European Sodium Fast Reactor: innovative design of reactor pit aiming at suppression of safety vessel

J. Guidez[1*], A. Gerschenfeld[1], A. Grah[2], H. Tsige-Tamirat[2], K. Mikityuk[3], J. Bodi[3], E. Girardi[4]

[1]CEA, Paris-Saclay, France
[2]JRC, Petten, Netherlands
[3]PSI, Villigen AG, Switzerland
[4]EDF, Paris-Saclay, France

[*] Corresponding Author, E-mail: Joel.GUIDEZ@cea.fr

All existing sodium fast reactors, built or operated, have a safety vessel around the main reactor vessel. The safety vessel function is to contain the primary sodium in case of the main vessel leakage while avoiding the reduction of the primary sodium level below inlet windows of the intermediate heat exchangers and therefore interruption of the core cooling by natural convection. In this accidental situation, the reactor will be shut down and never start again and an unloading of the core will be necessary. This unloading however will take at least one year because it is necessary to wait until residual power reduces to an acceptable level. In this long-term situation with a safety vessel filled with sodium (and recalling a sodium leak occurred in the Superphenix drum vessel), the question of the safety authorities could be: what happens in case of a leakage of the safety vessel? In addition, it is also asked to have a reactor designed for severe accident mitigation. Under these conditions it becomes useful to have a reactor pit design able to receive a sodium leak and to fulfil the safety vessel functions. That's why one of the new safety measures proposed in the EU ESFR-SMART project [1] is to design a reactor pit that can withstand sodium leakage from the main vessel taking therefore the confinement functions of the safety vessel. This option also has a number of advantages, amongst others a much more effective radiative decay heat removal by the pit cooling system. The purpose of this paper is to present this reactor pit design allowing the suppression of the safety vessel, with a certain number of pre-calculations and related sizing.

KEYWORDS: safety vessel, sodium fast reactor, ESFR-SMART

Introduction

The ESFR-SMART project is a four-year project that began in September 2017. It follows the Euratom CP-ESFR project which was also a follow-up of the European Fast Reactor (EFR) project. One of the purposes of the ESFR-SMART project is to improve the reactor safety, and make a proposal for new safety options, based on both present (*e.g.* ASTRID) and previous projects experience.

A document presenting a list of proposals for the new safety measures has been prepared [1]. Then a pre-dimensioning of the reactor was carried out. The list of these options and the pre-dimensioning of the entire reactor can be found in [2].

One of these options was the removal of the safety vessel and the resumption of its functions by a reactor pit capable of confining primary sodium in case of the reactor vessel leak.

The purpose of this paper is to explain the overall design of the reactor pit and to make preliminary parametric calculations of temperature distributions.

Reminder on the safety vessel of a sodium fast reactor

Reminder of functions

All existing SFRs have a safety vessel (see an example of Superphenix safety vessel in

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Figure 1~~Figure 1~~) around the main vessel. The function of this safety vessel is to confine the primary sodium in case of the main vessel leakage, so as to avoid lowering of the primary sodium free level below the inlet windows of the intermediate heat exchangers and thus providing an efficient natural convection through the core. In case of the main vessel leakage, the reactor is not recoverable and the core must be unloaded. Due to the need to wait for reduction of the residual power of the assemblies, this handling could take a significant duration (ie higher than one year) especially in the ESFR SMART design without external sodium storage. The safety vessel must therefore remain filled with sodium for a long time. The potential danger in these conditions is that the reactor pit is not designed to withstand a sodium leak from this safety vessel. Moreover, this safety vessel leak would also lead to interruption of the core cooling by natural convection, leading to a very difficult overall situation.

Provisions to avoid double leakage

A number of measures have been taken to prevent leakage of the safety vessel: slight overpressure between the two vessels to detect a possible leak and choice of different materials to avoid a common failure mode on corrosion. It is recalled that it is a problem of corrosion on welds that led to the leakage of the Superphenix storage drum vessel, and that this leak was taken up by the safety vessel of this storage drum [3].

