Design Evolutions of the Molten Salt Fast Reactor

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Abstract. CNRS has focused R&D efforts on the development of a new reactor concept called the Molten Salt Fast Reactor (MSFR), characterized by a circulating liquid fuel and a fast neutron spectrum. This paper presents the new design proposed for the fuel circuit in the frame of the SAMOFAR European project and focuses on the design studies of the emergency draining system of the MSFR. These new designs result from physical and preliminary safety studies such as optimizing the use of the molten salt both as fuel and coolant, defining the operating procedures or minimizing the fuel leakage risks. Additional requirements are considered for the emergency draining system to be able to confine the fuel and to evacuate the residual heat over very long time periods (months) with no human intervention and to guaranty that under no circumstance the salt may reach criticality in this area.

Key Words: Molten Salt Reactors, design studies, emergency draining system, neutronic and thermal studies

1. Introduction

Molten salt reactors are liquid-fueled reactors so that they are flexible in terms of load following capabilities or fuel composition, but they are very different in the design and safety approach compared to solid fueled reactors. Since 2004, the National Centre for Scientific Research (CNRS, Grenoble-France) has focused R&D efforts on the development of a new molten salt reactor concept called the Molten Salt Fast Reactor (MSFR), selected by the Generation-IV International Forum (GIF) due to its promising design and safety features. The MSFR, with a fast neutron spectrum and operated in the Thorium fuel cycle, may be started either with ^{233}U, enriched U and/or transuranic elements as initial fissile load. This concept has been recognized as a long term alternative to solid fueled fast neutron systems with a unique potential (negative temperature and void coefficients, lower fissile inventory, no initial criticality reserve, simplified fuel cycle, wastes reduction…). In the frame of the SAMOFAR European H2020 project started in 2015 for four years, safety analyses and studies are currently developed to define a safety approach dedicated to such liquid circulating fuel fast reactors. In parallel the operation procedures of the reactor are being defined. These operation and safety studies require a correct definition of the design of the different parts of the MSFR systems, leading to design evolutions and optimizations presented in this paper.

After a general presentation of the MSFR concept in section 2 including also a presentation of the new design of the fuel circuit as proposed in the frame of the SAMOFAR project, section 3 focuses on the design studies of the emergency draining system (EDS) of the MSFR through thermal and neutronic calculations.

2. MSFR System

The reference MSFR is a 3000 MWth reactor with a total fuel salt volume of $18m^3$, operated at a mean fuel temperature of 725°C. The fuel salt considered in the simulations is a molten binary fluoride salt with 77.5 mole% of lithium fluoride; the other 22.5 mole% are a mix of heavy nuclei fluorides (fissile and fertile matters). The MSFR plant includes three circuits involved in power generation: the fuel circuit, the intermediate circuit and the power conversion circuit. These circuits are associated to other systems composing the whole power plant: the emergency draining system, the routine draining system to the storage areas and the reprocessing units [1].

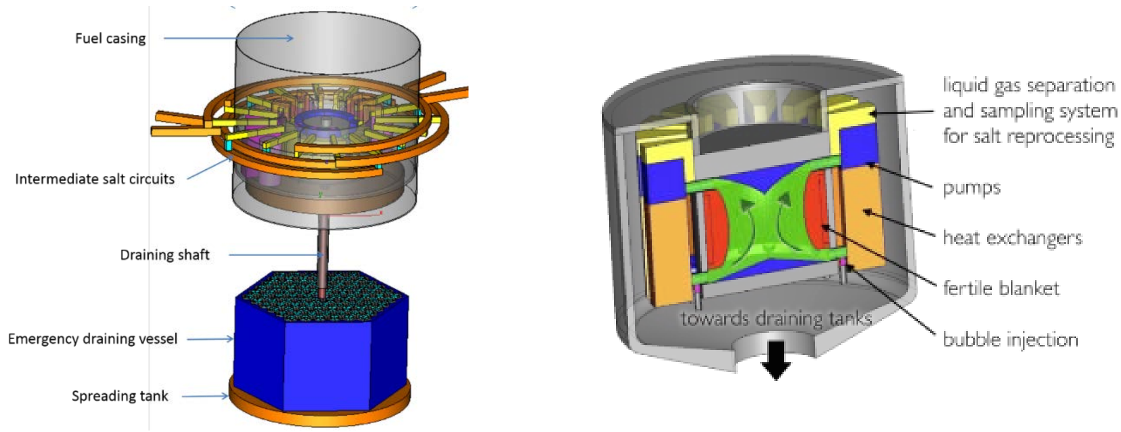

FIG. 1. Schematic view of the MSFR fuel circuit and emergency draining tank (left) and zoom on the fuel circuit (right).

