ACCURATUS CORPORATION

A Review of Selected Properties of Commercially Available Technical Ceramics

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PREFACE

Accuratus Ceramic Corporation was founded in 1977 by Dr. Jay E. Comeforo, an internationally respected ceramic scientist. In1983 a new entity was created, Accuratus Corporation, when Dr. Comeforo retired selling the company to his management team and an outside investor.

The company specializes in supplying and precision machining a wide range of non-metallic materials, primarily ceramics. With a broad base of science and engineering experience, the company also offers technical assistance in ceramic engineering design, and ceramic material selection, to custom applications.

Unlike metals, ceramics historically have been regarded as unpredictable engineering materials due to their brittle nature, or lack of plastic deformation before catastrophic failure. However, with a better understanding of the strengths and limitations of the various ceramics manufactured, engineers are able to take advantage of the wide range of unique and outstanding ceramic properties to achieve their design objectives.

Thus, with this “design optimization through material science” belief, we offer herewith UNBIASED data and opinions on all materials discussed in this review and others upon request.

Product engineering evolves through the continuous research and development process. Accuratus’ philosophy is to assist our customers in bringing technically superior products to their expected level of performance.

Your comment, if any, is cordially invited.

A REVIEW OF SELECTED PROPERTIES OF COMMERCIALLY AVAILABLE TECHNICAL CERAMICS

INTRODUCTION

Material selection for a specific engineering application requires knowledge of pertinent material properties and correlation of those properties to the ultimate design objectives of a project. Ceramics, being ionically and/or covalently bonded solids, possess a number of unique material properties. Spectacular examples of improvements in ceramic properties can be found throughout the electronics revolution of the past several decades as ceramic suppliers have striven to meet the accelerating demands of the electronics industry. These outstanding property improvements are inducing other existing and emerging technologies to evaluate the benefits of using ceramics to meet their unique requirements. This basic drive for higher performance is the source of the constant flow of new applications and new compositions being developed to meet ever growing engineering demands.

This brochure is intended to provide the basic material properties of selected commercially available ceramics to those scientists and engineers considering ceramics in their designs. The interrelationship between properties and fundamental bonding and microstructure are also discussed because most ceramic bodies are complex chemical systems; polyphase, polycrystalline solids having grains and grain boundaries of different composition.

DENSITY

The density figures reported in Table I refer to theoretical density, which assumes a defect free crystalline phase and the absence of voids. Bulk density is the measured density of a body and includes all lattice defects, phases and porosity. The ceramics described in this paper are all available at greater than 95% of theoretical density except as noted.

TABLE I – THEORETICAL DENSITY (except as noted)

MATERIALS	DENSITY (grams/cc)
1020 Steel (for reference)	7.80
Zirconia (YTZP)	6.10
Alumina	3.98
Aluminum Nitride	3.26
Silicon Carbide	3.21
Silicon Nitride	3.18
Beryllium Oxide	3.01
Boron Carbide	2.52
MACOR® Machinable Glass Ceramic	2.52 (bulk)
Boron Nitride (hexagonal alpha phase)	2.28

HARDNESS

Hardness is not a basic material property, being a function of complex interactions between fundamental material properties and the test apparatus. In single crystal materials, hardness is related to the atomic structure of the crystal and the presence and mobility of dislocations within the structure. In polycrystalline materials, like ceramics, the hardness is highly dependent upon the microstructure.

Tests commonly used for measuring hardness include scratch, abrasion and penetration tests. Each test derives an empirical number specifically related to the characteristics of the test. The Knoop hardnesses listed in Table II are derived from an indentation test wherein a small rhombus shaped diamond point is pressed against the ceramic surface at a specific load and the size of the resulting damage is measured. As a relative point of reference, a fully hardened and nitrided tool steel has a Rockwell C hardness of 65 or Knoop value of approximately 700. The alumina listed in Table II has an Rc hardness of approximately 85 or Knoop value of 2000.