Difficulties related to the uncertainties in scenario

The scenarios of vessel leakage are diverse, from corrosion leakage to leakage on a severe accident with mechanical energy release. This leads to high uncertainties in the temperatures and leakage rates, which make it difficult to demonstrate the safety vessel mechanical strength against the corresponding thermal shocks. Moreover, the French licensing authority requires considering the double leakages in order to verify that the situation does not lead to cliff-edge effect in term of radiological releases in the environment. This demonstration was required after the SPX external sodium storage leak. It is particularly required if the core unloading is high.

Conclusion

The safety vessel is a proven option, especially demonstrated during the incident at the Superphénix storage drum, and is adopted in all existing fast reactors. However, the evolution of safety standards leads us to look at other options where its functions could be directly taken over by a reactor pit capable of withstanding a sodium leak, and thus a long-term mitigation situation. It was an option that had already been looked at in the EFR project with a vessel anchored in the pit, which option was later abandoned for reasons of feasibility and design difficulties.

Figure 1: Arrival of the safety vessel inside the reactor pit of Superphenix

General description of the reactor pit design proposed in the ESFR-SMART project

The proposed design of the reactor pit is composed of the following domains (see Figure 2~~Figure 2~~ and
Figure 3~~Figure 3~~):

- A mixed concrete/metal structure with a water cooling system inside the concrete supports the thick metal slab to which the reactor vessel is attached. Together with the reactor roof, it provides a sealed containment which must keep its integrity in all the cases of normal or accidental operations [1].
- Inside the concrete/metal structure, blocks of insulating materials (non-reactive with sodium) are installed. Alumina is selected as reference material for the insulation blocks. A conventional insulation layer could be considered in future to increase insulation effects (outside the scope of the paper).

A metallic liner is placed on the surface of the insulation blocks. The gap between the reactor vessel and the liner must be small enough (350 mm was chosen) to avoid decrease of the primary sodium free level below the intermediate heat exchanger (IHX) windows in case of sodium leakage from the reactor vessel. During normal operation, the primary sodium free level is 1350 mm below the roof. In case of primary sodium leak about 300 m^3 of sodium will leave the reactor vessel to fill the gap and the new equilibrium free level of the primary sodium will be about 3070 mm below the reactor roof. With this level of sodium inside the primary circuit, there is still a 1090 mm sodium level above the upper IHX openings, which allows a sodium inflow into the IHX and a good natural convection and core cooling. If the sodium temperature decrease to 180°C , the volume of remaining sodium will decrease of about 205 m3 due to the change in the density, It would cause the sodium level to go down to around 50mm above the IHX entry bottom. And the natural convection remains possible.

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- The oil cooling system is installed next to or even inside the liner (Figure 2~~Figure 2~~).
- Finally, a special concrete with alumina (aluminous concrete) which could withstand, without significant chemical reaction with sodium, a leakage of the liner could be used between the liner and the insulation (blocks of alumina).

Two independent active cooling systems are proposed in the reactor pit (we use the acronyms DHRS-3 for the combination of these two systems):

- The oil cooling system (DHRS-3.1) close to the liner (Figure 4~~Figure 4~~a). The oil under forced convection can remove the heat transferred by radiation from the reactor vessel at high temperature. Conversely to water, the adopted synthetic oil is resistant to high temperatures above 300°C and reacts with sodium without producing hydrogen. As an example the commercial oil called
- ”Therminol SP“ [4] can be used in normal operation at temperatures up to 315°C.
- The water cooling system (DHRS-3.2) for the concrete cooling is installed in the concrete (Figure 4~~Figure 4~~b) and aims at maintaining the concrete temperature under 70°C in all possible situations, even if the oil system is lost.

Both oil and water circuits work during normal operation and have to maintain the concrete temperature below 70°C. This margin is intended to ensure the concrete integrity and to protect it from thermal degradation. During the reactor shutdown the oil system alone has to be able after few days to remove all the decay heat generated by the fuel. In case of the reactor vessel leak and loss of the oil system, the water system should be able to remove the decay heat generated by the core and to maintain the concrete below 70°C.

