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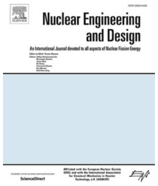

Nuclear engineering and design nuclear heat supply system for a small district heating reactor

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ABSTRACT

Small Modular Reactors (SMRs) are currently considered to be a potential solution for decarbonizing the district heating sector. The LUT Heat Experimental Reactor (LUTHER) is a concept for a small modular nuclear heating plant that is being designed to meet the demands of Nordic district heating networks while also incorporating high safety standards. This paper presents an extension of the work pursued by LUT University by proposing a reactor module that allows for easy scaling of unit sizes ranging from 2 MW to 120 MW. The pressure tube assembly geometry, which has been developed specifically for the LUTHER reactor module, was analyzed by modeling two significantly different-sized variants that utilize this unique structure. The modular design of LUTHER enables complete factory-assembly and the use of standard road transport for unit sizes up to 120 MW. This design prioritizes high inherent safety, targeting for siting near population centers. The proposed heating reactor concept offers a viable means of decarbonizing the district heating sector by replacing existing combustion-based production with emissions-free nuclear heat.

1. Introduction

According to the International Energy Agency (IEA, 2022), the amount of heat globally produced in 2021 for district heating (DH) networks was nearly 16 EJ. From this, nearly 90 % was produced from fossil fuels from which the resulting CO2 emissions have accounted for about 3.5 % of global emissions. These emissions must be reduced by at least 20 % by 2030 compared with 2021 to reach the Net Zero Scenario by 2050 (IEA, 2022). In Europe, ca. 25 % of district heat is produced from renewable sources, and while this number is much higher in the Nordic countries (Finnish Energy Association, 2023, p. 11), there is still a substantial share of DH production left to be decarbonized.

Small Modular Reactors (SMRs) have been proposed as a solution to decarbonize district heating production. According to the International Atomic Energy Agency (IAEA), SMRs are defined as advanced nuclear reactors that have an electrical power capacity of less than 300 MWe per unit. According to this definition, the corresponding maximum thermal output translates to ca. 1000 MW_{th}. SMRs are anticipated to offer savings in cost and construction time (IAEA, 2023).

SMRs can also be applied for heat-only production. (Lindroos et al., 2019) found both the NuScale, a combined-heat-and-power (CHP)-producing SMR, as well as the DHR-400, a heat-only SMR, to be cost-effective alternatives for DH production in a city-level district heating and cooling grid. Leppänen (Leppänen, 2019) points out that the advantages of dedicated heating reactor technology include a small unit size as well as low operating temperatures and pressures, which may considerably reduce the manufacturing costs of reactor components. (Saari et al., 2023) concludes that heat-only nuclear reactors producing hot water at modest temperatures hold the potential to be highly competitive carbon–neutral DH producers.

Despite the apparent benefits, there are only a handful of SMR concepts designed for heat-only purposes. One of them is the LUT Heat Experimental Reactor (LUTHER). This light-water modular pressure-channel reactor concept is based on research performed at LUT university. It is designed to operate at a low temperature, low pressure, and low core power density, specifically targeting the district heating demand in Finland (Truong et al., 2021). This paper proposes a concept for a heat supply system for the LUTHER heating reactor, focusing on the scalability, modularity, and manufacturability of the reactor module. The reactor design is explained only as far as required to describe this concept. The engineered safety features and containment are only briefly discussed when they influence the fluid system geometry.

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The outline of this paper is as follows: Section 2 establishes the current framework for district-heating nuclear reactors and presents the recent developments in heat-only SMRs. In Section 3, we provide the rationale behind the proposed concept and explain the used design methodology. Section 4 describes the design of a 24 MW LUTHER heat supply system and the structure of its scalable reactor module. In Section 5, the design is analyzed against the rationales from Section 3. Finally, in Section 6, we discuss the novelty of the proposed design and compare it against existing heating reactor concepts. The last section draws conclusions.

2. Background

As is well known, nuclear energy has been used for heating applications since the early days of its commercial adoption. The world's first civilian nuclear power reactor, AM-1, had a heat output capacity of 10 MW. Shortly after its initiation in 1954, it began supplying district heating to the town of Obninsk in the Soviet Union (Lipka and Rajewski, 2020). In Nordic countries, with cold winter conditions, reactors exclusively targeted for heat production were already studied in the late 1960s. A joint Finnish-Swedish study from 1975 to 1977 produced the preliminary design for a nuclear district heating plant SECURE (Safe Environmentally Clean Urban Reactor), a 200-MW$_{th}$ nuclear district heating plant for the municipal space-heating system of a city of up to 100,000 inhabitants (Bento and Mankamo, 1978). Since then, the concept was further developed by ASEA Atom (Pind, 1987). Unfortunately, over the past three decades, the Nordic countries have exhibited only marginal interest in nuclear heating applications.

Reactors exclusively targeted for heat production have raised renewed interest due to their inherent safety, simplicity, and consequential potential for cost competitiveness. The amount of energy stored in the primary circuit as latent heat and the amount of decay heat released after reactor shutdown is much lower in a low-temperature level small-heating reactor compared to conventional Light Water Reactors (LWRs). The typical maximum supply temperature to the district heating network is 120 °C (e.g. (Leppänen, 2019)). With these low-temperature levels, relevant for district heating applications, a sufficient boiling margin can be achieved at pressure levels below 1.0 MPa. These low operating pressures lead to a more lightweight construction of the reactor pressure vessel (RPV), thus enabling manufacturing in a wider range of workshops at a fraction of the cost of a traditional nuclear power plant RPV. Finally, removing the turbine island, unnecessary for heat-only production, brings significant savings as traditionally 15 % of the total CAPEX of a nuclear power plant is formed from its costs (World Nuclear Association, 2020).

Due to the recent emergence of Small Modular Reactors (SMRs), nuclear heating applications have begun to gain new momentum. There are close to a hundred different SMR technologies being developed in various stages of maturity around the globe. SMRs seek economy of scale through large numbers deployed rather than large size of individual units. (Ingersoll, 2009) states that both their lower power output and their physical smallness contribute to their associated benefits in the areas of plant safety, fabrication, operations, and economics. According to (Hidayatullah et al., 2015), the construction time for SMRs can be substantially reduced through modularization, by which the structures, systems, and components are shop-fabricated, then shipped, and assembled onsite.

