HIGH TEMPERATURE (Al_2O_3) INSULATION AND LIGHT WEIGHT CONDUCTORS

by

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SUMMARY

The search by the electronic industry for components that are light weight, more compact, are capable of operating in very high temperature and all environmental conditions is now proving rewarding.

The properties of such a flexible, transparent, thin film of aluminum oxide insulated wire or strip (with a melting point of 2050°C.) is unique for applications in the electronic, missile, atomic reactor, aerospace, and aircraft industries. The oxide film is highly flexible, suitable for all windings of any size and shape of coil (magnetic). Briefly touched upon are the ultraviolet, proton gamma radiation uses, as well as high vacuum and cryogenic applications.

Since the film is inorganic and chemically inert, it does not age or deteriorate in storage and has good dielectric properties (1000 volts per mil). In brief, components designed around this unique material will keep abreast of present day and future technology.

Designers of electro-magnetic components can now achieve higher ratings per unit of weight and a reduction in size. With proper design, less insulation will be required and the dielectric losses are reduced.

The use of an aluminum conductor (round or rectangular wire or strips) will save 50% in weight, which is a distinct improvement in commercial applications such as linear motors, medical instruments, etc., where lower mass will result in lower inertia. Rotary equipment with low mass simplifies dynamic balancing. As vibration from dynamic imbalance is reduced, greater sensitivity and improved high frequency response in moving coil applications results from this lower mass. In all, it is a dream come true for most engineers.

INTRODUCTION

Compared to copper, aluminum with Al_2O_3 insulation operates cooler and will not oxidize. When operating temperatures of above 100° C., copper will form an invisible film of cuprous oxide; above 200° C. cuprous and cupric oxide are formed readily on the surface, thus reducing the conductance as ultimately severe corrosion occurs and eventually the conductor is rendered useless. Even nickel coated copper is subject to a galvanic action of the two metals. In a high temperature operation, migration of atoms is created.

Performance of electrical components in high temperature is seriously handicapped due to the lack of suitable insulating materials as the components are subjected to severe physical stresses in environmental conditions. When failure occurs in organic insulation, the failure remains permanent owing to the electrically conductive carbon paths that are formed throughout the insulation as well as other endangering problems, such as lack of adhesion, oxidation, evaporation, and aging.

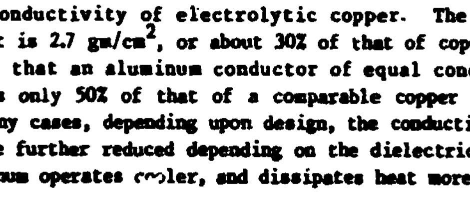
Aging is accompanied by weight loss in organic material where shrinkage results in the resin portion causing it to lose its bond in the slot cells, thus creating failure. Variation of temperature or rotating speed causes mechanical abuses of the insulation. Thermal degeneration is faster close to the current-carrying conductors where the temperature is at a maximum; Therefore, the failure is induced at the hottest spot of the winding.

Aluminum conductor and Al_2O_3 insulation, which is ceramic in nature, is free of galvanic action or oxidation. In case of a breakdown, the insulation does not create tracking of a permanent conductive path throughout the insulation. In fact, oxide from the air creates a new insulated oxide and could repair itself. Therefore, it is a good reason to consider the relation between operating temperature and insulation life. A component made with high temperture insulated material will be more reliable and will protect itself and its payload from instant heat and pressure.

CONDUCTORS

For several decades aluminum has been successfully employed in the electrical engineering field and in various other applications such as in transformers, generators, etc., using bulky interleaving materials such as paper, plastics, or laquer as insulation—far from satisfactory.

TABLE I—Thermal and electrical conductivities of aluminum and copper.



Aluminum for electric conductors has a resistance of about 34.5 ohms/mm^2, which is equal to approximately 62% of the conductivity of electrolytic copper. The specific weight is 2.7 gm/cm^2, or about 30% of that of copper. This means that an aluminum conductor of equal conductivity weighs only 50% of that of a comparable copper conductor. In many cases, depending upon design, the conductive weight can be further reduced depending on the dielectric loss, as aluminum operates cooler, and dissipates heat more rapidly.

