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Neutronics Design of the INEL Facility for Boron Neutron Capture Therapy Clinical Trials

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ABSTRACT

The PBF reactor at INEL has been redesigned for BNCT treatment of Glioblastoma Multiforme. Analysis indicates that the design goals of 1.0E+10 $n/cm^2 \cdot s$ epithermal neutron flux at the beam port can be met without exceeding the design goals of 2.6E-11 $cGy/(n/cm^2)$ for the fast neutron KERMA and 2.0E-11 $cGy/(n/cm^2)$ for the gamma KERMA. These design goals result in a 10 minute patient treatment time with low nondesirable doses.

INTRODUCTION

The Idaho National Engineering Laboratory (INEL) is currently involved in a collaborative national BNCT program that will culminate in clinical trials for the treatment of a particularly lethal and presently incurable brain tumor - Glioblastoma Multiforme. This program is expected to utilize the Power Burst Facility (PBF), located at the INEL, as the epithermal neutron source. The PBF is a light water moderated and cooled research reactor that has been in operation since 1972. The PBF reactor is currently on standby status and modifications for BNCT have been proposed. When completed, the modifications will lead to the patient treatment facility illustrated in Figure 1.

This paper will focus on the neutronics analyses being carried out at the INEL in support of the PBF core and filter design effort for BNCT. Neutronic analysis of the redesigned PBF core will be discussed first. This will be followed by a discussion of the PBF filter and beam tube analysis. Key results from both the core and the filter analyses will be presented throughout the paper.

DESCRIPTION OF THE PBF REACTOR CORE

The PBF reactor[1,2] is a light water cooled and moderated reactor which has been primarily used for reactor safety and fuel performance research. Because of its high metal content, the PBF reactor is a good source of epithermal neutrons. PBF may be operated in either steady state (up to 28 MW_t) or transient modes.

The PBF core currently consists of 2496 fuel pin positions surrounded by a ring of stainless steel reflector pins. Dummy aluminum pins and other core equipment are located outside of the reflector pins. Situated among the fuel pin locations are 4 transient and 8 control rods. Furthermore, about 100 fuel pin locations are filled with stainless steel reactivity shim pins.

The core is designed to deliver epithermal neutrons into a centrally located 8-1/4" diameter experimental test space. The test space is isolated from the core by a 7/8" inconel In-Pile Tube (IPT).

NEUTRONICS ANALYSIS OF THE PBF CORE

The PBF core has been redesigned for BNCT applications. Three of the most prominent changes are:

1. The partially fueled assemblies on the patient side of the core will be filled with fresh fuel rods.
2. The inconel IPT of the as-built core design will be replaced by an aluminum tube having 1/4" thick walls.
3. The aluminum IPT will have an internal structure to exclude most of the water.

The first change listed above changes the PBF core from its original "peak-in-the-center" design to an asymmetric configuration which enhances the ex-core leakage into the filter and beam tube. This change is made possible by the fact that 595 fresh fuel pins are still available at PBF.

The change from an inconel to an aluminum IPT is due to the relatively high neutron absorption of inconel. Inconel's extraordinary strength will not be needed during the proposed steady-state operation of PBF for BNCT.

The third change above is a result of previous PBF safety experience. A sudden voiding of a water-filled IPT is known to give a positive reactivity of $2.98 ± 0.25 for the current PBF configuration.[2]

The proposed PBF core design for BNCT is the asymmetrical configuration shown in Figure 2. It has 116 stainless steel shim rods, 18 flux-wire holder pins and 2562 lattice locations for fuel pins.

Design and operational analysis of this new PBF core is based on two-dimensional 4-group half-core symmetric diffusion theory analysis using the PDQ-7 code.[3] Three-dimensional models with thermal reactivity feedback have also been developed and are used with the PDQ flux synthesis option.

The 4-group cross sections are based on ENDF/B Version IV data. Local corrections for transport effects have been made for the flux-wire holders, control rods and transient rods. This 4-group diffusion theory approach to the PBF core has been extensively benchmarked against experimental measurements taken from the existing core. These comparisons lend credibility to the current design calculations for the modified core.

