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Ethylene Propylene Cable Degradation During LOCA Research Tests: Tensile Properties at the Completion of Accelerated Aging

Larry D. Bustard

This report documents a part of the Qualification Testing Evaluation (QTE) Program being conducted by Sandia National Laboratories.

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for the
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ABSTRACT

Six ethylene-propylene rubber (EPR) insulation materials were aged at elevated temperature and radiation stress exposures common in cable LOCA qualification tests. Material samples were subjected to various simultaneous and sequential aging simulations in preparation for accident environmental exposures. Tensile properties subsequent to the aging exposure sequences are reported. The tensile properties of some, but not all, specimens were sensitive to the order of radiation and elevated temperature stress exposure. Other specimens showed more severe degradation when simultaneously exposed to radiation and elevated temperature as opposed to the sequential exposure to the same stresses. Results illustrate the difficulty in defining a single test procedure for nuclear safety-related qualification of EPR elastomers. A common worst-case sequential aging sequence could not be identified.

EXECUTIVE SUMMARY

Six different ethylene-propylene rubber (EPR) materials were aged during three experiments using elevated temperature and radiation stress exposures common during cable LOCA qualification tests. The material samples were subjected to various simultaneous and sequential aging simulations in preparation for accident environmental exposures (in progress). Five of the EPR materials were representative of those used by manufacturers of safety-related electrical cable for nuclear power plant application. The sixth material, EPR-1483, was originally formulated for a Sandia National Laboratories fire-retardant aging study.

In the first experiment, two EPR materials were exposed to six different accelerated aging methods to simulate EPR aging in a combined radiation and thermal environment. The accelerated aging techniques included both sequential and simultaneous exposures to radiation and elevated temperature stresses. Dose-rates between 60 krd/hr and 850 krd/hr were employed. The tensile properties of one of the EPR materials was very sensitive to the order of radiation and elevated temperature exposure. The sequence of irradiation followed by elevated temperature exposure more severely degraded tensile properties than did the reverse order sequence. Simultaneous exposure of the EPR material to the two stresses yielded similar tensile properties as the sequential exposure of irradiation followed by elevated temperature aging. The tensile properties of the other EPR material was not sensitive to the method of aging.

In the second experiment, five commercial EPR materials were exposed to three accelerated aging methods to simulate EPR aging in a combined radiation and thermal environment. The three aging methods employed the same elevated temperature and radiation stresses but differed in the order and nature of stress application (two sequential orderings and one simultaneous exposure). Tensile properties of two of the five EPR materials were sensitive to the order of sequential application of stresses while tensile properties of two other EPR formulations were sensitive to the exposure sequence used (sequential or simultaneous).

The third experiment differed from the previous two by the use of a different elevated temperature facility. This experiment did not, as in the case of the previously mentioned experiments, provide well controlled fresh air

flow past the samples during thermal aging. One EPR material was exposed to four different radiation and elevated temperature exposures. The sequence of elevated temperature exposure followed by irradiation did cause more ultimate tensile elongation degradation than the reverse order sequence. Simultaneous exposure to the two stresses yielded similar tensile property degradation as the elevated temperature followed by irradiation exposure sequence. A similar sequential dependence has been observed in the literature.

Literature information and our data illustrate the difficulty associated with defining a single aging test procedure for all EPR elastomers that would establish nuclear safety-related qualification. For sequential aging procedures employing dose-rates of approximately 1 Mrd/hr and elevated temperature exposures for approximately a 1-week duration, we cannot identify a common worst-case sequence applicable for all EPR tensile specimens. We do recognize that other variables in our tests may impact this conclusion. We are currently investigating the importance of air flow and oxygen replenishment rates during testing. In addition, we are evaluating the influence that our aging techniques and large acceleration factors (i.e., large dose rates and high thermal aging temperatures) have on our findings.

ACKNOWLEDGEMENTS

My appreciation is extended to E. Salazar, R. Trujillo, K. Gillen, and R. Clough for many helpful discussions concerning polymer aging and properties. L. Jones, J. Lewin, and T. Gilmore helped me use the LICA facility. I thank J. Kubas for performing tensile measurements and K. Miller for providing thermal aging facilities. Finally, I thank D. Furgal for editing this report.

