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RADIATION SURVEY AND DOSIMETER INTERCOMPARISON STUDY AT THE HEALTH PHYSICS RESEARCH REACTOR

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RADIATION SURVEY AND DOSIMETER INTERCOMPARISON STUDY AT THE HEALTH PHYSICS RESEARCH REACTOR*

G. D. Kerr and D. R. Johnson

ABSTRACT

A combined radiation survey and dosimeter intercomparison has been completed at the DOSAR Facility within the general environs of the Health Physics Research Reactor (HPRR). Detectors used in the survey were a "Phil" miniature G-M counter, a Hurst proportional counter, and a BF_3 proportional counter for measurements of gamma-ray absorbed-dose rates in a small tissue sample, fast-neutron absorbed-dose rates in a small tissue sample, and thermal neutron flux, respectively. Since an instrument for measuring dose from intermediate energy neutrons (0.5 eV to 100 keV) as a separate component is not available, a Rossi tissue-equivalent ionization chamber and a Bonner detector which both respond over the entire neutron energy spectrum were intercompared with the above detectors. Response of the Rossi ion chamber is proportional to absorbed dose in a small mass of tissue, and that of the Bonner detector is proportional to maximum dose equivalent in a man-size torso irradiated by parallel beams of neutrons. Intercomparisons were made using conversion factors between the different dose concepts presented in NBS Handbook 63.

Ratios of dose measured with the Rossi chamber to those measured with the Hurst, Phil, and BF_3 detectors were 1.11 in the direct radiation field of the HPRR, 1.08 in the "skyshine" radiation field outside the reactor control building, and averaged 1.05 in radiation fields at six locations inside the shielded control building. Ratios of maximum dose equivalent measured with the Bonner detector to those determined by the Hurst and BF_3 detectors in the same fields as before were 1.12, 0.96, and 0.85, respectively. These data indicated that dose contributions by intermediate energy neutrons were not significant and gave an added measure of confidence to results obtained in the radiation survey.

In order to relate "in-air" measurements to maximum dose equivalent likely to be delivered to a person in the scattered radiation fields at the control building, measurements were made about the midsection surface of a 30-cm-diam by 60-cm-tall cylindrical water phantom. These data gave a dose-equivalent distribution about the phantom which varied by a factor of 1.5 from lowest to highest.

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The results indicated also that dose-equivalent in a small tissue mass is an acceptable parameter for relating "in-air" measurements to maximum dose-equivalent rates in the scattered radiation fields at the control building. Maximum dose-equivalent rates obtained in the above manner are given for a number of survey locations in the control building.

INTRODUCTION

The Health Physics Research Reactor (HPRR) is a small fast reactor which utilizes highly enriched uranium fuel alloyed with 10% of molybdenum by weight for improved metallurgical properties. Due to the small size of the core, which is 20 cm in diameter by 23 cm in length, the reactor serves as an intense source of fast fission neutrons during steady-state operations of up to 10 kw and during self-limiting prompt critical pulses of 10^{16} to 10^{17} fissions. Maximum size pulses have an integrated energy of 0.9 kwhr.

The reactor is housed in a "low-scatter" building located in a valley approximately two miles southeast of the main Oak Ridge National Laboratory area. This structure is shown in the upper portion of Fig. 1. A building housing the HPRR control room, offices, and laboratories is shown in the lower portion of the photograph. Walls and roof of the control building are of poured concrete ranging in thickness from 12 to 24 in. to provide shielding against scattered radiation. Additional shielding is provided by an earth fill along the rear of the building which faces a hill located between the two structures. The hill provides a natural shield against direct radiation from the reactor.

Fig. 1. Photograph of DOSAR Facility Showing Reactor Building (Upper Right) and Control Building (Lower Left).

INSTRUMENTS

In a radiation survey, the most accurate results are obtained when each radiation component can be measured separately. Because difference methods are based on the subtraction of components from a total dose measurement, and in many cases involve a small difference in two large numbers, large errors are possible. Components of interest in this case were gamma rays and neutrons which were further characterized by energy as thermal (<0.5 eV), intermediate (0.5 eV to 150 keV) and fast neutrons (>150 keV). Therefore, detectors selected for the radiation survey were a "Phil" miniature G-M counter for gamma-ray dose-rate measurements,[1,2] a Hurst proportional counter and a Radsan dose integrator for fast-neutron dose-rate measurements,[2-4] and a BF_3 proportional counter for thermal neutron flux measurements by the cadmium-difference technique. Descriptions of the associated electronics used with these counters are given in the literature.[2,4,5]

Response of the Phil dosimeter to gamma rays is proportional to absorbed dose in a small tissue mass for quantum energies above 50 keV.[1,2,6] It has an inherent low sensitivity to fast neutrons with some response to thermal neutrons which is reduced by use of a ^6Li shield.