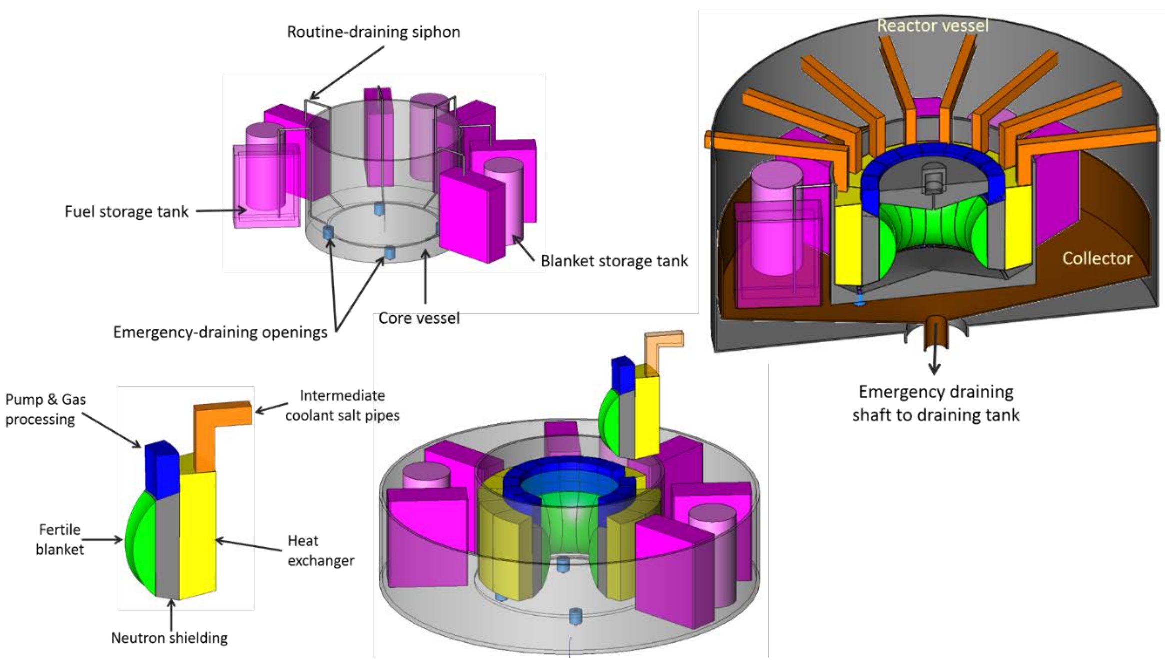

FIG. 2. Schematic representation of a cooling sector (bottom left), cooling sector arrangement in the core vessel (bottom right), storage tank arrangement around the core vessel (top left), and reactor vessel (top right).

The fuel circuit (FIG.1. right), defined as the circuit containing the fuel salt during power generation, includes the core cavity and the recirculation loops (also called 'sectors' in the following) comprising the inlet and outlet pipes, a gas injection system, salt-bubble separators, pumps and fuel heat exchangers. Recent thermal-hydraulic studies have shown that a torus shaped compact core (typical size of ~2.3m) improves thermal flow [2].

To prevent the risk of fuel salt leakage through pipe rupture highlighted by preliminary safety studies [3], an improved design of the fuel circuit is being studied in the frame of the SAMOFAR Euratom project of the Horizon2020 program. The core is enclosed in a vessel that serves as the container for the fuel salt as illustrated in FIG.2. (top). 16 cooling sectors are arranged circumferentially around the vessel (FIG.2., bottom right), inserted from the top.

3. Draining system

3.1.General Layout

In case of severe anomaly, the fuel must be drained into the Emergency Draining Tank (EDT) located under the core. A simplified representation of the Emergency Draining System (EDS) is given FIG.3.

