

PRELIMINARY FUNCTIONAL SAFETY ASSESSMENT FOR MOLTEN SALT FAST REACTORS IN THE FRAMEWORK OF THE SAMOFAR PROJECT

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In the last decades, the research activity for the development of innovative nuclear systems tries to answer the current needs of safety, reliability and sustainability, including safety assessment and risk analysis.

In this framework, the European project SAMOFAR aims at furnishing the experimental proof of concept of the Molten Salt Fast Reactor (MSFR) and its safety assessment at its present conceptual stage. For this purpose, the Integrated Safety Assessment Methodology (ISAM) is selected and analysed as conceptual methodology and a wide survey on risk analysis tools, international standards and best-practices aims at defining an operational procedure suiting MSFR analysis, including functional safety assessments.

Well-established practices applying “Functional Safety” to conceptual systems do not exist; therefore this work proposes and uses a new method based on functional modelling and on the Functional Failure Mode and Effect Analysis (FFMEA). This approach allows studying systems with a preliminary design, identifying functions deviations able to compromise safety, listing Postulated Initiating Events (PIEs) and recognizing lack of information, criticalities and necessity of supplementary provisions in the current design. Therefore, this methodology aims at influencing the design from its earliest stages. The paper focuses on the application of FFMEA to the MSFR in normal operation conditions.

I. INTRODUCTION

The Generation IV International Forum (GIF) in its Technological Roadmap defined four goal areas to advance nuclear energy in its next, fourth generation: sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection¹. Among them, improved safety and higher reliability is recognized as an essential priority in the development and operation of nuclear energy systems. Nuclear energy systems must be designed so that during normal operation or anticipated transients safety margins are adequate, accidents are prevented, and off-normal situations do not deteriorate into

severe plant conditions². Therefore, the roadmap towards the deployment of next generation nuclear systems includes very detailed safety assessment and risk analyses in both operational and accidental conditions through both probabilistic and deterministic tools.

Along with five other concepts, the Molten Salt Fast Reactor (MSFR) was selected by the Generation-IV International Forum (GIF) due to its promising design and safety characteristics³. In this general framework, the European project SAMOFAR (Safety Assessment of Molten Salt Fast Reactor) of the Horizon2020 program aims at furnishing the experimental proof of concept of the unique safety features of the MSFR, providing a complete safety assessment of the reactor and updating the conceptual design of the MSFR with all improvements and recommendations from the performed studies⁴. Because of the unique characteristics of the MSFR, very different in terms of design and safety characteristics compared to solid-fuelled reactors (including a liquid circulating fuel and a fast neutron spectrum), and its preliminary design phase, the safety assessment of the reactor has to rely on the basis of nuclear safety and technological neutral methodologies. For example, one of the safety objectives for New Nuclear Power Plants set out in WENRA⁵ is: “reducing potential radioactive releases to the environment from accidents with core melt, also in the long term”. This objective is not directly applicable to the MSFR as the core melt accident is undefined for this type of system. To provide a complete safety assessment taking into account Molten Salt Reactors specificities a methodology is selected (the Integrated Safety Assessment Methodology - ISAM)⁶ and adapted to the peculiar case of MSFR, including functional modelling and the application of Functional Failure Mode and Effect Analysis (FFMEA), nevertheless well-established practices to apply a functional safety approach to a conceptual system do not exist.

The aim of this work is to define and use a new method based on functional analyses that allows to study systems whose design is still at the preliminary phase, to identify functions deviations able to compromise system safety (in

terms of Postulated Initiating Events PIEs, the most challenging conditions for the safety of the plant), to recognize criticalities, lack of information and potential limitations in the current design and to suggest the eventual need of supplementary safety provisions.

Therefore, this methodology aims at influencing the direction of the concept and design development since its earliest stages.

After a description of the MSFR concept in section II, this paper introduces the selected methodology for the MSFR safety assessment and its operational practices in section III. The application of the tool and its results are presented in section IV, while the obtained objectives and possible further developments are summarised in section V.

II. DESCRIPTION OF THE SYSTEM

II.A. General description

The MSFR is characterized by a circulating liquid fuel playing also the role of coolant and possesses therefore interesting characteristics in terms of reactor operation (e.g. load-following capabilities) or design choices (core geometry, fuel composition, specific power level, etc.), but is very different in terms of design and safety approach compared to solid-fuelled reactors. The MSFR is an isobreeder reactor with a fast neutron spectrum. The main characteristics of the reference MSFR design at the beginning of the SAMOFAR project are listed in table I.