CONTENTS

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1.0 INTRODUCTION

Ethylene-propylene-diene terpolymer (EPDM) and ethylene-propylene copolymer (EPM) are elastomer materials used to formulate certain cable insulations. Insulations based on EPDM and EPM are typically called either ethylene-propylene (EP) or ethylene-propylene-rubber (EPR) and are used in some electrical cabling in nuclear power plants.

When used as part of a safety-related system the EPR electrical cable must be qualified.[1-3] Type testing is the preferred qualification method.[1] NUREG-0588, Rev. 1,[1] a recent Nuclear Regulatory Commission (NRC) report entitled "Interim Staff Position on Environmental Qualification of Safety-Related Electrical Equipment" indicates that when "significant radiation and temperature environments may be present... the synergistic effects to these parameters should be considered during the simulated aging portion of the overall test sequence. The testing sequence used to age the equipment (or material) should be justified and the basis documented in the qualification report."[1]

As part of a NRC sponsored research program, we are investigating whether qualification test results are sensitive to the order of aging and accident stress application. We are also investigating the importance of simultaneous versus sequential stress exposures.

In preparation for LOCA research experiments, we have aged several commercial EPR tensile specimens using different radiation and elevated temperature stress sequences and techniques. These aging experiments had two goals:

1. To provide tensile specimens for EPR LOCA research tests.

2. To provide an engineering basis for selecting aging parameters for EPR cable LOCA research tests.

We have accumulated sufficient aging data to illustrate that tensile properties for some EPR materials are sensitive to the order and manner in which they are irradiated and thermally aged. Tensile properties for other EPR materials did not depend on the order and technique of radiation and elevated temperature exposures.

In this report we highlight some of our data and discuss its significance toward qualification testing of nuclear grade safety-related EPR insulated cable.

2.0 EXPERIMENTAL

2.1 Materials

We tested five commercial EPR products. Prior to aging, we removed jackets and sheaths from EPR insulated conductors and then carefully stripped the insulation from stranded copper conductors. For one commercial cable, we were unable to separate the jacketing from the insulation because of bonding between the two materials. In this case, we obtained sheets of the same EPR insulation from the cable manufacturer and cut the sheets into strips. We also obtained sheets of material for a second EPR product. For this EPR material, we exposed both compression molded and extruded forms to the environmental stresses. The five commercial cables for which we obtained insulation test samples included:

- A three conductor control cable with a flame-retardant EPR insulation formulation. Each conductor was not individually jacketed. The cable met the requirements of IEEE Std 383-1974.[2] The cable was purchased from the manufacturer by Sandia National Laboratories in 1981.

- A two conductor instrumentation cable with a flame-retardant EPR insulation. Each conductor was not individually jacketed. This cable was nuclear qualified for LOCA conditions according to suggestions of IEEE Std 323-1974[2] and IEEE Std 383-1974[3] (qualification test report on file). The cable was purchased from the manufacturer by Sandia National Laboratories in 1981.

- A three conductor control cable with an EPR insulation. Each conductor was individually jacketed. The cable satisfied IEEE Std 383-1974.[2] The cable was purchased from the manufacturer by Sandia National Laboratories in 1977.

- A two conductor instrumentation cable with an EPR insulation. Each conductor was individually jacketed. Recommended practices of IEEE Std 323-1974[2] were used to develop a qualification test (qualification test report on file). This cable was purchased from the manufacturer by Sandia National Laboratories in 1981.

- A single conductor low voltage power cable with an EPR insulation covered with a jacket. The cable met the requirements of IEEE Std 383.[3] The cable was purchased from the manufacturer by Sandia National Laboratories in 1981.

In addition to the commercial cable materials, we tested a Burke Industries* EPR formulation used in a Sandia National Laboratories fire-retardant aging study (in progress). This formulation has been coded by Burke Industries as 1483 EPR (Table 2-1).

