INSULATION AGING
A HISTORICAL AND CRITICAL REVIEW

E. L. Brancato
Head, Consultant Staff
Naval Research Laboratory
Washington, D. C. 20375

ABSTRACT

The role of insulation functions is reviewed. In this light, a history of thermal evaluation is outlined with special emphasis given to the milestones set by Steinmetz, Lamme, Montsinger and Dakin. The philosophy of functional evaluation and temperature classification is discussed.

The aging phenomenon, applicable to various systems, is analyzed with a point of view of identifying those knowledge gaps that bar the development of specific aging technologies. Emphasis is given, in this discussion, to the aging problems in multi-stress and/or multi-environmental conditions. The need for a better acquaintance with material response is stressed to develop multi-factor testing, identify material compatibilities, and develop nondestructive aging techniques.

FOREWORD

Dr. Thomas W. Dakin is endowed with an immense scientific perception and with a matching quality in human sensitivity and consideration. It is a privilege, therefore, to be invited to present a paper at "The Thomas W. Dakin Symposium on High Voltage Insulation", and gratifying to dedicate these pages to a personal friend and to a scientist who played such a vital and conclusive role in the understanding of the thermal aging phenomena in insulation systems and materials.

His contribution has made possible the successful implementation of thermal aging techniques and evaluation of their data for a wide spectrum of electrical apparatus.

This success, however, whetted the appetite of the insulation fraternity for analogous solutions to aging with other stresses such as electrical and/or mechanical and with other environments such as humidity and/or radiations. Indeed, desire has mounted for a search for a universal solution that would allow the evaluation and prediction of the useful life of insulation systems when subjected to a simultaneous combination of stresses and environments. While the need of the producers and users of electrical systems continues to feed this ambition the road to this important goal disappears in a murky fog of our ignorance. In the attempt to penetrate this fog I have set for myself the task of embracing a description of some of the problems and suggesting some intuitive directions, in the light of the history and experience with thermal evaluation.

In preparing this narrative I have borrowed liberally from a number of publications I have authored or co-authored, and refer to numerous papers which have contributed to the mosaic of this art-science.

INTRODUCTION

The phenomenon of aging is one that mankind would prefer to ignore while industry prefers to explore. The contrast in preference is not unnatural, since an individual would be psychologically crushed by the knowledge of his expiration date. On the other hand, both the manufacturer as well as the user of equipment have a vital need to know that an appartus will continue to function for a length of time expected by the user.

In the field of electrical insulation, the last hundred years have been replete with many milestones increasing the understanding of dielectric phenomena [1]. Around 1875 Maxwell presented his theory of dielectric absorption or interfacial polarization. In 1889 Paschen revealed his experience with the electric breakdown of gas in relation to the product of electrode separation and pressure. A decade later, Townsend outlined his ionization-by-collision theory of breakdown in gases. About twenty years later, in 1922, Wagner announced his thermal breakdown theory for solids. It was not until about 1930 that the development of quantum mechanics finally explained the difference between conduction in metals and in insulators. In spite of this remarkable advancement in the understanding of dielectric phenomena, there were very few clues gathered on the nature of "aging" and on techniques to predict useful life of electrical insulating materials and systems.

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Around 1900 there were, by today's standards, very few types of insulating materials and these materials had had sufficient use to have acquired a temperature-life rating. There were so few that one can catalogue the family groupings. Class A included such fibrous materials as paper, cotton, etc. and most of the natural resins and gums. These were to be used at moderate temperatures not exceeding 90°C. Class B materials had higher heat resistance and embraced the family of mica, asbestos, or other refractory materials used in combination with other binding materials. These materials at 125°C had comparable life to Class A materials at 90°C. Class C materials were essentially mica and other refractory materials capable of withstanding temperatures up to incandescence (as found in some heating appliances). Because of the accumulated service experience on these simple materials, the need for accelerated aging was not pressing. However, in the 1930's there was a revolution in the materials area which probably was sparked by the participation of organic and polymer chemists in electrical industry. As a result of their participation there developed an increasing flow of synthetic materials with tailored properties that replaced many of the original and service-proven insulating materials. The industry's ability to produce new materials tailored to special requirements of electrical systems exerted pressure on the designer to employ the product effectively and above all reliably.

The concept of reliability embodies the parameter of "time", and provides the challenge, the history and problems of which are the subjects of this paper.

It is possible to characterize the useful properties of newly developed materials in a relatively short period. The knowledge of the characteristics of materials permits the engineer to design electrical systems for the specified function at minimum size and weight. However, the successful functioning of an electrical system is only one of the two necessary parameters to make a design viable. The second parameter is the level of assurance that the equipment will perform for a length of time that is acceptable to the user. In other words, while a measure of performance and dimensions may be easily obtained for a novel design, the absence of field experience (which is obviously missing for new materials) provides little or no clue of the life that may be expected in operation. Consequently, some form of testing is required to obtain an indication of expected performance life.

THE ROLE OF INSULATION

In order to test a system for expected performance life, one must gain a clear notion of what the insulation is expected to do [2]. That the material normally must withstand electric stress is correct; however, in many cases it must also endure other stresses. Most of the time the insulation has as a prime function the support of electric conductors. In a motor the torque is the result of the force created by current in the conductor and surrounding magnetic field. In cables as well as in electric apparatus a short circuit can create enormous mechanical forces between conductors. These aspects remind one that insulation must have electrical as well as mechanical properties that will continue to isolate the conductor over normal and abnormal load conditions.