3.1.1. Emergency draining procedure and gravitational transfer to the draining tank

The draining may be actively triggered by monitoring the reactor status or passively started by devices sensitive to excessive fuel temperature or electrical power loss. To this end, opening devices based on different principles are placed at the bottom of the core vessel. Those systems must be redundant and reliable (draining must be effective in case of emergency but must be avoided if it is unwanted). The salt evacuation is assumed to take place through a free space, the collector, with a funnel shape at its lower portion, terminating in a vertical shaft that leads to the passively cooled EDT. The diameter of the vertical shaft is such that, even if it is full of fuel, criticality cannot be reached, while in the event of a leak it cannot be clogged up.

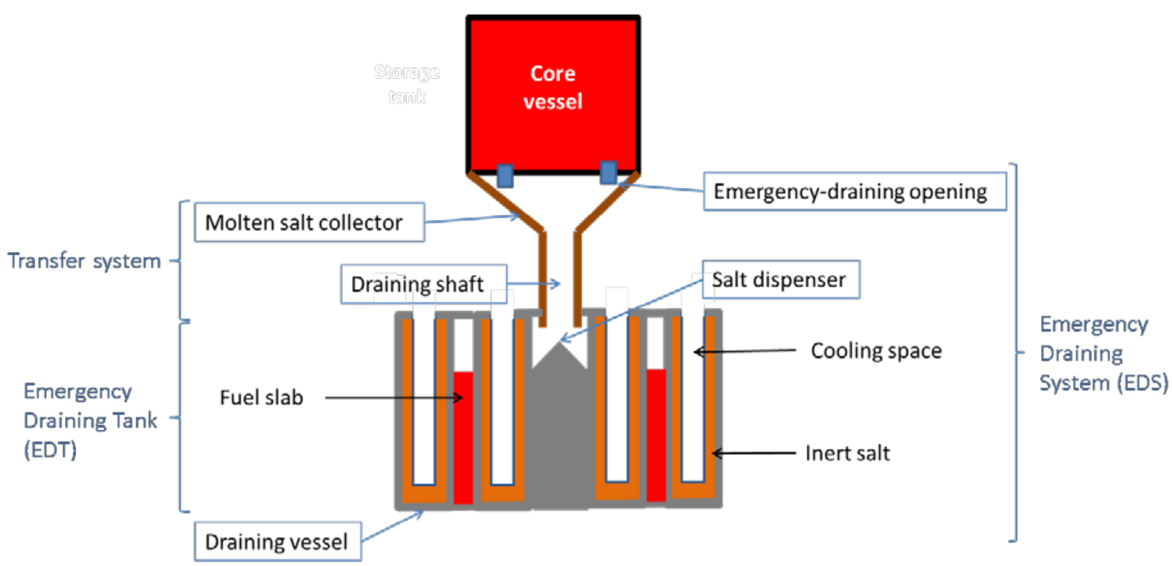

FIG. 3. Schematic overall representation of the draining system - vertical cross-section

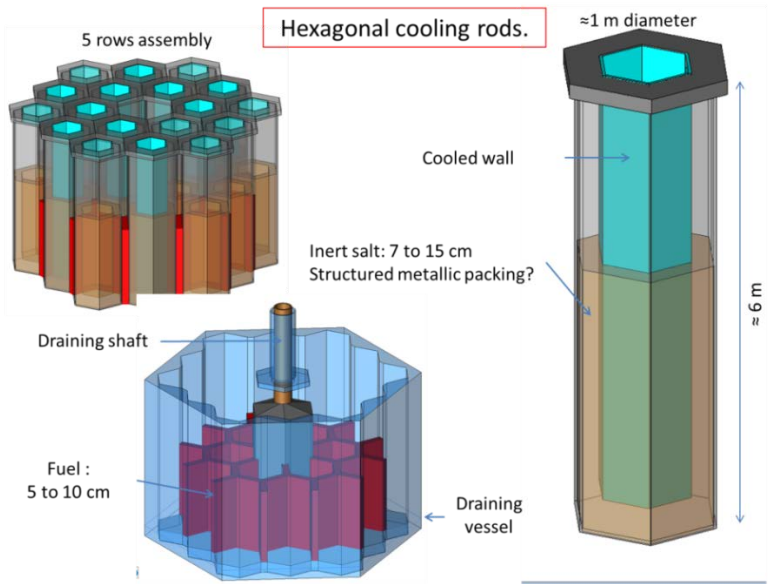

FIG. 4. The emergency-draining tank (hexagonal version) is composed of a thick metallic casing (blue) containing cooling rods (center) between which the fuel salt (red) spreads. Below, these cooling rods are removed to show the fuel salt and the partition inert block.

