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# UPDATED FLUX INFORMATION FOR NEUTRON SCATTERING AND IRRADIATION FACILITIES AT THE BNL HIGH FLUX BEAM REACTOR

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## Introduction

The HFBR is a heavy water, $D_2O$, cooled and moderated reactor with twenty-eight fuel elements containing a maximum of 9.8 kilograms of $^{235}U$. The core is 53 cm high and 48 cm in diameter and has an active volume of 97 liters. The HFBR, which was designed to operate at forty mega-watts, 40 MW, was upgraded to 60 MW and is presently operating at 30 MW. In a normal cycle the HFBR operates 24 hours a day for thirty days, with a six to fourteen day shutdown for refueling and maintenance work.

While most reactors attempt to minimize the escape of neutrons from the core, the HFBR's $D_2O$ design allows the thermal neutron flux to peak in the reflector region and maximizes the number of thermal neutrons available to nine horizontal external beams, H-1 to H-9, used for neutron scattering and capture reactions, supporting physics, chemistry and biology experiments. The higher energy neutrons peak within the core region. Materials for irradiation experiments are introduced and irradiated in any of seven vertical thimbles, V-10 to V-12 in the $D_2O$ reflector, V-13 and V-14 at the core edge, or V-15 and V-16 inside the core center.

All horizontal beam tubes were built tangential to the direction of the emerging neutrons, except for the H-2 beam tube, which "looks" directly at the core and has been used for neutron cross section measurements utilizing fast neutrons and for the TRISTAN fission product studies. While most beam tubes use ambient temperature neutrons, the H-9 beam tube has a liquid hydrogen moderator system to provide an intense beam of cold neutrons < 5 milli-volts (meV). This Cold Neutron Facility (CNF) provides very low energy neutrons for both inelastic scattering physics and for small angle scattering biological structure experiments. Inelastic scattering experiments are also performed at H-4M, H-5, H-7 and H-8 beam lines. H-1A and H-4S beam lines are used for diffraction of powder samples, while H-6M and H-6S are used for diffraction of single crystal samples.

## Modifications

In recent years, there have been some beam modifications and new instrumentation introduced at the HFBR. A high resolution neutron powder diffractometer instrument is now operating with a resolution of $5x10^{-4}$ at horizontal beam line H-1. To study scattering from liquid surfaces, a neutron reflection spectrometer was introduced on the CNF beam line at H-9. In the past year, a fourth beam line has been added to the CNF line at H-9. This beam is used solely for the testing of new instrumentation design, without interfering with the ongoing experiments at the HFBR.

The existing beam plug at the H-6 beam line has recently been removed and a new plug, which will feature super mirrored surfaces, is now being installed. This new plug should enable neutron beams to be extracted further from the reactor with minimal scattering loss. Since H-6 was a dual beam port, it is hoped that this change will allow two to four additional experiments to be performed at this beam port in the future.

Last year, the vertical beam thimble, V-13, a fixed port filled with thirty year old samples used for HFBR material surveillance studies was replaced by a new thimble and charging station at the core edge creating an irradiation facility to substitute for the original V-13.

The two in-core thimbles feature a 1/2 thermal to fast ($>$ 0.1 MeV) neutron flux ratio. These thimbles are used for radiation damage studies (due to gamma rays and fast neutrons), as well as for fast neutron reaction activation studies; the two core edge thimbles with a 8/1 thermal to fast ratio have a thermal neutron flux density of $5\text{x}10^{14}$ n/cm$^2$/s and have been used for producing $^{64}$Cu for use as a positron source and for medical radionuclide sources; the three thimbles in the $D_2O$ reflector with thermal to fast ratios varying from 360/1 to 1500/1 are used for production of thermal neutron activated nuclides with little or no accompanying fast neutron activated interfering nuclides and thermal neutron activation analysis. All thimbles, except V-11, are accessed by mechanical means using a four inch long aluminum sample capsule, attached to a quarter inch diameter aluminum tubing that is 37 feet long. The V-11 thimble is part of a hydraulic system which utilizes a plastic or aluminum capsule inside a light water insert within the heavy water cooling system. Aluminum capsules require a fifteen minute waiting period for radiation cooling, while the plastic capsule allows activated samples to be withdrawn with only a thirty to forty second transit time delay. Plastic capsules allow for the production and measurement of short lived activation products.