TABLE I. Characteristics of the reference MSFR

Thermal power (MWth)	3000
Thermodynamic efficiency (%)	45
Mean fuel salt temperature in fuel circuit (°C)	725
Fuel salt temperature rise in the core (°C)	100
Total fuel salt volume (m3)	18
Fuel salt volume in the core (m3)	9
Total fuel salt cycle in the fuel circuit (s)	3.9

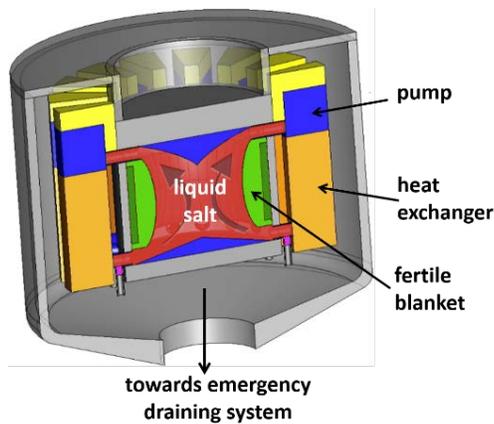


Fig. 1. Schematic view of the fuel circuit

The MSFR includes three closed circuits involved in power generation (the fuel circuit, the intermediate circuit and the power conversion circuit -BoP-) and an open circuit acting as heat sink. The fuel circuit (see Fig.1. and details in section II.B) contains the fuel salt during power generation.

The selected fuel salt is a molten binary fluoride salt with 77.5 mol% of lithium fluoride; the remaining 22.5 mol% are a mix of heavy nuclei fluorides (fissile and fertile matters). The fertile matter is $^{232}\text{ThF}_4$ and the possible fissile matters are $^{233}\text{UF}_4$ and/or $^{\text{enr}}\text{UF}_4$ and/or $(\text{Pu-MA})\text{F}_3$. The fluids of the intermediate and conversion circuits have not been selected yet but several options are proposed and will be studied in the frame of the SAMOFAR project. For the intermediate circuit, fluoride salts are considered for their better chemical compatibility with the fuel and the possibility to work at low pressure. The proposed energy conversion fluids are mainly helium, supercritical water or supercritical CO_2 . The main fluid compositions are summarized in table II.

TABLE II. MSFR main fluids composition

Fuel molten salt – Initial composition	Option 1: $\text{LiF-ThF}_4\text{-}^{233}\text{UF}_4$ (77.5-20-2.5 mol %) Option 2: $\text{LiF-ThF}_4\text{-}^{\text{enr}}\text{UF}_4\text{-}(\text{Pu-MA})\text{F}_3$ (77.5-6.6-12.3-3.6 mol%) with U enriched at 13%
Fertile blanket salt - Initial composition	LiF-ThF_4 (77.5-22.5 mol %)
Intermediate fluid composition	Option 1: Fluoroborate Option 2: FLiNaK Option 3: LiF-ZrF_4 Option 4: FLiBe
Energy conversion circuit fluid	Option 1: helium Option 2: supercritical water Option 3: supercritical CO_2

These circuits are connected to other auxiliary and safety systems composing the whole power plant; in particular, there are two types of draining systems: the Emergency Draining System (EDS) and the routine draining system to the storage areas⁷. The emergency draining is used in case of in-core anomaly during reactor operation and can be activated thanks to passive and active devices, whereas the routine draining is used for normal shutdown and triggered only by active means. This paper focuses on the fuel circuit analysis taking into account its interaction with the other systems.

II.B. Fuel circuit description

The fuel circuit includes the core cavity and the cooling sectors allowing the extraction of the generated heat. The fuel salt volume is distributed half in the core and half in recirculation cooling sectors. A compact torus shaped core is optimized to improve the fuel flow and limits the recirculation zones⁸.

To prevent fuel leakages through a pipe rupture highlighted by preliminary safety studies⁹, an integrated geometry of the fuel circuit (see Fig.2) was proposed and is currently studied in the frame of the SAMOFAR project. This solution foresees a vessel (Fig.2 Top right) used as container for the fuel salt in which the cooling sectors are disposed.

