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A NEW NEUTRON DOSE EQUIVALENT METER

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Abstract

The design and performance of a new neutron dose equivalent meter or "rem meter" are described. Key design elements include a 6.38-inch diameter polyethylene moderator sphere loaded with Tungsten Carbide powder to 5% tungsten by weight, and a 2-mil thick cadmium foil absorber located at a radius of 5 cm.

A detailed response function for the new rem meter (dubbed the Model 652) was derived over the neutron energy range from thermal to 20 MeV using Monte Carlo transport techniques. Compared with the standard Eberline NRD rem meter, the new design is about 1.5 kg lighter, and is 28% more sensitive per unit dose of Cf-252.

It is shown that for a large variety of standard and operational neutron spectra, the model 652 rem meter provides a response accuracy of $\pm 15\%$.

Development of this technology is presently ongoing under a Department of Energy (DOE) grant to San Jose State University.

I. INTRODUCTION

Neutron dose equivalent meters or "rem meters" are used universally by health physicists for field measurement of neutron dose equivalent. In fact, it is the only instrument available for reliable dose equivalent measurements in a variety of neutron fields and under conditions where the neutron spectrum may be poorly known.

The design basis of all rem meters is to provide an energy response per unit fluence which closely mimics the shape of the true fluence to dose function. Current commercial designs feature a large polyethylene moderator which surrounds a thermal neutron detector (e.g., a $^{10}\text{BF}_3$ counter tube). A neutron absorber such as cadmium surrounds the counter tube to further "fine tune" the instrument response. The two most widely used commercial rem meters in the US are the Eberline NRD, based on a 9-inch spherical moderator system developed by Hankins at Los Alamos in the 1960s, and the "Snoopy" based on a cylindrical moderator system developed by Andersson and Braun in Sweden almost a generation ago. These instruments have continued in service to this day with only minor design modifications.

Current technology suffers from two serious limitations. First, response accuracy at intermediate neutron energies is

poor. Figure 1 [1] compares the response of the Eberline

Fig. 1. Eberline NRD response vs. NCRP 38 function.

NRD rem meter with the DOE-mandated fluence to dose function, which is derived from NCRP Report No. 38. The response of the ideal rem meter would closely mimic the shape of the conventionally true curve. The NRD response is seen to over-respond in the energy range from epithermal to about 0.5 MeV. The ratio of the two curves (response/true) gives the traditional energy response curve (response per unit dose versus energy). The ideal rem meter would show a flat response. The actual energy response is shown in Figure 2 [1]. The peak over response at 10 keV is a factor of 7.5 for a MeV normalization. The

Fig. 2. Eberline NRD energy response.

response of the Andersson-Braun meter, is a bit better than this, but it suffers from a non-uniform directional response. For a variety of typical operational spectra, the over response is not so severe. For example, a nuclear Regulatory Commission sponsored study [2] of neutron dosimetry at commercial power plants showed that current rem meters over respond by up to a factor of 2. In view of the new ICRP neutron quality factors which also represent about a factor of 2 increase, and which are expected to be adopted by both the DOE and NRC in the near future, the conservatism inherent in current rem meter measurements is in our opinion far too restrictive.

Current rem meters are also limited by a serious under response at high energies. Even with a bare Cf-252 or ^{241}Am -Be source calibration, present rem meters seriously underestimate neutron dose above 20 MeV, which makes them unsuitable for dosimetry around high-energy accelerators.

One of our design goals was to enhance and extend the high-energy response to several hundred MeV. Work is in progress using the Los Alamos High-Energy Transport Code (LAHET) to characterize and optimize the new design out to 500 MeV. A key parameter in the optimization is the amount of tungsten incorporated into the poly moderator. Neutron generation via (n,xn) reactions determines the degree of response enhancement above the $(n,2n)$ threshold of 8 MeV.

The first phase of our work, as reported here, focuses on improving the response accuracy over the energy range from thermal to 20 MeV. Further optimization of the new design using Monte Carlo simulations will be carried out at San Jose State University under a DOE Grant. It is expected that a prototype will be built and tested over the next year. The final design may very well exceed the performance of the model 652 reported on here.

