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A CASE STUDY TO TEST MOZAIK FOR DIFFERENT OPTIMIZATION PROBLEMS

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ABSTRACT

We present four different shape optimization problems based on the existing beam port facility of the Penn State Breazeale Reactor and their results obtained by the modular optimization code package, MOZAIK. Each model problem has a different beam tube configuration with the same optimization goal: to determine an optimal D_2O moderator tank shape for the given beam tube arrangement that maximizes the thermal neutron beam intensity at the beam tube exit end. In this study, the power of the automated search process was demonstrated and its capabilities were tested. In addition, the performance of the beam port was analyzed using alternative beam tube arrangements. All alternative arrangements indicate that higher thermal neutron beam intensity can be obtained at the beam tube exit end using a smaller volume of D_2O in the system than is used in the existing beam port configuration. Moreover, the results show that MOZAIK is ready for deployment to address shape optimization problems involving radiation transport in nuclear engineering applications.

Key Words: Shape optimization, modularity, beam port, TORT

1. INTRODUCTION

MOZAIK, a modular optimization code package, was developed for geometric shape optimization problems in nuclear engineering applications [1–3]. In order to test its capabilities and its performance, four different optimization model problems based on the current beam port configuration of the Penn State Breazeale Reactor's (PSBR's) beam port facility were considered. Optimization calculations were performed by defining the goal of the optimization as determining the optimal D_2O moderator tank shape for the given beam tube configuration that maximizes the thermal neutron beam intensity at the beam tube exit end.

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MOZAIK was designed as a modular optimization code sequence that performs a state space search for shape optimization problems. With the problem geometry divided into cells comprised in the “search problem domain”, and by changing the material distribution in each cell independently, the geometric shape optimization problem is translated into a state space search [1, 4]. In this approach, a specific material distribution over the search problem domain is called a “state”. The collection of all states is called the “search space”. Usually, the search sequence starts from an “initial state” which is a guess based on experience or previous calculations. The “evaluation” or “cost function” is a function representing a weighted average of several criteria; “goodness” of the shape (i.e., state) is quantified with weights reflecting the relative importance of each criterion. The objective of the search is to find a “goal state” that minimizes/maximizes the cost function over the entire search space. In this way, a number of material distributions are generated and the material distribution (goal state) is sought that optimally satisfies the given criteria. In this paper, the term “optimal” refers to the material assignment to cells in the search problem domain that minimizes the cost function among all visited states during the search sequence. The modular structure of MOZAIK was detailed in [1, 2].

A comprehensive study was conceived to demonstrate the power of the automated search process and to test its capabilities. For this purpose, four different shape optimization problems based on the existing beam port facility of the PSBR were designed. Each model problem has a different beam tube configuration with the same optimization goal. In the optimization calculations, the 3D discrete ordinates code TORT [5] was used to model neutron transport in the physics module, and the Min-max optimization algorithm [1, 6] was employed in the optimizer module. In order to evaluate the performance of the optimization calculations, the thermal neutron beam intensity at the beam tube exit for the existing beam tube configuration was also computed by TORT and denoted as “reference output”.

The results of the calculations and the performance evaluation of the code package are presented in this paper. They are meant to complement the preliminary results presented in [3] for the tangential beam tube at the same location as the existing configuration. The purpose of the additional models considered here is to explore the potential for improving the thermal beam by employing alternative locations and orientations of the beam tube itself.

2. OPTIMIZATION MODEL PROBLEMS

2.1. Neutronic Model

A schematic of the current beam port configuration of PSBR (BP-4) and its simplified computational model are depicted in Fig. 1. The TORT neutronic model of the PSBR’s beam port facility includes a drum-shaped D_2O moderator tank, a graphite reflector block behind the tank, an air gap in the moderator tank called the “reentry gap”, a bismuth gamma shielding disk at the entrance of the beam tube and the pool water surrounding the configuration. In the model shown in Fig. 1b, a boundary neutron source is defined at the PSBR core-D_2O tank interface to simulate the core neutrons migrating across this interface [1]. For this purpose, the PSBR core and D_2O moderator tank were modeled by MCNP [7]. In addition, a streaming operator was developed to compute the neutron beam intensity at the beam tube exit end without performing an expensive and inaccurate neutron transport calculation along the entire $\sim$ 3m length of the beam tube [1].