Copper clad aluminum wire is re-inforced with EC grade aluminum conductor of an improved design developed to give electric power new versatility in construction. In addition to the contribution of its high strength to the conductor, it adds to the total conductivity of the conductor, so that it performs a dual function of strength and conductance. Of course, it is lightweight in all given gages of wire. It is also corrosion resistant, making it easily applicable to magnet wire, cables, etc. Copper clad aluminum is a composite material; The interdiffusion of copper and aluminum atoms occurs so that the materials are inseparable. They are joined in a metallurigical bond. Furthermore, when the composite rod is drawn to fine wire sizes, its concentricity and the proportions of both metals remain unchanged. The same concept can be applied for copper clad steel, which is a lead cable for the semiconductor industry, among others.

CONDUCTOR CHARACTERISTICS

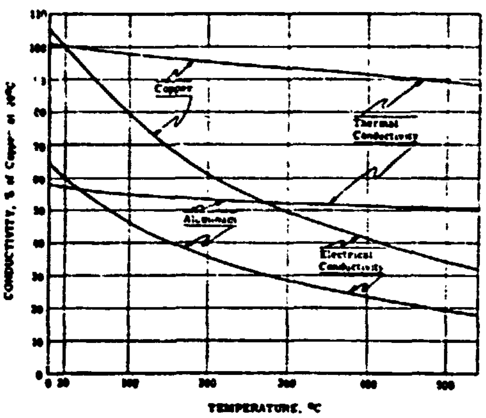
	Copper	Cu/Al	Aluminum
Density LBS/IN^3	0.323	0.121	0.098
Density GM/CM^3	8.91	3.34	2.71
Resistivity OHMS/CMF	10.37	16.08	16.78
Resistivity Microhm-CM	1.724	2.673	2.790
Conductivity (IACS %)	100	61-63	61
Weight % Copper	100	26.8	....
Tensile K PSI-Hard	65.0	30.0	27.0
Tensile KG/MM^2-Hard	45.7	21.1	19.0
Tensile K PSI-Annealed	35.0	17.0	17.0*
Tensile KG/MM^2-Annealed	24.6	12.0	12.0
Specific Gravity	8.91	3.34	2.71

*Semi-annealed

Copper clad aluminum lends itself to shaping, forming, and drawing. Wire is produced from .003" diameter and rectangular wire from .001" and is very suitable for winding fine, small coils. Larger wire is suitable for lightweight cables.

The adaptation of aluminum wire or foil and/or copper clad aluminum conductor is a step to attain improved operation and reliability through better balance in components with the following results:

1) This material can be operated at a greater speed than copper wire using less power in movable coils.
2) "Hum" has been reduced so that a decible measurement of so .. levels in stationary coils has been reduced.
3) Load capacity of given ratings have been effectively increased.
4) Core losses have been decreased and efficiency increased.
5) Operating temperatures are from -450° F. to 1000° plus F.



Comparison of thermal and electrical conductivities of copper and aluminum at various temperatures.

FORMATION

Note the increasing demand in the electronic industry for wire or strip to be lighter in weight—almost weightless—and an insulation so thin—almost spaceless—that should withstand 1000° F. or higher temperatures, and survive almost any environmental conditions.

Additionally, there is an increasing demand that it be:

a) Sufficiently flexible, to allow winding in any form, including miniature coils and edgewinding of rectangular wire wound under great stress.

b) Sufficiently thick, to insure good insulation and abrasion resistance, as well as thermal shock resistance, etc.

Permaluster, Inc., has pioneered in this technical advancement after years of research and has obtained such an inorganic, flexible insulated film that is produced continuously on wire and strip aluminum.

The oxide film is formed by an electo-chemical method which is a conversion process for thickening the naturally occuring film several hundred times or more. This method is known as "anodizing." Permaluster's patented process is similar to anodizing except:

1) It is performed with high speed (justifying cost).

2) It eliminates mechanical contact to avoid racking spots.

3) It is controlled to eliminate crazing when bent.

Owing to the strict control methods employed in the processing, the oxide coating may be formed homogeneously in varying thicknesses and pre-structures. The resistance of the formed alumina film is about 1800 ohms per cm^2.

