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Insulation

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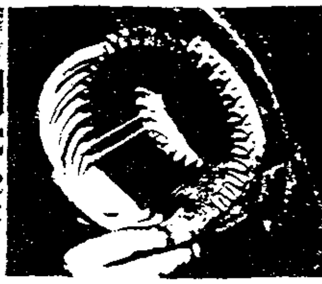

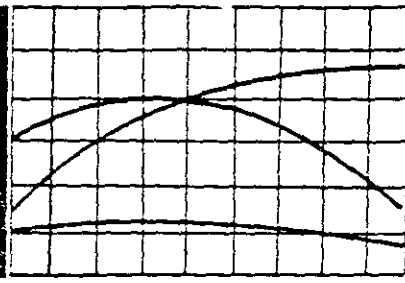

General Considerations For Insulation Selection

Third of a series of monthly articles on insulation engineering fundamentals by Graham Lee Moses, Manager, Insulation Development Section, Westinghouse Electric Corporation, East Pittsburgh, Penn. Mr. Moses is widely recognized as leading authority on insulation and is the author of more than 100 technical articles and papers as well as a book on electrical insulation. He has figured importantly in many insulation developments.

Electrical insulation is used on electric equipment because it offers high resistance to the flow of electric current, and therefore is capable of directing and guiding the current in its proper paths along the conductors. The primary purpose of insulation is electrical, and originally this was thought to be its only purpose. With the development of better insulations and larger, higher voltage machines, engineers have imposed mechanical and thermal duties on insulation. When insulation requirements became more severe and voltages were increased, the problems were solved by adding thicker insulation. These early insulations consisted mainly of untreated cotton cloth or other organic fabrics. The first processing consisted of applying natural gums such as shellac and boiled linseed oil in alcohol carriers.

With industrial expansion and electrification, and the creation of many new industries using electrical devices, the requirements for electrical insulation pyramided by leaps and bounds. In today's and tomorrow's industrial, transportation, and defense applications, insulation is being subjected to ever increasing stresses, both physical and electrical, ever increasing temperatures, and more serious contaminating environments. In the present and the future, as well as the past, the success of an insulation for a specific device depends upon the environmental and service conditions as well as upon the designer's choices of suitable materials and fabrication processes. The art of selection and applying insulation has always been a difficult one to exercise with mathematical precision such as can be used in the solution of mechanical and electrical design problems. In the past, insulating materials have been selected on an empirical basis, and insulation systems have been designed by a "cut-and-try" approach. With the tremendous advances that have been made in the control of insulation materials and processes, and the better understanding of their characteristics, it can be predicted that the insulations of the future will be designed on a more scientific basis with corresponding increases in effectiveness. There is, however, no short cut to experience and understanding of the specific problems of application and use of the final product.

There are many factors involved in selecting a suitable insulation system for every design of machine and device. The insulation engineer must cooperate closely with the electrical and mechanical designers and there must be a common understanding of the mutual problems. This cooperation and collaboration is difficult because there have been so few suitable yardsticks for measuring insulation properties. In the past, materials have been evaluated separately under considerably different conditions from those under which they are used. The data from such evaluations bear little relation to how the component materials will act in a composite insulation system in a machine. It must be recognized that the characteristics of insulating materials change as they are handled and fabricated into the final product. In many cases, the dielectric levels of the materials diminish with handling. In other cases where the systems are fabricated into a thoroughly integrated composite system, the properties may actually be greatly enhanced by processing. From this it can be seen that the selection of materials based on their individual characteristics from handbook data may not produce the best design. However, the insulation designer must start with the basic component and follow their evaluation through the whole procedure of fabrication and use.

The evaluation of insulating materials and systems should involve the following steps:

1. Laboratory tests on each component material with the tabulation of the useful properties and characteristics aimed at the solution of the final problem.

2. Tests and manufacturing experience to determine the effect of fabrication methods and processes on the insulation system characteristics in final form. This may involve destructive tests on the actual equipment or accelerated tests on models, such as are now being recognized by AIEE.

3. Service data should be obtained to equate actual operating life of the complete apparatus in service with the factory and laboratory tests to give the designer confidence of the adequacy of his designs.

