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THE EFFECTS OF RADIATION ON SILICONE RUBBER WIRE AND CABLE INSULATION

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For presentation at the Seventh Annual Wire and Cable Symposium, Asbury Park, New Jersey, December, 1958.

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Nuclear energy promises to play an increasingly important role in future marine propulsion equipment, central stations, and aircraft power plants. Several nuclear reactors are now being used in these applications and many others are in the development or construction stage.

Regardless of the use of the nuclear energy, all nuclear power plants require various control and energy transfer components, including wire and cable. For the practical operation of the plant, many of these components must be exposed to nuclear radiation.

Performance requirements for wire and cable installed near nuclear reactors usually include:

1. Reliability. Whenever large amounts of energy are transmitted, a service interruption is always expensive. In nuclear power plants, replacement costs of even inexpensive components are sometimes extremely high.
2. Thermal stability. Wire and cable must often be installed in regions of high ambient temperatures. In addition, power cable temperatures may be increased by conductor losses.

3. Moisture resistance. In nuclear power plants, wire and cable sometimes must be placed in moist locations. Also, water may condense on the walls of conduit housing wire and cable.
4. Radiation resistance. In many nuclear power plants, the only practical location for some wire and cable is in a region of appreciable nuclear radiation.

Since wire and cable must be flexible, at least during the construction of nuclear plants, various types of rubber are used for insulation. However, the chemical structure which imparts elasticity to rubber is often easily damaged by nuclear radiation. Consequently wire and cable insulation is inherently one of the more critical components in nuclear power plants.

Silicone rubber insulation has proved its merit in meeting the first three of the above requirements. To determine its ability to meet the fourth requirement, a program to evaluate the radiation resistance of silicone rubber insulation has been initiated.

PROGRAM FOR EVALUATING RADIATION RESISTANCE

This radiation resistance evaluation program consists of several phases:

1. Basic mechanism of radiation damage;
2. Effects on physical properties;
3. Permanent effects on dielectric properties;
4. Transient effects on dielectric properties;
5. Combined effects of high temperature and radiation.

Because the performance of insulation on wire and cable is not easily predicted from data determined on slab samples, silicone rubber slabs were used to determine only the general effects of irradiation. Further tests were then made on insulation already applied to wire and cable.

All studies are being made using a multikilocurie Cobalt 60 gamma radiation source. The environment of this source is air of approximately 25C; the duty period of the source varies between 0.7 and 0.9 over a one week period. For experiments requiring an ambient temperature of 200C, a small oven is used.

Radiation intensity is measured in terms of dose rate, the rate at which samples receive energy from the radiation field. Dose rates employed in this program are usually between 0.1 and 0.5 megarads per hour.

Studies have indicated that radiation damage of silicones is proportional to the product of dose rate and exposure time. This product is known as the total dose and is measured in megarads. Life of insulation in a radiation field is therefore expressed in megarads rather than in hours at a particular irradiation rate.

Many investigators have shown that there is a number of factors which may influence radiation resistance measurements. One such factor is the sample container. In this evaluation program, samples of silicone rubber to be irradiated are either wrapped loosely with aluminum foil (essentially transparent to gamma radiation) or are exposed with no protective wrapper. No significant effect of a wrapper has been observed.

Another possible factor is the amount of time which elapses after the samples are removed from the radiation field until measurements are made. Properties of some irradiated materials have been shown to slowly decay with time after the irradiation is completed. This decay in properties is usually not found with silicone rubber, however.

Even so, in this program, the properties are usually measured at least two days and often a month after the removal of the samples from the radiation source. During this interval, the samples are exposed to normal laboratory atmospheric conditions.

BASIC EFFECTS OF RADIATION ON SILICONE RUBBER

As is the case for other types of rubber, the effects of radiation on silicone rubber are due to ionization. Gamma rays break chemical bonds between atoms resulting in charged particles, or free radicals, throughout the elastomer.

In silicone rubber, the ionized fragments exist primarily during irradiation. After irradiation, essentially all of these fragments disappear. They have an average life of less than one second under most conditions.

Since the ionized fragments are electrically charged, some changes in electrical properties are to be expected. Since these fragments dissipate rapidly after the removal of the radiation field, the induced changes in electrical properties disappear.

These ionized fragments of the material are chemically active and cause reactions that permanently alter the chemical structure of the rubber. These chemical reactions usually also produce gases that evolve from the rubber.

Since the changes in chemical structure are permanent, those physical and dielectric properties dependent upon the chemical structure of the elastomer may be expected to be permanently affected.

In silicones, gamma radiation prefers to attack the chemical bonds associated with the organic groups rather than the stronger silicon-oxygen bonds which impart the basic silicone properties. Thus, the silicone character is retained although some gas is evolved and more cross-linking results. This cross-linking tends to transform silicone rubber to a hard and brittle resin-like material. In contrast, some organic rubbers used as wire insulation are softened by irradiation and finally become liquid.

Although the physical properties of silicone rubber are permanently affected, the dielectric properties are generally affected only during irradiation. Those small permanent effects which are produced are probably due to rearrangement of the chemical structure. Since the rearranged structure remains that of a silicone, changes in dielectric properties are small.

There are a number of factors which affect the radiation resistance of elastomers.

Test data indicate that at high temperatures, radiation increases the rate of oxidation, even in oxidation resistant materials including silicones. But in silicones, the oxidation products are similar in structure to the original material. As in the case of oxidation from thermal aging, radiation induced oxidation has few effects on the dielectric properties.

Silicone rubbers differ among themselves in types of gum, fillers, and additives used. Because of these differences in composition, certain silicone rubbers may have superior radiation resistance.

Nuclear applications of wire and cable usually involve neutron and beta, as well as gamma radiation. For practical reasons, however, only gamma radiation is normally employed in radiation resistance tests. Because of the composition of silicone elastomers, data obtained using gamma radiation can be converted to neutron and beta radiation resistance data.

RADIATION RESISTANCE DETERMINED BY SLAB SAMPLES

Data obtained from slab samples indicate that all silicone rubbers have essentially the same degree of resistance to radiation at 25C. Figure 1 shows that 50 megarads of irradiation increases the hardness, reduces the elongation, and also decreases the tensile strength of one common silicone rubber. All of the major dielectric properties are relatively unaffected as is indicated by Figure 2.

These data suggest that radiation induced failure of silicone rubber wire insulation is more likely to be due to embrittlement and lack of toughness than to any changes in the electrical characteristics.