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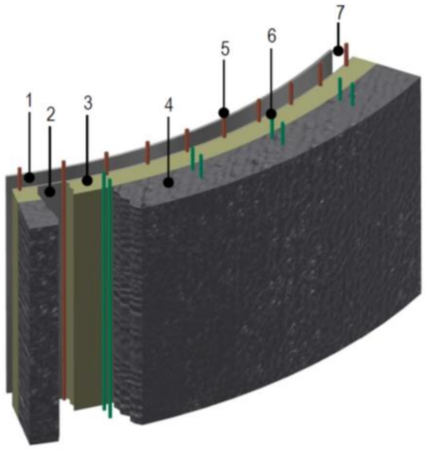


Figure 2: Detail of the reactor pit design

1 – Reactor vessel
2 – Liner
3 – Insulation
4 – Concrete/metal structure
5 – Oil cooling system (DHRS-3.1)
6 – Water cooling system (DHRS-3.2)
7 – Gap

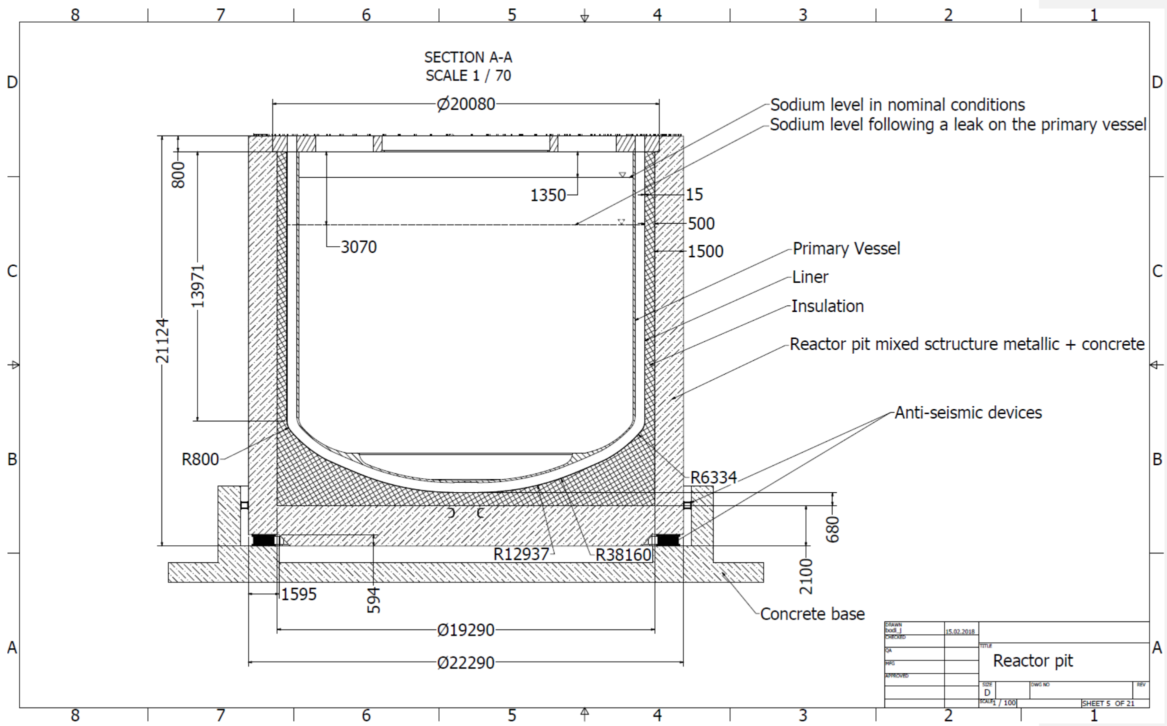
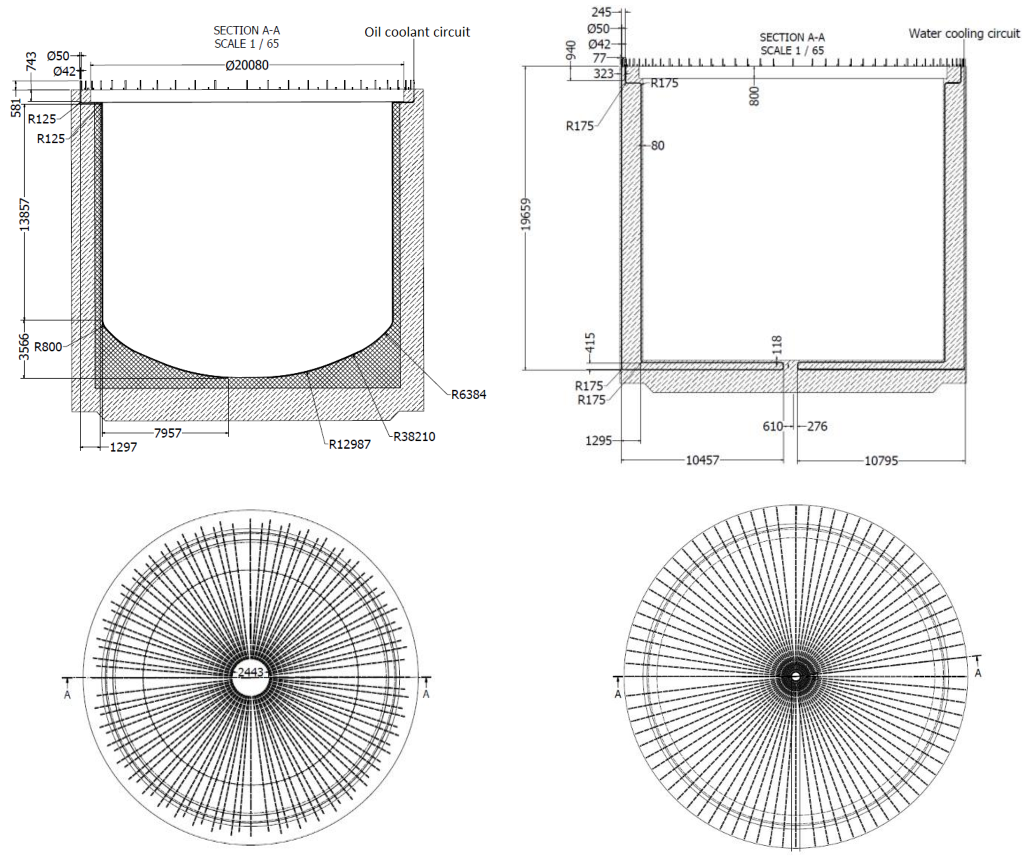