Primary Functions of Insulation

The primary use for insulation in electric apparatus is to separate circuits and conducting parts of different voltages. There are three distinctly different methods of providing such insulation, differing in effectiveness and magnitude:

1. Separation in an insulating fluid, usually air.

2. Creepage across an insulating surface or through porous insulation.

3. Dielectric barrier action by a solid structure or a continuous insulating film, possessing intrinsic dielectric strength well above that of the equivalent air spacing.

All three of these methods are generally employed to some extent on any specific equipment. However, one or more may predominate in a particular construction depending upon design and economics. Usually it is not practical to completely inclose all of any circuit component in a solid dielectric sheath, even though such a system is the most effective method. The dielectric barrier method of insulation provides the greatest reliability and the most effective use of space because of the very high level of insulation strength obtainable in a given space. It is in the area of dielectric barriers where differences in materials, and techniques of fabrication, play important roles in the scientific design and manufacture of insulation.

Important though the basic materials are, the dielectric strength of composite insulation systems is frequently more dependent upon the technique of fabrication than upon the inherent characteristics of the components. Identical components may be combined and processed differently and yet have dielectric breakdown levels that vary by as much as ten to one. Fibrous materials when treated with varnishes and resins offer excellent examples of the important effect of processing. Here the degree of consolidation of the composite materials predominates in establishing the insulation breakdown level as this determines if a dielectric barrier is produced. In mica insulating products, the size and grade of the splittings as well as the manner in which they are laid and overlapped are of great importance in establishing the insulation strength level. Even here, the extent of impregnation, degree of fill, and consolidation of the composite structure, make major contributions to the insulation breakdown level. On many materials such as varnished papers, varnished cloths, and the like, where the varnish treatment is depended upon to provide the dielectric barrier, only multiple films will create breakdown strength significantly better than the creepage spacing corresponding to the insulation thickness. Every varnish film will have some holes, thus each additional multiple coat of varnish on a cloth or paper merely reduces the probability of there being a pinhole clear through the resultant film. The importance of these factors of processing and fabrication, and their effect on insulation quality cannot be overemphasized. Users and manufacturers alike should fully understand that while the properties of the component insulating materials used are important, the intrinsic potentialities of high grade insulating systems are obtained only where suitable fabrication techniques are employed by skilled workmen with thorough quality control procedures.

Mechanical Requirements

Insulation must have satisfactory mechanical strength in the completed windings and physical supports to withstand all the forces that it may encounter during operation. In addition, it must have the strength to withstand the abuse which occurs during fabrication, forming, processing, and installation in the equipment. The more important of the mechanical properties that an insulation should possess are:

1. Flexibility to withstand bending and forming during appplication and installation without loss of insulating level.

2. Tear strength particularly where isolated sheets of insulating material extend to provide creepage distances.

3. Shear strength to provide physical support to the winding and other insulating components, and to withstand the magnetic and rotational stresses, as well as vibration and shock.

4. Flexural strength particularly in the supporting members such as wedges and coil washers.

5. Tensile strength is particularly important to insulation during winding and fabrication.

6. Bond strength between wires particularly on mush-wound coils which may be subjected to vibration and shock, and to rotating field coils subjected to centrifugal forces.

7. Abrasion resistance is important to insulating surfaces and individual parts to withstand handling during fabrication of coils and assembly in the equipment. Sometimes this is important later because operating hazards may produce coil movement.

Electrical Characteristics

1. Dielectric breakdown strength is the most important electrical property of most insulations. This is particularly true where the insulation is used as a dielectric barrier; and may not be as important on physical support and creepage surfaces. Serious consideration must be given the possibility of reduction in the level of this property which may occur during forming and installation.

2. Insulation resistivity must be high so that the insulation is effective and so that minimum heating of the dielectric occurs during operation.

3. Power factor is a variable requirement depending upon the end use of the material or apparatus. A low dielectric loss is always a desirable property although its importance

with the application. Power factor is not a reliable indication of dielectric strength.

2. Dielectric constant may or may not be significant depending upon whether a distorted voltage distribution is important. An unbalanced design may result from using different materials having widely different dielectric constants, particularly at higher operating voltages as the dielectric stress will be concentrated on the material having the lower dielectric constant.

