

# New safety measures proposed for European Sodium Fast Reactor in Horizon-2020 ESFR-SMART project

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## Abstract

Following up the previous European projects EFR and CP-ESFR, a new Horizon-2020 project, called ESFR-SMART, was launched in September 2017. This project, starting from the CP-ESFR design, will apply the new safety rules taking into account the lessons learned from the Fukushima accident, in order to increase the safety level of this European Sodium Fast Reactor (ESFR). In order to reach these new safety objectives, propositions are made to simplify as much as possible the design by using all the positive features of the Sodium Fast Reactors (SFR), i.e. low coolant pressure; high level of natural convection; possibility of decay heat removal by atmospheric air; high thermal inertia and long grace time before the human intervention.

These new safety objectives are presented in the paper from viewpoint of severe accidents prevention, defence in depth principles, extreme natural events to take into account, mitigation measures, etc. In all the cases, even in case of severe accident, early or significant radioactivity release requiring evacuation of the population will be avoided.

This paper gives a first list of propositions about ESFR, e.g.:

- Improved primary sodium confinement: The new design of the pit will be able to receive and confine the sodium in case of leak from the primary vessel. The level of sodium in the primary vessel in this case will remain high enough to assure natural convection through the core. A massive metallic roof above the pit assures the sodium containment even in the case of the worst severe accidents. Other measures are taken to avoid, even in this case of severe accident, primary sodium leaks in the above-roof area.
- Secondary loops design efficient in natural convection: Even in case of loss of feed water in the steam generators and loss of electricity supply for the secondary pumps, the measures taken on the secondary loops aim at ensuring an efficient decay heat removal by active or passive ways. These measures will include an optimized geometry of the secondary loops to promote the natural convection of the secondary sodium, the use of passive thermal pumps to increase the cooling flow rate, and the use of the steam generators modules to promote the cooling of their external surfaces by the natural convection of atmospheric air.
- Core design with improved safety parameters: special geometry and composition will significantly decrease a global void reactivity effect, and contributes to prevention of the severe ac-

cidents and mitigation of their consequences. Three types of control rods will be considered, including active and passive measures, i.e. activated by physical parameters, e.g. sodium temperature or flowrate.

- Three different systems will allow safe decay heat removal in all situations aimed to achieve the practical elimination of the loss of this function.

In conclusion, the paper gives a first review of the new propositions to enhance the ESFR safety. Some of these safety measures need additional R&D work for validation and some of them will be assessed in more details at the next phases of the ESFR-SMART project. The compliance of this new design with all safety rules has not yet been established at this stage of the project and will be studied later in dedicated tasks.

## 1. Introduction

A conceptual design of the 1500 MWe European Sodium Fast Reactor was studied in the FP7 CP-ESFR project [1]. It features an integrated reactor concept with six secondary loops. The Horizon-2020 EU ESFR-SMART project aims at proposing a Sodium Fast Reactor, with different safety improvements on the design, trying to take into account the recommendations following the Fukushima accident and the safety objectives envisaged for Generation-IV reactors.

The paper gives a first review of the improvements proposed to enhance this ESFR safety. These safety measures have been integrated into a whole plant design reassembly and will be later calculated and assessed in more details during the next phases of the ESFR-SMART project.

At the end of this project, the additional R&D needed for implementation of the promising safety measures will also be recommended.

## 2. General safety objectives for Generation-IV SFRs

For Generation-IV SFRs, a probabilistic objective of the core-meltdown accident prevention is proposed, with the same value as for Generation-III Pressurized Water Reactors (*i.e.*, a core damage frequency below  $10^{-5}$  per reactor-year for all events including hazards, with considerations of uncertainties). An additional and prescriptive reduction of the core-meltdown probability is not justified and might be even counterproductive. Indeed, the current probabilistic objectives are already ambitious and at the edge of representativeness. *De facto*, the probabilistic objective hardening, for already highly unlikely events, could increase complexity of the plant and its operation, and then reduce its everyday-life safety, for a marginal gain in terms of core-meltdown probability.

We remind that, despite this high level of core-meltdown prevention, mitigation provisions for this accident are adopted under the fourth level of defence in depth. In the event of a core-meltdown accident, the objective is to have very low radiological releases, and according to current thresholds, such that no off-site measures have to be implemented. If measures are nevertheless needed (*e.g.* restrictions on the consumption of crops), these must be limited in time and space, with sufficient time for their implementation. The even-temporary evacuation of populations should not be necessary and only their sheltering, limited in time and space, would be possible.

On the other hand, the effort for Generation-IV SFRs should focus on the safety demonstration. In particular, for Generation-IV SFRs, for which limited experience feedback is available, the safety demonstration will rely primarily on deterministic methods so as to cover the defence-in-depth levels and to implement the core-meltdown-accident prevention and mitigation provisions. Probabilistic methods, whenever relevant, will provide an additional insight.

