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AVIONIC RADOME MATERIALS

R. H. Cary

Advisory Group for Aerospace Research and Development
Paris, France

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Advisory Report No.75

AVIONIC RADOME MATERIALS

Edited by

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at the request of the North Atlantic Military Committee.

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PREFACE

This report is complementary to AGARD Advisory Report No.53 on "Radomes Advanced Design", which described the design of radomes and concluded giving data required on materials suitable for consideration by the radome designer for aircraft, missile, etc. application. In this report the relevant data is given on the properties on radome materials in use and those which are considered candidates for possible application in avionics systems.

Inorganic and organic radome materials used for walls, core, and coatings are reported on together with electrical, mechanical, thermal and environmental properties. This report does not claim to be exhaustive on the material properties, since there is such a large variation in manufacturers products and variations in their construction, but has aimed to include a comprehensive description of the radome materials particularly for airborne microwave application.

The information given here will, however, allow the basic selection of materials and manufacturing process to be made for relatively conventional applications. For those applications where the state of art is in any way being strained, it is expected that the developer will follow the necessary material evaluation exercises for the particular case. Not all information has been available, and space has been left for the user to add his own observations and values.

The panel wish to thank the various organisations and institutions in the NATO countries who have kindly co-operated with forwarding information. As often many workers have measured a particular property, in this document often an average of the data is quoted.

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INTRODUCTION

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INTRODUCTION

1.1 General

The ideal radome material is one which is electrically very transparent to electromagnetic energy such that a minimum power is lost in transmission through the material, and structurally must retain its physical integrity throughout the entire flight trajectory in the presence of resulting aerodynamic loads, thermal stresses, environmental conditions, and to endure as long as required by the life of vehicle. The ideal radome material electrically is one which behaves as free space over all wavelengths. No such material exists which will give the necessary structural and physical protection to the vehicle, and hence the selection of a material is a compromise, and is one which has properties that will reasonably satisfy both electrical, mechanical and physical requirements.

The material requirements of each may be divided into:-

a) electrical

b) mechanical

c) thermal

d) manufacture and environmental

From a study of electrical, structural and environmental conditions the radome materials main interesting properties will be derived form:-

(i) The requirements to pass electromagnetic radiation with the minimum transmission loss, which has been shown to be dependent on the materials dielectric constant and loss tangent.

(ii) The requirement of being capable of being constructed into a suitable structure, which demands knowledge of the materials mechanical properties such as density, strength, durability etc. such that it is suitable to last the life of the vehicle under loads.

(iii) The requirement to withstand the thermal conditions, where a knowledge of the materials conductivity, emissivity, thermal shock and behaviour with temperature change, is necessary.

(iv) The requirement for the material to be manufactured, such that it can withstand the environmental, contamination conditions etc. which could degrade the materials.

There is a considerable choice of materials which may satisfy certain of the radome requirements. They may vary in their dielectric constant, strength, working temperature range etc. and quite often the requirements are such that no material is ideally suited to all the requirements and the best compromise is chosen. For instance a low dielectric constant may be chosen for a wide frequency band application, whereas a high dielectric constant may be chosen for a relative narrow frequency band minimum aberration requirement. A high density material like alumina may be chosen because it satisfies a high temperature requirement but a lighter material may satisfy a low temperature operation with consequent weight advantage. Materials which satisfy radome requirements are to be found in resin-glass sandwich or solid laminate composites, for the lower temperatures, or among ceramic type materials for the higher temperatures.

The number of types, grades etc. of materials as made by various manufactures, which could be used as radome materials is so vast that individual description of all their properties is beyond the scope of this study. Particularly this is so, as new formulations grades, types of materials are being continually marketed, and others replaced. In consequence a resume of general characteristics of the materials, and the exact characteristics of a particular manufacturers brand of a material unless unique will not necessarily be given. Some indication will be attempted to give the level of the better characteristics obtainable from a type of material. It must be appreciated that where radomes are of a composite nature much will depend upon the ratio of the ingredient materials and the method of manufacture.

Radome materials may be divided into those forming the:-

a) wall : detailed in Section 2

b) core : detailed in Section 3

c) finish and coating detailed in Section 4

and in each Section the electrical, mechanical, thermal and environmental properties need to be considered.

Occasionally a particular property is not detailed and space is left for it to be included when known, or to insert other details and notes as become available.

1.1.1 Units used and Conversions

FUNCTION	UNIT USED	CONVERSION
ELECTRICAL		
Dielectric Constant (ε)	Dimensionless	
Loss Tangent (Tan δ)	Dimensionless	
Volume Resistivity	ohm cm	
Dielectric Strength	kv/mm	
MECHANICAL		
Specific Gravity	Dimensionless	
Density	gm/cm^3	1 gm/cm^3 = 62.421 lb/ft^3
Stress and Elastic Moduli	N/m^2	1 N/m^2 = 1.45×10^{-4} lb/in^2
Poissons Ratio	Dimensionless	
Hardness	Knoop or Molus	
Viscosity (absolute)	Poise	1 Poise = 2.089×10^{-3} lbf s/ft^2 lbf sec/ft^2
THERMAL AND RADIATION		
Specific Heat	cals/kg ^{o}C	1 cal/Kg^{o}C = 10^{-3} BTU/lb^{o}F
Thermal Conductivity	cals/cm sec ^{o}C	1 cal/cm sec^{o}C = 241.9 BTU/ft hr ^{o}F
Diffusivity	cm^2/sec	1 cm^2/sec = 0.155 in^2/sec
Emissivity	Dimensionless	
Thermal Expansion	per ^{o}C	1/^{o}C = 0.5555/^{o}F
Temperature	^{o}C	
Radiation	Rads	

1.2 REQUIRED PROPERTIES MATERIALS FOR RADOMES

The objective of this section is to state the various properties which are likely to be of importance for choosing a suitable radome material for the particular users application.

The required properties are listed as follows:-

1.2.1 REQUIRED ELECTRICAL PROPERTIES OF RADOME MATERIALS

Dielectric Constant and Loss Tangent with material density

Dielectric Constant and Loss Tangent with frequency

Dielectric Constant and Loss Tangent and temperature

Dielectric Constant and Loss Tangent and humidity absorption

Dielectric Constant and Loss Tangent and radiation effects

Volume resistivity

Dielectric Strength.

1.2.2 REQUIRED MECHANICAL PROPERTIES OF RADOME MATERIALS

Specific Gravity

Youngs Modulus

Shear Modulus

Tensile Modulus and Strength

Poissons Ratio

Flexural Modulus and Strength with Temperature

Flexural Strength with Humidity

Flexural Strength with Thermal Ageing

Impact Strength

Hardness

Porosity

1.2.3 REQUIRED THERMAL PROPERTIES OF RADOME MATERIALS

Specific Heat

Thermal Conductivity

Thermal Expansion

Emissivity

Diffusivity

Thermal Shock

Ablation Data

Flammability

Temperature working range

1.2.4 REQUIRED PROCESSING AND ENVIRONMENT PROPERTIES OF RADOME MATERIALS

Manufacture and Cost Effectiveness

Temperature

Radiation, Sunlight and Nuclear

Rain erosion

Ageing

Storage

Fuel Contamination

Oils Contamination

Detergents Contamination

Salt Contamination

Water Absorption

1.2.5 TEST METHODS OF MATERIALS

The following lists some of the U.S.A. and U.K. test methods which could be employed to evaluate the properties of radome materials.

1.2.5.1 Electrical Test Methods

Dielectric constant and loss tangent	Low and medium temperature	- Shorted waveguide - Phase bridge - Cavity
	High temperature	- Phase bridge (rotating disc)

(* Note:- in some cases figures are given from low frequency capacitance bridge measurements. In general these will not be applicable to the microwave band).

Volume Resistivity	ASTM/D 257	BS 2782/202 A BS 2782/202 B
Dielectric Strength	ASTM/D 149	BS 2782/201 A BS 2782/201 C

1.2.5.2 Physical Property Test Methods

General all normal properties		DTD 5537 Recommendations BPF Recommendations
Specific Gravity (density)	ASTM/D 792 Federal Test Std. 406/5011	BS 2782/509A
Resin Content	Federal Std. 406/7061	

1.2.5.3 Mechanical Test Methods

Tensile Strength and Modulus	ASTM/D 638-68 ASTM/D 651 Federal Test Std. 406/1011	BS 2782/301 A
Compressive Strength and Modulus	ASTM/D 695 Federal Test Std. 406/1021 General Dynamics A052	BS 2782/303 B BS 2782/303 C
Flexural Strength and Modulus	ASTM/D 790-66	BS 2782/304 A BS 2572
Interlaminar Sheer	Federal Test Std. 406/1042 A Mil Handbook 17 Short Beam	
Elongation at Break	ASTM/D 638-68	
Impact Strength	ASTM/D 256	BS 2782/306 B IZOD - Notch

Hardness	ASTM/D 785 Rockwell	Brinell (5mm ball, 125 Kg weight)

1.2.5.4 Thermal Test Methods

Expansion	ASTM/D 696-44	
Deflection Temperature	ASTM/D 648	BS 2782/102 G
Conductivity	ASTM/D 977	Lee's Disc

1.2.5.5 Environmental Test Methods

Water Absorption	ASTM/D 570	BS 2782/502 F BS 2782/503 B
Chemical Contamination	ASTM/D 543	
Rain Erosion	ASTM/STP 408	R.A.E. Farnborough UK Test Method

PART II

WALL MATERIALS

INDEX TO PART II

WALL MATERIALS

2.1 Introduction

Radomes are usually either of solid wall construction or have walls separated by a core as in a sandwich construction. The materials used for sandwich walls are usually equally suitable for solid walls. Conventional organic resins such as polyester, epoxy, polyimide with reinforcement, such as glass fibres, form wall materials for radome applications particularly for temperatures encountered by aircraft, and have been used in solid and sandwich constructions. For higher temperatures, inorganic materials such as alumina, Pyroceram, and silica have been used usually as solid wall constructions. Information on the properties of these conventional radome materials is given in some detail. Information is also given on other materials which are not in general usage, but have found successful application such as silicone resin, quartz reinforcement, and materials which are new and promises to have considerable application in the future such as PRD49 reinforcement are also included.

Further information is given on materials which are candidates for radomes both inorganic and organic.

This section 2, is divided into inorganic and organic wall materials. Description of the materials is given with electrical, mechanical, thermal and environmental properties.

The Section 2.2 describes the following inorganic materials:

- 2.2.1 Alumina
- 2.2.2 Pyroceram
- 2.2.3 Silica
- 2.2.4 Cordierite
- 2.2.5 Mullite
- 2.2.6 Steatite
- 2.2.7 Silicon Nitride
- 2.2.8 Boron Nitride
- 2.2.9 Beryllium Oxide
- 2.2.10 Spinel
- 2.2.11 Magnesium Oxide
- 2.2.12 Glass-Ceramic Mexim
- 2.2.13 Glass-Mica Composite
- 2.2.14 Glass-Aluminium Phosphate Composite

The Section 2.3 describes organic materials which are combined with inorganic and organic reinforcements to form composite structures.

In Section 2.3.2 Basic Fibre Reinforcements - S, E, D, Glass, Quartz, Silica, PRD49, are described.

In Section 2.3.3 - 9, properties of Polyester, Epoxy, Polyimide, Silicone, Phenolic, and Diallyl Phthalate, resins, combined with reinforcements are given.

Phenolic, Silicone, DAP., composites are not so generally used as polyester, epoxy or polyimide, but the designer should not loose sight of these materials and others which could be concidered for a new project. In the case of resin-glass laminates, the choice of resin type, reinforcement type and content and manufacturing technique, all of which significantly affect properties, is such that the number of possible combinations become prohibitive for complete coverage here, even if complete information existed. The approach followed will be to give the general properties of typical conventional constructions. Inevitably, the radome designer will find himself having to predict the performance of a laminate from the properties of its constituent parts and for a particular manufacturing technique. This is somewhat easier for electrical properties since, given dielectric constants and loss characteristics for the parts and the resin or glass content to be achieved in the envisaged manufacturing process, a fairly accurate estimate of the laminate properties can be calculated. For structural and environmental properties, various broad statements, based upon those of the constituent parts and upon previous experience, may be made, but normally quantitative assessment will be obtained by sample measurement; the samples, necessarily, having been made by the selected manufacturing process.

2.2 INORGANIC WALL MATERIALS

Inorganic wall materials come into their own particularly when organic materials fail due to loss of strength at higher temperatures. Most organic materials are not suitable at 250°C and even the best can only survive a short term at 500°C. In general density, dielectric, mechanical, thermal, and environmental properties are those of most interest. Details are given individually of radome inorganic candidate materials, but a brief comparison of some of the most common candidate materials is given in Table 2.2.

TABLE 2.2

Property	Alumina 99%	Pyro-ceram	Silica: Slip Cast Fused	Silica: with Woven Quartz	Cordierite Rayceram	Silicon Nitride: Dense	Silicon Nitride: Reaction Bonded	Boron Nitride: Dense	Boron Nitride: Pyrolytic	Beryl Oxide 99%
Density gr. c.c.	3.9	2.6	2.2	1.8	2.45	3.2	2.4	2.0	1.25	2.95
lb. ft^3	244	162	137	112	153	200	150	125	78	185
$\frac{\lambda}{2}$ Weight Factor $\frac{gr.c.c}{\sqrt{\varepsilon}}$ 20°C 10 GHz	1.26	1.1	1.2	0.96	1.1	1.15	1.02	0.97	0.72	1.25
Dielectric Constant 10 GHz 25°C/43°F	9.6	5.65	3.42	3.05	4.85	7.9	5.6	4.5	3.1	6.6
500°C/832°F	10.3	5.8	3.55	3.04	5.05	8.2	5.7	4.6	3.2	7.2
1000°C/1632°F	11.4	6.1	3.8	3.02	-	-	5.8	4.78	3.3	8.0
% ε change v. 100°C/180°F	1.2	0.5	1	0.1	0.8	0.75	0.4	0.6	0.6	1.5
Loss Tangent 10 GHz 25°C/43°F	.0001	.0002	.0004	.0009	.002	.004	.001	.0003	.0003	.0003
500°C/832°F	.0005	.001	.001	.001	.008	.0045	.0025	.0006	.0006	.0005
1000°C/1632°F	.0014	-	-	-	-	-		-	.0008	.0014
Flexural Strength 25°C $N/m^2 \times 10^6$	270	235	44		125	400		100	100	260
500°C	250	200	54		120	400		60	-	200
1000°C	220	75	66		-	-		-	-	100
43°F p.s.i $\times 10^3$	40	34	6.3		18	57	25	14	14	35
832°F	37	29	7.8		17	57		9	-	29
1632°F	35	11	9.5		-	-		-	-	14
Youngs Modulus 25°C $N/m^2 \times 10^9$	380	120	48	18	128	300		70	13	320
500°C	350	120	48	-	125	300		50	-	300
1000°C	285	100	-	-	120	-		-	-	210
43°F p.s.i $\times 10^6$	54	17	7	2.5	18	43	15	10	1.75	46
832°F	50	17	7	-	17.6	43		7	-	42
1632°F	41	14	-	-	17	-		-	-	30
Poissons Ratio 0-800°C	0.28	0.245	0.15	0.07-0.18		0.26			0.23	0.34
Coeff. Thermal Conductivity BTU.ft.hr °F	20	2.2	.46	2.4	1.4	12	6	14	16	120
cals.cm.sec °C	.09	.009	.0019	.01	.006	.05		.06	.07	.5
Coeff. Thermal Expansion 10^{-6} in. in. °F	4.5	2.5	0.30		1.3	1.8	1.4	1.8	2.1	4.6
10^{-6} cm. cm. °C	8.1	4.0	0.54		2.3	3.2		3.2	3.8	8.3
Specific Heat cal gram. °C	0.27	0.2	0.18	0.25	0.18	0.2	0.2	0.3	0.29	0.26
Thermal Shock	Fair	Good	Very Good	Very Good	Good	Very Good	Very Good	Very Good	Very Good	Very Good
Water Absorption	0%	0%	5%	→ 20%	0%	-	→ 20%	0%	Closed Cell	0%
Rain Erosion	Excellent	Very Good	Poor	Poor to Fair	Very Good	Very Good	Good	Very Good	Good	Very Good

2.2.1 ALUMINA. Al_2O_3

Aluminium oxide is one of few current materials in usage for higher temperature radomes where the conventional resin-glass fabrication has failed due to softening of the resin. Thus its main area of application is for vehicles in the Mach 3 speed and above region, and has thus been used widely for ceramic radomes for missiles, and has been considered for certain special cases for aircraft installation.

While certain of its electr. al, physical and mechanical characteristics are such that they almost ideally suited for high temperature radomes, it does have certain disadvantageous properties.

Electrically its dielectric constant (near 9.6 ambient) is well suited for radome design particularly where minimum aberration is required, and its loss tangent is extremely low and even at high temperatures is quite acceptable for radome use. It has unfortunately a high temperature coefficient of dielectric constant, limiting the performance of the radome if required to work even at one frequency if a wide temperature range is to be encountered in operation. The high dielectric constant also results in tighter tolerances required for manufacture than for a lower dielectric constant material.

Its specific gravity near 3.28 grams/cc results in a generally heavy radome though the high dielectric constant helps to reduce the mechanical thickness, where a particular electrical thickness is required.

The material is one of hardest materials and in consequence is extremely good for rain erosion resistance, but on the other hand is difficult and costly to grind to shape.

The material for ceramics is mechanically strong, but the strains and tensions which the material suffers under thermal loads, can leave little for aerodynamic and structural loads. The material also has a high thermal expansion and is thus liable to be limited in thermal shock conditions, particularly if under other loads and impacts as for example rain. While as a guide 300°C thermal shock = considered typical safe for alumina microwave missile radome, a 400°C differential may well result in failure. It is difficult to generally forecast the thermal shock limits as each flight envelope and environment conditions, radome shape and thickness, will give rise to special analysis of the radomes limitations.

Alumina can be manufactured to a high degree of purity and density, thereby ensuring homogeneity and even electrical characteristics. A dense material may be near 99.5% while a different method of production may achieve 95%. The final product characteristics depends much on the manufactured process. Many have been tried: slip casting, isostatic and mechanical pressing, flame spraying, electrophoretic are some examples. Most successful production of alumina products use pressing processes. Coors, Wesgo, Norton (U.S.A.), Desmarquest (France), Lodge (U.K.), among others, have demonstrated that reasonable homogeneity and repeatable products can be attained. (Ref 39)

Alumina radomes are not excessively expensive products but the cost does increase if thickness correction has to be made, and often the attachment pieces, to match the differential properties of the alumina to the main body, can add costly problems to be solved. Further the cost of radomes can be high, if only a few are required.

ELECTRICAL PROPERTIES : ALUMINA TABLE 2.2.1.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(1) Fig 2.2.1.1.1	Fully dense, near 9.6, at 9.5 GHz
Dielectric Constant v. Frequency	(1)(2)(3)(4)(5) Fig 2.2.1.1.2	Within the tolerance of measurement the dielectric constant remains nearly constant over the microwave length band.
Dielectric Constant v. Temperature	(1)(2)(3)(4)(5) Fig 2.2.1.1.3	The dielectric constant change with temperature is near linear, at 1.2% per 100°C. This large change when operating over a wide frequency band can present design problems, and may be overcome by the addition of certain titanates but a higher dielectric constant.
Loss Tangent v. Frequency	(1)(2)(3)(4)(5) Fig 2.2.1.1.4	Though the loss tangent rises with frequency. The loss as a radome would be negligible.
Loss Tangent v. Temperature	(1)(2)(3)(4)(5) Fig 2.2.1.1.5	Even at high temperature the loss is negligible.
Dielectric Constant v. Humidity	(1)(3)	Humidity has a negligible effect on the denser alumina.
Dielectric Constant v. Radiation	(6)(7)	Unaffected by large doses of solar ultra violet radiation. Safe nuclear radiation is 10^{10} rads, above which marked rise in loss tangent and dielectric constant.
Volume Resistivity v. Temperature	(1) Fig 2.2.1.1.6	A higher grade insulator even at high temperature.
Dielectric Strength v. Temperature	(1) Fig 2.2.1.1.7	Maintains dielectric strength with temperature.

MECHANICAL PROPERTIES : ALUMINA TABLE 2.2.1.2

Property	Reference Fig	Remarks
Specific Gravity	(8)(3)	95% density: near 3.7 grams/cc 99% density: near 3.85 grams/cc
Youngs Modulus v. Temperature	(1)(4) Fig 2.2.1.2.1	37.8×10^{10} N/m^2 at ambient falls to 30×10^{10} N/m^2 at 1000°C
Youngs Modulus v. Porosity	(1)(4) Fig 2.2.1.2.2	A 5% porosity gives a 16% reduced modulus at room temperature.
Shear Modulus v. Temperature	(1)(9) Fig 2.2.1.2.3	15×10^{10} N/m^2 at room temperature Varies little up to 500°C
Rupture Modulus	(1)	near 3.4×10^6 N/m^2 at Room temperature
Poissons Ratio	(1)(4)(9) Fig 2.2.1.2.4	near 0.26 up to 900°C
Flexural Strength v. Temperature	(1)(4)(9) Fig 2.2.1.2.5	260×10^6 N/m^2 ambient, varies little up to 750°C
v Porosity	(1)(4) Fig 2.2...2.6	Decreased by inclusion of pores 5% porosity reduces strength to 200×10^6 N/m^2. Surface condition and grain size effects strength.
Tensile Strength v. Temperature	(1)(4)(9) Fig 2.2.1.2.7	Varies considerably with grain size, surface condition, but a but a dense homogeneous material would give 140×10^6 N/m^2 at room temperature, falling slightly at 500°C.
Compressive Strength v. Temperature	(1)(9) Fig 2.2.1.2.8	Near 2000×10^6 N/m^2 at room temperature for dense alumina.
Impact Strength	(1)	7 in lb
Hardness	(1)(11)	Extremely hard material 1750 kg/mm^2 KNOOP(1), 2000 KNOOP (11)

THERMAL PROPERTIES : ALUMINA

TABLE 2.2.1.3

Property	Reference & Fig	Remarks
Temperature Working Range	(1)(4)(8)(9)	1700°C (except limiting by thermal shock) Melting Temperature 2015°C
Specific Heat v. Temperature	(1)(4)(8)(9) Fig 2.2.1.3.1	175 cals/kg/°C ambient rising non linearly. (Dense alumina)
Conductivity v. Temperature	(1)(4)(8)(9)(11) Fig 2.2.1.3.2	.09 Cals/°C sec cm ambient (Dense alumina)
Diffusivity v. Temperature	(1)(8) Fig 2.2.1.3.3	0.117 sqcm/sec ambient (Dense alumina)
Expansion v. Temperature	(1)(9) Fig 2.2.1.3.5	8.1×10^{-6} °C average 0° to 1000°C
Emissivity v. Temperature	(1)(9) Fig 2.2.1.3.4	0.7 at 500°C (Dense alumina)
Ablation	(1)	Negligible
Thermal Shock	(2) (4) (9)	Sensitive to thermal Shock. Thickness of material, heat transfer ability are important in determining the level of thermal shock. A guide is that Mach 3 condition can sometimes be the limit with a possible 300°C + thermal shock, particularly if also subject to rain impact.
Flammability	(1)	Non-inflammable

ENVIRONMENTAL PROPERTIES : ALUMINA

TABLE 2.2.1.4

Properties	Reference & Fig	Remarks
Temperature	(1) (8) (9)	Maintain useful Electrical and Mechanical properties for Radomes to over 1000°C, but may be limited by thermal shock.
Humidity & Water Absorption	(1) (8) (9)	As the material density is high and any cells tend to be closed, humidity and water absorption is minimal.
Rain Erosion	(4)(10)	An excellent material to withstand rain erosion. 4200 minutes at 500 mph in 1 in/hr. rainfall on the RAE whirling arm rig exhibited little or no erosion.
Radiation Solar Nuclear	(6)(7)	Unaffected by large and prolonged solar radiation. Some electrical and mechanical degradation above 10^{10} rads dosage.
Contamination Oils Fuels Detergents Salts Acid	(1)(8)	Oils Fuels Detergents have negligible effects. Salt has negligible effect though absorption and volume resistivity, with usually no deleterious effect on a radome performance. Generally resistant to corrosives.
Storage & Ageing	(1)	Ageless Store to avoid shocks vibration and abrasives

ALUMINA: Dielectric Constant v. Density
Room Temperature 9.5 GHz

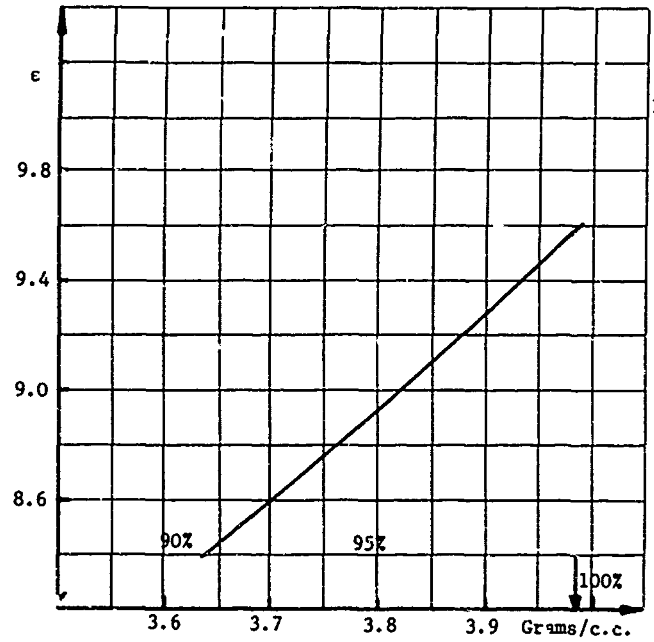


Fig 2.2.1.1.1

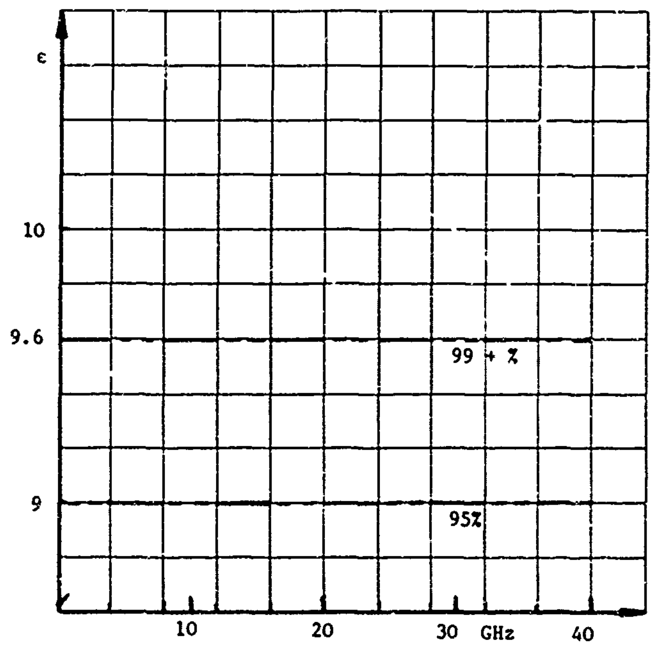


Fig 2.2.1.1.2

ALUMINA: Dielectric Constant v. Frequency
Room Temperature

ALUMINA: Dielectric Constant v. Temperature 9.5 GHz

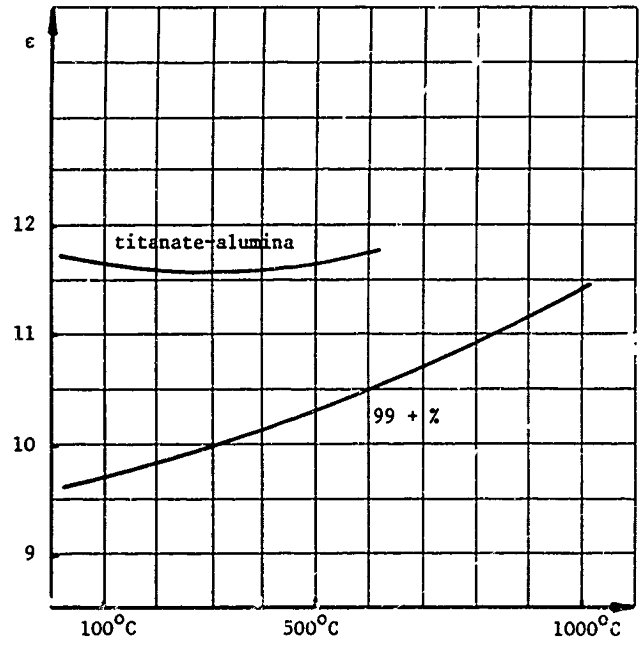


Fig 2.2.1.1.3

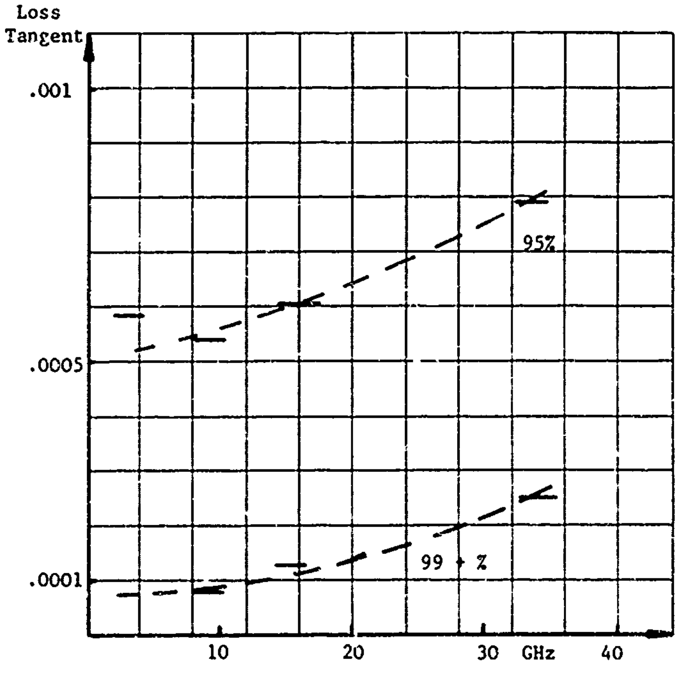


Fig 2.2.1.1.4

ALUMINA: Loss Tangent v. Frequency Room Temperature

ALUMINA: Loss Tangent v. Temperature 9.368 GHz

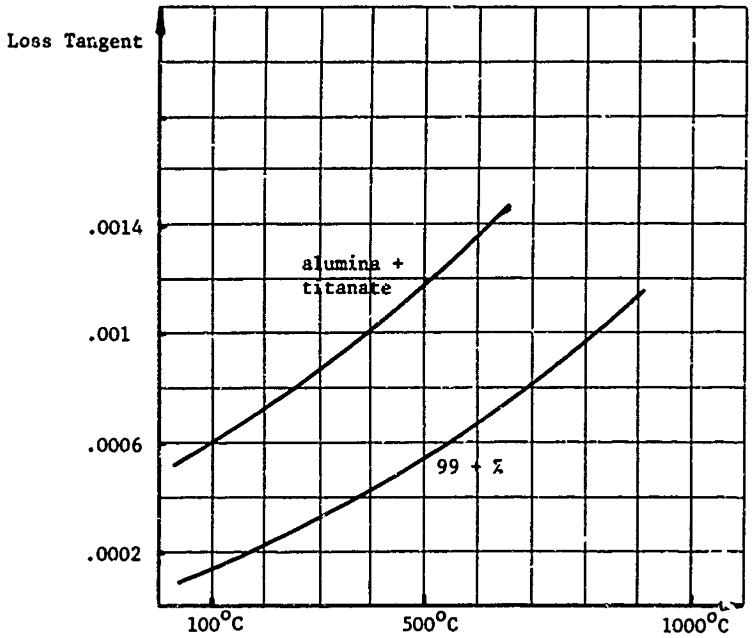


Fig 2.2.1.1.5

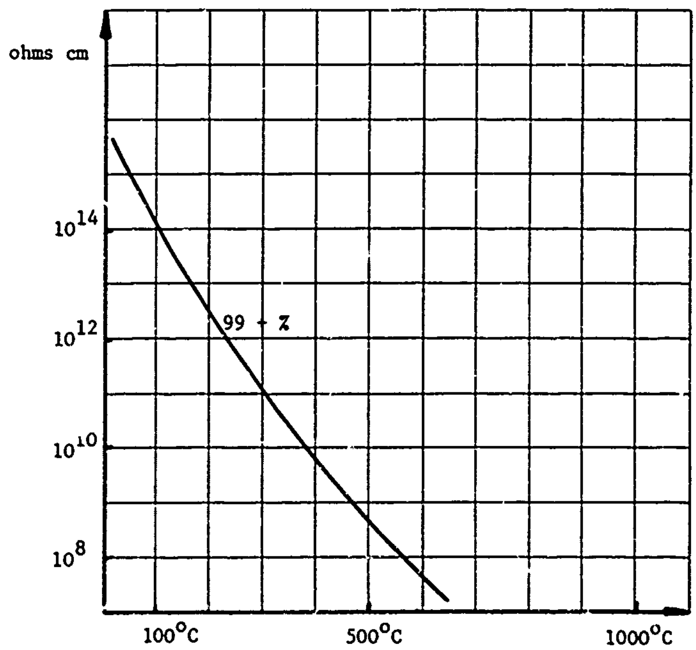


Fig 2.2.1.1.6

ALUMINA: Volume Resistivity v. Temperature

ALUMINA: Dielectric Strength v. Temperature

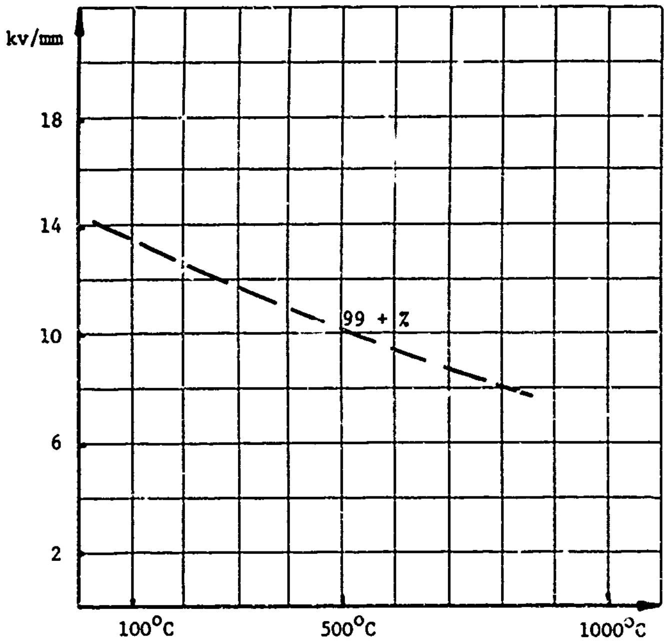


Fig 2.2.1.1.7

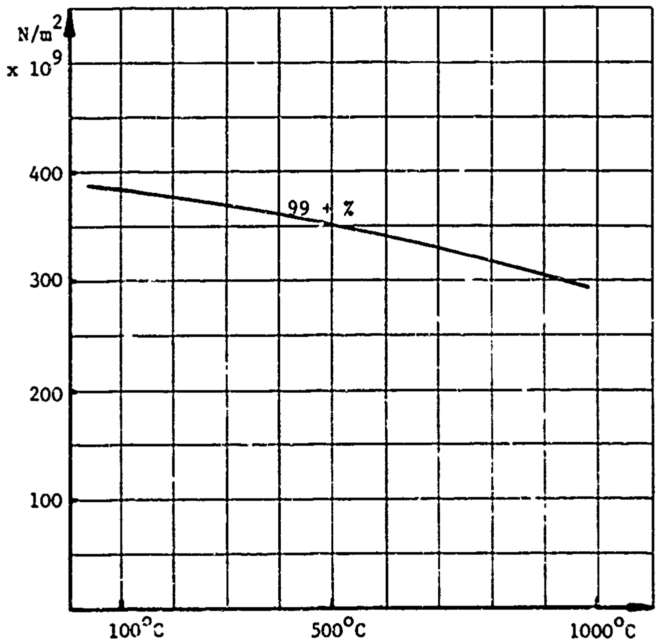


Fig 2.2.1.2.1

ALUMINA: Youngs Modulus v. Temperature

ALUMINA: Youngs Modulus v. Porosity

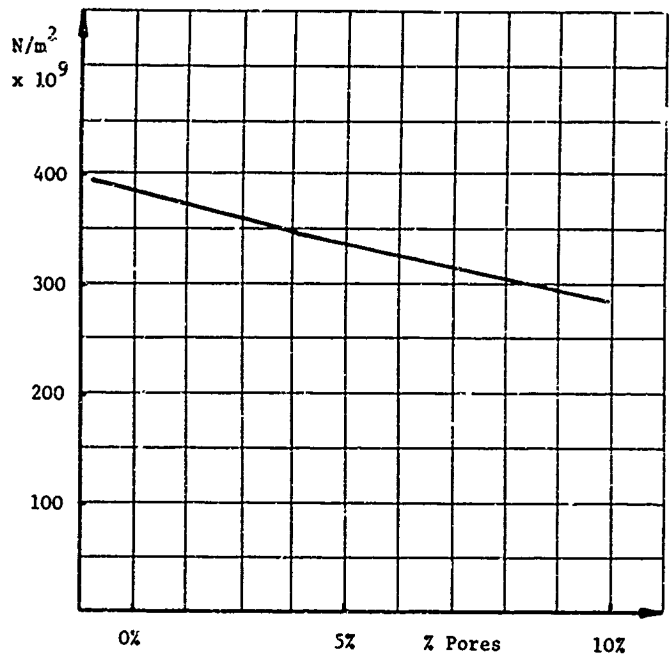


Fig 2.2.1.2.2

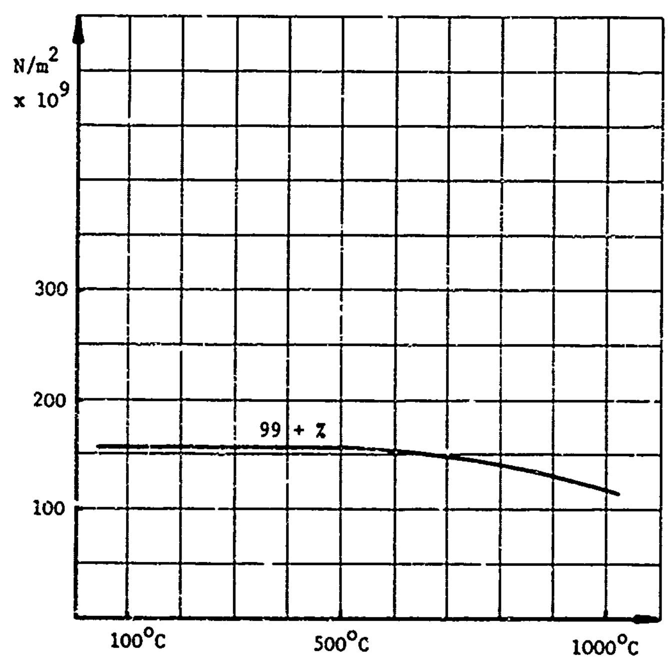


Fig 2.2.1.2.3

ALUMINA: Shear Modulus v. Temperature

ALUMINA: Poissons Ratio v. Temperature

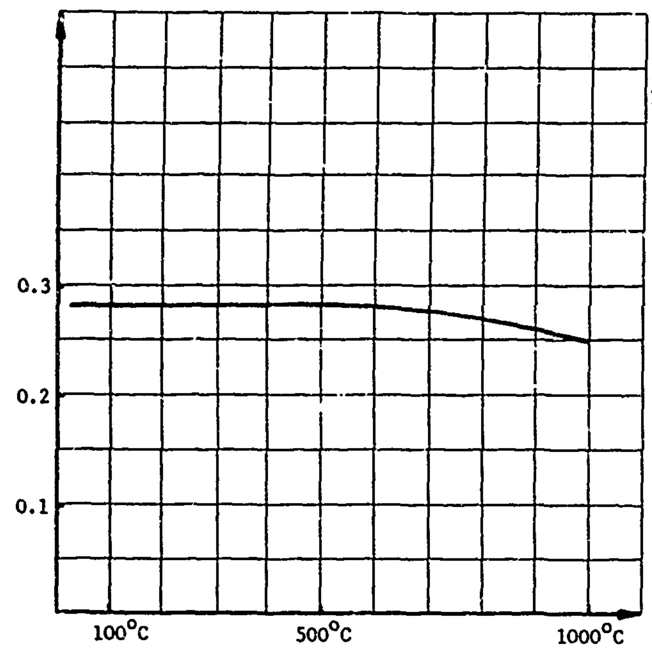


Fig 2.2.1.2.4

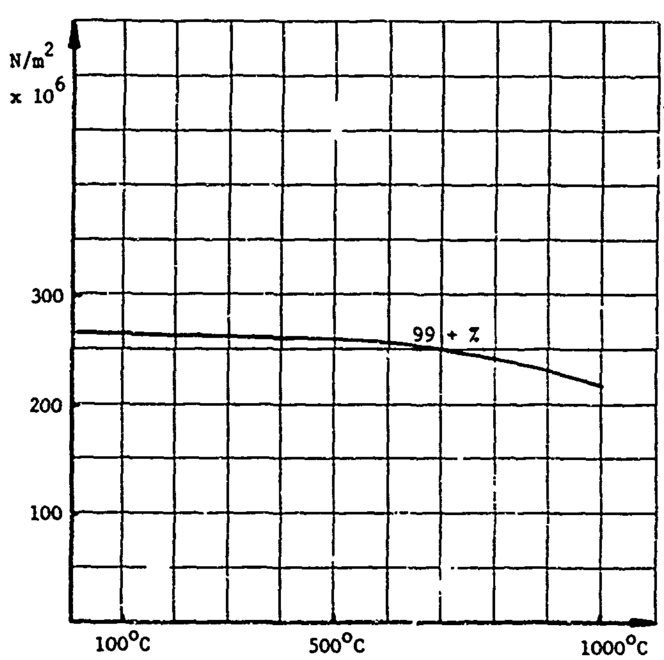


Fig 2.2.1.2.5

ALUMINA: Flexural Strength v. Temperature

ALUMINA: Flexural Strength v. Porosity 20°C

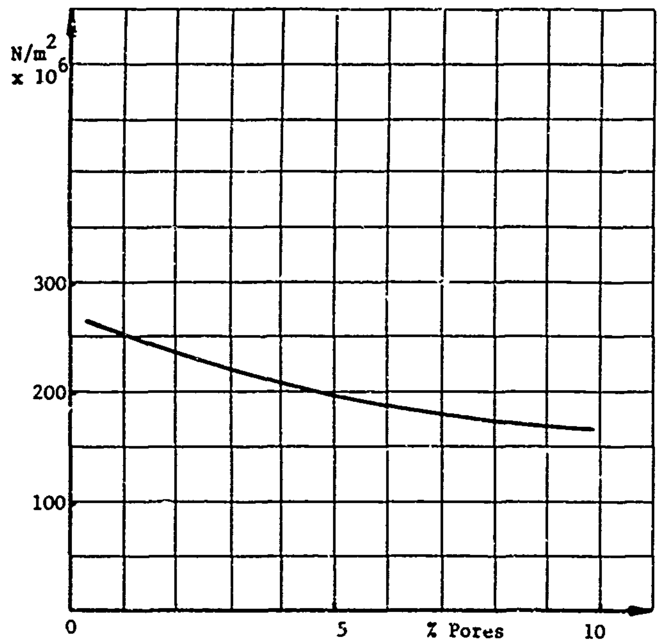


Fig 2.2.1.2.6

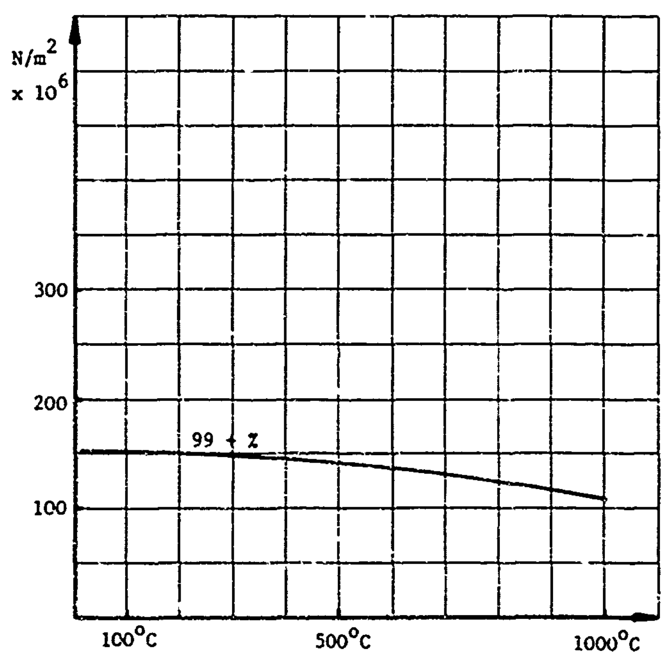


Fig 2.2.1.2.7

ALUMINA: Tensile Strength v. Temperature

ALUMINA: Compressive Strength v. Temperature

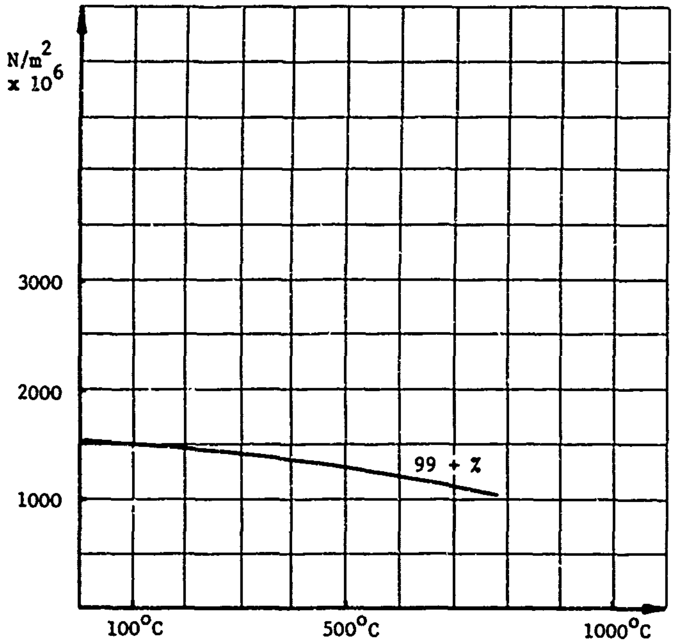


Fig 2.2.1.2.8

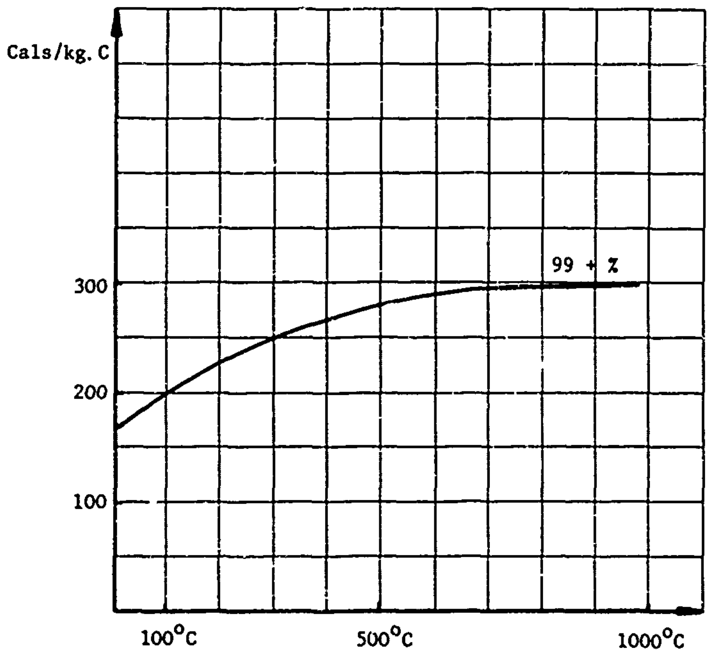


Fig 2.2.1.3.1

ALUMINA: Specific Heat v. Temperature

ALUMINA: Thermal Conductivity v. Temperature

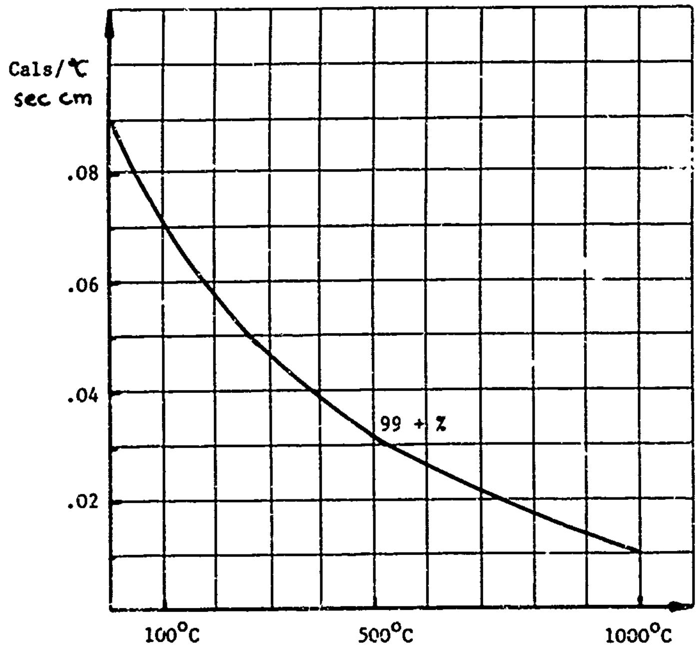


Fig 2.2.1.3.2

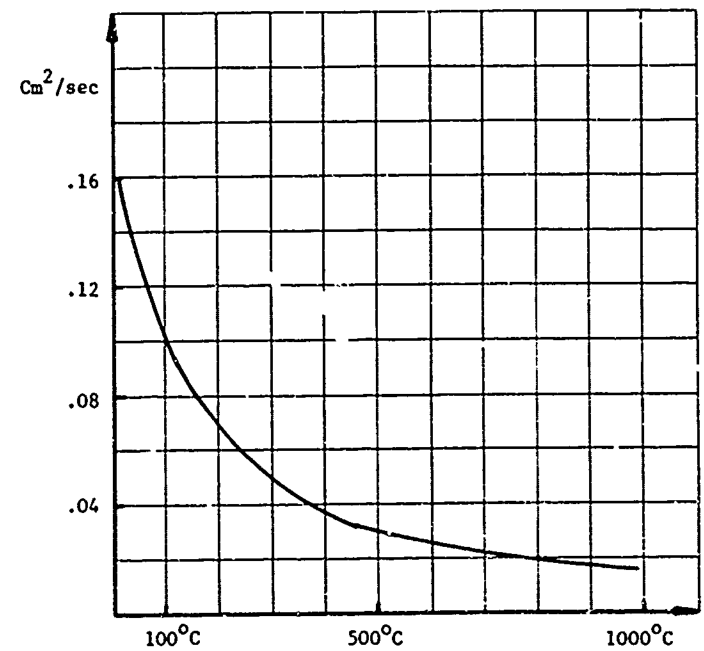


Fig 2.2.1.3.3

ALUMINA: Thermal Diffusivity v. Temperature

ALUMINA: Emissivity v. Temperature

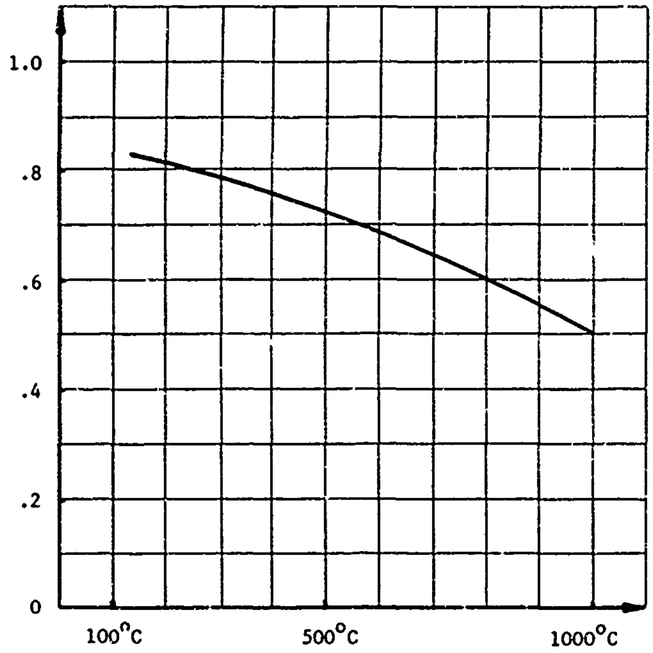


Fig 2.2.1.3.4

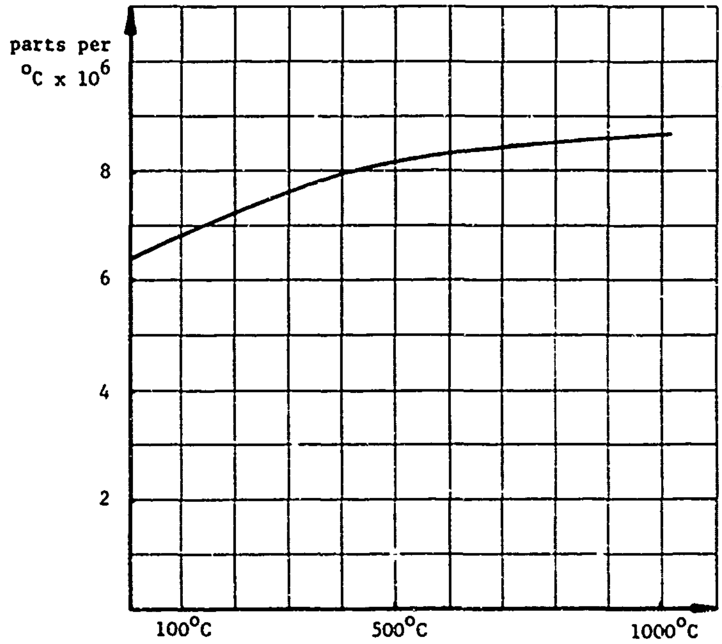


Fig 2.2.1.3.5

ALUMINA: Expansion v. Temperature

2.2.2 GLASS CERAMIC PYROCERAM

Pyroceram is a trademark referring to a glass ceramic material developed by the Corning Glass Co. (USA). It has been used in production of missile radomes as it has a high temperature capability where conventional resin-glass materials are inadequate. It is mainly used for radomes for vehicles in the Mach 3 and above speeds.

Of the Pyroceram materials No. 9606 is the standard commercial type for radome applications though other variants are available with various emphasis on particular properties.

Pyroceram 9606 has electrical, mechanical, thermal characteristics which put it in direct competition with alumina.

Electrically it has a dielectric constant of 5.65 at microwavelengths which is suitable for designing radomes of low aberration, and being lower than alumina, the thickness tolerance can be slightly relaxed. The change of dielectric constant with temperature is small, being only near 0.5% per 100°C, which ensures that the electrical thickness of the radome alters very little with the radome required to operate over a wide range of temperature. In this respect it is a more suitable material than alumina, where titanate additives have to be added in an attempt to stabilise temperature. The loss tangent of Pyroceram 9606 is low near 0.0003 at ambient, but rises steeply to 0.001 at 400°C and 0.01 at 900°C. At much higher temperature the attenuation loss would become significant but not necessarily prohibitive.

The specific gravity near 2.62 gm/cm^3 makes it a lighter material than alumina, but for the same electrical thickness due to higher dielectric constant of alumina, the weight of a half-wave radome is slightly less for one of alumina.

Mechanically the material is strong, with a modulus of rupture (flexural strength) at ambient at 240×10^6 N/m^2, which is somewhat less than alumina, and falls off at the higher temperatures. The mechanical properties can depend on the surface finish, and if the material has to be ground to thickness, some differences in its strength properties may result. The material is hard and has very good rain erosion characteristics. The material is generally considered to be somewhat better from thermal shock than alumina.

The manufacturing process are such that the final products are not subject to any large density changes and in consequence only minor changes of dielectric constant with material samples or batches is noted. The cost of Pyroceram radomes are competitive to alumina.

ELECTRICAL PROPERTIES : PYROCERAM 9606 **TABLE 2.2.2.1**

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(12)	Dielectric constant near 5.65 Very little density change in product on effecting dielectric constant.
Dielectric Constant v. Frequency	(5) (12) Fig 2.2.2.1.1	Negligible change over Microwave band.
Dielectric Constant v. Temperature	(5) (9) (12) Fig 2.2.2.1.2	Has low change of dielectric constant with temperature near 0.5% per 100°C.
Loss Tangent v. Frequency	(5) (12) Fig 2.2.2.1.3	Slight rise over microband. Would not effect radome performance at low temperature.
Loss Tangent v. Temperature	(5) (9) (12) Fig 2.2.2.1.4	Rises with temperature could become significant over 1000°C.
Dielectric Constant v. Humidity	(12)	Negligible effect.
Dielectric Constant v. Radiation		
Volume Resistivity v. Temperature	(9) Fig 2.2.2.1.5	Unlikely to effect radome design 10^{15} ohm cm ambienc : 10^{9} at 500°C
Dielectric Strength v. Temperature	(12)	14 kv/mm at 20°C

MECHANICAL PROPERTIES : PYROCERAM 9606 **TABLE 2.2.2.2**

Property	Reference Fig	Remarks
Specific Gravity	(12)	2.6 gm/cm^3 - 2.62 gm/cm^3 (maximum)
Youngs Modulus v. Temperature	(9) (12) Fig 2.2.2.2.1	Maintained with temperature 120×10^9 N/m^2 ambient.
Youngs Modulus v. Porosity		Porosity negligible
Shear Modulus v. Temperature	(9) (12) Fig 2.2.2.2.2	Maintained with temperature 50×10^9 N/m^2 ambient
Rupture Modulus	(9) (12) Fig 2.2.2.2.3	Falls with temperature 285×10^6 N/m^2 ambient
Poissons Ratio	(12) Fig 2.2.2.2.4	Near .245
Flexural Strength v. Temperature	(12) Fig 2.2.2.2.5	280×10^6 N/m^2 ambient
Tensile Strength v. Temperature	(9) (12) Fig 2.2.2.2.6	Falls sharply near 1000°C
Compressive Strength v. Temperature		
Impact Strength		
Hardness	(12)	619 kg/mm^2

THERMAL PROPERTIES : PYROCERAM 9606

TABLE 2.2.2.3

Property	Reference & Fig	Remarks
Temperature Working Range	(9) (12)	Up to 1000°C Melting point 1350°C
Specific Heat v. Temperature	(9) (12) Fig 2.2.2.3.1	.18 ambient cals/grams °C
Conductivity v. Temperature	(9) (12) Fig 2.2.2.3.2	.009 cals/°C sec cm
Diffusivity v. Temperature	(9) (12) Fig 2.2.2.3.3	.019 cm^2/sec.
Expansion v. Temperature	(9) (12) Fig 2.2.2.3.4	variable with temperature, near 4×10^{-6} over 1000°C
Emissivity v. Temperature	(9) (12) Fig 2.2.2.3.5	.83 at 100°C .6 at 1000°C
Ablation		Negligible
Thermal Shock	(4) (9) (12)	Low expansion rate, and other factors makes the material able to withstand a degree of thermal shock somewhat better than alumina.
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : PYROCERAM 9606

TABLE 2.2.2.4

Properties	Reference & Fig	Remarks
Temperature	(12)	Maintains useful electrical and mechanical properties for radomes to 1000°C, but may be limited by thermal shock.
Humidity & Water Absorption	(12)	Material is non porous and unaffected by humidity or water absorption.
Rain Erosion	(4) (12)	A very good material: 16 hours at 500 mph 1 in/hr. rain, slight erosion.
Radiation Solar Nuclear	(7)	Unaffected by long exposures to ultra-violet radiation. Safe nuclear radiation 10^{10} rads. Likely to withstand 400°C thermal radiation shock.
Contamination Oils Fuels Detergents Salts Acid	(12)	Oils, fuels, detergent, salt have negligible effect. Affected by some acids in concentrated form.
Storage & Ageing	(12)	Store to avoid shocks, abrasion and vibration. Inert.