The streaming operator attenuates the angular neutron flux emanating from a surface within the beam tube (e.g., exiting face of the Bi disk) to the beam tube exit end. In this way, TORT performs transport calculations on the neutronic model to compute the angular fluxes at the exit surface of the Bi disk which are subsequently used by the streaming operator to calculate the neutron beam intensity at the beam tube exit end.

This model was used to test and validate modules of MOZAIK separately and the whole code package and its features prior to the actual optimization calculations [1–3]. At the same time, the tools necessary specifically for the optimization calculations of the PSBR were developed and tested with this model. The selected physics code, TORT, and the requisite data, such as source distribution, cross sections, and angular quadratures, were comprehensively tested with this computational model. In addition, a computational study was designed to determine the ideal mesh size for this neutronic model that yields reasonably accurate results at a reasonable computational cost (i.e., time and memory requirements).

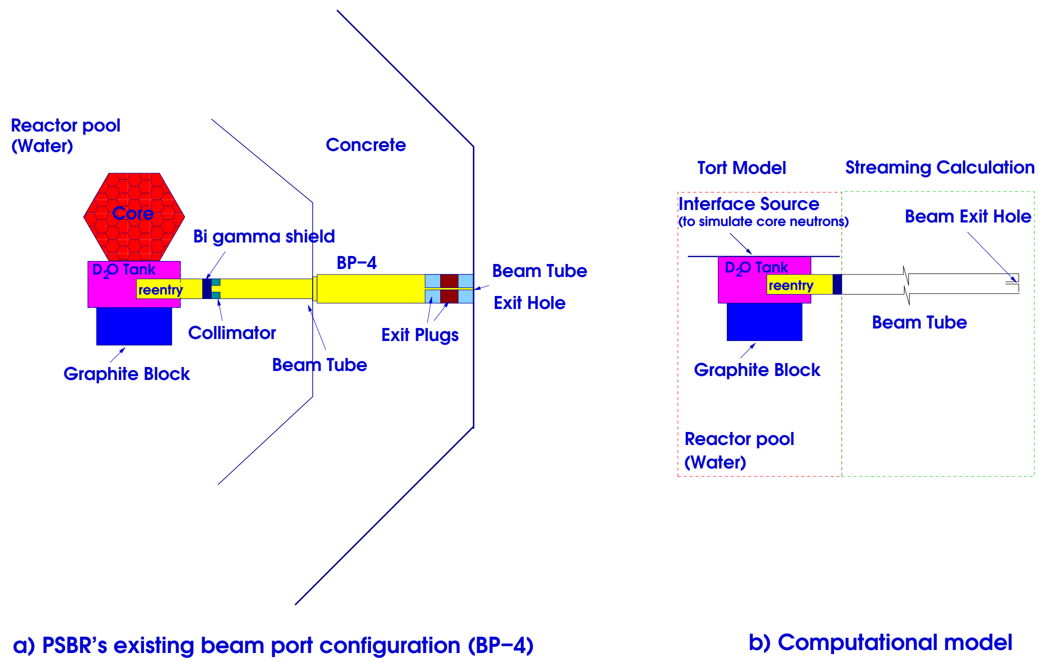

Figure 1. PSBR's existing beam port configuration and its computational model.

2.2. Computational Models for the Optimization Calculations

For the first optimization problem, a new model configuration was obtained by modifying the neutronic model presented in Fig. 1b. The new model configuration, denoted *Tangential-1*, shown in Fig. 2, was defined by (1) removing the D_2O moderator and graphite block from the neutronic model shown in Fig. 1 and filling the problem domain with water, (2) placing the beam tube at the same location as the existing tangential configuration of PSBR, and (3) placing the Bi gamma shielding disk at the junction between the beam reentry gap and the beam tube. The problem search domain was defined adjacent to the PSBR core. In addition, a source module was developed to compute the material-dependent boundary source at the interface between the PSBR core and the problem search domain while the material distribution (state) changes in the problem search domain during the optimization. This configuration was used to achieve the preliminary results presented in [2].