Additional verification of the overall approach to core modeling has been obtained through the use of the two-dimensional transport code TWODANT.[4] TWODANT is well suited for core analysis because of its very efficient Diffusion Synthetic Acceleration (DSA) algorithms on <u>both</u> the inner and outer iterations. A comparison of PDQ and TWODANT calculated power distributions for the new PBF core is shown on Figure 3. Even though the PDQ and TWODANT results may differ by a few percent on individual assemblies, eigenvalues and reactivity effects of design changes calculated by each code are nearly identical. Hence, PDQ will be used as the basic design tool, while TWODANT will be used for verification.

The excess reactivity of the proposed PBF core and the excess available by complete utilization of the remaining fuel inventory is sufficient for 10,000 to 15,000 BNCT treatments. (Each treatment will require ~5 MW-hours.) This number is well above the number of treatments proposed for the initial clinical tests of BNCT.

DESCRIPTION OF THE PBF FILTER AND BEAM TUBE

The PBF filter starts on the patient side of the core bismuth shield. The 6" bismuth shield is the interface between the core and the filter. Its purpose is to attenuate the core gamma source while transmitting neutrons from the core to the filter. Bismuth's high neutron scattering helps increase the core power near the patient while its low neutron absorption does not allow the production of a large capture gamma source.

A 39.4" (100 cm) region of filter follows the bismuth. The filter is composed of Al plates (with .3% natural Li by weight) cooled by D_2O. The purpose of the filter is to slow the core leakage neutrons down to epithermal energies. Aluminum is well suited for this application since its fast cross section is larger than its epithermal cross section. (Fast neutron contaminant in the neutron beam is undesirable due to the H recoil reaction in tissue.) Neutrons which slow down all the way to thermal energies are preferentially absorbed by the lithium without producing gamma rays.

The aluminum filter is followed by 16 mils of cadmium followed by 3" of bismuth. The purpose of the cadmium is to eliminate nearly all of the remaining thermal neutrons in the beam. Thermal neutrons are a beam contaminant in BNCT since they tend to burn the skin or scalp. They also do not penetrate to the tumor regions. The further 3" of bismuth strongly attenuates the cadmium produced gamma rays. Gammas are also a beam contaminant since they tend to penetrate tissue too deeply.

A 65" (165 cm) bismuth lined cone follows the 3" bismuth shield. The purpose of the cone is to concentrate and collimate the epithermal neutrons without increasing the gamma contaminant. The beam port may be closed between irradiations by a set of movable shutters placed in the cone as illustrated in Figure 1. The shutter doors are each composed of 7" of borated polyethylene followed by 3" of lead. These relative thicknesses were found to be optimal for typical PBF beam port neutron and gamma flux spectra.

PBF FILTER AND BEAM TUBE ANALYSIS

Neutron leakages from the core bismuth shield into the filter were calculated during the PBF core analysis. It is important to note that the bismuth shield and most of the filter were included so that the leakages (i.e., partial currents) taken at the bismuth-filter interface would be accurate. These calculations were carried out with the DOT 4.3 code[5] with the same core model and cross sections used earlier for TWODANT. Even though DOT is slower than TWODANT in execution for eigenvalue problems (i.e., DOT does not have outer iteration DSA), it was chosen for this calculation due to its selective angular flux edits and its built-in edit capabilities. DOT produces edits by material zone rather than by coarse mesh geometric zones. The fine detail of the PBF core forces a TWODANT model to have an unusually large number of coarse mesh zones.

Results from the DOT PBF core calculations indicate that 4.3% of all core neutrons leak through the bismuth into the filter. The 4 group angular fluxes from this calculation also provide the fixed boundary source to the filter calculations. DOT was chosen for the deep penetration filter problem because TWODANT is not quite fully developed for such application. Specifically, the damped DSA feature[6] of DOT appears to be effective in accelerating inner iterations which are otherwise slowed by large amounts of negative flux fix-up. TWODANT currently has no such feature and simply abandons the DSA algorithm if trouble is detected. Furthermore, DOT has an empirical yet generally reliable correction algorithm[7] for scattering cross section truncation errors, as well as a spatially and energy dependent variable angular quadrature feature.

