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TEPLATOR: nuclear district heating solution.

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ABSTRACT

The innovative concept for district and process heat production is presented using already irradiated nuclear fuel from commercial light water power reactors. This fuel is not burnt up to its regulatory and design limits.

The TEPLATOR is a critical assembly derived by the state of the art computational tools using better moderation, more optimal fuel lattice pitch, lower fuel temperature, lower coolant pressure for producing commercial heat with a cost of less than 4 EUR/GJ. Investment cost for building the TEPLATOR district heating station is below 30M EUR (for both using prices of 2019). Different TEPLATOR variants are proposed; using either used BWR, PWR or VVER irradiated fuel assemblies (FAs). TEPLATOR can also be operated with fresh fuel, if the stockpile of irradiated FAs is exhausted.

TEPLATOR DEMO is a 50 MWt district heating plant using 55 FAs from VVER-440, producing 98 C hot water. TEPLATOR DEMO is coupled to a thermal storage system *allowing shaving off morning and evening district heating peaks. TEPLATOR DEMO coolant is used at atmospheric pressure, the system has three loops, three main circulation pumps, three heat exchangers and heat generation is regulated by standard control mechanisms. TEPLATOR variants using BWR and PWR square lattice fuel were also considered. The engineering constraints show potential for a higher output (< 250 MWt) and/or higher temperatures (< 200 C) as customers require.*

The TEPLATOR solutions is especially suitable for countries that have thousands FAs stored either in interim storage casks or spent fuel pools. These FAs are now financial liability which, once used for heat production, can turn into a sizeable financial asset.

1 INTRODUCTION

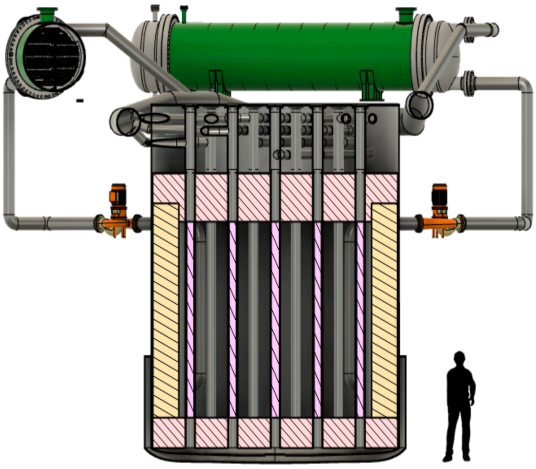
The TEPLATOR is an innovative concept for future district and process heat production. The TEPLATOR facility will use already irradiated fuel from conventional light waters reactor (which are not burnt up to its regulatory and design limits). In order to harvest additional energy from already used FAs, the TEPLATOR is a critical assembly derived by the state-of-the-art computational tools using better moderation, more optimal fuel lattice pitch, lower fuel temperature and lower coolant pressure. Different TEPLATOR variants are proposed; using either used BWR, PWR or VVER irradiated fuel assemblies with output power range between 50 and 200 MW(t). The initial TEPLATOR DEMO operates at 50MWt with VVER440 fuel.

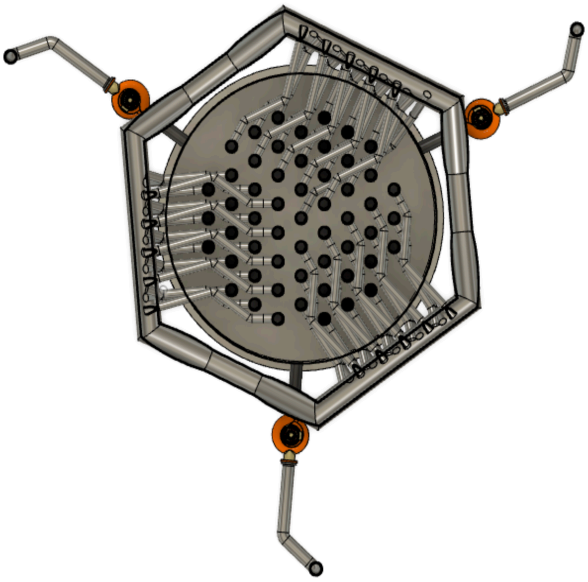
The TEPLATOR is designed for clean district heating energy production for cities with 100 000 or more inhabitants. It will replace the out-dated conventional heating plants based on fossil fuels. The TEPLATOR will produce heat without any emissions and with negligible fuel costs. TEPLATOR solutions are especially suitable for countries that have thousands LWR FAs stored either in interim storage casks or spent fuel pools. These FAs are now financial liability which, once used for heat production, can turn into a sizeable financial asset. The calculated investments cost for the first TEPLATOR DEMO 50 MWt facility is 30 M EUR. Then the final price of produced heat is 4 EUR/GJ (using prices of 2019).