Table 2-1. Ethylene Propylene Rubber Formulation (1483 EPR)

Components	Constituents	Amount (Parts/Hundred Rubber)
Base Compound	Nordel 2722 EPDM	90
	DYNH #1 LDPE	20
	ZnO (zinc oxide)	5
	Parafin wax	5
	Zn salt of mercaptobenzimidazole (ZMB)	2
	Low-temperature reaction product of acetone and diphenzlamine (Aminox)	1
	Treated, calcined clay	60
	Vinyl-silane coagent	1
	SRF (soft reinforcing furnace) black	2
Curing Package	Litharge	5
	Dicumyl peroxide (Di-Cup R)	5
Fire-Retardant Package	Dechlorane plus 25	33
	Antimony trioxide (Sb_2O_3)	12

*2250 South 10th Street, Jan Jose, CA 95112

The base compound was prepared by Burke Industries. Curing and flame-retardant ingredients were added to the base compound by the Plastics Shop at Sandia National Laboratories. A two-roller mill was used to compound the curing and flame-retardant ingredients with the EPR base compound. The rubber was then molded in a flashing mold and cured for 10 minutes at 177°C (350°F). The sheets of EPR were cut into predetermined-size strips (2.8 mm x 6.4 mm x either 102 mm or 152 mm) using a stainless steel die.

EPR-1483 is sim. to compositions A and B given by Vaidya.[4] Candidate formulations "very similar to A and B have been qualified for reduced wall nuclear control cable and instrument wire following IEEE-383 type testing, and are in commercial use."[4]

2.2 Facilities

We used the Low Intensity Cobalt Array (LICA) facility[5,6] for EPR insulation radiation exposures at both ambient and elevated temperatures. During these exposures, we provided fresh air to the test chambers at a rate of either 30 ± 20 cc/min or 60 ± 20 cc/min. The volume of each LICA sample chamber is approximately 1.8 liters. Therefore our air flow rates correspond to one to two "complete" air changes per hour.

We performed single stress elevated temperature exposures using either the thermal aging facilities developed by K. T. Gillen, R. L. Clough, and L. H. Jones[5,6] or the thermal ovens of the Climate, Centrifuge, and Devices Testing Division at Sandia National Laboratories. The former thermal aging facility uses self-contained aging cells inside air circulating ovens. Fresh air flow to each aging cell is independently controlled and was set to 60 ± 20 cc/min for a 0.9 liter aging cell and 24 ± 20 cc/min for a 0.4 liter aging cell. The latter thermal aging facility uses air-circulating ovens but without self-contained aging cells. Fresh air supply to these ovens is uncontrolled and depends on leakage into the oven. We purposely opened the oven door momentarily on five of the seven days to increase the fresh air supply to the oven.

An Instron™ testing machine with pneumatic jaws was used to measure sample ultimate tensile strength and ultimate tensile elongation. Initial jaw separation was

50.8 mm (2 in); the samples were strained at 127 mm (5 in)/min. An Instron® electrical tape extensometer clamped to the sample monitored the strain and measured the elongation.

3.0 PROCEDURES AND RESULTS

We performed three screening experiments on the EPR materials to evaluate their tensile property sensitivity to the order of radiation and elevated temperature exposures. We also investigated the importance of simultaneous versus sequential stress exposures.

3.1 Experiment I

During this experiment strips of EPR-1483 and strips of a commercial EPR insulation (EPR A) were exposed to six different aging simulations. For each elevated temperature and radiation exposure, forty strips each of EPR A and EPR-1483 were placed in the same exposure chamber. (Tensile tests were performed after completion of aging using three randomly chosen test specimens of each formulation.) Air flow during both irradiation (chamber volume = 1.8 liters) and single stress elevated temperature exposures (chamber volume = 0.9 liters) was maintained at 60 + 20 cc/min. Doses and dose rates are reported in rads (EPR) which is equivalent to 0.88 rads (air). The six aging simulations were:

1. Thirty day simultaneous exposure to 120 ± 1°C (248 ± 2°F) and 60 ± 4 krd/hr, measured in rads (EPR) at the center of the chamber. Measured dose-rate gradients across the sample population were +30/-22 percent of the chamber center dose-rate. The chamber was rotated 180° midway through the exposure to minimize the effect of these gradients.

2. Twenty-eight day single stress exposure to 120 ± 1°C (248 ± 2°F) followed by a 28 day irradiation at 65 ± 5 krd/hr, measured in rads (EPR) at the center of the chamber. Ambient temperature during irradiation was 28 ± 1°C (82 ± 2°F). The chamber was rotated 180° midway through the exposure to minimize the effect of the +25/-21 percent dose-rate gradients.