The filter calculations were carried out with the 67 group coupled P_3 neutron-gamma BUGLE-80[8] cross section library. The basic library was augmented by the addition of bismuth, cadmium and deuterium cross sections. The bismuth cross sections were received from the Radiation Shielding Information Center (RSIC). The neutron-only cadmium cross sections in BUGLE-80 were expanded to neutron-gamma by adding (n,γ) production cross sections based on experimental data.[9] Gamma attenuation for the cadmium was neglected. The neutron-only deuterium cross sections in BUGLE-80 were expanded to neutron-gamma by adding the hydrogen gamma attenuation cross sections. Gamma production by neutron absorption in the deuterium was neglected.

The filter and beam port model employs DOT's unique variable quadrature feature. The standard level-symmetric S_8 quadrature is used throughout the model except for regions in or near the bismuth cone. A biased 166-direction quadrature set[10] is used in and near the cone to permit very fine angular resolution of the neutron streaming paths.

Expansion of the 4-group core neutron source to the 47-group BUGLE neutron structure was accomplished using predetermined spectral weight functions in reverse. The spectral functions were obtained from auxiliary one-dimensional calculations performed with the ANISN code.[11] This change from a 4 group to a 47 group neutron energy structure precluded the use of any of the normal DOT options for coupling eigenvalue problems to fixed source problems.

The energy spectrum of the beam port neutron flux is shown in Figure 4. The neutron fluxes are concentrated in the epithermal energy range between 1 eV and 10 keV. The slight dip in the energy spectrum at 35 keV is due to an aluminum resonance.

The spatial variation of the beam port fluxes and currents is shown in Figure 5. The beam is relatively flat over most of the beam port face. Furthermore, the slight oscillation is believed to be a residual ray-effect. Such oscillations are much more pronounced if the biased 166-direction quadrature set is not used. The angular variation of the beam port fluxes can be deduced from Figure 5. Since the currents are nearly equal to the fluxes, the beam is very anisotropic and nearly perfectly collimated. The flux to current ratio for the entire beam port face is 1.13.

An independent filter and beam tube model based on Monte Carlo techniques has also been employed for verification. This model uses the locally-developed RAFFLE code.[12] Interface currents for this model at the filter entrance are determined as described previously. However, this model employs a 94 neutron group cross section library based on ENDF/B Version V with ultrafine representation of anisotropic scatter and a pointwise resonance representation. Gamma transport can either be calculated directly in an independent run using the neutron-generated sources (and any external sources), or during the neutron calculation using a coupled solution that employs a point-flux statistical estimator based on buildup factors. This latter approach is an inexpensive way to estimate gamma contaminant and is particularly useful in optically thick regions.

Comparison results from the deterministic (DOT) and statistical (RAFFLE) approaches are given in Table 1. The results given in Table 1 compare favorably with the preliminary design requirements for PBF. The differences in the RAFFLE and DOT results are attributed to the difficulties in each method. Monte Carlo methods are subject to statistical limitations while discrete ordinates methods are plagued with ray effects and spatial truncation errors. Furthermore, the cross sections and filter input sources for each method were not exactly identical. The differences between the statistical and deterministic results are also expected to decrease as the respective models are refined. Nevertheless the fact that both models predict achievement of the PBF design goals is significant. Furthermore, if the lithium is removed from the filter, even higher epithermal neutron fluxes are obtained. These results are given in braces in Table 1. The penalty for removing the lithium is that the gamma KERMA is increased. Nevertheless, the PBF BNCT design requirements are still met.

