A Case Study to Bound the Search Space of the Optimization Problem for the PSBR Beam Tube

Kürşat B. Bekar*[1] Yousry Y. Azmy[1], Kenan Ünlü[1] and Jack Brenizer[1]
[1]*Department of Mechanical and Nuclear Engineering*
Penn State University, University Park, PA 16802, U.S.A

Abstract

We present a simple methodology for reducing the extent of the search space of the modular optimization code package developed for the size and shape optimization of the beam tube assembly at the Penn State Breazeale Reactor (PSBR). In this method, we express the origin of the neutron output at the beam tube exit in two components depending on the location of their last scattering collision in (i) the Bi gamma shield; or (ii) the moderator (e.g. H_2O or D_2O) illuminating the beam tube. We compute the contribution of these two components to the neutron flux at the beam tube exit by performing numerical experiments using the three-dimensional particle transport code TORT on a model configuration. We illustrate the results of this approach with various moderator materials, comparing the strength and spectrum of the outgoing neutron beam, and indicating how those affect the search space size. Results demonstrate that the neutrons originating at the beam tube base contribute more output neutrons at the beam tube exit than neutrons from all other origination locations. Hence, this result enables defining a small search space, thus reducing the optimization procedure's computational time.

KEYWORDS: TORT, beam tube, optimization, search space limitation

1. Introduction

A higher thermal neutron output for a beam tube of a research reactor can be obtained by determining the optimal size and shape of the beam tube assembly, i.e. the moderator tank, reflector materials, re-entry hole and the beam tube itself. A modular optimization package for this purpose was developed and applied to a simplified model for the beam tube facility of the Penn State Breazeale Reactor (PSBR). [1] In the optimization problem, the search space was defined by filling the problem domain with water and placing a fixed size beam tube in it. The optimal size and shape of the D_2O moderating material was searched in the search space by performing D_2O-H_2O replacement via the Min-Max algorithm.

Preliminary results show that the moderator tank has almost hemi-spherical optimal shape, and therefore the existing drum-shaped D_2O moderator tank is over-designed. Furthermore, since the PSBR core is over-moderated due to the presence of ZrH, the neutrons leaking out of the core into the D_2O tank are well thermalized. Hence we conclude that the principal function

*Corresponding author, Tel. 814-865-8429, Fax. 814-865-8499, E-mail: kbb141@psu.edu

of the D_2O is reflection rather than moderation because during the optimization process the D_2O material clusters around the beam tube base (re-entry hole) on the side opposite to the reactor core where the neutrons originate. As a consequence of this accumulation, the extent of the search space of the optimization problem can be reduced by restricting the D_2O-H_2O replacement to a region around the beam tube base.

In order to verify this result, a simple decomposition method is defined to determine the contribution of the neutrons at any location to the beam tube exit flux by placing thin highly black absorber material around the beam tube in the moderator tank. For this purpose, a simplified form of the existing tangential beam tube of the PSBR is modeled by TORT. [2,3]

In the model configuration, the D_2O moderator material is replaced with various materials, and the effect on the beam tube exit flux is observed and analyzed. In this way, sufficient information is acquired for restricting the extent of the search space for the optimization problem thus reducing the computation time of the search algorithm.

A similar experiment is performed for the radial beam tube configuration which is planned for the new beam tube arrangement of the PSBR to determine the contribution of neutrons originating at any location to the beam tube exit flux and to evaluate the effect of the location of the Bi gamma shielding disk on the exit flux. In this paper, the methodology of these calculations and its results are presented.

2. Decomposition Methodology

The plan of this work is to decompose the origin of the output neutrons at the beam tube exit into components and to use specially designed black absorber configurations to analyze their contribution to the neutron output through the beam tube for the model configuration.

