CONSIDERATIONS ON THE NEW SAFETY PARADIGM PROVIDED BY LIQUID-FUELLED REACTORS – ILLUSTRATION ON THE MSFR CONCEPT

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Abstract

Liquid-fuelled molten salt reactors may be different in terms of design, operation and safety issues compared to water-cooled nuclear power plants. This paper presents in a first part an analysis of the safety paradigm for such systems, based on the identification of safety-related innovations of such molten salt reactors. The second part of the paper is dedicated to an application to the Molten Salt Fast Reactor (MSFR) concept developed in France by CNRS to illustrate the safety principles application on a specific design representative of similar liquid-fuelled molten salt reactors.

For 15 years, the French CNRS with national and European partners has focused R&D efforts on the development of a new molten salt reactor concept called Molten Salt Fast Reactor (MSFR) selected by the Generation-IV International Forum for its promising design and safety features. The reference MSFR design, retained for illustration purpose in this paper, is a 3000 MWth breeder reactor containing 18m^3 of a liquid circulating fluoride fuel salt. Even if no commercial deployment of MSFR is foreseen in the near future, this MSR concept is one of the most studied in the world up to now, with many publications and communications available including on safety issues. The MSFR technological innovations related to safety will be detailed and a preliminary analysis of the safety principles application to MSFR is presented in this paper.

1. INTRODUCTION

Liquid-fuelled molten salt reactors (MSRs) may be different in terms of design, operation and safety issues compared to large water-cooled nuclear power plants (NPPs). This paper presents in a first part an analysis of the safety paradigm resulting from the most significant innovations compared to water-cooled NPPs. The second part of the article is dedicated to an application to the Molten Salt Fast Reactor (MSFR) concept developed in France by CNRS.

Various concepts of MSRs are currently being developed worldwide. The safety considerations presented in this article are focused on the particular MSR concepts having the higher differences compared with water-cooled reactors, i.e.:

- MSR concept with liquid fuel circulating inside and outside the core region where the fission reactions occur.
- MSR concept with continuous extraction of the fission gases naturally released from the salt. The extracted fission gases are located outside the fuel circuit.
- MSR concept with limited pressure in the process, provided both by the salts selected in MSRs, which are chemically inert, enabling to avoid by design significant energetic reactions with other elements, such as air, water or other fluids; and by the process pressure in the core region, that may be limited compared to the high pressure of the primary circuit of water-cooled reactor.

The new safety paradigm for these MSR concepts are briefly listed in section 2 and their application is illustrated in section 3 on the example of the MSFR design by consideration of a top-down approach of the fundamental safety functions.

2. NEW SAFETY PARADIGM OF MOLTEN SALT REACTORS COMPARED TO WATER-COOLED REACTORS

Compared to water-cooled reactors using solid fuel, the main basic safety differences provided by the considered MSR concepts are the following.

The fuel is mobile and is circulating. This means that the fuel can be removed from the core vessel. In reactors using solid fuel, the safety systems and barriers must be implemented in the core or in the vicinity of the core. Accident situations occurring in the core region, typically severe accident, must be managed by the safety systems and the barriers which may also be damaged by the accident consequences. One of the main safety objectives for the solid fuel reactors is to avoid a common cause failure on the safety features resulting from the consequences of the accident. For MSRs with circulating fuel, an additional opportunity is provided by the capability to remove the fuel outside the region where the accident occurs and to use safety features which are not damaged by the initiating accident. Nevertheless, this capability requires sufficiently reliable fuel transferring systems (e.g., passive draining of the tanks), and the implementation of dedicated safety systems and barriers in all the possible location of the liquid fuel. When transferring the salt, its physical characteristics are not significantly changed so moving the salt may not bring specific challenge and uncertainties, contrary to the core melt phenomena in reactors having solid fuel.
The fuel drained in a dedicated system allows to perform differently the safety functions:

- Decay heat removed by dedicated systems not implemented in the core region (allowing a diversified and less constrained design) and taking benefit of the possible reduction of heat fluxes by fuel salt spreading in the draining system.
- Subcriticality of the fuel salt by adequate geometry of the draining system (e.g., not moderated system, fuel salt spreading) and possibly additional neutron absorbers.
- Confinement of the fuel salt with another barrier.