3. Twenty-eight day irradiation at 65 ± 5 krd/hr, measured in rads (EPR) at the center of the chamber, followed by a 28 day, 120 ± 1°C (248 ± 2°F) elevated temperature exposure. Ambient temperature during irradiation was 28 ± 1°C (82 ± 2°F). The sample chamber was rotated 180° midway through the irradiation to minimize the influence of the +25/-21 percent dose-rate gradients.

4. Fifty-five hour irradiation at 850 ± 60 krd/hr, measured in rads (EPR) at the center of the chamber, followed by a 28 day, 120 ± 1°C (248 ± 2°F) elevated temperature exposure. Ambient temperature during irradiation was 46 ± 1°C (115 ± 2°F). Measured radiation dose-rate gradients were less than +3 precent. (Lowest dose-rate was at the center of the chamber.)

5. Twenty-eight day, 120 ± 1°C (248 ± 2°F) elevated temperature exposure followed by a 55 hour irradiation at 850 ± 60 krd/hr, measured in rads (EPR) at the center of the chamber. Ambient temperature during irradiation was 46 ± 1°C (115 ± 2°F). Measured radiation dose-rate gradients were less than +3 percent. (Lowest dose-rate was at the center of the chamber.)

6. Seven day simultaneous exposure to 139 ± 1°C (248 ± 2°F) and 290 ± 20 krd/hr, measured in rads (EPR) at the center of the chamber. Dose-rate gradients across the sample population were +65/-28 percent of the chamber center dose-rate. The chamber was rotated 180° midway through the exposure to minimize the influence of these gradients.

Arrhenius techniques were used to choose the elevated temperature exposures for thermal aging. Our thermal aging calculations are based on a nuclear plant containment ambient environment of approximately 55°C (131°F), a life of approximately 40 years, and an EPR activation energy of 24 kcal/mole (1.04 eV). We chose the activation energy values as representative of single stress thermal degradation data found in the literature for EPR.[7] Our choice of thermal aging parameters is consistent with the guidance of IEFE Std 383-1974,[3] Section 1.3.5.2. It does not, however, account for possible synergisms between radiation and elevated temperature stresses.

Table 3-1 summarizes tensile properties for EPR-1483 after each of these aging conditions while Table 3-2 provides similar information for the EPR A samples.

3.2 Experiment II

In this experiment insulation samples representative of five commercial EPR cables were exposed to three different aging simulations.

1. Seven day elevated temperature exposure at 139 ± 2°C (282 ± 4°F) (except for 8 hours at 136°C [277°F]) followed by a seven day irradiation at approximately 300 krd/hr at an ambient temperature of 35 ± 2°C (95 ± 4°F).

2. Seven day irradiation at 300 krd/hr at an ambient temperature of 35 ± 2°C (95 ± 4°F) followed by a 7 day elevated temperature exposure at 139 ± 2°C (282 ± 4°F).

3. Seven day simultaneous exposure to 139 ± 1°C (282 ± 2°F) and 300 krd/hr.

Arrhenius techniques were used to choose the elevated temperature exposures for thermal aging. Our thermal aging calculations are based on a nuclear plant containment ambient environment of 55°C (131°F), a life of about 40 years, and an EPR activation energy of 24 kcal/mole (1.04 eV). We chose the activation energy value as representative of single stress thermal degradation data found in the literature for EPR.[7] Our choice of thermal aging parameters is consistent with the guidance of IEEE Std 383-1974,[3] Section 1.3.5.2. It does not, however, account for possible synergisms between radiation and elevated temperature stresses.

During each irradiation, we placed samples for all five commercial EPR insulations in the same exposure chamber. Air flow was maintained at 60 ± 20 cc/min (chamber volume 1.8 liter). The influence of large radiation gradients across the exposure chamber was reduced by compartmentalizing the chamber and ensuring the same compartment position was used for each of the three aging simulations. EPR A, EPR B and EPR C samples were exposed to 260 ± 30 krd/hr while EPR D and EPR E samples were exposed to 330 ± 50 krd/hr. (Uncertainties reflect both measurement uncertainties and gradient contributions.)

