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Publication date
2018

Document Version
Final published version

Published in
Fourth International Conference on Physics and Technology of Reactors and Applications (PHYTRA4)

Citation (APA)
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PHYTRA4 - The Fourth International Conference on Physics and Technology of Reactors and Applications.
Marrakech, Morocco, September 17-19, 2018, on CD-ROM, GMTR, Rabat, Morocco (2018)

PRELIMINARY ASSESSMENT OF THE FREEZE-PLUG MELTING BEHAVIOR IN THE MOLTEN SALT FAST REACTOR

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ABSTRACT

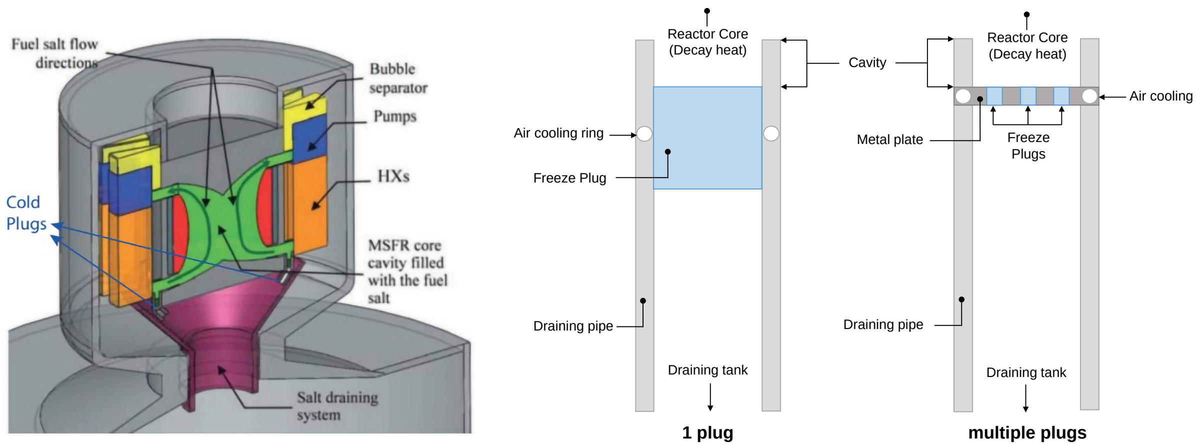
This paper focuses on the freeze-plug, a key safety component of the Molten Salt Fast Reactor, one of the six Generation IV nuclear reactors that must excel in safety, reliability, and sustainability. The freeze-plug is a valve made of frozen fuel salt, designed to melt when an event requiring the core drainage occurs. It must melt passively, relying on the decay heat, and before the reactor incurs structural damages. This work aims at preliminarily investigating the freeze-plug melting behavior, assessing the influence of various design parameters (e.g., sub-cooling temperature, number of plugs, height of cavity above the plug). An apparent heat capacity method available within COMSOL Multiphysics® was adopted for the simulations. Results showed that the single-plug designs generally outperform the multi-plug ones, where melting is inhibited by the formation of a frozen layer, whose thickness is strongly dependent on the sub-cooling temperature and the cavity height, on top of the metal grate. The P/D ratio negligibly influences melting and, therefore, should be chosen to minimize the draining time. Due to the absence of significant mixing in the draining cavity, acceptable melting times (i.e., below 1000 s) were observed only for cavity heights up to 0.1 m. Such distance from the core is considered not sufficient to host all the cooling equipment on the outside of the draining pipe and to protect the plug from possible large temperature oscillations in the core. Hence, it is concluded that a freeze-plug design based only on decay heat to melt is likely unfeasible. A suggested design improvement, preserving passivity, consists in enhancing melting via heat stored in metal structures adjacent to the draining pipe.