Elevated temperatures can cause a number of effects. The material may be inherently weaker at elevated temperatures and a failure may occur in the case of a thermoplastic simply because of the melting of the material. This can be a very short time failure, because of the short length of time required for the temperature to rise to the melting point. On the other hand, long term elevated temperature can cause internal chemical effects on material. For instance, internal polymerization can occur during which materials develop higher molecular weights. This can lead initially to higher tensile strengths, but unfortunately also to lower elongation capabilities. The materials may become brittle to the point where simple vibration or impact may cause a mechanical fracture.

When one adds to the inherent properties of the material the effect of environment, the prediction of insulation behavior becomes more complicated. As a simple example, the presence of air around a heated insulation can lead to simple oxidative degradation; depending upon the material involved this can mean either embrittlement or softening of the material. An obvious extension of this type of degradation is the effect of other chemicals in the atmosphere around the insulation. Solvents or other active chemicals can react with the basic insulating material to the detriment of the latter.

One factor which did not become obvious before the appearance of many new insulations is that of compatibility. If, for example, a given magnet wire insulation is impregnated with, or dipped into, a varnish, it is entirely possible that at room or elevated temperatures a chemical reaction can occur between this insulation and the varnish to the detriment of either or both.

The manufacturing process itself may constitute a damaging or aging action. The electrical insulation must be very hearty in order to withstand the mechanical abuse that it gets while being installed in equipment. One has only to observe an automatic winding machine winding coils into a stator of a fraction horsepower motor to appreciate this point. Thus, the mechanical stresses are often very severe compared to the subsequent abuse the insulation gets in service. Normal in-service mechanical stresses may originate from vibration caused by changing magnetic fields, as well as by most mechanical movements. A second stress that may seriously influence life expectancy is abrasion, which generally occurs due to sliding contact between insulation and metal as temperatures change from high to low values, or vice versa.

To recapitulate, insulation is expected to resist voltage stress as well as to provide mechanical support over a wide range of temperatures under exposure to many ambients including oxygen or chemicals in combination with other insulations, without too rapid a rate of degradation so that the desired life may be attained.

HISTORY OF THERMAL EVALUATION

While many have wrestled with the problem of insulation aging, and have contributed to an improved understanding, three papers, over a span of 35 years, have become milestones on the road towards the ability to assess life performance of electrical materials and systems.

As early as 1913, Steinmetz and Lamme [3] published a paper "Temperature and Electrical Insulation" which reflected the situation at that time and outlined the theory that insulation deteriorates over a period of time at a fixed temperature. However, they held a belief that electrical insulation suffered insignificant deterioration below 90°C but that above 100°C the rate of deterioration rapidly increased until 125°C where the life was expected to be shortened to a matter of a few weeks. In other words, it was thought that aging did not begin until a definite temperature had been exceeded. Moreover, it was judged at that time that if the insulation was given a chance to cool to room temperature between intermittent duty heat cycles, the actual hours of accumulated thermal aging would be decreased (as compared to continuous duty) because the insulation would have a chance to "recover".

By the late twenties a higher figure of 105°C was taking hold as the representative temperature for Class A materials, although V. M. Montsinger [4] in his 1930 paper "Loading of Transformers by Temperature" advocated a more conservative value of 95°C. In addition, Montsinger believed that the end-of-life criterion was purely the mechanical failure of the insulation and that it was "hopeless to judge the rate of deterioration of insulation by its electrical strength." This idea stemmed from the belief that the electrical strength of insulation increased in general with age until the material actually cracked open. At the same time he introduced the idea that the mechanical deterioration was a continuous reaction to temperature, and that the rates could by some means or other be determined. This was in sharp contrast with Steinmetz, who held that no deterioration could occur below a critical temperature for the material.

The data accumulated by Monsinger over a period of 9 years on the tensile strength of paper, aged in oil and in air, suggested a general law for insulation aging that is represented by a straight line on semilog paper with a linear temperature scale. The curve was expressed by the equation:

$$\gamma = A \exp[-mt]$$

where

γ = life

A and m are constants that characterize the insulation

t = temperature in °C

A milestone product of this classic study of Montsinger's was an initial demonstration of what might be called an 8 to 10 degree rule. In effect, this empirical relation states that the thermal life of insulation is halved for each increase of 10°C or conversely doubled for each decrease of 10°C. Additional data obtained during the subsequent years substantiated this rule defining it as the 10 degree rule.

While Montsinger provided a practical relation that served to improve the predictability of aging, the current solution was fathered by Dakin's [5] study of the basic cause of thermal aging of electrical insulation. In 1948, he published a classical paper proposing a chemical rate theory interpretation of thermal deterioration. This was a logical approach since the observed physical changes during the thermal aging were found to be a reflection of internal chemical change. Thus, it not only provided a more satisfactory explanation, but moreover, it allowed the obtainment of a more correct coefficient of deterioration than was permitted by the 10 degree rule. This more descriptive relationship is of the form

$$\gamma = A \exp[B/T]$$

where

γ = life

A and B are constants determined by the activation energy of the particular reaction.

T = temperature in K

Taking the logarithms of both sides

$$\ln \gamma = \ln A + B/T$$

Thus, if the log of life of the insulation is plotted against the reciprocal of the absolute temperature a straight line should result. This relationship was generally confirmed except where second and higher order chemical reactions entered into the aging phenomena. Thus, Dakin's use of the Arrhenius description of chemical rate phenomena became the backbone of the existing knowledge of thermal aging, and has served the practitioner well ever since.

