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Radiation Dosimetry at the BNL High Flux Beam Reactor and Medical Research Reactor

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Abstract: Radiation dosimetry measurements have been performed over a period of many years at the High Flux Beam Reactor (HFBR) and the Medical Research Reactor (BMRR) at Brookhaven National Laboratory to provide information on the energy distribution of the neutron flux, neutron dose rates, gamma-ray fluxes and gamma-ray dose rates. The MCNP Particle Transport Code provided Monte Carlo results to compare with various dosimetry measurements performed at the experimental ports, at the treatment rooms and in the thimbles at both the HFBR and BMRR.

Keywords: HFBR, BMRR, neutron, gamma-ray, fluxes, dose rates, MCNP

INTRODUCTION

HFBR is a heavy water (D₂O) cooled and moderated reactor, which was designed to operate at a power level of 40 mega-watts (MW). It was later upgraded to 60 MW and it was last run at 30 MW using a twenty-four hour, thirty day continuous operating cycle. The HFBR has 9 horizontal beam tubes, H-1 to H-9, which support up to 16 beam line experiments. These beam line experiments are used for neutron scattering research in solid state and nuclear physics, chemistry and biology. The HFBR also has 7 vertical thimbles, V-10 to V-16, where samples are inserted for fast neutron and gamma-ray material damage studies, for medical radio-nuclide production and research and for neutron activation analysis

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and thermal neutron damage studies. Thin foil dosimetry has been used at both the beam lines and the thimbles to characterize the energy distribution of the neutron flux. HFBR neutron fluxes at an in-core thimble, at a core edge thimble and at a D₂O reflector thimble provided values in all energy ranges from thermal energies, $E_n < 0.5$ eV, up to the fast neutron energies ($E_n > 0.11$ MeV). At the horizontal beam lines, neutron and gamma-ray dose rates have been measured with an Eberline ASP1 “rem-ball” {a 0.229 m (nine inch) polyethylene sphere} neutron sensitive instrument utilizing a BF₃ detector[1] and with a small ion chamber with a 0.6 cm³ active volume.

BMRR is a light water (H₂O) cooled and graphite moderated reactor, which is operated weekdays on demand at a power level of up to 3 MW for both medical and biological research. Its primary use is for Boron Neutron Capture Therapy (BNCT) research and human patient clinical trials for brain tumors (glioblastoma multiforme). It has two treatment rooms, featuring a) an epithermal neutron beam (ENIF) and b) a thermal neutron beam (TNIF), horizontal tubes and a broad beam facility to irradiate large objects.

Dose rate and flux dosimetry measurements have been performed. Radiation dosimetry information was generated via use of activation foils, thermoluminescent dosimeters (TLDs), personnel monitoring badges featuring both ⁶LiF and ⁷LiF chips, an Eberline ASP1 "rem-ball" neutron sensitive instrument and an NRC ADM multi-purpose gamma sensitive instrument.

In both the ENIF and the TNIF, the neutron beam port is located 0.9144 m (3 feet) above the floor and almost in the center of the reactor wall. The last portion of radiation shielding in both beam ports are shields of bismuth. There are removable collimators mounted on the bismuth face to help to collimate the neutron beams emerging from the ports.

Neutron and Photon transport calculations were performed using the Monte Carlo program [2] MCNP-4B2. The energy dependent spatial distributions of prompt gamma-rays and prompt neutrons from thermal energies (0.01-0.4 eV) up to fast energies (0.1-10 MeV) were calculated in one run. ENDF/B-VI continuous neutron cross section data were used, including appropriate thermal neutron scattering function $S(\alpha,\beta)$ for D₂O in the HFBR.

HFBR THIMBLE DOSIMETRY

Thermal, resonance and fast neutron activation reaction dosimeters have been exposed over the past thirty years in many vertical irradiation thimbles[3,4], in a) the reflector region, in b) the core edge region and in c) the in-core region.

The comparison of the neutron fluxes in the D₂O reflector thimble V-10 are shown in Table 1. The measurement was performed at a power level of 30 MW with the dosimetry sample located at the bottom of the thimble, 0.18 m (7.1 inches) below the core mid-plane.

Table 1. Comparison of Neutron Fluxes in HFBR V-10 Thimble

Neutron Energy	Experiment n/m ² /s	Calculation n/m ² /s	Calculation/Expt.
< 0.5 eV	$1.57 \pm 0.09 \times 10^{18}$	2.61×10^{18}	1.66
0.5 eV - 0.1 MeV	$2.01 \pm 0.32 \times 10^{16}$	1.44×10^{16}	0.72
> 0.11 MeV	$2.84 \pm 0.62 \times 10^{15}$	1.54×10^{15}	0.54

All Energies	$1.59 \pm 0.10 \times 10^{18}$	2.63×10^{18}	1.65
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The MCNP calculation was performed for a power level of 40 MW at the same location and the neutron fluxes were renormalized to 30 MW in Table 1 to allow a direct comparison.