Out of the 25 land-based water-cooled small modular reactor concepts reported in the International Atomic Energy Agency's (IAEA) Advanced Reactors Information System (ARIS) database (Iaea, 2022), five are primarily designed for low-temperature heating applications, such as district heating or desalination. These include the pool-type reactors DHR-400 (CN) and RUTA-70 (RU); the pressure water reactor Happy200 (CN); and the Teplator (CZ), a heavy water (D_2O) moderated pressure-channel heating reactor utilizing spent VVER fuel (Skoda et al., 2020). Table 3 in Appendix A presents the main technical parameters for the SMRs primarily developed for district heat production.

In Finland, the concept of small nuclear heating reactors has recently resurfaced as VTT Technical Research Centre of Finland Ltd. and LUT University have both announced the development of their own reactor concepts for DH applications. Both are LWRs, with low-pressure and low-core power density, designed to operate at pressure levels below 1.0 MPa. The primary market for the two heating reactor concepts is in the Nordic district heating sector. VTT's LDR-50 is an integral PWR-type heating module, utilizing natural circulation for primary system heat transfer (Leppänen et al., 2021). The core and primary system are completely enclosed in a hermetic steel vessel, enabling both boiling/condensation and convection for decay heat removal. The reactor power control of LDR-50 relies on absorber rods; the reactor scram can be executed either by dropping these rods or by employing emergency boration. The heat transfer is totally passive enabling walk-away safety. In contrast, LUT university's LUTHER is a pressure channel-type reactor with forced cooling. It is a non-integral design utilizing off-the-shelf components to the maximum extent (Truong et al., 2021). The core region is comprised of pressure tubes inside a calandria vessel and the whole primary system is planned to be enclosed in a leak-tight reinforced concrete containment. It uses movable fuel assemblies to control the reactivity and to compensate for fuel burnup during operation (Truong et al., 2021). While the LDR-50 maximum heat output is 50 MW, the LUTHER reactor output is scalable from 2 MW to 120 MW thermal. Out of these two heating reactors, LUTHER development started first in 2019, but the LDR-50 has reached a more mature state of development, entering the basic design phase. LUTHER is still in its early conceptual design phase.

3. Design requirements and methodology

As noted by (Kadac and Berte, 2006), for nuclear energy to emerge as the energy source of choice, not only must the environmental benefits be accepted but the cost must be competitive with alternative sources of energy. To effectively compete with the existing, combustion-based heat production technologies, there are three sets of requirements that the proposed design needs to satisfy. First, it must provide a reliable and stable supply of heat according to local network standards while also being able to adjust the output to respond to varying loads. Secondly, it needs to be economically competitive. To attract a sufficiently wide demand, it needs to scale to fit networks of variable sizes. Finally, it must possess a sufficient level of safety to be situated in proximity to inhabited areas and receive community approval. The potential of the suggested reactor concept to establish a presence in the Nordic DH market hinges on the extent to which the aforementioned criteria are fulfilled.

3.1. Performance requirements

The proposed reactor is designed to operate in Finnish district heating networks that already exist in all major population centres. The networks are owned by municipal energy companies that often also supply the heat to the network. The current standard for production maximum output temperature in Finland is 115 °C (Energiateollisuus, 2006). Setting the minimum reactor output temperature level requirement to 120 °C allows for heat transfer losses between the primary, intermediate, and DH circuits. In Finland, the sizes of municipal DH network sizes vary between 100 MWh/a – 7,500 GWh/a, the constant heat load requirement for the smallest being only a few MWs (Finnish Energy Industry, 2024). For commercial applications, 24 MW is considered the minimum and 120 MW as the maximum unit size. According to (Häkkinen et al., 2023), there is room for almost a hundred heating reactors of 24 MW$_{th}$ to be distributed to 19 cities or regions in Finland.

Given the seasonal and even diurnal fluctuations in demand within the DH networks, the heating plant should possess a certain degree of adjustability in terms of both power output and temperature levels.

Usually in traditional NPPs, neutron poisons are used for reactivity control. Boric acid dissolved in the PWR primary coolant is used to adjust reactivity and compensate for fuel burnup. Nevertheless, the soluble poison can be replaced by alternative methods of reactivity control. According to Leppänen (2019), eliminating boron simplifies the water chemistry, reduces tritium production, and removes yet another complicated system from the reactor design. Truong et al. (2021) developed a pressure channel concept for LUTHER which enables controlling reactor power without relying on neutron poisons. This method of operation enables efficient load following. It also increases safety because excess reactivity is not loaded into the core at the beginning of the cycle.

3.2. Economical requirements

In pursuit of cost-effectiveness, the heating reactor should, to the greatest extent feasible, employ commercially available components. The advantages of favoring standard process equipment include economies of scale and the consistent product quality associated with industrial production technology. Additionally, employing well-established technology implies access to a wide range of potential suppliers, contributing to cost-effectiveness through the benefits of a market economy, as well as enhancing security by eliminating the need to rely on a single supplier. Tailored solutions should be avoided whenever feasible.

By lowering the temperature levels to below 180 °C and consequently reducing the pressure in the primary circuit to below 1.0 MPa, we can simplify the mechanical design of the pressure boundary. Consequently, the dimensions of the reactor assembly can be downsized to a level at which practically any well-established pressure vessel manufacturing workshop can produce this critical component, which traditionally is considered one of the most expensive components of any NPP.

To fully leverage the advantages of factory mass production, the units need to be transported to the site as complete assemblies. For numerous potential district heating supply sites, road transport stands as the sole cost-effective delivery method. Consequently, modules designed for small to mid-sized DH networks should be sufficiently compact to fit on a truck trailer and ideally small enough to be accommodated within a standard shipping container. The maximum authorized width for motor vehicles and their trailers in the European Economic Area is 2.55 m (EU Directive 96/53/EC, 1996). In Finland, abnormal transport permits are not needed if the total width of the vehicle does not exceed 4.00 m and the height remains under the general maximum permissible height of 4.40 m (free dimension limits) (Centre for Economic Development, 2020). The inner dimensions of a standard 20 ft shipping container are 5.867 m × 2.352 m × 2.385 m (L × W × H) (ISO, 2020). These envelopes are to be considered when designing the reactor modules.

3.3. Safety requirements

District heating plants are usually located near consumers whereas gigawatt scale nuclear power plants are often located far away from population centres due to extensive emergency planning zone requirements. Numerous studies (e.g. (Bento and Mankamo, 1978; Ingersoll, 2009; Locatelli et al., 2014)) suggest that the reduced power output of SMRs, leading to a smaller source term, would promote the downsizing of the designated safety zones associated with nuclear energy. However, in order to be located near the consumption, a high level of safety must be guaranteed.