TABLE II – HARDNESS

MATERIALS	**Knoop Microindentation Hardness Kg/mm^2 (100g load) @ Room Temp.**
Diamond (for reference)	7000
Boron Carbide	3200
Silicon Carbide	2800
Silicon Nitride	1600
Alumina (1000°C)	1500
Beryllia	1200
Aluminum Nitride	1100
Zirconia	1100
MACOR® Machinable Glass Ceramic	250
Boron Nitride (hexagonal alpha phase)	205
1020 Steel (for reference)	<200

MELTING POINT

The melting temperature of a ceramic is dependent upon the atomic bond strengths in the body. The melting point is essentially independent of the microstructure, however, the polyphase nature of ceramics results in a melting point that is a weighted average of the melting points of the constituents present in the ceramic body. Some materials such as carbon, do not melt but decompose or sublimate when heated. Table III lists melting or decomposition points at a pressure of one atmosphere. During testing a protective atmosphere may be required to prevent oxidation.

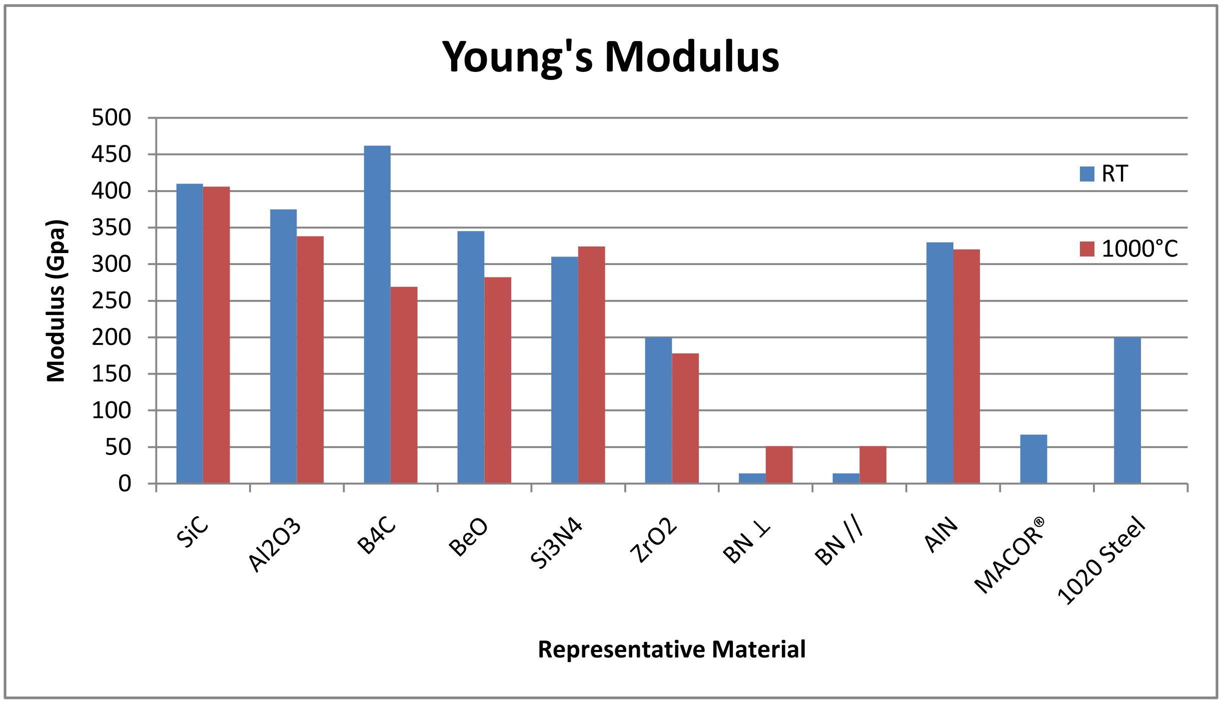
TABLE III – MELTING POINT

MATERIALS	**APPROXIMATE TEMPERATURE (°C)**
Zirconia	2765
Boron Nitride	2700 (decomposes)
Beryllia	2570
Silicon Carbide	2450 (decomposes)
Boron Carbide	2425 (decomposes)
Aluminum Nitride	2300 (decomposes)
Alumina	2050
Silicon Nitride	1870 (decomposes)