2.1 Radial Beam Tube Configuration

The origin of the beam tube's exit flux is expressed in three components: uncollided, forward scattering and scattering components,

$$\psi_e(r,E,\mu_0) = \psi_{unc}(r,E,\mu_0) + \psi_{Bi}^{Base}(r,E,\mu_0) + \psi_{Bi}^{Side}(r,E,\mu_0) \quad (1)$$

The first component, $\psi_{unc}(r,E,\mu_0)$, is defined as almost mono-directional uncollided neutrons which are moving parallel to the beam tube axis, having the last scattering collision in the moderator materials (e.g. H_2O or D_2O) and passing through the Bi disk without any collision. The second component, $\psi_{Bi}^{Base}(r,E,\mu_0)$, the forward scattering component, is defined as the neutrons which are moving parallel to the beam tube axis, coming to the surface of Bi from the beam tube base and having the last scattering collision in the Bi disk. The third component, $\psi_{Bi}^{Side}(r,E,\mu_0)$, is defined as the neutrons which are moving parallel to the beam tube axis, coming to the surface of Bi from everywhere except the beam tube base and having the last scattering collision in Bi. Since dry air inside the beam re-entry gap has low scattering and absorption probabilities, it does not significantly affect the uncollided and forward scattering components while neutrons are streaming from the beam tube base to the surface of the Bi disk.

In order to compute these components separately, a set of black absorber configurations are prepared for the model configuration of the radial beam tube.

A schematic of the model configuration of the radial beam tube is given in Fig. 1. It includes only the D_2O drum enclosed in an aluminum cylindrical chamber, the re-entry gap of the beam tube, a Bi disk used for gamma shielding before the beam tube entrance and three different black absorber locations. The advantage of this model is that black absorbers can be placed at the "source interface" since the beam tube is perpendicular to that interface. The "source interface" is the plane separating the PSBR core and the D_2O tank; the TORT calculation is based on a neutron distributed source computed on this interface with MCNP. [4] The geometric configuration of the model was represented on a Cartesian grid for the TORT model by means of the BOT3P-GGTM code. [5] The cross-section data for this problem were mixed from the ANSL-V, ENDF/B-V Based Multi-group Cross Section Libraries originally developed for the Advanced Neutron Source (ANS) Reactor studies. [6] For this model problem, a 26-group library was prepared in ANISN/DOT3 format by collapsing the first 14 groups of the 39-group neutron library into 1 group via a spectrum computed by the MCNP reference model.

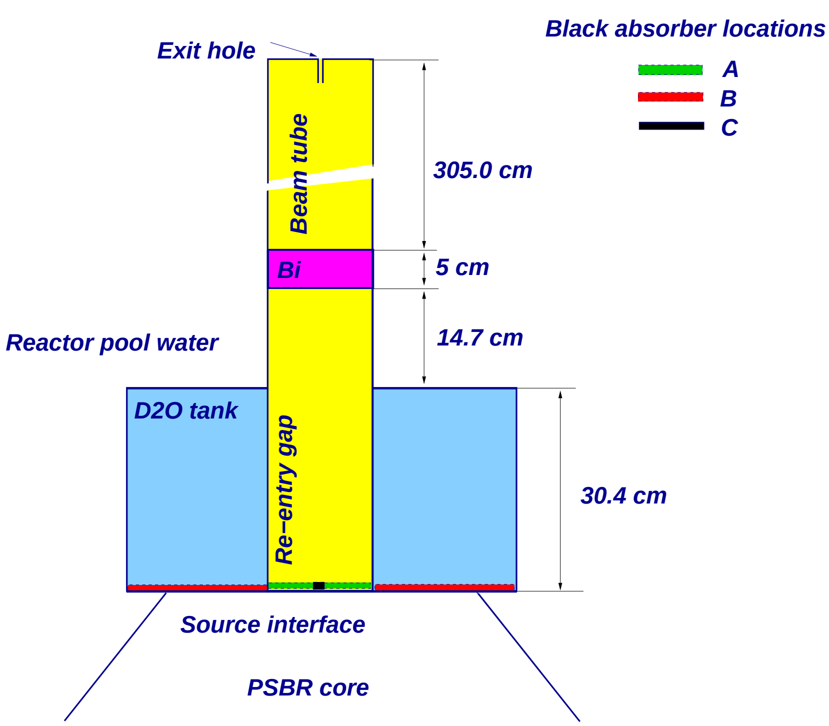
The following configurations are prepared to compute each of the three components of the neutron output:

1. By placing absorber A and C at the source interface, $\psi_{Bi}^{Base}(r, E, \mu_0)$ and $\psi_{unc}(r, E, \mu_0)$ are blocked (see Fig. 1), hence the scattering component, $\psi_{Bi}^{Side}(r, E, \mu_0)$, dominates the exiting neutron beam.

2. By placing absorber A and B at the source interface, $\psi_{Bi}^{Base}(r, E, \mu_0)$ and $\psi_{Bi}^{Side}(r, E, \mu_0)$ are blocked (see Fig. 1), hence the uncollided component,$\psi_{unc}(r, E, \mu_0)$, dominates the exiting neutron beam.

