Feasibility Studies on a Hexagonal-Lattice Core for a World-Class Cold Neutron Source

Dylan Prévost,[1] Zeyun Wu,[2, 3] Robert E. Williams[2]

[1]*Department of Nuclear Engineering, Texas A&M University, College Station, TX 77840 USA*
[2]*NIST Center for Neutron Research, 100 Bureau Drive, Mail Stop 6101, Gaithersburg, MD 20899 USA*
[3]*Department of Materials Science and Engineering, University of Maryland, College Park, MD 20742 USA*
prevost@tamu.edu, zeyun.wu@nist.gov, robert.williams@nist.gov

INTRODUCTION

Cold neutrons have kinetic energies less than 5 meV and wavelengths greater than 4 Å. They can be transported over tens of meters through super-reflecting neutron guides with minimal losses. Cold neutrons are used to investigate the structure of larger molecular systems such as biological materials, polymers and aggregates, due to their preferential interaction with light elements and general ignorance towards heavy ones. Intense beams of cold neutrons are obtained from slowing down a source of thermal energy neutrons – which may be from either a research reactor or spallation neutron source – through some cryogenic moderator such as liquid hydrogen or deuterium. The present reactor at the NIST Center for Neutron Research (NCNR) – NBSR – is such a cold neutron source (CNS) facility which provides cold neutron beams for over 2,000 scientists performing various experiments annually.

Feasibility studies on a replacement reactor for the NBSR are underway at NCNR with the primary purpose of optimized cold neutron production. Low enriched uranium (LEU) fuel is required for the new reactor to conform to nuclear non-proliferation agreements. The low thermal power rate of 20 MW is taken as a priority with a fuel cycle length designated as 30 days. A horizontal split compact core with a large D_2O reflector tank is currently proposed and studied, with the expectation of achieving much better cold neutron performance than the present NIST reactor (NBSR) [1]. A preliminary core design has been completed using MCNP6 modeling and simulation [2]. The physics performance characteristics of the proposed new core indicate that the new design is competitive with the most notable existing advanced cold neutron sources [3].

In previous studies, only rectangular shaped fuel elements were considered because they have similar external dimensions as the NBSR fuel elements [4]. However, from a compact core standpoint, a square lattice is not the most effective geometry for a tight configuration. Moreover, the previous studies also showed that the square lattice of the fuel elements left little room to accommodate vertical insertion blade-type control elements. As a result, all control blades had to reside in the D2O reflector, which made the design cumbersome (in that case the control blades must penetrate the reflector tank) and neutronically uneconomical.

In this summary, a preliminary feasibility study on a hexagonal core lattice is performed to render an alternative geometry for the new reactor (HEX core) to provide sufficient space for the control elements. The identical LEU fuel (U_3Si_2/Al) with U-235 enrichment 19.75% is used in the new design. The maximum thermal power and fuel management scheme remain the same as the previous investigations (three 30-day cycled batches for each batch of three fuel elements). The horizontal split compact core concept is also applied in the hexagonal lattice core design, with the objective of creating maximum thermal flux traps between the split core halves. A detailed description of the model for the hexagonal lattice core is presented in the following section.

HEXAGONAL LATTICE CORE

An optimized hexagonal-lattice core design which conserves lattice element volume was conceived (see Fig. 1), in order to pursue the objectives of (1) novel spatial

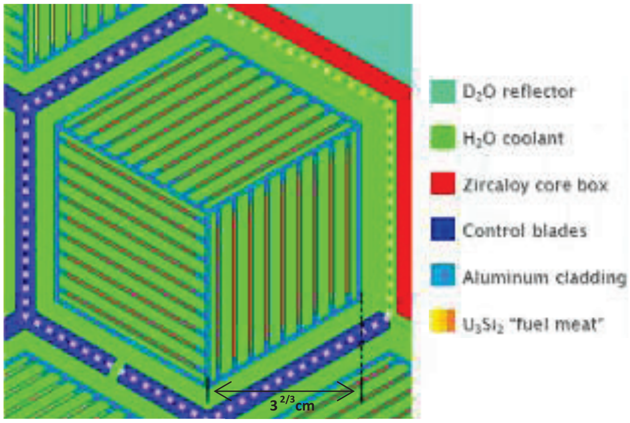

Fig. 1. Planar view of the hexagonal fuel elements at the mid-plane. The white segmented line defines a single lattice element. Yellow, light orange, and dark orange denote fuel at different depletion values. Note that the true design will feature curved fuel plates for mechanical fuel integrity purposes; this discrepancy is deemed neutronically insignificant for the purposes of this study.