The mechanism of the anodic film formation and the fine structure of the film are not fully understood, but information is derived from the available evidence that under the influence of the elctrolyte and the mechanical solvent action, aluminum ions migrate from the metal surface through the barrier layer to the oxygen rich upper portion of the film where the ions react with the aluminum oxide to form an anhydrous alumina. The oxide layer formed differs in character from the more porous outer layer. The alumina has an electrostatic charge and can function to absorb other inorganic or organic material.

PROPERTIES OF Al_2O_3

This step in the creation of aluminum oxide insulated film is an advancement in the technology of processing for applications in electro-magnetic coils. Thinner insulation with high dielectric strength, lower dielectric losses, and more compact components are the results. The inorganic insulated film with its advantageous dielectric properties will withstand:

1) Higher temperature (to the melting point of the conductor).
2) Fungus, corona and contaminants
3) Thermal or storage aging
4) Oxidation
5) Radiation
6) Corona
7) Thermal shock
8) High frequencies

9) Cryogenics (liquid gasses)

In addition, it will not outgas in high vacuum.

ELECTRICAL PROPERTIES

1) Breakdown Voltage: The porous film of Al_2O_3 as produced on EC[2] grade and high purity material without impregnation is approximately 30 to 40 volts per micron (0.00004"). The material composition affects the breakdown voltage which increases with the increasing purity of the metal. The film is homogeneous, uniformly thick without cracks, controlled to any thickness. The dielectric strength varies nearly in a linear fashion with the thickness as per Figure 3.

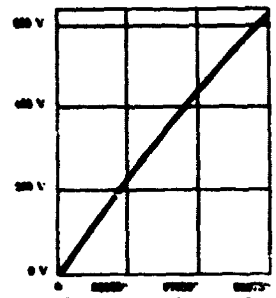


Fig. 1—Thickness of film vs. breakdown voltage (rms). The dielectric strength of the oxide film is approximately 35 to 40 volts rms per micron (0.00004").

2) Resistivity: The resistivity of the aluminum oxide varies with temperature and humidity. When the film is unsealed, it may vary 7×10^7 to 3×10^{12} ohms/cm. Under ideal conditions in a dry atmosphere, resistivity of 5×10^{15} ohms/cm. was obtained at 20° C. after charging for 60-80 seconds.

TABLE IV—Properties of thin film Al_2O_3 insulation.

Specific gravity (20°C)	4 (approx.)
Apparent average density (20°C)	2.5
Melting point	2050°C (3722°F)
Elongation (%)	10 (maximum)
Coef. of linear thermal expansion	8×10^{-6}
Refractive index	1.59
Reflectivity (%)	70
Emissivity (at 6 μ thickness)	≈ 50%
Specific resistivity (ohms cm) (20°C)	*10[illegible] (average)
(250°C)	10[illegible] (average)
Dielectric strength (volts rms/micron)	*35-40
Dielectric constant (20°C) (at 1 Mc/s)	**8.5-9.5
Loss factor (tan delta) (20°C)	**0.0004

NOTES:
*Since aluminum oxide is hygroscopic and shows a considerable water absorption at relative humidities in excess of 90%, these figures relate to values obtained in air with relative humidity between 35% and 65%.
**These figures relate to values obtained in dry air.

3) Dielectric Constant: The dielectric constant (permittivity) of Al_2O_3 film lies between 8.5 and 9.5 when measured in dry air at one megahertz. Similarly, loss factor (tan delta) is 0.0004 under like conditions.

MECHANICAL PROPERTIES

1) Hardness: The film is ceramic in nature and will resist surface scratches and abrasion. The degree of hardness depends on the porosity and the depth of the oxide layer. Tests made on numerous samples of varying degrees of porosity by means of scratching the surface with a needle having a constant load of 130 grams showed that breakthrough was achieved in the most porous sample after 16 strokes and the least porous sample after 48 strokes.

2) Flexibility: The film is highly flexible, unlike other forms of ceramic insulation, and retains the inherent qualities as long as the metallic base material is not subjected to undue strains. If the base material is over stretched or sharply bent, it exhibits cracking, when separation of the film may occur. A hard temper metal will not allow small diameter bending. In bare state, such wire will over stretch on the upper part of the bend, and the surface will be distorted at the lower bend. Owing to the firm bond between the aluminum substrate and the innermost layer of aluminum oxide, the insulated conductor can be made flexible, provided also that the temper of the conductor is such that it exhibits a good degree of ductility. Ductile wire and strip were wound around a mandrel having diameter four times the thickness of the conductor without flaking or cracking of the insulation.