Figure 3: Drawing of the reactor pit design



a) b)

Figure 4: Drawings of the reactor pit cooling systems: (a) oil and (b) water

Main design-basis scenarios

The reactor pit must be designed for the following three main scenarios:

- *Scenario 1: Normal operation*: The main vessel is at about 400°C. The operation of the oil cooling system is sufficient to maintain the correct thermal conditions in the pit (*i.e.* less than 70° C for the concrete of the mixed structures).
- *Scenario 2: Operation in exceptional decay heat removal regime*: The safety studies should take into account exceptional situations of successive losses of decay heat removal systems. In this case, in exceptional situations of Categories 3 and 4, the reactor vessel is allowed to reach temperature of 650°C. The two cooling systems (oil and water) must make it possible to maintain the concrete temperature below 70°C while playing an important role in the decay heat removal.
- *Scenario 3: Operation in accident situation of sodium leakage*: In a situation of little leak, vigorous sodium cooling is possible with the redundant and available DHRS, to bring the sodium to a temperature corresponding to the handling temperature (180°C).Therefore, the maximum temperature of the sodium in the gap should not exceed 200°C. The demonstration of the oil cooling system availability in case of reactor vessel leakage is difficult and we assume as hypothesis that the oil cooling system is no longer available. The operation of the water cooling system alone must be sufficient to maintain the concrete temperature below 70°C

  NB: But other studies need later to be performed, taking in account a leakage due (or combined) with a high thermal transient (e.g., due to failure of DHR system) and if the failure is due to the severe accident.. In this case the sodium temperature will be higher

