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Article

Reactor Core Conceptual Design for a Scalable Heating Experimental Reactor, LUTHER

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Abstract: In this paper, the conceptual design and a preliminary study of the LUT Heating Experimental Reactor (LUTHER) for 2 MWth power are presented. Additionally, commercially sized designs for 24 MWth and 120 MWth powers are briefly discussed. LUTHER is a scalable light-water pressure-channel reactor designed to operate at low temperature, low pressure, and low core power density. The LUTHER core utilizes low enriched uranium (LEU) to produce low-temperature output, targeting the district heating demand in Finland. Nuclear power needs to contribute to the decarbonizing of the heating and cooling sector, which is a much more significant greenhouse gas emitter than electricity production in the Nordic countries. The main principle in the development of LUTHER is to simplify the core design and safety systems, which, along with using commercially available reactor components, would lead to lower fabrication costs and enhanced safety. LUTHER also features a unique design with movable individual fuel assembly for reactivity control and burnup compensation. Two-dimensional (2D) and three-dimensional (3D) fuel assemblies and reactor cores are modeled with the Serpent Monte Carlo reactor physics code. Different reactor design parameters and safety configurations are explored and assessed. The preliminary results show an optimal basic core design, a good neutronic performance, and the feasibility of controlling reactivity by moving fuel assemblies.

Keywords: conceptual design; small modular reactor; pressure-channel type reactor; movable fuel assemblies; district heating

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1. Introduction

In colder climate regions, such as the Nordic countries, heating plays an essential role in energy markets and is one of the dominant sectors of the final energy use. In the European Union (EU), heating and cooling take up approximately 50% of the total final energy consumption, of which 75% is still generated by the direct use of fossil fuels [1]. In Finland, particularly, district heating had a share of about 46% of the national heat market in 2016 [2]. Fossil fuels, mainly coal and gas, and peat, are still the primary source of fuels for district heat production in Finland [3]. Consequently, the heating and cooling sector contributes significantly to the total annual greenhouse gas (GHG) emissions in Finland.

Due to the current trend of consumption and energy production, the EU established the heating and cooling policy and strategy in 2016 to reduce GHG emissions by 2030 [1]. The EU's climate and energy goals aim to decarbonize by reducing the use of fossil fuels and increase energy efficiency in the heating and cooling sector. Furthermore, Finland, in particular, has ambitious long-term goals of becoming a carbon-neutral country while securing the national energy supply, as well as improving the current energy systems and technology by 2050 [1].

These ambitious decarbonization plans from the EU and Finland make nuclear heating an attractive option. Additionally, due to the current trend towards decentralized energy systems and the recent difficulties in the construction of large units, there is a keen interest in small reactors (i.e., small modular reactors or SMRs). Furthermore, the cost-effective production of low-temperature heat with dedicated small reactor units calls for a reactor design with simplified reactor core and safety systems. It also needs to be easy to manufacture and should utilize off-the-shelf components as far as possible. Finally, the smallish unit size (20 to 120 MWth) is naturally conducive to serial production, which is expected to help keeping the unit cost competitive with realistic alternatives.

LUT has started the conceptual designing of a dedicated district heating reactor with the aims of cost-effectiveness, modularity, simplification, and safety. The LUT Heating Experimental Reactor (LUTHER) is a light-water modular pressure-channel reactor designed to operate at a low temperature, low pressure, and low core power density. The smallest LUTHER core is designed to produce 2 MWth power to experiment and demonstrate the novel means of reactivity control and the feasibility of a pressure-channel district heating reactor. Commercially deployable powers of 24 MWth and 120 MWth are also studied and briefly discussed in the paper. The process of conceptually designing the LUTHER started with a basic fuel assembly utilizing low enriched uranium (LEU) fuel and off-the-shelf reactor components. As a major design feature, LUTHER uses movable fuel assemblies, located inside fuel channels, for reactivity control and fuel burnup compensation, thereby eliminating both conventional control rods and soluble boron. In this paper, the basic design and features of LUTHER are presented, which is supported by the first core design calculations that show the feasibility of the new core design and reactivity control by movable fuel assemblies.