Key Words: MSFR; freeze-plug; melting; design improvement

1. INTRODUCTION

The Molten Salt Fast Reactor (MSFR) is one of the six nuclear reactors selected within the Generation IV International Forum (GIF) [1] that must excel in safety, reliability, and sustainability, to help meeting the world's rising energy needs, while accommodating the concerns about waste storage, proliferation, and accidents grown in a large part of the public and political parties, especially following the Fukushima Daichi accident. The Euratom SAMOFAR project [2] is currently coordinating the research efforts on the MSFR; its main goal is to prove the safety and the reliability of the current reactor design, or, on the other hand, to identify weak points to be further improved.

The current MSFR concept [3] is a fast-spectrum, 3000 MW_{th}, breeder reactor operating in the thorium fuel cycle. The liquid fuel and coolant is a mixture of lithium, thorium, and uranium fluorides; it operates at ambient pressure around 750°C and is characterized by a strong negative temperature feedback coefficient. This makes the MSFR particularly interesting from the point of



(a) MSFR fuel circuit.

(b) Freeze plug designs (vertical cross sections).

Figure 1: **Left: Schematic view of the MSFR fuel circuit and draining system ([7]). Right: Vertical cross sections of the freeze-plug designs featuring both one-plug and multiple-plug configurations.**

view of safety, but also in terms of waste production and optimization of fuel consumption. Indeed, the fast spectrum and the continuous on-line reprocessing and recirculation lead to high burnup, actinides burning, and, thus, low radioactivity inventory. Figure 1a shows a schematic cross section of the MSFR primary circuit. The salt rises in the core cavity and flows out towards sixteen identical sectors, each containing a helium bubble separation system, a pump, a heat exchanger, and a helium injection unit (not shown). The core cavity is surrounded by a toroidal blanket, where breeding takes place. Axial and radial reflectors are also present to improve the neutron economy and increase the breeding ratio.

This paper focuses on a key safety component of the MSFR: the freeze-plug. It is a valve made of frozen fuel salt, designed to melt in case of an event requiring the drainage of the core, like heat exchangers failure or power outrage. During these accidents, without a proper heat sink, the decay heat released by fission products causes a temperature rise in the core that could eventually compromise the reactor structural integrity. When the plug melts, on the other hand, the liquid salt is drained by gravity into a tank placed underneath the core, where it is safely cooled down without return to criticality thanks to the geometry of the tank.

The freeze-plug valve was first developed and used at Oak Ridge National Lab (ORNL) during the Molten Salt Reactor Experiment [4]. Formed by first pumping the salt into the core by pressure difference and then applying a cooling gas flow to the outside of the draining pipe, the plug was designed to melt when the cooling supply was turned off, by either exploiting the residual heat in the pipe or turning on external heaters. The reference MSFR configuration includes a vertical freeze-plug at the base of each of the sixteen sectors of the primary circuit (Figure 1a); the plugs are based on the ORNL design, but must melt passively. Within SAMOFAR, several numerical and experimental activities are currently ongoing to accurately study the solidification/melting processes governing the functioning of the freeze-plug (e.g., [5–7]).

This work aims at preliminarily investigating, via numerical simulations, the melting behavior of

Table I: **Freeze-plug design parameters varied in this study.**

Parameter	Values considered
Number of plugs	1, 7
Cavity height, H_c (m)	0.01, 0.05, 0.1, 0.15
P/D ratio	1.05, 1.25, 1.5
Sub-cooling, ΔT_{sub} (K)	5, 10, 15, 20, 25

the freeze-plug valve as currently conceived for the reference MSFR concept, assessing the influence of various design parameters, such as the plug position along the draining pipe and the sub-cooling temperature at nominal conditions. Melting simulations were run adopting an apparent heat capacity method within the Finite Element tool COMSOL Multiphysics® [8]. Since only few design parameters are currently set for the freeze-plug, the conclusions drawn here could guide the future development of the component.