3) Fatigue: Tests have indicated that there is no fatigue loss due to the anodic film, even with a film thickness more than fifteen microns. This is owing to the flexibility of the film; there is no stress concentration between the metal and the film.

4) Strength: Tensile strength and elongation are not altered by the anodic film. With very thin material, allowance should be made for the thickness of the metal that is converted to oxide. There is no reduction in fatigue strength even at relatively high stresses. The alumina film has significant strength when detached from the metal.

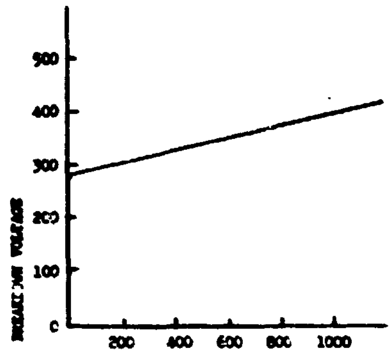
5) Corona: As insulation is exposed to high voltage, the critical voltage is reached when visible or audible discharge occurs. This is the corona start voltage (CSV), and it is here that the ambient air becomes ionized and permits free flow of current. Most insulations exposed to this corona effect suffer erosion. It is also attacked by ozone produced from the oxygen of the atmosphere. Such chemical erosion within the body of the insulation is concentrated and results in a serious degradation of the quality of the insulation and causes premature failure of the system.

6) High Temperature: Heat is a very important factor in the use of a barrier type electrolyte, as it thickens the barrier layer for higher dielectric strength. Heating changes the electrical resistance and modifies the physical constance of the film; therefore, the pre-anodized aluminum heated up to 1000° F. leads to an increase in resistance and an apparent thickening of the barrier layer. It also influences the flexibility of the film. It will not blister or peel, although the thermal expansion of the film and the conductor is different.

Since the aluminum oxide melts at 3722° F. (2050° C.), the temperature maximum at which Permaluster insulated conductor may be safely employed is dictated by the melting point of the metallic conductor, which for aluminum is 1218° F. (659° C.). The insulation properties of the oxide film improves as the temperature increases as the moisture factor is eliminated. It holds its dielectric properties whether it is operated at 50° C., 500° C., or -400° F. (cryogenic), thus making it suitable for Classes H and C insulation as well as exceeding Mil-Spec. for high temperature application.

It is insensitive to thermal shock. The insulated conductor can safely carry short term overload currents while in a high ambient temperature and can be subjected to sudden changes of temperature having a wide differential without deterioration.

Thermal conductivity of the Al_2O_3 is relatively close to the aluminum conductor as the film is minute. It has the ability to radiate heat rapidly in high temperature. A small coil with less weight and with high thermal conductivity will facilitate the transmission of heat. To achieve such a performance, the round wire has been replaced with flat wire or aluminum foil where all voids in the windings are filled.



TEMPERATURE IN °F.
Annealed EC aluminum wire, Permaluster anodically processed of aluminum oxide
Film thickness 8 microns (.0003")

7) Radiation: Inorganic Al_2O_3 film has in initial conductivity at zero dose rate of 10^{-12} $(ohms/cm)^{-1}$, the conductivity increases at the same magnitude the dose rate increases; thus the dose rate of 10^3 roentgens/sec., the conductivity will have increased to 10^{-9} $(ohms/cm)^{-1}$. When materials are subjected to a short duration extreme intensity gamma pulse as encountered in nuclear explosions (where the intensity may reach to more than 10^7 roentgens/sec. in a fraction of a microsecond) the resistance of most organic insulations diminishes in value, while the inorganics including Al_2O_3 will recover rapidly after 10 to 100 microseconds.

Al_2O_3 is successfully applied in a radiation environment. A typical reaction environment of 8 x 10^{12} NV/cm^2/sec. for neutrons and 6 x 10^{12} 1 mev/cm^2/sec. for gamma radiation, where the equivalent absorbed dose for each is approximately equal to 1 x 10^8 rads, has shown no deleterious effects.