CFD model

The objective is the development of a simple CFD model to compute the steady-state heat transfer from the reactor vessel through the reactor pit. The CFD computations were performed with ANSYS CFX which is a parallelized high-performance computational fluid dynamics (CFD) software tool. It is based on finite volume technique applied to solve the Navier-Stokes equations [5]. To achieve results with low computation time, the reactor pit is divided into several sections and the CFD analysis is performed for every section. The drawing of the geometry for one section, the “elementary cell” of the reactor pit structure, is shown on Figure 5~~Figure 5~~. For the calculation example, the oil cooling system is installed inside the liner of the special wavy shape (see Figure 6~~Figure 6~~).

The following simplifications and assumptions are applied at this stage of computations:

- The gap between the reactor vessel and the liner is considered as vacuum for first CFD computations to minimize the CPU time.
- The material of the insulation layer is assumed to be glass wool for the current study.
- Only steady state computations are performed.

Fast solution is important (computation time below a minute) to be able to perform the large amounts of parametric studies. The resulting CFD model geometry is shown on Figure 6~~Figure 6~~. The domains for the CFD model on Figure 6~~Figure 6~~ are as follows (λ is the thermal conductivity):

- The outer surface of the reactor vessel wall is shown on the left-hand side (red).
- The gas gap (white); λ = 0.026 W m^{-1} K^{-1}. For the steady-state computations the heat transport parameters (density and specific heat) are set to very low values and the solution of the flow is switched off.
- The stainless steel liner of the wavy shape is proposed (blue); λ = 60.5 W m^{-1} K^{-1} with the pipes of the oil cooling system inside (dark blue).
- The insulation layer (yellow); λ = 0.04 W m^{-1} K^{-1}.
- The concrete structure (grey); λ = 1.4 W m^{-1} K^{-1}.
- The right-hand side surface interfaces the environment (black).

The boundary conditions for the CFD model on Figure 6~~Figure 6~~ are as follows:

- Fixed temperature of the reactor vessel wall (red surface at the left) for different axial levels (T_{vw} = 400, 500, 600 and 700°C). This is intended to represent the different levels of the heat source inside the vessel.
- The heat sink is the environment outside of the concrete structure (black surface at the right). As a first approximation the following data is taken for the heat transfer: T_a = 50°C, k = 6 W m^{-2} K^{-1}, where k is the heat exchange coefficient. For later calculations, the heat sinks will include the water cooling system.
- The other outer surfaces are defined as “symmetric”, *i.e.* adiabatic.

Calculations were made first without taking into account the oil cooling system in order to see if one could reach, with the only heat removal to the environment, required temperature level in the concrete domain.

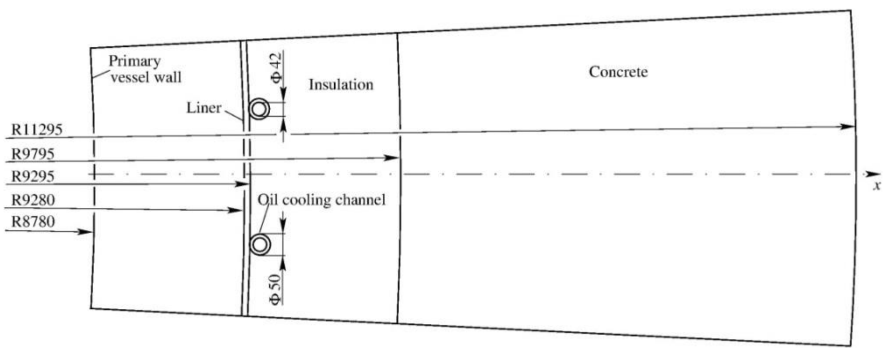


Figure 5: Drawing of an “elementary cell” of the reactor pit model

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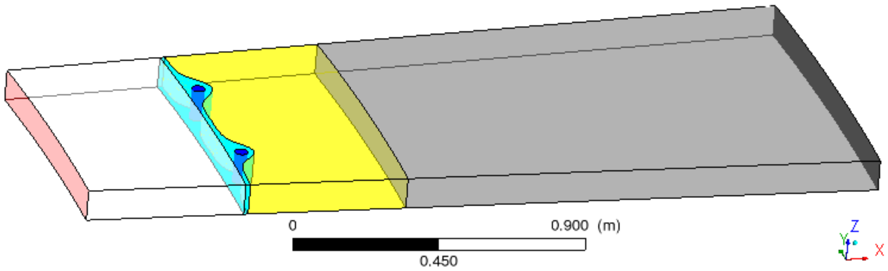

