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TEMPERATURE DEPENDENT PROPERTIES OF POTTING MATERIALS (REV.)

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DISCLAIMER

TEMPERATURE DEPENDENT PROPERTIES OF POTTING MATERIALS (REV.)

BDX-613-1519, UNCLASSIFIED Final Report, Published April 1976

Prepared by J. M. Walker, D/814, under PDO 6984803

The physical properties: mechanical, electrical, and thermal of a general purpose epoxy potting compound, filled with either glass microspheres, aluminum oxide or beta-eucryptite and catalyzed with either an aliphatic amine, a liquid aromatic amine eutectic blend, or a liquid anhydride are discussed. The properties of a CTBN modified epoxy are also included. Twelve formulation-cure cycle combinations were chosen for evaluation. The temperature dependent properties from -65° to 400°F (-54° to 204°C) for the 12 combinations are given.

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SUMMARY

An expansion of available physical properties data for potting materials has been necessitated by increasingly stringent temperature requirements and the need for data to be used in computer modeling of stress patterns and nuclear safety investigations associated with some electrical assemblies. A chart based on Bendix Kansas City supplied room temperature data is available (A. J. Quant and C. W. Hatcher, *Encapsulating Resins Properties Chart*, Sandia Corporation Albuquerque, May 1971), but knowledge of material behavior throughout the temperature range is based primarily on past experience and speculation.

Twelve formulation-cure cycle combinations were chosen for evaluation. Only three of the twelve are frequently used in production applications. Another three combine these commonly used formulations with alternate cure schedules designed to maximize the effect of cure on physical properties. The remaining combinations contain either new materials or materials not previously considered for use in encapsulants. They were selected for desirable physical properties such as low coefficients of thermal expansion and high mechanical stress and thermal shock resistance.

The physical properties of these materials: thermal, mechanical, and electrical, were obtained at various temperatures between -65° and 400°F (-54° and 204°C).

It had been anticipated that new room temperature data could be compared with data previously charted. However, many of the values obtained from electrical testing were related to fluid medium, test specimen configuration, or a particular piece of equipment, and could not be correlated.

The best overall agreement between the current room temperature data and that previously obtained exists for an epoxy-glass microspheres (GMB) material using either diethanolamine or Epon Z as a catalyst, despite a difference in GMB source and formulation. The aluminum oxide filled encapsulant had lower mechanical properties at room temperature than were previously charted. Some of the electrical properties were also different.

The remaining materials had not been previously tested at any temperature so no comparisons were available. As a whole, this testing provides a foundation for future testing and comparison of encapsulants.

DISCUSSION

SCOPE AND PURPOSE

This work was done under PDO 6984803, High and Low Temperature Properties of Potting Materials. The objective was to determine the physical properties: mechanical, electrical, and thermal of various potting materials at discrete temperature points in the range of -65 to 400°F (-54 to 204°C) for use in computer models involving stress and nuclear safety investigations associated with several kinds of electrical assemblies. The investigation included the use of high temperature postcures in addition to standard cure cycles to determine their effect on the physical properties.

ACTIVITY

Selection of Materials and Cure Schedules

A variety of resin-filler-catalyst combinations are used for encapsulating electronic assemblies. The encapsulants chosen for this evaluation included the most frequently used formulations in combination with additional postcures at elevated temperatures as well as some recent developments in the field of filled encapsulants. A list of these materials, their formulations and cure schedules is given in Table 1. Only the beta-eucryptite filler and the CTBN (carboxyl terminated butadiene acrylonitrile) copolymer modifier are new, but the anhydride curing agent has not been used previously for filled encapsulants. The physical properties tested and the temperatures used for testing are shown in Tables 2 and 3.

Beta-eucryptite was chosen because of its negative coefficient of thermal expansion, the CTBN as a modifier for epoxy because of its ability to improve the thermal and mechanical shock resistance of an encapsulant, and the anhydride curing agent because of its excellent high temperature capabilities and ease of handling. High temperature postcures were used in addition to the standard cures to determine and maximize the effect of cure on physical properties. Evaluation of a silica filled epoxy was originally considered, but testing was discontinued when it became apparent that void free castings deeper than one inch (25.4 mm) were difficult to obtain using the existing formulation.

Equipment Changes and Test Methods

It was difficult to duplicate the results and even some of the tests that were used to prepare the original Quant and Hatcher chart (A. J. Quant and C. W. Hatcher, *Encapsulating Resins Properties Chart*, Sandia Corporation Albuquerque, May 1971). This was particularly true of the electrical properties. Initially,

Table 1. Material Formulas and Cure Schedules

Material	Formula (pbw)	Time (Hours)	Temperature (°F)	(°C)
GMB	25	24	150	66
Epoxy	75			
DEA	9			
GMB	25	4	R.T.	R.T.
Epoxy	75	4	130	54
Epon Z*	15	16	200	93
GMB	25	4	R.T.	R.T.
Epoxy	75	4	130	54
Epon Z	15	16	200	93
		4	300	149
Al_2O_3	300	4	130	54
Epoxy	100	16	200	93
Epon Z	20			
Al_2O_3	300	4	130	54
Epoxy	100	16	200	93
Epon Z	20	4	300	149
Al_2O_3	300	4	130	54
Epoxy	100	16	200	93
Epon Z	20	4	300	149
		4	400	204
Al_2O_3	500	8	200	93
Epoxy	100	24	300	149
NMA	90			
DMP-30**	1			
Al_2O_3	500	8	200	93
Epoxy	100	24	300	149
NMA	90	24	400	204
DMP-30	1			
Beta-Eucryptite***	85	24	150	66
Epoxy	100			
DEA	12			
Beta-Eucryptite	185	4	130	54
Epoxy	100	16	200	93
Epon Z	20			

Table 1 Continued. Material Formulas and Cure Schedules

Material	Formula (pbw)	Time (Hours)	Temperature (°F)	(°C)
GMB	25	24	150	66
Hycar CTBN 1300 X 8****	7.5			
Epoxy	67.5			
DEA	12			
GMB	25	4	R.T.	R.T.
Hycar CTBN 1300 X 8	7.5	4	130	54
Epoxy	67.5	16	200	93
Epon Z	15			

*Shell Chemical Company
**Rohm & Haas
***Foote Mineral Company
****B. F. Goodrich Chemical Company

the testing of dielectric constant and dissipation factor was done on a 2.0-inch (50.8 mm) diameter disc, 0.125 inch (3.18 mm) thick. However, the fixturing and test method were such that it was difficult to maintain the various test temperatures during testing. As a result, a two fluid method using a Balsbaugh test cell was employed. With this method the specimen thickness was not critical, the test procedure was faster, and four-place accuracy was possible. The only drawback was a lack of test capability at 10 megahertz. The technique is satisfactory and all subsequent tests were made using the Balsbaugh test cell.

A problem involving the dielectric strength data also arose. The fluid medium used in this test has been changed from Monsanto's Intertine to Dow Corning's DC200 because of the hazards of using chlorinated biphenyls. This has affected the test results since, according to ASTM D149, the values obtained are related to the fluid medium and cannot be interpolated. In general, the room temperature values were significantly lower than those previously obtained and may be considered representative of the whole group of values at the various temperatures. Dielectric strength values were obtained using the short time test method with one inch diameter electrodes and a 500 volt per second rise rate.

Table 2. Properties Evaluated

Property Tested	Test	Specification
Mechanical	Tensile	ASTM* D638
	Compressive	ASTM D695
	Flexural	ASTM D790
Electrical	Volume Resistivity	ASTM D257
	Dielectric Constant	ASTM D150
	Dissipation Factor	ASTM D150
	Dielectric Strength	ASTM D149
Thermal	Thermal Expansion	ASTM D696
	Heat Distortion Temperature	ASTM D648
Specific Gravity		
Glass Transition Temperature		

*American Society for Testing and Materials

Volume resistivity measurements were made using a direct method and a 60 second electrification time coupled with an applied direct voltage of 500 volts.

Specimen Preparation

In previous testing at Bendix all test specimens were machined from large blocks. Machining each specimen is both time consuming and expensive, especially since the more abrasive fillers, such as aluminum oxide, require diamond tipped cutting tools. In order to reduce machining costs many of the specimens have been molded to size and then machined to remove the meniscus and obtain the desired thickness. The combination of molding and machining has an added advantage in that this duplicates production procedures. At first only the tensile, volume resistivity, and thermal expansion specimens were molded. However, molding proved so successful that after October, 1973, the dielectric constant-dissipation factor specimens were also molded. Specimen configurations are given in Table 4.

The differences between values obtained from machined versus molded specimens have not been studied specifically but a dramatic

Table 3. Test Temperatures

Class	Material	Temperatures Tested
A	DEA Catalyzed Filled Epoxy	-65°F (-54°C), -40°F (-40°), 0°F (-17.8°), R.T., 165°F (74°C), 250°F (121°C)
B	Epon Z Catalyzed Filled Epoxy	-65°F (-54°C), -40°F (40°C), 0°F (17.8°C), R.T., 165°F (74°C), 200°F (93°C), 300°F (149°C), 400°F (204°C)
B	Nadic Methyl Anhydride* (NMA) Catalyzed Filled Epoxy	-65°F (-54°C), -40°F (-40°C), 0°F (-17.8°C), R.T., 165°F (74°C), 200°F (93°C), 300°F (149°C), 400°F (204°C)

*Allied Chemical Company

difference is not anticipated. Some overall variation in the mechanical properties data has been observed but this deviation occurs in both molded specimens and those cut from slabs.

GMB from the 3M Company were used in all formulations involving glass microspheres because 3M's Type B40A are replacing Emerson & Cuming GMB in most production applications. The new formulation is 75 parts resin to 25 parts filler compared to 70 parts resin and 30 parts GMB for the original formulation. The epoxy resin used throughout this study was Epon 828 from the Shell Chemical Company.

Although the mechanical properties data were obtained by testing at discrete temperatures, an approximation of the ultimate stress and elastic modulus at any temperature can be obtained by plotting the existing values as a function of temperature. Semi-logarithmic plots of maximum stress as a function of temperature have been included in Appendix A of this report. Also, in order to expand the usefulness of the thermal expansion coefficient, charts of linear thermal expansion in percent, as a function of temperature, have been included in Appendix B.

An evaluation of thermal shock behavior had originally been included in the thermal properties testing. Two techniques, the SCR-173 Nut and Bolt and the SCR-417 Hollow Cylinder were chosen

Table 4. Specimen Configuration

Test	Test Specimen Configuration	Standard Test Specimen Number*
Mechanical		
Tensile	Dog bone	196B
Compressive	1 by 0.5 by 0.5 inch**	5
Flexural	6 by 0.5 by 0.25 inch	40F
Electrical		
Dielectric Constant	3.25 by 3.25 by 0.125 inch	
Dissipation Factor	3.25 by 3.25 by 0.125 inch	
Dielectric Strength	4 inch dia. by 0.125 inch	245
Volume Resistivity	4 inch dia. by 0.125 inch	245
Thermal		
Thermal Expansion	0.485 inch dia. by 2 inches	240A
Heat Distortion Temperature	5 by 0.5 by 0.5 inch	50
Glass Transition Temperature	0.25 by 0.25 by 0.25 inch	
Density	1 by 0.5 by 0.5 inch	

*Standard Test Specimens, SC-4540C (M), Standard Division - 2221, Sandia Laboratories
**1 inch equals 25.4 mm

as the test specimen configurations. However, it was not possible to obtain the proper hardware for the "nut and bolt" test and the hollow cylinder method was found to be dependent on pour depth.

Additional investigation of potential thermal shock tests suited for low density and other filled encapsulants was equally unsuccessful so this test was discontinued (J. M. Walker, *Low Density Epoxy Encapsulant* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1411, September 1975, pp 36-38).

Because of the volume of data generated by this project it would be difficult, if not impossible, to analyze and compare each specific bit of information. Consequently, the physical properties data are included in tabular form in Appendix C without individual analysis. However, there are some general conclusions that can be drawn from the test results. These conclusions can be subdivided into three categories covering the effects of the catalyst, the postcure, and the filler on the behavior of the encapsulant. The three catalysts can be compared primarily with regard to thermal behavior. As expected, diethanolamine (DEA) had the poorest heat resistance. The low heat distortion and glass transition temperatures are reflected in the flexural behavior at 165°F (74°C) and in the coefficient of thermal expansion. At 165°F (74°C) the flexural specimens deflected to the maximum of the equipment [1.5 inches (3.8 cm)] but did not break. At this same point the coefficient of thermal expansion essentially doubles. Both changes indicate that a substantial alteration in material behavior has taken place. A similar transition in flexural behavior occurs for the standard cured Epon Z catalyzed resin and all cures of the Epon Z and NMA/DMP-30 catalyzed resin systems show a change in thermal expansion properties but at a much higher temperature. These results validate the restrictions placed on the use of diethanolamine catalyzed resins at elevated temperatures and confirms the use of Epon Z as a curing agent when higher heat resistance is required. Even though we traditionally cure Epon Z catalyzed encapsulants about 50°F (28°C) below the manufacturers recommended cure temperature in order to accommodate thermally sensitive electronic components, the heat distortion temperature of the standard cured Epon Z catalyzed encapsulant is still about 80°F (45°C) higher than that of the DEA catalyzed resin system. The NMA/DMP-30 catalyzed material had an even higher heat distortion temperature but it requires a 300°F (149°C) cure. This would be a major drawback when encapsulating the more sensitive electronic components. Whatever the resin-catalyst combination happens to be, it is desirable, if not imperative, that the glass transition point (Tg), which corresponds to the heat distortion temperature, be above the ultimate use temperature of the encapsulant. This insures the maximum amount of continuity in the physical properties.

Several high temperature postcures were used in addition to the standard cures to determine and maximize the effect of cure on physical properties. It was anticipated that the data would provide a clear indication of postcure that could be translated into a few specific statements. Unfortunately, the data was sufficiently erratic that few absolute conclusions could be reached. In general, the values varied as much from sample to sample as they did from postcure to postcure. Exposed surfaces of the postcured parts were discolored during the postcure but these areas were removed during machining and had no effect on the results. One area that did show the influence of postcure was linear thermal expansion (Appendix B). For example, the transition point of the NMA/DMP-30 catalyzed encapsulant was shifted from approximately 275°F (135°C) to around 320°F (160°C) after curing an additional 24 hours at 400°F (204°C).

When the Epon Z catalyzed materials were postcured at 300° and 400°F (149° and 204°C) the anomalous flexural behavior at 300°F (149°C) was eliminated. The specimens no longer deflected to the maximum of the equipment but broke in the prescribed manner. It is also interesting to note that little additional benefit was derived from the 400°F (204°C) postcure. The 300°F (149°C) postcure provides the bulk of the increase in ultimate strength. The electrical properties are also relatively unchanged after the 300°F (149°C) postcure. It would appear that the addition of a 4-hour 300°F (149°C) postcure to the standard cure essentially optimizes the physical properties.

The final area of significance is the effect of the various fillers or modifier on the physical properties. Since these systems are all about 50 percent by volume filler the kind of filler used has a definite effect on the behavior of the encapsulant. For example, the glass microballoon filled epoxies all have an ultimate tensile strength at room temperature of between 5300 and 6700 psi (37 to 46 MPa) and a tensile modulus of between 400,000 and 500,000 psi (2.8 and 3.4 GPa). In contrast, the aluminum oxide filled epoxies have ultimate tensile strengths in the range of 9000 to 11,000 psi (62 to 76 MPa) and modulus values between 1 million and 3 million psi (6.9 and 20.6 GPa). A brief comparison of the effects of filler on room temperature physical properties is given in Table 5. The aluminum oxide specimens were also categorized by catalyst since there does appear to be more of a difference between NMA/DMP-30 and Epon Z catalyzed materials at room temperature than between Epon Z and DEA catalyzed encapsulants under similar conditions. The major differences appear to be in flexural ultimate, modulus, and volume resistivity.

The Hycar CTBN 1300 x 8 modifier has been included in the category of fillers although its true function is to flexibilize the epoxy and to provide stress relief by means of a crack terminating mechanism. In the cured system the CTBN is precipitated as rubber microgels which are evenly dispersed throughout the encapsulant. These microgels help to prevent crack propagation during thermal cycling. The addition of the CTBN had virtually no effect on the conventional room temperature physical properties. There was some loss in high temperature properties but this is normal for a flexibilized resin. Similarly, there was a corresponding gain in low temperature properties.

Most of the materials evaluated in this project are being used as filled encapsulants. The remainder have this capability. Each possesses a unique combination of properties suitable for specific applications. It was not the purpose of this study to recommend

Table 5. Room Temperature Properties as a Function of Filler Type

Property	Value Range
GMB	
Density (g/cm^3)	0.78 to 0.83
Tensile ultimate (psi)*	5300 to 6100
Compressive ultimate (psi)	12000 to 17250
Flexural ultimate (psi)	7000 to 8000
Modulus (psi x 10^6)	0.40 to 0.48
Dielectric constant	2.6 to 3.3
Volume Resistivity (ohm-cm)	1 to 5 x 10^{14}
Dielectric strength (volts/mil)**	350 to 400
Al_2O_3-Z	
Density (g/cm^3)	2.39
Tensile ultimate (psi)	10000 to 11000
Compressive ultimate (psi)	25000 to 31000
Flexural ultimate (psi)	17100 to 17700
Modulus (psi x 10^6)	1.3 to 1.9
Dielectric constant	6.0 to 6.5
Volume resistivity (ohm-cm)	1 to 21 x 10^{16}
Dielectric strength (volts/mil)	330 to 400
Al_2O_3-NMA/DMP-30	
Density (g/cm^3)	2.43
Tensile ultimate (psi)	9000 to 11000
Compressive ultimate (psi)	25000 to 28000
Flexural ultimate (psi)	12500 to 14400
Modulus (psi x 10^6)	2.0 to 3.0
Dielectric constant	5.5 to 5.7
Volume resistivity (ohm-cm)	3.6 to 4.0 x 10^{16}
Dielectric strength (volts/mil)	345 to 350
Beta-Eucryptite	
Density (g/cm^3)	1.73 to 1.74
Tensile ultimate (psi)	8100 to 9300
Compressive ultimate (psi)	22000 to 28000
Flexural ultimate (psi)	12000 to 13400
Modulus (psi x 10^6)	1 to 1.7
Dielectric constant	4.7 to 6.3
Volume resistivity (ohm-cm)	8.5 to 30 x 10^{13}
Dielectric strength (volts/mil)	300 to 330

Table 5 Continued. Room Temperature Properties as a Function of Filler Type

Property	Value Range
CTBN-GMB	
Density (g/cm^3)	0.789 to 0.80
Tensile ultimate (psi)	5300 to 6700
Compressive ultimate (psi)	11900 to 12800
Flexural ultimate (psi)	6700 to 8600
Modulus (psi x 10^6)	0.45 to 0.50
Dielectric constant	2.8 to 3.1
Volume resistivity (ohm-cm)	2.9 to 4 x 10^{14}
Dielectric strength (volts/mil)	350 to 400

*1 psi equals 6894 Pa
**1 mil equals 25.4 μm

one material, catalyst or cure schedule over any other. Instead, this evaluation was designed to provide a better understanding of the behavior of these materials throughout the applicable temperature range.