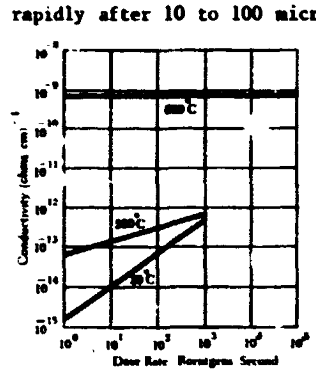


Fig. 2—Alumina (Al_2O_3) conductivity at various temperatures in gamma radiation.

In a report by Idaho Nuclear Radiation and Argonne National Laboratories was described the design of an Annular Linear Induction Pump for the Mark II Loop, placing the most stringent requirements on the sodium pump. The four-pole version of the pump used 24 coils, and the five-pole version used 30 field coils. The field coils were designed to consist of flat ribbon wound pancake type coils of fully anodized EC aluminum. The Al_2O_3 insulated conductor was wound without interleaving and was successfully operated as the primary of a 60 hertz, one phase, 230 volts AC stepdown transformer at 425° C. for over 500 hours without malfunction or failure (ANL-7369-Argonne National Laboratory), THE DEVELOPMENT OF PUMPS FOR USE IN FAST-REACTOR-SAFETY INTEGRAL-LOOP EXPERIMENTS by L. E. Robinson and R. D. Carlson.

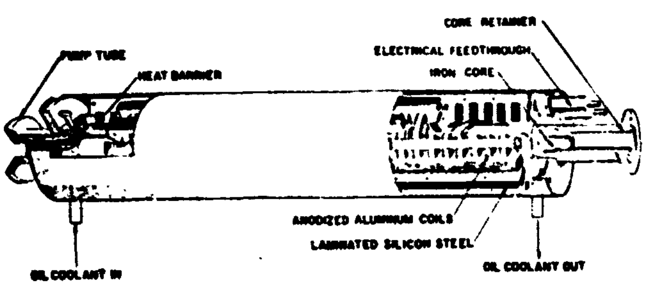


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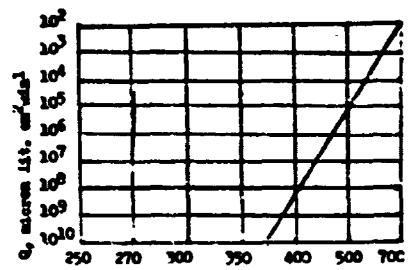
Fig. 3. Annular Linear Induction Pump for Mark II Integral Sodium TREAT Loop

8) Low Temperature: Aluminum with oxide film excels in super cold environments; it is insensitive to abrupt changes at low temperatures, remains tough, ductile and strong. The high thermal conductivity of aluminum (the ability to transfer heat rapidly) makes it especially effective in high energy absorption.



Temperature in degrees Kelvin
Under pressure in liquid hydrogen

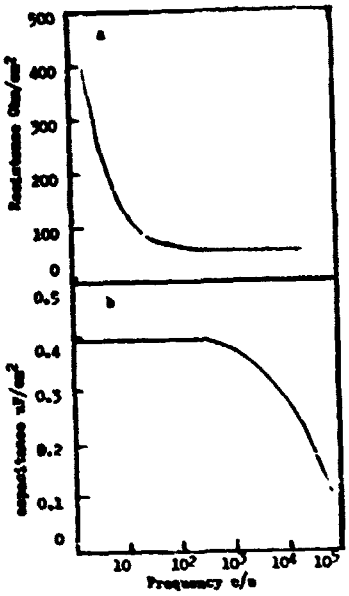
At sub-zero temperatures the tear resistance is as high or higher than that at room temperature. Aluminum has been used to stabilize super-conducting magnets and reacts only slightly in increases in magnetic field in resistivity or about 5KG. In a typical room temperature, under zero stress, zero field resistivity of high purity aluminum is at 2.53 + 10^{-5} ohm/cm. Pure aluminum, oxidized with low strain was found to have low resistivity even in a high magnetic field. In cryogenic applications at -450° F. in a magnetic field, such material operated easily at 120,000 gauss. The less strained aluminum retained its properties in high magnetic field. Its magno-resistance exhibited a predominately saturating behavior.