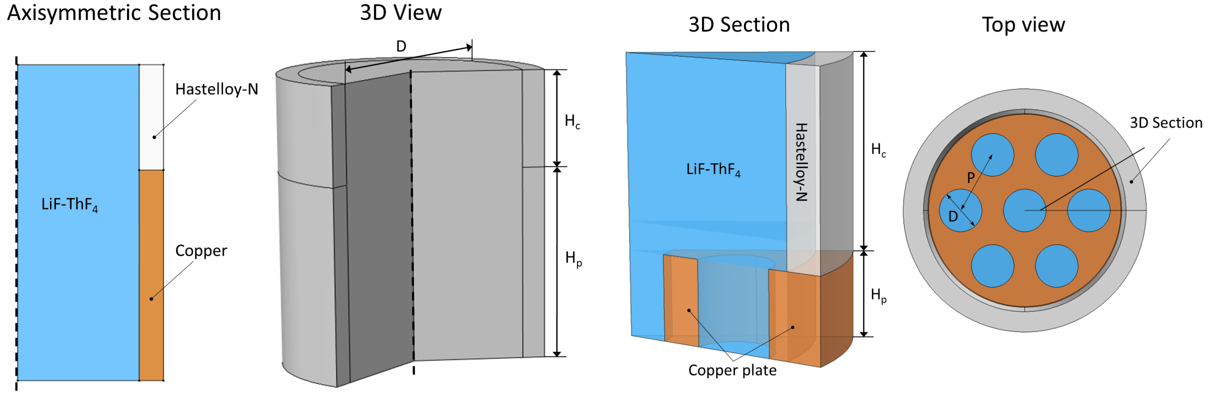
The remainder of the paper is organized as follows. In Section 2, the freeze-plug design is described, together with the parameters varied in the assessment; moreover, some details of the simulations in COMSOL are provided. In Section 3, the results of the melting simulations performed for the different plug designs are presented. Finally, in Section 4, some conclusions are drawn, together with some recommendations for future studies on the freeze-plug valve.

2. DESCRIPTION OF THE WORK

2.1. Study Design

Figure 1b shows the vertical cross sections of the freeze-plug designs considered in this work: a single plug, occupying the full width of the draining pipe, along with a design consisting of 7 smaller plugs in a copper plate (see also Figure 2b, for the top view of the latter). The latter design is based on the supposition that having multiple plugs inside a plate could accelerate melting by reducing the total volume that needs to melt and by increasing heat transfer through the sides of the plugs. To guarantee passivity, the plug(s) must rely only on the transfer of decay heat from the core cavity to the plug, mainly through the draining pipe walls, to melt. The valve has to melt before the fuel salt reaches the critical temperature of 1200°C, to avoid structural damages [9]; however, there is no definitive estimate for how long this will take: between 480 s [9] and 1600 s [10]. For this reason, an average melting time threshold of 1000 s was considered throughout the assessment.

Table I shows the design parameters varied in this study. The ratio of pitch (P, i.e., the distance between the centers of two adjacent plugs, see Figure 2b) to diameter (D) and the sub-cooling (ΔT_{sub}) were investigated due to their influence on the steady-state shape of the freeze-plug; moreover, the latter increases the energy required to melt the plug. After power loss, and consequent shutdown of the reactor, the mean velocity in the core is expected to decrease rapidly; this, together with the salt temperature rise, leads to a quite rapid increase of the bulk Richardson



(a) Geometry and materials of the 1-plug design.

(b) Geometry and materials of the 7-plugs design.

Figure 2: **Geometries and materials used for the simulations of the 1-plug (left) and the 7-plugs (right) designs. D is the plug diameter, P the pitch (the distance between the centers of two adjacent plugs), H_c the cavity height, H_p the height of the copper pipe section or of the plate hosting the multiple plugs.**

number, which suppresses mixing of decay heat in the cavity above the plug [11]. Hence, conduction dominates the heat transfer to the freeze-plug after power loss. For this reason, convection was not accounted for in this work; this significantly reduces the computational effort, but is a conservative approximation. The height of the cavity above the plug (H_c, i.e., the distance from the core, see Figure 2b), therefore, is a relevant parameter because it strongly affects the total heat flux reaching the plug. Figure 3 shows the expected increase of the Richardson number with time for the cavity heights considered in this assessment.