2 TEPLATOR - GENERAL IDEA

The design philosophy is to use only proven, known, verified, and tested high TRL components. This ensures low investments costs and low risks. The design itself includes 3 circuits. The primary circuit includes a so-called calandria, a core with the spent LWR fuel FAs, three heat exchangers and three pumps. The core is made from Zr channels in which the fuel is inserted. The space between the channels is filled by the moderator, heavy water. The coolant flows in all channels, through a system of pipes to the collector. Three pipes are led out of this collector, each of which is led into a separate heat exchanger. The coolant passes through the primary side of the heat exchanger and returns to the fuel channels through the pump and the lower distribution chamber. A secondary or intermediate circuit transfers the heat from the primary circuit to the district heating circuit. The secondary circuit heat transfer fluid (HTF) could either be water or another fluid (based on the operating parameters). The intermediate circuit includes two storage tanks connected to the circuit serving as an energy storage system for shaving off demand peaks. These storage tanks are also able to simultaneously dissipate and store heat from the residual power of the fuel, i.e. the intermediate tanks are designed to be able to absorb decay heat of the core in DBAs. The tertiary or district heating circuit, which distribute the heat to the end customer, is therefore separated from the core by two sets of heat exchangers.

Table 1: Project parameters of TEPLATOR DEMO





MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	UWB Pilsen & CIIRC CTU Prague Consortium, Czechia
Reactor type	Channels in Reactor Vessel
Coolant/moderator	Heavy Water (D_2O)/ Heavy Water (D_2O)
Thermal/electrical capacity, MW(t)/MW(e)	50 / does not produce electricity
Primary circulation	Forced circulation
NSSS Operating Pressure (primary/secondary), MPa	Ambient/Ambient
Core Inlet/Outlet Coolant Temperature (oC)	45 / 98
Fuel type/assembly array	VVER-440 / hexagonal with 126 fuel pins
Number of fuel assemblies	55
Fuel enrichment (%)	Spent fuel (< 1.2 wt% U-235 equivalent)
Core Discharge Burnup (GWd/ton)	2.3
Refuelling Cycle (months)	10 months with online option
Reactivity control mechanism	Moderator height, Control blades
Approach to safety systems	Inherent and passive safety with built/in decay heat sink
Design life (years)	60
Plant footprint (m2)	≤ 2 000
RPV height/diameter (m)	6.5 / 3.7
RPV weight (metric ton)	Transportable by all standard means
Seismic Design (SSE)	0.3g
Fuel cycle requirements / Approach	LEU - reuse of LWR spent FAs, possibility to run on fresh SEU (≤1.2% U235)
Distinguishing features	District heating zero CO_2 source with zero fuel cost, low pressure.
Design status	Conceptual design

The general 3D model of TEPLATOR DEMO primary circuit is shown in Figure 1:

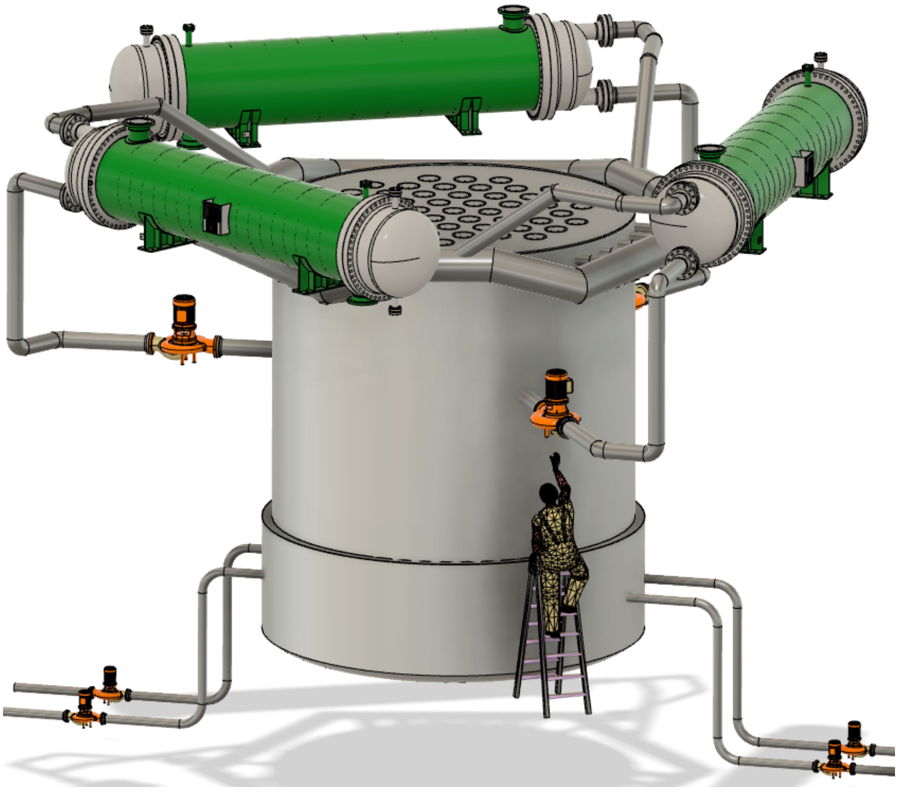


Figure 1: TEPLATOR DEMO primary circuit

3 DESIGN CONCEPTS

The schematic description of a basic thermal design can be found below. All three circuits are shown there and also the energy storage circuit with a heat accumulator.

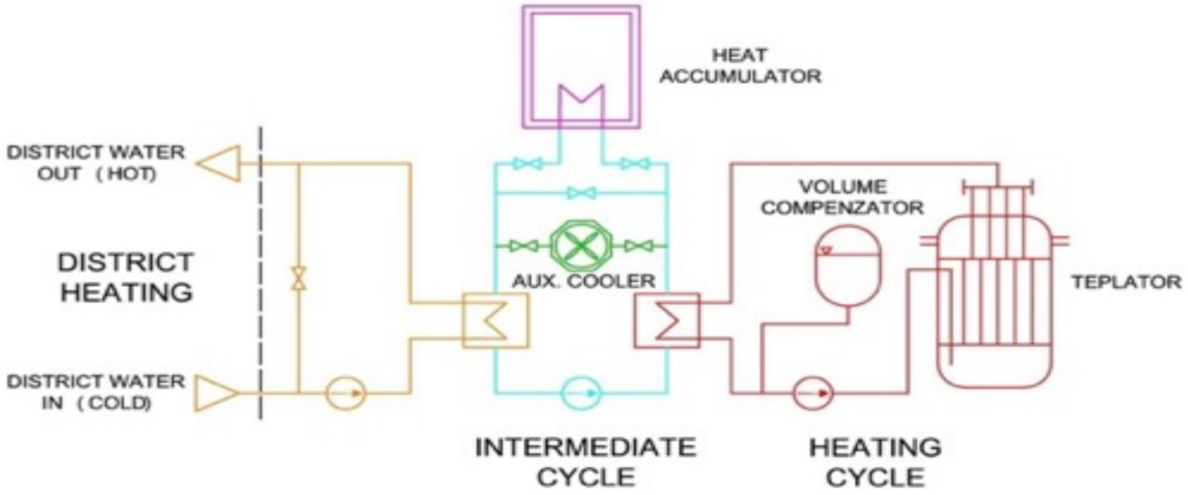


Figure 2: Basic thermal diagram

The TEPLATOR operates only with liquid phase, no steam generation or electricity production is expected.

The TEPLATOR core consists of equally spaced channels filled with spent nuclear fuel from LWR reactors [1]. More customization options are possible, the initial DEMO is the reuse of

VVER-440 spent nuclear fuel. In that case, totally 55 fuel assemblies are placed in large-pitched hexagonal array. Typical VVER-440 spent nuclear fuel had 3.6 wt% U-235 initial enrichment, 35 GWd/ton average burnup and 30 years of cooling. Alternative use of slightly enriched fresh fuel (< 1.2 wt% U-235) is possible. Each fuel assembly is placed in a coolant tube filled with heavy water or alternatives for temperatures up to 98 C. Atmospheric pressure of heavy water moderator eliminates the need for a thick and expensive pressure vessel. The TEPLATOR is a heat generator with typical operation up to 10 months each year (typical heating season) with an option to be refuelled online.

Two independent reactivity control systems are deployed. Reactivity control under normal operation is achieved by changes in moderator level in the reactor pool. Safety-shutdown system is based on three borated steel blades that can be dropped in the core. Due to the low temperatures, relatively short cycle and use of spent fuel the excess reactivity is quite small.

The TEPLATOR internals consist of the fuel channels, channel outlets, absorber blades, absorber blades drive mechanism, I&C systems, reflector and bottom collector. Through the bottom collector the coolant (heavy water) is distributed back to individual channels. The calandria is a stainless-steel vessel, since the TEPLATOR works on low pressure, it does not need to be very thick. The space between fuel channels and calandria is filled with heavy water which serves as a moderator, the total volume of heavy water in calandria is around 30 m^3. The core is surrounded by a graphite reflector.