The Hurst proportional counter is constructed with polyethylene walls and filled with either ethylene or cyclopropane to provide a homogenous chamber. A pulse integration system can be used to provide a convenient readout of absorbed dose in the ethylene chamber. Absorbed dose in tissue can be obtained from these measurements, since absorbed dose* per n/cm^2 delivered to ethylene divided by that delivered

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*Absorbed dose from kerma assuming charged particle equilibrium.

to tissue has a ratio 1.45 (±10%) for neutrons of energy from 0.1 to 20 MeV.[2] Dose contributions from neutrons with energies of less than 150 keV were not measured because of the bias energy level used to exclude gamma-ray-produced pulses. There is also a reduced sensitivity to neutrons below 300 keV due to this energy bias, but a correction factor based on pulse counts per unit of measured dose can be applied to compensate for these effects.[7]

Since a suitable detector for measuring dose contributions from intermediate energy neutrons as a separate component is not available, several dosimeters having a response to all neutron energy components were intercompared with the above detectors. These instruments were a Rossi tissue-equivalent ionization chamber[8] for measuring gamma-ray-plus-neutron dose rates and a Bonner detector[9] whose output is approximately proportional to the maximum dose-equivalent in a human torso for neutrons in the energy range thermal-7 MeV.

In this study a Rossi chamber was used which had 3.5% by weight of nitrogen. Hence, the chamber was sensitive to low energy neutrons as well as fast neutrons due to the $^{14}N(n,p)^{14}C$ reaction. For stability of operation, the ion collection voltage was provided by a battery pack. Chamber output currents were measured with the aid of a vibrating reed electrometer and strip chart recorder.

The Bonner detector consisted of a 4-mm-diam by 4-mm-thick $^{6}LiI(Eu)$ scintillator embedded in the center of a 30-cm-diam polyethylene sphere. Neutrons are moderated by the polyethylene and detected by (n,α) reactions in the scintillator. Pulses from a photomultiplier viewing the crystal were fed to a noninverting amplifier and counted with a decade scaler.

PROCEDURES

Instrument Calibrations

The BF_3 detector was calibrated in the thermal neutron facility (a graphite cube, 1.5 m along each side) at the HPRR using results of a previous study in which thermal neutron flux has been obtained as a function of reactor power by bare and cadmium-covered gold foil measurements.[10]

Other detectors were calibrated with a ^{60}Co gamma-ray source or Pu-Be neutron source, both certified by the National Bureau of Standards. A conversion factor of 0.87 rad/r (11) was used with the ^{60}Co source to calibrate the Phil and Rossi dosimeters.

Calibration of the Radsan was carried out using a pulser and oscilloscope to set discriminator levels and check amplifier linearity. The alpha-particle source in the Hurst dosimeter was used to set the low energy bias level for proper rejection of gamma-ray-produced pulses. An absorbed dose conversion factor of 4.0×10^{-9} rad per n/cm^2 was used with the PuBe source[12] to calibrate the Hurst dosimeter.

In the calibration of the Bonner detector, a conversion factor of 4.1×10^{-8} rem per n/cm^2 was used with the PuBe source. This was obtained by weighting maximum dose equivalent which is a function of neutron energy[13] by published PuBe spectra.[12] Prior to calibration, a base level was set which gave adequate rejection of gamma-ray-produced pulses. To obtain the best fit between response of the instrument and maximum dose equivalent, the calibration factor for the detector was reduced by 20%.[14]

Normalization of Data

All data were normalized to a reactor power level of 1 kw by measuring the elapsed time of each steady-state run and the ^{32}P activity induced in a sulfur foil located in a fixed position near the reactor core. Activation of a "standard" sulfur foil has been related to integrated reactor power by fission analysis of small fuel samples exposed inside the reactor core. In all cases, timing of a reactor operation was started at 1/e of the selected power level. However, the measurements with "rate" instruments were not commenced until the reactor had reached the desired power level.