TABLE I

Beam Port Results Compared with PBF Design Requirements

	Design Requirement	RAFFLE Results*	DOT Results
Beam port epithermal neutron flux @ 26 MW_t ($n/cm^2.s$)	1.00E+10	1.71(±.51)E+10 [1.86(±.43)E+10]**	1.17E+10 [1.42E+10]
Fast-neutron KERMA (cGy/(n/cm^2)***	2.6E-11	2.52(±.32)E-11 [1.85(±.43)E-11]	1.67E-11 [1.41E-11]
Gamma KERMA (cGy/(n/cm^2))	2.0E-11	5.28(±.67)E-12 [1.52(±.08)E-11]	8.15E-12 [1.84E-11]

*RAFFLE uncertainties are at the 95% confidence level
**Results for the no lithium case
***cGy = centigray = rad

SUMMARY

The PBF reactor core can be redesigned for application to BNCT and preliminary filter and beam tube facility calculations have been performed. The results indicate that the PBF BNCT design goals can be achieved. The requirements result in a 10 minute treatment time to deliver a 10 Gy $^{10}B(n,\alpha)^7Li$ dose to the tumor cells containing 25 ppm ^{10}B. The nondesirable dose (fast or thermal neutrons, gammas) is almost negligible and should result in near ideal conditions for the demonstration of epithermal neutron BNCT.

ACKNOWLEDGMENTS

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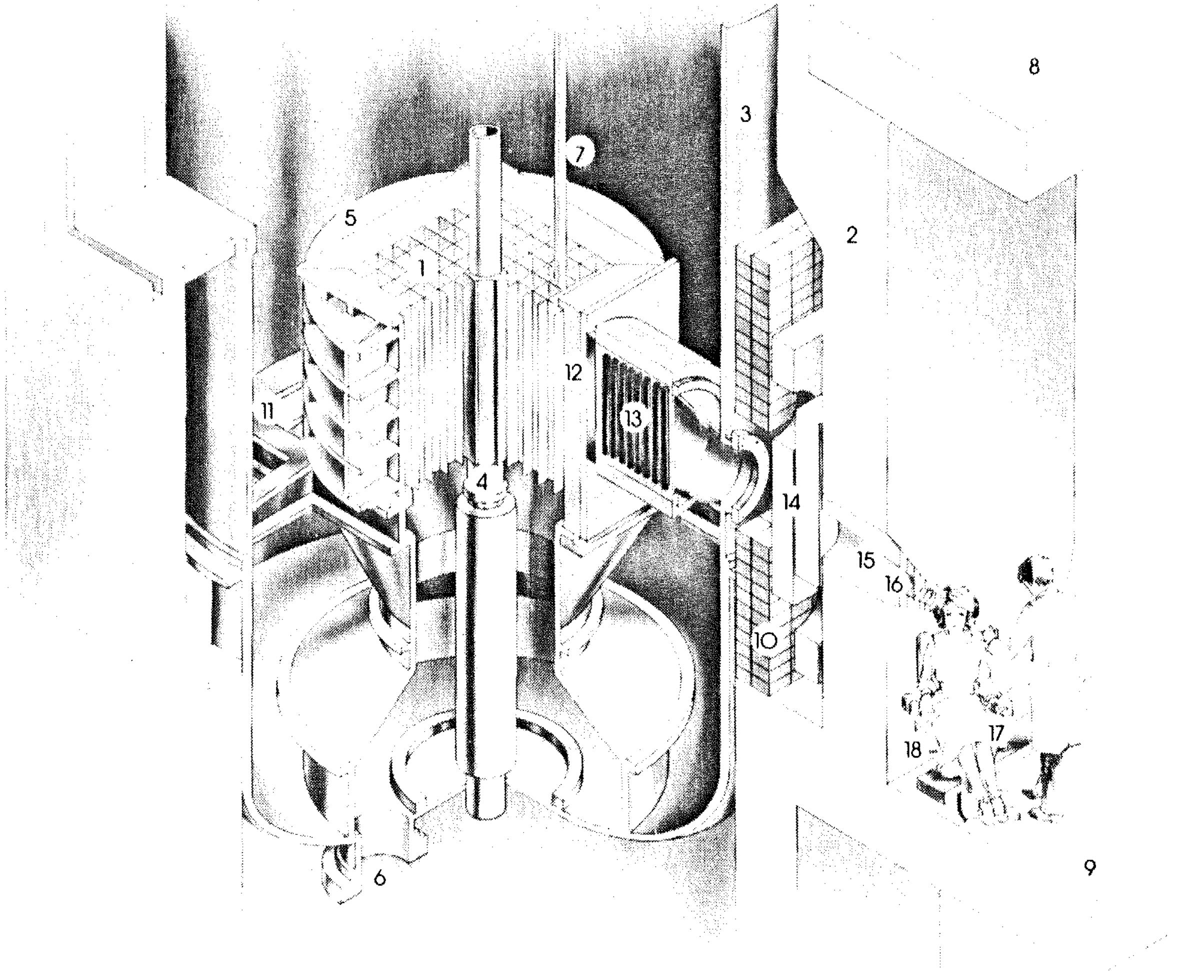

