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ESFR-SIMPLE project: towards a ESFR-SMR design

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ABSTRACT

The ESFR SMART project, which took place from 2017 to 2022, made it possible to define a Sodium Fast Reactor (SFR) design based on past SFR experimental feedbacks and intended to meet post-Fukushima safety criteria. The main options retained are recalled here: a heterogeneous core with low sodium void reactivity effect and mitigation measures (corium transfer tubes), a sodium-resistant pit well, a metallic thick slab, and finally comprehensive set of measures allowing decay heat removal by natural convection. These studies were carried out during this project with a power of 3600 MWth which was the power of the initial EFR project initiated during the operation of Superphenix. The new ESFR-SIMPLE project, starting at the end of 2022, uses the same technical options but with reduced power. This choice could more easily allow the construction of a SFR prototype in Europe. Design options were chosen so that the reactor could be assembled off-site, then shipped by rail or ship to the construction site, which requires a vessel diameter limit of around 10 m. The paper presents the first design studies with a particular attention to the core and primary circuit sizing. The proposed ESFR-SMR results in a 360 MWth reactor. This power reduction may also allow some simplifications compared to the initial high-power concept, particularly in terms of passive evacuation of residual power. This last point will be more deeply investigated by the ESFR-SIMPLE project in the next years.

Keywords: EFSR-SIMPLE, ESFR-SMART, SMR, core design

1. INTRODUCTION

For 20 years, the Generation IV International Forum (GIF) [1] has proposed and defined a series of ambitious objectives for future nuclear reactors. Among the proposed concepts, the SFR currently stands out from three other fast-spectrum Generation-IV systems (Gas, Lead Fast Reactors and fast Molten Salt Reactors) by its maturity and its experience feedback. The 3600 MWth European Sodium Fast Reactor (ESFR) concept has been developed for more than 10 years by 25 countries in two European projects (FP7/CP-ESFR [2] and H2020/ESFR-SMART [3]). Building on the advances made, a new European project on reactor safety is proposed and focused on innovation and advanced technologies. The FP9/ESFR-SIMPLE project (European Sodium Fast Reactor - Safety by Innovative Monitoring, Power Level flexibility and Experimental research) [4] brings together a consortium of research centres, industries, universities, Technical Safety Organisations (TSOs) and Small and Medium Enterprise (SME) with the aim of improving the attractiveness and safety of future SFRs. The consortium is presented in Figure 1. The project is coordinated by the CEA, and will run from 2022 to 2026.

The safety measures implemented in CP-ESFR and ESFR-SMART have allowed a significant design simplification and advances, as it will be presented in section 3. In order to take a further step towards the GIF goals, the ESFR-SIMPLE project will explore the impact of the new safety measures based on the following assessments foreseen in these 4 years.

- 1) A new design of the 3600 MWth (the ESFR) core based on a metallic fuel;
- 2) A simplified secondary circuit design;
- 3) Passive pumps for improvement of Decay Heat Removal (DHR);
- 4) Artificial Intelligence (AI) to support monitoring of selected reactor components, in particular, Steam Generator (SG) tube rupture;
- 5) A small power MOX core and correspondingly simplified reactor systems, including a dedicated heat storage for improved flexibility.



Figure 1. Consortium of the ESFR-SIMPLE project.

The last activity aims at designing a Small Modular Reactor (SMR) version of ESFR, referred to as ESFR-SMR. This reactor could be a good design basis for a SFR prototype to restart a construction project of a European reactor.

Technical objectives for this SMR are based on:

- A constraint for the vessel to be feasible in a factory and transportable to the power plant site;
- To take as much as possible of the safety options developed in ESFR-SMART. If possible, take benefit of the limit in power to simplify these systems.

The objective of this paper is to present the design obtained for this SMR after one year of project and its main performances. The section 2 discusses the context and the global objectives of a Gen IV reactor. Section 3 highlights the main options developed in ESFR-SMART and that will be kept as much as possible for the ESFR-SMR. Section 4 presents the pre-conceptual design of the ESFR-SMR system, by downscaling the ESFR system design. The different thresholds are highlighted. Section 5 presents the core design obtained after an optimization process with specific constraints and objectives. The conclusion highlights the next steps to come.