The Fukushima accident lessons have led to new guidelines so as to make the plant more robust against natural hazards:

- to ensure that sufficient design margins are available on the equipment necessary to avoid cliff edge effects in terms of off-site radiological consequences, for natural hazards more severe than those considered in the plant reference design domain;
- to favour a significant plant autonomy, regarding the amounts of time necessary for a possible external intervention;
- to promote the provisions enabling the implementation of internal or external means of intervention, on the site in a damaged state.

In general, the intended objectives are similar to those of the Generation-III PWR reactors. For Generation-IV SFRs, these lessons are considered from the design early stages, taking into account the concept specificities, for example by promoting passivity or autonomy. These and other measures for reactivity control are described in more detail in the following sections. For Generation-IV reactors the methodology of practical elimination is to be applied since the beginning of the design studies, to identify the severe accident situations that would not be mitigated under economically reasonable conditions, and to make them extremely rare with a high level of confidence through appropriate design and operating provisions.

### **3. Reminders of the SFR assets and sensitive points**

The document produced by IRSN for the 2014 Permanent Group [3] presents a review of the assets and of the sensitive points of each type of Generation-IV reactors and in particular of the SFRs.

The SFRs safety demonstration benefits from many positive aspects:

- the capability to remove the reactor core decay heat by natural convection, without intake of external water and with the atmospheric air as the final heat sink;
- the large margin between the sodium temperature during normal operations and its boiling point;
- the favourable character of the concept towards dosimetry and environmental impact, during operation;
- the primary circuit significant thermal inertia, which provides significant grace periods before need of human intervention;
- the absence of pressurization of the primary circuit and of the secondary circuits;
- the simplicity of core operations and the absence of neutron poisons in normal operations (no xenon effect unlike thermal-spectrum reactors);
- the efficient trapping by sodium of the main fission products (in particular iodine and caesium).

On the other hand, the reactor design will have to take into account the SFRs sensitive points identified in the previous projects, and which deserve special attention, namely:

- At nominal conditions, the core is not in its most reactive configuration.
- The power density is generally high.
- A significant portion of the core may have a positive sodium void effect.
- Sodium reacts chemically with many elements, in particular with water, air and concrete, resulting in energy releases that may be significant, as well as in hydrogen production in case of reaction with water. In contact with air, the aerosols coming from a sodium fire will turn into sodium hydroxide and then into sodium carbonate, before being found relatively quickly under the form of sodium bicarbonate, completely harmless.
- The liquid sodium opacity and temperature make it difficult to inspect the structures under sodium.
- Although some components may be designed with provisions so as to facilitate interventions and replacements, these are still difficult for sodium circuits and components.
- Unloading sub-assemblies from the core lasts longer than in a water reactor.

It is proposed for ESFR-SMART to fulfil the achievement of safety objectives:

- on the one hand, by controlling the SFRs sensitive points such as the core neutron reactivity potential, the sodium chemical reactivity, the under sodium inspection;
- on the other hand, by relying upon the SFRs favourable characteristics, the plant natural behaviour and the passivity facilitated by the coolant efficiency, the grace and autonomy periods, *etc.*

We will detail in the following chapters a list of new safety measures for the ESFR reactor, aimed to improve implementation of the three main safety functions (plus some provisions for sodium chemical reactivity control).

## 4. Safety measures to improve the control of the reactivity

Several measures are proposed for further studies in the ESFR-SMART R&D framework, with the goal to ensure that the core reactivity control in ESFR-SMART is even better than in CP-ESFR.

### **New core concept with reduced sodium void effect**

In order to prevent core power excursion in case of loss of flow transients, it is proposed to adopt, at the first stage, a core with a close-to-zero global sodium void effect. (Ref 7) This new core concept may provide an even more favourable natural behaviour on most of the accidental transient sequences such as ULOF, ULOHS, UTOP, *etc.*

### **Passive control rod**

Passive control rods are proposed as self-actuated reactivity control devices for the core. The absorber insertion into the reactor is thus passively obtained, *i.e.* without any use of instrumentation and control (I&C), when some criteria on physical parameters are met, *e.g.* low primary sodium flow rate or high primary sodium temperature.

### **Ultra-sonic measurements for knowledge of the core geometry**

It is suggested to study the potential of ultrasonic means at the core periphery to monitor its global geometry during operations and to verify the absence of significant gaps between subassemblies (thus further preventing the risk of significant core compaction).

