DESIGN AND SAFETY STUDIES OF THE MOLTEN SALT FAST REACTOR CONCEPT IN THE FRAME OF THE SAMOFAR H2020 PROJECT

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Abstract

Since more than 15 years, the National Centre for Scientific Research (CNRS, France) has focused R&D efforts on the development of a new molten salt reactor concept called the Molten Salt Fast Reactor (MSFR) selected by the Generation-IV International Forum (GIF) due to its promising design and safety features. Studies are performed to ascertain whether MSFR systems can satisfy the goals of Generation-IV reactors.

Molten salt reactors are liquid-fueled reactors, allowing a large flexibility in terms of operation (load-following capabilities…) or design (core geometry, fuel composition, specific power level…) choices. They are characterized by features different in terms of design, operation and safety approach compared to solid-fueled reactors. In the frame of the European SAMOFAR (Safety Assessment of Molten Salt Fast Reactors) project of Horizon2020, dedicated studies are performed on these topics. An overview of these studies will be presented in this article.

Firstly, an innovative design of the MSFR fuel circuit (defined as the circuit containing the fuel salt during power generation) and of the emergency draining system has been defined and is under optimization in terms of safety. Such reactors also call for the definition of dedicated operational procedures different from that of solid-fueled reactors, requiring the use of specific modelling tools (multiphysics and system codes). A system code is thus under completion and validation in the frame of SAMOFAR to define the start-up and load following procedures of the MSFR, including the evaluation of safety transients. Finally, a safety approach dedicated to liquid circulating fuel reactors has been developed on the basis of the ISAM methodology of the GIF taking into account other safety methodologies and guidelines. An application procedure and the required tools have been proposed. The approach is being applied to the MSFR, allowing a preliminary identification of initiating events, lines of defence and confinement barriers for the concept.

I. INTRODUCTION

Since more than 15 years, the National Centre for Scientific Research (CNRS, France) has focused R&D efforts on the development of a new molten salt reactor concept called the Molten Salt Fast Reactor (MSFR) selected by the Generation-IV International Forum (GIF) due to its promising design and safety features [1,2,3]. Studies are performed to ascertain whether MSFR systems can satisfy the goals of Generation-IV reactors.

Molten salt reactors are liquid-fueled reactors, allowing a large flexibility in terms of operation (load-following capabilities…) or design (core geometry, fuel composition, specific power level…) choices. They are characterized by features different in terms of design, operation and safety approach compared to solid-fueled reactors [4,5]. In the frame of the European SAMOFAR (Safety Assessment of Molten Salt Fast Reactors) project of Horizon2020, dedicated studies are performed on these topics. An overview of these studies and results will be presented in this article.

II. INTEGRATED DESIGN OF THE MSFR

The MSFR plant includes three main circuits involved in power generation (see Figure 1): the fuel circuit, the intermediate circuit and the power conversion circuit. These circuits are associated to other systems composing the whole power plant: an emergency draining system, a routine draining system and storage areas, and bubbling and chemical processing units.

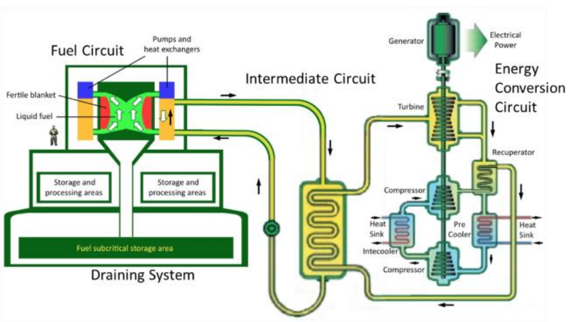

Figure 2: MSFR power plant

The main characteristic of the MSFR is the fuel in the form of a molten salt. This fuel salt circulates in the fuel circuit where it is cooled down and plays therefore the role of coolant as well.

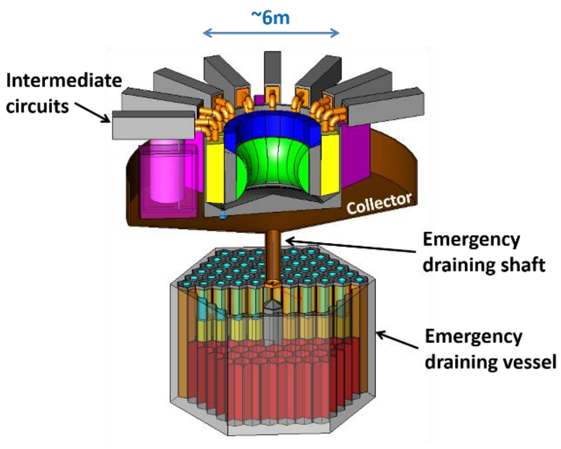

Figure 2: New design of the MSFR system, including the fuel circuit and the Emergency Draining System (EDS)

The fuel circuit is defined as the circuit containing the fuel salt during power generation and includes the core cavity and the cooling sectors allowing the heat extraction. An integrated geometry of the fuel circuit [2,3] (see Figure 3) has been developed in order to prevent the risk of fuel leakages highlighted by preliminary safety and optimization studies [5].

