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Reactor Core Conceptual Design for a Small Modular LUT Heat Experimental Reactor

Thinh Truong, Heikki Suikkanen, Juhani Hyvärinen
LUT University – School of Energy Systems / Nuclear Engineering
P.O. Box 20, FI-53851, Lappeenranta, Finland
thinh.truong@lut.fi, heikki.suikkanen@lut.fi, juhani.hyvarinen@lut.fi

ABSTRACT

In this paper, the conceptual design and a preliminary study of LUT Heat Experimental Reactor (LUTHER) for a 2-MW_{th} power are presented. LUTHER is a light-water modular pressure-channel reactor designed to operate at low temperature and pressure and low core power density. The LUTHER core utilizes low enriched uranium (LEU) to produce scalable low-temperature outputs for low-temperature applications, targeting specifically the district heating demand in Finland. This work is contributing to decarbonizing in the heating and cooling sector. The main principle in the development of LUTHER is to simplify core design and safety systems, which along with using commercially available reactor components will lead to lower fabrication costs and enhanced safety. LUTHER also features a unique fuel assembly design with movable individual fuel assembly for reactivity control and burnup compensation.

2-dimensional (2D) and 3-dimensional (3D) fuel assemblies and reactor cores are modeled with the Serpent Monte Carlo reactor physics code developed by the VTT Technical Research Centre of Finland, Ltd. Various possibilities of reactor design parameters and safety configurations are explored and assessed. Preliminary results show an optimal basic core design, a good neutronic performance, and feasibility of controlling reactivity by moving fuel assemblies.

1 INTRODUCTION

In colder climate regions, such as the Nordic countries, heating plays an important 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 from 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 wood-derived fuels were and are still the main 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 the climate.

Due to the current trend of consumption and production of energy, 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 sectors. 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 topic again. Additionally, due to the trend towards de-centralized energy systems and recent difficulties in the construction of large units, there is a strong interest in small reactors. Furthermore, cost-effective production of low-temperature heat with dedicated small reactor units calls for a reactor design with a simplified core and safety systems. It also needs to be easy to manufacture and should utilize off-the-shelf components as far as possible.

LUT Heat Experimental Reactor (LUTHER) is conceptually designed to supply nuclear heating specifically for low-temperature applications such as district heating and desalination. LUTHER is a light-water modular pressure-channel reactor designed to operate at low temperature, low pressure, and low core power density. As a major design peculiarity, LUTHER features movable fuel assemblies for reactivity control, eliminating both control rods and soluble boron. The reactor utilizes commercially available low enriched uranium (LEU) fuel to produce small, scalable thermal power outputs, targeting specifically the district heating demand in Finland.

In this paper, the basic design features of LUTHER are presented, which is supported by the first core design calculations that prove the general neutronic feasibility of the design and the feasibility of reactivity control by movable fuel assemblies.

2 DESIGN FEATURES OF LUTHER

2.1 Fuel channel and assembly design

LUTHER fuel channel with a fuel assembly inside is presented in Figure 1, and the design dimensions are given in Table 1.

The fuel assembly design is based on the VVER-1000 Robust Westinghouse Fuel Assembly (RWFA) with modifications to the lattice pitch and the length of fuel elements as a compromise between mechanical design and reactor physics. It consists of 54 fuel pins and features a central tube used for mechanical support and instrumentation. The fuel pins comprise of LEU ceramic pellets coated with ZIRLO^{TM} (zirconium low oxidation) cladding. Light water is used as the moderator outside the fuel channel and as the coolant inside the pressure tube.

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, forms a pressure boundary to contain the light-water coolant pressure of 1.25 MPa. The given thickness was chosen to assure the integrity and adequate strength for screwing end-fitting plugs of the pressure tubes. This configuration allows the calandria vessel (i.e. the moderator tank) to be designed for low temperature and low pressure, which lowers the costs of fabrication and manufacture.

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 selected 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, good thermal resistance (0.08 W/mK at 400ºC), 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 [4][5].

The central tube of a fuel assembly is an annular cylinder with an inner diameter of 3.6 cm, a thickness of 0.6 mm, and it is made of the same material as the fuel cladding. The central tube 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 replacing control rods and soluble boron.

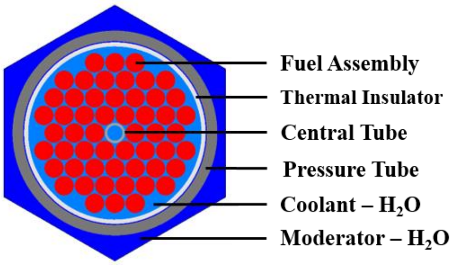

Figure 1: Schematic view of the LUTHER fuel channel with fuel assembly inside.