## 5. Safety measures to improve the confinement of radioactive materials

### **Recovery of the safety vessel functions by the reactor pit**

The CP-ESFR safety vessel function was to contain the sodium in the event of the main vessel leakage, while maintaining in it a level of sodium sufficient to allow the sodium inlet into the intermediate heat exchanger (IHX) and keeping a sodium circulation for the core cooling. To recover this function by the reactor pit (hence suppressing the safety vessel), it is necessary to overlay the reactor pit with a metal-sheet liner so as to withstand the reception of a possible sodium leak and to bring it closer to the main vessel so that the volume between vessel and pit remains identical to the volume between the two vessels. This option will be studied trying to take benefit from the following anticipated advantages (see ):

- The replacement of the safety vessel by a liner with a DHR system attached, which can favour increased decay heat removal capabilities through the reactor pit.
- The simplification of the safety demonstration with respect to a potential question related to the double leak of the two vessels.
- A fault tolerant structure well adapted to the mitigation functions.
- The main vessel in-service inspection remains possible, as the main vessel still remains accessible from the reactor pit, by the top of the space between vessel and liner).

A special arrangement of the reactor pit is necessary in order to be able to operate in normal conditions, to deal with an accidental sodium leak of the primary vessel and to be able to cope with severe accident mitigation. A “mixed” steel-concrete structure for the reactor pit is proposed for ESFR-SMART. A sacrificial material is provided between this “mixed structure” and the metal sheet liner. This material has to be chemically compatible with sodium and must protect the mixed structure even in case of leak through the inner sheet liner. For the liner material, an expansion coefficient is recommended as low as possible. Two independent active cooling systems will be installed in the reactor pit. The first system is an oil DHR circuit attached to the liner. Conversely to water, oil is able to support high temperature, but is likely to decompose in case of too high temperatures. The feasibility of implementation of an oil circuit close to the reactor vessel needs to be investigated both in case of normal operation and considering of all plausible accidents. Two possibilities have to be studied: this oil circuit located inside or outside of the liner. The second system is water active cooling circuits installed inside the concrete pit wall. This system is able to maintain the concrete temperature under 70°C in all situations, and even if the oil circuit is lost. Studies will notably be led as regards the thermomechanical constraints on the metal sheet liner in case of a main vessel leak. The sacrificial material could be, for example, an inert-to-sodium concrete (cf. the EFR Project) with moreover thermal properties (insulating and refractory material), and the metal sheet liner being a lost casing when pouring this concrete.

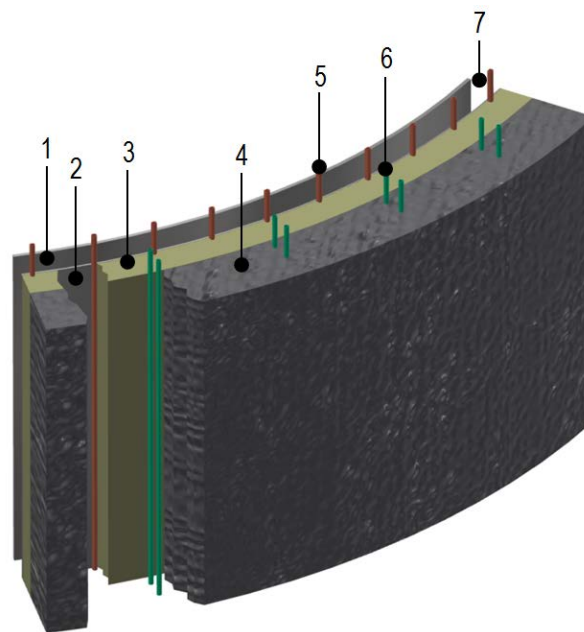


Figure 1. Detail of the ESFR-SMART reactor pit

- |                    |                                              |         |
|--------------------|----------------------------------------------|---------|
| 1 – Reactor vessel | 4 – Concrete                                 | 7 – Gap |
| 2 – Liner          | 5 – Oil decay heat removal system (DHRS-3.1) |         |
| 3 – Insulation     | 6 – Water concrete cooling system (DHRS-3.2) |         |

### Massive metallic roof

Superphenix experience feedback [4] leads to the recommendation that the roof is hot at its bottom part (so as to minimize the aerosol deposits) and has no water cooling. This last recommendation will be a key point for demonstrating the practical elimination of a huge entry of water into the primary circuit. The EFR massive metallic roof is therefore taken over, which presents many other advantages such as neutron shielding and mechanical resistance. Its thickness will be defined by the industrial manufacturing contingencies, but should be about 80 cm. In the upper part, a heat insulator will eventually be installed so as to limit the heat flux to be evacuated during nominal conditions by air flow in forced convection or even natural convection.

### Leak tightness of roof penetrations

It is proposed to study penetrations featuring improved leak tightness during operation with the goal to avoid (as far as possible) primary sodium leakage through the roof in case of an energetic core meltdown scenario. Such leakages would be difficult to determine, and can thus lead to very conservative overpressures in the containment, making it necessary to implement systems such as dome or polar table which are expensive, quite complex and the suppression of which could facilitate the reactor operation.