There were some inconsistencies in the data obtained in this study. Wherever possible the room temperature properties data generated by this study was compared with the values given on a resin properties chart prepared by Quant and Hatcher. The best agreement existed between the values for DEA catalyzed epoxy-GMB even though there has been a formulation change and a change in suppliers of the hollow glass microspheres.

ACCOMPLISHMENTS

Twelve formulation-cure cycle combinations representing the more widely used encapsulants and several candidates for future use were evaluated at discrete temperature intervals between -65°F (-54°C) and 400°F (204°C). The physical properties: mechanical, electrical, and thermal thus obtained have been compiled and are presented in tabular form.

Appendix A

MAXIMUM STRESS AS A FUNCTION OF TEMPERATURE

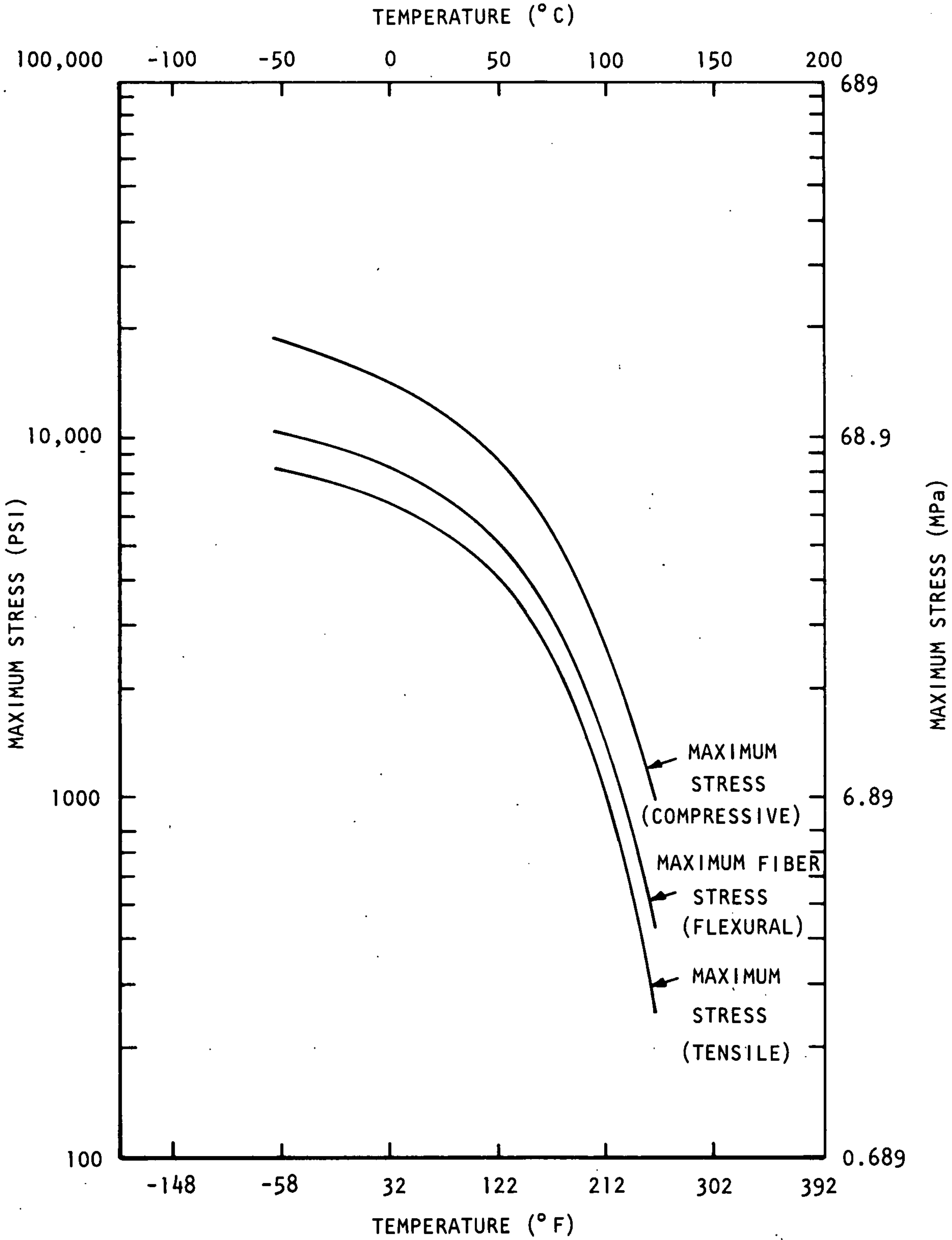

Figure A-1. Maximum Stress As a Function of Temperature for DEA Catalyzed Epoxy-GMB Processed and Cured According to P.S. 9927085.

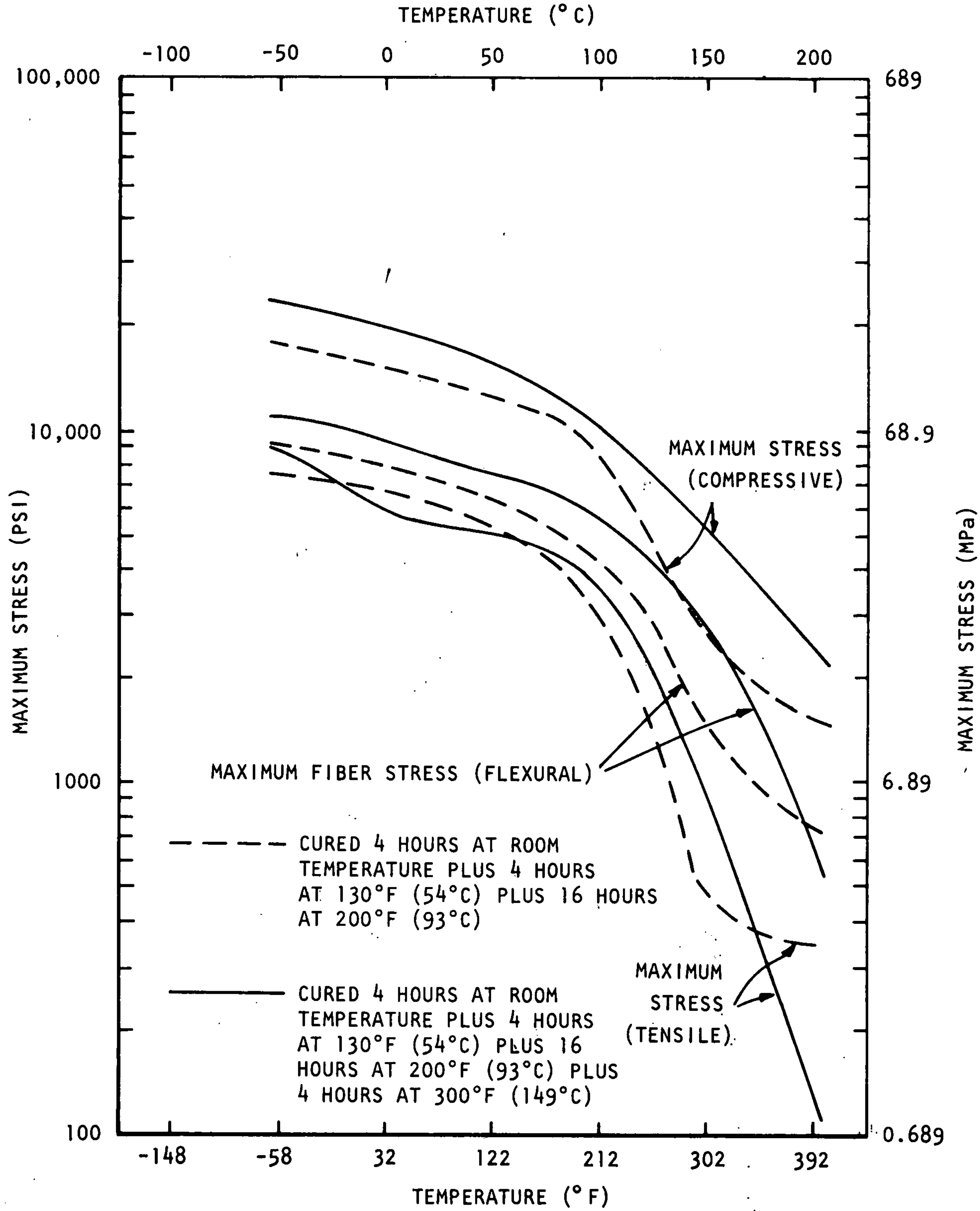

Figure A-2. Maximum Stress As a Function of Temperature for Epon Z Catalyzed Epoxy-GMB

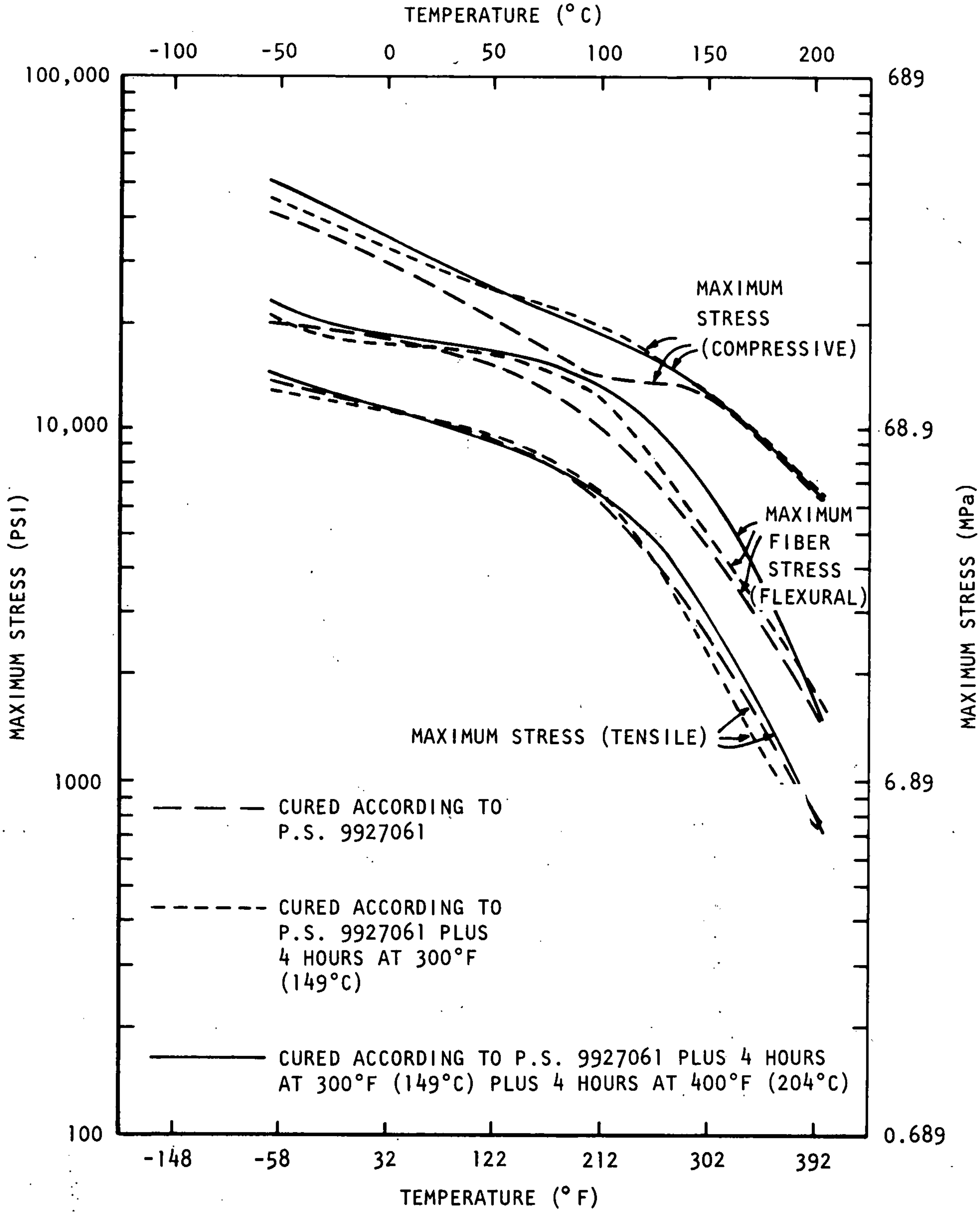

Figure A-3. Maximum Stress as a Function of Temperature for Epon Z Catalyzed Epoxy-Al_2O_3

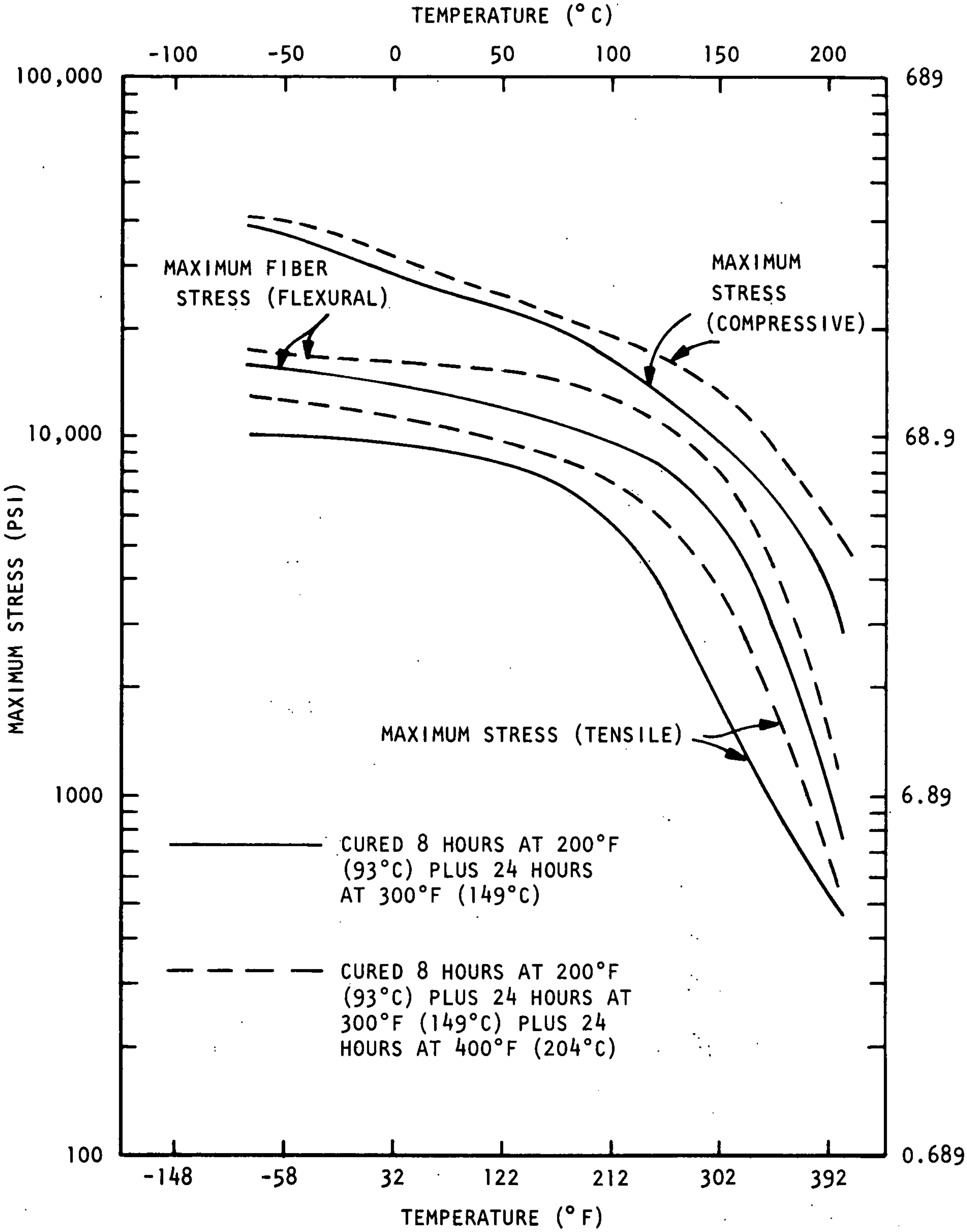

Figure A-4. Maximum Stress as a Function of Temperature for NMA/DMP-30 Catalyzed Epoxy-Al_2O_3