Slab samples have also been exposed to gamma radiation at an elevated temperature, 200C. Data from these studies are similar to those obtained from samples irradiated at 25C in that the physical properties are damaged much more severely than the electrical characteristics. These data show, however, that high temperatures accelerate the changes in physical properties by a factor of 4 to 10 times.

Also, when irradiation is at 200C, differences in radiation resistance between stocks are greater. This is demonstrated by the doses required to decrease the ultimate elongation to 40 percent:

Silicone Rubber	Dose, Megarads At 25C	Dose, Megarads At 200C
*Silastic 675, cured 24 hrs/480F	55.	18.
Silastic S-2201, vulcanized only	65.	14.
Silastic 80, cured 24 hrs/480F	65.	7.

DIELECTRIC PROPERTIES DURING IRRADIATION

Due to the presence of charged particles in the rubber during irradiation, certain dielectric properties may be affected. Since these charged particles disappear rapidly in silicone rubber when irradiation ceases, most of the effects on the dielectric properties occur only during irradiation.

*Silastic is a registered trademark for Dow Corning silicone rubber.

Electric strength measurements were made on silicone rubber coated glass cloth. The cloth, 7 mils thick, was dispersion coated with Silastic S-132 to a nominal thickness of 10 mils. Fifty measurements using 1/4 inch ASTM electrodes in air were made during irradiation at a rate of 0.06 megarads/hour; fifty other measurements were made out of the radiation field under otherwise identical conditions. No significant effect of radiation on the electric strength was found.

Measurement of volume resistivity, dielectric constant (specific inductive capacity), and dissipation factor (power factor) were made on 2 inch diameter slab samples using the guarded cell shown in Figure 3. Measurements were made on samples of two representative silicone rubbers, Silastic 80 and Silastic 675. Silastic 80 is similar in composition to a wide number of silicone rubbers used as wire and cable insulation. Silastic 675 is similar to those silicone rubbers used in extreme low temperature applications. Neither sample had been irradiated prior to this sequence of measurements.

With the sample in place, the cell and the ends of the test leads were completely submerged in silicone fluid so that air, ionized by the radiation, would not interfere with the measurements. Although silicone fluid is also ionized to some extent during irradiation, measurements showed that under these conditions it is a much better dielectric environment than air.

The volume resistivity of these samples of silicone rubber remained greater than 0.5×10^{14} ohm-cm, the limit of the measuring system used, for dose rates from 0.02 to 0.20 megarads/hour. In the absence of radiation, the volume resistivity is between 10^{14} and 10^{15} ohm-cm.

No statistically significant change in dielectric constant was measured.

The dissipation factor was affected, however, as shown in Figure 4. During irradiation, the dissipation factor is appreciably less than prior to or immediately after the exposure. This effect, which is not damaging, is more pronounced at the lower frequencies and is not evident at all at 10 kilocycles at dose rates up to 0.20 megarads/hour. In the case of Silastic 675, a phenyl containing silicone rubber, the transient effect had an exponential component which was not found with Silastic 80. The time constant of this exponential component is approximately six minutes.

As shown in Figure 5, Silastic 675 is more resistant to this effect. In neither rubber, however, is this effect normally considered damaging.

These data on the four basic dielectric properties of silicone rubber during irradiation indicate that the electrical characteristics of silicone rubber insulation are not damaged during irradiation.

RADIATION RESISTANCE OF SILICONE RUBBER MEASURED ON WIRE AND CABLE SAMPLES

Usually the performance of wire and cable insulation can not be easily predicted from data obtained from slab samples. To determine the resistance of silicone rubber wire and cable insulation to irradiation, tests were made on four different wire and cable constructions:

A. Silastic 80 insulated MIL-W-8777A type MT-14 wire;

B. Silastic 80 insulated No. 14 stranded copper wire, 3/64 inch wall, vulcanized only;

C. Silastic S-2070 insulated No. 18 stranded copper wire, 1/64 inch wall, vulcanized only;

D. Silastic 916 insulated 3 conductor cable: Three No. 20 stranded copper conductors, 15 mil wall, silicone resin impregnated braid, Silastic 916 jacket, 1/64 inch wall; post-cured 4 hours/480F.

Because of space limitations in the radiation field, only small wire and cable samples, three to six feet long, were irradiated.

The performance required of wire and cable insulation is electrical in nature. The samples were functionally evaluated, therefore, by measuring dielectric properties only. The dielectric properties must be maintained even when the insulation is flexed by vibration or slight movement of associated parts. To make the tests more functional, the dielectric measurements were made after wrapping at least three turns of the wire or cable around a 10X mandrel.

Breakdown voltage, insulation resistance, capacitance and dissipation factor of each sample were measured using water at 23C as the outer electrode. To determine water resistance, all measurements were made immediately after submerging the samples and repeated 24 hours later.

Data from these tests, plotted in Figures 6 and 7, indicate the approximate radiation resistance of these silicone rubber insulations. For radiation exposures at 25C, life in excess of 50 megarads can be expected in most applications. In those cases where the insulation is not subjected to appreciable movement, life may be in excess of 200 megarads.

For most nuclear applications, except those within the primary reactor shielding or in close proximity to other radioactive materials, a life of 50 megarads is equivalent to several years.

Greater life can be obtained if the silicone rubber is reinforced with glass. One way in which this can be accomplished is to insulate the cable with glass reinforced silicone rubber tape.

Since data obtained from slabs indicate radiation resistance at 200C is much less than at 25C, additional samples of wire and cable insulation have been irradiated at 200C.

These samples also show that radiation damage at 200C is much more severe than at 25C. This is apparent from the appearance of two samples shown in Figure 8. Both samples of Silastic 916 insulated 3 conductor cable received a dose of 50 megarads; the one irradiated at 25C can pass a 1X mandrel test, the other is cracked prior to flexing. Although the sample irradiated at 200C is cracked, the insulation remains on the cable and is still a good dielectric.

Figures 10 and 11 show that as long as the physical integrity of the insulation is maintained, the electrical performance as insulation is essentially unaffected. This physical integrity is determined by several factors:

1. Severity of radiation exposure;
2. Requirements of the application;
3. Wire or cable construction;
4. Composition of silicone rubber.

Whereas silicone rubber may be usable as wire and cable insulation in some applications at 25C for doses from 50 to 200 megarads, the life at 200C is much less. At this temperature, the life is estimated to be between 5 and 40 megarads depending upon the application requirements, silicone rubber used, and insulation construction. Where high voltage, moisture, and flexing of the insulation are not found, the life may approach 100 megarads at 200C.