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FIGURE 1: Boron Neutron Capture Therapy Facility at PBF
Conceptual Design

Figure 2. Modified PBF Core Design (Half-Core Symmetry).

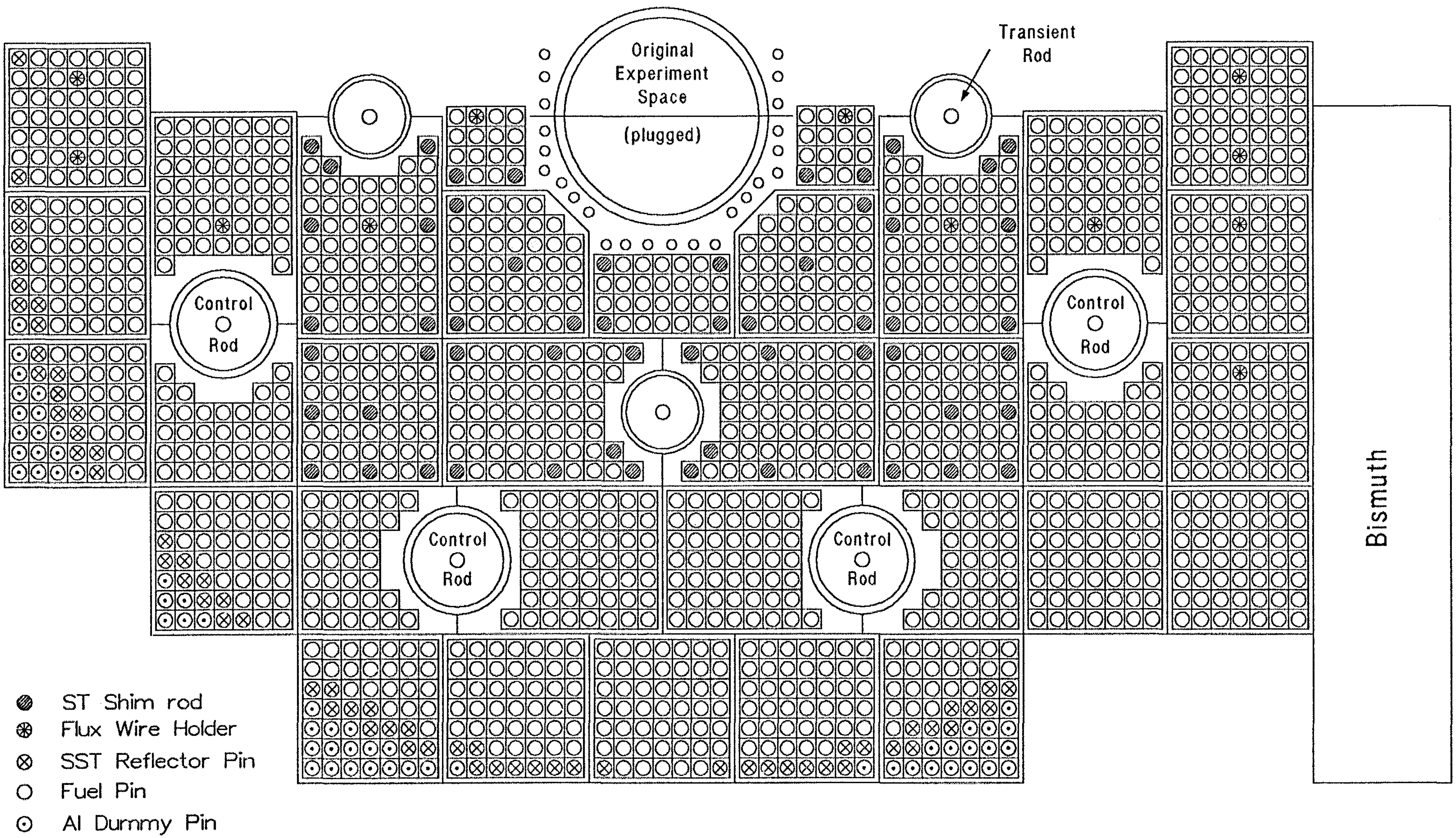
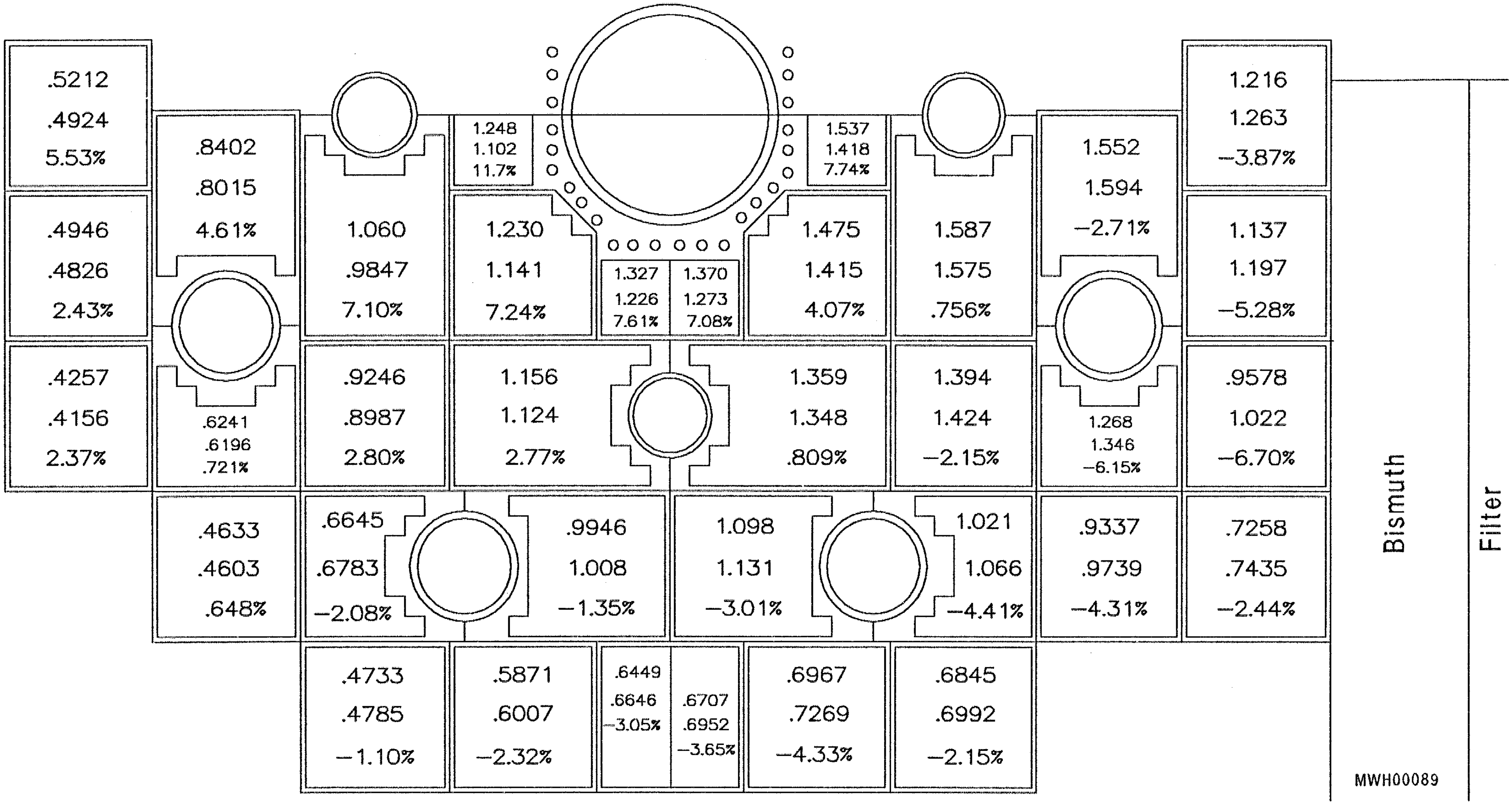


