A Novel Compact Core Design for Beam Tube Research Reactors

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INTRODUCTION

Research reactors can generally be categorized into three different types based on their main purpose of utilization (although many of them are multi-purpose reactors): Material test reactors (MTR), isotope production reactors, and beam tube reactors [1]. The materials test reactor principally aims to investigate radiation damage by mostly fast neutrons in fuel or structure materials. The isotope production reactor is mainly used to produce radioactive isotopes or sources, and also to dope materials with stable elements via nuclear transmutation with thermal neutrons. And the beam tube reactor primarily intends to provide beams of slow (i.e. thermal, cold, or hot) neutrons to allow scattering experiments on samples in many fields of science and research. During design or construction of a research reactor with a primary utilization purpose, exclusive considerations must be taken into account to meet the distinct application objective of the reactor [2].

In recent decades, beam tube research reactors have become the largest community of users worldwide, and the number of neutron beam users continues to increase. One significant reason for this trend is the result of the ever-growing neutron scattering instrumentation and technology, which enables new kinds of research. In order to meet the continuing demand of potential neutron beam users in the near future, several countries around the world have been building new beam tube reactors over the past few years [3-7]. The present research reactor (National Bureau of Standards Reactor, NBSR) at the NIST (National Institute of Standards and Technology, campus at Gauthersburg, MD, USA) Center for Neutron Research has been in service as a major neutron source for almost 50 years, and preliminary research is under way for a replacement beam tube research reactor with the primary purpose of providing quality cold neutron beams for experiment instruments [8].

Among those recently developed or proposed neutron beam reactors [3-7], the highest design priority is given to reactors with a compact core concept [9], which is characterized with a small-size core with a high power density. A compact core is capable of producing a high thermal neutron flux in a large volume outside of the reactor core, where beam tubes can be placed to extract neutrons for scattering experiments. Characteristics of the compact core concept include: the active core volume is made as small as possible for a given reactor power; the core is surrounded with a moderator (reflector) of high quality and large volume to maximize the thermal flux production; the reactor power is chosen as high as possible to obtain a high absolute value of the thermal flux. Fig. 1 shows a typical compact core scheme, in which the light water cooled core is situated in the center of the reactor and is surrounded by a large volume of heavy water in a cylindrical tank. The reflector tank is immersed in a light water pool which functions as both thermal and biological shielding of the reactor.

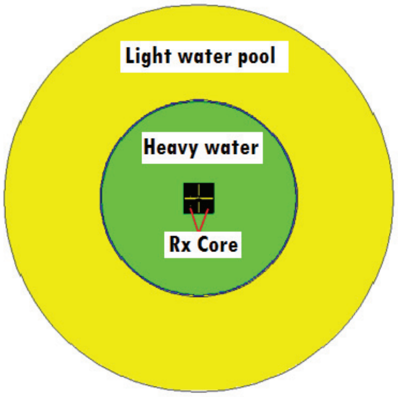

Fig. 1. Schematic of a compact core configuration.

In this summary, we propose a novel compact core design for beam tube reactors, in which a horizontally split layout of fuel elements is employed for the purpose of realizing maximum thermal flux in the reflector. The primary objective of this design will be optimization of cold neutron production in the replacement reactor of the NBSR [8]. The performance of the split core was evaluated with MCNP6 [10] modeling and simulation. The superiority of the design was verified by performance comparison of two contemporary core designs with almost same amount of fissile material loading and identical power and fuel cycle length.

HORIZONTAL SPLIT CORE

One commonly used fuel element (FE) in beam tube reactors consists of MTR curved fuel plates, which are typically composed of a uranium-enriched fuel meat clad with aluminum alloys. Some parameters of the fuel element, such as the volume of fuel meat in a fuel plate and the number of fuel plates in a fuel element, are normally determined by utilized fuel type, reactor power, and fuel residence time in the design. Detailed description and optimization of fuel element design are outside the discussion scope of this summary; for simplicity, a standard 17-plate fuel element was adopted for the core studies here. The geometry and external dimensions of the model fuel element are similar to the fuel presently used in the NBSR, and more information about the fuel element can be found in Ref. [11]. However, the vertical gap in the existing NBSR fuel element was removed for compact design purpose, and low enriched uranium (LEU) fuel was used to comply with existing non-proliferation policy. The LEU fuel used in the study is U_3Si_2/Al dispersion fuel with U-235 enrichment 19.75%. For simplification, the fuel plates are modeled without curvature in MCNP. The fuel meat has a rectangular shape with embedded fuel meat dimensions of 60 cm long, 6.134 cm wide, and 0.066 cm (26 mil) thick. Under this design, the calculated U-235 mass in a fresh fuel element is 391.47 gram.

As stated in the introduction, a compact core concept was embraced in the study, and thereby the inverse flux trap principle [9] was fully extended in the design. The flux trap was assumed to occur in easily accessible locations in the reflector tank to maximize the thermal flux that can be readily extracted for neutron experiments. Based on this simple argument, and also inspired by the vertically split fuel element design in NBSR [11], a horizontally split core was proposed. The innovative fuel element radial layout scheme of the split core is illustrated in Fig. 2.

