PRELIMINARY DESIGN STUDIES OF THE DRAINING TANKS FOR THE MOLTEN SALT FAST REACTOR

E. Merle-Lucotte, M. Allibert, D. Heuer, M. Brovchenko, A. Laureau, V. Ghetta, P. Rubiolo
LPSC-IN2P3-CNRS / UJF / Grenoble INP
53 rue des Martyrs, F-38026 Grenoble Cedex, France

ABSTRACT

R&D efforts have been focused on the development of a new concept of molten salt reactor called the Molten Salt Fast Reactor (MSFR). The reference MSFR design is a 3000 MWth reactor with a total fuel salt volume of 18 m^3, operated at a mean fuel temperature of 750°C. The first confinement barrier of the reactor includes a salt draining system. In case of a planned reactor shut down or in case of accidents leading to an excessive increase of the temperature in the fuel circuit, the fuel configuration may be changed passively by gravitational draining of the fuel salt in dedicated draining tank located under the reactor and designed to provide adequate reactivity margins while insuring a passive cooling of the fuel salt to extract the residual heat from the short to the long term. The present preliminary assessment of this sub-critical draining system has been performed to identify the physical constraints and to give some orders of magnitude of characteristic time periods.

1 Introduction

In the frame of developing future energy resources and reducing the nuclear wastes, the concept of molten salt reactor offers very good potential. Molten salt reactors are liquid-fuelled reactors so that they are flexible in operation but very different in the design and safety approach compared to solid-fuelled reactors.

Molten Salt Reactors (MSRs) are one of the reference nuclear systems identified by the Generation-IV International Forum (GIF) [1]. Since 2004, the National Centre for Scientific Research (CNRS, Grenoble-France) has focused R&D efforts on the development of a new MSR concept called the Molten Salt Fast Reactor (MSFR) [2,3,4]. 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 TRU elements as initial fissile load. The MSFR was chosen by the Generation IV forum (GIF) in 2008 as representative of a molten salt reactor fitting the Gen IV criteria, because of its fast spectrum (sustainability and waste minimization) and the use of Thorium as fertile element (proliferation resistance) [1]. This is a homogeneous reactor the main safety characteristics of which are due to the presence of a liquid fuel salt in its core without any other moderator and construction materials than the salt components.

Conceptual design activities are currently underway so as to increase the confidence that MSFR systems can satisfy the goals of Generation-IV reactors in terms of sustainability (Th breeder), non-proliferation (integrated fuel cycle, multi-recycling of actinides), resource savings (closed Th/U fuel cycle, no uranium enrichment), safety (no reactivity reserve, strongly negative feedback coefficient) and waste management (actinide burner).

In such a liquid-fuelled reactor, the fuel configuration may be changed passively by gravitational draining of the fuel salt in dedicated draining tanks located under the reactor, in case of a planned reactor shut down or in case of incidents/accidents leading to an excessive increase of the temperature in the fuel circuit,. This sub-critical draining system has to be designed to provide adequate reactivity margins while insuring a passive cooling of the fuel salt to extract the residual heat from the short to the long term. This paper will focus on preliminary design studies of this system, addressing both physical and safety issues. The objectives of these studies are to define the constraints and to give some orders of magnitude of time periods characteristic of the draining system, as for the period available to drain the fuel salt in normal and accidental situations without damaging the core (called 'grace period'), and the period during which passive cooling of the fuel salt will be guaranteed.

2 The MSFR System

2.1 Description of the MSFR Concept

The reference MSFR design is a 3000 MW_{th} reactor with a total fuel salt volume of 18 m^3, operated at a mean fuel salt temperature of 750°C [3,4,5]. The reactor includes three different circuits: the fuel circuit, the intermediate circuit and the power conversion circuit. The fuel circuit, defined as the circuit containing the fuel salt during power generation, includes the core cavity, the inlet and outlet pipes, a gas injection system, salt-bubble separators, the pumps and the fuel heat exchangers.