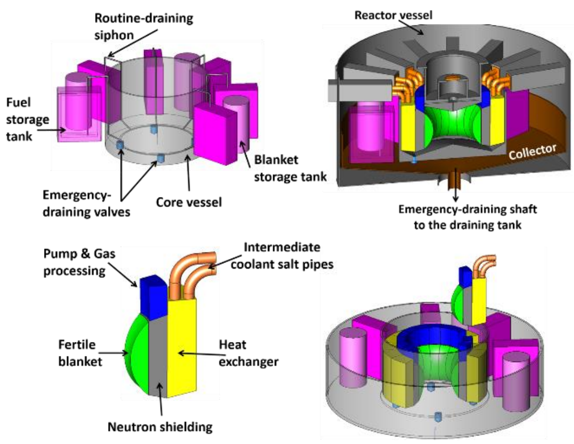

Figure 3: Schematic view of the integrated design of the MSFR fuel circuit

This integrated geometry includes a vessel used as container for the fuel salt, in which the 16 cooling sectors are disposed circumferentially. Each sector comprises a heat exchanger, a circulation pump, a gas processing system, and a fertile blanket tank. A neutron shielding in B_4C is positioned between the blanket and the heat exchangers to protect the heat exchangers from the neutron flux and to increase the breeding ratio. In addition, thick reflectors made of nickel-based alloys are located at the bottom and at the top of the vessel to protect the structures located outside the core.

Finally, in case of incident/accident during power production, the fuel can be drained gravitationally toward an emergency draining tank designed to passively remove the residual heat over a short to long period of time (the residual heat associated to the fuel salt, at reactor shutdown, represents around 3.8% of the nominal power). The fuel circuit is connected to this Emergency Draining System (EDS) through active and passive gates or plugs located in the bottom reflector.

III. SYSTEM CODE AND PROCEDURE DEFINITIONS

As mentioned, the characteristics of the MSFR require also dedicated studies and definition of specific operation procedures.

For example, the core negative feedback coefficients (density effect and Doppler Effect) are both negative and act rapidly since the heat is produced directly in the coolant. Although the fuel circulation drifts the delayed neutron precursors in low importance areas, reducing the effective fraction of delayed neutrons, the core presents a very intrinsically stable behaviour to reactivity insertions [4,6].

Within the framework of the design and the safety assessment of a complex system such as the MSFR, a fundamental role is played by the power plant simulator. This tool has to be able to properly model all the power plant subsystems and to simulate efficiently their coupled dynamic behaviour, from the reactor core to the electrical grid. In the framework of the SAMOFAR project, the development of a power plant simulator aims at (i) the analysis of the MSFR plant dynamic behaviour, (ii) the definition of the control strategies and operational procedures for the different reactor operation modes (full power, start-up, shut-down, load following, …). The simulator is developed conjointly by LPSC/CNRS (fuel circuit) and POLIMI (intermediate and conversion circuits).

For the fuel circuit modelling, to take into account the dynamics due to the delayed neutrons, the LiCore (Liquid Core) code has been developed. The code uses the Java language and is based on a point kinetics neutronic model that can take into account the precursor position [6]. The precursors are followed with this code even during an evolution of the state of the reactor over time, i.e. during transients. The LiCore code is able to calculate a transient faster than real-time which is a very important point for the MSFR system code. Load following transients from 1.5 to 3 GW have been calculated with several time constants as displayed in Figure 4. One can notice the excellent behaviour of the MSFR core in case of an important load following solicitation, as already established by precise multiphysics core calculations [4]. The main limitations will come from the intermediate circuit that will have to be designed to perform such load following transients.

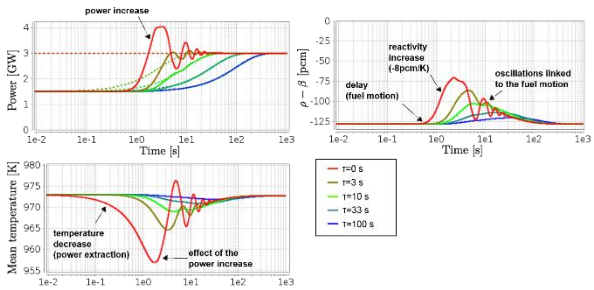

Figure 4: Load following transients from 1.5 to 3 GW, calculated with the LiCore code by varying the power extracted in the heat exchangers with different time constants

The LiCore code may also be used to calculate incidental transients, for example loss of flow transients. A dedicated pipe composed of empty cells representing the emergency draining tank has been added in the LiCore code to allow also calculations of incidental transients leading to a draining of the fuel salt if a given mean fuel temperature is reached. An instantaneous loss of the intermediate flow at 10 s is illustrated in Figure 5, with a draining occurring when the fuel reaches a temperature chosen by the user (1000 K on this example).