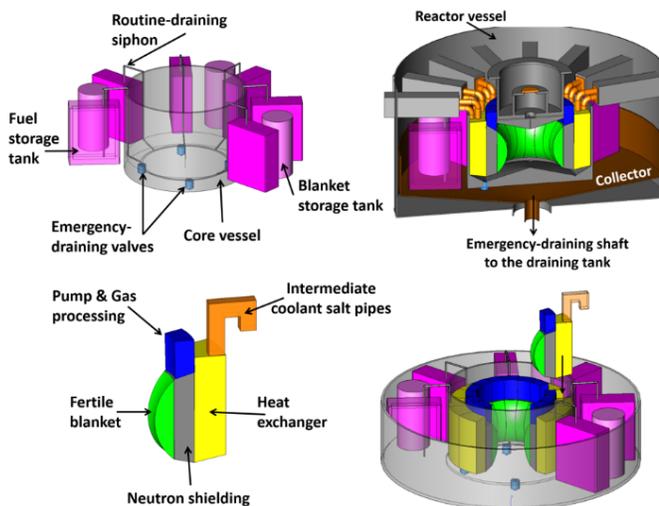


Fig. 2. Schematic representation of a cooling sector (bottom left), cooling sector arrangement in the core vessel (bottom right), storage tank arrangement around the core vessel (top left), and reactor vessel (top right)

Reflectors are located at the bottom and the top of the vessel; the bottom reflector includes openings for the EDS. The siphons for routine core draining and filling are placed on the sides of the vessel. The 16 cooling sectors are arranged circumferentially around the vessel (Fig.2 Bottom right). Each sector (Fig.2 Bottom left) comprises a heat exchanger, a circulation pump, a gas processing system, and a blanket salt tank. To protect the heat exchanger and the structures located outside the core, a neutron shielding (B_4C) is positioned between the blanket and the heat exchangers. Each sector can be removed once it is disconnected from the cooling circuit and the gaseous fission product removal circuit allowing its replacement in case of failure of a component.

The sectors are connected to the intermediate circuits through the heat exchangers, which could be plate heat exchangers or channel heat exchangers (e.g. Printed Circuit Heat Exchangers). The zones in which the fuel salt

circulates are connected directly to the reactor core. The zones in which the intermediate fluid circulates are leak-proof. In the present study, four intermediate circuits are considered, each of them feeding four cooling sectors in order to continue to cool the core even if one circuit fails.

An in-core gas bubbling system is used to clean the salt from metallic particles created by fission products or by wall erosion resulting from corrosion. The removal of metallic particles is important to avoid abrasion on the walls or metallic particle deposits that could block the heat exchangers. In addition, fuel salt and fertile salt samplings are regularly performed to control and adjust their chemical composition and the fissile/fertile inventory.

II.C. MSFR safety peculiarities

As stated above, MSFR features are different from most of the existing reactors making the standard safety definitions difficult to apply directly. The objective of this part is to identify the characteristics of the concept that are related to safety.

MSFR peculiarities mostly derive from the circulating molten salt playing the role of fuel and coolant at the same time. One of the consequences of the fissile matter liquid state is the possibility of a passive reconfiguration of the geometry of the core. In case of incident during power production, the fuel can thus be drained gravitationally toward a draining tank allowing a passive removal of the residual heat. Furthermore, the fuel processing is available thanks to online fuel puncture and loading done by fluid transfer during reactor operation.

The daily/frequent adjustment of the fuel composition, thanks to the online fuel processing and loading during reactor operation, allows having low reactivity reserves in core; nevertheless, it involves the risk of reactivity insertion due to incorrect fuel composition at loading. Nonetheless, the reactor is able to manage quite important reactivity insertions, thanks to negative feedback coefficient, around -8 pcm/K coming half from the density effect and half from the Doppler effect, providing intrinsic reactor stability^{10,11}. Unlike solid-fuelled reactors, the negative feedback reactions act very rapidly since the heat is produced directly in the coolant. Moreover, in this circulating-fuel system, the fraction of delayed neutrons is reduced because the fuel motion drifts the delayed neutron precursors in low importance areas. The MSFR design characteristics also strongly influence the reactor operation and control rods are not foreseen in the core, the reactor being driven by the heat extraction^{10,11}.

Due to the relatively high speed and the turbulences in the core, the fuel is continuously mixed, therefore the fuel composition should remain relatively homogeneous and the fuel irradiation reasonably uniform.

The constraints on the fuel circuit structures are quite different from those of a LWR (Light Water Reactor) primary circuit. The fuel circuit is at low pressure

(atmospheric pressure) but the structures have to stand higher temperatures and the heat exchangers, pumps and fuel circuit instrumentations are in contact with the fuel and under irradiation. However, the sector components irradiation is relatively low and it can be noted that no structure is located in the high-flux region of the core.

