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THE EFFECT OF RADIATION ON INSULATING MATERIALS USED IN WESTINGHOUSE MEDIUM MOTORS

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THE EFFECT OF RADIATION ON INSULATING MATERIALS USED IN WESTINGHOUSE MEDIUM MOTORS

by

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ABSTRACT

The effects of radiation on the insulating properties of materials used in Westinghouse medium motors was investigated toward the end of aiding the qualifications of these motors for use in a reactor environment. A comparison of changes induced by heat-aging alone and heat-aging and irradiation is made. The results indicate that most materials should be able to withstand an accumulated dose of 10^7 rads during the course of their operational life.

I. INTRODUCTION

Along with the increase in power reactors there will be a corresponding increase in the need for radiation resistant motors to perform control and other functions. The Buffalo Medium AC Motor and Gearing Division, recognizing this need, requested the Radiation and Nucleonics Laboratory to examine the individual insulating materials and greases with respect to the effects caused by radiation on the electrical and, where pertinent, physical parameters.

The first step in this effort was to conduct a literature survey of previous radiation effects tests conducted on the pertinent insulating materials. The information, thus obtained, provided us with an approximate indication of the relative radiation resistance of the various types of materials.

This information, however, is not sufficient by itself to permit a realistic evaluation of material conduct in a radiation environment. The reason is that these materials are subject to thermal aging stresses as a result of continuous motor operation. Any study program of this type must include these stresses as well as the effects resulting from radiation.

Ideally, one would like to monitor the materials within the motor while in operation in the presence of radiation. Such a test is not feasible for many reasons. We, therefore, set up a more modest testing program which should however provide reasonably realistic information on which to base judgements of the reliability of the materials under actual operating conditions in a radiation background. The program consisted basically of performing electrical and physical tests on the materials conditioned in two ways: (1) Heat-aged in an oven equivalent to 20 years of operation, and (2) Heat-aged plus irradiated to a dose of 10^7 rads. The radiation source for all material types was our

Van de Graaff accelerator producing 2 MeV electrons. The same electrical and physical tests were performed on off-the-shelf material to provide us with benchmark parameters for the succeeding tests.

The remainder of this report, covering the efforts of this program, will be divided into five sections. Section II will discuss the motor types involved and the material categories. A brief summary of expected radiation effects on materials in these categories will be presented in Section III as well as a summary of the information obtained during the literature survey on the pertinent materials. Section IV will cover the heat-aging, irradiation, and testing procedure used in this study. The results of the tests will be presented in Section V followed by a discussion in Section VI.

II. MOTOR MATERIALS

The materials from three types of stator insulation systems were involved in this study: (1) the LLT Standard Class B (130°C), (2) the LLT Standard Class F (155°C), and (3) the LLT Standard Class H (180°C). The materials which are constituents of these systems serve two basic functions: (1) They separate the various electrical components from one another and from the stator iron and all of the structural parts. (2) They protect themselves and the electrical components from attack of contaminants and other destructive forces. Without going into great detail on individual functions, we will classify all of these materials into three categories.

1. Turn-to-Turn Insulation. The basic purpose of materials in this category is to provide insulation between wires in a coil. The primary insulating material is the coating on the wires. A secondary material is an impregnating varnish which fills air gaps and fixes the wires in position.

2. Phase Insulation. The materials in this category, in the form of laminated sheets, serve to insulate the coils in phase groups from either each other or "ground" represented by the structural part of the motor.

3. Sleevings and Tapes. The sleevings and tapes perform dual functions of housing or binding as well as insulating.

Table 1 lists the materials that have been tested for each motor in each of the three categories mentioned above. It should be stressed that this is not an all-inclusive list of all the materials used by the Buffalo AC Medium Motor and Gearing Division in their motors. The list has been confined to those materials generally found in their standard motors as well as some that are being planned as future substitutes.

III. RADIATION EFFECTS ON INSULATING MATERIALS

The material in this section represents an abstract of information from References 1, 2 and 3.

A. General

There are essentially three basic types of radiation which can result in major effects on materials: (1) neutrons, (2) charged particles (protons, electrons, alpha particles, etc.) and (3) gamma and x-rays. Each type of radiation produces characteristic patterns of material damage somewhat dependent on the energy of incoming radiation. The damage can be discussed under two categories: displacement and ionization. Displacement refers to the physical damage produced by knocking an atom from its normal position to another location. Ionization is the ejection of orbital electrons from an atom to form ionized atoms and free electrons. The effects due to displacement are permanent in that they remain after the source of radiation has been removed. Permanent effects can be wholly or partially annealed in many cases by the application of heat or other environmental conditions. Ionization effects can be transient, i.e., property changes occur during irradiation which disappear upon removal of the radiation source, or they can be permanent. In the following paragraphs, we will confine our discussion to electron, gamma and x-ray effects which are generally of the ionization variety, since the Buffalo Medium Motors and Gearing Division's immediate interest was in the effects produced by radiation in this category.