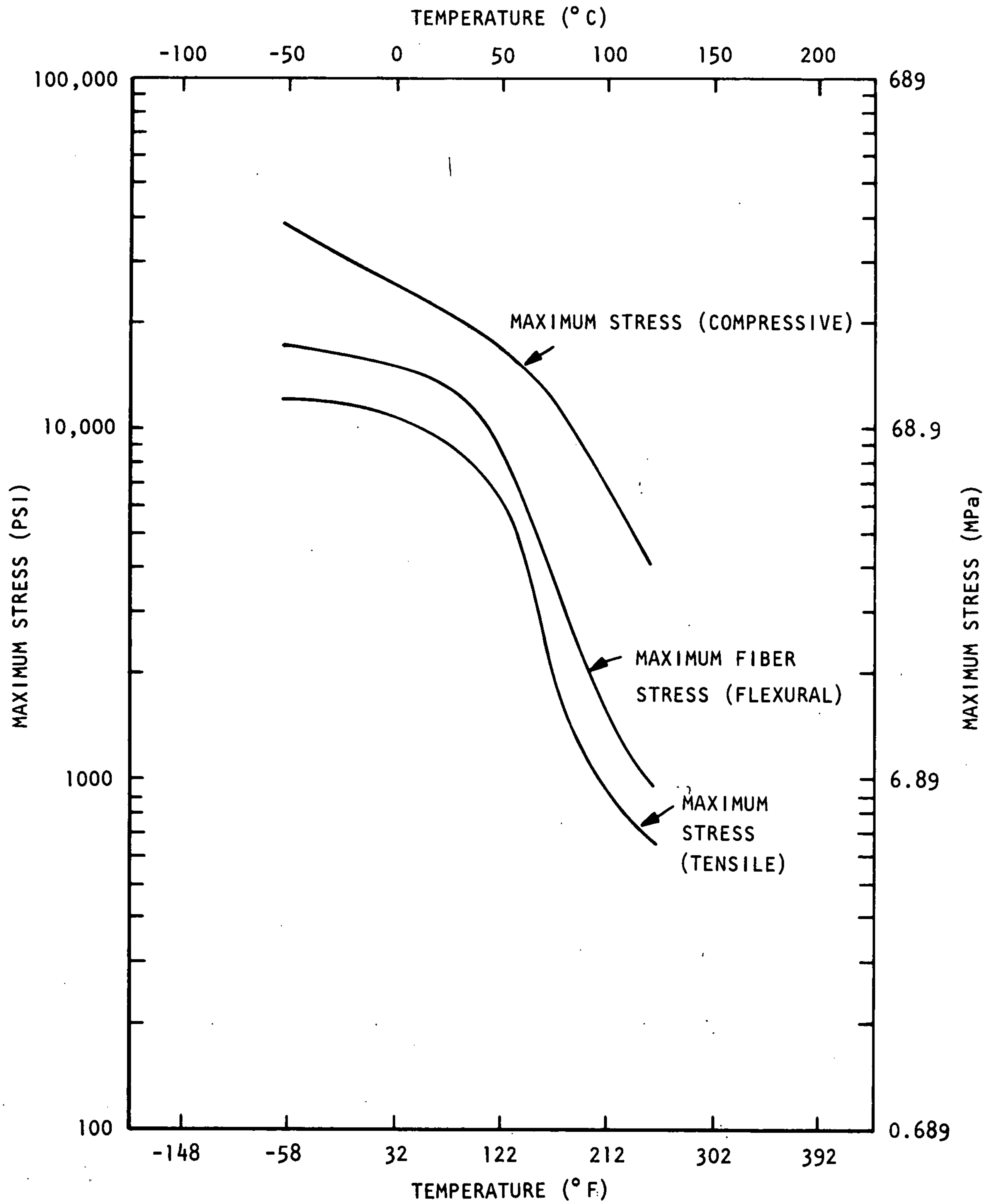

Figure A-5. Maximum Stress As a Function of Temperature for DEA Catalyzed Epoxy-Beta-Eucryptite Cured for 24 Hours at 150°F (66°C)

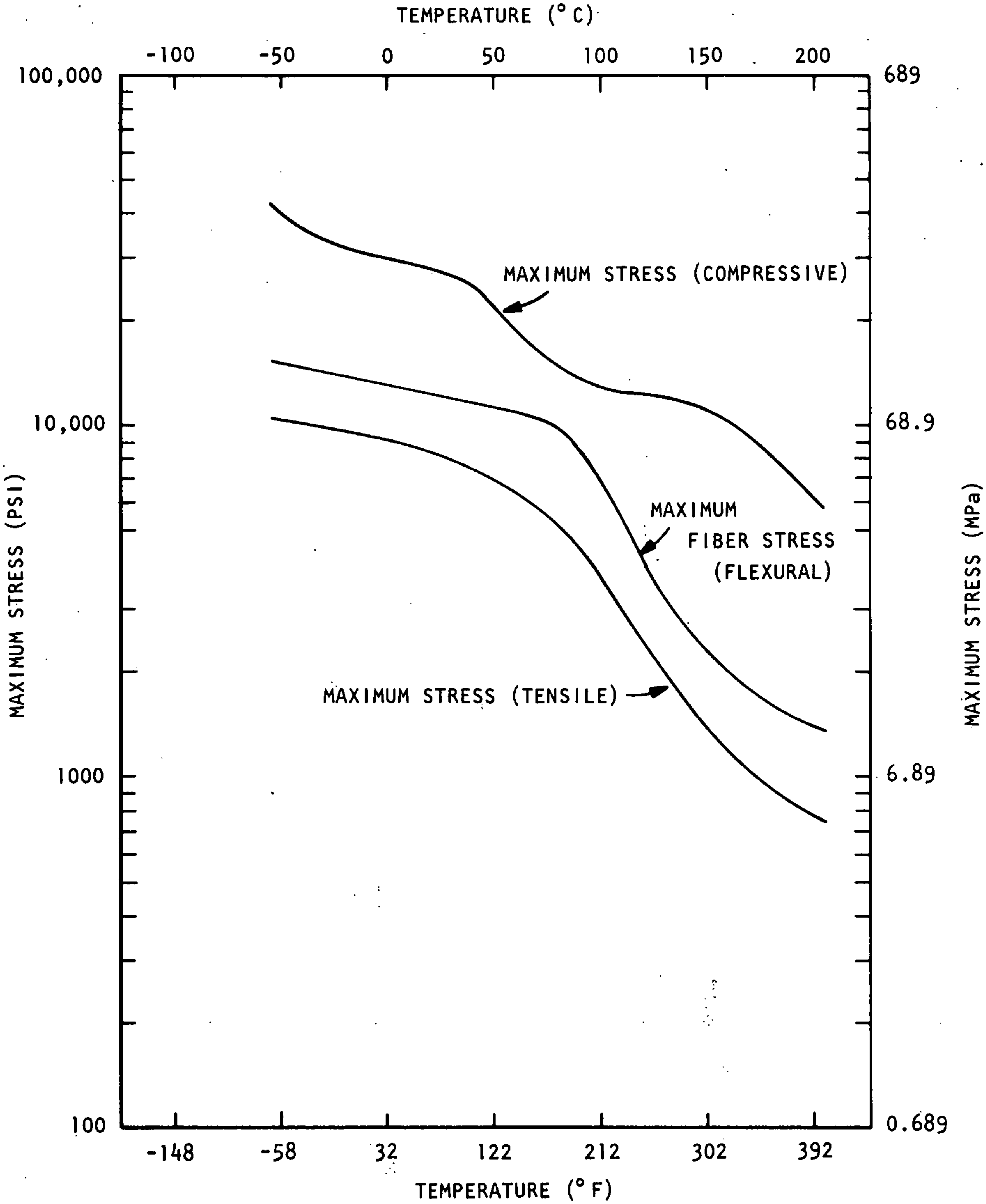

Figure A-6. Maximum Stress As a Function of Temperature for Epon Z Catalyzed Epoxy-Beta-Eucryptite Cured for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

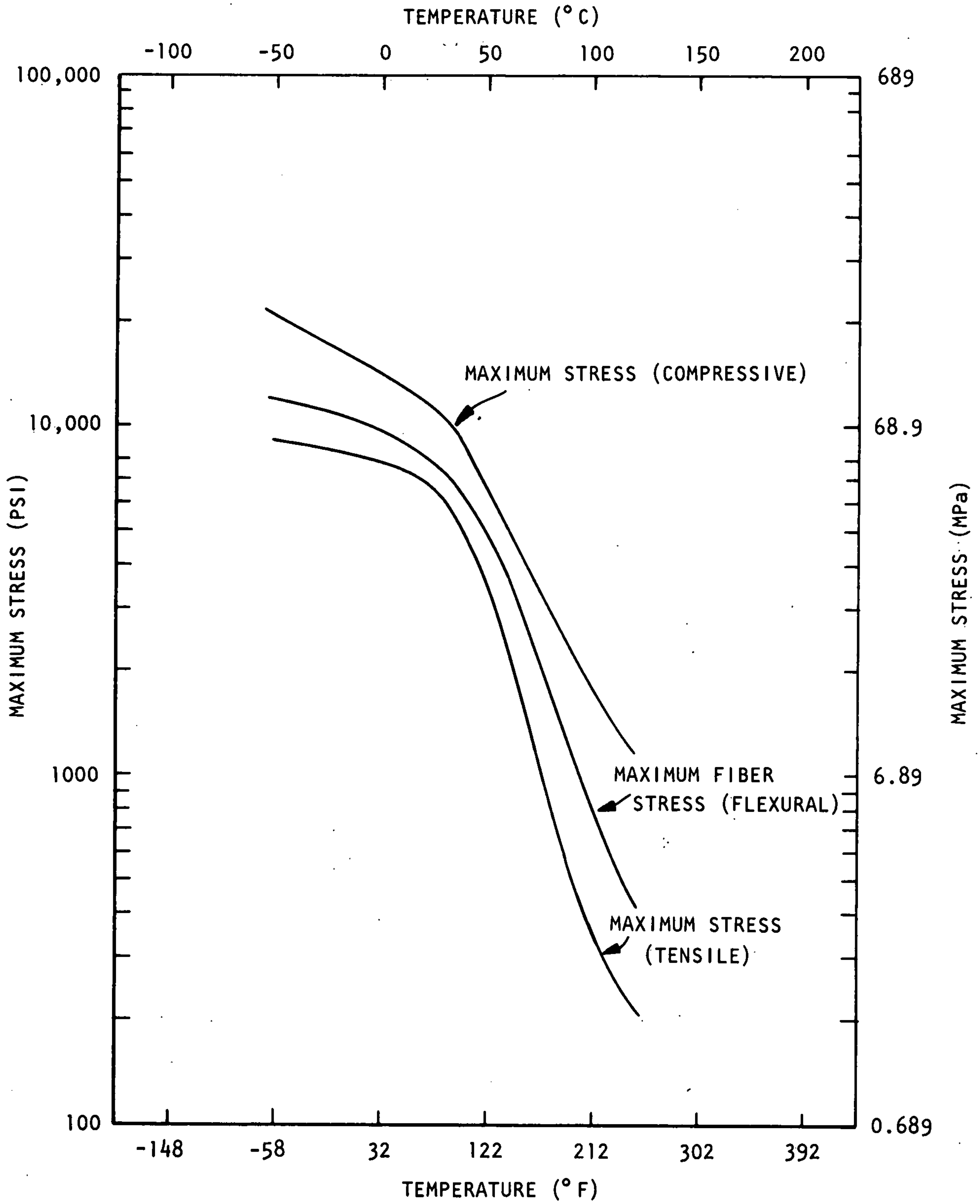

Figure A-7. Maximum Stress As a Function of Temperature for DEA Catalyzed CTBN Modified Epoxy-GMB Cured for 24 Hours at 150°F (66°C)

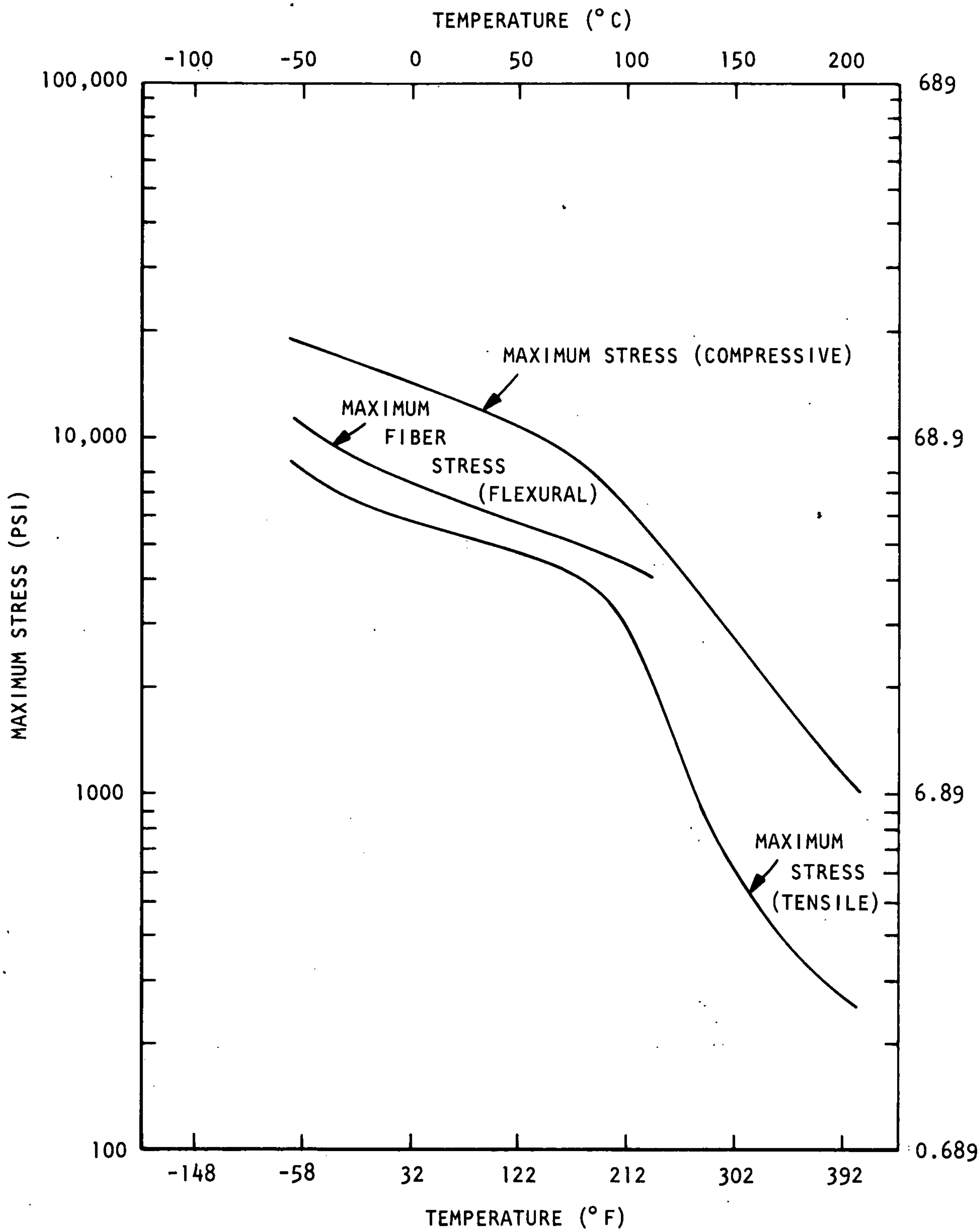

Figure A-8. Maximum Stress As a Function of Temperature for Epon Z Catalyzed CTBN Modified Epoxy-GMB Cured for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

Appendix B

THERMAL EXPANSION AS A FUNCTION OF TEMPERATURE

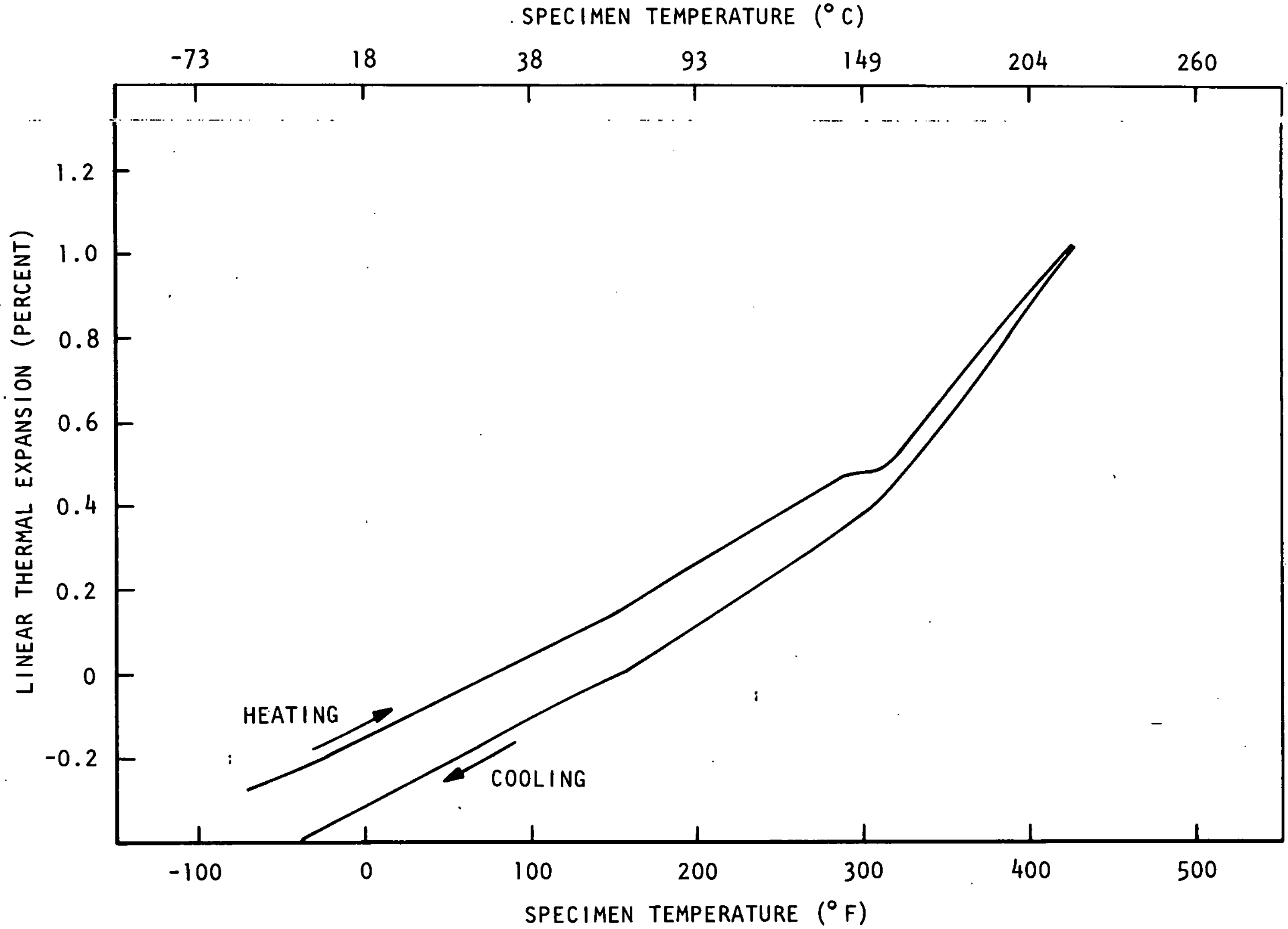

Figure B-1. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalyzed Epoxy-GMB Cured at Room Temperature for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C) Plus 4 Hours at 300°F (149°C)