The core is liquid. The concept of “molten core” used as severe accident for water-cooled reactors cannot be similarly used for MSRs. The notion of severe accident for MSRs needs to be questioned. In water-cooled reactors, the severe accident is a key concept used in the application of the defence-in-depth principle. In water-cooled reactors the core melting leads to consequences significantly higher than the consequences of any design basis accident, that damages the safety systems and barriers implemented in the core region and that brings also significant uncertainties in the prediction of the reactor physics. This includes the possible vapor explosion resulting from molten fuel and coolant interaction, the possible reconfiguration in a more reactive geometry, the possible release of stored energy in the fuel towards the fuel circuit, including the possible aggression of safety systems and confinement barriers. Also, in this case, the highly radioactive fission gases generated during the reactor operation are released and must be confined in the containment. Due to the severity of both the loadings and the radioactive level of fission gases to confine, the application of the defence-in-depth principle is built around this severe accident:

- A high level of prevention against severe accident is required: implementation of measures associated to the three first levels of defence-in-depth, complemented by additional measures (identified as level 3 in the WENRA approach, or as level 4a in the IAEA approach).
- Dedicated measures of mitigation of the severe accident consequences are additionally required: associated with the level 4 of defence-in-depth.
- The severe accident situations which cannot be reasonably mitigated are identified and must be demonstrated practically eliminated (i.e., demonstrated with a high confidence level as having a very low probability to occur).

On molten salt reactors, severe plant conditions remain to be defined but they are not expected to bring so much differences as in water cooled reactors regarding the dispersible source term, the loads to the barriers and the changes in physical behaviour.

The fission gases are continuously extracted from the core region. In solid fuel reactor, one of the main safety challenges is related to the confinement of the fission gases which are high radioactive materials that can naturally be released. Their confinement in accident conditions requires to implement several leaktight barriers designed to withstand severe loadings as it is the case in water-cooled reactors, or to implement a highly resistant barrier capable to maintain its leaktightness in accident conditions as this is expected with the TRISO fuel used in high-temperature gas-cooled reactors (HGTRs). In MSRs the amount of fission gases involved during accidents occurring in the core region is much more limited. The main part of the fission gases generated during the reactor operation is located outside the core and, therefore, is not to be managed as core accident consequences. Nevertheless, these fission gases released from the core must be managed in leaktight systems, and sufficiently cooled if needed. Compared to the fission gases located into the core of water-cooled reactors, the safety challenges related to the MSR fission gases are intrinsically much less difficult to manage in normal and accident conditions because the potential energy is limited to the residual heat of the gas. The fission gases and other volatile species are continuously and naturally released from the salt. The other fission products and radioactive materials are mainly kept in the salt even in accident conditions. The salt recuperation is the main issue to achieve the confinement of these fission products.

For MSRs, the ultimate safety objective which is to limit any radiological releases is obviously relevant, and the defence-in-depth principle is also relevant for demonstrating its achievement. Nevertheless, the need and the capability to postulate a credible accident which could severely damage all the safety systems and barriers, similar to the severe accident of water-cooled reactors, have to be assessed taking into account the safety characteristics of the MSRs.

3. APPLICATION EXAMPLE ON THE MSFR CONCEPT

The new safety paradigms presented in section 2 are applied here in the example of the concept of Molten Salt Reactor (MSFR). After a brief presentation of this MSFR concept, the analysis is declined on the three safety functions: decay heat removal, confinement, and reactivity control, with a focus on the first one which has been more studied up to now.

3.1. Presentation of the MSFR concept

For 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) at the centre of successive European projects (EVOL, SAMOFAR, SAMOSAFER) and selected by the Generation-IV International Forum (GIF) due to its promising design and safety features [1,2,3]. Studies are performed to ascertain how MSFR satisfies the goals of Generation-IV reactors.