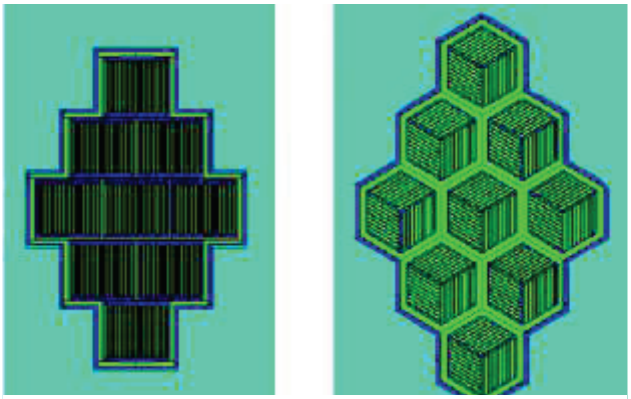

Fig. 2. Core-half designs for the prior square-lattice design (left) and the newly proposed hexagonal-lattice design (right).

allowance for vertical-insertion control blades, (2) fuel economy, (3) heat removal capability, and (4) thermal neutron flux peaking in the flux trap. The general design philosophy is to create a more intimate geometry for the uranium fuel – beyond simply what is provided by the nature of the new hexagonal lattice – which doesn't sacrifice operational integrity. The vertical length and thickness of the fuel plates were not altered, namely they have the same dimension as the ones in the rectangular shape fuel: 60 cm in length and 0.066 cm (26 mil) in thickness. Each hexagonal fuel element has been designed as three conjoined rhombic arrangements of 9 parallel fuel plates in each – an optimal number of plates determined from basic geometric principles and desired ratio of fuel volume to inter-plate (chimney) coolant volume. Note the rectangular shape fuel element has 17 fuel plates and these plates are flat in the model but would be curved in reality. A schematic view of the core-half for the prior square-lattice and current hexagonal-lattice design is shown in Fig. 2. Each core-half consists of 9 fuel elements.

Table 1 compares the fuel, coolant, and structure (Al-6061) volume in the square-lattice fuel element and HEX-lattice. It can be seen that the three components almost remained the same amount in the fuel element in terms of volume fraction. The total fuel mass is reduced about 5.5% from the previous fuel element, which is more economical in the fuel utilization, but the benefit would need to be justified by neutronic performance. The light-water coolant fraction was slightly increased and distributed away from the center of each fuel element, which reduces neutron capture near the fuel without affecting heat removal capabilities. A dramatic reduction in the volume of structural material was determined acceptable, providing the structural rigidity of the hexagonal design and the neutronic benefits associated with reducing aluminum content in the core. However, all these alterations must be justified through several series of MCNP6 KCODE calculations, and the most favorable iterations guide the development of the various component dimensions.

Table I.Inventory Comparison of the fuel element (FE)

Quantity	Sq. Lat. FE	Hex Lat. FE
Fuel vol. (cm^3)	412.94	390.26
Coolant vol. (cm^3)	2379.33	1952.23
Structural vol. (cm^3)	1203.89	1016.86
Fuel fraction (%)	9.60	9.07
Coolant fraction (%)	62.45	67.32
Structural fraction (%)	27.95	23.61

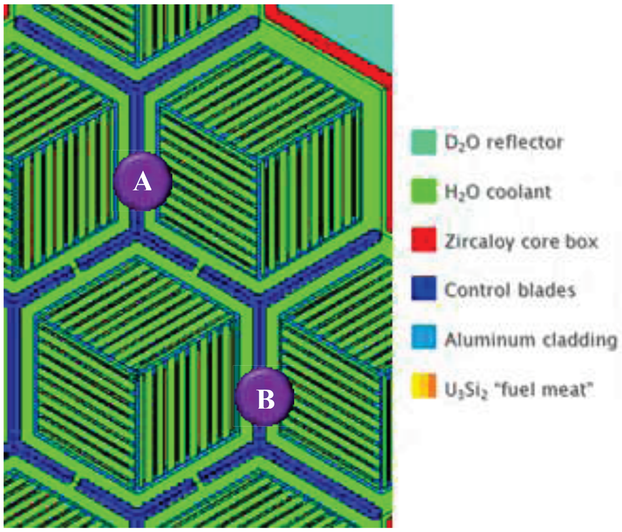

Fig. 3. Final control blade design. All blades assume one of two specific shapes, type-A or type-B, depending on the blade's location in the core lattice. There are eight blades in total, four in each core half. Note that the blade thickness has been augmented in this image solely for illustrative purposes.