B. Electrons

In their passage through matter, electrons primarily interact with atomic electrons. For low energy electrons, most of their energy is lost in ionization. At high energies, i.e., energies much greater than their rest energy, 0.511 MeV, losses due to radiative interactions (Bremsstrahlung) may approach ionization losses. In general, the expected effects of electron bombardment of materials may be attributed basically to ionization interactions giving rise to changes in the structure.

Although the average energy lost by an electron per collision is small (about 10 eV), the probability of electron interaction is very high with the result that the electron range in materials is very short compared with chargeless neutrons, gamma rays and x-rays. It is obvious then from the preceding, that the electron range for a given electron energy is inversely dependent upon the electron density and, therefore, in materials with a high Z such as lead, their range is quite small.

C. Gamma and X-Rays

These are both forms of high energy electromagnetic radiation. They have the same general nature as ultraviolet or visible light, exhibiting simultaneously some of the behavior of wave phenomena and some of the behavior of particles. The energy of electromagnetic radiation is transmitted in packets or more commonly photons.

X-ray radiation can be classified into two types: characteristic and continuous. Characteristic x-rays, which as their name implies, have discrete energies characteristic of the particular element concerned, result from transitions between electronic energy levels of the atom. Continuous x-rays, also called bremsstrahlung, i.e., braking (slowing down) radiations, cover a considerable range of energies. These are produced when electrons (or beta particles) of high speed are slowed down as a result of interaction with matter. Thus, any source of high energy betas will produce bremsstrahlung when the betas are slowed down in material. Gamma rays originate in nuclei and result from transitions between nuclear energy levels. They are generally more energetic than x-rays.

There are three ways in which electromagnetic radiation interacts with an absorbing material; namely, the photoelectric effect, the Compton effect, and pair production.

In the photoelectric effect, a photon of electromagnetic radiation, with energy greater than the binding energy of an orbital electron in an atom, interacts with the latter in such a way that the whole of the photon energy is transferred to an electron which is consequently ejected from the atom. If E is the energy of this photon and B is the binding energy of the electron in the atom, the difference, i.e., E-B, is carried off as kinetic energy by the ejected electron. The photoelectron, as it is called, behaves like a beta particle of the same energy in its passage through matter. The photoelectric effect increases with increasing atomic number of the absorber and with decreasing photon energy.

The Compton effect process occurs when a photon makes an elastic (or "billiard ball") collision with an outer electron of an atom of the absorbing material. Such an electron is loosely bound so that it behaves as if it were completely free. In the collision, both momentum and energy are conserved, and part of the energy of the incident photon is transferred to the electron; at the same time the photon is deflected, i.e., scattered, from its initial path. Since the Compton effect involves interaction between a photon and an electron, its magnitude is dependent on the number of orbital electrons in the atom of the absorber; this is the same as the atomic number. The Compton interaction is thus directly proportional to the atomic number of the absorber, so that, like the photoelectric effect, is significant for materials of high atomic number.

When a gamma-ray photon with energy in excess of 1.02 MeV passes near the nucleus (and to some extent the outer electrons) of an atom, the photon can be annihilated in the strong electric field with the formation of an electron-positron pair. Since the energy equivalent of the total mass of an electron and a positron is 1.02 MeV, this is the minimum energy necessary for the production of a pair of particles. Any energy of the gamma ray in excess of 1.02 MeV appears mainly as kinetic energy of the electron and positron. Pair production increases with the atomic number of the absorbing material and with increasing photon energy in excess of 1.02 MeV. Since both the photoelectric and Compton effects decrease with increasing photon energy, whereas pair production increases, it is evident that the latter process will become of greater importance at high energies. For absorbers of high atomic number, it becomes the dominant type of interaction for gamma rays with energies in excess of about 5 MeV.

The electrons produced in these interactions in the process of being slowed down will produce bremsstrahlung radiation and ionize atoms along their paths. Thus, the overall effects to materials are ionization and heating. At higher energies the photons may possess sufficient energy to cause some displacement damage. Gamma and x-rays are highly penetrating, as previously mentioned, but because they interact with atomic electrons to a great extent, materials containing a high electron density are better suited for attenuating electromagnetic forms of radiation.