The reference salt composition, LiF-ThF_4 [12] was used in all simulations. The draining pipe above the plug was assumed made of Hastelloy-N [3], while the pipe adjacent to the freeze-plug (or the plate holding the multiple plugs) of copper (Figure 2). Table II summarizes the material properties used for this assessment. Note that the solid LiF-ThF_4 properties are given for 816 K and calculated by a weighted average based on molar mass percentage; moreover, given the absence of data on the thermal conductivity for the solid phase, it was supposed to be equal to the liquid one. Following previous studies on reactor draining [14], the pipe diameter was set at 0.2 m, while the thickness of the draining pipe was kept constant at 0.02 m. Finally, the aspect ratio of all plugs was assumed to be 1.

2.2. COMSOL Model and Implementation

The melting process was simulated adopting the widely used apparent heat capacity method, available in the Finite Element tool COMSOL Multiphysics® [8]. As shown in Figure 2, a 2D, axisymmetric model was adopted for the single plug, while a 3D slice of 30°, with symmetry boundary conditions on the interior surfaces, was used as domain for the 7-plug design. Simulations were run in two steps (Figure 4):

1. A steady-state calculation to determine the initial conditions prior to melting. The sub-cooling temperature was applied as boundary condition to the exterior of the draining

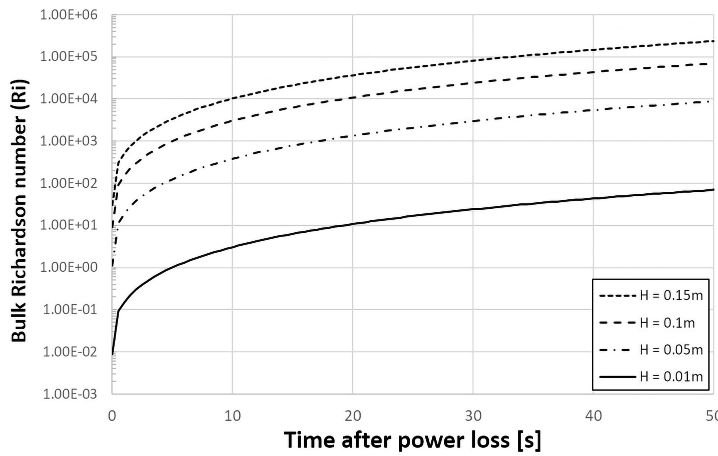
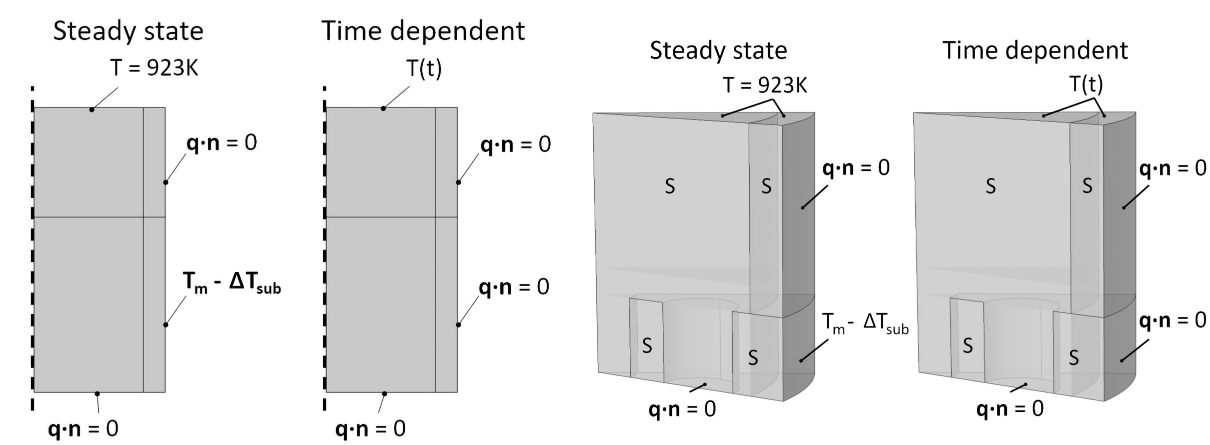