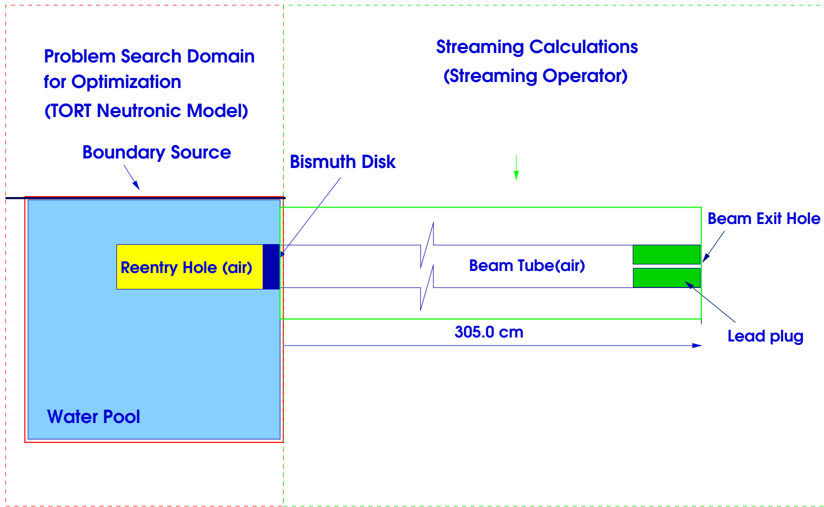

Figure 2. Computational model for the optimization calculations (Tangential-1).

Using the same model configuration with three new beam tube arrangements, three new optimization problems were designed with (1) a tangential beam tube placed adjacent to the core interface, denoted *Tangential-2* (see Fig. 3a); (2) a radial beam tube placed away from the core interface, denoted *Radial-1* (see Fig. 3b); and (3) a radial beam tube placed adjacent to the core interface, denoted *Radial-2* (see Fig. 3c). Four different optimization calculations were performed by MOZAIK to test the capabilities of the code package and to evaluate the optimal D_2O tank shapes produced by each model. In the three new models shown in Fig. 3, the dimensions of the beam tube, the reentry gap, and the Bi disk were fixed as those in the existing beam tube configuration.

3. NUMERICAL RESULTS

The neutron beam intensity at the beam tube exit end for the existing beam tube configuration depicted in Fig. 1b was computed by TORT and the streaming operator, and it was denoted as the reference value. Then, the optimization calculations were performed, and the calculated optimal values were compared with the reference value to determine the improvement in the thermal neutron flux yield due to changes in the D_2O shape. In the calculations, the Min-max search algorithm was used with a simple cost function defined to guide the search algorithm toward the goal of the optimization problem.

In order to speed up the search process, one of the most important features of MOZAIK, *dual mesh support*, which provides coarse meshing for the optimizer module and fine meshing for the physics module, was enabled. For the same purpose, dynamic scheduling was also enabled to

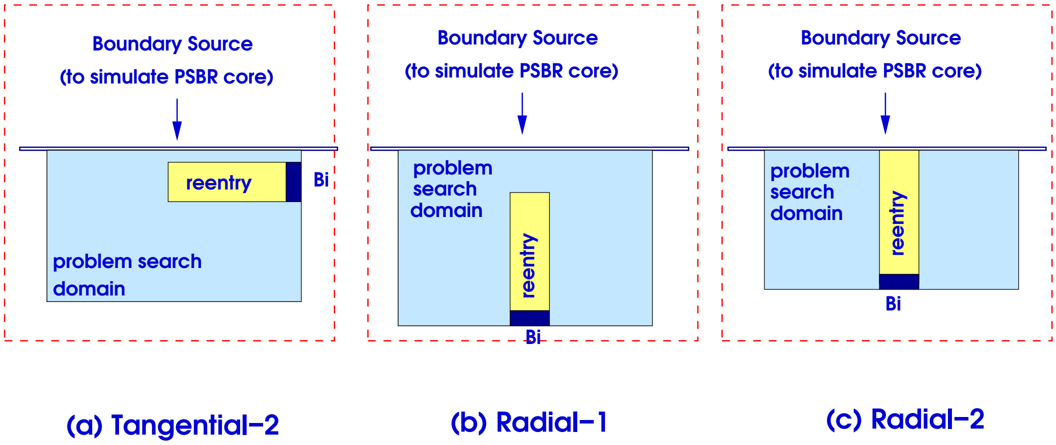

Figure 3. Model problems for optimization calculations.

balance the computational load among the participating processors while running MOZAIK's physics module on different states at the same search level concurrently on multiprocessor computers.

In addition, a new source module was designed to express the source parameters in terms of the material distribution as it changes in the search problem domain during the optimization sequence by performing artificial neural network calculations. Using this source approximation eliminated the more expensive MCNP simulations to obtain the material-dependent boundary neutron source during the optimization. In order to test the performance and success of the new source module after MOZAIK completes the optimization problem, real neutron boundary sources are computed by MCNP with the best state data (the material distribution that produces highest neutron beam intensity at the beam tube exit end in one optimization iteration) of every other five optimization iterations. Subsequently, TORT was executed for the state data and corresponding real neutron boundary source. A comparison between the results for the real source and the new source module is presented in Fig. 4. Although there is a difference between the results based on the approximate source module and the results with the real source, this difference is reasonably small in magnitude as shown in Fig. 4.