5. Corona resistance is always a desirable property, but it is much more important for operation at six thousand volts and above, where corona activity is greater.

6. Arc resistance may be important in some parts of a device if it may be subjected to arcing but often is of little consequence.

7. Track resistance is desirable where surfaces may be subject to high electric stresses on occasions, but where no arc should ever occur.

8. Moisture resistance is a highly desirable property in most electrical insulation. Most materials have good electrical properties when dry, but these properties deteriorate rapidly when the surfaces are wet or moisture is absorbed into the solid insulation. The differences in effect of moisture on a material may be a determining factor in the practical selection of the best material, process, or design.

Chemical Characteristics

1. Thermal stability of insulation can be considered a chemical characteristic. It is one of the most important properties of an insulation or an insulation system.

2. Resistance to the common solvents and oils may be of great importance depending upon the end use. Normal solvent cleaning is damaging to some materials. Most insulation components and varnishes include solvents which should not be damaging to those materials adjacent thereto. Many electrical machines and devices are exposed to oil vapors which should not be deleterious to the insulation characteristics.

3. Resistance to weak acids and alkalis is a desirable property although the need will be determined largely by the end uses, and protection offered to the insulation by the equipment enclosure.

4. Ozone degradation is usually the result of corona which is ordinarily of little importance on machines operating below six thousand volts.

5. Flammability is being given more and more emphasis as an insulation requirement. Often, fires will follow electrical failures which may result in more consequential damage than resulted from the original failure. Thus, resistance to fire and self-extinguishing properties are highly desirable.

Temperature Classification of Insulation

It has long been recognized that the operating temperature of insulation is a major factor in determining its life expectancy. The rating of electric machinery is dependent to a large extent on its temperature rise, and therefore on the hottest-spot temperature of the insulation. Because of this limitation, temperature is important in establishing machine design characteristics. The temperature classification of insulating materials was first proposed by Lamme and Steinmetz in an AIEE paper in 1913. Shortly thereafter, AIEE Standard No. 1 was written classifying insulating materials according to their temperature stability. This original classification has been used with relatively little change since it was first established over forty years ago. The major changes have been adding of new insulating materials, such as fiber glass, and new insulation classes, such as H, as they were developed. This classification of insulating materials by AIEE, ASA, NEMA, and others defines and classifies insulations as follows:

Class O—Class O insulation consists of cotton, silk, paper, and similar organic materials when neither impregnated* or immersed in a liquid dielectric.

Class A—Class A insulation consists of: (1) cotton, silk, paper, and similar organic materials when either impregnated* or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) organic varnishes (enamel) as applied to conductors.

Class B—Class B insulation consists of mica, asbestos, fiber glass and similar inorganic materials in built-up form with organic binding substances. A small proportion of Class A materials may be used for structural purposes only.** Fiber glass or asbestos magnet wire insulations are included in this temperature class. These may include supplementary organic materials, such as polyvinylacetal or polyamide films.

Class H—Class H insulation consists of (1) mica, asbestos, fiber glass and similar inorganic materials in built-up form with binding substances composed of silicone compounds, or materials with equivalent properties; (2) silicone compounds in rubbery or resinous forms, or materials with equivalent properties. A minute proportion of organic materials may be used only where essential for structural purposes during manufacture.**

Class C—Class C insulation consists entirely of mica, porcelain, glass, quartz and similar inorganic materials.

**An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibers, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substances in order to be considered suitable, must have good insulating properties; must entirely cover the fibers and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load or at the temperature limit specified: and must not unduly deteriorate under prolonged exposure to operating temperature.*

***The electrical and mechanical properties of the insulated winding must not be impaired by the application of the hottest-spot temperature permitted for the specific insulation class. The word "impaired" is here used in the sense of causing any change which could disqualify the insulating material for continuously performing its* *intended junction; whether creepage spacing, mechanical support, or dielectric barrier action.*