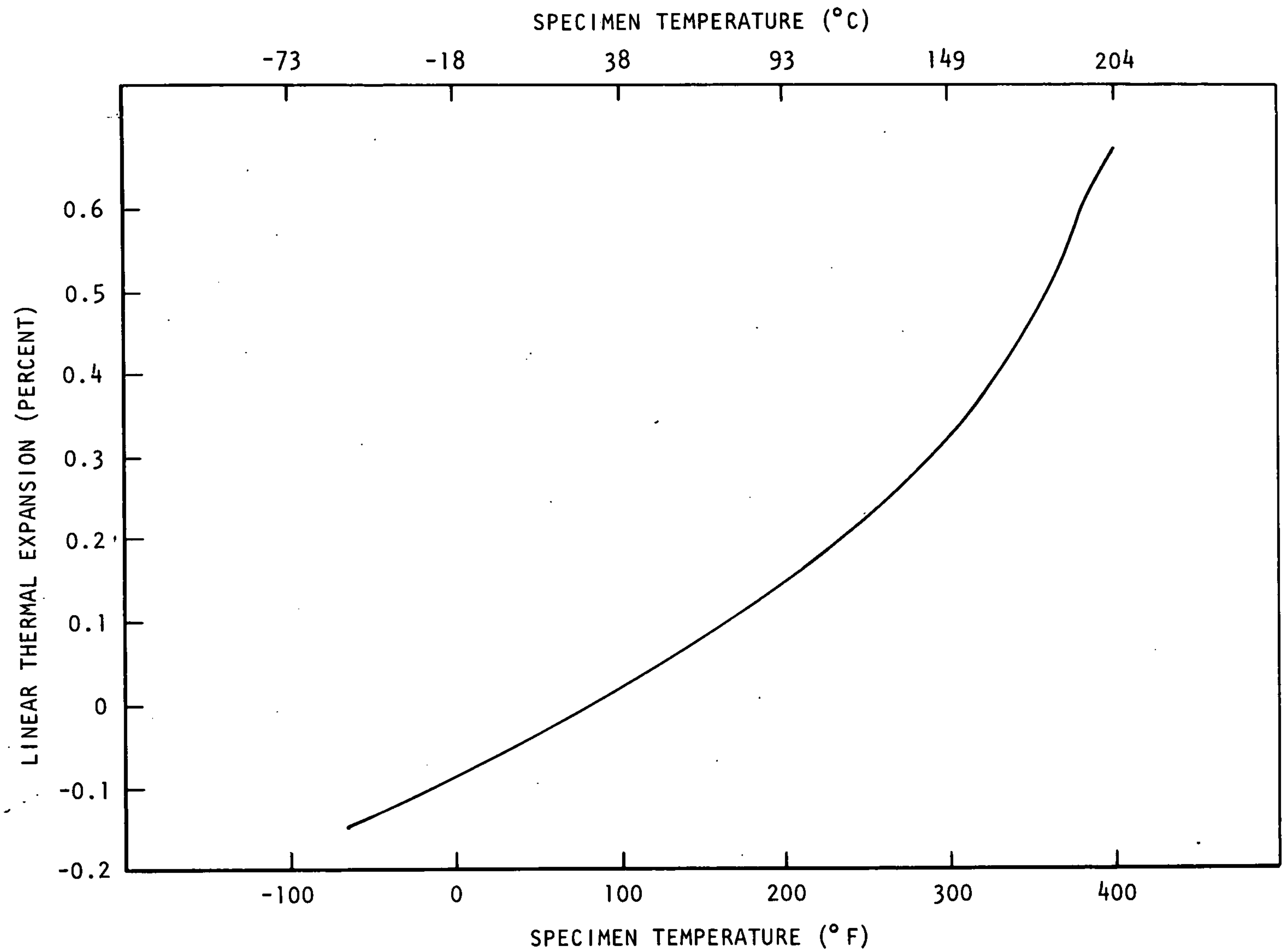

Figure B-2. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalyzed Epoxy-Al_2O_3 Cured According to P.S. 9927061

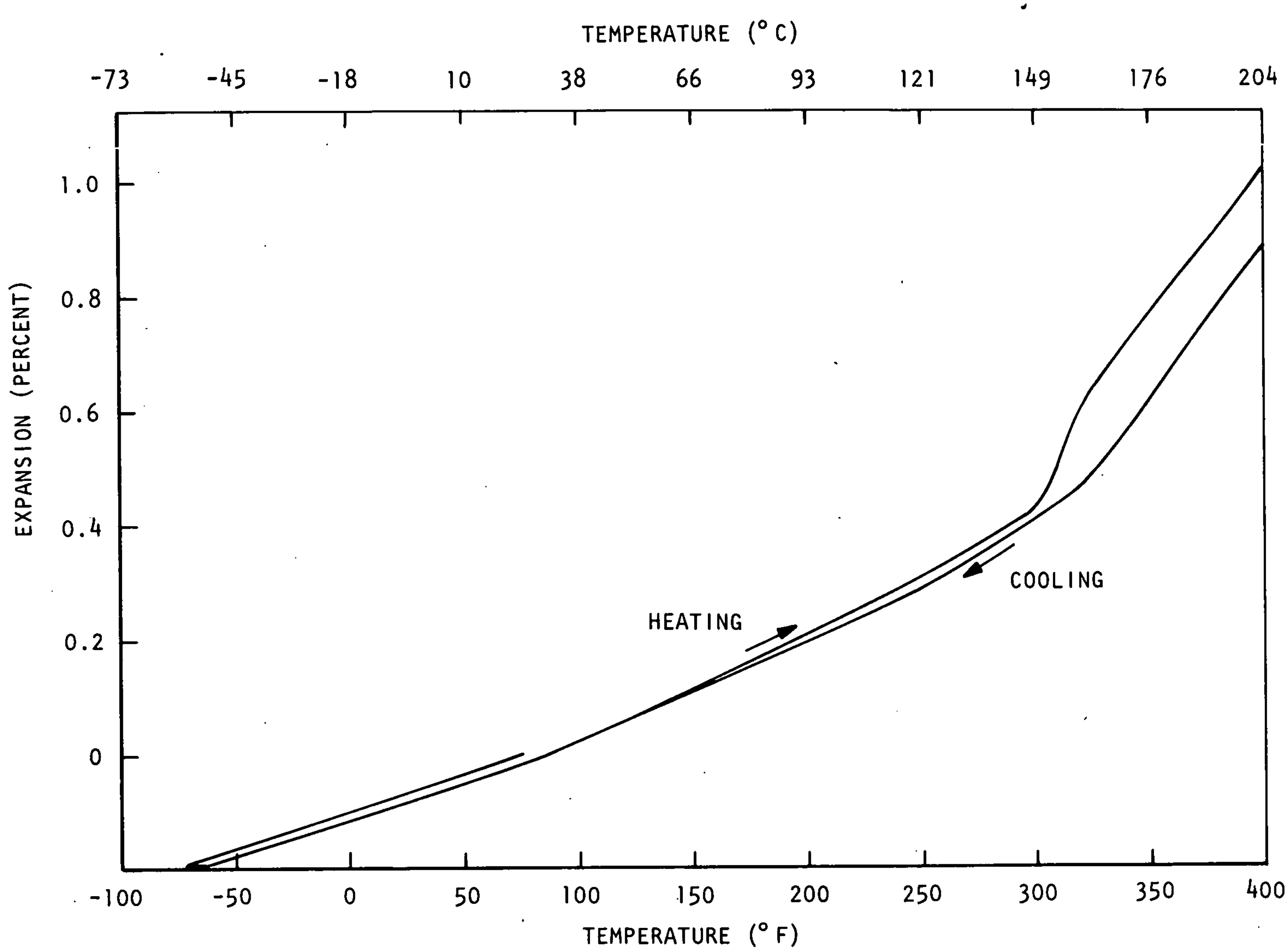

Figure B-3. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalyzed Epoxy-Al_2O_3 Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C)

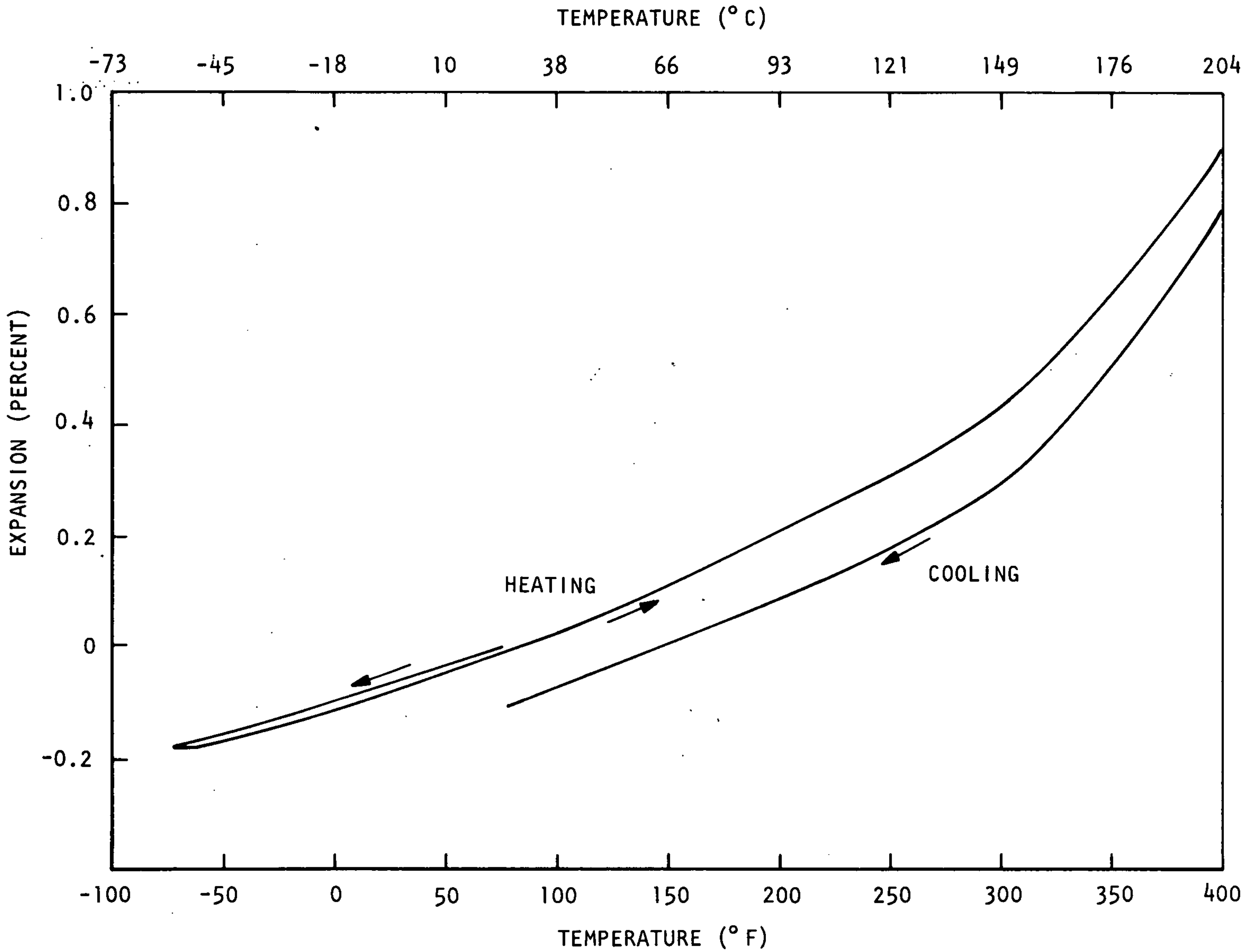

Figure B-4. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalyzed Epoxy-Al_2O_3 Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C) Plus 4 Hours at 400°F (204°C)

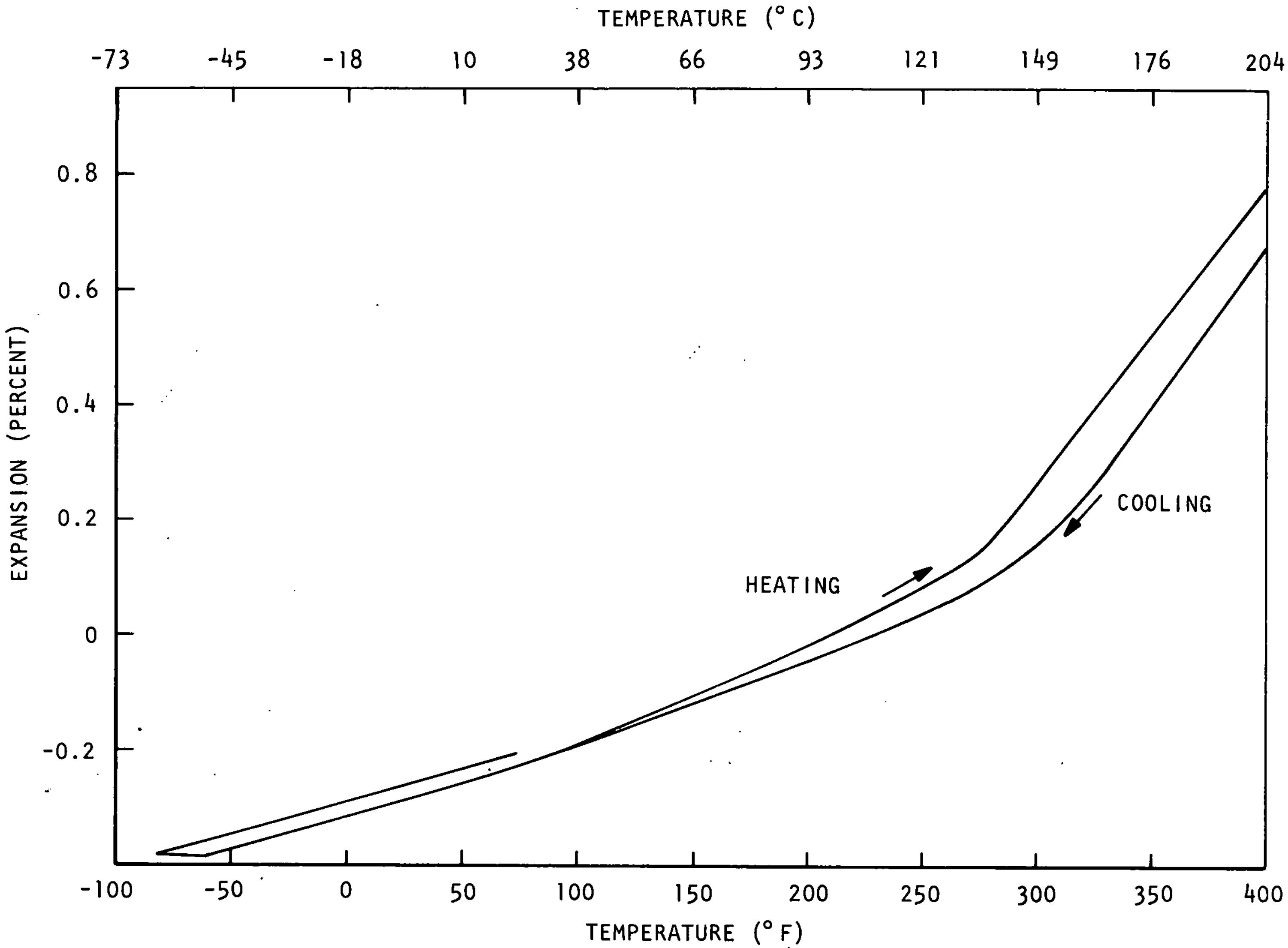

Figure B-5. Linear Thermal Expansion in Percent As a Function of Temperature for NMA/DMP-30 Catalyzed Epoxy-Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C)