To overcome these difficulties, the following options will be studied:

- For large components, pump and heat exchanger penetrations: they are already firmly bolted for earthquake issues. It is proposed to weld a sealing shell so as to ensure the leak tightness in fast overpressure transient. These components are not intended to be frequently handled, but if this handling is required, a grinding will enable to remove them easily.
- For rotating plugs: independently of the possible inflatable seals, the leak tightness with eutectic seals, which are liquefied during the handling phases so as to enable the rotation [4, 5], is recommended. Conversely, when operating the reactor, these seals are solidified and the design retained should eventually be such that there is no leakage possibility in the case of a severe accident with energy release. The design and safety investigations will be necessary to reach this goal.
- Consistently with this strategy, to improve the primary sodium confinement in the main vessel, it is also proposed to consider:
  - an integrated primary cold trap, likewise at Superphenix, so as to avoid any primary sodium circulation outside the vessel;
  - a sufficiently low argon pressure in the cover gas to avoid any sodium-fountain effect of a plunging pipe.

### In-vessel core catcher (Figure 2).

The mitigation of a severe accident with core meltdown will be achieved by means of a corium receiver, also called core catcher, located at the bottom of the vessel, under the core support plate. Transfer tubes, coming from the core, emerge above the core catcher so as to channel the molten corium. The use, as in the Russian reactor BN 800, of molybdenum, characterized by a high melting temperature, will notably be studied as regards its potential for avoiding melting of the core catcher structure and facilitating the power removal by conduction. The use of hafnium-type poisons will be studied as regards avoidance of any potential re-criticality. The core catcher will be designed for the whole core meltdown.

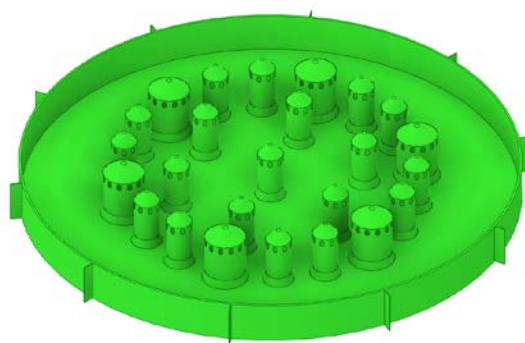


Figure 2: ESFR-SMART core catcher

## 6. Safety measures to improve heat removal from the core

### Hydraulic diodes

The possibility will be studied to equip the primary pump or diagrid connection with hydraulic diodes (anti reverse flow devices) enabling to limit the return flow towards a primary pump in case of spurious stopping and thus to increase the residual flow rate in the core.

### Decay heat removal (DHR)

The secondary circuits are the normal power removal circuits (). Their use for DHR in case of all primary pumps trip is very useful since that allows creating, in the IHX, a cold column essential for the establishment of a good natural convection in the primary circuit. The secondary circuit design () will be optimized so as to enable a good heat removal by air in natural convection, that is to say, in the extreme situation when both the feed water and the electrical power supply have been lost.

For this purpose, several provisions are taken:

- A loop design enabling an easy establishment of natural convection will be adopted.
- The CP-ESFR design for steam generators (SGs), with six modules per loop will be kept. We will take advantage of the large exchange surface, related to the SG modular design, to have opportunities for cooling these modules by air in natural or forced convection (through hatch openings, likewise at Phenix reactor, as shown in ). This will be the heat sink for the secondary loop. We will call this system DHRS-2 (Decay Heat Removal System) or secondary DHRS (see Figure 5).
- Finally it is foreseen to add one or more thermal pumps in the secondary circuits (see 3 in Figure 3). Thermal pumps are passive electromagnetic pumps using thermoelectricity provided by the difference in temperatures and with no need of external electricity supply (Figure 6). They provide the flow rate also in nominal conditions.

In addition to the secondary DHR loops, there will be two independent cooling circuits in the reactor pit, one with oil system brazed on the liner and one with water inside the concrete (see red and green tubes in Figure 1), capable to maintain the whole pit at temperatures below 70°C. Suppressing the safety vessel will make these devices attached to the liner much more efficient, and should be able to assure a large part of the Decay Heat Removal, maybe 100% or close to 100% . We will call this system DHRS-3 or DHRS-Pit.