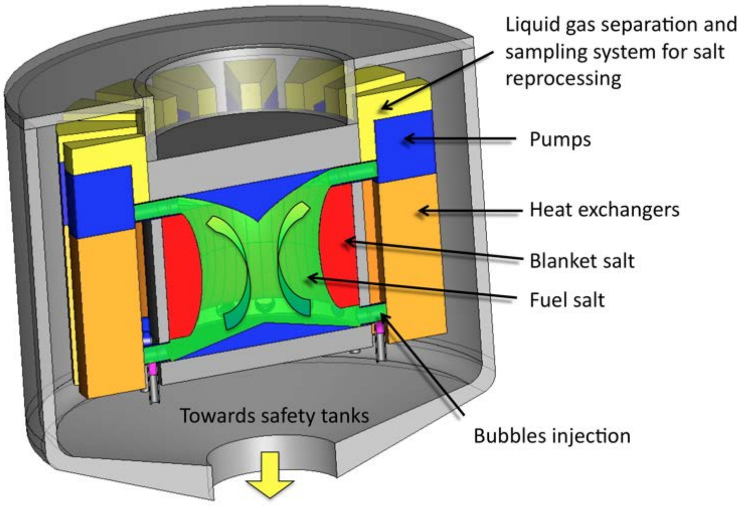

Fig.1. Schematic conceptual MSFR design (fuel salt in green, fertile blanket salt in red)

As shown in the sketch of fig. 1, the fuel salt flows from the bottom to the top of the core cavity (note the absence of solid matter in core). After exiting the core, the fuel salt is fed into 16 groups of pumps and heat exchangers located around the core and it travels through the circuit in about 3-4 seconds.

The fuel salt considered in the simulations is a molten binary fluoride salt with 77.5% of lithium fluoride; the other 22.5% are a mix of heavy nuclei fluorides. This proportion, set throughout the reactor evolution, leads to a fast neutron spectrum in the core. The total fuel salt volume is distributed half in the core and half in the external part of the fuel circuit (salt collectors, salt-bubble separators, fuel heat exchangers, pumps, salt injectors and pipes).

The external core structures and the fuel heat exchangers are protected by thick reflectors made of nickel-based alloys, which have been designed to stop more than 99% of the escaping neutron flux. The radial reflector includes a fertile blanket (50 cm thick - red area in Fig. 1) to increase the breeding ratio. This blanket is filled with a fertile salt of LiF-ThF_4 with initially 22.5 mole % of ^{232}Th. This blanket is surrounded by a 20cm thick layer of B_4C, which provides protection from the remaining neutrons.

Fuel salt cleaning [6,7] involves two processes: 1) the mechanical extraction of rare gases and some noble metals via an on-line bubbling process; 2) the removal of other fission products via batch processing of small fuel salt samples (typical rate ~10 to 40 liters/day) at an on-site facility near the reactor.

2.2 Confinement Barriers of the MSFR

Safety considerations tend to keep the fuel inside three physical barriers that are, for heat transport and conversion:

- the wall between fuel salt and intermediate salt in intermediate heat exchangers,
- the wall between intermediate salt and conversion fluid,

- the wall insulating the conversion fluid from atmosphere in a closed conversion loop.

Three fuel salt confinement barriers in the MSFR can then be identified by analogy with PWRs as shown in figure 2 [8]:

- Pink: the fuel circuit (heat exchangers, pumps, ...), the bubbling reprocessing unit and the draining system (the tanks and pipes) totally within the fuel casing. Note that the first barrier is exposed to a small, even negligible, neutron flux and is not submitted to high pressure. However, it must locally undergo high temperatures (700 °C at the hottest locations) and corrosion from the salt.
- Light blue: the reactor vessel, the intermediate circuit and the draining system's water circuit.
- Grey: the reactor containment structure (the building) and the emergency cooling chimney, not shown on the drawing.

The first fuel salt barrier is called the "fuel casing". It encompasses several distinct spaces. The fuel casing includes critical and sub-critical spaces in which the fuel salt is located during normal reactor operation, during power production or when the fuel is drained. The critical space includes all the fuel circuit devices that are in contact with the salt when the reactor is generating power. In the event of reactor shutdown, the fuel salt is transferred to the draining tank and, in case of prolonged shutdown, to the storage tanks. Spaces for fuel salt processing or annex fuel salt storage within which discrete fuel samples are handled ("processing space" and "storage space" in figure 2) are also an integral part of the first confinement barrier. The sub-critical space corresponds to the draining system of the fuel salt.

