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CHARACTERIZATION OF DOSIMETRY OF THE BMRR HORIZONTAL THIMBLE TUBES AND BROAD BEAM FACILITY

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CHARACTERIZATION OF DOSIMETRY OF THE BMRR HORIZONTAL THIMBLE TUBES AND BROAD BEAM FACILITY

ABSTRACT: The Brookhaven Medical Research Reactor was a 5 mega-watt, light-water cooled and heavy-graphite moderated research facility. It has two shutter-equipped treatment rooms, three horizontally extended thimble tubes, and an ex-core broad beam facility. The three experimental thimbles, or activation ports, external to the reactor tank were designed for several uses, including the investigations on diagnostic and therapeutic methods using radioactive isotopes of very short half-life, the analysis of radiation exposure on tissue-equivalent materials using a collimated neutron beam, and the evaluation of dose effects on biological cells to improve medical treatment. At the broad beam facility where the distribution of thermal neutrons was essential uniform, a wide variety of mammalian whole-body exposures were studied using animals such as burros or mice. Also studied at the broad beam were whole-body phantom experiments, involving the use of a neutron or photon beam streaming through a screen to obtain the flux spectrum suitable for dose analysis on the sugar-urea-water mixture, a tissue-equivalent material. Calculations of the flux and the dose at beam ports based on Monte Carlo particle-transport code were performed, and measurements conducted at the same tally locations were made using bare or cadmium-covered gold foils. Analytical results, which show good agreement with measurement data, are presented in the paper.

Introduction

The Medical Research Reactor at the Brookhaven National Laboratory (BMRR) was a 5 mega-watt (MW), light-water cooled and heavy-graphite moderated research facility [1], which had been operated from 1960 until its permanent shutdown at the end of December 2000. Built next to the clinical center of the Medical Department, the BMRR had two hospital-standard and physician-managed treatment rooms; the epithermal neutron irradiation facility (ENIF) and the thermal neutron irradiation facility (TNIF). While the ENIF had been upgraded in 1994 to perform clinical trials of neutron capture therapy (NCT) for patients suffered from malignant brain tumors, the TNIF had been modified in the 1980's for treating animals with eye melanoma and for irradiating tissue-equivalent biological cells.

In addition to the cross-core symmetrically built ENIF and TNIF, which had been reported on earlier [2], the BMRR had three horizontally extended thimble tubes cast in a dense concrete shield with no shutters, and a broad beam facility (BBF). The BBF was located at the end of a heavy-graphite formed thermal column followed by a 15 cm thick lead shield and a 2 mm thin retractable screen of natural cadmium. These facilities, which were external to the reactor tank, were for irradiating samples. One of these horizontal thimbles, which passed tangent to the BMRR core along the northeast-southwest direction, was equipped with a pneumatic blower to transport an experimental cylinder into and out of the tube shroud and thus was called the pneumatic (Pn) tube. This tube was built at 20 cm above the core mid-plane and its tip was located at 52.4 cm from the core axial centerline. At the exact mid-plane of the core along the north-south direction, a radially extended thimble was constructed for sample irradiation using a direct beam emerging from the reactor core. It had been specifically used in the NCT program in the 1990's to evaluate the drug uptake of gamma-tagged ^{10}B- and ^{157}Gd-compounds in the blood flow of the clinical trial patients, based on the detection method of prompt-gamma neutron activation [3]. Located at 20 cm below the core mid-plane along the northwest-southeast direction, there was another tangential thimble designed for sample moderation experiments. In this thimble, a bare and a moderator-shielded sample were individually inserted into the thimble port for activation. Through a comparison of the accumulated dose, the sample property and the moderator's nuclide cross-sections could be characterized. This thimble has its exit inside of the TNIF facility.