The absence of fuel cladding implies that the definition of the first barrier will be necessarily different from solid-fuelled reactor. In addition, the fuel location in the MSFR is more dispersed, in fact a significant part of fissile inventory is located outside the core even if in the core vessel (in the fuel recirculation cooling sectors) and fuel and fertile salts sampling are performed during reactor operation for processing purpose, as well as injections of cleaned salt. The possibility to lose a part of the salt in the connection pipes between the fuel circuit and the draining tank during the transfers should not be excluded.

Finally, the safety analysis of the MSFR is limited by the available knowledge on the reactor and its operations; the design is still in development and the operating procedures (start-up, shutdown and maintenance) are under definition in the frame of SAMOFAR.

III. DESCRIPTION OF THE METHODOLOGY

Because of the unique characteristics of the MSFR and its preliminary design, the safety assessment of the reactor has to rely on the basis of nuclear safety and technological neutral methodologies. To accomplish this purpose, the Integrated Safety Assessment Methodology (ISAM)⁶ is selected and analysed as a conceptual methodology. Successively, a wide survey on risk analysis operational tools, nuclear international standards and best practices is performed in order to define a complete and operational methodology that well suits to the MSFR analysis, including functional safety assessments and Functional Failure Mode and Effect Analysis (FFMEA).

III.A. The ISAM

The ISAM proposed by the Risk and Safety Working Group (RSWG) in 2011 is meant *to provide valuable insights into the nature of safety and risk of Gen IV systems*⁶ contributing to the achievement of Gen IV safety objectives. It combines both probabilistic and deterministic tools, both quantitative and qualitative, some focusing on high level issues, others on more detailed issues in order to provide a robust guidance based on a good understanding of risk and safety issues. It relies on 5 complementary analytical tools:

- Qualitative Safety features Review (QSR): a checklist of “good practices and recommendations” as complete as possible and structured according to the principles of the defence in depth, which should help identifying

the assets and vulnerabilities of a design, as early as possible in the design phase;

- Phenomena Identification and Ranking Table (PIRT): a table that aims at identifying all plausible phenomena significantly contributing to risk;
- Objective Provision Tree (OPT): a tree-structured tool that helps identifying all provisions needed to sketch the design safety architecture in order to guarantee the safety functions;
- Deterministic and Phenomenological Analyses (DPA): a major point of the overall safety assessment including neutronic analyses, thermal-hydraulic analyses, thermo-mechanical calculations, reactor physics analyses, materials behaviour models, structural analysis models and accident simulations that must guide concept and design development;
- Probabilistic Safety Analysis (PSA): a rigorous, systematic and comprehensive tool for the identification of sequences of events that can cause the loss or the damage of complex engineered systems and for the estimation of their likelihoods; all the ISAM is structured with the aim of performing the PSA, as its conclusive step.

These tools for enough flexibility allow a graded approach to the analysis of technical issues of varying complexity and importance.⁶

III.B. Bibliographic review of methodologies

The ISAM tools are reviewed, completed and adapted, when needed, to better reflect the international standards/rules and to better suit the peculiar case of the MSFR.

Other methodologies and standards are analysed to check the consistency and the adequateness of ISAM to address the safety related concerns raised by the design and the assessment of innovative systems: in particular the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and IAEA International Standards. The INPRO is a stepwise approach with a hierarchic structure: Basic Principles (BP), User Requirements (UR) and Coordinated Criteria (CC), which must be fulfilled by an Innovative Nuclear System (INS) to determine if the system is sustainable or not¹². Similarly, the IAEA International standards are theoretically deducted in a structured way, starting from the general safety principles until the specific safety guides different for each kind of nuclear facility. The lower levels of both of them, which are supposed to be directly applied by the plant operators are developed for existing nuclear plants, therefore they cannot be used as they are for the peculiar case of the MSFR, nevertheless they can inspire the safety goals and requirements systematically listed in the QSR, whose fulfilment is one of the objectives of the designer.¹³

A widely accepted approach in the process industry is the one described in the IEC EN 61508, whose major idea is that the safety of systems must be studied and pursued from the early design by risk analysis tools; one of its main activities is to define the Safety Instrumented Functions (SIFs) that must be further and deeply analysed in order to understand the effective risk reduction needed and the necessity to implement them in terms of safety systems and in terms of additional safety requirements. Functional Safety Assessment in the context of IEC EN 61508 constitutes a milestone for safety to drive the design.¹⁴ Well-established practices to apply a functional safety approach to conceptual and innovative nuclear systems do not exist, therefore the idea is to enrich the ISAM with other risk analysis tools in order to both select a list of hazards as complete as possible and to include the functional approach to improve the efficiency of the analysis and the detailed design definition. A wide bibliographic survey is performed to find the most suitable methods to be included in the ISAM among the most usual risk analysis practices; three of them are integrated in the ISAM (FFMEA, Master Logic Diagram and Lines of Defence approach) and the FFMEA, since its functional approach, is the technique used to perform the following analyses.

