to withstand a repetitive axial bending stress.

2506 **Flexural Fatigue Endurance Limit (ASTM D671-71)**—Ability of a material to withstand a repetitive cantilever-type bending stress.

2507 **Flexural Strain (ASTM D790-71)**—The maximum strain occurring in the outer fibers at the failure of a material subjected to beam-type flexural stress.

2508 **Viscoelastic Creep (ASTM D2990-77)**—Strain occurring under a given constant load expressed as a function of time and environment—limited to polymeric materials that exhibit viscoelastic properties.

2509 **Static Modulus (Elastomer) (ASTM D412-75)**—The tensile stress of an elastomeric material required to produce a specified ultimate elongation (often specified as 100 to 200% modulus).

2510 **Deflection Temperature (ASTM D648-72)**—Temperature at which a polymeric material exceeds a specified deflection when a specified beam loading stress is applied.

2511 **Heat Aging (ASTM D573-67)**—Deterioration of an elastomeric material when exposed to a specified time and temperature in an air oven.

2512 **Compression Set (ASTM D395-69)**—The failure of an elastomeric material to recover original thickness after sustained compressive stress.

3000 **PHYSICAL PROPERTIES**—Properties related to the physical/chemical nature of materials.

3100 **Thermal Properties**—Properties defined in terms of temperature or heat quantities.

3101 **Maximum Service Temperature**—The maximum temperature at which a material will perform its intended function for a specified period of time. (Failure criteria must be described in every case.)

3102 **Healing Temperature**—The temperature at which a specified property or condition will revert to its original value or state. (Special tests and/or definitions may be required for some materials.)

3103 **Melting Point**—The temperature at which melting begins, described as the solidus and/or liquidus temperature.

3104 **Heat of Fusion**—The quantity of heat absorbed or liberated in the change from solid to liquid or liquid to solid.

3105 **Boiling Point**—The temperature at which a liquid boils.

3106 **Heat of Vaporization**—The quantity of heat absorbed or liberated in the change from liquid to vapor or vapor to liquid.

3107 **Flammability**—The susceptibility of a material to burn, as determined by any specified test. (Primarily devoted to plastics.)

3108 **Specific Heat Capacity**—The amount of heat per unit mass necessary to produce a unit increase in temperature.

3109 **Enthalpy**—The sum of the internal energy and the product of the specific volume and the pressure.

3110 **Thermal Diffusivity**—The thermal conductivity divided by the product of density and heat capacity.

3111 **Thermal Emissivity**—A quantity lying between zero and unity, depending on the nature of the material surface. It is the ratio of the radiating power of a nonblack body to that of a black body. The quantity is used to calculate the rate of emission of radiant energy.

3112 **Thermal Conductivity**—The calculation of transfer of heat by conduction, through unit thickness, across unit area for unit difference in temperature.

3113 **Prandtl Number**—A dimensionless number related to the ratio of momentum diffusivity divided by thermal diffusivity. The Prandtl number is the product of specific heat and viscosity divided by thermal conductivity.

3114 **Thermal Expansion**—Change in length with rise in temperature.

3115 **Entropy**—A quantity depending on the quantity of heat in a body and on its temperature, which, when multiplied by any lower temperature, gives the unavailable energy, or unavoidable waste, when mechanical work is derived from the heat energy of the body.

3116 **Free Energy of Formation**—The change in free energy when a compound at standard conditions is formed from the elements of the same standard condition.

3117 **Heat of Formation**—The heat of reaction when a compound at standard conditions is formed from the element at the same standard conditions.

3118 **Free Energy Function**—Free energy is the sum of enthalpy (H) minus the product of temperature (T) and enthalpy (S).

3119 **Heat of Sublimation**—The net heat change when a material is transformed from a solid to a vapor without forming a liquid phase.

3120 **Thermal Stability**—The observed or measured effect of exposure to elevated temperature.

HANDBOOK FORMAT	PROPERTY CODES	Update Code 0.0.0

3200 Electrical/Magnetic Properties

3201 **Electrical Resistivity**—The reciprocal of the conductivity of a material. The conductivity of a material is the electric current density per unit potential gradient in an isothermal system.

3202 **Dielectric Strength**—The maximum electric intensity that a dielectric material can withstand without breakdown.

3203 **Dielectric Coefficient**—A number that describes the ability of a dielectric material to neutralize the electrical charge across parallel conducting plates.

3204 **Dissipation Factor (ASTM D150)**—The tangent of the loss angle or the cotangent of the phase angle.

3205 **Magnetic Permeability**—A magnetic constant used to determine the flux density within a material.

3206 **Arc Resistance (ASTM D495)**—The resistance to the formation of a conducting path through a material as determined by a specific test method.

3207 **Seebeck Potential**—The electrical potential resulting from dissimilar metal junctions at different temperatures.