Table 3-1. Relative Tensile Properties of EPR-1483 After Aging

Aging Method	Center of Chamber Dose Rate in EPR (krd/hr)	Center of Chamber Total Dose in EPR (Mrd)	Ultimate Tensile Strength T/T_o	Ultimate Tensile Elongation e/e_o
1. Unaged	0	0	1.00 ± .05 (10.6 ± 0.5 MPa)	1.00 ± .09 (340 ± 30%)
2. Simultaneous 30 day radiation and thermal exposures	60 ± 4	43 ± 3	0.79 ± .07	0.41 ± .10
3. Sequential 28 day thermal then radiation exposures	65 ± 5	44 ± 3	0.98 ± .07	0.47 ± .10
4. Sequential 28 day radiation then thermal exposures	65 ± 5	44 ± 3	1.01 ± .10	0.41 ± .05
5. Sequential 28 day thermal then 55 hour radiation exposures	850 ± 60	47 ± 3	0.97 ± .08	0.35 ± .04
6. Sequential 55 hour radiation then 28 day thermal exposures	850 ± 60	47 ± 3	0.93 ± .06	0.32 ± .04
7. Simultaneous 7 day radiation and thermal exposures	290 ± 20	49 ± 3	0.83 ± .06	0.41 ± .05

NOTES: (1) Errors reflect one standard deviation of three measurements.
(2) Insulation thickness is nominally 2.8 mm.

Table 3-2. Relative Tensile Properties of EPR A After Aging

Aging Method	Center of Chamber Dose Rate in EPR (krd/hr)	Center of Chamber Total Dose in EPR (Mrd)	Ultimate Tensile Strength T/T_o	Ultimate Tensile Elongation e/e_o
1. Unaged	0	0	1.00 ± .03 (8.7 ± 0.3 MPa)	1.00 ± .08 (360 ± 30%)
2. Simultaneous 30 day radiation and thermal exposures	60 ± 4	43 ± 3	~0.2*	< .03*
3. Sequential 28 day thermal then radiation exposures	65 ± 5	44 ± 3	0.85 ± .03	0.33 ± .04
4. Sequential 28 day radiation then thermal exposures	65 ± 5	44 ± 3	0.26 ± .07*	< .03*
5. Sequential 28 day thermal then 55 hour radiation exposures	850 ± 60	47 ± 3	0.99 ± .21	0.31 ± .04
6. Sequential 55 hour radiation then 28 day thermal exposures	850 ± 60	47 ± 3	0.21 ± .02	0.06 ± .03
7. Simultaneous 7 day radiation and thermal exposures	290 ± 20	49 ± 3	0.26 ± .02	0.03 ± .03

NOTES: (1) Errors reflect one standard deviation of three measurements.
(2) Insulation thickness is nominally 0.8 mm.
* Samples were extremely brittle and sometimes cracked in the pneumatic jaws used for the tensile measurements.

During each single stress elevated temperature exposure, the samples were divided in half and placed in two 0.4 liter aging cells. Air flow to each cell was maintained at 24 ± 20 cc/min.

Tables 3-3 and 3-4 summarize the results of this experiment. EPR C and EPR D are flame-retardant formulations of EPR. The individual conductors of a multiconductor cable were not jacketed for these reduced wall insulation formulations. For EPR A, EPR B, and EPR E, conductors of a multiconductor cable were individually jacketed.

3.3 Experiment III

In this experiment, EPR-1483 insulation samples were exposed to four different aging simulations:

1. 47 ± 3 Mrd total dose in EPR at a dose-rate of 960 ± 70 krd/hr at an ambient temperature of 46 ± 1°C (115 ± 2°F).

2. 48 ± 3 Mrd total dose in EPR at a dose-rate of 960 ± 70 krd/hr at an ambient temperature of 46 ± 1°C (115 ± 2°F) followed by 7 days of elevated temperature exposure at 136 ± 2°C (277 ± 4°F).

3. Seven days of elevated temperature exposure at 136 ± 2°C followed by 46 ± 3 Mrd total dose in EPR at a dose-rate of 960 ± 70 krd/hr at an ambient temperature of 46 ± 1°C (115 ± 2°F).