IAEA Safety Standard No. SSR-2/1 Rev. 1 (IAEA, 2016) establishes design requirements for the structures, systems, and components of nuclear power plants. The fundamental safety functions identified in the technical requirements of (IAEA, 2016) are (i) control of reactivity; (ii) removal of heat from the reactor and from the fuel store; and (iii) confinement of radioactive material. To meet these criteria, the proposed design must facilitate two independent methods for reactor shutdown. It should also incorporate means to transfer heat from the core, even during disturbances in the forced cooling systems and in the event of coolant loss. Furthermore, the design must establish adequate barriers to contain radioactive materials and prevent the dispersion of active substances to the district heating network and the surroundings of the heating plant.

In addition to the previous, LUTHER design adopts the requirement for a pressure tube structure from previous research. The pressure channel approach was chosen by (Truong et al., 2021) in anticipation of benefits to safety. The pressure tube structure enables implementation of key safety functions in a manner different from vessel reactors. Differences between the two types of reactor types are compared against each other in Table 5 in Appendix C.

3.4. Design methods

The investigation into LUTHER reactor module geometries commenced with the modeling of a 24 MW variant, a unit size previously proposed for application in municipal District Heating (DH) networks (Häkkinen et al., 2023; Teräsvirta et al., 2020). The determination of the pressure channel diameter and lattice pitch was based on previous research conducted at LUT University (Truong et al., 2021). Notably, this study placed significant emphasis on ensuring manufacturability and design simplicity. Once a consensus had been established regarding the structural configuration of the pressure-tube bundle, exploration ensued into geometries for larger variants. The modeling process was executed employing 3D CAD software (Solid Edge 2022, Siemens Digital Industries Software).

The height of the pressure channels was derived from the height of the fuel elements, allowing for adequate space to facilitate vertical movement within the active height of the reactor. Dimensioning of the primary circuit loops was performed through thermal hydraulic calculations to guarantee sufficiently low flow velocities in various sections of the primary system. Ultimately, the resultant dimensions were compared against constraints arising from the limitations associated with road and maritime transportation.

4. Design

4.1. Core design

In LUTHER, heat is generated in a pressurized water reactor (PWR) through the fission of enriched uranium fuel. Light water is employed both as moderator and as coolant, transferring heat from the reactor to the primary heat exchangers. Chemical shim or neutron absorber rods are not employed to control reactivity. Instead, movable fuel elements are used. One third of the fuel assemblies are moved using electric actuators. Lowering these control assemblies below the reactor core serves as the primary method for reactor shut-down. The reactor achieves criticality when the control fuel assemblies are raised up to the core. Full power is achieved when these assemblies are raised approximately 50 % inside the active core. Burn-up is compensated for by the gradual, slow raising of the bundles.

The fuel assemblies are housed within pressure tubes through which lightly pressurized coolant flows. Light water, located within a calandria vessel that surrounds the pressure tubes across the entire active core height, serves as the moderator. By dividing the moderator medium into two separate containers, an alternative method for reactor shutdown is facilitated; Draining the calandria vessel brings the reactor to a subcritical state.

Both the stationary and the movable fuel elements share the same cross-sectional geometry. Fuel assemblies comprise of 61 fuel rods enclosing uranium dioxide fuel pellets inside a zirconium alloy cladding. The 61 fuel rods are arranged in a triangular lattice pattern, with an inner diameter of 8.001 mm and outer diameter of 9.144 mm maintained at a 9.6 mm lattice pitch. A central tube with a diameter of 9.6 mm provides mechanical support. These assemblies are encased in pressure tubes featuring an inner diameter of 91 mm and outer diameter of 101 mm arranged in a hexagonal array with a 10.8 mm lattice pitch. Fig. 1 illustrates cross sections of the fuel assembly and a reactor core for a 24 MW heating reactor module equipped with 61 pressure tubes.

The active core height for the 24 MW module is 88.57 cm. Reactor size scales up by increasing the number of fuel elements and extending the active core height. The average power output of a single fuel element ranges from 300 kW to 550 kW, depending on the element height. Table 1 provides the essential dimensions of fuel elements for the 24 MW module. Further details regarding the reactor core design can be found in (Truong et al., 2021).

4.2. *Reactor core structure*

The reactor core consists of an arrangement of staggered pressure tube bundles. Depending on the size of the reactor module, these bundles can contain 2–8 pressure tubes, which are connected from their upper ends to vertical collector pipes. These collector pipes extend outward from three diamond-shaped sections that collectively form the hexagonal pattern for the pressure tubes. The collector pipes are linked to the primary loops hot leg, creating three distinct manifolds.

The pressure tubes are welded at their lower ends to a tube sheet, which, together with an elliptical bottom header, forms an inlet chamber to which the cold leg is connected. Fig. 2 illustrates the geometry of a 24 MW_{th} reactor module with a single primary loop and the structure of a single pressure tube bundle. The overall dimensions for the 24 MW version are approximately 1.8 m × 1.9 m × 3.9 m and the total surface area of the pressure tubes is ca. 60 m^2. The key dimensions for LUTHER modules ranging from 2 MW to 120 MW are provided in Table 4 in Appendix B.

4.3. *Thermal hydraulics*

The required coolant mass flow for heat transfer is calculated from:

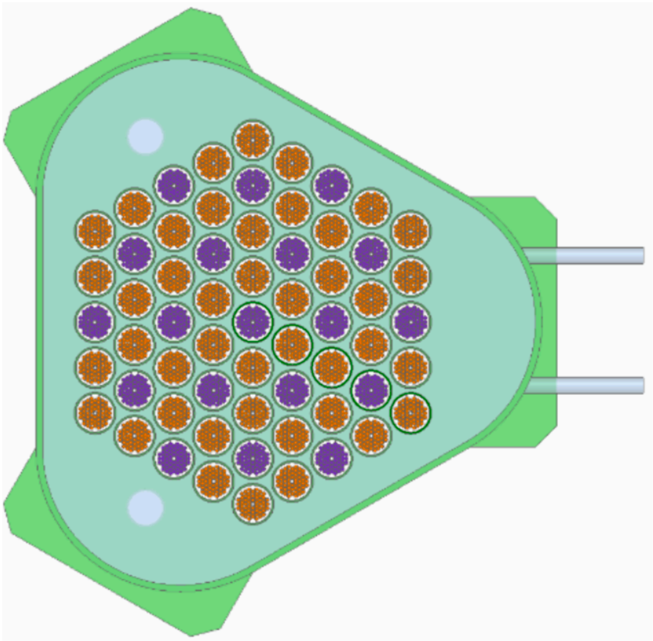

Fig. 1. Cross-section of the 24 MW heating reactor. Movable fuel assemblies are coloured purple. Calandria coolant enters and exits from right. Two calandria vessel drainpipes are visible on the left.