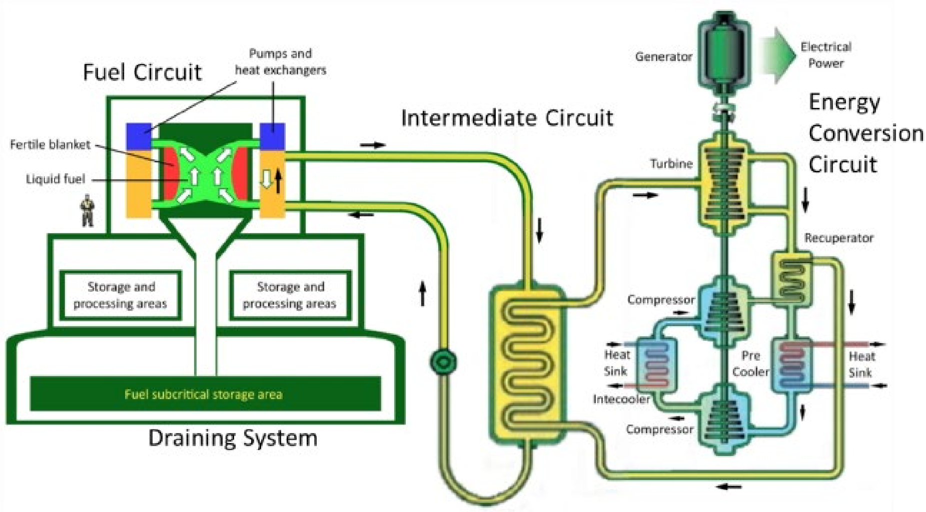

FIG. 1. MSFR power plant.

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

The fuel circuit (see Fig. 2) 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] has been developed in order to prevent the risk of large fuel leakages. This integrated geometry is made of a vessel used as container for the fuel salt, in which several 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 laterally the heat exchangers from the neutron flux. In addition, thick reflectors made of nickel-based alloys are located at the bottom and at the top of the vessel to protect the vessel and structures located outside the core and to increase the breeding ratio.

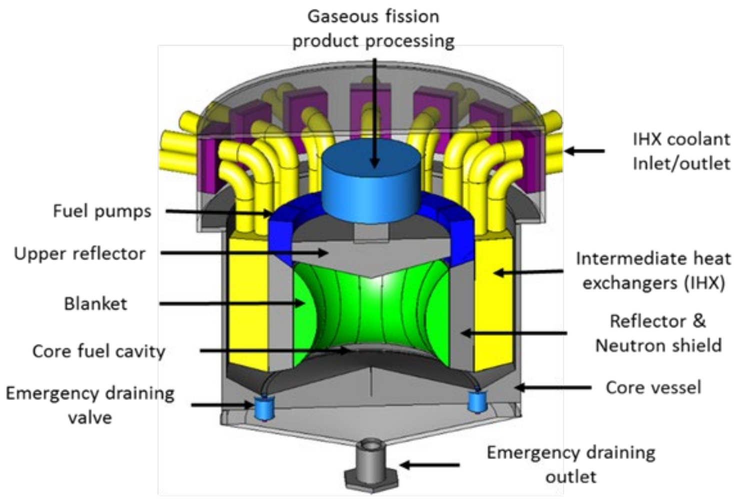

FIG. 2. MSFR fuel circuit components [4], the fuel salt itself being not displayed here.

Finally, in case of accident during power generation, the fuel salt can be drained gravitationally toward an emergency draining tank designed to maintain subcritical the fuel salt, and passively remove the residual heat towards emergency cooling systems. The residual heat associated to the fuel salt initially represents about 4% of the nominal power [5]. This value, evaluated for the reference MSFR breeder in the Thorium fuel cycle), is representative of various MSFR breeder configurations (^{238}U/Pu and Th/^{233}U fuel cycles). The fuel circuit is connected to this Emergency Draining System (EDS) through active and passive devices located in the bottom reflector. In normal operation and in case of Anticipated Operational Occurrences (AOO) and also in case of some Design Basis Conditions (DBC) if the conditions physically allow it, the management of these events should take place in the fuel circuit or if necessary drained in the normal storage tanks and not necessarily in the EDS.