The broad beam facility (BBF), with dimensions of 1.55 m wide, 1.68 m high and 1.1 m deep, was located at the south side of the reactor. Core neutrons, which reached the BBF after streaming through a 1.44 m thick graphite layer and the following 15 cm thick lead wall, were predominately in the thermal

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neutron energy range (<0.4 eV). The lead shield, which contained a retractable cadmium filter for thermal neutron removal, could make the BBF into a gamma source facility. Attached to the lead wall inside of the BBF was a removable thin screen set, designed to alter the beam spectrum for sample studies. When an experiment of mammalian whole-body exposure was conducted, an animal as large as a burro could fit within the BBF room or a large number of mice could fit in place simultaneously for irradiation. Another subject of interest for the broad beam use was the whole-body phantom experiment, in which a tissue-equivalent, sugar-urea-water mixture was irradiated by a neutron or a photon beam, with a selected spectrum through the use of filters or screens.

Experimental Thimble Tube Facilities

There were three horizontally built thimble tubes at BMRR, extending from the core edge to the outer face of the biological shield, as shown in Figure 1. The three thimbles were reworked from surplus Brookhaven Graphite Research Reactor experimental tubes. Each of the three tubes was made of stepped steel cylinders of 21.6 cm inside diameter at the small end, 25.4 cm inside diameter in the second stage, and 26.7 cm inside diameter at the face of the biological shield. They were cast into the dense concrete biological shield (density of 6.4 g/cm^3) in line with the 10 cm by 10 cm openings through the heavy graphite reflector (density of 1.6 g/cm^3). No shutters were provided for these facilities. Shielding plugs close these tubes when they were not in use, or when equipment supporting an experiment was not placed at a tube opening.

The primary mission of the three thimbles was to perform rapid multi-sampling through a direct beam of high flux particles (up to 10^{13} neutrons or photons per cm^2-sec-MW) in order to meet the specific needs of experiments; such as neutron-activated gamma-rays from biological compounds, which were used for drug tracking [3]. To avoid interference between the neighboring thimbles from back scattered neutrons or neutron induced photons, when multiple experiments were being performed at the three thimble facilities simultaneously, these three horizontal tubes were constructed at different heights, about 20 cm apart from each other vertically.

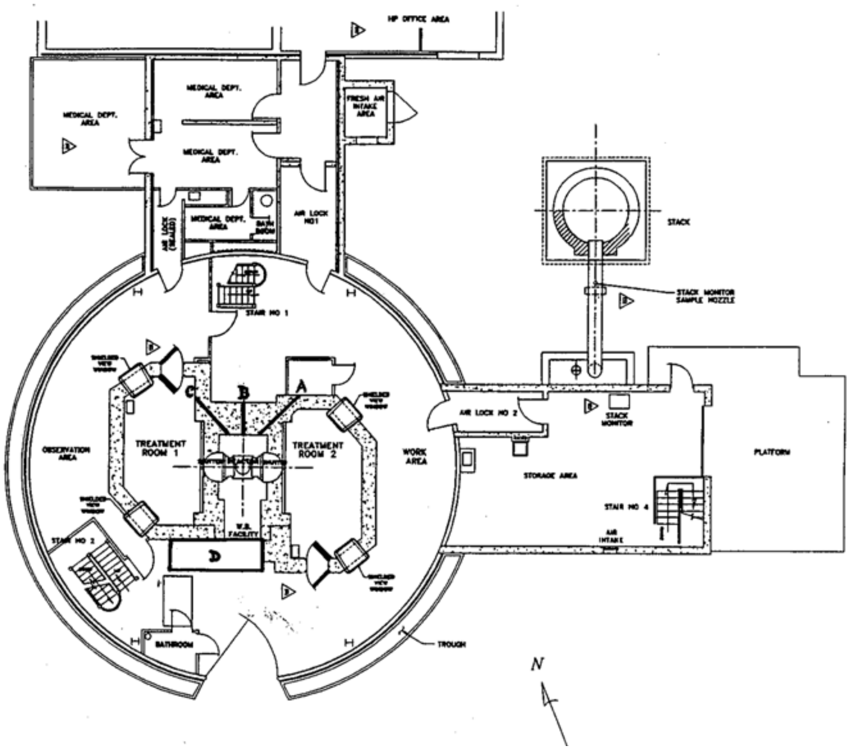

Figure 1. Experimental facilities surrounding the BMRR core included two treatment rooms (room 1, room 2), three horizontal thimble tubes (A, B, C), and one broad beam facility (D).