Figure 3. PDQ-7 / TWODANT COMPARISON
(Control Rods Out XY Geometry Model)
Relative Power Density (RPD)

1st no. = PDQ-7 Calculated Value
2nd no. = TWODANT Calculated Value
3rd no. = Percent Difference Between PDQ and TWODANT



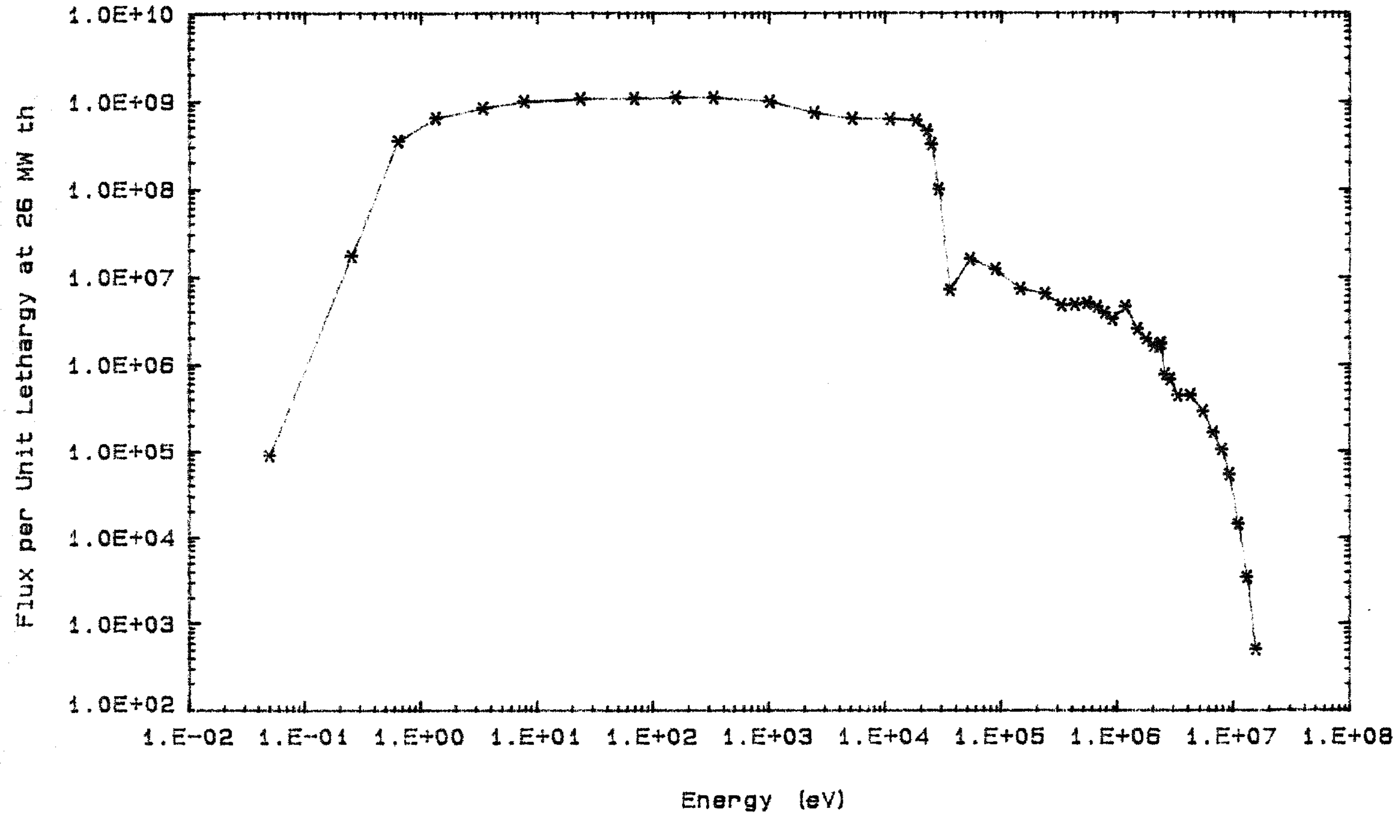


Figure 4: Energy Spectrum of the Beam Port Neutrons

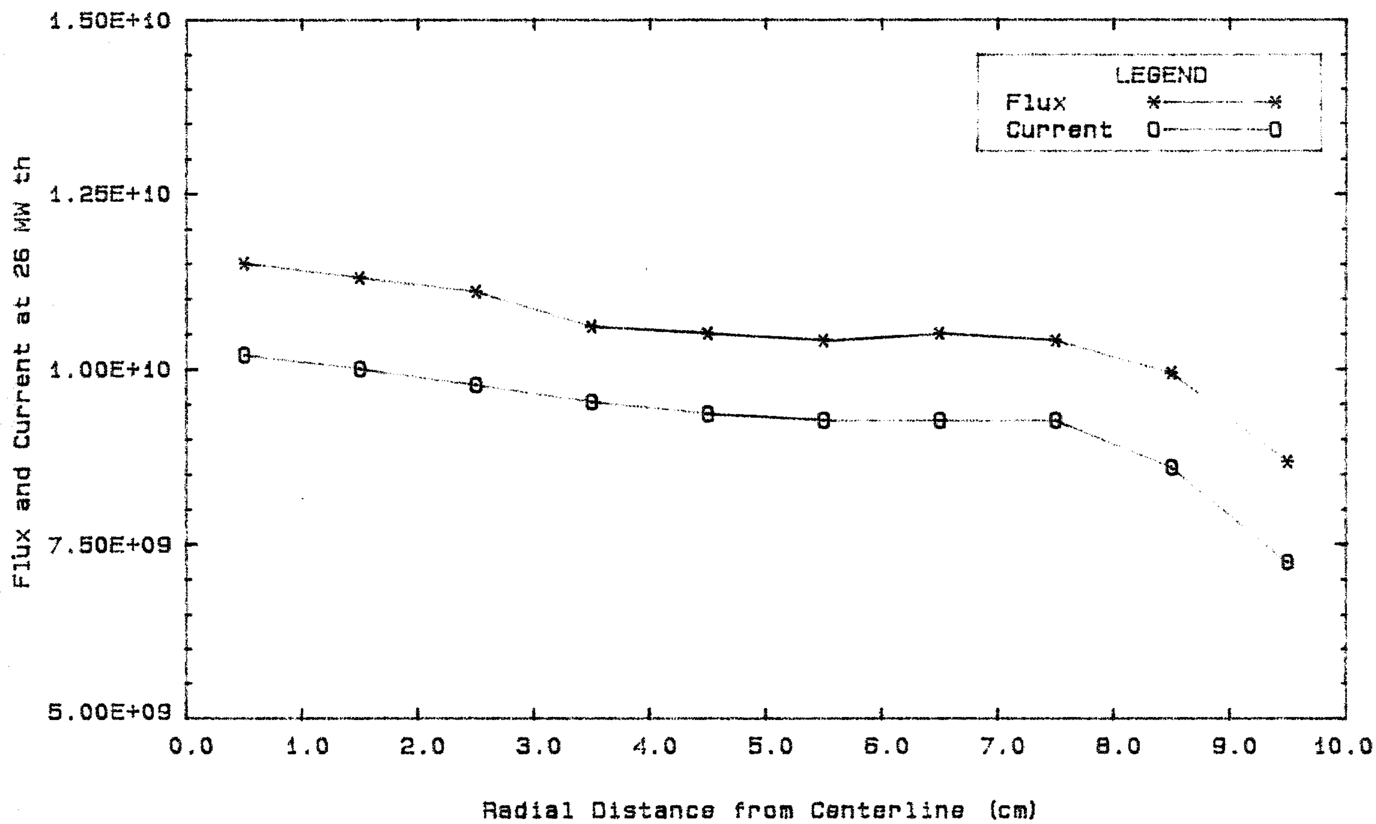


Figure 5: Radial Shape of the Beam Port Flux and Current