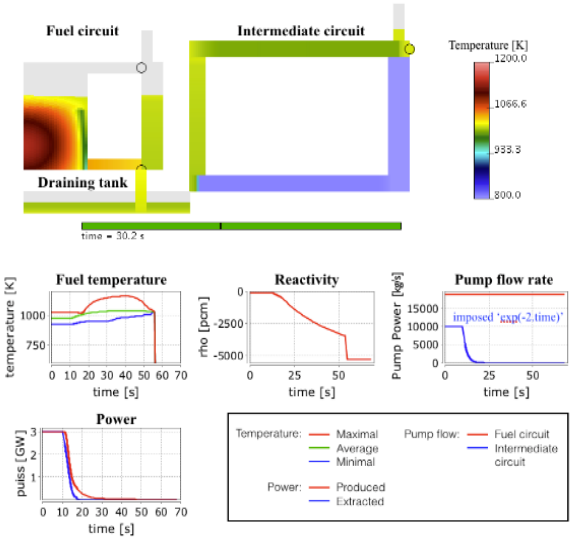

Figure 5: Loss of intermediate flow at 10s leading to an emergency draining of the fuel in the emergency draining system: view of the MSFR circuits modelled (top) and results of the calculations (bottom)

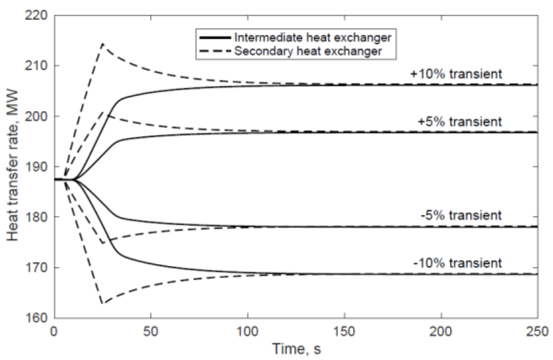

Figure 6: Evolution of the heat transfer rates in the heat exchangers for gas mass flow rate transients in the intermediate circuit

Regarding the modelling of the intermediate and the energy conversion systems of the MSFR, the chosen approach is the object-oriented modelling, which allows satisfying the modularity and efficiency requirements. The adopted modelling language is Modelica [7]. It allows a description of single system components (or objects) directly in terms of physical equations and principles, and to connect different components through standardized interfaces (or connectors). Different studies of the behaviour and the design of the intermediate and energy conversion circuits are done as shown in Figure 6.

IV. SAFETY ANALYSIS METHODOLOGY FOR LIQUID FUELED REACTORS

Driven by the IRSN, a safety approach dedicated to liquid circulating fuel fast reactors has been developed, together with the definition of its application procedure and of the required tools for the application to the MSFR. The objective was to define a risk assessment methodology which could be applied from the earliest stages of design to licensing, operation and decommissioning. This methodology takes into account the Generation-IV safety requirements, the international safety standards, the available return of experience and the peculiarities of this kind of reactor with the help of available risk analysis tools. The idea is to achieve a safety which is “built-in” and not “added-on” providing with a detailed understanding of safety related design vulnerabilities, and resulting contributions to risk. As such, new safety provisions or design improvements as well as R&D needs could be identified, developed, and implemented if necessary. The MSFR technology being at its first stages of design will benefit from such an approach. The methodology is based on the Integrated Safety Assessment Methodology (ISAM) developed in the framework of the GIF [8]. ISAM is a tool kit of useful analysis tools for Gen IV systems. Some of these tools are primarily qualitative, others quantitative. Some are primarily probabilistic, others deterministic. Some focus on high-level issues such as systemic response to various phenomena, others focus on more detailed issues. This diversity helps to provide a robust guidance based on a good understanding of risk and safety issues.

The ISAM tools have been reviewed, completed and adapted, when needed, to better reflect the European standards/rules, the available return of experience and to better fit the scope of the SAMOFAR project. In addition, review of the usual risk analysis methods (HAZOP, FMEA, etc.) has been performed to analyse how they can be integrated within the ISAM framework (see Figure 7). This adapted method has then been declined to be applied to the MSFR technology. A focus has also been made on the safety-related subjects to be examined as a priority at the basic design stage of the MSFR.