2.2 Reactor core design

A 2-MW$_{th}$ LUTHER core design shown in Figure 2 comprises of 19 vertically oriented fuel assemblies arranged in a hexagonal lattice. A fuel channel is individually connected to thermal collectors positioned above the core. This design choice is made to allow access to an individual fuel assembly in the channel for maintenance and refueling.

Since light water is used as both a coolant and a moderator, the LUTHER design is limited in the selection of the lattice pitch, which affects directly to the spacing clearance between the fuel channels. Thus, the minimum lattice pitch is also restricted by the radial space requirements associated with the clearance for end-fitting plugs of the pressure tubes. The first design iteration assembly lattice pitch value of 10.5 cm was selected for the present analysis. This value was chosen as a compromise between the optimal infinite multiplication factor and providing sufficient space for end-fitting plugs.

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 very small; hence, there is a significant leakage of neutrons, mainly fast neutrons [6]. Consequently, neutron reflector is desirable in reducing the neutron leaks, and this present study does not cover the reflector section.

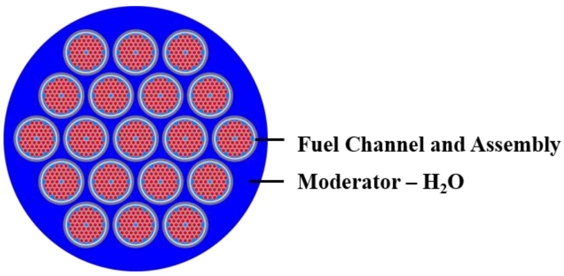

Figure 2: Schematic view of the 2-MW$_{th}$ LUTHER core.

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

Reactor core	
Design thermal power [MW_{th}]	2
Equivalent core diameter [m]	0.48
Active core height [m]	0.48
Number of fuel assemblies	19
Linear power rate (ave.) [kW/m]	38.53
Core power density (ave.) [kW/l]	22.94
Mass inventory of UO_2 fuel [tons]	0.25
Heat transport system	
Reactor coolant pressure [MPa]	1.25
Reactor coolant inlet / outlet temp. [^oC]	150 / 180
Reactor moderator pressure [MPa]	0.101325
Reactor moderator temp. [^oC]	40
Single channel flow rate (ave.) [kg/s]	1.58
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 (ave.) [kW/channel]	105.3
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) [wt.%]	4.95
Number of central tubes	1
Central tube inner / outer diameter [mm]	3.6 / 4.8

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. Serpent code is used in this research for calculating the multiplication factor, assembly power distribution, characteristics of reactivity feedbacks, reactivity control, and core criticality safety.

The design was analyzed on two levels: 2D single fuel assembly (1) and 2D and 3D whole 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. The primary objective of the second level analysis is to determine the feasibility of controlling reactivity by moving the selected fuel assemblies.

3.1 Fuel assembly analysis

With the chosen design parameters, infinite multiplication factor (k_∞) of a fuel assembly is calculated and drawn as a function of hydrogen/heavy-metal (H/HM) ratio in Figure 3. The result shows the limited selection of lattice pitches for the fuel assembly and fuel channel. At this first stage of study, the H/HM ratio in the fuel assembly was optimized to achieve the maximum k_∞. Furthermore, the figure also shows the reactivity effect when the moderator tank is drained completely, which yields the H/HM ratio of 1.70.

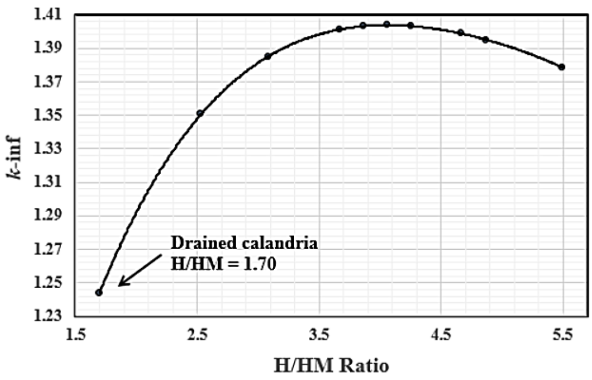

Figure 3: k_∞ of a fuel assembly as a function of H/HM ratio with a fuel rod pitch of 0.96 cm and an assembly pitch of 10.5 cm.