2. Conceptual Design Features of LUTHER

2.1. LUTHER Design Concept

The objective of this research is to propose a small modular reactor with simplifications made in the reactor core and safety systems for the district heating purpose in Finland, replacing current fossil-fueled plants, and enabling serial production with associated cost and time savings. The simplification of the reactor systems is necessary because district heating reactors have to be sited relatively close to consumers (urban areas). Simplification will lead to an easily understood safety justification and lower infrastructure costs, thereby improving both societal acceptance and the economy of nuclear power. The reactor is proposed to be situated in a below-grade level bedrock or rock cavern, which can be used both as a physical protection barrier against external threats or radioactivity release and as a passive heat sink for decay heat removal.

In keeping with the simplified design concept, LUTHER uses movable fuel assemblies to control the reactivity and to compensate for fuel burnup during operation. This concept eliminates the use of conventional control rods and soluble boron in the systems, giving materials and equipment savings.

For the district heating network in Finland, the outlet temperature range of the facility should be 90–120 °C, depending on the network structure, reactor operation mode, and peak demands between seasons [4]. The LUTHER cooling system is a pressurized water loop with an intermediate loop coupling the reactor circuit to the district heating network. LUTHER's conceptual core is designed to operate at the temperature of 150–180 °C and pressure of 1.25 MPa in the primary circuit. The advantages of operating at low temperatures, along with utilizing pressure-channel tubes, are that manufacturing costs are expected to be significantly lower, and safety systems are considerably simpler than the systems in a reactor design using a conventional pressure vessel.

2.2. Fuel Channel and Assembly Design

To ensure safety and reliability without excessively high research and development costs, LUTHER design is aimed to utilize many of its features from conventional water reactors and off-the-shelf components. A schematic view of LUTHER fuel channel with a fuel assembly inside is presented in Figure 1a, and the first design dimensions are given in Table 1.

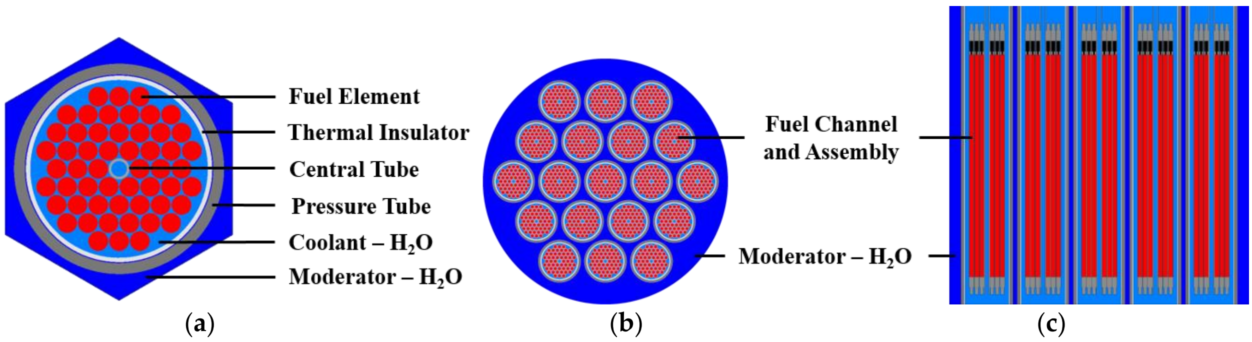


Figure 1. (**a**) Schematic view of the fuel channel with fuel assembly inside. Schematic views of the 2 MWth LUTHER core: radial (**b**) and axial (**c**).

Table 1. Basic LUTHER core, fuel channel, and fuel assembly design parameters.

Reactor Core	
Design thermal power (MWth)	2/24/120
Equivalent core diameter (m)	0.48/1.05/1.82
Active core height (m)	0.48/1.05/1.82
Number of fuel assemblies	19/91/271
Linear power rate (average) (kW/m)	3.853/4.411/4.292
Core power density (average) (kW/L)	22.94/26.26/25.55
Mass inventory of UO_2 fuel (tons)	0.25/2.60/13.36
Effective multiplication factor	0.91/1.23/1.33
Heat transport system	
Reactor coolant pressure (MPa)	1.25
Reactor coolant inlet/outlet temperature (°C)	150/180
Reactor moderator pressure (MPa)	0.101325
Reactor moderator temperature (°C)	40
Single channel flow rate (average) (kg/s)	0.807/2.02/3.39
Fuel channel	
Pressure tube inner diameter (cm)	8.7
Pressure tube thickness (mm)	5
Thermal insulator inner diameter (cm)	8.2
Thermal insulator thickness (mm)	2
Fuel channel pitch (cm)	10.5
Thermal power output (average) (kW/channel)	105.3/263.7/442.8
Fuel assembly	
Number of fuel rods	54
Fuel pellet diameter (mm)	7.844
Fuel cladding thickness (mm)	0.5715
Fuel rod outer diameter (mm)	9.144
Fuel rod lattice pitch (cm)	0.96
Enrichment of the fuel (95% TD) (%)	4.95
Number of central tubes	1
Central tube inner/outer diameter (mm)	7.2/9.6