D. Summary

When any particle of radiation comes close enough to an atom, it is either scattered or absorbed. In either case, the interaction results in a transfer of energy from the incident radiation to the material. Most of this energy is ultimately degraded into heat, and in some cases, for example, when metals are exposed to gamma radiation, the only noticeable effect produced is a rise in temperature. However, in other cases, some of this absorbed energy becomes available for other purposes -- the breaking of chemical bonds, the displacement of atoms from their normal lattice positions, the excitation of electrons in solids from valence bands to conduction bands, etc. When this happens, the properties of the irradiated materials may be appreciably altered.

E. Dosimetry

Throughout the remainder of this presentation, we will be mentioning the upper limits of radiation dosage that materials have been tested or have been found to degrade seriously. It is necessary at this point to clarify the units that will be used in this connection. Nuclear radiation can be examined in two distinctive ways, intrinsically and extrinsically. An intrinsic description of radiation is a description of the radiation per se, that is, an indication of the number of particles passing through a given area (together with the radiation energy distribution or spectrum) in units such as neutrons per square centimeter (abbreviated n/cm^2 or nvt). An intrinsic description of radiation may also be formulated in terms of the effect of its interaction with some agreed-on standard matter, such as air. The roentgen (abbreviated R) is defined as the amount of radiation which will cause 2.08×10^9 ionizations in 1 cm^3 of dry air at 0°C and 1 atm. Extrinsic descriptions, on the other hand, depend on both the radiation and the material irradiated. The most widely used description is based on the energy deposited by the radiation in a unit mass of material. The rad, defined as 100 ergs/gm, is the commonly used extrinsic unit. Many times throughout this material, the units "rads(Si)" will be observed. Rad(Si) is actually an intrinsic unit since it is defined as the field of radiation which will produce 100 ergs/gm in silicon. As a rough rule of thumb, 1 rad (Si) ≈ .87 R. This holds approximately true for most light elements and organics as long as the energy of the incoming radiation is not very high. A radiation environment will generally be characterized in either intrinsic or extrinsic units. Conversion from one system to another is a rather complex procedure and is beyond the scope of the present presentation. However, an illustrative example may prove beneficial in clarifying the definitions and the procedure involved.

An equivalent definition of the roentgen is that it represents the radiation field in which 1 gm of air absorbs 83.8 ergs. If the 1 gm of air were replaced by 1 gm of soft tissue and the photon energy were not too high, the amount of energy absorbed would be about 93 ergs. Since 1 rad equals 100 ergs/gm, then the conversion for this case is that a 1 R field gives rise to approximately 0.93 rads. It should be emphasized that this holds true only for tissue under the circumstances indicated. The amounts of energy absorbed by materials in a radiation field will depend on the material and on the type and energy of the radiation. To further illustrate the latter, Table 2 shows the fluences of several types of external nuclear radiation equivalent to 0.93 rads in tissue; i.e., it gives the intrinsic measures that correspond to this particular extrinsic dose.

TABLE 2

COMPARISON OF RADIATION FLUENCES RESULTING IN THE DEPOSITION OF 0.93 Rads IN SOFT TISSUE

Radiation	Energy	Fluence
Gamma Rays	1 MeV	1.92×10^9 photons/cm^2
Beta particles	1 MeV	4.51×10^7 betas/cm^2
Thermal neutrons	0.025 eV	9.6×10^8 n_t/cm^2
Fast neutrons	2 MeV	1.92×10^7 n_f/cm^2

It can be readily seen that since gamma rays are more penetrating, they will not lose as much energy per unit path length as beta particles, and hence more will be necessary to result in the loss through absorption of a given amount of energy. Both types of neutrons exchange energy primarily via collisions with ionization producing protons, but thermal neutrons will also engage in interactions which result in gamma rays which are likely to escape the immediate vicinity of the interaction.

The foregoing paragraphs serve to illustrate the complexity of the conversion from extrinsic to intrinsic units. The numbers quoted above apply only for one well-documented material, soft tissues. Depending on the material, similar information may be obtainable in the literature.

F. Organics in General

Organic insulating and dielectric materials experience both temporary and permanent changes in characteristics when subjected to a radiation environment such as that found in space and the field of a nuclear reactor or radioisotope source. Data indicate that the temporary effects are generally rate sensitive with a saturation of the effect at the higher radiation levels. The enhancement of the electrical conductivity is the most important of the temporary effects with increases of several orders of magnitude being observed. The magnitude of the increase is dependent upon several factors including the material being irradiated, ambient temperature, and the radiation rate.