Figure 3: **Trend of salt bulk Richardson number after power loss for increasing height of the draining cavity above the freeze-plug. The increase quickly suppresses heat transfer by convection.**

Table II: **Relevant material properties used in this study.**

Property	**$LiF\text{-}ThF_4$** [12] Solid	Liquid	**Hastelloy-N**	**Copper**
Thermal conductivity ($Wm^{-1}K^{-1}$)	1.5	1.5	23.6	401
Density (kgm^{-3})	4502	4390	8860	8960
Specific heat capacity ($Jkg^{-1}K^{-1}$)	815	1000	578	377
Latent heat (Jkg^{-1})	$1.59 \cdot 10^5$ [13]		-	-
Melting temperature, T_m (K)	841		-	-



(a) Boundary conditions of the 1-plug design.

(b) Boundary conditions of the 7-plugs design.

Figure 4: **Boundary conditions imposed for the simulations of the 1-plug (left) and the 7-plugs (right) designs.** S **stands for "symmetry" boundary conditions.**

pipe, in the region of the freeze-plug, while a temperature of 923 K was applied to the cavity top to simulate the mean nominal temperature in the core. All other exterior surfaces were modeled as adiabatic;

2. A time dependent calculation, lasting 2000 s, to simulate conditions after power loss, including the plug melting. Here, all exterior surfaces were modeled as adiabatic except the cavity top, where a time-dependent temperature boundary condition was imposed. It was derived from the following time-trend of the decay heat in the reactor [10]:

$$Q(t) = 6.45908 \cdot 10^6 - 6.9200 \cdot 10^5 \ln(t[s]) \qquad (\text{W/m}^3); \tag{1}$$

by using a lumped capacitance model and assuming no external heat losses, so that

$$Q(t) = \rho c_p \frac{\mathrm{d}T(t)}{\mathrm{d}t}, \tag{2}$$

and applying a polynomial fit to the resulting mean temperature trend, it was found

$$T(t) = -0.0001t^2 + 0.5244t + 923 \qquad (\text{K}). \tag{3}$$

A tetrahedral mesh was used in all simulations, significantly refined in the region of the plug (max element size = 10^{-3} m) in order to ensure a smooth melting front; elsewhere, the default “extremely fine” COMSOL mesh was used. The phase change temperature range defining the “mushy” region was selected to be ΔT = 4 K, to guarantee that $\Delta T \leq \Delta T_{sub}$, thus limiting the numerical error of the apparent heat capacity method.

3. RESULTS

Figure 5 summarizes the results of this study, showing melting times at increasing cavity heights, for all P/D ratios and sub-cooling temperatures considered. For the 7-plug design, melting times are shown for both the full thickness of the plug (including any salt layer above the copper plate) and only for the portion in contact with the copper plate edge, whose height is equal to H_p (Figure 2b). This makes it possible to distinguish the effect this salt layer has on the melting times.

In general, unlike the 1-plug design, melting times for the 7-plug configuration are driven by the thickness of the frozen layer above the plate. Figure 6 illustrates the phenomenon for plugs located 0.10 m from the core with sub-cooling of 20 K. Here, one can clearly see how the contact edges of the plugs melt long before the frozen layer above the copper plate. Indeed, the layer is melted from the bottom up, by heat conducted through the draining pipe and through the copper plate, rather than by conduction through the molten salt in the pipe, due to the (much) higher conductivities of the Hastelloy-N and copper.

Not surprisingly, therefore, the 1-plug design becomes more favorable as the cavity height increases and the frozen layer on top of the copper grate of the 7-plug design rises. At a cavity height of 0.15 m, the single-plug strongly outperforms the 7-plug configurations, none of which even melted within 2000 s. Moreover, the correlation between melting times and sub-cooling becomes stronger with the cavity height, as both factors contribute to increase the frozen layer on top of the plate. When the cavity height is 0.01 m, no frozen layer forms, and, consequently, all plugs melt rapidly, with a weak dependency on the amount of sub-cooling.

