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DOSE EQUIVALENT LiF TLD NEUTRON AND PHOTON AREA MONITOR

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A passive area monitor has been demonstrated that can measure neutron and gamma-ray dose equivalents. The Monitor combines the neutron moderator shield of a Snoopy remmeter with a LiF TLD thermal neutron and gamma-ray detector. This area monitor can be a valuable aid in evaluating personnel LiF TLD albedo neutron dosimeter exposures. Calibrated with PuBe, the Monitor will read the actual neutron dose equivalent -60 to +160 percent over the neutron energy range from thermal to 14 MeV. Calibrated with Co^{60}, the Monitor will read the actual gamma-ray dose equivalent from -40 to +0 percent from 38 keV to Co^{60}.

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EXECUTIVE SUMMARY

The area monitor, hereafter called the Monitor, is now the U.S. Navy's most accurate means for routine measurements of total neutron and photon dose equivalents. Operational costs are low since it uses the same dosimeters and issue cycle as the Navy's DT-583 personnel badges. The Monitor has the advantage of being "passive" and, therefore, can integrate low-level radiation exposures over long periods of time.

We compared the response of the Monitor to that of the AN/PDR-70 (Snoopy) remmeter in six orientations using nine neutron sources: thermal, 2 keV, 24 keV, 144 keV, 600 keV, 14 MeV, Cf^{252} (which is used to calibrate personnel badges), PuF (which simulates fission spectra), and PuBe (XM9335 XWO -1/UDM). Also, the responses from three photon sources were evaluated: Co^{60}, Cs^{137}, and x-rays having effective energies of 25 keV, 38 keV, 70 keV, 117 keV, 169 keV, and 210 keV. Quality assurance tests of prototypes and production models of the Monitors were matched within a few percent.

The Monitor and the Snoopy agreed within about 10 percent in the 600 keV neutron beams and with each of the isotopic sources. In the intermediate energy beams, i.e., 24 keV, the Snoopy overresponded by more than a factor of four (contrary to the results of its acceptance tests) while the Monitor overresponded by less than a factor of three. In the thermal beam, the Snoopy indicated 65 percent of the actual dose equivalent while the Monitor indicated only 38 percent. The Monitor recorded 60 percent of the 14 MeV dose equivalent, compared to 40 percent for the Snoopy.

The ratio of the response for neutrons incident at the end versus the side of the Monitor increased with energy from 0.27 for thermal to 0.86 for PuBe neutrons. Directional response for the Snoopy shows a similar effect;[1] however, large errors at thermal energies due to the cable connector of the Snoopy are not present in the Monitor.

The photon response of the Monitor is relatively inde[illegible]dent of the energy above 7 degrees keV, and orientation (±6 percent). Normally, incident photons cause no false neutron response. However, 100 mrem from gamma rays into either end of the Monitor may produce a false neutron reading of 10 mrem or less. This is the result of the photon sensitive thermoluminescent dosimeters (TLDs) being nearer the ends of the Monitor than the TLD's sensitivite to both neutrons and photons.

FOREWORD

This report describes a demonstration of a passive area monitor that can measure both neutron and gamma-ray dose equivalents. Thus, the area monitor can be a valuable aid in evaluating personnel radiation exposures. Funding for this work was provided by Naval Sea Systems Command, Code CEL-R, as part of a continuing program on the monitoring and control of personnel radiation exposure.

The authors would like to thank R. Schwartz and A. Wassen of the National Bureau of Standards (NBS) for tests done in the monoenergetic neutron beams. N. Scofield of Naval Surface Warfare Center (NSWC) prepared programs for analysis of the multisphere, D. Hankins of Lawrence Livermore Laboratory provided helpful information, and J. Restorff of NSWC produced the final report.

Approved by:

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CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The area monitor, hereafter called the Monitor, is now the U. S. Navy's most accurate means for routine measurements of total neutron and photon dose equivalents. We compared the response of the Monitor to that of the AN/PDR-70 (Snoopy) remmeter in six orientations using nine neutron sources. This report describes the design of the Monitor production model, Figure 1, and the comparison of response characteristics of the production models to the Snoopy in various neutron and photon fields. Figure 2 shows an exploded view of both the Monitor and the Snoopy. Production models had been evaluated to assure that equal response was maintained. Additionally, the Monitor was evaluated in several naval environments, both as prototypes and early production models. Results of the tests are given herein.

BACKGROUND

Environments in which personnel may be exposed to low levels of ionizing radiation needed an integrating Monitor to document total neutron and gamma-ray dose equivalents. In the past, posted personnel badges containing Harshaw NG67 thermoluminescent dosimeters (TLDs) mounted on a 4-inch x 4-inch x 2-inch Lucite block were used. TLDs were chosen because they can measure dose equivalents down to several mrem and, therefore, are capable of monitoring unrestricted areas receiving very small exposures. Overresponse of TLDs to intermediate neutrons had been recognized, and corrections of these responses had to be determined with the Snoopy remmeter. Corrections to personnel badge readings can now be obtained from the Monitor data.

Several trial designs for Monitors were tested before selecting the one reported here. Among the trial designs were: putting the TLDs in the centers of 4-inch x 4-inch x 4-inch and 6-inch x 8-inch x 10-inch Lucite blocks; in the centers of 5-inch, 8-inch, and 10-inch diameter polyethylene spheres; in place of the boron trifluoride detector in the Snoopy remmeter; and in a Snoopy remmeter in which the detector tube hole was filled with polyethylene. Linearity versus neutron energy increased with the size of the moderator, and the most accurate response was obtained with TLDs in the polyethylene filled Snoopy.