CONCLUSIONS

Some salient conclusions which may be drawn from these studies are:

1. Dielectric properties of silicone rubber insulation are not permanently affected to a significant degree by gamma irradiation.
2. Dielectric losses during irradiation are no higher than before or after the exposure.
3. Physical properties of silicone rubber wire and cable insulation are damaged by irradiation. The affected properties are primarily hardness, elongation, and tensile strength.
4. Irradiation at 200C has the same general effects as irradiation at 25C except that the rate of damage is accelerated 4 to 10 times.
5. Differences in radiation resistance between silicone rubber stocks is greater when irradiated at 200C than at 25C.
6. Since wire and cable insulation must perform both electrically and physically, the effects of radiation on physical properties limit the life. At 25C, the expected life is between 50 and 200 megarads; at 200C, between 5 and 40 megarads, depending upon the insulation construction, the requirements of the application, and the silicone rubber used. For many nuclear applications, this life may be a number of years, depending on the radiation intensity involved.

7. For those applications where a life greater than 5 megarads is necessary, all of the generalized information necessary to predict insulation performance is not yet available. To accurately determine the expected performance, specific irradiation tests must be made on the insulation being considered.

FIGURE 1. PHYSICAL PROPERTIES OF SILASTIC 80 AFTER GAMMA IRRADIATION AT 25C

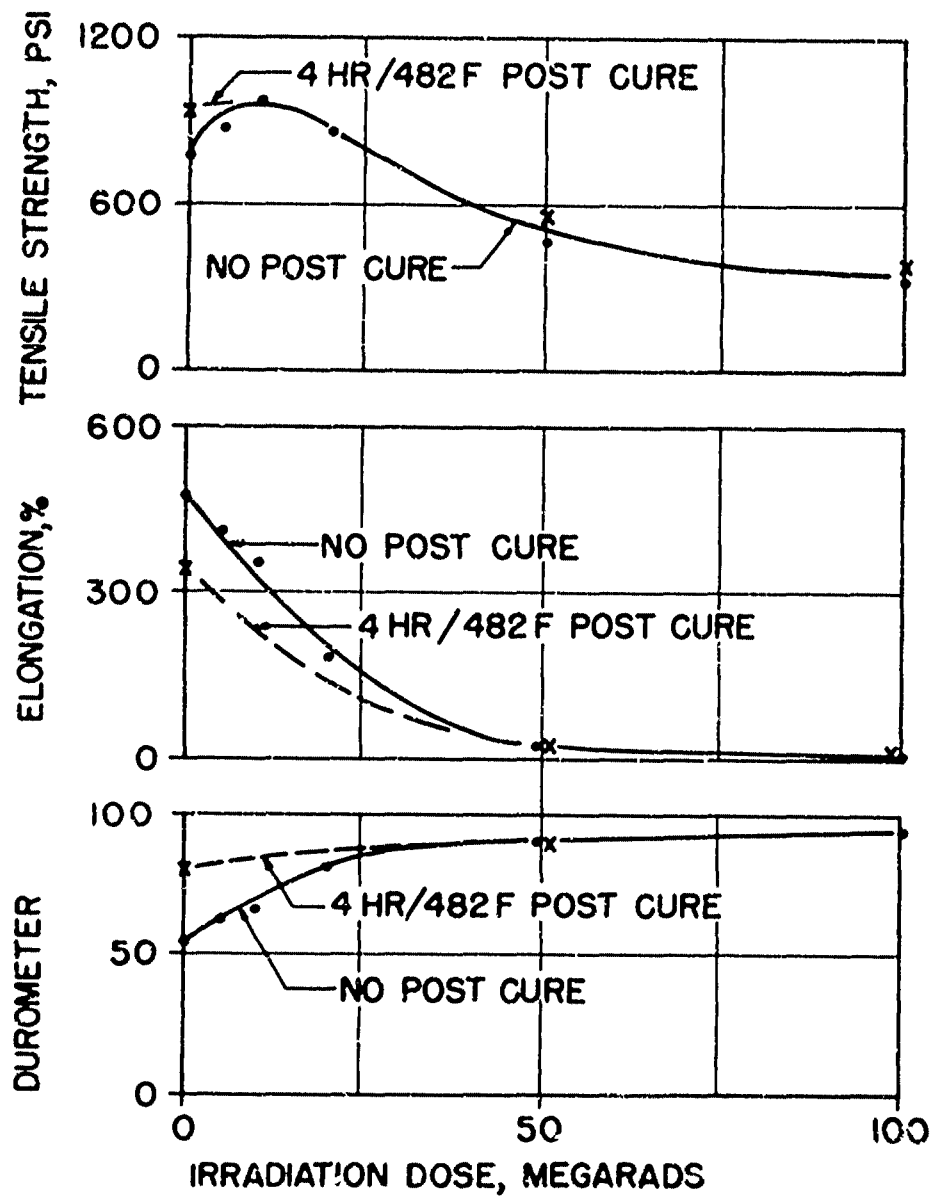

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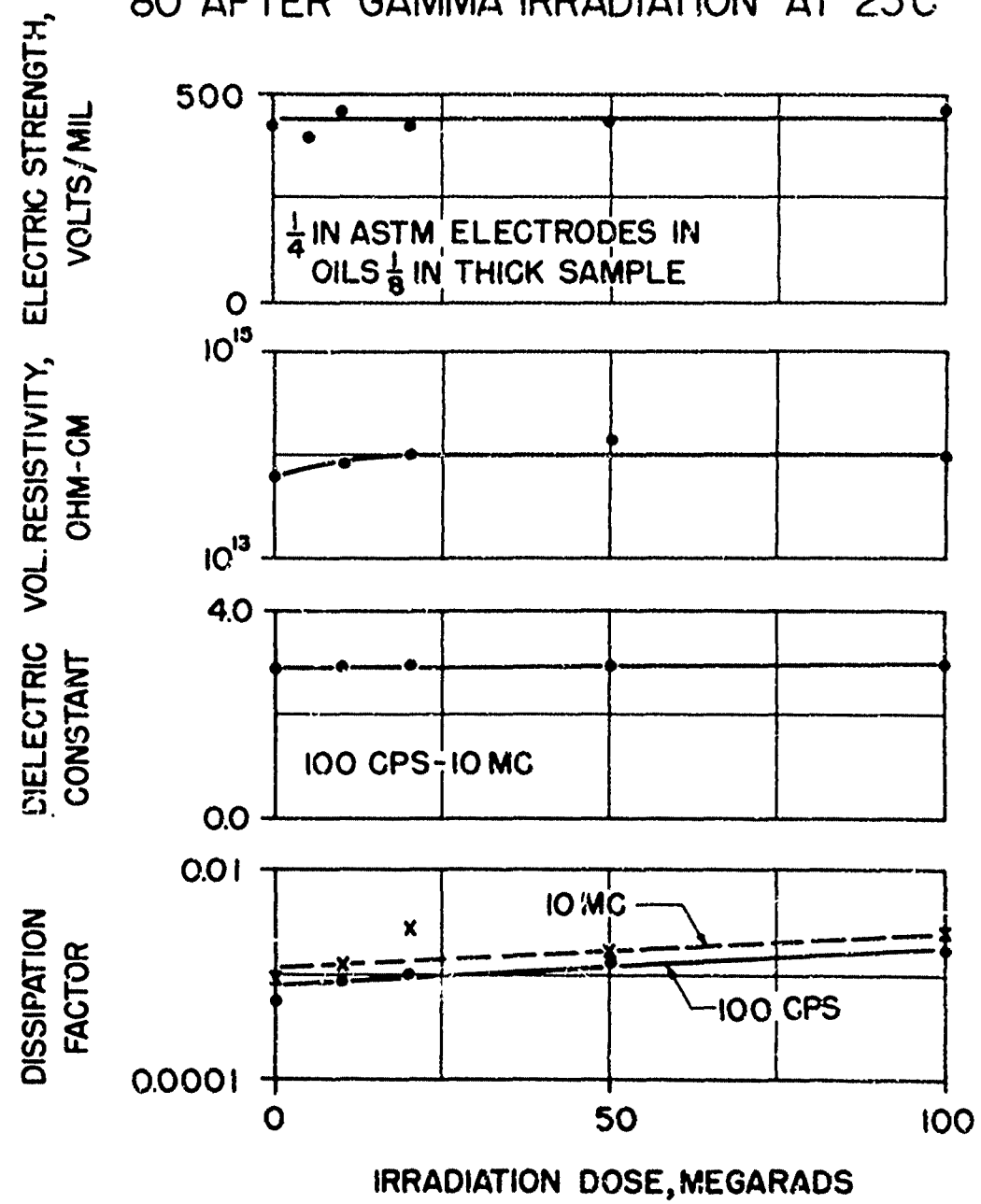
FIGURE 2. DIELECTRIC PROPERTIES OF SILASTIC 80 AFTER GAMMA IRRADIATION AT 25C



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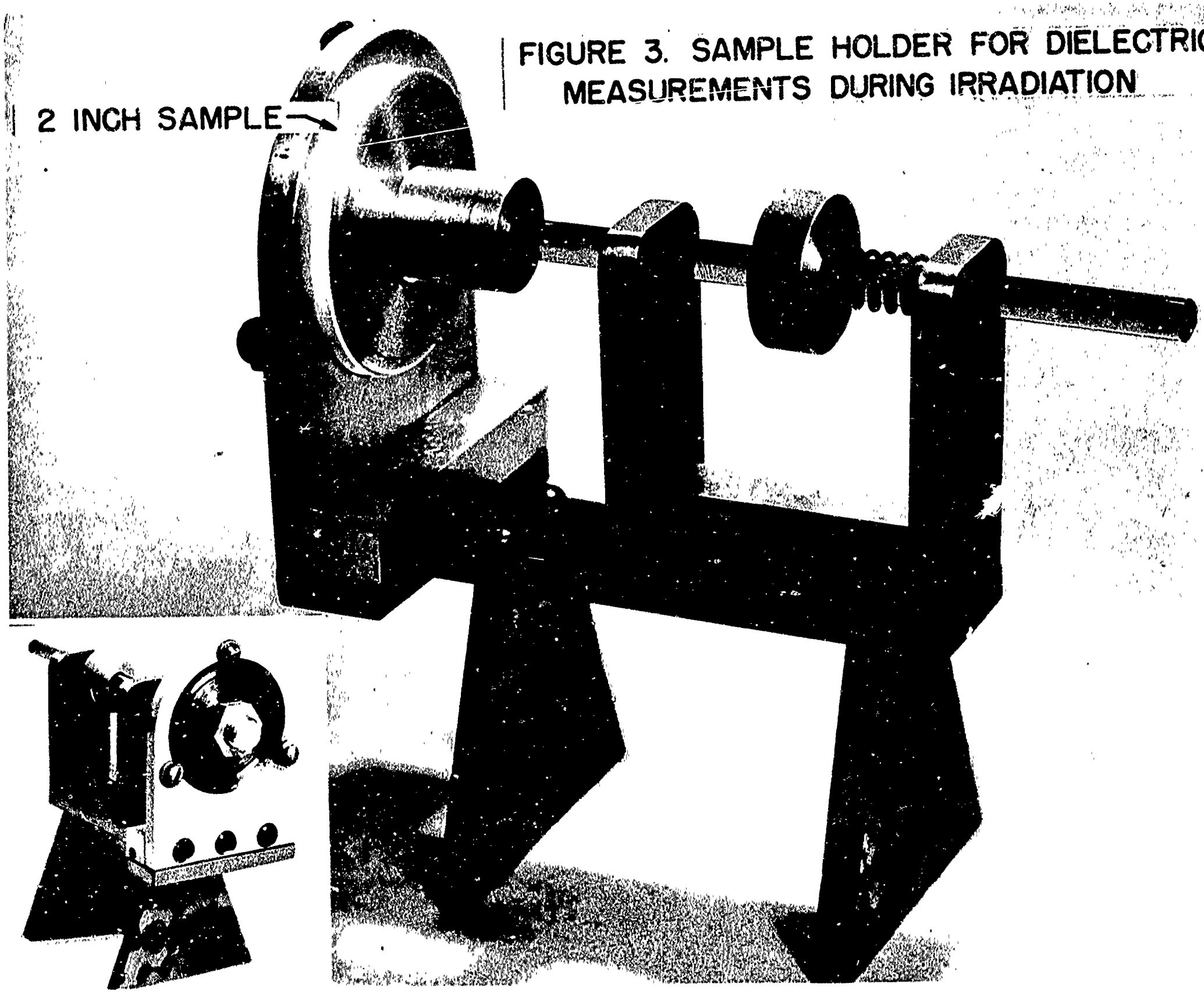