9) Frequency: Specific resistance of anhydrous and partially hydrated alumina is very high. The anodic film is approximately 5MΩ/cm^2 per 1.5 x 10^{-3} cm film. There is no significant change over a wide frequency range. At frequencies above 1KHz/S R, it is nearly constant. At 25Ω/cm^2 changes will appear with varied film thicknesses. At frequencies below 10 KHz/S, capacitance is nearly constant at 0-99u F/cm^2. Figure shows some indication of fair representation of the impedance component of Permaluster tested base Al_2O_3 insulated material at room temperature.

Different values and properties can be obtained if the pores are sealed or impregnated.

The impedance obtained in high frequency gives a more uniform response, as the mass of a moving system limits high frequency response of acoustic transducers.

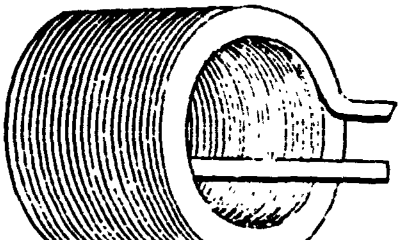
By reducing the weight of the mass by more than 50%, frequency can be increased. The more dense the material, the faster the sound waves travel. For a given frequency, mass of the magnetic coil exhibits a major portion for the length of the wave to cycle. Lightweight aluminum rectangular wire, edge wound, with thin Al_2O_3 insulation, improved the design objective in obtaining the maximum power output per pound of weight and condensed unit for moving transducer coil and waveguides.



Frequency dependence of balancing series (a) resistance (b) capacitance for annealed aluminum oxide - Film thickness 1.5×10^{-3} cm.

Steady state low frequency voltage would be distributed across a sheet winding in direct proportion to the turn impedance giving an essentially linear distribution of such voltage across the turns.

The capacitance and inductance between adjacent or physically close turns and the capacitance to ground are uniform throughout a continuous sheet coil. Coils wound from Al_2O_3 thin insulated strip have no interlayer capacitance, but only interturn capacitance; total capacitance of the coil is thus reduced.



Waveguide wound, for transmission of signals, using coil made of anodized aluminum rectangular wire, edge wound. Such coils are fast moving, lightweight, suitable for actuators, voice coils, servo systems, shakers, etc.

10) Vibration: An edge wound flat wire coil produced a flux density of 18 kilogauss in an air gap (using 3 lbs. of Alnico 5 - 7 magnetic core) to provide a 6 lb. force for displacement and acceleration as shown in chart. The improved moving voice coil unit has an efficiency of 50% in the frequency range from 400 - 10,000 Hz. in a maximum acoustic output of 20 watts with a high degree of reliability. Of course, higher frequency is no problem. The film is extremely tough and exhibits little deterioration under extensive mechanical vibration for extended periods of time. Coils wound with thin film insulated aluminum conductor have been successfully subjected to vibration tests both at room temperatures and elevated temperatures. Under 24 G vibration, applied at various frequencies between 50 cps and 5000 cps for one hour along each axis, no change in resistivity and only a slight change in inductance was recorded. During the test the current flowing through the coil increases to raise the temperature to its limiting value and then reduces again.

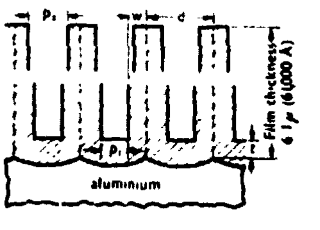
11) High Vacuum: Aluminum oxide insulation may be used effectively in high vacuum. The film showed no effects under pressure below 10^{-12} Torr at 500° C. Other tests indicated that when Al_2O_3 was impregnated with carbon-free silicons, there was no evidence of any hydrocarbon residue when operated above 400° C. in extremely low pressure.

12) Design Consideration: Aluminum also has a high heat capacity with high capacitance for even voltage distribution. Aluminum strip or rectangular wire winding permits higher current density, due to each turn having lateral radiating edges exposed to the cooling medium, thus providing effective heat dissipation. This permits considerable design latitude in either reducing the cross section of the aluminum used or increasing the current rating for equivalent heat rise. Layer-to-layer temperatures are nearly uniform; hot spots inherent in conventional windings are virtually eliminated. The use of a thin high temperature dielectric film on flat material will require 1) less voltage, 2) minimal amount of insulation, 3) minimal amount of thermal insulation. It renders greater volume in equal space and affords greater mechanical strength.