PYROCERAM 9606: Dielectric Constant v. Frequency
Room Temperature

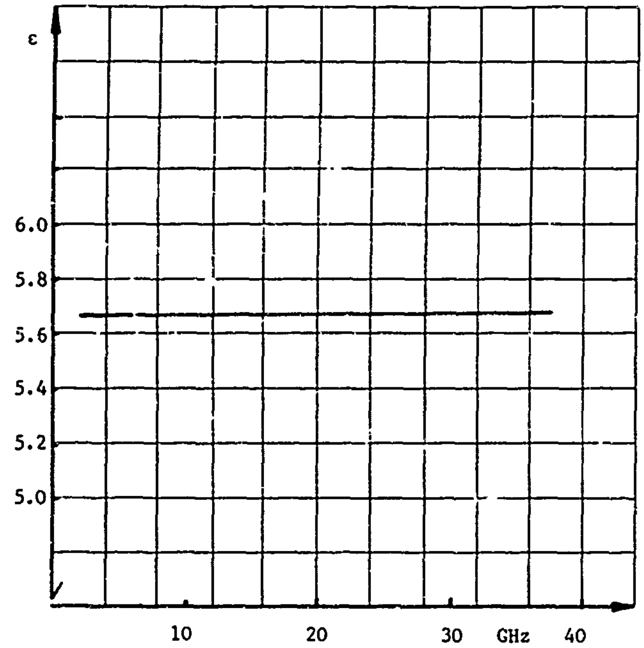


Fig 2.2.2.1.1

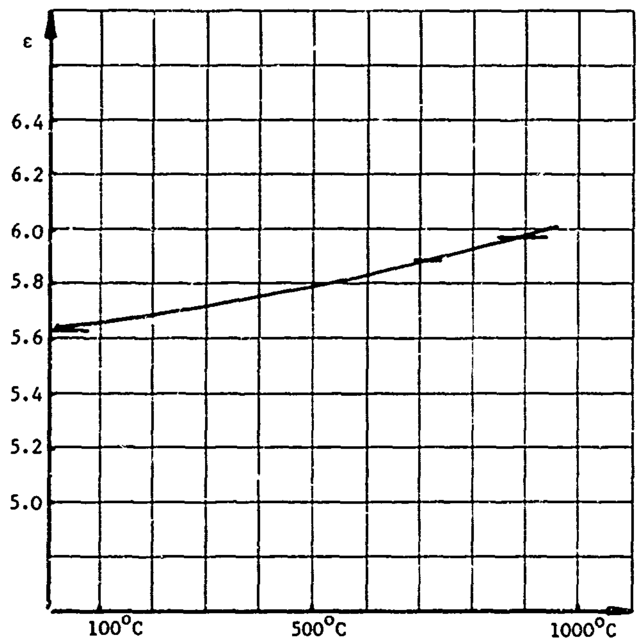


Fig 2.2.2.1.2

PYROCERAM 9606: Dielectric Constant v. Temperature
9.5 GHz

PYROCERAM 9606: Loss Tangent v. Frequency
Room Temperature

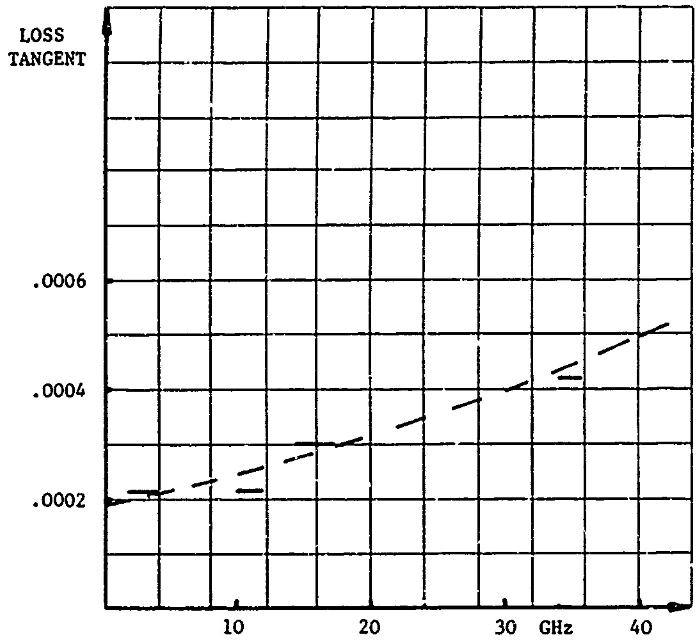


Fig 2.2.2.1.3

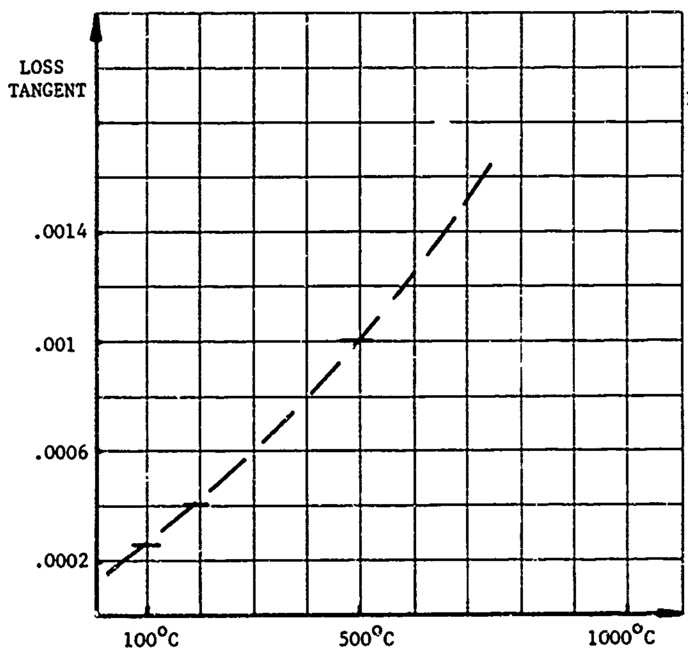


Fig 2.2.2.1.4

PYROCERAM 9606: Loss Tangent v. Temperature
9.368 GHz

PYROCERAM 9606: Volume Resistivity D.C. v. Temperature

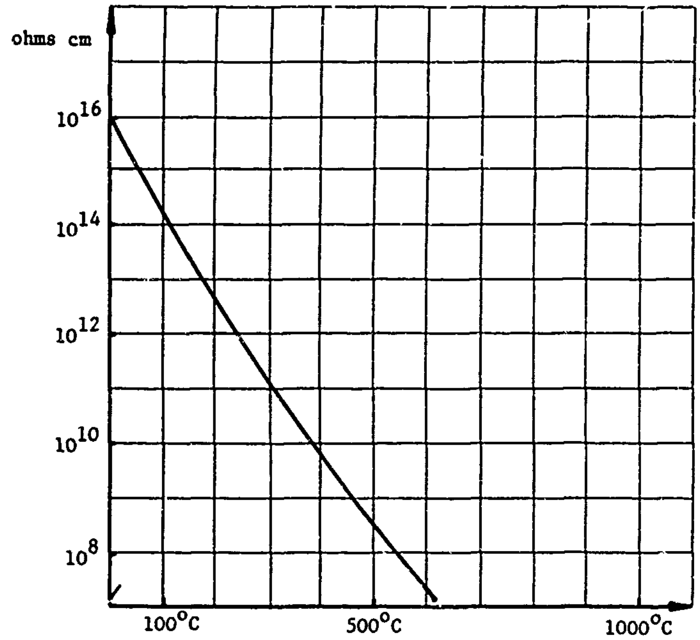


Fig 2.2.2.1.5

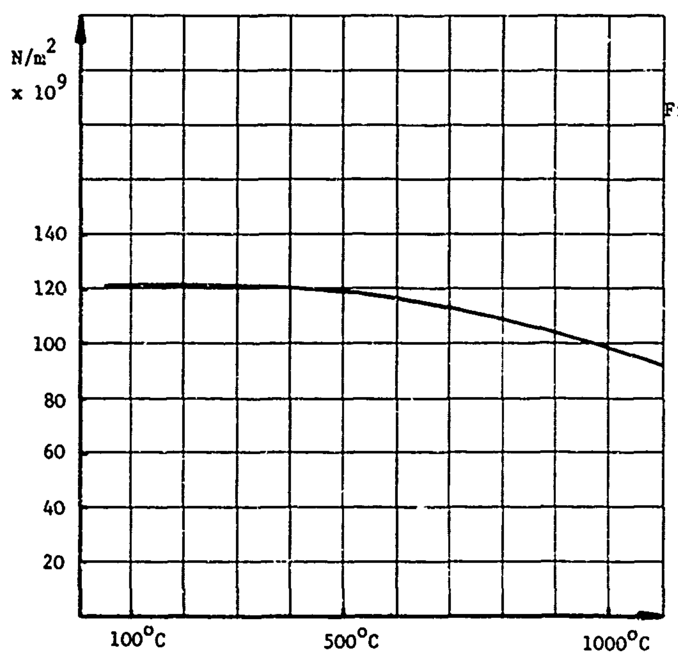


Fig 2.2.2.2.1

PYROCERAM 9606: Youngs Modulus v. Temperature

PYROCERAM 9606: Shear Modulus v. Temperature

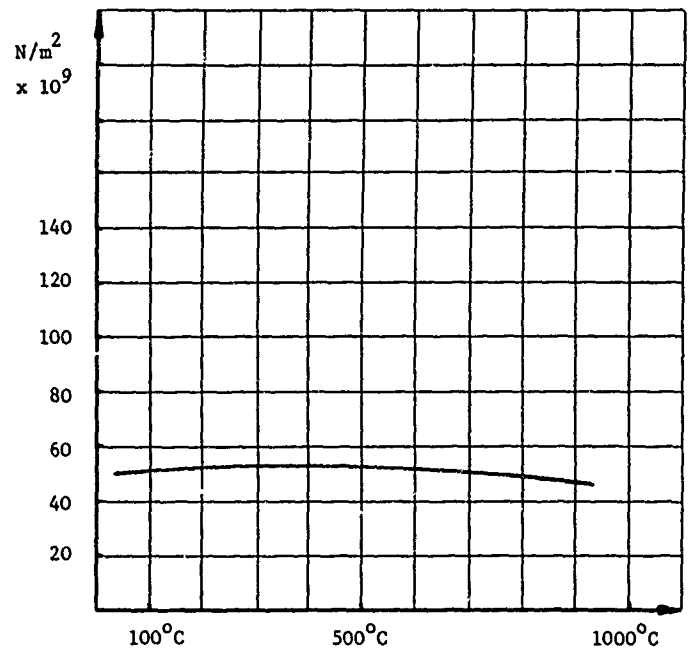


Fig 2.2.2.2.2

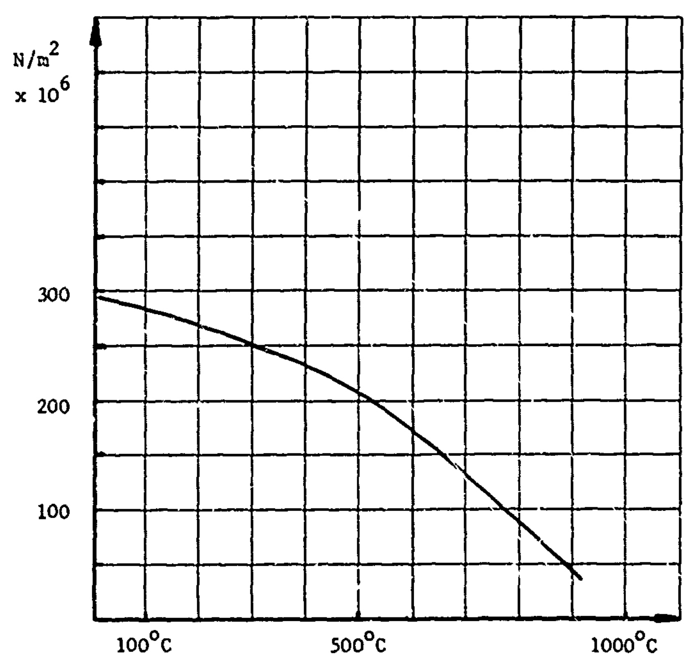


Fig 2.2.2.2.3

PYROCERAM 9606: Rupture Modulus v. Temperature

PYROCERAM 9606: Poissons Ratio v. Temperature

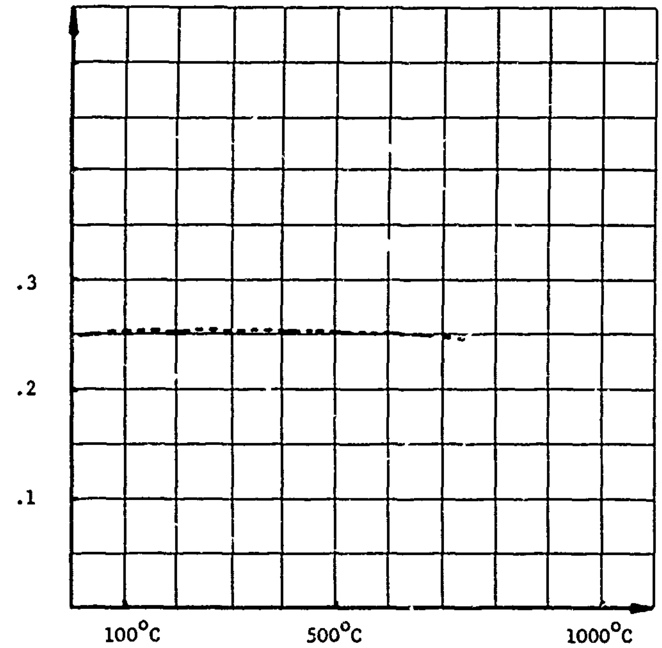


Fig 2.2.2.2.4

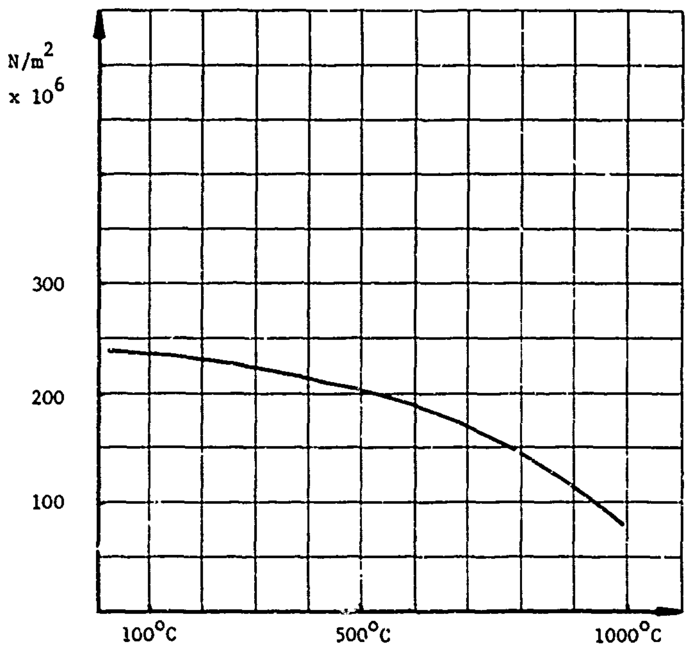


Fig 2.2.2.2.5

PYROCERAM 9606: Flexural Strength v. Temperature

PYROCERAM 9606: Tensile Strength v. Temperature

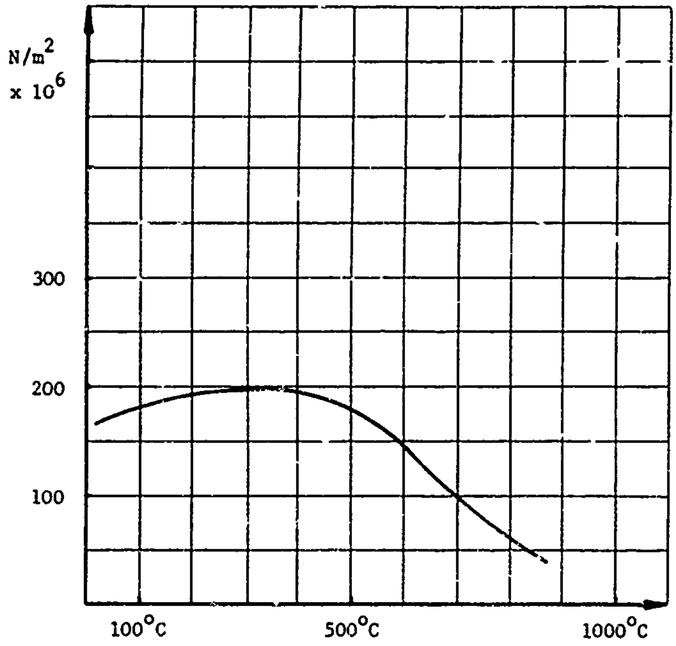


Fig 2.2.2.2.6

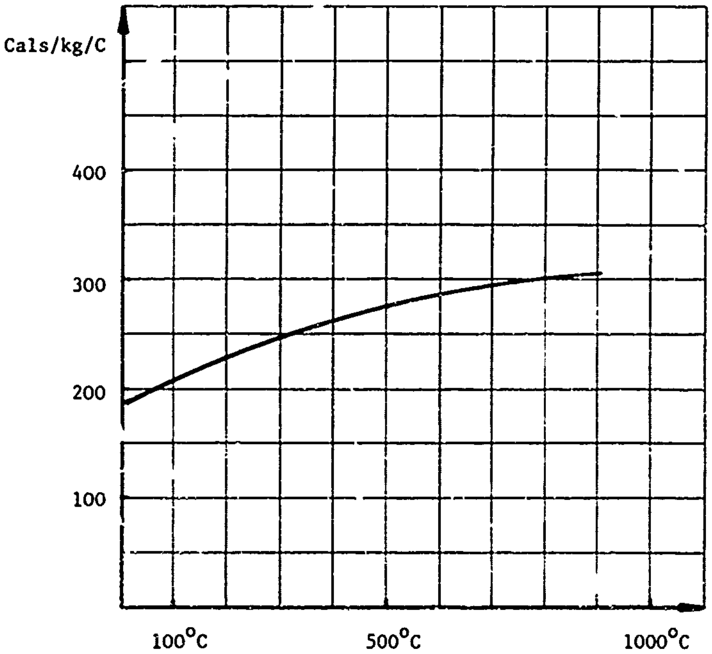


Fig 2.2.2.3.1

PYROCERAM 9606: Specific Heat v. Temperature

PYROCERAM 9606: Thermal Conductivity v. Temperature

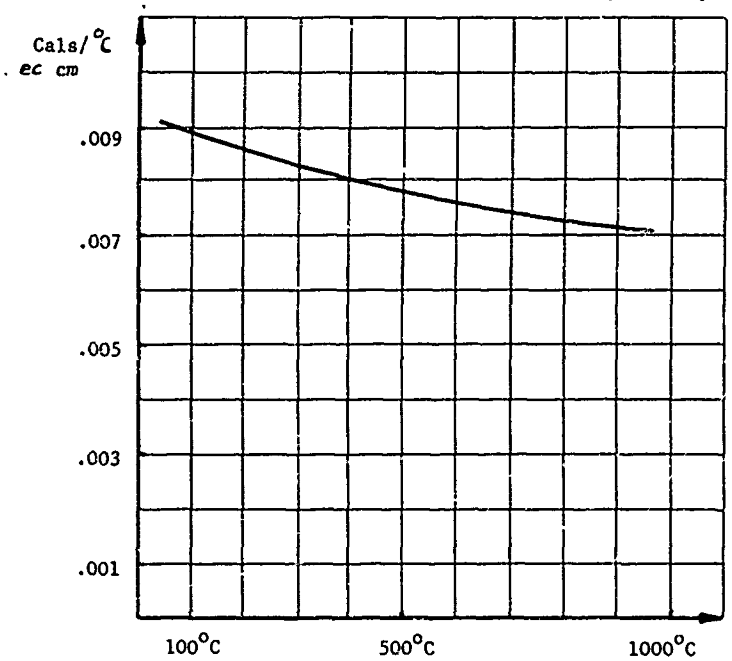


Fig 2.2.2.3.2

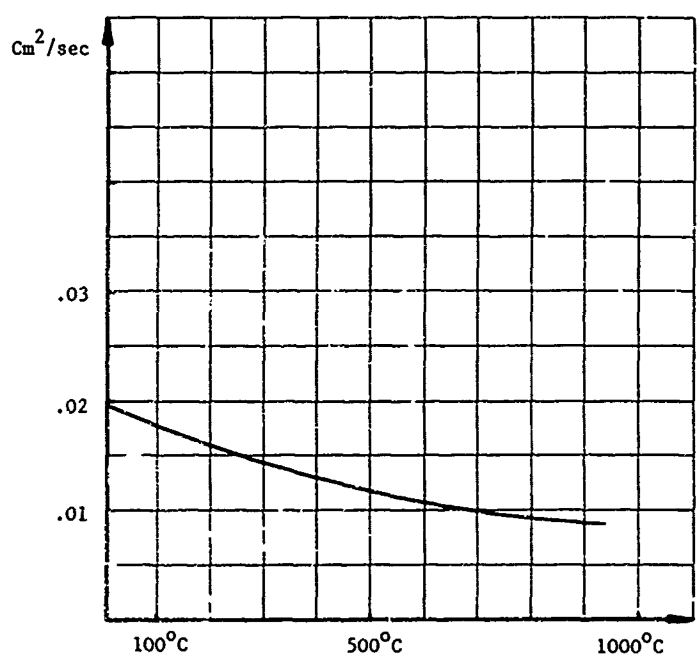


Fig 2.2.2.3.3

PYROCERAM 9606: Thermal Diffusivi*y v. Temperature

PYROCERAM 9606: Expansion v. Temperature

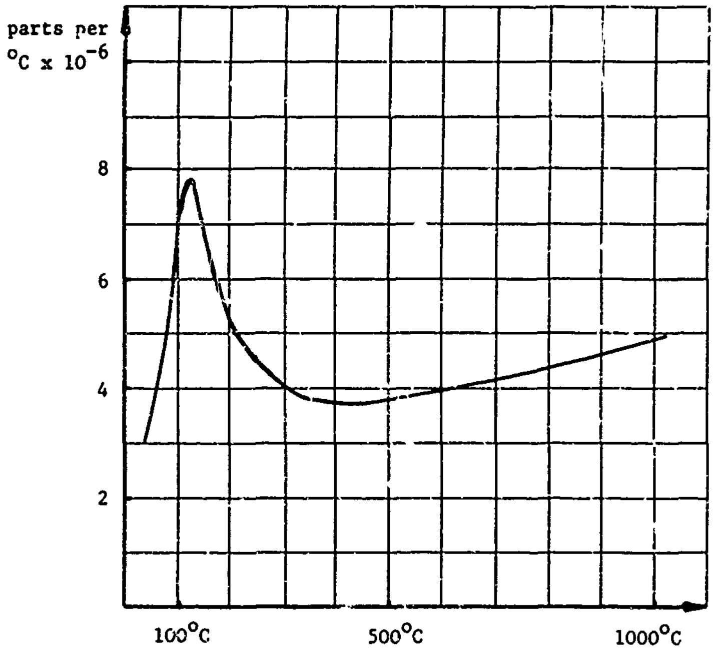


Fig 2.2.2.3.4

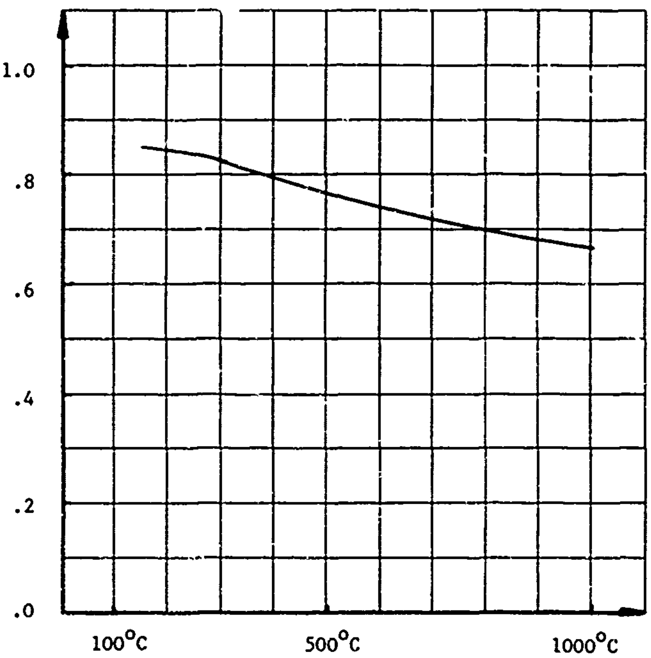


Fig 2.2.2.3.5

PYROCERAM 9606: Emissivity v. Temperature

2.2.3 SILICA AND REINFORCED SILICA

Silica (SiO_2), in a suitable form, is a radome material for use at high temperatures, and while not at present having the popularity of alumina and Pyroceram, is available for usage. One form is quartz, but a fused silica is the material most suitable for shaped radomes. They have been developed particularly at Georgia Tech. (USA). The properties which the material possess of particular interest are its good electrical qualities, resistance to thermal shock and rain, is relatively cheap, and is claimed to be comparatively easy to manufacture the material into radomes, and machine with diamond tooling. (15)

Electrically the low dielectric constant can have certain advantages in low reflection losses, and the stability of the dielectric constant which changes only 0.6% per 100°C makes the material well suited for maintaining electrical performance over a wide temperature range.

Mechanically the material is comparatively weaker than alumina or Pyroceram, but does maintain its mechanical strength (modulus of rupture 35×10^6 N/m^2) at high temperature, such that over a 1000°C it becomes competitive. (29)

Thermally the material has an expansion coefficient an order less than alumina or Pyroceram, which considerably improves its thermal shock capability.

Silica when heated to its liquid phase can produce clear quartz mainly of use for very small shaped windows. Fused silica formed by a sintering slip casting process is typical of the usual process of radome manufacture and have been extensively developed by Georgia Tech. (USA). The slip cast radome shrinkage is small compared to slip cast alumina, and consequently it is claimed its thickness can be controlled more readily. Large radomes may be manufactured by this process. A consequence of the slip cast manufacturing process is the product of a porous nature, which presents problems of sealing.

The properties quoted are typical of current manufactured forms. It is anticipated that in the future there will be improvements in the mechanical properties, possibly with reinforcing materials.

Due to the Porous nature of slip cast fused silica to prevent water absorption (30) a silicone resin SR-80 has been used, but chars at high temperature to give some loss. A further coating of thin chromic oxide to slow the heat flux and prevent carbonisation within the radome and minimise the loss has been shown (31).

The ablative performance of high purity slip cast fused silica has been investigated under simulated re-entry temperatures and has indicated that the radome surface can exceed the melting temperature without significant loss of material for short periods (32), at Mach 8 to 12. When silica forms a melt layer on its surface it results in a more rain erosion resistant material than char formed ablatives (33).

Reinforced silica has been described (34) with orthogonally woven quartz yarn (Astroquartz) to produce a relatively tough dielectric material termed AS-3 DX. Its improved rain erosion resistance is described in (35)(33). A summary of its properties is given in Table 2.2.3.

TABLE 2.2.3 PROPERTIES OF QUARTZ REINFORCED SILCA AS-3DX(34)

ELECTRICAL			
Dielectric Constant 8.5 GHz	70°F(24°C)	3.05	Note negligible change with temperature
	1472°F(900°C)	3.02	
Loss Tangent:- 8.5 GHz	70°F(24°C)	0.0009	Note low loss
	1472°F(900°C)	0.0012	
MECHANICAL:-			
Density:-	1.78 gm/cc		
Ultimate strength			
Tensile(Z)	70°F(24°C)	4348 psi (29 x 10^6 N/m^2)	
	1800°F(1105°C)	5146 psi (35 x 10^6 N/m^2)	
(X-Y)	70°F(24°C)	3406 psi (23 x 10^6 N/m^2)	
	1800°F(1105°C)	4150 psi (28 x 10^6 N/m^2)	
Compression(Z)	70°F(24°C)	22144 psi (150 x 10^6 N/m^2)	
	1800°F(1105°C)	27120 psi (186 x 10^6 N/m^2)	
(X-Y)	70°F(24°C)	19832 psi (137 x 10^6 N/m^2)	
	1800°F(1105°C)	20592 psi (140 x 10^6 N/m^2)	
THERMAL			
Thermal Expansion	0.294 10^6/°F	(70-1300°F)	
	0.470 10^6/°C	(24-800°C)	
Specific Heat	70°F(24°C)	0.185 BTU/Lb °F	
	1800°F(1105°C)	0.295 BTU/Lb °F	
Thermal Conductivity	70°F(24°C)	0.382 BTU/Hr °F Ft	
	1300°F(800°C)	0.575 BTU/Hr °F Ft	

ELECTRICAL PROPERTIES : SILICA

TABLE 2.2.3.1

Property	Reference Fig	Remarks
Dielectric Constant ~. Density	(8)(9)(15) Fig 2.2.3.1.1	Dense silica, like Quartz, dielectric constant 3.84; but fused silica slip cast dielectric constant near 3.4.
Dielectric Constant v. Frequency	(5)(9) Fig 2.2.3.1.2	Little change over microwave band.
Dielectric Constant v. Temperature	(1) (5) (9) Fig 2.2.3.1.3	Dense silica has less slope than slip cast, but both low.
Loss Tangent v. Frequency	(1) (5) (9) Fig 2.2.3.1.4	Low loss at all microwave lengths. Impurities can increase loss.
Loss Tangent v. Temperature	(1) (5) (9) Fig 2.2.3.1.5	Low loss even at 1000°C for radome usage
Dielectric Constant v. Humidity	(6)	Dense silica (non porous) optical type negligible change with humidity. Marked change of dielectric constant according to humidity take up with slip cast silica.
Dielectric Constant v. Radiation		
Volume Resistivity v. Temperature	(8) Fig 2.2.3.1.6	
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : SILICA

TABLE 2.2.3.2

Property	Reference Fig	Remarks
Specific Gravity	(8)(4)	2.2 grams/cc Max. density near 2 grams/cc SLIP CAST.
Youngs Modulus v. Temperature	(4)(9)(12)(15) Fig 2.2.3.2.1	near constant with temperature Dense silica 75 x 10^9 N/m^2 Less dense 40 : 10^9 N/m^2
Youngs Modulus v. Porosity	(4)(9)(12)(15) Fig 2.2.3.2.2	Decreases with porosity
Shear Modulus v. Temperature	(4) (9) (12) Fig 2.2.3.2.3	
Rupture Modulus		Slip cast 35 x 10^6N/m^2 ambient 50 x 10^6N/m^2 1000°C
Poissons Ratio	(4)(9)(12)(15) Fig 2.2.3.2.4	0.15 at 25°C
Flexural Strength v. Temperature	(4)(9)(12)(15) Fig 2.2.3.2.5	increases with temperature varies according to density
Tensile Strength v. Temperature		35 x 10^6 N/m^2 ambient (Density near 2gr/cm^3)
Compressive Strength v. Temperature		160 x 10^6 N/m^2 ambient
Impact Strength		80 x 10^6 N/m^2 (Density 2gr/cm^3)
Hardness	(8)	6 - 7 MOHS less according to porosity 570 kg/mm^2 at 25°C (Knoop)

THERMAL PROPERTIES : SILICA

TABLE 2.2.3.3

Property	Reference & Fig	Remarks
Temperature Working Range		Max. use temperature 1200°C Dense silica (Corning 7941 used in re-entry vehicles) could be higher.
Specific Heat v. Temperature	(4) (8) (9) Fig 2.2.3.3.1	Does not vary much for dense or porous silica
Conductivity v. Temperature	(4) (8) (9) Fig 2.2.3.3.2	Depends on density near 2gr/cm^3; 0.0019 at 25°C; 0.0024 at 800°C
Diffusivity v. Temperature	(4) (8) (15) Fig 2.2.3.3.3	Depends on density near 2gr/cm^3; 0.0059 at 25°C; 0.0047 at 800°C
Expansion v. Temperature	(4) (8) (15) Fig 2.2.3.3.4	0.54 x 10^{-6}°C Dense up to 1.5 x 10^{-6}°C with increased porosity
Emissivity v. Temperature	(9) (12) Fig 2.2.3.3.5	
Ablation		Slip cast fused silica ablates at very high temperature
Thermal Shock	(15)	Good thermal shock characteristics; claimed better than alumina and Pyroceram.
Flammability		non-inflammable

ENVIRONMENTAL PROPERTIES : SILICA

TABLE 2.2.3.4

Properties	Reference & Fig	Remarks
Temperature		Melts at 1680°C
Humidity & Water Absorption	(4)	Very dense material nearly no effect from humidity. Slip cast can absorb. 5-12% according to porosity.
Rain Erosion	(4) (10)	Dense material pitted by 1"/hr. rain at 500 mph in 6 minutes. Slip cast material according to density eroded quicker.
Radiation Solar Nuclear	(7) (16)	Unaffected by solar radiation Safe nuclear radiation rating 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid		Little effected by oils, fuels, detergents, etc. apart from absorption by pores, which can change dielectric constant
Storage & Ageing		Avoid shocks, vibration, abrasions, and moisture. Inert.

SILICA: Dielectric Constant v. Density
Room Temperature 9.5 GHz

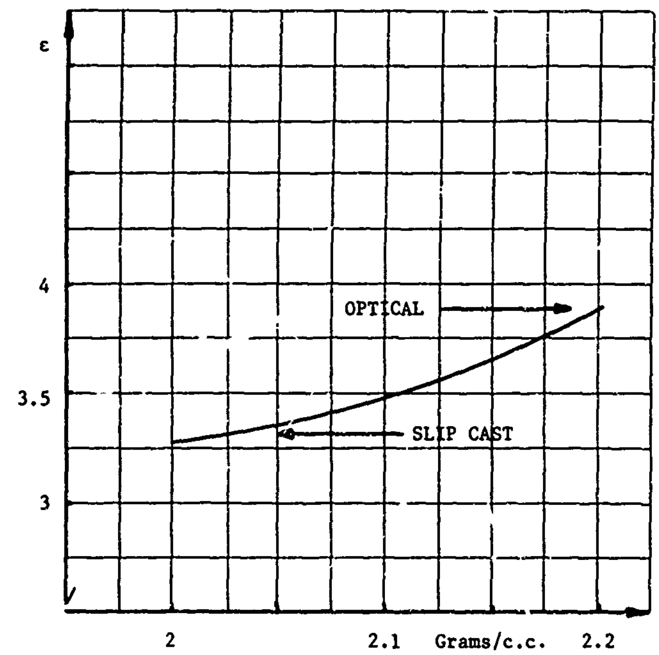


Fig 2.2.3.1.1

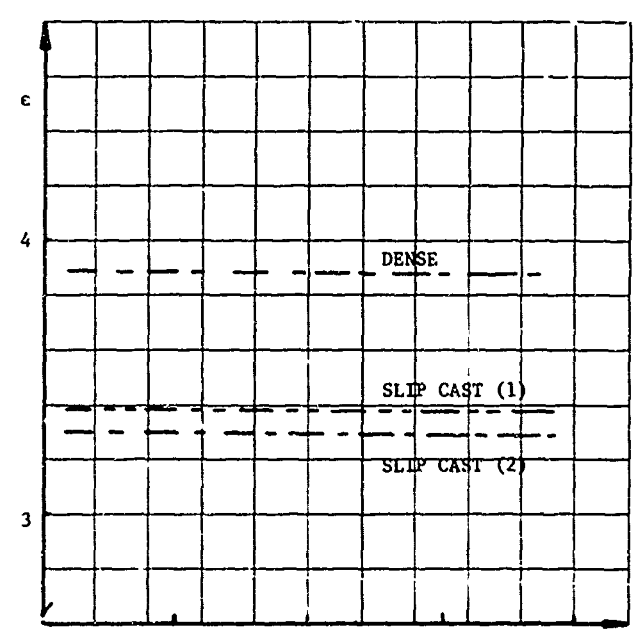


Fig 2.2.3.1.'

SILICA: Dielectric Constant v. Frequency
Room Temperature

SILICA: Dielectric Constant v. Temperature 9.5 GHz

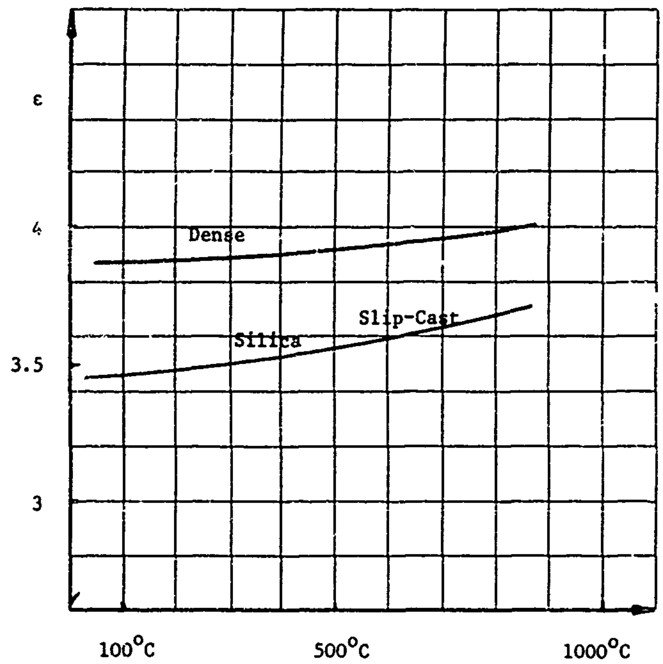


Fig 2.2.3.1.3

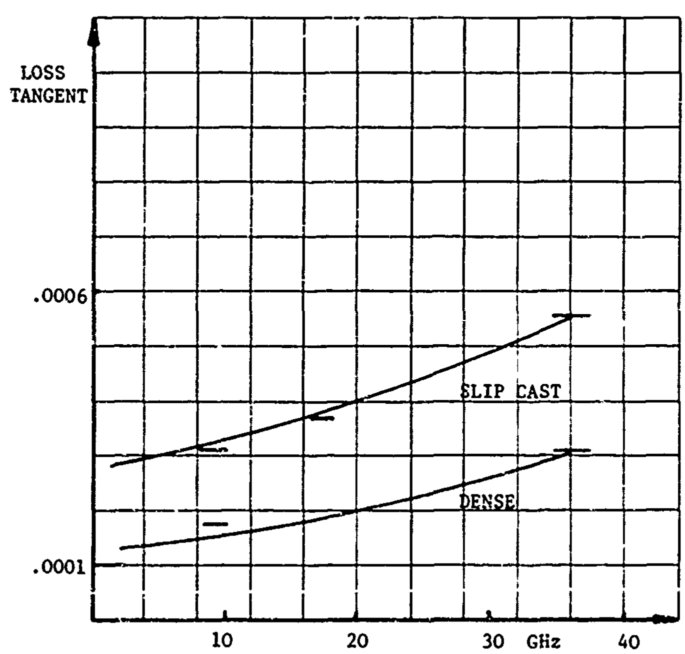


Fig 2.2.3.1.4

SILICA: Loss Tangent v. Frequency
Room Temperature

SILICA: Loss Tangent v. Temperature
9.368 GHz

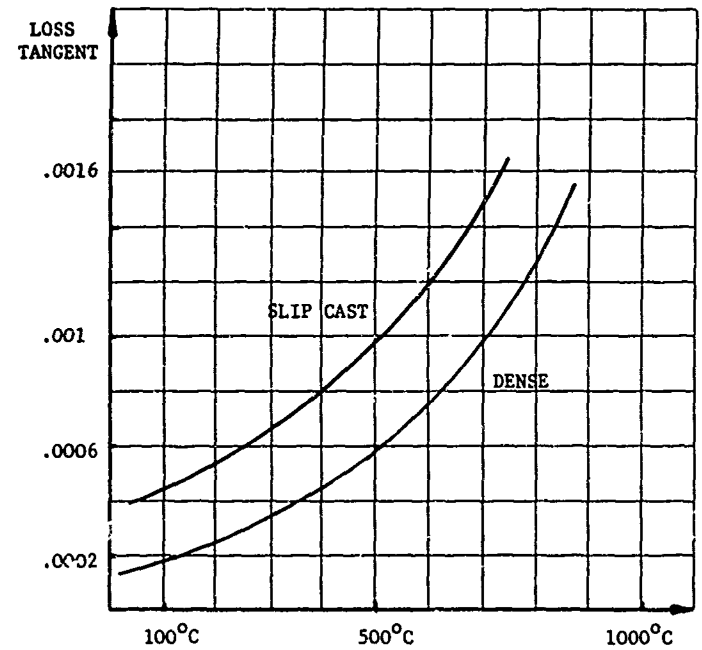


Fig 2.2.3.1.5

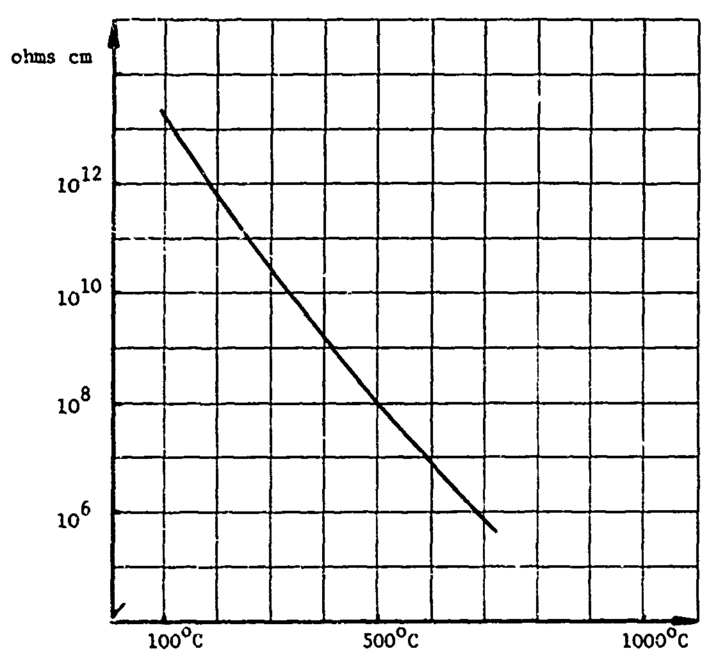


Fig 2.2.3.1.6

SILICA: Volume Resistivity v. Temperature

SILICA: Youngs Modulus v. Temperature

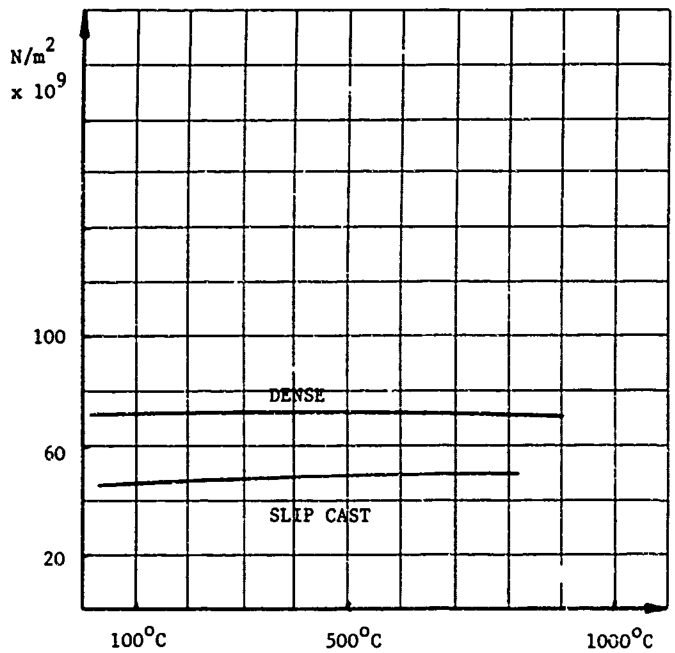


Fig 2.2.3.2.1

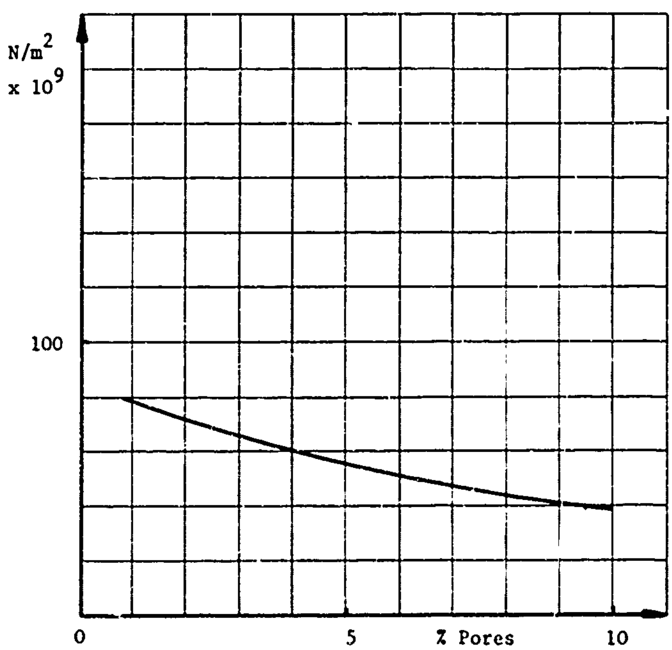


Fig 2.2.3.2.2

SILICA: Youngs Modulus v. Porosity

SILICA: Shear Modulus v. Temperature

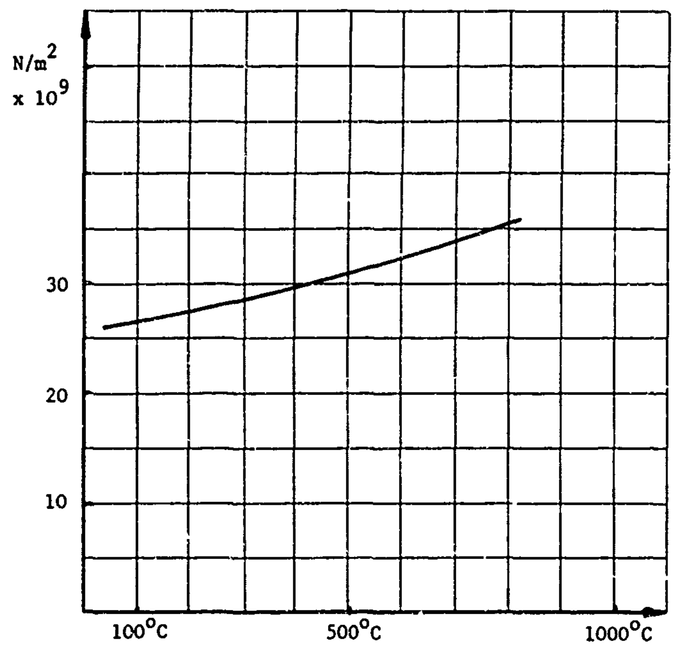


Fig 2.2.3.2.3

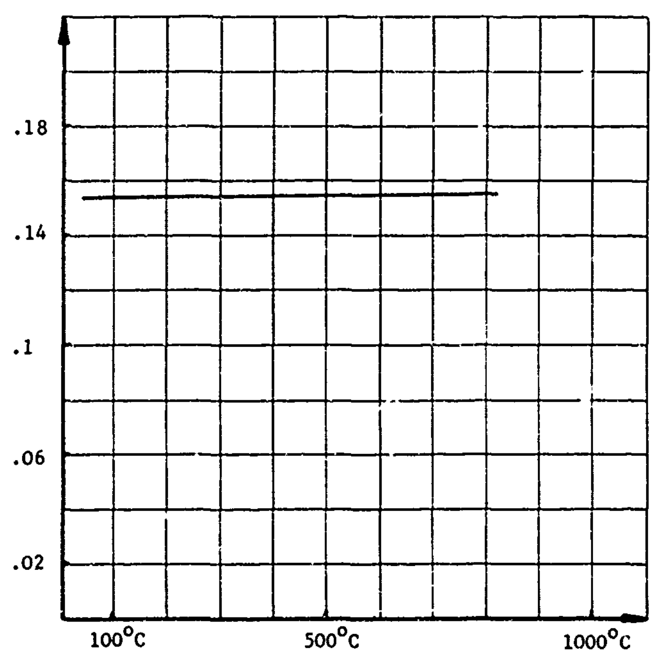


Fig 2.2.3.2.4

SILICA: Poissons Ratio v. Temperature

SILICA: Flexural Strength v. Temperature

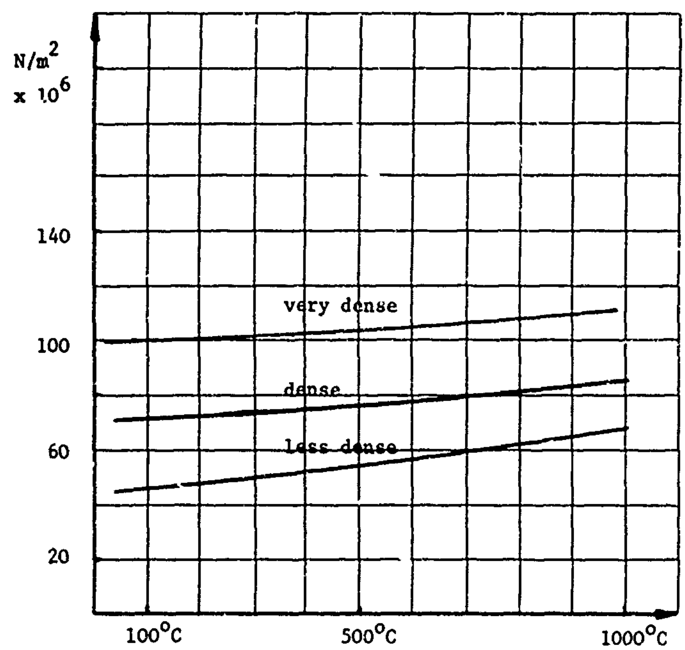


Fig 2.2.3.2.5

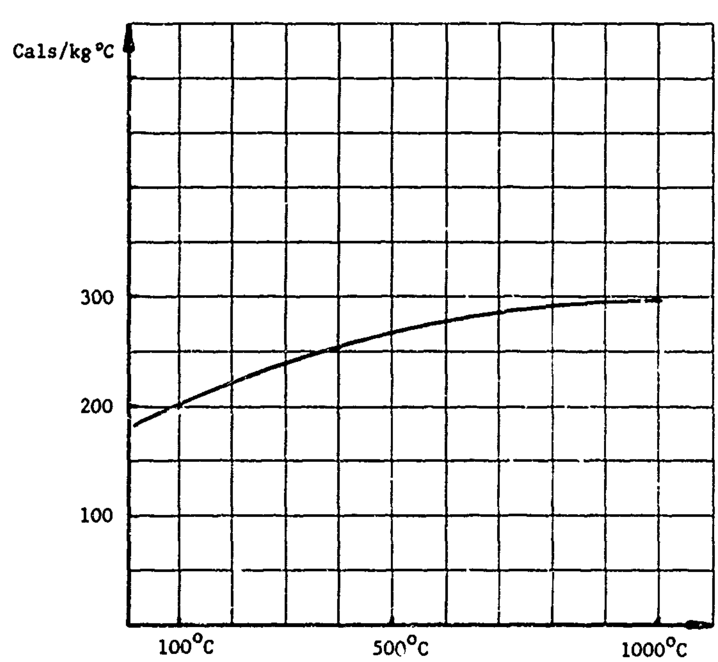


Fig 2.2.3.3.1

SILICA: Specific Heat v. Temperature

SILICA: Thermal Conductivity v. Temperature

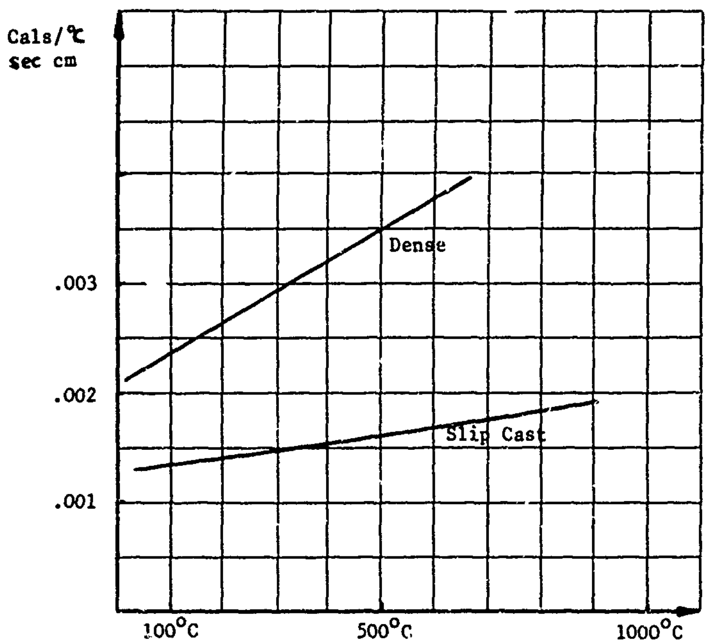


Fig 2.2.3.3.2

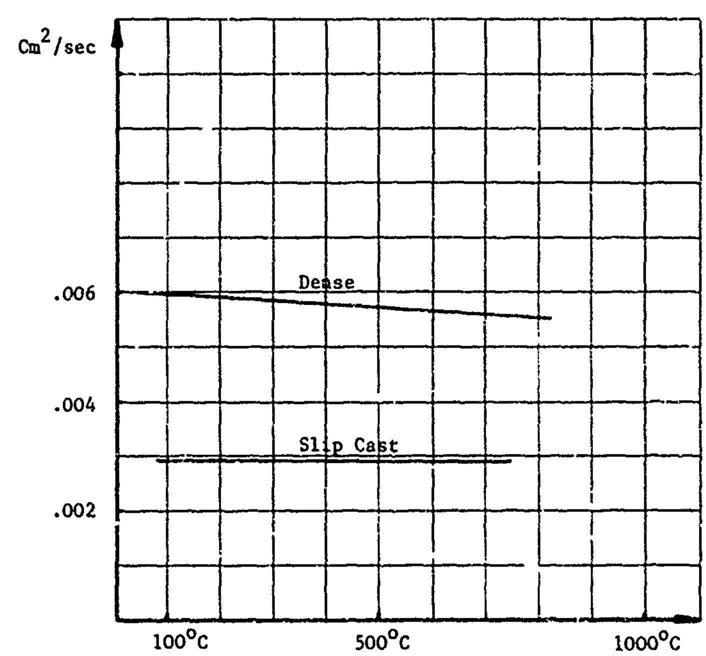


Fig 2.2.3.3.3

SILICA: Thermal Diffusivity v. Temperature

SILICA: Expansion v. Temperature

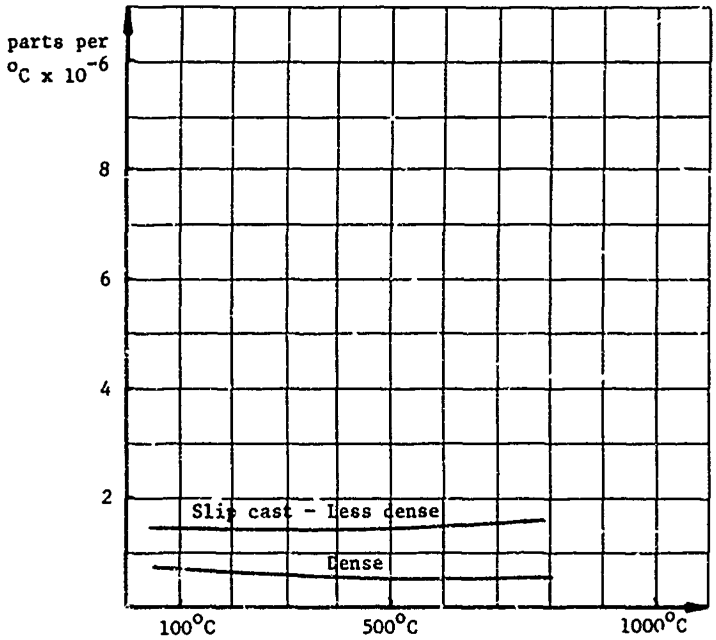


Fig 2.2.3.3.4

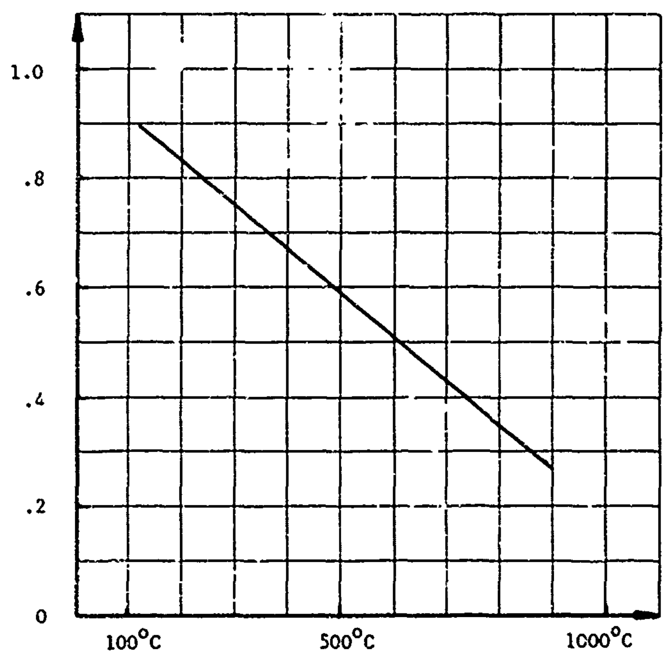


Fig 2.2.3.3.5

SILICA: Emissivity v. Temperature

2.2.4 CORDIERITE: $2MgO.2Al_2O_3.5SiO_2$

Cordierite is another ceramic material which mixes oxides to obtain advantageous properties over the basic materials. Compounding of the basic materials can produce cordierite with a degree of porosity which may not be entirely suitable for radomes. Processes have been established for obtaining dense or a vitreous type of cordierite which overcomes the porosity (18). The material is a contender for usage particularly for high temperature and thermal shock conditions.

Electrically, the dielectric constant of near 4.8 has the advantage of small change of dielectric constant with temperature (0.4% per 100°C). The loss tangent is reasonably low at low temperatures, but for radome usage would tend to become excessive towards 800°C.

Mechanically it is considerably weaker at low temperatures than alumina, but a type termed Rayceram (18) has nearly as good flexural strength as alumina at 800°C.

Thermally the material has very low expansion coefficient and conductivity compared to alumina and very good thermal shock properties.

It does appear to be a candidate for radomes in the Mach 5-6 region, but above its electrical loss may be limiting.

Its manufacture may be by slip casting and iso-static pressing as per alumina, or taken through a process which vitrifies it into a glass-ceramic type material.

ELECTRICAL PROPERTIES : CORDERITE

TABLE 2.2.4.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(4) (6) (18) Fig 2.2.4.1.1	Material of high density near 2.45 grams/cc considered for radome usage.
Dielectric Constant v. Frequency	(4)(6)(18) Fig 2.2.4.1.2	Near 4.85 over microwave band
Dielectric Constant v. Temperature	(4)(6)(18) Fig 2.2.4.1.3	Little change with temperature (0.4% per 100°C)
Loss Tangent v. Frequency	(4)(6)(18) Fig 2.2.4.1.4	Low loss at ambient.
Loss Tangent v. Temperature	(4)(6)(18) Fig 2.2.4.1.5	Rapid rise with temperature Possible radome loss excessive near 800°C
Dielectric Constant v. Humidity		Material for radomes usually relatively non porous.
Dielectric Constant v. Radiation		Not affected by solar ultra violet. From formulation estimated safe nuclear rating 10^{10} rads.
Volume Resistivity v. Temperature	(4)(6)(18)(8) Fig 2.2.4.1.6	
Dielectric Strength v. Temperature	(6) (8)	15 kv/mm at 20°C 10 kv/mm at 300°C

MECHANICAL PROPERTIES : CORDIERITE

TABLE 2.2.4.2

Property	Reference Fig	Remarks
Specific Gravity	(4)(6)(8)(18)	2.45 gm/cm³ dense material 2.2 gm/cm³ bulk material
Youngs Modulus v. Temperature	(4)(8)(18) Fig 2.2.4.2.1	retains modulus with temperature
Youngs Modulus v. Porosity		
Shear Modulus v. Temperature		
Rupture Modulus		
Poissons Ratio	(4) (18)	0.27
Flexural Strength v. Temperature	(4)(8)(18) Fig 2.2.4.2.2	
Tensile Strength v. Temperature	Fig 2.2.4.2.3	
Compressive Strength v. Temperature	Fig 2.2.4.2.4	
Impact Strength		
Hardness		7 MOHS

THERMAL PROPERTIES : CORDIERITE

TABLE 2.2.4.3

Property	Reference & Fig	Remarks
Temperature Working Range	(8)	Melts 1430°C Max. working temperature 1250°C
Specific Heat v. Temperature	(4)(8) Fig 2.2.4.3.1	.19 at 20°C - 100°C .22 100°C - 500°C
Conductivity v. Temperature	(4)(8) Fig 2.2.4.3.2	Low thermal conductivity .006 cals/sq cm per sec per °C alters little with temperature.
Diffusivity v. Temperature	Fig 2.2.4.3.3	
Expansion v. Temperature	(8)	Low expansion coefficient 1.1×10^{6} per °C at 20°C 1.5×10^{6} per °C at 100°C 2.5×10^{6} per °C at 500°C
Emissivity v. Temperature		
Ablation		
Thermal Shock		Considered to be better than alumina
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : CORDIERITE

TABLE 2.2.4.4

Properties	Reference & Fig	Remarks
Temperature	(4) (8)	Working max. temperature 12°0°C
Humidity & Water Absorption	(6)	Dense material has little absorption
Rain Erosion	(18)	good rain erosion resistance (Rayceram)
Radiation Solar Nuclear		Unaffected by solar ultra violet should withstand 10^{10} rads nuclear radiation.
Contamination Oils Fuels Detergents Salts Acid		Oils, fuels, detergents, very corrosive negligible effect.
Storage & Ageing		Store free from shocks and abrasions. Inert.

CORDIERITE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

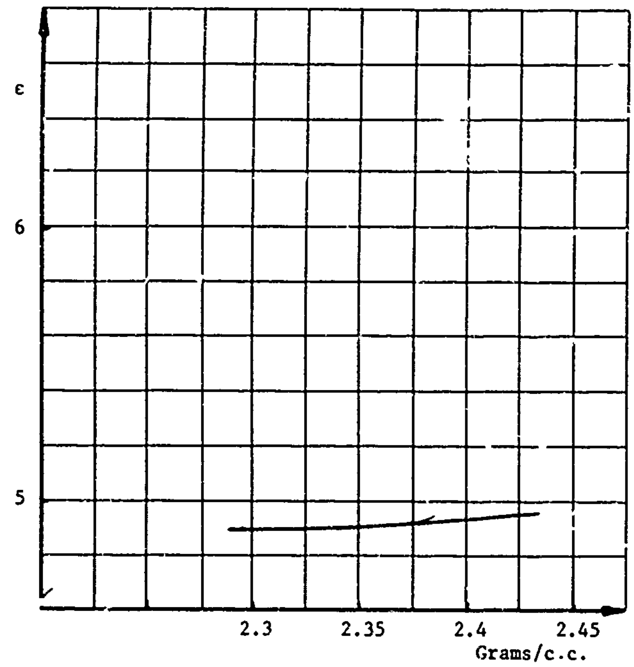


Fig 2.2.4.1.1

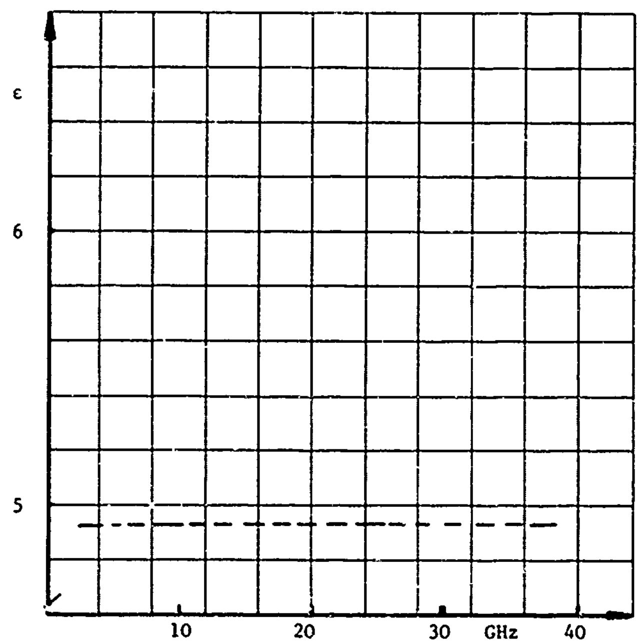


Fig 2.2.4.1.2

CORDIERITE: Dielectric Constant v. Frequency
Room Temperature

CORDIERITE: Dielectric Constant v Temperature 9.5 GHz

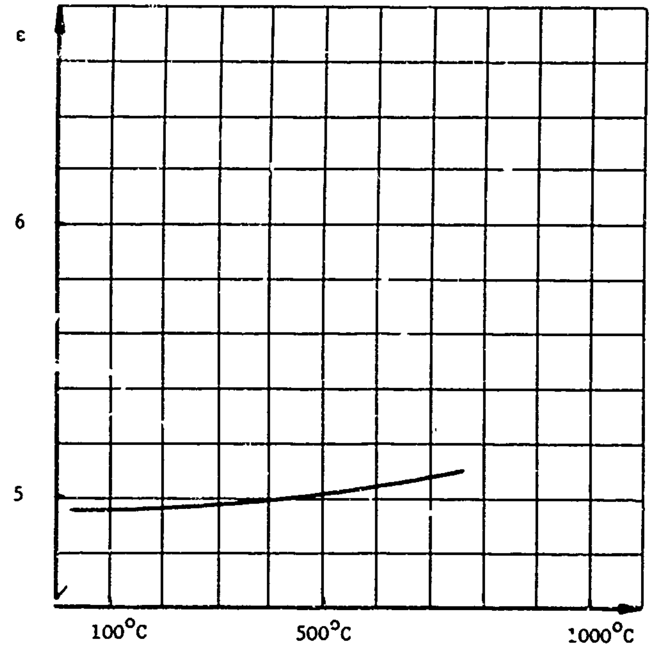


Fig 2.2.4.1.3

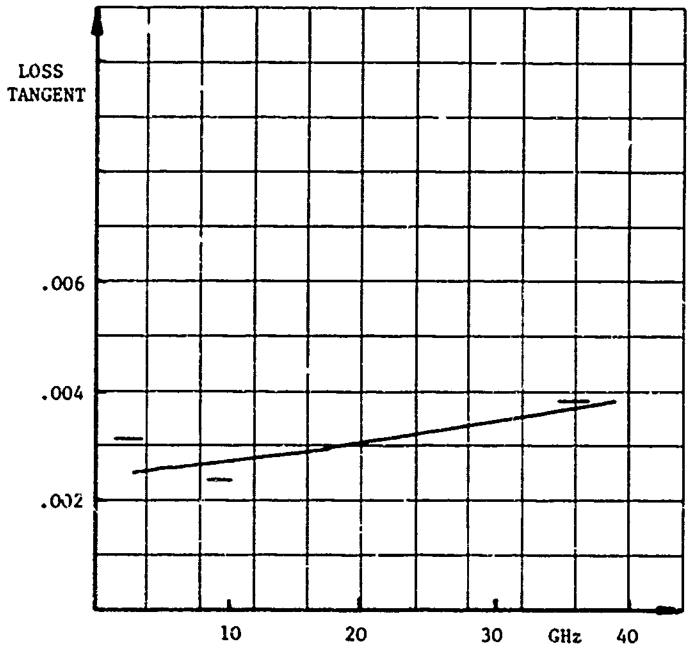


Fig 2.2.4.1.4

CORDIERITE: Loss Tangent v. Frequency
Room Temperature

CORDIERITE: Loss Tangent v. Temperature
9.368 GHz

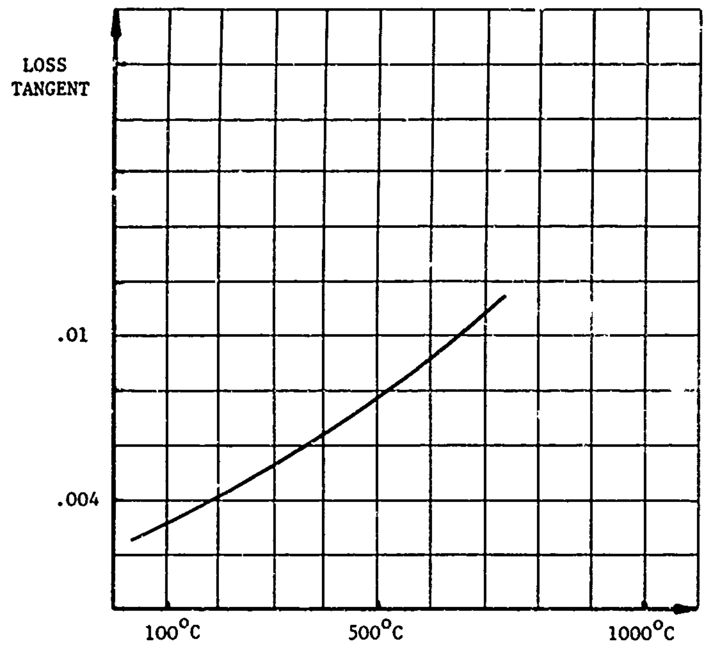


Fig 2.2.4.1.5

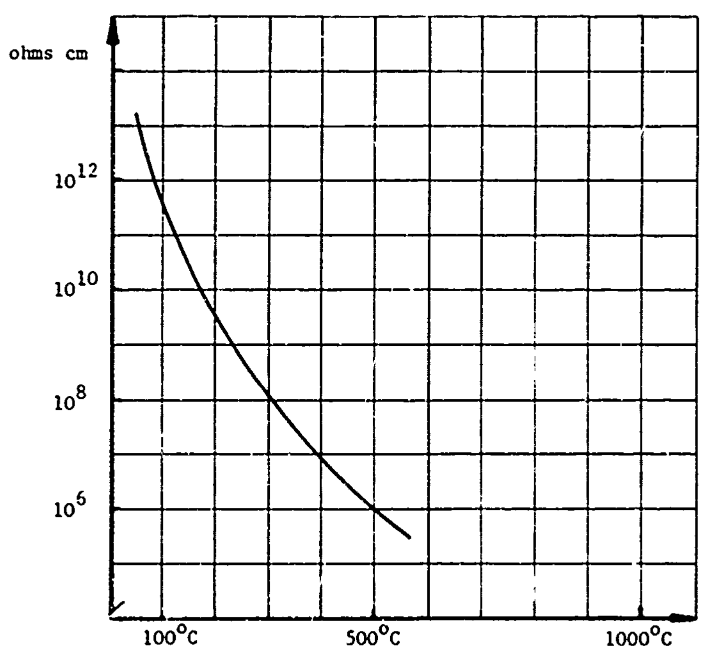


Fig 2.2.4.1.6

CORDIERITE: Volume Resistivity v. Temperature

CORDIERITE: Youngs Modulus v. Temperature

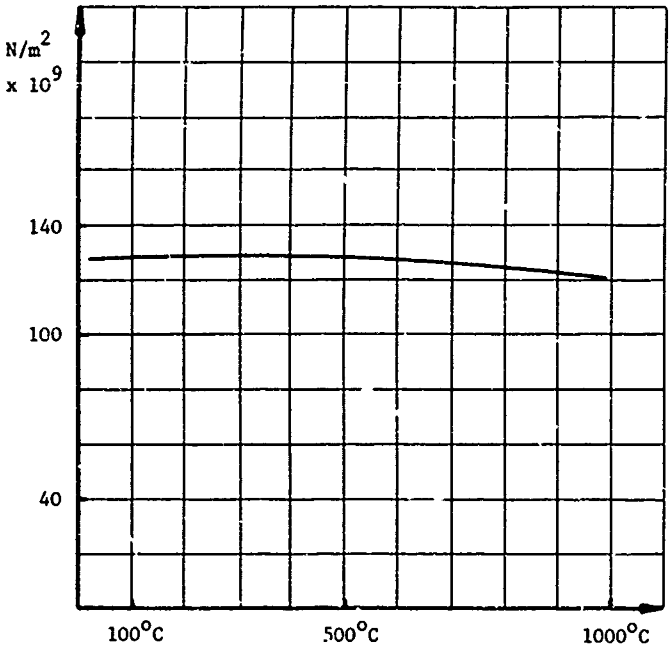


Fig 2.2.4.2.1

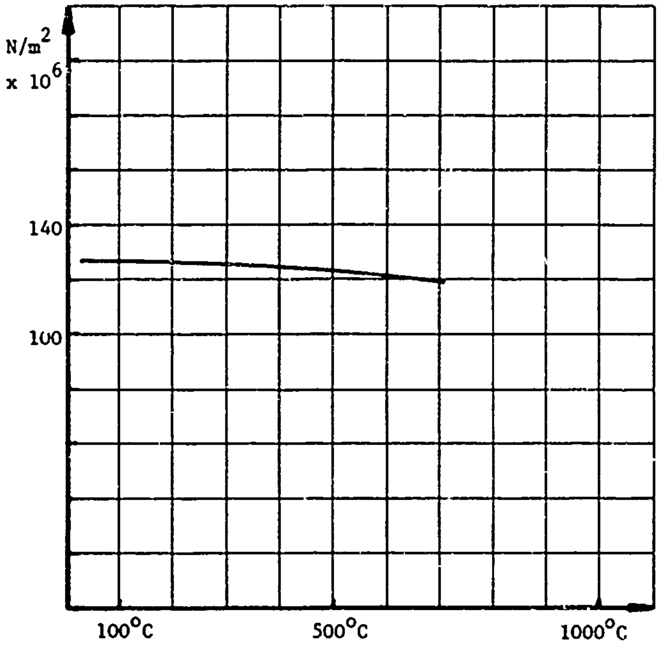


Fig 2.2.4.2.2

CORDIERITE: Flexural Strength v. Temperature

CORDIERITE: Tensile Strength v. Temperature

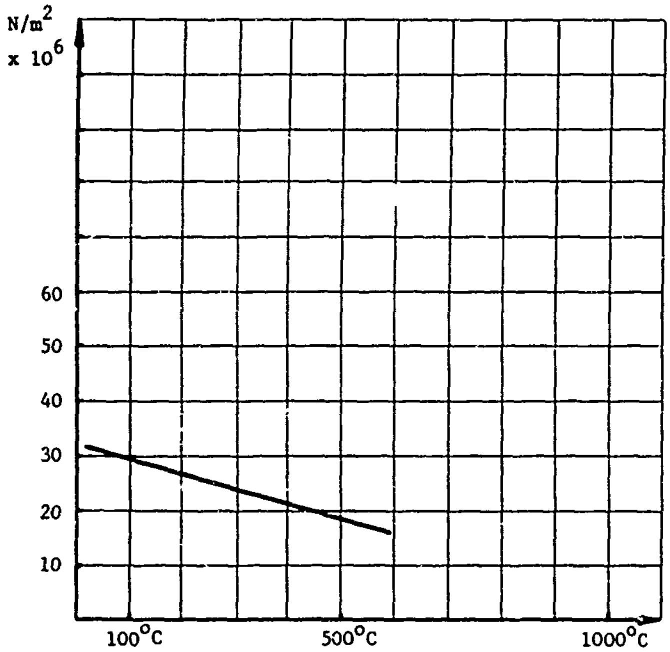


Fig 2.2.4.2.3

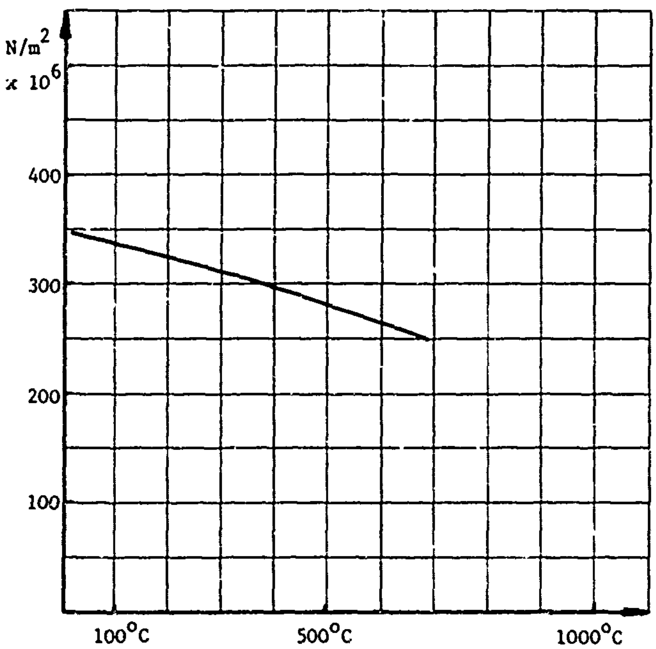


Fig 2.2.4.2.4

CORDIERITE: Compression Strength v. Temperature

CORDIERITE: Specific Heat v. Temperature

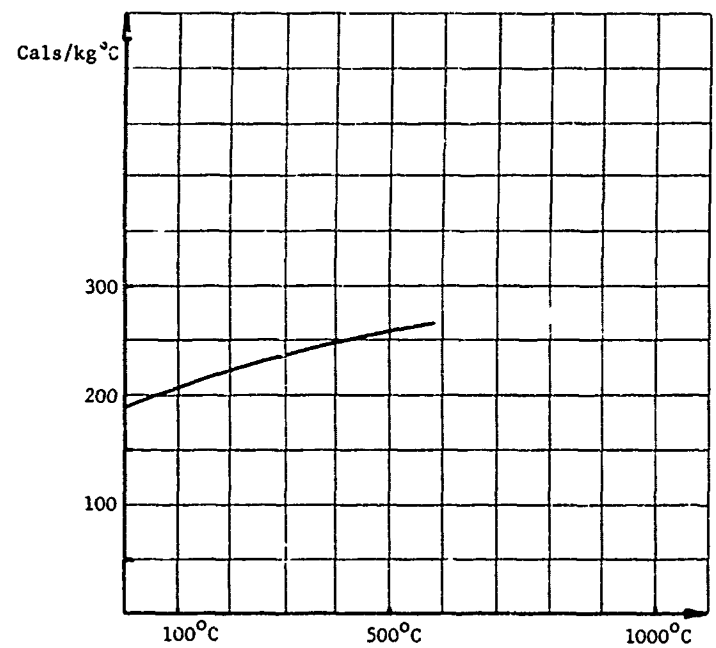


Fig 2.2.4.3.1

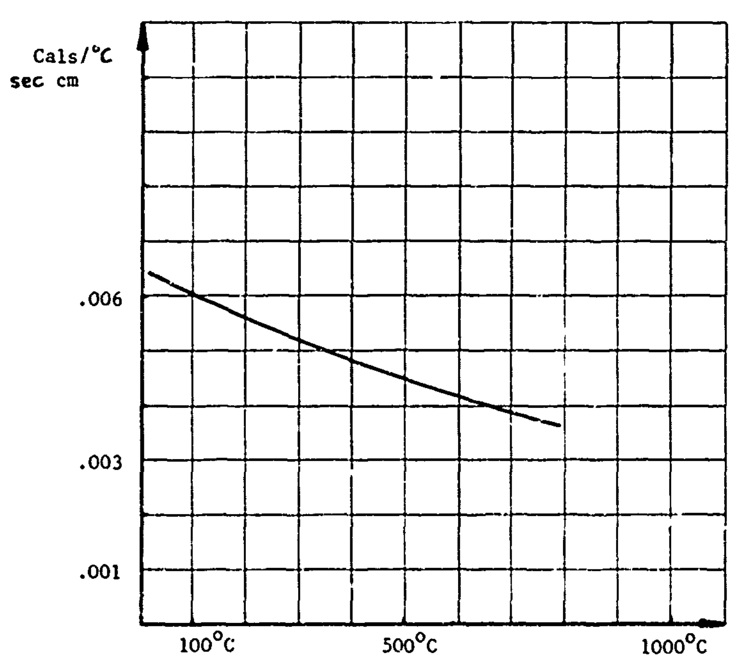


Fig 2.2.4.3.2

CORDIERITE: Thermal Conductivity v. Temperature

CORDIERITE: Thermal Diffusivity v. Temperature

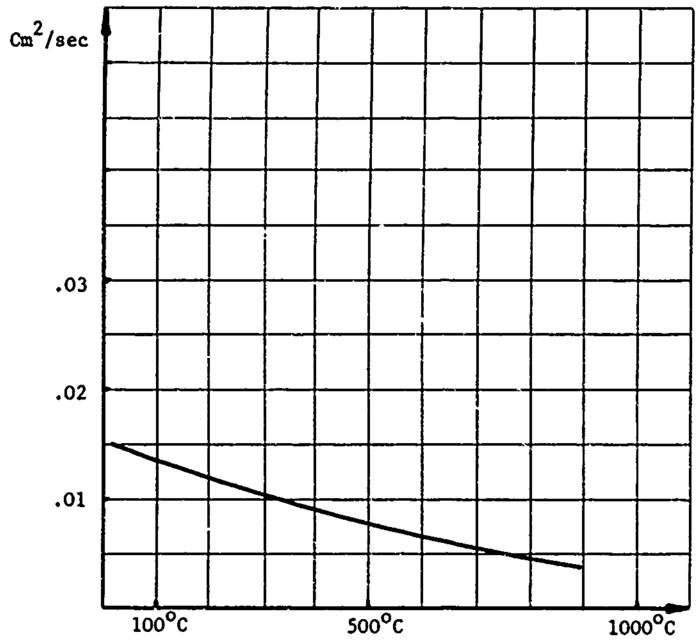
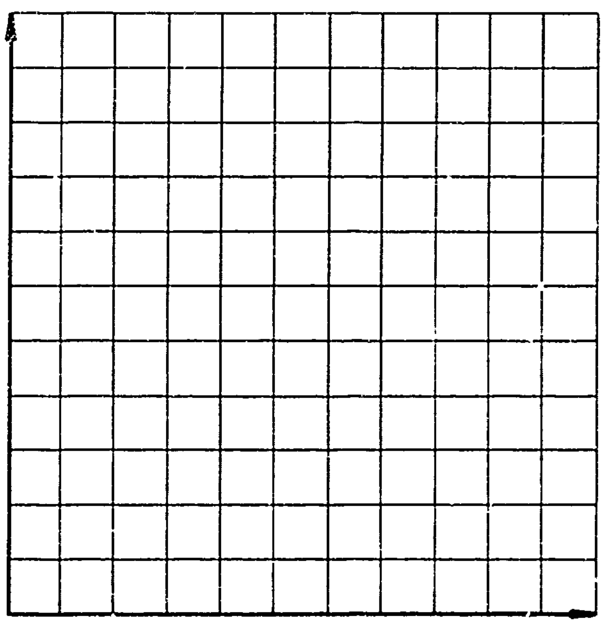


Fig 2.2.4.3.3



2.2.5 MULLITE, $3Al_2O_3\ 2SiO_2$

This material is a candidate for high temperature radome application and is of interest in that it has most of the properties of alumina but it is claimed has improved thermal shock. Experimental radomes have been made with this material.