FIGURE 3. SAMPLE HOLDER FOR DIELECTRIC MEASUREMENTS DURING IRRADIATION

FIGURE 4. DISSIPATION FACTOR OF SILICONE RUBBER DURING AND AFTER IRRADIATION

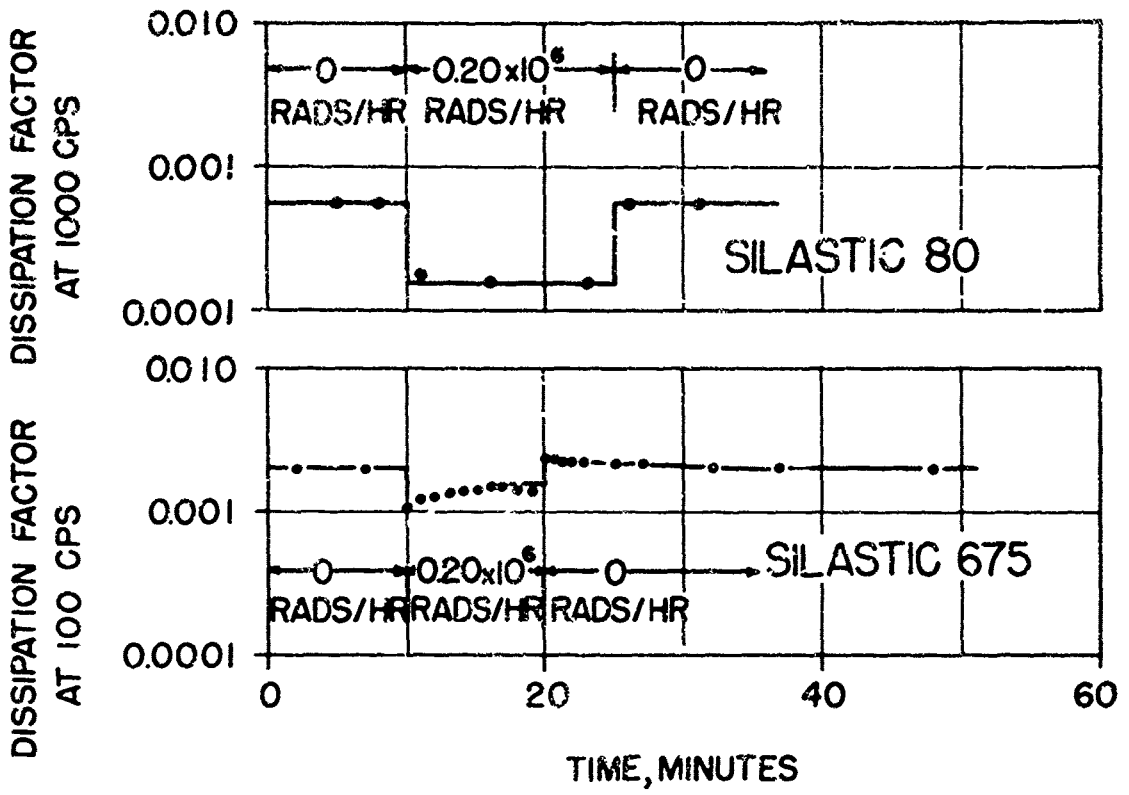

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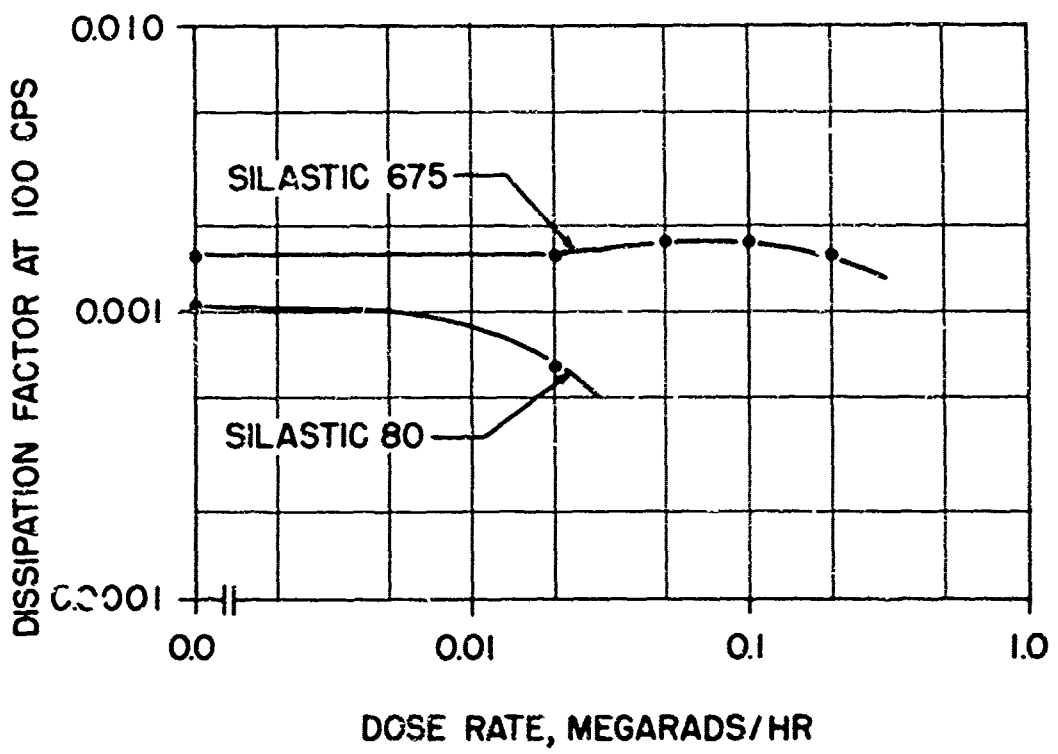
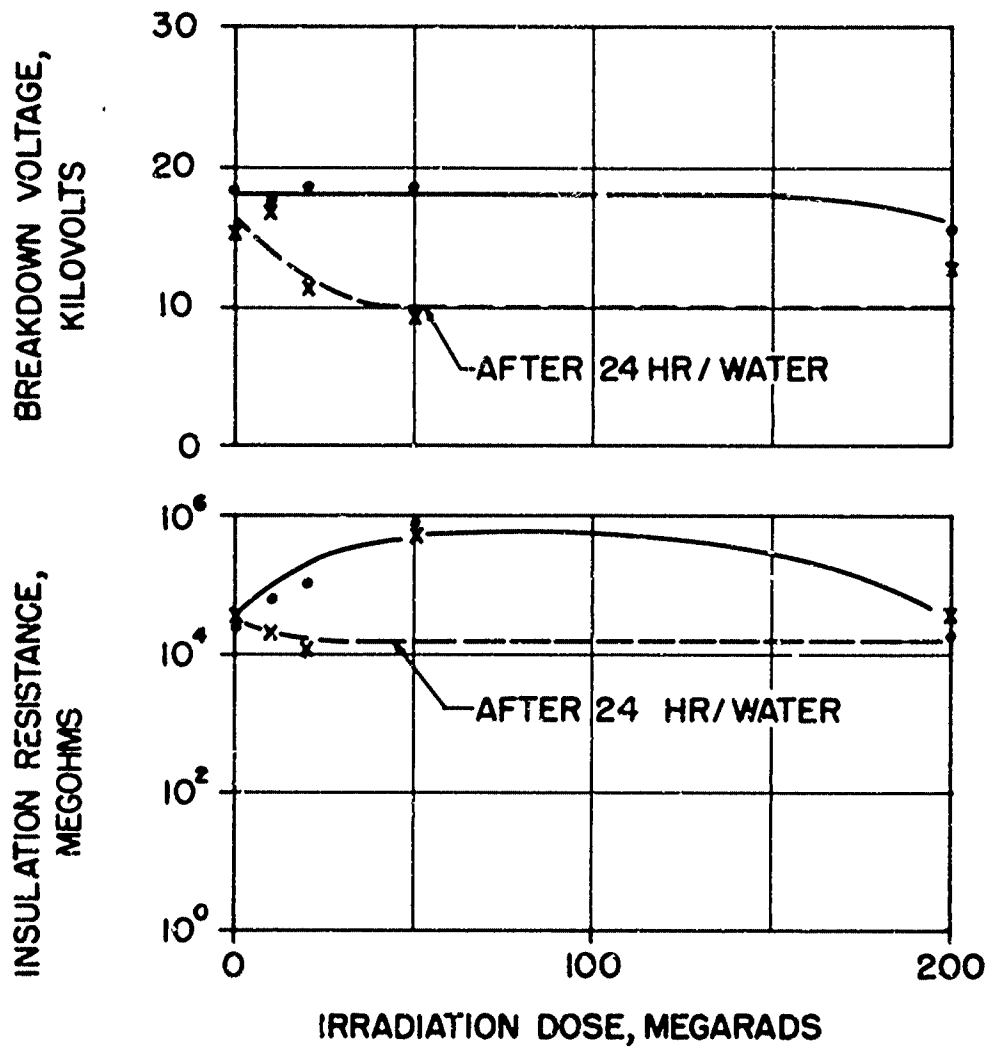
FIGURE 5. DISSIPATION FACTOR OF SILICONE RUBBER DURING IRRADIATION