Measurements

Instrument intercomparisons were made near the HPRR to investigate their response to a fission neutron and gamma-ray spectrum. One problem associated with this direct field intercomparison was low activation rates of sulfur foils and high sensitivities of the detectors. Hence, a large separation distance of 10 m between the reactor core and detectors was chosen to reduce operating time of the reactor. Both the detectors and reactor were positioned at a height of 2 m above floor-level. Nominal reactor power levels of several watts or less were chosen which gave negligible dead-time losses for each radiation measurement.

For measurements inside and outside the control building, the reactor was operated at a nominal power level of 2 kw. This power level was selected because it permitted radiation measurements to be made with standard error of ±10% or less in most cases and allowed extended reactor operation without concern about temperature scrams.

INSTRUMENT COMPARISONS

To compare the Rossi ionization chamber with the Hurst, Phil, and BF_3 detectors, it was only necessary to convert the thermal neutron fluences measured by the BF_3 detector to absorbed dose since the other instruments all have a response proportional to absorbed dose in a small tissue sample. A conversion factor of 2.7×10^{-11} rad per n/cm^2 was used to obtain absorbed dose in a small sample of tissue-equivalent plastic from thermal neutron fluences.

For purposes of intercomparison with the Bonner detector, measurements made with the Hurst dosimeter and the BF_3 detector were converted to maximum dose-equivalent rates assuming plane beam irradiation of a human-size torso. With the Hurst dosimeter, maximum dose equivalent from fast neutrons was obtained for absorbed dose in a small tissue sample by use of appropriate absorbed dose buildup factors (1.3 for HPRR radiation field and 1.5 for other fields) and an appropriate quality factor (9.4 for the HPRR radiation field and 10 for other fields) as based on data in NBS Handbook 63.[13] Thermal neutron fluence measurements were converted to maximum dose equivalent by use of the conversion factor 1.0×10^{-9} rem per n/cm^2.[13]

Results of the intercomparison in the direct radiation field of the HPRR are given in Table 1. These data show that the ratio of the reading of the Rossi dosimeter to those of the Hurst-plus-Phil dosimeter and BF_3 detector was 1.11 and the ratio of the reading of the Bonner detector to those of the Hurst dosimeter plus BF_3 detector was 1.12. In this case, differences in response to low-energy neutrons and gamma-rays were at a minimum since dose contributions are due

Table 1. Intercomparison of Detectors in Radiation Field of the HPRR with Reactor and Detectors at a Height of 2 m and at a Separation Distance of 10 m.

Detector	Absorbed* Dose Rate (rad/kwhr)	Dose-** Equivalent Rate (rem/kwhr)
Hurst Fast Neutron Dosimeter	46.6	580
"Phil" Gamma-Ray Dosimeter	6.53	
BF_3 Thermal Neutron Detector	0.06	2.50
Rossi Tissue-Equivalent Ion Chamber Dosimeter	59.0	
Bonner Neutron Dosimeter		650

*Absorbed dose rate in a small mass of tissue.

**Maximum dose equivalent rate in a human torso assuming broad, parallel neutron-beam irradiation.

mainly to fast-fission neutrons and fission gamma rays which have an average energy of approx 1 MeV.

Survey locations at the control building are shown in Fig. 2 and results of measurements made at each location are given in Table 2. At survey point (A) located in the "skyshine" radiation field, the intercomparison gave a ratio of the reading from the Rossi dosimeter to those of the Hurst-plus-Phil dosimeter and BF_3 detector of 1.08, and that of the Bonner detector to those of the Hurst dosimeter plus BF_3 detector of 0.96. Intercomparisons at six heavily shielded locations inside the control gave the following results: ratios of the reading from the Rossi dosimeter to those of the Hurst-plus-Phil and BF_3 detector ranging from 1.03 to 1.10 with an average of 1.05, and ratios of the reading from the Bonner detector to those of the Hurst dosimeter plus BF_3 detector ranging from 0.66 to 1.05 with an average of 0.85. All measurements were taken one meter above floor level.

RADIATION SURVEY

The ultimate objective in a radiation survey is to assess dose equivalent likely to be delivered to critical organs of a person in the radiation field. However, extensive information about the radiation field is necessary to determine dose equivalent to various critical organs which are located at different body depths. For this reason, maximum dose equivalent at any location in a human torso is taken to represent the dose from chronic, low-level irradiation of the whole body.