III.C. The FFMEA

The Functional Failure Mode and Effect Analysis (FFMEA) aims at investigating systematically component failures that could affect system functionality and at identifying the hazards for the system when sufficient design details are not available to allow more specific evaluations at component level¹⁵.

The preliminary step is to collect the available design information and design intents and systematically list all the systems and main components of the plant in the Plant Breakdown Structure, subdividing them into subsystems sufficiently independent from the functional point of view. Successively, the main functions of the plant active and passive systems (process functions, safety functions, investment protection functions, etc.) are enumerated in the Functional Breakdown Structure (FBS) and organized and specified in sub-functions; then each of them can be correlated to one or more than one of the components. Consecutively the FFMEA table is compiled, postulating the loss of the function rather than the specific failures of systems and components; in this way, it is possible to overcome the lack of information in the design¹⁶. For all the components and systems of the plant, both passive and active, the identification of failure modes is performed by simply denying each component functions in a specific operational state, therefore conceptually the failure represents the negation of one or more functions performed by the component. Consequently causes and consequences of the failure are investigated and possible improvements

are recommended. Finally, the FFMEA helps to recognize component failures that can take the role of Postulated Initiating Events (PIEs), the most representative in terms of challenging conditions for the safety of the plant. Each elementary accident initiator is associated to the related PIE. In such a way, it is possible to focus safety studies on the most relevant accidental sequences¹⁵.

This approach allows studying MSFR safety assessment, notwithstanding its very preliminary state of design, to identify functions deviations able to compromise system safety, to list Postulated Initiating Events (PIEs) and to recognize critical components, lack of information and/or criticalities of the design and necessity of supplementary safety provisions. Therefore, this methodology aims at influencing the direction of the concept and design development from its earliest stages; hence the safety will be intended to be “built-in” rather than “added-on”.

In the next section, the paper focuses on the application of FFMEA to process functions of the MSFR in normal operation conditions (power production) and focusing on the fuel circuit taking into account its interaction with the other systems of the plant.

IV. RESULTS

The results obtained through the application of the methodology are organised into 3 sections: the first one presents the files obtained through the application of the methodology; the second one lists the PIEs that summarize the table in few scenarios, that are considered the most severe for the plant; the third one identifies some of the design open points that emerged from the application of the methodology.

IV.A. The application of the FFMEA methodology

The objective of this paragraph is to show the results produced by the application of the methodology.

At the end of the application of the FFMEA, three documents are available:

- The Plant Breakdown Structure (PBS);
- The Functional Breakdown Structure (FBS);
- The FFMEA table.

The PBS contains a systematic, hierarchical list of all the systems and sub-systems present in the design according to the current information and intents.

The following list is an extract of the original file.

- 1. Active fuel zone
 - 1.1. Fuel circuit containment structure
 - 1.1.1. Core vessel
 - 1.1.2. Upper and lower closure of the core cavity
 - 1.1.2.1. Upper closure of the core cavity
 - 1.1.2.1.1. Upper reflector
 - 1.1.2.1.2. Expansion Vessel system
 - 1.1.2.1.2.1. Expansion Vessel (fuel salt free surface)
 - 1.1.2.1.2.2. Vertical inlet pipe for the fuel from the core to the expansion tank
 - 1.1.2.1.2.3. Radial fuel outlet pipes (x4)
 - 1.1.2.1.2.4. Removable condenser lid
 - 1.1.2.1.2.5. Pressurised sampling device
 - 1.1.2.1.2.6. Opening for fuel transfer in the upper reflector (Sampling and injection)
 - 1.1.2.1.2.7. Connexion from the pressurised sampling device to the reprocessing unit through the reactor building (for fuel salt samples transfer-sealed system)

The FBS contains the definition of the main functions (process functions, safety functions, investment protection

functions) of all the components and the systems, hierarchically organised from the more general ones (higher-level function) to the more detailed ones (lower-level function).

The following list is an extract of the original file to illustrate the work done.