The installation of an in-line collimator to increase the flux of neutrons through effective focusing, while reducing the rate of gamma contamination (gamma dose per neutron), was an option of thimble use for sample irradiation. When the material of the collimator was of low mass or hydrogen-rich, the flux of thermal neutrons beyond the collimator, where the sample was irradiated, would be increased by energy moderation, as well as by focusing. To make the thimbles a photon source for gamma irradiation, either using cadmium sheet or sample holders of ^{6}Li- and ^{10}B-rich materials to shield thermal neutrons were considered. Tests indicated that these methods were more cost-effective than the use of a custom-made collimator.

Experimental Broad Beam Facility

The broad beam facility, BBF, located at south side of the reactor core behind the graphite-piled thermal column was a small room surrounded by the biological shield on the top, bottom, and two sides, as shown in Figure 2. It was opened to the entire south face of the reflector. A 20-ton, dense concrete rolling door provided full access to the room when opened, and completed the shield when closed. The facility was 1.55 m wide, 1.68 m high and 1.1 m deep.

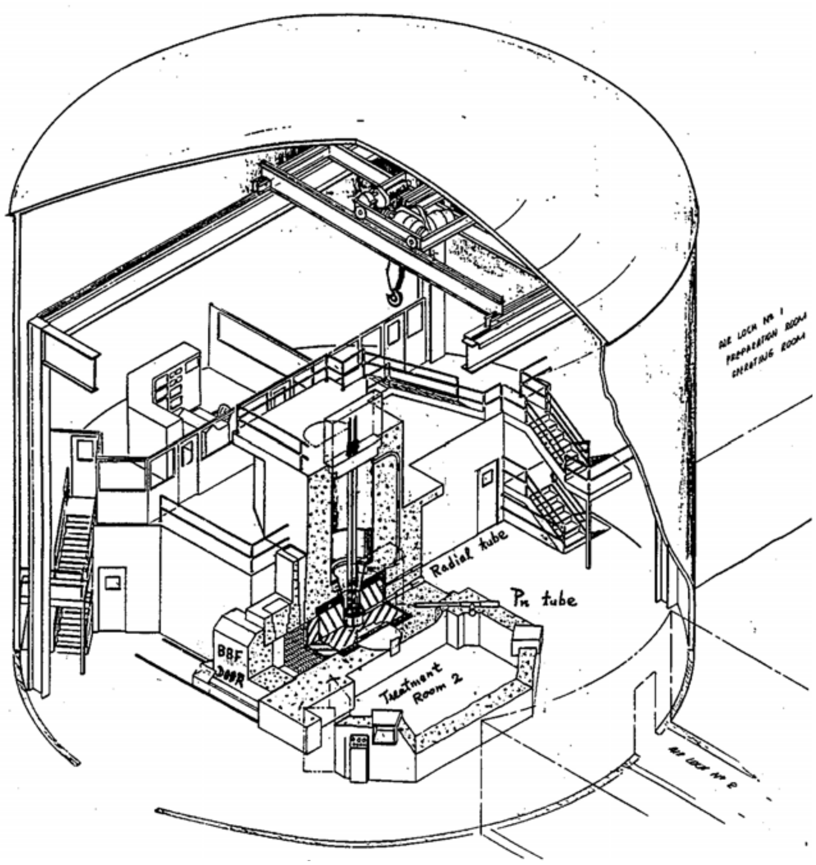

Figure 2. The BBF at south of the BMRR was a 1.55 m by 1.68 m by 1.1 m room enclosed by lead shield and dense concrete. It had been used for the whole-body phantom and mammalian exposure studies.

A beam emerging from the core traveled through 98 cm of the graphite reflector. The beam was further slowed down by a 46 cm thick graphite wall, which was cooled on the core side face by the inlet cooling air. A 15 cm lead wall abutted against the graphite and served as a gamma filter. Before diffusing into the shielded room, neutrons might pass through one or more retractable screens, which extended over the entire face of the facility and could be used to alter the energy, the spectrum, or the constituents of the beam. The cadmium filter at the lead wall could be lowered to absorb most thermal neutrons, thus making the room into a gamma source facility.