Figure 6: The CFD model of an “elementary cell” of the reactor pit model

Analytical solution for verification

The current CFD model without local heat sinks (the cooling systems) is convenient for verification by comparison to an analytical solution. This requires one-dimensional model of the heat transfer by radiation in the gap and by heat conduction in the solids. The heat path is from the hot reactor vessel wall towards the outer concrete surface facing the environment. The heat flow due to radiation in the gap between a hot surface (index 1) and a cold surface (index 2) can be written as:

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \qquad (1)$$

Hereby T is the (absolute) temperature and $\sigma = 5.67 \cdot 10^{-8}$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant. Assuming emissivity of stainless steel for both surfaces ($\varepsilon_1 = \varepsilon_2 = \varepsilon = 0.4$ for stainless steel) and full visibility ($F_{12} = 1$) and for $A_1 \approx A_2 = A$ the temperature of the cold surface yields:

$$T_2 = \left(T_1^4 - \frac{\dot{Q}}{A\sigma}\left(2\frac{1-\varepsilon}{\varepsilon} + 1\right)\right)^{1/4} \qquad (2)$$

Heat conduction through a cylindrical solid wall in direction of the radius r can be written as

$$\dot{Q} = -\lambda A(r)\frac{dT}{dr} \qquad (3)$$

Hereby λ is the thermal conductivity of the solid and $A(r) = 2\pi rh$ the cylindrical surface at the radius r and for a segment of the height h. The integration between the radii r_1 and r_2 with the corresponding temperatures T_1 and T_2 yields the temperature at the outer radius

$$T_2 = T_1 - \frac{\dot{Q}}{\lambda}\frac{\ln\left(r_2/r_1\right)}{2\pi h} \qquad (4)$$

CFD results without the cooling system

For this computation the oil cooling channels in the liner on Figure 6~~Figure 6~~ are not taken into account. The liner is considered to be flat (equal thickness) and without pipes. The temperature along the heat path in the centre of the domains is shown on Figure 7~~Figure 7~~. On Figure 7~~Figure 7~~a, the constant-temperature boundary condition is applied at the primary vessel wall (T_{vw} = 400, 500, 600 and 700°C, red surface on Figure 6~~Figure 6~~). In the nearly-vacuum domain of the gap the heat transfer takes place by means of radiation and the temperature is almost identical to the boundary condition. The temperature of the metal liner is also very close to the temperature of the vessel (since the cooling system is not modelled in this case). As expected, the main temperature drop takes place in the insulation layer. However, the temperature in the concrete is mostly above the required limit of 70°C as shown on Figure 7~~Figure 7~~b. Furthermore, on Figure 7~~Figure 7~~a and b the CFD results are compared with the analytical solutions of Eq.(2) and Eq.(4). The maximum deviation of the temperature is less than 5°C.

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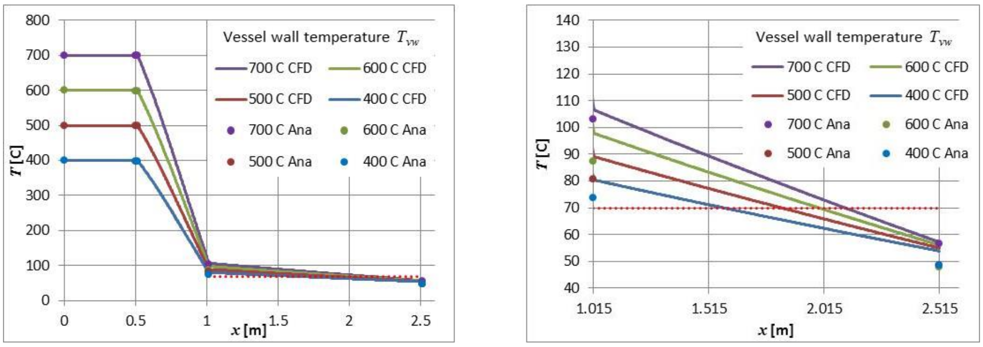

a) b)