The reference value given in Table 1 was computed as 4.41×10^{-9} n/cm^2-s per fission event by TORT and the streaming operator. MOZAIK determined the optimal shapes for the four model problems in 217, 138, 123, and 153 optimization iterations, for Tangential-1, Tangential-2, Radial-1, and Radial-2, respectively. In order to smooth the produced optimal shapes and make them more amenable to standard fabrication processes, an independent shape verifier/smoothing module was developed and was applied to the optimal shapes. After producing the smoothed shapes, the module generated a neutronic model with this shape for TORT and the streaming operator, and computed the thermal neutron beam intensity at the beam tube exit for the configuration with the smoothed optimal shape. This computation is based on an actual interface neutron source.

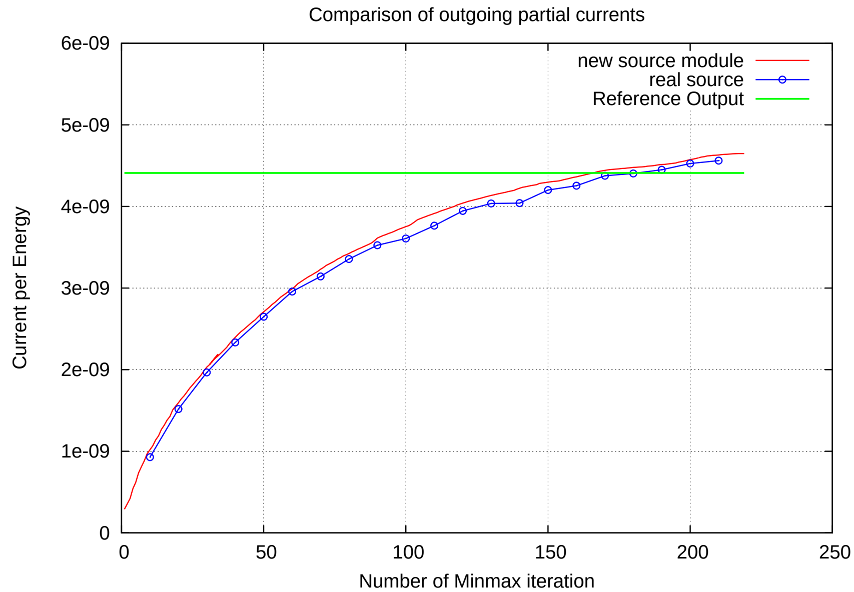

Figure 4. Comparison of the thermal neutron partial current at the beam tube exit end computed by TORT and the streaming operator using the new source approach and the real source.

Table I. Outgoing partial current per energy per fission event in the thermal group computed at the beam tube exit end by TORT and the streaming operator for four beam tube arrangements

	Tangential-1 (existing conf.)	Tangential-2	Radial-1	Radial-2
Current Shape	4.41e-09	N/A	N/A	N/A
Optimal Shape	4.83e-09	6.12e-09	4.88e-09	7.88e-09
Smoothed Shape	5.84e-09	7.13e-09	4.63e-09	8.67e-09

The neutron beam intensities at the beam tube exit ends, which were computed for each model problem with the obtained optimal shape and for its smoothed version, are given in Table 1. For each model problem, the difference between the results of the two models (with/without smoothing) is due to the usage of a coarser mesh structure for TORT in the optimization calculations than the mesh applied in the transport calculation with the smoothed shape, and the source approximation in the source module as well as the numerical errors incurred in the physics solution methods and algorithms.

Optimal shapes obtained by MOZAIK and their smoothed versions for the four optimization problems are shown in Fig. 5. These four optimal shapes indicate that MOZAIK's optimizer module first prefers placing D_2O in the region around the beam tube base and beam reentry gap within the search problem domain as these locations contribute more significantly to the thermal neutron beam intensity at the beam tube exit end. Because the primary effect of the D_2O in the system is to reflect thermal neutrons back into the core rather than moderating fast neutrons escaping the core into the thermal range before streaming into the beam tube.