Table 1
Essential parameters for fuel elements and pressure tube assemblies for the 24 MW_{th} variant of the heating reactor.

Fuel pellet material	UO_2
Fuel pellet density (g/cm^3)	10.42
Fuel pellet diameter (mm)	7.844
Fuel clad material	ZIRLO^{TM}
Fuel clad inner diameter (mm)	8.001
Fuel clad outer diameter (mm)	9.144
Fuel rod inner gas composition	Helium
Fuel rod end plug material	Zircaloy-4
Internal fuel rod spring	Stainless steel 302
Fuel rod lattice configuration	Triangular array
Number of fuel rods in an assembly	61
Pressure tube material	Zr-2.5 %Nb
Pressure tube inner/outer diameter (cm)	9.1/10.1
Pressure tube thickness (mm)	5.0
Normal thermal power (MW)	24
Fuel assemblies stationary	42
Fuel assemblies movable	19
Fuel assemblies total	61
Control assembly raising rate	<600 mm/min
Shutdown speed	<4 s
Fuel assembly pitch (cm)	10.8
Core equivalent diameter (cm)	88.57
Core active height (cm)	88.57
Planned fuel cycle	18 months
(Can be divided into two 9 month periods)	

$$\dot{m}c_p = \frac{\dot{Q}}{\Delta T_{core}}, \tag{1}$$

where $\dot{m}$ is the coolant mass flow, c_p is the Isobaric specific heat for water, $\dot{Q}$ is the thermal output of the reactor, and ΔT_{core} is the temperature difference between incoming and exiting coolant. Choosing $T_{Out} = 120\,^{\circ}C$ and $\Delta T = 25\,^{\circ}C$, we obtain a mass flow of 226 $\frac{kg}{s}$ for the 24 MW variant.

The maximum flow velocity is set to 10 m/s to avoid excessive erosion inside piping. For the 24 MW variant with a single loop, the manifold gradually increases from DN 100 to DN 200. With these pipe diameters, the coolant flow velocity within the primary circuit stays below the specified limit. For larger variants, three primary loops are employed.

4.4. *Primary circuit design*

The primary system of the heating plant is a closed circuit with forced cooling induced by centrifugal pumps. The LUTHER design implements all normal-operation related heat transfer functions by active means, guaranteeing accurate process control and the capability of load-following.

Light water coolant at 95 °C is pumped into a bottom header from where it is distributed to the pressure tubes. A flow distributor head ensures even distribution of the coolant. Within the pressure tubes, the coolant heats up to 120 °C as it passes through the fuel assemblies. The horizontal collector pipes gather the coolant from the bundles and direct it to the hot leg(s), then onward to the primary heat exchanger(s) where the heat is transferred to an intermediate circuit. After passing through the heat exchangers, the cooled water returns to the inlet of the primary coolant pumps at approximately 95 °C.

In the 36 MW version and smaller variants, there is a single cooling loop with two primary cooling pumps (PCPs) operating in parallel during normal operation (2 × 50 %). Redundancy is applied for availability. Larger variants feature three loops, each with one PCP in its cold leg (3 × 33 %). There are two nitrogen-pressurized pressurizers, one connecting to the hot leg of the primary circuit by a surge line and the other connecting to the bottom header. Fig. 3 illustrates the geometry of the primary circuit in a 24 MW reactor variant. A larger, 120 MW variant

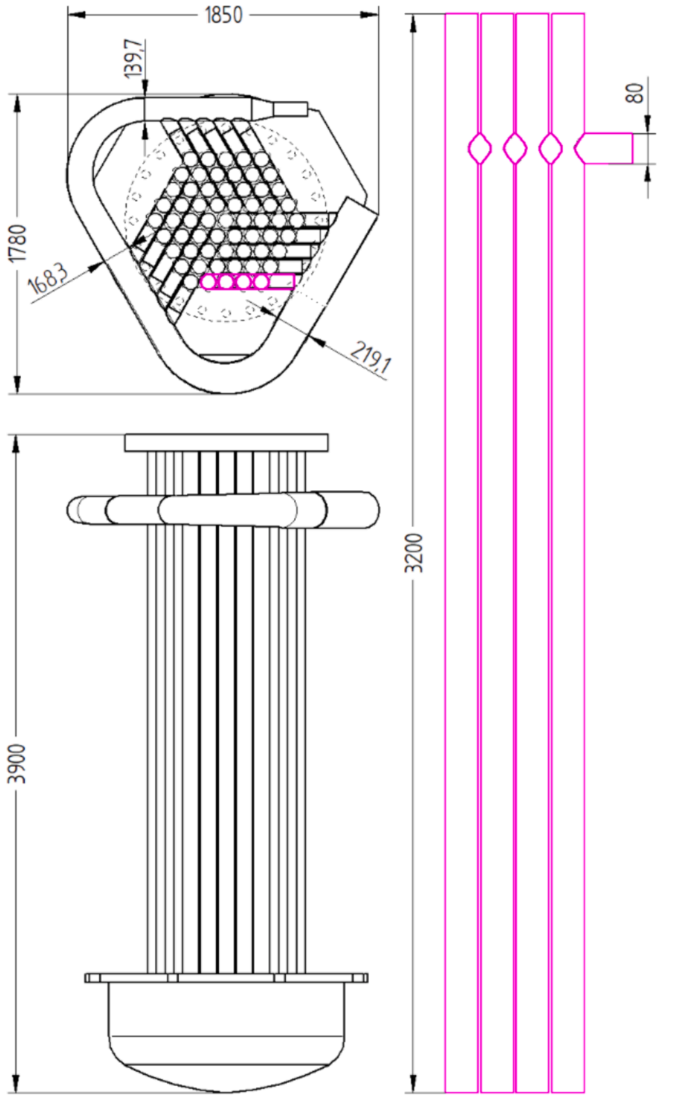

Fig. 2. The structure and main dimensions of a 24 MW reactor module. On the right an outline of a single pressure tube bundle is depicted.

is depicted in Fig. 4.