ELASTIC MODULUS

The elastic modulus or Young's modulus is a proportionality constant relating the stress in a body to the elastic strain induced in the body due to an externally applied force. It is related to atomic bond strength and varies with changes in inter-atomic distance. Note that this relationship only applies to a material whose response to an applied load is elastic i.e. strain resulting from an applied load is recovered when the load is removed. The elastic modulus also varies with crystallographic orientation in anisotropic crystals. An awareness of this anisotropy should be maintained even when considering apparently isotropic polycrystalline ceramics. Young's modulus decreases with increasing temperature due to increased atomic vibration and a corresponding increase in inter-atomic spacing. Figure I compares the Young's Modulus of several ceramics and a common carbon steel.

Figure I



STRENGTH

Measuring the compressive strength of a ceramic body is a standard procedure. However, the material characteristics and their interrelationships resulting in a given strength are very complex and not well understood. Generally, the measured compressive strength is significantly lower than theoretical strength. Factors limiting the achievement of theoretical strength in polycrystalline ceramics include slip along crystallographic planes, the type, size and nature of flaws present, anisotropic expansion characteristics of individual crystals and grain size effects.

Flexural testing (Modulus of Rupture) is a routine procedure commonly used to measure the strength of ceramics. By definition, bend strength or Modulus of Rupture is the maximum tensile stress at failure. The measured strength is critically dependent upon the size of specimen tested and whether a three point or four point flexural test is used. These effects are due to the distribution and size of flaws present in a ceramic and the distribution of the tensile stress field within the ceramic

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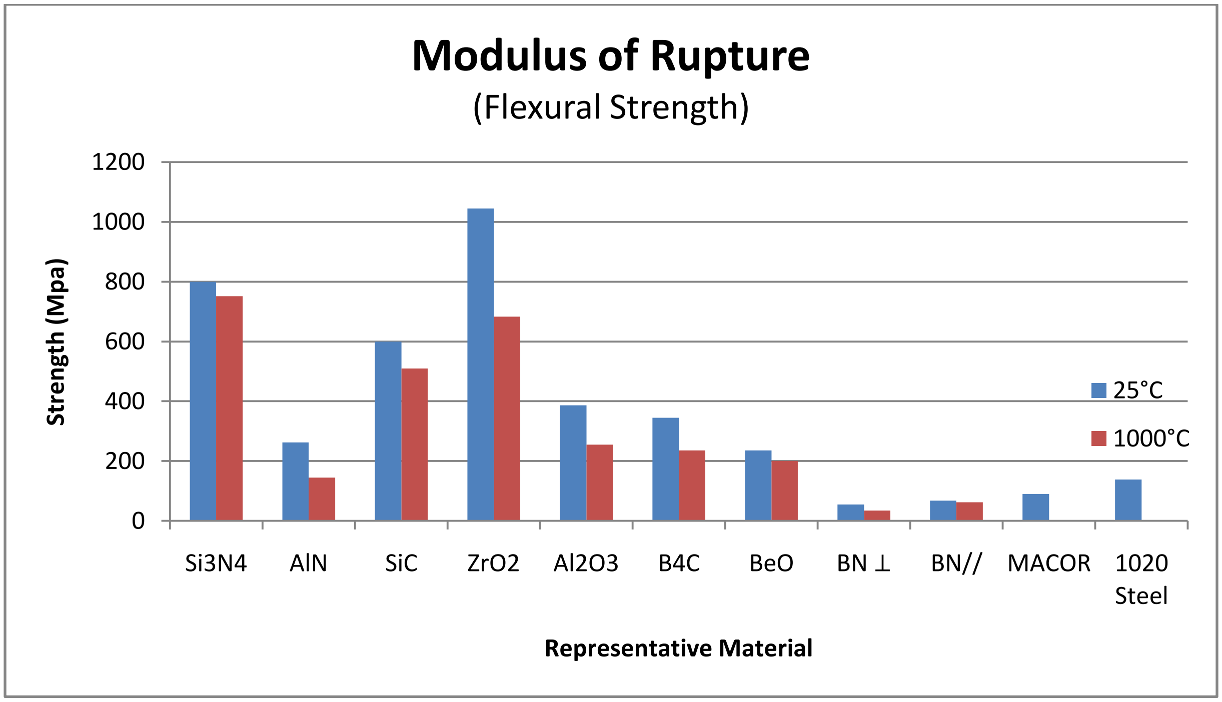
Flexural testing causes maximal tensile stress only on the surface of a body, therefore, it is imperative that test specimens be carefully prepared using standardized techniques to minimize data scatter or error due to surface damage incurred during specimen fabrication.