3.1.2. Draining tank description

The draining tank is a large hexagonal vessel containing the fuel salt and in which cooling rods are placed. The inside of each rod is filled with a thick layer of inert salt, leaving space in the central part for cooling channels (FIG.4.).

The cooling fluid (water, gas…) has to be selected. The case of water has been used for the preliminary studies presented below even if this solution is not optimized regarding safety.

The center of the vessel holds a compact block on top of which is the dispenser. Above is the draining shaft fitted with spewing slits (6 for a hexagonal vessel) letting the fuel salt flow towards the openings between the cooling rods. The rods that are in the immediate periphery of the central block are adjusted so that the salt cannot flow between it and themselves. The same applies to the rods in contact with the external walls of the vessel. In this way, the central block and the external walls of the vessel need not be cooled.

Finally, in its required functions, the draining in the EDT has to be reversible and the core can be refilled with fuel from the EDT, but the system allowing this transfer has to be defined.

3.2.Preliminary thermal studies

In the EDT, the fuel salt fills a narrow space, between cooling rods, to prevent its overheating due to its poor conductivity. The rods serve as a thermal inertia system in order to maintain the fuel at liquid state as long as possible and to reduce the power to be evacuated by the cooling system. Indeed, the fuel's residual heat is stored as sensible heat in the materials and as latent fusion heat in the inert salt. The inert salt's fusion temperature is a parameter that remains to be selected to best adjust the time during which the fuel remains liquid. Cooling is ensured for an indefinite duration thanks to a cooling fluid fed into the center of the rods.

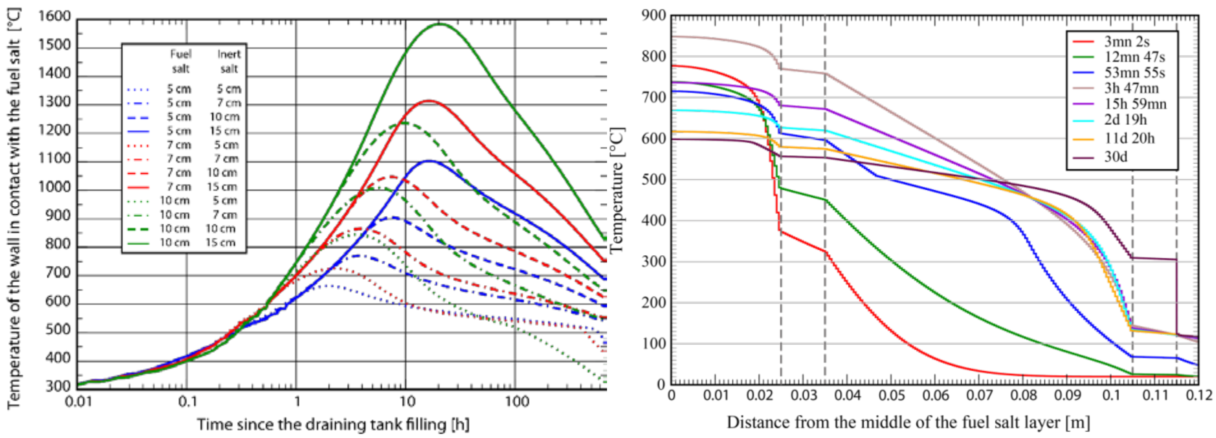

FIG. 5. Time evolution of the temperature of the metallic wall in contact with the fuel salt (left) and Temperature spatial distribution for the "5cm fuel salt and 7cm inert salt" case after various cooling times (right).

Several parameters are available to control the thermal transfer in the EDT such as: the thermal conductivity of the metallic walls and their thickness, the amount of inert salt and its thermal conductivity (possibly improved thanks to a metallic structured packing) and the geometry of the system.

The objective of the preliminary thermal calculations was to show that it is possible to keep the fuel at liquid state, the fuel salt melting point being 585°C, and limit the maximal temperature reached at the metallic wall. In a first approach, we used a 1 D model with one layer of fuel placed between two flat partitions that separate it from two layers of inert salt, these possibly in contact with the cooling fluid.