II. DESIGN PROCESS

There are several factors, under the control of the rem meter designer, which affect the response function. These are:

- a) the size and shape of the moderator,
- b) the amount and location of neutron absorbers in the moderator, and
- c) the addition of neutron generating materials.

We decided to stay with the basic Hankins geometry as exemplified by the Eberline NRD, to take advantage of the excellent directional response afforded by a spherical moderator. Historically, rem meters relied primarily on a large moderator size to contour the response function. Our approach was to examine a range of smaller diameter spheres and use absorption extensively as a means for shaping the response function.

Another novel feature is the uniform loading of the moderator with a material capable of neutron generation. Two

mechanisms were considered: fast fission and the (n,xn) nuclear reaction. For example, the use of a depleted uranium loading was considered and rejected. First, because the cross section is low, and second, because of the stigma of incorporating radioactive material into an instrument. Lead, gold, tantalum, and tungsten all have decent (n,xn) cross sections (about 2 barns). However, tungsten in the form of Tungsten Carbide (WC), stands out for a number of reasons. It is not an exotic material, and at about \$15/pound, it is inexpensive. Both the carbon and the tungsten atoms increase the effectiveness of the polyethylene moderator by increasing the elastic scattering cross section of the mixture. Finally, tungsten's absorption resonance structure in the energy region of 0.1 to 1 keV is ideal in contouring the detector response function at intermediate neutron energies. For this reason, it is essential that the Tungsten Carbide be distributed in the outer shell of the moderator sphere. Also, the uniform loading compared to a single layer around the detector tube, enhances the efficiency of the (n,xn) reaction below 20 MeV.

An incoming neutron with energy above the $(n,2n)$ threshold in tungsten may produce one or more new neutrons via this process. Because the emitted neutrons share the original neutron's energy, they are lower in energy and more likely to be absorbed in the counter tube. In this way, it is possible to enhance and extend the high-energy response of a rem meter, at least above about 10 MeV.

The design criteria used were to obtain the closest fit possible between the rem meter response function and the true fluence to dose curve, without incurring a weight penalty or a loss in response sensitivity. The Los Alamos Monte Carlo transport code, MCNP, running on a Sun Sparc Work Station was used to calculate the new rem meter response function and to evaluate the impact of varying the design parameters.

The basic calculational model was used as early as 1991 [1] to determine the response function of a stock Eberline NRD rem meter. The Eberline NRD was modeled in great detail using production schematics provided by Eberline. These calculations were benchmarked with measurements to show that the basic model was able to predict the response of a nominal NRD rem meter to within 15%. This model served as a starting point for the present design work.

A design consideration, implicit in any rem meter, is the choice of "true" response function to mimic. Unfortunately, there are a number of functions or curves from which to choose. DOE contractors follow the NCRP 38 fluence to dose conversion curve, while in many countries, the ICRP 60 recommendations have already been fully implemented. Figure 3 (following page) shows the "old" and "new" fluence to dose conversion functions. The conversion function for ambient dose equivalent was calculated by Leuthold, et al [3] using the ICRP 60 quality factors. The absolute magnitudes of these two functions differ by up to a factor of two, which can be accounted for during calibration. But the really frustrating aspect is the shift of the knee in the new curve to

lower energies. The neutron energy region from 50 to 250 keV dominates personnel dose at nuclear power plants.

Fig. 3. Neutron Fluence to Dose Equivalent and the Effective Quality Factor.

This region is bracketed by the knee in the curve. Thus, a rem meter designed to fit one curve will automatically be inaccurate for another. The good news, however, is that current rem meters fit the new curve better than the old one. Our initial design effort was to meet the conversion function currently in force within the DOE complex. However, the technology can readily be applied to fit the ICRP conversion function, and this will be a goal of future work.

A not so obvious factor impacting rem meter response accuracy has to do with the type of calibration it undergoes. Different calibration spectra have the effect of shifting the response function vertically relative to the true curve, with the result that the degree of fit changes for better or worse over some energy regions. Since rem meters are almost always calibrated with a fast neutron source, our analysis used a bare Cf-252 source calibration to assess the response of the new design to a variety of operational neutron spectra.