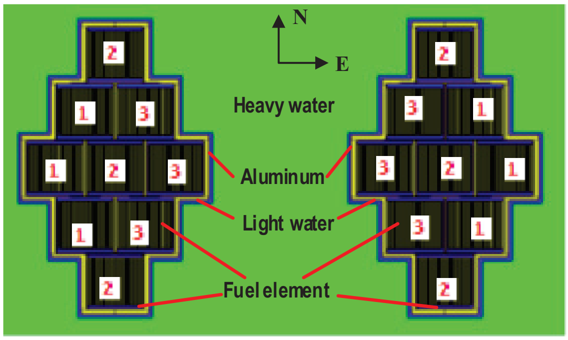

Fig. 2. Split Core with 18 Fuel Elements Layout

As shown in Fig. 2, the split core consists of 18 fuel elements that are placed into two horizontally split regions. Each region consists of 9 fuel elements and represents a half core of the reactor. The core regions are isolated from the reflector by core boxes in an irregular diamond shape (see Fig. 2). The fuel elements in those core regions are close-packed with a hexagonal lattice. The two core regions are cooled and moderated by light water, and surrounded by a large volume of heavy water reflector. The core boxes separate heavy water and light water. The thermal flux trap between the core halves provides locations for neutron beams, and in the proposed design liquid deuterium cold neutron sources will be placed there.

To highlight salient characteristics of the horizontally split core design, two other compact core designs were also studied with fuel element layouts similar to the Australian OPAL reactor core with 16 FEs [5] and the China Advanced Research Reactor (CARR) core with 20 FEs [3]. The outer dimensions of the reflector tank and light water pool in all designs remained the same; the only differences existing between them were the number of FEs and FE arrangement scheme in the compact core. Detailed fuel element layouts for 16 FE core and 20 FE core are depicted in Fig. 3 and Fig. 4, respectively (the colors used for different materials match those of Fig. 2).

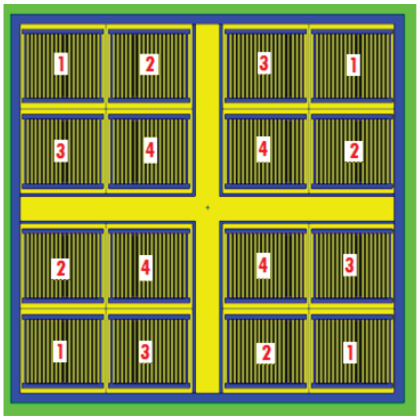

Fig. 3. 16 Fuel Element Core

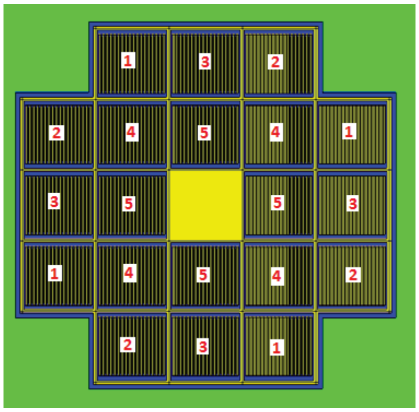

Fig. 4. 20 Fuel Element Core

To achieve a consistent comparison, all the cores discussed above were simulated at 20 MW thermal power with operational cycle length 30 days. The fuel element described above was used in all the cores. The equilibrium core was achieved by applying a standard out-in fuel loading strategy and using a multiple-batch fuel management scheme [12]. For simplicity, the number of fuel batches used for the 16 FE core, 20 FE core and 18 FE split core are four, five and three, respectively. The batch numbers of the fuel elements in the core are shown as the red index numbers in Fig. 2 - Fig.4.

RESULTS

Control elements of the cores are not modeled in this study. Rather, an end of cycle (EOC) fuel inventory is obtained and used for the core performance calculations [13]. The unperturbed radial flux behaviors in thermal and fast groups at EOC for the three cores are depicted in Fig. 5. These fluxes were extracted in the mid-plane of the cores, and only fluxes in the radial direction with highest thermal flux are presented. Since the 16 FE core and 20 FE core are approximately cylindrically symmetric, the fluxes from these cores represent the average radial flux behavior in the cores. However, due to the unique configuration of the split core, the radial fluxes will certainly be different in different radial directions, and the ones shown in Fig. 5 were extracted from the direction along the south to north axis as shown in Fig. 2.

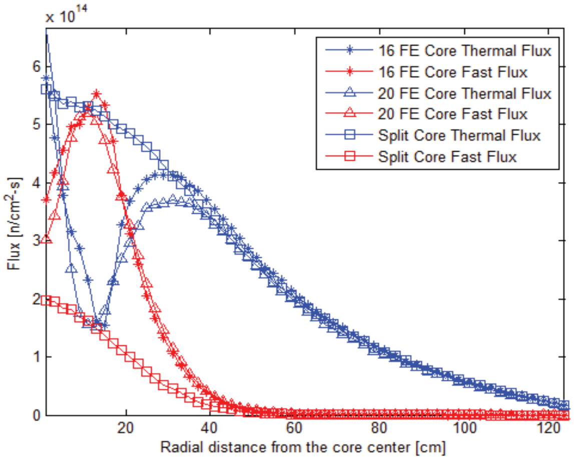

Fig. 5. Unperturbed radial flux behavior at EOC for the three cores.