A neutron dosimetry program has begun to measure and calculate the energy dependent neutron and gamma ray flux densities and/or dose rates at horizontal beam lines and vertical irradiation thimbles.

Irradiation Thimble Dosimetry

Activation reaction dosimeters have been exposed in three vertical irradiation thimbles, V-10 (reflector region), V-14 (core edge) and V-15 (core center), i.e., $^{54}$Fe(n,p), $^{58}$Fe(n,g), $^{59}$Co(n,g), $^{27}$Al(n,$\alpha$), $^{58}$Ni(n,p), $^{46}$Ti(n,p), $^{47}$Ti(n,p), and $^{48}$Ti(n,p). In addition, for V-10 a series of bare and cadmium covered dosimeters were activated for the above reactions and $^{197}$Au(n,g), $^{176}$Lu(n,g), $^{93}$Nb(n,g), $^{55}$Mn(n,2n), $^{237}$Np(n,g), $^{238}$U(n,g), $^{237}$Np(n,f) and $^{238}$U(n,f).

To carry out the neutron and photon transport computations, Monte Carlo code MCNP4A was used. Processed on an IBM RISC-6000 work station at BNL, both prompt neutron and prompt gamma flux densities 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 $D_2O$. For a steady state flux estimate in a fresh core, premliminary runs were performed to predict the critical ($k_{eff}=1$) control rod bank positions. Relative to the core mid-plane, a main rod tip at +15.735 cm and auxiliary rod tip at -26.9 cm, showed 99% confidence compared to measured rod positions at HFBR startup. A value of $<\mu>$ = 2.61 neutrons/fission ($9\text{x}10^{16}$ n/sec/MW) was used for normalization at 40 MW operating power. The dosimeter samples, which were inserted into vertical thimbles, were simulated by a 0.2 cm thick aluminum shell filled with air in a sphere of 2 cm ID (2.4 cm OD). Energy distributions had been calculated at various axial locations in the thimbles. The statistical uncertainty (standard deviation/mean) is mostly $<$ 5% for neutrons between 0.023 - 0.55 ev. Neutrons and gamma ray fluxes at various axial positions were calculated in all thimbles, but only the neutron flux at the thimble bottom of V-10 and V-14 and at the core mid-plane of V-15 were measured. These measured and calculated flux densities are given in the following tables and renormalized to an operating power level of 30 mega-watts, MW.

V-10 Reflector Region Neutron Flux Densities

| E (MeV) | Expt. | Calc. | Expt/Calc |
|---|---|---|---|
| $< 5\text{x}10^{-7}$ | $1.57\text{x}10^{14}$ (6%) | $2.60\text{x}10^{14}$ (<5%) | 0.60 |
| $5\text{x}10^{-7}$-0.1 | $2.01\text{x}10^{12}$ (16%) | $1.47\text{x}10^{12}$ (???) | 1.37 |
| $>$ 0.11 | $2.84\text{x}10^{11}$ (22%) | $6.14\text{x}10^{10}$ (???) | 4.63 |
| $>$ 1.0 | $1.03\text{x}10^{11}$ (23%) | $3.29\text{x}10^{10}$ (???) | 3.13 |
| Total | $1.59\text{x}10^{14}$ (6%) | $2.62\text{x}10^{14}$ (<5%) | 0.61 |