4.5. Scalability

The reactor structure is assembled from identical pressure-tube bundles connected to a single tube sheet. The pressure tubes, collector pipes, and bundle cross section geometries are essentially the same for all unit sizes ranging from 2 MW to 120 MW thermal output. The nominal power of a LUTHER reactor module is scaled up by increasing the number and length of fuel assemblies within the core. Consequently, only the length and number of pressure tubes in a bundle vary depending on the module size. Flow velocities inside the pressure tubes remain essentially constant for all module sizes as the cross-sectional flow area increases in direct proportion to the increasing reactor power. This feature enables easy scalability for the LUTHER reactor core.

For modules of 50 MW and larger, three loops are employed with pipe diameters of up to DN 300. However, with a pressure tube outer diameter of 101 mm, the maximum reactor size is constrained to 120 MW. Beyond this limit, the flow velocities in the collector pipes exceed the set limit of 10 m/s. Table 2 provides relevant parameters for two selected reactor sizes, while Table 4 (Appendix B) presents flow

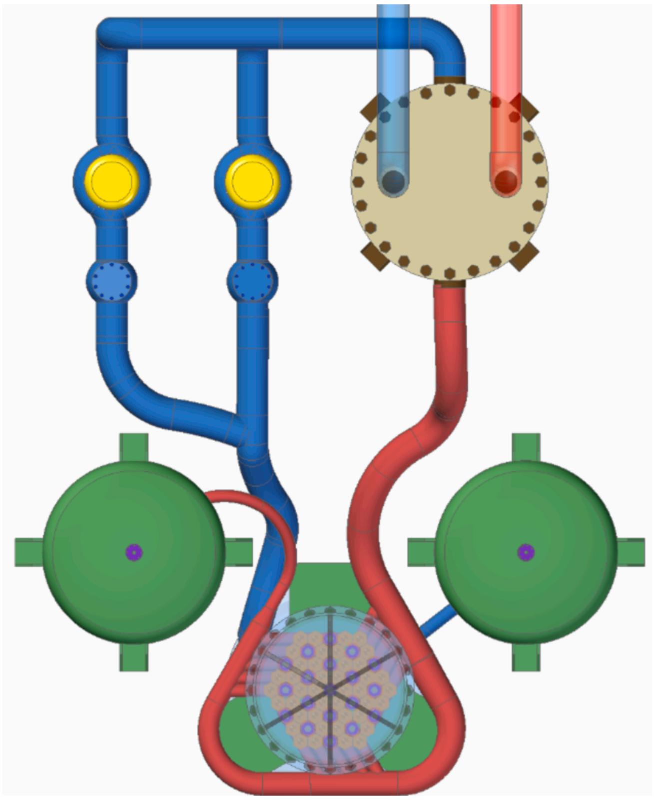

Fig. 3. A single loop 24 MW reactor primary heat supply system. The hot leg is colored red and cold leg blue. The primary heat exchanger is shown in the upper right corner. Two primary circulating pumps are shown on the left. One pressurizer is connected to the hot leg and the other one connects to the bottom header.

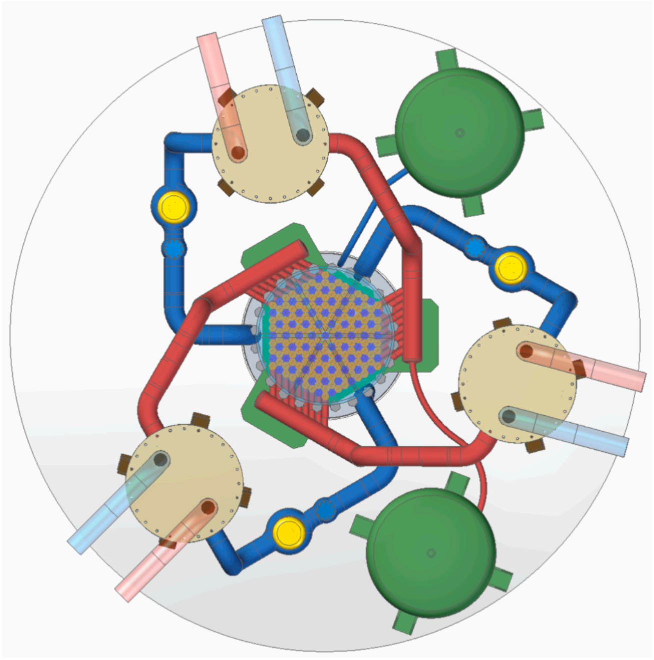

Fig. 4. A three loop 120 MW reactor primary heat supply system. The three hot legs are each connected to separate heat exchangers. The cold legs connect to a common inlet chamber at the bottom of the reactor module. There are two pressurizers, from which one connects to a hot leg and the other one to the bottom header. The circular boundary outlines the containment structure.

Table 2

Parameters for the 24 MW_{th} and 120 MW_{th} heating reactors.

Thermal power [MW]	24	120
Fuel assembly power [kW]	400	550
Coolant mass flow [kg/s]	226	1 132
Pressure tubes in bundle	4	8
No of bundles	15	27
Pressure tubes total	61	217
Primary circuit diameter [DN]	200	250
No of primary loops	1	3
No of PCPs	2	3
No of HXs	1	3
Pressure tube tot. surface area (m^2)	62	344

velocities in different sections of the primary system for all variants ranging from 2 MW to 120 MW.

4.6. Engineered safety features

The primary safety system designed for the reactor trip involves lowering the control fuel assemblies below the active reactor core. These control fuel assemblies are suspended by electromagnets, which are de-energized when the criteria for a reactor scram are met. Gravity causes one-third of the assemblies to descend below the active reactor core, resulting in a subcritical state. The reactor remains subcritical as long as the control assemblies stay below the bottom level of the reactor core.

The second method for reactor shutdown is draining the Calandria vessel. Two fail-safe drain valves, connected to the bottom of the Calandria vessel, open to discharge the water inventory into the reactor pit with these valves activating if for some reason the first scram method fails. The drainpipes are equipped with float valves to prevent the Calandria from refilling due to rising water in the reactor pit. These two different emergency shutdown methods for the reactor can be designed to activate based on different criteria, such as the neutron flux reaching its maximum limit for the first method, and high-pressure values in the primary circuit for the second method.

The outer surfaces of the multiple pressure tubes constitute a substantial heat transfer area. When wetted, this area can be utilized for evaporative cooling, facilitating heat dissipation to the surroundings.