3.2. Analysis of the safety functions

The structure of the safety systems presented here after is not a fully optimised configuration simply since the MSFR concept is at its preconceptual stage but a first view of the plant to allow the analysis and further optimisation by different specialists in the frame of national and international collaborations.

3.2.1. Decay heat removal: systems considered at the preconceptual design level

A definition of the systems foreseen to extract heat during the various normal operation state of the MSFR concept has been led, then used as a basis for a preliminary identification of the operational states of the reactor as described below. This is presented in Fig. 3 that displays an overview of the three main circuits of the MSFR implemented for power extraction with the associated DHR systems: fuel circuit, intermediate circuit and a part of the energy conversion circuit (just the connection to the intermediate circuit, the turbine for example being not displayed).

Fuel circuit:
The fuel circulates upward in the core; then crosses the central expansion vessel in the upper reflector toward the pumps (potential degassing). The core is surrounded by pumps sending the fuel into Intermediate Heat Exchangers (IHX) to heat the intermediate salt (green circuit) that transfers heat then to Conversion Heat Exchangers (CHX).

As long as the salt is fully in the fuel circuit, it remains critical, and it can be maintained in safe conditions at near zero neutronic power. In this state the residual power still needs to be removed.

Reactor Casing (RC):
This casing contains all systems likely to contain fuel salt: the fuel circuit, the storage tanks, the Emergency Draining System (EDS, reversible draining), or if necessary also in a Core Catcher (CC) as an ultimate solution in case of failure of the previous systems, including EDS. The residual heat is extracted from the Reactor Casing through three possible ways, depending on the location of the fuel salt: the Backup Heat Exchangers (BHXs) on the intermediate circuit when the salt is in the fuel circuit, and the Emergency Heat Exchangers (EHXs) when the salt is in one of the recuperation systems (i.e., EDT or CC). If three barriers are demonstrated to be needed, BHXs exchange heat between a bypass of the intermediate circuit and a dedicated circuit connected to the Atmospheric Heat Exchangers (AHXs). The need of this intermediate circuit is still to be verified. EHXs extract heat from the reactor casing to the dedicated circuit connected to AHXs. All the proposed DHR systems are designed to operate in natural circulation.

Reactor Building (RB):
This building contains the reactor casing and among others the systems ensuring the heat transfer from the Reactor Casing to the outside atmosphere.
The first steps (filters, decays for a few thousand seconds) of the gas process unit will be located in the reactor casing and then punctures, like that of the salts, will go to the reactor building for the following processing steps.

Auxiliary Building:
This building contains the intermediate circuits, with their pumps and tanks, and the conversion heat exchangers (CHX) and possibly the chemical processing unit.
It is assumed that the extracted heat that cannot be converted in the turbine can be transferred to the environment through DHX (Dumping Heat Exchanger) connected to the CHX.