A three point flexural test fixture has two rolls for specimen support and a single roll located midspan for load application. A four point test fixture has two rolls for specimen support and two rolls for load application spaced equidistant from the support rolls. Application of a load to a specimen in three point flexure results in a peak stress line on the face opposite the load roll. In four point flexure, the peak stress occurs on the surface area between the two load rolls on the face opposite the load application.

Tensile failure of ceramics is due to incipient cracking at flaw sites followed by crack growth through the body. A number of researchers have developed relationships between flaw size and stress at fracture showing that flaw size is inversely proportional to the square of the stress at failure. This relationship illustrates why three point bend strength data should be used very cautiously in design work due to the low probability of finding the critical flaw along a single line of peak stress and the corresponding artificially high strength. Four point bend strengths are better in this regard because an area of the ceramic is subjected to peak tensile stress increasing the probability of applying peak stress to the critical flaw. However, this applies only to one surface. In fact, the specimen volume above the neutral axis is in compression during a flexural test.

As ceramic materials become more consistent and flaw size and distribution become more uniform, the values reported by different flexural test modalities will tend to approach one another and more realistically approximate the true strength of a ceramic. Figure II presents four point flexural strength data for a number of ceramics and a common carbon steel.

Figure II

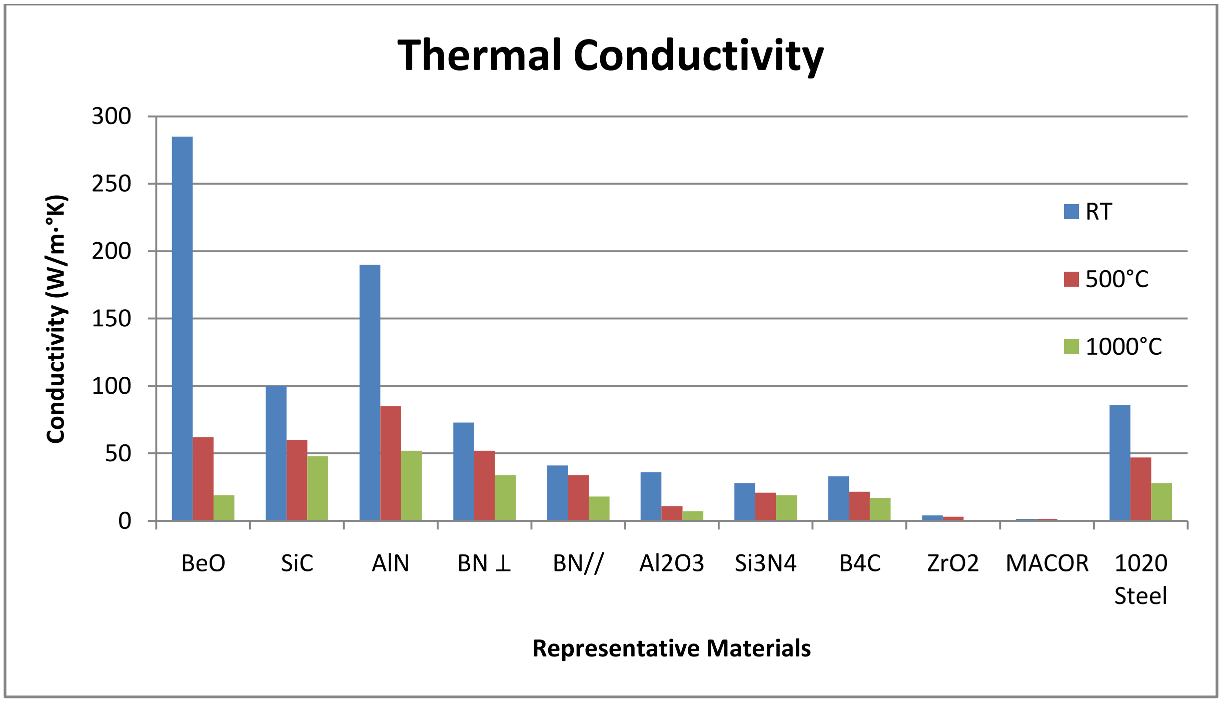


THERMAL CONDUCTIVITY

Thermal conductivity in ceramic materials is primarily a function of phonon and photon energy transfer. Phonons, being quantized lattice vibrations, move most easily through uncluttered, simple crystals. Solid solutions, grain boundaries and crystals with large differences in the size and weight of their constituent elements all tend to scatter lattice vibrations reducing thermal conductivity. Radiation (photon transport) increases with approximately the fourth power of temperature and becomes a significant heat transfer mechanism above 400°C. Radiation is strongly influenced by the emissive and absorptive characteristics of the material. Photons are scattered by pores, grain boundaries and inclusions in a material thus reducing radiation heat transfer.

Phonon and photon transfer exhibit a negative and positive temperature dependence respectively. Increasing temperature reduces the mean free path of phonons and thereby decreases thermal conduction in crystalline materials. In glasses where the mean free path of phonons is extremely short due to the disordered structure increasing temperature will tend to increase thermal conductivity as the heat capacity and radiation increase. The relative contribution of each energy transfer mechanism will determine the shape of the conductivity versus temperature curve for a material. Figure III presents thermal conductivity data for a number of polycrystalline ceramics at various temperatures.