Electrically the dielectric constant is near 6.9 for dense material, but for typical bulk material is near 6.6 with a 3% porosity. The dielectric change with temperature is near 0.4% per 100°C which is considerably less than alumina. Its loss tangent remains acceptable over a wide temperature range.

Mechanically Youngs modulus and its strength is generally less than alumina.

Thermally its expansion coefficient, specific heat, conductivity are less than alumina, which gives rise to the claim its thermal shock properties are better.

Manufacturing can be performed in the same manner as alumina, and its hard surface similarly requires diamond grinding to thickness if necessary.

Mullite has good rain erosion resistance and is considered to be suitable for Mach. 5 to 6 applications.

ELECTRICAL PROPERTIES : MULLITE

TABLE 2.2.5.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(2) (8) Fig 2.2.5.1.1	Max. density 3.15 grams/cc
Dielectric Constant v. Frequency	(2) (5) (6) Fig 2.2.5.1.2	Constant over microwave band.
Dielectric Constant v. Temperature	(2) (5) (6) Fig 2.2.5.1.3	Lower dielectric constant change than alumina.
Loss Tangent v. Frequency	(2) (5) (6) Fig 2.2.5.1.4	Little change
Loss Tangent v. Temperature	(2) (5) (6) Fig 2.2.5.1.5	Reasonably low over wide temperature range.
Dielectric Constant v. Humidity	(6)	Typical bulk material 3% porous by volume, results in some change, due to humidity, in dielectric constant according to pick-up.
Dielectric Constant v. Radiation	(6) (7)	No change with solar ultra violet or 10^{10} rads. Nuclear radiation.
Volume Resistivity v. Temperature	(8) Fig 2.2.5.1.6	
Dielectric Strength v. Temperature	(8)	12 kv/mm ambient

MECHANICAL PROPERTIES : MULLITE

TABLE 2.2.5.2

Property	Reference Fig	Remarks
Specific Gravity	(2) (8)	Max. dense 3.16 grams/cc Bulk material 3.05 grams/cc.
Youngs Modulus v. Temperature	(2) (8) Fig 2.2.5.2.1	Low compared to alumina.
Youngs Modulus v. Porosity	(2) (8) Fig 2.2.5.2.2	Varies according to porosity.
Shear Modulus v. Temperature		
Rupture Modulus		
Poissons Ratio		.271
Flexural Strength v. Temperature		
Tensile Strength v. Temperature	(1) (2) (6) Fig 2.2.5.2.3	Weaker than alumina
Compressive Strength v. Temperature	(1) (2) (6) Fig 2.2.5.2.4	Weaker than alumina
Impact Strength		
Hardness		6-7 MOHS (not as hard as alumina)

THERMAL PROPERTIES : MULLITE

TABLE 2.2.5.3

Property	Reference & Fig	Remarks
Temperature Working Range	(8)	Melts 1850°C Working range 1650°C
Specific Heat v. Temperature	(2) (8) Fig 2.2.5.3.1	Varies according to porosity
Conductivity v. Temperature	(2) Fig 2.2.5.3.2	Considerably less than alumina
Diffusivity v. Temperature	(8) Fig 2.2.5.3.3	
Expansion v. Temperature	(6) (8)	Coefficient 20-500°C 4 $\times 10^{-6}$ per °C 20-1000°C 4.5 $\times 10^{-6}$ per °C
Emissivity v. Temperature		
Ablation		
Thermal Shock	(2)	Considered a better material than alumina at high temperatures
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : MULLITE

TABLE 2.2.5.4

Properties	Reference & Fig	Remarks
Temperature	(2) (8)	Working range → 1650°C
Humidity & Water Absorption	(2)	Material slightly porous will absorb water
Rain Erosion	(2) (10)	Among the best materials;4 hr in 500 mph 1"/hr rainfall showed negligible damage.
Radiation Solar Nuclear	(2)	Unaffected by solar ultra-violet Safe nuclear dosage 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid		Unaffected by oils, fuels, detergents, or weak corrosives.
Storage & Ageing		Store free from shocks and abrasions. Inert.

MULLITE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

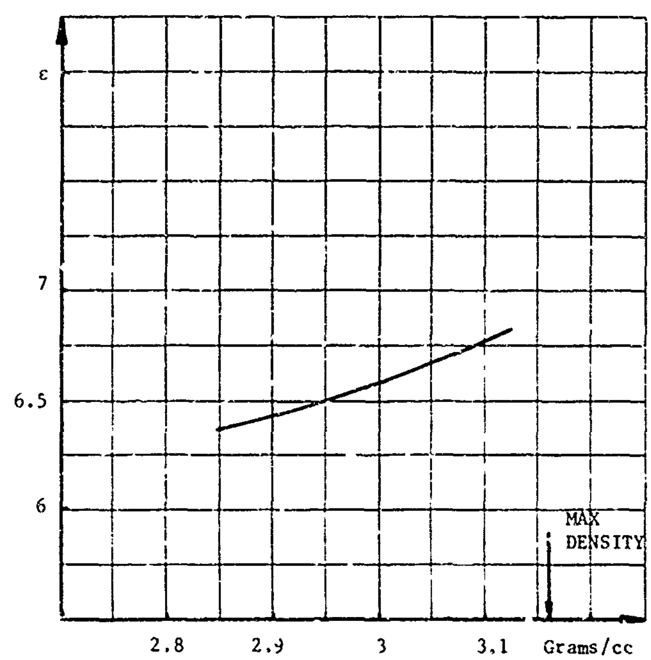


Fig 2.2.5.1.1

MULLITE: Dielectric Constant v. Frequency
Room Temperature

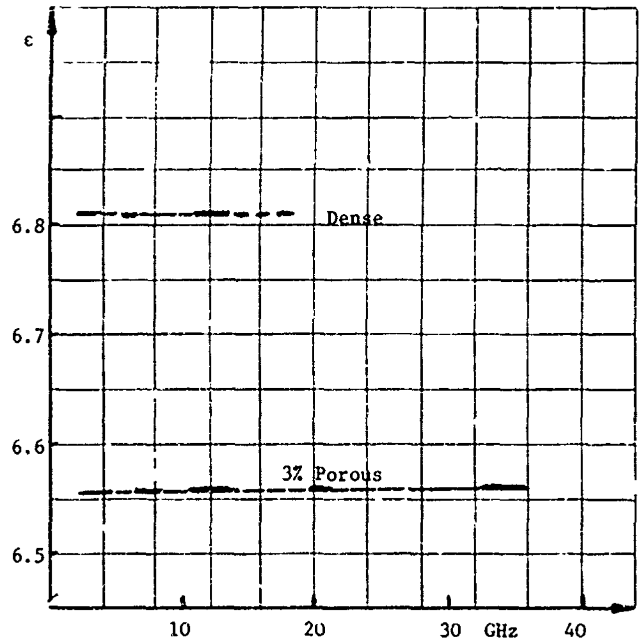


Fig 2.2.5.1.2

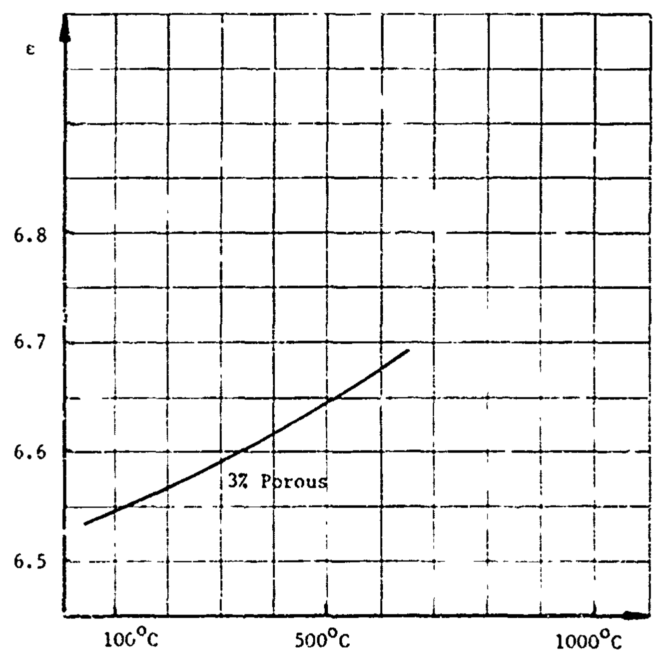


Fig 2.2.5.1.3

MULLITE: Dielectric Constant v. Temperature
9.5 GHz

MULLITE: Loss Tangent v. Frequency
Room Temperature

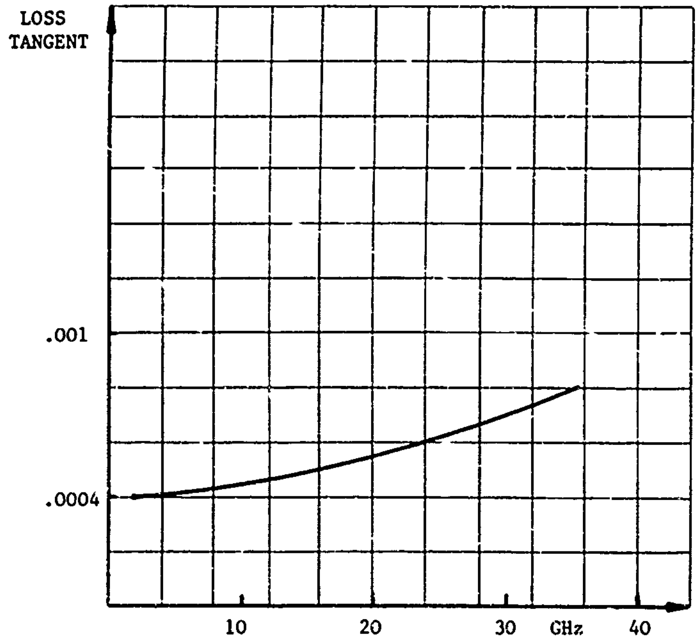


Fig 2.2.5.1.4

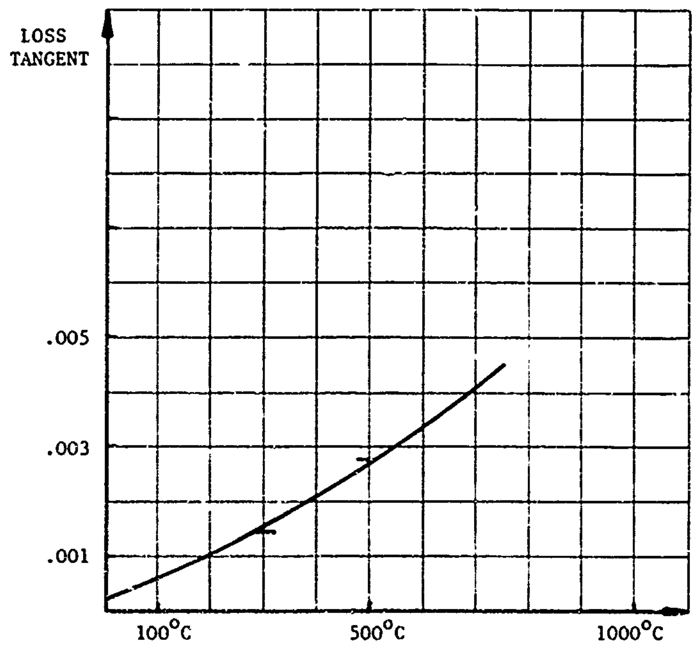


Fig 2.2.5.1.5

MULLITE: Loss Tangent v. Temperature
9.368 GHz

MULLITE: Volume Resistivity v. Temperature

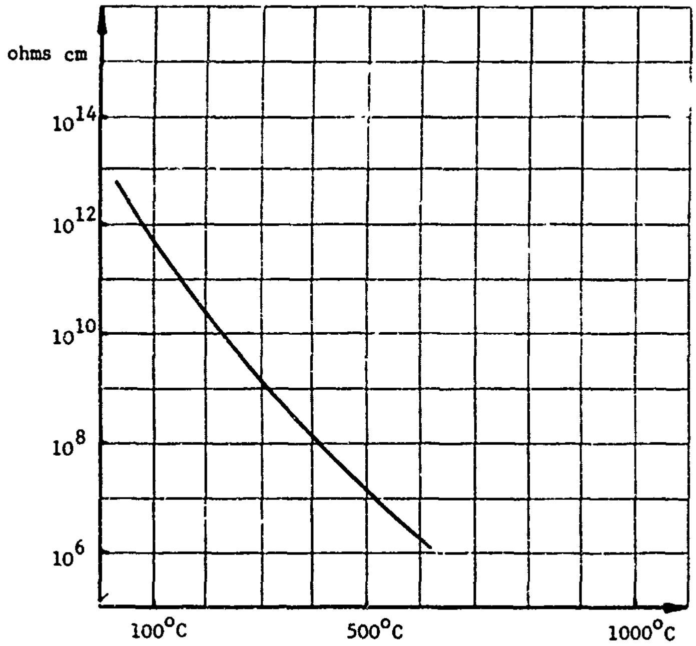


Fig 2.2.5.1.6

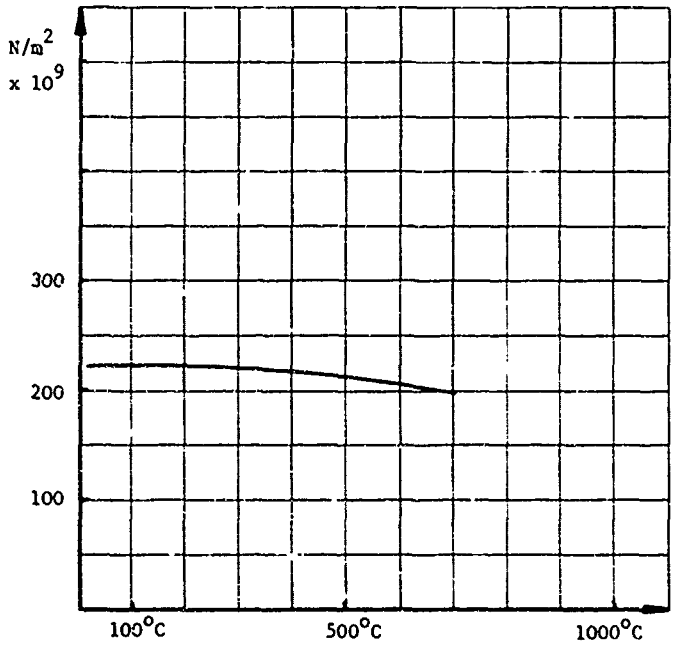


Fig 2.2.5.2.1

MULLITE: Youngs Modulus v. Temperature

MULLITE: Youngs Modulus v. Porosity

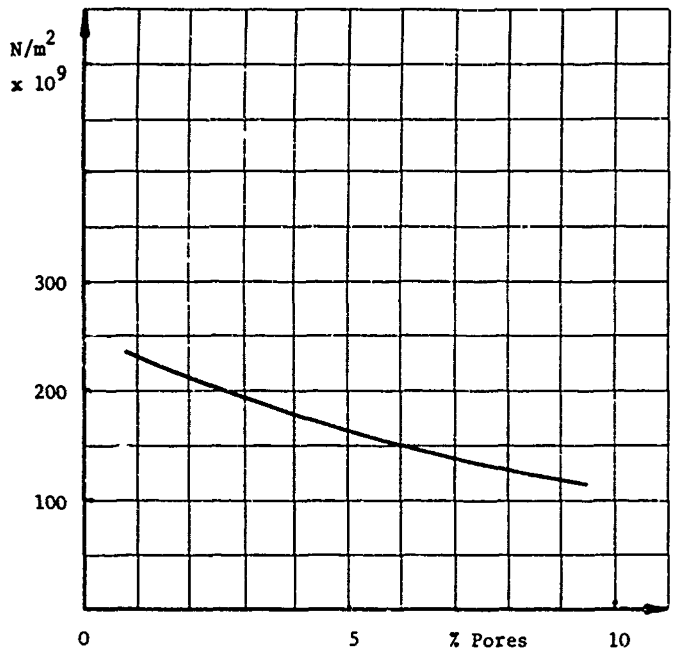


Fig 2.2.5.2.2

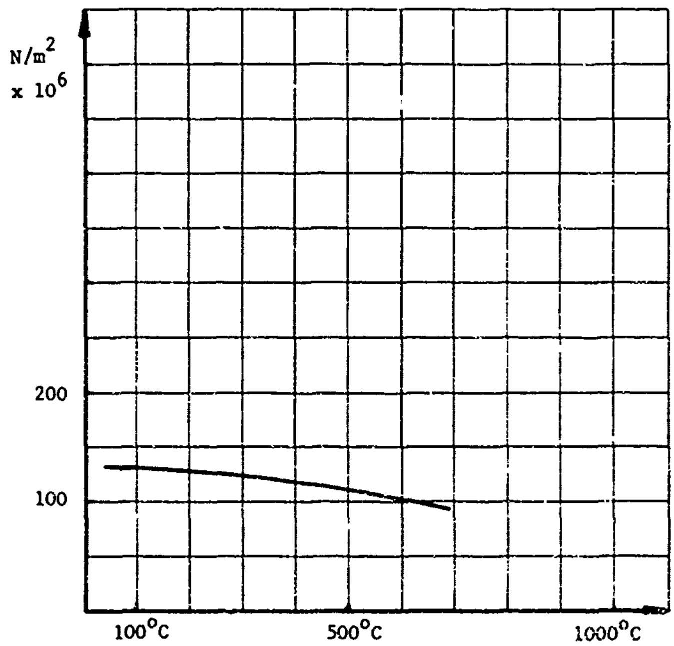


Fig 2.2.5.2.3

MULLITE: Tensile Strength v. Temperature

MULLITE: Compressive Strength v. Temperature

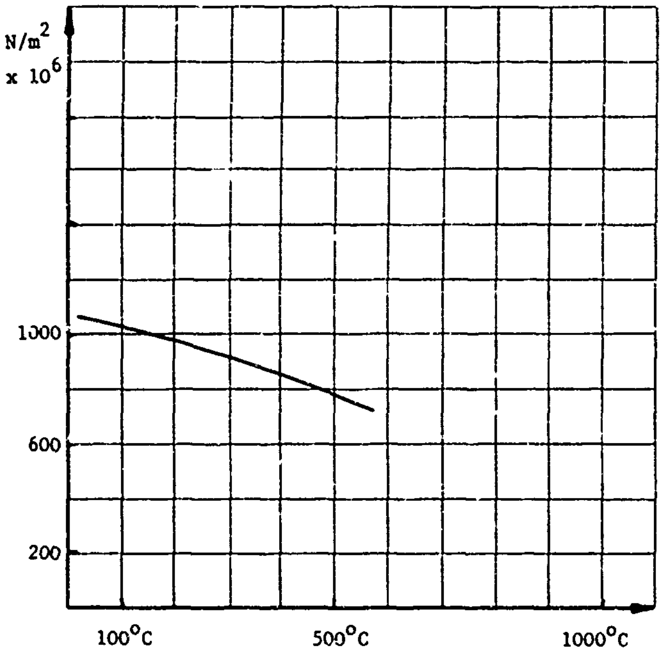


Fig 2.2.5.2.4

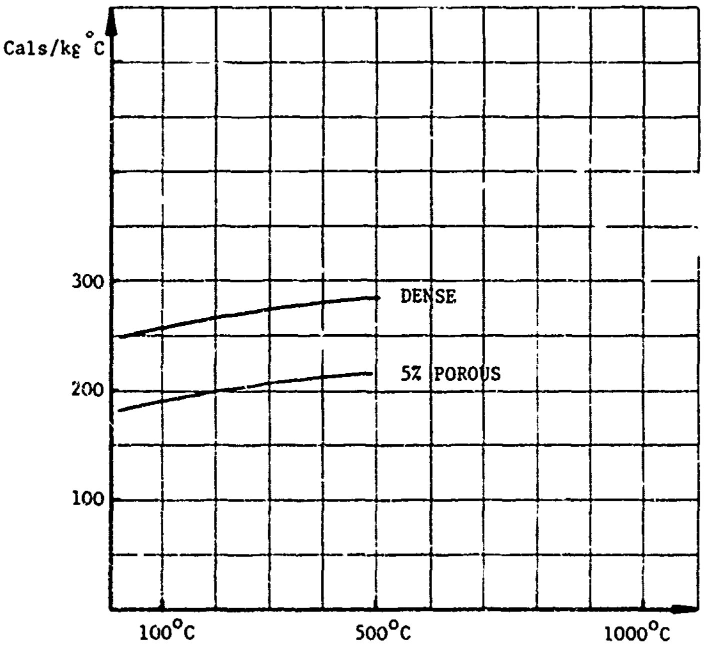


Fig 2.2.5.3.1

MULLITE: Specific Heat v. Temperature

MULLITE: Thermal Conductivity v. Temperature

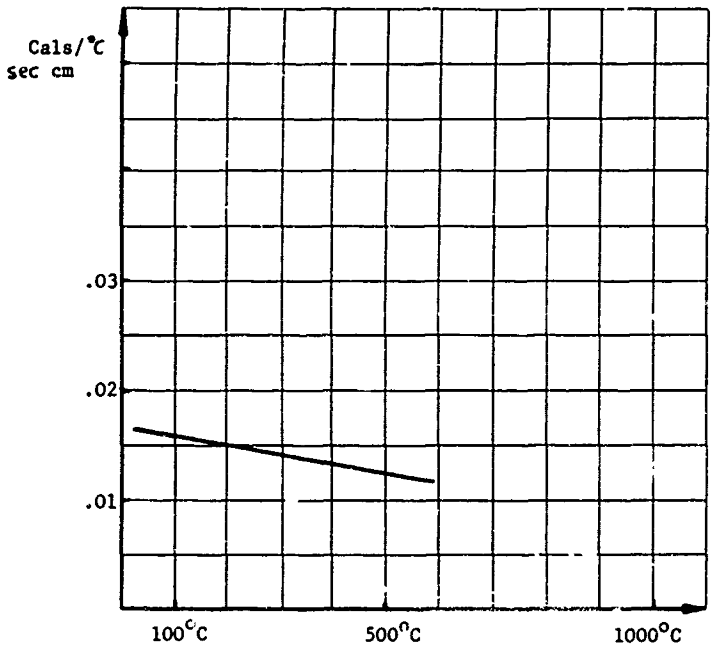


Fig 2.2.5.3.2

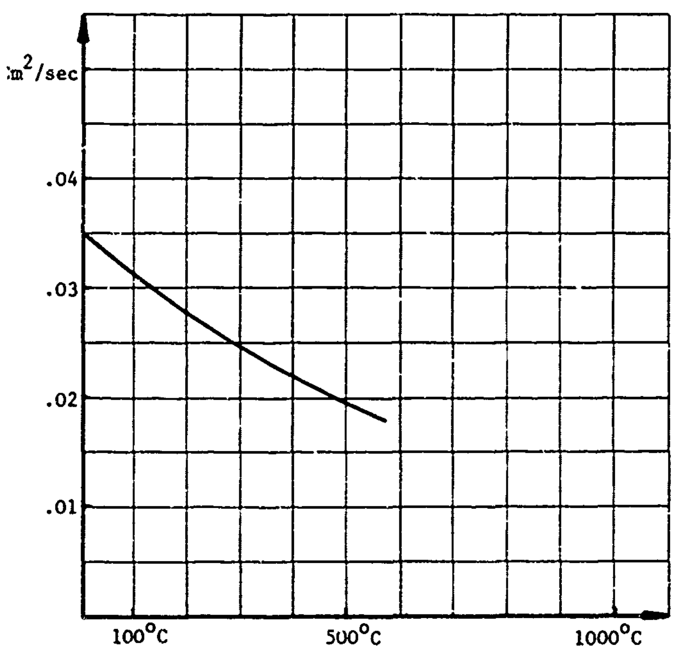


Fig 2.2.5.3.3

MULLITE: Thermal Diffusivity v. Temperature

2.2.6 STEATITE $MgOSiO_2$

Steatite is a type of porcelain whose electrical characteristics are suitable for radomes, but is usually not considered as its mechanical properties are not as good as alumina. A few of its properties are:-

Specific Gravity	2.8 grams/cc
Porosity	0
Dielectric Constant	5.7 at 20°C
Loss Tangent	.0005
Volume Resistivity	10^{13} at 20°C 10^{7} ohm-cm at 600°C
Dielectric Strength	35 kv/mm
Youngs Modulus	110×10^{9} N/m^2
Tensile Strength	70×10^{6} N/m^2
Compressive Strength	900×10^{6} N/m^2
Flexural Strength	140×10^{6} N/m^2
Impact	3 in Lb
Hardness	7.5
Specific Heat	0.2 cals/gram °C
Thermal Conductivity	0.006 cals/ cm sec °C
Diffusivity	0.012 sq cm/sec
Expansion	8×10^{-6} °C
Rain Erosion	290 min in 1"/hr. 500 mph rain deeply pitted.
Temperature Max. Working	1250°C

2.2.7 SILICON NITRIDE Si_3N_4

Of interest to high temperature radomes is silicon nitride, which has been evaluated (4) (20) (21) (22) (23) to show that it has acceptable electrical properties, mechanical strength rain erosion, as well as excellent thermal shock resistance. It is formed by the reaction of silicon with nitrogen. Silicon powder is moulded to shape by pressing slip casting or flame spray and subsequently reacted with nitrogen. By this method a porous material of density near 2.5 grams/cc is produced. A denser material near 3.2 grams/cc more suitable to the more exacting radome requirements is produced by silicon powder reacted with nitrogen to form silicon nitride powder, which is hot pressed to the required shape.

Electrically the dielectric constant is dependent on the porosity, a very dense material of near 3.2 grams/cc will be near 7.9, while a reaction bonded material of 2.5 grams/cc would be near 5.5. The dielectric constant change with temperature is considerably less than alumina, being near 0.6% per 100°C. The loss tangent near 0.003 at ambient, and remains reasonably low at high temperatures to be acceptable for radome usage. Impurities can give high loss and variable dielectric constant. (36)(37)

Mechanically the properties are dependent upon the porosity, but dense material is of very high strength and the reaction bonded material is still reasonably strong.

Thermally the conductivity and expansion coefficient are low, and the thermal shock resistance is excellent.

Dense material has a high degree of rain erosion resistance, the even reaction bonded is still fair. (35)

The problems of the material are that reaction bonded being porous, presents problems of sealing against humidity and water absorption, while the dense material requires heavy pressures and costly press tools. Porous silicon nitride has been sealed with a silicone resin (30) which at 2000 F (1255°C) decomposed completely and the carbon component was released as CO_2 leaving a silica powder which would not be expected to cause loss.

A major problem is to obtain consistent properties, this applies to both reaction sintered (38) and to dense silicon nitride (37).

ELECTRICAL PROPERTIES : SILICON NITRIDE   TABLE 2.2.7.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(2) (3) Fig 2.2.7.1.1	Max. Density near 3.2 grams/per cc gives dielectric constant of near 7.9.
Dielectric Constant v. Frequency	(2) (3) (4) Fig 2.2.7.1.2	Little change in microwave band
Dielectric Constant v. Temperature	(2)(3)(4)(11) Fig 2.2.7.1.3	Change of dielectric constant with temperature is small.
Loss Tangent v. Frequency	(2) (3) Fig 2.2.7.1.4	Little change over microwave band, with pure material. Impurities cause high loss.
Loss Tangent v. Temperature	(2)(3)(4) Fig 2.2.7.1.5	Little change with temperature
Dielectric Constant v. Humidity		Dielectric constant changes according to humidity pick-up and porosity.
Dielectric Constant v. Radiation		Not affected by solar ultra violet or 10^{10} rads nuclear radiation.
Volume Resistivity v. Temperature	(23) Fig 2.2.7.1.6	10^{13} at 20°C 10^{10} at 500°C
Dielectric Strength v. Temperature		High dielectric strength

MECHANICAL PROPERTIES : SILICON NITRIDE   TABLE 2.2.7.2

Property	Reference Fig	Remarks
Specific Gravity	(2) (4) (23)	3.2 grams c c dense material (hot pressed) 2.5 grams c c typical reaction bonded.
Youngs Modulus v. Temperature	(4)(20)(21)(22)(23) Fig 2.2.7.2.1	
Youngs Modulus v. Porosity	Fig 2.2.7.2.2	decreases with porosity
Shear Modulus v. Temperature		
Rupture Modulus		
Poissons Ratio	(23)	.25 reaction sintered .26 hot pressed
Flexural Strength v. Temperature	(23) Fig 2.2.7.2.3	
Tensile Strength v. Temperature		
Compressive Strength v. Temperature	(23)	350×10^7 N/m^2 hot pressed 100×10^7 N/m^2 reaction bonded
Impact Strength		
Hardness		Depends on density. 7-9 MOHS

THERMAL PROPERTIES : SILICON NITRIDE

TABLE 2.2.7.3

Property	Reference & Fig	Remarks
Temperature Working Range	(2)	1600°C
Specific Heat v. Temperature	(2) (4) (8) Fig 2.2.7.3.1	
Conductivity v. Temperature	(2) (4) (8) Fig 2.2.7.3.2	low conductivity
Diffusivity v. Temperature		
Expansion v. Temperature	(2) (23)	hot pressed 3.2×10^{-6}/°C reaction bonded 2.6×10^{-6}/°C
Emissivity v. Temperature		
Ablation		
Thermal Shock		Very good thermal shock characteristics
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : SILICON NITRIDE

TABLE 2.2.7.4

Properties	Reference & Fig	Remarks
Temperature		Up to 1600°C
Humidity & Water Absorption		Depends on porosity
Rain Erosion	(10) (12)	dense material very good. Reaction bonded good. (Moderate erosion 300 minutes 500 mph 1"/hr rain)
Radiation Solar Nuclear		Unaffected by solar ultra violet safe nuclear rating 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid		Porous material absorbs contaminants, unaffected chemically. Dense material unaffected by oils, fuels, etc.
Storage & Ageing		Store in dry surroundings. Inert.

SILICON NITRIDE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

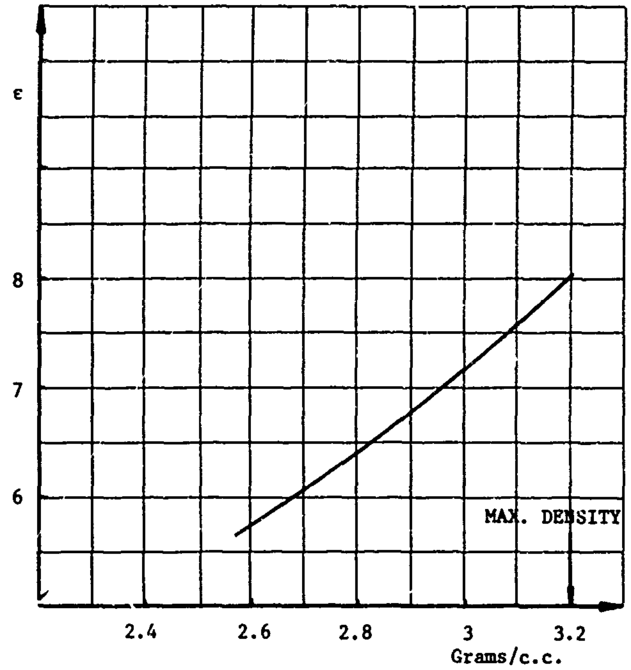


Fig 2.2.7.1.1

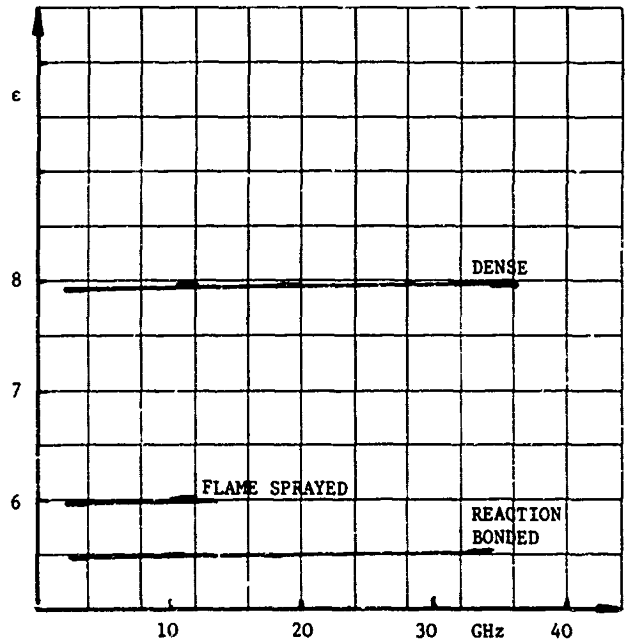


Fig 2.2.7.1.2

SILICON NITRIDE: Dielectric Constant v. Frequency
Room Temperature

SILICON NITRIDE: Dielectric Constant v. Temperature
9.5 GHz

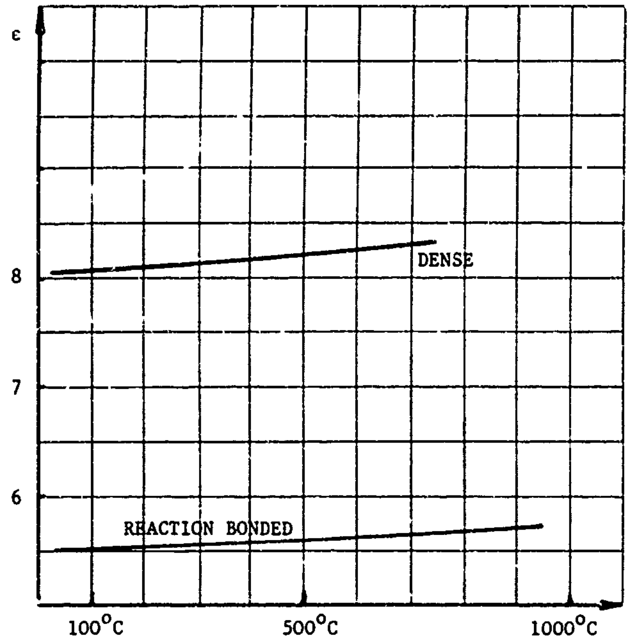


Fig 2.2.7.1.3

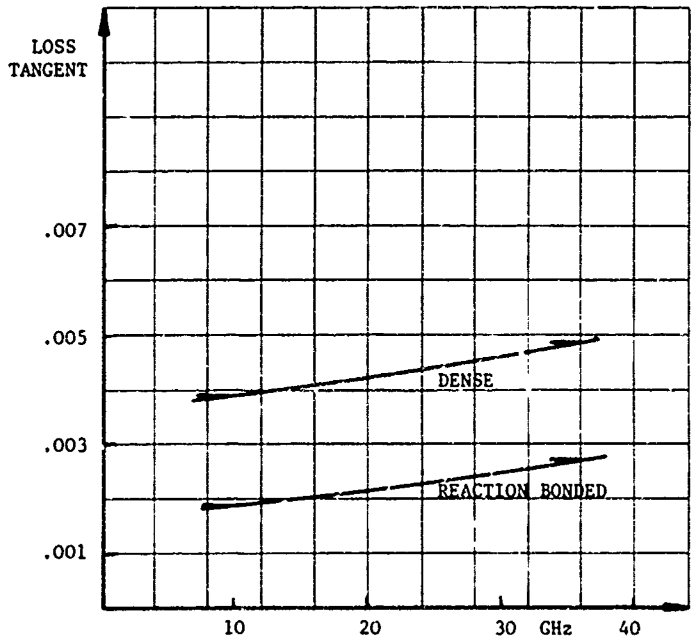


Fig 2.2.7.1.4

SILICON NITRIDE: Loss Tangent v. Frequency
Room Temperature

SILICON NITRIDE: Loss Tangent v. Temperature
9.368 GHz

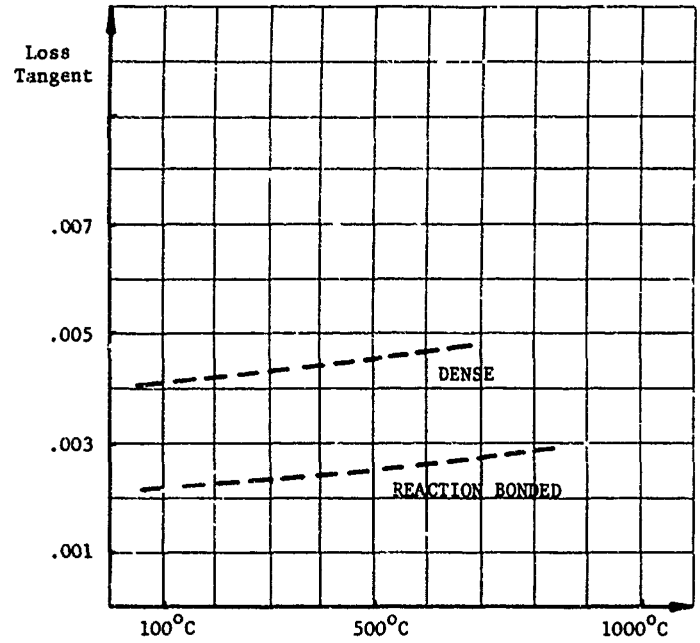


Fig 2.2.7.1.5

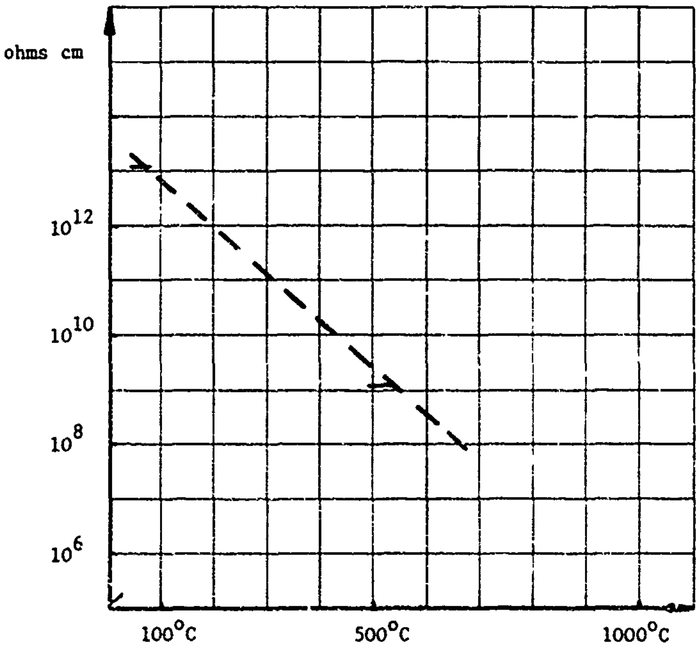


Fig 2.2.7.1.6

SILICON NITRIDE: Volume Resistivity v. Temperature

SILICON NITRIDE: Youngs Modulus v. Temperature

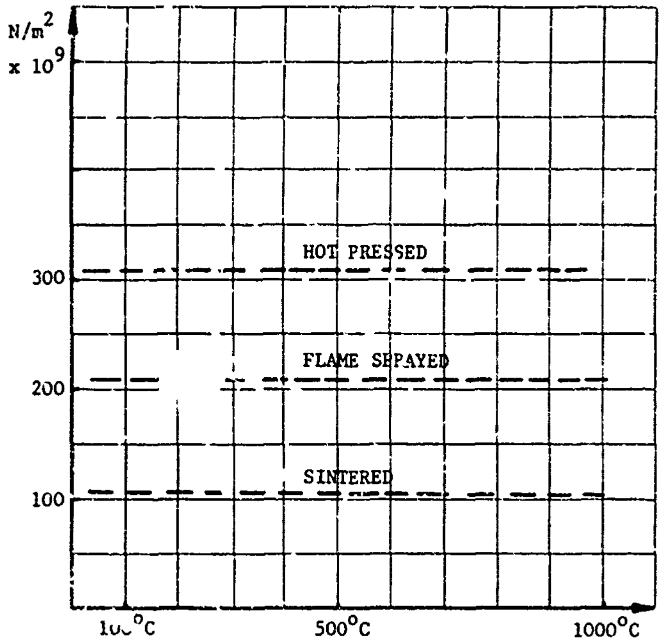


Fig 2.2.7.2.1

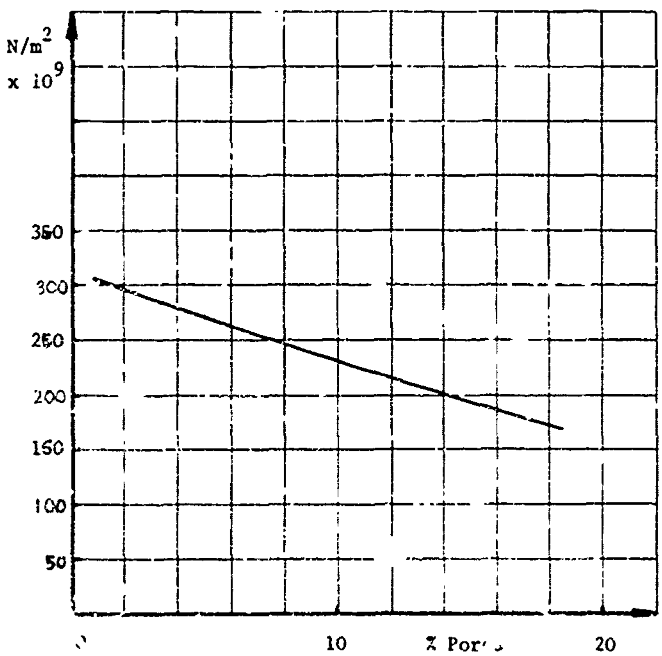


Fig 2.2.7.2.2

SILICON NITRIDE: Youngs Modulus v. Porosity

SILICON NITRIDE: Flexural Strength v. Temperature

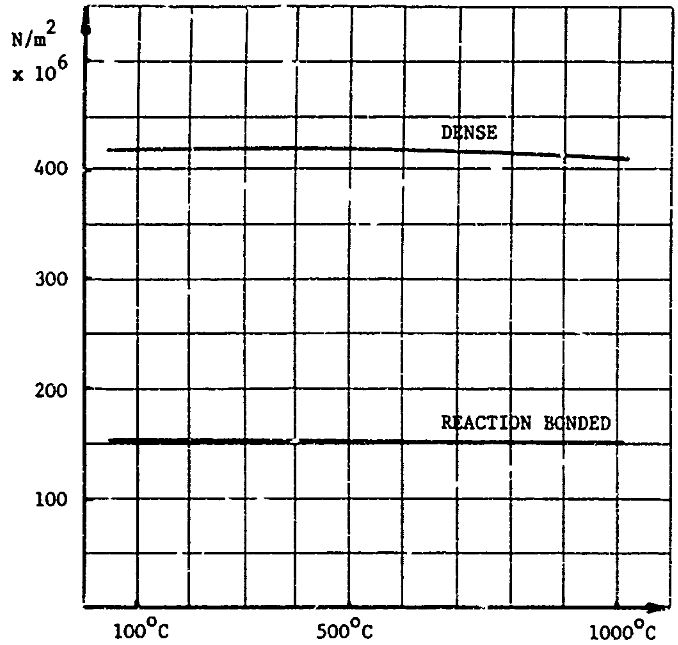


Fig 2.2.7.2.3

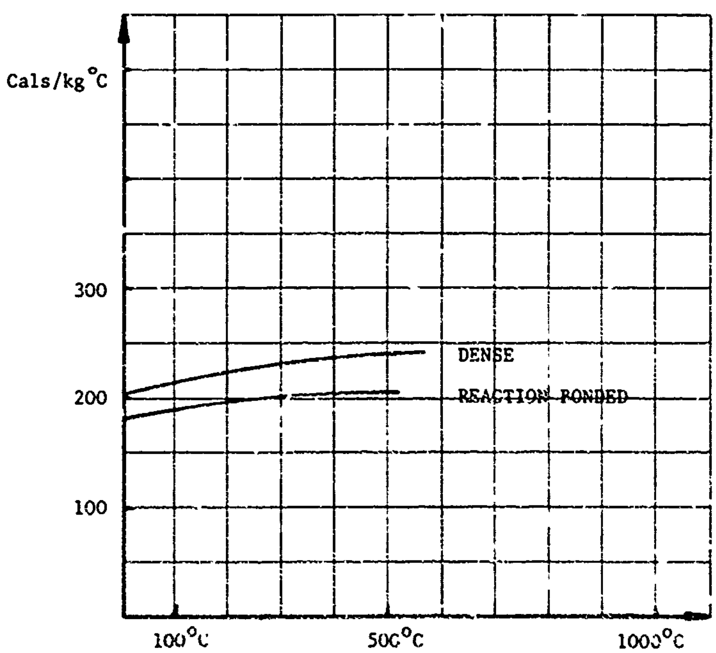


Fig 2.2.7.3.1

SILICON NITRIDE: Specific Heat v. Temperature

SILICON NITRIDE: Thermal Conductivity v. Temperature

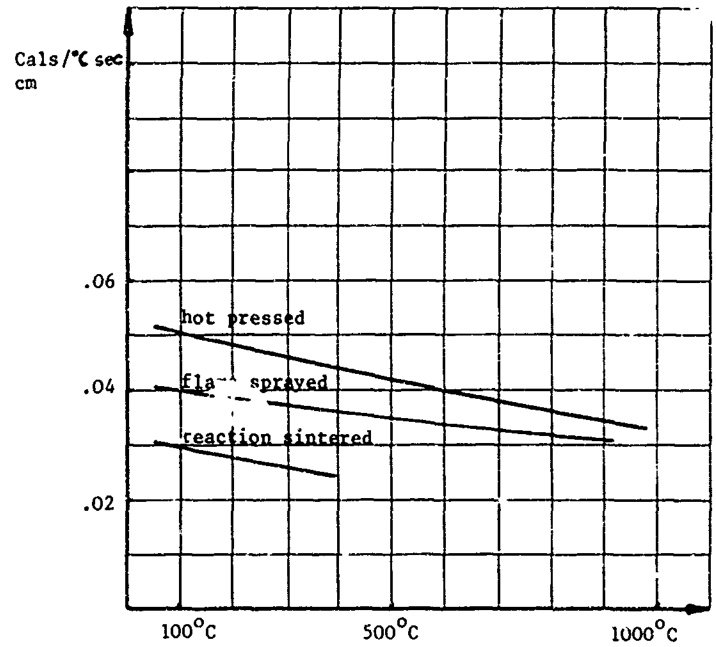
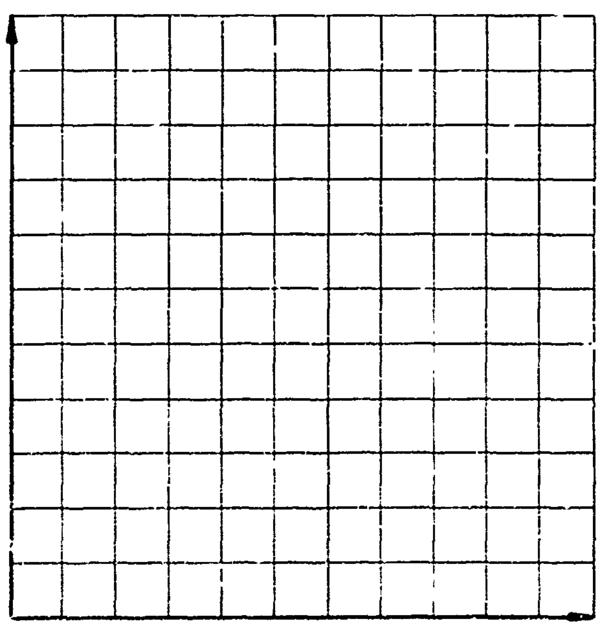


Fig 2.2.7.3.2



2.2.8 BORON NITRIDE: BN

Boron nitride is among the materials whose properties have been evaluated for high temperature microwave radome usage (4) (9) (11) (15) (24). Two forms have been manufactured hot pressed dense material and an isotropic pyrolytic type of less density.

Electrically both forms of material are suitable for radome usage. The dense material has a dielectric constant of near 4.4 with a very low change of dielectric constant with temperature characteristic 0.3% per 100°C. The less dense material dielectric constant is near 3. Both materials have loss tangents which are low.

Mechanically the material is reasonably strong. At room temperature the flexural strength is near 100 x 10^6 N/m^2 but it falls off with temperature to near 30 x 10^6 N/m^2 at 750°C. It is its rather poor mechanical properties comparative to Silicon Nitride for example which lessens this material as a choice for radomes, for high temperatures.

Thermally the expansion coefficient is high and its conductivity is comparative to alumina. Various forms of boron nitride have good thermal shock resistance.

The material's rain resistance is poor due to its softness, and would be another limiting factor in its choice for certain environment operations.

ELECTRICAL PROPERTIES : BORON NITRIDE — TABLE 2.2.8.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(4) (9) (17) Fig 2.2.8.1.1	Theoretical 2.34 grams per cc. Hot pressed near 2.0 grams per cc. Pyrolytic near 1.25 grams per cc.
Dielectric Constant v. Frequency	(4) (6) Fig 2.2.8.1.2	Little change in microwave band.
Dielectric Constant v. Temperature	(4) (9) (24) Fig 2.2.8.1.3	Small change with temperature
Loss Tangent v. Frequency	(4) (6) Fig 2.2.8.1.4	Low loss
Loss Tangent v. Temperature	(4) (9) (25) Fig 2.2.8.1.5	
Dielectric Constant v. Humidity		Tends to be non porous (humidity collects on surface)
Dielectric Constant v. Radiation		Unaffected by solar ultra violet.
Volume Resistivity v. Temperature		5×10^9 at 20°C
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : BORON NITRIDE — TABLE 2.2.8.2

Property	Reference Fig	Remarks
Specific Gravity	(4) (9)	Hot pressed 2.0 grams per cc. Pyrolytic 1.25 grams per cc.
Youngs Modulus v. Temperature	(4) (9) Fig 2.2.8.2.1	
Youngs Modulus v. Porosity		
Shear Modulus v. Temperature		
Rupture Modulus	(9)	Hot presset 100×10^6 N/m^2 at 20°C 30×10^6 N/m^2 at 750°C
Poissons Ratio	(4)	0.23 Pyrolytic
Flexural Strength v. Temperature	(4) (25) Fig 2.2.8.2.2	
Tensile Strength v. Temperature		18×10^6 N/m^2 at 20°C
Compressive Strength v. Temperature		210×10^6 N/m^2 at 20°C
Impact Strength		
Hardness		1 → 2 MOHS - Soft material

THERMAL PROPERTIES : BORON NITRIDE

TABLE 2.2.8.3

Property	Reference & Fig	Remarks
Temperature Working Range		Melts 2730°C Working range up to 1500°C could be higher in certain conditions.
Specific Heat v. Temperature	(4) (11) (17) Fig 2.2.8.3.1	
Conductivity v. Temperature	(4) (11) (17) Fig 2.2.8.3.2	
Diffusivity v. Temperature		
Expansion v. Temperature	(4) (25)	Varies with axis and manufacturing process.
Emissivity v. Temperature		
Ablation		Sublimes at high temperature.
Thermal Shock		Hot pressed very good (could be suitable for Mach 5). Pyrolytic suitable for very high thermal shocks.
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : BORON NITRIDE

TABLE 2.2.8.4

Properties	Reference & Fig	Remarks
Temperature	(4)(9)(11)(17)	Could be limited by mechanical strength
Humidity & Water Absorption		Material is close cell type and does not absorb water.
Rain Erosion		Poor due to softness.
Radiation Solar Nuclear		Unaffected by ultra violet
Contamination Oils Fuels Detergents Salts Acid		Not affected by oils, fuels, etc.
Storage & Ageing		Store free from pressures and abrasion Inert.

BORON NITRIDE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

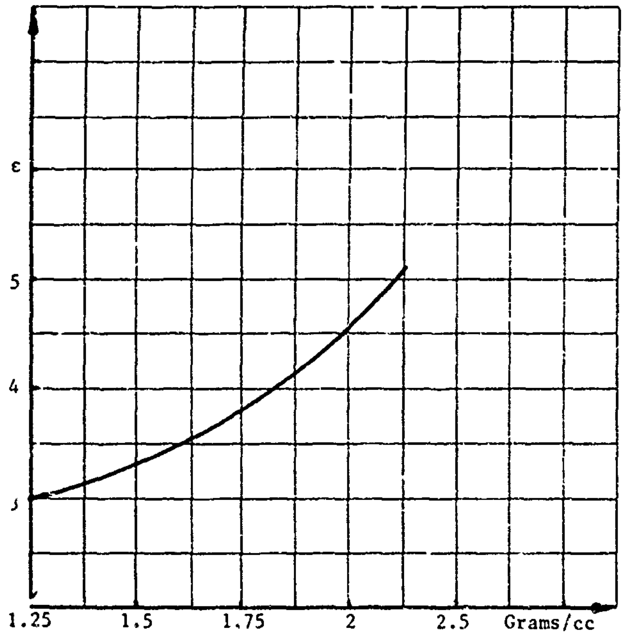
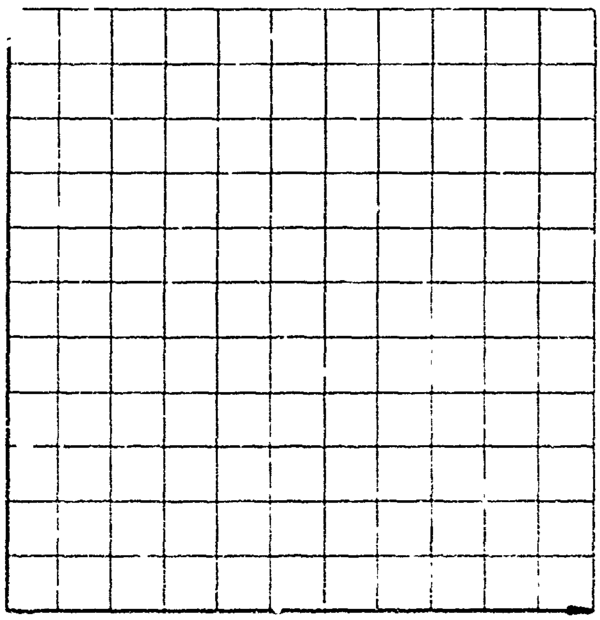


Fig 2.2.8.1.1



BORON NITRIDE: Dielectric Constant v. Frequency
Room Temperature

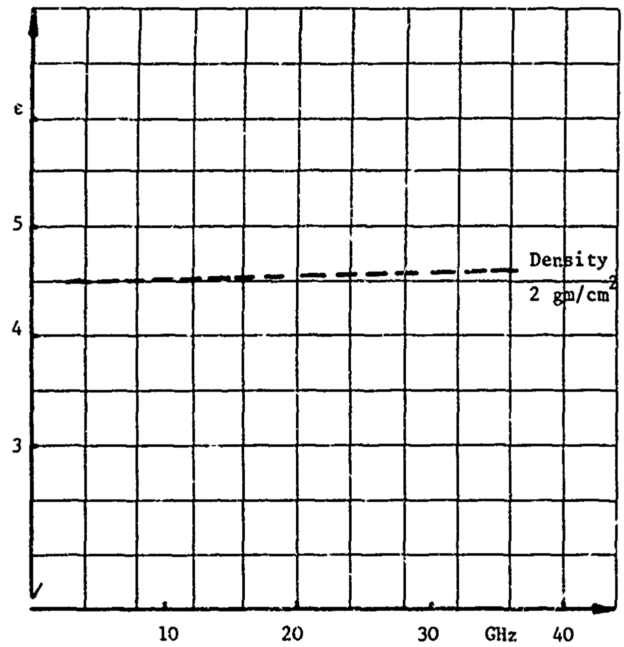


Fig 2.2.8.1.2

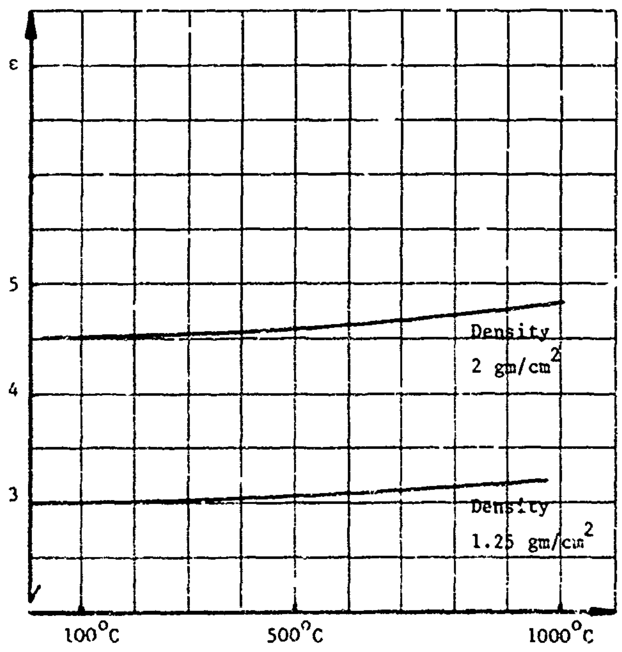


Fig 2.2.8.1.3

BORON NITRIDE: Dielectric Constant v. Temperature
9.5 GHz

BORON NITRIDE: Loss Tangent v Frequency
Room Temperature

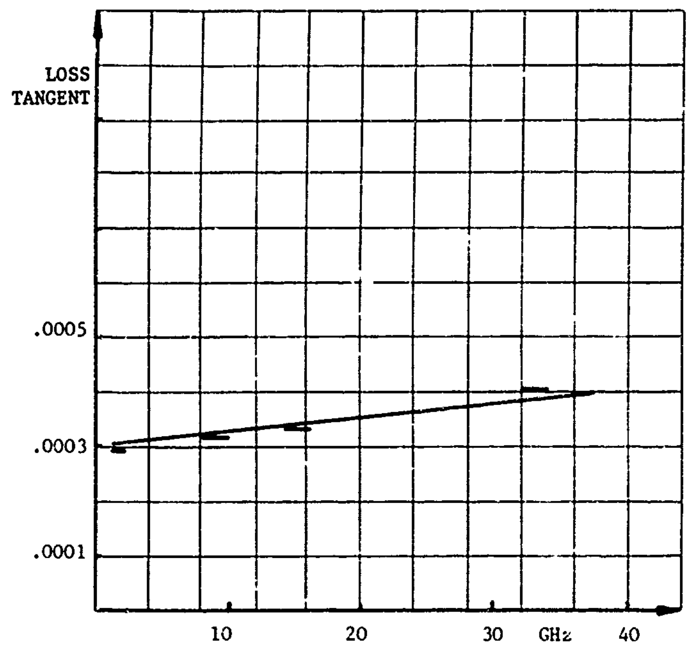


Fig 2.2.8.1.4

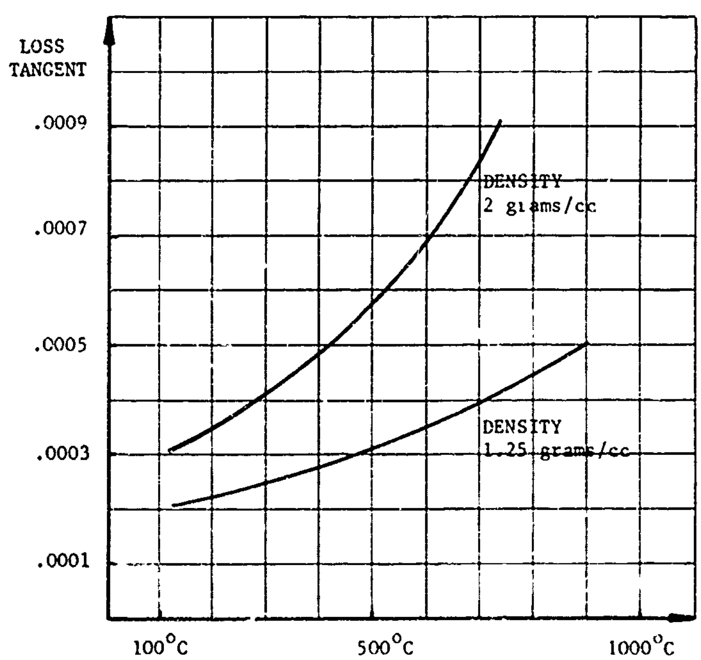


Fig 2.2.8.1.5

BORON NITRIDE: Loss Tangent v Temperature 9.368 GHz

BORON NITRIDE: Youngs Modulus v. Temperature

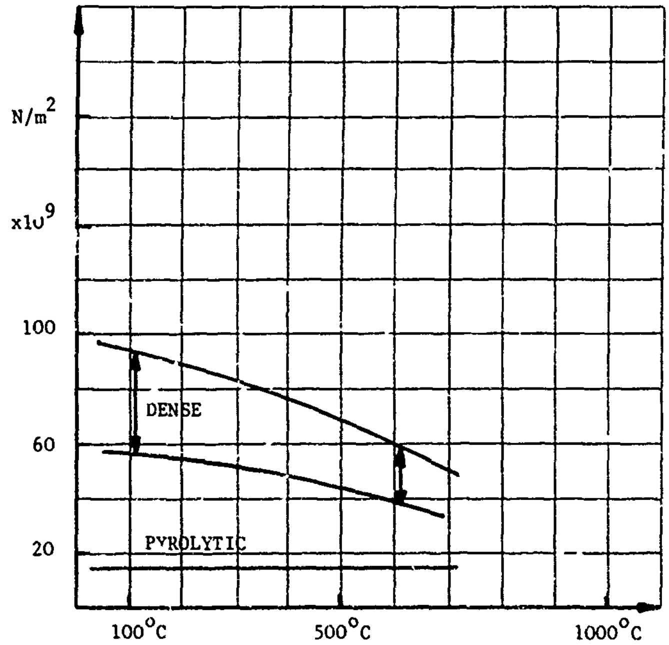


Fig 2.2.8.2.1

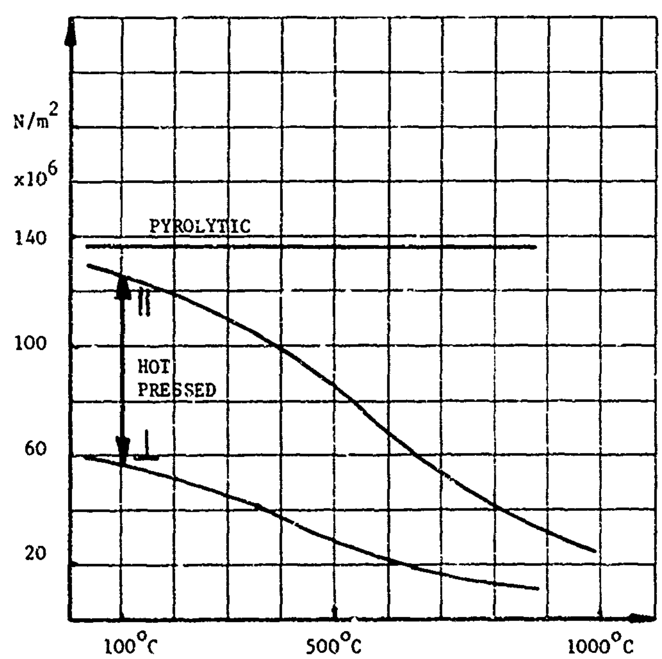


Fig 2.2.8.2.2

BORON NITRIDE: Flexural Strength v. Temperature

BORON NITRIDE: Specific Heat v. Temperature

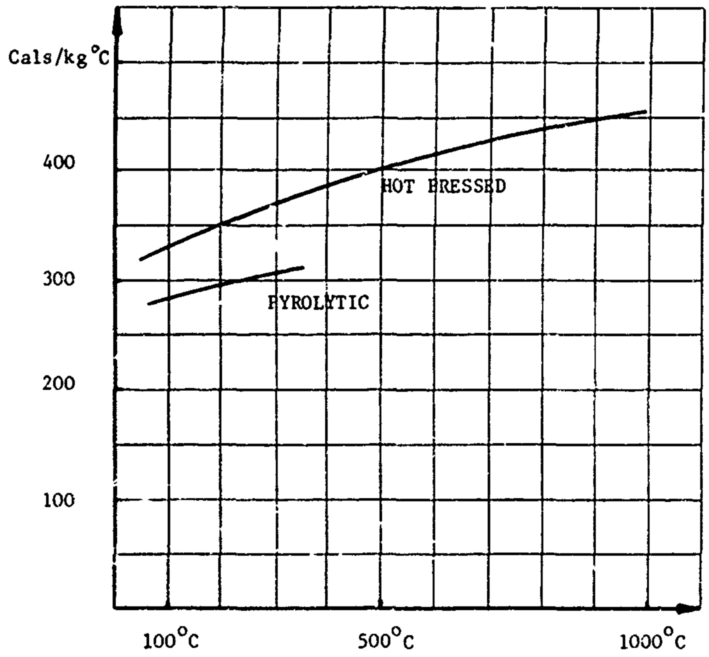


Fig 2.2.8.3.1

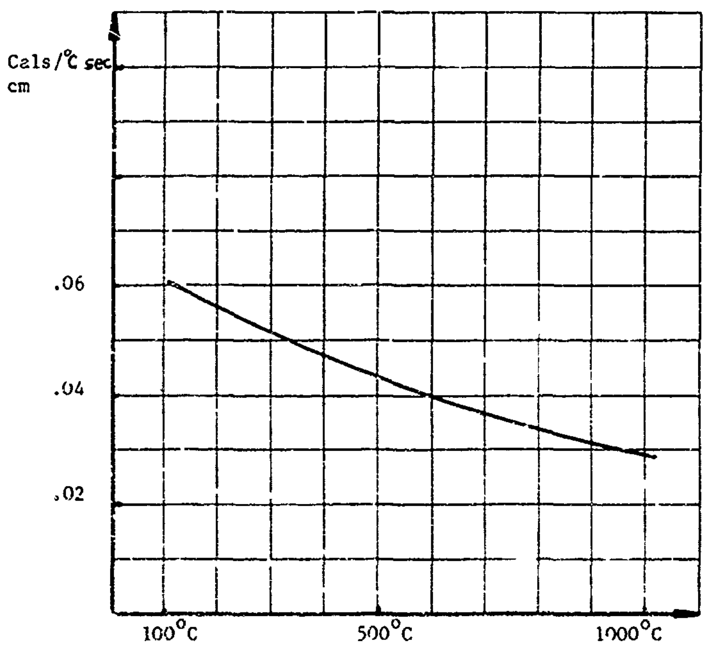


Fig 2.2.8.3.2

BORON NITRIDE: Thermal Conductivity v. Temperature

2.2.9. BERYLLIUM OXIDE BeO

Beryllium oxide is a candidate radome material for high temperature operation and thermal shock conditions (1) (4) (9) (25). It has a number of disadvantages which makes it less attractive. It can be made by pressing and casting; a dense material in general being preferred for radome application.

Electrically its dielectric constant is at 20°C near 6.6 at maximum density, the usual product is near 6.4. The change of dielectric constant with temperature is near 2% per 100°C, which would limit the design of a wideband, wide temperature range radome. The loss tangent is low at room temperature and should be usable up to very high temperatures 1500°C without undue loss.

Mechanically, its flexural strength of 280 x 10^6 N/m^2 at 20°C is well maintained to 750°C when it falls to 140 x 10^6 N/m^2 at 1000°C, makes this material competitive to alumina.

Thermally the specific heat and conductivity is much greater than alumina and has a similar expansion coefficient. Its thermal shock resistance is good initially, but tends to be poor under high levels of shock.