The convection within the fuel layer is simulated by an equivalent conductivity profile. The inert salt (LiF-ZrF_4 used for these preliminary calculations) is static, even in the liquid state. This approach, though quite simplified, demonstrates that the fuel can be kept in the liquid state for a long time. It gives rough estimates of the wall temperature evolution, as shown FIG.5. (left). In these calculations, the only parameters that vary are the thickness of the fuel layer and that of the inert salt. Increasing the inert salt thickness acts positively on the inertia but negatively on the thermal isolation, so that the maximal temperature increases. The amplitude of the temperature variations depends on the thickness of the fuel salt layer. In this respect, a 5 cm thickness (dotted curves) seems to be favorable. Observe that maintaining the salt in the liquid state for durations up to 700h (one month) seems attainable. Improving the inert salt's thermal conductivity would limit the fuel's heating.

The time evolution of the thermal profile for a fixed geometry, displayed in FIG.5. (right), shows that for rather long delays (>12h) a solid fuel layer forms on the walls. This layer will be eliminated by the action of the residual power, if the cooling fluid is removed. Observe also that, with this example, the cooling fluid becomes necessary only more than one hour after draining.

3.3.Geometrical considerations

The total volume available for the salt in the EDT is larger than 18 m^3, in the event that the intermediate fluid or the fertile salt is mixed in with the fuel salt (we took 36 m^3).

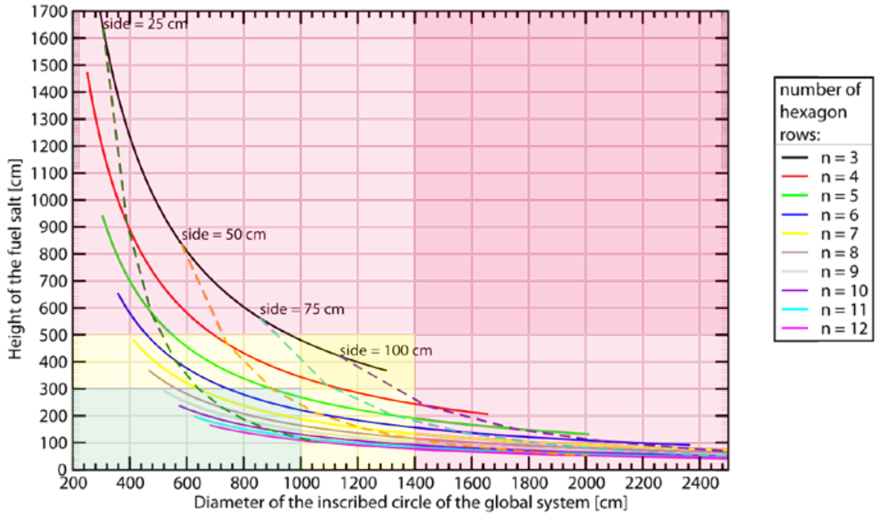

FIG. 6. Height of the fuel salt as a function of the size of the global system for several number of hexagon rows. Configurations in the pink area are excluded, in yellow possible and in blue advisable.

From the general layout description, an infinite number of configurations could be created depending on the number and the side length of the hexagonal cooling rods. Those characteristics have to be selected based on thermal and neutronic analysis but also in order to have a relatively compact design. FIG.6. gives the height of the fuel as a function of the inscribed circle diameter of the draining tank for several number of cooling rods rows. The 3 colored zones delimit the excluded (pink), possible (yellow) and advisable (blue) geometries. The advisable tank configurations have a fuel salt height lower than 3 meters and an inscribed circle diameter lower than 10 meters.

The configuration with 5 rows of hexagons of 50 cm side has been used for criticality studies. With these parameters, the salt height reaches approximately 3 m (the total height of the system is then 6 m) and the diameter of the inscribing circle is around 9 m.

3.4. Criticality studies

The draining system geometry should be defined in order to ensure a subcritical configuration under any circumstances and at each stage of the draining. In this context, criticality studies have been performed with the Monte Carlo simulation code Serpent [4]. As the configuration of the draining system is not fixed yet, the objective was, by doing parametric studies, to find constraints on the geometry to help the sizing of the system. To ensure a sufficient margin to criticality, a configuration is validated if the eigenvalue (k_{eff}) is lower than 0.95 which is the value used for normal conditions in fuel building and for radioactive package waste. The simulations are done with a fuel at initial core composition, FLiNaK as inert salt and Ni-alloy as structural material [5].