The primary coolant (D_2O) enters the core of TEPLATOR with the temperature of 45 °C. It flows through the fuel channel and then it leaves the individual channels at 98 °C at the channel outlet. This outlet is attached to the collector where the primary coolant is collected. From the collector the coolant is distributed to the three heat exchangers where it heats the secondary heat transfer fluid (HTF). The primary coolant flows through the pump, then through the pipe on the inside of the calandria to the bottom collector where it is distributed again to the individual channels. Roughly 20 m^3 of D_2O is required in the primary circuit.

The TEPLATOR is a three-loop design, thus it has three primary heat exchangers (HE) to transfer the heat from the primary to the secondary circuit. The heat exchanger is a horizontal type with U-shaped tubes and water-water heat exchange. Each of the HE has a heat transfer surface about 520 m^2 and is capable, under forced circulation, of cooling the TEPLATOR core on its own: decay heat under emergency conditions can be safely removed by HE to the energy storage tanks using natural circulation.

As the TEPLATOR operates under ambient pressure, the function of a PWR pressurizer is replaced by a volume compensator attached to the primary circuit. The compensator is linked to the heavy water management systems.

The secondary circuit is an intermediate loop that separates the primary circuit and the tertiary circuit while transferring heat from the primary to the third circuit. The secondary circuit consists of the secondary side of primary heat exchangers (HE I) and the primary side of secondary heat exchangers (HE II). As part of this circuit the energy storage system, consisting of two tanks, can be connected having identical heat transfer fluid (HTF) as the secondary HTF. This energy storage system is based on thermal energy storage (TES) heat mechanism which serves several purposes: 1) TEPLATOR power fluctuations, 2) compensation and smoothing of the demand curve and 3) emergency and safety heat sink.

4 SAFETY FEATURES

The TEPLATOR operating conditions (e.g., fuel/coolant temperature, pressure, linear heat rate) are much lower than those for which the used FAs were certified and used in LWRs. The safety features establish defence-in-depth against radiological hazards. Hence, the TEPLATOR leverages the inherent safety characteristics of the basic LWR reactor design and supplements them with passive and active safety features that emphasizes improvements in safety [2].

The TEPLATOR secondary circuit provides large volumes of fluid that are available to provide cooling to the core in the event of accidents, including by passive means.

The TEPLATOR places all reactivity devices in low-temperature, low-pressure moderator, eliminating pressure-driven ejection of reactivity devices from the design. The separation of moderator from coolant also provides two separate heat removal means in the event of accidents and ensures that moderator temperature feedback to the core physics is negligible in normal operation.

The TEPLATOR has two separate shutdown systems. These are two fully-capable fast-acting means of shutdown for use at the third level of defence in depth, fully independent of each other.

4.1 Decay Heat Removal System and Emergency Core Cooling System

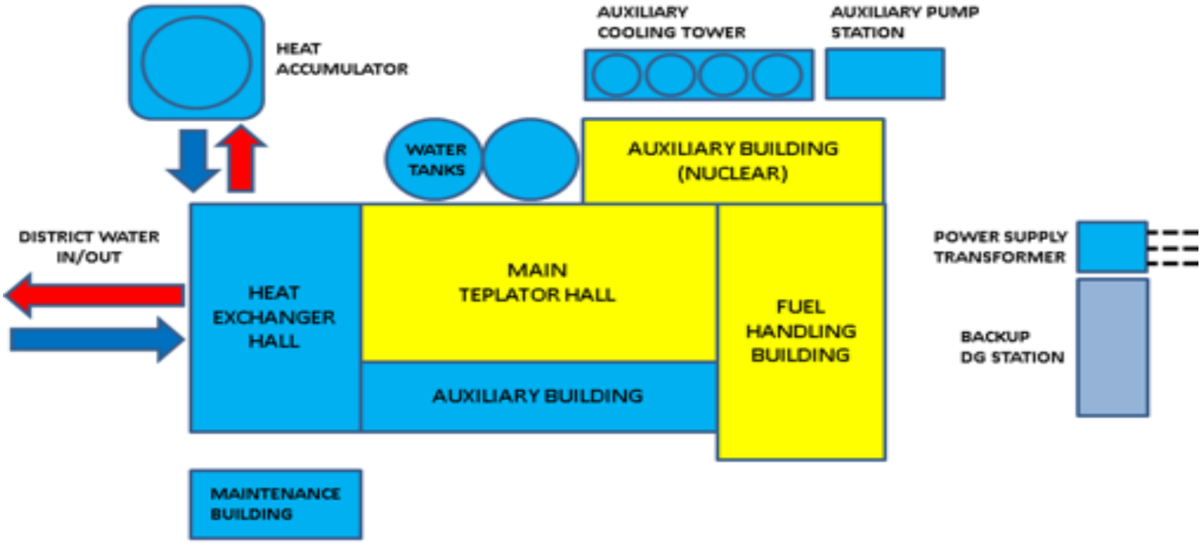
Decay heat removal system is integrated as the energy storage system interconnected to the secondary circuit. During TEPLATOR shut down, heat generated in the core is transported by natural circulation inside the cooling loops. This heat is removed in the primary heat exchanger using thermal energy storage (TES) [3]. The TES system consists of two tanks, a ‘cold' and a 'hot’ one. In order to remove decay heat from the TEPLATOR, heat transfer fluid (HTF) from the cold tank flows via natural convection through the secondary side of the primary heat exchanger (HE I) to the hot tank. The volume of both tanks is designed to be sufficient enough for removing decay heat for long enough that the auxiliary cooler dissipates the heat.