ORIGIN OF FUNCTIONAL EVALUATION

The period between World War I and World War II spawned an abundance of new insulating materials. The characterization of the useful properties of the newly developed materials was performed in a relatively short period following their development. With this knowledge the characteristics of materials permitted the engineers to design electrical systems to perform the expected function. However, in the absence of field experience (which systems embodying new materials obviously did not have) all that could be done up to 1940 was simple evaluation of insulating materials where the insulating materials were merely exposed to elevated temperatures for a period of time, and the magnitudes of changes in the mechanical and electrical properties were measured as a function of temperature and exposure time. This data contributed greatly to expand and check the "10° Rule" and later the chemical rate relationships as proposed by Dakin.

While the above data gave clues to the behavior of the insulating material under a set of conditions for a given time, it was unable to predict the length of useful life of electrical apparatus emboyding these dielectric materials. This problem was encountered at the Naval Research Laboratory around 1947 when the Navy asked the question "How can we make aircraft motors lighter and smaller without raising their operating speeds?"[6] The obvious option was to operate the machinery at higher temperature, and to use the newer materials which had better temperature resistance. However, at that time all we knew about these materials was that a number of specific properties retained their levels better than in the more conventional materials. We had no idea what the chemical and physical interaction would be in the combined environment a motor would experience. The most common elements of this environment contained temperature, humidity, and voltage and mechanical stresses. It became apparent to us that what should be done was to expose insulation systems to a combined environment of stresses and temperature as a function of time. It does not come as a surprise to the reader that when there is a physical problem, reasonable people frequently arrive at similar solutions. In fact, the electrical industry had also reached the same conclusion. One of its chief spokesmen was K. N. Mathes [7]. He verbalized the solution to the obtainment of life performance of insulation materials and systems and phrased it "Functional Evaluation". He stated that testing should duplicate as closely as possible the kind of environmental exposure which an insulation experiences in actual equipment. The test should be an accelerated test in order that an answer could be arrived at in a reasonable length of time.

Following Mathes' declaration of "Functional Evaluation" both the Navy and industry vigorously applied themselves to the development of test methods embodying this philosophy.

The Navy dedicated itself to the development of evaluation techniques needed to compare the expected lives of new insulations. A research program was initiated at the Naval Research Laboratory in 1952. Then later around 1965 when techniques for the evaluation of electrical components and systems were being firmed a good portion of the evaluation was transferred to the Navy Ships Research and Development Laboratory.

This research, while benefitting the Navy, also had considerable impact upon national and international standards. To illustrate a few highlights, the data generated by the Navy confirmed Dakin's thesis that the thermal aging process was governed by the well known chemical laws, the Arrhenius relations. The influence of electrical and mechanical stresses, and the effect of humidity, were clearly demonstrated [8,9]. In this connection, NRL established the level of mechanical stress which has been universally adopted in the applicable standards. One of the problems that faced industry, and government designers as well, was the level of the life-line at which temperature ratings could be compared for various insulations. The Navy provided much of the long-term temperature-life data needed to establish this standard. Humidification, which was employed as a searching agent for failures, was difficult to standardize. However, when the AIEE 510 (later renamed IEEE 117) Test Procedure was being developed, the Navy took the initiative to investigate this factor and produced a technique and chamber design that was incorporated in the procedure [10].

Over the years, all thermal aging data was universally treated as an Arrhenius relationship. However, an interesting question arose, in connection with naval aircraft wire aging, as to whether life predictions could be made when the operating temperatures were variable. This was demonstrated to be possible by integrating the effects dictated by the Arrhenius laws [11]. In addition, a significant contribution was made to the economics of the thermal evaluation procedures. In general, in order to obtain a life-temperature characteristic curve a year of experimental time is required. As a result of a detailed statistical analysis the validation of truncated data techniques as applied to thermal aging was accomplished which substantially reduced the testing time required [12].

DEVELOPMENT OF THERMAL EVALUATION

In parallel to the early work by the Navy, industry also conducted research to develop evaluation techniques. Industry concentrated primarily on test models simulating magnet wire applications and complete insulation systems for rotating machinery.

By 1952, John Dexter [13] had experimented with modifications of the standard NEMA wire twist sample formerly used for voltage breakdown testing. By 1954 a large amount of data had been accumulated at various temperatures and voltage stresses. This work with the work of others of the AIEE committees led to the very useful documents AIEE 57, 65, 510, and 511.

Simultaneously, Cypher and Harrington [14] developed a test model of a motor suitable for functional evaluation of an insulation system at lower cost than for a full sized motor. These model motors were appropriately named "Motorettes".

This development was followed logically by other "Modelettes", among which are the "Armette", the "Formette", and even the "Hermette".

Work on the motorette has continued over the years. The last concerted effort on revising IEEE 117 (formerly AIEE 510) was undertaken by a working group which met at the IEEE Power Group Summer Meeting in June 1968. The development of a highly improved humidity and condensation chamber for use in a portion of the motorette test cycle was reported along with a demonstration of the effect of the time of exposure to this humidity on the end results.

To the present day, the Dakin-Arrhenius plot is being used to display the results of the life test. It is generally agreed by serious investigators that the curves for two different materials will give a comparative evaluation of the performance of these materials under the exact conditions of test.

TEMPERATURE CLASSIFICATIONS

With the development of new dielectric materials, additional temperature classes were added so that the temperature classification of materials agreed with that of equipment, as follows:

Class	Limiting Hot Spot Temperatures
O	To 90°C
A	105°C
B	130°C
F	155°C
H	180°C
C	Over 180°C

Three basic considerations were formally recognized which good designers and investigators had recognized all along:

1. All parts of an electrical equipment do not necessarily operate at the same temperature. If, for example, the hottest portion of an equipment is at 150°C, there are other portions which may be at well under 100°C. Obviously, a material which will withstand the higher temperature is not needed at the lower temperature, and to use it might be uneconomical. A single class of insulating materials need not be used in every part of the complete insulation system.