To obtain information on angular distribution of dose and on maximum dose equivalent to a person in the radiation fields at the

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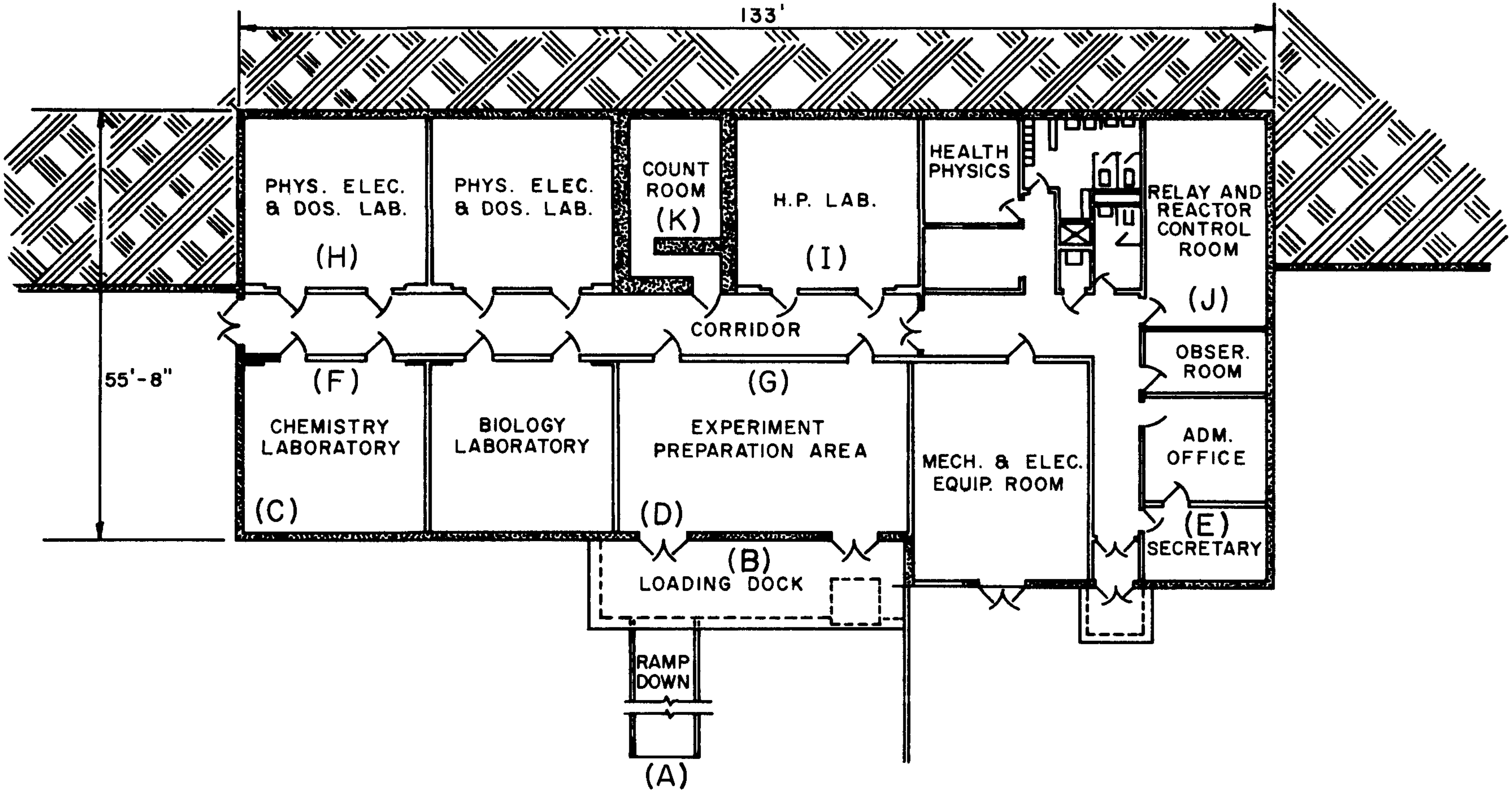

Fig. 2. Diagram of Reactor Control and Laboratory Building of DOSAR Facility Showing Radiation Survey Locations.