Figure 7: The temperature along the heat path (in x direction); computation (CFD) and analytical solution (Ana); a) the whole length; b) the concrete domain. The dotted red line denotes the temperature limit of 70°C.

CFD results with the cooling system

For this computation a constant average temperature T_{cc} at the oil cooling channel walls (see Figure 5~~Figure 5~~) is set as boundary condition. The aim is to understand the interaction between the reactor vessel wall temperature, the oil cooling system temperature, and the maximum concrete temperature. The final goal is to estimate the power removed by the oil cooling system.

On
Figure 8~~Figure 8~~ the temperature field for the computed elementary cell is depicted. The hot reactor vessel with the constant temperature of the vessel wall equal to T_{vw} = 700°C is on the left-hand side. The temperature of the oil cooling channel walls is set to T_{cc} = 200°C. Most of the heat transfer takes place between the vessel wall and the cooling channel. The maximum concrete temperature is slightly below 70°C.

Parametric calculations of the power removed by the oil cooling system at different temperatures (

Figure 9~~Figure 9~~) were evaluated with grey body factors of vessel and liner equal to 0.4 that is a typical value for stainless steel. If necessary this value could be increased by liner surface processing to increase its emissivity and the associated decay heat removal capacity. Calculations were performed for various oil temperatures (

Figure 9~~Figure 9~~). An average temperature of about 200°C is proposed for operation which is far below the operating range of the “Therminol SP” oil (315°C).

The power removed by radiation from the reactor vessel at 400°C (~nominal core inlet temperature) is about 3 kW/m^2 .The surface of the reactor vessel, radiating towards the oil cooling system, is about 1050 m^2. So at nominal operation, approximately 3 MW will have to be removed in order to maintain the oil at an average temperature of approximately 200°C.

In exceptional regime of decay heat removal (situations in category 3 and 4) the system can then remove (the main vessel being at 650°C), a power of about 15 MW. This value doesn’t take into account the exchanges by gas convection between vessel and liner, and could be also increased by special processing of the liner surface to increase its emissivity coefficient. The value of 15 MW corresponds to the decay heat power level after about three days.

For Scenario 2 (See Section “Main design-basis scenarios”) we assume that the average oil temperature (and therefore the liner) is at ~200°C. For Scenario 3 we assume that the other DHRS guarantee that the primary sodium is at about 200°C and the oil system is out of operation, therefore the liner will

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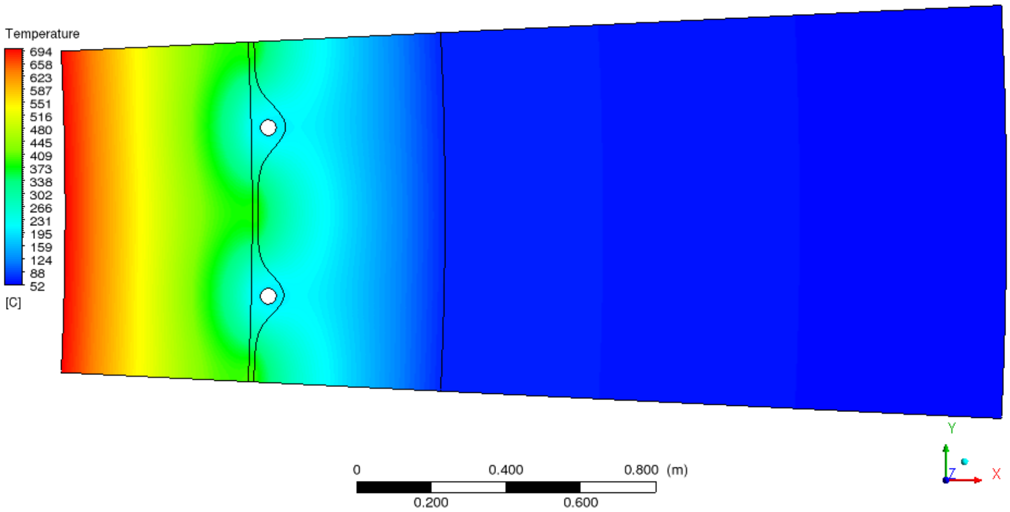