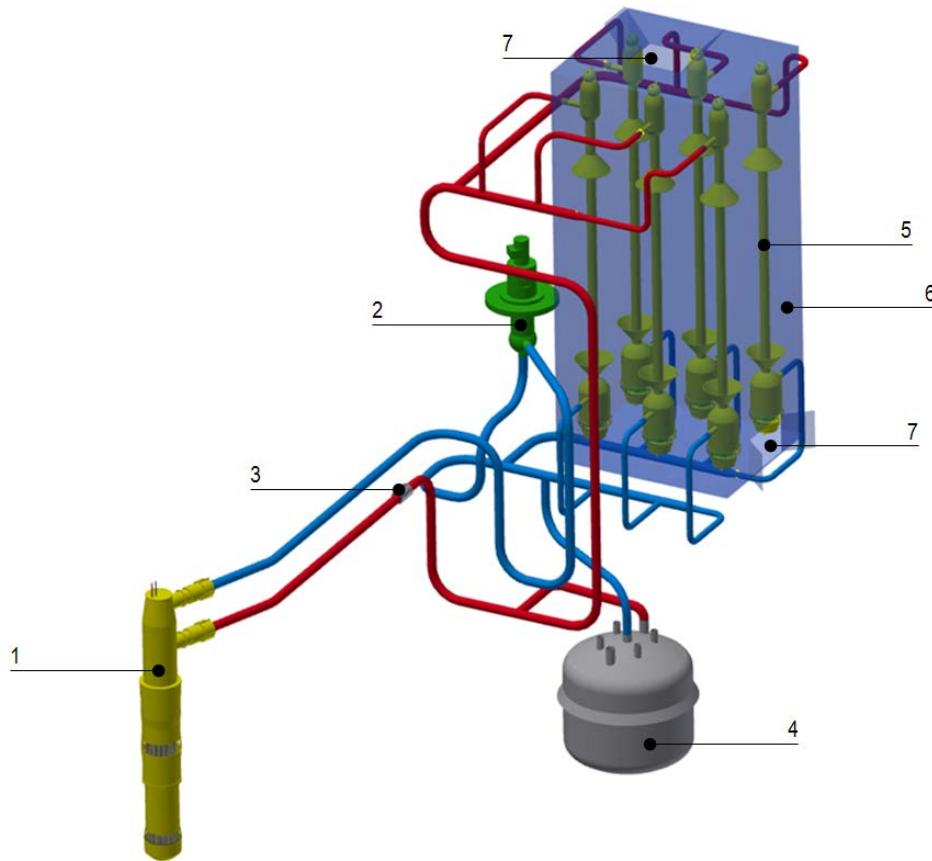


Figure 3. View of the ESFR-SMART secondary loop (DHRS 2):

- 1 – Intermediate heat exchanger
- 2 – Secondary pump
- 3 – Thermal pump
- 4 – Sodium storage tank
- 5 – Steam generator
- 6 – Decay Heat Removal System (DHRS-2)
- 7 – Openings for air circulation

If the safety analysis (demonstration of practical elimination of loss of DHR function) establishes that these DHR systems are not sufficient, it is proposed to add cooling circuits by sodium/air heat exchangers connected to the IHXs piping. These circuits, which we will call DHRS-1 or primary DHRS (see Figure 4), have several advantages compared to independent systems located in the primary circuit (formerly used in the CP-ESFR design):

- No additional roof penetrations are required (gain on the main vessel diameter).
- The cold column is maintained in the IHX, which is the guarantee of a good natural convection in the primary circuit through the core.
- This circuit can use the already existing purification circuit of the corresponding secondary loop and minimizes the number of sodium circuits to be managed by the operator.
- It is still available even when the secondary loop is drained.

The DHRS-1 circuit ability to operate in natural convection will be assessed together with the possible addition of a thermal pump (Figure 4) to further increase its capabilities and help for the starting of the operation.

General view of ESFR-SMART primary and secondary DHRS systems is shown in Figure 5.