It should be noted that this classification of insulations originally applied primarily to materials. The extension of this classification to insulation systems and apparatus has been an evolutionary process. The present letter system of temperature classification is based almost entirely on whether the essential components are organic or inorganic: and whether or not the composite insulation is impregnated with resin. and if so. what resin. In the last five years. a new concept has been developed jointly by designers and users of electric equipment. This is the concept of "functional evaluation" of insulation systems which is based on classifying insulations by tests rather than by their chemical compositions. The advent of many new kinds of synthetic resins in the past 15 years has made it impractical to continue to classify insulating materials according to their chemical composition. Many of the synthetic organics have vastly better thermal endurance and electrical properties than their counterparts which occur in nature. It has been found that insulation systems made up of some of these synthetics cannot be classified as to their temperature stability except by testing them in specific combinations under the conditions of use. while they are performing their intended functions. Here again. it is important to recognize the different functions that insulating materials and systems must perform in service. The functions may be physical. chemical. or electrical and they may provide low voltage spacing or high voltage dielectric barrier action.

This new concept of the temperature classification of insulating materials and insulation systems according to functional evaluation by tests was recognized in the 1954 revision of AIEE Standard No. 1. Future revisions of AIEE Standard No. 1 are contemplated wherein methods for functional evaluation of insulation. and temperature classification of insulating materials and insulation systems. will be provided in official AIEE Testing Procedures. Separate test procedures will provide for the evaluation of insulating materials and simple combinations thereof. There will be distinctly different test procedures for the complete insulation systems to permit testing them according to the specific conditions of use on equipment. An excellent example of the latter type of test procedure is AIEE Standard No. 1-C.

Table I—Typical Temperature Allowances for Specific Electric Machinery

Insulation class	Hottest-spot temperature. deg. C	Permissible rise, deg. C* By thermometer**	Permissible rise, deg. C* By resistance or by embedded detector**
O	90	35	45
A	105	50	60
B	130	70	80
C	Not established		
H	180	110	120

**Based upon a 40 C ambient.*
***Based upon a hot-spot allowance with the thermometer method of 15° C for Class O and Class A insulation; 20° C for Class B; 30° C for Class H and a hot-spot allowance with the resistance method of 5° C for Class O and Class A insulation; 10° C for Class B; 20° C for Class H.*
Other types of equipment have different hottest-spot temperature allowances and permissible observable rises.

The relationship between the life of an insulated winding and the operating temperature is very complex. The subject required a great deal of study and test work before engineers could draw any rational conclusions as to temperature effects and make predictions as to the probable life of insulation under specific operating temperatures. It must be recognized that insulation does not fail by immediately breaking down when it reaches any critical temperature. Failure occurs by a gradual mechanical deterioration with time at temperature. The question, "How hot may an insulation be permitted to operate?" can be answered only with the knowledge of how long must it last. It is the time-temperature relationship which determines the rate at which the mechanical strength of most insulation decreases. As organic materials age thermally. they become weaker and brittle. and are more susceptible to disintegration under the influence of vibration. shock. differential expansion. and other mechanical forces. The dielectric strength of an insulation usually is not related to its mechanical strength. The electrical strength generally increases in the early stages of thermal aging. even while mechanical strength is decreasing. Often. the dielectric strength of an insulation will not fall below its initial level until its mechanical strength has been reduced to near the failure point. Unless disturbed mechanically, the dielectric barriers and spacing separators may provide adequate insulation for long periods. When physical disintegration of the insulation occurs. electrical failure is usually prompt. AIEE Standard No. 1 clearly states that how long an insulation will last electrically depends not onv on the class of material used. but also on the magnitude of the physical forces tending to disrupt it. Thus. the thermal endurance of an insulation is dependent on how much time the insulation is in use and how much load is carried by the equipment during the actual period of use. The factors of variable load and intermittent use are particularly important in determining insulation life when equipment is overloaded and normal operating temperatures are exceeded.