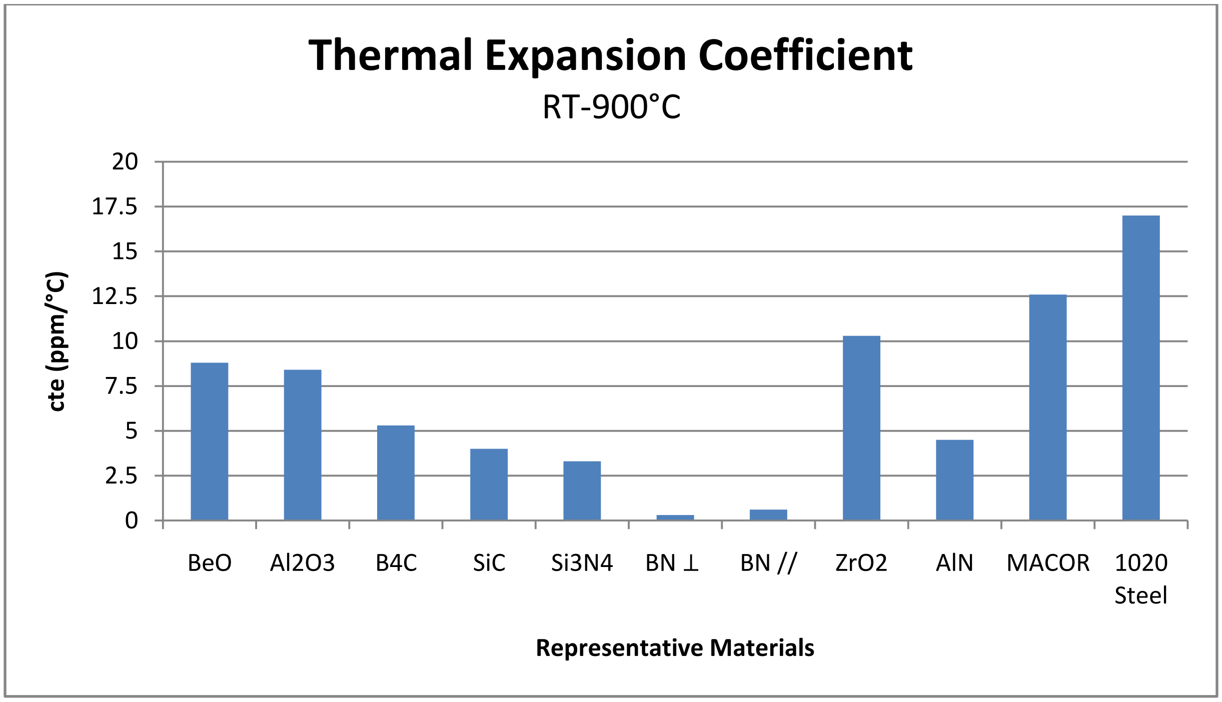
Figure III



THERMAL EXPANSION

The coefficient of thermal expansion of a crystalline material is related to the atomic vibrations within its structure. Ionically bonded ceramics exhibit moderate expansion coefficients with increasing temperature due to their close packing and increasing inter-atomic spacing with increasing atomic vibration. Conversely, covalent solids generally exhibit low expansion coefficients because the atomic vibrations can be accommodated more easily by the open space within the structure and bond angle shifts. Expansion rates vary with crystallographic orientation which has a deleterious effect on the ability of a polycrystalline ceramic to tolerate repeated thermal cycling. Additionally, many crystals such as crystalline quartz undergo polymorphic transformations at certain temperatures resulting in sudden volumetric changes. These sudden changes in volume make the ceramic very vulnerable to cracking when the transformation temperature is crossed even at very slow heating or cooling rates. Figure IV presents thermal expansion coefficients for several ceramic materials and a common carbon steel.

Figure IV



THERMAL SHOCK

Thermal shock refers to the mechanical stresses induced in a ceramic piece when various regions of the piece are exposed to temperature differentials. The ability of a ceramic to withstand thermal shock is dependent upon the interplay of a number of properties, the most important of which are thermal expansion, thermal conductivity, mechanical strength, and Young's modulus. For the best thermal shock resistance, the thermal expansion and Young's modulus should be low and the thermal conductivity and mechanical strength high.