In addition to this 1996 measurement, there had been a pair of 1 mm thick and 0.76 mm radius cobalt foils exposed in the V-10 facility [5] during 1966. The thermal neutron flux value (2200 m/s value) of 1.46×10^{18} n/m²/s at 30 MW can be compared to the flux value of 1.57×10^{18} n/m²/s in Table 1. These fluxes measured thirty years apart are in good agreement.

The comparison of the neutron flux values in the core edge region thimble, V-14, are shown in Table 2. Again the measurement was performed at a power level of 30 MW with the dosimetry sample located at the bottom of the thimble, 0.155 m (6.1 inches) below the core mid-plane. The calculation was again renormalized from 40 MW to 30 MW to allow a direct comparison.

Table 2. Comparison of Neutron Fluxes in HFBR V-14 Thimble

Neutron Energy	Experiment n/m ² /s	Calculation n/m ² /s	Calculation/Expt.
< 0.5 ev	$4.96 \pm 0.50 \times 10^{18}$	6.34×10^{18}	1.28
0.5 ev - 0.1 Mev	$4.99 \pm 1.00 \times 10^{18}$	5.10×10^{18}	1.02
> 0.11 Mev	$5.99 \pm 0.60 \times 10^{17}$	9.30×10^{17}	1.55
All Energies	$1.06 \pm 0.08 \times 10^{19}$	1.24×10^{19}	1.17

The comparison of the neutron flux values in the in-core thimble V-15 are shown in Table 3. In this thimble, three different sets of measurements were made; the first measurement was made in 1976 at a power level of 40 MW with the sample located 0.216 m (0.85 inches) below the core midplane; the second measurement was made in 1989 at a power level of 60 MW with the sample at the core midplane; the third and final measurement was made in 1996 at a power level of 30 MW with the sample at the core midplane. The calculated values were again renormalized from 40 MW to 30 MW. All three of these measurements are also normalized to 30 MW in the Table to provide a direct comparison.

Table 3. Comparison of Neutron Fluxes in HFBR V-15 Thimble

Neutron Energy	1996 Expt. 10 ¹⁸ n/m ² /s	1989 Expt. 10 ¹⁸ n/m ² /s	1976 Expt. 10 ¹⁸ n/m ² /s	Calculation 10 ¹⁸ n/m ² /s	Calculation /1996 Expt.
< 0.5 ev	1.23 ± 0.10	1.20 ± 0.10	1.16 ± 0.13	1.77	1.48
0.5 ev to 0.1 Mev	10.3 ± 1.55	11.0 ± 1.64	7.06 ± 0.85	13.7	1.28
> 0.11 Mev	2.64 ± 0.26	2.40 ± 0.24	4.38 ± 0.53	3.67	1.46

All Energies	14.2 ± 1.14	14.6 ± 1.17	12.6 ± 0.76	19.1	1.35
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In addition to the above measurements, there was a Co-Al wire determination [3] of the thermal neutron flux in the V-11 hydraulic tube thimble performed at 40 MW power level in 1968. The result renormalized to 30 MW gives a 2200 m/s flux of 8.2×10^{17} n/m²/s.

HFBR BEAM LINE DOSIMETRY

Various thermal, resonance and fast neutron reaction foils were irradiated at a number of horizontal beam lines [5,6,7]. At the H-1 beam tube tip, the 30 MW 2200 m/s neutron flux was measured to be 4.6×10^{18} n/m²/s. At the sample position outside the reactor, after passing through both the beam tube collimator and a monochromator crystal and then being scattered at a particular angle, the thermal neutron flux drops to about 10^{11} n/m²/s.

It is of interest to note that the H-1 beam tip is located at a radial distance of 0.33 m (13 inches) from the core center and an axial position 0.1524 m (6 inches) below the core midplane. The vertical thimble V-14 is located 0.287 m (11.3 inches) radially from the core center and the bottom of the thimble is 0.18 m (7.1 inches) below the core midplane. Since these beam tips are close to the same radial and axial location, the thermal neutron flux values should be about the same. The H-1 2200 m/s flux given above is 4.6×10^{18} n/m²/s and the V-14 Table 2 thermal flux is 5.0×10^{18} n/m²/s. There is again excellent agreement from measurements, which had also been made thirty years apart.