3.1.3. Collector and draining shaft

When the EDS is triggered, the fuel flows through the transfer system (represented FIG.7.) to reach the EDT. In this study, we considered the case of a blockage preventing the fuel to flow and leading to an accumulation of fuel in the collector and draining shaft. In a first approach, the draining shaft and the collector have been studied separately. The draining shaft is a cylinder of 1 or 2 meters high, with a radius between 15 and 30 cm and a wall thickness of a few centimetres. Two boundary cases have been studied: one with a 30 cm wall thickness and one with no wall.

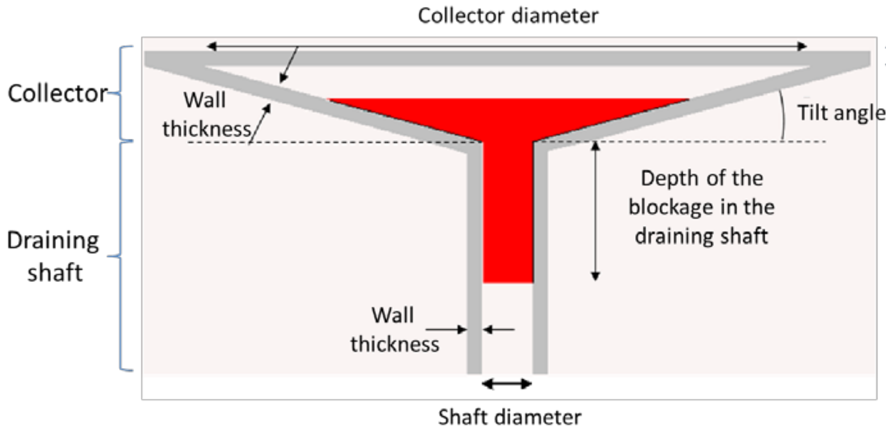

FIG. 7. Schematic drawing of the collector and draining shaft

FIG.8. (left) shows the radius and height of the shaft for which the eigenvalue is 0.95 when the draining shaft is filled with fuel. Thus, the points located under the curves are configurations where the eigenvalue is lower than 0.95 whereas the points located above the curves are configurations where the eigenvalue is higher than 0.95. It can be noticed that the radius and height foreseen for the draining shaft are always in the first configuration even with a 30 cm thick hastelloy wall. Thus, the draining shaft does not pose criticality issues.

The collector can be assimilated to a cone. For this second study, we fix the diameter of the collector to 12 meters and we consider that the whole fuel volume (18 m^3) is located in the collector. The configuration studied forms a bounding case as the wall thickness is set to 30 cm and a lid is added on the top of the collector to simulate the reflection from the structures located above it. The multiplication factor displayed as a function of the tilt angle of the collector (see FIG.8. right) shows that the eigenvalue is below 0.95 in two cases: when the tilt angle is below 16° or when it is over 89°. Only the first option, with a small tilt angle can be adopted. However, a tilt angle higher than 2° would be advisable regarding hydraulic consideration in order to ensure the flow of the fuel in the collector.

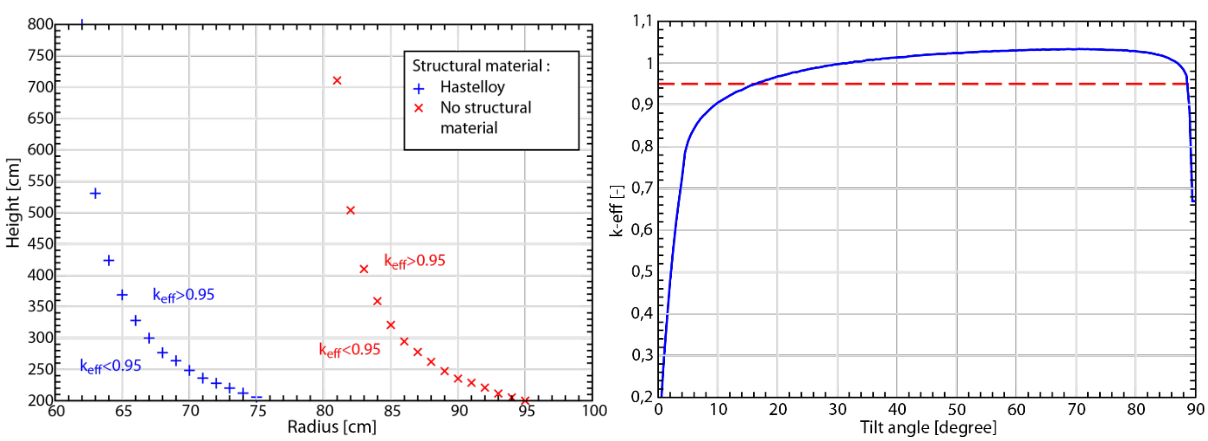

FIG. 8. Height of the draining shaft as a function of its radius for a multiplication factor of 0.95 (left) and multiplication factor as a function of the tilt angle of the collector (right).