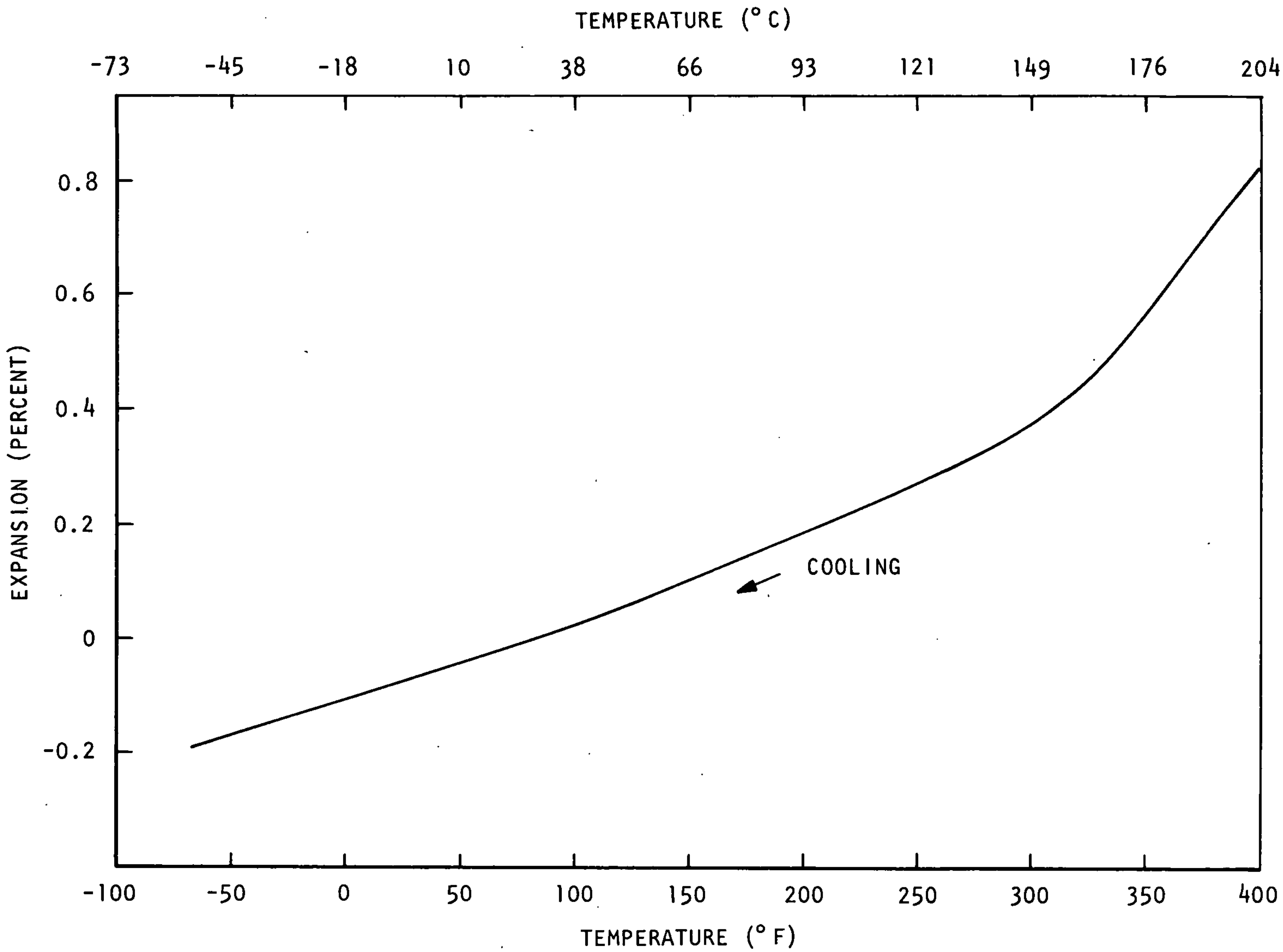

Figure B-6. Linear Thermal Expansion in Percent As a Function of Temperature for NMA/DMP-30 Catalyzed Epoxy-Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C) Plus 24 Hours at 400°F (204°C)

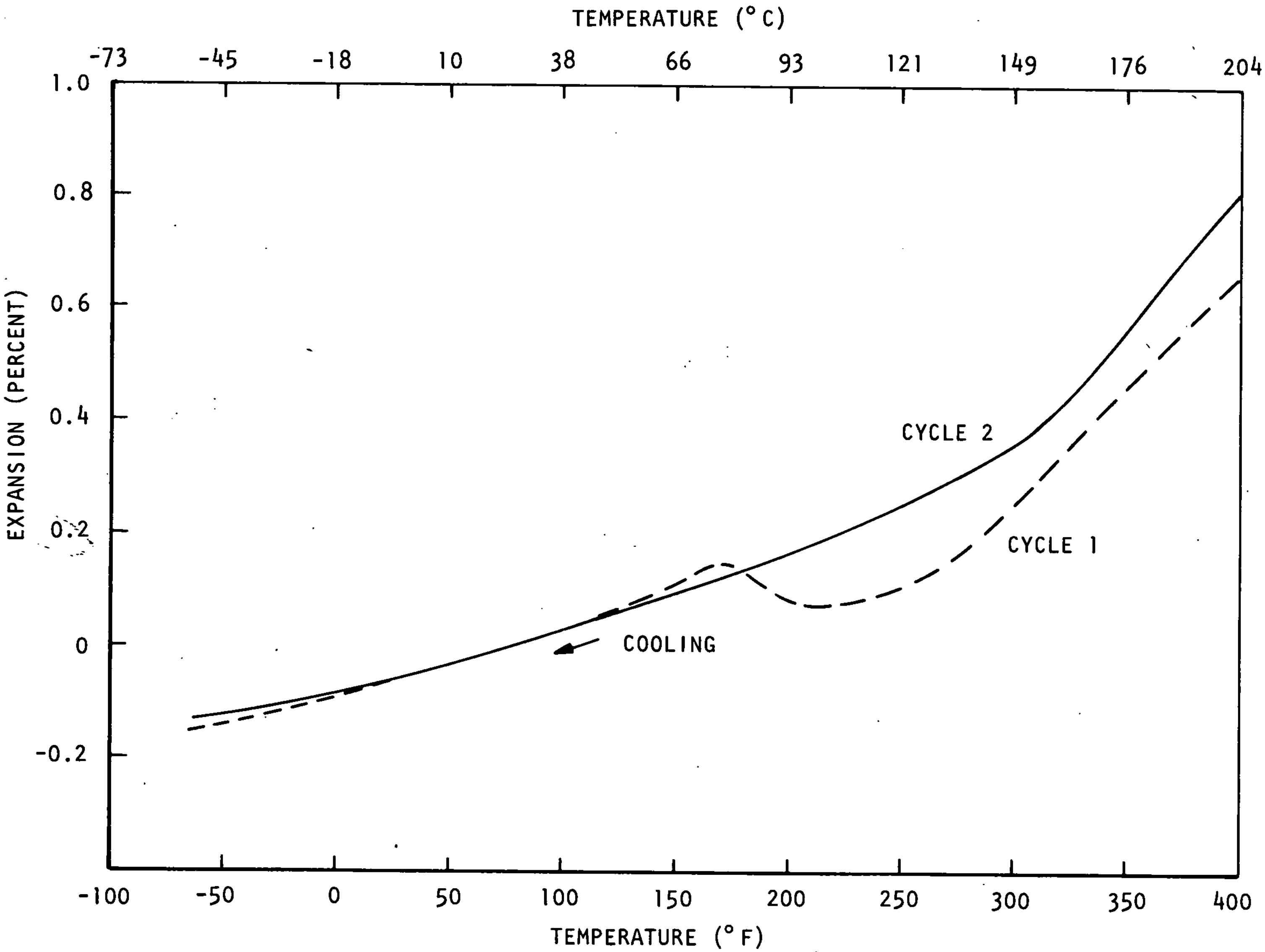

Figure B-7. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalzyed Epoxy-Beta-Eucryptite Cured for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

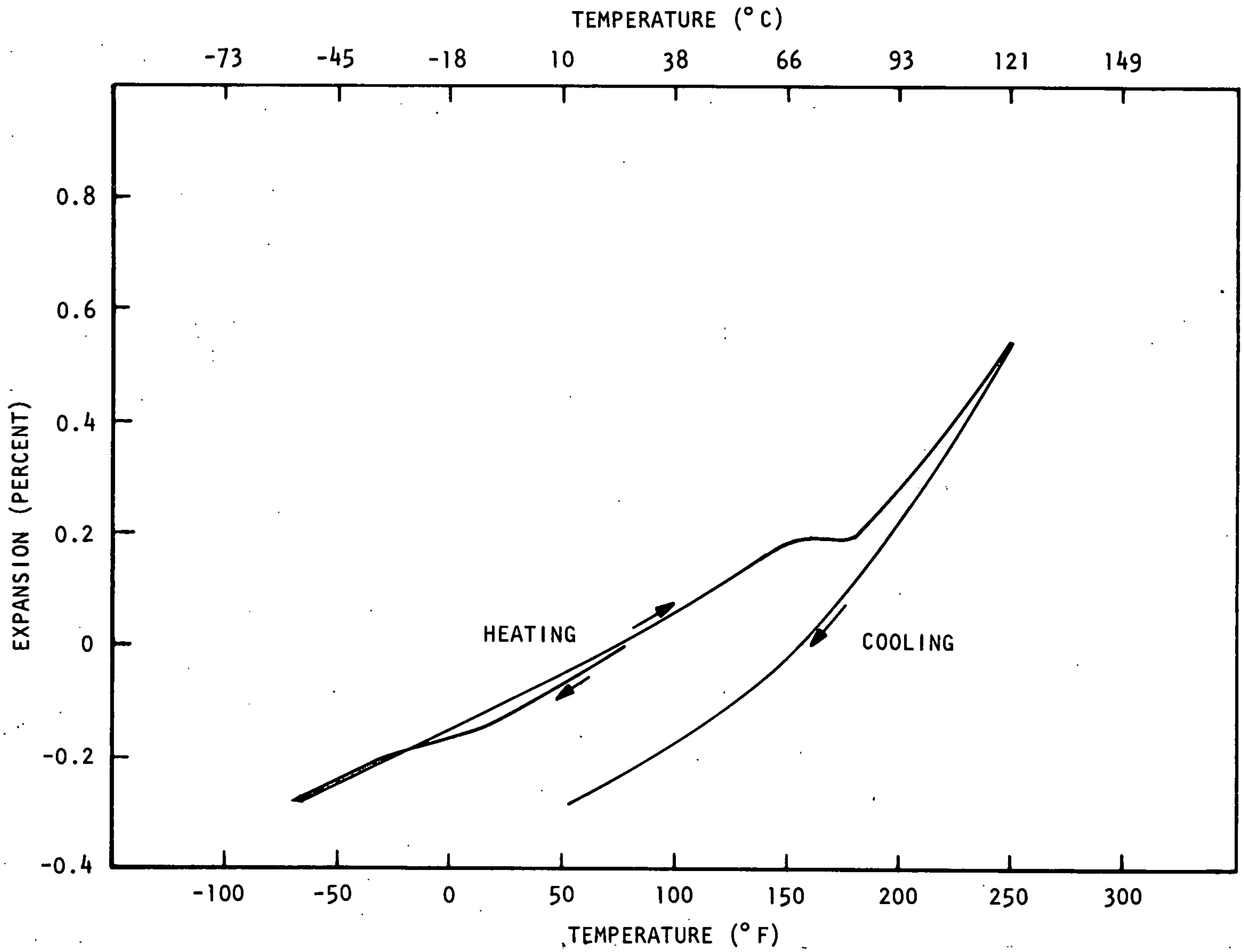

Figure B-8. Linear Thermal Expansion in Percent As a Function of Temperature for DEA Catalyzed CTBN Modified Epoxy-GMB Cured for 24 Hours at 150°F (66°C)

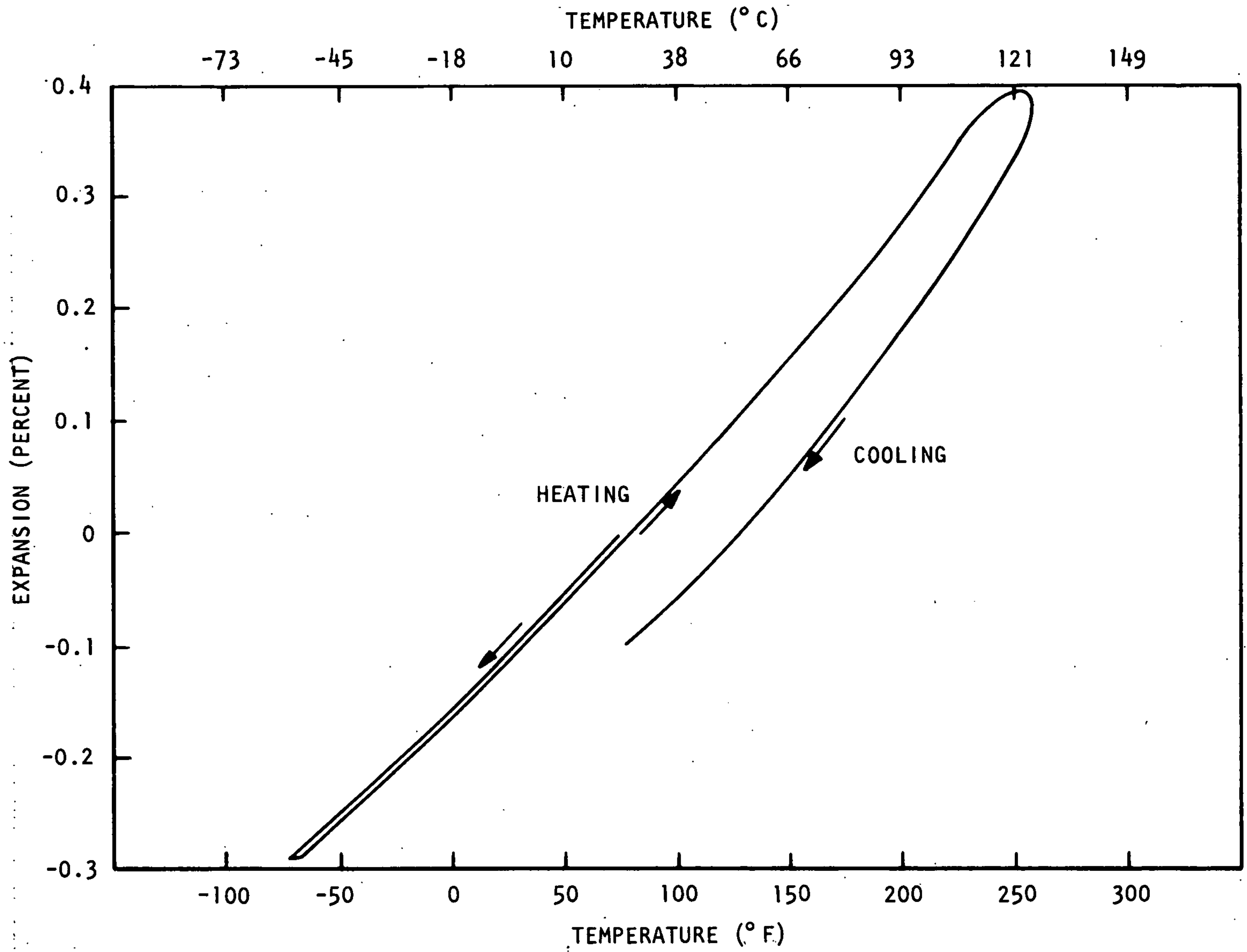

Figure B-9. Linear Thermal Expansion in Percent As a Function of Temperature for Epon Z Catalyzed CTBN Modified Epoxy-GMB Cured for 4 Hours at Room Temperature Plus 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

Appendix C

PHYSICAL PROPERTIES DATA

Table C-1. Mechanical Properties of DEA Catalyzed Epoxy-GMB Processed and Cured According to P.S. 9927085

Variable	Test Temperatures -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)
	Tensile Properties According to ASTM D-638					
Maximum Stress (psi)†	8130 (610)* 9**	7870 (570) 9	7050 (470) 9	5540 (470) 9	2630 (360) 9	260 (10) 10
Strain at Maximum Stress (Percent)	1.6 (0.12) 9	1.6 (0.20) 9	1.4 (0.15) 9	1.2 (0.18) 10	3.3 (0.76) 9	2.6 (0.35) 10
Elastic Modulus (psi x 10^6)	0.53 (0.02) 9	0.50 (0.02) 9	0.53 (0.03) 9	0.48 (0.01) 10	0.25 (0.01) 9	0.02 (0.001) 10
	Compressive Properties According to ASTM D-695					
Maximum Stress (psi)	20280 (50) 5	16700 (230) 5	14680 (40) 4	11960 (230) 5	5320 (60) 5	1060 (10) 5
Strain at Maximum Stress (Percent)	5.5 (0.08) 5	4.6 (0.11) 5	4.2 (0.10) 4	3.7 (0.22) 5	4.8 (0.13) 5	9.1 (0.34) 5
Elastic Modulus (psi x 10^6)	0.52 (0.01) 5	0.47 (0.02) 5	0.55 (0.02) 4	0.48 (0.02) 5	0.27 (0.01) 5	0.02 (0.001) 5
	Flexural Properties According to ASTM D-790					
Maximum Fiber Stress (psi)	10520 (210) 4	10020 (330) 4	8960 (410) 5	6980 (240) 4	N/A***	450 (30) 5
Deflection at Maximum Stress (in.)††	0.24 (0.004) 4	0.23 (0.01) 4	0.21 (0.01) 5	0.18 (0.001) 4	N/A	0.35 (0.01) 5
Elastic Modulus (psi x 10^6)	0.49 (0.003) 4	0.48 (0.002) 4	0.47 (0.006) 5	0.44 (0.006) 4	N/A	0.02 (0.001) 5

*Standard Deviation
**Number of Test Specimens
***N/A (Not Available)
†1 psi = 6.89 x 10^3 Pa
††1 inch = 2.54 cm

Table C-2. Electrical Properties of DEA Catalyzed Epoxy-GMB Processed and Cured According to P.S. 9927085

Variable	Test Temperatures -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)
	Dielectric Constant According to ASTM D-150					
100 Hz	2.65	2.69	2.79	2.92	3.11	4.15
1000 Hz	2.49	2.58	2.72	2.87	2.87	3.81
10000 Hz	2.42	2.49	2.61	2.83	2.92	3.51
0.1 MHz	2.42	2.48	2.59	2.69	2.82	3.21
1 MHz	2.35	2.42	2.48	2.62	2.80	3.12
	Dissipation Factor According to ASTM D-150					
100 Hz	0.01	0.004	0.016	0.013	0.053	0.056
1000 Hz	0.003	0.003	0.026	0.012	0.019	0.013
10000 Hz	0.024	0.028	0.031	0.016	0.011	0.054
0.1 MHz	0.017	0.020	0.034	0.025	0.013	0.037
1 MHz	0.016	0.019	0.026	0.031	0.025	0.032
	Dielectric Strength According to ASTM D-149					
Short Time 1/8 inch** (Volts/Mil)*	732	562	645	371	331	225
	Volume Resistivity According to ASTM D-257 (Ω·cm)					
-65°F (-54°C)	3.9×10^{15}					
-40°F (-40°C)	1.8×10^{15}					
0°F (-18°C)	4.1×10^{14}					
75°F (24°C)	1.8×10^{14}					
100°F (37.8°C)	1.6×10^{14}					
150°F (66°C)	3.8×10^{13}					
200°F (93°C)	1.0×10^{12}					
250°F (121°C)	4.8×10^{10}					
300°F (149°C)	7.9×10^{9}					
350°F (177°C)	4.5×10^{9}					