In addition, a normalized power distribution of a fuel assembly is calculated and presented in Figure 4. Due to the tighter fuel rod lattice pitch, the assembly power distribution is not uniform; in another word, there is less neutron moderation inside the assembly than outside. Hence, fuel burnup is not optimal, and power peaks occur on the fuel pins located at the outer ring of the lattice; the relative pin power peak is 1.42. The fuel assembly design at this preliminary design phase consists of identical fuel pins with the same uranium enrichment of 4.95 wt.%. The design is likely to be optimized in the future possibly with gadolinium fuel pins and pins with different enrichments.

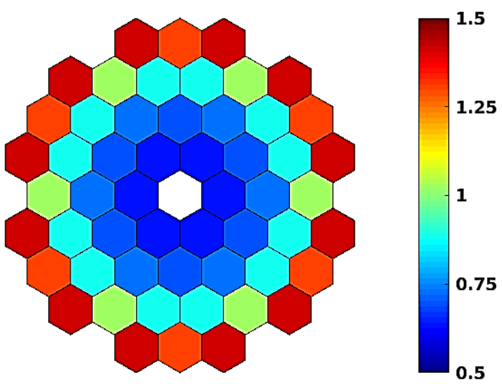

Figure 4: Normalized power distribution in a single fuel assembly with identical 4.95%-U enriched fuel rods.

Furthermore, a fuel burnup calculation was performed for an infinite fuel assembly without burnable absorbers. The result is shown in Figure 5 such that the fuel burnup at the end of the cycle (EOC) is approximately 39 MW/kgU.

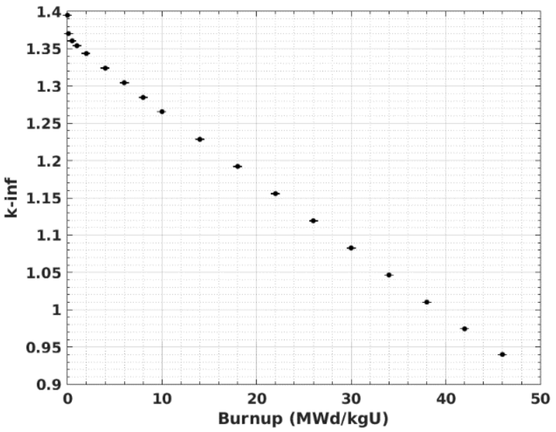

Figure 5: k_∞ of a fuel assembly without burnable absorbers as a function of burnup.

3.2 Fuel assembly reactivity worth analysis

Figure 6 shows one possible core configuration with the channels for movable fuel assemblies highlighted with a light blue color. To calculate for the reactivity effect of fuel assembly withdrawal, the highlighted fuel assemblies were moved out of the core at 10% increments, starting from the 0% withdrawal position. Figure 7 presents the reactivity worth of fuel assembly with a polynomial fit, exhibiting a similar reactivity effect with control rods, with the total reactivity worth of the fuel assembly is approximately 17000 pcm.

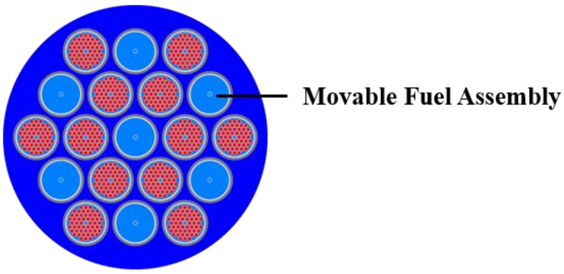

Figure 6: One possible configuration for the movable fuel assemblies.

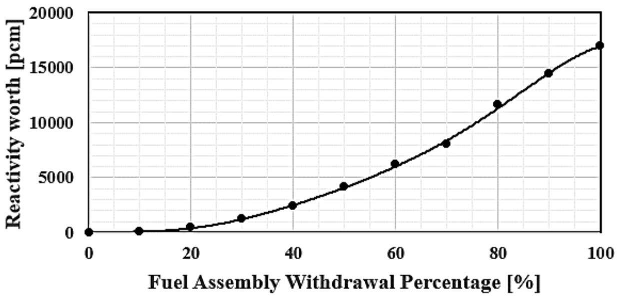

Figure 7: Fuel assembly reactivity worth of the 2-MW_{th} LUTHER core.

4 CONCLUSIONS

In conclusion, the development of LUTHER pressure-channel reactor is feasible and has considerable potential in decarbonizing heating and cooling sector in order to meet the EU and Finland's ambitious goals. This work provides an early conceptual understanding for a light-water pressure-channel reactor with the unique features of movable fuel assemblies replacing control rods and soluble boron in reactivity control.

Furthermore, an exploration and assessment of different thermal powers at 24 MW_{th} and 120 MW_{th} for LUTHER core are also considered and are needed to study further in addition to the 2-MW_{th} core.

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