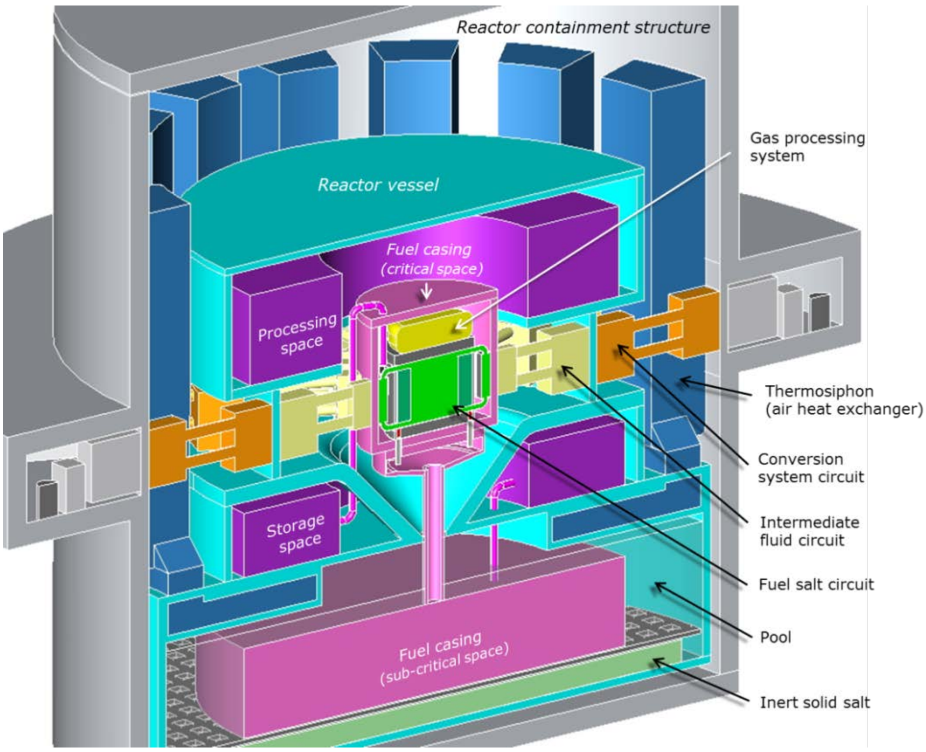

Fig 2. Layout of the MSFR reactor systems showing the 3 containment barriers

The fuel casing system of the sub-critical space is considered as conjoined with the critical space since both are liable to be in contact with the fuel salt during normal reactor operation. The sub-systems that are necessary for the fuel salt confinement and cooling, including transfers from the critical to the sub-critical space and vice versa, are the following:

- fuel salt tank with a possibly partitioned geometry, all the sub-reservoirs being interconnected;
- water pool in which the tank is immersed;

- the air heat exchangers distributed along the periphery within the reactor building; they are necessary to ensure natural water convection;
- draining plugs/valves composing the collector sub-system;
- piping for salt distribution and gas evacuation; this will include a vertical shaft located between the collector sub-system and the draining tank;
- dilution salt supply at the bottom of the pool.

Some of these sub-systems (fuel salt tank, water pool and heat exchangers) will be detailed in section 3.

2.3 Residual Heat in the MSFR

The simulations of the reactor's evolution give the isotopic composition at anytime during reactor operation [3,5]. We consider here the steady state composition of the fuel and fertile salts, which is the enveloping case for this study. The residual power and the corresponding cumulated energy are displayed in Fig.3 for the three components which will require a cooling in the reactor building after the reactor shutdown: the fuel salt, the fertile salt and the bubbling reprocessing unit.