*1 mil = 2.54×10^{-5} m
**1 inch = 2.54 cm

Table C-3. Mechanical Properties of Epon Z Catalyzed Epoxy-GMB Cured at Room Temperature for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

Variable	Test Temperatures							
	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Tensile Properties According to ASTM D-638							
Maximum Stress (psi)†	7600 (590)* 8**	7390 (458) 8	7360 (500) 8	6140 (210) 8	4130 (167) 9	3960 (200) 10	500 (80) 8	340 (20) 9
Strain at Maximum Stress (Percent)	1.3 (0.11) 8	1.2 (0.21) 8	1.3 (0.14) 8	1.6 (0.39) 8	0.97 (0.22) 9	1.1 (0.22) 10	5.2 (2.0) 8	0.91 (0.22) 9
Elastic Modulus (psi x 10^6)	0.57 (0.02) 8	0.53 (0.05) 8	0.63 (0.10) 8	0.42 (0.91) 8	0.46 (0.09) 9	0.38 (0.07) 10	0.03 (0.01) 8	0.06 (0.01) 9
	Compressive Properties According to ASTM D-695							
Maximum Stress (psi)	18160 (250) 5	17080 (208) 5	16420 (110) 5	13810 (50) 5	11250 (184) 5	9840 (60) 5	2610 (40) 5	1480 (30) 5
Strain at Maximum Stress (Percent)	4.60 (0.3) 5	4.3 (0.16) 5	4.10 (0.13) 5	3.70 (0.19) 5	3.3 (0.15) 5	3.40 (0.11) 5	13.0 (0.83) 5	8.5 (0.21) 5
Elastic Modulus (psi x 10^6)	0.55 (0.02) 5	0.68 (0.03) 5	0.68 (0.04) 5	0.66 (0.02) 5	0.55 (0.001) 5	0.46 (0.01) 5	0.03 (0.001) 5	0.02 (0.001) 5
	Flexural Properties According to ASTM D-790							
Maximum Fiber Stress (psi)	9860 (300) 4	9440 (252) 4	8990 (350) 5	7610 (120) 5	5470 (38) 5	4970 (160) 5	N/A***	720 (60) 4
Deflection at Maximum Stress (in.)††	0.22 (0.01) 4	0.22 (0.005) 4	0.20 (0.004) 5	0.17 (0.005) 5	0.13 (0.002) 5	0.15 (0.003) 5	N/A	0.29 (0.04) 4
Elastic Modulus	0.50 (0.006) 4	0.48 (0.006) 4	0.50 (0.003) 5	0.46 (0.004) 5	0.44 (0.003) 5	0.38 (0.005) 5	N/A	0.03 (0.001) 4

*Standard Deviation
**Number of test Specimens
***N/A (Not Available)
†1 psi = 6.89 x 10^3 Pa
††1 inch = 2.54 cm

Table C-4. Electrical Properties of Epon Z Catalyzed Epoxy-GMB Cured at Room Temperature for 4 Hours Plus 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

Variable	Test Temperatures							
	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Dielectric Constant According to ASTM D-140							
100 Hz	2.72	2.90	2.95	3.03	3.12	3.25	4.59	14.95
1000 Hz	2.63	2.79	2.87	2.96	2.99	3.00	3.25	5.14
10000 Hz	2.57	2.68	2.44	2.88	2.94	2.92	2.99	3.34
0.1 MHz	2.57	2.68	2.75	2.86	2.94	2.97	2.97	2.50
1 MHz	2.52	2.60	2.65	2.77	2.93	2.92	2.95	2.88
	Dissipation Factor According to ASTM D-150							
100 Hz	0.061	0.023	0.014	0.014	0.064	0.138	0.434	0.868
1000 Hz	0.022	0.026	0.021	0.016	0.022	0.014	0.148	0.519
10000 Hz	0.017	0.023	0.024	0.022	0.012	0.015	0.044	0.139
0.1 MHz	0.018	0.025	0.029	0.029	0.016	0.009	0.016	0.047
1 MHz	0.017	0.020	0.023	0.024	0.020	0.016	0.013	0.024
	Dielectric Strength According to ASTM D-149							
Short Time 1/8 inch* (Volts/Mil)**	589	475	539	396	357	302	206	124
	Volume Resistivity According to ASTM D-257 (Ω·cm)							
-65°F (-54°C)	9.8×10^{14}							
-40°F (-40°C)	4.6×10^{14}							
0°F (-18°C)	2.3×10^{14}							
75°F (24°C)	1.1×10^{14}							
100°F (37.8°C)	1.5×10^{14}							
150°F (66°C)	1.2×10^{14}							
200°F (93°C)	4.6×10^{13}							
250°F (121°C)	2.2×10^{13}							
300°F (149°C)	1.5×10^{13}							
350°F (177°C)	6.0×10^{11}							
400°F (204°C)	2.3×10^{10}							

*1 inch = 2.54 cm
**1 mil = 2.54×10^{-5} m

Table C-5 Mechanical Properties of Epon Z Catalyzed Epoxy-GMB Cured at Room Temperature for 4 Hours Plus 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C) Plus 4 Hours at 300°F (149°C)

Variable	Test Temperatures							
	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Tensile Properties According to ASTM D-638							
Maximum Stress (psi)†	8550 (530)* 8**	8700 (473) 8	6500 (750) 9	5350 (390) 8	4590 (229) 8	4030 (60) 9	930 (210) 9	110 (5) 10
Strain at Maximum Stress (Percent)	1.70 (0.20) 8	2.00 (0.20) 8	2.10 (0.28) 9	1.49 (0.14) 8	1.50 (0.11) 8	1.46 (0.07) 9	4.63 (0.37) 9	3.00 (0.31) 10
Elastic Modulus (psi x 10^6)	0.57 (0.06) 8	0.57 (0.06) 8	0.34 (0.03) 9	0.40 (0.01) 8	0.40 (0.01) 8	0.36 (0.03) 9	0.05 (0.01) 9	0.01 (0.0004) 10
	Compressive Properties According to ASTM D-695							
Maximum Stress (psi)	21900 (850) 4	22880 (1024) 4	20280 (1490) 4	17250 (970) 4	13150 (473) 4	11400 (160) 4	5260 (310) 4	2260 (190) 5
Strain at Maximum Stress (Percent)	6.56 (0.14) 4	6.29 (0.29) 4	5.66 (0.24) 4	6.02 (0.35) 4	5.54 (0.49) 4	7.95 (0.14) 4	13.5 (2.1) 4	17.5 (0.46) 5
Elastic Modulus (psi x 10^6)	0.47 (0.02) 4	0.47 (0.02) 4	0.44 (0.03) 4	0.43 (0.02) 4	0.41 (0.02) 4	0.38 (0.02) 4	0.18 (0.04 4	0.06 (0.002) 5
	Flexural Properties According to D-790							
Maximum Fiber Stress (psi)	10480 (240) 4	11120 (238) 4	10260 (260) 4	8030 (180) 4	7310 (84) 4	5380 (130) 4	2830 (100) 4	570 (8) 4
Deflection at Maximum Stress (in.)††	0.22 (0.003) 4	0.24 (0.01) 4	0.23 (0.01) 4	0.18 (0.04) 4	0.20 (0.003) 4	0.17 (0.004) 4	0.36 (0.04) 4	0.30 (0.01) 4
Elastic Modulus (psi x 10^6)	0.56 (0.002) 4	0.53 (0.01) 4	0.51 (0.003) 4	0.46 (0.002) 4	0.42 (0.005) 4	0.37 (0.01) 4	0.21 (0.006) 4	0.02 (0.001) 4

*Standard Deviation
**Number of Test Specimens
***N/A--Not Available
†1 psi = 6.89 x 10^3 Pa
††1 inch = 2.54 cm

Table C-6. Electrical Properties of Epon Z Catalyzed Epoxy-GMB Cured at Room Temperature for 4 Hours Plus 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C) Plus 4 Hours at 300°F (149°C)

Variable	Test Temperatures							
	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Dielectric Constant According to ASTM D-150							
100 Hz	2.60	2.79	2.96	3.25	3.30	3.46	4.28	9.89
1000 Hz	2.55	2.64	2.77	2.99	3.31	3.27	3.44	4.46
10000 Hz	2.49	2.57	2.67	2.91	3.24	3.19	3.21	3.23
0.1 MHz	2.47	2.48	2.62	2.79	3.03	3.05	3.07	3.17
1 MHz	2.48	2.41	2.47	2.61	3.08	3.11	2.19	2.99
	Dissipation Factor According to ASTM D-150							
100 Hz	0.003	0.032	0.022	0.014	0.035	0.070	0.379	0.742
1000 Hz	0.036	0.021	0.026	0.016	0.020	0.029	0.103	0.416
10000 Hz	0.022	0.017	0.023	0.023	0.015	0.016	0.033	0.108
0.1 MHz	0.014	0.016	0.026	0.029	0.021	0.017	0.015	0.033
1 MHz	0.014	0.015	0.019	0.025	0.033	0.028	0.016	0.014
	Dielectric Strength According to ASTM D-149							
Short Time 1/8 Inch* (Volts/Mil)**	447	399	415	341	301	224	230	115
	Volume Resistivity According to ASTM D-257 (Ω·cm)							
-65°F (-54°C)	1.7×10^{16}							
-40°F (-40°C)	3.3×10^{15}							
0°F (-18°C)	6.4×10^{14}							
75°F (24°C)	5.2×10^{14}							
100°F (37.8°C)	5.3×10^{14}							
150°F (66°C)	6.8×10^{14}							
200°F (93°C)	2.6×10^{14}							
250°F (121°C)	1.3×10^{14}							
300°F (149°C)	1.7×10^{13}							
350°F (177°C)	3.2×10^{11}							
400°F (204°C)	2.8×10^{11}							

*1 inch = 2.54 cm
**1 mil = 2.54×10^{-5} m

Table C-7. Mechanical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Processed and Cured According to P.S. 9927061

Variable	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Test Temperatures							
	Tensile Properties According to ASTM D-639							
Maximum Stress (psi)†	13650 (740)* 9**	12650 (1434) 10	11680 (870) 10	10350 (790) 10	8330 (240) 10	6800 (330) 10	2550 (270) 10	790 (130) 8
Strain at Maximum Stress (Percent)	0.68 (0.06) 9	0.65 (0.12) 10	0.61 (0.06) 10	0.67 (0.10) 10	0.75 (0.04) 10	0.81 (0.24) 10	5.97 (1.1) 10	2.58 (0.60) 8
Elastic Modulus (psi x 10^6)	2.42 (0.30) 9	2.37 (0.16) 10	2.33 (0.31) 10	1.90 (0.17) 10	1.72 (0.08) 10	1.47 (0.15) 10	0.49 (0.14) 10	0.035 (0.005) 8
	Compressive Properties According to ASTM D-695							
Maximum Stress (psi)	41120 (1210) 5	39000 (353) 10	33830 (1330) 10	25330 (190) 10	17500 (421) 10	14500 (590) 10	12560 (490) 10	6170 (300) 4
Strain at Maximum Stress (Percent)	4.87 (0.34) 5	5.65 (0.70) 10	4.69 (0.37) 10	3.92 (0.14) 10	10.0 (1.26) 10	13.49 (1.5) 10	15.14 (0.34) 10	12.04 (0.63) 4
Yield Stress (psi)	No Yield	No yield	No yield	No yield	17.330 (153) 10	13510 (528) 10	No yield	No yield
Yield Strain (percent)	N/A				2.44 (0.15) 10	1.976 (0.18) 10		
Rupture Stress (psi)	31920 (5680) 5	36480 (883) 10	30580 (508) 10	23560 (570) 10	16631 (630) 10	13.420 (880) 10	13560 (487) 10	6170 (298) 4
Rupture Strain (percent)	7.51 (1.71) 5	9.0 (1.5) 10	9.4 (0.49) 10	11.2 (0.82) 10	13.5 (0.60) 10	16.5 (0.86) 10	15.14 (0.34) 10	12.04 (0.63) 4
Elastic Modulus (psi x 10^6)	1.25 (0.11) 5	1.89 (0.18) 10	1.98 (0.16) 10	1.61 (0.08) 10	1.41 (0.06) 10	1.18 (0.06) 10	0.53 (0.09) 10	0.11 (0.005)
	Flexural Properties According to ASTM D-790							
Maximum Fiber Stress (psi)	19780 (500) 5	19.910 (601) 5	17750 (780) 5	17110 (100) 5	12290 (966) 4	11940 (240) 5	N/A***	1480 (30) 5
Deflection at Maximum Fiber Stress (in.)††	0.099 (0.003) 5	0.110 (0.004) 5	0.105 (0.006) 5	0.11 (0.001) 5	0.086 (0.009) 4	0.126 (0.011) 5	N/A	0.406 (0.009) 5
Elastic Modulus (psi x 10^6)	2.24 (0.056) 5	2.07 (0.056) 5	2.00 (0.057) 5	1.91 (0.029)	1.69 (0.00) 4	1.47 (0.022) 5	N/A	0.045 (0.013) 5

*Standard Deviation
**Number of Test Specimens
***N/A--Not Available
†1 psi = 6.89 x 10^3 Pa
††1 inch = 2.54 cm

Table C-8. Electrical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Processed and Cured According to P.S. 9927061

Variable	Test Temperatures -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
	Dielectric Constant According to ASTM D-150							
100 Hz	5.92	6.10	6.09	6.33	6.54	6.59	6.48	7.33
1000 Hz	5.83	3.97	6.10	6.27	6.41	6.40	6.39	6.75
10000 Hz	5.71	5.78	5.94	6.20	6.36	6.40	6.35	6.65
0.1 MHz	5.80	5.85	6.03	6.27	6.53	6.53	6.55	6.69
1 MHz	5.70	5.72	5.91	6.13	6.44	6.49	6.54	6.39
	Dissipation Factor According to ASTM D-150							
100 Hz	0.016	0.018	0.009	0.008	0.013	0.008	0.009	0.063
1000 Hz	0.015	0.018	0.013	0.007	0.008	0.006	0.006	0.027
10000 Hz	0.013	0.019	0.016	0.012	0.006	0.003	0.004	0.014
0.1 MHz	0.017	0.019	0.017	0.019	0.010	0.005	0.002	0.008
1 MHz	0.013	0.016	0.016	0.019	0.021	0.013	0.008	0.009
	Dielectric Strength According to ASTM D-149							
Short Time 1/8 inch* (Volts/Mil)**	416	433	411	409	383	378	371	210
	Volume Resistivity According to ASTM D-257 (Ω·cm)							
-65°F (-54°C)	2.0×10^{17}							
-40°F (-40°C)	6.1×10^{16}							
0°F (-18°C)	4.1×10^{16}							
75°F (24°C)	2.1×10^{16}							
100°F (37.8°C)	8.6×10^{15}							
150°F (66°C)	4.6×10^{15}							
200°F (93°C)	7.3×10^{14}							
250°F (121°C)	1.4×10^{14}							
300°F (149°C)	2.0×10^{13}							
350°F (177°C)	3.7×10^{12}							
400°F (204°C)	1.3×10^{11}							

*1 inch = 2.54 cm
**1 mil = 2.54×10^{-5} m

Table C-9. Mechanical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Processed and Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)*	11360** (1210)9	11590 (1690)8	13180 (640)9	11000 (720)9	8570 (630)9	7500 (190)8	2370 (190)9	740 (60)8
Strain at Maximum Stress (Percent)	0.68 (0.08)9	0.60 (0.20)8	0.86 (0.04)9	0.85 (0.10)9	0.74 (0.09)9	0.87 (0.06)8	6.00 (1.3)9	2.40 (0.40)8
Elastic Modulus (psi x 10^6)	2.43 (0.23)9	2.39 (0.58)8	2.13 (0.25)9	1.75 (0.07)9	1.57 (0.10)9	1.30 (0.07)8	0.49 (0.17)9	0.04 (0)8
Compressive Properties ASTM D695								
Maximum Stress (psi)	45460 (1900)5	41370 (820)5	37060 (500)5	27480 (210)5	22530 (480)5	20150 (220)5	13110 (140)5	6750 (170)5
Strain at Maximum Stress (Percent)	5.84 (0.26)5	5.40 (0.47)5	5.81 (0.68)5	6.05 (0.27)5	8.71 (0.68)5	9.99 (0.36)5	13.72 (0.36)5	12.35 (0.36)5
Stress at Yield (psi)	39800 (1340)5	37320 (1430)5	33620 (610)5	25370 (370)5	21220 (1140)5	19060 (210)5	12220 (350)5	6750 (170)5
Strain at Yield (Percent)	8.23 (0.45)5	8.17 (0.43)5	8.83 (0.35)5	9.65 (0.78)5	11.60 (0.39)5	12.74 (0.35)5	15.86 (0.13)5	12.35 (0.36)5
Elastic Modulus (psi x 10^6)	1.43 (0.04)5	1.55 (0.09)5	1.32 (0.20)5	1.05 (0.10)5	1.06 (0.10)5	0.93 (0.06)5	0.36 (0.03)5	0.024 (0.004)5
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	21180 (1280)4	19350 (1680)5	17860 (220)4	17760 (380)4	14570 (410)4	13590 (580)5	5050 (150)5	1630 (60)5
Deflection at Maximum Stress (in.)***	0.122 (0.01)4	0.117 (0.013)5	0.113 (0.001)4	0.137 (0.006)4	0.133 (0.009)4	0.175 (0.015)5	0.649 (0.05)5	0.440 (0.02)5
Elastic Modulus (psi x 10^6)	2.24 (0.02)4	2.13 (0.04)5	1.99 (0.03)4	1.89 (0.03)4	1.55 (0.02)4	1.26 (0.03)5	0.60 (0.15)5	0.039 (0.002)5

*1 psi equals 6894 Pa.
**psi, followed by standard deviation and number of test specimens.
***1 inch equals 25.4 mm.