Consideration is given to life expectancy, reliability and normal stresses in performance. It is important to choose a dielectric with thermal stability when the rate of heat generation at some point will exceed the ability of the material to dissipate it. Heat is generated by conduction current flow, principally ionic or by hysteresis under alternating stress. The heat generation rate is an increasing function of temperature in the electric field. An insulation with thermal stability should not be the limiting factor as it is the most important part of the component.

13) The Oxide Film Structure: The Al_2O_3 insulated film can be varied in processing to meet different requirements. Permaluster produces such film that is flexible to allow winding in any form, including miniature coils and edge winding of rectangular wire under great stress. A film thickness sufficiently thick to insure good insulation and abrasion resistance can be produced.

Owing to the porosity of the oxide surface, the film exhibits hydroscopic properties, and its resistivity changes with relative humidity as well as with temperatures ranging from 10^8 Ohm/cm to 10^{12} Ohm/cm. If relative humidity is a factor, additional inorganics or organics can be impregnated into the pores of the film.



Structure of pores on anodic porous fig. type film. Pore varies with operating conditions.

14) Impregnated Films: Inorganic coatings have the advantage of resistance to environmental conditions, with no degradation by exposure to radiation. Al_2O_3 produced anodically is an intergral part of the conductor. The inner layer of the oxide film is relatively compact and anhydrous, and on the surface is highly absorbent and ready to absorb either dissolved substances or molecules in state of colloidal dispersion. It is axiomatic that absorbing is a function of the porosity of the outer layer of the film. It is probable the oxy-type anions are a part of the pores that are capable of hydrogen bonding.

The conductivity of the outer layer provides the means of transporting anions hydroxyl ions from solvents or water toward the condensed layer, and hydrogen ions are easily bonded or fused with other substances. The transistion frequency of protons in a hydrogen bond has been found to be on of the order of infrared frequencies (10^{13} to 10^{14} per second). On this basis, the proton mobility in hydrogen bonded structures differs from the electron mobility in metal itself by only 1 or 2 orders in magnitude. The pore diameter of the surface of the film is in the order of 10.50 millimeter microns, or their density is between 100 to 800 pores per square micron, sufficient to absorb other materials. In some areas of applications, porous surface could have value, since it is chemically active surface. It acts as a good agent for mechanical bonding; other advantages include its retention of photo-litho emulsions, and it serves as a base for electroplating, printed circuitry and painting.

Pores can be impregnated with various materials, i.e., organics to inhibit water absorption, organo-ceramics for use in high temperatures. The Georgia Institute of Technology (WADC Tech. Report 58-13) sealed the film with Colloidal Silica in an electrophoresis deposition, also with a true liquid of ceramics that wet the inside pores by gelling a hydrolized solution of ethyl silicate so the particles of silica were trapped in the pores of the coating.

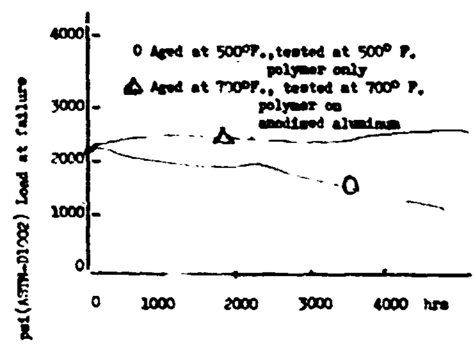
Actually, the barrier layer of the oxide is sufficiently protective for organo-ceramic filling of the pores. There is no danger that a carbon conductive path will pass the barrier layer in high temperature operation. In fact, even the organic material will operate at twice the temperature without effect.

15) Impregnation With Inorganic Material: The anodic porous base coating with a barrier layer is a refractory, flexible film and can absorb or seal other organic and inorganic film with or without an organic vehicle. Another anodic or eletrophoretic process can be applied for forming another composite film that is absorbed into the pores of the anodic base insulated layer. Barrier type electrolytes can be used. Tests performed showed that higher dielectric strength and flexibility were obtained after vacuum annealing at 450° to 500° C.