4. Seven day simultaneous exposure to 136 ± 2°C (277 ± 4°F) and 340 ± 80 krd/hr for a total dose of 57 ± 14 Mrd.

During radiation exposures, air flow to the sample chamber was maintained at 30 ± 20 cc/min (chamber volume 1.8 liters). Radiation gradients across the sample populations were ±1 percent for the 960 krd/hr exposure and ±24 percent for the 340 krd/hr exposure. Stated uncertainties for dose-rate and total dose include contributions associated with dose-rate gradients. During single stress elevated temperature exposures, air flow past the samples was uncontrolled. Fresh air supply to the air circulating oven depended on leakage and momentary opening of the oven door five times during the 7 day exposure.

Table 3-3. Relative Tensile Properties of EPR Insulation After Aging

			EPR A (1) extruded (2) 0.76 mm nominal thickness		EPR B (1) extruded (2) 0.76 mm nominal thickness		EPR C (1) extruded (2) 0.64 mm nominal thickness		EPR G (1) compression molded (2) 1.6 mm nominal thickness	
Aging Method	Total Dose in EPR (Mrd)	Dose Rate in EPR (krd/hr)	T/T_o	e/e_o	T/T_o	e/e_o	T/T_o	e/e_o	T/T_o	e/e_o
Unaged	0	0	1.00 ± 0.07 (8.8 ± 0.6 MPa)	1.00 ± 0.02 (420 ± 10%)	1.00 ± 0.06 (7.1 ± 0.4 MPa)	1.00 ± 0.09 (330 ± 30%)	1.00 ± 0.09 (14.0 ± 1.3 MPa)	1.00 ± 0.08 (400 ± 30%)	1.00 ± 0.07 (12.2 ± 0.8 MPa)	1.00 ± 0.02 (513 ± 10%)
Sequential radiation then thermal exposures	44 ± 5	260 ± 30	0.22 ± 0.03	0.05 ± 0.03	1.00 ± 0.14	0.52 ± 0.06	0.96 ± 0.09	0.48 ± 0.04	0.77 ± 0.06	0.26 ± 0.02
Sequential thermal then radiation exposures	44 ± 5	260 ± 30	0.93 ± 0.09	0.36 ± 0.03	1.10 ± 0.09	0.45 ± 0.05	0.82 ± 0.09	0.43 ± 0.04	0.84 ± 0.07	0.33 ± 0.03
Simultaneous radiation and thermal exposures	44 ± 5	260 ± 30	0.23 ± 0.02	0.05 ± 0.03	0.59 ± 0.07	0.30 ± 0.04	0.59 ± 0.06	0.33 ± 0.06	0.55 ± 0.04	0.13 ± 0.02

NOTES: (1) Errors represent one standard deviation for each set of measurements.
(2) T = ultimate tensile strength; e = ultimate tensile elongation.

Table 3-4. Relative Tensile Properties of EPR Insulation After Aging

			EPR D (1) extruded (2) 0.76 mm nominal thickness		EPR E (1) compression molded (2) 1.6 mm nominal thickness	
Aging Method	Total Dose in EPR (Mrd)	Dose Rate in EPR (krd/hr)	T/T_o	e/e_o	T/T_o	e/e_o
Unaged	0	0	1.00 ± 0.04 (15.2 ± 0.6 MPa)	1.00 ± 0.04 (240 ± 10%)	1.00 ± 0.04 (8.4 ± 0.3 MPa)	1.00 ± 0.13 (380 ± 50%)
Sequential radiation then thermal exposures	55 ± 8	330 ± 50	0.62 ± 0.03	0.21 ± 0.04	1.41 ± 0.06	0.34 ± 0.07
Sequential thermal then radiation exposures	55 ± 8	330 ± 50	1.05 ± 0.05	0.33 ± 0.04	1.31 ± 0.09	0.29 ± 0.05
Simultaneous radiation and thermal exposures	55 ± 8	330 ± 50	0.75 ± 0.04	0.25 ± 0.04	1.24 ± 0.07	0.42 ± 0.06

NOTES: (1) Stated errors represent one standard deviation for each set of measurements.
(2) T = ultimate tensile strength; e = ultimate tensile elongation.

Table 3.5 summarizes the results of this experiment.