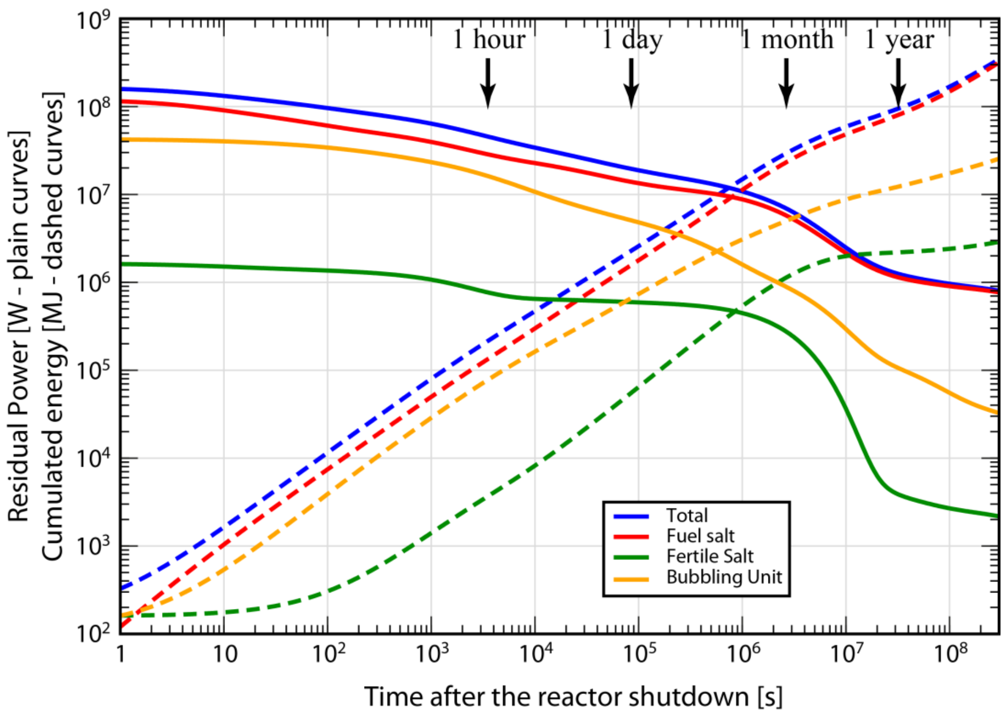

Fig 3. Evolution of the decay power (solid curves) and the corresponding cumulated energy (dashed curves) in the fuel salt, the fertile salt and the bubbling reprocessing unit after the reactor shutdown

2.4 Initial Draining Conditions

The residual power, and thus the fuel temperature at the beginning of the draining, depends on the operating conditions. Three typical cases may be considered: a planned draining, a precautionary draining and an accidental draining [8,9].

<u>Planned draining</u>

When the fuel draining is planned far in advance (for maintenance for instance), it could be advantageous to first decrease the power of the core to reduce the amount of residual heat after the shutdown. As time is not limited in this case, the core temperature may be also lowered by introducing anti-reactivity (for example by increasing the amount of bubbles in the core). The fuel mean temperature may be reduced to 650°C and the residual heat to less than 1% of the nominal power in a few hours.

Precautionary draining

This situation corresponds to a draining requested by the detection of anomalous phenomena when the reactor operates at nominal power. The mean fuel temperature is about 750°C and the residual heat is equal to 3.7% of nominal power after the reactor shutdown (see Fig 3).

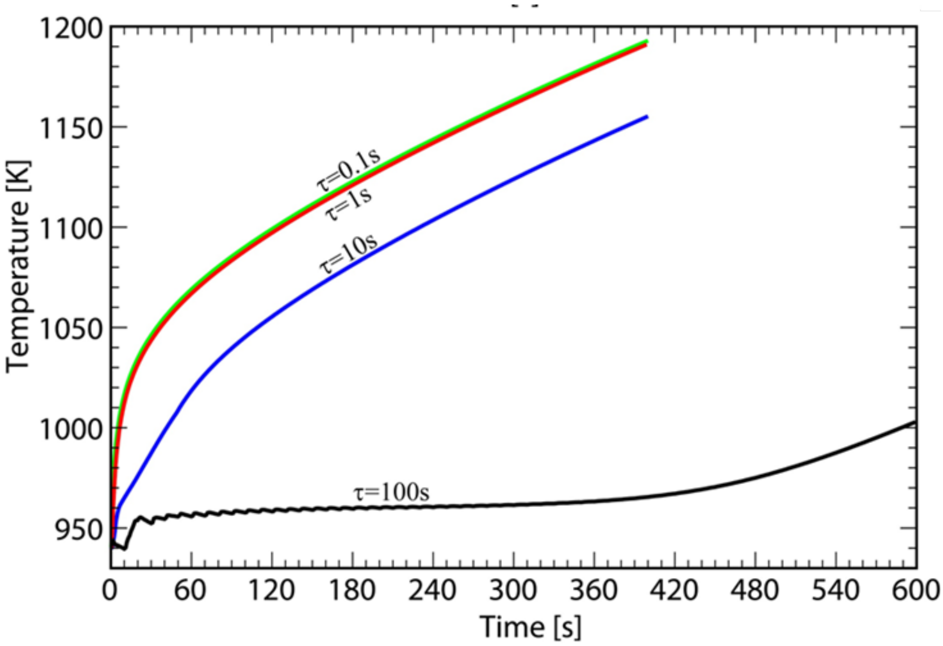

Fig 4. Mean fuel salt temperature after an exponential loss of cooling with a characteristic time of 1s, 10s and 100s (C_p constant here)