G-495

FIGURE 6. BREAKDOWN VOLTAGE, INSULATION RESISTANCE OF MIL-W-8777A TYPE MT-14 WIRE AFTER IRRADIATION AT 25C

SAMPLE: 3 TURNS ON 10X MANDREL IN WATER AT 23C.

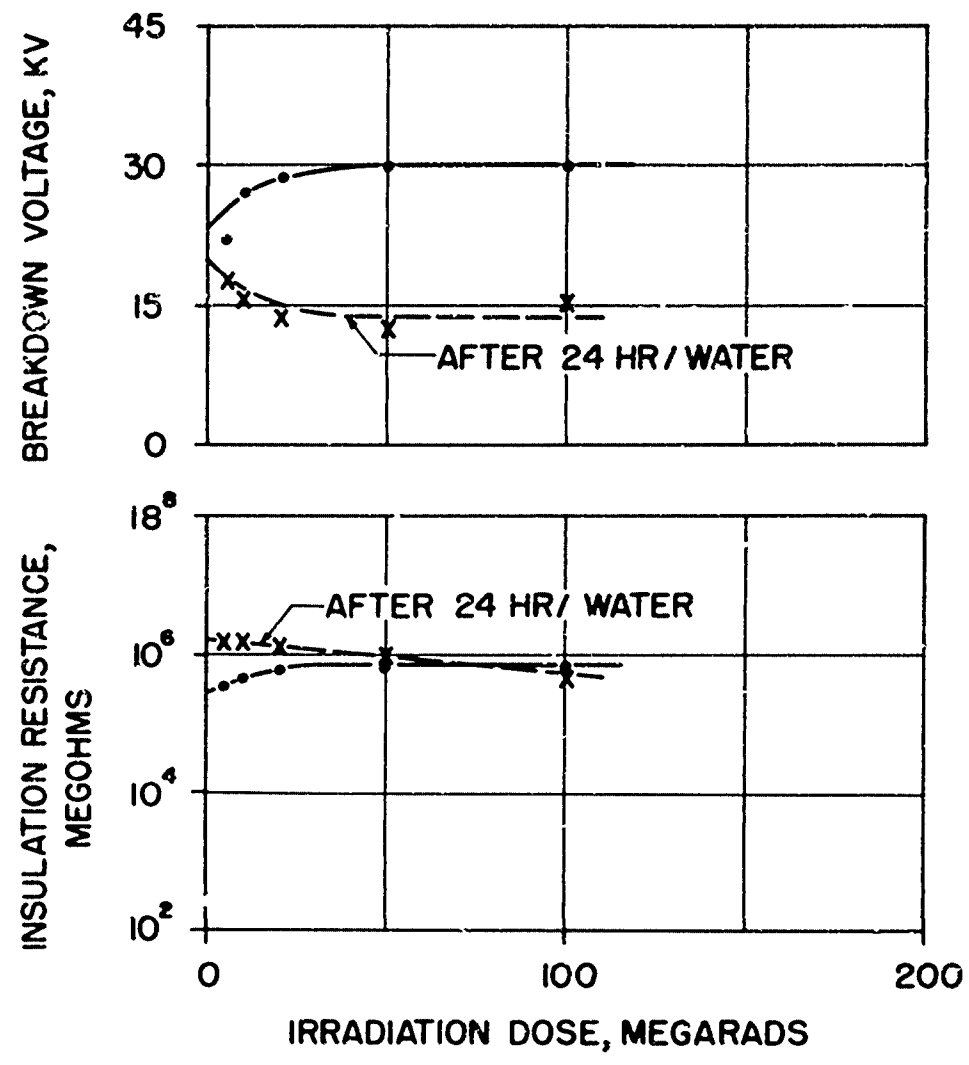


G-496

FIGURE 7. BREAKDOWN VOLTAGE, INSULATION RESISTANCE OF SILASTIC 80 INSULATED WIRE AFTER IRRADIATION AT 25C

INSULATION: $\frac{3}{64}$ IN WALL SILASTIC 80, VULCANIZED ONLY, ON NO. 14 STRANDED COPPER WIRE.