A test which serves to compare the thermal shock resistance of brittle materials consists of quenching specifically sized rods of the materials into a water bath held at a specific temperature, usually near room temperature. The mechanical strength of the samples quenched from different temperatures is then measured. The temperature differential at which initiation or propagation of cracking occurs is clearly indicated when the strength value is plotted versus quenching temperature difference. The quenching temperature difference at which a strength reduction is encountered is referred to as the critical temperature difference. A higher critical temperature difference indicates greater the thermal stress resistance of the material.

TABLE IV - RELATIVE RESISTANCE TO THERMAL SHOCK FRACTURE

MATERIAL	CRITICAL TEMP. DIFFERENCE (°C)
Silicon Nitride (hot pressed)	900
Silicon Carbide (hot pressed)	415
Zirconia	300
Beryllia 99.5%	300
Alumina pressureless sintered 97.5%	300
Boron Carbide	200
MACOR® Machinable Glass Ceramic	200

CREEP

Creep is a plastic deformation and is a function of time, temperature, load and environment. It is usually a design consideration for ceramic components only at elevated temperatures. In single crystals, creep is associated with slip along crystal planes. In polycrystalline ceramics creep is more strongly influenced by diffusion and movement of grain boundaries. In glassy materials, creep is a function of viscous flow. Generally, creep increases with increasing load and temperature. Research has shown that several preferred mechanisms can be induced in a material simply by changing temperature, stress or microstructure.