III. RESULTS

A cutaway view of the new design (Model 652) is shown schematically in Figure 4. The moderator consists of two sections: an inner sphere and an outer shell, both of which are loaded with Tungsten Carbide at a weight percentage of 5% W. This weight percentage is achieved by mixing one gram of WC for every 17.7 grams of CH_2 . The resultant density is 1.732 g/cm^3 .

A 2-mil thick cadmium foil is wrapped over the inner sphere, at a radius of 5 cm. Cadmium appears to offer better selectivity in shaping the response function than other neutron absorbers. However, the use of Tungsten Boride (WB_2) loading in the inner sphere is being investigated as an alternative to the use of cadmium.

Fig. 4. Schematic View of New Rem Meter, Model 652

Despite the increase in density, the smaller outer diameter of 16.2 cm results in a weight saving of 1.66kg (3.65 pounds) compared with the stock Eberline NRD. The sensitivity is also increased, being 28% higher for a bare Cf-252 source spectrum. Specifically, the calibration factor for the Model 652 is $3.51\text{e-}4$ counts/pSv, while that for the Eberline NRD is $2.74\text{e-}4$ counts/pSv.

In Figure 5, (following page) the Model 652's response function is compared graphically with the NCRP 38 conversion function. A 2 MeV normalization is used to simulate the effect of a bare Cf-252 source calibration. The agreement between the two curves is excellent around 100 kev, a region of great importance at nuclear power plants. The response of the stock Eberline NRD is contrasted with that of the Model 652 in Figure 6 (following page). Note the Model 652's enhanced response above 10 MeV.

To assess the response accuracy of the Eberline NRD and Model 652 rem meters, their response functions were folded in with a variety of operational and standard source spectra. The relative response of each rem meter with respect to the true dose equivalent (per NCRP 38) is given in Table I. All of the neutron spectra were derived from the International Atomic Energy Agency (IAEA) compendium of Neutron Spectra [4].

For nuclear power plant spectra, both BWR and PWR, the Eberline NRD is seen to over respond by up to a factor of two, while the Model 652 response is within 15%. For fast spectra, at least those with a 15 MeV upper limit, both rem meters respond accurately. The response accuracy of the Model 652 rem meter is $\pm 15\%$ for all of the spectra considered.

Fig. 5. Model 652 Response Function vs. NCRP 38 Curve

Fig. 6. Model 652 & Eberline NRD Rem Meter Response Functions vs. NCRP 38 Curve

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TABLE I

Relative Response of Eberline NRD & Model 652 Rem Meters vs NCRP 38 True Dose

Type of Spectrum	Eberline NRD	Model 652
BWR - Location E/3-X29	1.29	0.87
PWR - Location F/5	1.84	1.09
PWR - Location G/3	1.52	0.97
PWR - Location H/12	1.42	0.93
PWR - Location I/1-IV	1.74	1.05
PWR - Location I/1-RV	1.94	1.14
PWR - Location J/3	1.69	1.04
PWR - Location 2/E-2	1.32	0.92
PWR - Location 3/E-3	1.17	0.91
15 MeV Photons on Tungsten	1.00	0.97
18 MeV Photons on Tungsten	1.05	0.88
18 MeV Photons on Tungsten - thru 90 cm of concrete	0.98	0.86
14 MeV Photons on Tungsten - Room Scatter	1.44	0.93
14 MeV Photons on Tungsten - Skyshine	1.55	0.97
5 Tonnes Natural Uranium Pile	1.42	0.91
Tokamak Fusion Test Reactor, Root	1.08	0.98
Tokamak Fusion Test Reactor, Wall	1.27	0.97
Bare $^{238}\text{PuO}_2$ Source	1.06	1.09
$^{238}\text{PuO}_2$ W/25.4 cm diameter CH_2 sphere	1.02	0.96
Cf-252, Room Scatter	1.15	0.93
Cf-252, Skyshine	1.16	0.93
Cf-252 in 15 cm radius D_2O sphere	1.18	1.02
Bare ^{241}Am -Be Source	0.88	1.02
Low Flux Reactor, 1/E spectrum	1.11	0.96
GODIVA Reactor	1.02	0.95

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