The LUTHER primary cooling system maintains a water inventory supported by two pressurizers, which also function as water accumulators and are pressurized with nitrogen. The water volume of each accumulator is sized to ensure the flooding of the reactor core in the event of a leak or rupture anywhere within the primary system.

The primary circuit is designed to facilitate natural circulation for residual heat removal to the heat exchanger. Loop length is minimized, and pipes are routed straight between the reactor core and the primary heat exchanger, which is positioned at an elevated level relative to the heat source. As a result, any leaks from the primary circuit are directed into the reactor pit. The filled reactor pit participates in cooling the reactor from the outside in severe accidents.

To ensure the retention of potential radioactive activity originating from the reactor core, an intermediate circuit is employed between the primary system and the district heating network. The pressure level for the intermediate circuit is set 0.5 bar higher than that of the primary circuit. This pressure differential serves as a buffer, preventing the escape of activity from the primary circuit in the event of a heat exchanger leak. The selection of pressure levels for both the intermediate and primary circuits below the normal operating pressure of the DH network establishes two successive barriers, effectively containing radioactive materials within the plant in the event of an accident with a radioactive release.

Since neither of the methods for shutting down the reactor and maintaining it in a subcritical state relies on soluble poisons, there is no risk of a boron dilution accident, even if demineralized water from the intermediate circuit were to leak into the primary circuit. Fig. 5 illustrates the engineered safety features in a cross-section of the LUTHER primary system.

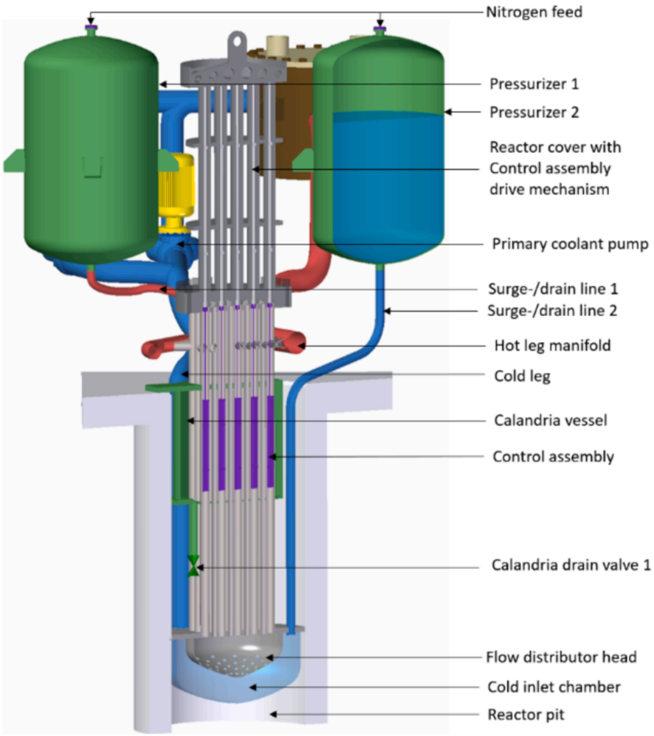

Fig. 5. Primary system engineered safety features. Only one of the two calandria drain valves is visible in this sectional view.

5. Analysis

5.1. Performance

The LUTHER heating reactor can provide a controllable heat supply at up to 115 °C to the DH network. The movable control assemblies enable smooth reactor power adjustment and load following. The proposed module design enables the use of movable control assemblies while allowing unobstructed coolant flow and fuel replacement. The reactor core design supports modular construction and easy scalability. It is well-suited for series production because the building blocks of the reactor core remain essentially the same, regardless of the size of the reactor module.

The simple design resembles that of shell and tube heat-exchangers, equipment that is well known and manufactured in dozens of workshops around the Nordics. With the chosen pressure tube diameter and lattice pitch, the reactor module scales from 2 MW gradually up to 120 MW, which is a sufficient size for most Nordic DH applications. If more power is needed, multimodule units can be considered.

5.2. Economics

The proposed design boasts a compact footprint. The LUTHER 24 MW reactor core structure stands at less than 4 m in height, with a diameter of under 1.9 m. When fully deployed, including the attached reactor cover unit, the total height exceeds just over 6 m. This represents a substantial reduction in size compared to the envelopes of other documented heating reactor units. Indeed, as observed in Table 3 in Appendix A, the LUTHER module proves smaller than any previously reported heat-only reactor. This reduced envelope size contributes to a decrease in construction material and building volume requirements.

The LUTHER heating reactor units are eminently suitable for transport. Modules up to 50 MW stay within the maximum legal width limit of 2.55 m prescribed for highway travel in the European Economic Area. Additionally, none of the module dimensions presented in Table 4 exceed the free dimension limits set for abnormal transports. Consequently, no special permits or specialized equipment are required for the road transport in Finland for any of the proposed modules. As a result, the entire module can be manufactured within a controlled factory environment and subsequently transported to the site, thereby minimizing on-site activities. Furthermore, as indicated in Table 4, reactor modules up to 36 MW can fit within a standard 20-foot shipping container. This not only facilitates maritime transport but also enables seaworthy packing and storage at the site for the smaller reactor variants.

The simplified design of LUTHER holds the potential for numerous economic advantages. The omission of control rods and chemical shim for reactivity control results in a reduced requirement for supporting systems. Additionally, the non-integral design allows for the utilization of off-the-shelf components for pumps, valves, and heat exchangers as the equipment is not customized to fit an integrated module. The utilization of mass-produced, well-established, and proven pumps, valves, and heat exchangers offers a wide range of vendor options. Diversifying the supplier base is expected to enable competitive tendering and enhance delivery reliability, in addition to operational reliability arising from proven components being used with a wide industrial experience base (Fortum, TVO, Fennovoima, Åf, 2019).

5.3. Safety

The proposed primary system design strives to implement a high level of inherent safety. The design incorporates two independent methods for reactor scram, both operating on a fail-safe principle. Radioactivity is retained within adjacent barriers formed by the fuel itself, the primary circuit, and, ultimately, a leak-tight containment. Furthermore, the higher pressure of the intermediate circuit prevents primary-secondary leaks. The selected shell and plate-type primary heat exchangers establish a distinct pressure boundary between the primary and secondary circuits. For the 24 MW variant, coolant inventory is maintained by two accumulators, each with a water volume matching that of the primary circuit. The reactor pit and primary circuit geometry ensure that coolant always collects in the reactor pit, regardless of the point of leakage within the primary circuit. Although residual heat transfer from the primary circuit is not presented in this paper, the geometry of the primary circuit allows for natural convection through the primary heat exchanger. In addition, the pressure tubes constitute a heat transfer surface that can be utilized in abnormal and accident conditions for decay heat removal.