The material should be reasonably rain erosion resistant due to its hardness. It has been used for small windows to pass high transmission systems, because of its good electrical and thermal conductivity, but manufacture of large shaped radomes presents problems of processing. The toxic nature of Beryllium oxide requires expensive equipment for handling purifications, machining and general manufacture of the final products, which is one of the main disadvantages of the material as a candidate for radome usage.

ELECTRICAL PROPERTIES : BERYLLIUM OXIDE

TABLE 2.2.9.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(1)(4)(9)(25) Fig 2.2.9.1.1	A dense material is sought fc. radome usage.
Dielectric Constant v. Frequency	(1) (25) Fig 2.2.9.1.2	
Dielectric Constant v. Temperature	(1) (9) (25) Fig 2.2.9.1.3	Similar change of dielectric constant with temperature as alumina.
Loss Tangent v. Frequency	(1) (9) (25) Fig 2.´.9.1.4	Low loss
Loss Tangent v. Temperature	(1) (9) (25) Fig 2.2.9.1.5	Low loss over wide temperature range
Dielectric Constant v. Humidity		Dense material preferred
Dielectric Constant v. Radiation		Unaffected by ultra violet
Volume Resistivity v. Temperature	(1) (8)	10^{14} ohm cm at 100°C 10^{9} at 1000°C
Dielectric Strength v. Temperature	(1)	14 kv/mm at 20°C 12 kv/mm at 400°C

MECHANICAL PROPERTIES : BERYLLIUM OXIDE

TABLE 2.2.9.2

Property	Reference Fig	Remarks
Specific Gravity	(1) (8)	max. density 3.01 grams/cc usual dense material 98% 2.95 grams/cc.
Youngs Modulus v. Temperature	(1) (8) (25) Fig 2.2.9.2.1	remains high to 1000°C
Youngs Modulus v. Porosity		Decreases with density
Shear Modulus v. Temperature	(17)	150 x 10^{9} N/m^{2} at 20°C
Rupture Modulus		
Poissons Ratio	(17)	1.67 (Density 3) 1.95 (Density 2.93)
Flexural Strength v. Temperature	(1) (8) (25) Fig 2.2.9.2.2	
Tensile Strength v. Temperature	(1) (8) (25) Fig 2.2.9.2.3	Falls off with temperature
Compressive Strength v. Temperature	(1)(8)(9)(25) Fig 2.2.9.2.4	Gradually falls with temperature
Impact Strength		
Hardness		9 MOHs 1500 Kg/mm^{2} KNOOP

THERMAL PROPERTIES : BERYLLIUM OXIDE   TABLE 2.2.9.3

Property	Reference & Fig	Remarks
Temperature Working Range		melting point 2550°C max. working tmep. near 2000°C
Specific Heat v. Temperature	(1)(4)(8)(9)(25) Fig 2.2.9.3.1	very high specific heat
Conductivity v. Temperature	(1)(4)(8)(9)(25) Fig 2.2.9.3.2	very high conductivity
Diffusivity v. Temperature	(1) Fig 2.2.9.3.3	
Expansion v. Temperature	(1)(4)(9)(9)(25)	20 - 100°C 8 x 10^{-6}°C 20 - 500°C 7.7 x 10^{-6}°C 20 - 1000°C 9.1 x 10^{-6}°C
Emissivity v. Temperature	(1) (9) Fig 2.2.9.3.4	
Ablation		
Thermal Shock		Very good
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : BERYLLIUM OXIDE   TABLE 2.2.9.4

Properties	Reference & Fig	Remarks
Temperature		Max. working temperature near 2000°C
Humidity & Water Absorption		dense material unaffected
Rain Erosion		Very good rain erosion resistance
Radiation Solar Nuclear		Unaffected by solar ultra violet should have a safe nuclear radiation of 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid		Unaffected by oils, fuels, and mild corrosives.
Storage & Ageing		Store - dry and free from abrasion. Inert.

BERYLLIUM OXIDE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

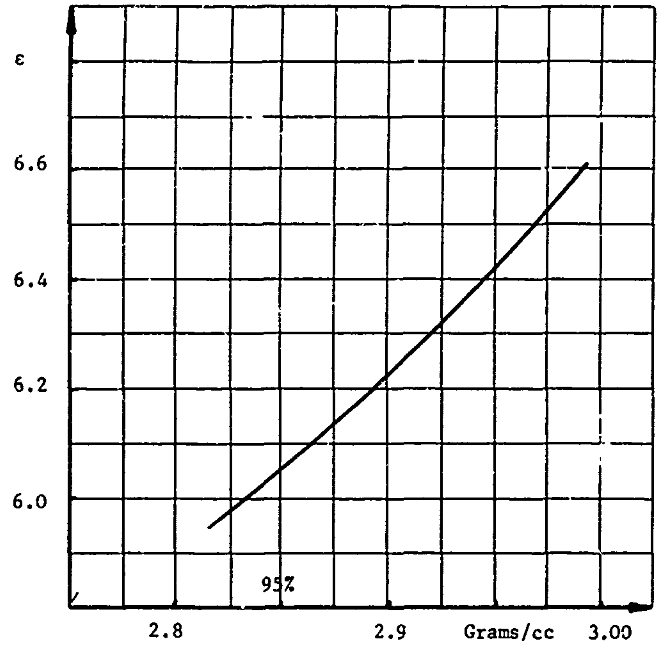


Fig 2.2.9.1.1

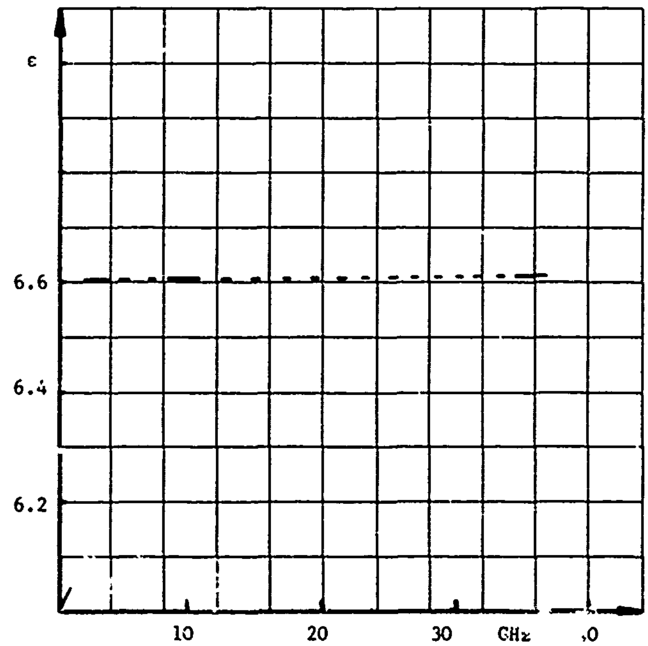


Fig 2.2.9.1.2

BERYLLIUM OXIDE: Dielectric Constant v. Frequency
Room Temperature

BERYLLIUM OXIDE: Dielectric Constant v. Temperature 9.5 GHz

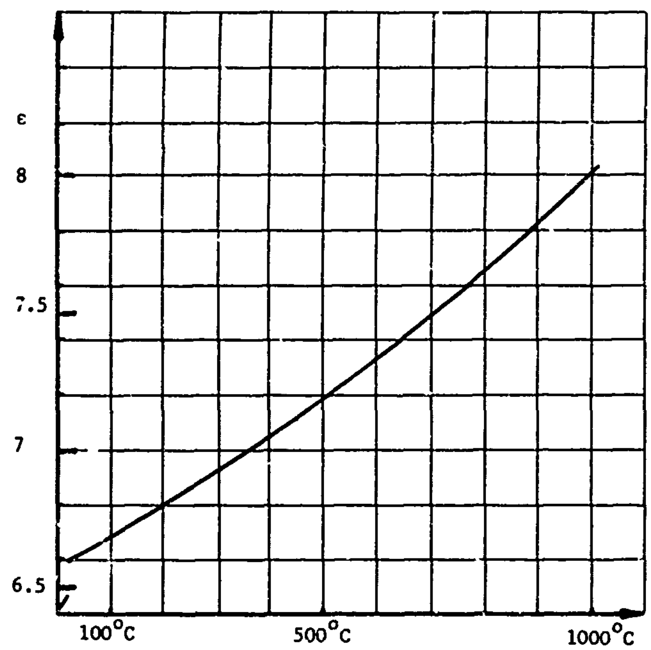


Fig 2.2.9.1.3

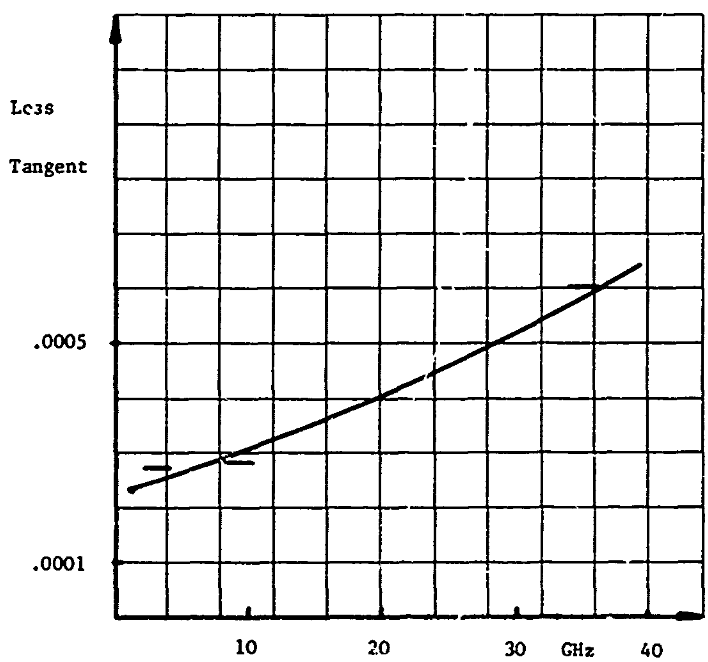


Fig 2.2.9.1.4

BERYLLIUM OXIDE: Loss Tangent v. Frequency
Room Temperature

BERYLLIUM OXIDE: Loss Tangent v. Temperature 9.368 GHz

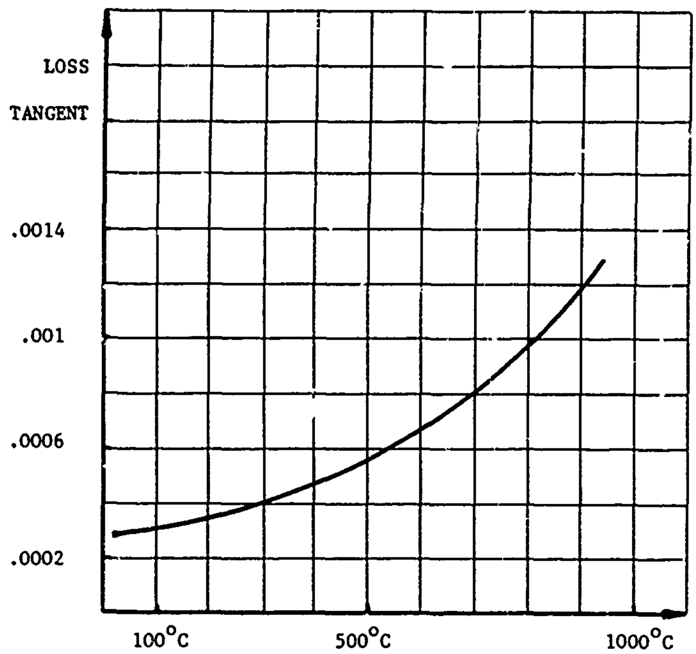


Fig 2.2.9.1.5

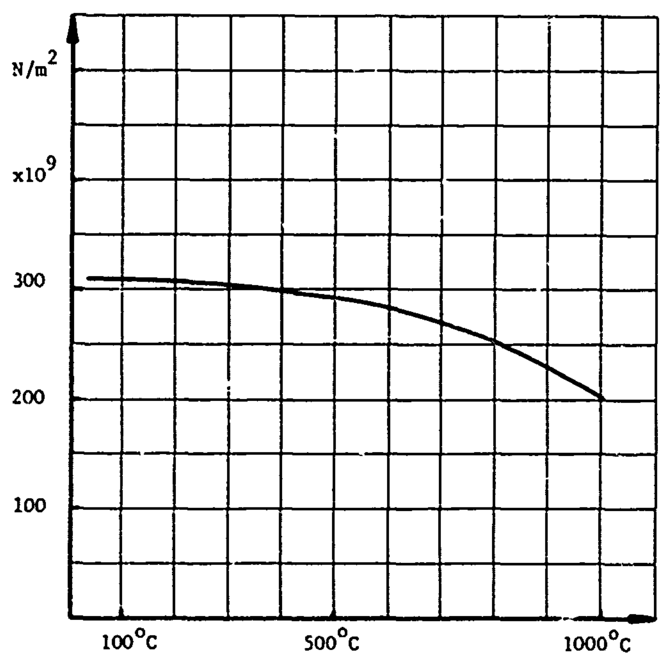


Fig 2.2.9.2.1

BERYLLIUM OXIDE: Youngs Modulus v. Temperature

BERYLLIUM OXIDE: Flexural Strength v. Temperature

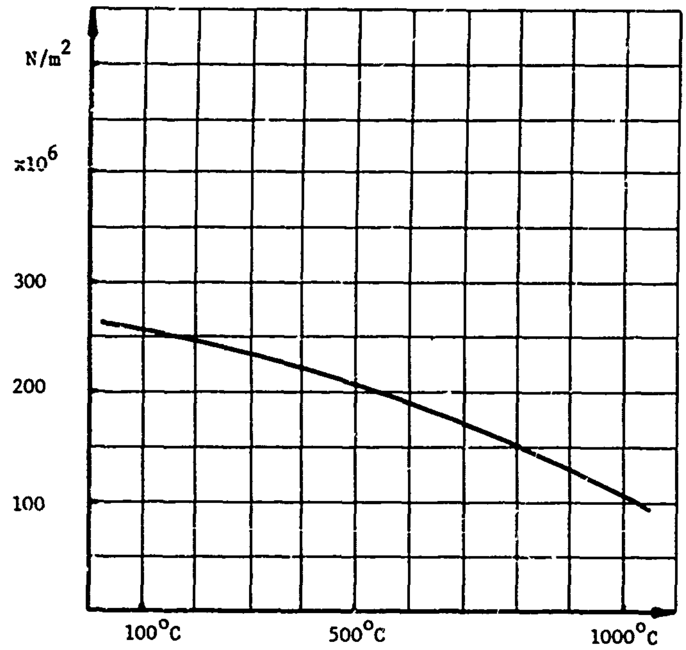


Fig 2.2.9.2.2.

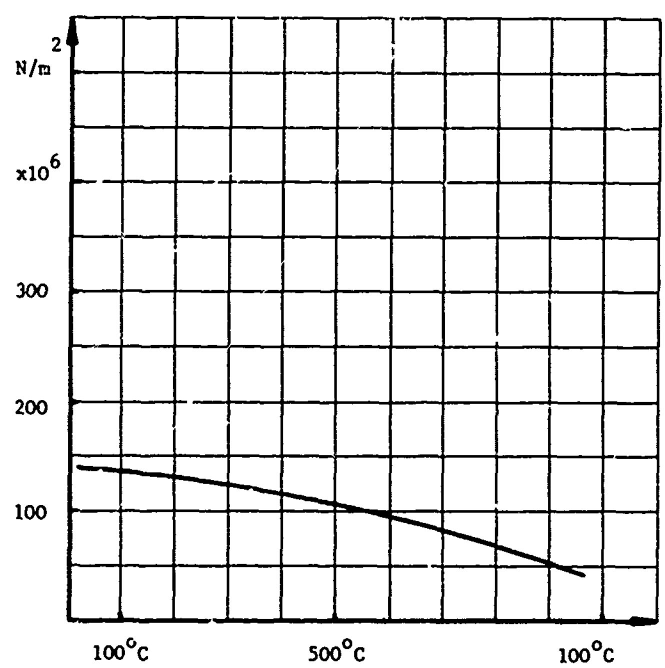


Fig 2.2.9.2.3

BERYLLIUM OXIDE: Tensile Strength v. Temperature

BERYLLIUM OXIDE: Compression Strength v. Temperature

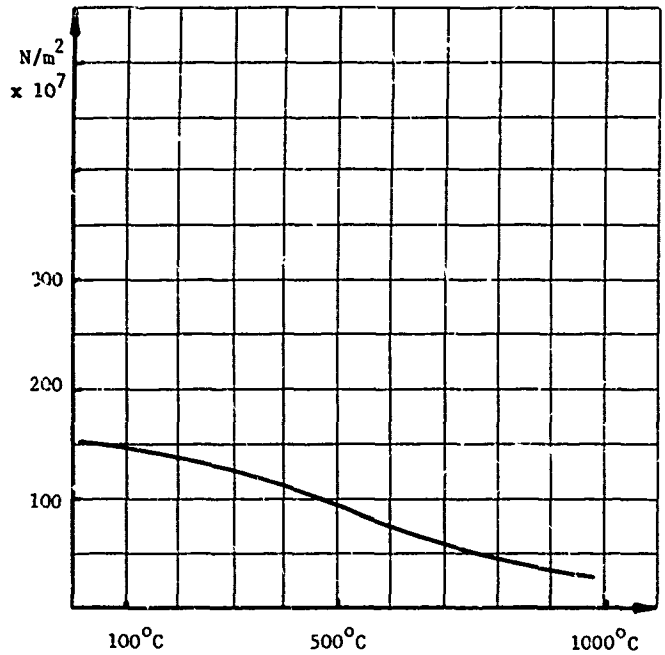


Fig 2.2.9.2.4

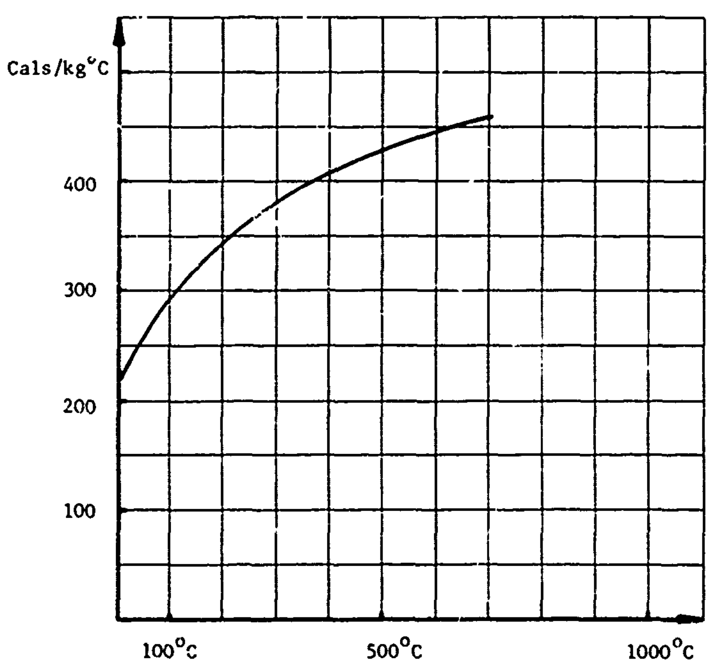


Fig 2.2.9.3.1

BERYLLIUM OXIDE: Specific Heat v. Temperature

BERYLLIUM OXIDE: Thermal Conductivity v. Temperature

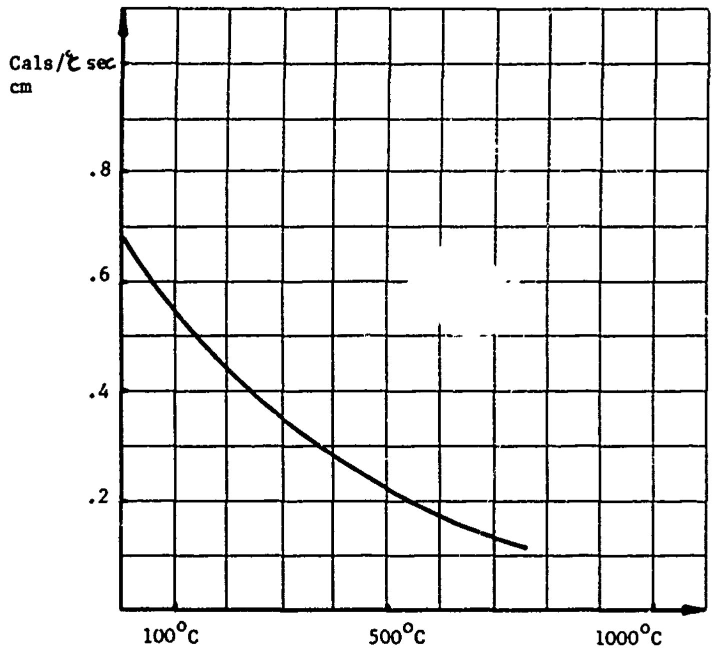


Fig 2.2.9.3.2

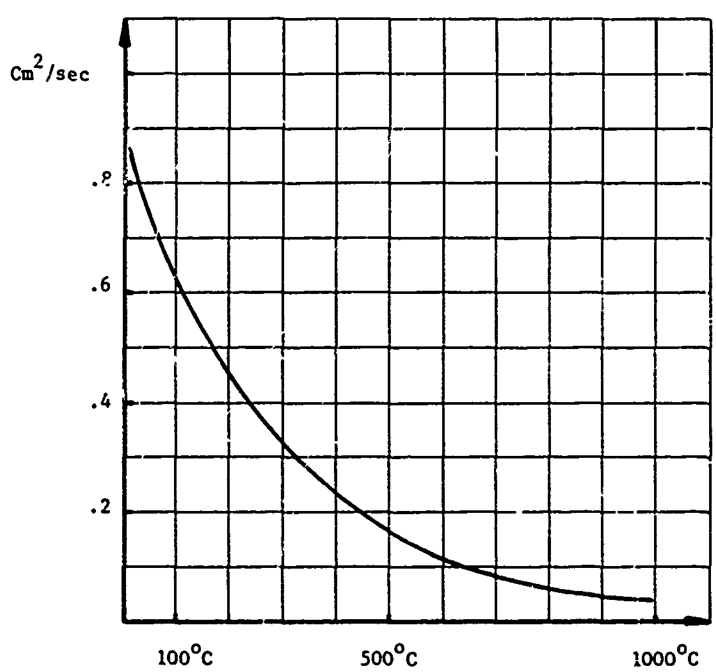


Fig 2.2.9.3.3

BERYLLIUM OXIDE: Thermal Diffusivity v. Temperature

BERYLLIUM OXIDE: Emissivity v. Temperature

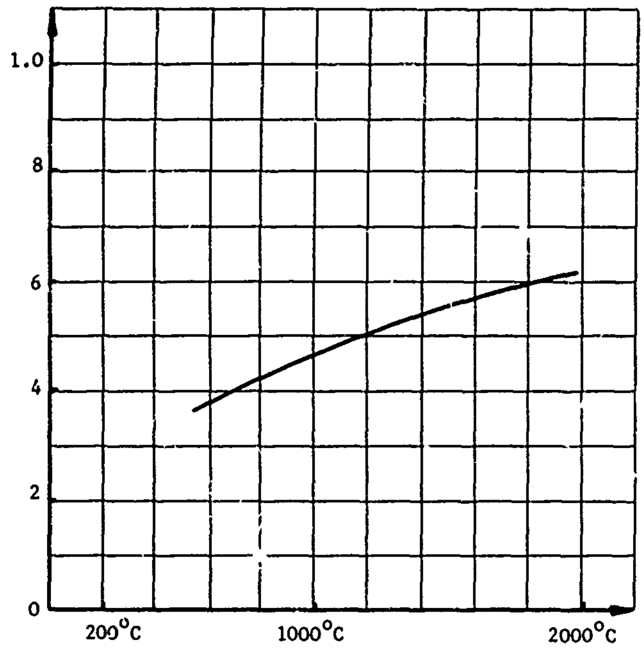
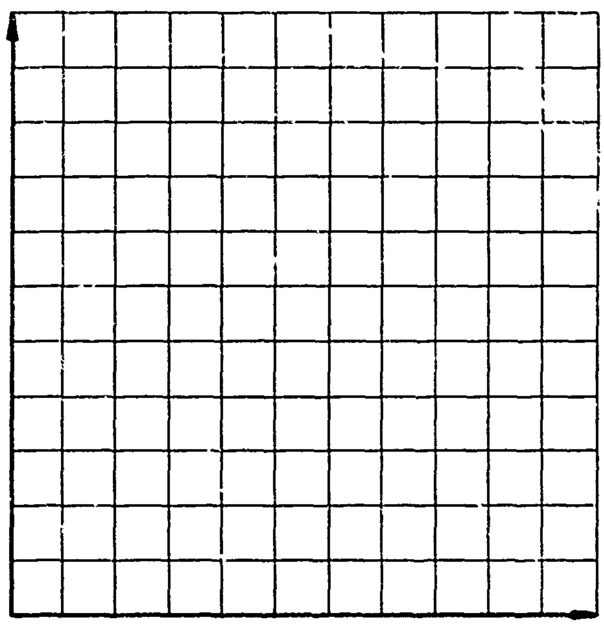


Fig 2.2.9.3.4



2.2.10 SPINEL. $MgO\ Al_2O_3$ AND $MgO\ Al_2O_4$

Variants of alumina are candidates for radomes, among these is Spinel, which is lighter than alumina, having a specific gravity of near 3.59 gm/cm^3. Its melting point is slightly higher than alumina.

Electrically the material is suitable having a dielectric constant of 8.?5 at ambient with low loss. It has the disadvantage of alumina that its dielectric constant changes with temperature.

Mechanically its properties are generally somewhat poorer than alumina, though $MgOAl_2O_4$ has some advantages.

Thermally, Spinel is similar to alumina, except its conductivity is less. Its thermal shock properties are considered possibly similar or slightly better to alumina.

While no serious problems are envisaged in the manufacture of a Spinel radome, the material does not seem to have any outstanding advantage over alumina for radomes. A formulation, $MgOAl_2O_4$ can be processed to have unusual combination of optical and dielectric properties which makes it a desirable material for optical, I.R. and microwave windows. Excellent transmission in both IR and microwave regions makes this material $MgOAl_2O_4$ suitable for dual purpose windows. (19).

ELECTRICAL PROPERTIES : SPINEL

TABLE 2.2.10.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(6)(8)(9)	Little change due to material near to true density 3.59 grams/cc.
Dielectric Constant v. Frequency	(6)(5)(9) Fig 2.2.10.1.1	Little change over microwave band
Dielectric Constant v. Temperature	(6)(5)(9) Fig 2.2.10.1.2	8.25 at ambient. Has a dielectric constant change of 1.5% per 100°C.
Loss Tangent v. Frequency	(6) Fig 2.2.10.1.3	Low loss at microwave frequencies
Loss Tangent v. Temperature	(6)(5)(9) Fig 2.2.10.1.4	Values still suitable for radome usage even at very high temperatures.
Dielectric Constant v. Humidity	(6)	Dense material giving negligible humidity effect on dielectric constant.
Dielectric Constant v. Radiation	(6)(7)	Ultra violet no effect. Nuclear radiation 10^{10} rads negligible change in dielectric constant.
Volume Resistivity v. Temperature	(8) Fig 2.2.10.1.5	High resistivity
Dielectric Strength v. Temperature		High strength

MECHANICAL PROPERTIES : SPINEL

TABLE 2.2.10.2

Property	Reference Fig	Remarks
Specific Gravity	(8)	3.59 gm/cm^3
Youngs Modulus v. Temperature	(8) (9) Fig 2.2.10.2.1	230×10^9 N/m^2 at ambient Modulus of Elasticity $240 \times 10^9/m^2$ ambient $96 \times 10^9/m^2$ 1000°C
Youngs Modulus v. Porosity		Non porous
Shear Modulus v. Temperature	(8) (9) (19) Fig 2.2.10.2.2	90×10^9 N/m^2 at ambient MgO Al_2O_3 115×10^9 N/m^2 at ambient MgO Al_2O_4
Rupture Modulus	(8) (9) (19)	85×10^6 N/m^2 (Ambient) Mgo Al_2O_3
Poissons Ratio	(19)	.2608 MgO Al_2O_4
Flexural Strength v. Temperature	(8) (9) (19) Fig 2.2.10.2.3.	slightly less than alumina of ambient Mgo Al_2O_4 similar to alumina at 1000°C
Tensile Strength v. Temperature	(8) (9) Fig 2.2.10.2.4	130×10^6 N/m^2 at ambient
Compressive Strength v. Temperature	(8) (9) (19)	190×10^7 N/m^2 at ambient MgO Al_2O_3 280×10^7 N/m^2 at ambient MgO Al_2O_4
Impact Strength		
Hardness	(8) (19)	8 MOHS not quite as hard as alumina (MgO Al_2O_3) 1300 Kg/1mm (200g load) (MgO Al_2O_4)

THERMAL PROPERTIES : SPINEL

TABLE 2.2.10.3

Property	Reference & Fig	Remarks
Temperature Working Range	(4)(6)(8)(9)	Melting point 2140°C
Specific Heat v. Temperature	(4)(8)(6) Fig 2.2.10.3.1	Similar to alumina
Conductivity v. Temperature	(6)(8)(9) Fig 2.2.10.3.2	Half that of alumina
Diffusivity v. Temperature	(6)(8) Fig 2.2.10.3.3	
Expansion v. Temperature	(4)(6)(8)(9) Fig 2.2.10.3.4	Similar to alumina
Emissivity v. Temperature		
Ablation		
Thermal Shock	(9)	Comparable with alumina
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : SPINEL

TABLE 2.2.10.4

Properties	Reference & Fig	Remarks
Temperature	(4)(6)(8)(9)	Melting point 2140°C Maximum working temperature 1900°C
Humidity & Water Absorption	(6)	Dense material negligible humidity and water up take
Rain Erosion	(4)(9)	Very good, but less resistance than alumina
Radiation Solar Nuclear	(6)	Ultra violet no effect Radiation safe dose 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid	(6)	Not effected by oils, fuels, detergents, or weak corrosives.
Storage & Ageing	(6)	Store free from shocks. Inert.

SPINEL: Dielectric Constant v. Frequency
Room Temperature

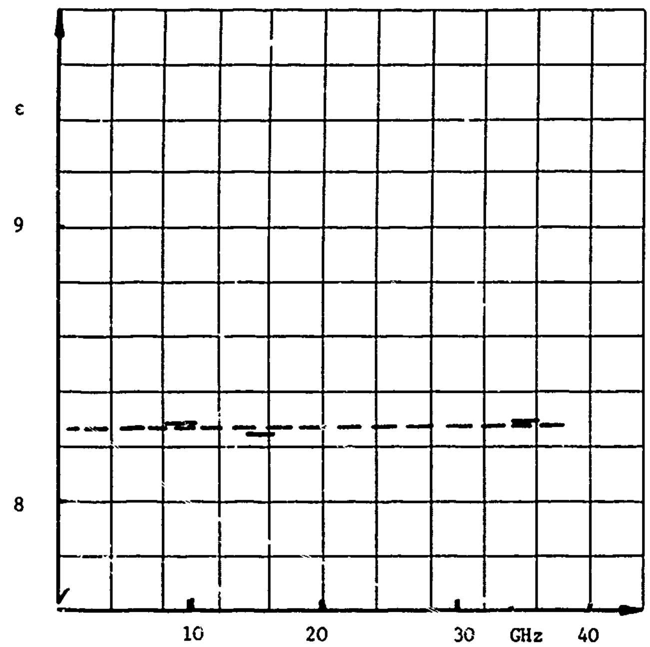


Fig 2.2.10.1.1

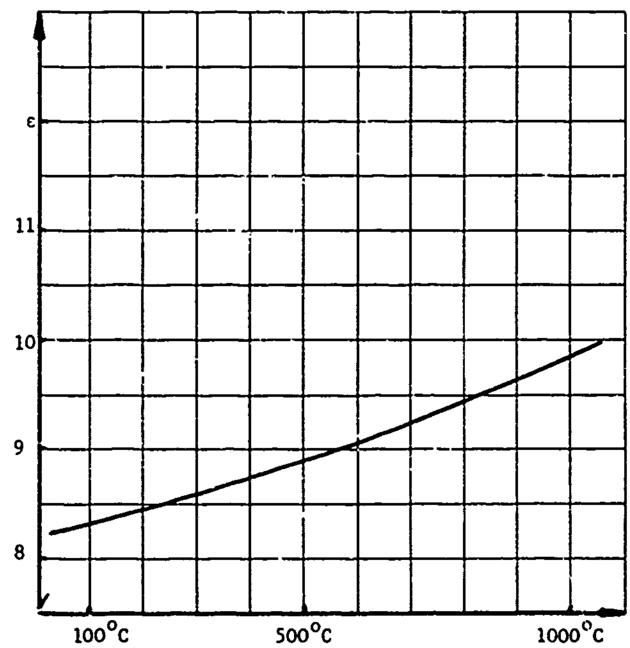


Fig 2.2.10.1.2

SPINEL: Dielectric Constant v. Temperature 9.5 GHz

SPINEL: Loss Tangent v. Frequency
Room Temperature

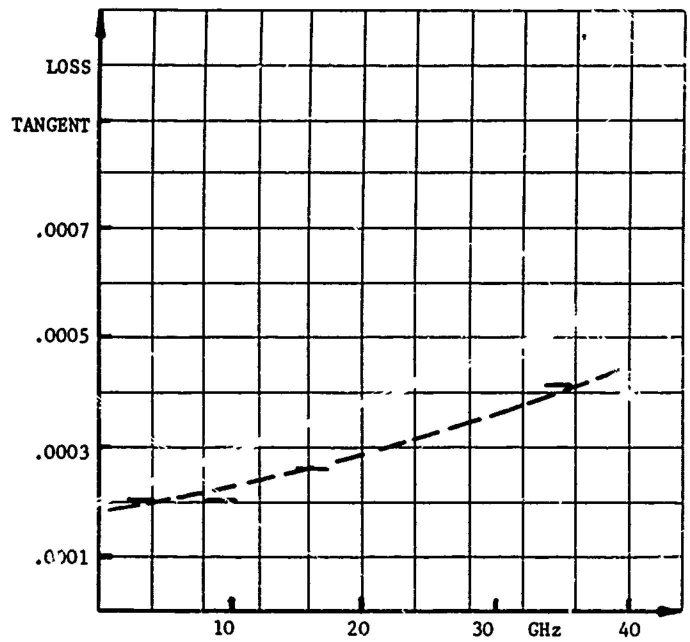


Fig 2.2.10.1.3

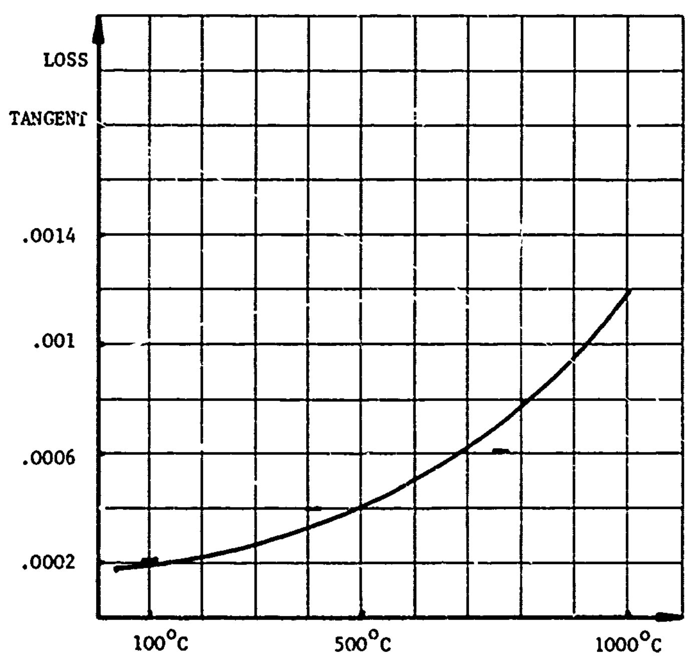


Fig 2.2.10.1.4

SPINEL: Loss Tangent v. Temperature 9.368 GHz

SPINEL: Volume Resistivity v. temperature

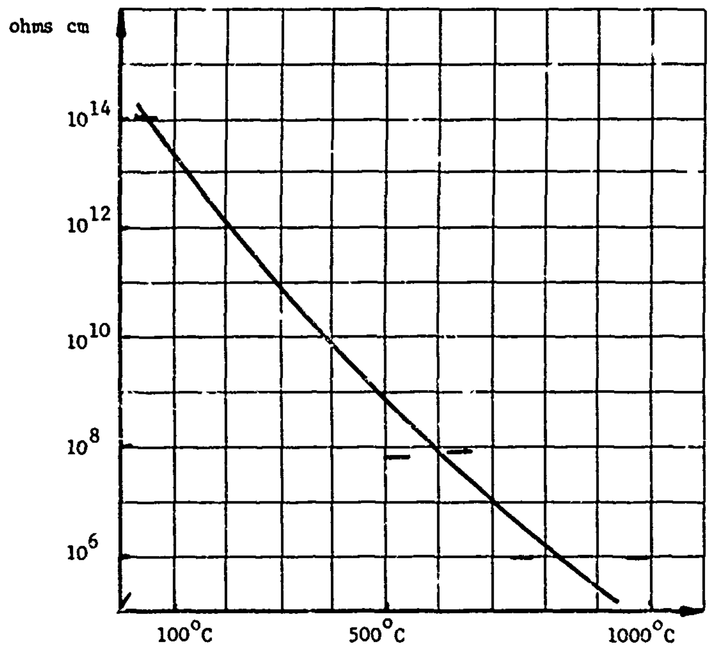


Fig 2.2.10.1.5

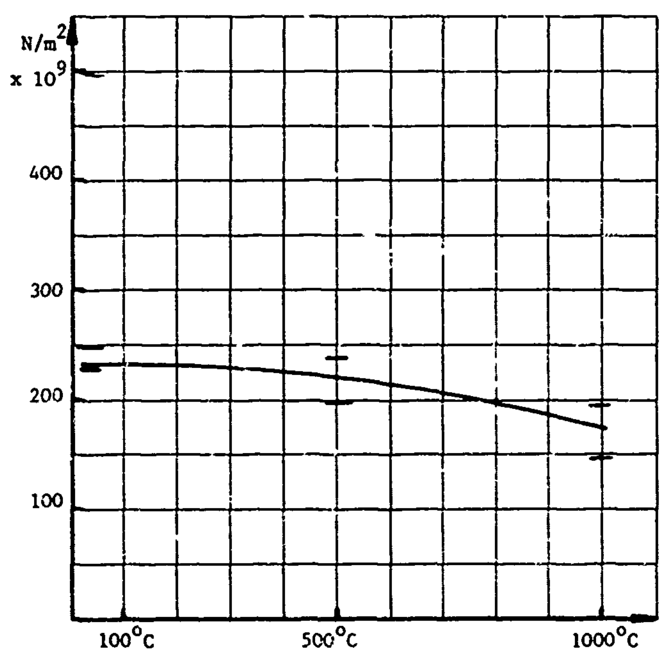


Fig 2.2.10.2.1

SPINEL: Youngs Modulus v. Temperature

SPINEL: Shear Modulus v. Temperature

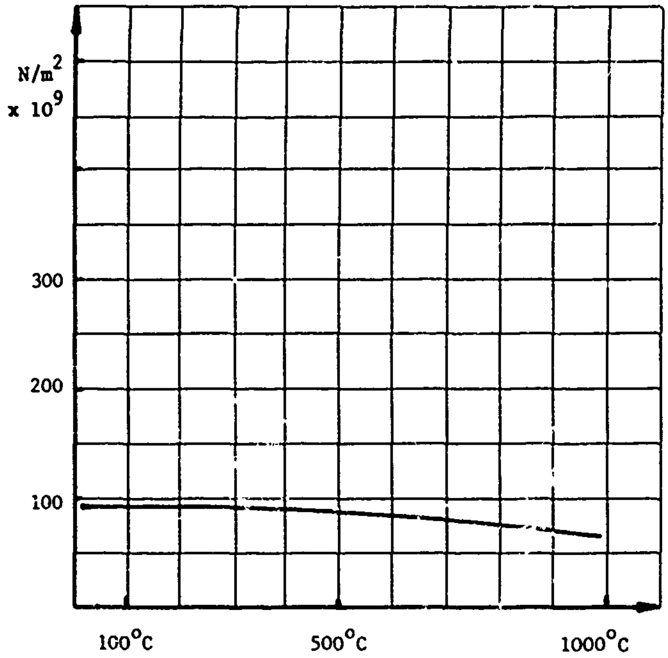


Fig 2.2.10.2.2

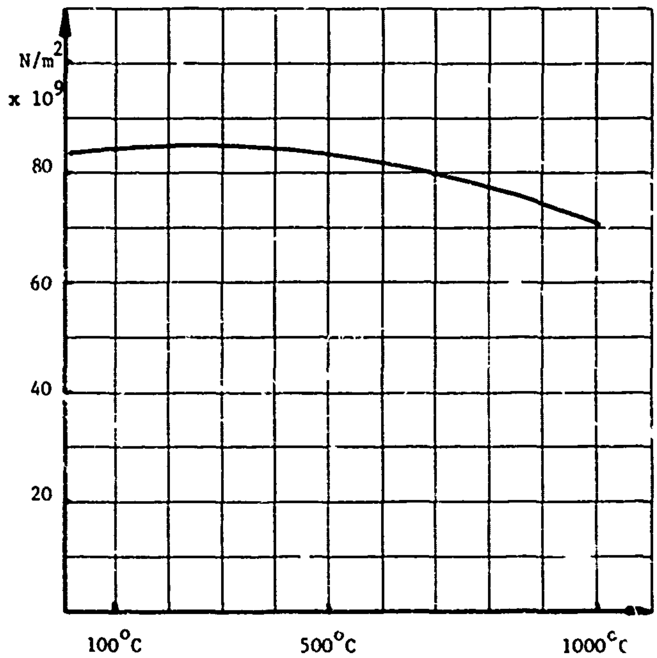


Fig 2.2.10.2.3

SPINEL: Flexural Strength v. Temperature

SPINEL: Tensile Strength v. Temperature

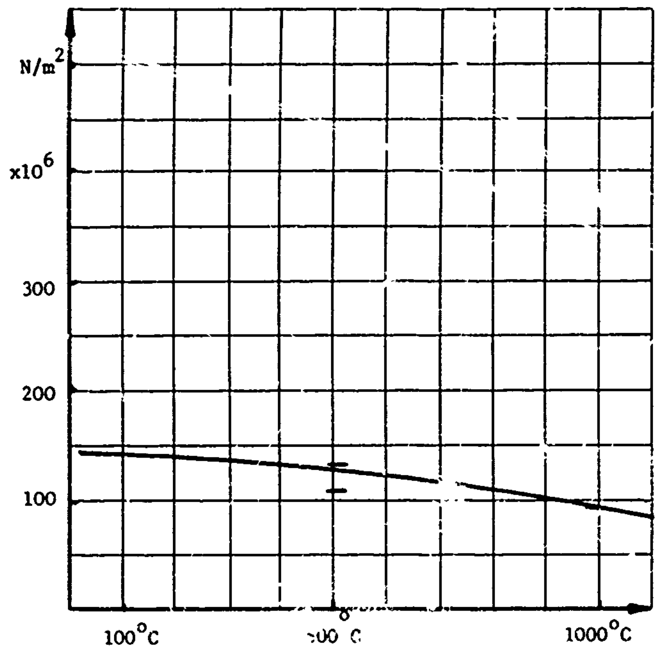


Fig 2.2.10.2.4

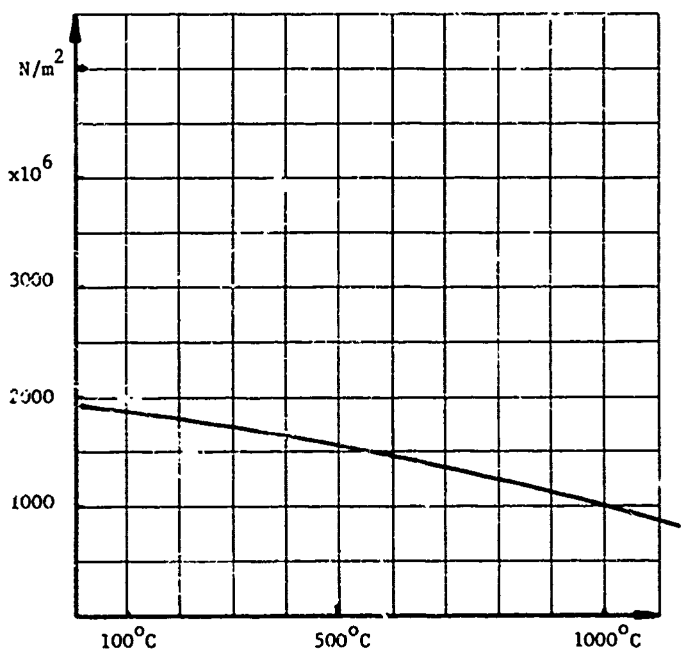


Fig 2.2.10.2.5

SPINEL: Compression Strength v. Temperature

SPINEL: Specific Heat v. Temperature

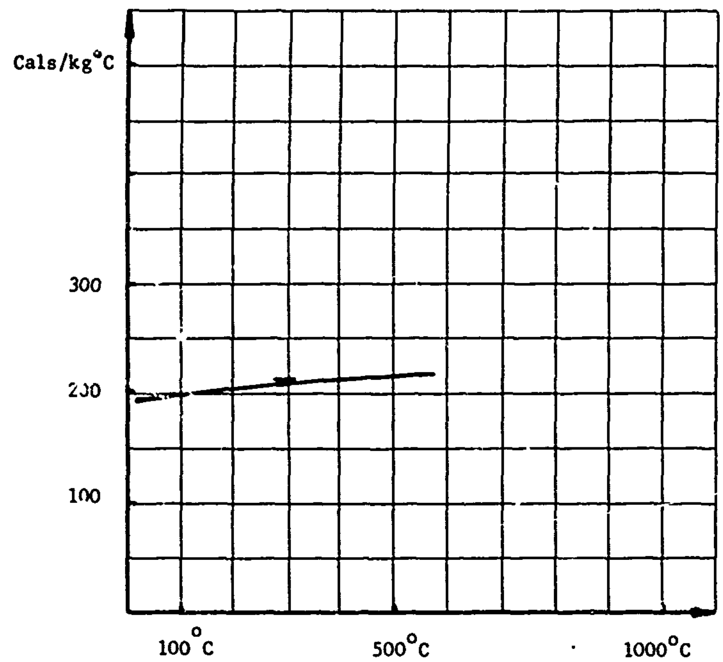


Fig 2.2.10.3.1

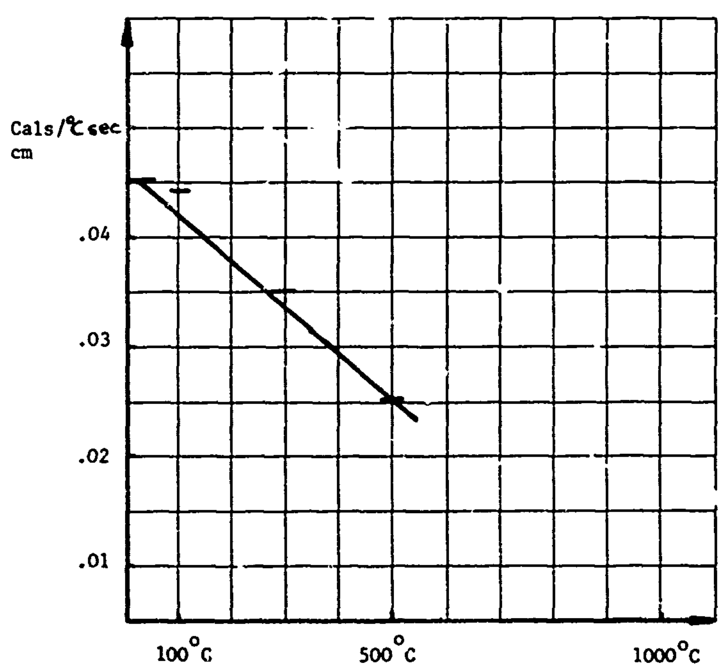


Fig 2.2.10.3.2

SPINEL: Thermal Conductivity v. Temperature

SPINEL: Thermal Diffusivity v. Temperature

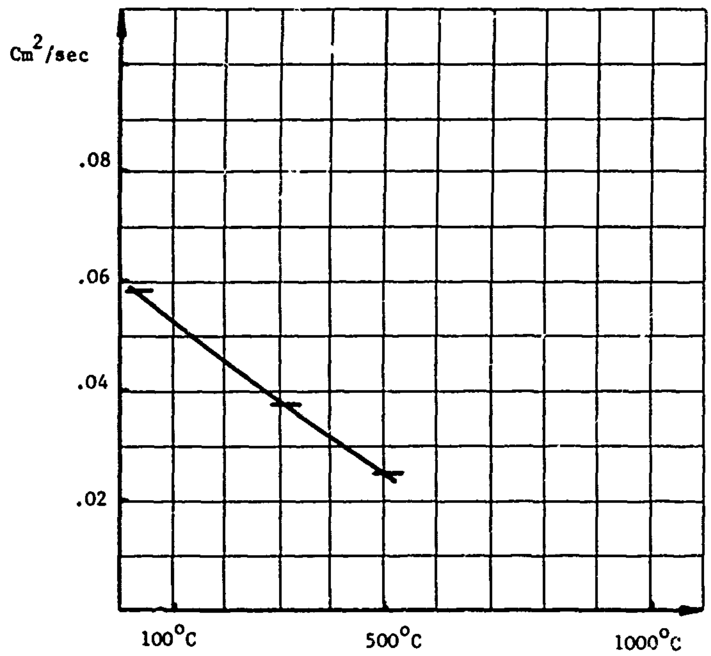


Fig 2.2.10.3.3

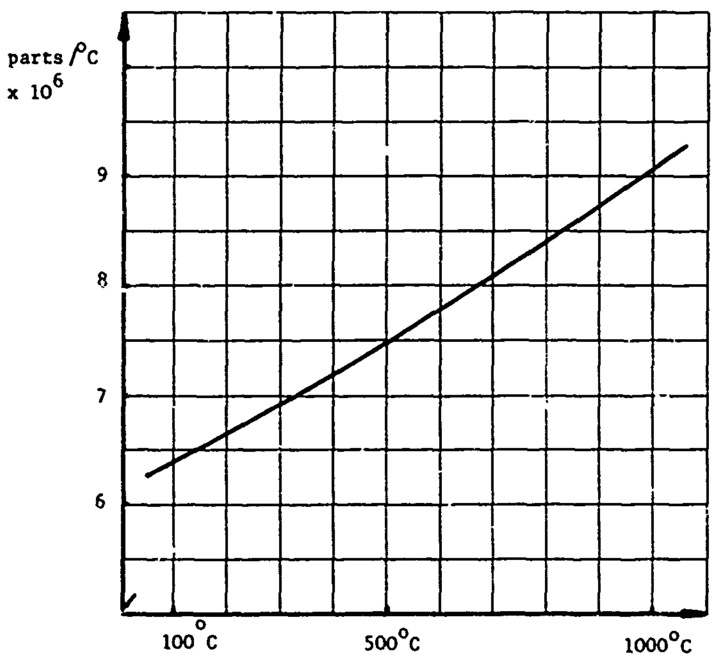


Fig 2.2.10.3.4

SPINEL: Expansion v. Temperature

2.2.11 MAGNESIUM OXIDE. MgO

Though it is thought that magnesium oxide has not yet been used as a radome, it is a material candidate for very high temperatures.

Electrically its dielectric constant near 9.6 at maximum density of 3.58 grams per cc rises, similarly as alumina, to near 10.6 at 1000°C. Its loss tangent is low in the microwave band is maintained at high temperatures.

Mechanically it is weaker than alumina at lower temperatures, but becomes more comparative at high temperature.

Thermally it is comparable in its properties with alumina, except it has a higher expansion coefficient which may limit its thermal shock capacity. It has a higher maximum working temperature than alumina.

ELECTRICAL PROPERTIES : MAGNESIUM OXIDE

TABLE 2.2.11.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(6)(8) Fig 2.2.11.1.1	Dense material 9.6
Dielectric Constant v. Frequency	(6)(8) Fig 2.2.11.1.2	Little change over microwave band
Dielectric Constant v. Temperature	(5)(6)(9) Fig 2.2.11.1.3	Rise similar to alumina
Loss Tangent v. Frequency	(5)(6)(9) Fig 2.2.11.1.4	Low loss material
Loss Tangent v. Temperature	(5)(6)(9) Fig 2.2.11.1.5	Low loss over wide temperature range
Dielectric Constant v. Humidity		If dense material not likely to be affected by humidity
Dielectric Constant v. Radiation		Unaffected by solar radiation and 10^{10} rads nuclear radiation
Volume Resistivity v. Temperature	(1)(6)(9) Fig 2.2.11.1.6	
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : MAGNESIUM OXIDE

TABLE 2.2.11.2

Property	Reference Fig	Remarks
Specific Gravity	(8)(17)	3.58 grams per c.c. 100% MgO
Youngs Modulus v. Temperature	(8)(9) Fig 2.2.11.2.1	
Youngs Modulus v. Porosity		
Shear Modulus v. Temperature	(9) Fig 2.2.11.2.2	
Rupture Modulus		
Poissons Ratio		
Flexural Strength v. Temperature	(17) Fig 2.2.11.2.3	
Tensile Strength v. Temperature	(8)(9) Fig 2.2.11.2.4	is maintained to high temperature
Compressive Strength v. Temperature		
Impact Strength		
Hardness		6 MOHS 585 Knoop/mm^2

THERMAL PROPERTIES : MAGNESIUM OXIDE

TABLE 2.2.11.3

Property	Reference & Fig	Remarks
Temperature Working Range	(8)(17)	Melting point 2800°C Maximum working 2400°C
Specific Heat v. Temperature	(8) Fig 2.2.11.3.1	similar to alumina
Conductivity v. Temperature	(8) Fig 2.2.11.3.2	
Diffusivity v. Temperature	(8) Fig 2.2.11.3.3	
Expansion v. Temperature	(8) Fig 2.2.11.3.4	more than alumina
Emissivity v. Temperature		
Ablation		
Thermal Shock	(9)	poorer than alumina
Flammability		non-inflammable

ENVIRONMENTAL PROPERTIES : MAGNESIUM OXIDE

TABLE 2.2.11.4

Properties	Reference & Fig	Remarks
Temperature	(8)	Maximum working 2400°C
Humidity & Water Absorption		Dielectric properties and mechanical strength effected by degree of porosity
Rain Erosion		
Radiation Solar Nuclear		Unaffected by solar radiation
Contamination Oils Fuels Detergents Salts Acid		Oils, fuels, detergents little effect on dense material
Storage & Ageing		Free from shocks abrasion inert

MAGNESIUM OXIDE: Dielectric Constant v. Density
Room Temperature 9.5 GHz

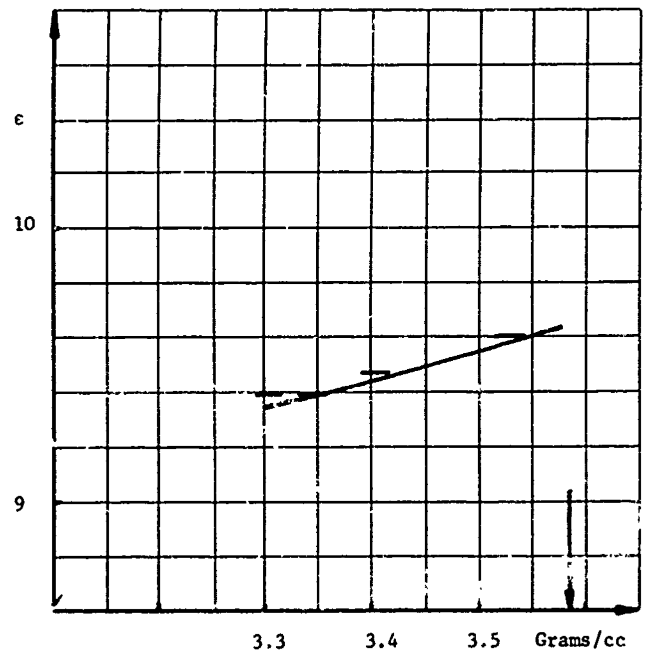


Fig 2.2.11.1.1

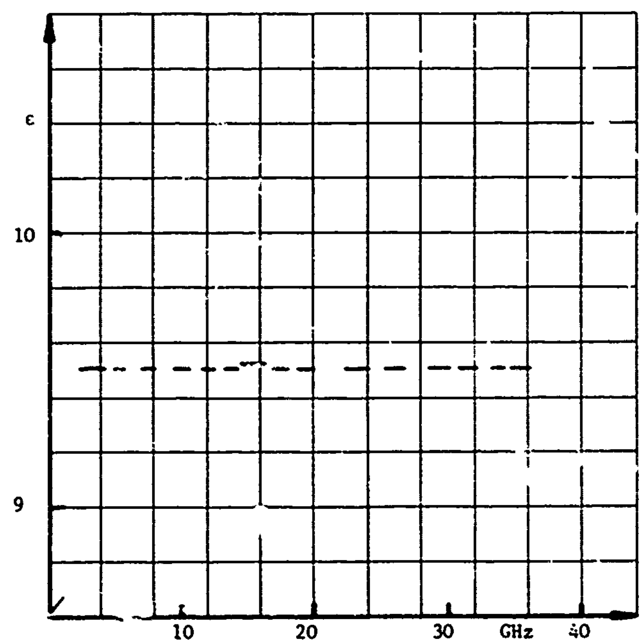


Fig 2.2.11.12.

MAGNESIUM OXIDE: Dielectric Constant v. Frequency
Room Temperature

MAGNESIUM OXIDE: Dielectric Constant v. Temperature
9.5 GHz

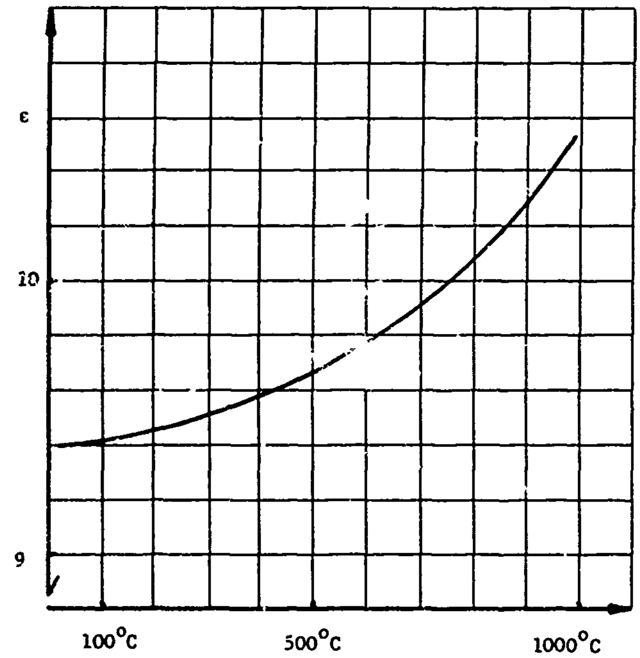


Fig 2.2.11.1.3

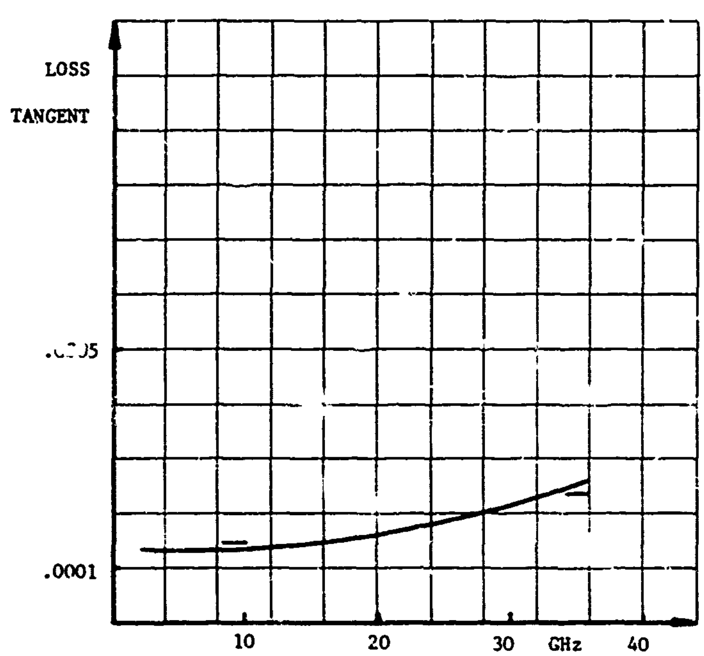


Fig 2.2.11.1.4

MAGNESIUM OXIDE: Loss Tangent v. Frequency
Room Temperature

MAGNESIUM OXIDE: Loss Tangent v. Temperature
9.368 GHz

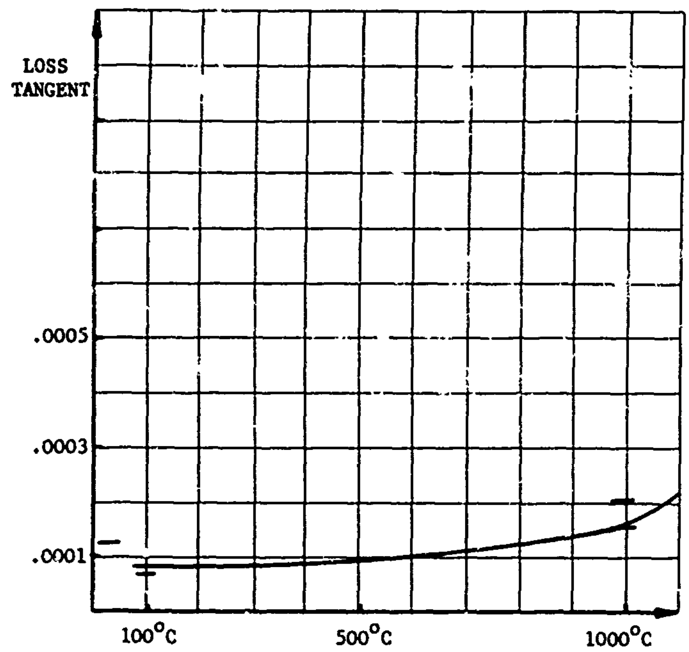


Fig 2.2.11.1.5

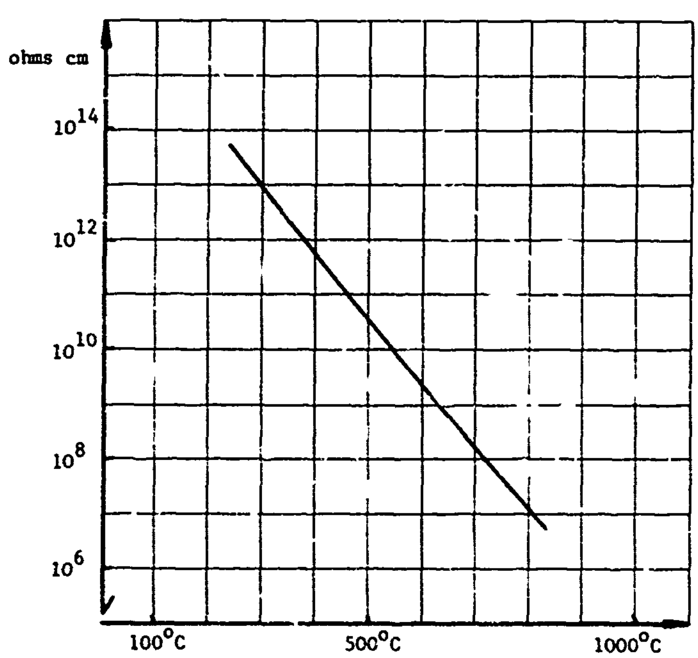


Fig 2.2.11.1.6

MAGNESIUM OXIDE: Volume Resistivity v. Temperature

MAGNESIUM OXIDE: Youngs Modulus v. Temperature

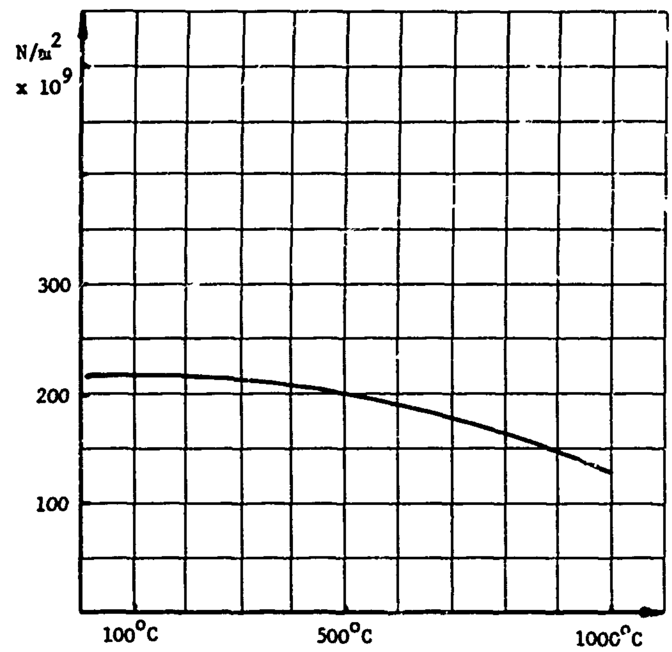


Fig 2.2.11.2.1

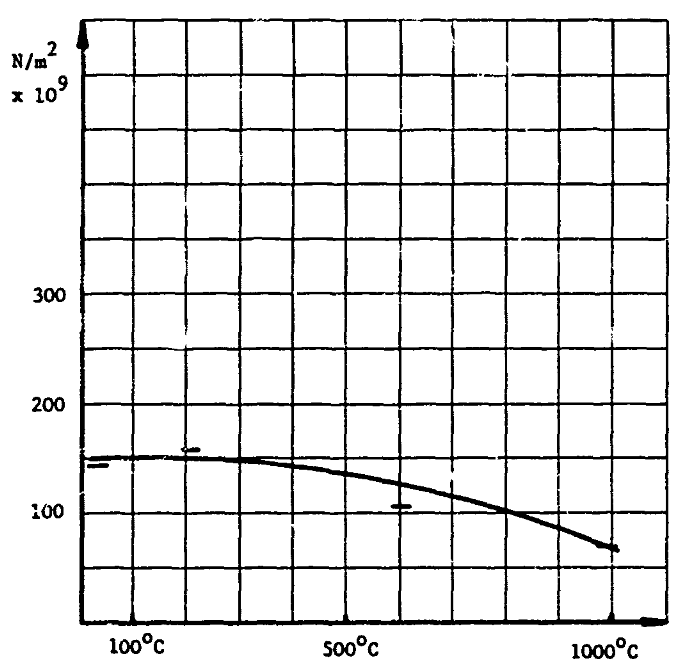


Fig 2.2.11.2.2

MAGNESIUM OXIDE: Shear Modulus v. Temperature

MAGNESIUM OXIDE: Flexural Strength v. Temperature

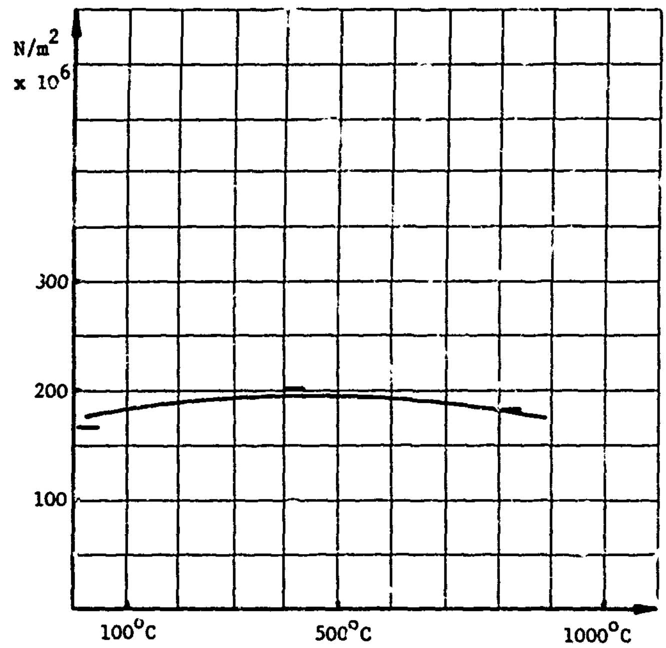


Fig 2.2.11.2.3

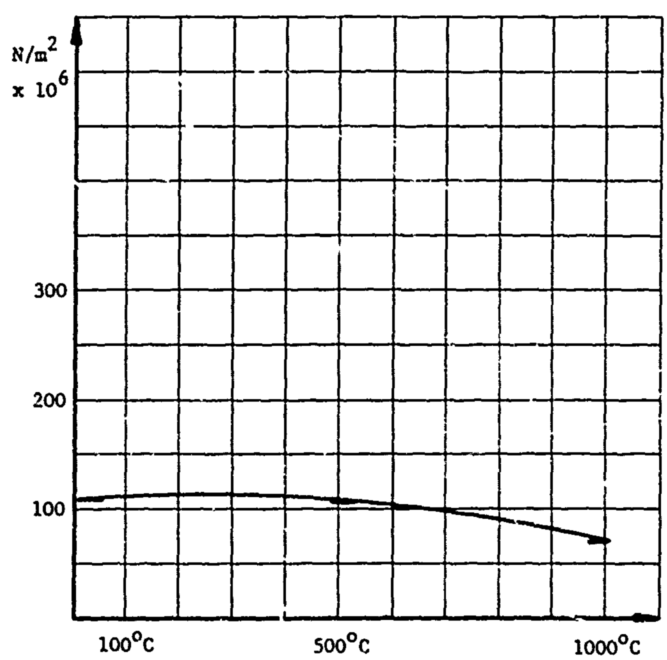


Fig 2.2.11.2.4

MAGNESIUM OXIDE: Tensile Strength v. Temperature

MAGNESIUM OXIDE: Specific Heat v. Temperature

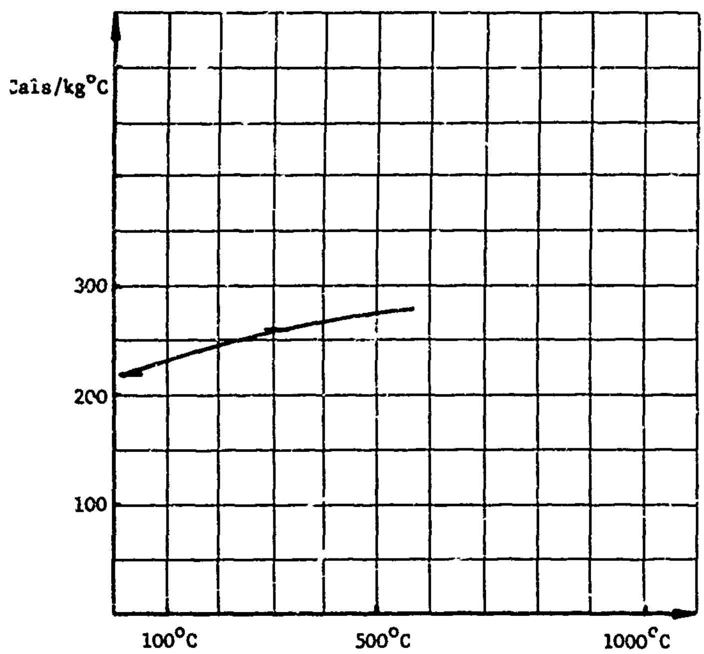


Fig 2.2.11.3.1

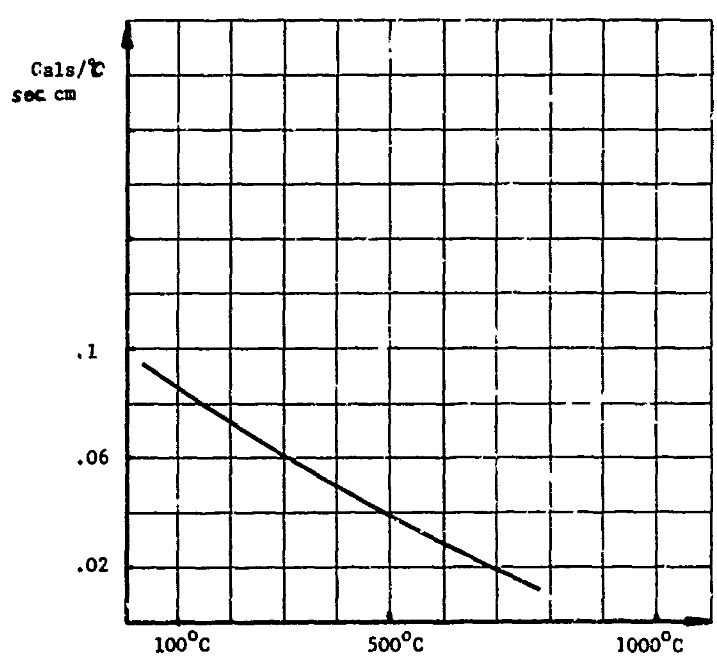


Fig 2.2.11.3.2

MAGNESIUM OXIDE: Thermal Conductivity v. Temperature

MAGNESIUM OXIDE: Thermal Diffusivity v. Temperature

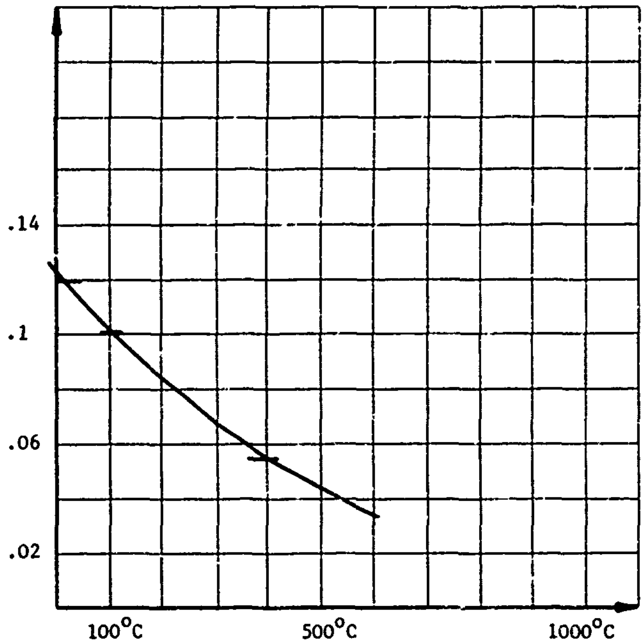


Fig 2.2.11.3.3

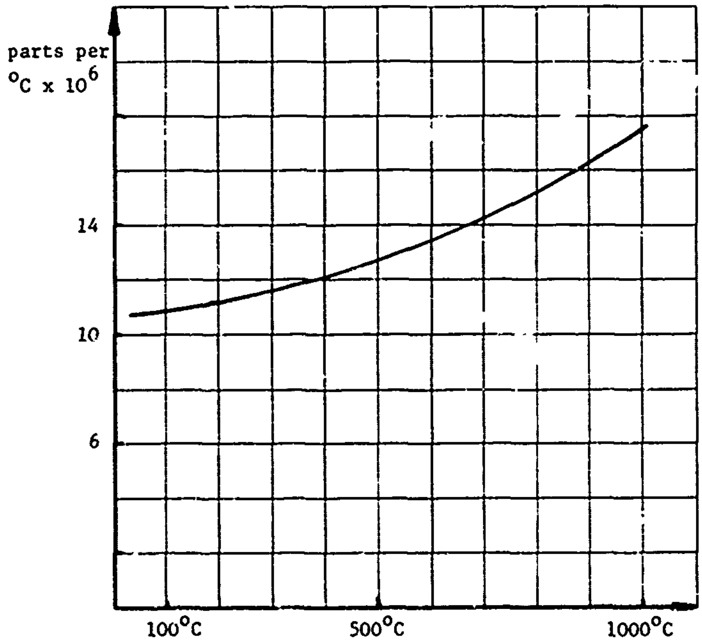


Fig 2.2.11.3.4

MAGNESIUM OXIDE: Expansion v. Temperature

2.2.12 GLASS-CERAMIC - MEXIM

A family of glass ceramic materials based on formulations of ZnO, Al_2O_3, SiO_2, BaO, called Mexims have been fabricated by the GEC Stafford (UK). It is suitable for high temperature radome usage, and experimental radomes have been tested.