### V-14 Core Edge Region Neutron Flux Densities

| E (MeV) | Expt. | Calc. | Expt/Calc |
|---|---|---|---|
| $< 5\times10^{-7}$ | $4.96\times10^{14}$ (10%) | $6.37\times10^{14}$ (<5%) | 0.78 |
| $5\times10^{-7}$-0.1 | $4.99\times10^{14}$ (20%) | $5.14\times10^{14}$ (<5%) | 0.97 |
| $> 0.11$ | $5.99\times10^{13}$ (10%) | $1.23\times10^{14}$ (<10%) | 0.49 |
| $> 1.0$ | $2.38\times10^{13}$ (11%) | $4.93\times10^{13}$ (<10%) | 0.48 |
| Total | $1.06\times10^{15}$ (8%) | $1.24\times10^{15}$ (<5%) | 0.85 |

### V-15 Core Center Region Neutron Flux Densities

| E (MeV) | Expt. | Calc. | Expt/Calc |
|---|---|---|---|
| $< 5\times10^{-7}$ | $1.20\times10^{14}$ (8%) | $1.78\times10^{14}$ (<5%) | 0.68 |
| $5\times10^{-7}$-0.1 | $1.10\times10^{15}$ (15%) | $1.36\times10^{15}$ (<5%) | 0.81 |
| $> 0.1$ | $2.40\times10^{14}$ (10%) | $3.70\times10^{14}$ (<10%) | 0.65 |
| $> 1.0$ | $9.35\times10^{13}$ (11%) | $1.39\times10^{14}$ (<10%) | 0.67 |
| Total | $1.46\times10^{15}$ (8%) | $1.91\times10^{15}$ (<5%) | 0.76 |

## Discussion

There are significant differences between the experimental and calculated values in the above tables. In every case, calculated values exceed measurements but boundary conditions are different. To simplify the calculations, a fresh core with twenty-eight new fuel elements was assumed. Normally, samples are 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 thirty day fuel cycles. The control rod tip was 15.735 cm above the core mid-plane for the calculations, while these measurements were performed in an equilibrium core, when the control rods were out of the reactor. The active neutron source volume ratios in these two cases is 0.80. The tables show 0.76 and 0.85 for those samples in V-14 and V-15 near the core. For the calculated values, the quoted uncertainty is strictly statistical based on the number of histories with no systematic error estimated.

Since the equilibrium core is used for most sample irradiations, the measured values quoted in the above tables should be used by recent and future facility users. Continued measurements are planned for other thimbles and various axial locations. In addition, calculations with boundary conditions closer to the actual measurement conditions will also be performed.

## Beam Line Dosimetry

Cadmium covered and bare gold foils were irradiated at the H-8 beam line. Preliminary results indicate a thermal neutron flux density at the sampling position on the order of $10^7$ n/cm$^2$/sec and a cadmium ratio of about 1000. No calculational results are available because of the seven to eight orders of magnitude reduction in the flux density compared to those in the vertical thimbles. Beam line flux densities will require much larger numbers of neutron histories for the Monte Carlo results to have any statistical significance.

Concurrent with gold foil dosimetry at the H-8 beam line, neutron dose rates were measured using a large volume $BF_3$ detector and found to be 2.4 rem/h. This unshielded dose rate was measured at a distance of several cm from the beam aperture at a neutron energy of 41 milli-ev (meV). Gamma dose rate measurements were also taken with a 0.6 cm$^3$ ion chamber (active volume) to be 22 R/h. Plexiglass shields (1/16" thick) were placed between the beam aperture and the chamber. The gamma dose rate was 14.1 R/h with one shield and was reduced to 0.5 R/h with ten thicknesses. This indicates the gamma dose rate is caused by low energy (< 100 keV) gamma-rays. A subsequent measurement was conducted using a NaI detector, which confirmed a strong absorption peak in the region 10 to 25 keV.

## Conclusion

Further work on neutron and gamma-ray dosimetry for the various horizontal beam lines and vertical thimbles are planned, when the HFBR restarts operation in the future. At present users should rely on the measured values in the above tables for the latest neutron information for those specific vertical thimbles.

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