6. Discussion

The nearly 50 % reduction in the carbon emissions from the Finnish district heating (DH) production during the last decade owes mainly to the transfer from burning fossil-based fuels and high carbon fuel peat to biomass, such as wood-based fuels from e.g., logging residue chips (Finnish Energy Association, 2023, p. 16). Further increasing the share of renewables in DH production has become challenging in the heating market as there is now a deficit of wood fuels driven by competition and recent economic sanctions imposed on Russia (Finnish Energy Association, 2023, p. 3). The increasing costs drive the competitiveness of other heat supply technologies less dependent on economic fluctuations. Heat-only reactors can help reduce cost and build more resilient supply chains.

Recently, Small modular reactors (SMRs) have attracted interest as a replacement for combustion-based heat production in the Nordic DH sector. Especially heat-only SMRs have been recognized as a cost-efficient way to produce base load to district heating networks. As the plant is designed only for heat production, it inherently has fewer systems than a unit designed for electricity or combined heat and power production. Low-power and low-temperature applications allow for lighter-weight structures leading to lower CAPEX costs. Reactors with 10 MW – 50 MW power output have been suggested (Häkkinen et al., 2023) as optimum for various-sized DH networks. Despite the apparent benefits, only a handful of designated heat-only reactors have been or are being developed. This paper introduces a nuclear heat supply system for one of them, the LUTHER heating reactor.

6.1. Comparison to other heat-only reactors

LUTHER is not the first reactor concept to utilize pressure channel arrangement. CANDU SMR, a horizontal pressure tube, pressurized heavy water reactor and TEPLATOR, a pressure tube-type heat-only reactor both rely on this configuration. Especially the larger LUTHER variants with three primary loops resemble somewhat the TEPLATOR reactor module. Both heating reactors incorporate vertically aligned pressure tubes in their geometry. The LUTHER heating reactor differs in terms of fuel enrichment, the used reactor coolant, and module geometry. Whereas CANDU SMR and TEPLATOR use low- or non-enriched fuel and rely on D_2O as moderator to achieve criticality, LUTHER uses standard LWR low enriched uranium and is cooled and moderated by light water. While heavy water moderation enables a sparse pressure-channel arrangement allowing the coolant pipes to run between the pressure tubes, this type of geometry is unattainable for the LUTHER heating reactor. In fact, the most distinctive difference of LUTHER, separating it from previous pressure-channel reactor designs is its tightly packed structure, necessitated by the light water moderator. The uniquely small channel lattice pitch helps minimize the reactor footprint and is of obvious advantage in nuclear materials control (Safeguards by Design), as individual pressure tubes cannot be accessed while the reactor is online.

While integral designs with natural convection undoubtedly offer benefits, a case can be made for the advantages of the non-integral design of LUTHER. Vessel reactors must be designed and manufactured such that catastrophic vessel failure is excluded with high confidence. This drives the complex manufacturing and oversight requirements associated with reactor pressure vessels. In a pressure tube reactor, the impact of a mechanical failure of any component of the primary system is more benign than in vessel reactors. A breach of the largest weld seam in the primary system pressure boundary concerns only a limited section, not the whole reactor core area. Furthermore, a separate reactor core structure enables wide use of off-the-shelf components, such as the main heat exchangers, mass-produced for conventional process industry needs.

Integral design is often accompanied by the natural convection of coolant. This walk-away passive safety-feature comes with a trade-off. Coolant mass flow maintained by coolant density differences complicates reactor control in load following operation. Forced cooling generated by centrifugal pumps allows flexible control of reactor temperature while following load. In addition, the safety case is less sensitive to the failures of individual components because failure of the pressure boundary cannot cause catastrophic consequences.

Naturally circulating reactors require larger heat exchange surfaces, tailor-made for installation in the vessel, and therefore larger primary vessels. The footprints of LUTHER modules are less than for any heating reactors with the same reactor power output. Evaporation from wetted primary system surfaces has also been considered as means for decay heat removal in accident conditions. This feature would remove the need for traditional engineered safety systems such as Emergency Core Cooling Systems, reducing the number of required systems and further minimizing the footprint.

Pool type reactors DHR 400 and RUTA-70 operate at atmospheric pressures. Their maximum heat output level is below 100 °C. This is below the current Finnish norm for DH output temperature of 115 °C. If atmospheric pressure pool type reactor were to be used in Nordic DH networks, the low output temperature would need to be primed. LUTHER reactor output temperature is 120 °C. Therefore, it can serve as the single primary source for heating in DH networks even during the coldest winter months. The higher output temperature of LUTHER also provides the possibility for efficient desalination. Multi-stage flash distillation (MSF), the most common desalination technique, typically functions at high temperatures of 90–120 °C (Semiat, 2010; Garg, 2019). These temperatures are beyond the range of pool type reactors operating in atmospheric pressures. Finally, the reactor power output of Happy and DHR 400 is larger than required for most municipal DH networks in Finland. Operating nuclear reactors continuously on partial loads is inefficient. The scalability of LUTHER ensures that the size of the deployed units can be adapted to the needs of smaller municipalities as well as those of larger cities.

6.2. Design novelty and future work

This paper introduced a novel concept for a pressure channel heating reactor module. While the design adopts some features from shell and tube heat-exchangers, applying their tightly packed structure to an SMR module has to date been unreported. The novelty of the design lies in its scalability. Reactor modules from 2 MW to 120 MW can be fabricated using basically the same pressure tube bundle structure. The unique structure of its pressure tube bundle and the significantly small module size provide LUTHER with potential for a cost-effective alternative to previously reported heat-only reactor modules.

The rest of the primary system is only briefly discussed in the current study. The next steps in plant development are studies of the primary circuit and the basic design of safety systems. Within these areas, research regarding natural convection within the primary circuit and the potential to apply passive cooling for residual heat removal are being explored. In future, an experimental or CFD study of the primary system is recommended. In addition, safety analysis for relevant transient cases and severe accident management should be performed.

The entire primary system of LUTHER will be enclosed in a leak-tight reinforced concrete containment structure. However, the present paper does not describe plant structures other than the reactor pit. Similarly, the balance of the plant remains to be designed. Smaller LUTHER variants suit multi- module deployment and would benefit from synergies emerging from the joint balance of plant systems. Redundancy can be applied either only to the active components or by implementing two entirely independent intermediate cooling circuits. A study related to the structures and systems around the primary system is called for.

