DETERMINATION OF THE SERVICE LIFE FOR THE EXCORE NEUTRON DETECTOR CABLES IN SEABROOK STATION

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ABSTRACT

A study of the service life of the excore neutron detector cables in Seabrook Station has been performed. Cable irradiation in the UMass-Lowell research reactor (UMLRR) to a total gamma plus neutron dose of over 10 gigarad has shown no significant degradation in the electrical properties of the cable specimens. An overview of the analytical and experimental programs that support this summary result is described in this paper.

I. INTRODUCTION

The University of Massachusetts Lowell (UMass-Lowell) and North Atlantic Energy Service Corporation have performed a combination of analytical and experimental studies to help determine the service life for the excore neutron detector cables in Seabrook Station. The specific cables under study were supplied by Gamma-Metrics as part of the overall neutron flux monitoring system in Seabrook. The primary performance-related property of interest is the loss of insulation capability with increasing neutron and gamma exposure. Gamma-Metrics indicates that the detector cables have been qualified to 3.2×10^9 rad exposure in a ^{60}Co gamma environment.[1]

A preliminary analysis of the neutron and gamma radiation fields at the excore detector locations in Seabrook estimated that the equipment qualification dose to the cables would be reached at the end of Cycle 4.[2] These calculations used a 2-D model of Seabrook within the DORT discrete ordinates transport code[3] to quantify the neutron and gamma fluxes over four cycles of operation. The fluxes in the vicinity of the detector cables were then converted to dose rate using standard flux-to-tissue dose conversion factors[4] and finally integrated over time to provide total dose.

Since cable replacement was clearly an undesirable option – from both a cost perspective and from concerns about radiation exposure to workers during cable replacement – a research effort was initiated to establish the actual service life of the excore detector cables in Seabrook Station. This project involved both analytical and experimental studies, with a focus on the following items:

1. Based on flux data from Ref. 2, re-evaluate the cable dose rates in Seabrook using material-specific flux-to-dose conversion factors (i.e. using polymer kerma factors rather than tissue kerma factors).
2. Provide analytical support for a cable irradiation program in the UMLRR.
3. Perform the actual irradiation and testing of several cable specimens in the UMLRR.

II. FLUX-TO-DOSE CONVERSION FACTORS

There does not appear to be a formal standard on the subject of flux-to-dose conversion factors but, generally speaking, radiation-induced effects in a particular material should be correlated to the energy absorbed in that material, not to the energy absorbed in human tissue. Thus, the cable dose estimates obtained from Ref. 2 were re-computed using kerma factors generated for a generic polymer insulation material. The polymer dose rates were also compared to energy absorption rates in air and to the dose rate in tissue (using the same tissue conversion factors used in Ref. 2), as an illustration of the variability that can be obtained from different flux-to-dose conversion assumptions.

The kerma factor data for this analysis were extracted from the BUGLE-93 cross section library[5] and processed into a form suitable for use in this study. The recently developed BUGLE-93 library contains data for 47 neutron groups and 20 gamma groups. This library is based on ENDF/B-VI data and it was derived from the same 199/42 group cross sections[5] used for the XSDRN calculations performed as part of this study (see below).

Kerma factor information was included as part of the BUGLE-93 library so that energy deposition rates can be computed from calculated neutron and gamma spectra. Since the energy absorption rate per unit volume of a particular material is simply the product of a macroscopic energy absorption cross section and the flux, we have

$$\frac{\text{energy absorption rate}}{\text{volume}} = \langle \Sigma\phi \rangle = \left\langle \sum_i N_i \sigma_i \phi \right\rangle$$

$$\text{with units} \Rightarrow \left(\frac{\text{at}}{\text{b}-\text{cm}}\right)\left(\frac{\text{eV}-\text{b}}{\text{at}}\right)\left(\frac{\text{neut}}{\text{cm}^2-\text{s}}\right) \Rightarrow \frac{\text{eV}}{\text{cm}^3-\text{s}}$$

and if the desired unit of dose rate is rad/hr, a units conversion can be computed, giving

$$\text{dose rate} = \frac{\langle \Sigma\phi \rangle}{\rho}\left(5.7672 \text{x} 10^{-11}\right)\left(\frac{\text{rad}}{\text{hr}}\right) \qquad \text{(for neutrons)}$$

where the brackets, < >, imply integration over energy and the summation index i refers to individual isotopes in a given material. Also note that the above factor for neutron dose rate would be multiplied by 10^6 for the gamma dose rate since the base gamma kermas have units of MeV-barn/atom.