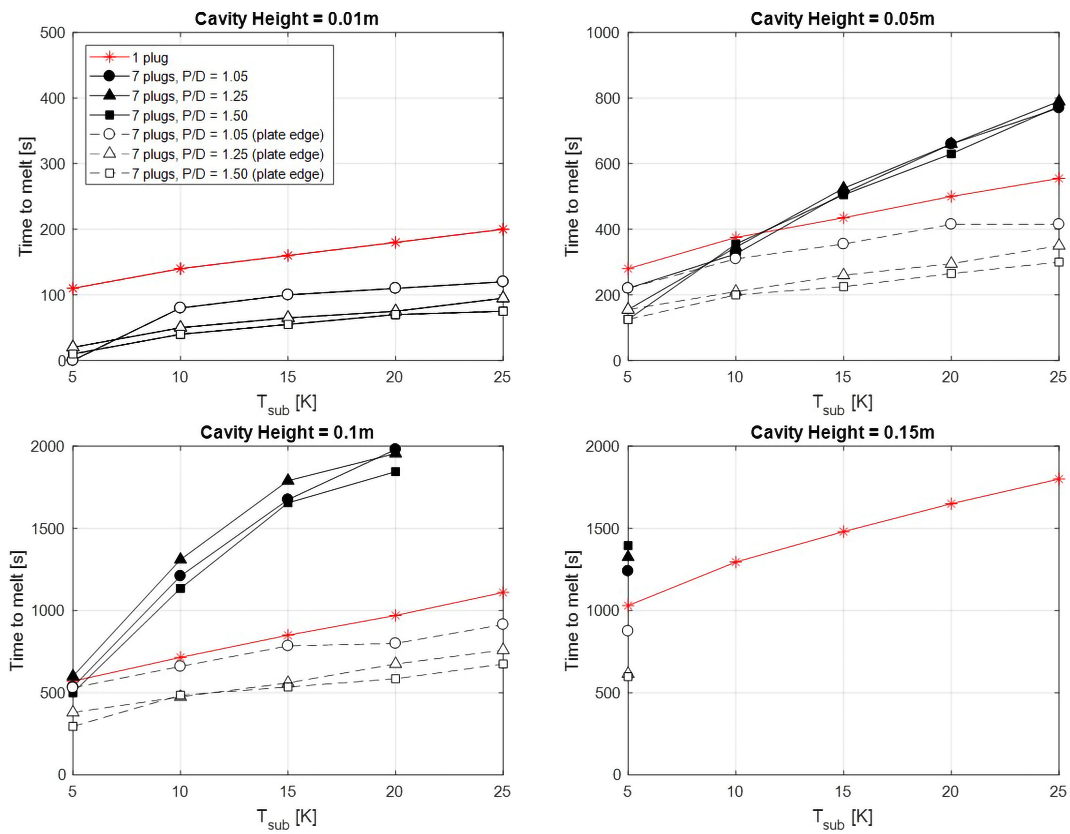


Figure 5: **Melting times as a function of sub-cooling for all $\mathrm{P/D}$ ratios and cavity heights. For the 7-plug design, melting times are shown for both the full thickness of the plug and only for the portion in contact with the copper plate edge (indicated with "plate edge"), to highlight the effect of the salt layer on top of the plate (the two melting times are equal for a cavity height of 0.01 m because no frozen layer is formed). Limited data are shown for a cavity height of 0.15 m because most models did not melt within the simulation time of 2000 s.**