In addition to technical issues, challenges remain to be overcome in permitting district heating SMRs. The smaller source term of SMRs is expected to enable smaller emergency planning zones and regulations updates to this direction are underway in the U.S. and in Finland (Sainati et al., 2015; NRC, 2023; STUK, 2023). Cost-effective deployment of SMRs, including district heating reactors, requires standardized production of components and modules. At the moment, nuclear legislation in Nordic countries fails to recognize the possibilities arising from series production and the subsequent implications to safety. The regulatory guidelines in Finland are currently under development and could benefit from more scientific studies in this area.

Furthermore, potential business models should be explored. Municipal power companies usually do not have the resources to act as a full-fledged nuclear licensee. Most likely larger utility companies with experience from operating nuclear plants would operate fleets of SMRs but whether the municipal power companies would own their plants or merely buy the heat remains a question.

7. Conclusions

The paper introduces a preliminary heat supply system concept for a small modular nuclear reactor dedicated to heat production. The design of the pressure channel-type reactor module meets the performance criteria expected of a modular district heating unit. The innovation inherent in this design primarily resides in its scalability, which not only accommodates deployment within heating networks of various sizes but also enables efficient series production. The proposed reactor assemblies can be scaled to achieve reactor powers of up to 120 MW. Furthermore, all module sizes are suitable for standard road transport. Modules sized up to 36 MW can be accommodated within standard sea containers.

Safety is considered in the design with two diverse reactor shut-down methods, successive physical barriers preventing the release of active substances and robust inherent means for fuel cooling in the primary system. The proposed reactor design holds the potential to serve as the foundation for a secure and dependable heating unit, capable of producing cost-effective low-temperature heat for energy and industrial applications.

The LUTHER heating reactor strives to emerge as a promising solution for generating carbon-free heat in an economically viable manner. It possesses the potential to emerge as a competitive alternative to the combustion of fossil and wood-based fuels. This research primarily focused on the geometry of the reactor module and did not address the surrounding structures. Future studies on the LUTHER heating reactor are planned to cover the design of the reactor building, the optimisation of decay heat removal in transients and accidents, and demonstration of the inherent safety of LUTHER concept. Walkaway safety features are needed to ensure that heating reactors can be sited in close proximity to populated areas and can facilitate the replacement of fossil-fueled and other combustion-based heating plants in already existing district heating networks.

CRediT authorship contribution statement

Antti Teräsvirta: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Juhani Hyvärinen:** Writing – review & editing, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A

Table 3
Comparison of heat-only modules (Iaea, 2022; Leppänen et al., 2021).

	Happy 200	DHR400	RUTA-70	Teplator	LDR50[1]
Reactor type	PWR	pool-type	pool-type	channel-type	PWR/integral
Rated power [MW]	200	400	70	50	50
Primary circuit inlet pressure [Mpa]	0.6	0.3	atm	atm	0.5
Reactor outlet Temperature [°C]	120	98	102	98	120
Module height [m]	6	26	17.25	6.5	20
Module Diameter [m]	2.3	10.0	3.2	3.7	3.3
Cooling method	forced	forced	natural/forced	forced	natural
Reaction control method	control rods	control rods	control rods + absorber rods	moderator level adjustment	control rods + emergency boration

[1] Parameters as reported in latest available scientific publications.

Appendix B

Table 4
Estimated main parameters for LUTHER reactor module variants 2 MW – 120 MW.

Thermal power [MW_{th}]	2	6	12	24	36	50	90	120
Tubes in bundle	1	2	3	4	5	6	7	8
No. bundles	6	9	12	15	18	21	24	27
Pressure tubes total	7	19	37	61	91	127	169	217
Pressure tube height [m]	1.8	2.2	2.7	3.2	3.6	4.1	4.6	5.0
Pressure tube total surface area [m^2]	4	13	32	62	104	165	247	344
Module width [m]	0.7	1.1	1.5	1.9	2.2	2.5	3.0	3.3
Module height [m]	2.4	2.8	3.3	3.9	4.3	4.8	5.3	5.8
No primary loops	1	1	1	1	1	3	3	3
Coolant mass flow [kg/s]	19	57	113	226	340	472	849	1132
Collector pipe outer diameter [mm]	32	40	50	80	80	80	80	80
Flow speed in collector pipes [m/s]	3	5	5	4	5	6	7	9
Hot/cold leg diameter [DN]	80	80	100	200	300	200	200	250
Flow Speed in hot/cold leg [m/s]	4	4	5	7	5	5	9	7

Appendix C

Table 5
Comparison between vessel type and LUTHER pressure tube type reactor characteristics.

Design/Characteristic feature	Vessel reactors	LUTHER pressure tube reactors
Excess reactivity management	Sizable excess reactivity loaded in the core.	No excess reactivity loaded.
	Excess reactivity is compensated by absorber materials: burnable absorbers, shim control rods, chemical shim (PWRs).	Reactor is made critical by assembling a critical mass by pulling movable control elements halfway in the core. Reactivity losses due to heat up to full power, fission product poisoning and fuel depletion are compensated by further (slow) insertion of fresh fuel.
	Sizable reactivity accident physically possible through rapid ejection of control rods or rapid insertion of unborated water (PWRs).	Reactivity insertion accident potential limited by control bundle movement restrictors.
Reactor shutdown mechanisms	Primary shutdown mechanism: insertion of control rods	Primary shutdown mechanism: drop of the control bundles out of the core, disassembling the critical system.
	Diverse reactor shutdown: boration of coolant (slow; both PWR and BWR).	Diverse reactor shutdown: draining of the calandria removes enough moderator to make reactor subcritical.
Mechanical design of reactor pressure boundary	Catastrophic failure of reactor vessel causes core-wide mechanical loads and fuel damage. Therefore, vessel failure must be excluded with very high confidence, leading to demanding requirements on vessel manufacture.	Catastrophic failure of largest individual weld seam or cross section is always localized and affects mechanically at most one fuel bundle at a time.
Coolability in accident conditions	In case of coolant loss, reactor vessel must be reflooded or else fuel will melt.	In case of coolant loss, each pressure tube acts as heat exchange surface, able to remove decay heat even from a dried-out fuel bundle. Radiative heat transfer inside the fuel bundle is sufficient to keep cladding temperature well below LOCA criteria.

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