DESIGN

The design of the Monitor is based on the Andersson-Braun remmeter[2] (see Figure 1). The cylindrical moderator was mounted on a 0.6-cm thick aluminum, L-shaped mounting bracket. The moderator was modified to accept a polyethlyene card holder that holds two Harshaw NG67 cards, each card holding a Li^6 fluoride (TLD 600) and a Li^7 fluoride (TLD 700) chip. The NG67 cards are the same type cards used in DT 583 neutron personnel badges. The cards, mounted on a polyethylene holder, slid into the center of the Monitor. When the card holder was inserted into the Monitor, the four TLD chips were laid on the central axis of the Monitor. The two TLD 700 chips are located between the TLD 600 chips and the ends of the Monitor. All remaining space of the Monitor was filled with high-density polyethylene. This new Monitor contains a greater amount of polyethylene than the Snoopy remmeter, which extends the Monitor's moderating capabilities.

COST REDUCTION

A substantial cost reduction was achieved in the production of the Monitor. The Monitor, which is constructed similarly to the Snoopy remmeter, contains a cylindrical, borated-elastomer, thermal-neutron attenuator. Previously, a cylindrical mold was used to form this attenuator. A flat mold was designed and constructed that produced this neutron attenuator at a far lower cost with no change in response (see part no. 4 in Figure 1).

PRODUCTION VERSUS PROTOTYPE

A 0.6-cm thick aluminum security case replaced an L-shaped bracket of the same material. The production Monitor uses only high-density, virgin polyethylene, while the prototypes used the black polyethylene outer moderators borrowed from Snoopys. Production elastomers were made from flat molds as described above. The Monitor and remmeter are compared in Figure 2.

DOSE EQUIVALENT DETERMINATIONS

TLDs were read on a Harshaw model 2271 reader using the method of Cox and Lucas.[3] The thermoluminescent output was assumed to be directly proportional to the dose delivered. After the TLDs were read, a 100 mrem calibration gamma-ray dose was given to the cards, and the chips were read again. These second readings were used as individual TLD sensitivity factors in the dose equivalent calculations.[4] The neutron and gamma-ray dose equivalents were determined by the method of Luerson and Johnson.[5]

It was of interest to note that when the dosimeter reader system was calibrated for the per nel dosimeter badge, the dose equivalent conversion factor for neutrons, badge to M itor, was 1.11 to 1. Due to attenuation of gamma rays in the Monitor, the ratio for gamma rays was 0.69 to 1.

NEUTRON RADIATION STUDIES

FACILITIES

Neutron energies and sources in this study include: thermal, 2 keV, 24 keV, and 144 keV monoenergetic neutron beams from the National Bureau of Standards (NBS) reactor; 600 keV neutron beam from the NBS Van deGraaff; 14 MeV from the D-T generator at the U.S. Naval Academy; an NBS calibrated PuBe source located at the Naval Surface Warfare Center (NSWC); a PuF source located and calibrated at NSWC using the multisphere neutron spectrometer and the appropriate response functions;[6] an NBS calibrated Cf^{252} source located at the Naval Research Laboratory, and the NBS Cf^{252} source.[7]

The NBS neutrons of various energies were produced by filters. The 2 keV neutron beam is produced using a scandium filter. Scandium has several unwanted energy windows, one at 8 keV and the other at 800 keV. An $Al_{0.43}Mn_{0.57}$ alloy scatterer is used in conjunction with a Ti filter to reduce unwanted neutron energies to about 3 percent of the 2 keV flux. Neutrons having energies of 25 keV are produced by using an FeAl filter. Higher energy flux in this beam amounts to about 1 percent of the total flux. Silicon filters are used to produce the 144 keV neutrons. Neutrons having 600 keV energies are produced in the NBS Van de Graaff by the Li^7 (p, n) Be^7 reaction.

Neutron dose equivalents were computed from log-log interpolations of the International Commission on Radiation Protection (IRCP) fluence to dose equivalent conversion factors.[8] Table 1 gives these and National Council on Radiation Protection (NCRP),[9] International Commission on Radiation Units and Measurements (ICRU), Report 20,[10] and American National Standards Institute (ANSI)[11] fluence to dose conversion factors.

PROCEDURE

The Monitors were exposed long enough to neutron beams to give about 100 mrem (500 mrem in the 14 MeV neutron exposures). In most cases, the exposures occurred within 2 days after the TLD chips were cleared and were read within 16 hours after exposure. The Snoopy remmeter was exposed with the long axis perpendicular to the neutron beam. At least 10^5 counts were recorded on an external counter connected to the phone jack on the electronic package. The 10^3 range on the ratemeter was used to avoid pulse pileup. Backgrounds, although very small, were taken before and after each exposure. The Snoopy and Monitor were normalized to the NSWC PuBe source.

The effect of the exposure through the 0.6-cm thick, L-shaped mounting bracket was evaluated by comparing A'/A and B'/B ratios. Figure 3 shows the geometry used in taking the measurements, which were taken in six different directions. In the unprimed directions A, B, and C, nothing blocks the incoming radiation. In the A' and B' directions, the radiation must pass through the aluminum mounting bracket. In the C' direction, the radiation is incident on the TLD mounting slot. Table 2 shows the results. Production Monitors, which are enclosed in 0.6-cm thick aluminum, match the A' and B' values within a few percent.

ERROR ANALYSIS

The minimum readable dose equivalent for neutrons on a Harshaw NG67 card was about 2 mrem. In practice, the minimum dose equivalent may vary from 2 to 20 mrem. This range results from the TLD's history between the time it was exposed until the time it was read and the quality control of the reader.

The handling procedure used in these studies minimized errors, so that the errors in reading the TLDs were about ±2 percent. This was confirmed by paired reading of the two TLD cards in each experiment.

Neutron source errors are listed in Table 3. Column 1 gives the energy of the neutron source, column 2 gives the fluence uncertainty, and column 3 gives the percentage contamination of the neutron beam with neutrons of unwanted energies. Column 4 shows the gamma-ray contamination of the neutron flux.

Overall errors were ±11 percent or less, except that the contribution of scattered radiation to the 14 MeV beam and the lack of NBS calibration for the PuF source resulted in 16 percent errors. Estimated errors are the square root of the sum of the squares of the calibration, neutrons of other energy, and reading errors.