Given the above relationships, the conversion from flux to dose in a particular material becomes straightforward. One simply identifies the material density, ρ in g/cm^3, and the individual atom densities of each component, N_i in atom/b-cm, and computes the macroscopic kerma for that material as,

$$\Sigma'_g = \frac{f}{\rho}\sum_i N_i \sigma_{ig}$$

where f is the units conversion factor given above, g is the energy group index, and the Σ' notation simply denotes that this quantity is a modified macroscopic kerma cross section. Finally, the desired dose rate in rad/hr is given as,

$$\text{dose rate} = \sum_g \Sigma'_g \phi_g$$

The above procedure was used to evaluate the flux-to-dose conversion factors for several materials. In particular, conversion factors for air (78% nitrogen and 22% oxygen with a density of 0.00122 g/cm^3) and a polymer insulation material (phenol with chemical formula C_6H_5OH and a density of 1.4 g/cm^3) were developed and compared to the tissue conversion factors used in Ref. 2.

The resultant energy-dependent macroscopic flux-to-dose conversion factors for both neutrons and gammas are presented in Fig. 1. The gamma conversion factors all have roughly the same shape and magnitude versus energy, with just enough difference to give about 20-30% variation in the absorbed dose rate, depending upon the specific gamma flux spectrum. The neutron flux-to-dose factors, however, differ significantly in shape and overall magnitude. From Fig. 1, the conversion factor for tissue is clearly much larger than the others over most of the energy spectrum. In comparing air and polymer, however, one must clearly specify the neutron spectrum before ranking the dose rates – since in a thermal neutron environment, energy absorption in air per unit flux is significantly greater than the dose rate in polymer per unit flux, but in a fast spectrum the reverse relationship is valid.

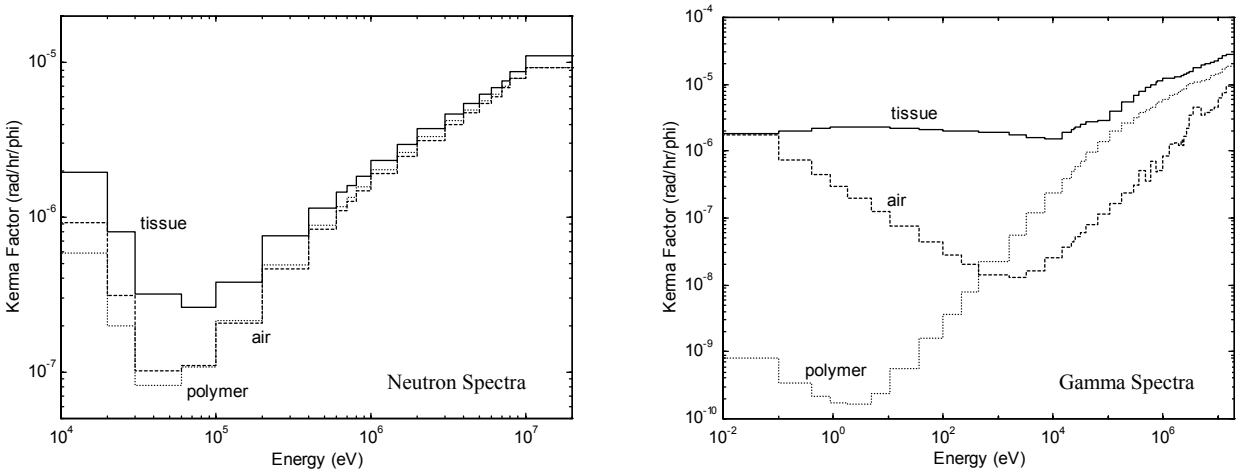

Fig. 1 Macro neutron and gamma kerma factors for air, polymer, and tissue.

The above comparisons imply two very important considerations when discussing neutron dose rates:

1. It is very important to consider the specific material of interest when quoting energy absorption rates, since the neutron kerma factors are so different.
2. It is also essential to consider the neutron spectrum carefully, since the strong energy dependence of the kerma factors requires precise knowledge of the weighting spectrum when converting flux to dose.

These statements are also generally valid when computing gamma dose rates, but the sensitivity to material specification and gamma spectrum is much lower than for neutron dose.