- P1. To generate electricity
 - P1.1. To generate heat by realizing fissions in the core cavity
 - P1.1.1. To provide fuel salt inventory in the core cavity
 - P1.1.1.1. To keep and preserve the integrity and leak-tightness of the core cavity
 - P1.1.1.2. To keep and preserve the integrity of the fuel salt recirculation sectors
 - P1.1.1.3. To add fuel salt to the core cavity
 - P1.1.1.4. To remove fuel salt from the core cavity
 - P1.1.1.5. To manage pressure/volume of the fuel salt
 - P1.1.2. To maintain controlled and self-sustained chain reaction in the core cavity
 - P1.1.2.1. To maintain the core critical geometry and mass

TABLE III. Extract from the FFMEA MSFR table

Process function	PBS elements	Op. Md.	Failure mode	Cause	Consequences	PIE
P1 To generate electricity						
P1.1 To generate heat by realizing fissions in core cavity						
P1.1.1 To provide fuel salt inventory in the core cavity						
P1.1.1.1 To keep and preserve the integrity and leak-tightness of the core cavity	Core vessel	NOp-P	Loss of containment leak-tightness	Rupture in the core vessel	The fissile fuel flows outside the core cavity; The chain reaction shuts down; The fissile fuel is collected in the collector; The fissile fuel is drained in the EDS and cooled down in order to remove residual head; Etc.	Loss Of Liquid Fuel

Each main function is correlated to one or more than one of the components (without any specification about their active or passive nature).

The FFMEA table is a specific table used to report the results of the analysis. The headings of the table are at least: the process function to be analysed, i.e. denied; the components, systems or equipment devoted to perform the function (PBS element); the reference operating mode (Op. Md.); the failure modes; possible causes; possible consequences; preventive and mitigation actions; the associated PIE.

The higher-level functions are automatically analysed through the breakdown of the lower level ones, the relationship being such that the failure of a lower-level function causes the failure of the higher-level functions.

A small extract of the original table is reported in the table III.

IV.B. Postulated Initiating Events

PIEs are generally determined by looking at the set of elementary failures that compromise process functions and induce consequences of safety concern, grouping events that induce similar consequences in the plant and selecting, as representative, the most severe elementary failure of the group of events. Therefore, an initial set of PIEs is identified after computing the FFMEA table, then it is analysed again to select the minimum set of PIEs that could be taken as reference to evaluate the most challenging plant conditions. From a safety point of view, the selected reference PIEs are the most representative accident initiators, in terms of radiological consequences, between a set of elementary events challenging the plant in similar ways and producing equivalent fault plant conditions¹⁷.

For each reference PIE, a deterministic analysis will have to verify the plant capacity to mitigate the consequences, to check the compliance with safety limits and to drive the choices for the selection of the reference design¹⁷. The set of these reference PIEs related to the core part of the system are listed in table IV.

TABLE IV: List of Postulated Initiating Events

PIE 1	Loss of Liquid fuel in the upper part of the core cavity: Breach in the upper reflector with rupture of the structure cooling system (without damages to the expansion vessel system);
PIE 2	Loss of liquid fuel in the upper part of the core cavity: Breach in the upper reflector with rupture of a radial fuel outlet pipe of the expansion vessel system (without damages to the structure cooling system)
PIE 3	Loss of liquid fuel in the bottom part of the core cavity: Rupture of a pipe of the reactivity control system

PIE 4	Loss of liquid fuel in the bottom part of the core cavity: Breach in the lower reflector (with rupture of the structure cooling system)
PIE 5	Loss of integrity of the core cavity: Complete (internal + external) rupture of the pressurised sampling device
PIE 6	Loss of integrity of the core cavity: Rupture of the blanket tank wall between fuel and fertile salt with rupture of the cooling circuit for internal structures
PIE 7	Loss of integrity of the core cavity: Breach of a heat exchanger plate/channel
PIE 8	Reactivity insertion accident: Accidental insertion of fuel
PIE 9	Loss of liquid fuel flow: Complete rupture of the fuel circuit pump
PIE 10	Overcooling: Over-working of the fuel circuit pump
PIE 11	Overcooling: Over-working of the intermediate circuit pump
PIE 12	Loss of pressure/volume control in the core cavity: Obstruction of the vertical inlet pipe for the fuel from the core to the expansion vessel
PIE 13	Loss of pressure/volume control in the core cavity: Rupture of the connection between the free surface of the fuel storage tank and the free surface of the core for the gas in the part between the core cavity and the valve
PIE 14	Loss of criticality geometry: The welded joints taking the recirculation sectors in the correct position collapse
PIE 15	Loss of reactivity control: Rupture/obstruction of reactivity bubble injector
PIE 16	Loss of chemistry control: External rupture of the gas separation chamber from the liquid part
PIE 17	Loss of chemistry control: External rupture of the gas separation chamber from the gases part
PIE 18	Loss of chemistry control: Rupture of horizontal bubble injector for salt cleaning

In the following section, an example of PIEs is discussed in detail as an example of the final output of the work.