RESULTS AND DISCUSSIONS

Neutron Energy Dependence

Table 4 shows the Monitor's response to exposures of various neutron energies. The data gives the following ratios: (1) Monitor's response to the Snoopy's response (Monitor/Snoopy); (2) Snoopy's response to the calibrated dose equivalent (Snoopy/Actual); and (3) Monitor's response to the calibrated dose equivalent (Monitor/Actual). Figure 4 shows a plot of the energy response of the Snoopy and the Monitor.

1. The Monitor/Snoopy ratio is 1.0 for the PuBe source, where both are calibrated. At lower energies, it is less than 1.0 while at 14 MeV it is 1.6. Apparently, filling the void of the boron trifluoride detector space of the Snoopy with high-density polyethylene accounts for the change in response.

2. Snoopy/Actual ratios increase from 0.6 at thermal to 4.2 at 24 keV, then decrease with increasing energy to 0.4 at 14 MeV.

3. Monitor/Actual ratios show the maximum overresponse of the Monitor was 2.6 in the region of 24 keV. Monitor responses were closer to the actual dose equivalent than the Snoopy's response in the range 2 keV to 14 MeV. Response of the Monitor to thermal neutrons was only about 38 percent of the actual dose equivalent delivered.

4. The difference between the present and the designer's Snoopy calibration[12] may be found in the sources used. The newly available monenergetic neutron beams are a more rigorous test of response versus energy than the broad spectrum of moderated sources available to the designer.

5. The original report of the Snoopy design shows a dose equivalent response to thermal neutrons.[12] However, this was obtained with thermal neutrons incident on the remmeter from all directions. Thus, the excess response from the open end of the moderator compensated for the normally low response.

Neutron Directional Dependence

Directional responses of the Monitor were evaluated in six directions. The data describing the relative responses are given in Table 2.

Column 1 compares A'/A and B'/B. These ratios show the attenuating effect of the 0.6-cm thick, aluminum mounting bracket. Dose equivalent ratios of the Monitor averaged about 0.8 ±0.01 over all energies. With the Snoopy, the attenuation of 0.6-cm thick aluminum was 0.96 ±0.01 using a PuBe source and a source to detector distance of 1 meter.

Column 2 compares B/A and B'/A'. These ratios test for asymmetry about the axis of rotation and for any effect of exposing the edge versus the flat side of the TLD chips. The mean ratios, excluding the response to thermal neutrons, was 0.97 ±0.06, indicating no asymmetry. The ratios for the thermal neutrons indicate some asymmetry, presumably because the slot into which the TLD card holder slides provides an entry path to the TLD chips for thermal neutrons.

Column 3 compares C'/A. These data show reduced sensitivity for neutrons entering through the end of the Monitor. The reduced sensitivity appears to be inversely related to the neutron energy.

Column 4 compares C/C'. There was no apparent response difference between neutrons entering the Monitor from either end except for thermals. This is because thermal neutrons can enter the Monitor on one end through the card holder slot. The mean ratio was 1.15 ±0.17 for all neutron energies excluding the thermal neutrons.

PHOTON RESPONSE

PHOTON ENERGY RESPONSE

The photon response of the Monitor was determined for Co^{60}, Cs^{137}, and x-rays having effective energies of 25 keV, 38 keV, 70 keV, 117 keV, 169 keV, and 210 keV.[13] Dose equivalents were determined by using ANSI exposure to dose conversion factors.[11] All exposures had 1 meter source to detector distances, and incident radiation was perpendicular to the plane of the cards. Responses of the Monitor per Roentgen and per rem for the various sources relative to Co^{60} are given in Table 5 and Figure 5. The maximum error in these data was about 5 percent.

PHOTON DIRECTIONAL RESPONSE

Photon irradiation through the aluminum brackets reduce the dose equivalents an average of approximately 6 percent (see Table 6). Irradiation of the flat ends of the Monitor gave a smaller dose equivalent compared to the cylindrical surfaces. The slide slot had no apparent effect on the gamma-ray dose equivalents.

PHOTON EFFECT ON NEUTRON DOSE EQUIVALENT

Computed neutron dose equivalents require knowledge of the net gamma-ray dose equivalent. Since the TLD 600 and TLD 700 chips are not collocated, varying photon distributions throughout the Monitor can produce erroneous neutron dose equivalents. However, for gamma-ray irradiation normal to the cylindrical axis, this effect was negligible since gamma-ray dose equivalents were uniform along and normal to the Monitor's cylindrical axis. The dose equivalents for gamma-ray irradiation, directed through the ends of the Monitor, varied along the cylindrical axis. The maximum false neutron dose equivalent, presented in Table 7, is 10 mrem per 100 mrem photon dose equivalent delivered from the flat sides.

CONCLUSIONS

The Monitor is made from a Snoopy neutron remmeter by replacing the boron triflouride tube with LiF TLDs and filling the space with polyethylene. It has flatter response to neutrons of various energies than the remmeter.

In the 14 MeV neutron field, the Monitor response was somewhat greater than the Snoopy. In the 1 [illegible]eV to 5 MeV range, the Monitor's response was comparable to the Snoopy. This was expected since both are calibrated with a PuBe source. Overresponse of the Monitor in the intermediate neutron energy range, e.g., neutrons with energies between [illegible] keV and 600 keV, was not as large as the Snoopy's. Response of the Monitor to thermal neutrons was significantly reduced when compared with that of the Snoopy.

Comparing the end to the side of the Monitor, we see that the Monitor's directional response is a major improvement over the remmeter. The large variation of response versus orientation observed for thermal neutrons in the Snoopy[1] has been eliminated. The hole in the Snoopy, into which the detector is inserted, provides an entry for thermal neutrons even if the electronic package is attached.[1] The Monitor, on the other hand, has only hairline cracks on each side of the TLD card holder that restricts entry of thermal neutrons into the instrument.