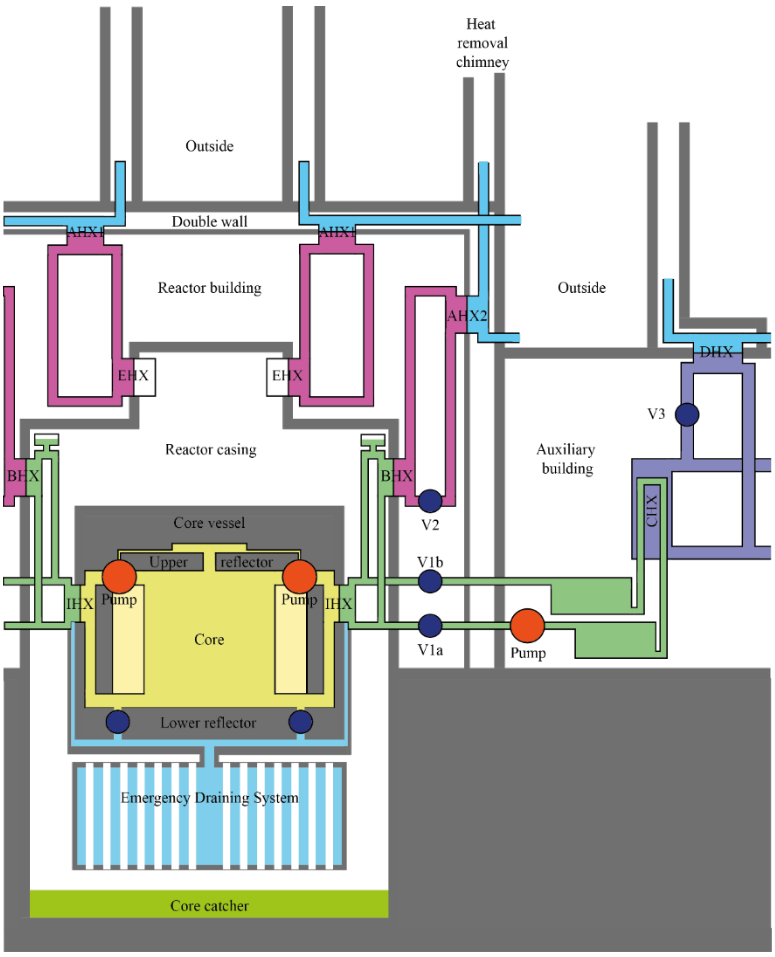

FIG. 3. Components related to the heat extraction in the MSFR system, with the fuel circuit in yellow, the intermediate circuit in green and a part of the energy conversion circuit in purple (from left to right).

In addition, all the possible locations of the salt during normal operation have to be defined because they correspond to different heat removal (transition from one system to another) and confinement strategies (opening of the fuel circuit, or even of other circuits connected to the fuel circuit in case of bypass). This work results in the identification of the following normal operation states: Reactor in Power (RP), Normal Shutdown (NS) on CHX + DHX, Maintenance Shutdown (MS), Maintenance Cold Shutdown (MCS), and Start-up of the reactor.

As mentioned in section 3.1, the liquid fuel salt is processed during reactor operation through two processes: a bubbling on-line processing and a chemical processing unit probably located on-site and cleaning some ten litres of salt per day. This leads to a reduction of the fission product content in the fuel salt (resulting in a reduction of the radioactive content and of the decay heat in the fuel circuit), more precisely this corresponds to a transfer of these fission products to other locations on the reactor site. As a perspective, the decay heat removal issues have to been studied also in these two process units (gas and chemical).

3.2.2. Confinement

The confinement prevents, in any case, the dispersion of large amounts of radioelements in the environment.

The difference between MSRs and LWRs lies in several items, in particular the radioactive elements (chemical forms, locations) and the presence of potential dispersion vectors (pressurized gases, water). For instance, in LWR, fission gases (Kr, Xe) and dispersible species (Cs, I) are accumulated inside the core during the reactor operation and can be dispersed in the atmosphere by the large amount of water vapor that should be released in accident conditions where fuel rods are damaged. In vented MSRs, the radioactive elements are distributed into two different locations. First, the fission gases are not accumulated in the core but possibly in a location that would not be affected by a core accident. Second, some radioelements such as Cs and I remain stable inside the liquid fuel or, at worst, might give condensable gaseous species over overheated fuel resulting in aerosols if the gas in contact with the salt is cooled down. The MSFR concept avoids the presence of water in the reactor building to preclude the formation of a dispersion vector for aerosols due to pressure increase, or even fuel salt (salts are partly soluble in liquid water). Another major difference concerns the basic confinement items. In solid fuel reactors, the fission products are firstly confined in elements (e.g., clads or particles) containing a very small fraction of the whole radioactive inventory. Mainly in severe accident conditions the whole radioactive inventory is concerned. In liquid fuel MSRs, the fission products are contained in larger tanks (e.g., fuel circuit, fission gas storage tank).