The 46 cm thick graphite wall was fabricated from 10 cm by 10 cm blocks of AGHT graphite and AGOT reactor grade graphite. AGOT has a lower boron impurity content than AGHT. AGOT, because of its lower neutron absorption, is considered to be a higher grade graphite. The assembled structure was 1.66 m high and 1.54 m wide. Since this wall was kept stationary by the lead walls on one side and bracketed on the other, keys and dowels were not needed to assembly the 232 blocks.

The lead gamma shield, also assembled from blocks, was 1.66 m high by 1.54 m wide by 0.15 m thick and weighed 5 tons. Preliminary testing was done on samples of various lead alloys, i.e., corroding, chemical, acid-copper, common de-silverized, and scrap lead of unknown analysis, by irradiation in the Brookhaven Graphite Research Reactor at a flux 10^{10} neutrons/cm^2-sec-MW for several minutes or days. Specimens were counted over a period of several hours. Corroding lead conforming to ASTM Specification B29-55 was chosen as the shield material because it created less activity and decayed faster than the other lead alloys. Calculations indicated that, of the thermal neutron incident on the shield, 50% would be scattered, 11% absorbed in the lead, and 39% transmitted to the broad beam facility.

For access from the top, a round plug, approximately 30 cm in diameter, constructed of dense concrete was set in the ceiling of the facility. With the additional of special shielding and a remote handling device, it was possible to insert or discharge small specimens through this top plug while the reactor was operating. Instrument lines could be run into the facility via an offset trough.

Without protection, the dense concrete walls would become active after a time; therefore, a non-activating lining fabricated of a 0.95 cm thickness of B_4C sandwiched between layers of plywood was mounted on the exposed surfaces, anchored to uni-strut sections cast flush into the concrete at convenient locations.

The shielding door of the broad beam facility was moved horizontally by an electric motor. The door was constructed in two sections so as not to exceed the crane capacity, each being a monolithic dense concrete block. The lower block was cast into a carriage that rolled along tracks; it contained 1.8 m^3 of concrete and also weighed 10 tons including the 1.1-ton carriage. The upper section contained 2 m^3 of concrete and also weighed 10 tons.

The assembled door was 91 cm thick, 213 cm high and 213 cm wide and generously overlapped the cave opening on all four sides. The 1.3 cm operating clearance between the vertical face of the reactor wall and the door was backed by a 7.6 cm by 15 cm steel plate shield.

The reactor could not be started with the facility door out of the fully closed position, and its opening during operation would result in an automatic reactor scram unless an administratively controlled shorting plug was installed to bypass this scram trip. This scram shorting plug was used to allow opening the door with reactor power less than 10 KW, to avoid the requirement to completely shutdown the reactor during experiments, which required a number of exposure cycles. The door opening was coordinated between the reactor operator and the local door control station via the facility intercom.

An electric gear motor drove the carriage through a roller chain transmission at the rate of 61 cm per minute. The motor was powered from the PH-8 feeder 440 VAC distribution panel. The drive was equipped with an emergency manual override for use in the event of a power failure.

Monte Carlo Model Calculations

Simulation of the BMRR, including the in-core fuels and moderator, the core edge reflector, the ex-core shutters, the downstream thermal column, and the treatment rooms with their lead block shielding, had been thoroughly performed during 1992-1999, by the use of the Monte Carlo particle transport code MCNP [5]. This statistical-based computer code that has been developed and periodically updated by the Los Alamos National Laboratory is a general purpose Fortran compiled software package, which can be used to model any single particle motion or coupled neutron photon transport in a three-dimensional geometry consisting of different material regions. For the in-core and the core edge parameter analyses, detailed geometrical configuration of the key elements plus a full set of material cross sections (including the cross section sets for thermal neutron treatment) must be incorporated into the model input for code processing in order to obtain results with high statistical accuracy. For the ex-core irradiation studies, there are multiple material regions through which most of the core particles are slowed down via inelastic scattering before reaching the target samples or dosimeters (unless they have been absorbed or they have leaked from the system). In the MCNP model, a homogenized reactor core can be set up, followed by segmented material zones, to expedite the code run, while maintaining the source strength to its down stream areas.