Electrically the dielectric constant varies according to formulation but typically is near 6. There are formulations of the material whose change of dielectric constant with temperature is as low as 0.5% per 100°C, similar to Pyroceram. Its loss is very low, less than 0.0003 in the microwave band at 20°C, and remains low to 500°C, 0.001.

Mechanically and thermally over the range of temperature tested, it appears to have similar properties to Pyroceram. Its very low thermal expansion coefficient ensures its good thermal shock properties.

The rain erosion resistance, though inferior to Pyroceram, shows that it is still a strong candidate for exposure to rain, in that it withstood 300 minutes of 1"/hr. 500 mph rain with some slight surface erosion, and also survived 30 rocket sledge firings into 1 in/hr. rain with no visible damage.

ELECTRICAL PROPERTIES : GLASS CERAMIC "MEXIM" TABLE 2.2.12.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density		Very little density change with controlled material
Dielectric Constant v. Frequency	(13) Fig 2.2.12.1.1	Very little change over microwave band
Dielectric Constant v. Temperature	(13) Fig 2.2.12.1.2	Formulation NK2/2746 0.5 per 100°C
Loss Tangent v. Frequency	(13) Fig 2.2.12.1.3	Low loss over microwave band
Loss Tangent v. Temperature	(13) Fig 2.2.12.1.4	NK2/2746 retains low loss at temperature NK2/2186 loss increases 0.001 at 500°C
Dielectric Constant v. Humidity		Humidity negligible effect
Dielectric Constant v. Radiation		No change with solar u/v Not tested with nuclear, but should stand 10^{10} rads
Volume Resistivity v. Temperature	(13) Fig 2.2.12.1.5	
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : GLASS CERAMIC "MEXIM" TABLE 2.2.12.2

Property	Reference Fig	Remarks
Specific Gravity	(13)	2.44 grams per cc. NK2/2714 3.7 NK2/2746
Younge Modulus v. Temperature		
Younge Modulus v. Porosity		Material has porosity less than 1%
Shear Modulus v. Temperature		
Rupture Modulus	(13) Fig 2.2.12.2.1	Maintains its strength at high temperature
Poissons Ratio		
Flexural Strength v. Temperature		
Tensile Strength v. Temperature		
Compressive Strength v. Temperature		
Impact Strength		0.43 Nm at 20°C 0.33 Nm at 700°C
Hardness		

THERMAL PROPERTIES : GLASS CERAMIC "MEXIM" TABLE 2.2.12.3

Property	Reference & Fig	Remarks
Temperature Working Range	(13)	Tested to 900°C
Specific Heat v. Temperature	(13) Fig 2.2.12.3.1	0.26 ambient
Conductivity v. Temperature	(13) Fig 2.2.12.3.2	.0074 ambient
Diffusivity v. Temperature		
Expansion v. Temperature	(13) Fig 2.2.12.3.3	2.5 x 10^6 °C ambient Coefficient increases with temperature slightly
Emissivity v. Temperature		
Ablation		
Thermal Shock		Has good resistance to thermal shock, able to withstand over 400°C rise on outer surface of radome in 1 sec.
Flammability		Non-inflammable

ENVIRONMENTAL PROPERTIES : GLASS CERAMIC "MEXIM" TABLE 2.2.12.4

Properties	Reference & Fig	Remarks
Temperature	(13)	Tested to 900°C
Humidity & Water Absorption	(13)	Negligible effects Long water soak 0.06% increase in weight Dielectric constant change less than 1%
Rain Erosion	(13)	Good rain erosion resistance 300 minutes of 1"/hr. 500 mph rain with slight surface erosion
Radiation Solar Nuclear		
Contamination Oils Fuels Detergents Salts Acid	(13)	Negligible effects from oils, fuels, detergents, strong acids may damage
Storage & Ageing	(13)	Store free from shocks and vibration Inert

GLASS CERAMIC "MEXIM": Dielectric Constant v. Frequency
Room Temperature

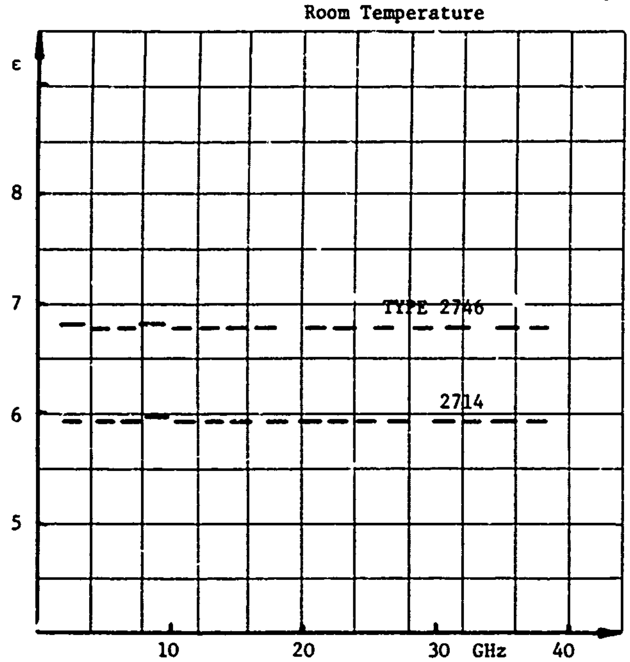


Fig 2.2.12.1.1

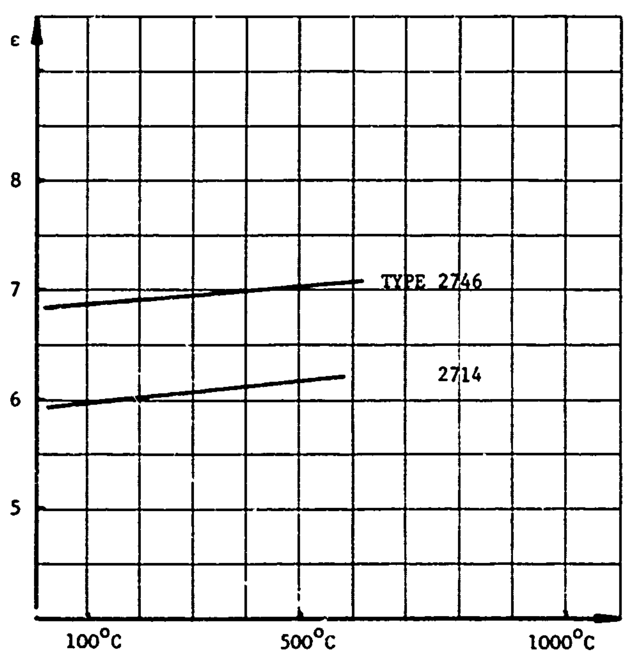


Fig 2.2.12.1.2

GLASS CERAMIC "MEXIM": Dielectric Constant v. Temperature
9.5 GHz

GLASS CERAMIC "MEXIM": Loss Tangent v. Frequency
Room Temperature

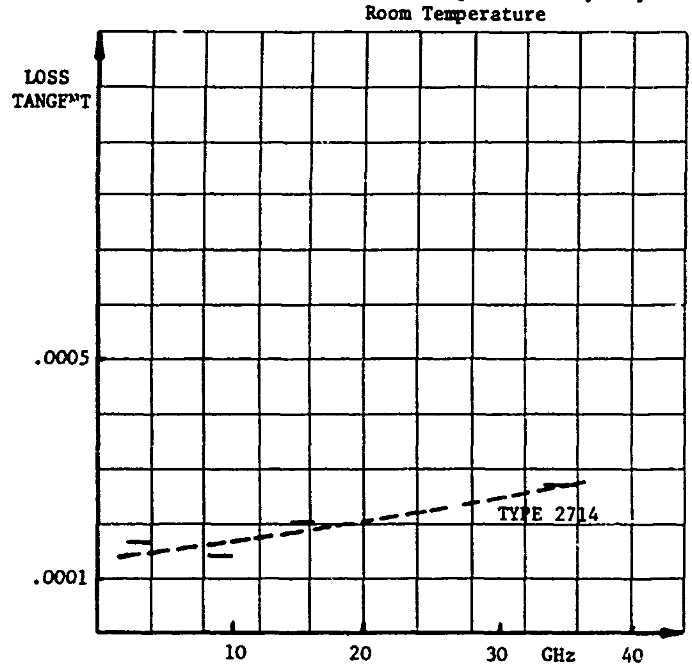


Fig 2.2.12.1.3

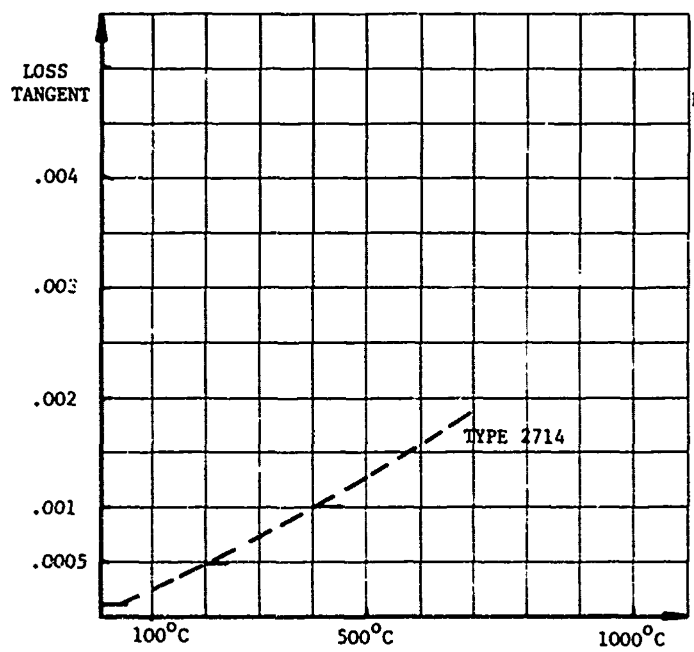


Fig 2.2.12.1.4

GLASS CERAMIC "MEXIM": Loss Tangent v. Temperature
9.368 GHz

GLASS CERAMIC "MEXIM": Volume Resistivity D.O.
v. Temperature

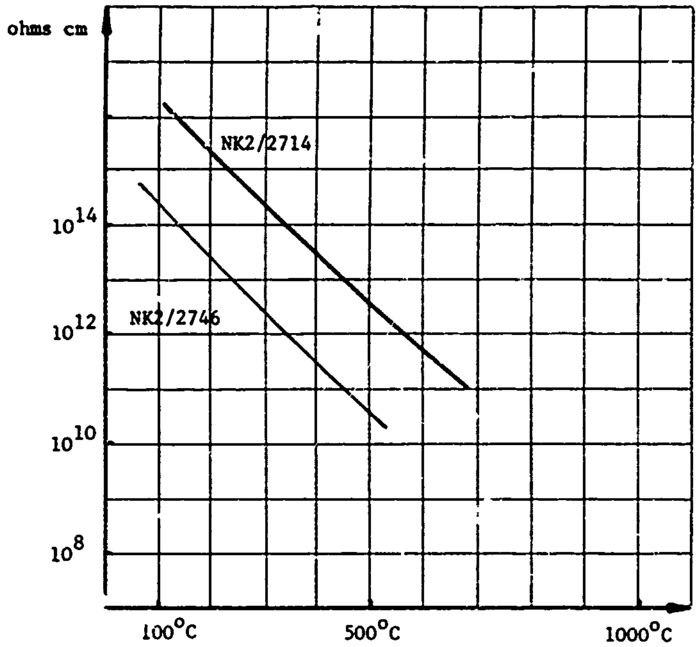


Fig 2.2.12.1.5

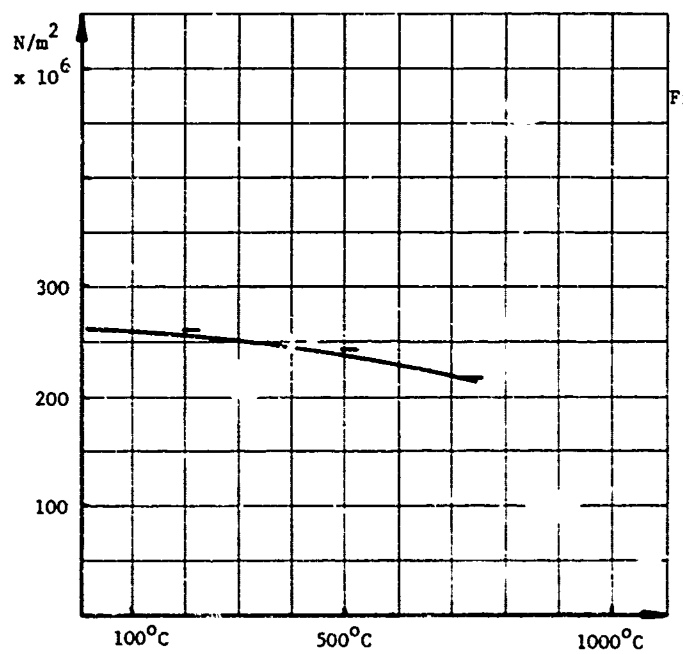


Fig 2.2.12.2.1

GLASS CERAMIC "MEXIM": Rupture Modulus v. Temperature

GLASS CERAMIC "MEXIM": Specific Heat v. Temperature

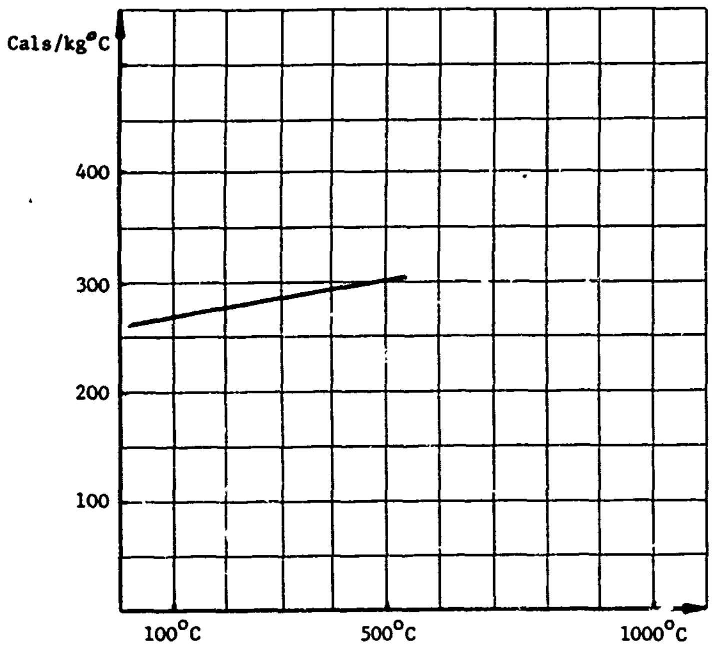


Fig 2.2.12.3.1

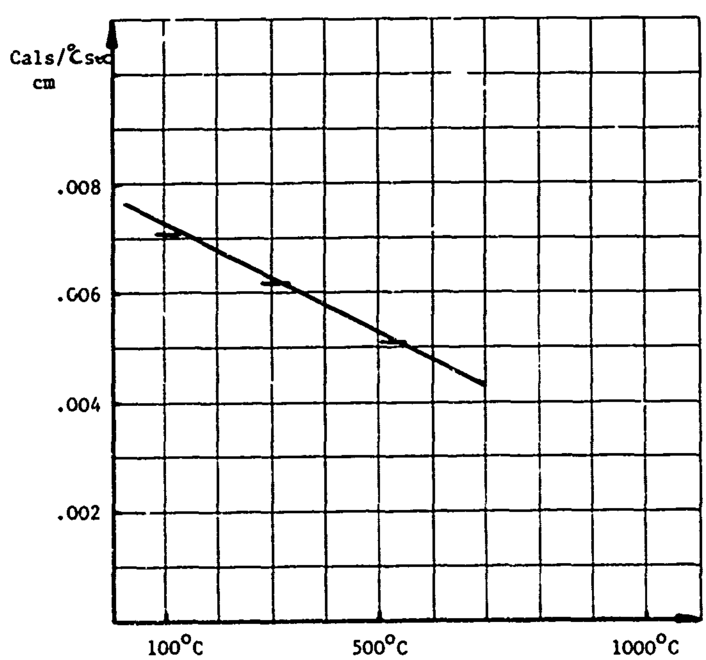


Fig 2.2.12.3.2

GLASS CERAMIC "MEXIM": Thermal Conductivity v. Temperature

GLASS CERAMIC "MFXIM": Expansion v. Temperature

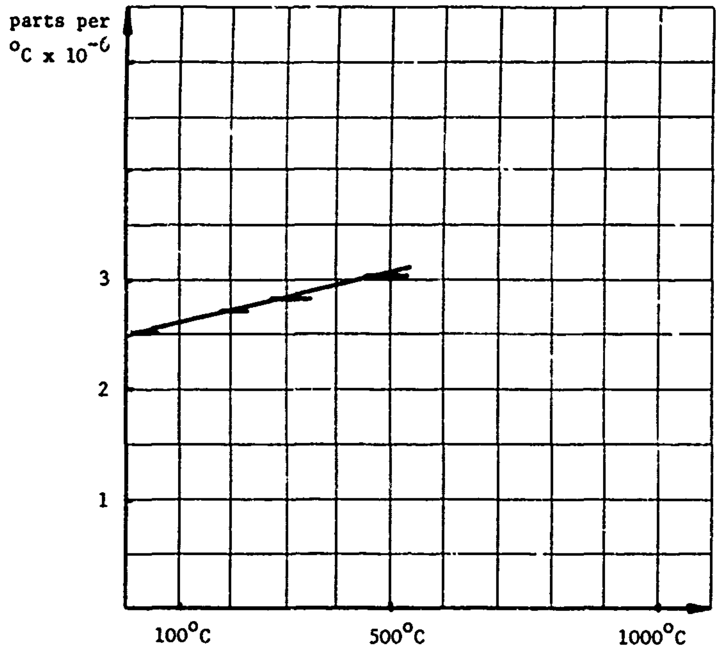
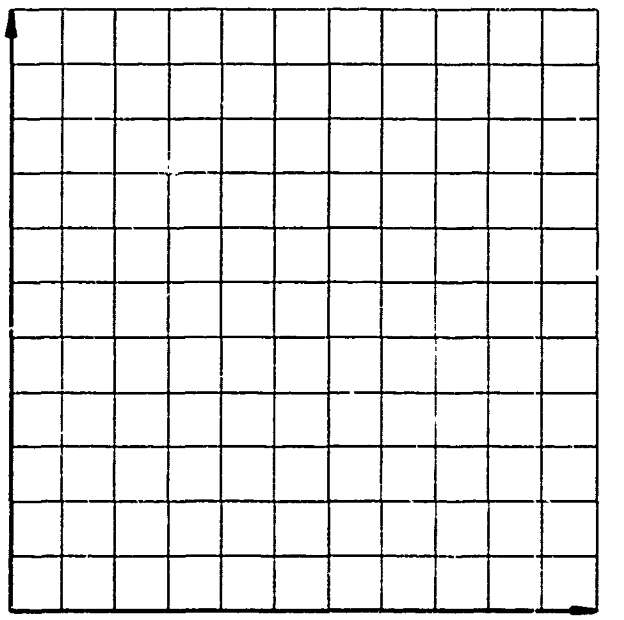


Fig 2.2.12.3.3



2.2.13 GLASS-MICA COMPOSITE

High grade mica has been mixed with powdered electrical glass and fused at a high temperature and pressure, to produce a high grade insulating material which has the advantages of glass and mica. Glass bonded the mica platelets into a homogeneous mass while the mica acted to relieve the brittleness of glass. Synthetic mica has been produced to replace the material mica and bonded with glass to form Supramica (14).

Electrically the dielectric constant is near 7 and its loss tangent 0.003, Supramica has a higher dielectric constant near 9. Mechanically it is a strong material, but is limited by its low thermal characteristics, as its heat distortion point is near 430°C. It has not found wide application as a radome material due to the fabrication process requiring very high pressure which has resulted in expensive tooling, thermal limitation of 430°C, its poor rain erosion characteristics, and its relatively high density.

ELECTRICAL PROPERTIES : GLASS-MICA TABLE 2.2.13.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(14)	Manufacture control of non porous product ensures close tolerance and dielectric constant.
Dielectric Constant v. Frequency	(6) (14) Fig 2.2.13.1.1	Dielectric constant stable over microwave frequency band.
Dielectric Constant v. Temperature	(6) (14) Fig 2.2.13.1.2	
Loss Tangent v. Frequency	(6) (14)	
Loss Tangent v. Temperature	(6) (14) Fig 2.2.13.1.3	
Dielectric Constant v. Humidity	(6)	Dielectric constant stable due to non-porosity and non-hygroscopic.
Dielectric Constant v. Radiation		
Volume Resistivity v. Temperature	Fig 2.2.13.1.4	
Dielectric Strength v. Temperature	(14)	20 kv/cm ambient

MECHANICAL PROPERTIES : GLASS-MICA TABLE 2.2.13.2

Property	Reference Fig	Remarks
Specific Gravity	(14)	3.0 to 3.8 according to grade
Youngs Modulus v. Temperature		
Youngs Modulus v. Porosity		
Shear Modulus v. Temperature		
Rupture Modulus		
Poissons Ratio		
Flexural Strength v. Temperature	(14) Fig 2.2.13.2.1	105×10^6 N/m^2 ambient
Tensile Strength v. Temperature	(14)	42×10^6 N/m^2 ambient
Compressive Strength v. Temperature	(14)	245×10^6 N/m^2 ambient
Impact Strength		
Hardness	(14)	550 knoop

THERMAL PROPERTIES : GLASS-MICA

TABLE 2.2.13.3

Property	Reference & Fig	Remarks
Temperature Working Range	(14)	Heat distortion 430°C
Specific Heat v. Temperature	(14)	0.17 cal/gm °C
Conductivity v. Temperature	(15)	0.0012 cal/sq cm/sec/°C/cm
Diffusivity v. Temperature		
Expansion v. Temperature	(15)	10.5×10^{-6} coefficient expansion °C
Emissivity v. Temperature		
Ablation		
Thermal Shock		
Flammability		non-inflammable

ENVIRONMENTAL PROPERTIES : GLASS-MICA

TABLE 2.2.13.4

Properties	Reference & Fig	Remarks
Temperature	(14)	Heat distortion 430°C
Humidity & Water Absorption	(14)	Non porous water absorption nil.
Rain Erosion	(4) (10)	relatively poor rain erosion characteristics. Impact of rain drops on outside caused inner surface to "spall", (break up). Severely eroded 20 minutes at 500 mph in 1 in/hr. rain.
Radiation Solar Nuclear		Unaffected by U.V. and 10^{10} rads.
Contamination Oils Fuels Detergents Salts Acid		stable material
Storage & Ageing		stable material avoid mechanical shocks

GLASS MICA: Dielectric Constant v. Frequency
Room Temperature

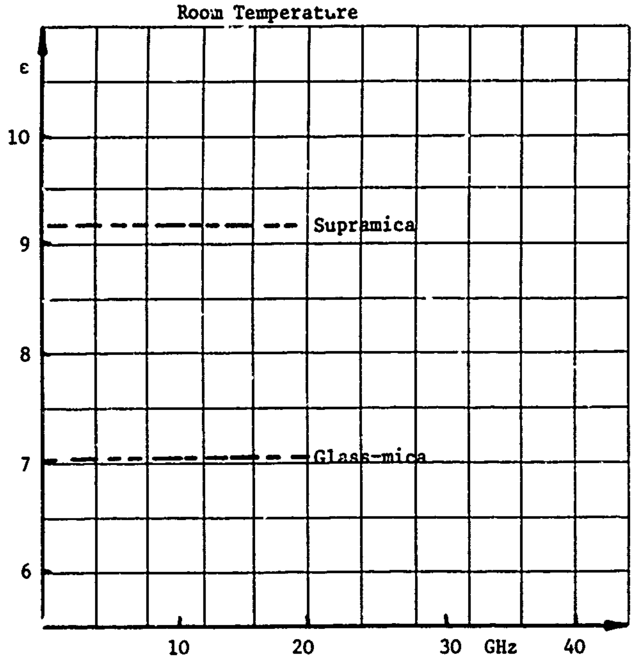
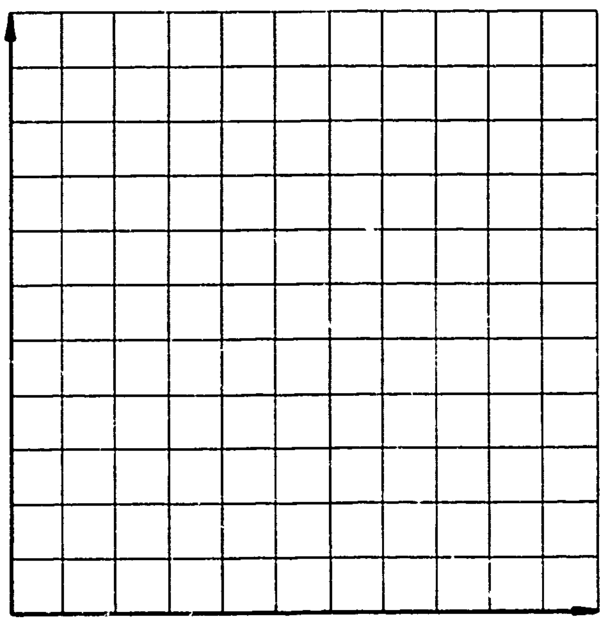


Fig 2.2.13.1.1



GLASS-MICA: Dielectric Constant v. Temperature
9.5 GHz

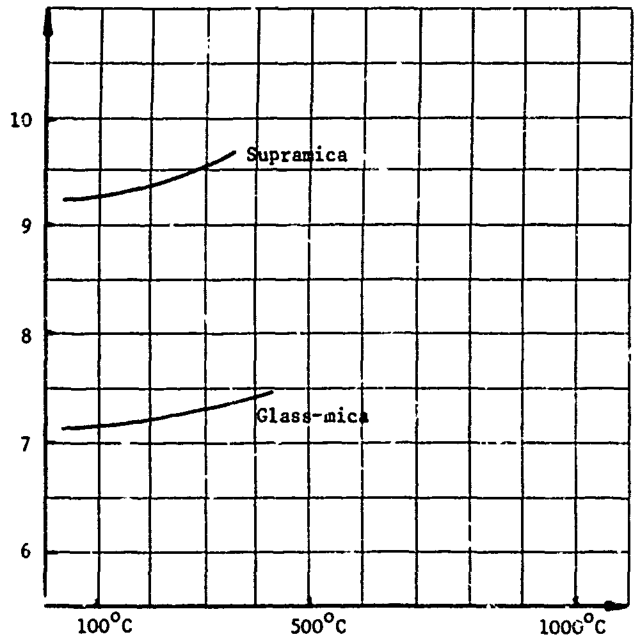


Fig 2.2.13.1.2

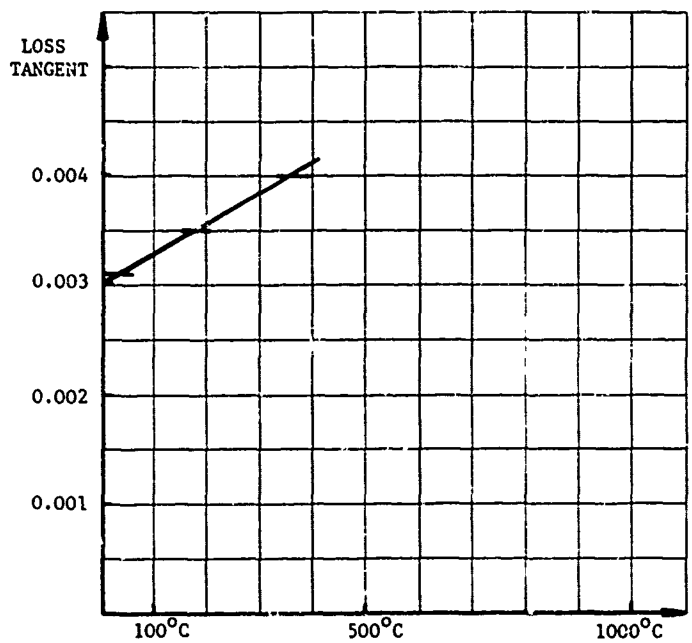


Fig 2.2.13.1.3

GLASS-MICA: Loss Tangent v. Temperature
9.368 GHz

GLASS-MICA: Volume Resistivity v. Temperature

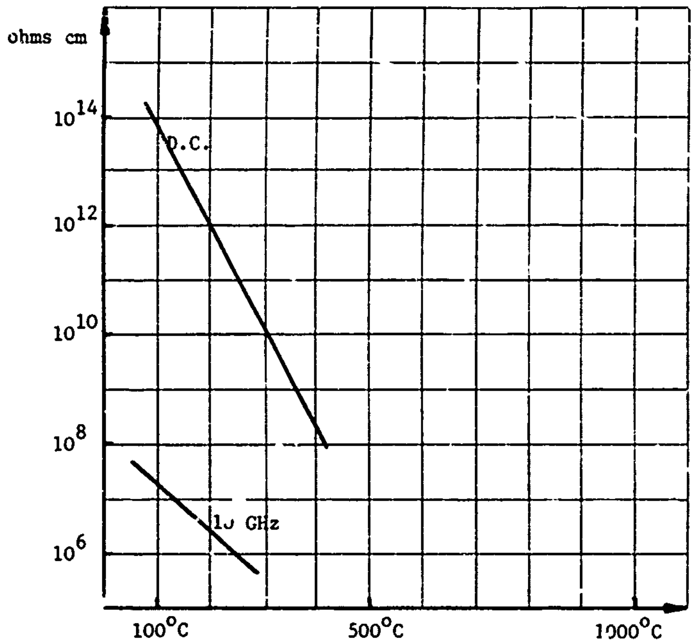


Fig 2.2.13.1.4

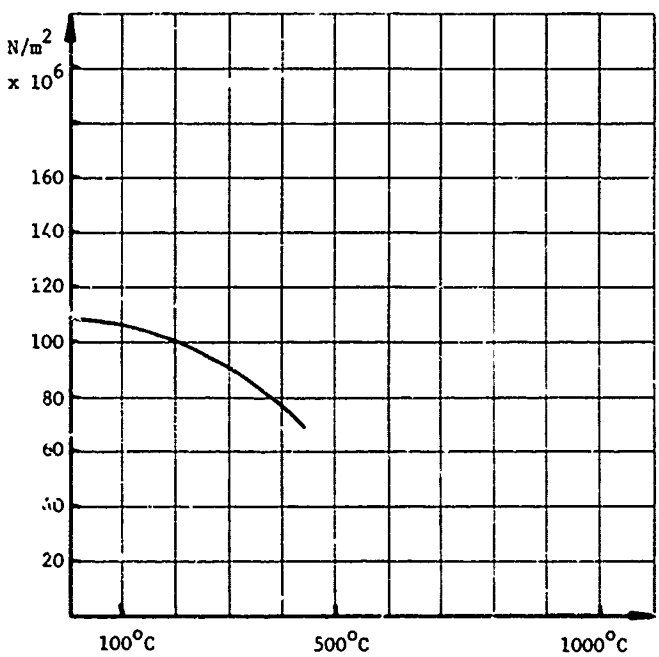


Fig 2.2.13.2.1

GLASS-MICA: Flexural Strength v. Temperature

2.2.14 GLASS-ALUMINIUM PHOSPHATE

Aluminium phosphate has been considered as a base material for a composite radome using glass cloth or glass filament as the re-inforcement. (26). The composite is to be capable of long term operation at 300°C and up to 500°C for short term. Experimental radomes for assessment have been made and have shown they have certain disadvantages mainly of low mechanical strength, humidity and water absorption problems causing dielectric constant to change and loss to increase, and very poor rain erosion resistance. In 1"/hr. rain 500 mph test the material eroded to a depth of 0.25 inch in 5 minutes. (10). Unless these problems are overcome it would not appear a competitor to the high temperature resin composites, for general usage up to 300°C. As most resins ablate or char above 300°C this material can be a candidate for consideration for usage in some cases at higher temperatures.

An example is given in Ref 28, where for a high altitude drone operating at Mach 4 for 5 minutes a glass reinforced aluminium phosphate (trade name Chem Ceram from Whitaker) radome is described. The drone has a low drag nose radome of 0.06" (1.5 mm) thickness and length 30" (750 mm) joined to a stainless steel ring, and details are given of its tensile and compressive stresses.

ELECTRICAL PROPERTIES : GLASS-ALUMINIUM PHOSPHATE TABLE 2.2.14.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	(27)	3.45 at 1.80 specific gravity Room Temperature
Dielectric Constant v. Frequency	(27)	3.45 at 10 GHz
Dielectric Constant v. Temperature	(27)	3.45 at 25°C 3.58 at 500°C
Loss Tangent v. Frequency	(27)	0.0082 at 25°C at 10 GHz
Loss Tangent v. Temperature	(27)	0.0082 at 25°C 0.0113 at 500°C
Dielectric Constant v. Humidity		
Dielectric Constant v. Radiation		
Volume Resistivity v. Temperature		
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : GLASS-ALUMINIUM PHOSPHATE TABLE 2.2.14.2

Property	Reference Fig	Remarks
Specific Gravity	(27)	1.8
Youngs Modulus v. Temperature	(27)	Flexural Modulus 21×10^9 Nm^2 at 25°C 15×10^9 Nm^2 at 500°C
Youngs Modulus v. Porosity		
Shear Modulus v. Temperature		
Rupture Modulus	(26)	56×10^6 N/m^2 Ambient
Poissons Ratio		
Flexural Strength v. Temperature	(27)	150×10^6 Nm^2 at 25°C 80×10^6 Nm^2 at 500°C
Tensile Strength v. Temperature	(27)	240×10^6 Nm^2 at 25°C 230×10^6 Nm^2 at 500°C
Compressive Strength v. Temperature	(27)	80×10^6 Nm^2 at 25°C 56×10^6 Nm^2 at 500°C
Impact Strength		
Hardness		

THERMAL PROPERTIES : GLASS-ALUMINIUM PHOSPHATE

TABLE 2.2.14.3

Property	Reference & Fig	Remarks
Temperature Working Range	(26)	Max. Temp. 550°C
Specific Heat v. Temperature	(27)	200 cals/kg °C at 300°C
Conductivity v. Temperature	(27)	0.0015 cals/°C sec cm at 500°C
Diffusivity v. Temperature		
Expansion v. Temperature		
Emissivity v. Temperature		.73 at 500°C
Ablation		
Thermal Shock		
Flammability		

ENVIRONMENTAL PROPERTIES : GLASS-ALUMINIUM PHOSPHATE

TABLE 2.2.14.4

Properties	Reference & Fig	Remarks
Temperature	(27)	Continuous 500°C
Humidity & Water Absorption		Absorbs water
Rain Erosion	(4) (10)	Eroded to a depth of 0.25 inch in 5 minutes at 500 mph 1"/hr. rain.
Radiation Solar Nuclear		
Contamination Oils Fuels Detergents Salts Acid		
Storage & Ageing		

2.2.15 REFERENCES TO SECTION 2.2

(1) British Ceramic Research Association (UK) Data

(2) Atomic Weapons Research Establishment (UK) Data

(3) Plessey Allen Clarke Research Station (UK) Data

(4) J D Walton Jr Radome Engineering Handbook. Dekker (USA)

(5) Tables of Dielectric Materials MIT (USA)

(6) Royal Radar Establishment (UK) Data

(7) "Radiation Effects Design Handbook". Battelle Memorial Inst Ohio (USA)

(8) H Salmang. "Ceramics - Physical and Chemical Fundamentals" Butterworth 1961

(9) "A Survey of High Temperature Ceramic Materials for Radomes" compiled by Melpar for AFML
Wright-Patterson Air Force Base Ohio (USA) 1964

(10) Royal Aircraft Establishment (UK) Data

(11) 'Symposium of Pure Oxide Coatings for Use in Rockets' Norton Coy. (USA)

(12) Corning Glass Works USA Data

(13) GEC (UK) Data

(14) Mycalex Corp (USA) Data

(15) Georgia Tech Data USA

(16) J B Rittenhouse "Space Materials Handbook" Lockheed Missiles and Space Coy. July 1968. AFML-TR-68-205.

(17) J E Hove and W C Riley "Modern Ceramics" John Wiley

(18) Raytheon Coy (USA) Data

(19) D J Johnson, et al "A New Material for Electromagnetic Windows IR Domes and Radomes". Proc 11th Symposium on Electromagnetic Windows Georgia Tech August 1972

(20) Torti Norton Coy. "Hot Pressed Silicon Nitride" Proc 11th Symposium of Electromagnetic Windows August 1972, Georgia Tech

(21) J D Walton Jr "Reaction Sintered Silicon Nitride" Proc 11th Symposium of Electromagnetic Windows August 1972, Georgia Tech

(22) D J Godfrey "The Fabrication Properties of Silicon Nitride Ceramics". Jour Brit Inter-planetary Soc Vol 22 pp 353-368 1969.

(23) J Lucas Group Research Centre (UK) Data Sheet

(24) S H Bomar et al "High Temperature Complex Permittivity Measurements", Georgia Tech "11th Symposium of Electromagnetic Windows" August 1972

(25) J D Walton Jr "State of Technology of Ceramic Radomes"
2nd International Conference on Electromagnetic Windows, Paris September 1971

(26) G Tarrants and R A Ireland. "Ceramic Radomes for Aerospace Vehicles" Proc Intern Conf Electromagnetic Windows Paris France September 1967

(27) Brunswick Corporation Tech Bulletin 1005

(28) D E Norris (Motorola) "Mechanical Design and Testing of a 1200°F Glass Reinforced Aluminium Phosphate Radome "page 23, 12th Symp Elect Windows, Georgia Tech 1974

(29) J Y Simon (Dodes C A N) "Development of Slip Cast Fused Silica Radomes page 103 12th Symp Elect Windows, Georgia Tech 1974.

(30) J M Burns and F A Shukis (Raytheon) "Thermal Evaluation of Porous Ceramic Radome Materials", 12th Symp Elect Windows, Georgia Tech 1974.

(31) H L Bassett and J B Langley, "High Temperature Radome Effects", Oral Communication and Paper page 39, 12th Symp Elect Windows, Georgia Tech 1974.

(32) W G Burleson and K N Letson (USAMC) "Ablation of SCF Silica Simulating Re-entry" page 77, 12th Symp Elect Windows, Georgia Tech 1974

(33) G F Schmitt (AFML) "Influence of Antenna Window Materials on Erosion at Hypersonic Velocities" page 121, 12th Symp Elect Windows, Georgia Tech 1974

(34) T M Place (Philco-Ford) "Design Properties for 3D Reinforced Silica", page 47, 12th Symp Elect Windows Georgia Tech 1974

(35) J S Waugh and S D Goldstein "Rain Erosion Evaluation of 3D Silica and Reaction Sintered Silicon Nitride", page 128, 12th Symp Elect Windows, Georgia Tech 1974

(36) D R Messier and P Wong (AMMRC) "Silicon Nitride A Promising Material for Radome Applications", page 62, 12th Symp Elect Windows, Georgia Tech 1974.

(37) G S Perry and T R Moules (AWRE) "Microwave Properties of Silicon Nitride" page 67, 12th Symp Elect Windows, Georgia Tech 1974

(38) J N Harris (Georgia Tech) "Slip Cast Reaction Sintered Silicon Nitride for Radome Applications" page 72, 12th Symp Elec Windows, Georgia Tech 1974.

(39) P Sykes "Alumina Radomes - Materials and Methods of Manufacture", Report 3/73, MOD, ROF Patricroft Manchester UK.

2.3 ORGANIC RESINS AND REINFORCEMENT MATERIALS FOR RADOME WALLS (ref. 11, 12, 26)

2.3.1 GENERAL

The majority of the requirements of the wall materials of civil and military airborne radomes have been satisfied by the use of resins laminated with reinforcements, such as glass fibres. Polyester and epoxy resins have been the more commonly used and occasionally silicone or phenolic. In extreme cases, which are growing more common, the application of the high temperature resin polyimide is becoming more noticeable. Some radomes have used organic materials without reinforcement (such as polyethylene, nylon, acrylics, etc) but as the occasion is rare they are not described.

2.3.2 BASIC FIBRE REINFORCEMENTS (ref. 1, 2, 11, 12, 26, 30)

2.3.2.1 General

Basic to the general application of resins to the radome field is the reinforcement necessary to impart adequate structural properties. Generally, these reinforcements are of the glass fibre types which may be present in knitted, woven or filament wound form. The quality of the resultant structure is dependant upon the manufacturing process but also on the particular types of glass or other basic material used in the manufacture of the fibre. Some compromise may be necessary between mechanical and electrical properties since generally the better electrical materials possess inferior strength.

In addition to the basic fibre properties and their structural and electrical implications certain fibre finishes are employed to ensure adequate wetting out and bond between resin and fibre.

The following briefly outlines the properties of radome laminate reinforcements as necessary background to the use of laminated structures for radomes.

Glass mechanical properties are summarised in Table 2.3.2.1.1 and electrical characteristics -v- temperature in Figure 2.3.2.1.1.

2.3.2.2 S. Glass

This is a silica-alumina-magnesia composition which is basically a high strength glass not developed especially for radome applications. Structural properties are summarised in Table 2.3.2 in addition it is worth noting that tensile strength is maintained to about 1.65GN/M^2 at 650^{o}C.

Table 2.3.2.1.1

Glass	S.G.	Tensile Strength N/m^2	Youngs Mod N/M^2	Dielectric Constant (9,375MHz)	Loss Tangent (9,375MHz)
S Glass	2.49	4×10^9	85×10^9	5.21	0.0068
E Glass	2.54	3.45×10^9	72×10^9	6.13	0.0039
D Glass	2.16	2.4×10^9	52×10^9	4.0	0.0026
Quartz	2.2	1.7×10^9	72×10^9	3.78	0.0002
PRD. 49 III	1.45	3.45×10^9	137×10^9	3.85	0.01

2.3.2.3 E. Glass

Based upon line-alumina-borosilicate and developed for electrical applications but not specifically for radomes. A relatively cheap and commonly used reinforcement. Compared with S glass shows a greater reduction of tensile strength at temperature e.g. $1GN/M^2$ at 650^oC.

2.3.2.4 D. Glass

Developed for radome applications and typified by lower dielectric constant and loss than other glass fibres. However, is also lower in strength and high in cost, resulting in application where electrical performance is particularly critical.

2.3.2.5 Quartz (Fused Silica Fibres)

Produced by attenuation of quartz crystals and have a silica content of about 99.5%. Particularly good properties are resulting from the use of high quality quartz in the initial melt. Dielectric constant and loss are particularly low as is specific gravity. The greater similarity of dielectric constant with that of resin leads to a reduction in composite dielectric variations when errors in percentage constituency are present. Strength is good but very dependant upon manufacturing variables such as fibre diameter, fibre gauge length, the thermal history of the melt and also the atmosphere in which the test takes place. Very high tensile strengths have been reported, i.e. about $6.9GN/M^2$ but these are not commercially viable. The thermal properties are good with low expansion and Youngs Modulus increases with temperature from about $72GN/M^2$ at 20^oC to $80GN/M^2$ at 900^oC, which is an unusual property.

2.3.2.6 Silica

These fibres have a lower silica content than quartz which may be in the region 91 to 99.2%. Produced by acid leaching of E glass usually followed by firing at 670^oC to 800^oC to compact the fibres.

2.3.2.7 PRD. 49

A fairly recent addition to the range of useful radome reinforcements is PRD. 49. This is manufactured by DuPont and is at present in its Mk. III form. The exact nature of the material is undisclosed but it is of a polyamide type and is covered by MIL Y 83370.

Within its operating temperature range, which is lower than for glass, it has been demonstrated as having tensile properties superior to E Glass. Dielectric constant is much lower than for the glasses which allows a better match to the resin properties and consequently a more uniform product. Loss tangent is also marginally lower.

2.3.2.8 Weaves and Finishes

A wide range of cloth weaves and fibre finishes are available from which a choice according to application must be made.

Various weave forms and cloth weights exist such as plain, twill and satin. In addition types such as uni-directional and staple fibre are available for special applications. Generally, the lower weight clothes in plain or twill are reserved for medium strength and medium complexity shapes. For high strength and for complicated shapes heavyweight satin types may be employed (e.g. 181) but it is worth noting that the uniformity of thickness and resin content is not as good as plain weave. The effect of glass reinforcement type on tensile strength, for example, is shown in Figure 2.3.2.8.1.

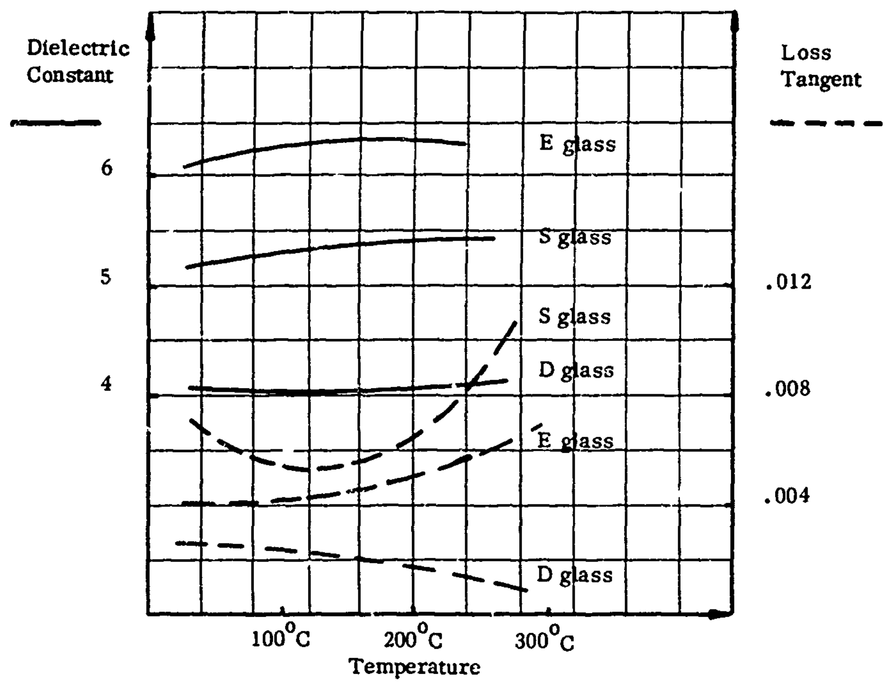
Most of these cases are fairly well balanced in their dielectric properties relative to the fibre run directions. Cases do however occur when, as for unidirectional types, this is not so. Such variation, whether or not it is a help or hindrance in the design, must be measured and accounted for.

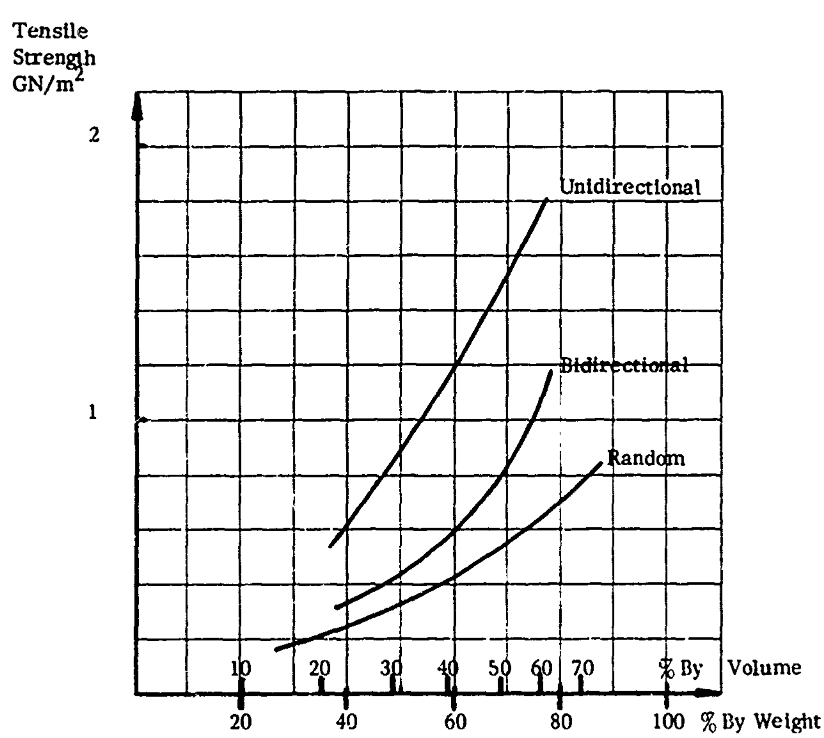
Chemical finishes are applied to fibres in order to assist in wetting out with an improvement in appearance, void content and strength.

Commonly used materials are:-

Methacrylate Chromic Chloride	for polyesters, epoxides and phenolics.
Amino Silane	for melamine, epoxides and phenolics.
Methacrylate Silane	for polyester.
Vinyl Silane	for polyester.
Epoxy Silane	for epoxy.
Universal silane	for polyester.

Electrical Properties of Glasses FIG. 2.3.2.1.1





Effect of Glass Reinforcement on Tensile Strength FIG. 2.3.2.8.1
(polyester resin composites)

2.3.3 ORGANIC RESIN COMPOSITES (ref. 1,2,11,12.26)

2.3.3.1 General

According to the application the designer will select a resin system, reinforcement and manufacturing method. He will carry out this selection with a knowledge of typical laminate electrical, mechanical, thermal and environmental characteristics and of the relative merits of the manufacturing processes available.

Because of the number of variables it is not possible to cover all types of laminate in detail. The following therefore summarise a wide range of types and a more limited number of characteristic types are given in detail.

In order to provide general information which may be regarded as reasonably typical of the major broad classifications of resin types and laminate compositions, the following information has been assembled from makers data and other sources. It is to be appreciated that details will vary from manufacturer to manufacturer for the same nominal system. However general trends and characteristics will be similar.

2.3.3.2 Electrical Properties of Organic Resin Composites

The microwave properties for materials gathered piecemeal from many sources, for both this section and the summary charts, reflect the difficulty in obtaining precision in such measurements and perhaps, the variability of properties of composites even when of the same nominal constituent parts. It is assumed that the commonly used shorted waveguide method is employed for most, if not all cases, at both room and elevated temperature. The precautions necessary to ensure accuracy are well known and will not be recalled here but it is noted that these must be strictly adhered to.

In many cases, in makers data, properties at much lower frequencies (1MHz region) are given. The user should be cautioned against paying heed to these for microwave design, since a considerable reduction in both dielectric constants and loss tangents is the norm when moving from such frequencies to the microwave region. To see these trends well demonstrated the attention of the reader is drawn to reference 25.

High voltage and conductivity properties are not commonly available. However in view of increasing concern in connection with lighting strike protection and static discharge interference a greater interest in these quantities is being expressed by radome designers. It is to be expected therefore that more comprehensive data will be appearing.

It should be noted that extrapolation of basic dielectric constant information is possible, with fair accuracy, by application of the equation:-

$$\text{Log}\,\epsilon = \frac{V_R}{V_T}\,\text{Log}\,\epsilon_R + \frac{V_F}{V_T}\,\text{Log}\,\epsilon_F$$

Where ϵ is resultant dielectric constant

ϵ_R is resin dielectric constant

ϵ_F is reinforcement dielectric constant

V_R is volume of resin

V_F is volume of reinforcement

$V_T = V_F + V_R + V_v$ where V_v is the volume occupied by voids.

It is however, stressed that final accurate data for electrical, or for that matter mechanical, properties can only be obtained by the measurement of samples manufactured in the fashion required and using the precise applicable build.

2.3.3.3 Mechanical Properties

Similar words of caution as for the electrical case, regarding the variability of mechanical data and its critical dependence on composite build and constituents have been noted.

In some cases orientation of fabric is not stated, but is essential for a proper comparison of the different types. In general however it will be assumed to be for the optimum orientation.

In the case of polyesters and epoxies, within their respective operating temperature ranges the mechanical properties are similar and are more dependent on reinforcement type. For this reason one table is referred to for both cases.

Various significant comments have been noted in reference 2 and are precised as follows.

"Due to the fibre nature of reinforcement fabrics and inevitable crimp there exist primary and secondary moduli. Note: in all cases where the distinction has been made primary moduli are given - further information in this respect may be found in reference 26. Resin reinforcement combinations, in the main, display an onset of crazing at 25 to 75% of the ultimate stress which, while having little effect upon short term mechanical behaviour, does degrade wet environment resistance.

Flexural properties are widely used as a means of GRP control but caution must be exercised when applying these to design. The mode of failure is frequently open to doubt, as is also the validity of the beam formula for laminates, since the fibre stress at failure is higher than for the tensile or compression ultimate. This doubt is greatest for woven fabrics and less so for directional materials with very little fibre crimp. It is stressed that particular combinations of resins and fibre finish treatments can significantly effect results."

2.3.3.4 Thermal Properties

For specific cases thermal property information is limited. It is noted that the mechanical implications of thermal expansion are not normally significant even when the material interfaces with metals. It is however very significant to the electrical performance of a radome. Thermal properties are sensitive to resin/glass ratio but properly descriptive information has not been found. In general representative figures are given.

2.3.3.5 Environmental Properties

Of the environmental influences rain erosion susceptibility is perhaps the most difficult to quantify. It is of course also very dependent upon manufacturing variables. This subject has been thoroughly reviewed and referenced in reference 11 and will not be enlarged upon here. In view of the many assessment methods, which makes comparison difficult, the wide range of materials considered, of which radome types form a small part, comment here will be limited to a relative merit comparison.

2.3.3.6 Manufacturing

The particular manufacturing process selected will depend upon such factors as number of radomes to be produced, flexibility for the incorporation of design modifications and unit to unit repeatability. At one end of the scale the hand lay-up process exhibits maximum flexibility and minimum tooling costs but is relatively inaccurate. At the other end injection moulding in matched metal moulds is highly accurate but has the least flexibility and high tooling costs.

Other factors, such as the shear complexity of producing a multilayer sandwich, unit size, incorporation of metallic elements, glass content requirement and resistance to moisture, will also affect choice of manufacturing technique. Most of the manufacturing methods employed are practised by most manufacturers but in a few instances specific developments have been made for which the developers have a natural preference. All methods have their advantages or otherwise in connection with cost, flexibility, product quality etc; these are summarised in Table 2.3.3.6.1.

Table 2.3.3.6.1 Manufacturing Technique Summary

METHOD	ADVANTAGES	DISADVANTAGES
Hand lay-up	Flexible in application and can be used for complicated builds. Offers cheapest tooling.	Accuracy demands high skill but even then is limited. Achievable laminate thickness limited to about 0 3cm. Labour content in any job is high.
Vacuum bag	Flexibility as for hand lay-up but tooling marginally more expensive. Product quality better than for hand lay-up.	Accuracy demands high skill but even then is limited. Achievable laminate thickness limited to about 0.3cm. Labour content in any job is high.
Autoclave	Generally as for vacuum bag but also lends itself to the preparation of pre-preg laminates and the processing of resins producing reaction products.	Accuracy demands high skill but even then is limited. Achievable laminate thickness limited to about 0.3cm. Labour content in any job is high.
Filament Winding	Produces a high strength laminate with good electrical homogeneity. Flexible in application and tooling costs better than for matched moulding.	High dielectric constant leads to relatively thin walls. Machining operations allow moisture pick-up during manufacture and if sealing coats are damaged also during operation. Machining produces some variability in wall strength. Has been criticised for poor performance under rain erosion when protective coating is damaged.
Match Moulds	Produces laminate of good electrical homogeneity and a strength which when coupled with relatively high wall thickness (low dielectric constant) produces a strong radome. Machining not necessary. Good resistance to moisture.	Lacks flexibility and has highest tooling costs.

2.3.4 POLYESTER RESINS AND COMPOSITES (ref. 1,2,11,12,26)

The polyester and the epoxy resins are the most popular resins for usage in composites for radomes. The polyester resin can be manufactured with a variety of reinforcements to form composites with good electrical properties, high mechanical strength, good weather and chemical resistance easy handled and of low cost. There is a considerable choice of manufacturers producing various brands of polyesters which are suitable for consideration for radome manufacture. There is a general dividing line between conventional polyester resins and modified resins having improved temperature characteristics. This section therefore considers these two types of resin constituents of polyester composites separately.

The minimum requirement for polyester laminates used for radome application is given in Mil R 75755B (U.S.A.) and D.T.D. 933A (U.K.).

The polyester resin has the advantage of low cost, good electrical, physical, chemical, weathering and thermal properties, combined with easy handling. It is suitable for moderate temperature application and for radomes using either inorganic or organic reinforcement materials.

The general requirements for polyester resins are covered in Mil-R-7575 and Mil-R-25042.

2.3.4.1 Chemical Description of Polyester Resin

Polyesters are obtained by a condensation reaction involving esterification of organic carboxylic acids or their anhydride, having two or more carboxyl groups, with alcohols, having two or more hydroxyl groups.

The polyesters used for the manufacture of reinforced plastics are unsaturated and are modified by the addition of a vinyl monomer, such as styrene or vinyltoluene, which adjusts viscosity and, more important, effects cross-linking between polyester chains.

Cross-linking, normally known as the curing process, is brought about by free radicals supplied by a catalyst, usually an organic peroxide. Cure is normally carried out at room temperature, but a higher temperature may be used, depending on the reactivity of the catalyst. In the former case, an accelerator, often cobalt naphthenate, is used to activate the catalyst. Adjustment of the amounts of catalyst and accelerator or selection of an elevated cure temperature permits wide versatility and a large measure of control over the processing of these resins.

Since the direct reaction of peroxides and accelerators can be explosive, it is essential that they are never mixed together, but that one is mixed with the resin before adding the other.

Cure involves several phases. Initially, the free radicals from the catalyst are consumed by reaction with the inhibitor, which is added to the polyester to give the required shelf life. This stage is fairly slow, a useful factor in that it allows impregnation of the reinforcement.

It is followed by fairly rapid gelation as the exothermic cross-linking reaction proceeds. In relatively thin section laminates, the heat evolved is dissipated very rapidly, but some caution is necessary where thick sections and large quantities of resin are involved.

The resin then hardens quite quickly, but cure continues over an extended period. This last part of the process can be hastened by post cure at elevated temperature, often for about four hours at 80°C.

Resins are available in cold and hot cure forms and satisfy a wide range of radome applications.

Modified polyesters can extend operating temperature range up to about 155°C, depending on the particular application. One such modification, obtained by replacing the styrene with triallyl cyanurate, is commercially available and designated TAC polyester, a well-known example being Vibrin 135. This latter resin has the additional desirable properties of low viscosity and long shelf life.

2.3.4.2 Properties of Conventional Polyester Resin (ref. 4,8)

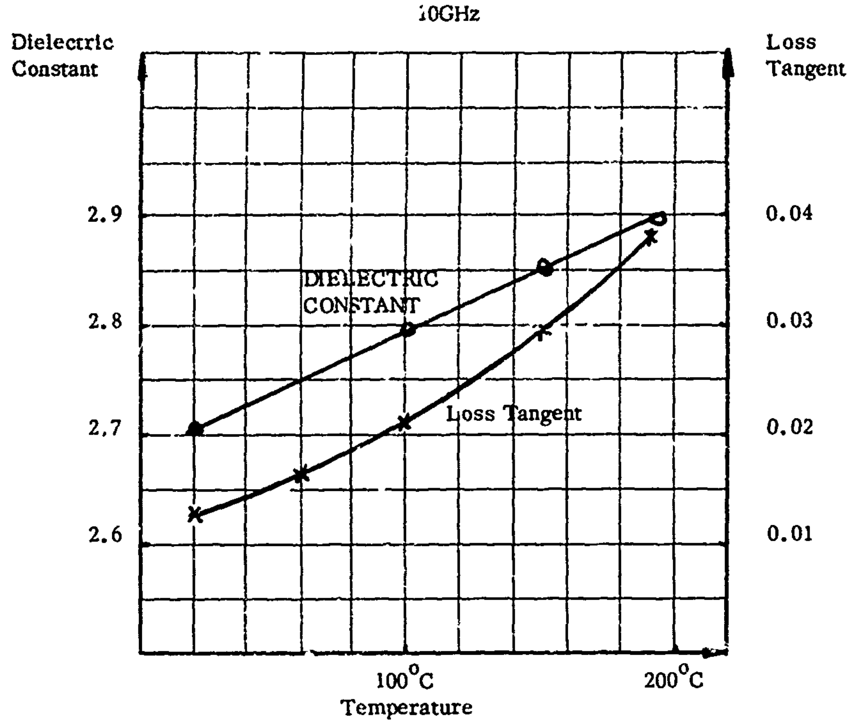
A typical conventional unmodified polyester resin has the following properties:- Table 2.3.4.2.1.

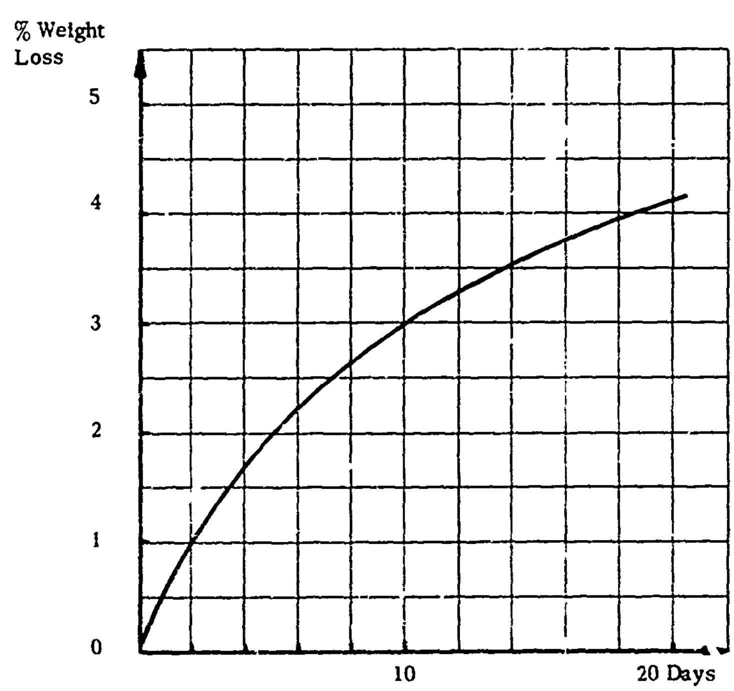
Table 2.3.4.2.1 Conventional Polyester-Resin Characteristics

PROPERTY		REMARKS				
Physical :	Colour	Medium yellow				
	Viscosity	360 centistokes at 25°C				
	Specific Gravity	1.11 uncured				
	Expension Coeff.	$62 \times 10^{-6}/^{o}C$				
	Water Absorption	10mg in 24 hours				
	Acid Value	20mg KOH/g				
	Volatiles	32%				
	Storage	9 months at 20°C 1 month at 40°C				
Electrical :	Dielectric Constant	2.7 (10GHz/25°C) (Figure 2.3.4.2.1)				
	Loss Tangent	0.013 (10GHz/25°C) (Figure 2.3.4.2.1)				
	Surface Resistivity	8×10^{14} ohms				
	Volume Resistivity	2×10^{15} ohms				
Thermal :	Heat Distortion ($182 \times 10^6 N/m^2$ Load)	Cure at 100°C for	3 hr	24 hr	7 days	14 days
		Distortion Point	98°C	106°C	116°C	121°C
	Heat: Weight Loss	24 hours at 200°C 0.9%: 7 days 2.5% (Figure 2.3.4.2.2)				
Curing :	Hot Cure Times	MEK PEROXIDE CATALYST % of Resin weight	0.007	0.01	0.02	
		GELATION TIME AT 82°C minutes	30	23	15	
	Cold Cure Times	MEK PEROXIDE CATALYST % of Resin weight	0.02	0.03	0.04	
		COBALT NAPH. ACCELERATOR % of Resin weight	0.02	0.03	0.04	
		GELATION TIME at 25°C minutes	130	60	30	
	Pot Life		20°C	25°C		
		Catalyst 0.007% (Hot cure)	3 weeks	2 weeks		
		Catalyst & Accelerator (Cold cure)				
		0.02% each	3 hours	2 hours		
		0.03% each	75 min	50 min		
Radiation, Chemical and Solvent Resistance :	Sunlight	Avoid Ultra Violet Light				
	Oxidising Acids	Non-resistant				
	Mineral Acids	Good Resistance				
	Oils	Good Resistance				
	Benzene, Alcohol	Poor Resistance				
	Esters; Ketones	Poor Resistance				
		% Weight Increase				
			1 day	7 day	14 day	
Acetone			2.1	3.6	11.0)	Sample post cured 1 hour at 120°C
25% H_2SO_4			0.1	0.3	0.4)	
Chloroform			4.2	-	-)	
Acetone			0.7	1.7	2.4)	Sample post cured 1 day at 150°C
25% H_2SO_4			0.05	0.1	0.15)	
Chloroform			1.0	2.1	4.2)	

Dielectric Constant and Loss Tangent v. Temperature (Conventional Unmodified Resin) 10GHz

FIG. 2.3.4.2.1





Weight Loss v Time at 200°C (Bakelite SR 17449. Polyester)

FIG. 2.3.4.2.2

2.3.4.3 Properties of High Temperature Modified Polyester Resin (ref. 13, 14)

The conventional polyester has been modified to improve its properties. Notably is the triallyl cyanurate (TAC) modified polyester with improved thermal properties for operation at much higher temperatures with acceptable mechanical strength. A USA commercially available example of this resin is Vibrin, to which the following data mainly applies. Attempts have been made also to produce a lower loss polyester resin as well as higher temperature operation, an example of this being Plessey (UK) RP12. The information in Table 2.3.4.3.1 is drawn in the main from US-Rubber, Vibrin data, in the form of 135 and 136-A, which are by far the most commonly used of the triallyl cyanurate modifications.