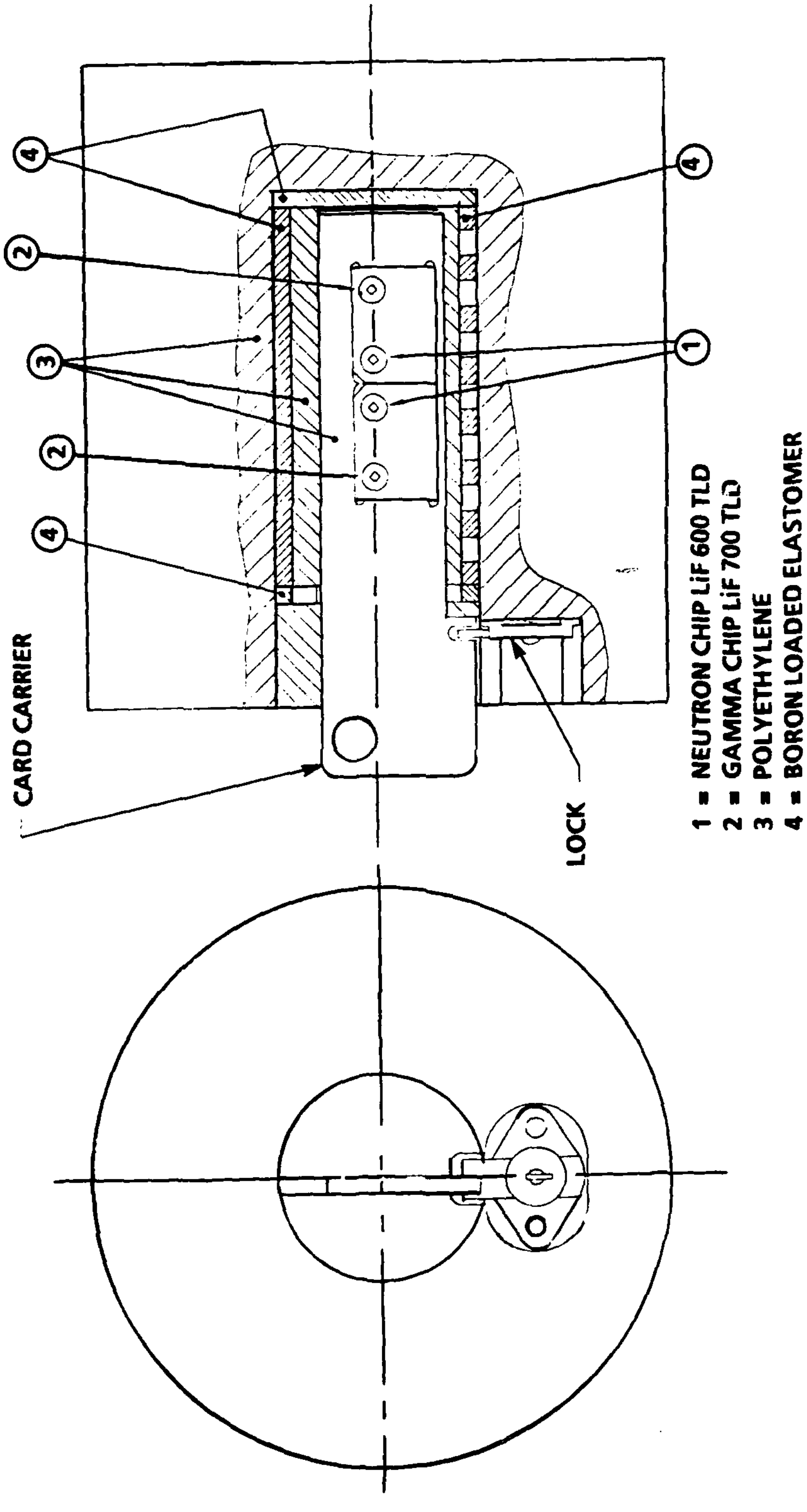

FIGURE 1. NEUTRON AND PHOTON AREA MONITOR BASED ON SNOOPY REMMETER AND LiF (TLD)