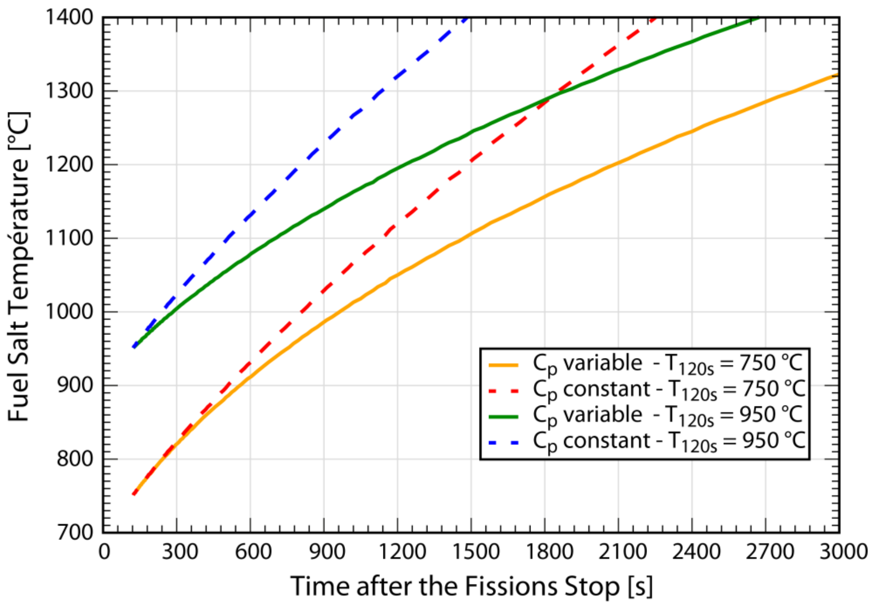

Fig 5. Adiabatic heating of the fuel salt by the decay heat

Accidental draining

In the case of failure of the standard draining system, the fuel salt temperature will raise but the core will stay sub-critical (negative temperature feedback coefficients). The fuel temperature will increase at a rate depending on the reduction pace of heat extraction, because delayed neutrons maintain fissions. When this reduction of heat extraction is modeled as an exponential with a characteristic time of less than 10s, the fuel salt temperature is raised by 200°C in about 2 minutes by delayed fission power, as shown in Figure 4. This first period of 120 s corresponds to the decay fissions leading to a fast heating in the core without enough inertia in the cooling system (red and green curves).

The adiabatic temperature raises by decay heat only is presented in Figure 5. The first period of 120 s has been not displayed in this study. Instead we have fixed the initial temperature after these 120 seconds to 750°C with enough inertia in the reactor cooling system (see black curve of Fig. 4) or 950°C if not (red, green and blue curves). Two cases have been simulated: with a value of C_p varying as (-1.111 + 0.00278 $T_{(K)}$.10^3) [4] or with a constant value of C_p equal to 1594 J/kg/K (corresponding to its value at 700°C). The second case has been calculated since the variation of C_p has been validated experimentally only on the interval [594K – 634K] [10].

While limiting the acceptable temperature rise to 500°C before core damaging for instance, we can estimate the grace period available for the complete fuel draining to about 30 minutes in the case of an instant blockade of heat extraction, whereas a progressive heat extraction reduction in about 2 minutes leads to a grace period close to 1 hour. It illustrates the importance of inertia in the fuel circuit (fuel circulation inertia or thermal inertia) to improve the safety limits.

In absence of remediation measures, the fuel circuit will break at intentionally weak points when the containing material will reach a temperature depending on its nature. For Ni-based alloy this temperature could be in the 1250-1350°C range, slightly below partial melting. This event will occur about 20 minutes after reaching the damage limit, i.e. 100°C higher in temperature.

3 Draining System

We consider first three components of the draining system that are the collector (around the fuel circuit), a vertical shaft and the draining tank (immersed into water). These components are not in contact with the fuel salt during reactor operation. The collector and the shaft are in contact with the molten salt during draining only (a few minutes) whereas the draining tank should keep the liquid fuel for long durations in a sub-critical geometry and at a controlled temperature.

The salt possible content is larger than the fuel salt volume to collect a part of the intermediate salt coolant or the fertile salt along with the fuel in accidental situation. We have considered in these preliminary studies a volume of $36m^3$, twice that of the total fuel salt volume. We remind that the functions devoted to the draining tank are:

- To keep a subcritical geometry, including in presence of water (liquid and vapor)
- To control the heat flux removed from the fuel to maintain it liquid, for long durations if needed, in order to be able to recover the fuel by liquid transfer.

Due to the poor thermal conductivity of the molten salts combined with criticality issues, the salt layer thickness has to be limited to avoid high temperatures far from the cooled walls. Flat tanks with a large surface and a small thickness have been considered, immersed in a pool of water for cooling as previously mentioned. The sections 3.1 and 3.2 below present the optimization of these surface and thickness values, determined respectively by thermal and criticality considerations. The exact geometry of the draining tanks, relying on precise engineering and design studies, has not yet been determined at the preliminary stage of development of the MSFR concept. Section 3.3 will finally deals with the heat exchangers of the draining system.

3.1 Draining Tanks Geometry Optimization: Thermal Issues

The goal of this section is to list the thermal constraints on the tank design (salt and walls configurations).