TABLE I: CRITICALITY CALCULATIONS RESULTS FOR THE TRANSFER SYSTEM WITH SEVERAL SHAFT RADII AND COLLECTOR ANGLES.

Shaft radius \ tilt angle		10°	15°	20°
30 cm	$k_{eff,max}$	0.90534	0.94298	0.96727
	Depth of the blockage	70 cm	50 cm	50 cm
	Δρ	+767 pcm	+439 pcm	+270 pcm
50 cm	$k_{eff,max}$	0.91894	0.94792	0.96925
	Depth of the blockage	130 cm	80 cm	70 cm
	Δρ	+3287 pcm	+1670 pcm	+984 pcm

A third study focuses on the transfer system as a whole when the 18 m^3 of fuel salt are distributed between the collector and the draining shaft (as in FIG.7.) by blockage in the draining shaft at a given depth. Table I summarizes the results obtained for shaft radius of 30 and 50 cm and collector angles of 10, 15 and 20° and gives the maximal eigenvalue obtained, the corresponding depth of the blockage in the shaft and the reactivity increase compared to the situation where all the fuel is in the collector.

The reactivity increase is bigger when the shaft radius is large and the collector angle is small but the reactivity amounts involved are limited. The sizes foreseen for the draining shaft poses no criticality issues and the collector should be designed with a tilt angle between 2° and 15°.

3.1.4. Draining tank

The coolant being under selection, water properties have been used as reference for the following criticality calculations. This choice was considered interesting to highlight the neutron moderation and capture by water. The most critical step in the draining tank sizing is to determine the fuel salt and the inert salt layer thicknesses. FIG.9. gives the multiplication factor as a function of the hexagons' side length (radius of the circumscribing circle) for fuel salt and inert salt layer thicknesses of 5, 7, 10 and 15 cm. All those configurations are subcritical for all the hexagon side lengths chosen. As a result, the fuel and inert salt layer thicknesses are determined according to thermal considerations, thermal issues being here far more constraining than criticality.

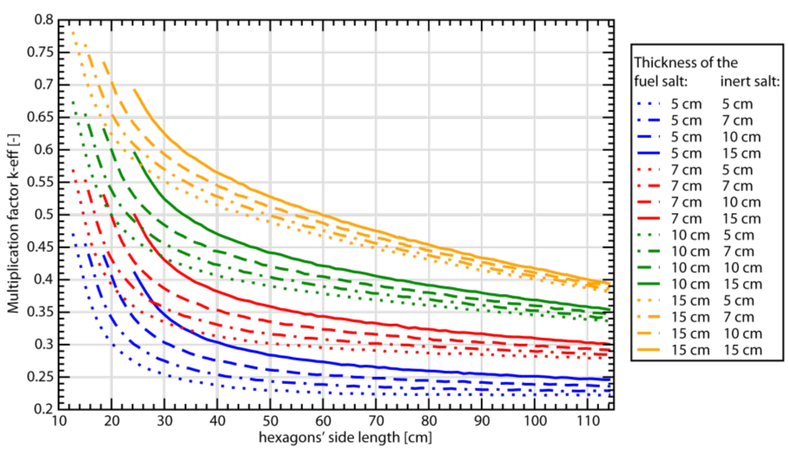

FIG. 9. Variation of the multiplication factor as a function of the hexagon side length.