Results of the four MOZAIK applications demonstrate that the existing drum-shaped D_2O tank with the current beam tube arrangement is not an optimal design. The results indicate that the Radial-2 model produces the highest thermal neutron output at the beam tube exit end among all considered configurations; it improves the thermal neutron beam intensity by a factor of 1.8 compared to the existing beam tube arrangement. Because its base is so close to the core interface, most of the core neutrons escaping from the core enter the beam reentry gap directly, and the vast majority contribute to the thermal neutron beam at the beam tube exit end. In addition, for this model configuration the fast neutron contribution to the neutron beam at the beam tube exit end is almost as low as the contribution in the other model configurations because the PSBR hydride fuel elements yield a softer spectrum at the core-tank interface.

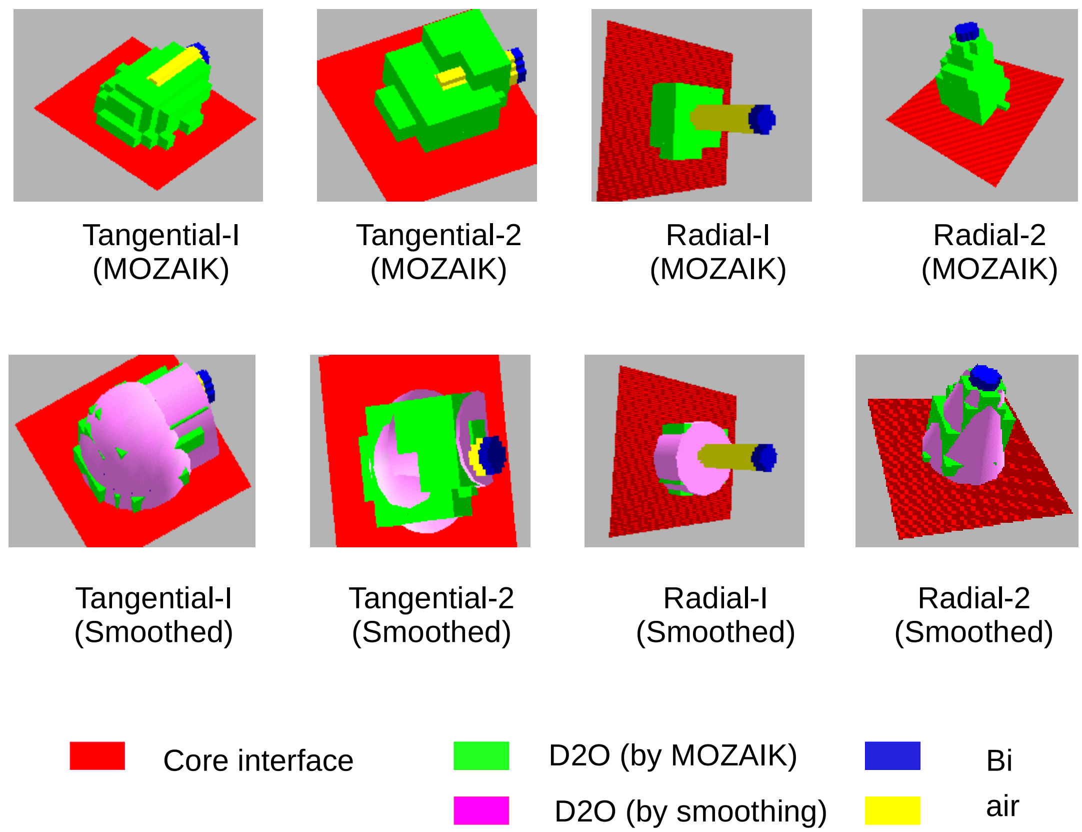

Figure 5. Optimal shapes obtained by MOZAIK and their smoothed versions for four model configurations (water cells are not shown in the sketches).

The Tangential-2 model, in which the beam tube is placed near the core interface, is the second-best model. It improves the thermal neutron beam intensity by a factor of 1.4 compared to the existing beam tube arrangement. For the optimal tank shape for this case, the volume of D_2O is almost one-third of the current moderator tank's volume.

Radial-1 with the optimal tank shape produces a neutron beam intensity at the beam tube exit end comparable to that produced by Tangential-1. This is not surprising because these two model configurations have similar neutronic features, namely, the neutrons coming from the core have to travel almost 11 cm through D_2O before reaching the beam reentry hole. In other words, the neutron scalar flux at the beam tube base for these two configurations is of comparable magnitude.