Until recently. the engineer's concepts of insulation aging have been based on a simple mathematical relationship wherein the insulation life was assumed to be reduced by half for each approximately 7° to 12° C inase in temperature. While this was useful approximation. recent more nprehensive tests have indicated that ulation aging is an inverse function the absolute temperature and requires treatment as a chemical rate enomenon. Special graph paper is ilable with an inverse absolute temperature scale on the abscissa and a arithmic scale for life on the ordite. Where the thermal life of insulaon fits this concept, as expressed in following formula, the life data ots a straight line on this special aph paper:

where $y = A e^{bx}$

y = Insulation life in hours (or days)

x = Reciprocal of the absolute temperature $\left(\frac{1}{273 + {}^\circ C} \right)$

$e = 2.718$

A and b = Empirical constants

A typical example of the application of this concept and mathematical treatment to the life of an insulation system is shown in Figure 1. This curve recognizes the variability of insulation life and instead of precisely defining life as a single line. shows that it may have a wide range during which probability of failure varies. Tests and operating experience have indicated that for most equipment. 95% of the failures will lie within such a range as illustrated with a few random failures above the maximum and below the minimum limits of this range.

It is generally believed that thermal aging of insulation makes it vulnerable to the many other damaging and contaminating influences. In the early stages of thermal degradation, the varnish treatment and internal resin bonds become brittle, weak, and porous. One criterion of increasing vulnerability and impending trouble is believed to be the loss of the initial level of moisture resistance. Other deteriorating influences may then be the cause of actual failure. and the absence of roasted-out insulation may obscure the fact that thermal aging was in fact the underlying cause.

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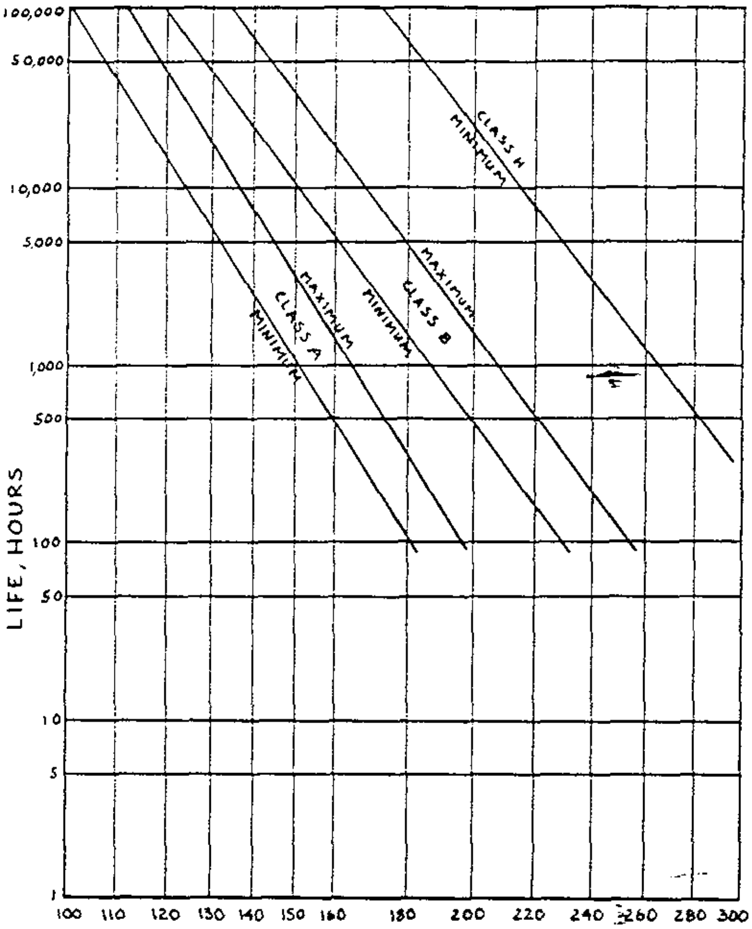

Figure 1, Modern concepts of insulation life (thermal endurance) as a function of operating temperature. The expected range of variability is shown for Classes A and B, but the upper limits for Class H have not been established.

NBS Electron Tube Information Service

The National Bureau of Standards has established a tube information service for accumulating and disseminating technical data on both domestic and foreign radio tubes. At the present time. nearly 10.000 cards. filed by tube type number. are appropriately referenced to manufacturers' source material. In addition. about 10 percent of these cards, selected mainly from the high-use miniature and subminiature types, have been coded on punched cards for mechanical sorting.