2. The temperature capability of a given material is influenced strongly by the environment to which it is exposed. Hence, the temperature capability of a material should be defined in terms of the conditions under which it is tested. To take an extreme case, an insulating material exposed to an atmosphere which would degrade it chemically in a very short period of time has no value as an insulation in that atmosphere at any temperature, except very low temperatures where the chemical reaction would progress at a very low rate. The same insulation might be rated for 200°C service under different environmental conditions. No one temperature limit can describe the temperature capability of a given material under every ambient or operating condition.

3. In addition, the temperature at which one can operate a material depends upon the required life of the equipment. Equipment which is designed to last only a short period of time can use insulation at higher temperatures in order to get an appropriately economical design.

PHILOSOPHY OF THERMAL CLASSIFICATION

During the past two decades much experimental work has been done to investigate the concept of temperature classification of magnet wire insulation based on the possible linear relationship between the logarithm of life and the reciprocal of absolute temperature as first demonstrated by Dakin [5]. Prior to this approach, temperature classification was based solely on the type of materials involved [3]. In view of the development of synthetic resins this type of classification was no longer meaningful.

The IEEE and ASTM, acknowledging Dakin's interpretation of thermal aging, began to explore methods of evaluation that could be conducted in the laboratory under accelerated test conditions to obtain data that could be used for classification purposes. To this end, IEEE sponsored the development of the necessary test procedures [15,16,17]. However, laboratory accelerated aging provides only a comparative measure of expected life of the various insulations tested. The utilization of this approach for the prediction of service life of a new insulating material or system requires the aging (by accelerated laboratory conditions) of established types of insulations that have had a 15 to 20 year acceptable service experience. For example, insulation "A" has been proven through field experience to have earned a temperature rating of 105°C for a normal life expectancy of 15 to 20 years. This same insulation under laboratory test yields an extrapolated life of 5 years at 105°C. Then, based on this information, a newly developed insulation "B" which also yields 5 years of extrapolated life at 105°C would also qualify for the same temperature rating. In like manner, if in this laboratory test insulation "C" yields 5 years of extrapolated life at 130°C, it would qualify for a 130°C temperature rating.

It follows, then, that the reference life value evolves from a class of insulations that has demonstrated its performance during an adequate span of time. The concepts of thermal evaluation of insulating materials and systems and their implementation have been nationally and internationally adopted. As a result of this, the use of new materials to improve existing designs or to meet the challenge of more sophisticated electrical or electronic systems has become widespread. The accepted method of thermal classification owes its success to the use of the chemical rate law to evaluate aging; to the formulation of functional evaluation techniques to implement the rate laws; and to the principle of relative aging factors to assess life performance.

CAUSES OF AGING

The aging process of insulation in cables, capacitors, rotating machinery, transformers, electronic systems, etc., differs in each system because of the different utilization and stress conditions. While temperature is the most frequent cause of insulation aging, it is not, by any means, the only or the most dominant factor. Electrical equipment has been known to fail by voltage stress (surface or internal discharges), by mechanical stress, by environmental conditions of heavy humidity, or chemical contaminants, etc. For example, Boulter [18] asserts that while thermal endurance may be the predominant factor in determining the rating of smaller and lower voltage machine insulations, it is unrealistic to expect the same to be true in larger machines. He states: "Short term or immediate changes in physical and electrical properties with temperature change must be recognized, particularly when this leads to a change of state or an irreversible change in the structure of the insulation system".

Boulter also asserted that voltage effects are more important in high voltage machines. Corona endurance and dielectric properties take on added significance in determining machine rating. Also, electromechanical forces that may be neglected in small machines become major design considerations in large machines. In addition, it has been recognized that the operating environment may play a large role in determining insulation life and machine rating. Heat aging for most materials is quite different in the dry hydrogen gas atmosphere used in large generators than it is in smaller air cooled units.

Cables

Underground cables are one of the major vehicles for distribution of electrical energy. They differ from other electrical equipment in that the oxygen supply is limited in the cables.

Historically, underground transmission cables have been designed for 40 year performance. In fact, there exist in some of the big metropolitan areas cables that were built even more than 40 years ago. At that time, cable construction was based on oil impregnated cellulosic paper. Since then, demand for electricity has grown dramatically and rapidly. Industry, in response to this trend, has found it more efficient to increase operating voltage rather than current, because the losses were so much greater in the copper than in the dielectric of the existing cables. However, at 550 kV, the dielectric loss is found to be almost as large as the conductor loss, which means that increases in voltage with existing systems do not result in increased efficiency [19].

An attempt was begun,at least 10 years ago, to extend the use of low loss extruded dielectrics, such as polyethylene, to voltages (e.g., 138 and 230 kV) substantially above those for which they have been used commonly. This approach has received a setback during the past 5 years. A rash of failures in 5-10 year old 15 kV polyethylene insulated cables revealed the problem of "trees". This phenomenon of partial breakdown, having the appearance of a small tree, was entirely unexpected and exemplifies the trouble one may run into when introducing a new system.

Much work is now being expended to explain the mechanism of treeing and to eliminate or reduce its incidence. Use of hermetically sealed enclosures to exclude water and oxygen, as is done for paper-laminated structures, might eliminate the treeing problem, however, at an increasing cost of the system.