The variation of thermal neutron beam intensity at the beam tube exit end with the amount of D_2O added to the system by MOZAIK's optimizer module is presented in Fig. 6. Figure 6 indicates that with a proper shape half the amount of D_2O currently used in the moderator tank produces the same thermal neutron intensity at the beam tube exit end. In other words, designing a system with the proper shape increases the output using a smaller amount of moderator material and therefore saves space around the beam tube devices. This might enable an individual moderator chamber design for each beam tube if several beam tubes are being placed around the reactor core.

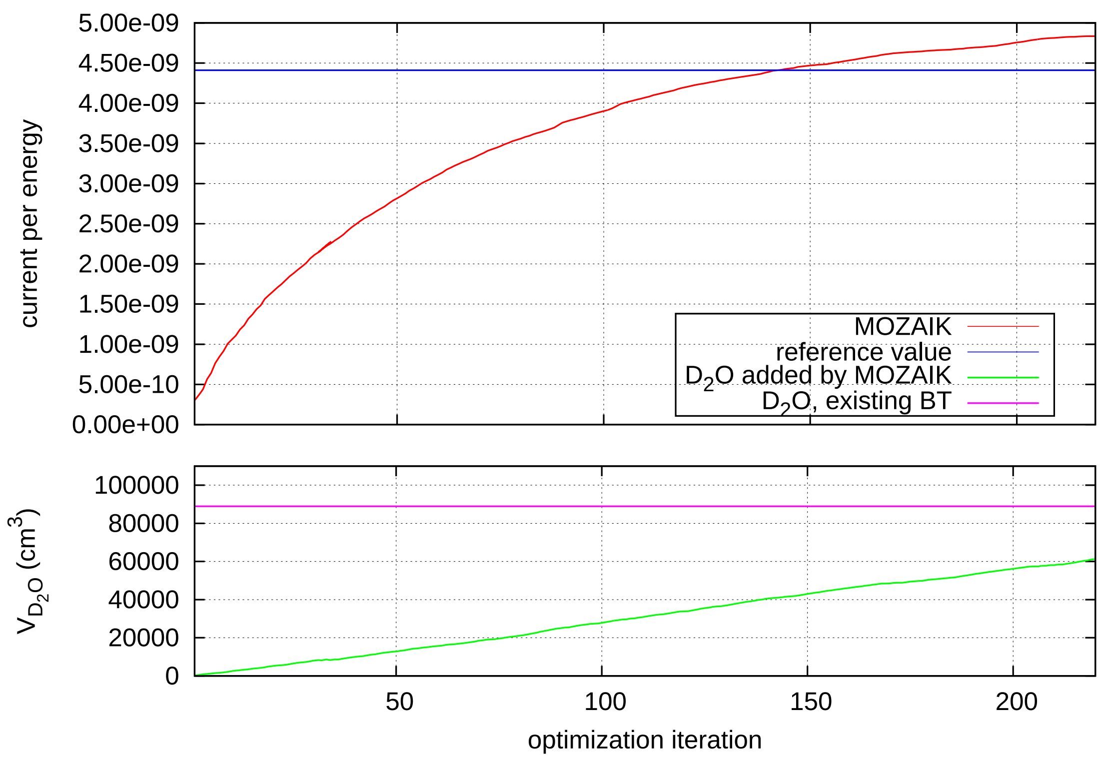

Figure 6. Change in the neutron beam intensity and D_2O moderator material during the optimization for the Tangential-1 model.

It is worth noting here that the goal of the optimization exercise was limited to maximizing the thermal neutron beam intensity at the beam tube exit end. In reality, experimentalists would also demand a low gamma beam intensity, which typically tends to prefer tangential beam arrangements.

4. CONCLUSIONS

In this paper, four different shape optimization problems and their optimal results obtained by the modular optimization code package, MOZAIK, are presented.

Armed with the results of this study, we suggest that moving the beam tube closer to the core interface increases the neutron beam intensity at the beam tube exit end for both the tangential and radial beam tube configurations. All alternative arrangements show that a higher thermal neutron beam intensity can be obtained at the beam tube exit end using a smaller volume of D_2O in the system. This enables an individual moderator chamber design for each beam tube if several beam tubes are being placed around the reactor core.

All of these results show that MOZAIK is viable, effective, and ready for deployment to address shape optimization problems involving radiation transport in nuclear engineering applications. Its modular feature and multiprocessing capability at the search level encourage its use for shape optimization problems in nuclear applications where many radiation transport codes lack parallel execution capability.

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