Oxide pores can be "sealed" with Tetraethyl orthosilicate, which is a refractory binder, a gelling agent for impregnation of porous material and is highly heat resistant. A hydrolized silicate gel heated to silica becomes a hard, vitreous type material; a pure silica bonding agent which has the advantage of being insoluble in water. It is impervious to most acid and is excellent in high temperatures. Hydrolization, using ethyl silicate solution, can be accomplished, as it penetrates completely into the porous Al_2O_3 to a complete hardness after heating.

A water solution of porcelain enamel or combinations of inorganic frits with or without resin combination, can be applied to create a strong bond with the oxide base. A strong intermolecular bond is responsible for the inertness of the base coating.

16) Organic Impregnation: A silicon-oxygen network interspersed with organic groups can be stabilized to a valuable film in conjunction with aluminum oxide. The solvent of the silicon mixture will oxidize and vaporize with other organic components, while the inorganic silica matrix remains (crosslined organopolysiloxans) are almost unsurpassed for heat resistance. With aluminum oxide, the structure can withstand over 1400° F. without deterioration. A number of modified silicon resins have been used, such as silicon alkyds, or modifications with acrylics, epoxies or phenolics with a silicon content of about 25%. Such different varieties of resin combinations can be formulated either by blending or co-polymerization to obtain heat resistance up to 1000° F. Such combinations are excellent in thermal shock resistance. Resin can be applied in pure form or can be combined with other resinous material. A mixture of resins put together to develop suitable properties that are compatible with the base Al_2O_3 can be achieved.



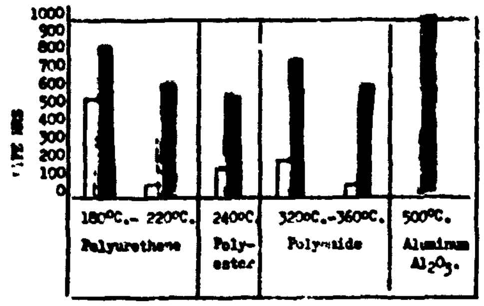
Heat aging of poly-(amide-imide) adhesive on aluminum and anodized aluminum.

The choice of resin to be impregnated into the pores depends upon the application. The choice of an organic binder is made where little or no carbon residue remain, though it will have no effect on the insulation, as the pores are protected by the refractory oxide film that has a melting point three times that of aluminum.

High temperature polymers offer versatility for use in electronic insulation and show stability in performance when impregnated into the Al_2O_3 "prime coat"; Greater dependability has been achieved at high operating temperatures (about 850° F.).

Thermal aging of insulation in organic material is probably responsible for most failures found in the component. Thermal aging itself does not produce failures, but it renders insulation vulnerable to other factors, such as moisture, penetration, brittleness, loss of thermal expansion before complete failure. Figure shows some experiments with organic film over Al_2O_3.

Such organic overcoat is produced in a cured or quasi-cured state. A coil can be formed and wound in any shape when a quasi-cured state is required. When heated, the turns bond together to form a solid structure. By employing this method, cores are eliminated; The coil becomes very strong and self-supporting.



Thermal aging of EC aluminum wire, anodically insulated films. Dark bars indicate aluminum and oxide wire.

CONCLUSION

Most insulations are based on a thermal theory. Should a weak area in the organic insulation be heated more than other areas, and if the heat is not removed as rapidly as it is generated, the weak spot grows hotter and the resistance will be lower. As the temperature continues to rise in operation, instability occurs; this will be followed by a breakdown in the weakest point of the insulation. This will not occur in Al_2O_3 insulation. In fact, the aluminum oxide insulation improves at temperatures above 220° F. The choice of insulation is often a decided factor that will govern the performance and reliability of the components. In applications where peak load is energized during low demand period, overall losses are always less in high temperature design. Examples are transformers, generators, solenoids, alternators, magnets, etc., whether for environmental or terrestrial operation.

It will make good sense to construct electronic components by using lightweight conductors to improve operation: better balance and higher efficiency operation through the reduction of mass. It will make good sense to use aluminum oxide thin film insulation for better dissipation of heat, higher current flow, and consequently higher temperature operation in adverse environments.