4.2 Containment System

The TEPLATOR containment system includes a reinforced concrete containment structure (the reactor building) with a reinforced concrete dome and an internal steel liner, access airlocks, equipment hatch, building air coolers for pressure reduction, and a containment isolation system.

5 PLANT LAYOUT ARRANGEMENT

As the TEPLATOR DEMO facility is more than just a reactor itself, the plan layout of the TEPLATOR is illustrated below.



The TEPLATOR facility consists of one main structure which further contains nuclear and non-nuclear sectors/buildings. Nuclear sectors are the main TEPLATOR hall, the fuel handling building, and the auxiliary nuclear building. Non-nuclear sectors are the heat exchanger hall and the auxiliary building. Other buildings and structures within the facility layout are a heat accumulator, water storage tanks, auxiliary cooling towers with a pumping station, transformers of power supply and backup diesel generators. Heating / Chilling Supply system is located in the heating exchanger hall next to the main TEPLATOR hall.

6 DESIGN AND LICENSING STATUS

The TEPLATOR project completed its preconceptual design and the works on preliminary/basic design will start in the Q4 of 2020. The commercial demonstration unit with thermal power of 50 MW is in the preliminary phase. The preliminary phase includes the feasibility study, the site location selection and obtaining the license for construction. Once the feasibility study is done and the site location is approved, the environmental impact assessment report will be carried out and will be submitted to the regulatory authorities.

7 FUEL CYCLE APPROACH

The unique feature of TEPLATOR is the reuse of spent nuclear fuel from commercial LWRs which is normally considered a waste. This can be achieved due to significantly lower operation parameters (far from regulatory limits) when compared to the conditions in large LWRs. Based on heating or cooling demand, the core can be operated up to 10 months each year with subsequent refuelling of fuel assemblies. Online refuelling is optional as well as usage of fresh SEU assemblies.

8 WASTE MANAGEMENT AND DISPOSAL PLAN

When removed from the core, reused fuel will be stored and cooled in the fuel handling building and thereafter transported back to the original spent fuel storage.

9 DEVELOPMENT MILESTONES

2019- 2020	Preliminary studies and pre-conceptual design
2020-2021	Conceptual design phase and technology validation
2021-2023	Design phase - Basic design Detail design / Licensing
2024-	Start of DEMO unit construction, first unit in service at 2027

10 CONCLUSION

The TEPLATOR is an innovative way of district heating or cooling using spent nuclear fuel. Before the full scale TEPLATOR can be build, the demonstration unit needs to be utilized. The demonstration unit DEMO has a 50 $MW_{(th)}$ and, after a careful optimization of physical parameters, the first steps in the constructional design were taken and first 3D model of TEPLATOR was obtained. Cost-wise TEPLATOR is well competitive with natural gas and helps improving ecological use of spent nuclear fuel.

ACKNOWLEDGMENTS

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REFERENCE:

[1] J. Závorka, M. Lovecký, R. Škoda, „BASIC DESIGN OF THE TEPLATOR CORE - CONSTRUCTION", Nuclear Energy for New Europe 2020, Portorož, Slovenia, 7. - 10. 09 2020.

[2] A. Fořtová, M. Zeman, J. Jiřičková, „TEPLATOR: Residual heat removal by energy storage", Nuclear Energy for New Europe 2020, Portorož, Slovenia, 7. - 10. 09 2020.

[3] J. Škarohlíd, O. Burian, A. Fořtová, M. Zeman, R. Škoda, „Thermal energy storage for TEPLATOR: technology, utilisation and economics", Nuclear Energy for New Europe 2020, Portorož, Slovenia, 7. - 10. 09 2020.