The preceding discussion clearly points to the need of meaningful "accelerated" life tests which have the approval of the material suppliers, the cable manufacturers, and the ultimate users, i.e., the utility companies. Accelerated life tests have been performed for many years and yet their validity is still questioned. This uncertainty is believed to be a reflection of our ignorance regarding the significance of the interaction of the various stresses.

The urgency to develop meaningful accelerated life tests for underground solid dielectric cables is dramatically reflected in a multi-million dollar contract the U.S. Department of Energy has let (1977) to study the aging process in solid dielectric cables and to develop aging tests for prediction of cable life from them. There is a considerable apprehension that acceleration of one aging factor in combination with another may yield results which cannot be reliably extrapolated. Still more apprehension exists about the validity of extrapolation when two factors are accelerated simultaneously.

The status, and need of knowledge, on capacitors, transformer insulation, synthetic insulators for outdoor H.V. transmission, and electronics is amply stated in a report which has been prepared for the National Academy of Sciences [19]. However, for the sake of completeness of this paper a brief synopsis of the needs for each type is included herein.

Capacitors

Although a capacitor is a simple electrical device compared to other electrical equipment, the electrical stresses within it are probably the highest of any common insulation system. In the quest for increased energy storage at higher voltage there has been a continuous evolution in design. More recently composite dielectrics have been introduced for power capacitor application to reduce the losses and to increase the voltage levels. However, the lack of proven aging techniques inhibits the exploitation of composite dielectrics as well as any new dielectrics that may become available. To develop the needed aging techniques the report suggests research to identify the variables dictating the loss factor stability and the aging rate of polymer films, and more similar chemical and physical diagnostic techniques.

Transformer Insulation

The most common insulation system of power transformers generally consists of cellulosic paper and pressboard impregnated with mineral oil. The life of such a system is governed by the oxidation and thermal decomposition of the cellulose, oxidation of the oil, and catalytic effects of degradation products. The replacement of the paper insulation with more stable materials offers the best hope for improvement in the life of insulation systems.

There are two basic problems hindering the use of new materials. First, there is a need for improved correlation between the results of life tests conducted on the material itself and its performance in the insulation system of the transformer. Second, there is no reliable method available for measuring the life of a complete transformer without testing a full size unit.

Even in conventionally designed transformers there is a practical need to assess more reliably the extent of cellulose degradation (due to oxidation, partial discharges, or temperature) so that the user has a better notion of the remaining useful life of a particular transformer in service.

Electronics

Insulating materials for electronic applications must be capable of functioning over a wide frequency band, ranging from dc to microwave bands, and frequently must also act as packaging material. The satisfaction of electrical and mechanical requirements in the same insulating member complicates the design and has impeded work on aging. Most of the aging work is concentrated on the mechanical properties such as the flexibility of conductors, and the number of times a connector or IC chip may be inserted into a socket before the pins break off.

While the effects of contaminants and corrosion influence the aging of power systems, their effects on electronic systems are many fold magnified. The increased impact of these factors becomes evident when one considers that conducting lines on printed circuit boards may be separated by a space of less than 0.1 mm. Thus, the slightest amount of ionic conductivity in the contaminant or electrolytic corrosion of a conductor can cause catastrophic failure.

Insulation Systems for Nuclear Reactors

One of the most difficult and yet most vital needs in the technology of accelerated aging is associated with nuclear reactor electrical systems. The justification of this assessment is based on the stringent requirement reactor safety. One of the prerequisites for safety is that the emergency electrical equipment must be capable of operating at any time during the plant's lifetime of 40 years. The major role of the emergency equipment is to minimize the radioactive material losses that might emanate from the primary containment shell when there is a "loss-of-coolant accident (LOCA)". This accident occurs when the reactor core cooling water mains are all ruptured. Water pumps for emergency flooding and fans for atmospheric filtering within the containment must then operate continuously at full load in the severe environment of radiation, steam, and decontamination chemical sprays for a period as long as a year or until neutralization is achieved.

Though the probability of the occurrence of this event is very small, the IEEE Nuclear Power Engineering Committee is deeply involved in the development and publication of standard procedures to qualify all of the equipment for safe operation until shutdown of the reactor. Well-defined stages of environmental aging must be described and the endurance capabilities proven, to provide assured performance. The logical approach to this goal is by simulation of the total aging process by accelerated exposure techniques.

The qualification test for large equipment is focused primarily on the handling of a single specimen, such as the 150 h.p. motor-driven fan assembly of the air filter system. This assembly is put through an aging cycle which is based on a combination of engineering compromises and extrapolations in which both accelerated aging time and combined-environment simulation are kept to a minimum. The actual LOCA simulation subjects the assembly to a very severe and rigorous test, but again it calls for sequential exposures rather than a combined-environment exposure [20]. Thus, the combined degradation effects of the initial high dose rate of radiation, high temperature, high pressure steam, and decontamination chemicals so important to a realistic assessment are not obtained. In spite of the work that has already been accomplished in the standards organizations, dealing with radiation effects on materials, there is still no comprehensive catalog available of tests dedicated to material selection. This particularly true with regard to the two major uncertainties, namely, the dose rate effect and the combined-environments effect. A long range effort is necessary for the development of new techniques for modeling the kinetics of concurrent reactions so that accelerated testing can be performed reliably. First order kinetics may no longer be applicable for analyzing aging proceeses occurring from a combination of stresses. In other words, "What comes next after the Arrhenius rate equation?" Whatever does will definitely be more complex in the radiation field.