RESULTS

Design alterations were performed on an item-by-item basis until all components of solely the two core halves, under the given physical and operational constraints, were optimized for neutron multiplication (k_{eff}); this includes the design of the control blades (see Fig. 3).

Upon realization of the current HEX core design, the operational parameters of the 1 mm-thick control blades were shown to conservatively meet those required by the NRC licensing restrictions for NBSR [4], and were in fact

Table II. Performance parameters for HEX core's combined eight control blades at the start and end of a 30-day fueling cycle (1.00E+6 active histories at 293°K)

Value	Startup (SU) fuel	End-of-cycle (EOC) Fuel
CBH	~2.0 cm	~14.0 cm
ρ_{ex}	8.27% Δk/k	1.58% Δk/k
SDM	19.63% Δk/k	25.04% Δk/k
TBW	32.1% Δk/k	35.0% Δk/k

more favorable. These requirements state that (1) excess reactivity (ρ_{ex}) cannot exceed 15% Δk/k, (2) shut-down margin (SDM) must exceed 3% Δk/k, and (3) total blade worth (TBW) must exceed 25% Δk/k. These values for HEX core – calculated by MCNP simulations – are summarized in Table 2. The relatively low critical blade heights (CBH, expressed in relation to the core mid-plane), high ρ_{ex} levels, and ample SDMs achieved by the current control blade design demonstrate the ease of controlling the reactivity in the newly configured core geometry. While the eight individual control blades have varying reactivity worth values, only the two "type-B" blades furthest from the center of the core in each core half deviate significantly in worth from the rest; these blades feature the greatest individual worth values.

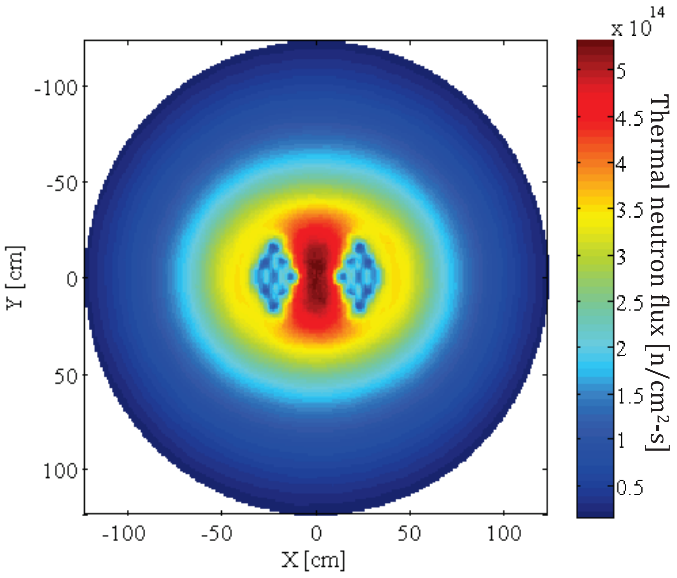

Fig. 4. Thermal flux profile of the HEX core at the mid-plane.

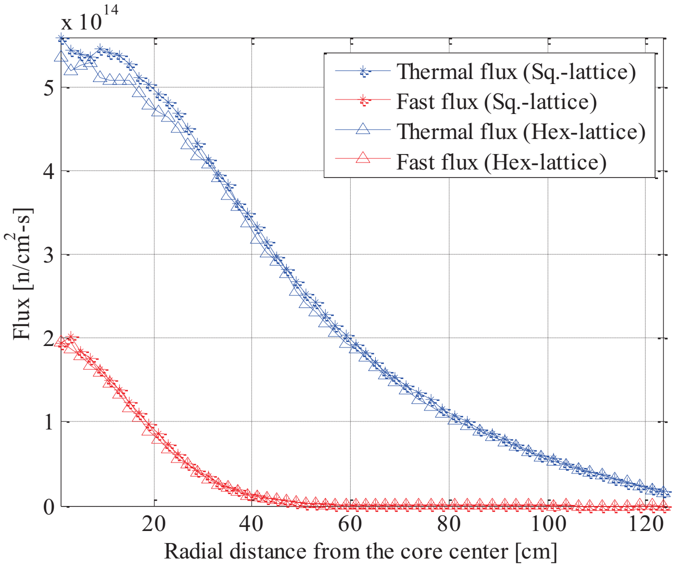

Fig. 5. Flux trap comparison of the two core designs, along the axis X=0, shown in Figure 4.