Table C-10. Electrical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Processed and Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C)

Electrical Properties	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	6.02	6.21	6.28	6.50	6.52	6.55	6.60	7.52	
1 kHz	5.89	6.05	6.12	6.46	6.50	6.53	6.54	6.70	
10 kHz	5.75	5.88	5.96	6.34	6.47	6.50	6.50	6.58	
100 kHz	5.61	5.71	5.81	6.15	6.40	6.47	6.47	6.48	
1 MHz	5.57	5.64	5.73	6.04	6.26	6.48	6.48	6.43	
Dissipation Factor ASTM D150									
100 Hz	0.015	0.017	0.014	0.003	0.004	0.004	0.010	0.279	
1 kHz	0.014	0.017	0.018	0.008	0.004	0.003	0.006	0.041	
10 kHz	0.016	0.019	0.017	0.015	0.006	0.003	0.004	0.013	
100 kHz	0.009	0.011	0.015	0.002	0.002	0.006	0.003	0.009	
1 MHz	0.012	0.015	0.016	0.021	0.022	0.018	0.007	0.010	
Dielectric Strength ASTM D149									
Volts/Mil	433	395	425	330	360	355	365	353	
Volume Resistivity ASTM D257									
-65°F									1.4×10^{17}
40°F									9.2×10^{16}
0°F									6.0×10^{15}
75°F									7.4×10^{14}
100°F									1.3×10^{15}
150°F									1.1×10^{15}
200°F									2.3×10^{14}
250°F									4.8×10^{13}
300°F									7.8×10^{12}
350°F									4.4×10^{11}
400°F									4.2×10^{10}

Table C-11. Mechanical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Processed and Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C) Plus 4 Hours at 400°F (204°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)	15000 (720)7	13380 (1240)8	11850 (1280)8	10140 (1250)8	8110 (1150)8	7230 (950)8	3210 (800)8	720 (26)8
Strain at Maximum Stress (Percent)	0.96 (0.08)7	1.04 (0.13)8	1.05 (0.18)8	0.94 (0.07)8	0.96 (0.07)8	1.06 (0.10)8	2.92 (0.94)8	3.23 (0.42)8
Elastic Modulus (psi x 10^6)	2.04 (0.22)7	1.73 (0.39)8	1.53 (0.42)8	1.67 (0.17)8	1.07 (0.35)8	1.13 (0.16)8	0.65 (0.27)8	0.029 (0.005)8
Compressive Properties ASTM D695								
Maximum Stress (psi)	50520 (1470)5	46700 (1960)5	41370 (1460)5	31110 (1070)5	23320 (1480)5	21150 (1510)5	13870 (1600)5	6400 (340)5
Strain at Maximum Stress (Percent)	9.08 (1.44)5	8.14 (0.15)5	8.31 (1.06)5	10.45 (0.9)5	10.41 (0.56)5	12.2 (0.34)5	14.31 (0.81)5	10.80 (0.05)5
Stress at Yield (psi)	44600 (4810)2	40500 (140)2	36320 (1360)2	27560 (850)2	20040 (60)2	17920 (790)2	12140 (760)2	
Strain at Yield (Percent)	7.04 (0.52)2	5.69 (0.13)2	6.84 (1.04)2	2.75 (0.13)2	2.64 (0.07)2	3.55 (0.06)2	4.87 (0.45)2	
Stress at Rupture (psi)	3780 (40)2	3950 (70)2		7680 (470)2	7090 (50)2	6100 (480)2	4010 (930)2	1540 (30)2
Strain at Rupture (Percent)				6.85 (0.32)2	6.60 (0.18)2	8.87 (0.14)2	11.66 (0.41)2	
Elastic Modulus (psi x 10^6)	1.19 (0.32)5	1.26 (0.30)5	1.17 (0.19)5	1.34 (0.14)5	1.10 (0.06)5	0.99 (0.06)5	0.66 (0.10)5	0.05 (0.02)5
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	23110 (2450)4	21040 (1660)5	19100 (1670)5	17760 (760)4	15300 (1360)5	13010 (1290)5	6910 (1900)4	1470 (100)4
Deflection at Maximum Stress (in.)	0.14 (0.02)4	0.13 (0.014)5	0.13 (0.017)5	0.15 (0.009)4	0.17 (0.16)5	0.16 (0.012)5	0.35 (0.12)4	0.39 (0.04)4
Elastic Modulus (psi x 10^6)	2.17 (0.13)4	2.05 (0.04)5	1.95 (0.07)5	1.78 (0.13)4	1.39 (0.05)5	1.32 (0.13)5	0.79 (0.24)4	0.04 (0.003)4

Table C-12. Electrical Properties of Epon Z Catalyzed Epoxy-Al_2O_3 Cured According to P.S. 9927061 Plus 4 Hours at 300°F (149°C) Plus 4 Hours at 400°F (204°C)

Electrical Properties	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	5.77	5.88	6.10	6.38	6.44	6.62	6.72	6.82	
1 kHz	5.65	5.74	5.94	6.32	6.39	6.54	6.67	6.55	
10 kHz	5.54	5.63	5.74	6.20	6.35	6.52	6.66	6.43	
100 kHz	5.60	5.65	5.72	6.11	6.47	6.48	6.70	6.43	
1 MHz	5.54	5.59	5.73	5.91	6.48	6.55	6.68	6.58	
Dissipation Factor ASTM D150									
100 Hz	0.016	0.017	0.013	0.005	0.004	0.003	0.007	0.177	
1 kHz	0.013	0.015	0.018	0.009	0.004	0.003	0.004	0.049	
10 kHz	0.012	0.013	0.017	0.017	0.005	0.004	0.003	0.016	
100 kHz	0.011	0.012	0.013	0.019	0.007	0.008	0.002	0.008	
1 MHz	0.011	0.011	0.009	0.020	0.022	0.019	0.008	0.011	
Dielectric Strength ASTM D149									
Volts/Mil	417	453	432	364	362	340	351	316	
Volume Resistivity ASTM D257									
-65°F									2.01×10^{17}
40°F									9.7×10^{16}
0°F									7.2×10^{16}
75°F									7.6×10^{15}
100°F									6.5×10^{15}
150°F									2.6×10^{15}
200°F									3.1×10^{14}
250°F									5.2×10^{13}
300°F									1.21×10^{13}
350°F									3.9×10^{11}
400°F									5.8×10^{10}

Table C-13. Mechanical Properties of NMA/DMP-30 Catalyzed Epoxy-Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)	10130 (680)4	9990 (370)4	9610 (1290)4	9160 (420)4	7660 (440)4	6500 (380)4	1800 (300)4	470 (9)3
Strain at Maximum Stress (Percent)	0.44 (0.08)4	0.43 (0.06)4	0.46 (0.05)4	0.49 (0.09)4	0.51 (0.02)4	0.47 (0.06)4	0.73 (0.16)4	2.11 (0.06)3
Stress at Yield (psi)								1640 (230)4
Strain at Yield (Percent)								3.12 (0.82)4
Elastic Modulus (psi x 10^6)	2.68 (0.25)4	2.53 (0.25)4	2.28 (0.19)4	2.40 (0.71)4	1.71 (0.06)4	1.67 (0.16)4	0.69 (0.24)4	0.03 (0.002)3
Compressive Properties ASTM D695								
Maximum Stress (psi)	39080 (590)4	36630 (410)4	32540 (100)4	25640 (110)4	21020 (170)4	17280 (340)4	9930 (50)4	3440 (30)4
Strain at Maximum Stress (Percent)	5.3 (2.4)4	3.9 (0.40)4	4.28 (0.31)4	3.65 (0.13)4	3.53 (0.62)4	2.98 (0.38)4	15.78 (0.46)4	9.70 (0.43)4
Stress at Rupture (psi)	39080 (590)4	33830 (570)4	29630 (260)4	25130 (370)4	19310 (320)4	15700 (480)4	9930 (50)4	3440 (30)4
Strain at Rupture (Percent)	5.3 (2.4)4	6.93 (0.88)4	7.45 (0.68)4	8.18 (0.35)4	7.65 (0.53)4	8.88 (0.97)4	15.78 (0.46)4	9.70 (0.43)4
Elastic Modulus (psi x 10^6)	3.25 (2.35)4	4.00 (0)4	1.77 (0.28)4	3.29 (0.61)4	1.88 (1.02)4	1.20 (0.23)4	0.35 (0.03)4	0.04 (0.002)4
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	15730 (960)4	15350 (1230)4	15150 (1380)4	12480 (1340)4	10900 (950)4	10630 (450)3	5820 (2210)4	770 (130)4
Deflection at Maximum Stress (in.)	0.08 (0.002)4	0.08 (0.006)4	0.08 (0.007)4	0.07 (0.008)4	0.08 (0.007)4	0.08 (0.01)3	0.45 (0.12)4	0.25 (0.04)4
Elastic Modulus (psi x 10^6)	2.11 (0.08)4	2.06 (0.09)4	2.05 (0.12)4	2.07 (0.09)4	1.67 (0.08)4	1.62 (0.04)3	1.50 (0.34)4	0.03 (0.001)4

Table C-14. Electrical Properties of NMA/DMP-30 Catalyzed Epoxy-Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C)

Electrical Properties	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	5.45	5.55	5.56	5.57	5.55	5.59	5.38	6.46	
1 kHz	5.42	5.49	5.52	5.55	5.53	5.57	5.50	6.71	
10 kHz	5.33	5.40	5.46	5.52	5.52	5.56	5.50	6.51	
100 kHz	5.48	5.53	5.57	5.65	5.70	5.73	5.65	6.18	
1 MHz	5.46	5.49	5.46	5.62	5.71	5.74	5.68	5.97	
Dissipation Factor ASTM D150									
100 Hz	0.826	0.006	0.004	0.002	0.004	0.005	0.001	0.125	
1 kHz	0.010	0.009	0.006	0.003	0.002	0.003	0.003	0.036	
10 kHz	0.010	0.011	0.009	0.005	0.003	0.003	0.002	0.045	
100 kHz	0.009	0.012	0.0011	0.008	0.005	0.001	0.002	0.039	
1 MHz	0.011	0.013	0.0013	0.013	0.0010	0.008	0.006	0.025	
Dielectric Strength ASTM D149									
Volts/Mil	414	353	428	348	338	325	351	344	
Volume Resistivity ASTM D257									
-65°F									1.35×10^{17}
40°F									6.85×10^{15}
0°F									1.75×10^{17}
75°F									3.63×10^{16}
100°F									1.14×10^{16}
150°F									3.49×10^{15}
200°F									7.50×10^{14}
250°F									2.47×10^{14}
300°F									2.82×10^{13}
350°F									2.23×10^{12}
400°F									3.36×10^{11}

Table C-15. Mechanical Properties of NMA-DMP-30 Catalyzed Epoxy Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C) Plus 24 Hours at 400°F (204°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)	12560 (920)5	12020 (1030)5	12200 (340)5	10820 (630)5	8480 (630)5	8480 (360)5	4130 (140)5	550 (34)5
Strain at Maximum Stress (Percent)	0.568 (0.055)5	0.528 (0.064)5	0.542 (0.094)5	0.588 (0.088)5	0.532 (0.055)5	0.626 (0.052)5	6.74 (0.456)5	10.16 (1.295)5
Elastic Modulus (psi x 10^6)	2.72 (0.180)5	2.75 (0.482)5	2.47 (0.169)5	2.97 (1.734)5	1.85 (0.216)5	1.61 (0.080)	0.334 (0.061)5	0.023 (0.001)5
Compressive Properties ASTM D695								
Maximum Stress (psi)	40260 (850)5	38640 (770)5	35060 (1790)5	28160 (480)5	21560 (300)5	20360 (230)5	14360 (430)5	5000 (140)5
Strain at Maximum Stress (Percent)	5.13 (0.38)5	6.49 (1.12)5	5.26 (0.36)5	5.87 (0.942)	5.54 (0.419)5	8.79 (0.734)5	11.06 (0.907)5	10.51 (0.417)5
Stress at Rupture (psi)	37680 (1450)5	34120 (1980)5	33100 (3170)5	25480 (2350)5	19260 (500)5	19520 (500)5	12960 (480)5	4500 (230)5
Strain at Rupture (Percent)	6.47 (0.375)5	8.86 (1.71)5	6.97 (0.776)5	8.86 (0.315)5	9.44 (0.611)5	11.04 (0.435)5	13.62 (0.915)5	11.27 (0.424)5
Elastic Modulus (psi x 10^6)	1.13 (0.067)5	2.39 (0.452)5	1.12 (0.048)5	1.03 (0.043)5	0.847 (0.129)5	0.790 (0.146)5	0.570 (0.076)5	0.0531 (0.0014)5
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	17500 (1560)4	16600 (140)2	15350 (2400)4	14400 (450)4	14400 (200)5	13000 (260)5	8360 (130)5	1210 (65)4
Deflection at Maximum Stress (in.)	0.109 (0.012)4	0.099 (0)2	0.102 (0.018)4	0.113 (0.006)4	0.121 (0.004)5	0.123 (0.007)5	0.188 (0.009)5	0.328 (0.015)4
Elastic Modulus (psi x 10^6)	1.86 (0.03)4	1.95 (0.03)2	1.81 (0.09)4	1.58 (0.06)4	1.60 (0.03)4	1.41 (0.04)5	1.03 (0.04)5	0.045 (0.002)4

Table C-16. Electrical Properties of NMA/DMP-30 Catalyzed Epoxy-Al_2O_3 Cured for 8 Hours at 200°F (93°C) Plus 24 Hours at 300°F (149°C) Plus 24 Hours at 400°F (204°C)

Electrical Properties	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	5.606	5.623	5.766	5.652	5.643	5.654	5.437	6.189	
1 kHz	5.508	5.545	5.671	5.628	5.599	5.721	5.410	5.989	
10 kHz	5.386	5.442	5.591	5.590	5.571	5.696	5.401	5.763	
100 kHz	5.389	5.411	5.445	5.606	5.480	5.728	5.525	5.723	
1 MHz	5.346	5.355	5.449	5.560	5.462	5.729	5.612	5.694	
Dissipation Factor ASTM D150									
100 Hz	0.0094	0.0072	0.0047	0.0033	0.0040	0.0042	0.0043	0.0352	
1 kHz	0.0126	0.0113	0.0073	0.0040	0.0035	0.0033	0.0025	0.0311	
10 kHz	0.0125	0.0151	0.0119	0.0065	0.0044	0.0025	0.0028	0.0238	
100 kHz	0.0125	0.0133	0.0133	0.0102	0.0058	0.0058	0.0083	0.0124	
1 MHz	0.0085	0.0103	0.0128	0.0141	0.0109	0.0096	0.0038	0.0100	
Dielectric Strength ASTM D149									
Volts/Mil	344	348	351	345	328	316	352	368	
Volume Resistivity ASTM D257									
-65°F									8.0×10^{16}
40°F									8.0×10^{16}
0°F									1.2×10^{17}
75°F									4.01×10^{16}
100°F									8.83×10^{15}
150°F									8.03×10^{15}
200°F									2.73×10^{15}
250°F									1.04×10^{15}
300°F									2.01×10^{14}
350°F									4.26×10^{13}

Table C-17. Mechanical Properties of DEA Catalyzed Epoxy-Beta-Eucryptite Cured for 24 Hours at 150°F (66°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)
Tensile Properties ASTM D638						
Maximum Stress (psi)	12100 (1220)10	12140 (820)10	11380 (640)10	9290 (410)10	1940 (290)10	680 (80)9
Strain at Maximum Stress (Percent)	0.71 (0.09)10	0.76 (0.09)10	0.72 (0.05)10	0.72 (0.07)10	10.08 (1.42)10	3.81 (0.38)9
Elastic Modulus (psi x 10^6)	1.96 (0.10)10	1.87 (0.15)10	1.87 (0.09)10	1.70 (0.04)10	0.18 (0.03)5	0.02 (0.003)9
Compressive Properties ASTM D695						
Maximum Stress (psi)	38200 (2830)5	35390 (390)5	28940 (500)5	22010 (240)5	12810 (150)5	4180 (120)5
Strain at Maximum Stress (Percent)	11.50 (5.25)5	9.35 (0.77)5	9.85 (0.22)5	14.24 (0.93)5	19.64 (0.09)5	12.02 (0.87)5
Elastic Modulus (psi x 10^6)	2.19 (0.51)5	1.37 (0.19)5	1.54 (0.08)5	1.67 (0.06)5	0.33 (0.02)5	0.046 (0.002)5
Flexural Properties ASTM D790						
Maximum Fiber Stress (psi)	15960 (1560)4	17520 (650)4	15510 (580)4	13470 (870)9	NA*	990 (80)4
Deflection at Maximum Stress (in.)	0.10 (0.01)4	0.12 (0.005)4	0.12 (0.02)4	0.10 (0.008)9	NA	0.50 (0.05)4
Elastic Modulus (psi x 10^6)	1.78 (0.03)4	1.62 (0.02)4	1.60 (0.04)4	1.48 (0.07)9	NA	0.02 (0.001)4

*NA (Not Available)

Table C-18. Electrical Properties of DEA Catalyzed Epoxy-Beta-Eucryptite Cured for 24 Hours at 150°F (60°C)

	Test Temperature						
Electrical Properties	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)	Ohm·cm
Dielectric Constant ASTM D150							
100 Hz	4.60	4.81	5.19	5.86	7.71	42.17	
1 kHz	4.51	4.59	4.95	5.44	6.35	11.40	
10 kHz	4.35	4.41	4.71	5.15	5.70	8.20	
100 kHz	4.24	4.41	4.66	4.95	5.35	6.82	
1 MHz	4.15	4.29	4.43	4.72	5.11	6.13	
Dissipation Factor ASTM D150							
100 Hz	0.024	0.032	0.034	0.063	0.169	3.89	
1 kHz	0.023	0.029	0.033	0.043	0.099	0.42	
10 kHz	0.024	0.028	0.033	0.032	0.060	0.196	
100 kHz	0.019	0.025	0.035	0.033	0.040	0.112	
1 MHz	0.024	0.025	0.031	0.035	0.049	0.07	
Dielectric Strength ASTM D149							
Volts/Mil	413	428	457	329	294	177	
Volume Resistivity ASTM D257							
-65°F							3.9×10^{15}
40°F							2.1×10^{15}
0°F							9.2×10^{14}
75°F							3.2×10^{14}
100°F							1.7×10^{14}
150°F							3.3×10^{13}
200°F							1.8×10^{11}
250°F							1.1×101^{0}
300°F							3.7×10^{9}
350°F							1.3×10^{9}