The LUTHER fuel assembly design is based on the VVER-1000 Robust Westinghouse Fuel Assembly (RWFA) with modifications to the lattice pitch, and the number and length of fuel elements. The Westinghouse fuel pins comprise LEU ceramic pellets coated with ZIRLO^{TM} (zirconium low oxidation) cladding. The original pin lattice pitch was modified and selected to be 0.96 cm for the present analysis as a compromise between mechanical design and reactor physics. Since low-temperature (i.e., highly dense) light water is used as the moderator outside the fuel channel and as the coolant inside the pressure tube, tighter lattice pitch for the fuel pins is preferred in order to optimize the neutronic performance. The first fuel assembly design consists of 54 fuel pins and a central tube used for mechanical moving support for the channel and instrumentation, which is fitted inside a pressure channel.

The fuel channel is a 5 mm thick pressure tube made of zirconium 2.5 wt % niobium alloy (Zr 2.5 wt % Nb), similar to a Canada Deuterium Uranium (CANDU) fuel channel, which forms a pressure boundary to contain the low-pressure light-water coolant at 1.25 MPa and a 54-element fuel assembly. The given thickness was chosen to assure the integrity of the channel during any transients and adequate strength for end-fitting plugs of the pressure tube. This configuration allows the calandria vessel (i.e., the moderator tank) to be designed for low temperature and low pressure (i.e., atmospheric pressure), thereby reducing the vessel's wall thickness, which lowers the costs of fabrication and manufacture and simplifies component quality control [4].

To maximize the economy of generated nuclear heat and assure the safety of the core from thermal stresses on pressure tubes and boiling of the moderator, a 2 mm thick thermal insulator is added inside each fuel channel, as shown in Figure 1. A ceramic silica bonded yttria-stabilized zirconia, also known as zirconium oxide cylinder (ZYC), manufactured by Zircar Zirconia, Inc. is proposed as a material for a thermal insulator in the LUTHER fuel channel. Yttria-stabilized zirconia (YSZ) material features an ideal insulator in a high-temperature in-core environment with low neutron absorption, excellent thermal resistance (0.08 W/mK at 400 °C), good dimensional stability and hot strength, low mass (0.48 g/cm^3 with porosity of 91%) and low heat storage, and lastly machinability to any intricate shapes with tight tolerances [5,6]. The choice of using the ceramic thermal insulator over a calandria tube filled with insulating gas, which is commonly used in CANDU reactors, was due to the design criteria of keeping the core dimension as small as possible and keeping the simplified concept in LUTHER.

The central tube is a 1.2 mm thick annular cylinder with an inner diameter of 7.2 mm, and it is made of the same material as the fuel cladding. The central tube, as part of the assembly, is attached to the fuel assembly drive mechanism, similar to the conventional control rod drive mechanism in nuclear power plants; however, in this case, the whole fuel assembly is raised or lowered inside the pressure tube. The capability to move selected fuel assemblies serves as a means for reactivity control, fuel burnup optimization, and as a shutdown mechanism, thus obviating the need for control rods and soluble boron. Additionally, the annular configuration allows instrumentation to be inserted into the fuel assembly for measurements or irradiation purposes.

2.3. Reactor Core Design

A 2 MWth LUTHER core design, shown in Figure 1b,c, comprises 19 vertically oriented fuel channels, accommodating movable fuel assemblies inside, arranged in a hexagonal lattice. These fuel channels are surrounded by the atmospheric-pressure light-water moderator, which is contained in a low-pressure calandria vessel. Light water in the calandria vessel serves as a neutron moderator and a passive heat removal medium, and it is currently maintained at 40 °C. The calandria vessel is also designed with the capability to drain the moderator, which can act as a means to shut down the reactor.