3300

Other Physical Properties

3301 **Viscosity**—A number that indicates the resistance of a fluid to flow.

3302 **Surface Tension**—Two fluids in contact exhibit phenomena because of molecular attractions that appear to rise from a tension in the surface of separation.

3303 **Vapor Pressure**—The pressure at which a liquid and its vapor can exist in equilibrium at a given temperature.

3304 **Density**—Mass per unit volume.

3305 **Porosity**—The amount of connected and unconnected pores contained in a material.

3306 **Speed of Sound**—The magnitude of the velocity of sound transmission in a material.

3307 **Isothermal Compressibility**—The fractional increase in volume per unit increase in pressure at constant temperature.

$$\beta_t = \left(\frac{-1}{v}\right)\left(\frac{dv}{dp_T}\right)$$

3308 **Reflectance (ASTM E429)**—The ratio of reflected to incident radiation.

3309 **Water Vapor Permeability (ASTM E398)**—The rate of transfer of water vapor through a barrier material.

3310 **Water Absorption (ASTM D570)**—The rate of absorption of water by material when immersed.

3311 **Gas Permeability (ASTM D1434)**—The steady-state rate of transmission of a gas through a material in the form of film, sheeting, and laminates.

3312 **Weathering**

3313 **Wetting Characteristics**

3314 **Permeability**—The steady-state rate of transmission of a liquid or gas through a material.

3315 **Critical Constant**—The temperature above which a substance cannot exist in two phases, no matter how great the pressure.

3316 **Critical Temperature**—That temperature above which a gas cannot be liquified by pressure alone.

3317 **Critical Pressure**—The pressure under which a substance may exist as a gas in equilibrium with the liquid at the critical temperature.

4000 CHEMICAL/NUCLEAR PROPERTIES (Including Effects of Impurities)

4100 **Compatibility (Surface Reactions)**—A description of the surface effect of materials that undergo reactions with the following (list types of effects: roughness, protective film, etc.).

4101 **Reactions with liquid. Na, NaK, or caustic**

4102 **Reactions with gases**

4103 **Reaction with aqueous media**

4104 **Reactions with organics**

4105 **Reactions with fuel and fission or transmutation products**

4106 **Reactions with plasma**

4107 **Reactions with other substances**

HANDBOOK FORMAT	PROPERTY CODES	Update Code 0.0.0

4200 Metallurgical and Other Material Properties

4201 Time-Temperature Transformations—Transformation diagrams that describe the microstructural changes of a material in terms of time and temperature.

4202 Diffusion Characteristics—Description of the diffusion process in a material or system under specified conditions including chemical gradients, temperature gradients, microstructure of base material, and system impurities.

4203 Recrystallization Temperature—The approximate minimum temperature at which complete recrystallization of a cold-worked metal occurs within a specified time.

4204 Grain Growth—A description of the change in size of grains in polycrystalline metal, usually occurring during heating at elevated temperatures.

4205 Glass Transition Temperature (ASTM D747-64)—Temperature or temperature range for the change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.

4206 Oxygen Redistribution—The redistribution of oxygen or oxygen vacancies in metal oxide compounds.

4207 Grain Size

4300 Nuclear Properties

4301 Cross Section—The average number of individual processes occurring per target nucleus per incident neutron.

4302 Burnup—The proportion of the total material that is consumed before the reactor must be shut down for recharging (average and peak).

4303 Energy/Event—Total energy released per fission or fusion which ultimately appears as heat in a defined reactor system.

4304 Attenuation—An expression describing the decrease in the rate, amount, or energy of a substance as it penetrates another.

4305 Gas Generation—A description of the gases created within a substance during irradiation.

4306 Other

ISOTOPIC SPACE POWER MATERIALS HANDBOOK

HANDBOOK FORMAT	PROPERTY CODES	Update Code 0.0.0

5000 **TRIBOLOGICAL BEHAVIOR**—The friction and wear behavior of a material considering key parameters such as pressure of contact, surface roughness, substrate properties for coatings, and impurities in coolant in the following situations.

5100 **Liquid Metal Service**

- 5101 **In contact with itself**
- 5102 **In contact with other materials**

5200 **Inert Gas Service**

- 5201 **In contact with itself**
- 5202 **In contact with other materials**
- 5203 **Endurance life**
- 5204 **Load-carrying capacity**
- 5205 **Coefficient of friction**
- 5206 **Wear life vs load**
- 5207 **High-temperature performance**

5300 **Air Service**

- 5301 **In contact with itself**
- 5302 **In contact with other materials**
- 5303 **Endurance life**
- 5304 **Load-carrying capacity**
- 5305 **Coefficient of friction**
- 5306 **Wear life vs load**
- 5307 **High-temperature performance**

5400 **Other Media**

- 5401 **In contact with itself**
- 5402 **In contact with other materials**

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