Material	Volume heat capacity ($MJ/K/m^3$)	Conductivity (W/m/K)	Diffusivity (mm^2/s)	Diffusion distance (cm) after			
				2 min	20min	40min	1h
Fuel salt	6.7	1	0.15	0.4	1.3	2	2.3
Hastelloy N	4.07	17	4.2	2	6.5	9	11

Tab 1: Contributions to thermal inertia and heat transfer for durations corresponding to the draining period, when the fuel is still in the core and to the beginning of the draining tank heating

For durations comparable to the draining time (120s), heat diffusion takes place in stainless steels on a distance of approximately 2 cm as shown in Table 1. During such time, only the collector or the shaft walls will heat up. As the salt heat diffusivity is much lower than the metallic walls one, the salt will form a thin solid film along the walls that should be recovered by heating afterward. The same phenomenon will take place in the tank during the first minutes after draining but this film will disappear with time due to the wall heating.

Figure 6 presents a possible configuration where the tank walls are made of several layers: one layer of Hastelloy in contact with the fuel, then a neutron absorption layer (containing B_4C) and the casing metallic wall (made of Hastelloy) in contact with the water. This provides a neutron protection (see section 3.2) and a way to control the heat transfer between salt and water. Moreover the fuel is not in direct contact with the first barrier.

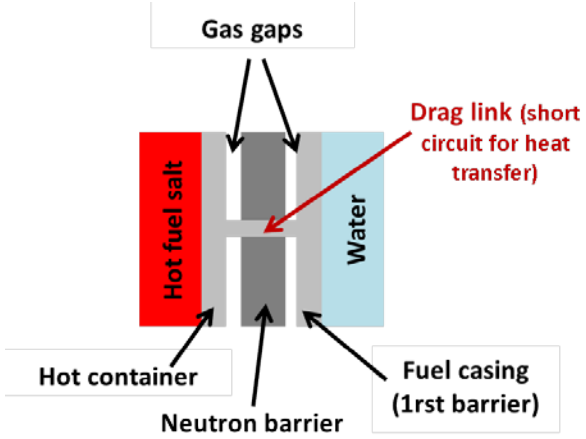

Fig 6. Example of transversal structure of the draining tank walls (not to scale)

Firstly, the fuel salt is thus contained between two such walls whose thermal conductivity can be chosen during the system design. For a given value of thermal conductivity, the cooling of the fuel salt (decay heat evacuation) will require a given exchange surface, which will fix the thickness of the salt layer since the fuel salt volume is equal to 18 m^3.

Secondly, the thermal inertia of the tank walls enables the absorption of the heat produced by the salt during a certain time after draining, while another time period results from the thermal diffusivity through the wall as $t= L^2/D$ with L the transfer thickness and D the diffusivity equal to $\lambda/(\rho.C_p)$. These two times have to be of the same order of magnitude.

Finally, the time to transfer the heat produced in the salt to the wall has to be considered. A pessimistic evaluation of this time equal to $1/3\ L^2/D$ is obtained by assuming a heat transfer by conduction only, without any convection nor radiation in the salt layer, through a mean distance (uniform heat deposit).

A possible configuration satisfying these three constraints is thus composed of:

- Wall = 1 cm of hastelloy / 8 cm of (60% B_4C and 40% of drag link in hastelloy) / 1 cm of hastelloy
- A salt layer of 5 cm thick

The total external wall surface is then equal to 767 m^2. The specific heat flux is 47 kW/m^2 for wall temperatures of 700°C (internal) and 20°C (external). The heat to be transferred (see Fig 3) is equal to 74 kW/m^2 at t = 120 s and 47 kW/m^2 at 1000 s. The thermal inertia of the walls is then equal to 130 GJ corresponding to 63mn of heat by the fuel salt (decay heat), while the diffusion time in the wall is of 39mn to which one has to add 45mn for the transfer time in the fuel salt layer. Under such conditions, the fuel salt will start heating during 10 to 20mn since the exchanged heat is too low. The cooling of the fuel salt will then start, the heat exchange capacity becoming higher than the production. A thermal steady state is reached after more than one hour.

3.2 Draining Tanks Geometry Optimization: Criticality Issues

The draining tank geometry has also to guaranty the sub-criticality of the fuel salt on the long term. The sizing of this tank thus relies on criticality calculations presented in this section. The multiplication coefficient for different configurations of the draining tanks has been calculated through simulations based on the neutronic code MCNP and the database ENDF-B6.