Absorption of energy, excitation of charge carriers from non-conducting to conducting states, and the return of these carriers from conducting to non-conducting states are considered responsible for the induced conductivity.

The cumulative results of the temporary effects as pertains to the electrical parameters of insulating materials are a reduction in breakdown and flashover voltages as well as an increase in leakage current or conductance -- the latter also being identified as a decrease in the materials insulation resistance. However, these temporary changes in electrical characteristics are often not large enough to prevent the use of organic insulators and dielectrics in a radiation environment. This is especially true if the designer considers these changes and makes allowances to minimize their effects. Where the designer is under severe space limitations or the application includes a high radiation exposure rate, however, it may be necessary to limit insulating material considerations to the inorganics.

Permanent effects of radiation on organic insulating and dielectric materials are normally associated with a chemical change in the material. Most important among these chemical reactions that occur are molecular scission and cross-linking. These chemical reactions or changes modify the physical properties of the material. A softening of the material, decreases in tensile strength and melting point, and a greater solubility could be the result of chain scission. Cross-linking leads to hardening, an increase in strength and melting point, a decrease in solubility, and an increase in density. Thus, the permanent effects of radiation on organic materials is predominantly a change in the physical properties. This physical degradation, however, may also be disastrous to the electrical characteristics of component parts such as printed circuit boards, wire insulation, and connectors. Radiation induced embrittlement of insulating structures, such as these, were the insulation cracks or flakes could in turn cause a circuit to fail electrically through an "open" or "short" circuit. This is often the case when an insulator or dielectric material fails in a radiation environment, i.e., physical degradation followed by failure of electrical properties. Changes in dielectric loss or dissipation factor and insulation resistance have also been recorded as permanent effects from exposure to a radiation environment. These changes, however, are often quite small, and it would be the more uncommon application where they would offer any problem.

G. Summary of Literature Survey Study

The relative radiation resistance of representative organic insulating materials is given in Figure 1, obtained from Reference 2. It is immediately apparent that their resistances vary rather widely, from Teflon, unusable after a dose of $<10^5$ rads (Si), to phenolics, still usable at $\sim 10^{10}$ rads (Si). Most organics, however, are satisfactory to a dose of 10^6 rads (Si).

Shown in Figure 2 is a listing of materials tested in this study and their relative radiation resistance abstracted from Figure 1. Certain materials, such as laminates, have been broken down into their component organics. Though we have listed their individual radiation resisting abilities, one should not surmise that the resistance of a composite material is either the average of the individual organics or that of the least resistant component. There exist other factors, such as radiation-induced changes in the bonding or chemical interactions between neighboring layers that must be taken into account. From the data in Figure 2, it appears that most materials should be able to withstand $\sim 10^7$ rads (Si). However, it should be pointed out that these tests do not include thermal aging.

The materials which appear most suspect are silicone rubber and polyamide. However, materials in these categories vary in composition and makeup and, therefore, the materials subjected to testing may not be indicative of the response of the materials used in Westinghouse motors. For example, from the test reports the only polyamide mentioned is nylon which differs considerably in properties from Nomex, the polyamide used in Westinghouse motors.

Unfortunately, there is little information with regard to changes in electrical parameters as a function of dose. The limited amount uncovered on the pertinent materials is presented in Figure 3. From this, one can surmise that the resistance to radiation-induced changes in the insulating properties for materials not shown will approximate the resistance to physical change within an order of a magnitude.

IV. TEST PROCEDURES

A. General

The first step taken toward testing the motor materials was to consult with Research Laboratory specialists on insulating materials in the various categories listed in Section II. The purpose was to determine the physical and electrical tests that would be most pertinent for the materials in line with the functions they serve in motors. The materials and the selected tests are listed in Tables 3, 4 and 5, which will be discussed in greater detail in the next section. Additional information was obtained on the sizes, shapes and quantities of material samples for good test results and adequate statistics. A sufficiently large quantity of each material was obtained from the Medium Motors and Gearing Division to satisfy these requirements.

A test plan was also formulated during this meeting which was followed throughout the remainder of the program with two exceptions discussed later. In accordance with this plan, the number of test specimens of each material was grouped into three sets with each set containing the predetermined number required for adequate statistics. One set was tested as off-the-shelf material, to provide benchmark parameter values. The second and third sets were heat-aged to the equivalence of approximately twenty years of operation. Upon removal from the oven, the second set was distributed to the testing groups and the third set was electron-irradiated by a 2 MeV Van de Graaff accelerator. At the termination of the irradiation, this set was forwarded for testing. Thus, at the completion of the testing, three sets of data were obtained for each material type enabling the determination of the effect of heat-aging and irradiation on the electrical and physical parameters.