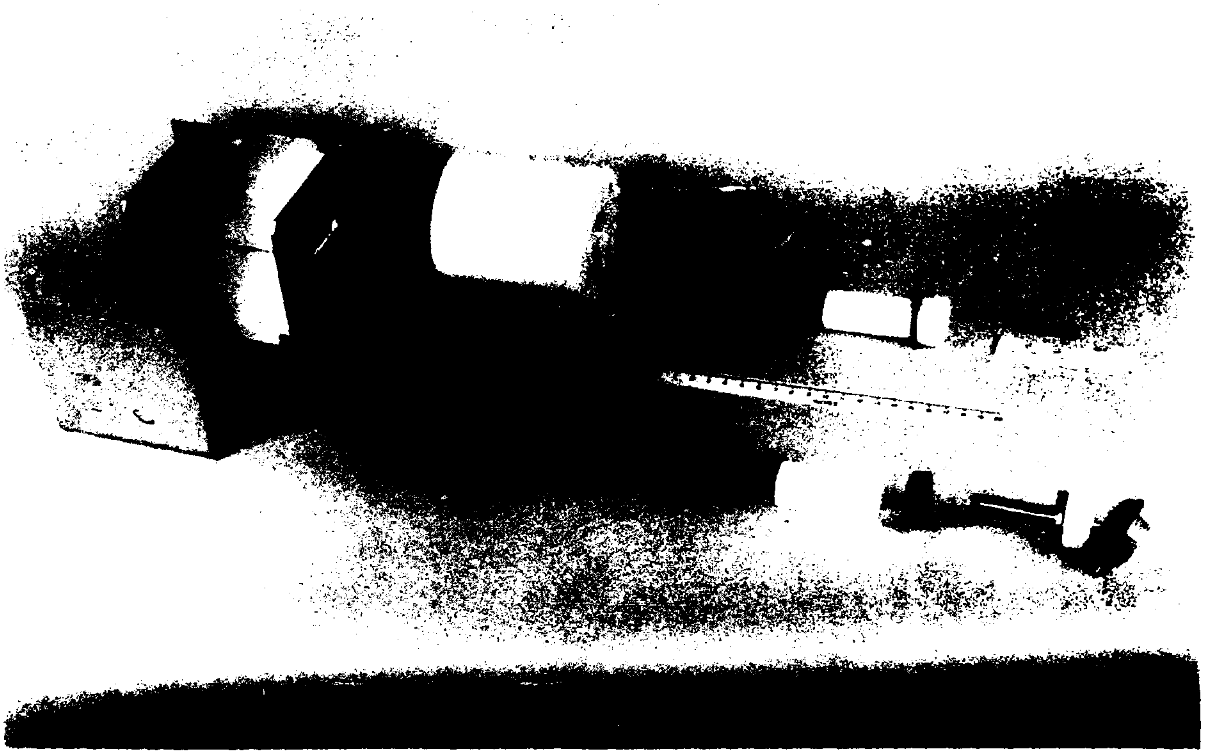

FIGURE 2. EXPLODED VIEW OF AREA MONITOR AND SNOOPY REMMETER

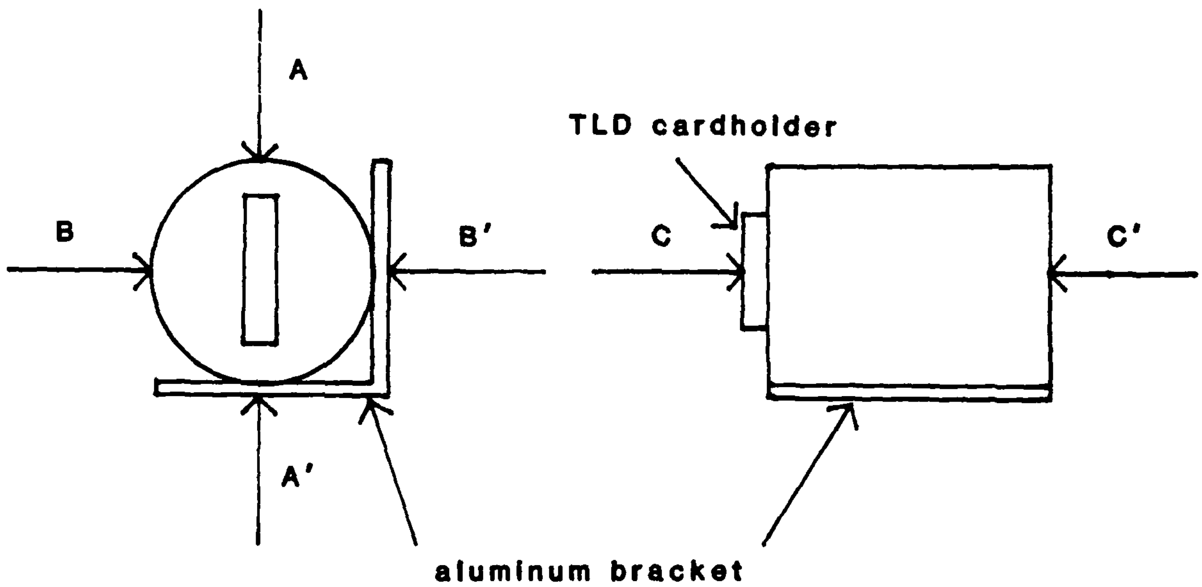

FIGURE 3. SIX DIRECTIONS OF INCIDENT RADIATION ON AREA MONITOR

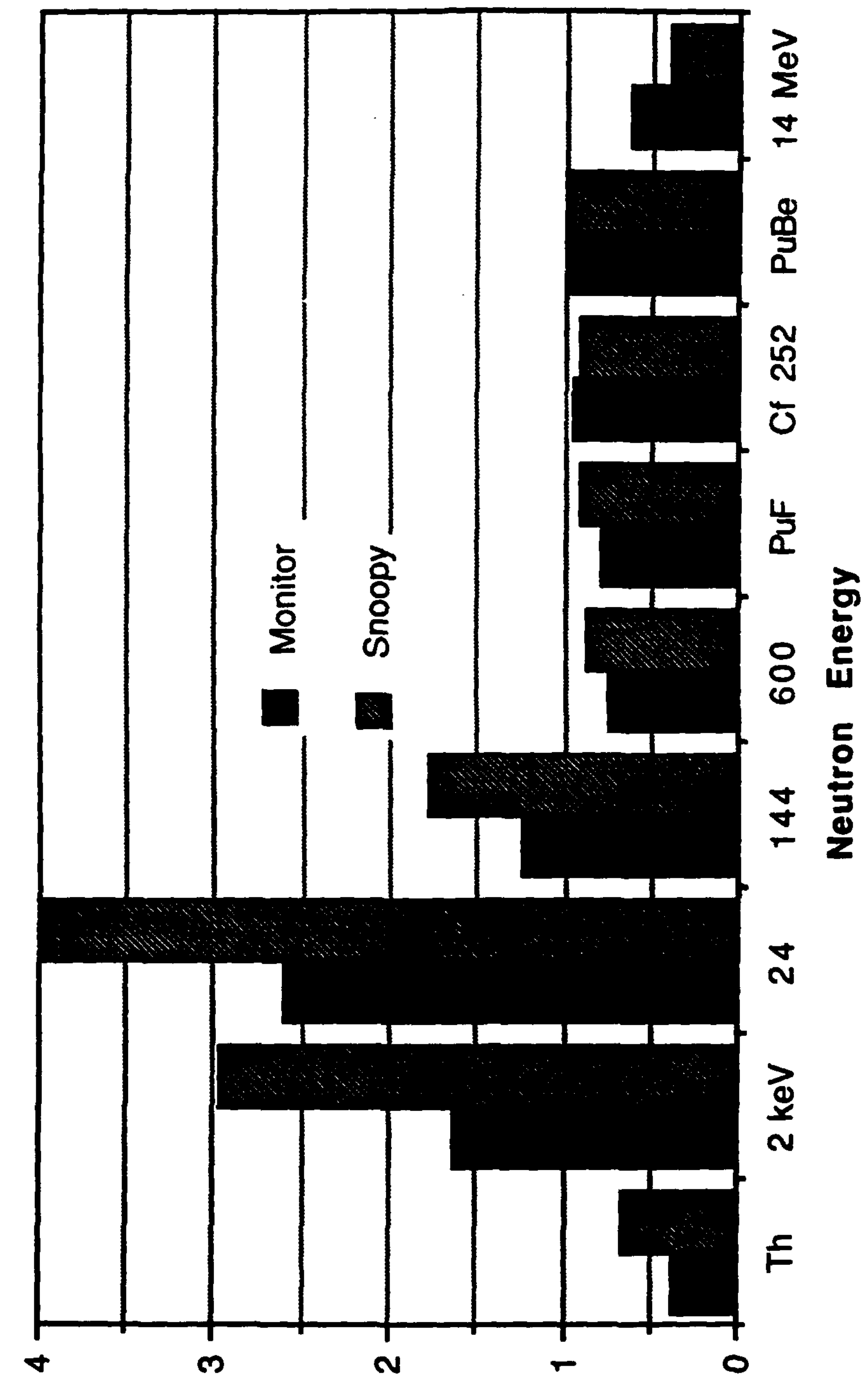

FIGURE 4. AREA MONITOR AND SNOOPY RESPONSE

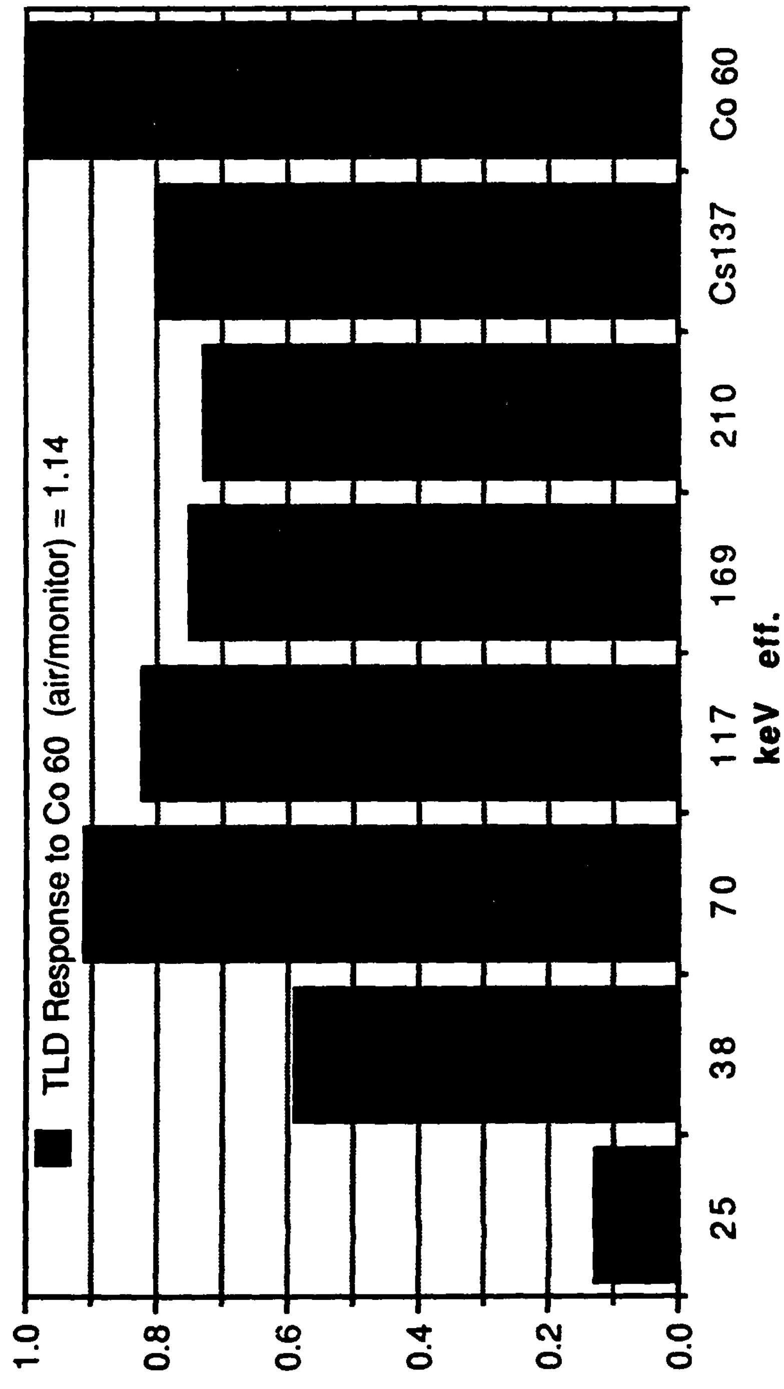

FIGURE 5. AREA MONITOR GAMMA AND X-RAY RESPONSE

TABLE 1. NEUTRON FLUENCE TO mREM CONVERSION FACTORS

^{E}NEUTRON	NCRP* n cm^{-2} mrem^{-1}	ICRP** n cm^{-2} mrem^{-1}	ICRU† n cm^{-2} mrem^{-1}	ANSI/ANS†† n cm^{-2} mrem^{-1}
THERMAL	9.79×10^{5}	9.79×10^{5}	9.50×10^{5}	9.80×10^{5}
2 keV	9.82×10^{5}	9.82×10^{5}	9.84×10^{5}	9.84×10^{5}
24 keV	8.68×10^{5}	8.67×10^{5}	8.79×10^{5}	5.09×10^{5}
144 keV	1.52×10^{5}	1.51×10^{5}	1.69×10^{5}	1.19×10^{5}
600 keV	3.66×10^{4}	3.66×10^{4}	1.07×10^{5}	3.55×10^{4}
14 Mev	NOTE 1			
Cf^{252}‡	2.88×10^{4}	2.88×10^{47}	2.41×10^{4}	2.88×10^{4}
PuBe‡‡	2.61×10^{4}	2.61×10^{4}	2.45×10^{4}	2.51×10^{4}
PuF	NOTE 1			