In a first time, we have considered 18 salt layers of 5 cm in parallel, separated by water. We have considered three parameters: the water thickness between two salt layers, the composition of the walls between the salt and the water (with/without B_4C and Hastelloy) and finally the water density (in case of water evaporation). The results are presented in Figure 7: each wall configuration presents a peak of reactivity for the low values of water density. This results from the competition between the neutron thermalization and their capture in the water. We can conclude from this study that 1cm of Hastelloy is enough to have a sub-critical configuration of the tank, whatever the water density is, B_4C being not mandatory here.

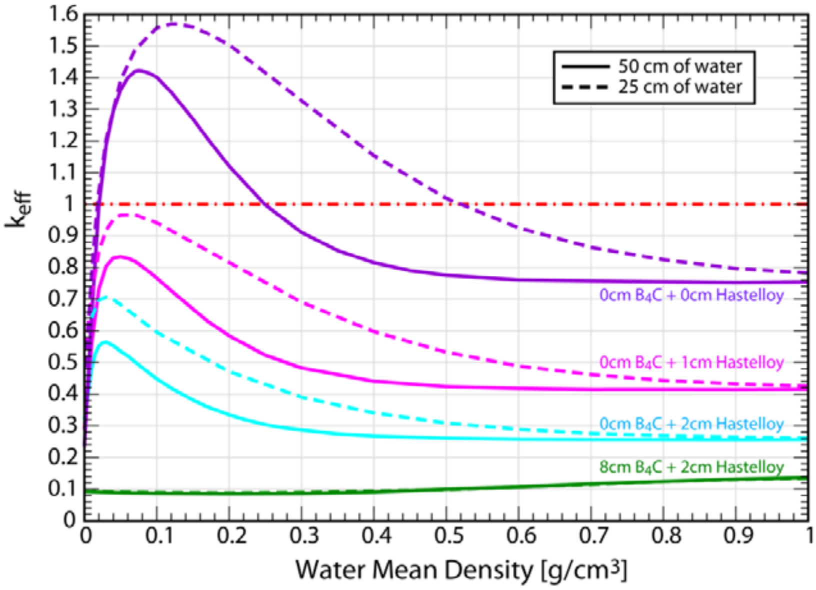

Fig 7. Draining tank criticality as a function of the water density, while considering 18 salt layers separated by water

Another configuration has been simulated, corresponding to a single salt layer. The results for two different thicknesses of this salt layer are presented in Figure 8 as a function of the water density. The curves obtained here do not present any maximum, even for low values of water density.

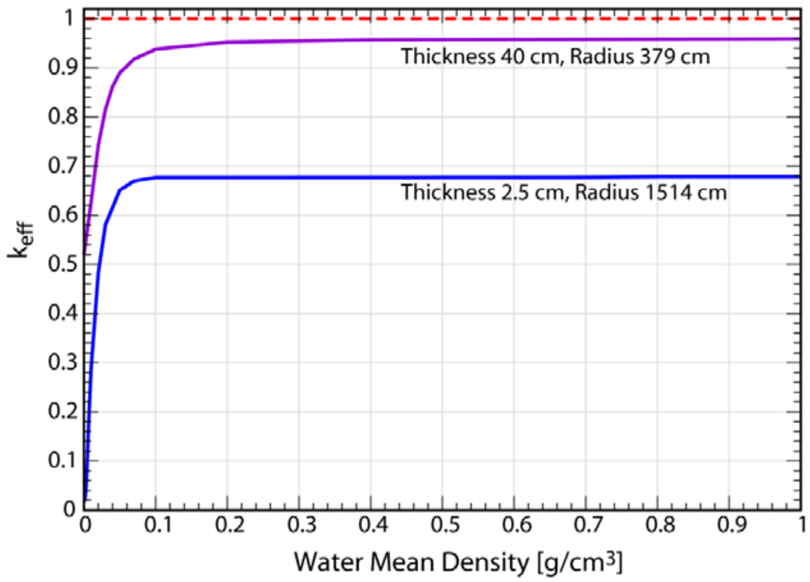

Fig 8. Draning tank criticality as a function of the water density, while considering one single salt layer

3.3 Heat Extraction of the Draining Tanks

The decay heat released in the draining tanks is transferred to water in a large pool surrounding the tanks and used as a thermal buffer for safety. The general concept is then to transfer this heat to the air in chimneys leaning against the reactor building. Heat pipes or thermo-siphons are considered for this transfer. In this paper only the draining tanks are evaluated and grace periods, in case of failure of components, are given.

Water cooling

Figure 9 presents the water mass necessary to limit the heat extraction to a given value for two cases: one for the decay heat released in the fuel salt and one for the total decay heat in the accidental case of draining of fuel and gas processing medium. If we consider for instance that the heat extraction to air is proportional to the water temperature (green curve for the fuel alone) a 3000 m^3 of water would allow a heat extraction limited to 11 MW which is the value reached more than two days after draining (Fig.3).