A 10.5 cm lattice pitch for fuel channels was selected for the present analysis. This value was chosen as a compromise between the optimal infinite multiplication factor and sufficient spacing for the mechanical design of the end-fitting plugs of the pressure tube. Each pressure tube is individually connected to a thermal collector positioned above and below the core, where heat from the primary circuit is transferred to the district heating network via an intermediate water loop. This design choice is made to allow access to an individual fuel assembly in the channel for maintenance and refueling and to ensure coolant availability to the core during any accidents, i.e., fuel channel rupture, loss of coolant accident (LOCA). Furthermore, 24 MWth and 120 MWth cores are designed with a similar configuration, with each comprises 91 and 271 fuel assemblies, respectively.

Furthermore, the present LUTHER core design does not include a radial or axial reflector region. It is expected that in a bare light-water reactor core, the migration area is minimal; hence, there is a significant leakage of neutrons, mainly fast neutrons [7]. Consequently, a neutron reflector is desirable in reducing the neutron leaks, and further studies on neutron reflectors and material selection are needed.

3. LUTHER Design Calculations

In this study, the reactor physics calculations were performed using the Serpent Monte Carlo code developed by the VTT Technical Research Centre of Finland Ltd [8]. Serpent code is used in this research for calculating the multiplication factor, power distribution, and reactivity control.

The design was analyzed on two levels: 2D single fuel assembly (1) and 2D and 3D reactor core (2). The first level analysis is aimed at optimizing the design parameters concerning the reactivity of the fuel assembly and mechanical design of the channel. Additionally, power distribution calculation was performed in a fuel assembly, and the primary objective of the second level analysis is to determine the feasibility of controlling reactivity by moving selected fuel assemblies.

3.1. Fuel Assembly Analysis

With the proposed design parameters tabulated in Table 1, the infinite multiplication factor of a fuel channel containing a fuel assembly is presented as a function of hydrogen-to-heavy-metal (H/HM) ratio in Figure 2. In this calculation, the lattice pitch of fuel pins is fixed at 0.96 cm, and the lattice pitch of fuel channels is varied that corresponds to the H/HM ratio. As the lattice pitch of fuel channels enlarges, the H/HM ratio increases (i.e., the amount of moderator increases), as well as the space clearance between pressure tubes. In this current design, the result shows a tight optimum range of H/HM ratio, which induces a problem of selecting a lattice pitch for the fuel channels. Due to the high moderation power and large neutron absorption of "cold" light water, current LUTHER design is limited in the selection of the channel lattice pitch. Thus, the minimum lattice pitch is also restricted by the required space clearance for end-fitting plugs of the pressure tube.

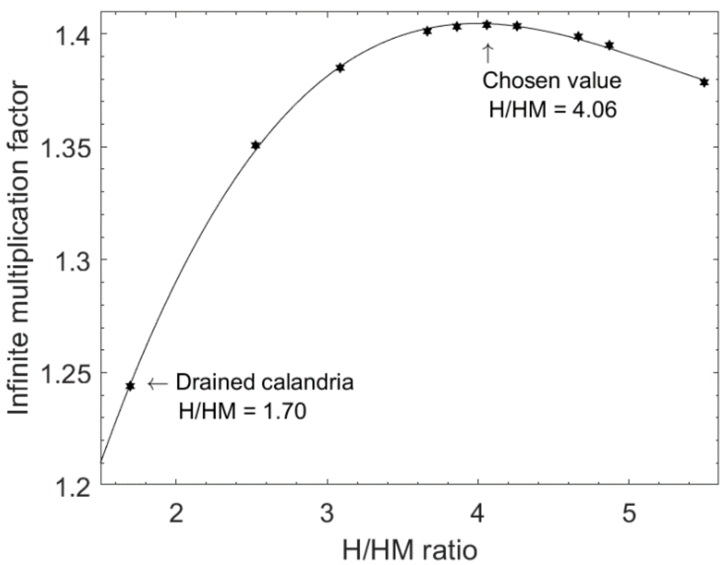


Figure 2. k_∞ of a fuel channel as a function of H/HM ratio with a fuel pin lattice pitch of 0.96 cm; the average relative statistical error is $\pm 3.0 \times 10^{-5}$.

At this first stage of the study, the H/HM ratio in the fuel channel was optimized to approximately 4.06, achieving the maximum k_∞. This results in a fuel channel lattice pitch of 10.5 cm and an 8 mm gap clearance between the pressure tubes.

Furthermore, Figure 2 also shows the reactivity effect when the moderator of a fuel channel is drained completely, which yields the reactivity change of approximately −9.16 %$\Delta k/k$ and the H/HM ratio of 1.70. Therefore, calandria draining looks promising as a diverse means of reactor shutdown, in addition to the primary means of dropping selected fuel assemblies out of the core.