2. FAST REACTORS POTENTIALITIES

Thanks to the fast spectrum, the use of a fuel composed of wastes issued from PWR fuel is possible: depleted uranium and plutonium. Depending on the reactor design, different operating modes can be envisaged, thanks to the possibility of creating plutonium from ^{238}U . Based on the assumption of self-sustaining reactors and a closed cycle, the reactor will only use depleted uranium. Some advantages of the fast reactor spectrum can be highlighted:

- Operation with available wastes only depending on the depleted uranium stock;
- No more need for uranium mines, no more expensive imports linked with geopolitical risks;

- No more need for uranium enrichment plants;
- Reduction of waste and easier management of remaining waste.

Within the six families of fourth generation reactors listed by the GIF, four are fast reactors. Sodium-Cooled Reactors (SFRs) are the best-known fourth-generation reactors, with about twenty reactors built and operated around the world, giving SFRs the greatest experience feedback among them. Based on these elements, Europe is maintaining skills in this area to be able to develop sustainable nuclear power in a timely manner, making it possible, with increased societal acceptance, to fight against global warming. The work presented here is a part of this context.

3. ESFR-SMART SELECTED OPTIONS

The European ESFR-SMART project was initially issued from the European SFR project EFR (European Fast Reactor) initiated during the last years of operation of Superphenix (SPX) for a power of 3600 MWth. Thirty years ago, on the basis of the Superphenix operating period, a technical expert group proposed to modify several systems designs which had been proposed for SPX. Some of them are included in the ESFR-SMART reactor [5][6][7].

Core design

Based on the ASTRID project, the MOX fueled core was designed with low (less than +1%) void effect and by improving its resistance to severe accidents both in prevention and mitigation: introduction of discharge tubes allowing the preferential flow of corium towards the recuperator, and with a dedicated system of passive control rods stopping the reactor without any active order from the I&C system.

Slab and large components

- **Fixing large components:** for SPX, the primary pump was rotating on a ring. To comply with new seismic standards, all large components will be firmly fixed on the slab.
- **Adoption of a thick slab:** on SPX the reactor slab had water cooling pipes embedded in the concrete. This design brought intrinsic safety problems, linked to the close coexistence of water and sodium. It also led to a slab that was too cold, resulting in Na aerosols condensation. EFR made the choice of a 80 cm thick steel slab. This slab remains hot in the lower part (no deposits), limits the heat flow upwards due to the poor efficiency of pure conduction, and remains leak tight in the event of severe accidents. Extensive thermal calculations and manufacturing tests were carried out to validate this choice.

Fuel handling

The SPX experience made it possible to develop gas cask handling. The storage drum is then removed.

Safety

- **Removal of the safety vessel:** the role of the safety vessel close to the primary vessel is to recover sodium leaks in the event of a leak from the primary vessel, while maintaining a sufficient sodium level to allow core cooling by natural convection. A more robust solution is a pit with a liner embedded in aluminous concrete, which does not react with sodium and allows long-period fuel handling without risk of second vessel rupture. This option will be retained, in principle, for ESFR-SIMPLE, but with a different industrial implementation.
- **Severe Accident:** the ESFR-SMART project aimed to further simplify the design to meet post-Fukushima safety demands, based on:
 - developing passive systems which use as much as possible natural convection (efficient in sodium);

- strengthening resistance to severe accidents (see next section on core design);
- favoring intrinsic safety rather than the use of specific systems with regard to specific accident scenarios.

Primary circuit

The safety vessel is removed [3]. The pit has to resist a hot sodium leak. Several cooling oil circuits are located between the liner and the main vessel. The slab located above the primary vessel is derived from the thick EFR slab. The slab penetrations are designed to be sealed even in the event of overpressure in the primary vessel: rotating plug with solidified eutectic, large components firmly fixed and even welded. No primary sodium circuit leaves out the vessel. These provisions make it possible to justify, even in the event of a theoretical severe accident, the impossibility of ejection of primary sodium. This makes it possible to remove a dome or polar table above this thick slab.

Secondary circuits and the return to the modular Steam Generator (SG)

The modular SGs and the general design allow the evacuation of residual power by simply opening the hatches of the SG casings. One additional modification is the suppression of flexible pipes, for straight pipes with bellows (Figure 2).