The MCNP model developed for the flux and dose estimate at the three thimbles, starting from the core edge down to the ex-core graphite-reflector, can be observed from the three individual screen plots shown in Figure 3. The left plot shows the Pn tube at a height of 20 cm above the core mid-plane. The middle and right plots show the radial tube and the moderation tube, at the exact core mid-plane and at 20 cm below that plane, respectively.

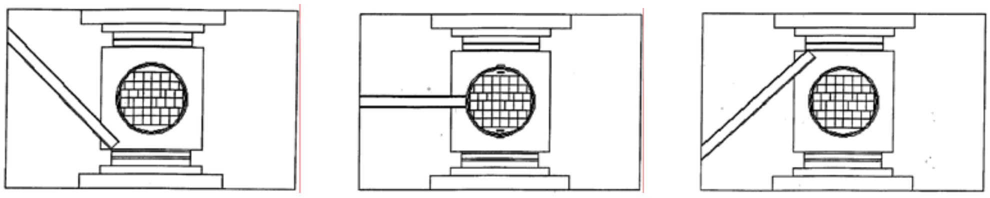

Figure 3. Horizontal cross-section of the Pn tube (l), radial tube (m), and moderation tube (r) at core edge of BMRR (MCNP model).

By expanding the MCNP model from a full core geometry (in-core and core edge areas) to a full reactor geometry (in-core, core edge, ex-core, and downstream shielding areas) in order to include the outermost BBF, sets of criticality test-runs must be performed based on the material used in the reactor core. These materials are shown and are labeled in figure 4, as the reactor core (labeled #1), the graphite moderator and reflector (#2), the lead shield (#3), the bismuth shield (#4), the 2 half-moon shutters (#5), the dense concrete shield (#6), the 3 experimental thimbles (#7), the cadmium filter (#8), the ENIF (#9), the TNIF (#10), the BBF (#11) and its rolling door (dark area). The calculated effective-criticality factor (K_{eff}) versus the actual criticality obtained from an equilibrium core can be used to check the model adequacy.

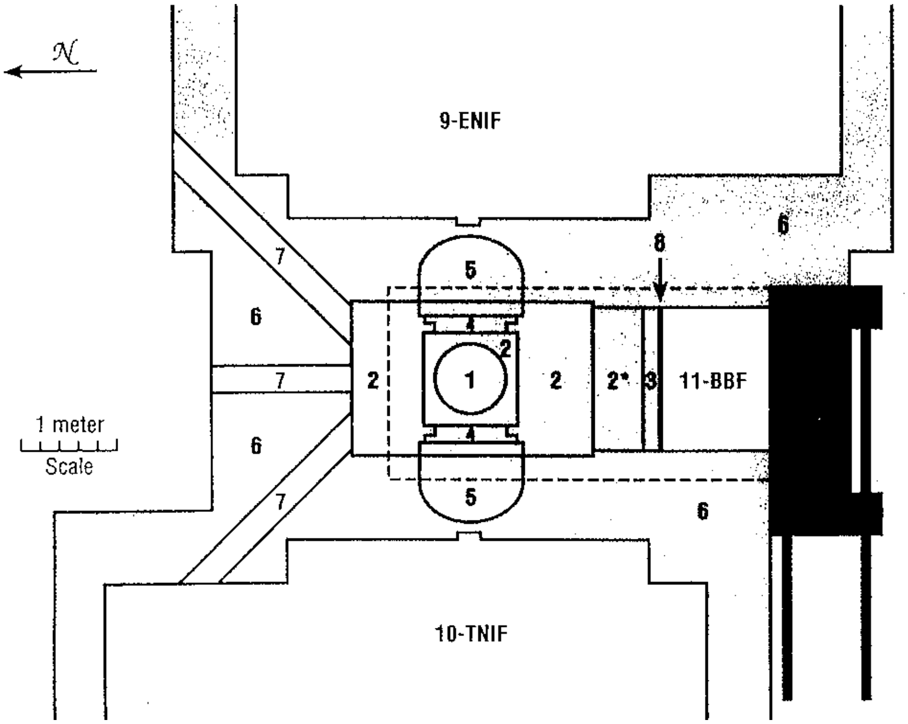

Figure 4. A mid-plane cross-section of the BMRR shown by the MCNP model, including all experimental facilities around the core.