ELECTRICAL CONDUCTIVITY

A wide range of volume resistivities related to several conduction mechanisms are available in ceramic materials. Electronic conduction will occur in transition metal oxides such as ferric oxide due to the presence of unfilled d and f orbitals and the mobility of those electrons under an applied electric field. Ionic conductivity is a function of the energy required to move ions from one position to another within a structure. This conduction mode is common in the ceramics and glasses exhibiting moderate to high bulk resistivity. Semiconducting properties can be modified through the admixing of high and low conductivity materials, doping, or the development of lattice defects. Table V lists the volume resistivities of a number of ceramic materials.
Surface Resistivity of a ceramic is generally lower than its bulk resistivity because of contaminants or moisture present on a surface.

TABLE V – VOLUME RESISTIVITY

MATERIAL	**$\Omega\cdot cm^2/cm$ (Room Temp.)**
Alumina	$>10^{14}$
Beryllia	$>10^{14}$
MACOR® Machinable Glass Ceramic	$>10^{14}$
Silicon Nitride	$>10^{14}$
Zirconia	10^{10}
Boron Nitride (hexagonal alpha phase)	$>10^{12}$
Aluminum Nitride	10^{11}
Silicon Carbide (dopant level dependent)	10^{2} to 10^{6}
Boron Carbide	1

DIELECTRIC PROPERTIES

The dielectric constant arising in electrically insulating ceramic components is a combination of electronic and ionic polarization and, in some cases, dipole orientation. Typical dielectric constants for several materials are listed in Table VI.

TABLE VI – DIELECTRIC CONSTANT

MATERIAL	**@ Room Temperature 1 MHz**
Aluminum Nitride	10.0
Alumina	9.6
Silicon Nitride	7.0
Beryllia	6.5
MACOR	5.9
Alpha Boron Nitride	4.1

Dielectric losses occurring in ceramic materials are due to a variety of mechanisms including ionic mobility, atomic vibration and dipole rotation. The losses occurring in ceramic materials are primarily vibrational resulting from high frequency resonances. These effects will vary with frequency and temperature. These loss mechanisms result in heating of the dielectric material. The dielectric can be represented as a resistor in parallel with a perfect capacitor. The ratio of the loss current flowing through the resistance to the current flowing through the capacitance is the dissipation factor of the material. This ratio is also the tangent of the angle representing the deviation of the voltage-current phase angle from the theoretical 90° of a perfect capacitor and hence is also referred to as the loss tangent. Table VII lists the dissipation factors of a number of ceramic dielectrics. These values will vary with frequency and temperature.

TABLE VII-DISSIPATION FACTOR

MATERIALS	**@ Room Temperature 1 MHz**
Alumina (99.5%)	.0003
Beryllia	.0004
Alpha Boron Nitride	.001
MACOR	.002
Aluminum Nitride	.002
Silicon Nitride	.004

The dielectric strength of a material is affected by three failure modes: corona, thermal failure and intrinsic breakdown. Corona breakdown is a discharge occurring at internal voids causing erosion and locally intense electric fields eventually leading to failure. Thermal failure occurs at elevated temperatures or is caused by self heating of the material due to dielectric losses. As the temperature increases, the leakage currents also increase ultimately resulting in puncture. Intrinsic breakdown occurs when the field strength exceeds the intrinsic dielectric strength of the material. Essentially, the applied electric field accelerates electrons to a velocity sufficient to liberate bonded electrons upon collision culminating in an avalanche of electrons and dielectric failure. Typical room temperature dielectric strengths are listed in Table VIII for a sample thickness of 6.35 mm (1/4 inch).

TABLE VIII DIELECTRIC STRENGTH

MATERIAL	AC kV/mm (Room Temperature)
MACOR® Machinable Glass Ceramic	40
Boron Nitride hexagonal alpha phase	15.6
Aluminum Nitride	10
Beryllia	9.6
Alumina	8.8

More specific information on the materials discussed is available from Accuratus. If you need data for a material property not listed or would like to discuss the application of a ceramic to solve a specific design problem, please contact Accuratus. We will be pleased to work with you to develop a superior solution.

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