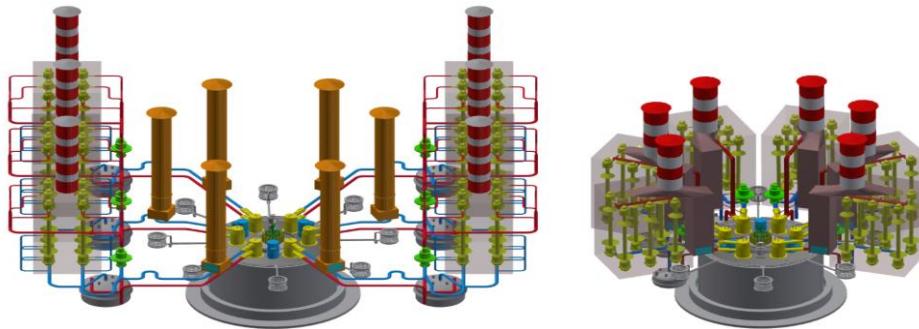


Figure 2. Comparison of the secondary circuits with flexible (left) and straight pipes (right).

- **Secondary loops:** a simplification of the secondary circuits was proposed with the removal of the secondary pump expansion tank.
- **Steam Generators:** the modular SGs are much simpler to calculate and construct. They are easy to protect against sodium/water reactions, unlike monolithic SG like in SPX where detection and then repairing are much more difficult. In addition, modular SGs allow easy evacuation of residual power by natural convection.

Decay heat removal systems

All cooling circuits inside the primary vessel have been removed. The decay heat removal is then ensured by three specific defense-in-depth systems [8].

- The oil (Therminol® SP) circuits around the main vessel, based on an air/oil or water/oil heat exchanger [3];
- The sodium secondary circuits in natural convection through the modular SGs;
- An external circuit connected to each intermediate heat exchanger, also operating in natural sodium/air convection and capable of ensuring all of the decay heat removal alone. All of these options have been designed and calculated. ESFR SIMPLE will adopt most of these options. However, the smaller size of the ESFR-SMR should allow even further simplifications.

4. PRELIMINARY SYSTEM DESIGN

4.1. Design constraints and hypothesis

To design the ESFR-SMR while coping with the constraints of fabrication and transportability, the following approach has been performed:

- Based on a literature review, the geometrical constraints are defined, in terms of maximum height and diameter of the primary vessel;
- Parametric studies have been realized on potential SMR systems, by downscaling the ESFR-SMART;
- Valuable design spaces are presented depending on different choices.

The height limit is taken as a reference from the NuScale design [9]. It corresponds to a maximum value of 14.75 m for the primary vessel.

The maximum allowable diameter of the primary vessel depends on the transportation requirements. The PRISM was designed to be fully transported by road or rail with a 6.6 m of diameter for the primary vessel [10]. In the same document, it was however mentioned that a primary vessel with a 10 m diameter can be transported by barge. The SPX diagrid (9 m) was built in Italy and came by road transportation.

All these limits are kept for the preliminary design phase of the ESFR-SMR system (Table I).

Table I. Design constraints on the primary vessel.

Design constraints (m)	Transportation by road or rail	Transportation by ship
Primary vessel height	14.75	14.75
Primary vessel diameter	6.6 - 9	10

To start the early pre-design calculation of the ESFR-SMR, some assumptions have to be considered. As a reminder, the objective is to downscale the ESFR-SMART by keeping as much as possible feature options.

For the core pre-design, we assume that:

- The fuel sub-assembly is based on the same pin geometry than the one of ESFR-SMART [6]. However, the number of pins per sub-assembly is slightly reduced to ease the definition of the core pattern without significant impact on the core size;
- The radial protection layers are considered almost unchanged: the number of radial rings of reflectors and neutron protection are taken from ESFR-SMART design. This seems reasonable because it mainly depends on the neutron flux level and spectrum that might not change so much with the core size;
- As the ratio of the core diameter to the storage diameter is smaller in a SMR, the dimensioning of spent fuel storage is easier than in ESFR-SMART. The ratio between allocated position to the spent fuel and number of fuel sub-assemblies is increased from one-half to a full core.
- The set of control rods includes six peripheral rods and another one in the center, like in the Phenix reactor. On the other hand, the SMR includes more CRs per fuel SA as compared to Phenix and ESFR-SMART designs. This relatively high number of CRs in SMR is to enhance the CR driveline expansion reactivity feedback; the enhanced feedback may improve core behavior under accident conditions.