At the H-8 beam line, neutron dose rates were measured using a “rem-ball” detector and the effective fast neutron dose rate, $E_n \approx 1$ Mev, was 24 mSv/h (2.4 rem/h). The thermal neutron dose rate was determined from the 2200 m/s neutron flux measured at the sample position at the beam line using bare and cadmium covered gold foils. A cadmium ratio of about 650 indicated a highly thermalized beam and a 2200 m/s flux of 1.5×10^{11} n/m²/s gives a dose rate of about 0.55 Sv/h (55 rem/h). Gamma-ray dose rate measurements were taken with a 0.6 cm³ ion chamber and determined to be 0.22 Gy/h (22 r/h).

BMRR EPITHERMAL TREATMENT ROOM

In the beam center of the ENIF, there is a six inch thick collimator of polyethylene and Li₂CO₃ (93% enriched in ⁶Li, 45% by weight). There is a concave cavity in the collimator, which is 0.2 m in diameter on the reactor side, which tapers to 0.12 m on the room side. At the 0.12 m opening in the collimator, the 2200 m/s neutron flux $\approx 3.4 \times 10^{11}$ n/m²/s, the epithermal neutron flux $\approx 8.2 \times 10^{12}$ n/m²/s and the fast neutron flux $\approx 2.0 \times 10^{11}$ n/m²/s. The MCNP calculations give a thermal neutron flux of 2.8×10^{11} n/m²/s, an epithermal neutron flux of 6.6×10^{12} n/m²/s and a fast neutron flux of 1.7×10^{11} n/m²/s.

In the ENIF, experimental comparisons have been made with 1) BNCT patients in place in front of the collimator, with 2) a tissue equivalent head phantom in place to mock up the patient’s head position and with 3) the room empty in order to study the impact of the patient on the background flux and dose rate values.

Neutron and gamma-ray dose rates were measured using TLD personnel monitoring badges with ⁶LiF and ⁷LiF chips. The results are listed in Table 4. The neutron dose rate at a distance of 0.3 m from the opening in the collimator was measured with the Eberline ASP1

“rem-ball” to be 1 Sv/h (100 Rem/h). At the same time, the NRC ADM multi-purpose gamma sensitive instrument was used to measure the gamma-ray dose rate at 0.3 m from the opening of the collimator to be 1 Gy/h (100 R/h). These values can be compared to the values for the neutron and gamma-ray dose rates of 2.66 Sv/h (266 Rem/h) and 1.38 Gy/h (138 R/h) from Table 4. The values from Table 4 were measured at the collimator face rather than 0.3 m away and should be larger due to the geometric factor, which may have a 1/r or a 1/r² dependence. This can be seen to be indeed the case.

Table 4. Epithermal Room Neutron and Gamma-ray Dose Rates

Location in Room	Empty Room	Empty Room	Phantom in Place	Phantom in Place	Patient in Place	Patient in Place
	N Sv/h	γ Gy/h	N Sv/h	γ Gy/h	N Sv/h	γ Gy/h
Door	0.21	0.015	0.13	0.008	0.14	0.013
North Window	0.32	0.032	0.19	0.025	0.18	0.037
South Window	0.2	0.017	0.11	0.009	----	----
0.9144 m (3 ft) high Opp.Wall	0.45	0.055	0.13	0.032	0.13	0.047
2.438 m (8 ft) high Opp.Wall	0.41	0.041	0.15	0.032	0.15	0.04
0.6096 m (2ft) right 3O’Clock	0.35	0.048	0.29	0.048	0.52	0.068
0.6096 m (2ft)down 6O’Clock	0.45	0.045	0.28	0.03	0.65	0.085
0.6096 m (2 ft)left 9O’Clock	0.32	0.064	0.24	0.051	0.27	0.094
0.6096 m (2ft)up,12 O’Clock	0.26	0.15	0.23	0.23	0.3	0.24

1.219 m (4ft) right 3O'Clock	0.29	0.025	---	---	0.14	0.078
Collimat.	2.66	1.38				

From Table 4, it can be seen that the neutron and gamma-ray dose rates fall off rapidly as you move away from the center of the beam. For the empty room, there is a reduction in the neutron dose rate at the reactor face by a factor of five to ten in all directions (3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock) at a distance of 0.6096 m from the beam center, compared to the collimator center value. There is a similar reduction of ten to thirty in the gamma-ray dose rate. For the area above the collimator, there appears to be much less gamma-ray shielding, resulting in a much larger gamma-ray dose rate under all conditions.

By comparing the data with the patient in place to the data for the empty room, there is obviously neutron scattering back from the patient to the face of the reactor. However, the scattering of the gamma radiation back to the reactor face is much larger. Although there is a significant reduction in the neutron dose rate at the 0.9144 m beam center position on the wall opposite the patient, there appears to be much less change in the gamma-ray dose rate. This would indicate that there is much more absorption of neutrons than gamma-radiation by the patient, which is of course, the preferred situation. It might be noted that the head phantom absorbs more gamma radiation than do the actual patients being exposed.