The advantages of the split core can be readily identified by spotting the radial thermal flux behavior in Fig. 5 in terms of the maximum thermal flux (MTF) and its location. Moreover, the fast fluxes are significantly depressed in the locations with high thermal fluxes in the split core design. This salient property will definitely enhance the accessibility of fluxes in the core because a major component of the heat load to cold neutron sources is due to fast neutrons. It should also be noted that a radial beam tube placed along the south-north axis in the split core design will not view the fuel directly, which improves the quality of the cold neutron beam extracted by the proposed approach [8].

To quantitatively compare the features of the split core concept, some important figures of merit (FOM) for beam tube type research reactors were also evaluated for the three designs shown in Fig. 2 - Fig. 4. Table I shows a comparison of the resulting FOM. The performance of the split core is superior to the other two designs in terms of qualify factor and effective volume fraction, which are the two most important quality indicators for beam tube reactors. The definition of quality factor and effective volume fraction are given at the bottom of Table I.

Table I. Figures of merit of the three cores

Core Type	16 FE Core	20 FE Core	Split Core
Max. ϕ_{th} in reflector ($\times 10^{14}$ n/cm^2-s)	4.32	3.88	5.62
Max. ϕ_{th} occurs radial location (cm)	29.00	31.00	0.00
Quality factor[a] ($\times 10^{13}$ MTF/MW$_{th}$)	2.16	1.94	2.81
Effective volume fraction[b] (%)	27.29	23.20	36.37

[a] Defined as the ratio of maximum thermal flux (MTF) to the total thermal power of the reactor

[b] Defined as the fraction of volume with thermal flux greater than 3×10^{14} n/cm^2-s in the reflector tank.

The power distributions of the cores at EOC were also calculated using MCNP6. Table II summarizes the power peaking factors (PPF) estimated for the three different cores. The axial PPF and the fuel element-wise PPF are similar in all three core designs, whereas the total PPF and the plate-wise PPF of the split core are slightly higher than those of 16 FE and 20 FE core. However, they still stay at an acceptable level based on recent thermal limit condition analyses performed on LEU fueled reactor [14]. Moreover, the peaking factors may be further mitigated with more refined studies on the design.

Table II. Power peaking factors (PPF) of the three cores

Core Type	16 FE Core	20 FE Core	Split Core
Total PPF	2.14	2.25	2.45
Plate-wise PPF	1.65	1.68	1.91
Fuel Element-wise PPF	1.05	1.14	1.10
Axial PPF	1.23	1.24	1.21

Comparisons of the axial power distribution (normalized to total thermal power) for the hot channel and average channel in three cores are illustrated in Fig. 6. Here the channel is defined as the flowing coolant area between two neighboring plates of a fuel element. As seen in the figure, the averaged axial power distribution of the threes cores are almost identical, whereas the split core has higher power factors in the hot channel. The acceptance of the power factors will require a detailed safety analysis of the design. The results presented here simply demonstrate that the advantageous flux behavior of the split core is achieved without significantly skewing the power distribution of the core.

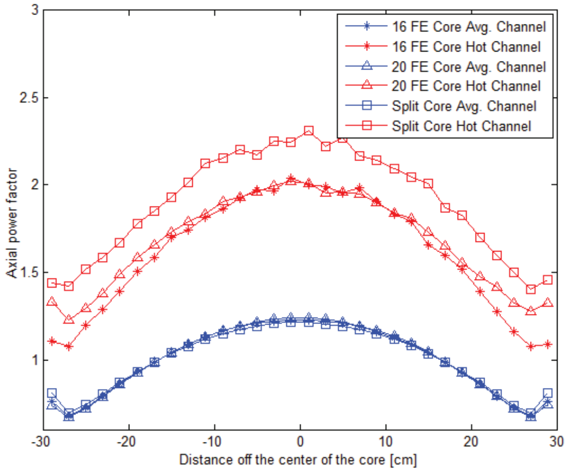

Fig. 6. Axial power distribution for the hot channel and average channel at EOC for the three cores.

CONCLUSION

This summary describes a new proposed compact core design for beam tube research reactors with a novel fuel element geometry arrangement. 18 MTR-type plate fuel elements were evenly placed in two horizontally split regions for the purpose of achieving higher thermal flux and acquiring more accessible spaces in the reflector. Preliminary results from MCNP calculations verify the superiority of the split core by comparing the basic core performance of the new design to that of the other two cores similar to currently existing reactors. This design is especially well suited to installation of two or more cold sources, since the available locations will have high thermal flux and very low fast flux.

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