In addition to the infinite multiplication factor calculation, the normalized power distribution of a fuel assembly is calculated and presented in Figure 3a. The fuel assembly design at this preliminary design phase consisted of identical fuel pins with the same uranium enrichment of 4.95 wt % and without burnable absorbers (e.g., gadolinium). Due to the tighter fuel pin configuration and semi-symmetrical geometry of the core, the calculation results in non-uniform power distribution in the fuel assembly. The main reason is due to the lack of moderator in the assembly's flow subchannels where there is less neutron moderation inside the assembly than outer edges. Hence, fuel burnup is not optimal, and power peaks occur on the fuel pins located at the outer ring of the lattice; the current relative pin power peak is 1.42. The design is needed to be optimized in the future, using either pins with different enrichments or with gadolinium doped fuel pins.

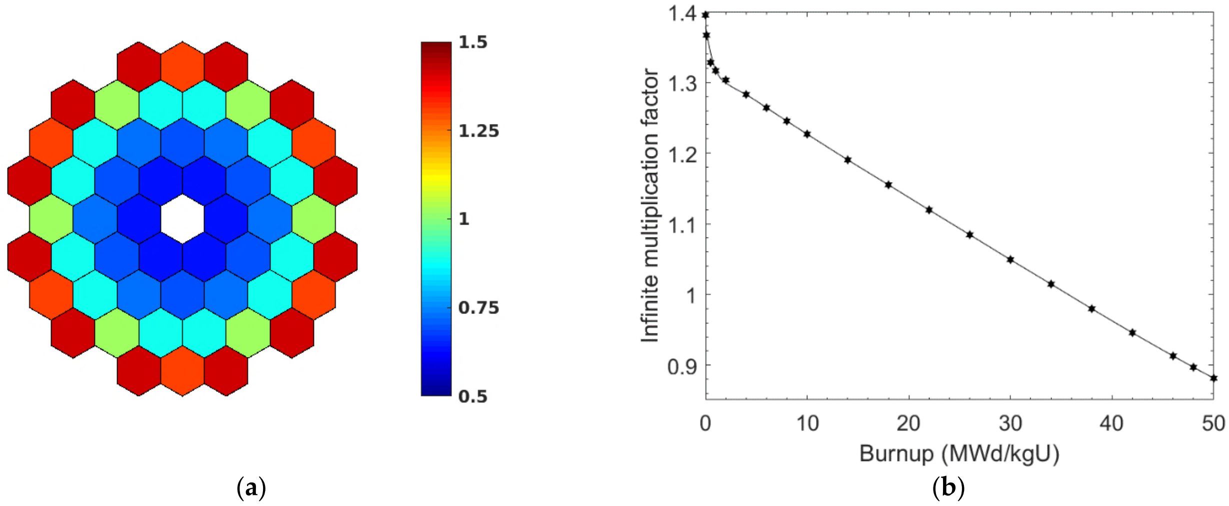
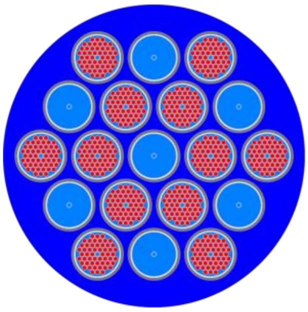


Figure 3. (**a**) Normalized power distribution in a single fuel channel assembly with identical 4.95 wt %-uranium enriched fuel pins; the average relative statistical error is $\pm 2.19 \times 10^{-4}$. (**b**) k_∞ of a fuel channel with a fuel assembly without burnable absorbers inside as a function of burnup, the average absolute error is $\pm 2.62 \times 10^{-4}$.