3. By placing absorber B and C at the source interface, $\psi_{Bi}^{Side}(r, E, \mu_0)$ and $\psi_{Bi}^{unc}(r, E, \mu_0)$ are blocked (see Fig. 1), hence the forward scattering component, $\psi_{Bi}^{Base}(r, E, \mu_0)$, dominates the exiting neutron beam.

Figure 1: Schematic view of the model problem configuration for the radial beam tube



In these configurations, each component is computed by directly blocking the source neutrons which generate the other two components. By evaluating this information, the search space can be reduced for the optimization problem. Furthermore, by changing the location of the Bi disk along the beam tube, its optimal location can be determined easily.

In the comparison given in the next section, the TORT code was executed on a 56x47x40 Cartesian grid with Upward-100 biased angular quadrature sets, 26 energy groups, and P_0 scattering order cross-section data. The directional boundary fluxes were computed at the outer surface of the Bi disk. Then, the angular flux emerging from the Bismuth disk is attenuated along the length of the beam, approximately 305.0 cm, tube by using a streaming operator as a post-process. [1] In this way, the outgoing angular flux is calculated at the beam tube's exit hole, a circular surface whose diameter is less than 1.0 cm.

2.2 Tangential Beam Tube Configuration

In this case the origin of the beam exit flux is expressed in only two components: forward scattering and scattering components,

$$\psi_e(r, E, \mu_0) = \psi_{Bi}^{Base}(r, E, \mu_0) + \psi_{Bi}^{Side}(r, E, \mu_0) \tag{2}$$

The methodology for the tangential beam tube is different from the radial beam tube because of the relative position of the beam tube's base to the source interface. In this configuration placing the black absorber at the source interface does not provide the desired information; rather it should be placed and arranged around the beam tube re-entry gap.

In these calculations, first a full-scattering source is computed for the model without the black absorbers. This is done by running TORT till convergence, then folding the converged flux with the scattering matrix to obtain the cell-wise scattering source. Then the black absorbers are placed in their proper locations in the model and only one inner iteration is performed by TORT with this scattering source acting as a distributed source to compute each component. In this methodology, the sum of the components overestimates the total exiting flux since both of them include the same scattering source in the re-entry gap. Hence, a reduction term should be defined to eliminate this problem,

$$\psi_e(r, E, \mu_0) = \psi_{Bi}^{Base}(r, E, \mu_0) + \psi_{Bi}^{Side}(r, E, \mu_0) - \psi_{Bi}^{Base,Side}(r, E, \mu_0) \tag{3}$$

A schematic of the model configuration of the tangential beam tube is given in Fig. 2. It includes only the D_2O drum enclosed in an aluminum cylindrical chamber, the re-entry gap of the beam tube, the Bi disk and two different black absorber locations.

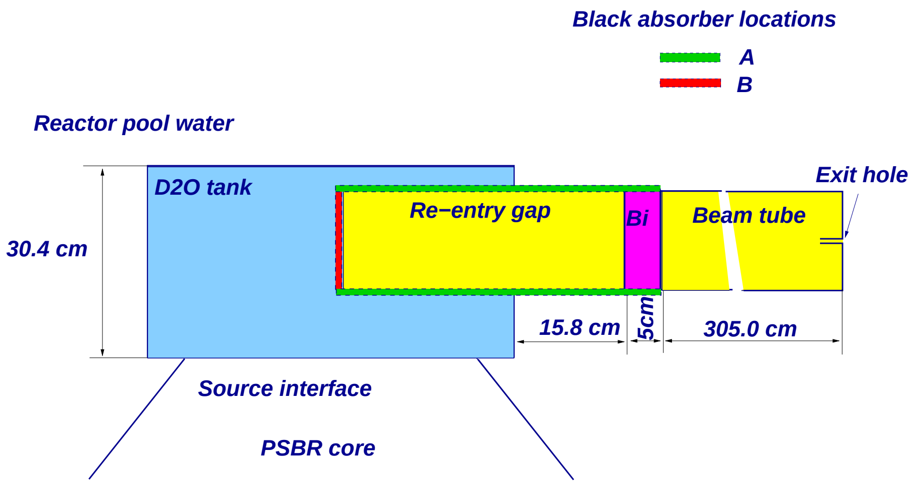
The following configurations are prepared to determine the components of the neutron output:

1. By placing a thin highly absorbing disk behind the beam re-entry gap in the moderator drum, $\psi_{Bi}^{Base}(r, E, \mu_0)$ can be blocked (see in Fig. 2), hence the scattering component, $\psi_{Bi}^{Side}(r, E, \mu_0)$, dominates the exiting neutron beam.