Figure 8: Temperature field, T_{vw} = 700°C, T_{cc} = 200°C

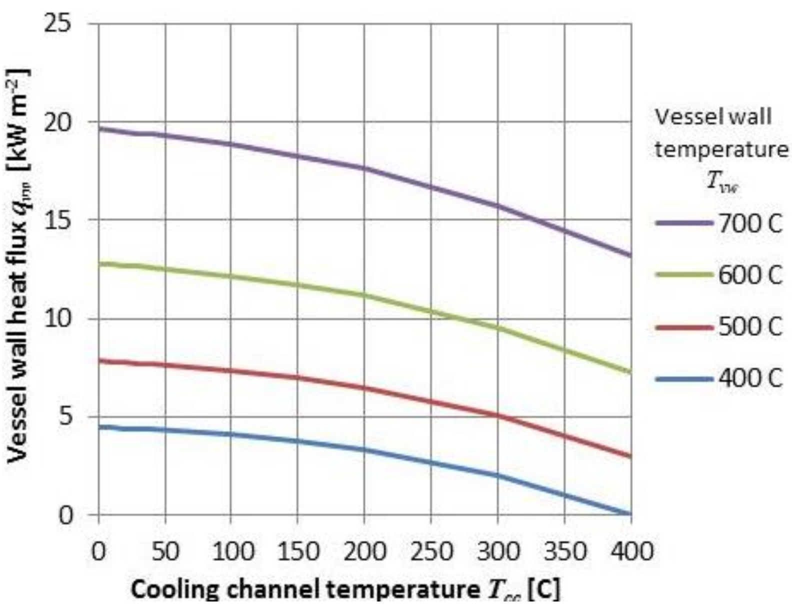

Figure 9: Power removed by the oil cooling system at different temperatures of the reactor vessel and the oil cooling channel wall

NB: thermal exchange have been calculated only with radiative and conduction effects. The exchanges by convection have not been taken in account and should be estimated later.

Conclusions

The paper presents the innovative design of the reactor pit for the European Sodium Fast Reactor. The aim of the innovations is to eliminate the safety vessel and to keep its safety functions (*i.e.* containment of the primary sodium in case of the reactor vessel leak without reduction of the primary sodium free level below the intermediate heat exchanger windows) by modifying the reactor pit geometry and by using the metallic liner on the reactor pit surface.

Two active (forced-convection) cooling systems are proposed: an oil cooling system close to the metallic liner and a water cooling system in the reactor pit concrete structure. The main goals of the cooling systems are 1) to keep the reactor vessel at acceptable temperature level and therefore provide its integrity as well as 2) to maintain the concrete temperature below 70°C in the three scenarios of operation envisaged (normal operation, decay heat removal without and with primary sodium leak). The conducted CFD analysis showed that if the oil cooling system could be designed to keep the liner temperature at about 200°C then this system alone can fulfil both goals. At the same time the water cooling system alone should be able to maintain the concrete temperature below 70°C in the three scenarios.

The proposed reactor pit design has several advantages: elimination of the safety vessel, better efficiency of the decay heat removal by the reactor pit cooling systems, and safer configuration in case of accidental or mitigation situations. Further detailed analysis will be conducted with both CFD and system codes in order to confirm the final configuration and the performance of the two systems in all scenarios. The final configuration should also be confirmed later by engineering studies, in particular regarding the design rules used in the nuclear industry

Acknowledgement

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