Table 2. Radiation Measurements at the DOSAR Control Building During HPRR Operations

Survey Location	Radiation Measurements					Maximum Dose-Equivalent Rate
	Hurst Fast-Neutron Dosimeter	Phil Gamma-Ray Dosimeter	BF_3 Thermal Neutron Detector	Rossi T.E. Ionization Chamber	Bonner Neutron Detector	
	$\left(\frac{\text{mrad}}{\text{kwhr}}\right)$**	$\left(\frac{\text{mrad}}{\text{kwhr}}\right)$**	$\left(\frac{\text{n/cm}}{\text{kwhr}}\right) \times 10^{+5}$	$\left(\frac{\text{mrad}}{\text{kwhr}}\right)$**	$\left(\frac{\text{mrem}}{\text{kwhr}}\right)$***	$\left(\frac{\text{mrem}}{\text{kwhr}}\right)$****
A	4.83	2.76	22.8	8.19	72.2	51.6
B	1.13	2.67	20.6			14.5
C*	0.080	0.99	4.50	1.13	1.26	1.90
D	0.43	1.13	4.54			5.54
E*	0.11	1.07	4.72	1.22	1.55	2.29
F*	0.065	0.71	3.39	0.82	1.08	1.45
G*	0.076	0.66	3.13	0.80	1.54	1.50
H*	0.047	0.53	2.43	0.61	0.87	1.06
I	0.024	0.26	0.84			0.52
J*	0.073	0.71	2.43	0.08	0.89	1.50
K	<0.01	<0.02	<0.01			<0.12

**Absorbed dose rate in a small mass of tissue.

***Maximum Dose-Equivalent Rate in a human torso assuming broad, parallel neutron-beam irradiation.

****Maximum Dose-Equivalent in a human torso from nondirectional radiation fields at control building.

control building, measurements were made about the midsection of a 20-cm-diam by 60-cm-tall cylindrical water-phantom with the Hurst and Phil dosimeters and BF_3 detector. This superficial measurement at the surface of the phantom was expected to be indicative of maximum absorbed dose or maximum dose equivalent since it has been shown recently that the maximum dose from both neutrons and gamma rays occurs at or very near the body surface for the two extreme cases of plane-beam or isotropic irradiation.[14-16]

Results of the measurements taken on the midsection surface of the phantom normalized to "in-air" measurements at survey location (A) are given in Table 3. Quality factors of 1 and 10 were used to convert absorbed-dose rates measured with the Phil and Hurst dosimeters respectively to dose-equivalent rates in a small tissue mass. Thermal neutron fluence measurements made with the BF_3 detector were converted to dose-equivalent in a small mass of tissue from standard man using the conversion factor 2.5×10^{-10} rem per n/cm^2.[13] These data indicate that a suitable parameter for relating "in-air" measurements to maximum dose equivalent rates to a person in the "skyshine" radiation field at the control building are dose equivalent rates in a small mass of tissue. A similar condition was found for radiation fields inside the shielded control building.

Maximum dose-equivalent rates obtained in the above manner are given in Table 2 for the survey locations shown in Fig. 2. Allowances made in estimating maximum dose-equivalent rates in these cases where the radiation reaches the person from widely different directions are in accord with recommendations of the NCRP.[17]

Table 3. Distribution of Dose about a 30-cm-diam by 60-cm-long Cylindrical Water Phantom Normalized to "In-Air" Measurements in "Skyshine" Radiation Field Outside of the HPRR Control Building.

Orientation	Dose-Equivalent Rates* Normalized to "In-Air" Measurements			
	Fast Neutron	Gamma Ray	Thermal Neutron	Total
"In-Air"	1.00	1.00	1.00	1.00
Toward Reactor Facility (Θ = 0°)	0.88	1.33	1.30	0.90
Perpendicular to Reactor Facility (Θ = 90°)	0.82	1.32	1.30	0.85
Away from Reactor Facility (Θ = 180°C)	0.55	1.10	1.19	0.58
Perpendicular to Reactor Facility (Θ = 270°)	0.68	1.22	1.21	0.71

*Dose-equivalent in a small mass of tissue.

CONCLUSIONS

The agreement obtained between detector systems from intercomparisons in the HPRR direct field and in the scattered radiation fields at the control building gave an added measure of confidence in instrument calibrations and in survey results respectively. It indicated also that dose contributions from intermediate energy neutrons were not significant.

Results of the survey were not used to set definitive values on dose or dose equivalent contributions from intermediate energy neutrons. The Rossi ionization chamber has a response to kerma from gamma-rays produced by capture reactions in the chamber, and the Bonner detector has a response that varies from maximum dose equivalent due to parallel beams of neutrons by as much as a factor of 3 over part of this energy range. In addition, use of an absorbed dose buildup factor of 1.5 and a quality factor of 10 with the Hurst dosimeter in unknown neutron spectra will tend to overestimate maximum dose equivalent assuming plane beam irradiation.

Results of the radiation survey have provided a better estimate of dose-equivalent rates to personnel at the control building during reactor operations and have been used to modify operational procedures at the facility.

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