Table 2.3.4.3.1 High Temperature Modified Polyester Resin Characteristics

PROPERTY		REMARKS
Physical	Colour	Clear Straw Liquid
	Viscosity	18-26 Poise (Disc at 25°C)
	Specific Gravity	1.21 uncured 1.34 cured
	Expansion Coeff.	50×10^{-6} °C
	Water Absorption	0.73% Gain after 25 hours at 25°C
	Storage	Uncatalysed 25°C 6 months, 70°C 72 hours catalysed 25°C 2 days
Electrical	Dielectric Constant	2.78 10GHz 25°C
	Loss Tangent	0.005 10GHz 25°C
	Dielectric Strength	19.5kV/mm 60Hz
Thermal	Heat Distortion Point	260°C
Curing	Cure Times	20 min at 80°C, 3 min at 100°C, 1½ min at 110°C
Chemical and Solvent Resistance	Distilled Water	1.3% % weight increase after 7 days
	Acetone	0.9
	30% Sulphuric Acid	0.15
	10% HCl	0.5
	10% Nitric	0.2
	10% Sodium Hydroxide	2.2%
	95% Ethyl Alcohol	0.8%
	Carbon Tetrachloride	0.15%
	Gasoline	0.1%

2.3.4.4 Electrical Properties of Polyester (Unmodified) Composite (ref. 3,9,12,25,26,30)

The dielectric constant of the composite depends on that of the resin (near 2.7 at 10GHz) and that of the reinforcement and also the ratio of the resin to reinforcement (Fig. 2.3.4.4.1). A typical E glass (dielectric constant of near 6) filament wound radome would have near 20% resin and a resultant dielectric constant near 4.7, whereas with woven cloth 33% resin would be typical giving a dielectric constant of 4.1. A quartz-cloth (dielectric constant 3.7) laminate of 35% resin results in a dielectric constant of 3.3. Thus the choice of reinforcement material, method of manufacture and using various percentage of resin, the radome designer can have a choice of dielectric constant from near 3 to near 5, as shown in Table 2.3.4.4.1:-

Table 2.3.4.4.1 (Polarisation Parallel to Fabric): Room temperature

Reinforcement	Resin	% Weight Unmodified Resin	Dielectric Constant	Loss Tangent
E glass filament wound	Bakelite 17449	20%	4.8	0.017
E glass Fabric 181E	Stypol 705	35%	4.37	0.015
E glass Fabric 181E	Selectron 5003	54%	4.21	0.01
E glass Cloth P6 4501	Bakelite 17449	49%	3.73	0.014
E glass Cloth S2-225	Stypol 40-2016	49%	3.57	0.007
E glass Stocking	Bakelite 17449	73%	3.2	0.012
Quartz Cloth	Bakelite 17449	30%	3.3	0.008
PRD49 Cloth III	Bakelite 17449	55%	3.1	0.015
Terylene Cloth 1500	Bakelite 17449	64%	2.9	0.015

Voids, which are undesirable, in the composite can effect the expected dielectric constant by lowering it as shown in (Fig. 2.3.4.4.2).

The loss tangent of the composite is near 0.015 with glass reinforcement, and less with quartz due to the latters low loss tangent. (Room temperature and 10GHz).

The dielectric constant of the composite does not alter significantly over the microwave band, but the loss tangent tends to increase towards higher frequencies (Fig. 2.3.4.4.3.)

The dielectric constant and loss tangent increases with temperature, for the polyester composite as shown in Figure 2.3.4.4.4. The effect of the change of dielectric constant can be significant where a radome is required to work over a wide temperature range.

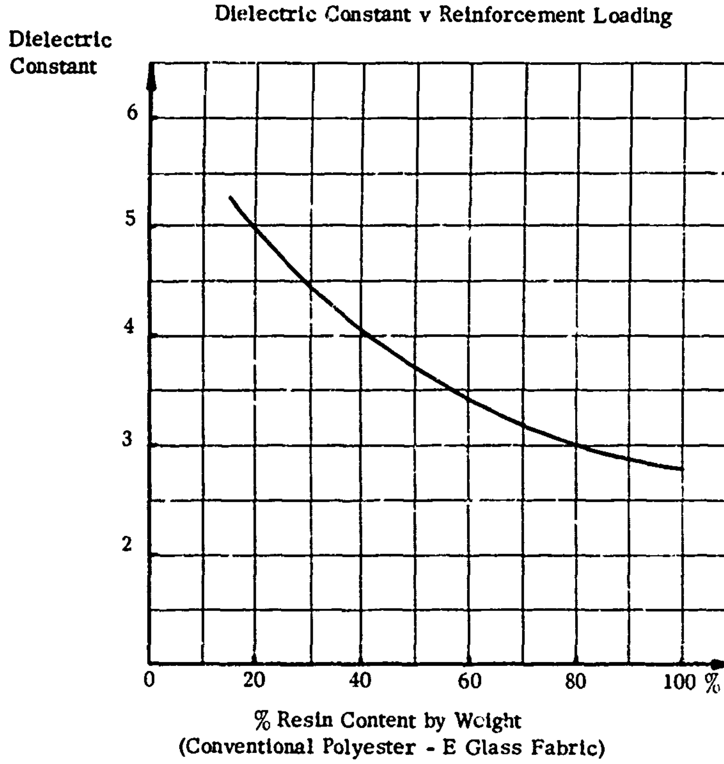
Another important factor is that even a near void free composite will pick up moisture as the constituents of the polyester composite can to some extent absorb moisture. The dielectric constant and loss tangent of a void free laminate subjected to 98% relative humidity at 40°C is given against time in Figure 2.3.4.4.5.

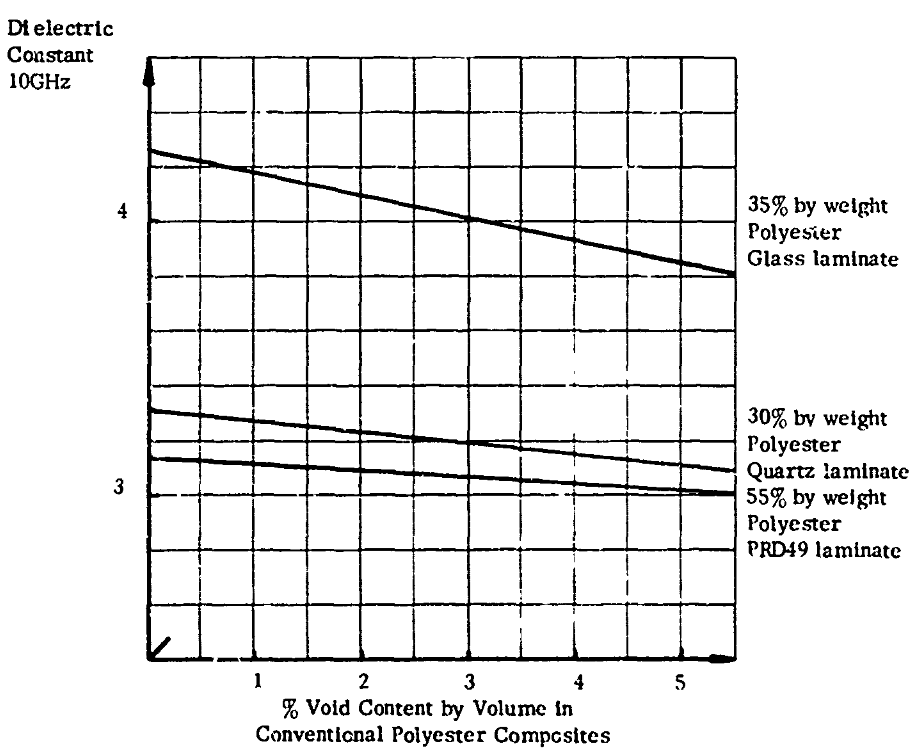
A summary of electrical properties is given in Table 2.3.4.4.2.

Table 2.3.4.4.2 Electrical Properties of Polyester (Unmodified) Composite

Property	Figure/Table Reference	Remarks
Dielectric Constant and Loss Tangent v. Reinforcement Type	Table 2.3.4.4.1	Dielectric Constant varies from 3 to 5 according to materials. Loss Tangent near 0.01
Dielectric Constant and Loss Tangent v. Reinforcement Content	Fig. 2.3.4.4.1	Dielectric Constant decreases with resin content. Loss Tangent near 0.01
Dielectric Constant v. Voids	Fig. 2.3.4.4.2	Dielectric Constant decreases with increased voids
Dielectric Constant and Loss Tangent v. Frequency	Fig. 2.3.4.4.3	Little change with dielectric constant. Loss tangent increases toward K_a (35GHz) band
Dielectric Constant and Loss Tangent v. Temperature	Fig. 2.3.4.4.4.	Dielectric constant and Loss Tangent increases with temperature
Dielectric Constant and Loss Tangent v. Humidity	Fig. 2.3.4.4.5.	Dielectric constant and Loss Tangent increases with humidity pick-up
Surface Resistivity		2×10^{12} ohm-cm E glass 30% resin
Volume Resistivity		30×10^{13} ohm-cm E glass 30% resin
Dielectric Strength		15kV/mm E glass 30% resin

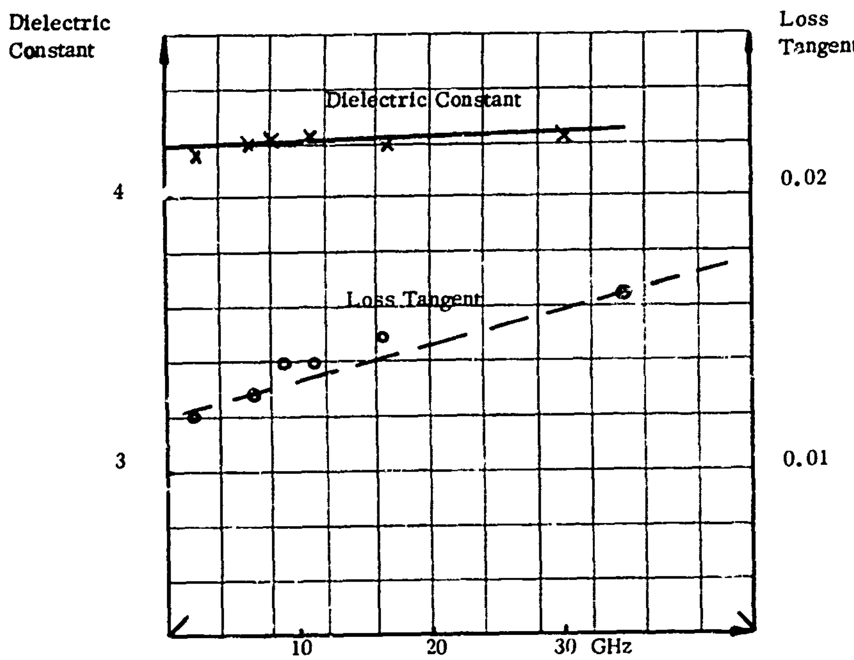
Dielectric Constant v Reinforcement Loading FIG. 2.3.4.4.1

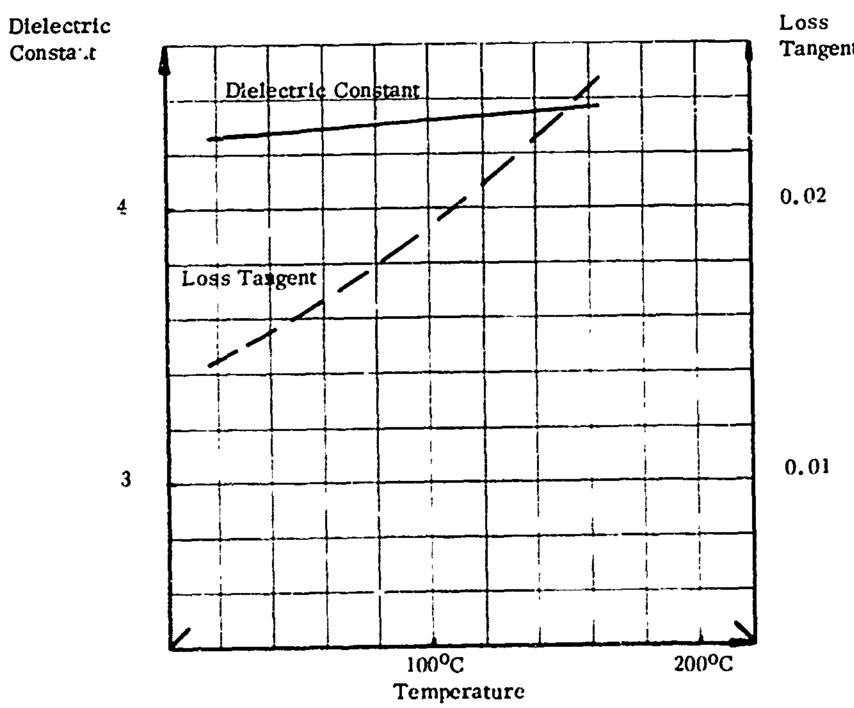




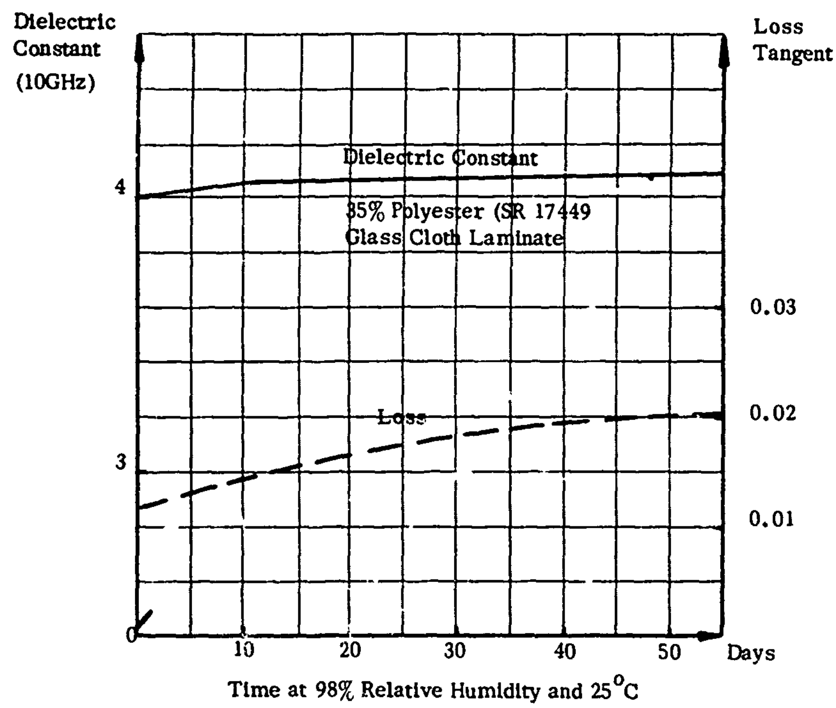
Dielectric Constant v Voids FIG. 2.3.4.4.2

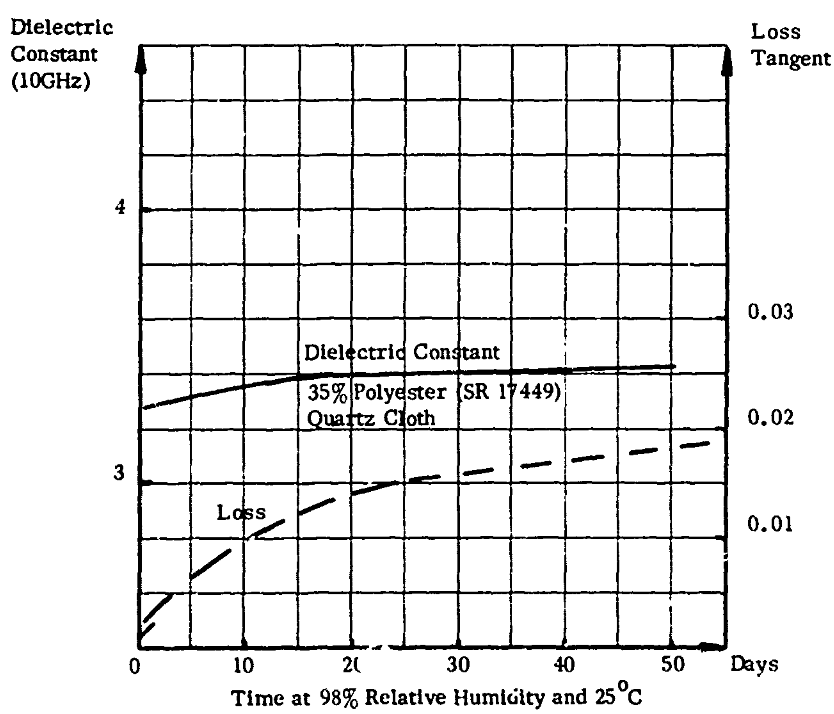
Dielectric Constant & Loss Tangent v Frequency FIG. 2.3.4.4.3
37% Polyecter (SR 17449) Glass Cloth Laminate





Dielectric Constant & Loss Tangent v Temperature FIG. 2.3.4.4.4
35% Polyester Resin - E Glass Fabric





Dielectric Constant and Loss Tangent v Humidity FIG. 2.3.4.4.5

Conventional Unmodified Polyester - Composites

2.3.4.5 Mechanical Properties of Polyester (Unmodified) Composite (ref. 1,2,4,8,12,26)

The mechanical properties vary according to resin content, the type of reinforcement and the method of manufacture. In general chopped stranded glass composites are not as strong as woven cloth or filament wound composites. Low reinforcement content usually results in a lower strength. Full times of curing are required to ensure strength, and importance must be attached to the recommended finish to the reinforcement.

The specification requirements for strength of conventional polyester composites calls for:- Table 2.3.4.5.1.

Table 2.3.4.5.1

SPEC. MIL. R 7575	GRADE A	GRADE B
Tensile Strength	275 MN/m^2	345 MN/m^2
after 2 hr in 100°C water	262	331
Compressive Strength	241	330
after 2 hr in 100°C water	225	275
Flexural Strength	345	448
after 2 hr in 100°C water	310	414
after 1 year outdoor	310	345
Flexural Modulus	17.2 GN/m^2	22 GN/m^2
after 2 hr in 100°C water	17.2	21.2
after 1 year outdoor	17.2	18.6

Spec. DTD.5537 calls for similar strength characteristics e.g. Flexural strength 380 MN/m^2 and 310 MN/m^2 after 1 year weathering.

Typical results of polyester (unmodified) composite with various reinforcements are:-

Table 2.3.4.5.2

	7781 E Glass PRE PREG	S2/225 E Glass Fabric	Satin Fabric E Glass	Quartz Cloth	PRD49 III Fabric
Tensile Strength	304 MN/m^2	310 MN/m^2	320 MN/m^2	200 MN/m^2	650 MN/m^2
Compressive Strength	266	280	290	200	240
Flexural Strength	386	422	490	300	300
Flexural Modulus	18.6 GN/m^2	18 GN/m^2	19 GN/m^2	16 GN/m^2	19 GN/m^2

Typical strength figures for different weaves of E glass fabric are given in Table 2.3.4.5.3.

Table 2.3.4.5.3

At Room Temperature	PLAIN WEAVE BS 3396/P6 40% Resin			SATIN WEAVE BS 3396/S2 40% Resin			DIRECTIONAL FABRIC BS 3396/S11			CHOPPED STRAND RANDOM MAT
ANGLE OF LOADING	0	90	45	0	90	45	0	90	45	All Angles 0 90 45
FLEXURAL STRENGTH MN/m^2	385	350	-	490	455	-	700	140	-	105 to 175
FLEXURAL MODULUS GN/m^2	17.5	14	-	19.6	17.5	-	31.5	10.5	-	7 to 10.5
TENSILE STRENGTH MN/m^2	280	240	125	310	280	170	560	70	85	100
TENSILE MODULUS GN/m^2	18	15.25	10.5	19.3	18	13.8	33	11.8	10.5	7
COMPRESSION STRENGTH MN/m^2	240	220	-	290	260	-	410	170	-	140
COMPRESSION MODULUS GN/m^2	20.8	15.3	-	22	20.8	-	34.5	12.5	-	10.5
SHEAR STRENGTH EDGEWISE MN/m^2	30	-	-	95	-	-	55	-	-	60
SHEAR MODULUS EDGEWISE GN/m^2	3.8	5	-	5.3	-	-	3.8	-	-	4.8
BOLT BEARING STRENGTH MN/m^2	210	190	190	250		230	240	220	230	140
POISSONS RATIO	0.125		0.35 to 0.5	0.125		0.35 to 0.5	0.25			-
CREEP	NEGLIGIBLE TO 70% OF ULTIMATE									
FATIGUE LIMIT AT 10^7 CYCLES	20 - 25% OF UTS									

The effect of temperature is shown in Figure 2.3.4.5.1 where the strength properties of a good laminate indicate that they can operate at 150°C long term, with a strength reduction of near 25% of the strength at room temperature. At 200°C the unmodified polyester will suffer near 50% reduction in strength, and will suffer further reduction on continuous heating.

Humidity has only a marginal effect on strength, but continuous immersion may give up to 10% reduction in flexural strength.

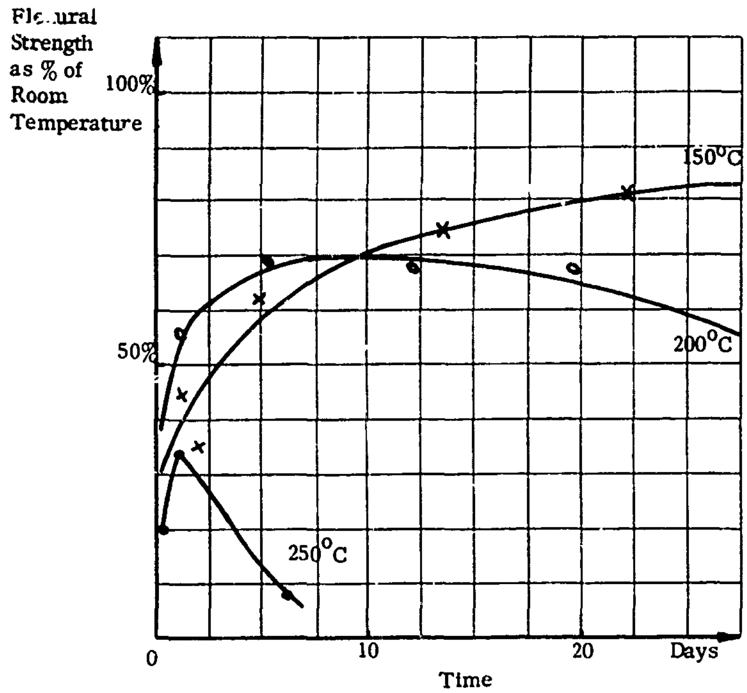
A summary of the mechanical properties is shown in the following table:-

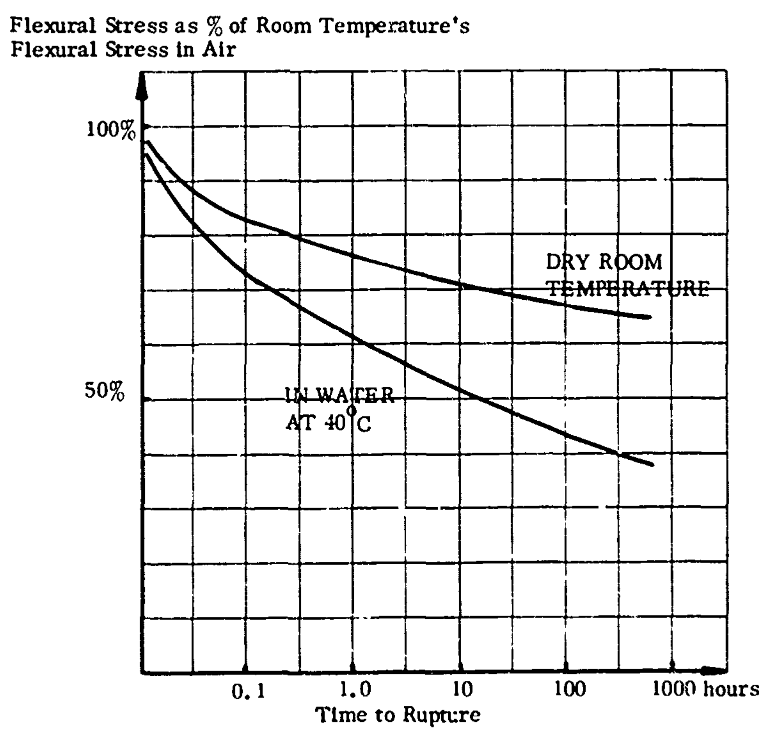
Table 2.3.4.5.4

PROPERTY	Figure/Table REFERENCE	REMARKS: TYPICAL VALUES: ROOM TEMP.
Tensile strength	TABLE 2.3.4.5.3	275 MN/m^2 (E glass cloth)
Compressive strength	TABLE 2.3.4.5.3	241 MN/m^2 (E glass cloth)
Flexural strength	TABLE 2.3.4.5.3	345 MN/m^2 (E glass cloth)
Flexural Modulus	TABLE 2.3.4.5.3	17.2 GN/m^2 (E glass cloth)
Youngs Modulus	TABLE 2.3.4.5.3	20 GN/m^2 (E glass cloth) 36 GN/m^2 (PRD 49)
Shear strength	TABLE 2.3.4.5.3	Interlaminar 33 MN/m^2
Impact strength		1.95 kgm/2.5cm (32/225/E Fabric 35% Resin)
Hardness		30 - 40
Poissons Ratio		0.125 (cloth Fabric) up to 0.25 (Directional Material)
Porosity		Very low when well manufactured
Flexural strength v. Temperature & Time	FIGURE 2.3.4.5.1	P8/225/E Glass Fabric. Resin Content 40% 75% at 150°C
Flexural stress Time to Rupture	FIGURE 2.3.4.5.1	S2/224E Glass Fabric. Resin Content 40% (DTD 5518)

Flexural Strength v Temperature and Time
(P8/225/E Glass Fabric 40% Unmodified Polyester Resin)

FIG. 2.3.4.5.1





Flexural Stress v Time to Rupture
(S2/224E Glass Fabric 40% Unmodified Polyester Resin)

FIG. 2.3.4.5.2

2.3.4.6 Thermal Properties of Polyester (Unmodified) Composite (ref. 1,2,3,4,8,11,12)

The unmodified polyester composite safe range of temperature of operation depends on the manufacturing technique, the precise resin and reinforcement formulation, its dimensions, environment and loads it is subjected to. It would be expected to operate from -60°C to +120°C for long term, and at 150°C for a limited life and 180°C for a very short term. The usual effect of heat is the loss of resin content of the higher temperatures as shown by percentage weight loss graph versus time. Figure 2.3.4.6.1.

The effect of rise in temperature is to increase the dielectric constant, loss tangent, and decrease the mechanical properties from those at room temperature, but are such as to be well suitable for many radome applications.

The thermal properties are such as to be able to survive severe thermal shock. A sudden flash of heat can cause charring to the surface, but in a laminated structure, the remainder of the structure remains intact but with some degradation. On solid laminate constructions of thickness near 7mm the remaining structure should be sufficient to prevent failure, but much would depend on loads.

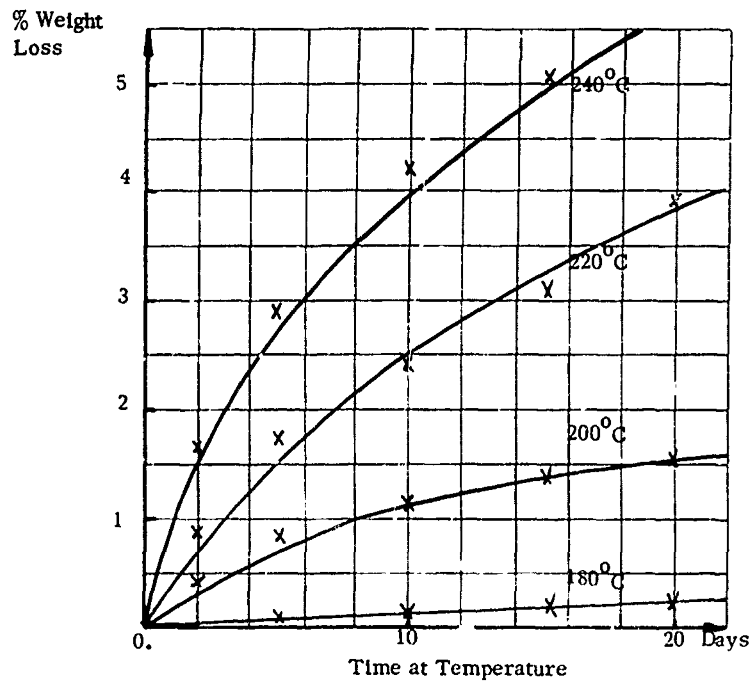
The expansion coefficient is not compatible with metals and radome to metal interfaces may, in some cases, have to allow for differential expansion.

A summary of the thermal properties is as follows:- Table 2.3.4.6.1.

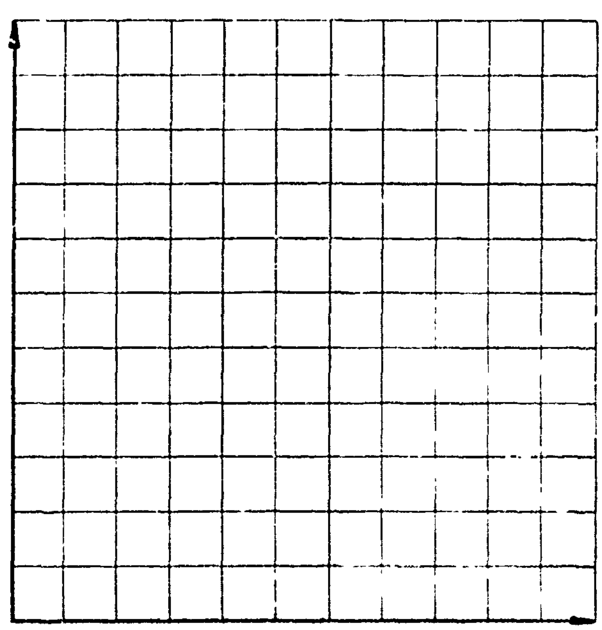
Table 2.3.4.6.1

THERMAL PROPERTY	Figure REFERENCE	REMARKS
OPERATIONAL RANGE	-	Will depend upon manufacture technique, reinforcement, precise resin formulation and the environment. Generally will not exceed 180°C short term and 120°C long term.
SPECIFIC HEAT	-	Approx. 0.40 in all cases but dependent on resin/glass ratio. Note figure for glass reinforcement some 20 times greater than for resin.
CONDUCTIVITY		7.5 to 16 x 10^{-4} cals/sec/cm/°C for laminates with 30 to 45% resin-E glass.
EXPANSION COEFFICIENT	-	In region of 16 x 10^{-6}/°C for laminates with 30 to 45% resin-E glass. Different according to reinforcement type.
FLAMMABILITY	-	Fire retardant grade not normally used due to elevated temperature properties being degraded. Not regarded as a fire hazard for radomes.
ABLATION/ CHARING	Figure 2.3.4.6.1	Not normally used under these conditions. Charring temperature near 400°C.
THERMAL SHOCK	-	No problem in operational temperature range.

35% Polyester (SR 17449)
Glass Cloth Laminate



Weight Loss v Time v Temperature FIG. 2.3.4.6.1



2.3.4.7 Environmental Properties of Polyester (Unmodified) Composite (ref. 2, 10, 11, 12)

The composite should withstand years of normal environmental conditions without significant changes in its properties. Radomes life would vary according to its position on the vehicle. For instance a nose radome would be subjected to greater loads and erosion than one in a more protected position.

The composite if substantially void and surface fibre free, absorbs water slowly and should only have a marginal effect on electrical and mechanical performance. It should be unaffected by icing, apart from the additional effects of the ice being present.

In the absence of surface protection coatin, the presence of voids also degrade rain erosion resistance.

The composite should withstand pressure differences and changes and, if protected by lightning conductors, should survive the normal strike without major damage.

The composite may fail under severe hail or bird strike.

The composite should remain in service unaffected by normal chemical and solvent materials such as oils, greases, detergents, acids etc. Space vehicles, subject to very long intense ultra violet may suffer degradation of material properties.

A summary of the environmental properties of polyester (unmodified) composites is as follows:- Table 2.3.4.7.1.

Table 2.3.4.7.1

PROPERTY	Figure REFERENCE	REMARKS
RAIN EROSION		Depends upon many conditions, such as surface smoothness, angle of attack, laminate thickness and backing. In general each application must be individually assessed where erosion is a criterion.
RADIATION ULTRA VIOLET..		Rated as good - approx. 10% loss of flexural strength at 2 cal/sq. cm/min. for 500 hr.
NUCLEAR.......		Safe rating 10^5 rad in air or vacuo
THERMAL		Surface damage at 50 cal/sq. cm/sec. CHARS at 100 cal/sq. cm/sec.
STORAGE/AGEING		Results given are from weatherometer accelerated weathering tests in which 300 hr is roughly equivalent to 1 year in the central portion of the North temperate zone. There is not direct correlation between the given surface conditions and structural properties but susceptibility to moisture and loss of chemical resistance might occur. Indoor conditions - No deterioration. Normal outdoor conditions:- Time to craze or crack >> 2500 hr. Time to chalk - slight up to 600 hr. considerable beyond 600 hr. Time to fade - considerable fading occurs very quickly. Erosion - No significant loss of thickness at 1600 hr. but some fibres exposed at 600 hr.
	Figure 2.3.4.5.1	Thermal Ageing

Table 2.3.4.7.1 (Contd)

PROPERTY	Figure REFERENCE	REMARKS		
CONTAMINATION	Figure 2.3.4.5.2	Generally as for basic resin. Water Immersion (6 mg in 24 hours) ·6% Resistance to Chemicals:-		
			Weight	Retention of Flexural strength
		Oil	+0.04%	101%
		Glycol	-0.03%	99%
		Acid 30% H_2SO4	+0.01%	99%

2.3.4.8 Electrical Properties of Modified Polyester Composites (ref. 3, 12, 13, 14, 15, 30)

The dielectric properties of modified polyester composites are similar to that of the unmodified. Typically a laminate with 35% resin and E glass the dielectric constant is near 4.2 and loss near 0.013 at room temperature and 10GHz, except for RP12 resin whose loss is near 0.006. Dielectric constant and loss tangent increase with temperature. The rate of change of dielectric constant being near 0.5% per 100°C (Fig. 2.3.4.9.i).

The electrical properties at room temperature of various reinforcements are as in Table 2.3.4.8.1.

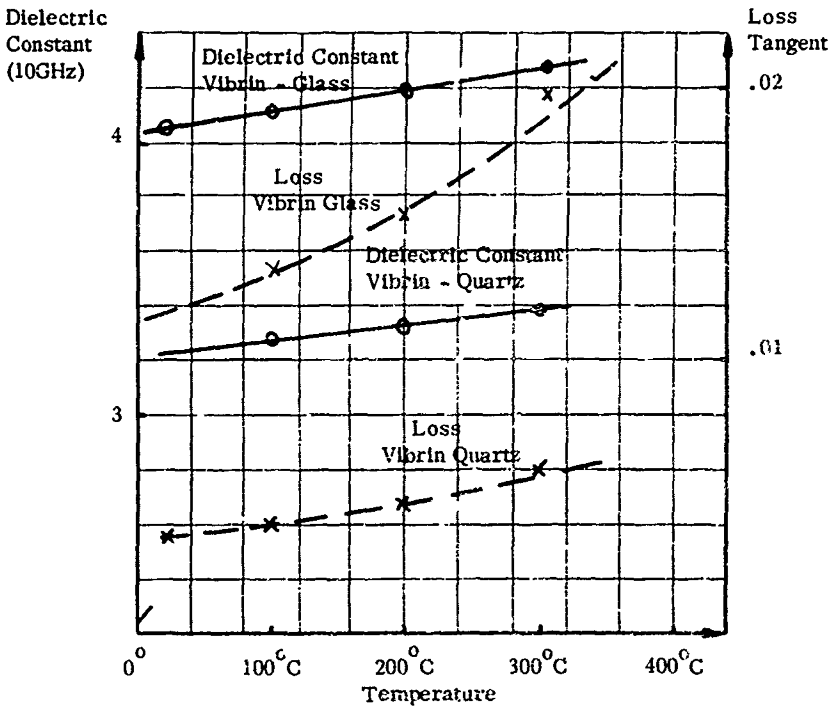
Table 2.3.4.8.1

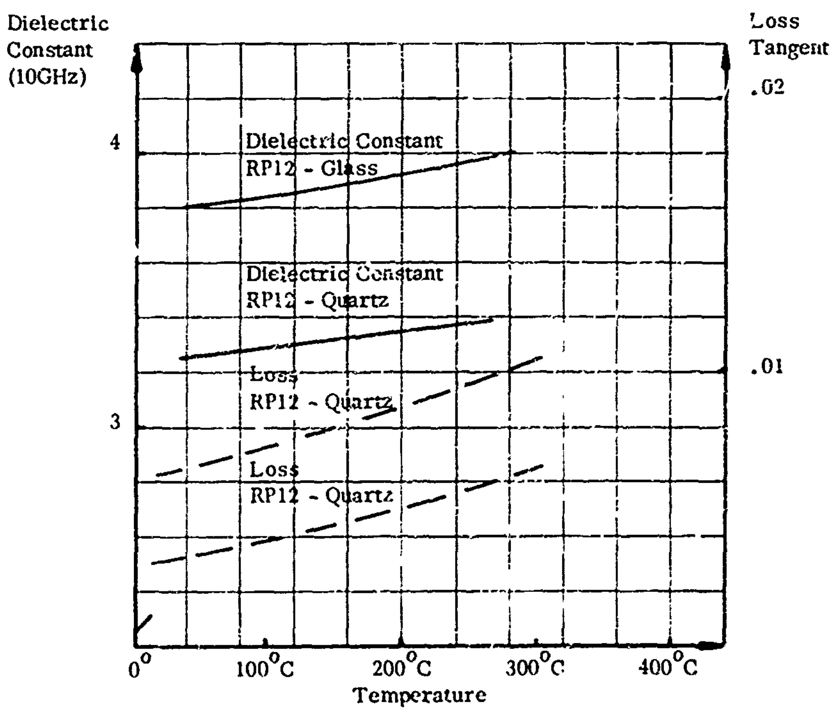
REINFORCEMENT	Resin (Modified)	% Weight Resin	Dielectric Constant	Loss Tangent
E Glass roving 30 End Filament wound	Vibrin 135	18%	4.93	0.012
S 994 Glass Filament wound	Vibrin 135	20.4	4.19	0.014
E Glass (Hollow) roving Filament wound	Vibrin 135	21.4	4.02	0.011
E Glass 181 Fabric	Vibrin 135	30.5	4.23	0.014
D556 Glass roving Filament wound	Vibrin 135	25	3.4	0.008
40 Ply 181 Garan E Glass	Vibrin 136A	37	4.2	0.015
12 Ply 181-114 Glass Fabric	Vibrin 135	36	4	0.015
E Glass Twill	Vibrin 135	33	3.76	0.02
D Glass Twill	Vibrin 135	39	2.92	0.017
E Glass Fabric	RP 12	35	4.2	0.006
Quartz Fabric	RP 12	35	3.1	0.003

The electrical properties are summarised as follows:-

Table 2.3.4.8.2

PROPERTY	Figure REFERENCE	REMARKS
Dielectric Constant v. Reinforcement	Figure 2.3.4.4.1	Calculated for E Glass Laminates at 10GHz
Dielectric Constant and Loss Tangent v. Temperature	Figure 2.3.4.8.1	33% resin dielectric constant increases 0.5% per 100°C RP12 resin has low loss only 0.007 at 200°C
Volume Resistivity	-	9.8×10^{14} ohm cm (12 ply 181-114 Fabric)
Dielectric Strength		11 kV/mm (12 ply 181-114 Fabric)





Dielectric Constant & Loss Tangent v Temperature of Modified Polyesters Vibrin & RP12 Composites

FIG. 2.3.4.8.1

2.3.4.9 Mechanical Properties of Polyester (Modified) Composite (ref. 12, 13, 14, 15, 30)

The main purpose of modifying polyester was to improve its temperature range. This has accomplished significantly with Vibrin and RP 12 commercial polyesters.

Typical Strength Figures for modified polyesters are:-

Table 2.3.4.9.1

	131 E GLASS FABRIC VIBRIN 135 (30%)	181-114 GLASS CLOTH VIBRIN 135 (38%)	E GLASS TWILL VIBRIN 135 (33%)	E GLASS CLOTH RP12 (35%)	D GLASS TWILL VIBRIN 135 (39%)	PRD 49 III RP12 (38%)
TENSILE STRENGTH	380 MN/m^2	350 MN/m^2	262 MN/m^2	250 MN/m^2	95 MN/m^2	600 MN/m^2
COMPRESSIVE STRENGTH	345 MN/m^2	350 MN/m^2	203 MN/m^2	-	-	-
FLEXURAL STRENGTH	465 MN/m^2	460 MN/m^2	283 MN/m^2	300 MN/m^2	141 MN/m^2	305 MN/m^2
FLEXURAL MODULUS	24.2 GN/m^2	22 GN/m^2	19.3 GN/m^2	17 GN/m^2	131 GN/m^2	19 GN/m^2

The improvement in temperature characteristic for the mechanical properties is indicated in Figure 2.3.4.9.1 where a typical Vibrin 135 laminate maintains a flexural strength of 300 MN/m^2 at 150°C and can withstand a short period at 260°C before gradually losing strength. In Figure 2.3.4.9.2 the flexural strength performance of Vibrin 136A is shown with a 38% resin content where at room temperature its flexural strength of near 465 MN/m^2 decreases to 310 at 260°C and 150 at 315°C and 75 MN/m^2 at 370°C. In Figure 2.3.4.9.3 is shown the Flexural modulus against time and temperature for Vibrin 135, where the importance of post cure is illustrated.

The change of mechanical properties due to heat and also to 30 day water immersion are, typically with Vibrin 136A, and 12 Ply 181 Garan, as follows:- Table 2.3.4.9.2.

Table 2.3.4.9.2 Strength of Modified Polyester - Glass Composite

	Room Temperature	½ Hour at 260°C	30 Day Water Immersion
Tensile Strength MN/m^2	345-413	241-310	310-379
Compressive Strength MN/m^2	310-379	172-241	276-345
Flexural Strength MN/m^2	450-483	240-310	413-450
Flexural Modulus GN/m^2	21.4-27	16.5-18.6	-

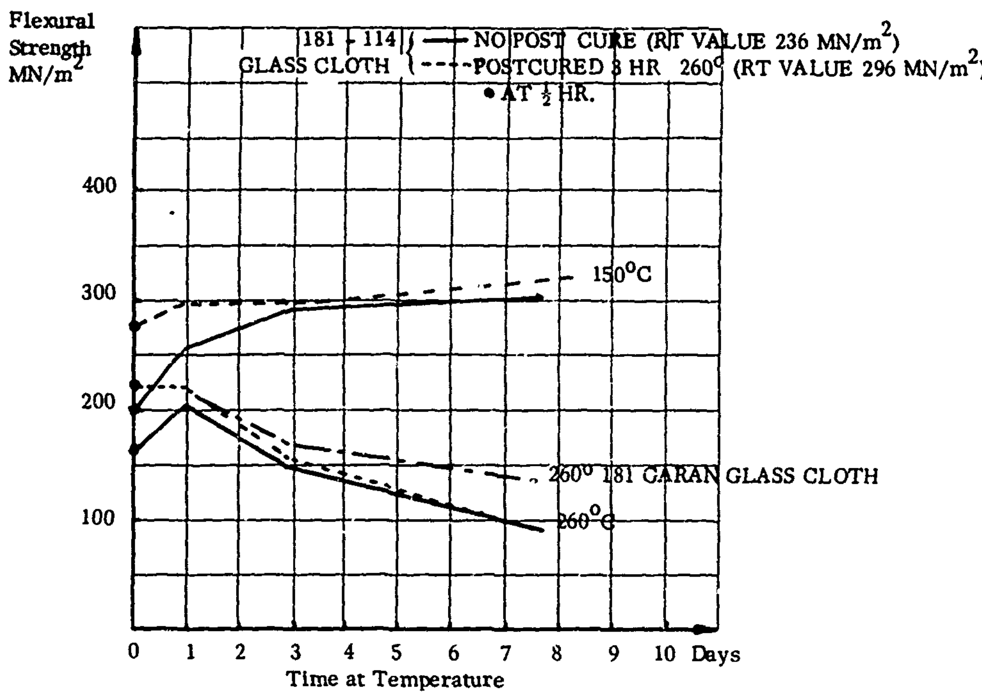
A summary of the mechanical properties is shown in the following table: Table 2. 3. 4. 9. 3.

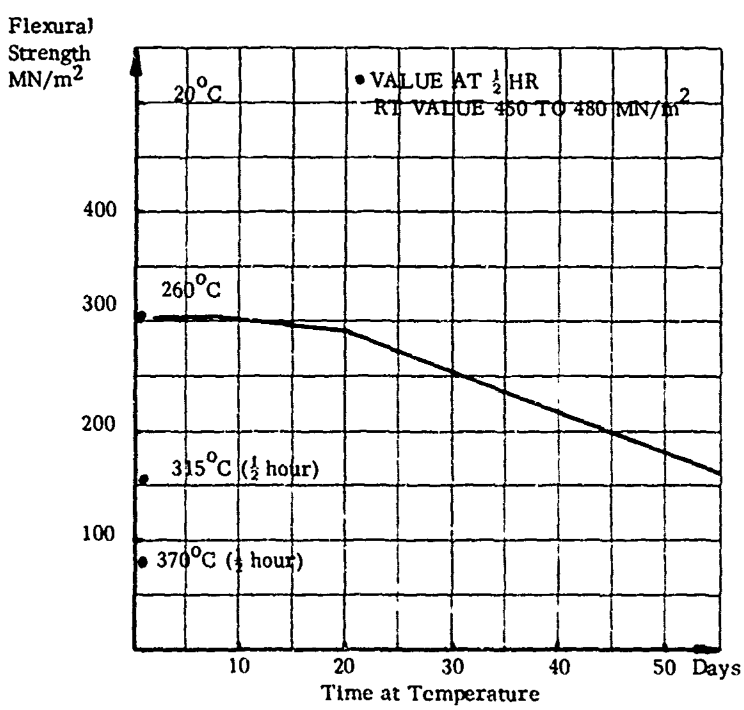
Table 2. 3. 4. 9. 3

Mechanical Properties	Figure / Table Reference	Remarks: Typical Values: Room Temperature (E glass fabric-Vibrin 135)
Tensile Strength	Table 2. 3. 4. 9. 1	380 MN/m^2
Compressive Strength	Table 2. 3. 4. 9. 1	345 MN/m^2
Flexural Strength	Table 2. 3. 4. 9. 1	465 MN/m^2
Flexural Modulus	Table 2. 3. 4. 9. 1	24. 2 GN/m^2
Impact Strength		2. 76kgm/2. 54cm.
Hardness		L-122 M-119 ROCKWELL
Flexural Strength v. Temperature & Time	Figures 2. 3. 4. 9. 1 and 2. 3. 4. 9. 2	300 MN/m^2 @ 150°C long term 150 MN/m^2 @ 260°C 6 days 150 MN/m^2 @ 260°C 60 days (Vibrin 136A)
Flexural Modulus v. Temperature & Time	Figure 2. 3. 4. 9. 3	18 GN/m^2 @ 150°C 8 days 12 GN/m^2 @ 260°C 8 days

Flexural Strength v Time and Temperature
Vibrin 135 & 181 - Glass Cloth

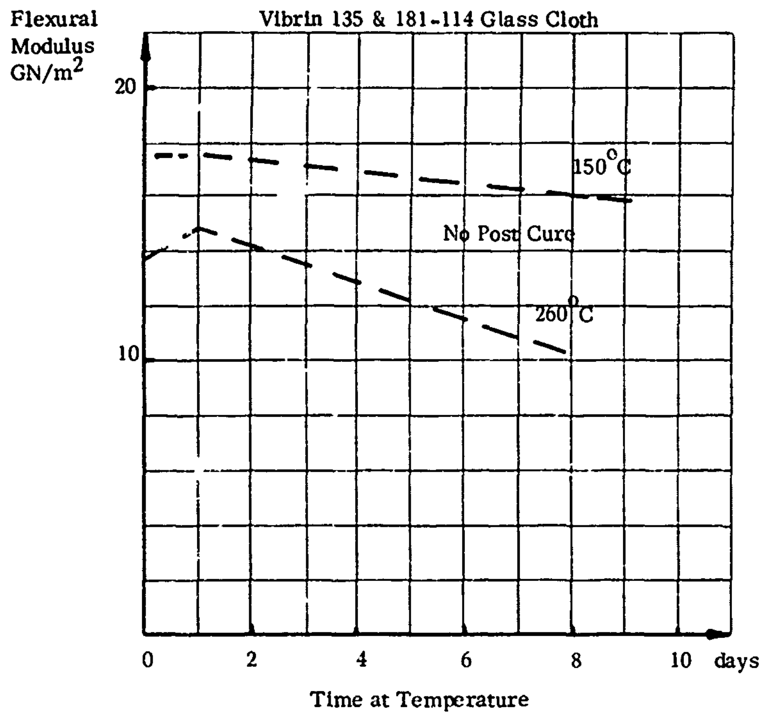
FIG. 2.3.4.9.1

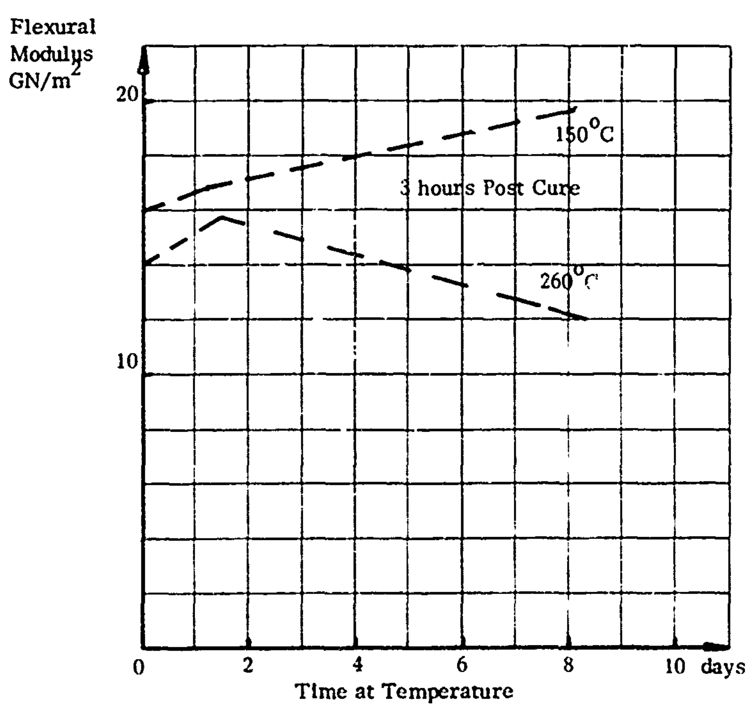




(38% Vibrin 136A & 12 PLY 181 GARAN)
Flexural Strength v Time and Temperature

FIG. 2.3.4.9.2





Flexural Modulus v Time & Temperature & Cure of Vibrin 135 - Glass Cloth Composite

FIG. 2.3.4.9.3

2.3.4.10 Thermal Properties of Polyester (Modified) Composite (ref. 12, 13, 14, 30)

Whereas the unmodified polyester was rated as 120°C long term 150°C limited term, there is a marked extension in rating for some modified polyesters. Typical of Vibrin 135 and 136A are long term 150°C to 230°C and 230°C to 370°C short term according to the manufacture and materials used. RP12 (Plessey) resin is typically 200°C long term and 280°C short term.

The change in dielectric constant and loss tangent was illustrated in 2.3.4.8.1 with temperature increase and the change in mechanical properties were similarly shown in Figure 2.3.4.9.1.

The properties of expansion, specific heat, conductivity, are similar to the summary of thermal properties of the unmodified resin as given in 2.3.4.6. The composite can survive severe thermal shock.

2.3.4.11 Environmental Properties of Polyester (Modified) Composite

The composite has the same properties as the unmodified composite (2.3.4.7) apart from its much improved temperature rating of safe 200°C long term and considerably higher short term.

2.3.5 EPOXY RESINS AND COMPOSITES (ref. 1,2,11,12,26)

A very wide range of epoxy materials is available and can be made into composites with a large range of reinforcement materials. They with polyesters, are foremost as candidate materials for radomes since they combine high mechanical strength with good electrical properties and chemical resistance, and their use in manufacture is well established.

The specification of epoxy composites is given in Mil R 9300, with particular reference to glass reinforcements.

Because a very wide range of epoxy materials is available a typical selection is necessary in this report.

The properties given here are typical of resins such as CIBA MY720 and SHELL 828. Where significant differences arise the fact is noted, and where, to provide information, other products must be considered the name of the product is given.

Mainly properties with NMA hardeners are given since these give excellent mechanical properties at elevated temperatures, have good weathering properties and are amenable to both fabric and filament wound constructions having low viscosity combined with good pot life. Where necessary however, other hardeners are included in order to provide information which is typical of other types but unavailable for them.

2.3.5.1 Chemical Description of Epoxy Resins

These resins contain reactive epoxide groups in which an oxygen atom is attached to two adjacent carbon atoms in the polymer chain, thus forming a three-membered oxide ring.

Polymerisation is effected through these epoxide groups using a cross-linking agent (usually referred to as the hardener) to form a tough, three-dimensional network. Curing is achieved without by-products, which leads to a dense, non-porous material and low shrinkage on cure. It is in this cured form, all the epoxide groups having reacted, that the resins are always used.

Early resin systems based upon the reaction of bisphenol-A and epichlorohydrin are still widely used, although other types have become available with improved properties. Among these are the epoxidised novolaks for higher temperature applications and cycloaliphatics for improved electrical performance.

Of the many curing agents which may be used, those which have found most application to radomes are the acid anhydrides, primary amines and boron trifluoride complexes with amines and ethers (Lewis acid catalysts).

Nadic methyl anhydride (NMA) as a curing agent mixes with liquid epoxies to produce a low-viscosity, long pot-life system, which has found considerable application in resin injection and filament winding.

More widely used are the aromatic amines, such as meta-phenylenediamine (MPD), 4,4'-diamino-diphenylmethane (DDM) and 4,4'-diamino-diphensylsulphone (DDS). MPD in particular provides a resin system with a viscosity suited to vacuum bag laminating and has an adequate pot life at room temperature. Mechanical and processing properties are good but dielectric properties vary considerably with temperature.

2.3.5.2 Properties of Epoxy Resin (ref. 3, 16, 17, 18, 19, 20)

Generally, these resins are superior to the conventional polyesters in some characteristics i.e. mechanical properties, toughness, low shrinkage on cure and good wetting and consequent good adhesion to many substrates. Mechanical and processing properties are good but dielectric properties vary considerably with temperature.

Of particular interest to pre-preg materials, where shelf life is a major consideration, are the Lewis acid catalysts. These show little or no activity at room temperature but at elevated temperature they act as catalysts which do not become part of the cured system. They are believed to attack the epoxide groups, with the formation of free radicals which then undergo polymerisation.

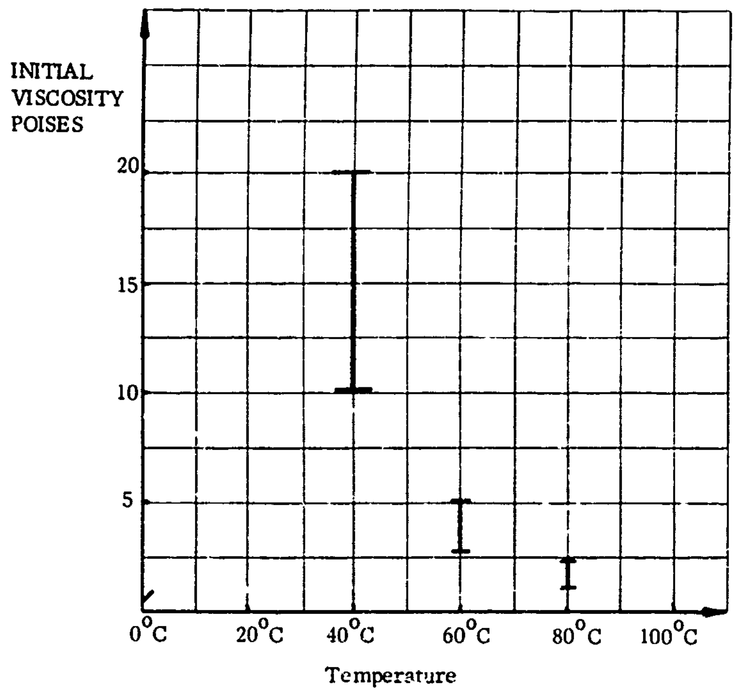
A summary of Epoxy-NMA resin characteristics is shown in Table 2.3.5.2.1.

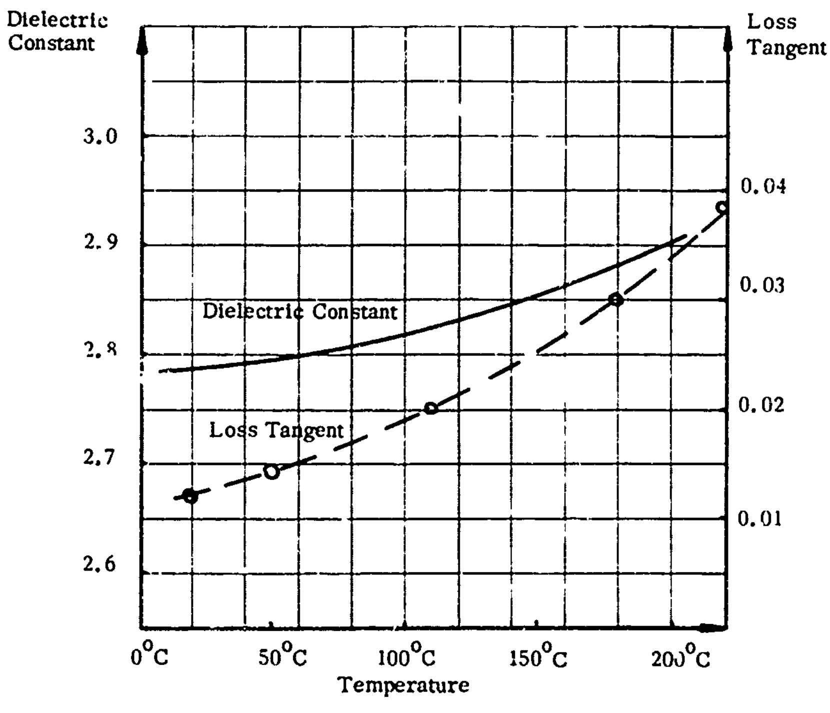
Table 2.3.5.2.1 Epoxy-NMA Resin Characteristics

Physical	Colour	Pale Liquid
	Viscosity	Adjustable: According to Proportion Curing agent and temperature. Typically less than 5 poises for filament winding and 15 for laminating (Fig. 2.3.5.2.1)
	Specific Gravity	1.20-1.22
	Expansion Coeff	$54 \times 10^{-6}/^{\circ}C$
	Water Absorption	30-40 mg (24 hours at 25°C)
	Storage	Resin 6 months in cool: kept well clear of hardener 12 months in cool.
Electrical	Dielectric Constant	2.78 (10GHz) (Fig. 2.3.5.2.2)
	Loss Tangent	0.012 (10GHz) (Fig. 2.3.5.2.2)
	Volume Resistivity	$+10^{15}$ ohms
	Dielectric Strength	10.5-11.5 kV/mm
Thermal	Heat Distortion Point	180-200°C (generally) 260° (special long cure)
	Heat: Weight Loss	0.6% at 200°C 200 hours (EPON 1310)
	Thermal Conductivity	5×10^{-4} cals/sec/cm/°C
Curing	Gel and Cure Times	Without accelerator: Gel 2 hr at 100°C; 1 hr at 120°C; Cure 8 hr at 160°C; [illegible] hr at 180°C With accelerator: ½ hr at 100°C; ⅓ hr at 120°C; 5 hr at 160°C; 2 hr at 120°C
Chemical and Solvent Resistance	Oil, Gasoline	Unaffected
	Organic Solvents	Good: but paint stripper, phenolic, and chlorinated compounds to be avoided.
	Inorganic Compounds	Good resistance for acids and alkalis up to 30% concentration, (generally better than polyesters to alkalis).

Initial Viscosity v Temperature
Epoxy - NMA Resin

FIG. 2.3.5.2.1





Dielectric Constant & Loss Tangent v Temperature
Epoxy - NMA Resin

FIG. 2.3.5.2.2

2.3.5.3 Electrical Properties of Epoxy Composites (ref. 3,9,11,12,25,26,30)

The dielectric constant of the composite depends on that of the resin (near 2.78 at 10GHz room temperature) and that of the reinforcement and the ratio of the resin to reinforcement present and is similar to that of polyester (Fig. 2.3.4.4.1). The loss tangent of the resin (near 0.012 at 10GHz room temperature) results in composite loss tangents according to the loss tangent of the reinforcement and percentage of resin.

Typical dielectric properties for various reinforcements, at room temperature and 10GHz are given in Table 2.3.5.3.1.

Table 2.3.5.3.1

Reinforcement	Resin	% Resin by Weight	Dielectric Constant	Loss Tangent
E Glass Roving 30 End Filament Wound	Epon 828 MMA/BMDA	18.9%	4.55	0.02
E Glass 181 Fabric	Epon 828/MPDA	38.2%	4.3	0.02
E Glass Fabric 227/T5	Epitoke 828 MNA/BDMA	30%	4.16	0.012
D Glass 556 Fabric	Epon 828	28%	3.52	0.011
Quartz Cloth 581/Volan	Epikote 828 MNA/BDMA	30%	3.32	0.07
PRD 49 III	Epoxy 828 MNA/BDMA	45%	3.18	0.012

Over the microwave band the dielectric constant of epoxy composites remains near constant but there is a general increase in loss tangent rising to 0.018 at Ka band (35GHz).

The dielectric constant and loss tangent increase with water absorption, which should be small for well made laminates (0.5% increase in weight after 30 days at 98% Relative Humidity at 40°C).

Voids are undesirable as they can lower the dielectric constant, similar to that for the polyester as shown in Figure 2.3.4.4.2, and can increase inhomogeneity in dielectric constant.

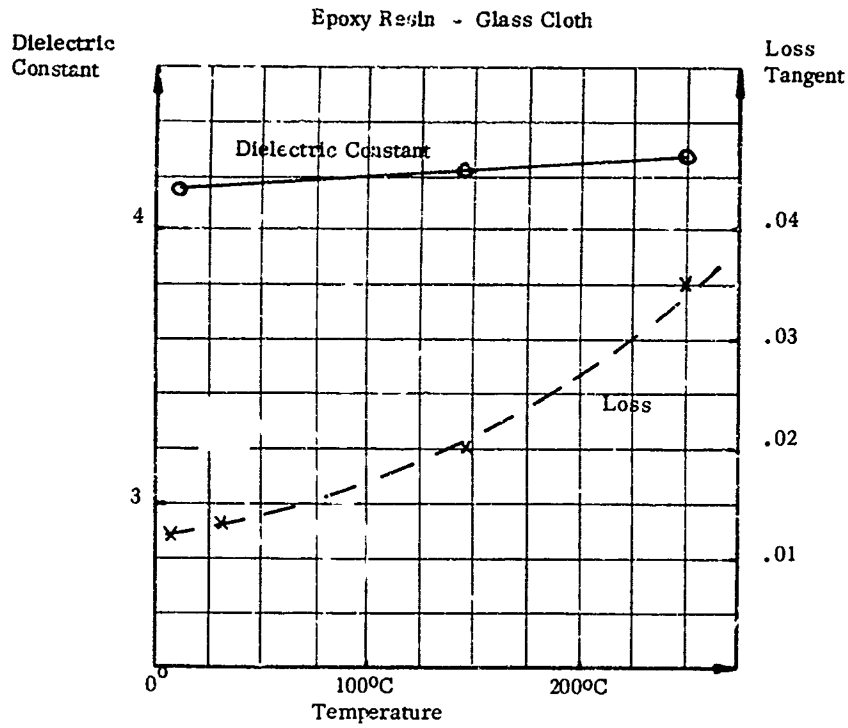
The loss tangent is similar to that of polyester composite, usually about 0.015 at room temperature and 10GHz, with glass reinforcement and 0.007 with quartz.

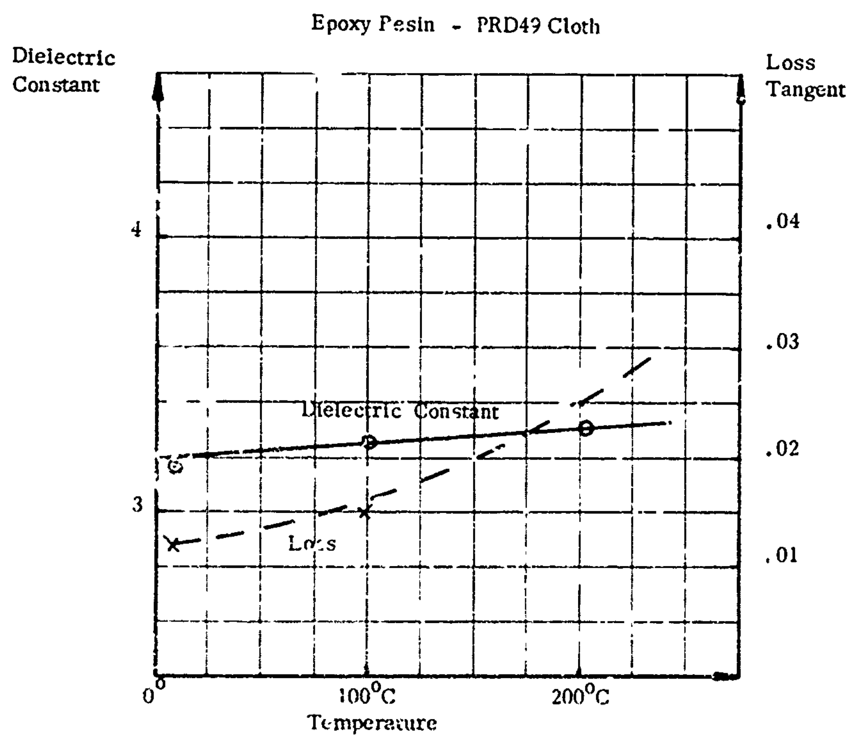
Both dielectric constant and loss tangent increase with temperature as shown in Figure 2.3.5.3.1. The change of dielectric constant with temperature (2% per 100°C) is greater than with polyester and can be significant if the radome has to operate over a wide temperature range and is sensitive to dielectric constant. The loss tangent increases from about 0.015 to near 0.03 at its higher operational temperature.

A summary of electrical properties is given in Table 2.3.5.3.2.

Table 2.3.5.3.2.

Property	Figure/Table Reference	Remarks
Dielectric Constant and Loss Tangent v Reinforcement Type	Table 2.3.5.3.1	Dielectric Constant varies from 3 to 5 according to materials. Loss tangent near 0.01
Dielectric Constant and Loss Tangent v Reinforcement	Figure 2.3.4.4.1	Dielectric Constant decreases with increase of resin constant. Similar to polyester composite.
Dielectric Constant and Loss Tangent v Voids	Figure 2.3.4.4.2	Dielectric Constant decreases with increased voids, as polyester composite.
Dielectric Constant and Loss Tangent v Frequency		Little change with dielectric constant over microwavelength band. Loss tangent increases towards 356GHz.
Dielectric Constant and Loss Tangent v Temperature	Figure 2.3.5.3.1	2% rise in dielectric constant per 100 ^{o}C. Loss tangent near 0.03 at 200 ^{o}C.
Dielectric Constant and Loss Tangent v Humidity		Dielectric constant and Loss Tangent increases with humidity pick up
Volume Resistivity		Above 10^{13} at room temperature
Dielectric Strength		Above 6kV/mm (BS 3953) usually near 10kV/mm.





Dielectric Constant & Loss Tangent v Temperature of Epoxy Resin - Composites

FIG. 2.3.5.3.1

2.3.5.4 Mechanical Properties of Epoxy Composites (ref. 1, 2, 9, 12, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26)

The mechanical properties vary according to resin content, type of reinforcement and manufacturing method. Low reinforcement content usually results in lower strength but not always in lower stiffness due to electrical constraints upon thickness.

The specification requirements for strength of epoxy composites calls for:- Table 2.3.5.4.1.