Results and Discussion

Flux and dose calculations and measurements were performed at the different experimental facilities during the startup of BMRR. Historical data documented before February 1960 are listed in Table 1 to serve as basis for comparison.

Table 1. Record of calculated integral neutron flux and measured gamma dose shown in the Log of BMRR Startup in 1960.

Thimble Tubes and BBF Room	Thermal Neutron Flux (#/cm^2-sec-MW)	Distance to the Core Center (cm)
Tangential Tube Tip	1.0 E+08	52.39
Radial Tube Tip	1.0 E+13	31.75
Radial Tube Exit	1.0 E+08	256.85
BBF (Cd screen up)	1.5 E+09	254.00
BBF (Cd screen down)	4.0 E+06	to the center of BBF room
Pn Tube Tip	3.3 E+12	52.39

In 1994, a fuel rearrangement in the BMRR core and a moderator replacement in the ENIF shutter were completed to facilitate the clinical trial of NCT-treated patients [4]. The core upgrade along with component repositioning and mechanism modification had permanently altered the flux and dose distributions at the in-core, the core edge, and certain ex-core areas. For reactor safety and procedure re-evaluation, sample irradiations using foils and badges were conducted, and calculations using MCNP full-reactor model were performed to predict the flux spectrum and dose level at the three thimble tubes and the BBF room. Results listed in Table 2 and plotted in Figures 5 - 9 are those obtained after 1998, two years before the permanent shutdown of BMRR.

Table 2. Integral flux of neutrons and prompt gammas calculated by the MCNP at 3 MW operating power since 1992 (thermal neutrons: < 0.4 eV, epithermal neutrons: 0.4 eV - 10 keV, fast neutrons: > 10 keV)

Thimble Tubes & BBF Room	Thermal Neutron (#/cm^2-sec)	Epithermal Neutron (#/cm^2-sec)	Fast Neutron (#/cm^2-sec)	Prompt Gamma (#/cm^2-sec)
Pn Tube (Tip)	5.45 E+12	3.35 E+12	1.99 E+12	5.61 E+12
Radial Tube (Exit)	3.02 E+08	1.28 E+09	2.58 E+09	7.72 E+09
BBF (Cd up)	1.28 E+10	< E+06	< E+04	1.61 E+10

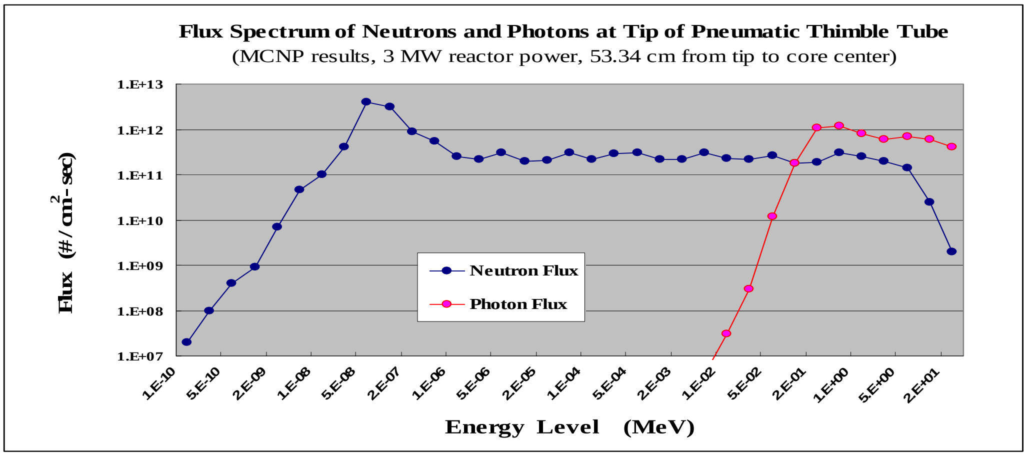

Figure 5. Log-Log scaled spectrum of neutron and photon flux at tip of the Pn tube calculated by the MCNP at 3 MW power.