MSR core region is not under pressure. The pressure in the fuel circuit is limited to values corresponding to the fuel velocity needs and the barostatic pressure (a few bars i.e., two orders of magnitude less than in LWR). Concerning the fission gases, a possible option not yet studied could be their storage in pressurized tanks in order to minimize their volume. If this option is selected, the consequence of the failure of the pressurized tanks must be mitigated by adequate design features.

The continuous release of fission gases out of the core requires a connection between the core vessel and the storage system. The detailed design of this connection has not been performed. Isolation devices and safety valves could be needed. In any case, confinement bypass must be precluded by design.

The behavior of noble metals (Mo, Pt group elements, etc.) appearing in the fuel salt is presently unknown. They could plate on the heat exchanger walls (the largest area available in the fuel circuit) or be separated from the fuel salt by filtration or bubble flotation. In any case, their solid and liquid state is a favorable factor for their confinement. However, as for the fuel salt, they produce a residual heat that is to be considered in the safety studies.

There are four main radioactivity sources in the MSFR concept: the fuel circuit, the fission gases' storage, the fresh and spent fuel storage tanks and the fuel treatment unit. This last unit is necessary for a semi continuous fuel composition tuning that eliminates any reactivity reserve need in the core. It could be located inside the reactor building or in another building. For this last option, confinement measures must be implemented. These detailed studies are not yet performed.

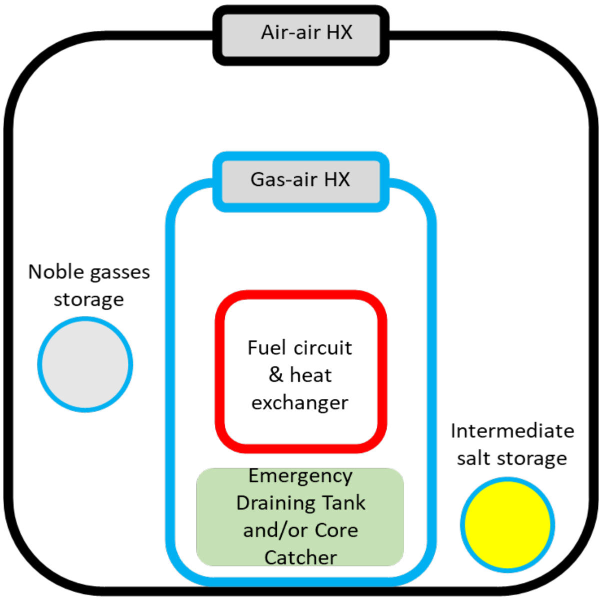

FIG. 4. Schematic representation of the three confinement barriers of the MSFR. The first, in red, is the Core Vessel containing the fuel circuit and the intermediate heat exchanger. The second, in light blue, is the Reactor Casing containing the DHR devices and the draining tanks, including the Core Catcher, and the third, in black, is the Reactor Building containing other radioactive sources.

As shown in Figure 4, the MSFR concept exhibits three confinement barriers for the salt in the reactor: the Core Vessel, the Reactor Casing and the Reactor Building. The number of barriers is not the result of a detailed safety analysis, it is simply a working assumption. The implementation of an adapted safety paradigm could lead to a reduced number of barriers.

The Reactor Building plays the role of protection for some external hazards. It could also confine other radioactive sources which are not in the Reactor Casing, and it may be the last confinement barrier.

The Core Vessel is the first confinement barrier for the fuel in the reactor. It contains the whole fuel circuit, including the heat exchanger between the fuel and the intermediate salt that carries the heat to its application location. It also contains part of the off-gas processing for the noble fission products.

The integrity of the core vessel could be at stakes if a core overheating occurred. Fuel draining will then happen either through the normal draining system, or the emergency draining system or by leakage of the Core Vessel. In case of leakage of the Core Vessel, the fuel and any other liquids (intermediate salt or liquid metal) will fall by gravity in the EDS that is meant to maintain subcritical and cool the fuel salt.