For the system design:

- To enhance the compactness of the primary vessel diameter, the heat transfer length of the intermediate heat exchanger (IHX) is the same than in ESFR-SMART [6];
- To reduce the primary vessel diameter, all the decay heat removal systems (DHRS) are considered to be positioned outside;
- The free design spaces available between components like rotating plugs and intermediate heat exchanger are considered constant, as it is supposed not to depend at first order of the component size.

4.2. Preliminary downscaling design

The following studies are done with the COPERNIC tool [11]. It allows quick evaluation of preliminary design and is mainly used as CEA to:

- Compare performances of well-known SFR designs (thermal inertia, sizes of components, fuel mass, etc.)
- Evaluate the pro-and-cons of specific design choices (fuel handling system, number of loops, etc.)
- Extrapolate concepts to another power range
- Make predesign calculations of specific system components.

Keeping all the design choices of ESFR-SMART, the core downscaling led to a reduce core power about ten times lower. The main dimensions are presented in the Table II.

Table II. System dimensions of the direct ESFR-SMART downscaling.

	ESFR-SMART	ESFR-SMR v0
Core Power (MWth)	3600	386
Fuel S/A	504	54
Number of IHX	6	4
Number of primary loops	3	4
Primary vessel diameter (m)	17.6	10.3

4.3. Margins for a design space

Starting from this point, parametric studies have been done:

- To evaluate the possibility of performance increase, without enlarging the primary vessel diameter.
- To allow a primary vessel reduction, without lowering too much the core power.

Based on the results, the constraint of the fuel handling system on the primary vessel diameter appears to be in top position. Considering the most promising system often used in the Japanese designs, a comparison has been made with the 2 rotating plugs option of ESFR-SMART and the pantograph solution, which requires only one plug. The results are presented in Figure 3.

The choice of increasing the number of loops to four for ESFR-SMR is potentially not optimum from the economic point of view regarding the core power. Besides, the increase from three to four loops has only a small impact on the vessel diameter.

In addition, the change in fuel handling system allows a 1.5 m gain in the vessel diameter.