SAMPLE: 3 TURNS ON 10X MANDREL IN WATER AT 23C.



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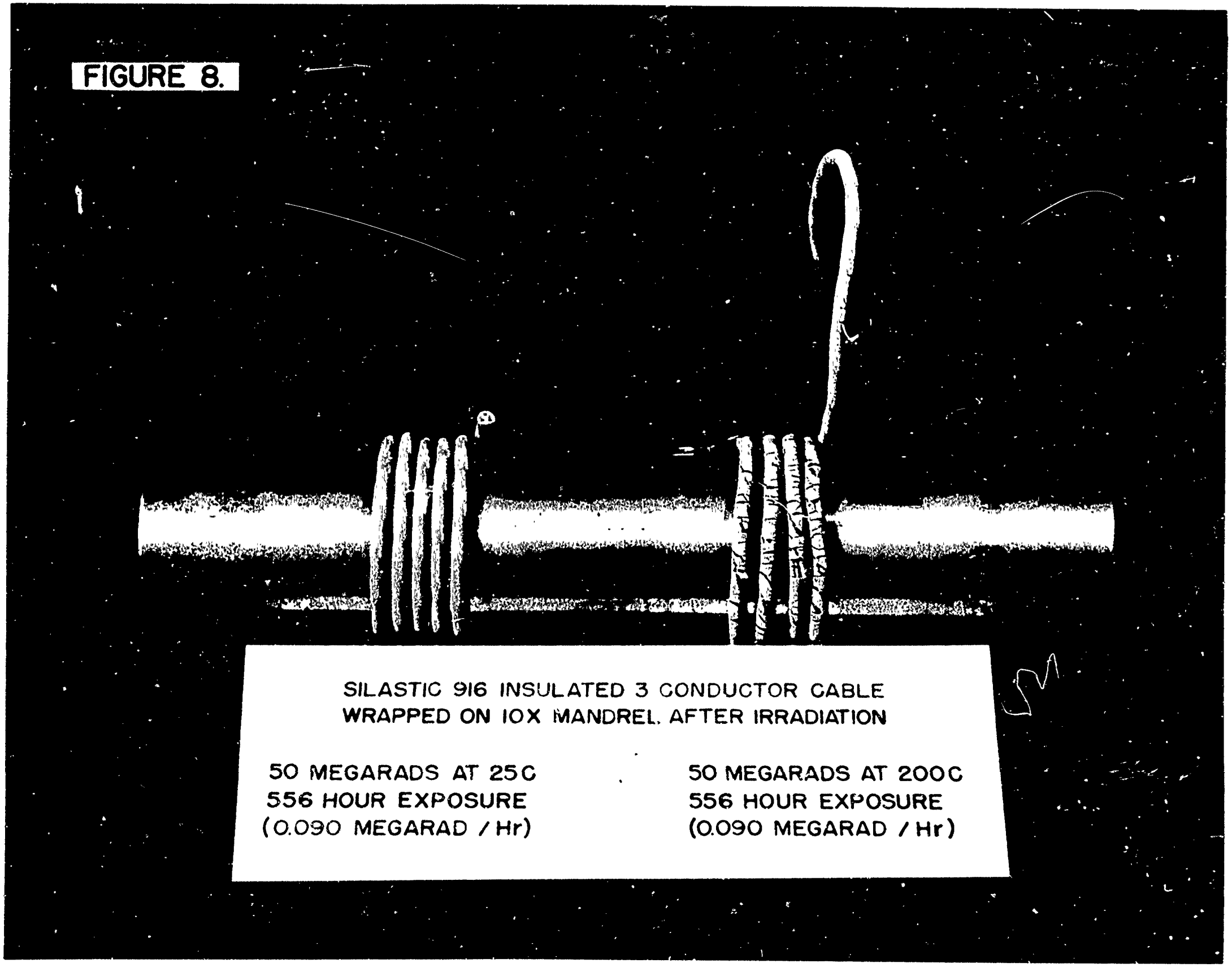
FIGURE 8.
SILASTIC 916 INSULATED 3 CONDUCTOR CABLE
WRAPPED ON 10X MANDREL. AFTER IRRADIATION
50 MEGARADS AT 25C
556 HOUR EXPOSURE
(0.090 MEGARAD / Hr)
50 MEGARADS AT 200C
556 HOUR EXPOSURE
(0.090 MEGARAD / Hr)

FIGURE 9. DIELECTRIC PROPERTIES OF SILASTIC S-2070 INSULATED NO. 18 WIRE AFTER IRRADIATION AT 200 C

IRRADIATION RATE: 0.10 MEGARAD / HOUR
SAMPLES: 3 FEET ON 10X MANDREL IN WATER AT 23 C.