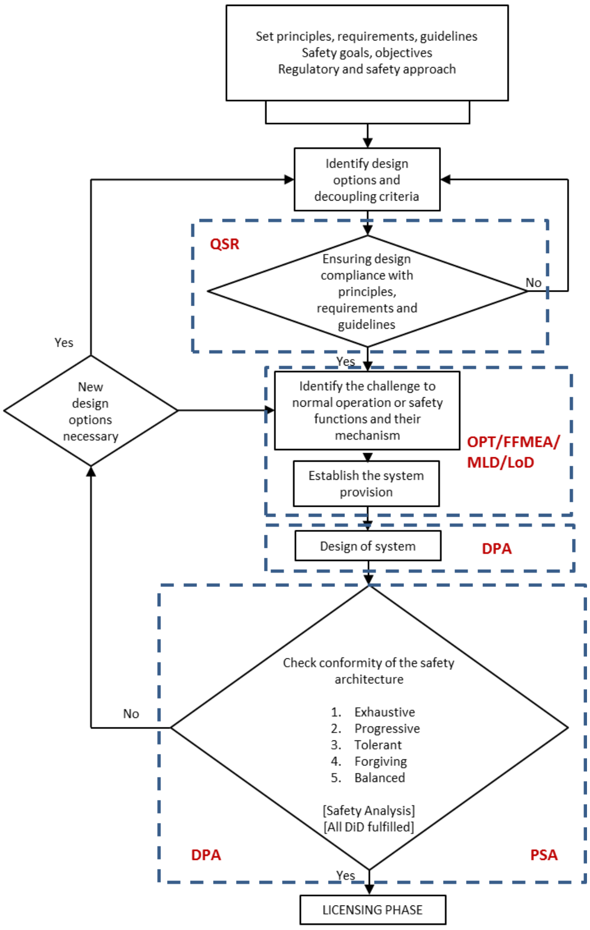

Figure 7: Flowchart of the MSFR design/safety assessment and relevance of the different tools

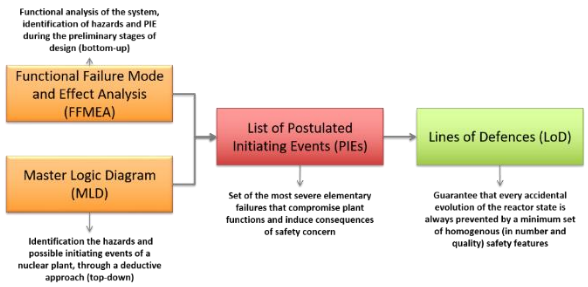

Figure 8: Complementarity between the FFMEA and the MLD methods

Finally, this methodology and the related recommendations are currently applied on the MSFR for the reactor by POLITO, CNRS and Framatome. The analysis using the Functional Failure Mode and Effects Analysis (FFMEA) and the Master Logical Diagram (MLD) has been done on the plant state corresponding to the nominal power production of the MSFR (see Figure 8) and a list of Postulated Initiating Events has been identified [9, 10].

These studies have also been used to provide a list of design key-points that are relevant for safety and should be further investigated such as the type of pumps used for the fuel circulation, the definition of the decay heat removal system or the components of the fission product removal systems. The need to further define the operation and accidental procedures has also been highlighted. For instance, the cases in which the emergency draining system, the routine draining system or in-core shutdown are used should be defined [9, 10].

The method of the Lines of Defence (LoD) is under completion for the MSFR during nominal power production. The main objective is to ensure that every accidental evolution of the reactor state is always prevented by a minimum set of homogenous (in number and quality) safety features - called Lines of Defence - before a situation with potentially unacceptable consequences may arise. It can therefore help the designer to determine whether sufficient safety provisions are put in place for a given risk.

Finally, first proposals of confinement barriers definition have been made.

V. CONCLUSION

Molten salt reactors with a liquid circulating fuel, like the MSFR concept developed initially at CNRS and now in the SAMOFAR European project, are very different in terms of design and safety approach compared to solid-fueled reactors. Dedicated tools and methods are required for their study and optimization, more general than the existing ones. An overview of the work performed to date on the MSFR in terms of design, simulation and safety approach has been presented in this article. In the future, the full application of these methodologies and tools will lead to more a more refined definition of the concept up to its validation, the first step for industrialization.

Acknowledgements

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Nomenclature

CNRS	National Centre for Scientific Research
GIF	Generation IV International Forum
IRSN	Institute for Radiological Protection and Nuclear Safety
ISAM	Integrated Safety Assessment Methodology
MSFR	Molten Salt Fast Reactor
POLIMI	Politecnico di Milano
POLITO	Politecnico di Torino
SAMOFAR	Safety Assessment of Molten Salt Fast Reactors

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