In the following section, we still discuss in greater detail some aspects of the procedure mentioned above.

B. Heat-Aging

One of the biggest problems in this project was to determine an oven temperature and heating period necessary to heat-age the materials at an accelerated rate. The difficulty is that each material has its own heat-age curve. The final decision on this problem was based on information supplied to us by the Medium Motors and Gearing Division and consultation with insulating materials specialists at the Research Laboratories. The materials in the various class systems were heat-aged for two weeks at the following temperatures: [ ]+ +a,b,c

The heat treatment was carried out successfully except for two class H laminates: [ ]+ These exhibited considerable warping and separation of +a,b,c the layers upon removal from the oven and were considered unsuitable for electrical testing. A second group, heat aged in the same manner, but with the samples placed between aluminum plates was also found unsuitable. A third group, heated to a temperature of 285°C for one week was found to be satisfactory.

There was one other deviation from this plan. It was found that off-the-shelf [ ]+ failed in heat-shock tests +a,b,c below 250°C, the temperature at which they were to be heat aged. In order to make sure that these samples would not be ruined by high oven temperatures, they were heat-aged in a 175°C oven for two weeks. This was done only for the class F wiring heat shock tests.

The electron irradiations were performed using the Radiation and Nucleonics Laboratory 2 MeV Van de Graaff Accelerator. All of the specimens received an electron fluence of 5×10^{14} e/cm^2 as measured by a Faraday cup arrangement. In terms of the total energy density deposited this fluence translates to 10^7 rads (Si). On the basis of the rough rule of thumb mentioned in Section III, 10^7 rads (Si) = 0.87×10^7 R. It must be stressed that this figure is approximately true only for most light elements and organics as long as the energy of the incoming radiation is not very high. Such a situation holds for the present circumstances.

C. Electrical and Physical Tests

The electrical and physical tests are in general standard and, therefore, will not be described in great detail. The tests are listed in Tables 3, 4 and 5 along with brief remarks concerning the tests applied with some particulars.

D. Additional Radiation Tests

C. V. Fields of Nuclear Energy Systems ran an extended irradiation experiment in which he subjected motorettes to ^{60}Co gamma dose of $\sim 10^8$ rads. He kindly asked us if we would like to include any of our specimen materials with his package. Because of space considerations, the sufficiently large quantities of material needed for testing purposes could not be introduced. We therefore limited ourselves to representative samples of materials. The testing also was limited to visual and manual checks to determine if flaking, layer separation, cracking, peeling, warping and changes in flexibility had occurred.

The following materials were subject to this type of tests.

[ ]+ +a,b,c

V. RESULTS

The results of the investigation are presented in Tables 3, 4 and 5 which will be discussed in more detail in the following subsections. Each table presents information on the tests run and, where necessary, the particular parameter determined. The tables also present the average value obtained for many samples tested in the off-the-shelf, heat-aged only and heat-aged and irradiated categories.

A. Laminate Materials

The results of the tests on laminate materials is presented in Table 3b. The first three laminates tested, [ ]+, display as one might expect, consistently similar results. In the dielectric breakdown test all three show small increases in the breakdown voltage after heat-aging and after irradiation with the exception of the heat-aged 12 mil samples. The small decrease indicated may be statistical. In any case the [ ]+ appear to be little affected by the heat and radiation induced stresses applied in this study. The [ ]+ was tested for insulation resistance, dielectric constant and power factor. The only noteworthy change is in the insulation resistance which increased 16.7% after heat aging and decreased 40% after heat-aging and irradiation compared to off-the-shelf values. These changes, however, represent less than an order of magnitude variation which for the parameter is small.

+a,b,c

+a,b,c

+a,b,c

Although mechanical parameters are not nearly as important as electrical parameters, some flexure tests were run on the [ ]+ since that material is often used as a top wedge where there might be some flexural stresses. The flexural strength was seen to increase 11% after heat-aging, then decrease to values 8% greater than off-the-shelf figures after irradiation.

+a,b,c

The dielectric breakdown tests performed on the [ ]+ and the [ ]+ indicated increases in the break- +a,b,c down potential less than 10% of the-off-the-shelf values. It should be pointed out that, as mentioned in the previous section, these materials did not survive the heat treatment originally given to all class H materials, namely two weeks in an oven at a temperature of 300°C. The tested samples which required heat treatment were subjected to a temperature of only 200°C for 1 week as insurance against curling and ply separation.