IV.B.I. Loss of Liquid Fuel Flow: Complete rupture of one or several fuel circuit pumps

The loss of liquid fuel flow could be generated by several disturbances in the core components. The selected event for the list of PIEs is the complete rupture of one or several fuel circuit pumps. This event involves the consequences listed below.

- The fuel salt does not circulate anymore in the corresponding cooling sectors; therefore, the heat extraction becomes inefficient.
- The fuel salt in the recirculation sectors becomes colder, the lower temperature achievable corresponding to the thermal equilibrium with the intermediate salt. The fuel salt may solidify if the intermediate salt working temperature is lower than the fuel solidification temperature.
- The mean temperature of the fuel salt in the core cavity increases.
- If the failure is not promptly detected, structural damages can occur to the components that are not designed to manage too high temperatures.
- The fuel salt volume increases because of the thermal dilation and the free levels may disappear; therefore, it could be more difficult to control the pressure in the involved sector and in the rest of the reactor.
- Broken pieces of the pump can circulate with the fuel salt and damage the other components; in particular, they can obstruct the heat exchanger plates/channels.
- The higher temperature of the fuel salt in the core cavity means an insertion of negative reactivity.
- Broken pieces of the pump can further damage the surrounding structures and can accelerate the shutdown of the chain reaction because of the pollution of the fissile zone.
- If the temperature of the fuel salt is higher than a predefined limit temperature, the EDS is automatically triggered, the fuel salt is drained in the EDS tank and it is cooled down by the EDS cooling system.
- If the temperature of the fuel salt is lower than a predefined level, the fuel salt continues producing power. The chain reaction is manually shutdown and the fuel salt is drained in the routine draining tanks to allow maintenance.

Deterministic analyses should be performed to evaluate the potential contribution of the natural circulation (if any) that would mitigate the consequences of the transient. Moreover, the influence of single pump failure is lowered by the presence of the other 15 correctly working

pumps in the other recirculation sectors, which can be sufficient to maintain the temperature sufficiently low. A very important question concerns the choice of the thresholds and the procedures for the EDS activation, which will be discussed in the following section.

IV.C. Design open points, procedures and phenomena

In addition to the identification of PIEs, the FFMEA is helpful to determine the lack of information on some systems, procedures or phenomena, to point out the potential limitations of the design and to make suggestions to enhance the safety of the concept. The objective of this paragraph is to list some open points emerged from the application of the methodology, regarding systems or procedures to further define and phenomena to further investigate. Some examples of this kind of results obtained follow.

Firstly, the FFMEA application allowed highlighting the lack of information on the fertile blanket cooling system and on the core structures cooling system. In the reference MSFR design, the intermediate salt is used as cooling fluid for the fuel, the fertile blanket and the core structures. However, the number of cooling circuits has to be stated. On one hand, from a safety point of view, it is preferable to have three independent and separated circuits cooling down the fuel salt, the fertile salt and the structures; in this way, the loss of one of them would not imply the loss of the cooling of the other systems. On the other hand, three different circuits would increase the complexity of the system: it is plausible that collectors or several heat exchangers would be necessary. If the option of a unique circuit is selected, valves would be necessary to isolate the circuits from each other in case of failure of one of them. The choice of the independence of the circuits is also influenced by the final use of the heat extracted from the core walls and the blanket. If it is used for power production, the cooling circuits have to be connected to the power conversion circuit and thus cannot be entirely autonomous from each other. Furthermore, in the reference MSFR design, one single intermediate circuit is proposed to cool down 4 recirculation sectors, therefore a total amount of four intermediate circuits is planned. Similarly, the number of circuits necessary to cool down the fertile blanket of the core structures has to be chosen.