Table C-19. Mechanical Properties of Epon Z Catalyzed Epoxy-Beta-Eucryptite Cured for 4 Hours at 130°F (54°C) Plus 16 Hours 200°F (93°C)

Variable	Test Temperature -65°F (-54°C)	 -40°F (-40°C)	 0°F (-18°C)	 75°F (24°C)	 165°F (74°C)	 200°F (93°C)	 300°F (149°C)	 400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)	11530 (1490)5	9220 (1870)5	9840 (750)5	8140 (240)5	5280 (55)5	5120 (210)5	1340 (25)5	750 (50)5
Strain at Maximum Stress (Percent)	0.563 (0.09)5	0.403 (0.135)5	0.470 (0.062)5	0.494 (0.078)5	0.504 (0.095)5	0.516 (0.070)5	30.98 (1.42)5	14.25 (1.06)5
Elastic Modulus (psi x 10^6)	0.764 (0.059)5	0.811 (0.185)5	0.795 (0.141)5	0.659 (0.078)5	0.624 (0.155)5	0.443 (0.045)5	0.110 (0.001)5	0.022 (0.001)5
Compressive Properties ASTM D695								
Maximum Stress (psi)	43600 (690)3	36130 (1220)3	31500 (440)3	28070 (250)3	15730 (120)3	13200 (170)3	12430 (150)3	5990 (90)3
Strain at Maximum Stress (Percent)	5.38 (0.56)3	5.02 (0.31)3	5.00 (0.20)3	9.13 (0.42)3	2.47 (0.26)3	12.26 (0.28)3	16.40 (0.35)3	10.90 (0.18)3
Stress at Rupture (psi)	38270 (610)3	31730 (1010)3	27630 (1250)3	26000 (690)3	14000 (0)3	11800 (600)3	11530 (230)3	5990 (90)3
Elastic Modulus (psi x 10^6)	1.21 (0.062)3	1.21 (0.092)3	1.09 (0.210)3	0.95 (0.116)3	1.05 (0.173)3	0.967 (0.106)3	0.258 (0.016)3	0.062 (0.001)3
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	14770 (1970)3	15570 (1330)3	13870 (830)3	12100 (350)3	9790 (190)3	9500 (350)3	2340 (210)3	1330 (150)3
Deflection at Maximum Stress (in.)	0.092 (0.014)3	0.101 (0.009)3	0.097 (0.003)3	0.098 (0.009)3	0.094 (0.001)3	0.113 (0.011)3	0.940 (0.126)3	0.380 (0.04)3
Elastic Modulus (psi x 10^6)	1.75 (0.017)3	1.72 (0.051)3	1.59 (0.051)3	1.40 (0.067)3	1.36 (0.031)3	1.16 (0.025)3	0.350 (0.001)3	0.0367 (0.0006)3

Table C-20. Electrical Properties of Epon Z Catalyzed Epoxy-Beta-Eucryptite Cured for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

	Test Temperature								
Electrical Properties	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	4.85	5.08	5.53	6.27	8.34	10.27	16.07	48.03	
1 kHz	4.67	4.86	5.19	5.65	6.69	7.72	10.55	15.89	
10 kHz	4.49	4.65	4.93	5.32	5.91	6.45	8.17	10.59	
100 kHz	4.45	4.58	4.79	5.20	5.80	5.92	6.91	8.63	
1 MHz	4.33	4.42	4.59	4.99	5.43	5.58	6.16	7.32	
Dissipation Factor ASTM D150									
100 Hz	0.027	0.03	0.03	0.093	0.17	0.264	0.31	1.038	
1 kHz	0.027	0.03	0.033	0.054	0.112	0.16	0.222	0.38	
10 kHz	0.026	0.03	0.035	0.037	0.07	0.96	0.149	0.193	
100 kHz	0.025	0.03	0.035	0.035	0.044	0.058	0.111	0.138	
1 MHz	0.023	0.026	0.035	0.035	0.037	0.045	0.074	0.124	
Dielectric Strength ASTM D149									
Volts/Mil	383	405	418	308	223	250	181	105	
Volume Resistivity ASTM D257									
-65°F									1.98×10^{17}
40°F									1.98×10^{17}
0°F									1.18×10^{14}
75°F									8.53×10^{13}
165°F									4.34×10^{13}
200°F									4.40×10^{13}
300°F									1.01×10^{12}
400°F									6.82×10^{9}

Table C-21. Mechanical Properties of DEA Catalyzed, CTBN Modified Epoxy-Epoxy-GMB Cured for 24 Hours at 150°F (66°C)

	Test Temperature					
Variable	-65°F (-54°C)	-40°F (40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)
Tensile Properties ASTM D638						
Maximum Stress (psi)	9470 (840)8	8600 (380)8	8470 (280)8	6730 (260)10	990 (140)10	210 (5.7)10
Strain at Maximum Stress (Percent)	2.04 (0.27)8	1.99 (0.18)8	1.95 (0.09)8	1.58 (0.12)10	8.90 (2.10)10	3.16 (0.37)10
Elastic Modulus (psi x 10^6)	0.52 (0.03)8	0.49 (0.06)8	0.47 (0.01)8	0.48 (0.03)10	0.15 (0.04)10	0.013 (0.001)10
Compressive Properties ASTM D695						
Maximum Stress (psi)	21640 (490)4	19050 (140)3	15930 (170)4	11990 (60)4	3860 (40)4	1190 (10)4
Strain at Maximum Stress (Percent)	6.18 (0.33)4	5.37 (0.25)3	5.05 (0.21)4	4.68 (0.13)4	11.83 (0.53)4	10.08 (0.22)4
Elastic Modulus (psi x 10^6)	0.50 (0.05)4	0.50 (0.03)3	0.44 (0.01)4	0.50 (0.01)4	0.09 (0.007)4	0.013 (0.001)4
Flexural Properties ASTM D790						
Maximum Fiber Stress (psi)	12380 (510)5	11620 (230)5	10360 (460)5	8560 (250)5	2130 (200)5	420 (5)5
Deflection at Maximum Stress (in.)	0.28 (0.01)5	0.27 (0.01)5	0.25 (0.02)5	0.22 (0.01)5	0.53 (0)5	0.39 (0.02)5
Elastic Modulus (psi x 10^6)	0.49 (0.01)5	0.47 (0.01)5	0.45 (0.01)5	0.45 (0.01)5	0.14 (0)5	0.015 (0)5

Table C-22. Electrical Properties of DEA Catalyzed, CTBN Modified Epoxy-GMB Cured for 24 Hours at 150°F (66°C)

Electrical Properties	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	250°F (121°C)	Ohm·cm
Dielectric Constant ASTM D150							
100 Hz	2.62	2.75	3.80	3.08	3.59	8.23	
1 kHz	2.47	2.60	2.88	3.04	3.32	4.02	
10 kHz	2.40	2.48	2.74	2.98	3.20	3.68	
100 kHz	2.43	2.49	2.69	2.99	3.26	3.58	
1 MHz	2.37	2.41	2.53	2.84	3.17	3.42	
Dissipation Factor ASTM D150							
100 Hz	0.121	0.04	0.021	0.014	0.100	0.728	
1 kHz	0.032	0.035	0.031	0.011	0.038	0.259	
10 kHz	0.021	0.028	0.037	0.018	0.019	0.071	
100 kHz	0.020	0.022	0.046	0.032	0.018	0.040	
1 MHz	0.017	0.023	0.039	0.042	0.031	0.034	
Dielectric Strength ASTM D149							
Volts/Mil	419	398	384	370	346	120	
Volume Resistivity ASTM D257							
-65°F							7.01×10^{15}
40°F							$1.83 \times 10-^{5}$
0°F							4.72×10^{14}
75°F							2.91×10^{14}
100°F							1.59×10^{14}
150°F							4.97×10^{13}
200°F							2.24×10^{11}
250°F							2.71×10^{9}
300°F							5.60×10^{9}
350°F							2.49×10^{9}
400°F							1.75×10^{9}

Table C-23. Mechanical Properties of Epon Z Catalyzed CTBN Modified Epoxy-GMB Cured for 4 Hours at RT Plus 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C)

Variable	Test Temperature -65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)
Tensile Properties ASTM D638								
Maximum Stress (psi)	8180 (470)4	7640 (260)4	6470 (850)4	5290 (40)5	4320 (120)5	3630 (120)5	640 (90)5	250 (8)4
Strain at Maximum Stress (Percent)	1.58 (0.17)4	1.75 (0.09)4	1.47 (0.22)4	1.20 (0.07)5	1.11 (0.11)5	1.10 (0.07)5	5.77 (2.73)5	2.69 (0.41)4
Elastic Modulus (psi x 10^6)	0.49 (0.02)4	0.48 (0.05)4	0.48 (0.01)4	0.48 (0.04)5	0.42 (0.04)5	0.37 (0.01)5	0.05 (0.03)5	0.015 (0.001)4
Compressive Properties ASTM D695								
Maximum Stress (psi)	18960 (120)4	17590 (70)4	15680 (100)4	12810 (20)4	9060 (20)4	7480 (90)4	2780 (100)4	1080 (2)4
Strain at Maximum Stress (Percent)	4.65 (0.13)4	4.68 (0.17)4	4.70 (0.14)4	4.18 (0.24)4	3.15 (0.13)4	3.18 (0.13)4	13.85 (0.68)4	8.20 (0.22)4
Elastic Modulus (psi x 10^6)	0.53 (0.02)4	0.49 (0.03)4	0.46 (0.02)4	0.45 (0.04)4	0.38 (0.02)4	0.33 (0.01)4	0.06 (0.015)4	0.016 (0.001)4
Flexural Properties ASTM D790								
Maximum Fiber Stress (psi)	11120 (310)5	10400 (320)5	8530 (270)5	6700 (160)5	5120 (130)5	4640 (100)4	NA*	NA
Deflection at Maximum Stress (in.)	0.250 (0.007)5	0.242 (0.004)5	0.210 (0.012)5	0.167 (0.005)5	0.141 (0.019)5	0.149 (0.003)4	NA	NA
Elastic Modulus (psi x 10^6)	0.49 (0.005)5	0.47 (0.009)5	0.45 (0.01)5	0.44 (0.008)5	0.36 (0.02)5	0.35 (0.004)4	NA	NA

*NA (Not Available)

Table C-24. Electrical Properties of Epon Z Catalyzed, CTBN Modified Epoxy-GMB Cured for 4 Hours at 130°F (54°C) Plus 16 Hours at 200°F (93°C) Plus 4 Hours at 75°F (24°C)

	Test Temperature								
Electrical Properties	-65°F (-54°C)	-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	165°F (74°C)	200°F (93°C)	300°F (149°C)	400°F (204°C)	Ohm·cm
Dielectric Constant ASTM D150									
100 Hz	2.74	2.79	2.97	3.04	3.20	3.60	4.54	15.97	
1 kHz	2.55	2.66	2.87	2.99	3.08	3.16	3.42	6.36	
10 kHz	2.48	2.55	2.75	2.93	3.02	3.06	3.14	3.42	
100 kHz	2.51	2.57	2.72	2.95	3.08	3.12	3.15	3.17	
1 MHz	2.46	2.50	2.60	2.85	3.00	3.06	3.10	3.05	
Dissipation Factor ASTM D150									
100 Hz	0.139	0.039	0.019	0.013	0.056	0.148	0.417	2.514	
1 kHz	0.034	0.03	0.027	0.012	0.021	0.05	0.143	0.682	
10 kHz	0.019	0.025	0.031	0.017	0.013	0.018	0.042	0.146	
100 kHz	0.019	0.022	0.034	0.025	0.016	0.01	0.016	0.047	
1 MHz	0.017	0.022	0.033	0.033	0.024	0.019	0.016	0.024	
Dielectric Strength ASTM D149									
Volts/Mil	384	465	553	347	357	328	259	115	
Volume Resistivity ASTM D257									
-65°F									7.81×10^{15}
40°F									6.39×10^{15}
0°F									3.7×10^{14}
75°F									3.91×10^{14}
100°F									2.76×10^{14}
150°F									4.86×10^{13}
200°F									2.39×10^{13}
250°F									2.60×10^{12}
300°F									3.42×10^{11}
350°F									1.09×10^{9}

Table C-25. Thermal Properties of Various Encapsulants

Variable	Epon Z/Epoxy/ Al_2O_3 Cure 1	Epon Z/Epoxy/ Al_2O_3 Cure 2	Epon Z/Epoxy/ Al_2O_3 Cure 3	NMA/DMP-30/ Epoxy/Al_2O_3 Cure 4	NMA/DMP-30/ Epoxy/Al_2O_3 Cure 5
Coefficient of Thermal Expansion (in./in./°C) ASTM D696					
-65°F to RT	25×10^{-6}	23×10^{-6}	22×10^{-6}	22×10^{-6}	22×10^{-6}
RT to 165°F	31×10^{-6}	31×10^{-6}	30×10^{-6}	28×10^{-6}	27×10^{-6}
165°F to 250°F					
165°F to 300°F	37×10^{-6}	39×10^{-6}	38×10^{-6}	44×10^{-6}	34×10^{-6}
300°F to 400°F	86×10^{-6}	105×10^{-6}	81×10^{-6}	94×10^{-6}	80×10^{-6}
Heat Distortion Temperature at 264 psi (1.82 MPa) ASTM D648	240°F (116°C)	309°F (154°C)	306°F (152°C)	NA	320°F (160°C)
Glass Transition Temperature	245°F (119°C)	316°F (157°C)	342°F (172°C)	275°F (135°C)	NA
Specific Gravity	2.39	2.39	2.39	2.43	2.43

Cure 1: 4 hours at 130°F and 16 hours at 200°F
Cure 2: 4 hours at 130°F, 16 hours at 200°F, and 4 hours at 300°F
Cure 3: 4 hours at 130°F, 16 hours at 200°F, 4 hours at 300°F, and 4 hours at 400°F
Cure 4: 8 hours at 200°F and 24 hours at 300°F
Cure 5: 8 hours at 200°F, 24 hours at 300°F, and 24 hours at 400°F

Table C-25. Continued. Thermal Properties of Various Encapsulants

Variable	DEA/Epoxy/ GMB Cure 6	Epon Z/Epoxy/ GMB Cure 7	Epon Z/Epoxy/ GMB Cure 8	DEA/CTBN/ Epoxy/GMB Cure 9	Epon Z/CTBN/ Epoxy/GMB Cure 7
Coefficient of Thermal Expansion (in./in./°C) ASTM D698					
-65°F to RT	33×10^{-6}	30×10^{-6}	30×10^{-6}	35×10^{-6}	35×10^{-6}
RT to 165°F	38×10^{-6}	35×10^{-6}	37×10^{-6}	39×10^{-6}	40×10^{-6}
165°F to 250°F	86×10^{-6}			73×10^{-6}	
165°F to 300°F		41×10^{-6}	41×10^{-6}		41×10^{-6}
300°F to 400°F		83×10^{-6}	84×10^{-6}		
Heat Distortion Temperature at 264 psi (1.82 MPa) ASTM D648	172°F (78°C)	240°F (116°C)	301°F (149°C)	165°F (74°C)	237°F (114°C)
Glass Transition Temperature	176 (80°C)	313 (156°C)	318 (158°C)	NA	243 (118°C)
Specific Gravity	0.810	0.825	0.826	0.789	0.800

Cure 6: PS 9927085
Cure 7: 4 hours at RT, 4 hours at 130°F, and 16 hours at 200°F
Cure 8: 4 hours at RT, 4 hours at 130°F, 16 hours at 200°F, and 4 hours at 300°F
Cure 9: 24 hours at 150°F
Cure 7: 4 hours at RT, 4 hours at 130°F, and 16 hours at 200°F

Table C-25 Continued. Thermal Properties of Various Encapsulants

Variable	DEA/Epoxy/ β-eucryptite Cure 9	Epon Z/Epoxy/ β-eucryptite Cure 1
Coefficient of Thermal Expansion (in./in./°C) ASTM D696*		
-65°F** to RT***	NA†	17×10^{-6}
RT to 165°F		25×10^{-6}
165°F to 250°F		
165°F to 300°F		33×10^{-6}
300°F to 400°F		86×10^{-6}
Heat Distortion Temperature at 264 psi (1.82 MPa) ASTM D648	174°F (79°C)	241°F (117°C)
Glass Transition Temperature	NA	NA
Specific Gravity	1.74	1.72

Cure 9: 24 hours at 150°F
Cure 1: 4 hours at 130°F and 16 hours at 200°F

*One inch equals 25.4 mm
**t°C equals (t°F - 32)/1.8
***Room temperature
†NA (Not Available)

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TEMPERATURE DEPENDENT PROPERTIES OF POTTING MATERIALS, J. M. Walker, D/814, UNCLAS Final, April 1976.

The physical properties: mechanical, electrical, and thermal of a general purpose epoxy potting compound, filled with either glass microspheres, aluminum oxide or beta-eucryptite and catalyzed with either an aliphatic amine, a liquid aromatic amine eutectic blend, or a liquid anhydride are discussed. The properties of a CTBN modified epoxy are also included. Twelve formulation-cure cycle combinations were chosen for evaluation. The temperature

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PLASTICS: Temperature Properties

TEMPERATURE DEPENDENT PROPERTIES OF POTTING MATERIALS, J. M. Walker, D/814, UNCLAS Final, PDO 6984803, BDX-613-1519, April 1976.

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dependent properties from -65° to 400°F (-54° to 204°C) for the 12 combinations are given.

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