In case of failure of pool heat extraction (adiabatic pool) and for the same volume of water (878GJ/t from 30° to 100°C) the grace period is of about 12h with the fuel only. After that, an emergency extraction system evacuating the water vapor inside the third barrier has to be triggered. Water vaporization (2.5 GJ/m^3) would provide emergency cooling for about 23 days.

In case of absence of water steel heating at the liquid fuel temperature provides energy storage of the order of 3GJ/m^3. 200 m^3 of steel (internals, tank and pool walls) may store 600 GJ produced in almost 6h in case of absence of water. This is an evaluation of the grace period to bring back water in the pool.

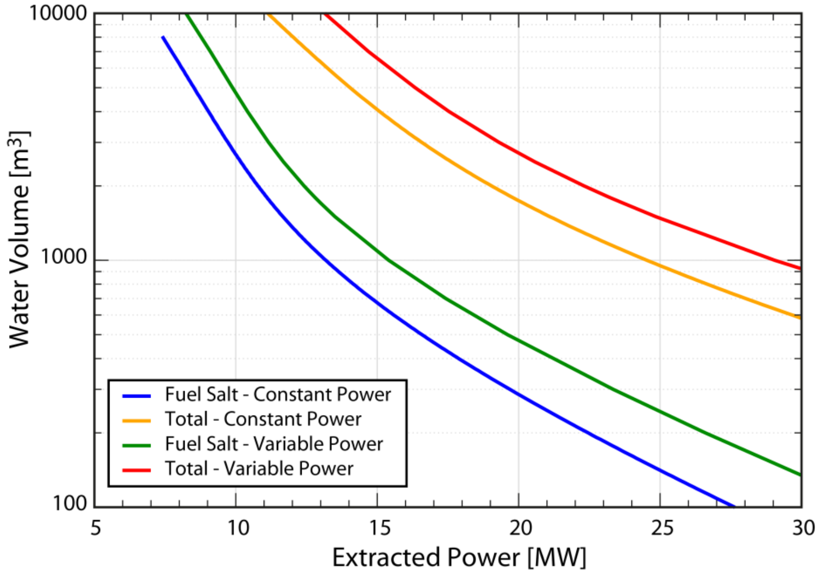

Fig 9. Water mass (in tons) necessary to absorb the residual heat by heating from 30°C to 100°C with the heat extraction given in abscissa (MW)

Air cooling

The decay heat is supposed to be transferred to the air by heat pipes or thermo siphons along the external building wall (3rd barrier). This last barrier should exhibit a high thermal conductivity (metallic walls or high conductivity concrete) to transfer the heat to air chimneys surrounding the building.

The presence of heat exchanges between the third barrier and the air is essential to provide passive extraction of decay heat in all circumstances and specially to increase the grace period in case of severe accident.

4 Conclusions

Molten Salts Reactors as the MSFR have some characteristics very promising in terms of safety and operation relying mainly on their liquid fuel. One of these special features of MSR is the possibility to change the fuel configuration passively by gravitational draining. The first confinement barrier of the MSFR thus includes a salt draining system. A dedicated draining tank will be located under the reactor and has to be designed to provide adequate reactivity margins while insuring a passive cooling of the fuel salt to extract the residual heat from the short to the long term. The present paper presented a preliminary assessment of this sub-critical draining system leading to:

- The identification of the physical constraints regarding thermal and critical issues;
- A preliminary evaluation of some orders of magnitude of time periods (named 'grace periods') characteristic of this system, as for the period available to drain the fuel salt in normal and accidental situations without damaging the core, and the period during which passive cooling of the fuel salt will be guaranteed. The results are summarized in Table 2.

Fuel position	System failure	Associated grace period
Core	After fuel circulation instant stop - without core damaging)	30 minutes
Core	After fuel circulation stop with inertia - without core damaging)	1 hour
Core	Extra draining delay - with core destruction	+20 minutes
Draining tank	Absence of water - no tank damaging	30 minutes to 1 hour
Draining tank	Absence of water - tank damaging	6 hours
Draining tank	Absence of heat extraction from water remaining liquid and unpressurized	12 hours
Draining tank	Absence of heat extraction from water - vaporization into the third barrier	23 days

Tab 2: Summary of the grace periods determined by the present preliminary evaluations

Some more precised simulations have to be performed with thermal-hydraulic tools, as well as calculations of the draining transients. Finally, the exact geometry of the draining tank, relying on precise engineering and design studies, has not yet been determined at the preliminary stage of development of the concept but will be part of the next step of R&D activities for the MSFR.

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