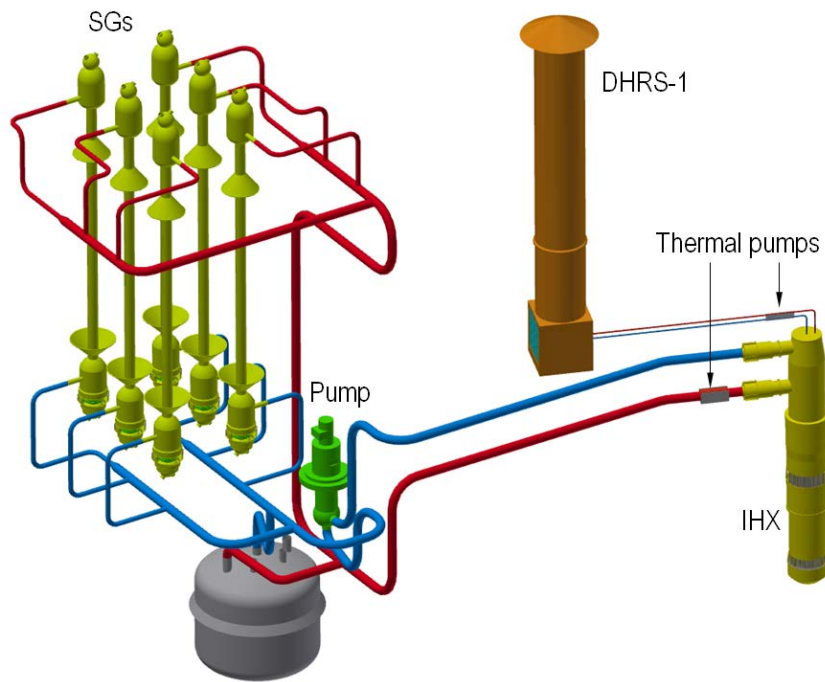


Figure 4. General view of ESRF-SMART secondary systems with DHRS-1

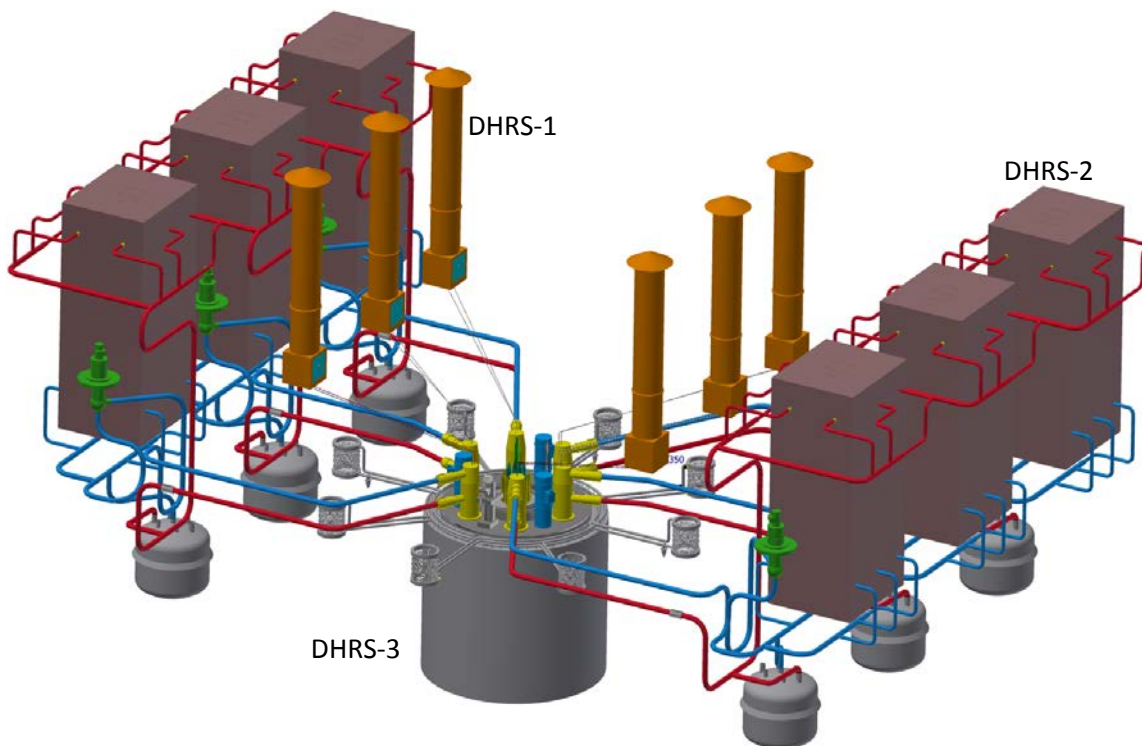


Figure 5. General view of ESRF-SMART primary and secondary DHRS systems

## 7. Safety measures to improve control of sodium fires

As the provisions to prevent any leakage of primary sodium have already been outlined in Section 5, this chapter will only focus on the risks related to a secondary sodium leakage. In this sense, it should be noted that releases are mainly a chemical risk considering that no or very little radioactivity is present in the secondary sodium circuit. Possible impacts of sodium fires on other safety systems should also be addressed.

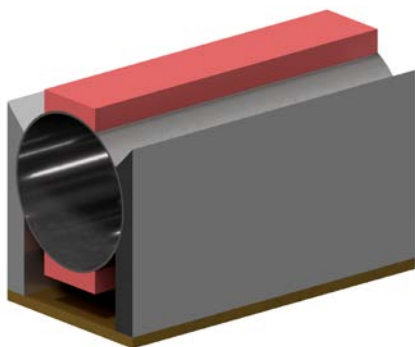


Figure 6. Thermal pump concept with permanent magnets shown in red and electrodes in grey

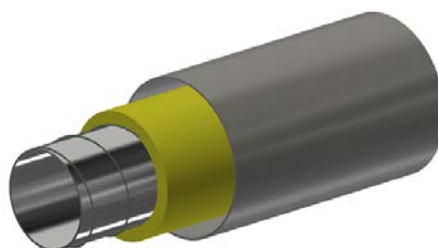


Figure 7. View of the double-wall piping with insulation/detection

### Double wall for piping with quick sodium fire detection

All secondary sodium circulation loops are protected against leakage by a double wall piping (Figure 7). The piping itself is covered with an insulation including quick sodium fire detectors. Complementary sodium smoke detectors can be added between the two pipings. This set of provisions will be studied with regard to its potential for justifying the secondary sodium fire control and its integration in a coherent set of design options aiming at simplifying the above-roof arrangement (for example, through possible suppression of a dome or a polar table).