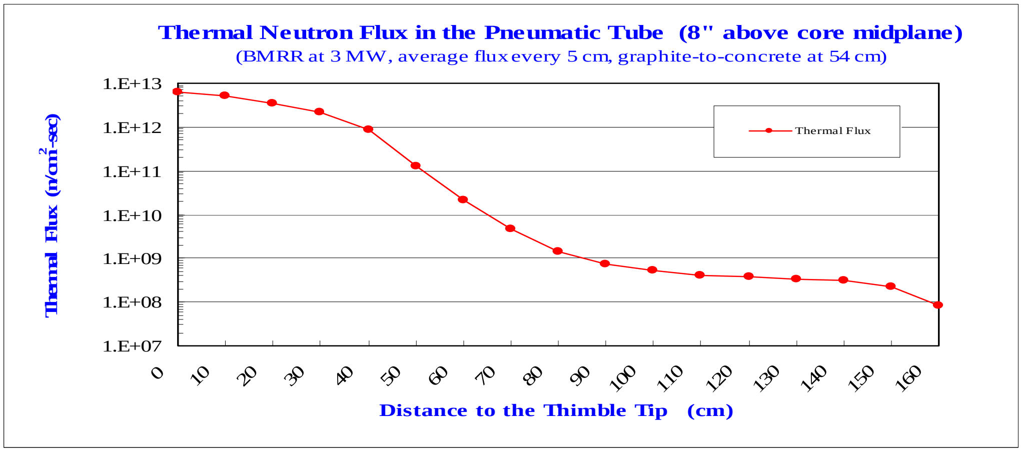

Figure 6. Thermal flux distribution along the pneumatic tube from graphite to concrete at 3 MW power (MCNP calculations).

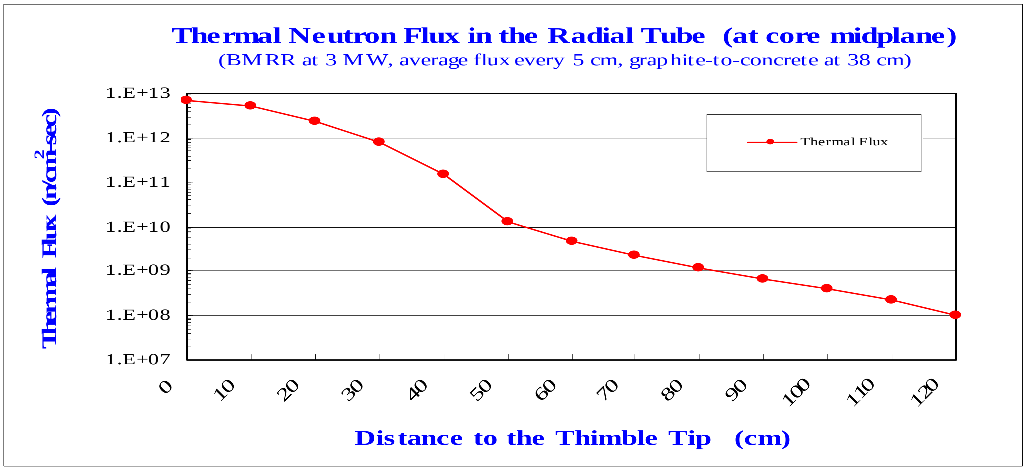

Figure 7. Thermal flux distribution along the radial tube from graphite to concrete at 3 MW power (MCNP calculations).