DISCUSSION

Thermal Aging

Thanks to Dakin's chemical interpretation of aging, the existing procedures are generally adequate as long as first-order kinetics are obeyed. However, testing time is, at present, entirely too long and too expensive. The validity of this statement becomes obvious when one considers that approximately a year is required to obtain an aging curve on a motorette system or simply on magnet wire. The direction of work should now turn to measuring the degradation near or at operating temperature for a relatively brief period of time, in hours or days, and integrating the differential changes over the expected life.

Paloniemi [21] has addressed himself to this question. He proposed a technique using Isothermal Differential Calorimetry. Kelen [22] acknowledges a potential drawback of accelerating aging because of the risk of changing the aging mechanism from that operating under normal service stress. To this end, his paper provides an in-depth survey of the available analytical methods.

Voltage Aging

There exists a need for voltage endurance testing of insulating materials and systems. Many documents have been published or are being developed, although only few address themselves to the fundamental aspects of the problem. In voltage endurance testing two approaches are available at this time. One attempts to increase the amplitude of the stress at constant frequency, while the other tries to maintain constant amplitude but increases the frequency. The first approach is limited by the breakdown strength of the material and does not allow much room for acceleration. The second one offers obviously much more flexibility in terms of frequencies but one has to be aware of the dependence of the materials' electrical properties on frequency. Unless the loss is tangent, is negligible or substantially independent of frequency over the proposed test range, the use of higher frequencies will lead to erroneous results. When the dielectric loss significantly increases with frequency, the temperature rise resulting therefrom would add its own aging effect.

Watson [23] indicates that the number and magnitude of discharge pulses may not remain constant as the frequency of the applied voltage increases.

It has been noted that electric stresses, in the absence of internal discharges, can cause changes in material properties. Some ascribe the changes to electrochemical reactions, while others express the suspicion that the observed changes are really caused by partial discharges but the corona detecting system is too insensitive [24].

Treeing in solid dielectrics remains still an unsolved problem. While considerable literature has been accumulated on this subject, the interpretation of the data has been more illuminating of the confusion that exists, than of the knowledge that is needed.

Mechanical Aging

As the sizes of turbine generators and transformers increase so do the mechanical forces that can stress the integrity of their insulation systems. Generally speaking, these forces consist of: (a) electromagnetic vibration at twice the power frequency, inducing fatigue, (b) differential expansion forces due to the temperature variations following load changes, and (c) impact forces due to electrical faults.

In recognition of these stresses, Maughan et al. [25] describe a comprehensive list of mechanical tests applicable to large rotating machinery. However, these tests are focused more on screening than on life prediction. McNutt and Patel [26] concern themselves with the mechanical and thermal environment of large transformers. To this end, they developed an experimental program employing small transformer models as specimens. They studied the relative effects of short circuits and calculated cumulative damage effects. These effects were reached by assessing the functional life of a transformer from its past stressage history and estimating the probability of failure over the next few short circuits. While each paper presented knowledge on aspects of aging neither provided the answers required to make life predictions. The status of mechanical aging is best summarized by Boulter [27] where he says:

> "In comparison to thermal and electrical ageing functional tests, national and industry standards have only rarely described mechanical ageing tests for electrical insulation systems. Most of the published material on mechanical testing relates to use of mechanical stresses for brief periods at normal service levels to serve as diagnostic aids in evaluating deterioration caused by another ageing stress, or short time exposure to relatively severe levels to evaluate the resistance of an apparatus to an externally applied mechanical stress that may be characteristic of specific applications.
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> "Wide recognition during the 1950s and 1960s that operationally induced mechanical stresses were, in some few cases, important contributors to insulation system ageing, was an important factor in developing the scope of TC 63's activities. Operationally induced mechanical stresses may arise from electrodynamic forces, from the mechanical operation of equipment and from thermal expansion or contraction of equipment components under varying conditions of service.
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> "The realization that service level mechanical stresses in certain types of power equipment could be more important in determining insulation and equipment life than thermal exposure and ageing, has led to the recent development of mechanical testing methods for insulation systems. However, the published work on mechanical ageing, either on actual equipment, or on functional test models, is only a very small fraction of the work published on thermal ageing, or even on voltage endurance.
>
> "A contributing factor to the lack of standardized mechanical stress functional tests of insulation systems is the slow development of accepted theories which relate accelerated mechanical stress ageing to service stress level ageing. There is as yet no general relationship, similar to the Arrhenius equation for thermal degradation of organic materials, or sufficient published data on frequency acceleration, to adequately define limits and acceptable extrapolations. Mechanical ageing of insulation systems has, thus, been largely limited to amplitude levels only slightly above service levels, and to a higher frequency of stress application, or reversal."

Nonetheless, Boulter suggests approach analogous to voltage aging and suggests caution in test acceleration by increasing the frequency of stress reversals. An excess frequency may create changes in the mechanism of insulation aging from what actually occurs in service. He further suggests that acceleration of frequency is most successful for low-amplitude stresses when the generated temperature due to increased energy dissipation remains nominal. He warns of unwanted resonance conditions that may be introduced by frequency acceleration, and reminds the reader that many systems are sensitive to the rate of mechanical strain application and well exhibit radically different results at different strain rates.

Combined Environment Aging

Most electrical equipment is subject to multiple stresses. To this author's knowledge there is no electrical component or electrical device that operates without electrical stress and concomittant temperature caused by electrical losses in the dielectric and/or in the conductor. In addition, a large segment of equipment in the machinery area subjects its insulation to mechanical stresses. As already discussed, the reactor-associated electrical equipment may also be subjected to ionizing radiation environment.