2. By covering the beam tube side-walls with a thin highly absorbing material, $\psi_{Bi}^{Side}(r, E, \mu_0)$ can be blocked (see in Fig. 2), hence $\psi_{Bi}^{Base}(r, E, \mu_0)$ dominates the neutron output.

3. By placing absorbers A and B at the same time, only neutrons in the re-entry gap contribute to the exit flux, hence the reduction term, $\psi_{Bi}^{Base,Side}(r, E, \mu_0)$, is computed.

Figure 2: Schematic view of the model problem configuration for the tangential beam tube



As a result, by comparing the magnitude of the neutron beam exiting the beam tube with those black absorber cases for the same moderator material, the effects of the various moderator material on ψ_e is easily compared. By evaluating this information, the search space can be reduced for the optimization problem.

3. Numerical Results

In order to test the methodology, one of the existing tangential beam tubes of the PSBR was modeled with a D_2O moderator at the beam tube entry; this is designated as the reference configuration, and various moderator materials such as H_2O, and graphite were attempted in the tank. Moreover, as an additional case, the same calculation was performed on the model with the moderator tank filled with dry air to determine the reflection effect inside the moderator tank. Then, all calculations were repeated to compute each component in Eqs. (1-3) separately by placing black absorber(s) at the proper locations described above to absorb the other components. We verify our methodology by comparing the sum of all components of the exit flux to its directly computed value. Subsequently, we determine the fractional contribution of each component to the neutron beam at the exit hole.

As a second case, the same calculations were performed on the analogous model for the radial beam tube.

Finally, we repeated the radial beam tube calculations for the purpose of determining the effect of the Bi location on the neutron output. The uncollided component does not change significantly with the location of the Bi disk. In contrast, the scattering components change depending on the Bi location, since they are almost proportional to the scalar flux in the moderator material, $\phi^{side}(r_{Bi}, E)$, near the location of the Bi disk. As a consequence, there should be an optimal Bi location at which the scattering components approach their maximum value. By changing the Bi location along the beam tube length from its original location to the source interface, we determined the optimal location of the Bi disk in the beam tube.

As a result of this case, we express the neutron output in terms of the uncollided component and the scalar flux in the moderator tank near the Bi surface;

$$\psi_e(r, E, \mu_0) = \psi_{unc}(r, E, \mu_0) + C(E) \times \phi^{side}(r_{Bi}, E) \tag{4}$$

where r_{Bi} is the relative location of the Bi disk in the beam tube and $C(E)$ is the proportionality coefficient between the scattering component and the scalar flux. By using this expression with the computed uncollided flux component and the scalar flux distribution along the beam tube length, the exit flux is calculated for any Bi location without performing further TORT calculations.

All results are given in Tables 1-3. In the tables, ψ_{exit} denotes the exit flux computed by TORT plus the streaming operators and ψ_e denotes the exit flux calculated by summing the components of the flux. The results show that the neutron output of the radial configuration with the same moderator tank, beam tube, and interface source properties is almost 2.5 times larger than the neutron output of the existing tangential beam tube configuration. The best moderator material is D_2O for both model configurations. Graphite can be selected as the second best moderator by comparing its results with the others.

The worst moderator material is H_2O due to its relatively high absorption cross-section. The configurations with air produce higher thermal fluxes than the configurations with H_2O for the tangential configuration. This is due to a larger re-entry gap created between the pool water, core, and the Bi disk by replacing the moderator material with air, thus increases the reflection rate of the neutrons from the pool water towards the beam tube exit hole. In contrast for the radial configuration, the model with H_2O produces higher thermal fluxes than the model with air since its source strength is higher than the source strength of the model with air.