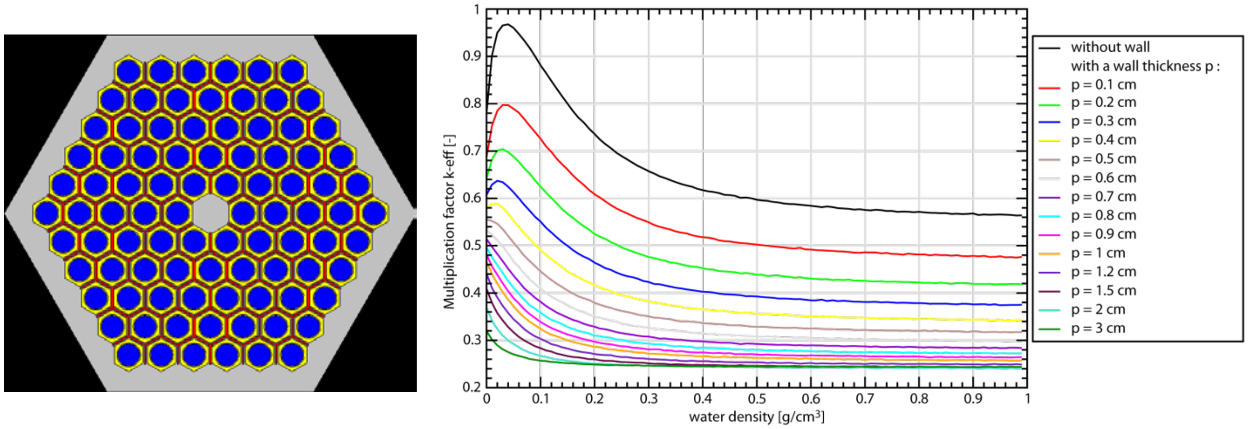

FIG. 10. Serpent geometry of the draining tank used for the study - longitudinal section (left) Variation of the multiplication factor as a function of the water density for different wall thicknesses (right).

In a second study, the thickness of the inert salt layer is set at 7 cm and the fuel salt at 5 cm, in accordance with the preliminary thermal studies, with 5 rows of 50 cm side hexagons (see FIG. 10.). The idea is to look at the impact of cooling water vaporization on the multiplication factor. The computations have been done for several wall thicknesses, considering that the walls between the fuel salt and the inert salt have the same size. The vaporization of the water can be assimilated to a decrease of the water density. Thus, the multiplication factor has been calculated as a function of water density for several configurations (see FIG. 10.). The first case studied is an unrealistic configuration without walls (black curve), to see a more significant effect. In this case, the variation of water density has a strong impact on the multiplication factor and almost leads to criticality for low water densities. Increasing the wall thickness leads to a lessening of the water vaporization effect. The wall thicknesses considered for the network structure being more than 1 cm for mechanical resistance and manufacturing considerations, a decrease of cooling water density should not cause criticality issues in the draining tank.

4. Conclusions and perspectives

This paper presents design optimization studies of the Molten Salt Fast Reactor. The segmented design of the fuel circuit described here has been optimized to suppress the risk of fuel leakage while offering a compact geometry for this circuit.

Regarding the Emergency Draining System designed for the MSFR, it allows to recover the fuel salt in case of in-core anomalies thanks to gravitational draining. The draining tank is a large vessel in which cooling rods composed of a thick layer of inert salt and a central cooling channel are placed. The preliminary thermal calculations in the draining tank show that the fuel and inert salt layer thicknesses can be chosen in order to cool the fuel efficiently while keeping it at liquid state for up to one month and to limit the maximal temperature reached at the metallic wall. Then, the choice of the draining tank configuration takes also into account geometrical considerations to have a relatively compact system. Finally, it has been demonstrated thanks to Monte Carlo simulations that the geometries foreseen for the draining tank ensure large margins to criticality. Regarding the transfer system, there is no criticality issues in the draining shaft configurations selected and the tilt angle of the collector have to be chosen between 2° and 15° to ensure the flow while having large enough criticality margins.

To account for the water-fuel salt interaction and to suppress a possible accident initiator, the design studies of the EDS tend to be oriented to coolants other than water, typically a gas-cooling system, in collaboration between CNRS, KIT and EDF. This task is undertaken in 2017 in the frame of the SAMOFAR project.

Finally, based on these new design orientations of the MSFR system, safety studies and analyses will be done to define a safety approach for this kind of liquid circulating fast reactors, and to assess the safety level of the system.

5. Acknowledgments

The authors wish to thank the NEEDS (Nucléaire : Energie, Environnement, Déchets, Société) French Interdisciplinary program and the IN2P3 department of the National Centre for Scientific Research (CNRS), Grenoble Institute of Technology, and the European programs EVOL (FP7) and SAMOFAR (H2020) for their support.

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