Table 2.3.5.4.1

Specification Mil 5 9300	Tensile Strength	Compressive Strength	Flexural Strength	Flexural Modulus
Room Temperature	330 MN/m^2	344 MN/m^2	517 MN/m^2	22 GN/m^2
$\frac{1}{2}$ hr. at 294°C	308 MN/m^2	67 MN/m^2	173 MN/m^2	13.8 GN/m^2

Typical results of epoxy composites with various reinforcements are shown in Table 2.3.5.4.2.

Table 2.3.5.4.2

Composite & % Resin	Tensile Strength MN/m^2	Compressive Strength MN/m^2	Flexural Strength MN/m^2	Flexural Modulus GN/m^2	Youngs Modulus GN/m^2	Inter-Laminar Shear MN/m^2
181 E Glass Fabric Epon 828 (32%)	480	485	630	232		
Eltrex Pre Preg EHG 250-65-50 (37%)	365	380	550	22.7		
U.S. Polymeric E 720E/7781 (35%)	338 to 416	346 to 447	632	22.1	19.4 to 21.5	41
Hexcel F161/7743 (550) (32.4%)	55 to 460	222 to 523	1100	35.7	11.9 to 36.5	64.5
E Glass Cloth BS3396 CIBA MY/720/HY/906	390	390	500	22	24	47
D556 Glass HTS 150 EPON 828 (34%)	242	364			18	25
PRD49 III Epoxy NMA CIBA MY/720/HY, 906 (35%)	608		258	20.1	35.9	15

The effect of temperature is shown in Figure 2.3.5.4.1 where the percentage of room temperature strength is shown with temperature. At 220°C the strength drops to 50%. In Figure 2.3.5.4.2 the flexural strength with ageing at temperature is shown.

In general the epoxy resin composite is superior mechanically to the conventional polyester, but is comparable with the high temperature polyesters. The working temperature depends upon manufacture techniques, reinforcement, precise resin formulation and the environment, but generally will operate at 150°C continuously, at 200°C for long term and for short term at 250°C.

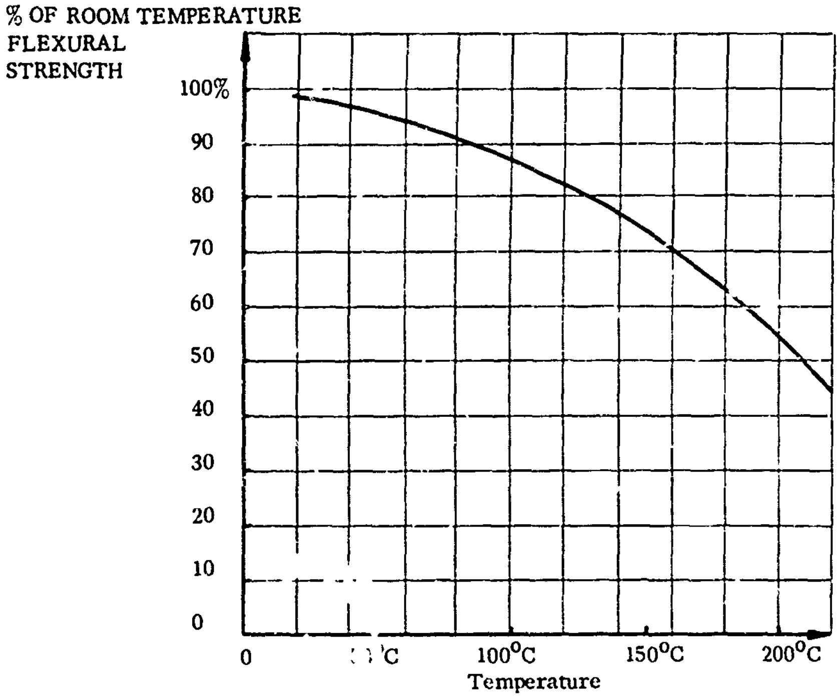
A summary of the mechanical properties of epoxy composites is shown in the table 2. 3. 5. 4. 3.

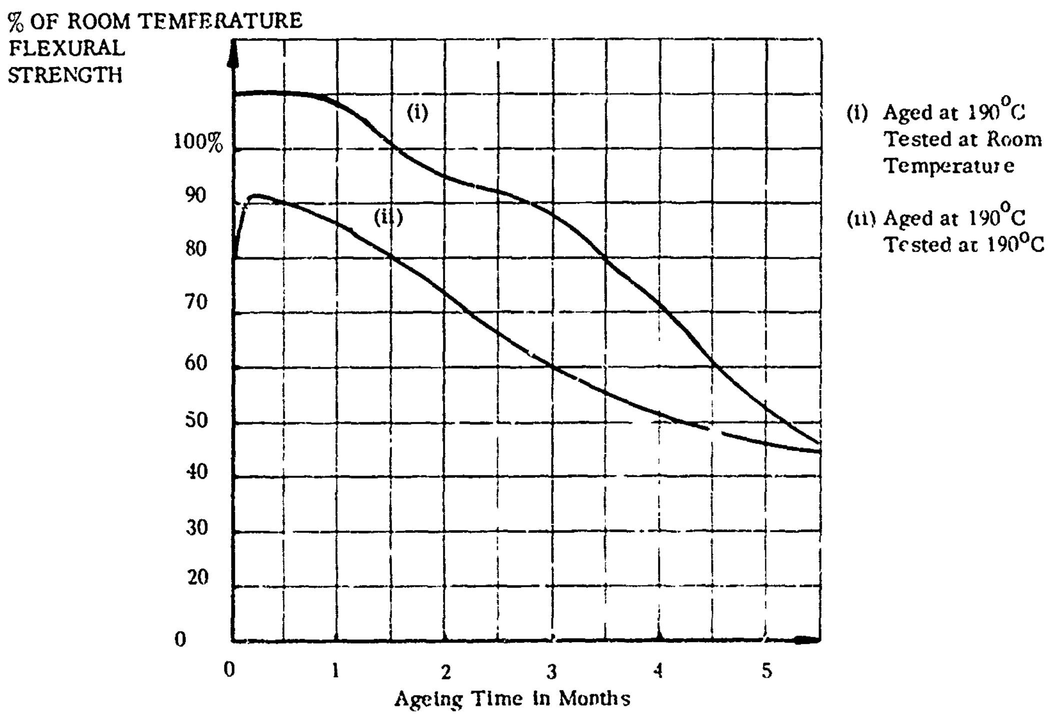
Table 2. 3. 5. 4. 3

Mechanical Property	Figure/Table Reference	Remarks: Typical Values. E Glass Fabric Laminate - NMA
Tensile Strength	Table 2. 3. 5. 4. 2	360 MN/m^2 (room temperature)
Flexural Strength	Table 2. 3. 5. 4. 2	550 MN/m^2 (room temperature)
Flexural Modulus	Table 2. 3. 5. 4. 2	22. 7 GN/m^2 (room temperature)
Porosity		Generally very small
Specific Gravity		1. 7 to 1. 9 according to resin ratio
Hardness		Near 70 Brinell
Fatigue Limit		Generally better than polyester
Flexural Strength v Temperature	Figure 2. 3. 5. 4. 1	Gradual decrease in flexural strength to 50% at 230°C
Flexural Strength v Temperature & Time	Figure 2. 3. 5. 4. 2	Gradually decrease in flexural strength to 50% at 190°C near 4 months
Compressive Strength	Table 2. 3. 5. 4. 2	380 MN/m^2 (room temperature)

Flexural Strength v Temperature
Epoxy Composite

FIG. 2.3.5.4.1





Flexural Strength v Ageing at Temperature
Epoxy Composite

FIG. 2.3.5.4.2

2.3.5.5 Thermal Properties of Epoxy Composites (ref. 2,3,11,12,17,18,19,20,24,26)

For high temperature operation epoxy resins, with, for example N.M.A. hardeners and glass reinforcements, give excellent mechanical properties. At room temperatures the flexural strength is typically 500 MN/m^2 and at 200°C is still 360 MN/m^2 which is generally stronger than similar polyester/ resin composites. At 240°C it is still near 240 MN/m^2 (Fig. 2.3.5.4.1). With P.R.D. 49 and epoxy resin, the ultimate operating temperature is somewhat lower due to the properties of P.R.D. 49.

The electrical properties, are generally worse than polyester, in that they have a loss tangent of near 0.032 at 200°C and a 2% change of dielectric constant with 100°C change, but are still acceptable for most radome applications (Fig. 2.3.5.3.1).

The thermal properties are such as to be able to survive severe thermal shock, and laminates can stand surface charring without serious mechanical strength loss and only degraded electrical performance.

The expansion coefficient is not compatible with metals and allowance in design may have to be made in some plastic and metallic constructions.

A summary of the thermal properties of Epoxy (NMA) composites is as follows:- Table 2.3.5.5.1.

Table 2.3.5.5.1

Thermal Property	Remarks
Operational range	Will depend upon manufacture technique, reinforcement, precise resin formulation and the environment. Generally will not exceed 290°C short term and 220°C long term.
Specific heat	Approximately 0.4
Conductivity	4.5 x 10^{-4} to 7 x 10^{-4} cals/sec/cm/°C for random mat and high strength laminates.
Expansion coefficient	Approx. 30 x 10^{-6}/°C random mat. Approx. 16 x 10^{-6}/°C balanced weave (0 and 90) Approx. 10 x 10^{-6}/°C (unidirectional high glass content in fibre direction)
Flammability	Not considered a fire hazard as radomes generally. Addition of retard agents reduces mechanical performance generally.
Ablation/Charring	Not usually used under these conditions, but some surface charring may be tolerable.
Thermal shock	No problem in operational temperature range.

2.3.5.6 Environmental Properties of Epoxy Composites (ref. 2, 10, 11, 12, 34)

The composites as used in radomes should withstand years of normal environmental conditions without significant changes in their properties. The life of a radome will vary according to its location on the vehicle. A nose radome would be subjected to rain erosion (particularly if not coated with a rain erosion protective coating) and to hail and bird impact.

Void free composites are important to withstand erosion and moisture pick-up.

The composite should withstand pressure differences and changes, and if protected by lightning conductors should survive the normal strike without major damage.

The composite should be negligibly affected by normal chemical and solvent materials, oils, acids, greases, detergents. Long and intense ultra violet will affect its mechanical properties, but under normal conditions for aircraft and missile applications, it should be unaffected. It can withstand high nuclear radiation (10^8 rads. no damage 10^{10} rads. slight deterioration).

The composite if substantially void and surface fibre free, absorbs water slowly and this should have only a small effect upon properties. No composite deterioration should result from icing.

Large cyclic changes in temperature may cause crazing of resin.

A summary of the environmental properties of the epoxy composite is as follows in Table 2.3.5.6.1.

Table 2.3.5.6.1

Property	Figure Reference	Remarks
Temperature	Figure 2.3.5.4.1	Some formulations. Should stand 200°C long term, more for shorter term.
Radiation Ultra-Violet		Ultra Violet resistance rated as good (10% loss of flexural strength at 2 cal/sq.cm/mm for 500 hours).
Nuclear		Nuclear: Unaffected by 10^8 rads. in air or vacuo. Some detectable changes with 10^{10} rads.
Thermal		Thermal: Surface Damage at 50 cal/sq.cm/sec. Begins to char at 100 cal/sq.cm/sec.
Rain Erosion		Can be protected by rain erosion protective coatings. If not possible to have a protective coating (due to temperature requirements) the erosion will depend on site on vehicle, surface smoothness, angle of attack laminate thickness etc.
Ageing		Indoor - no deterioration. Outdoor some surface decoloration and may in some cases craze with temperature cycles.
	Figure 2.3.5.4.2	Thermal ageing. A radome maximum operating temperature of 130°C, deterioration at 190°C.
Contamination		Very small loss in flexural strength and change in weight with immersion for 1 year at room temperature in: Hydrochloric Acid 37%; Nitric Acid 30%; Sulphuric Acid 70%; Greases; Sodium Hydroxide 50%; Oils; Benzene; Glycol Water immersion: 0.6% by weight after 24 hours immersion.

2.3.6. POLYIMIDE AND P.B.I. RESINS AND COMPOSITES (ref. 11, 12)

This relatively new resin system has outstanding electrical and mechanical performance at high temperature. Its particular significance is that its introduction extended the range of plastics applications into an area where the use of ceramics would previously have been necessary.

Application of this material for radomes has been slowed due to manufacturing problems and poor moisture absorption characteristics. These problems are, as would be expected, reducing with time and the number of applications is increasing. It is to be expected that this will be a major material for high temperature radomes of the future.

Autoclaved pre preg manufacture is common, but other techniques including filament winding are available. High temperatures and pressures are required for processing.

2.3.6.1 Chemical Description of Polyimide Resin

Polyimides are formed by the reaction of an aromatic dianhydride with an aromatic diamine. The initial reaction results in the formation of a soluble polyamic acid and it is in this form that the resins are generally supplied. Complete imidisation to an infusible, insoluble resin occurs on heating.

2.3.6.2 Properties of Polyimide Resin (ref. 12, 30)

Resulting from efforts to produce polymers of high thermal stability, the polyimide (PI) and polybenzimidazole (PBI) resin systems have emerged as the most promising for radome applications. These are examples of heterocyclic polymers which have excellent electrical properties, stable over a wide temperature range.

The mechanical properties of these resins are equivalent or superior to those of high grade epoxies at room temperature. They maintain performance to temperatures in excess of 310^{o}C for long term exposure and, in the case of PBI, to 650^{o}C short term.

Both PI and PBI resins suffer from void generation due to gaseous reaction products, with PBI being the worse of the two. Resin and processing changes are improving this situation, with reported void contents now in the region of 5%. compared with original values of 15% to 20%. PI resin systems have found more development applications and are now widely available.

Recent developments in the resins and processing techniques and attention to sealing, to eliminate difficulties associated with moisture affinity, make polyimide composites capable of meeting stringent high temperature requirements. Such developments should ensure that these materials will soon pass through their development phase into production scale use.

A summary of polyimide resin properties is in Table 2.3.6.2.1.

Table 2. 3. 6. 2. 1 Polyimide Resin Characteristics

Physical	Colour	Dark Brown Solid
	Viscosity	Solid at room temperature
	Specific Gravity	1.31
	Expansion Coeff.	18×10^{-6} °C (ASTM D 696)
	Water Absorption	Tends to be porous
Electrical	Dielectric Constant	3.2 10GHz 25°C
	Loss Tangent	0.005 10GHz 25°C
	Surface Resistivity	3×10^{15}
	Volume Resistivity	9.2×10^{15}
Thermal	Heat Distortion Point	350°C
	Heat; Weight Loss	Approximately 10% during cure. Subsequent loss negligible to about 370°C.
	Conductivity	0.00137 cal/sq. cm/sec/°C/cm
Curing	Cure Times	Typically cured for about 2 hours up to 175°C; post cured for long period with increasing temperature up to about 320°C. Schedules complex and tightly controlled for optimum properties.
Chemical and Solvent Resistance	Oils Greases	Excellent
	Detergents	Good
	Alkalis	Poor
	Mineral Acids	Dilute: Fair
Radiation Resistance	Exposure to 10^9 rads	Negligible effect

2.3.6.3 Electrical Properties of Polyimide Composites (ref. 9, 12, 27, 28, 29, 30)

The dielectric constant of the polyimide composite depends on that of the resin (near 2.7 at 10GHz) and that of the reinforcement and the ratio of resin to reinforcement present. Various combinations of reinforcement and resin are shown in table 2.3.6.3.1. giving a choice of dielectric constant from 3 to near 5.

Table 2.3.6.3.1

Reinforcement	Resin % Weight	Dielectric Constant	Loss Tangent	% Voids
E Glass 1581 Pre Preg	27%	4.4	0.01	2%
E Glass 1581	24%	4.1	0.01	-
E Glass Filament Wound	18%	4.1	0.009	-
Quartz 581	22%	3.0	0.006	4.9%
PRD49 III NR - 150	35%	3.3	0.006	-

Voids, which are difficult to prevent, in the composite can affect the dielectric constant as shown for the polyester Figure 2.3.4.4.2.

The polyimide dielectric constant does not alter significantly over the microwave band.

The dielectric constant and loss tangent of dry polyimide composites increase with temperature, as shown for various composites in Figure 2.3.6.3.1. The change in dielectric constant with temperature is relatively low. 1% per 100°C, up to 300°C, which commends its use for operation over a wide temperature range. Similarly attractive is the loss tangent which remains low.

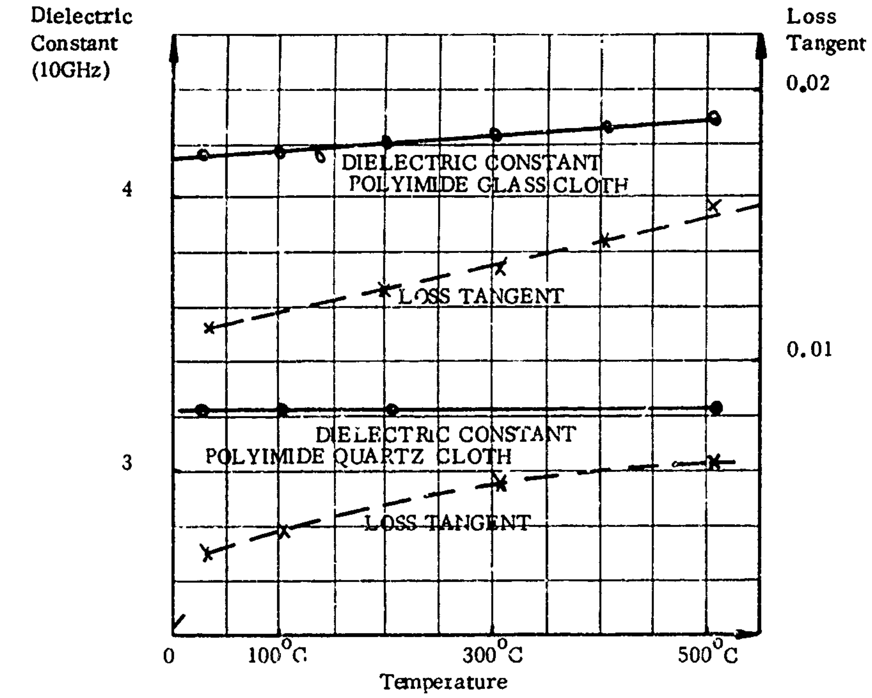
The affinity for moisture of polyimide resin can be very important even for short exposure periods. The change in the dielectric constant and loss tangent of a polyimide composite subject to humidity is shown in Figure 2.3.6.3.2. For applications subjected to moisture and where the control of dielectric constant is important, sealing of the polyimide composites is necessary.

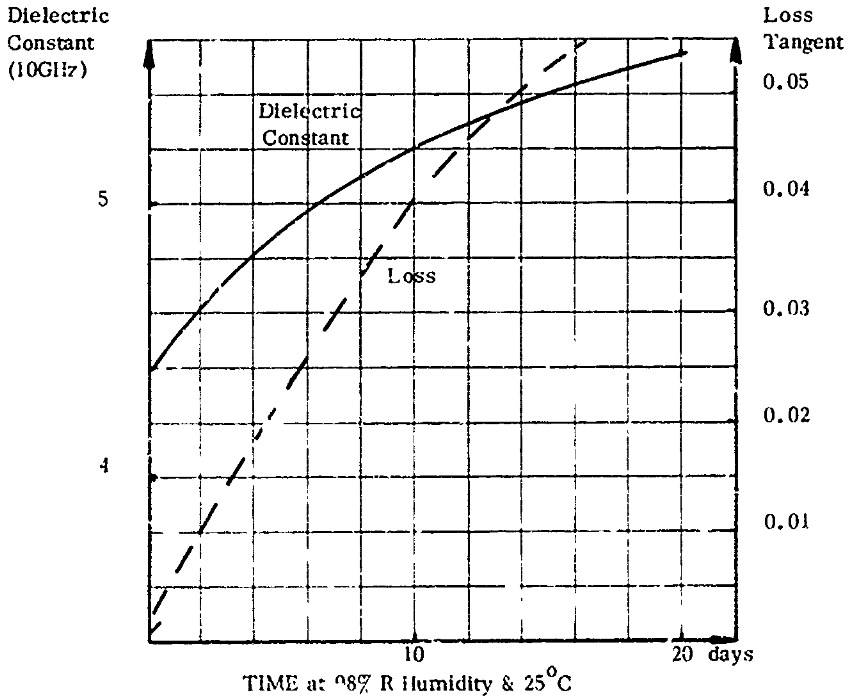
A summary of the electrical properties is as follows in Table 2.3.6.3.2.

Table 2. 3. 6. 3. 2

Electrical Property	Figure/Table Reference	Remarks
Dielectric constant and loss tangent vs reinforcement type.	Table 2. 3. 6. 3. 1	Dielectric constant varies from 3 to 5 according to materials.
Dielectric constant and loss tangent vs reinforcement .	Figure 2. 3. 4. 4. 1	Similar to polyester. Dielectric constant decreases with increases in resin constant.
Dielectric constant and loss tangent vs voids.	Figure 2. 3. 4. 4. 2	Similar to polyester. Dielectric constant decreases with voids.
Dielectric constant and loss tangent vs frequency.		Little change in microwave band.
Dielectric constant and loss tangent vs temperature.	Figure 2. 3. 6. 3. 1	Small increase in loss tangent and dielectric constant with temperature.
Dielectric constant and loss tangent vs humidity.	Figure 2. 3. 6. 3. 2	Large changes of dielectric constant and loss tangent with humidity pick up.
Volume resistivity.		When dry 10^{16} ohm/cm.
Surface resistivity.		When dry 3×10^{15} ohm/cm
Dielectric strength.		20kV/mm.

Polyimide Composites Dielectric Constant & Loss Tangent v Temperature FIG. 2.3.6.3.1





Unsealed Polyimide - Glass Cloth Composite
Dielectric Constant and Loss Tangent v Humidity FIG. 2.3.6.3.2

2.3.6.4 Mechanical Properties of Polyimide Composites (ref. 9, 12, 27, 28, 29, 30)

Polyimide polymers have been used to fabricate various, quartz, glass and PRD49 reinforcements and have mechanical properties comparable or considerably better than epoxy or polyester resin composites particularly at higher temperatures. While epoxy composites start to lose strength above 200°C, polyimide composites extend their strength to over 300°C and can be used for long periods at these temperatures, and higher for short periods.

Typical results of polyimide composites with various reinforcements are, at room temperatures, similar to epoxy composites. Table 2.3.6.4.1.

Table 2.3.6.4.1

	E Glass Fabric	Quartz Cloth	PRD49 III Fabric
Tensile Strength	200 MN/m^2	200 MN/m^2	350 MN/m^2
Compressive Strength	190 MN/m^2	180 MN/m^2	180 MN/m^2
Flexural Strength	360 MN/m^2	300 MN/m^2	280 MN/m^2
Flexural Modulus	23 GN/m^2	17 GN/m^2	22 GN/m^2

The effect of temperature is shown in Figure 2.3.6.4.1 on the mechanical properties of a polyimide E glass fabric composite. The reduction in strength at 300°C is near 20%.

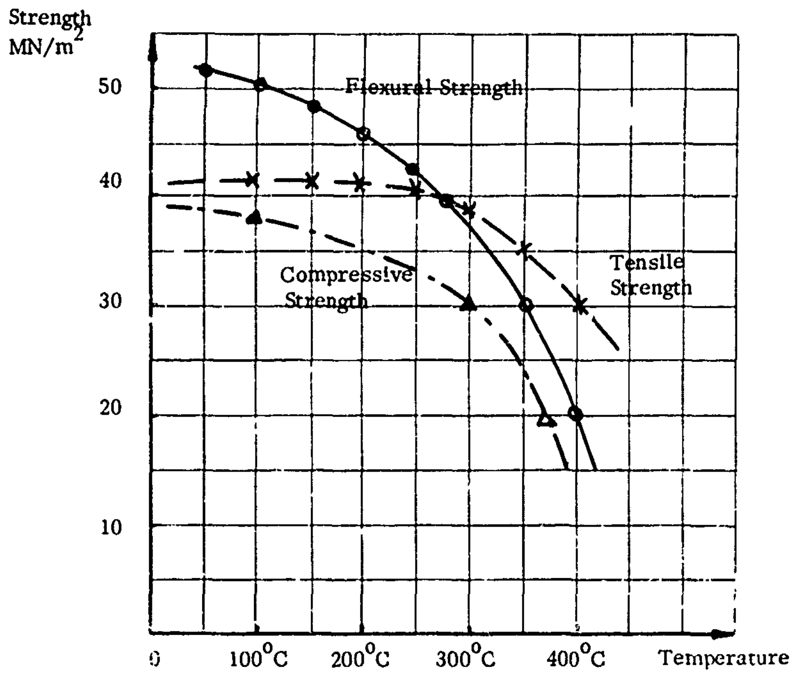
Void content, which at best is usually near 5% and often considerably higher, does not have a serious effect on mechanical strength.

The mechanical properties of polyimide composites are summarised in the following Table 2.3.6.4.2.

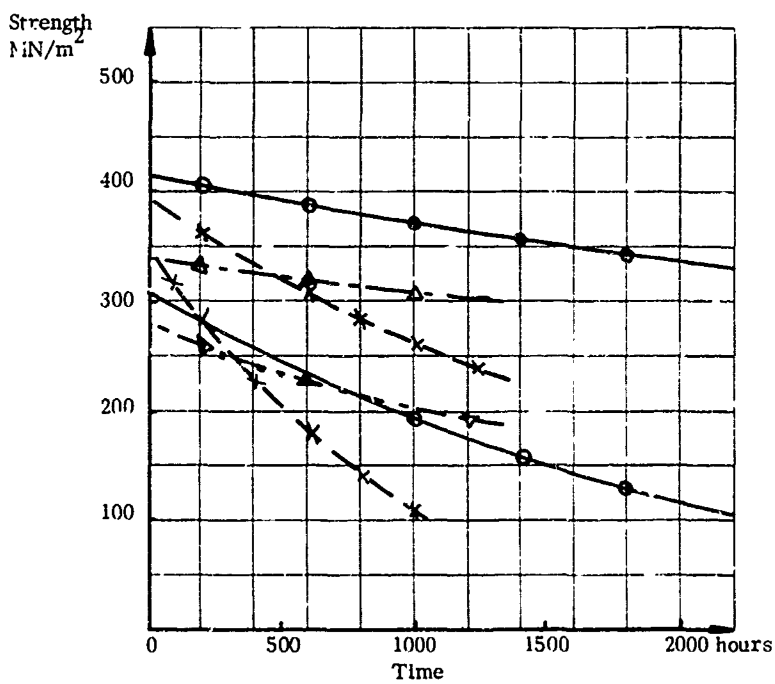
Table 2.3.6.4.2

Property	Figure Reference	Remarks Typical Values
Porosity		Voids near 5%, but may be more according to process.
Specific Gravity		1.7 to 2.0 depending on resin composite ratio.
Tensile Strength		220 MN/m^2 with glass reinforcement.
Compressive Strength		180 MN/m^2
Flexural Strength		360 MN/m^2
Flexural Modulus		23 GN/m^2
Strength v Temperature v Time	Fig. 2.3.6.4.1 Fig. 2.3.6.4.2 Fig. 2.3.6.4.3 Fig. 2.3.6.4.4	181 E Glass Fabric 24% resin (Low pressure moulding)

Strength v Temperature ½ hour Soak Conditions FIG. 2.3.6.4.1
Polyimide Composite (E Glass Cloth)



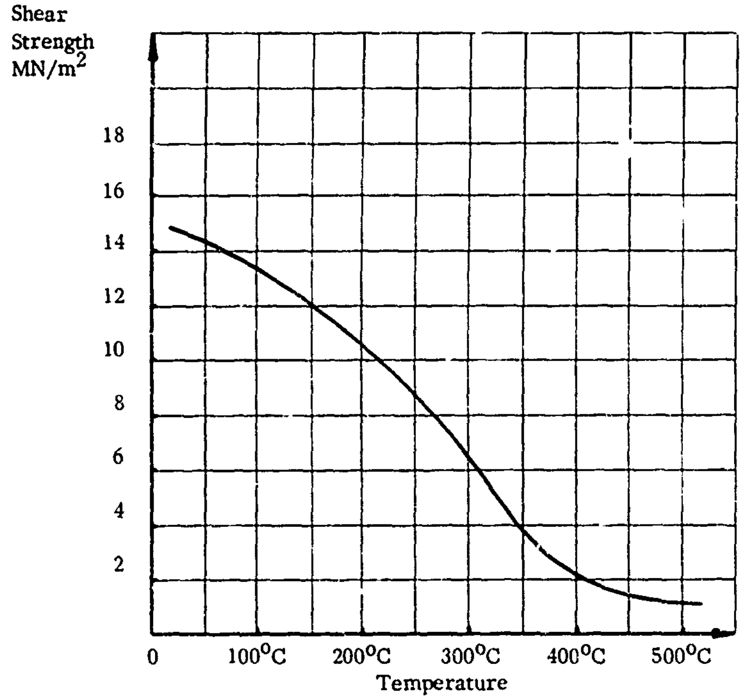
Room Temperature Strength :- Compressive 358 MN/m²
Tensile 407 MN/m²
Flexural 516 MN/m²

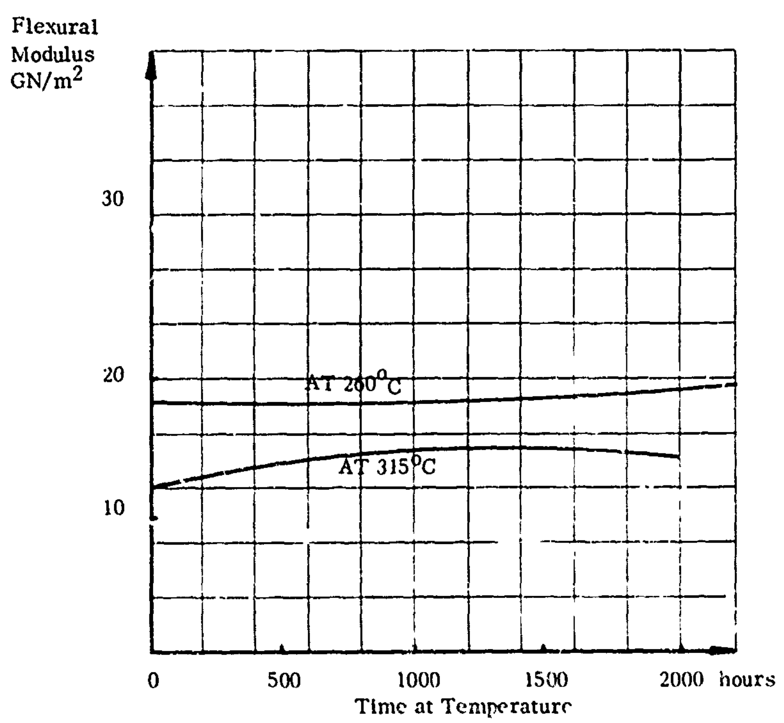


Strength v Ageing Time at Temperature (260°C & 315°C) FIG. 2.3.6.4.2
Polyimide Composite (E Glass Cloth)

Inter laminar Shear Strength (Restrained) v Temperature

FIG. 2.3.6.4.3





Flexural Modulus v Ageing Time at Temperature

FIG. 2.3.6.4.4

2.3.6.5 Thermal Properties of Polyimide Composites (ref. 12, 27, 28, 29, 30)

The thermal properties of polyimide are such as to enable composites, provided that they have suitable reinforcement materials, to operate at high temperatures. Above 450°C the effect of heat increases resin loss.

The dielectric constant and loss tangent change with temperature is shown in Figure 2.3.6.3.1. Mechanical property variations with temperature are shown in Figures 2.3.6.4.1 to 2.3.6.4.5.

Polyimide laminates are able to survive severe thermal shock.

A summary of the thermal properties of polyimide composites is given in the following table 2.3.6.5.1.

Table 2.3.6.5.1.

Property	Figure Reference	Remarks
Operational range		Long term 340°C, short term 500°C.
Specific Heat		- - - - - - - - - -
Thermal conductivity		20 J/m^2 °C
Coeff. Linear Thermal Expansion		12.8×10^{-6}/°C
Flammability		Not regarded as a fire risk as a radome
Thermal shock		Can withstand severe thermal shock
Thermal Mechanical Effects	Figure 2.3.6.4.1 - 5	Up to 200°C little change in mechanical properties. 20% decrease in strength near 300°C.
Thermal Electrical Effects	Figure 2.3.6.3.1	Dielectric constant and Loss Tangent show a small rise with temperature and is superior to polyester or epoxy resins.

2.3.6.6 Environment Properties of Polyimide Composites (ref. 11, 12, 30)

Polyimides are suitable for temperatures where epoxy and polyesters would fail and can give long service in environments of 350°C and short service at 500°C.

Humid environments result in considerable water pick up which can give large changes in dielectric constant and loss tangent, but have only a small effect on mechanical strength. In such environments sealing of the resin surface is likely to be necessary. Resistance to rain erosion, particularly if the composite has voids, is not good being of a similar order to polyesters and epoxies. Protection coating would normally be considered.

U.V. radiation environmental effects have little effect on polyimides, and they have excellent retention of physical properties after exposure to 10^9 rads from a cobalt 60 gamma source.

Resistance to dilute acids, organic solvents, esters, alcohols, hydraulic fluids and jet fuels is good. Strong alkalis can affect polyimides composites adversely.

Percentage Retention of Room Temperature Properties After Seven Days Exposure:-

Material	Flex Modulus	Flex Strength
Water Boiling	103%	112%
10% Nitic Acid	94%	80%
100% Carbon Tetrachloride	92%	76%
10% Ammonium Hydroxide	81%	77%
Jet Engine Fuel	95%	90%

The Environmental Properties of Polyimide Composites are summarised in the following table 2.3.6.6.1.

Table 2.3.6.6.1

Environmental Properties	Remarks
Thermal	350°C long service 500°C short service
Radiation	Ultra violet has negligible effect. Nuclear: 10^9 rads. safe. Thermal: can stand severe shock.
Humidity	5% water pick up, causing large electrical property changes but relatively little mechanical changes.
Rain erosion	Relatively poor.
Weathering	Can stand long term weathering but picks up moisture, with electrical degradation.
Chemical contamination	Dilute acids, fuels, greases, water little effect on strength. Strong alkalis reduce strength.

2.3.7 SILICONE RESINS AND COMPOSITES (ref. 12, 26, 30)

Glass and Quartz reinforcements filament wound and fabric radomes have been built with silicone resins for applications where operational temperatures near 300°C were required (which could not be met by polyester or epoxy). The designer now has an alternative in polyimide which has higher temperature and strength capabilities. Silicone composites have very good electrical characteristics but can suffer from moisture pick up when low pressure manufacture is used. The mechanical strength is relatively poor when compared with epoxy, polyester and polyimide. The properties depend very much on the manufacturing process with best results being obtained using hot processing with pressures above $28kg/cm^2$. The cost of manufacture can be high for a good void free radome particularly if it is large. Tooling is also expensive for high pressure moulding.

Requirements for silicones are given in Mil-R-25506.

2.3.7.1 Chemical Description of Silicone Resin

In silicone resins, chain growth and cross-linking reactions take place through the siloxane linkage, giving a polymeric structure containing alternate silicon and oxygen atoms.

Laminating resins are synthesised from a mixture of monomers and contain both methyl and phenyl groups attached to the silicon.

Resin is supplied in partially reacted form as a solution in toluene, which is suitable for preimpregnation and dries to a tack-free solid.

The curing process is a condensation reaction resulting in the formation of water as a by-product. Typical catalysts are amines and organometallic salts.

2.3.7.2 Electrical Properties of Silicone Composites (ref. 30, 31)

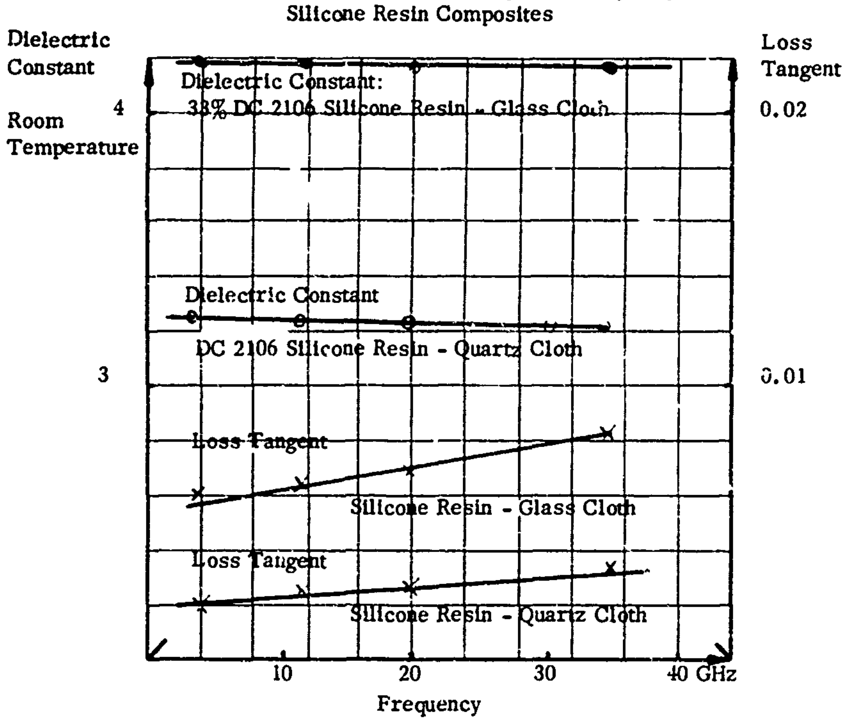
Silicone resin composites can have very low loss, particularly with quartz reinforcements, and a stable dielectric constant with temperature. Electrical properties are summarised in Table 2.3.7.2.1 and in Figure 2.3.7.2.1-3 where dielectric constant and loss tangent changes with frequency, temperature and humidity are given.

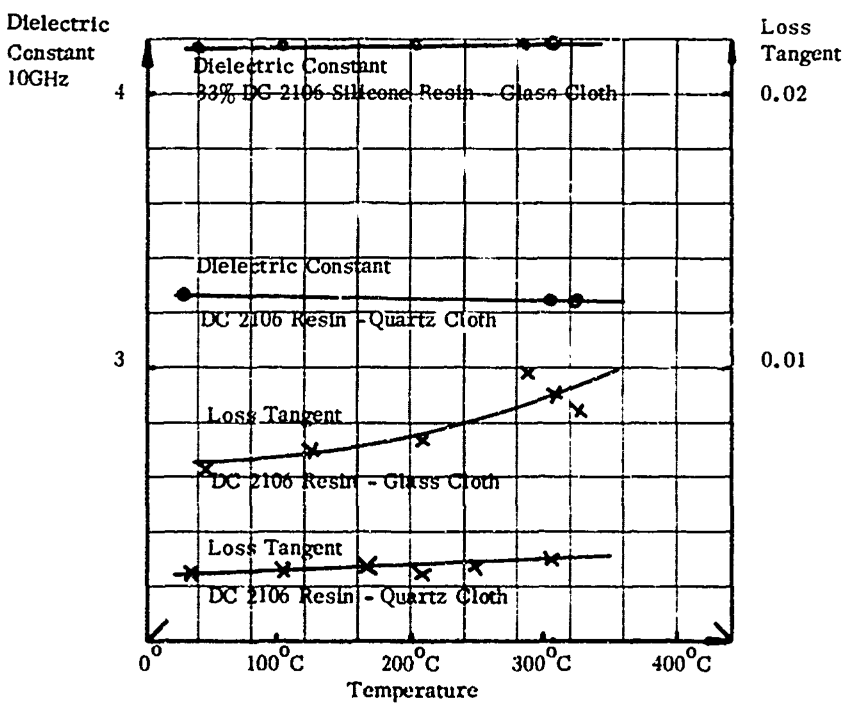
Table 2.3.7.2.1 Electrical Properties of Silicone Composites

Property	Figure Reference	Remarks
Dielectric Constant & Loss Tangent v Frequency	Figure 2.3.7.2.1	Low loss, particularly with quartz. Stable dielectric constant.
Dielectric Constant & Loss Tangent v Temperature	Figure 2.3.7.2.2	Stable dielectric constant with temperature.
Dielectric Constant & Loss Tangent v Humidity	Figure 2.3.7.2.3	Low pressure moulding can result in voids with high pick up giving high loss and change of dielectric constant; only improved if high pressure moulding used.
Dielectric Constant v Radiation		No noticeable change 10^9 rads.
Volume Resistivity		10^{14} ohm cm at room temperature.
Dielectric Strength		in air 23°C 10kV/mm.

Dielectric Constant & Loss Tangent v Frequency
Silicone Resin Composites

FIG. 2.3.7.2.1

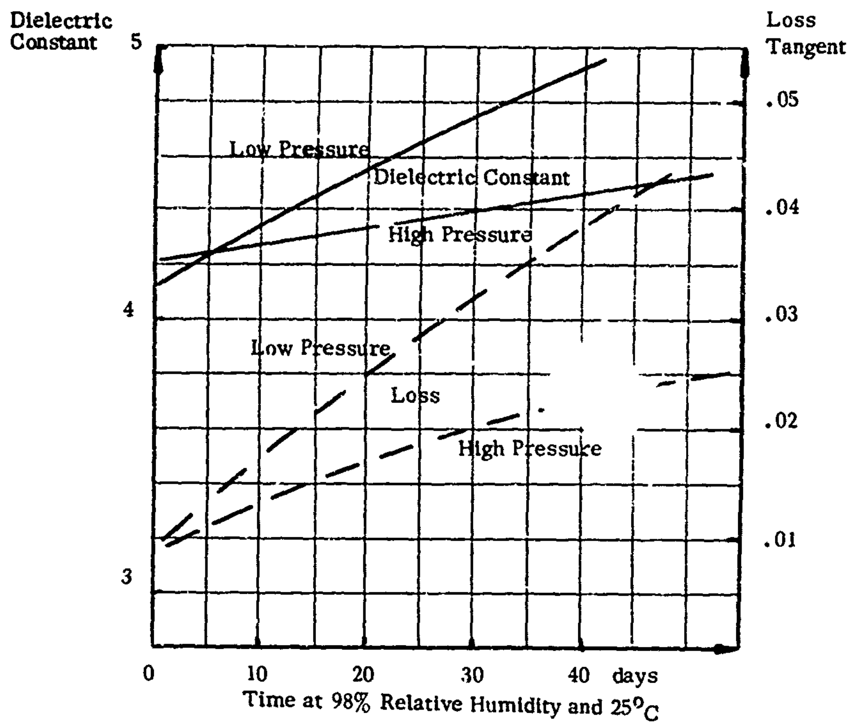




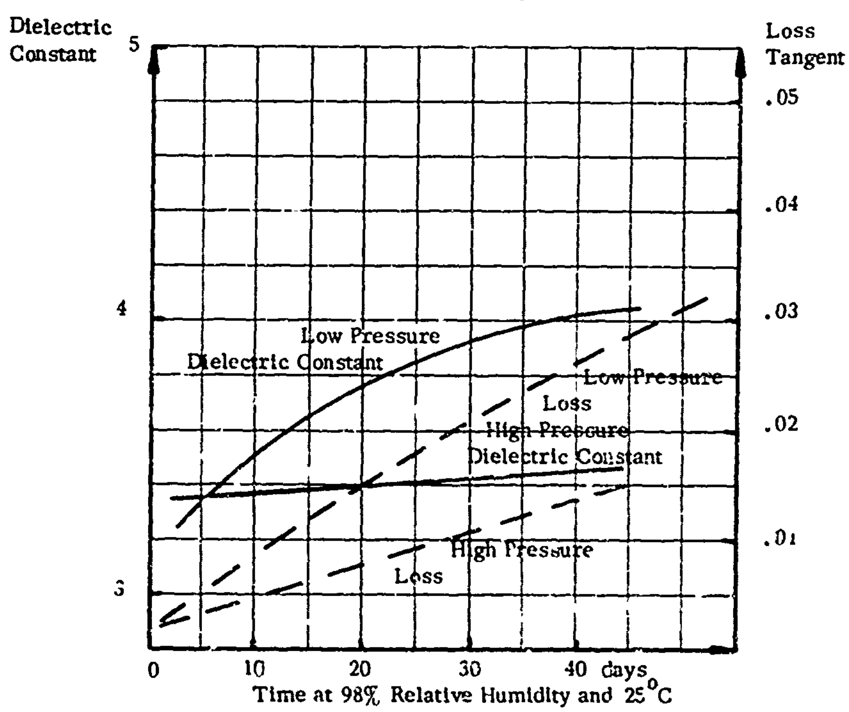
Dielectric Constant & Loss Tangent v Temperature
Silicone Resin Composites

FIG. 2.3.7.2.2

DC 2106 Silicone Resin - Glass Cloth



DC 2106 Silicone Resin - Quartz Cloth



Dielectric Constant and Loss Tangent v Humidity of Silicone Resin - Glass and Quartz Composites

FIG. 2.3.7.2.3

2.3.7.3 Mechanical Properties of Silicone Composites (ref. 30,31)

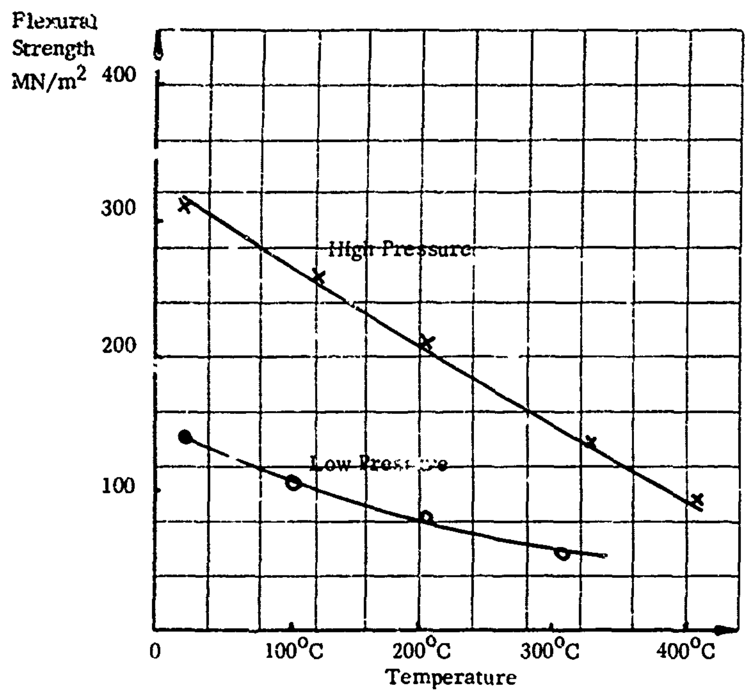
The mechanical properties are inferior to polyimide over the working temperature range of the silicone composite and also to epoxy and polyester over their working ranges. The mechanical properties are summarised in Table 2.3.7.3.1 and in Figure 2.3.7.2.1-3 which give strength properties against temperature.

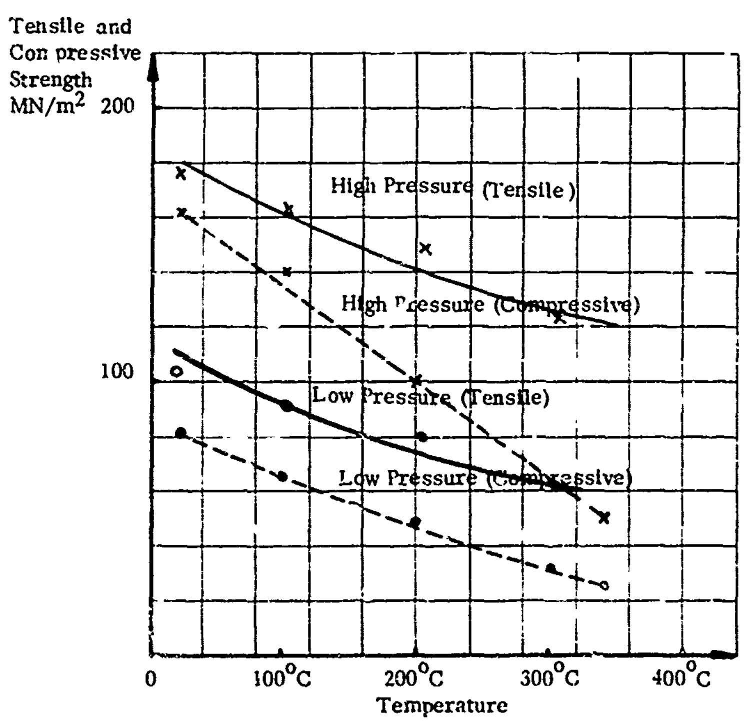
Table 2.3.7.3.1 Mechanical Properties of Silicone Composites

Mechanical Property	Figure Reference	Remarks
Specific Gravity		$1.86 g/cm^2$
Flexural Strength v Temperature	Figure 2.3.7.3.1	Low pressure moulding $130 MN/m^2$ at room temperature, High pressure moulding $300 MN/m^2$ at room temperature.
Flexural Modulus		High pressure moulding $12 GN/m^2$
Tensile Strength v Temperature	Figure 2.3.7.3.2	Low pressure moulding $100 MN/m^2$ at room temperature. High pressure moulding $170 MN/m^2$ at room temperature.
Compressive Strength v Temperature	Figure 2.3.7.3.2	Low pressure moulding $80 MN/m^2$ at room temperature. High pressure moulding $150 MN/m^2$ at room temperature.
Impact Strength		1.6 (kg m/m) notch (high pressure)
Hardness		90M (high pressure)
Humidity		Little effect on mechanical strength.

Flexural Strength v Temperature
(Glass Cloth - Silicone DC 2106 Resin Composite)

FIG. 2.3.7.3.1





(Glass cloth - Silicone DC 2106 Resin Composite)

Tensile and Compressive Strength v Temperature

FIG. 2.3.7.3.2

2.3.7.4 Thermal Properties of Silicone Composites (ref. 30)

The high temperature characteristics of silicone resin has enabled radome composites to operate up to 300°C continuously and for short term, to near the heat distortion temperature of 450°C. The properties are summarised in Table 2.3.7.4.1.

Table 2.3.7.4.1 Thermal Properties of Silicone Composites

Thermal Property	Remarks
Temperature Working Range	Up to 300°C long term Up to 450°C short term
Conductivity	0.0009 cal/sec/cm^2/°C/cm
Expansion	Perpendicular to laminate: 9 x 10^{-5}/°C (glass fabric) 1 x 10^{-4}/°C (quartz) Parallel to laminate: 5 x 10^{-6}/°C (glass fabric) 2 x 10^{-6}/°C (quartz)
Ablation	As temperature increased resin eventually starts to boil off.
Thermal Shock	Can stand severe thermal shock. No serious effect on laminate except for resin boiling off surface or charring.
Flammability	Not regarded as fire hazard.

2.3.7.5 Environmental Properties of Silicone Composites (ref. 30)

Silicone resin composite properties relative to environment are summarised in Table 2.3.7.5.1.

Table 2.3.7.5.1 Environment and Silicone Composites

Property	Remarks
Weathering	Little effect particularly on high pressure mouldings. Very little loss of strength.
Temperature	Heat distortion point 450°C. Operation long term 300°C.
Humidity and Water Absorption	Depends on pressure of moulding. Low pressure or composites with voids suffer increased electric loss and change of dielectric constant with water absorption.
Rain Erosion	Not particularly good, similar to polyester or epoxy resin composites.
Radiation	Solar: ultra violet negligible effect. Nuclear: 10^9 rads negligible effect.
Contamination	Resistance to Dilute acids - excellent Alkalis - good Solvents - fair Contamination by Oils, Greases, Gasoline - negligible.
Storage	Keep reasonably dry.

2.3.8 PHENOLIC RESINS AND COMPOSITES (ref. 12, 30)

Phenolic radomes have been constructed using high pressure moulding techniques and give high mechanical strength and relatively high temperature properties. They have been mainly used at UHF since their performance at microwave frequencies is usually inferior to that of polyester or epoxy resins in respect of loss and change of dielectric constant with temperature. A good void free radome requires high pressure moulding, which involves a high tooling cost.

Moulding pressures in the region of $1.3MN/m^2$ are often used and long post cure times may be required to obtain maximum temperature resistance.

Requirements for phenolic resin laminates are given in Mil-R-9299.

2.3.8.1 Chemical Description of Phenolic Resin

Many phenolics have been developed from a variety of different aldehydes and phenols. The cure is by condensation reaction and reaction by-products result. Consequently, the cure cycle and the time of application of pressure during cure are critical to the production of non-porous, high-quality composites. A typical modern version for radomes is a modified novolac (p. phenyl phenol resin) glasscloth laminate.

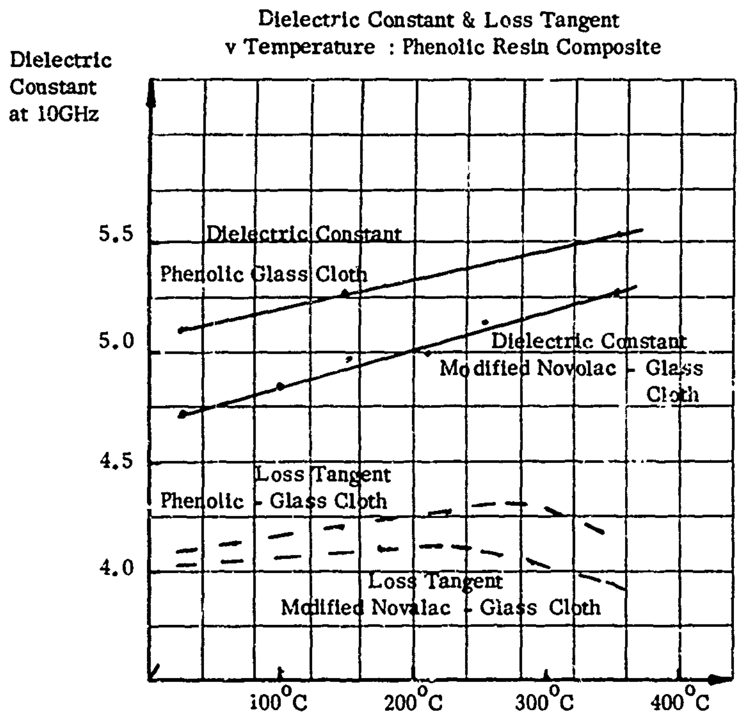
2.3.8.2 Electrical Properties of Phenolic Composites (ref. 3, 12, 26, 30, 32)

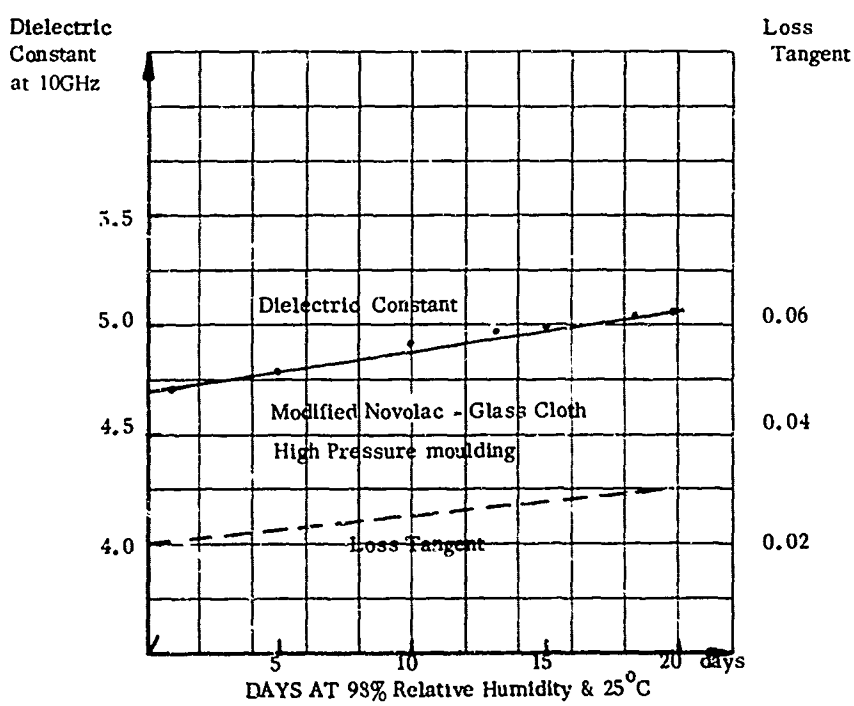
Dielectric constants from near 3.3 with quartz and up to near 5.3 with glass may be obtained. The loss tangent at 10GHz is near 0.025 at room temperature, and dielectric constant rises quickly with temperature. A summary is given in Table 2.3.8.2.1.

Table 2.3.8.2.1 Electrical Properties of Phenolic Composites

Electrical Property	Figure Reference	Remarks
Dielectric Constant and Loss Tangent		Dielectric Constant depends on reinforcement. usually between 3.3 and 5.3 Loss Tangent 0.035 at 10GHz 35% Resin 0.025 at 10GHz 20% Resin
Dielectric Constant and Loss Tangent with temperature	Figure 2.3.8.2.1	Dielectric Constant and Loss Tangent rise with temperature. Some laminates show a decrease in loss tangent at high temperature.
Dielectric Constant and Humidity	Figure 2.3.8.2.2	Unless void free, can absorb water to give large changes in dielectric constant and loss.
Dielectric Constant and Radiation		No noticeable change with 10^9 rads. Ultra violet can cause discoloration, but no serious electrical changes.
Volume resistivity		10^{14} ohm cm at room temperature
Dielectric Strength		10kV/mm in air, room temperature

FIG. 2.3.8.2.1





Dielectric Constant & Loss Tangent
v Humidity : Phenolic Resin Composite

FIG. 2.3.8.2.2

2.3.8.3 Mechanical Properties of Phenolic Composites (ref. 12,30)

The mechanical properties are good at room temperature, are little effected by moisture and are retained up to about 200°C, when high moulding pressures are used.

Mechanical requirements for phenolic glass fabric laminates are specified in MIL R9299 as follows:-

Table 2.3.8.3.1

GRADE A	Room Temperature	290°C
Tensile Strength	275MN/m^2	206MN/m^2
Compressive Strength	241MN/m^2	206MN/m^2
Flexural Strength	345MN/m^2	275MN/m^2
Flexural Modulus	20GN/m^2	20GN/m^2

The mechanical properties of a practical radome will depend on the method of manufacture and it may be difficult to meet specification, particularly with large structures, unless high cost tooling is used.

Mechanical properties of a glass fibre phenolic radome laminate may be summarised as follows:-

Table 2.3.8.3.2

SP Gravity	1.8 with 33% resin	
	25°C	260°C
Tensile Strength	330MN/m^2	144MN/m^2
Compressive Strength	413MN/m^2	200MN/m^2
Flexural Strength	468MN/m^2	230MN/m^2
Flexural Modulus	18GN/m^2	17GN/m^2

2.3.8.4 Thermal Properties of Phenolic Composites (ref. 30)

The thermal properties vary considerably according to manufacture but laminates are generally suitable for use up to 250°C and for shorter terms at higher temperatures. The properties are summarised as follows:-

Table 2.3.8.4.1

Thermal Properties	Remarks
Temperature Working Range	up to 250°C long term, some can stand 400°C short term
Conductivity	0.0002 cal/sec/sq.cm/°C/cm
Expansion Coefficient	0.000053/°C from -30°C to +100°C
Ablation	Ablates as temperature is raised and finally tends to char on surface
Thermal Shock	Can stand severe thermal shock without rupture
Flammability	Tends to self-extinguishing. Not regarded as a fire hazard as a radome.

2.3.8.5 Environmental Properties of Phenolic Composites (ref. 3, 12, 26, 30, 32, 33)

Phenolic composites have good to excellent weathering properties depending on composition and manufacture. They are little affected by radiation, and chemical contamination. Its rain erosion resistance is relatively poor like most inorganic composites. The properties are summarised as follows:-

Table 2.3.8.5.1

Property	Remarks
Temperature	Satisfactory for low temperatures and up to 200°C long term and above short term.
Humidity and Water absorption	Requires high pressure to minimise voids and water absorption which can seriously degrade electrical properties.
Rain Erosion	Poor: can suffer severe erosion particularly if resin starved.
Radiation	Ultra violet: no serious effect. Nuclear: can stand 10^9 rads without noticeable effect. Thermal: can stand severe thermal shock.
Contamination	Resistance to dilute acids: good alkalis: poor alcohols: good detergents: fair greases: good oils: good
Storage	Best kept dry but weathers well.

2.3.9 DIALLYL PTHLATE (DAP) COMPOSITE (ref. 12,30)

DAP radomes have been construcred and give good mechanical properties but in general are weaker than phenolic. They can be operated continuously at 200°C. Glass-fabric DAP can be processed by compression and transfer moulding at temperatures near 150°C but to exclude voids requires high pressures (near 200kg per sq cm). As radomes are usually small in number expensive tooling usually rules out this resin construction except for flat or near flat panels.

The electrical properties are generally worse than polyester or epoxy in that their loss is higher and the dielectric constant changes more rapidly with temperature and further it is prone to electrical changes due to moisture pick-up.

2.3.9.1 Chemical Description of DAP resin

Diallyl phthalate (dap) and diallyl isophthalate (daip) form a class of polyester resins, which have been used as laminating resins and as reactive diluents for conventional polyester resins, and are cured through additional reactions of phenyl reactive groups.

2.3.9.2 Properties of DAP Resin Composites (ref. 30,32)

A brief summary of DAP composite is:-

Table 2.3.9.2.1.

DAP Composite Property	Remarks
Electrical:	
Dielectric Constant	4.1 at 25°C: 4.4 at 180°C (Glass fabric - 33% DAP)
Loss Tangent	0.03 at 25°C and 10GHz: 0.05 at 180°C
Volume Resistivity	10^{14} ohm cm
Mechanical:	
Tensile Strength	150MN/m^2 at room temperature
Compression Strength	180MN/m^2
Flexural Strength	245MN/m^2
Thermal:	
Temperature	Long term 200°C - 220°C above which gradually loses resin.
Linear Expansion	0.00003.
Thermal Shock	Can stand severe shock without mechanical failure.
Flammability	Ablates, and eventually chars. Not a fire hazard as a radome.
Environment:	
Temperature	Operates low temperature to 200°C.
Humidity and Water Absorption	10mg water absorption in 24 hours.
Rain Erosion	Poor resistance, particularly if low resin content and voids.
Radiation	Solar U.V.: negligible effect. Nuclear: 10^9 rads safe rating
Contamination	Good resistance to dilute acids, alkalis, solvents, oils, and weathers well.

2.3.10 REFERENCES TO SECTION 2.3.

1. SBAC - Plastics Handbook

2. SBAC - Plastics Handbook Revision Draft (1973)

3. Plessey (Allan Clarke Research Centre - UK) Data

4. Bakelite Limited Technical Memorandum P 105 (revised April 1962)

5. Bakelite Limited Technical Memorandum P 101 (July 1958)

6. Bakelite Limited Technical Memorandum P 107 (June 1959)

7. Bakelite Limited Technical Memorandum P 110 (June 1959)

8. British Resin Products Limited - Cellobond A 2661 Information Sheet No. P 104/2

9. British Aircraft Corporation - Internal Records

10. How Plastics Resist Weathering - Article from "Materials in Design Engineering" - Oct. 1965. By J. Chottin r and E.B. Bowden.

11. AGARD Advisory Report No. 53 - Radomes, Advanced Design

12. RADOME Engineering Handbook - Walton

13. US-Rubber Vibrin Date Sheet - Vibrin 136A

14. US-Rubber Vibrin Data Sheet - Vibrin 135

15. Brunswick Corporation - Technical Bulletin No. 1001 (Defense Products)

16. CIBA (ARL) Limited - Instruction sheet C176 (1970)

17. Shell Chemical - Technical Bulletin RES/EP/113

18. CIBA-GEIGY (UK) Limited - Publication C39C (1971)

19. Shell Chemical - Technical Bulletin RES/P/187

20. Shell Chemical - Technical Bulletin EPON 1310

21. Owens-Corning Fibre Glass Technical Centre Publication on D Glass reinforced Epoxy - No ref.

22. Ferro Corp. - Technical Bulletin V2:11 Zero Twist Fabrics

23. Eltro - Bulletin EH-181 (1971)

24. Bexcel - Data Bulletin 117

25. Von Hippel - Dielectric Materials and Applications

26. MIL Handbook 17a

27. Brunswick Corporation - Technical Bulletin No. 1012

28. Paper given at Reinforced Plastics/Composite Division Conference in Washington D.C. FEB. 1970. "Quartz-Polyimide Processing for Advanced Radomes" - Luke C. May and Julius Hertz.

29. Brunswick Corporation - Technical Bulletin No. 1003

30. RRE (Mod - UK) Data

31. Brunswick Corporation - Technical Bulletin No. 1009

32. British Plastics Materials Guide 1970-1971

33. Batelle Inst.

34. Shell Chemical Co.

PART III

CORE MATERIALS AND SANDWICH CONSTRUCTIONS

INDEX TO PART III

CORE MATERIALS AND SANDWICH CONSTRUCTIONS

3.1 Introduction

The desirable electrical, structural and in some cases weight saving properties of the conventional sandwich constructions have been well documented and will not be further expanded here. (1) Skin materials of the sandwich can in principle be constructed from any of the organic laminates and, in some cases, inorganic materials given in Section 2. The major area requiring property information in this section has to do with the core materials.

In the A sandwich case, where the core normally has a dielectric constant close to unity, honeycomb and foam cores are common. Departures from this normal construction do occur such as when ducting of hot air for deicing purposes is required. These cases however are considered to be special and not within the scope of this document.

While rarely used, the B sandwich with its high dielectric constant core has interesting properties which might, in special cases, prompt its application. Again the choice of constituent parts can with due reference to dielectric constant, be made from Sections 1 and 2 and when necessary to Section 3.2.3 when artificially adjusted properties must be used.

Reinforced plastic honeycomb core materials are available in a variety of cell-wall resins and reinforcements, and cell-size and configurations. Efforts to produce ceramic honeycombs are discussed, but these have not yet found radome application. Foam materials have developed beyond the earlier commonly employed nitride rubber form, one of which in its "radome quality" form was marketed as Hycar. Polyurethane foams now form a major core material and a highly consistent version for radome application with improved thermal properties, is the Plessey (UK) P10. Syntactic foams are reported in this section and have proved to be of particular interest in the artificial dielectric field.

Strictly any mixture of materials aimed at providing a specific and not naturally occuring dielectric constant is artificial. However, normally the term artificial dielectric is reserved for combinations in which the mixture is not created for other reasons (e.g., glass for reinforcement), thus conventional laminates are excluded from this class but metal flake in syntactic foam is included.

Three specifically different types of artificial dielectrics are referred to. The first is where a very high dielectric constant material such as TiO_2 is mixed in with a normal plastic material. The second involves a random distribution of metallic particles and the third is the organized distribution of metallic elements.

The structural integrity of a sandwich construction and sometimes its electrical performance is highly dependent upon the bond achieved between core and skin materials. While the achievement in this area is largely dependent upon manufacturing methods and skills, which should strictly exclude this subject from this document, some common pitfalls and problems are discussed.

3.2 BASIC CORE MATERIALS

3.2.1 Honeycomb Core Materials

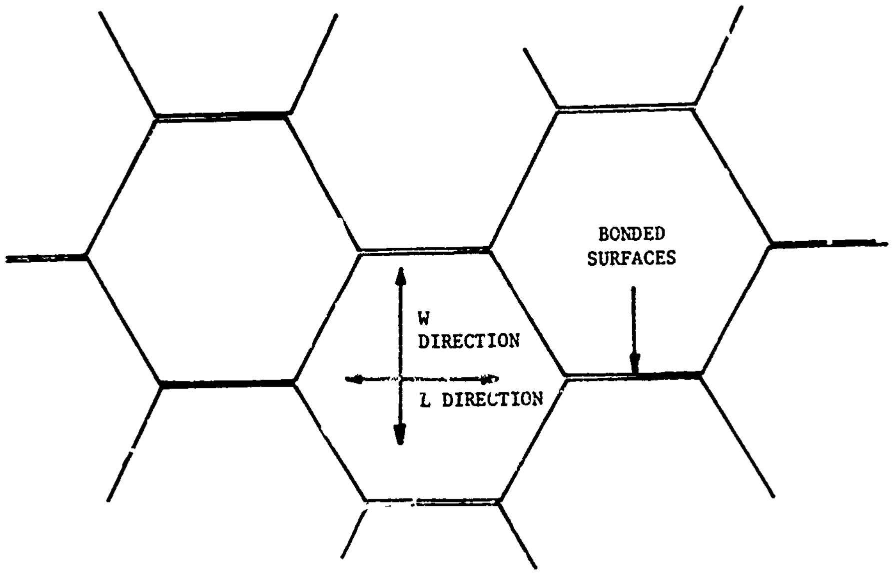
3.2.1.1 Reinforced Plastic Honeycomb Core Materials (2,3)

Honeycombs which have formed the most commonly used A and higher order sandwich core material, are available in a number of forms which will satisfy different types of construction and a wide temperature range. Typical of widely used medium temperature materials are Hexcel's range of glass fabric reinforced phenolics, polyesters etc. and also their honeycomb based upon Dupont's Nomex. These materials are reported in detail below.

Polyimide based honeycombs are available for higher temperature applications and can be used for temperatures within the normal polyimide range provided of course that skins and adhesives are compatible.

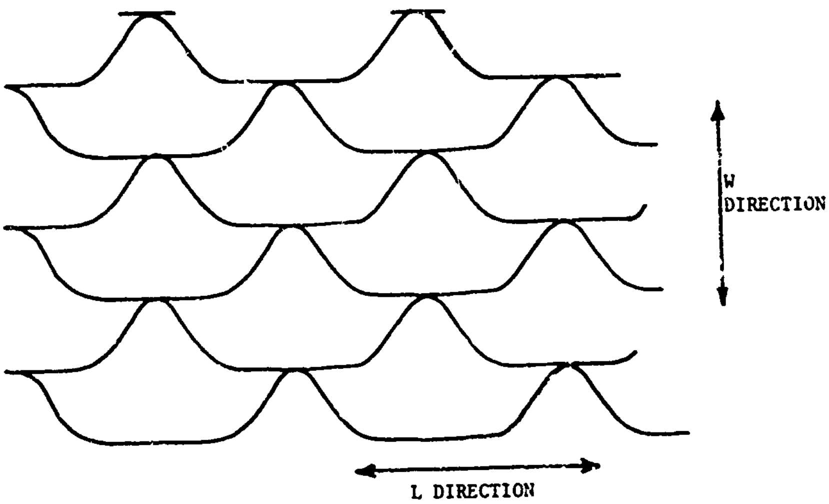
Honeycombs are available in a range of cell size and configurations allowing a choice of densities and forming properties. Cells of between 0.3 and 1.3 cm give densities in the range .04 gm/cc (2.5 lb/ft^3) to .14 gm/cc (12 lb/ft^3) but a size of 0.6 cm at about .08 gm/cc (5 lb/ft^3) is most often used for radomes. Various cell shapes are available for allowing forming around complex double curvature shapes, notable among which is the Hexcel Flex-Core.