BMRR THERMAL TREATMENT ROOM

In the TNIF, there is also a removable collimator mounted on the bismuth face of the reactor wall. It is also made of a mixture of polyethylene and Li_2CO_3 ($\approx 93\%$ enriched in ^6Li , which is 45% by weight). This collimator is 0.102 m thick with a similar conical cavity, which is 0.12 m in diameter on the reactor core side and which tapers to 0.02 m on the side facing the shielded room. At the 0.02 m opening in the collimator face, the 2200 m/s neutron flux $\approx 1.6 \times 10^{14}$ n/m²/s, the epithermal neutron flux $\approx 1 \times 10^{13}$ n/m²/s and the fast neutron flux $\approx 4 \times 10^{12}$ n/m²/s.

The MCNP calculations give neutron flux values at the opening in the collimator of a 2200 m/s value = 1.6×10^{14} n/m²/s, an epithermal value = 1.4×10^{13} n/m²/s and a fast value = 4.3×10^{12} n/m²/s.

Neutron and gamma-ray dose rates measured in the thermal neutron irradiation facility (TNIF) are listed in Table 5, where measurements have been made in the center of the beam, and at various positions inside of and outside of the entrance door, the viewing window, the back wall of the TNIF and the back wall of the enclosure.

In the TNIF, there is a large polyethylene enclosure built around the beam port exit, where the neutron beam leaves the reactor face and the collimator. The neutron and gamma-ray dose rate values in Table 5, provide an indication of the effectiveness of the radiation shielding of this polyethylene enclosure, the shielding viewing window, the entrance door and the back wall of the treatment room for reducing the neutron and gamma-ray dose rates. In general, the attenuation of both the neutrons and the gamma-rays is at least one order of magnitude and in the case of the viewing window for neutrons, three orders of magnitude.

In the case of the polyethylene enclosure, the attenuation for gamma-rays is only a factor of three.

Table 5. Thermal Room Neutron and Gamma-ray Dose Rates

Location in Room	Neutron Dose Rate (Sv/h)	Gamma-ray Dose Rate (Gy/h)
Door, Internal	0.00054	0.00096
Door, External	0.00006	-----
Window, Internal	0.0647	0.018
Window, External	0.00006	0.0006
Collimator Face	300.	20.
Collimator at 30 cm	60.	4.
Backwall, Internal	0.052	0.096
Backwall, External	0.0022	0.0036
Enclosure, Internal	2.21	1.44
Enclosure, External	0.115	0.535

OTHER DATA

The thermal and epithermal neutron flux values have been measured in the pneumatic (P_n) tube of the BMRR, in which samples can be charged into the reactor adjacent to the core. The measured flux values are $\approx 9.6 \times 10^{16}$ n/m²/s and $\approx 2.0 \times 10^{16}$ n/m²/s, while the calculated values are 5.4×10^{16} n/m²/s and 3.4×10^{16} n/m²/s, respectively. For the radial tube, which is used to extract neutrons from the reactor in order to test for levels of boron in blood samples using neutron activation analysis, the 2200 m/s neutron flux $\approx 2.5 \times 10^{11}$ n/m²/s and the epithermal neutron flux $\approx 1.3 \times 10^{10}$ n/m²/s. The only calculated values at the radial tube have been performed for a bare tube with no collimator in the tube. These values will overestimate the neutron flux values. They are 3.0×10^{12} n/m²/s and 1.3×10^{13} n/m²/s, respectively.

DISCUSSION AND CONCLUSIONS

The MCNP calculations which have been performed for the HFBR vertical thimbles used a fresh core of 28 new fuel elements, for which the critical control rod positions were

determined ($k_{\text{eff}} = 1$). Generally, the samples were irradiated in an equilibrium core, where only one set of seven fuel elements is new. The other twenty-one elements have been fissioning for up to three 30 day fuel cycles. Since the control rods are usually out of the core at the end of the fuel cycle when most of these measurements were made, the active neutron source volume ratio in these two cases is 0.80.

The MCNP calculations for the radial tube in the BMRR was calculated for the geometry of the reactor and the beam tube but the tube was empty. In the actual measurement, the beam tube has a steel collimator inserted but for which no details are available, so the calculations are much too large. Although the estimated uncertainties in the MCNP calculations are on the order of 5% to 10%, this is strictly an estimate of the statistical uncertainties and no estimate of any systematic uncertainties has yet been made.

In the ENIF treatment room, where the BNCT patients are treated, the flux and dose rates are concentrated in the center of the beam and the patient absorbs neutrons rather than gamma radiation as was noted above.

In the TNIF treatment room, the shielding effectiveness of the treatment room walls, entrance door and viewing window has been determined to be a factor of twenty-five or more for both neutrons and gamma-rays.

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