The split distance between the two core halves is yet to be optimized for flux performance in the intermediate flux trap; this feature was held constant so as to provide a more controlled comparison between the former and current design iterations. As shown in Fig. 4, the HEX core design features a very similar thermal flux distribution across the flux trap as the previous studies [3], likely due to this constraint. While the HEX core design features a marginally higher fast flux level in the center point and virtually equal fast flux levels at most calculated points beyond 40cm, the thermal flux of the previous design is equal or higher at all calculated points, most notably near the center of the flux trap (see Fig. 5). Due to the inherent moderator-to-fuel ratio increase – volume of D_2O moderator per unit volume of fuel – notable increases in thermal neutron flux inside each core box were achieved. The moderator pool receives a greater thermal neutron flux from the core boxes in the HEX core design, and thus the neutronic behavior in the flux trap has been changed to a degree which warrants a re-examination of the core split distance optimization.

CONCLUSION

The HEX core design achieves a number of successes over the previous split-core design. Given that much of the motivation of this work was based on implementation of control blades into a concept which lacked them, it is notable that neutron economy was well-preserved in the process of achieving conservatively effective reactivity control; start-up k_{eff} was in fact increased by 0.23% and peak thermal flux increased by ~25%. A useful metric in determining the efficacy of resources towards creating an environment for the production of cold neutrons – dubbed the "quality factor" (QF) – is the ratio of peak thermal neutron flux in a system to the total thermal power produced. Because HEX core's objectives are very focused in comparison to existing research reactors, it is fitting to pursue a design which out-performs all others in terms of some specific performance metric, namely this QF term. Table 3 offers a comparison of the HEX core

Table 3. Comparison of QF between NIST's existing and proposed designs NBSR and HEX core, respectively, the Advanced Test Reactor (ATR) at Idaho National Laboratory [5], and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory [6].

Reactor	**Total Power (MWth)**	**Quality Factor (neutrons/cm²-s-MWth)**
ATR	250	4.00E+12
NBSR	20	2.00E+13
HEX	20	2.35E+13
HFIR	85	2.94E+13

against some of the world's most advanced research reactors, in terms of QF. While HFIR remains the greatest cold neutron source in the world, it does so through use of HEU fuel (which will be replaced with LEU in the near future), and suffers a greater level of fast neutron contamination that is expected from the HEX design.

The new core design achieves these successes due to the hexagonal lattice fuel arrangement, a 13.5% reduction in cladding mass, and a 13.1% reduction in fuel element volume. In spite of a 5.5% reduction in fuel mass, no compromises in reactor performance were noted. Provided the favorable characteristics shown of the control blade design, refueling intervals longer than the prescribed 30 days may be considered. It can be speculated that with these quantitative benefits, the overall capital and continuous costs of the HEX core design will be less than the previously proposed split-core concept.

In future studies, the goal of cold neutron optimization in the HEX core system will depend on several interdependent variables. In addition to refining the modeling of the design with respect to such physical considerations as thermal hydraulics feedback, source definition, and transient material behaviors, important factors to consider in the study will include the guide tube size and position, core split distance, moderator-to-fuel ratio, and control blade assembly geometry. The design of the guide tubes is a process which seeks to maximize the cold neutron current at the entrance of the guide tubes. This is intimately interdependent to the transient control blade behavior, for flux peaking will vary axially as the blades are withdrawn throughout the course of a fuel cycle, and thus may warrant more sophisticated guide tube neutron fluence optimization studies over long periods of reactor operation. The moderator-to-fuel ratio holds the key to optimizing, independently, either fuel economy or peak cold neutron collection. A highly moderated core may concentrate thermal neutron flux more intimately around the fuel elements, increasing neutron multiplication per unit fuel. However, a smaller ratio of inter-fuel moderation would create a more leakage-dominated system which could offer a higher fast neutron current from the bounds of the core box, thus creating greater thermal neutron flux trapping in the moderator. Perhaps a metric can be developed which describes cold neutron production per unit fuel consumed throughout a full refueling cycle, with some designated preference towards cold neutron production. Such a parameter would guide a more comprehensive optimization of the HEX core concept, under the design constraints implemented in this study.

A final note should be made about the HEX design, as the point was brought to light upon review of this work. The HEX fuel element, represented best in Figure 1, bears a striking resemblance to a previously proposed fuel element concept for a gas-cooled fast reactor design developed at the Georgia Institute of Technology [7]. This coincidence was entirely unknown to those involved in the work, during the time in which it was performed.

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