NOTE 1:

PuF AND 14 MeV FLUENCE TO REM CONVERSIONS ARE CONTAINED IN THE NEUTRON SPECTRA UNFOLDING CODES USED IN THE ANALYSIS, REFERENCE 6 AND 14

*** ASSUMED LINEAR INTERPOLATION FROM REFERENCE 9**

**** ASSUMED LINEAR INTERPOLATION FROM REFERENCE 8**

† ASSUMED LINEAR INTERPOLATION FORM REFERENCE 10

†† LOG-LOG INTERPOLATION USING THE POLYNOMIAL COEFFICIENTS FROM REFERENCE 11

‡ BASED ON 2.5 MeV NEUTRON EFFECTIVE ENERGY

‡‡ BASED ON 3.7 MeV NEUTRON EFFECTIVE ENERGY

TABLE 2. RELATIVE RESPONSE TO NEUTRON IRRADIATION OF DIFFERENT SURFACES

$E_{NEUTRON}$	A'/A	B'/B	B/A	B'/A'	C'/A	C'/C
THERMAL	0.74	0.85	0.77	0.88	0.27	0.70
2 keV	0.84				0.41	
25 keV	0.78				0.40	
144 keV	0.70	0.75	0.97	1.03	0.45	1.39
600 keV	0.65				0.51	
PuF	0.86			0.88	0.73	1.05
Cf^{252}	0.79		0.98		0.65	1.13
PuBe	1.02			1.01	0.86	1.01
COMPARING	WITH/WITHOUT 1/4 INCH Al		EDGE/SIDE OF CARD		END/SIDE OF MONITOR	SOLID/SLOT END

TABLE 3. NEUTRON SOURCE ERRORS

$E_{NEUTRON}$	CALIBRATION	NEUTRONS OF OTHER ENERGY	GAMMA / NEUTRON
THERMAL	3%*	0.01%	4%††
2 keV	5%*	3.0 %	6%†
25 keV	10%*	3.0 %	2%†
144 keV	10%*	1.5 %	1%†
600 keV	2%*	566 to 606 keV	4%††
14 MeV	3%‡	15%**	N/A
PuF	15%**		30%††
Cf^{252}	6%**		6%††
PuBe	6%**		3%††

* REFERENCE 15
** INCLUDES ERRORS DUE TO ROOM GEOMETRY
† REFERENCE 15, RAD/REM
†† MEASURED TLD Co^{60} EQUIVALENT
‡ REFERENCE 16

TABLE 4. AREA MONITOR NEUTRON DOSE EQUIVALENT RESPONSE

$E_{NEUTRON}$	MONITOR / SNOOPY	SNOOPY / ACTUAL	MONITOR / ACTUAL	ESTIMATED ERROR (%)
THERMAL	0.59	0.65	0.38	4
2 keV	0.55	2.96	1.63	6
24 keV	0.62	4.19	2.60	11
144 keV	0.70	1.77	1.24	11
600 keV	0.86	0.86	0.74	3
PuF	0.87	0.91	0.79	16
Cf^{252}	1.05	0.90	0.95	7
PuBe	1.00	1.00	1.00	7
14 MeV†	1.58	0.39	0.62	16

† REFERENCE 17

TABLE 5. RELATIVE RESPONSE OF THE NAVY'S NEUTRON AREA MONITOR TO PHOTONS[13]

PHOTON ENERGY	RESPONSE PER ROENTGEN	RESPONSE PER REM
Co^{60}	1.00	1.00
Cs^{137}	0.85	0.80
210 KeV	0.91	0.73
169 KeV	0.96	0.75
117 KeV	1.10	0.82
70 KeV	1.22	0.91
38 KeV	0.66	0.59
25 KeV	0.087	0.126

NOTE: **THE RESPONSE OF THE DETECTORS IN AIR IS 1.44 TIMES THEIR RESPONSE IN THE MONITOR FOR Co^{60}**

TABLE 6. PHOTON DOSE EQUIVALENT RATIOS (NOT NORMALIZED) FOR VARIOUS DIRECTIONS OF INCIDENT PHOTONS

SURFACE EXPOSED	Co^{60}	Cs^{137}	140 keV EFFECTIVE	MEAN	S.D.
A	0.884	0.860	0.990	---	---
B	0.884	0.895	0.970	---	---
A and B	---	---	---	0.91	0.05
A'	0.812	0.799	0.772	---	---
B'	0.838	0.824	0.817	---	---
A' and B'	---	---	---	0.81	0.021
C	0.862	0.800	0.904	---	---
C'	0.853	0.857	0.865	0.89	---
C and C'	---	---	---	0.861	0.03
AVG. OVER SURFACE A,B,C,C'	0.87 ± 0.02	0.85 ± 0.04	0.93 ± 0.06	0.89	0.05

TABLE 7. INDICATED NEUTRON mREM DOSE EQUIVALENT CAUSED BY 100 mREM PHOTON EXPOSURE

SURFACE EXPOSED	Co^{60}	Cs^{137}	140 keV EFFECTIVE	MEAN	S.D.
A,A'	* * * * * * *	SMALL	* * * * * * * * * * * * * * * * * *		
B,B'	* * * * * * *	SMALL	* * * * * * * * * * * * * * * * * *		
C,C'	7.2	6.3	10.0	7.8	1.9