Using these new flux-to-dose conversion factors and the flux estimates in the vicinity of the Seabrook cables,[2] the dose rates to air, polymer, and tissue for Cycles 1-4 in Seabrook Station were computed and they are summarized in Table I. Notice that the gamma dose rates for all three materials are similar, with variations around 20-30%. However, the neutron dose rates vary by more than a factor of ten, with the polymer energy absorption rate falling between the two extremes (air and tissue). In particular, the neutron dose rate to the cable's polymer insulation is estimated to be more

than a factor of two less than that predicted using a tissue-equivalent conversion. When integrated over time, this represents an important reduction in the total dose estimate to the cable. With the new polymer flux-to-dose conversion factors identified here, the qualified service life of the excore detector cables would not be reached until near the end of Cycle 8 in Seabrook – a substantial improvement indeed.

Table I Dose rates (10^4 rad/hr) in air, polymer, and tissue at Seabrook's excore detector locations.

Cycle #	Air			Polymer			Tissue		
	Neutron	Gamma	Total	Neutron	Gamma	Total	Neutron	Gamma	Total
1	0.56	1.68	2.24	2.90	1.75	4.65	7.74	2.01	9.75
2	0.53	1.57	2.10	2.75	1.64	4.39	7.30	1.88	9.19
3	0.48	1.54	2.02	2.35	1.60	3.95	6.25	1.84	8.09
4	0.39	1.15	1.54	2.04	1.20	3.24	5.41	1.38	6.78

III. EXPERIMENTAL PROGRAM IN THE UMLRR

Although the use of material-specific kerma factors suggests a longer useful lifetime for the Seabrook cables, it only delays the cable replacement. Also, it appeared that the Gamma-Metrics' qualification dose of 3.2×10^9 rad was somewhat arbitrary and does not represent a limiting condition for the useful life of the cable. With the goal of providing data to support a higher equipment qualification limit, North Atlantic Energy Service Corporation decided to perform a cable irradiation program within the UMLRR. This work involved both the cable irradiation and testing component, and a separate analytical effort to plan, interpret, and generally support the experimental program.

A. Analytical UMLRR Computations

Much of the focus of the UMLRR analytical work was on characterizing the neutron and gamma flux levels and spectra in the radiation basket regions of the UMLRR (locations where the experiments were performed). All the calculations were performed with the XSDRN code[6] in 1-D geometry using the VITAMIN-B6 ENDF/B-VI 199 neutron group and 42 gamma group library.[5] The results from these computations were compared to the neutron and gamma environment expected in the vicinity of the detector cables in the Seabrook ex-vessel cavity region (using results from the DORT calculations in Ref. 2).

The computed fast flux for the base UMLRR configuration was normalized to measured data in the central radiation basket location to obtain absolute flux levels for the 1-D calculations. In particular, sulfur tablets were irradiated, the phosphorus activity measured, and an equivalent fast flux was determined based on known cross sections. Note here that the $^{32}S(n,p)^{32}P$ reaction is only sensitive to high energy neutrons. The experimentally-based result for the fast flux was 7.1×10^{11} n/cm^2-s in the central radiation basket at about 80% full power.

The neutron spectrum in the radiation basket from the XSDRN calculation and appropriate 47 group $^{32}S(n,p)$ reaction cross sections were used to simulate the same process as in the experimental procedure and the overall flux level was adjusted to give an equivalent fast flux, based only on the measured $^{32}S(n,p)$ reaction. The result of this process is an estimate of the absolute flux in the vicinity of the radiation basket — the integral $^{32}S(n,p)$ measurement gives the magnitude, and the XSDRN computation gives the distribution function in both space and energy.

With an absolute normalization, we can now make several comparisons. For example, a comparison of the neutron and gamma flux spectra in the UMLRR radiation basket with the spectra seen in the excore detector regions of Seabrook Station is presented in Fig. 2. Note that the magnitudes are quite different, as expected, and the Seabrook data have been scaled so that the spectra can be compared on the same set of axes. Of interest here, however, is the shape of the profiles, not their absolute magnitudes. Notice that, for different reasons, there are significant variations at the high and low end of the energy spectrum:

1. In the UMLRR the radiation basket is quite close to the core where we expect a high-energy fission spectrum, with a large compliment of high-energy fission neutrons diffusing into the region of interest. In Seabrook, however, there are very few high energy neutrons (> 1 MeV) that make it through the many layers of water and structure to the ex-vessel cavity region. Thus we see a significant difference in the greater than 1 MeV flux in the UMLRR versus Seabrook.
2. Considering the low energy end of the neutron spectrum, the UMLRR has a large amount of graphite and water which tend to slow down the high energy core neutrons and give a sizable thermal component in the radiation basket region. In Seabrook, there is a large attenuation of the low energy neutrons in the pressure vessel steel, which results in a relatively hard spectrum (mostly between 100 eV and 100 KeV) in the cavity and excore detector regions. Below 100 eV, the differences seen in Fig. 2 for the UMLRR and Seabrook neutron spectra are clearly justified.
3. For the gamma spectra shown in Fig. 2, we see that the Seabrook spectrum is shifted towards the high energy side relative to the UMLRR data. Again, this is exactly as expected because fission gammas tend to have lower energies than capture gammas. In the UMLRR, a large fraction of the gamma flux is due to prompt fission and in Seabrook, all the gammas result from neutron capture reactions, primarily in the vessel steel and bioshield structures.

Also of interest is the fact that the gamma flux and dose rate in the UMLRR are larger than the corresponding neutron contributions. In the reference UMLRR configuration at 80% full power, the calculated polymer dose rates in the central radiation basket are:

neutron dose rate	0.86×10^7 rad/hr
gamma dose rate	2.05×10^7 rad/hr
total dose rate	2.92×10^7 rad/hr

Recall that just the opposite distribution is true for Seabrook (see Table I, for example). Again, this is easily explained by the fact that the irradiation zone in the UMLRR is very close to the core and, in Seabrook, the zone of interest is outside the vessel. The vessel removes most of the thermal neutrons which produce the capture gammas. Thus, the gamma flux is usually low relative to the neutron flux just outside the vessel region. In the UMLRR, this is not the case, and the longer mean free path for gammas relative to fast neutrons causes the gamma flux to attenuate much more slowly, giving a larger gamma dose contribution in the radiation basket region.

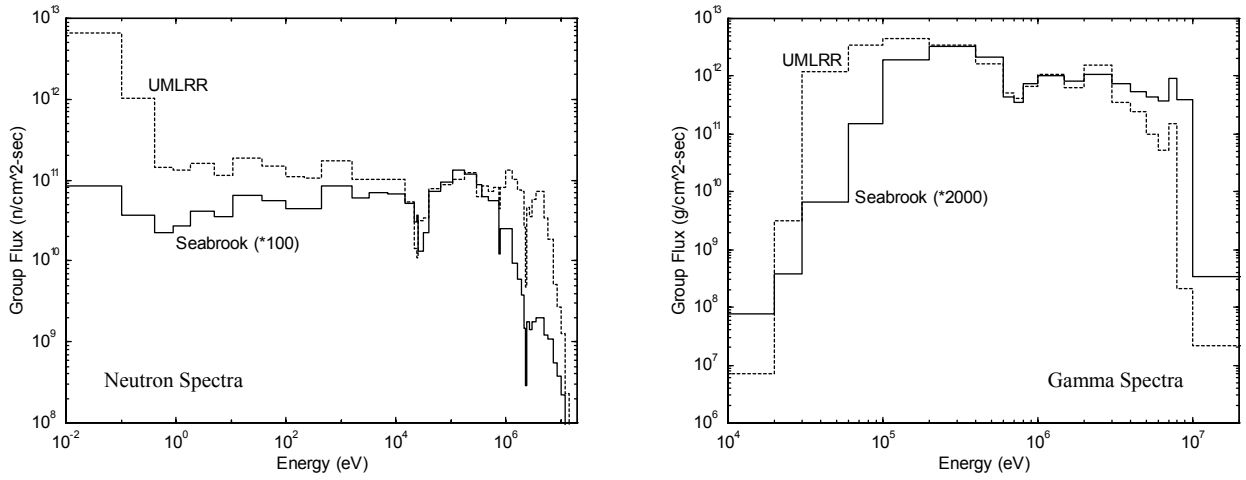

Fig. 2 Comparison of UMLRR and Seabrook neutron and gamma spectra.

Even with all these differences, cable irradiations in a UMLRR spectrum can still give information about the performance of the cables in Seabrook as long as a consistent basis for comparison is used. Although the spectra are quite different and the relative contribution of the neutron and gamma components are different, it has been assumed that a rad of absorbed energy causes the same damage to the cable insulation, independent of the initial energy source (neutron or gamma, high or low energy, etc.). This assumption allows one to simply use the total dose in the polymer insulation as the correlating parameter between the UMLRR irradiation environment and the actual cable environment in Seabrook Station.