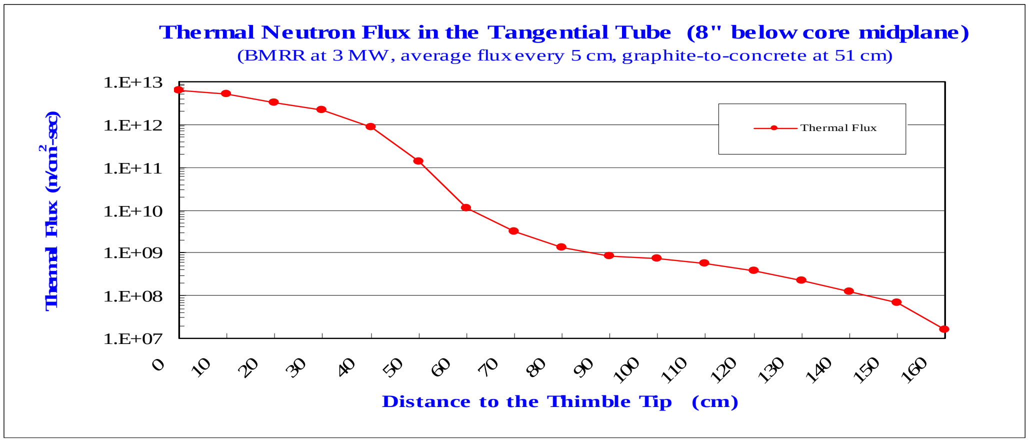

Figure 8. Thermal flux distribution along the tangential tube from graphite to concrete at 3 MW power (MCNP calculations).

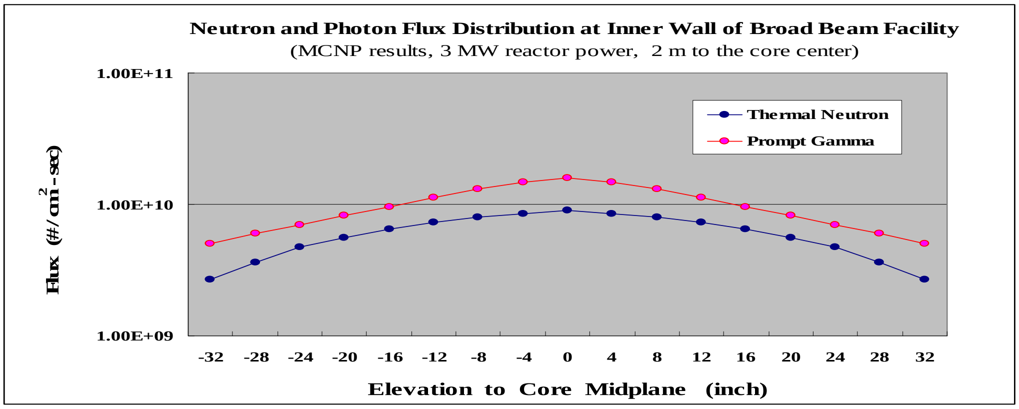

Figure 9. Flux distribution of neutrons and photons from ground to ceiling on the face of lead wall at BBF (MCNP calculations).

A modification of the BBF was proposed in 1996 to make it an equivalent or better thermal neutron irradiation facility for the cell-culture and small-animal experiments [4]. To achieve an optimal design by providing the BBF with a high flux and high quality (low dose) thermal neutron beam, with a limited change of the facility structure, MCNP calculations were performed. Table 3 lists the result from code runs based on the same full-reactor geometry, but with a 26.7 cm thick material change from graphite to bismuth in the ex-core reflector region at the lead wall of BBF. The improvement in sample resolution by reducing the dominate background dose from thermal neutrons was also evaluated, based on the assumption that the entire BBF room was covered by a 1 cm thick Li-poly liner (93%-enriched ^{6}Li, 45 wt% ^{6}Li$_2$CO$_3$), except at beam port location.

Table 3. Calculated and measured beam parameters at the broad beam facility at 3 MW power (as reported in reference [4]).

BBF vs. TNIF Status before and after the proposed modification	Thermal Flux of Neutrons (n/cm^2-sec)	Fast Neutron Dose per Thermal Neutron (cGy-cm^2/thermal neutron)	Gamma Dose per Thermal Neutron (cGy-cm^2/thermal neutron)
BBF-before (MCNP)	1.28 E+10	0.15 E-11	10.3 E-11
BBF-before (measured)	1.17 E+10	0.21 E-11	10.8 E-11
BBF-after (MCNP)	4.10 E+10	0.36 E-11	0.36 E-11
TNIF (MCNP)	5.10 E+10	2.80 E-11	0.80 E-11

Acknowledgement

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