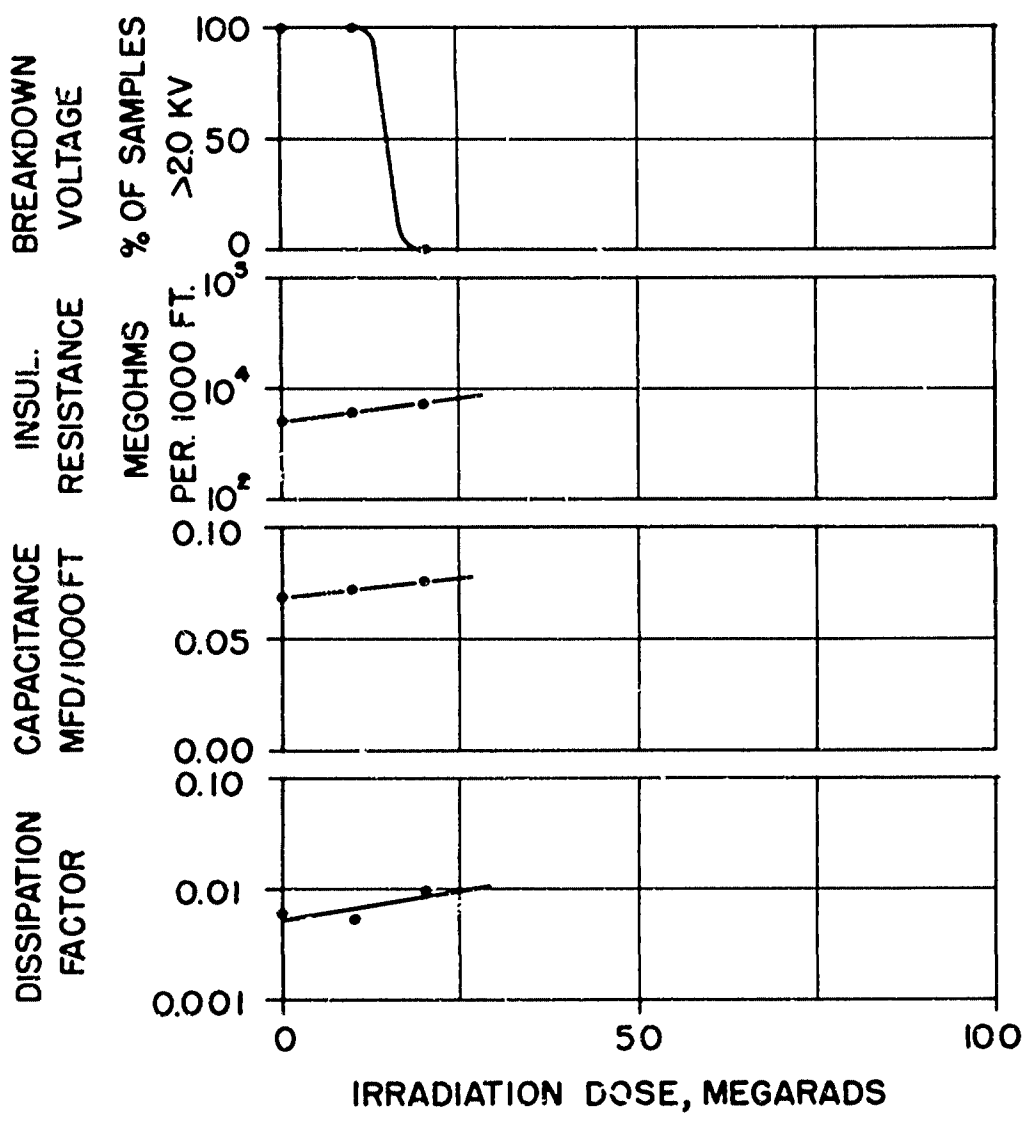

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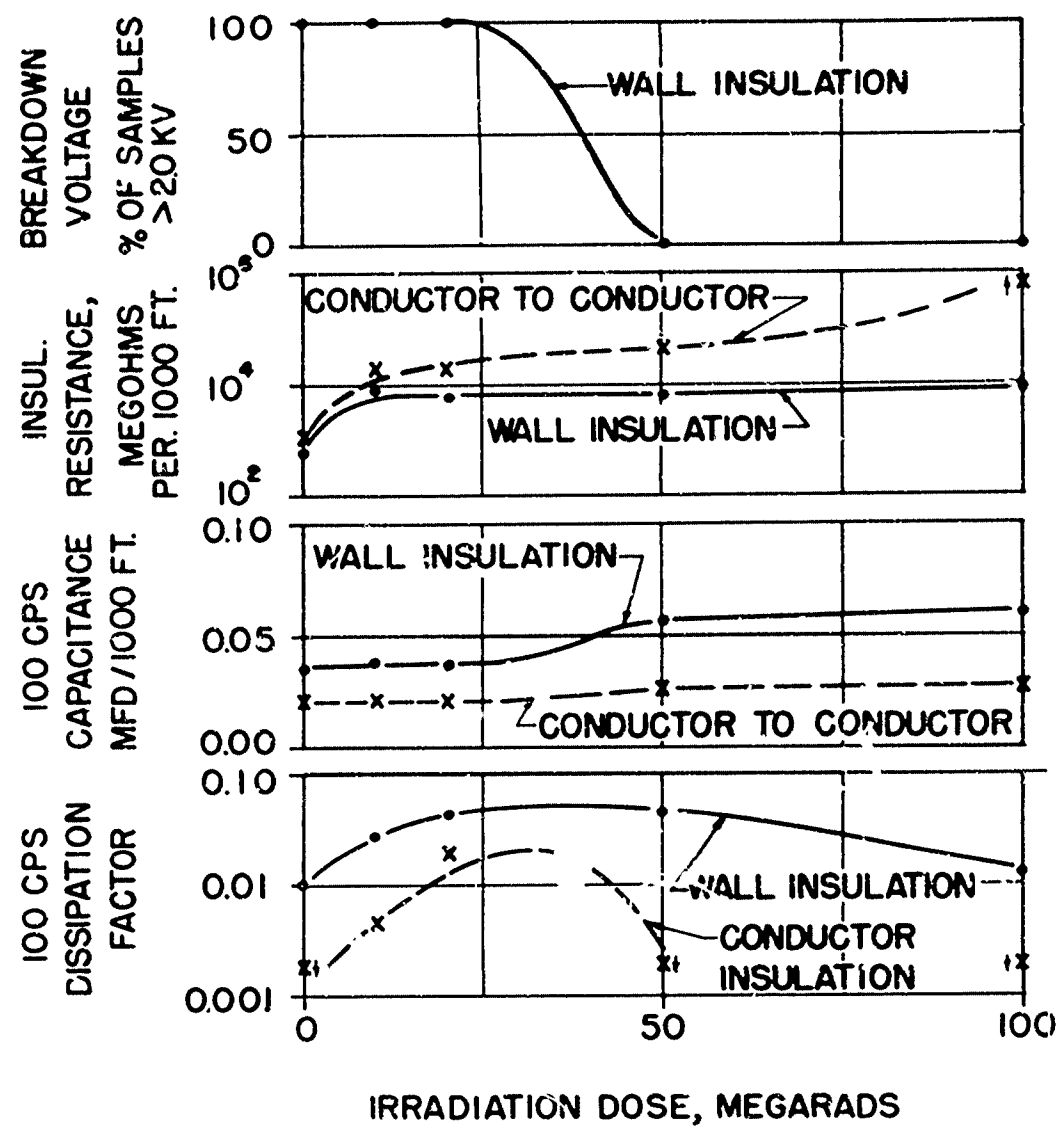
FIGURE 10. DIELECTRIC PROPERTIES OF SILASTIC 916 INSULATED 3 CONDUCTOR CABLE AFTER IRRADIATION AT 200C

IRRADIATION RATE: 0.10 MEGARADS / HOUR
SAMPLES: 3 TURNS ON 10X MANDREL IN WATER AT 23C



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