The remaining two laminates tested, [ ]+ also showed small overall increases (< 5%) in +a,b,c dielectric breakdown voltage after heat and irradiation treatment. The changes are so small that they can be considered negligible.

In review, the laminate materials tested all appear capable of withstanding the dose of 10^7 rads. On the basis of the small changes one might tentatively conclude that they might withstand considerably higher doses.

B. Sleeving and Tape Insulators

The test results for these materials are shown in Table 4. As before, all figures represent the average of many tests.

1. Sleeving

The [ ]+ dielectric breakdown voltage appears to be +a,b,c relatively unaffected by either the heat treatment or the irradiation. The voltage after heat-aging showing a 9.8% increase and, after irradiation, a decrease to a value 0.9% greater than for off-the-shelf material.

The [ ]+ material appears to be almost equally +a,b,c affected by heat and radiation showing breakdown voltage decreases of 15% and 25% respectively.

The [ ]$^{+}$ sleeving is considerably affected by heat as indicated by a 50% decrease in its breakdown voltage after heat-aging. Irradiation reduces this figure by an additional 5%. +a,b,c

From the literature survey, the tolerance of the [ ]$^{+}$ is expected to be excellent to > 10^8 rads. Previous tests revealed no changes in any properties at 10^8 rads. These results coupled with its resistance to heat stresses makes it an excellent candidate for use in motors with longer continuous operation and higher accummulated doses (> 10^8 rads). +a,b,c

The [ ]$^{+}$ is not quite as good. Both heat and radiation appear to affect it, although not too appreciably at a dose of 10^7 rads. However, information from previous studies (see Section III) indicates that [ ]$^{+}$ exhibits serious deterioration in its mechanical properties at a radiation dose of 10^8 rads and elevated temperatures (above room temperature) are likely even more seriously affect the properties. On this basis we conclude that this insulation is certainly good for 20 years of operation and a dose of 10^7 rads, but may be of questionable use for a higher operational period and higher radiation doses. +a,b,c +a,b,c

The [ ]$^{+}$ appears to be little affected by radiation. Its principle limitation would be thermal rather than radiative. Since no known studies on its radiation tolerance have been performed we cannot predict with certainty the affect of higher doses but it does demonstrate excellent resistance to a dose of 10^7 rads. +a,b,c

2. Tape

Both [ ]$^{+}$ show virtually identical changes in breakdown voltage after heat-aging and irradiation. Their breakdown voltages are reduced about 55% after heat-aging but the addition of radiation exposure results in virtually no change at a level of 10^7 rads. +a,b,c

Previous studies (see Section III) indicate excellent tolerance for both materials to at least 10^8 rads so that the use of the materials is probably limited only by long term temperature effects.

C. Wire and Cable Insulation Test Results

The results of these tests are given in Table 5b, with a listing of the test presented in Table 5a. The individual insulating materials and their corresponding PD Spec Nos. are shown in the first and second columns, respectively. The test numbers corresponding to tests listed in Table 5a are shown in the third column, with the results of the tests presented in succeeding columns. The results are given in terms mentioned in the remarks column of Table 5a. As before, the results shown represent an average of the group of samples tested.

1. [ ]+ +a,b,c

Both the double-build and triple-build samples exhibit sizable changes in the results of the dielectric strength and the scrape abrasion tests after heat-aging in comparison with off-the-shelf material. A similar comparison involving samples heat-aged and irradiated show far smaller changes in these tests. This apparently indicates that heat-aging and irradiation (at least to a dose of 10^7 rads) produce offsetting effects on[ ]+ This, however, is not unique. It has been observed previously in our laboratory in connection with other materials. The other tests indicate no significant heat or radiation effects. Previous studies of purely radiation effects on[ ]+(Section III) revealed that there was no indication of any deterioration in electrical and physical properties up to a dose of 1.5×10^8 rads (C). This information coupled with present results indicate that[ ]+appears to be satisfactory for a motor operation to at least a dose of 10^7 rads. +a,b,c +a,b,c +a,b,c

2. [ ]+ +a, b, c

Both the double and triple build [ ] display +a, b, c remarkably similar changes after heat treatment in the first two test results compared to [ ]+ respectively. +a, b, c Subjection of heat treated samples to radiation, however, appears to produce no appreciable difference in these test results in comparison to the heat-aged test results. The small differences seen are probably statistical. The [ ]+ passes the adherence and flexibility +a, b, c tests throughout. Heat-aging results in improvement in material with regard to the last two tests with no change in this improvement noted for the irradiated samples. Since most polyesters subjected purely to radiation doses of $\sim 10^8$ display small changes in mechanical and electrical properties, the [ ]+ appears to good material for +a, b, c use in motors to a dose of 10^8 rads.