The need for multiple stress and environmental aging has been obvious for many years. What has frustrated progress in this area is the absence of relations, comparable to the Arrhenius chemical rate law, descriptive of the effects of voltage or mechanical stress. Compounding this difficulty is the fact that there are synergistic reactions which cannot be anticipated without experimental or service experience.

Fort and Pietsch [28] demonstrated that consecutive thermal and voltage tests do not provide the same measure of aging as obtained when voltage and temperature are simultaneously applied. The results obtained from a sequential exposure of materials to thermal aging and radiation stresses can be misleading. There is experimental evidence in the literature confirming the above statement. Insufficient data are available to permit calculations of degradation rates needed to predict service life when more than one stress is acting simultaneously on the material. Exploratory work by Campbell [29] has demonstrated that in environments combining radiation with high temperatures the life of insulating materials is far different from that obtained in the individual environments or from sequential exposures to each environment. Each material is affected differently, with some showing an accelerated degradation while others have a longer life in some environmental combinations. For example, simultaneous aging at temperature in γ-ray radiation of a polyimide, a polyvinylformal, and a polysiloxane produces considerably longer lifetimes than just thermal aging at the same temperature. On the other hand, polytetrafluoroethylene deteriorated much more rapidly under the simultaneous action of heat and radiation.

SUMMARY

If the knowledge of the mechanisms of insulation aging were a T.V. signal, then when received the image would be somewhat clear for thermal, quite snowy for voltage and mechanical, and out of synchronism for multifactor stresses.

It is evident that whatever mastery the insulation profession has over thermal aging is largely due to the adoption of Dakin's use of the chemical rate equation. Unfortunately, no one has yet uncovered any corresponding relation applicable to voltage or mechanical aging. It is, of course, true that many practical mathematical expressions have been used such as the inverse power law relationship between lifetime and working voltage. However, empirically determined voltage dependent lifetime formulae are not generally valid for use outside the life range experimentally verified. Furthermore, there is no proof that the same dependency will apply to a different electrical system. Similar limitations and uncertainties apply to mechanical stress aging.

The only way out of this blind alley is aggressive research concentrated on the underlying physical processes responsible for aging. Such an attack should try to uncover the sensitivity of insulation materials to electric field, mechanical stress, temperature, and other environments such as radiation, chemicals, etc. In addition it should determine the microscopic morphology of materials for stress-time and environment-time conditions.

If the assault is successful it will provide a better comprehension of the mechanisms responsible for the molecular changes within the insulating materials. With a clearer view of the cause-effect-relationships, one will be able to use this knowledge for assessing single or multi-factor aging. Synergism, generally associated with combined-stress or environment aging, would become tractable.

In additon, the improved discernment fo the interactions would provide the impetus for the development of effective non-destructive means of sensing aging. A non-destructive test inherently requires a smaller number of specimens because the measurements are tailored to follow a variation in the material's property which property, after all, reflects a statistical averaging of the properties of its constituent molecules. On the other hand, a destructive test merely probes the weakest link which represents the characteristics of a small volume or few molecular species.

A side advantage of non-destructive testing rests on the ability to monitor the state of aging for probable life remaining. In contrast, a destructive test reveals either that the life of an insulation system has come to an end or that it is still operable but gives no clues of the life remaining.

There is one complexity injected in the use of a non-destructive measurement in that one must know or must determine the parameter that reflects aging. To illustrate, a quarter century ago, a project was started to research aging of polyvinyl-formal coated wire, by non-destructive means [30]. That wire was chosen because it had considerable service experience. The changes in dielectric properties were measured during temperature aging and a strong correlation was discovered between aging and dielectric loss. That is, that the time-loss curve decreased with temperature aging, reached a minimum, and then slowly rose again with time. The minimum loss point reflected the reduced mobility of the dipoles because of the increased viscosity of the resin (from the loss of plasticizer). This point in time corresponded to the end-of-life measured by conventional destructive testing of thermally aged specimens. Thus, the dissipation factor was found to provide a dependable aging index for polyvinyl formal resin. When the same approach was tried for Teflon$^{(R)}$ covered magnet wire, dielectric measurements proved of no value as an aging index, because the aging interactions did not materially change the dielectric properties of Teflon$^{(R)}$.

Lastly, compatibility of materials is still not well understood and hence is seldom predictable, yet this knowledge is essential in the application of insulating materials in electric systems. In explanation, two events are described to highlight the importance of this property. During the course of an IEEE round-robin aging of motorette systems [17], it was found that a group of motorettes using neoprene treated tie cords (the normal tie cords were wax treated) suffered premature failures. Analysis revealed wire failure under the tie cords from the reaction between the neoprene and the Formvar enamel. Another illustration of incompatibility moved the Navy to change its criterion of expected insulation life [31]. This had been brought about by the new polyester magnet wires, many of which were downgraded when treated with impregnating varnish [2].

In conclusion, there is much to learn about time response of electrical systems and materials to stresses and environments. The acquisition of this knowledge is vital to the electrical industry, if it is to employ new materials in innovative or more efficient systems. To this end, basic research on materials response must be encouraged and nurtured. This can be realized through a joint effort of industry, university, and government, as urged by the Conference on Electrical Insulation and Dielectric Phenomena in the National Research Council Report [19] on this general subject.

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REFERENCES

[1] L. J. Berberich, "Three Decades of Progress in Electrical Insulation". Insulation, March 1959.

[2] W. W. Pendleton, "Symposium on Aging Phenomena in Electrical Insulation - Introduction".