It is necessary when considering the properties of reinforced plastic honeycombs to consider two major directions. These are shown in Figure 3.2.1.1. Hexcel honeycombs with the designation "OX" possess a rectangular cell shape achieved by expansion of the normal hexagonal form in the W direction. This facilitates curving or forming in the L direction and imparts an improved W shear property at the expense of L shear. Flex-core departs considerably from the hexagonal shape and is shown in Figure 3.2.1.1.



THE HEXAGONAL CORE

FIG 3.2.1.1



HEXCEL FLEXCORE

3.2.1.1.1 Electrical Properties of Plastic Honeycomb Materials (Ref. 2)

The dielectric properties listed in Table 3.2.1.1.1 are for Hexcel's nylon phenolic honeycombs and can be taken as indicative of other types. Measurements were carried out at 9375 MHz and are valid for incidence angles up to 60 degrees. In only one case was loss tangent measured, but this value will be reasonably typical for all cases.

TABLE 3.2.1.1.1. ELECTRICAL PROPERTIES OF HEXCEL NYLON REINFORCED PHENOLIC HONEYCOMBS

HEXCEL HONEYCOMB DESIGNATION			DIELECTRIC CONSTANT			
TYPE	CELL SIZE (INCH)	DENSITY (lb/ft^3)	PERPENDICULAR POL^N		PARALLEL POL^N	
			E PAR. L	E PERP. L	E PAR. L	E PERP. L
NP	3/16	4.[illegible]	1.11	1.07	1.10-1.13	1.07-1.12
NP	3/16	6.0	1.14	1.08	1.13-1.16	1.08-1.14
NP	3/16	9.0	1.20	1.13	1.19-1.24	1.12-1.19
*NP	1/4	4.0	1.10	1.06	1.09-1.12	1.06-1.11
NP	1/4	6.0	1.13	1.08	1.13-1.16	1.08-1.15
NP	1/4	8.0	1.18	1.13	1.17-1.21	1.13
NP	3/8	2.5	1.06	1.04	1.06-1.07	1.03-1.06
NP	3/8	4.5	1.09	1.07	1.09-1.11	1.06-1.11
NPOX	1/4	4.0	1.08	1.10	1.09-1.13	1.09-1.12
NPOX	1/4	6.0	1.11	1.14	1.10-1.16	1.14-1.17
NPOX	3/8	2.5	1.04	1.06	1.04-1.09	1.05-1.08
NPOX	3/8	4.5	1.06	1.09	1.06-1.10	1.09-1.12

* LOSS TANGENT PARALLEL POLARISATION 0.002

LOSS TANGENT PERPENDICULAR POLARISATION 0.001

TABLE 3.2.1.1.2. REINFORCED PLASTIC HONEYCOMB STRENGTH (½" (1.25 cm) THICK SAMPLES)

HEXCEL HONEYCOMB DESIGNATION MATERIAL/CELL/DENSITY inches-lb/ft²	COMPRESSIVE					PLATE SHEAR					
	BARE		STABILISED			L DIRECTION			W DIRECTION		
	STRENGTH MN/m² TYP	STRENGTH MN/m² MIN	STRENGTH MN/m² TYP	STRENGTH MN/m² MIN	MODULUS MN/m²	STRENGTH MN/m² TYP	STRENGTH MN/m² MIN	MODULUS MN/m²	STRENGTH MN/m² TYP	STRENGTH MN/m² MIN	MODULUS MN/m²
HRP-3/16-4.0	3.5	2.4	4.2	3.3	390	1.8	1.4	79	1.0	.8	35
HRP-3/16-5.5	5.5	4.2	6.5	5.2	660	2.9	2.5	135	1.5	1.3	59
HRP-1/4-3.5	2.4	1.8	3.5	2.8	320	1.6	1.2	62	0.8	0.7	24
HRP-1/4-4.5	4.4	3.1	4.8	3.9	482	2.1	1.7	97	1.2	1.0	41
HRP-3/8-3.2	2.2	1.7	3.0	2.4	262	1.4	1.1	55	0.7	0.6	21
NP-3/16-4.5	3.6	2.5	4.6	3.2	550	1.9	1.3	93	0.9	0.6	36
NP-1/4-4.0	2.9	2.0	3.9	2.7	468	1.8	1.2	89	0.8	0.7	34
NP/OX-1/4-4.0	2.4	-	-	-	-	1.1	-	35	1.3	-	83
HRH327-3/16-4.0	-	-	3.0	-	345	1.9	-	200	0.9	-	69
HRH327-3/16-5.0	-	-	4.1	-	470	2.6	-	255	1.2	-	86
HRH327-1/4-4.0	-	-	3.0	-	345	1.9	-	200	0.9	-	69
HRH327-1/4-5.0	-	-	4.1	-	470	2.6	-	255	1.2	-	86
HRH327-3/8-4.0	-	-	3.0	2.2	345	1.9	1.4	200	1.0	0.7	83
HRH327-3/8-5.5	-	-	4.7	3.7	538	2.9	2.1	283	1.5	1.1	93
HRH10-3/16-2.0	1.0	0.6	1.0	0.7	76	0.8	0.5	29	0.4	0.3	15
HRH10-3/16-4.0	3.5	2.2	3.9	3.2	194	1.7	1.6	63	1.0	0.8	32
HRH10-1/4-1.5	0.6	0.3	0.7	0.4	41	0.5	0.3	21	0.2	0.16	10
HRH10-1/4-2.0	1.0	0.6	1.0	0.7	76	0.8	0.5	29	0.4	0.25	15
HRH10/OX-3/16-1.8	0.7	0.5	0.9	-	-	0.4	0.3	14	0.4	0.24	21
HRH10/OX-1/4-3.0	2.4	1.5	2.9	2.1	118	0.8	0.6	21	0.8	0.6	42
HRH10/F35-2.5	1.0	-	1.2	-	83	0.5	-	28	0.3	-	13
HRH10/F35-4.5	3.1	-	3.4	-	228	1.9	-	50	1.0	-	26

NOTES

HRP - Glass fabric reinforced heat resistant phenolic.

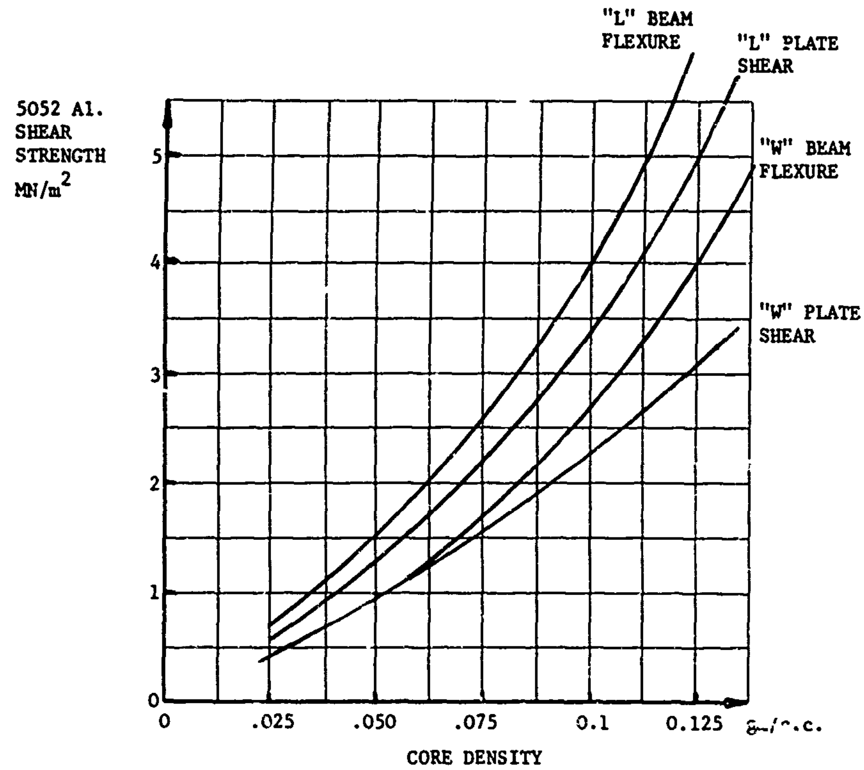
NP - Glass fabric reinforcement with initial web impregnation by a nylon modified phenolic and final dip with polyester.

HRH327 - Glass fabric bias weave with polymide resin.

HRH10 - Uses Du Pont's NOMEX which is a nylon-fibre paper treated with a heat resistant phenolic.

/OX - Indicates OX configuration.

/F - Indicate flexcore.



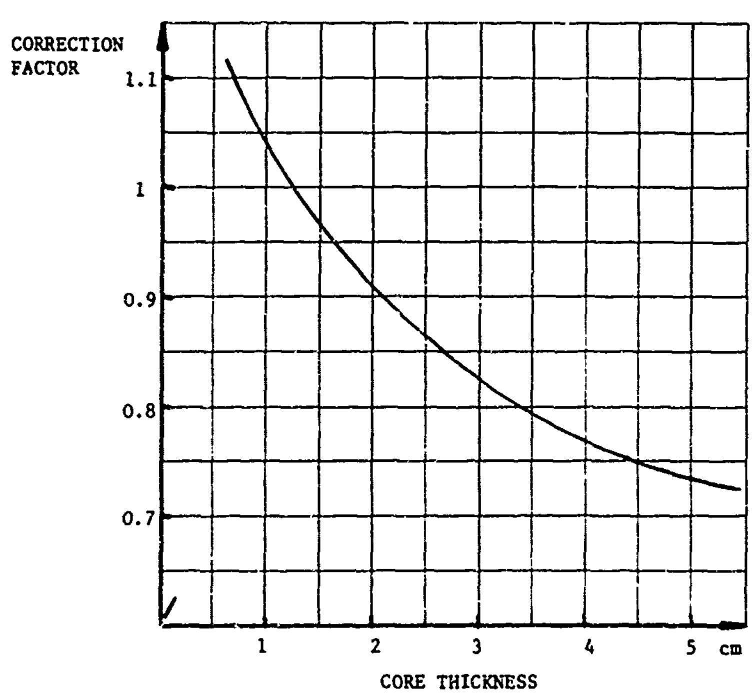


FIG 3.2.1.1.2

PLATE SHEAR & BEAM FLEXURE 5052 ALUMINIUM HONEYCOMB

HONEYCOMB STRENGTH v. TEMPERATURE v. TIME

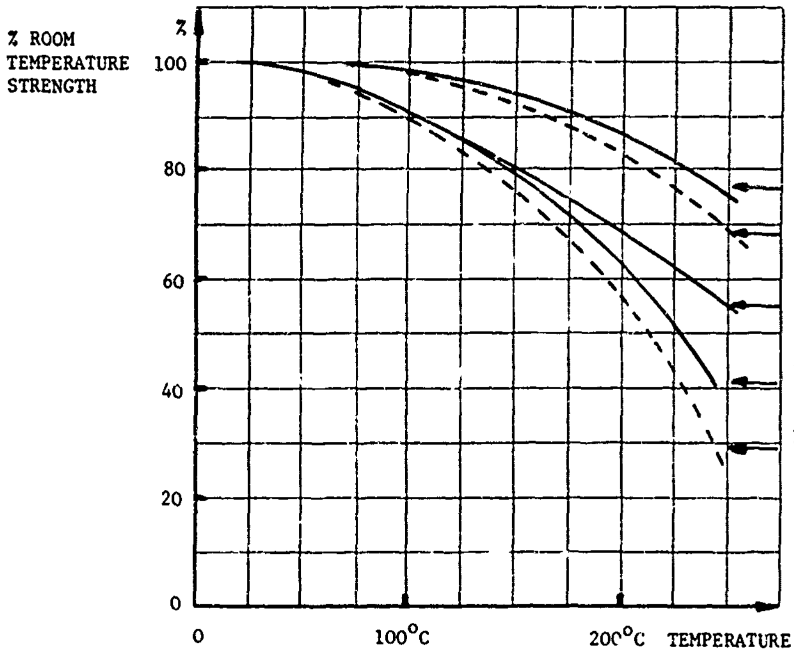


FIG 3.2.1.1.3.1

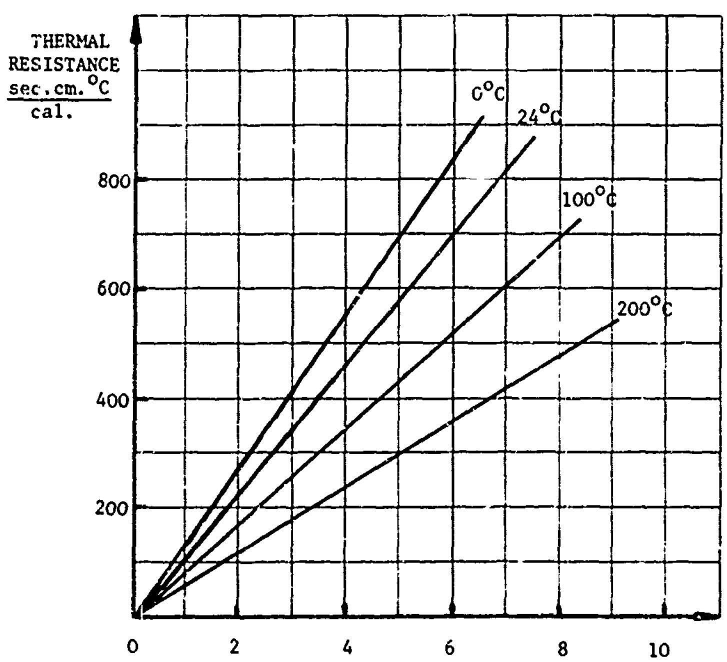


FIG 3.2.1.1.3.2

THERMAL RESISTANCE FIBREGLASS HONEYCOMB

3.2.1.1.2 Mechanical Properties of Plastic Honeycomb Materials (Ref 2)

The following data has been extracted from Reference 2 and it noted that the manufacturers recommend contact with them in order to establish exact data in some instances and more detailed information together with specific recommendations. Compressive plate shear properties are preferred. However, in some cases beam flexure is specified. Results are given for plate shear, but in Figure 3.2.1.1.2 the results of the two tests are compared. In the plate shear case samples were prepared to MIL-C-7438 and use a 5052 aluminum honeycomb. However, the comparison demonstrates the difference which arises out of the beam methods dependence upon facing thickness and material and upon loading materials.

For either plate or beam determined shear the value will be dependent upon core thickness. An approximate indication of the correction factor that applies to plate shear properties is also given in Figure 3.2.1.1.2.

Compressive and plate shear properties for used Hexcel products together with those for a range of flexcore and polvimide products are given in Table 3.2.1.1.2.

3.2.1.1.3 Other Properties of Plastic Honeycomb Materials (Ref 2)

The general properties of Hexcel materials are summarized as follows:

TABLE 3.2.1.1.3 PROPERTIES OF PLASTIC HONEYCOMB CORES

	HRP (°C)	NP (°C)	HRH327 (°C)	HRH10 (°C)
Max Service Temp	180	82	260	180
Flamability	E	E	E	E
Impact Resistance	F	F	F	E
Moisture Resistance	E	E	E	E
Fatigue Strength	G	G	G	E
Heat Transfer	Low	Low	Low	Low
Cost	Mod	Mod	High	Mod

Note: E = Excellent, G = Good, F = Fair.

The effect of exposure to various temperatures for 30 minutes and 100 hours are summarized in Figures 3.2.1.1.3.1. Thermal resistance of honeycomb materials has been obtained as a function of core thickness and is shown in Figure 3.2.1.1.3.2. The overall value for a sandwich is of course additionally affected by skin thickness and material and glue line properties.

3.2.1.2 Ceramic Honeycombs

Ceramic honeycomb materials are manufactured in the United States by the 3M Company, Technical Ceramic Products Division, Chattanooga, Tennessee. Presently they are used primarily for catalyst supports in air pollution control equipment, for gas heat exchangers, gas mixers and flame arrestors.

The honeycomb structures are available in three proprietary compositions; two are alpha alumina with differing porosities, and the third is cordierite ($2MgO.2Al_2O_3.5SiO_2$). Two basic cell geometries are available; a true honeycomb design having four or six sides to the cell, and a split cell design made up of alternating corrugated and flat walls having an appearance similar to corrugated paper shipping cartons. The corrugated walls are obtained by either dipping a paper carrier into a ceramic slip followed by assembly of the strips, or corrugating a flexible ceramic tape and assembly of the tapes. The structures are sintered after assembly.

Standard wall thicknesses range from 0.006 to 0.016 inch (0.015 to 0.041 cm) and cell widths range from 0.083 to 0.20 inch (0.218 to 0.508 cm). The various properties are of course dependent on the geometry of the structure of interest and the direction of interest. These ceramic honeycombs were developed for applications other than radomes, and have not been investigated for radome use. In the past, ceramic honeycombs have been considered for radomes, but manufacturing difficulties have prevented their successful exploitation. The newly developed technology for producing honeycombs may revive interest in this radome construction technique.

3.2.2 Foam Core Materials

The following includes materials which have found considerable application in the radome field. Other plastic foams exist which in a few cases may have been used and may have specific advantages. It is however not possible within the scope of this document, to recall all of these.

Polyimide foam is included in normal and syntactic form for its future potential. In fact in the latter form application has already been found.

Ceramic foams (as with ceramic honeycombs) have, despite their attractive weight saving properties, found little application due to manufacturing difficulties. Properties are included nevertheless so as to indicate current achievements.

3.2.2.1 Expanded Nitride Ebonite (Hycar)

This material has been used extensively as a core for radomes, as it is easier mouldable and is at low temperatures of reasonable strength and electrical properties. It is mostly superseded by other foam structures as it is limited by temperature and homogeneity.

This material can be supplied in the form of boards, manufactured from compounded butadiene/acrylonitrile copolymer, suitably expanded and vulcanised and having a closed cellular structure. The expansion can be accomplished without the use of chemical blowing agents or other substances likely to impair the electrical properties of the board. It is specified in the U.K. by D.T.D. 764.

The boards can be obtained of considerable size (60 cm x 100 cm, 2 ft x 3 ft) and thickness as required. Typical densities for the material are from 8 to 14 lb per cu ft (.11 to .22 gr.c.c.) for radomes.

The compressive strength varies with thickness and typically for a 0.2 inch (0.5 cm) thickness, is at least 200 psi (1.4×10^6 N/m^2).

The plastic yield is near 70°C and the boards should be moulded to shape at a somewhat higher temperature such that no blisters are produced.

The power factor at microwavelengths and room temperature should be near 0.0015 (9000 MHz) and its permittivity for a 10 lb. cu ft (0.16 gr per cc) dense material should be near 1.15.

The material in its manufacture is difficult to control for exact permittivity and can be denser at the middle of the thickness of the board. Due to its limited temperature capabilities it is not a material of future application.

3.2.2.2 Polyurethane Foams

Urethane type foams have found wide application for core sandwich radomes and have certain advantages over honeycomb core materials such as a continuous joint to the skin and no air pockets. Some of the foams are temperature limited, but there are types which can be operated continuously at 180°C and for shorter terms much higher.

Urethanes are produced by the reaction of polyols and isocyanates and the foaming action may be produced by the addition of water to form carbon dioxide gas, the quantity of water added determines the density of the foam unless it is confined to a given volume (Ref 1). The material is sometimes used as a foamed in place (Mil-C-8087), but is more often produced as boards which can be machined or moulded to shape.

High temperature polyurethane foams have been prepared from tolulene di-isocyanate and alkyd triallylcyaniviate copolymeric material and some properties of this type of core material are as follows (Ref 4 and 5)

Temperature:-	75°F (25°C)	400°F (200°C)
Compressive Strength:-	270 psi (1.8×10^6 N/m^2)	150 psi (1×10^6 N/m^2)
Shear Strength:-	85 psi (6×10^5 N/m^2)	40 psi (3×10^5 N/m^2)
Shear Modulus:-	7300 psi (5×10^7 N/m^2)	3400 psi (2.4×10^7 N/m^2)
Tensile Strength:-	100 psi (7×10^5 N/m^2)	70 psi (5×10^5 N/m^2)
Dielectric Constant:- 8.5 GHz	1.16	1.23
Loss Tangent:- 8.5 GHz	0.003	0.0024

Such a T.D.I. foam with extended temperature characteristics has been developed under the name P10 (Ref 4). This material has a closed cell structure and can be formed into slabs of uniform density. These can be sliced into thin sheets, machined and by heating to 210-220°C softened enough to enable the sheets to be formed around double curvatures without any spring back or splitting on cooling. A range of permittivities can be produced, and at 10 GHz controlled to close limits.

P10 is a rigid, closed cell foam which under load can withstand 200°C, and without load 250°C. On heating to near 220°C sufficient softening occurs to enable sheets of foam to be formed around double curvature shapes, typical densities available are from (3 lbs cubic ft) 0.05 grams/cc, but for radome usage a density of near (8 lb cubit ft) 0.14 grams/cc.

The mechanical properties of P10 are as follows:

Density v Tensile Strength (ASTM spec D1623-64)

Density	Tensile Strength
3 lbs cu ft (0.05 grams cc)	40 psi (28 x 10^4 N/m^2)
6 lbs cu ft (0.1 grams cc)	150 psi (10.5 x 10^5 N/m^2)
8 lbs cu ft (0.14 grams cc)	200 psi (14 x 10^5 N/m^2)

Density v Shear Strength (B.S. 2782)

Density	Shear Strength
3 lbs cu ft (0.05 grams cc)	50 psi (35 x 10^4 N/m^2)
6 lbs cu ft (0.1 grams cc)	120 psi (8.4 x 10^5 N/m^2)
8 lbs cu ft (0.14 grams cc)	250 psi (17.5 x 10^5 N/m^2)

Plastic Yield (ASTM Spec D648-56)

Comparing normal and P10 polyurethane foam (8 lb cu ft - 0.14 gr/cc)

Temperature	Deflection	
(^{o}C)	Normal Foam	P10
20	0	0
100	0.05" (0.125 cm)	0
120	collapse	0
150		0.005" (0.012 cm)
160		0.02" (0.05 cm)

Compression Strength (DTD 764 Appendix 1 Spec)

Comparing normal and P10 polyurethane foam (8 lb cu ft - 0.14 gr/cc)

Temperature	Compression	Strength
	Normal Polyurethane	P10
20^{o}C	210 psi (1.4 x 10^6 N/m^2)	410 psi (2.8 x 10^6 N/m^2)
100^{o}C	140 (0.98 x 10^6 N/m^2)	265 psi (1.9 x 10^6 N/m^2)
160^{o}C	30 (0.2 x 10^6 N/m^2)	195 psi (1.4 x 10^6 N/m^2)
190^{o}C	------	180 psi (1.3 x 10^6 N/m^2)

The thermal properties of P10 are:-

Conductivity	Density
0.0018 Btu/ft/hr/^{o}F (5.4 x 10^{-5} cals/sq.cm/sec^{o}C/cm)	3 lb/cu.ft (0.05 gr cc)
0.0022 Btu/ft/hr/^{o}F (6.6 x 10^{-5} cals/sq.cm/sec^{o}C/cm)	8 lb/cu.ft (0.14 gr cc)

The electrical properties of P10 at 9.375 GHz of dielectric constant and loss tangent for various densities are:-

Density	Permittivity	Loss Tangent
3 lb/cu.ft (0.05 grams cc)	1.06	0.001
6 lb/cu.ft (0.1 grams cc)	1.13	0.002
8 lb/cu.ft (0.14 grams cc)	1.17	0.002

The variation of dielectric constant and loss tangent with temperature for a density of 8 lb/cu.ft (0.14 grams cc)

Temperature (^{o}C)	Permittivity	Loss Tangent
20	1.17	0.002
50	1.17	0.002
100	1.17	0.002
150	1.16	0.002

3.2.2.3 Polyimide Foam

This material is relatively new and has not been fully assessed or necessarily developed to its maximum potential. It has the property of higher temperature operation than polyurethane. Over 300^{o}C (550^{o}F) is a typical operating temperature. It can provide an efficient thermal barrier because its thermal conductivity is low. It is at this stage of development not as stiff as that of the polyimide honeycomb. Densities of near 10 lb cu.ft (0.15 grams/cc) are typical of the foam which has a dielectric constant at 10 GHz near 1.2 and a loss tangent of 0.002. Its thermal conductivity is near 0.03 Btu/hr/ft^{o}F (1.2 x 10^{-4} cals/sq. cm/sec^{o}C/cm).

Polyimide foam has been suggested as a contender for a thermal barrier material as part possibly of a radome or attached to its internal surface to protect inside equipment.

3.2.2.4 Syntactic Foams (Ret 6)

The term syntactic applied to foams, covers these foams in which a low density microballoon filler such as Emerson Cumming's Eccospheres (glass or silica bubbles of approximately 100 μm diameter) is introduced into a resin matrix. Thus any resin, polyester, epoxy, polyimide, etc. in combination with microballoons constitutes a syntactic foam. This particular foam form is of value where a third material such as TiO_2 or metallic particles is to be mixed in, or, in some cases, where extreme mouldability of the core material is required. Thus one might reduce the density (and hence overall radome weight) by the syntactic foam approach and then if required return its dielectric constant to the same order the resin (or above) by artificial dielectric techniques.

Because of the wide choice of resin matrix available, syntactic foams can be designed to have considerably better mechanical and thermal properties than for the other plastic types. Thus in the case of a high temperature polyimide sandwich radome the choice of a syntactic core with polyimide as the resin matrix is desirable.

The normal manufacturing techniques for this type of sandwich involves an initial stage in which tiles of the syntactic foam are made and preformed. These are then incorporated between the skins in an Igloo fashion. In some material cases difficulties have been experienced in manufacturing large tiles and a size of about 30 cm square has been typical. More recently the incorporation of chopped fibers of about 0.5 cm length has decreased the tendency to cracking and allowed 1 m x 1 m panels to be made.

Typical properties for Eccospheres are listed in Table 3.2.2.4.1.

TABLE 3.2.2.4.1 PROPERTIES OF ECCOSPHERES (ELECTRICAL GRADES)

Designation	R Standard Electrical Grade	SI High Temp Low Loss	VT Surface Treated for Organic Systems
Composition	Sodium Borosilicate Glass	Silica	Silica
Bulk Density g/cc	0.166	0.152	0.164
True Particle Density g/cc	0.361	0.254	0.272
Particle Size Distribution (% Weight)			
> 175 μm	8	0	0
149-175 μm	7	14	14
125-149 μm	11	19	15
100-125 μm	10	12	16
62-100 μm	40	40	43
44-62 μm	10	15	7
< 44 μm	14	9	5
Packing Factor	0.46	0.559	0.603
Average Wall Thickness μm	2	1.5	1.7
Softening Temperature °C	482	1000	316
Dielectric Constant	1.3	1.2	1.2
Loss Tangent	0.002	0.0005	0.001

As with all material mixes the dielectric constant is first computed by the equation of Section 2.3.3.2 with knowledge of the properties of the individual constituent parts. Thus previously given data for resins is entirely applicable. The effect of temperature upon dielectric constant can also be computed.

The mechanical properties of syntactic foams are dependent upon the resin type used to form the matrix. The effect upon the properties of polyester resin with varying loadings is shown in Fig 3.2.2.4.1 and 3.2.2.4.2. The resin in this case was a general purpose polyester Interchemical IC-312. Properties for a glass microballoon filled epoxy (Epon 828) are given in Table 3.2.2.4.2.

TABLE 3.2.2.4.2. PROPERTIES OF EPON 828 AND GLASS MICROBALLOONS

Density gr/cc	0.6
Flexural Strength MN/m^2	30
Linear Expansion °C	31×10^{-6}
Dielectric Constant 10 GHz	1.9
Loss Tangent 10 GHz	0.015
Volume Resistivity Ohm-cm	1×10^{12}

It will be noted that generally achievable densities are not as low as for other foams which also applies to dielectric constant. This situation does to some extent limit this application of syntactics in conventional A sandwiches.

DENSITY v. VOLUME % RESIN

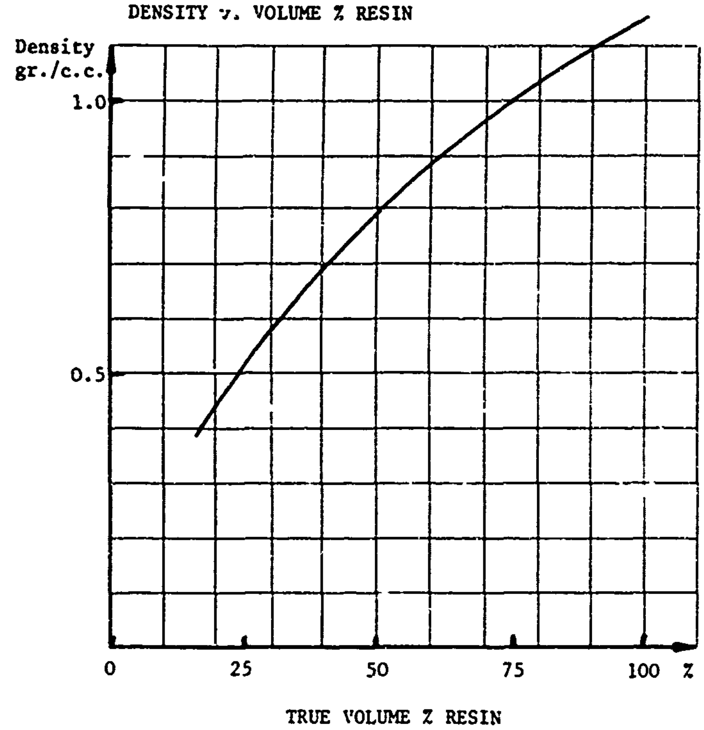


FIG 3.2.2.4.1

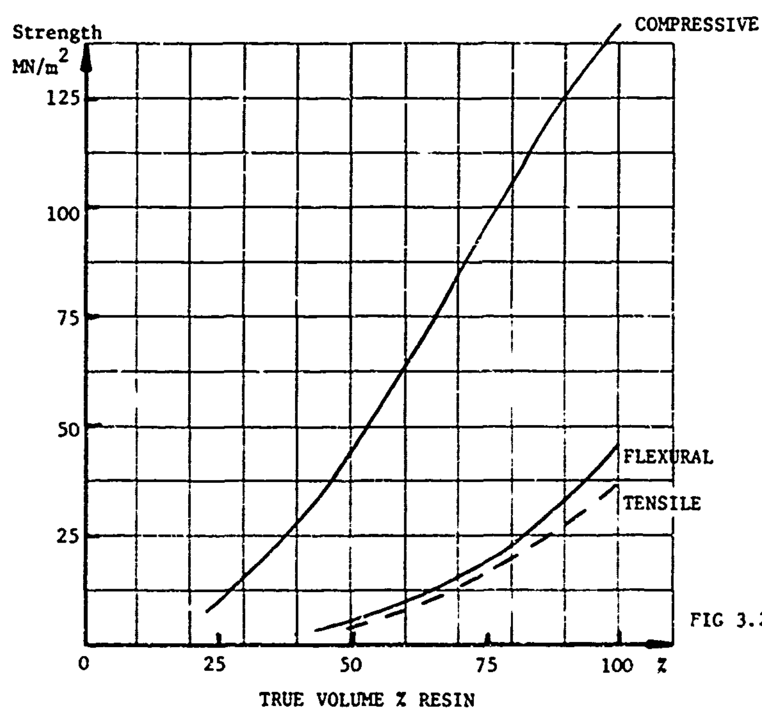


FIG 3.2.2.4.2

STRENGTH v. VOLUME % RESIN

3.2.2.5 Ceramic Foams

Ceramic foams have been considered on several occasions for the production of ceramic sandwich structures. Design calculations indicate that it should be possible to obtain radomes by this technique which have

(1) a bandwidth at normal incidence of ± 20 percent of the design frequency and high transmission efficiencies at incidence angles up to 45 degrees,

(2) a weight of two-thirds that possessed by a monolithic structure of the same size and design frequency, and

(3) low boresight error and reflection coefficient.

Alumina foam has been considered for radomes, and in particular fused silica has been extensively investigated at Georgia Tech. U.S. with A-sandwich structures (consisting of dense inner and outer skins enclosing a foam core). In general the design goals were met but the radomes were exceedingly difficult to construct. It is doubtful that production radomes could be built with adequate quality assurance or cost effectiveness.

Fused silica foams are manufactured in the United States, France, and Japan for refractory applications. Closed pore glassy foam can be prepared by carbonaceous foaming of a silica melt. Open pore foam is prepared by entraining air in a fused silica slip at room temperature, followed by drying and sintering. Because of the effect of product purity on electrical properties, only the open pore foam is of interest for radome applications. Silica foams derived from fused silica slips can be made in a range of densities from 0.4 gm/cm^3 (25 lb/ft^3) up to the density of slip-cast fused silica which is typically about 1.92 gm/cm^3 (120 lb/ft^3); the commercially available varieties are nominally 30 and 50 lb/ft^3 density. Property data given in this section are for slip-cast fused silica and open pore foams derived from fused silica slip, and detailed in Tables 3.2.2.5.1 to 3.2.2.5.4.

The fabrication difficulties associated with making A-sandwich radomes using ceramic foams are related to the shrinkage experienced on sintering. One fabrication approach is to cast the skins, prepare a whipped slip mixture containing enough gelling agent to prevent collapse of the foam, then assemble the skins and foam. After drying, the assembly is sintered to achieve the necessary strength and bond the parts together. However, the shrinkage of the foam core during sintering exceeds the shrinkage of the denser skins, so that cracking occurs in the core. A rather complex casting procedure can be employed to a[illegible]id cracking during casting, but no method to avoid cracking during sintering has been identified. A second fabrication approach is to slip-cast the skins, machine commercial foam blocks to the shape required for the core, and cement the assembly together. A-sandwich radomes can be made in this manner suc[illegible]ssfully, but the additional weight and non-homogeneity associated with the cement joints are undesi[illegible]le. In either of these fabrication methods, a severe penalty must be paid in complexity and labour cost.

Brief investigations of the feasibility of employing alumina foams in radomes have been conducted. Flat panels consisting of alternate layers of dense alumina and alumina foam were

ELECTRICAL PROPERTIES : Fused Silica Foam — TABLE 3.2.2.5.1

Property	Reference Fig	Remarks
Dielectric Constant v. Density	Georgia. Tech.	1.3 at 0.47 gm/cm^3; 1.6 at 0.80 gm/cm^3
Dielectric Constant v. Frequency		Negligible change over microwave band
Dielectric Constant v. Temperature		Increases with temperature in analogy with slip-cast fused silica
Loss Tangent v. Frequency		0.001 to 0.003; negligible change with frequency
Loss Tangent v. Temperature		Increases in analogy with slip-cast fused silica
Dielectric Constant v. Humidity		Increases with absorption of moisture
Dielectric Constant v. Radiation		
Volume Resistivity v. Temperature		Greater than 10^9 ohm-cm to 800°C; 10^5 at 1500°C
Dielectric Strength v. Temperature		

MECHANICAL PROPERTIES : Fused Silica Foam — TABLE 3.2.2.5.2

Property	Reference Fig	Remarks
Specific Gravity		0.4 to 1.92 gm/cm^3; 0.47 and 0.80 commercial
Youngs Modulus v. Temperature		
Youngs Modulus v. Porosity		1.9×10^9 N/m^2 at 0.4 gm/cm^2; 8.3×10^9 at 0.8 gm/cm^3
Shear Modulus v. Temperature		
Rupture Modulus		0.7 to 2.2×10^6 N/m^2 at 0.47 gm/cm^2; 3.4 to 4.8×10^6 at 0.80 gm/cm^3
Poissons Ratio		
Flexural Strength v. Temperature		Rises slowly to 1000°C, then falls sharply to almost zero at 1400°C
Tensile Strength v. Temperature		
Compressive Strength v. Temperature		2.0 to 6.2×10^6 N/m^2 at 0.47 gm/cm^3; 8.6 to 12×10^6 at 0.8 gm/cm^3 ambient temperature
Impact Strength		
Hardness		

THERMAL PROPERTIES : Fused Silica Foam — TABLE 3.2.2.5.3

Property	Reference & Fig	Remarks
Temperature Working Range	Georgia Tech.	To 1100°C in cyclic service; to 1400°C continuous of the time service.
Specific Heat v. Temperature		0.18 cal/gm °C ambient; o.25 at 500°C; 0.28 at 1900°C
Conductivity v. Temperature		3.1×10^{-4} cal/sec cm °C at 0.479 gm/cm^3; 4.1 $\times 10^{-4}$ at 0.80 gm/cm ambient temperature. Values approximately double at 1100°C
Diffusivity v. Temperature		
Expansion v. Temperature		Expansion coefficient 0.9×10^{-6}/°C to 1000°C. Drops sharply above 1200°C due to sintering
Emissivity v. Temperature		
Ablation		
Thermal Shock		Extremely resistant to thermal shock due to low thermal expansion
Flammability		Non-flammable

ENVIRONMENTAL PROPERTIES : Fused Silica Foam — TABLE 3.2.2.5.4

Properties	Reference & Fig	Remarks
Temperature		No limitations within working range listed in Table 3.1.2.3.3
Humidity & Water Absorption		Material is porous and absorbs water. No appreciable effect on strength
Rain Erosion		
Radiation Solar Nuclear		Undamaged by prolonged sunlight exposure
Contamination Oils Fuels Detergents Salts Acid		Porous material absorbs contaminants. Structural properties not affected
Storage & Ageing		Avoid vibration or shocks; inert

fabricated by an aerospace manufacturer in the United States. These were small coupons on the order of two inches square and contained seven and nine dense layers with six and eight foam layers respectively. Layer thicknesses were in the range of 0.050 inch, and cracking occurred in the foams due to differential shrinkage on sintering.

Fused silica foams can be prepared in either "commercial" or "high-purity" grades. The former contains about 99 percent SiO_2 and the latter about 99.6 percent SiO_2. The small difference in impurity level causes differences in physical and electrical properties between the two materials to be negligible.

Silicone nitride foam (Ref 5) has been shown to have very good electrical properties and capable of withstanding temperatures up to 1200°C. Measurement of its dielectric properties for a foam of dielectric constant 2.08 and loss tangent 0.0011 at 20°C, at 657°C was still 2.10 and 0.0005. Mechanically, it has high compression tensile and flexural strength, with strengths typically of a foam of density 0.8 gm/cc compressive 14 MN/m^2 (2000 lb/sq.in), flexural 4 MN/m^2 (600 lb/sq.in) and flexural, modulus 8.5 GN/m^2 (1.2×10^6 lb sq.in). Methods of applying skins remain to be solved.

3.2.3 Artificial Dielectrics

Two significantly different applications of artificial dielectric constants exist. The first is where for reasons of design a particular value of dielectric constant is desired as might be the case where optimum frequency of operation is to be changed for a radome where thickness is fixed and the required change in dielectric constant is outside of the range permitted by glass content variation. Alternatively a lightweight core may need to be raised in dielectric constant to match that of the skin. Secondly artificial dielectrics may be used to create a dielectric constant of unity or nearly so. In the former case the desired result can be achieved by the incorporation of a high dielectric titanate or of metallic particles into the matrix. In the case of metallic particles random or organized distributions can be used, but recent developments have used a random distribution which lends itself to more economical manufacture. The latter case always uses organized metallic elements which may be wires.

3.2.3.1 Titanate Loaded

Materials such as Titanium Dioxide and Strontium Titanate possess extremely high dielectric constants. (90-230). By including such material in a laminate or foam then depending on the quantity, the dielectric constant for the mixture can be adjusted.

The resultant dielectric constant for any mixture can be estimated using the formula of section 2.3.3.2 but it must be remembered that the mechanical properties of the mixture will eventually deteriorate as loading increases. Also large quantities of these materials can lead to manufacturing difficulties and possibly undesirably high inhomogeneity particularly with resin injection systems. In practice a limiting loading of the order of 20 to 30 percent (weight) would be experienced for low glass content laminates. Successful loading of resin glass composites with titanates have given a core dielectric constant of 16 of a B sandwich where the skins dielectric constant of 4 have matched the structure for wide frequency band usage.

Titanates have also been incorporated into foams but care must also be taken to note the increasing weight of the mixture with loading. Since these titanates are very dense often a large part of any initial weight advantage due to the use of foam can be lost by loading. Certain titanates have the additional advantage that over a significant range of temperature at dielectric constant/temperature coefficient is negative. Thus some correction for temperature effects can be effected. This was illustrated in Fig 2.2.1.1.3 for an alumina-titanate combination.

3.2.3.2 Metal Particle Loading (Ref 7)

Loading of low dielectric constant foams or resins with titanates to give higher dielectric constant does increase the weight significantly. Metallic particle loading allows a higher dielectric constant to be achieved with less added material and a consequent lower density. However, loss tangent does rise rapidly with increasing dielectric constant. Various particle types have been employed eg. flake in powder form, short strips, plating on microspheres etc.

Theories have been developed for the estimation of dielectric properties with particle type and loading. In practice these have met with mixed success due, in part, to the real difficulties during manufacture of achieving a true random distribution and orientation of particle. Improved processes have and are being developed which reduce this problem, but these are company confidential and are not available for discussion here. Various achievements in terms of dielectric constant and loss tangent have been reported. In (Ref 8) hollow glass microspheres coated with aluminium leaf powder in polyimide resin produced a material whose dielectric constant was 3.2 and loss tangent 0.015 at X Band with density 0.5 gr.cc, and compressive strength 7 MN/m^2. The performance of these materials with temperature is clearly dependent upon the constituents and particularly upon the resin matrix. Thus for a stable material such as polyimide very small changes in dielectric properties are seen. In one reported case a change dielectric constant of only 3.08 to 3.11 was given for the temperature range 20 to 320°C with no change of loss tangent. This field of development is still relatively new and theories are either not sufficiently developed or manufacturing process problems make their verification difficult. However, progress sufficient to allow the application of these materials has been made. Nevertheless it is not possible to quote given dielectric constant values for a range of specific loading because the achievement depends so largely on individual manufacturers skills.

For all normal loading quantities the mechanical properties can be taken as for unloaded basic foam.

3.2.3.3 Arrays of Metallic Elements

Many different types of metallic elements introduced into a low dielectric constant foam carrier or even laminate have been studied and are described in detail elsewhere (Ref 9 & 10). The main application of such artificial dielectrics has been in the field of microwave lens design where an increase of dielectric constant is wanted. While particularly favourable properties which one would naturally associate with a near unity dielectric constant can be realized their sensitivity to incidence angle and polarization have generally excluded their application to scanning antenna radomes. A few exceptions do exist and there are applications in non-scanning systems.

In such cases the use of an inductive wire grating, embedded into a laminate or number of laminates in the case of a sandwich has been made. The properties of such gratings are well understood and an example is given in Ref 10. If circular polarised radiation is present two gratings crossed in the form of a square lattice can often be used. However the polarisation sensitivity of a grating can sometimes extend the function of a radome to allow it for instance to act as a circular polarizer or a polarization filter.

3.3 References to Section 3

(1) V.A. Chase, Organic Radomes Chapter 4 "Radome Engineering Handbook", J.D. Walton Jr. Editor.

(2) Mechanical Properties of Hexcel Honeycomb Materials TSB120 June 1973.

(3) Hexcel Technical Literature TSB101.

(4) Plessey Co., Towcester, Northants, U.K. Data Sheet P10 Polyurethane Foam.

(5) G.M. Brydon and R.H.J. Cary, "Measurements on Some Radome Materials with Superior Dielectric and Temperature Characteristics", Electromagnetic Window Symposium, Paris, Sept 1967.

(6) Emerson and Cummings, Canton, Mass., U.S.A. Data Sheet "Eccospheres".

(7) L.E. Raburn et al, "Theoretical Calculation of the Loss Tangent of Artificial Dielectrics at Microwave Frequencies", 10th Symposium of Electromagnetic Windows, Georgia Tech., July 1970.

(8) S.A. Moorefield and J.R. Rogers, "Development of a Lightweight Advanced Aircraft Radome Based on Dielectric Loaded Foam Core Sandwich Construction", 10th Symposium of Electromagnetic Windows, Georgia Tech., July 1970.

(9) J. Brown, "Microwave Lenses", Methuen's Monographs p.27.

(10) R.H.J. Cary, "Loaded Dielectric Materials for Radomes", 2nd Conference of Electromagnetic Windows, Paris, Sept. 1971.

PART IV

PROTECTIVE FINISHES

INDEX TO PART IV

PROTECTIVE FINISHES

4.1 Introduction

Protective finishes are often applied to radomes to

(a) limit the absorption of water

(b) reduce rain erosion effects

(c) reduce static build up

(d) protect from heat flash, and

(e) improve performance in particularly adverse aerodynamic heating situations.

Sealants are of course only used on base materials which are of particularly poor moisture absorption characteristics. Thus both polyimide and slip-cast fused silica have received a lot of attention.

The range of choice for erosion protection materials has increased over recent years with the introduction of polyurethane elastomers and fluorocarbons to supplement the once exclusively used neoprene. Manufacturers of some erosion protectors also supply high resistance coatings which serve to discharge any friction induced static electricity. This of course, is not strictly radome protection, but rather reduces interference in avionics equipment (mainly communications).

Anti heat techniques simply increase, very greatly, the reflectivity of the radome, while ablation compounds are sometimes used to reduce friction heating in hypersonic situations.

4.2 Materials for Protective Finishes

4.2.1 Sealants

Where radomes are to some extent porous or hygroscopic attempts may be necessary to prevent ingress of contaminants, in particular water. Radomes on aircraft, or on missiles carried on aircraft, or on certain ground to air missiles on launching platforms can be subjected to various degrees of long term humidity and rain. Oils, greases, fuels, deicing and cleaning fluids etc are also possible sources of contaminants. While usually not seriously effecting mechanical strength, except in the case of honeycomb structures which have been known to burst on heating above 100°C, the ingress particularly of water can change the effective dielectric constant and loss tangent of the material, causing reflection transmission and phase delay variations. This in turn will produce attenuation and aberration.

The standard method of assessing water absorption is immersion in water of a standard size material and measuring the weight before and after 24 hours. (B.S. 972 and A.S.T.M. D570). Examples of results on some radome materials are:-

Alumina	near 0%
Pyroceram & Mexim	near 0%
Silica (Quartz)	minimal
Silica (Slip Cast Fused)	5-12% according to porosity
Cordierite (Rayceram)	minimal

Mullite	can be slightly porous 0.5%
Silicon Nitride (Dense)	minimal
Silicon Nitride (Reaction Bonded)	dependent on porosity
Boron Nitride	closed cell - minimal
Beryllium Oxide (Dense)	- minimal
Spinel	minimal
Magnesium Oxide	dependent on porosity
Glass-Mica	minimal
Glass-Aluminium Phosphate	absorbent
Polyester Laminate	0.5-1%
Epoxy Laminate	0.5-1%
Polyimide Laminate	1-2%
Silicone Laminate	depends on moulding pressure

Problem areas are likely to exist due to either porosity or hygroscopy with materials like slip cast fused silica, glass aluminium phosphate, polyimide, low pressure silicone and poor quality glass fibre resin laminates in general. In particular the soak test is not necessarily realistic, and a more realistic test is a water vapour permeability measurement over periods extending to long term. B.S. 2782 method 513A and B (U.K.) "Permeability to water vapour" outlines a method of determining permeability, (513A refers to temperate conditions and 513B to tropical) and permits evaluation of sealants.

The conventional thick layer of neoprene or polyurethane rain erosion coating serves as a good weather protection. Epoxy or polyester glass-fibre radomes for ground launched missiles were sometimes sealed with wax to maintain the electrical properties, but is of little use for aircraft, where every attempt has to be made to ensure minimum porosity. A smooth finish of resin on the surface with sometimes an additional polyurethane paint helps to seal epoxy or polyester glass-fibre laminates. In the radome design some allowance in the electrical properties as specified has usually to be made for some degree of humidity pick up.

The polyimide glass-fibre radome can present a major problem where it is subject to long term humidity, as it can continue to absorb up to 3%. The polyimide radical tends to make the material somewhat hygroscopic. Various sealants have been tried, subject to the B.S. 2782 (513B) method to an exposure of 8 days at 90% R.H. and 38°C, and indicate the difficulty of sealing polyimide glass fabric laminates:-

Surface sealant	Water absorption %
None	2.02%
PTFE spray	1.9
Polyester resin	1.86
Carnauba wax	1.76

Surface sealant	Water absorption %
Silicone grease	1.75
Epoxide based paint	1.67
Polyurethane paint	1.51

The best method of sealing is still being sought for polyimide resin.

Attempts to minimise the porous nature of slip cast fused silica (up to 12%) has been made by Georgia Tech. (U.S.A.) by, (1) fusion of the surface using arc-plasma jet of oxyacetylene torch, (2) surface sealing with a silicone resin, and (3) by impregnating the porosity with a silicone resin. The two silicone resin methods are preferred since the resin is easily applied and can be cured at moderate temperatures. Surface fusion, on the other hand requires specialized fusion and control equipment and must be carried out at high temperatures.

In thermal evaluation of porous ceramic radome materials such as slip cast fused silica, three-dimensional silica, and silicon nitride have been impregnated with a silicone resin SR-80. to prevent moisture absorption (Ref. 1). SR-80 is a silicone resin consisting of a siloxane (silicon-oxygen) skeleton with methyl groups (CH_3) satisfying the silicon bonds that are not linked to the oxygens. The resin is stable up to about 400°F (230°C) above which it slowly decomposes and near 400°C can char, and at higher temperature be converted to a dielectric silica if oxygen present.

4.2.2 Anti-Erosion Coatings

The sources of erosion of radomes are mainly, rain, dust, ice particles, sand and to a more serious level of damage, h[illegible] and stones. The magnitude of the problem varies enormously according to [illegible]hape, [illegible]at[illegible]n, construction, and material of the radome and the vehicle's speed, environment, and duration, and a study is usually required to ascertain whether it is necessary or cost-effective to include an erosion coating. Certain radome materials are excellent from rain erosion such as alumina and pyroceram, and need no protection. Glass fabric resin laminates are not in the same class and may be found to require protection. A.A. Fyall (Ref. 2) indicates a table of erosion resistance of typical materials possibly considered for radomes, when subjected to 1 in/hr rainfall at 500 m.p.h, and is summarised here with:-

Material	Time	Erosion
Alumina	4200 min.	negligible
Pyroceram	2580	slight pitting
Sapphire	1320	negligible
Steatite	290	pitted
Silicon nitride	105	pitted
Polyurethane coated Glass-fabric polyester	80	little damage
Neoprene coated Glass-fabric polyester	100	severe
Glass-fabric-resin laminate	15	severe

According to this data, in long term flights in rain, even at high speeds with such materials as alumina, or pyroceram, would not require protection, but for other reasons, such as structural, cost, or manufacturing problems, glass fabric-resin laminate construction may be preferred which will require protection. At very low speed and short duration flight probably no protection is necessary.

Another important factor is the angle of impact of the rain on the radome surface, and Fyall has suggested the erosion varies as the sine of the impact angle, which can modify the times or speed of the vehicle quoted, for a given erosion.

The materials which need most protection are the glass-fabric resin constructions which are the most common for aircraft radomes, except for high Mach numbers. Coatings of neoprene has been a well tried protection for glass-fabric resin laminates giving typically an 8 to 1 approximate improvement in life, and latterly polyurethane giving an even better protection and higher temperature performance. The thicker the protective material the longer the life, but as the material has little structural strength, its thickness detracts from the structural strength as the radome thickness usually is a finite thickness for best electrically performance. Furthermore the material represent additional weight with no structural advantage, hence is preferred to be applied with a minimum thickness to give a cost effective result, usually near 0.015" or 0.4 mm.

The materials are applied either like coats of paint or made in the form of a separate boot which is placed over the radome.

Rain erosion materials are an area where continual improvement is sought. The temperature limitations of polyurethane has led to fluorocarbon coating being considered. But none of these materials are ideal as they contribute little to the strength of the radome, introduce transmission loss which can become significant at the shorter wavelengths and higher temperatures.

4.2.2.1 Neoprene Anti-erosion Coatings

For many years neoprene elastomeric coatings represented the standard rain erosion radome coating, being one of the earliest materials used for this purpose. They have now been replaced by polyurethanes and fluorocarbons which provide substantially better rain erosion protection and higher temperature capability.

Neoprene coatings require primers and lengthy application schedules. They are usually applied by spray gun; multiple applications of dilute solutions are necessary to obtain coating thicknesses which effectively prevent rain damage, typically 0.008 to 0.012 inch. Coating quality and uniformity are dependent on operator skill. Curing times are on the order of three days and a dust-free environment must be maintained for spraying and curing. The coatings are not easily repairable in the field.

Both white and black neoprene coatings have been standardized; the applicable Mil Specs are MIL-C-27315 and MIL-C-7439B respectively. The Goodyear Tire and Rubber and the Gates Rubber Company are qualified suppliers under these Mil Specs.

Blistering of rain erosion resistant neoprene coatings on high speed radomes has been reported by C.J. Price (Ref. 3) who recommends a heat ageing schedule which reduced the blistering and increased the toughness of the coating.

Table 4.2.2.1.1 shows the effect of a 0.010 inch thick neoprene rain erosion coating plus a 0.001 inch thick antistatic coating on the power transmission characteristics of a typical filament wound radome at X-band. (Ref. 4).

TABLE 4.2.2.1.1 (REF. 4) EFFECT OF NEOPRENE RAIN EROSION COATING ON POWER TRANSMISSION OF A STREAMLINED HALF-WAVE WALL RADOME (X-BAND)

Antenna look angle	Frequency*	Power transmission, uncoated, %	Power transmission, coated, %
	F_L	82	76
0°	F_O	85	77
	F_H	76	64
	F_L	82	94
5°	F_O	85	75
	F_H	68	62
	F_L	86	96
10°	F_O	92	94
	F_H	76	79
	F_L	96	94
40°	F_O	92	94
	F_H	85	87

* F_L - lower range of X-band; F_O - middle range of X-band; F_H - high range of X-band.

4.2.2.2 Polyurethane anti-erosion coatings

Protection of aircraft radomes has utilized neoprene coatings initially against rain erosion. They provide inadequate resistance for the more recent and more advanced faster aircraft, as well as having disadvantages of difficult application procedures and to a certain extent poor weatherability. Research at AFML (U.S.A.) has indicated that compared to neoprene, polyurethane is an improved material, and initiated Olin Corp. (U.S.A.) to develop improved polyurethane coatings for glass-fibre resin radomes. (Ref. 5). Other firms and agencies have also produced improved polyurethane coatings, with the aim of good rain erosion, temperature, dielectric, weatherability, application, repair, properties, with some also including an anti-static layer.

The erosion performance of polyurethane coating compared to neoprene is shown in Fig. 4.2.2.3.1 where it offers at least five times the erosion resistance and has a failure time for a 0.012" polyurethane on glass-epoxy laminate of near 160 minutes at 500 M.P.H. in 1 inch/hour rainfall (AFML rig). At 600 M.P.H. the times of failure for elastomeric materials is near two-thirds that at 500 M.P.H.

The transmission properties of polyurethane coating measured at X Band (9.375 GHz after application was found to be 92% (Ref. 5). Another measurement indicated a near 4% transmission loss over X Band for identical radomes, one with and one without a U.K. manufacturers polyurethane coating, but of same electrical thickness. (Ref. 6). The loss is predicted to be more on K_u and K_a radomes and increased temperature.

Certain polyurethanes require the presence of moisture to cure coatings. If the ambient humidity is 50% or greater the uncatalyzed polyurethane will cure in 4 days, and with the use of a proper catalyst can be reduced to 1 hour between coats, and still requires some moisture, and near eight hours for complete application.

Among manufacturers producing polyurethane anti erosion coatings Hughson Chem Coy (Penn. U.S.A.) have developed a catalyzed elastomeric polyurethane coating material which does not rely on humidity to achieve its cure. I.C.I. and Dunlop (U.K.) have also supplied polyurethane rain erosion coatings.

Among the polyurethane materials which meet the military specification MIL-C-83231 entitled "Coatings, Polyurethane, Rain Erosion Resistant for Exterior Aircraft and Missile Plastic Parts" is "Astrocoat" a product of the Olin Corporation (U.S.A.), who have supplied the following data in Tables 4.2.2.2.1 and 4.2.2.2.2 (Ref. 7).

TABLE 4.2.2.2.1. RAIN EROSION ON COATED EPOXY LAMINATE SUBSTRATES AT 500 M.P.H. FAILURE TIME 1"/HR RAIN (THICKNESS COATING 0.012")

Astrocoat MIL-C-83231	
black	160 minutes
white	80 minutes
Neoprene MIL-C-7439	
black	40 minutes
white	20 minutes
Epoxy	3.5 minutes
Polyester	1.2 minutes

TABLE 4.2.2.2.2

PHYSICAL PROPERTIES

Physical properties of ASTROCOAT systems are as follows:

Tensile strength, psi (min)	2000
Elongation %	500
1/8" conical mandrel at $-40^{o}F$	Passes
Four days at $165^{o}F$ and 95% Relative Humidity	No Effect
Dielectric Constant at 9.375 GHz	3.158
Loss Tangent at 9.375 GHz	0.059
Water Immersion of Coated panels for 68 hrs.	No Effect
Temperature Resistance of coated panels	Serviceable up to $300^{o}F$
Shelf Life	One year

SOLVENT RESISTANCE

The immersion of ASTROCOAT Systems for one hour in commercial and military solvents is shown below:

SOLVENTS	ASTROCOAT RESISTANCE
Alcohol	Excellent
Xylene	Good
Mil-H-5606	Excellent
Mil-L-7808	Excellent
JP4	Excellent
Fuel B	Excellent
(Isooctane-toluene 70/30) Hexane	Excellent
Methyl Ethyl Ketone	Poor
Tetrahydrafurane	Poor

For use where the build up of static electricity must be prevented Astrocoat System Type II consists of a single primer coat, multiple coats of erosion resistant coating to 0.011" thick and one or two coats of antistatic topcoat, having a surface resistivity of near 1 meg ohm per square.

Minor scratched or damaged areas can be touched up by smoothing, cleaning with trichloroethane and reapplying Astrocoat with a brush.

The high loss tangent 0.059 at room temperature and X Band rises to 0.13 at $130^{o}C$, and is even higher at K_u and K_a bands, and can become a significant loss operationally in radome design. (Ref. 8).

4.2.2.3 Fluoroelastomer-anti-erosion coatings

Because of aerodynamic heating associated with supersonic flight, erosion resistant coatings with long term (hundreds of hours) thermal stability at temperature up to $500^{o}F$ ($300^{o}C$) are required for advanced systems where erosion prone glass fibre high temperature resin constructions are used. Polyurethanes are limited in service temperature to $300^{o}F$ ($167^{o}C$) for long term and $350^{o}F$ ($188^{o}C$) for shorter periods (up to 24 hours). At higher temperatures, current polyurethane anti-erosion coatings lose their elastomeric characteristics and rain erosion resistance very rapidly.

The improved rain resistance material sought must also have good dielectric, weathering, application, repair properties and incorporate preferably an anti-static coating. A.F.M.L. (U.S.A.) has evaluated candidate elastomeric/polymeric coatings including silicones, polyimides, amide-imides, fluorosilicones, carboxy-nitroso, silphenylene-dimethylsiloxane, with little success. G.F. Schmitt, Jr (Ref. 9) has reported that newly developed fluorocarbon coatings do meet the requirements. The erosion performance of these coatings as a function of thickness is compared in Fig. 4.2.2.3.1 where their erosion resistance is better than neoprene but not as good as polyurethane. However if long term exposure at higher temperatures are required the fluoroelastomer coating is superior, as shown in Fig. 4.2.2.3.2. It has long term thermal stability up to 500°F (near 300°C) and can withstand rainfall conditions of 1"/hour at 500 M.P.H. for an average 55-60 minutes. Coatings demonstrated a one way power transmission loss at room temperature at 9.275 GHz of 6%, and 10% with an additional anti-static coating. They can be applied to full 0.012" thickness in 3 hours using conventional spray techniques, cure at room temperature and maintain erosion resistance, transmission and anti-static properties for long periods, and is recommended where the temperature exceeds that of polyurethane coatings.

4.2.2.4 Ceramic type anti-erosion coatings

Certain ceramic materials such as alumina, and glass ceramics like Pyroceram and Mexim have very good rain erosion resistance and can also withstand higher temperatures than plastic coatings. However the advantages of the ease of fabrication, versatility of form, good structural and electrical properties of reinforced plastic radomes, are so compelling that this remains a most desirable method of fabricating radomes. A most desirable way of utilizing the inherent erosion resistance of ceramics and the advantages of plastic radomes would be to use a thin ceramic shell over the exterior of the plastic radome, states J.R. Williamson A.F.M.L. (Ref. 10) who has studied manufacturing processes for producing alumina coatings on glass reinforced plastic radomes for supersonic aircraft and missile applications. Rokide and plasma sprayed alumina coatings into female moulds are made on to which radomes were formed. Radomes were successfully tested at Mach 3 in 3200 ft. of rain of 2½"/hr with 1.9 mm drop size.

Tests in the U.K. by R.A.E. of thin ceramic and glass ceramic shells on 0.3 resin fibre glass radomes indicated they would break up under vibration and rain impact particularly if the shells were thin. Only when a very thick ceramic material was used and could withstand the shock in its own right did the material survive. At the K_u band microwavelengths the electrical desired thickness inferred that the radome would be entirely ceramic.

J.D. Walton Jr. (Ref. 11) evaluated various ceramic coatings for rain erosion protection and quoted results and prediction for Mach 2 speeds. Typically a coating of 0.040" of alumina on an epoxy was likely to fail at an angle of 45°.

J.S. Waugh (Ref. 12) selected a 3-D orthogonal silica composite structure for a radome material based on observations that the 3-D material had previously been shown to possess many of the desirable physical, chemical, and thermal characteristics of slip cast fused silica as well as exhibiting an order of magnitude increase in its resistance to impact loads. Samples of silica fibers held together by a plastic matrix showed significant damage when exposed to simulated rain with the fiber axis perpendicular to the rain impingement whereas a sample with the fiber axis parallel to the rain impingement direction showed no erosion. It appeared that a superior material could be obtained if a suitable high temperature matrix, such as slip cast fused silica could be combined with silica fibers to produce a highly impact resistant, thermally stable material of better rain erosion resistant properties.

4.2.3 Anti-static coatings

Static electricity builds up on the surface of radomes due to the friction with high velocity air and particles within the air. The build up can be such as to cause discharges which can result in interference with aircraft communication equipment and with damage to radome. The damage usually is in the form of pin holes through the radome to the edge of metallic scanners which come in close proximity to the radome inner surface. A ring of pin holes round the radome is typical of this happening.

Anti static coatings may be applied to the outer surface of the radome as a conductive paint. The resistance is high and the coating very thin so as not to cause any significant transmission loss. The resistance is low enough to allow the static charge to discharge softly and minimise electrical interference and not to spark through the radome to earthed metallic objects within the radome.

Where the anti-static requirements have to be combined with rain erosion protection, systems have been developed to combine erosion resistance coatings with a final electrically conductive top coat. A typical system is the Astrocoat Type II (Ref. 7) where a single primer coat is applied (0.025 mm), followed by multiple coats of erosion resistant polyurethane (up to 0.4 mm thick) and then one or two coats of anti-static top coat (0.025-0.05 mm) to give a surface resistivity of near 1 meg ohm per square and approved to MIL spec C 83231, and C 7439B.

4.2.4 Antiflash Materials

In certain instances protection against high energy band radiation inputs is necessary. This has been achieved by the incorporation of a highly reflective layer on the outer surface of the radome. Such a layer might be added separately, as with a white neoprene or actually incorporated into the radome build. This latter technique has been used by the British Aircraft Corporation where after moulding the main structure the mould was opened slightly and a further thin layer of TiO_2 loaded resin injected into a thin outer woven glass shape. In other cases pigments such as ZnO, TiO_2 and ZnS into plastic materials such as polyurethane, silicones, neoprene, etc.

In the case of a design which is critical in this respect the designer will make a special study of antiflash materials. Details of performance will therefore not be given, but the readers attention is drawn to Reference 2 for further information.

4.2.5 Ablative Coatings

Hypersonic and re-entry vehicles require the use of a heat shield to protect missile structure from aero-dynamic heating during flight. The use of radar for guidance etc, requires that a portion of the heat shield shall be electrically transparent during operation. Dielectric materials which char at high temperatures causing high dielectric loss are not preferred. An ablative material which changes the electrical thickness of the radome little during ablation without charring is preferred, hence a low dielectric constant material is implied.

Ablation is a process whereby a material expends mass to achieve heat absorption, blocking heat or the dissipation of heat. In the process material is physically removed from the surface. The actual mass loss depends upon the severity of the environment. In general the process of ablation is undesirable for any radome if it consists of a tuned structure. This is because loss of material on ablation inevitably results in a thickness change with consequential detuning and performance loss.

The different performances of the vehicles must also be considered e.g. a re-entry vehicle has a very high velocity for a short period, causing a high surface temperature, most of the energy being lost by re-radiation. A hypersonic vehicle on the other hand, has a lower velocity for a longer period and thermal conductivity of the material will be a factor of greater importance.

Tests on various materials have been carried out by AVCO. Corporation (Ref. 13) using a plasma arc, and dielectric measurements made during cooling.

For re-entry bodies, teflon-quartz is a favoured material having low dielectric constant, and producing a non-carbonaceous char. The addition of an oxidising agent improved the dielectric loss during ablation.

Another improved material is a poly formaldehyde termed Celcon, also used in conjunction with the quartz fibre.

For hypersonic vehicles a low density ablator 480-1B does not produce a carbonaceous char and has good dielectric properties. An epoxy-urethane material 8021 is similar to teflon in dielectric properties and has the advantage that it may be cast into shape. AVCOAT I is another material (with properties not as good as 8021).

Results of glass fibre resin tactical missile ablative radomes coated with AVCO 8021 are given in (Ref. 14).

Carlson (Ref. 15) has described a silicone ablator designated SLA 220. For relatively low heat flux exposure its attenuation is small, but for a heat flux level of 50 secs 19 BTU/ft^2/sec gave 2 dB attenuation one way at 35 GHz due to charring.

Markowitz (Ref. 16) quotes a 0.5 dB loss one way at 10 GHz with a heat flux of 165 BTU/ft^2/sec for 40 secs for a silicone ADL resin impregnating quartz fibre reinforced silica. The resin is said to be converted to SiO_2 upon pyrolysis.

Certain materials like slip cast fused silica form a very viscous layer at high temperatures on their surface, which modifies the radiation from the melt layer and its ablative properties (Ref. 17).

In the cases where ablative techniques must be employed, the designer should make a special study of the ablation process and of materials. Further detailed properties will not be recalled here, but the readers attention is drawn to Schmidt, Reference 18, for an overall summary of the subject and to reference 19 for detail.

4.3 References to Section 4

Ref. 1 Burns J.M. and Shukis F.A. "Thermal Evaluation of Porous Ceramic Radome Materials". 12th Symp. on Elect. Windows, June 74, Georgia Tech.

Ref. 2 Fyall A.A. Chapter 8 page 536. "Radome Engineering Handbook". J.D. Walton Ed. Dekker 1970.

Ref. 3 Price C.J. "Cause and Cure of Neoprene Coating Blisters on Supersonic Aircraft Radomes", 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 4 Chase V.A. Chapter 4 page 209, "Radome Engineering Handbook", J.D. Walton Ed. Dekker 70.

Ref. 5 Schmitt G.F. Jr. "Polyurethane Coatings for Subsonic Radome Rain Erosion Protection". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 6 B.A.C. Ltd, Warton, U.K. Test Note 1156.

Ref. 7 "Astrocoat" Publication by Olin Corp. Stamford, Connecticut, U.S.A.

Ref. 8 R.R.E. and Plessey Measurements (U.K.).

Ref. 9 Schmitt G.F. Jr. "Synthesis of Elevated Temperature Resistant, Erosion Resistant Polymeric Coatings". 11th Symp. on Elect. Windows, Aug. 72, Georgia Tech.

Ref. 10 Williamson J.R. "Manufacturing Techniques for Production of Rain Erosion Resistant Coated Structures". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 11 Walton J.D. Jr. and Gorton C.W. "Evaluation of Ceramic Coatings for Rain Erosion Protection". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 12 Waugh J.S. and Goldstein S.D. "A Rain Erosion Evaluation of 3D Woven Silica and Reaction Sintered Silicon Nitride". 12th Symp. on Elect. Windows, June 74, Georgia Tech.

Ref. 13 Poulin B., McHenry R.J., and Patrick A.J. "Antenna Windows for hypersonic and re-entry vehicles". 9th Symp. on Elect. Windows, June 68, Georgia Tech.

Ref. 14 Christiansen G.W. and Ott J.D. "Tactical Missile Ablative Radomes". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 15 Carlson D.L. and Strauss E.L. "Signal Transmission Through an RF Transparent Ablator During Low Heat Flux Exposure". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 16 Markowitz L. and Al. "RF Transparent Ablative Silica-Silicone Composite". 10th Symp. on Elect. Windows, July 70, Georgia Tech.

Ref. 17 Burleson W.G. and Letson K.N. "Ablation Tests of Slip Cast Fused Silica Simulating Ballistic Re-entry". 12th Symp. on Elect. Windows, June 74, Georgia Tech.

Ref. 1ᶜ Schmidt G.F. Jr. A.F.M.L. TR-65-29, Air Force Materials Symposium 1965, Wright Patterson Air Force Base, U.S.

Ref. 19 Ablation Handbook. "Entry Materials Data and Design". AVCO Corporation Technical Report AFML-TR-66-262, Nov 66 for Air Force Materials Lab, Wright Patterson Air Force Base.

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