Table 3-5. Relative Tensile Properties of EPR-1483 Insulation After Aging

Aging Method	Total Dose in EPR (Mrd)	Ultimate Tensile Strength (T/T_o)	Ultimate Tensile Elongation (e/e_o)
Unaged	0	1.00 ± .04 (9.8 ± 0.4 MPa)	1.00 ± .06 (320 ± 20%)
Radiation Only	47 ± 3	0.67 ± .05	0.28 ± .04
Sequential R then T	48 ± 3	0.76 ± .16	0.34 ± .07
Sequential T then R	46 ± 3	0.62 ± .04	0.19 ± .03
Simultaneous T and R	57 ± 14	0.55 ± .03	0.19 ± .03

NOTES: (1) Stated errors represent one standard deviation for each set of measurements.
(2) T = ultimate tensile strength; e = ultimate tensile elongation.

4.0 DISCUSSION

The tensile properties for the EPR A specimens were strongly dependent on the order in which radiation and elevated temperature stresses were applied. Exposure sequences of irradiation followed by elevated temperature caused substantially more degradation than did reverse order exposures. Examples are: (1) the sequential 28 day radiation and elevated temperature exposures (Table 3-2), (2) the 55 hour radiation and 28 day elevated temperature exposures (Table 3-2), (3) and the 7 day radiation and elevated temperature exposures (Table 3-3). For the EPR A specimens, simultaneous exposures to radiation and elevated temperature stresses produced comparable tensile property degradation as the radiation-then-elevated temperature sequential exposures. EPR A's tensile property behavior is therefore similar to that previously observed for certain polyvinylchloride and low density polyethylene materials.[8,9] A much smaller magnitude, but similar ordering effect, was observed for our EPR D specimens.

Contrasting the behavior of EPR A was the degradation of the EPR-1483 specimens. Tensile properties (Table 3-1) for these specimens exhibited neither an ordering effect nor a dependence on simultaneous versus sequential stress application techniques. Possible reasons for the contrasting behavior of EPR A and EPR-1483 include test specimen differences such as: thickness, geometry, processing techniques, and elastomer formulations.

Table 3-5 illustrates EPR-1483's tensile properties when an air circulating oven without well controlled air replenishment is used for thermal aging. A large tensile property sequence dependence such as exhibited by EPR A did not occur. However, the sequential elevated temperature exposure followed by irradiation did cause more ultimate tensile elongation degradation than the reverse order exposures. A similar ordering dependence has been observed by E. Oda et al.,[10] for the tensile properties of a fire-retardant EPR insulation material. In our experiment a simultaneous exposure to the stresses yielded similar tensile property degradation as the elevated temperature-then-irradiation exposure sequence. (Oda et al.[10] did not investigate simultaneous exposures.)

Tensile property degradation for the EPR B, EPR C, and EPR D specimens did not depend on the sequential ordering of radiation and elevated temperature exposures. A simultaneous radiation and elevated temperature exposure did produce more tensile property degradation for the EPR B and EPR C specimens than did sequential exposures to the same two stress levels.

Recent NRC guidance concerning qualification of safety related electrical equipment suggests that "the testing sequence used to age the equipment (or material) should be justified and the basis documented in the qualification report."[1] Our data and the work of E. Ota et al.,[10] illustrate the difficulty of defining a single test procedure for all EPR elastomers which would establish nuclear safety-related qualification. For sequential aging procedures employing dose rates of approximately 1 Mrd/hr and elevated temperature exposures for approximately 1 week duration, we could not identify a common worst-case sequence applicable for all EPR tensile specimens.

We do recognize that several variables besides those of aging sequence were varied both within our experiments and between Ota et al., and our experiments. These include:

1. Thickness and geometry of tensile specimens
2. Manufacturing techniques for tensile specimens
3. Elastomer formulations
4. Humidity level
5. Air flow rates during stress exposures
6. Oxygen replenishment during stress exposures
7. Elevated temperature stress level

Typically, the first three factors are controlled by the manufacturer when a cable is produced. Moreover, two of these factors, elastomer formulation and manufacturing techniques, are usually considered proprietary information. We are currently investigating whether better control of air flow and oxygen replenishment rates will permit identification of a common "worst case" sequential aging technique for EPR tensile property degradation. In addition, we are evaluating the influence that our aging techniques and large acceleration factors have on our conclusions.

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