3. [ ]+ +a, b, c

Only dielectric strength tests were run on the varnish which serves as an insulator only secondarily. These tests were run on twisted pairs of double and triple build [ ]+ The +a, b, c dielectric strengths of off-the-shelf samples of these wires were 9.1 kV and 12 kV. Varnished pairs displayed dielectric strengths of 9 kV and 11.8 kV. This indicates that for fresh material the insulating qualities of the varnish are negligible. The reduction in the dielectric strength is considerably less after heat-aging varnished pairs as compared with unvarnished pairs indicating an improvement in varnish insulating properties after heat aging. The combination of varnish and [ ]+ +a, b, c remained relatively unchanged after irradiation. Since the [ ]+ +a, b, c showed improvement after radiation we surmise that some changes in the combined materials were effected by the radiation. The effect of heat aging and radiation on the insulating properties of the combination of the [ ]+ appear to be small, thus, +a, b, c these materials readily qualify for materials to be used in class H motors to a radiation dose of 10^7 rads.

4. Cabling

The results of the dielectric strength tests on the two cable insulations reveal little changes after heat treatment. The irradiated [ ]+ showed a 63% decrease in the dielectric strength while the same parameter for the [ ]+ increased slightly. We expected even worse results for the [ ]+ on the basis of radiation studies previously reported. Two reasons might be offered to explain the smaller degradation observed in this study; 1) the cables were subjected to electrons which are not as penetrating as gamma radiation and thus only the outside portion was greatly affected and 2) the heat treatment prior to the radiation might have improved its radiation resistance to some extent. In any case we would not recommend the use of [ ]+ in a radiation environment. The suggested substitute, i.e., the [ ]+ appears to be excellent, at least to a dose of 10^7 rads.

+a,b,c
+a,b,c
+a,b,c
+a,b,c
+a,b,c

D. Results of the Additional Radiation Tests

The materials mentioned in Section IV D were inspected for imperfections and flexure changes after they had been subjected to $\sim 10^8$ rads. The laminates exhibited some discoloration and a slight stiffening, but there were no indications of laminate separation or cracking. The cork-neoprene sample exhibited a slight increase in stiffness as did the sleevings. However, no other changes were noted. The remaining materials showed no signs of radiation damage.

E. Test Results for Motor Greases

The greases used in Westinghouse motors had previously been the subject of a study by John Locante of NES. Since the radiation levels were higher and the tests quite stringent, we did not feel it necessary to duplicate the work. However, for completeness, a summary of his tests and results are given in the following paragraphs.

Samples of the lubricant were placed in a vented 1.5 inch x 10 inch aluminum tube. The tube was then placed adjacent to a 34 kilocurie cobalt-60 source and irradiated for a period of 79 hours. Dosimetry measurements were made at various locations in the tube using Dupont light blue calibration paper 100 MS-C, #CB-91639.

Following exposures to average levels of 1.2×10^8 rads, 1.5×10^8 rads, and $.8 \times 10^8$ rads, the irradiated grease, along with unirradiated grease taken from the same supply, were subjected to the Micro-Cone Penetration Test using standard apparatus conforming to ASTM D1403-56T. The results of the penetration tests are included in Table 6.

In general, it was found that as exposure was increased the grease underwent a change in thickness function to the point that, at 1.8×10^8 rads, sufficient change had taken place to cause the grease to increase in consistency from LGI #0 to NLGI #2 rating as the grease was "worked" or sheared, rather than decrease as in the unirradiated grease. The most commonly used greases, for ball bearing applications, have consistencies ranging between NLGI #1 and #3.

For information, the industry standard for lubricating greases is listed in Table 7. A consistency of #0 implies a very soft semifluid grease. Numbers 1, 2, 3 and so forth indicate progressively stiffer grease up to #6 which indicates a stiff, tacky, water pump lubricant-type material.

Based on the test results from irradiation and ASTM Micro-Cone Penetration measurements, the bearing lubricant undergoes no detrimental change in properties, as measured in terms of consistency.

VI. CONCLUSIONS

In summary, the results indicate that virtually all materials tested would appear to be satisfactory for use in motors for $\sim$20 years in a radiation environment for which the maximum accumulated dose was 10^7 rads. A final judgment on their abilities must, of course, be by the Westinghouse Medium Motors and Gearing Division. It should, however, be noted that the insulating materials would be subject to a simultaneous thermal and radiation environment which is different from the consecutive application made in our tests. However, it is not expected that the results would differ significantly.