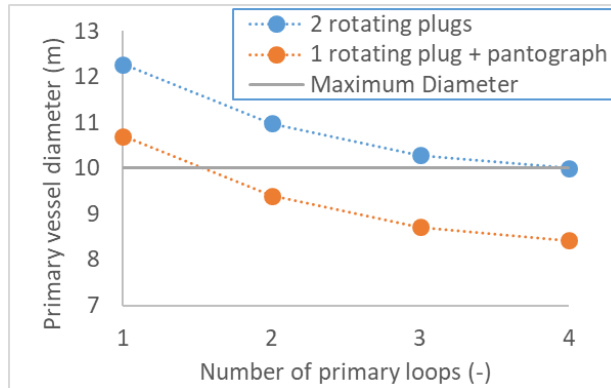


Figure 3. Influence of the fuel handling system on the primary vessel diameter

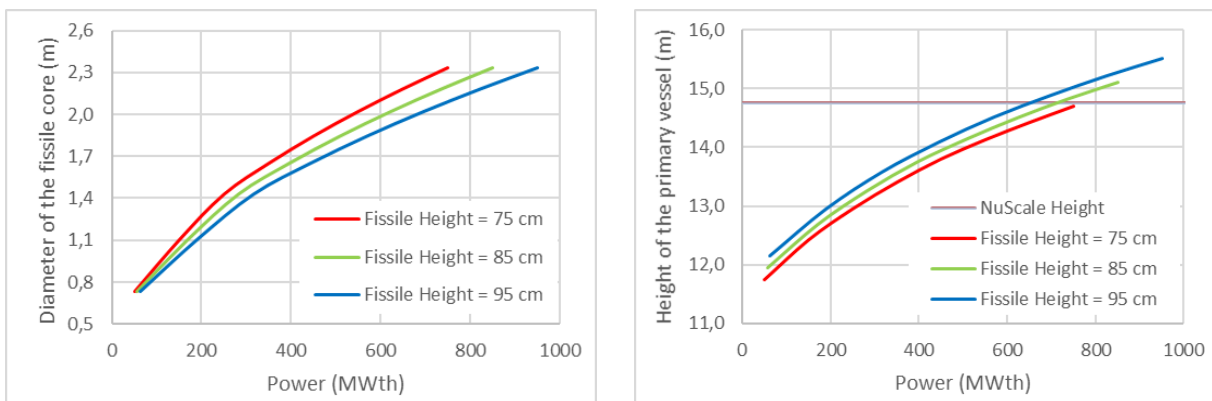


Figure 4. Influence of the fissile height on the core and vessel dimensions depending on core power

The primary vessel height is far below the limit of 14.75 m. To reduce the core diameter, an increase of the fissile height may be considered. However, as can be seen in Figure 4, the diameter reduction is limited to a couple of dozens of cm. In addition, the fuel height will be a result of the next optimization process on the code, as it largely pilots the intrinsic core behavior in transients.








Based on these results, a preliminary system based on a pantograph fuel handling system is chosen. The number of loops is proposed to be three as a preliminary design and an increment in the fissile height is requested as favorable if possible. These assumptions can be updated in the next step. Based on these options, a thermal power of 425–475 MWth seems to be potentially generated in a primary vessel of 9–10 m. The exact vessel dimensions will be defined during the refined design phase of the system, at the next project stage. The next section proposes to define the optimization process that has been carried out and that has led to the ESRF-SMR core design.

5. ESRF-SMR CORE DESIGN

5.1. The optimization process

The core design optimization has been performed with the SDDS tool [12]. Based on the previous study, a radial layout and sketch is proposed (Figure 5). The legend is available in Table III. Two different reloading schemes are proposed with four or six batches.

Table III. Type (legend of Figure 5) and number of S/A of the ESFR-SMR core.

S/A type	Number of S/A	S/A type	Number of S/A	
	Inner fuel	36	 Spent inner fuel storage	36
	Outer fuel	48	 Spent outer fuel storage	48
	CSD / DSD	6 / 1	 Corium discharge tubes	6
	Reflector	44 / 48 / 54		

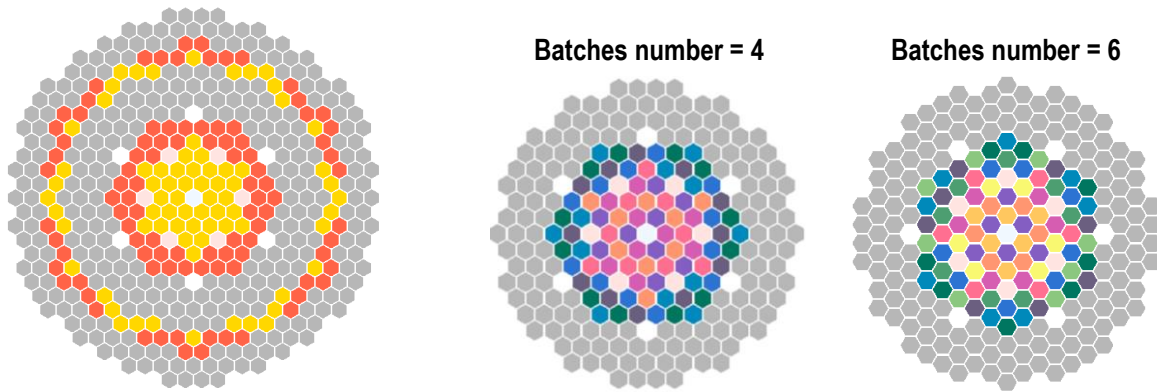


Figure 5. ESFR-SMR base design for the optimization process

Axially, the design scheme is the following.