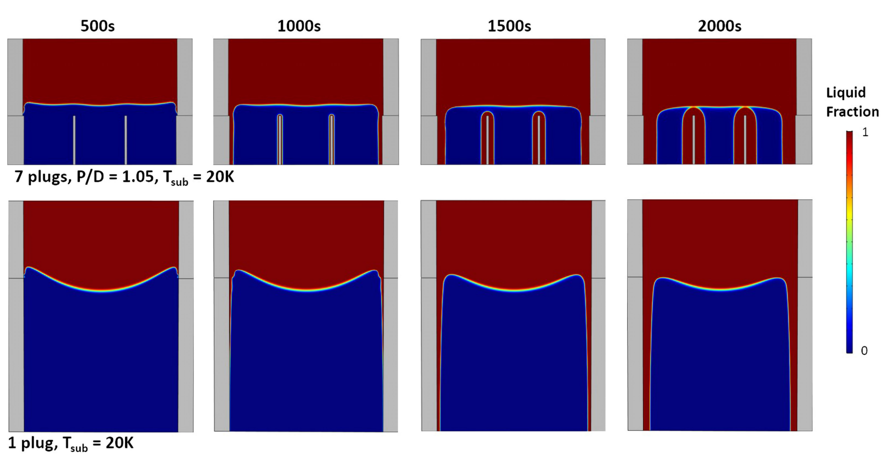


Figure 6: **Cross sections of melting process for 7-plug design with $\mathrm{P/D}$ = 1.05 (top) and 1-plug design (bottom), with plugs located 0.10 m from core and with 20 K sub-cooling. The frozen layer on top of the plate considerably delays the complete melting of the multi-plug valve.**

Focusing on the multi-plug configuration, the P/D ratio weakly influences the melting time. The three designs considered melted within 20 s of one another when the cavity height is 0.01 m, 10-17 s for $H_c = 0.05$ m, and 50-88 s when $H_c = 0.1$ m. The behavior of the P/D = 1.05 is slightly less favorable, though: the edges of this plug melted substantially later than in the other designs. Indeed, while the edges are melting, the plate is still insulated by the frozen layer above it (Figure 6), so the edges are melted by the heat transfered through the draining pipe and through the sides of the plate; with a P/D ratio of 1.05, however, heat transfer to the middle of the plate is limited by the thin copper walls between the plugs.

A final comment is due regarding Figure 6. The images highlight that the melting times estimated in this work for the multi-plug design are quite conservative. Realistically, the frozen layer will be continuously pushed against the copper plate by the hydrostatic pressure in the draining pipe. This will ensure that the frozen layer is in direct contact with the plate at all times, and will accelerate the melting process. One should assume, therefore, that more realistic melting times lie somewhere between the time required to melt the inside edges of the plugs and the times reported in this study.

4. CONCLUSIONS

This paper has presented preliminary results on the melting behavior of the freeze-plug, a key safety component of the Molten Salt Fast Reactor. The influence on melting time of some design parameters (plug position along the draining pipe, sub-cooling temperature at nominal condition, number of plugs, P/D ratio, height of the cavity above the plug) has been assessed.

Several conclusions and recommendations can be drawn:

- A single-plug design is generally favorable over a multi-plug one, especially for cavities greater than 0.05 m and for sub-cooling above 5 K. In the multi-plug design, melting is inhibited by the presence of a frozen layer on top of the plate. However, further study into the melting behavior of this layer, taking the sinking of the frozen salt into account, is required to better quantify the differences in melting time between the two designs;
- In a multi-plug configuration, the P/D ratio has a small influence on melting; therefore, its value should derive from the optimization of the draining time; and
- Melting times below 1000 s were observed only for cavity heights lower than 0.1 m (for all plugs and ΔT_{sub}), and at 0.1 m for $\Delta T_{sub} < 10$ K for the 7-plug design and $\Delta T_{sub} \leq 20$ K for the single plug. In the absence of a significant mixing in the draining cavity, therefore, the freeze-plug should be located within 0.1 m of the mixed flow to melt quickly enough.

The last observation likely renders unfeasible the free-plug design based only on the decay heat to melt. Indeed, despite the lack of constraints currently set regarding the position of the plug along the draining pipe, it is sensible to say it should be located some distance away from the reactor core, in order to allow room for electrical cooling equipment on the outside of the draining pipe, and to protect the plug from large temperature oscillations (during transient operations) that could cause a premature and unwanted melt. Within the SAMOFAR project, therefore, the design of the freeze-plug valve should be improved. To preserve passivity, melting could be enhanced by heat stored in metal structures adjacent to the draining pipe.

ACKNOWLEDGEMENTS

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 661891.

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