The results also illustrate that the contribution of the forward scattering component of the exit flux is dominant for both radial and tangential configurations for various moderator materials. In other words, more than 80% of the output neutrons originate at the beam tube base and make their last scattering collision in the Bi disk before streaming down the beam tube to the exit hole. These results explain the tendency of our optimization algorithm in preliminary results to concentrate much of the D_2O-H_2O replacement in the region around the beam tube base. [1] Armed with the results of the present study, our future optimization searches will reduce the extent of the search space to only that region thereby significantly reducing the number of computational cells whose material content must be determined to improve beam quality. Furthermore, these results support our conclusion that the primary task of the moderator material is to reflect rather than to moderate neutrons. This is evident from the fact that while the radial beam tube configuration includes no D_2O moderator between the beam tube base and the source interface, it produces higher thermal neutron flux than the tangential beam tube configuration. Similarly, the tangential beam tube configuration with air also produces reasonable thermal neutron output without any moderator.

For the radial beam tube configuration, the scattering components increase when the Bi disk moves closer to the core interface since the scalar flux increases in this direction. As a result of this, we conclude that the optimal location of the gamma shield should be near the location at which the scalar flux in the thermal groups is maximum. Moreover, the results also show that there is a linear correlation between the scalar flux and the scattering components. Therefore by computing the scalar flux distribution in the model configuration, the exit flux can be estimated easily for the different Bi locations by using Eq.(4). Figures 3 and 4 depict the exit flux computed by TORT plus the streaming operator as well as the exit flux calculated by using Eq.(4) when the tank is filled with D_2O and graphite, respectively. The proportionality constant, $C(E)$, which is computed as the ratio of the scattering component and the scalar flux near the Bi, remains almost constant when the Bi location changes. The relative error between ψ_{exit} and ψ_e is also given in Figs. 3 and 4, and is less than 3% for various Bi locations.

Table 1: Flux and its components in the thermal groups computed by TORT + streaming operator at the beam tube exit hole for the tangential beam tube for various moderator materials

Moderator Material	Flux per energy per fission event $(n/cm^2 - eV)$					Error (%)
	ψ_{exit}	ψ_e	ψ_{Bi}^{Base}	ψ_{Bi}^{Side}	$\psi_{Bi}^{Base,Side}$	$100 \times \frac{(\psi_{exit}-\psi_e)}{\psi_{exit}}$
D_2O	5.506E-09	5.404E-09	5.376E-09	1.095E-09	1.067E-09	1.85
H_2O	1.913E-10	1.846E-10	1.832E-10	5.106E-11	4.967E-11	3.50
Graphite	4.011E-09	3.880E-09	3.857E-09	9.021E-10	8.787E-10	3.02
AIR(dry)	3.346E-09	3.305E-09	3.283E-09	0.980E-09	0.958E-09	1.22

Table 2: Flux and its components in the thermal groups computed by TORT + streaming operator at the beam tube exit hole for the radial beam tube for various moderator materials

Moderator Material	Flux per energy per fission event $(n/cm^2 - eV)$					Error (%)
	ψ_{exit}	ψ_e	ψ_{Bi}^{Base}	ψ_{Bi}^{Side}	ψ_{unc}	$100 \times \frac{(\psi_{exit}-\psi_e)}{\psi_{exit}}$
D_2O	1.335E-08	1.312E-08	1.193E-08	1.096E-09	9.975E-11	1.74
H_2O	1.041E-08	1.022E-08	9.432E-09	7.763E-10	7.784E-11	1.83
Graphite	1.259E-08	1.244E-08	1.141E-08	9.389E-10	9.487E-11	1.20
AIR(dry)	7.185E-09	7.157E-09	6.108E-09	1.000E-09	4.932E-11	0.39

Table 3: Exit beam flux and the fractional contributions in thermal groups for the model with D_2O for various locations of the Bi disk

Bi Location r_{Bi} (cm)	Flux per energy per fission event $(n/cm^2 - eV)$		Error (%)	Fractional Contribution		
	ψ_{exit}	ψ_e	$100 \times \frac{(\psi_{exit}-\psi_e)}{\psi_{exit}}$	ψ_{Bi}^{Side}	ψ_{Bi}^{Base}	ψ_{unc}
5.0	2.2721E-08	2.2646E-08	0.33	20.72	78.18	1.10
6.0	2.2315E-08	2.1651E-08	2.97	21.36	77.48	1.17
8.0	2.1968E-08	2.1411E-08	2.53	23.02	75.88	1.09
10.0	2.1577E-08	2.1224E-08	1.63	24.26	74.70	1.03
12.0	2.1160E-08	2.0822E-08	1.60	24.84	74.25	0.92
14.0	2.0735E-08	2.0388E-08	1.67	24.90	74.25	0.85
16.0	2.0336E-08	2.0051E-08	1.40	24.80	74.37	0.83
18.0	1.9600E-08	1.9323E-08	1.41	23.56	75.67	0.77
24.0	1.8570E-08	1.8279E-08	1.57	22.11	77.11	0.78
28.0	1.7041E-08	1.6727E-08	1.84	20.71	78.59	0.71
34.0	1.5979E-08	1.5709E-08	1.69	17.23	82.07	0.69
38.0	1.5009E-08	1.4821E-08	1.25	14.14	85.11	0.75
44.0	1.4449E-08	1.4211E-08	1.65	10.84	88.39	0.77
49.1	1.3354E-08	1.3122E-08	1.74	8.35	90.89	0.76