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APPENDIX A

ABSORBED DOSE AND DOSE EQUIVALENT

The absorption of energy by matter when this matter is exposed to radiation is called absorbed dose. In dosimetry, the absorbed dose is defined as the amount of energy absorbed per unit mass of the material. The rad is the unit of absorbed dose and is 100 ergs/gram In SI units, 1 Gray equals 1 joule/kilogram

$$1 \text{ Gray (Gy)} = 100 \text{ rads} = 10^4 \text{ ergs/gram}$$

Some types of radiation are more effective in producing biological effects than others assuming the same absorbed dose. This effectiveness is related to the rate of energy transfer, called the linear energy transfer (LET), from the radiation to the matter as it traverses the matter. To compare the relative effectiveness of radiations, or the risks involved when exposed to various kinds of radiation, a new quantity is defined, the quality factor (QF). The QF is a measure of the risk of producing a biological effect as compared to 200 keV x-rays (see Table A-1). Inclusion of the QF into the absorbed dose relationship gives the dose equivalent, which has units of rem:

$$\text{Dose Equivalent (rem)} = \text{Dose (rads)} \times \text{QF}.$$

In SI units, dose equivalents are measured in Sieverts with

$$1 \text{ Sievert (SV)} = 100 \text{ rem} = 1 \text{ joule/kilogram}$$

TABLE A-1. QUALITY FACTORS FOR VARIOUS TYPES OF IONIZING RADIATION

Radiation	Quality Factor*
Gamma rays and x-rays	1
Beta rays and electrons of energy < 0.03 MeV	1
Beta rays and electrons of energy > 0.03 MeV	1.7
Thermal neutrons	3
Fast neutrons	10
Protons	10
Alpha particles	10
Heavy ions	20

* See Reference A-1 for illustration.
These approximate values are not used in this report.

A-1
International Commission on Radiation Units and Measurements, Radiation Quantities and Units, ICRU Report 10A, National Bureau of Standards, Handbook 84, U.S. Government Printing Office, Washington, DC, 1962.

APPENDIX B

AN/PDR-70 (SNOOPY) REMMETER

The U.S. Navy's AN/PDR-70 (Snoopy) radiac is a version of the Andersson-Braun[B-1] remmeter. The probe housing is a cylinder 8.5-inches in diameter and 9.4-inches long made of polyethylene. Hydrogen presents a large scattering cross section to neutrons. Therefore, through elastic collisions with the hydrogen atoms in the polyethylene, fast and epithermal neutrons give up a large part of their energies and eventually become thermalized neutrons with energies of about 0.025 eV.

A cylindrical B^{10} elastomer surrounds an inner polyethylene moderator. B^{10} has a high capture cross section for thermal neutrons. Neutrons thermalized in the outer moderator would not get through the borated elastomer to the detector located in the center of the inner moderator if it were not for the fact that 20 percent of the borated elastomer is taken up by uniformly distributed holes. Thus, the borated elastomer tends to attenuate incident thermal and intermediate energy neutrons. High energy neutrons not thermalized by the outer moderator pass through the borated elastomer and are thermalized by the inner polyethylene moderator. These thermalized high energy neutrons enter the BF_3 proportional counter, located in the center of the inner moderator, and produce pulses.

B-1
Andersson, I. Ö. and Braun, J., "A Neutron Rem Counter," ***Nukleonik*****, 6, Germany, 1964, p. 237.**

APPENDIX C

CORRECTION OF 14 MeV NEUTRON RESPONSE FOR SCATTERING

This appendix describes the method used to separate the direct neutron response from the scattered neutron response for the 14 MeV data. The 14 MeV exposures are done in a small, concrete-walled room so that scattered neutrons are an important part of the measured response.

In order to separate the scattered neutrons from the direct neutrons, it was assumed that the neutron generator behaved as a point source, i.e., the intensity followed an inverse square law constant plus a term with a 1/r coefficient.

direct neutrons C/r^2

scattered neutrons $A + B/r$

where A, B, and C are constants determined by measuring at three distances. The coefficients that were determined are shown below. Also shown are the total rem, direct rem, scattered rem, and the scattered fraction. Removing the scattered fraction from the response yielded the response to the 14 MeV neutrons.

				Result at 75 cm			
System	A	B	C	Total rem	Direct rem	scattered rem	scattered fraction
Snoopy	0.20	22.60	2804	1.000	0.498	0.502	0.502
Monitor	0.14	15.59	4486	1.144	0.798	0.346	0.302

The data shown below were taken using the NE213 at 100 cm and converted to 75 cm. This is possible because the NE213 is a spectrometer and clearly separates the direct and scattered neutrons by energy.

NE 213	Measured fluence 10^8 n/cm^2	ANSI fluence to rem conversion ($x10^{12}$)	Measured 100 cm mrem	Extrapolated 75 cm mrem
Direct	8.26	6.00	5.0×10^{-4}	8.8×10^{-4}
Scattered	4.27	3.00	1.3×10^{-4}	1.7×10^{-4}
Total	12.53	5.00	6.3×10^{-4}	1.1×10^{-3}
Scattered fraction			0.21	0.16

The fractional response due to scattered neutrons at 75 cm was: NE213, 16 percent; Snoopy, 50 percent; and Monitor, 30 percent. The rem computed from the NE213 spectrum is taken as the true dose equivalent to determine the resonse of the Snoopy and the Monitor. Finally, since the ANSI fluence to rem conversion was used here, the results were converted to the IRCP conversion which was used at all other energies.

	Measured total response	Calculated scattered fraction	75 cm scattered rem	75 cm direct rem	14 Mev response rem ANSI	14 Mev response rem IRCP	14 MeV Monitor / Snoopy ratio
NE213	1.35	0.16	0.22	1.13	1.00	1.00	
Snoopy	0.88	0.50	0.44	0.44	0.39	0.42	
Monitor	1.00	0.30	0.30	0.70	0.61	0.66	1.58

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