With this assumption, an approximate relationship between irradiation time in the UMLRR and an effective full power day (EFPD) in Seabrook for an equivalent total dose to polymer was developed. Over the first four cycles in Seabrook, the average dose rate to polymer was 4.0×10^4 rad/hr. Beyond Cycle 4 the total dose rate was assumed to be 3.2×10^4 rad/hr (which was the computed rate for Cycle 4 in Seabrook). This lower dose rate in the later cycles is due to the use of low leakage fuel management schemes beyond the first few cycles.

In the reference UMLRR configuration at 80% full power (800 kW), the calculated dose rate in the central radiation basket (position D1) was 2.9×10^7 rad/hr. For Cycles 1-4, this gives a conversion factor for dose equivalency of roughly 30 EFPD in Seabrook for each hour of irradiation in the UMLRR reference configuration at 80% full power. For Cycle 5 and beyond, this conversion factor becomes about 38 EFPD in Seabrook for each hour in the UMLRR.

The above conversion factors were used to plan the initial experimental program in the UMLRR. However, after a successful program had been established, it became desirable to demonstrate that a service life approaching the full life of the plant was achievable. To accomplish this, the irradiation times needed in the reference UMLRR configuration were rather long. Thus, several computations were made to evaluate the performance gain associated with modifying the irradiation geometry in the UMLRR. Two changes – the replacement of a partial fuel assembly with a full fuel element, and the movement of the radiation baskets one grid row closer to the core – were suggested, with more than a factor of three increase in the total dose rate in the central radiation basket in position D-2 (to 9.6×10^7

rad/hr). After experimental validation and some operational experience with the new arrangement, this new irradiation configuration was used in the second half of the experimental program. This new configuration gives a conversion factor for dose equivalency of roughly 124 EFPD in Seabrook for each hour of irradiation in the UMLRR. Thus, the new configuration represents a significant improvement over the original irradiation geometry.

B. Experimental Results

A complete test plan, which included irradiation and electrical tests on six 18 inch long cable specimens, was developed.[7] The six cable specimens were thermally aged and evaluated at Seabrook in accordance with the test plan. The specimens were then irradiated in the UMLRR on several occasions. There were two cable segments placed in each of three radiation baskets for each of the irradiation intervals. After each irradiation, the specimens were held for a period of radioactive decay and then subjected to the electrical and physical measurements of the test plan – primarily bulk electrical measurements of capacitance and resistance and careful visual examination of the cables.

Six separate irradiation times of 24 hours, 24 hours, and 48 hours in the reference configuration and 16 hours, 32 hours, and 32 hours in the new irradiation geometry with the higher dose rates were used. The two lead specimens in the center radiation basket received cumulative doses of about 0.7, 1.4, 2.8, 4.3, 7.4 and 10.5 gigarad to polymer for these irradiations. The doses to the samples in the baskets on either side of the central basket were roughly 75-85% of the lead samples.

The overall results from the irradiation, which included combined neutron and gamma radiation exposures up to 10 gigarad, showed no observable effect on the bulk electrical properties of capacitance and resistance for the specimens tested. Only minor variations in these electrical properties were observed for total exposures ranging from 0.5 gigarad to 10 gigarad. Some physical shrinkage and discoloration of the insulating materials were noted, particularly at the lower ends of the cables that were inserted in borosilicate glass (as a support structure). However, the physical changes apparently had no effect on the electrical properties of the cables and no compromise of cable integrity was observed. Therefore, all the experimental information obtained as part of this work supports significant extension of the service life of the Seabrook excore detector cables. The maximum experimental exposures evaluated in the UMLRR are comparable to cable exposures in Seabrook Station through about Cycle 24 of operation – justifying a 35-40 year service life for these particular cables.

IV. SUMMARY/CONCLUSIONS

A combined analytical and experimental program for evaluating the service life of the Gamma-Metrics' excore detector cables in Seabrook Station has been completed. The analytical work developed a set of polymer kerma factors for converting flux to absorbed dose and provided support for the experimental cable irradiation and testing program within the UMass-Lowell research reactor (UMLRR).

The experimental program exposed actual cable samples to a combined neutron and gamma radiation environment, with exposures up to 10.5 gigarad total dose. Only minor variations in electrical properties were observed over this range of radiation exposure, establishing a relatively long

service life for the excore detector cables in Seabrook Station. If desired, detailed irradiation data for the Seabrook excore detector cables can be obtained from North Atlantic Energy Service Corporation.

ACKNOWLEDGMENTS

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