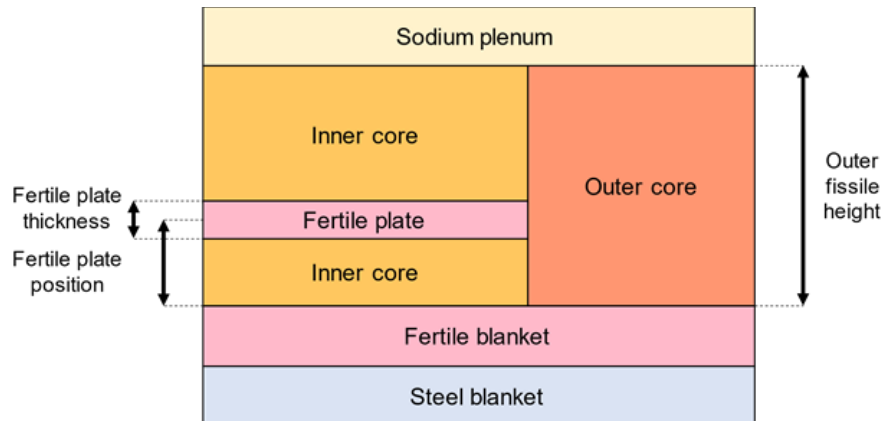


Figure 6. Axial shape of the core

For the optimization process, parameters range are defined in the Table IV. The targets are defined with the following objectives:

- To maximize the power at the core level
- To minimize the peak of sodium temperature during an Unprotected Loss Of Flow (ULOF) transient
- To maximize the margins to fuel melting in Unprotected Control Rod Withdrawal (UCRW) transient.

Table IV. Design range for the optimization process.

Parameter	Range
Power (MW _{th})	[360; 500]
Target discharge burn-up (GWd/t)	[70; 120]
Outer fissile height (cm)	[80; 120]
Fertile plate thickness (cm)	[10; 25]
Fertile plate relative position (% of Inner Fissile height)	[0; 50]
Plutonium average enrichment (%vol)	[20; 24]
Inner / outer fuel enrichment ratio	[0.8; 1]
Reflector material	{EM10; MgO}
Batches number	{4; 6}

Table V. Design constraints on the primary vessel.

Observable	Constraint
Fuel cycle length (EFPD)	> 300
Max. sodium temperature in ULOF (°C)	< 920
Margins to fuel melting in UCRW (W/cm)	> 0
Cladding dpa limit (dpa)	< 150
Total sodium void reactivity effect (pcm)	< 300

The constraints are defined in the Table V. The Pareto front is obtained with different cores as potential candidates. Based on their characteristics, two cores were selected. They are based on an equivalent design: the only difference comes from the reflector material. One is made of EM10 steel pins, the second is in MgO. The main performances are listed in the Table VI. These two designs are considered as enough representative of the different solutions obtained and can be updated at the next project stage.

Table VI. Performances of the two selected configurations for the preconceptual design of the ESFR-SMR core.

ESFR-SMR	MgO reflector	EM10 reflector
Power (MW_{th})	360	360
Plutonium average enrichment (%wt)	24.86	25.62
Batches number	6	6
Fuel cycle length (EFPD)	1830	1830
Max. sodium temperature in ULOF (°C)	908	912
Margins to fuel melting in UCRW (W/cm)	30	6
Sodium void reactivity effect (pcm)	-269	-456
Fissile Doppler constant (inner + outer core) (pcm)	-673	-549
Breeding gain (%)	-13.6	-14.1

The optimization process shows that the selected cores have a thermal power about 360 MW. The sodium voiding is negative and the breeding gain lower than -0.1. A sensitivity study would be required to show the possibility to go through a self-sustainable or breeder mode.

It should be also noticed than an increase of only one ring of the core (36 S/A) would lead to an increase of the core power of about 40% and with a very limited impact on the vessel diameter. This will require the system design of the vessel before fixing the limits.

6. CONCLUSIONS

Based on successive and past European projects, the design of a European Sodium Fast Reactor (ESFR) was proposed during the ESFR-SMART project. The main simplifications are based on the removal of the safety vessel, the removal of the cooling circuits in the primary vessel, the removal of the dome or polar table and the reduction of the secondary circuit length. The next step is done by the ESFR-SIMPLE project (still ongoing) with the objective to design a SMR (ESFR-SMR). This has been presented in this paper and the optimization process used during the project allows a preliminary design of a core about 360MWth, with a vessel diameter lower than 9m and three secondary loops. The further step on the system design of the primary vessel will define the different margins available and the potentialities to increase the core power by staying below the 10m of vessel diameter imposed for a possible construction in a factory.

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