## 8. Sodium/water reaction control

Rather conventional devices enable to efficiently control this risk. Modular SGs are retained for studies, considering the possibility to quickly detect sodium water reaction, followed by the depressurisation/isolation and draining of the faulty module. The choice of modular SG allows also minimizing the theoretical envelope accidents. In case of water/sodium reaction, the consequences on the plant operations are limited and the operation can continue with remaining modules. Mitigation means against risk of sodium-water-air reaction will have also to be studied.

## 9. Severe accident mitigation

A more robust design than CP-ESFR is proposed for severe accident mitigation studies:

- A core catcher is provided at the bottom of the vessel, designed for the whole core meltdown (see a starting design to be further developed in Figure 2).
- Mitigation devices inside the core (corium discharge tubes) will channel the molten fuel to the core catcher.
- The re-criticality of this core should be made impossible by disposition of dedicated material such as hafnium inside the core catcher.
- The reactor pit ( ) should accept sodium leakage and, with its upper thick metal roof, should form a solid, tight and that-can-be-cooled containment system.
- This corium long-term cooling will be managed by the diversified cooling measures provided in the SG and in the pit (DHRS-2 and DHRS-3).
- The use of DHRS-1 circuits may be done as a supplement so as to continue the reactor block cooling even with the three secondary circuits being drained.

## 10. In-service inspection

Although not yet addressed by the ESFR-SMART project, recent advances on in-sodium ultrasonic sensors and on robotics will be expected to enable inspections during periodic outages. Partial sodium draining (such as realized at Phenix) should enable visual inspections of the upper part, if required.

## 11. Dosimetry and releases

It is known that, during normal operations, the SFR releases are almost zero for gas. The only liquid radioactive release is the liquid used to wash fuel subassemblies or for washing and decontamination of components [4, 5]. In terms of the personnel dosimetry, this reactor design leads to a dosimetry much lower than on the water reactors [6]. This benefit will be kept for ESFR-SMART.

## 12. Simplicity and human factor

Starting from the CP-ESFR design [2], our approach has consisted in proposing the simplest possible reactor, while keeping the necessary lines-of-defence. It is expected that this simplicity should contribute to the whole reactor safety, by making it easier to operate. Compared to CP-ESFR, the following simplifications will be studied in that frame:

- dome (or polar table) suppression;
- safety-vessel functions taken over by the reactor pit;
- primary sodium containment improvement;
- natural convection cooling enhancement in the secondary side;
- optimized and simplified DHR dedicated circuits.

Passive and redundant systems which are independent of instrumentation and control or of the operators' action will enable the reactor reactivity control and its cooling by natural convection, even in the most severe cases of simultaneous loss of cooling water and electrical power supply. With all those improvements, the new design is then more forgiving; both with respect to the reactivity control, as well as at the intervention time required from the operator (enhanced grace period).

## Conclusion

The paper gave the first ideas about possible new safety measures proposed for European Sodium Fast Reactor studies in the frame of the Horizon-2020 EU ESFR-SMART project. The global view of the ESFR SMART primary system is shown in Figure 8.

The general principle of the studies was to increase the safety in operation, by increasing the simplicity of the design, avoiding adding new systems. For this purpose we tried to use at maximal level the possibilities given by the liquid metal coolant in terms of passivity, simplifications, operation and mitigation of the severe accident consequences:

In terms of passivity

- A low sodium void reactivity effect, to reduce drastically any energy release, even in case of accidental sodium boiling. That was obtained by a lot of various innovations, including increase of the fuel pin diameter, introduction of a sodium plenum above the fuel assemblies, axial heterogeneity (fertile and fissile parts) of the core, etc.
- Passive control rods able to shutdown the reactor without human intervention or active protection measures but passively at the abnormal variation of such physical parameters as coolant temperature or flow rate.
- Better design to enhance natural convection of sodium in the secondary loop, even without feed water supply and without electrical supply.
- Possibility of decay heat removal without feed water supply, but only by natural convection of atmospheric air through the casing containing the six modules of the steam generators (DHRS-2).

- A passive decay heat removal system (DHRS-1) on each loop connected to the intermediate heat exchanger and able to remove decay heat by passive way with atmospheric air, even if the secondary loop is drained.
- Thermal pumps, totally passive, able to maintain permanent flow rates in the secondary loops and in the DHRS-1, even without any electrical supply.