Figure 3: Comparison of the exit hole fluxes for the model with D_2O

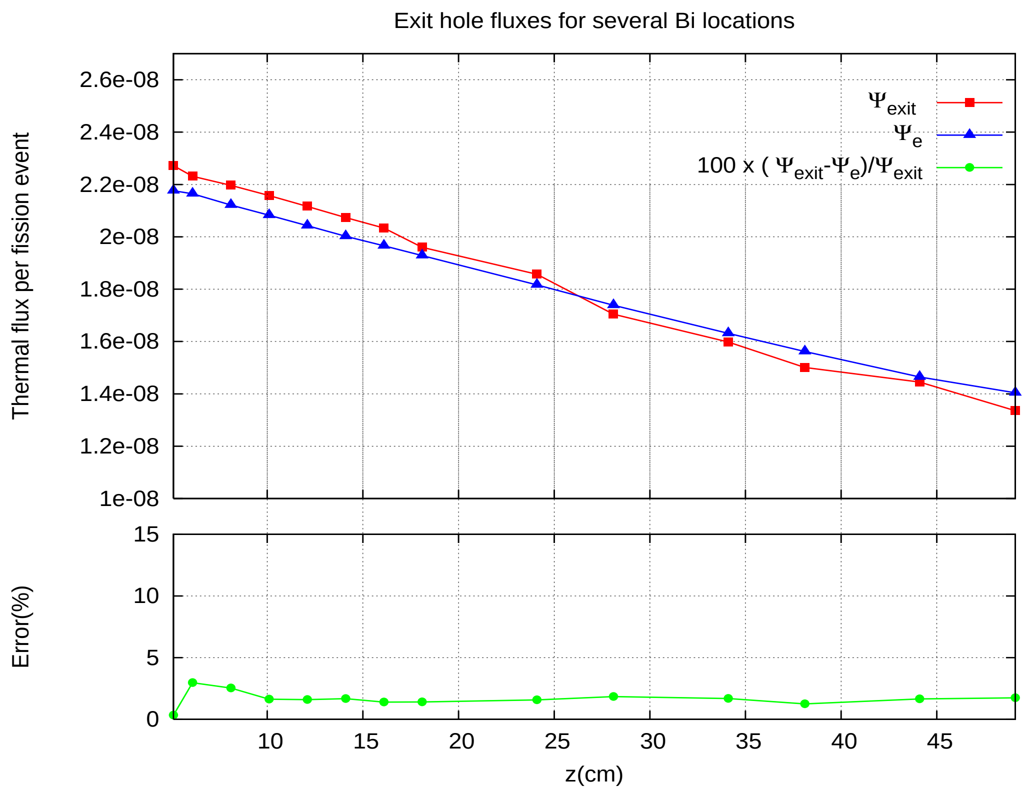
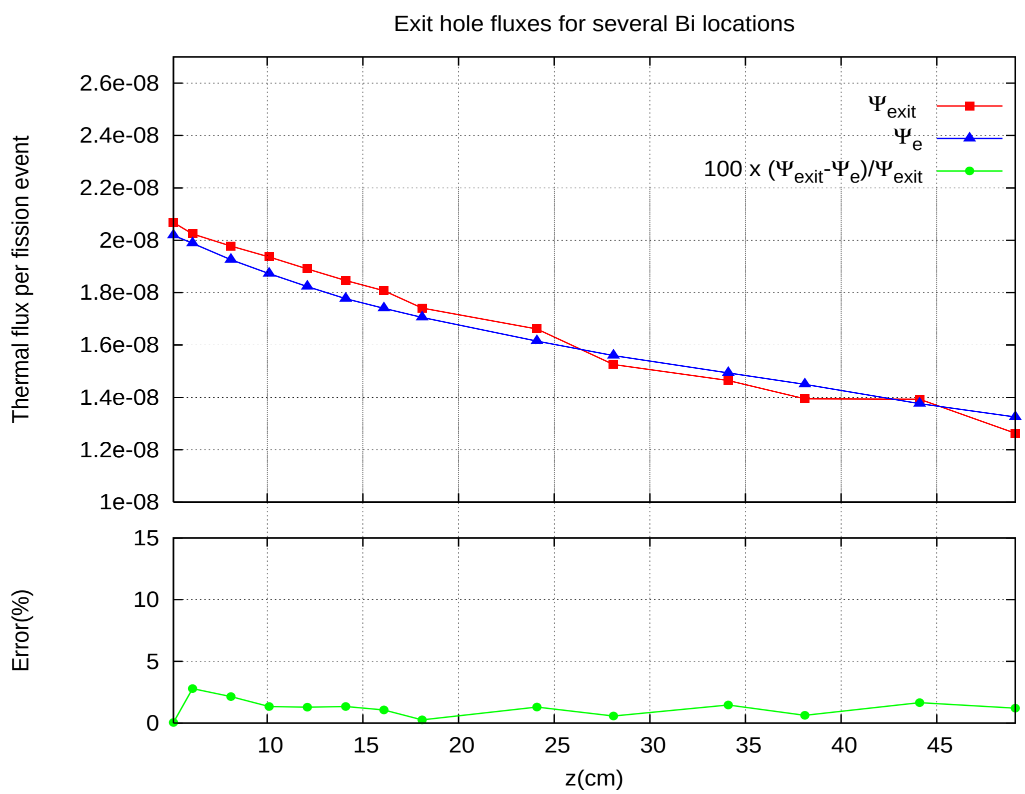