The only material we would definitely not suggest for use would be [ ]+, which has been proven to be extremely radiation sensitive +a, b, c
based on our and other people's experience. [ ]+, +a, b, c
which were highly suspect materials, passed their tests extremely well. In general, the materials appeared to suffer more damage from thermal conditioning than from irradiation. This would suggest that for a 10^7 rads total exposure the applicability of the insulating materials would be based more on their ability to withstand damage resulting from continued operation.

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This project required the cooperation and efforts of many groups. We would like to thank the following people and their supporting personnel for their contributions:

a,b,c

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2. C. L. Hanks and D. J. Hammon, "The Effect of Radiation on Electrical Insulating Materials", REIC Report No. 46, Radiation Effects Information Center, Battelle Memorial Institute, Columbus, Ohio, June 1969.

3. A. Charlesby, "Breakdown of Organic Materials under Irradiation", IEEE Transactions on Nuclear Science, Vol. NS-16, No. 6, December 1969.

TABLE 1

LIST OF INSUFLATING MATERIALS TESTED

Category	Material	Spec. No.
1. Laminates		
2. Sleevings and Tapes		
3. Wire, Varnish and Cable		

a,b,c

TABLE 3a

LAMINATE MATERIAL TESTS

Test No.	Test	Remarks
1		
2		
3		
4		
5		

a, b, c

TABLE 3b

LAMINATE MATERIAL TEST RESULTS

Material	Spec. No.	Test*	Off the Shelf	Heat Aged	Approximate Percent Change**	Heat Aged & Irradiated	Approximate Percent Change**

a,b,c

*The test numbers refer to tests listed in Table 3a.

**The listed figures represent the approximate percentage change from off-the-shelf values.

TABLE 4

RESULTS OF DIELECTRIC BREAKDOWN TESTS ON VARIOUS SLEEVING AND TAPE MATERIALS

Materials Tape	Spec. No.	Off-the-Shelf	Heat Aged	Approximate Per Cent Change**	Heat aged & Irradiated	Approximate Per Cent Change**

a,b,c

*The listed figures represent the approximate change from off-the-shelf values.

TABLE 5a

WIRE AND CABLE INSULATION TESTS

a,b,c

Test No.	Test	Remarks
1		
2		
3		
4		
5		

TABLE 5b

WIRE AND CABLE INSULATION TEST RESULTS

Material	Spec. No.	Test*	Off-the-Shelf	Heat Aged	Approximate Per Cent Change**	Heat Aged & Irradiated	Approximate Per Cent Change**

a,b,c

*The test numbers refer to tests listed in Table 5a.

**These listed figures represent the approximate percentage change from off-the-shelf values.

TABLE 5b (cont'd)

Material	Spec. No.	Test*	Off-the-Shelf	Heat Aged	Approximate Per Cent Change**	Heat Aged & Irradiated	Approximate Per Cent Change**

a,b,c

WESTINGHOUSE CLASS 3

TABLE 6

MOTOR AND FAN BEARING LUBRICANT IRRADIATION TESTING

		Micro-Cone Penetration			
Lubricant Condition	Unworked	60 Strokes	500 Strokes	1000 Strokes	50,000 Strokes
Unirradiated					
Irradiated 1.2×10^8 rads					
Irradiated 1.5×10^8 rads					
Irradiated 1.8×10^8 rads					

a,b,c

TABLE 7

NLGI LUBRICATING GREASE CONSISTENCY CLASSIFICATION

Consistency Number	ASTM Worked Penetration at 77°F and 60 Strokes
0	
1	
2	
3	
4	
5	
6	

a,b,c

Damage	Utility of Organic
Incipient to mild	Nearly always usable
Mild to moderate	Often satisfactory
Moderate to severe	Limited Use

a,b,c

RELATIVE RADIATION RESISTANCE OF ORGANIC INSULATING MATERIALS

Based upon changes in physical properties.

Figure 1

WESTINGHOUSE CLASS 3

FIGURE 2

RELATIVE RADIATION RESISTANCE OF PHYSICAL PROPERTIES
OF GENERAL CLASS OF MATERIALS TESTED

Key - Physical Damage

Mild to moderate damage - often usable

Moderate to severe damage - limited use

a,b,c

Gamma Dose, rads (Si)

FIGURE 3

ELECTRICAL DAMAGE CAUSED BY RADIATION

a,b,c