E. L. Brancato, K. N. Mathes and J. R. Perkins, "Historical Background in the Evaluation of Thermal Aging of Electrical Insulation". Proceedings of Conference on IEEE Winter Power Meeting, Jan 25-30, 1970, 70 CP 51 - PWR.

[3] C. P. Steinmetz and B. G. Lamme, "Temperature and Electrical Insulation", AIEE Trans., Vol 32, 1913.

[4] V. M. Montsinger, "Loading Transformers by Temperature", AIEE Trans., Vol. 49, 1930.

[5] T. W. Dakin, "Electrical Insulation Deterioration Treated as a Chemical Rate Phenomena", AIEE Trans. 1948.

[6] E. L. Brancato, L. M. Johnson, F. J. Campbell and H. P. Walker, "Reliability Prediction Studies on Electrical Insulation: Navy Summary Report", NRL Report 8095.

[7] K. N. Mathes, "Functional Evaluation of Insulating Materials", AIEE Trans., Vol. 67, pt. 2 pp. 1236-40, 1948.

[8] A. T. McClinton, E. L. Brancato and R. S. Phillips, "Voltage and Vibration Effect on Motor Insulation", Electrical Manufacturing, Nov 1953, pp. 109.

[9] R. S. Phillips and E. L. Brancato, "Functional Evaluation of Insulation Systems Employing Motorettes", NRL Memo Report 446, 23 Mar 1955.

[10] L. M. Johnson, "A Novel Condensation Chamber Proposed for the AIEE 510 Procedure", Proc. of Conf. on IEEE Winter General Meeting, 31 Jan 1963, CP 63-472.

[11] F. J. Campbell and E. L. Brancato, "Determination and Application of Thermal-Life Characteristics of Aerospace Wires", Pt. II, Insulation, Nov 1963, pp. 23.

[12] L. M. Johnson, F. J. Campbell and E. L. Brancato, "A Statistical Analysis of Methods Using Truncated Data to Shorten Thermal Evaluation Time", Proc. of 10th Electrical Insulation Conference, 1971.

[13] C. G. Currin and J. F. Dexter, "A Method for Evaluation of Thermal Stability for Magnet Wire Enamel", AIEE Publication S-61, pp. 26-30, June 1954.

[14] G. A. Cypher and R. Harrington, AIEE Trans. 71 Pt. III 251, 1952.

[15] "The Life Expectancy of Class A Random-Wound Motor Insulation as Determined by AIEE Standard No. 510 Test Procedure", AIEE Committee Report, September 1959.

This paper was presented at the T. W. Dakin Symposium on High Voltage Insulation, Pittsburgh PA, 10 May 1978

[16] L. M. Johnson, "An Analysis of the Intrinsic Characteristics of the AIEE Round-Robin Motorette", Conference Paper No. CP 61-349, presented at AIEE Winter General Mtg., February 3, 1961.

[17] "Refinements in IEEE No. 117 Test Procedure for Evaluation of Life Expectancy of Random Wound Motor Insulation Systems", IEEE Working Group No. 117.

[18] J. McCarthy, "Panel Discussion Examines Evolution of Thermal Evaluation", Insulation, p. 36-40, April 1968.

[19] "Research Needs to Assess the Long-Term Performance of Electrical Insulating Materials and Systems", The National Res. Council Conf. on Electrical Insulation and Dielectric Phenomena, Commission on Sociotechnical Systems, 1977.

[20] IEEE Standard 334-1974, "IEEE Standard for Type of Continuous Duty Class IE Motor for Nuclear Power Generating Stations".

[21] P. Paloniemi, IEEE Trans., E.I. Vol 7, 126 (1972), "Isothermal Differential Calorimetry as a Means to Measure Insulation Aging Rate Down to the Operating Temperatures".

[22] A. Kelen, "Short Time Ageing Tests," NORDIC Insulation Symposium, 1974.

[23] K. Watson, Private Communication, March 1978.

[24] CIGRE - SC 15 Colloquium, Helsinki, 8 Sept. 1977.

[25] C. V. Maughan, E. E. Gibbs, and E. V. Giaquinto, "Mechanical Testing of High Voltage Stator Insulation Systems", Conference Paper No. 70 TP 45-PWR, presented at the IEEE Winter Power Meeting, 25-30 Jan 1970.

[26] W. J. McNutt and M. R. Patel, "The Combined Effects of Thermal Aging and Short-Circuit Stresses on Transformer Life", IEEE PES Winter Meeting & Tesla Symposium 25-30 Jan 1976.

[27] International Electrotechnical Commission Technical Committee No. 63: Insulation Systems (DRAFT), "Mechanical Stresses as Ageing Factors of Electrical Insulation Systems", A. Boulter, 63 WG 7(GLoucester/Sec.)2, June 1976.

[28] E. M. Fort and H. E. Pietsch, "Aging of Insulation by Thermal and Electrical Stresses", Electrical/Electronics Insulation Conference Proc., Nov 1975, pp. 143, IEE Publication No. 75 CH 1014-0-EF54.

[29] F. J. Campbell, "Combined Environments versus Consecutive Exposures for Insulation Life Studies", IEEE Trans., Vol NS-11, 123 (1964).

[30] E. L. Brancato, "Non-destructive Testing of Insulation", AIEE Technical Paper 53-125, 1953.

[31] E. L. Brancato, L. M. Johnson, F. J. Campbell, "A New Navy Classification Criterion for Insulation Life", IEEE Trans. Electrical Insul., April 1978, Vol. EI-13, pp. 1402.

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