In terms of simplifications:

- Suppression of the safety vessel.
- Suppression of dome or polar table.
- Suppression of separated DHRS inside the primary vessel.
- Minimization of the number of sodium circuits.
- Very simple and massive reactor roof.

In terms of operation:

- New measures against sodium leaks and better protection of the building with strong separation of water and sodium circulation areas.
- Better concept to avoid any primary sodium leakage.
- Better access for handling operations (no polar table).
- Quick water sodium reaction detection and good protection against consequences based on choice of modular steam generators.
- Use of hydraulic diode to reduce in case of one pump failure the reverse flow through this pump and therefore reduce the core bypass.
- Mechanical measures at the level of the strongback to avoid any subsidence of the core support.
- Several design measures to avoid gas entrainment in the core.
- The reactor is very forgiving with a high inertial capacity and can stay stable a long time without operator actions.

In terms of mitigation of the severe accident consequences:

- Use of discharge tubes inside the core to drive the corium to the core catcher in mitigation situation.
- Low energy release with a new core conception and big margins with the massive solid roof and the pit able to receive sodium leaks.
- Ability to cool the primary vessel during long mitigation situations with two cooling circuits inside the pit and one dedicated in case of loss of the first one (DHRS-3)
- A dedicated core catcher able to receive a significant part of the fissile core, with materials against ablation, with efficient natural convection cooling and without any recriticality possibilities.

The proposed set of the modifications compared to the CP-ESFR design aims at consistency with the main lines of safety evolutions for Generation-IV SFRs since the Fukushima accident, but needs, as indicated in introduction, to be calculated and validated by other tasks during this four-year project

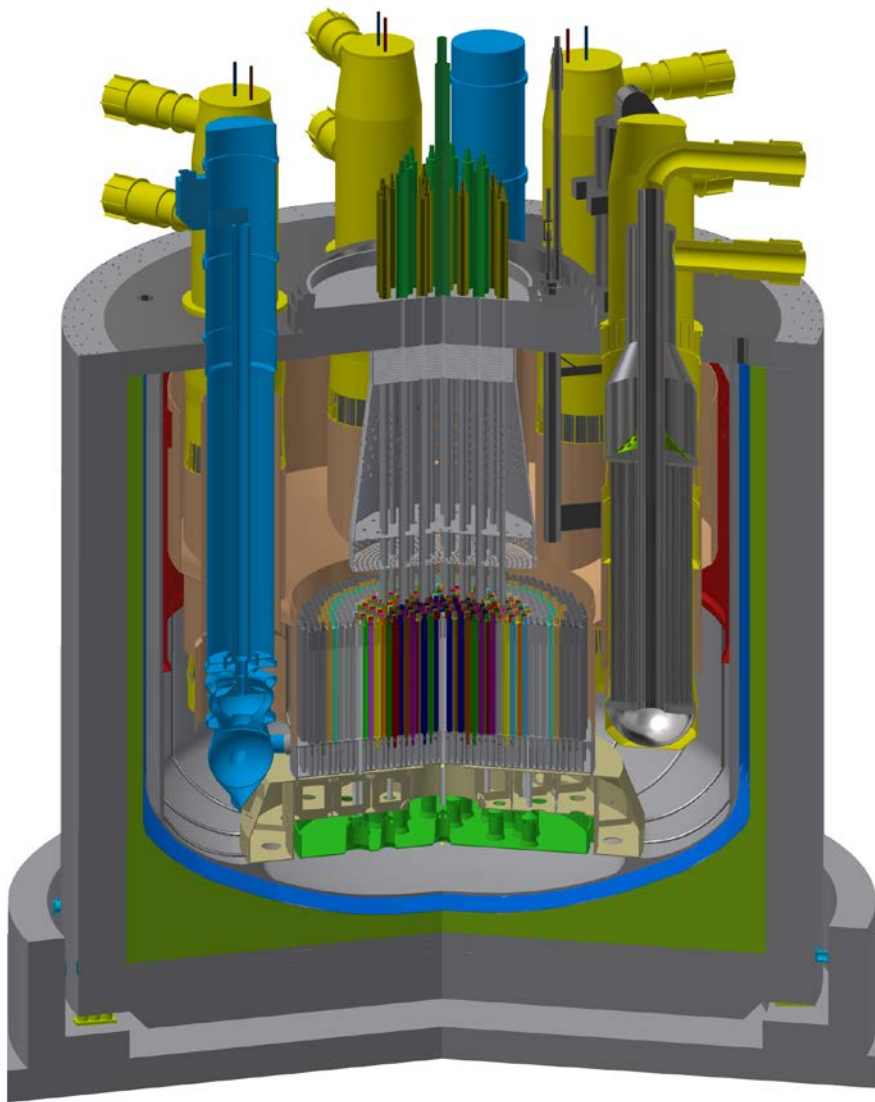


Figure 8. Global view of the ESFR SMART primary system

## Acknowledgement

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