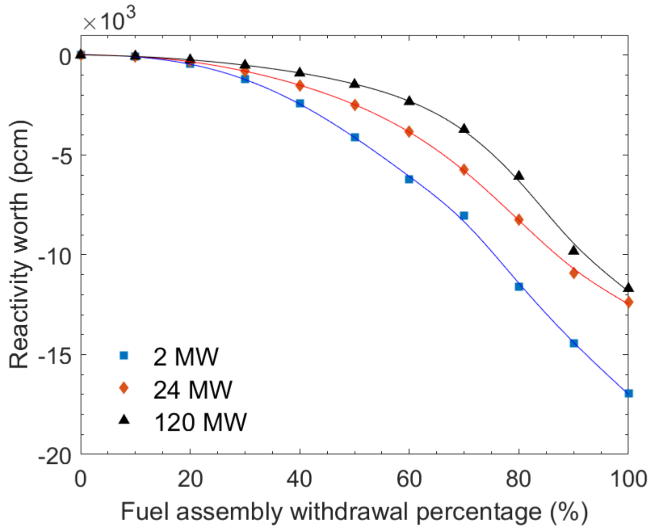
Furthermore, a fuel burnup calculation was performed for a fuel channel with a fuel assembly without burnable absorbers inside. The result is shown in Figure 3b, such that the fuel burnup at the end of the cycle (EOC) is approximately 36 MWd/kgU. A multi-batch loading pattern (e.g., three batches) is considered for optimizing the usage of the fuel.

3.2. *Reactivity Control by Moving Fuel Assemblies*

LUTHER is proposed to utilize moving fuel assemblies for reactivity control and possibly also for fuel burnup compensation, replacing conventional control rods and soluble boron. Figure 4a shows one possible configuration in a 2 MWth core with the fuel channels for movable fuel assemblies, highlighted with a light blue color. Other configurations, such as movable assemblies in the central ring, are also considered, which are not shown in this paper. To calculate for the reactivity effect of movable fuel assemblies' withdrawal, the highlighted fuel assemblies were moved out of the core at 10% of the increments. A similar configuration is applied in 24 MWth and 120 MWth cores. Figure 4b presents the reactivity worth of fresh movable fuel assemblies with a polynomial fit for configuration A, exhibiting a similar reactivity effect as control rods would provide. The total reactivity worth of the fresh movable fuel assemblies is approximately 17,000 pcm, 12,500 pcm, and 12,000 pcm for 2 MWth, 24 MWth, and 120 MWth cores, respectively, which shows a promising feasibility of controlling core reactivity.



(a)



(b)

Figure 4. (**a**) Configuration A of a 2 MWth LUTHER core with movable fuel assemblies. (**b**) Fresh fuel assembly reactivity worth of configuration A at various thermal powers; the average relative statistical error is $\pm 5.25 \times 10^{-5}$.

4. Conclusions and Future Work

In conclusion, the LUTHER pressure-channel reactor is a feasible concept. Scalable and modular designs have considerable potential in decarbonizing the district heating sector and are needed to meet the EU and Finland's ambitious climate goals. The preliminary proposed design shows reasonable dimensions and design parameters for a nuclear district heating reactor. This work provides an early conceptual understanding for a light-water pressure-channel reactor with the unique feasible feature of movable fuel assemblies, replacing control rods and soluble boron in reactivity control. However, the 2 MWth core seems too small to be feasible as an operating reactor; the LUTHER demonstration version needs to be somewhat larger to be properly operable. Recommendation of increasing the small core power to 6 MWth is proposed to make the LUTHER demonstration reactor operable.

Further studies and assessments are also needed to understand more and improve the LUTHER core design concept, and to complete the thermal-hydraulic system design to implement robust inherent safety characteristics. Future studies include improvement and optimization of the fuel assembly design, as well as the fuel channels, in order to maximize the neutronic economy while providing an adequate space clearance required for mechanical design and thermal hydraulics. From the preliminary analysis results, redesigning the fuel assembly is likely considered with a few possible changes, namely, the lattice configuration, design dimensions, and the number of fuel pins per assembly. Additionally, flattening assembly power distribution is also desirable, and implementations of possibly with gadolinium fuel pins and pins with different enrichments are considered.

In addition to optimizing the fuel assembly and fuel channel design, investigations and studies concerning reactivity feedbacks and reactor core behavior (e.g., fuel burnup, power distribution, reactivity control, and shutdown mechanisms) are necessary to develop the LUTHER conceptual core further. It is also expected that the power distribution in the core would be non-uniform and would centralize in the center of the core. To flatten the power in the core, a multi-batch loading pattern (i.e., three batches), core reflector, gadolinium fuel channels, and fuel channels with different average uranium enrichments need to be considered. Furthermore, for future work, thorough studies and understanding the neutronic behavior and reactor dynamics of moving fuel assemblies for reactivity control, reactor operation, and reactor shutdown are essential in the development of the LUTHER core, assuring the overall safety of the reactor.

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