If a unique circuit is chosen for the design, it is necessary to choose between different options for the disposition of the heat exchangers (HXs) for the fertile/fissile salt and for walls cooling. The proposition with the HXs for the walls and the fertile salt in series with the HX for the fuel salt is more advantageous from the thermodynamics point of view, because the outlet temperatures from the HXs with the fertile blanket and with the walls are supposed to be much lower than the outlet temperature from the core. The proposition with the HXs in parallel is more advantageous from the regulation

point of view: the core reactivity is regulated by the temperature mainly through the fuel heat exchanger; this proposition allows a direct control of the intermediate salt temperature, without taking into account the heat exchange with the other heat sources (i.e. walls and fertile blanket).

Another issue concerns the procedures related to the fuel salt draining that have to be more accurately specified. As currently defined, the EDS is intended for emergency situations and the routine storage tanks are designed for normal operation (start-up, shut-down and maintenance operations). However, the management of small deviations from normal operation is unclear as well as the limits for the use of each system. In case of small deviations from normal operation, it has to be defined in which conditions the deviation can be monitored in the core, if the routine storage tanks can be used for draining the fuel and allow maintenance or if the EDS is used in any abnormal situation. According to the current design, the fuel salt recovery from the EDS is not supposed to be fast as the use of the EDS implies that the reactor is strongly damaged and will not be used during a relatively long time period. Furthermore, the system for the reinjection of the fuel salt in the storage tank or in the core is not defined. However, if all the deviations are managed by the EDS, it will be important to design the system to recover the fuel salt and to re-inject it in the core cavity or to send it to the storage tanks or to the reprocessing unit if necessary. Another option would be to use the EDS not only for accidental conditions but also for incidental conditions or maintenance operations. In this option, a system for a fast reinjection of the salt in the storage tank has to be designed. The purpose of this second option would be to use the EDS as storage tank and the so called "storage tanks" as draining tank for start-up and shutdown. Finally, the EDS can be activated by active and passive means. Regarding the passive activation of the EDS, it is necessary to define which are the physical and chemical parameters implying the EDS activation and their thresholds. For instance, the fuel temperature, the fuel circuit pressure or other physical parameters could be chosen as activating parameters. Then, the threshold above which the EDS will be activated has to be selected: e.g. the maximum temperature above which the EDS will be triggered (the same for the pressure and for the other connected parameters, if any).

Among the phenomena that should be further investigated, the physico-chemical interactions between the fuel salt and the other fluids located inside the core cavity or susceptible to come in contact with the fuel during an accidental transient has to be studied. In theory, chemical reactions will not occur between the fuel and the intermediate salt because both are fluorides but further analyses should be performed, when the intermediate salt will be definitively chosen (different options are still taken into account for the intermediate salt). Regarding the other fluids susceptible to meet the fuel during an accidental transient, the processing fluid for the gaseous fission

products (lead), the cooling fluid for the routine draining tank (not defined) and the cooling fluid for the emergency draining system (water was considered in a first time as an option but other fluids are studied) are considered. Their interaction with the fuel salt has to be studied and above all, the absence of any dangerous reactions has to be assessed.

Finally, in many accidents/incidents, the role of the natural circulation of the fissile salt/fertile salt and intermediate salt is not clear. According to the current design, the natural circulation of the fuel salt seems difficult to achieve because of the lack of heights difference between the hot and the cold barycentre. Some design arrangements should be made if the natural convection in the fuel circuit is considered an actual option. The possibility to have natural convection in the fertile and intermediate circuits has to be determined as well and its efficiency should be evaluated once the design of those circuits will be fixed.

V. CONCLUSIONS

At the end of this first application of this methodology for the core process functions, several results are obtained.

A list of Postulated Initiating Events is produced, as reference accidents for the successive deterministic analyses that will be performed to assess the severity of the involved phenomena and transients. For each PIE, the evolution of the transient in terms of consequences, the involved components and some mitigation actions are supposed. Moreover open questions about the design, the involved phenomena, the procedures and the operating conditions are highlighted and where different options are available, both are considered with their advantages and drawbacks.

A collateral issue that emerged from the application of the methodology is the definition of safety barriers and consequently the definition of the severe accident. Since the very peculiar design of the MSFR, the traditional list of barriers of solid fuelled reactors (e.g. for the LWR: fuel cladding, primary circuit, reactor building) cannot be directly applied to the MSFR but it must be adapted. A bibliographic review has been performed among norms, international standards and choices already made for current reactors and the other Gen-IV reactors. Different options are selected and each one is analysed with its advantages and drawbacks. Due to the fact that each barrier must be leak-tight, their definition could influence the design, and the list and the classification of the hazards challenging the system. Even if the study is still on going, it already represents a further clear example of the objective and results of this methodology to include safety features since the early design in a holistic optics.

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