Figure 4: Comparison of the exit hole fluxes for the model with graphite



4. Conclusion

In this study, a method is introduced to reduce the search space of the optimization calculation performed on one of the beam tubes of the PSBR. The results show that D_2O is the best moderating material for this configuration and that the larger fraction of the source of the output neutrons is the forward scattering component. These results show that the preferred region for placement of a reflecting material is around the beam tube base in the search space. These also verify the results obtained by preliminary optimization calculations where the optimizer computed the optimal shape as a hemi-sphere around the beam tube base. Consequently, by developing this methodology, we can easily determine limits on the extent of the search space that affect directly the computation time of the optimization algorithm. Moreover, the results of the various moderator materials enable designing alternative moderator configurations for all the beam tubes of the PSBR.

References

1) K.B. Bekar, Y.Y. Azmy, K.Ünlü, ”Testing Optimization Sequence for the Beam Port Facility of PSBR”, International Topical Meeting on Mathematics and Computation, Supercomputing, Reactor Physics and Nuclear and Biological Applications, Avignon, France, Sept. 12-15, 2005, on CD-ROM, American Nuclear Society, La Grange Park, IL,(2005).

2) W.A. Rhoades, D.B. Simpson, ”The TORT Three-Dimensional Discrete Ordinates Neutron/Photon Transport Code” , Computational Physics and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, (1997).

3) K.B. Bekar, Y.Y. Azmy, K.Ünlü, ”TORT Modelling of the Beam Port Facility of PSBR and Comparison with MCNP”, Trans. of the American Nuclear Society, 92, 151 (2005).

4) X-5 MONTE CARLO TEAM, ”MCNP-A General Monte Carlo N-Particle Transport Code, Version 5” , Manual, Los Alamos National Laboratory, (2003).

5) R. ORSI, R. TINTI, ”BOT3P Version 3: The ENEA Bologna Pre-Processors of the DORT,TORT, THREEDANT and MCNP Transport Codes and Post-Processors of DORT and TORT” , Manual, ENEA Nuclear Data Center, Bologna, Italy, through the OECD Nuclear Energy Agency Data Bank, Issy-Les Molineaux, France, (2003).

6) R.Q. WRIGHT, J.P. RENIER, J.A. BUCHOLZ, ”ANSL-V, ENDF/B-V Based Multigroup Cross Section Libraries for Advanced Neutron Source(ANS) Reactor Studies Supplement 1” , Manual, Oak Ridge National Laboratory, (1995).