The need for another container could be questioned by the Defense-in-Depth principle application for the MSFR. The absence of specific, energetic and complex phenomena, compared to core melting in LWRs, may represent a paradigm change that could change the allocation of safety provisions among the different levels of Defense-in-Depth. At the end, the safety objectives in terms of radiological releases must be in line with international standards, but the way the safety provisions are implemented could be adapted to the specificities of the concept.

3.2.3. Reactivity control

The reactivity control function includes these two separated aspects:

- The capability to shut down the reactor (i.e., shutdown of the chain reaction) and maintain the reactor subcritical.
- The elimination of reactivity insertion leading to unacceptable consequences (i.e., elimination of reactivity insertions that cannot be controlled).

One has also to notice these two additional elements concerning reactivity control in the MSFR:

- Considering the intrinsic characteristic of liquid fuel (strong neutronics feedbacks, including both Doppler and expansion), the management of reactivity in the fuel circuit could be bring back to heat removal issues.
- One has to take into account the risk of potential reconfiguration of the fuel in a more reactive geometry.

At this design level, it is not intended to implement control rods in the fuel circuit. To achieve the control of reactivity, some design characteristics of the MSFR may be considered in addition to the classical approach that includes a combination of fuel and reactor design, the use of inherent reactivity feedbacks, and other engineering features to shut down the reactor:

- The loading of fresh fuel in the MSFR concept is foreseen to be done during reactor operation. From a safety point of view, such a continuous loading of fresh fuel allows potential reactivity insertion to be small compared to reactors with a long fuel-cycle period, which could require initial reactivity excess compensating for fuel burn-up. The burn-up of fissile material may be reduced by the continuous breeding of fertile material in the core.
- The MSFR concept offers an additional capability to shut down the reactor by rapidly and passively draining the fuel salt, to drain tanks designed with a geometry that ensures subcriticality at any salt temperature including salt freezing. The draining activation will be both active (e.g., signal opening a valve) and passive (e.g., melting of freeze plug, pressure difference…). In accident conditions associated with the failure of the core vessel, the leaking salt will also be redirected into the reversible emergency draining system.
- Additional neutronic absorbers can also be implemented in the various tanks liable to collect the salt if necessary.

Reactivity insertion in the MSFR could result from events similar to the ones likely to occur in LWRs and also from an accidental concentration of fissile material by abnormal chemistry processes or through errors in on-line refueling:

- When caused by chemistry processes, reactivity insertion events can be prevented by monitoring and, where possible, exerting control of chemistry parameters and the consideration of any accident situation which could favor the fissile material concentration (e.g., precipitation of fissile material, collapse of gas bubbles accumulated in the core region).
- Potential effects of overcooling or freezing of fuel salt (such as impact on core reactivity, and fuel salt content) is subject to discussions in safety assessments. The physical conditions that could lead to the loss of reactivity control due to a high fissile concentration have to be identified and prevented by preferably favoring the inherent salt characteristics, control of the salt composition, and adequate provisions.
- When potential for reactivity insertion events may be introduced by refueling errors, prevention measures not yet defined will be put in place.

One of the main consequences of concepts as the MSFR with liquid fuel dissolved in the coolant is related to the significant coupling between the flow of fuel salt in the core and the core neutronics. This coupling is due in particular to the fact that a significant fraction of the delayed neutron emitters will be outside the fission region in the core, so this fraction does not contribute to the fission reactions. Then, any fuel salt flow reduction increases the core reactivity and vice versa. This effect will be compensated by other favorable phenomena that will occur when the flow decreases. A core temperature increase leads to two effects (in addition to the Doppler effect): it increases the transparency of the salt to neutrons whose leakage increases, and it also leads to an expansion of the salt volume in the circuit. The additional volume resulting from this expansion might be located, by design, outside the core region, thus not contributing anymore to the nuclear (fissions, captures…) reactions. The first feedback effect (transparency) together with the Doppler effect is the main contributor to stabilize the core in case of temperature increase.

Tools dedicated to the study by simulation of both normal operation and accidental transients are developed, such as the TFM-OpenFOAM 3D neutronic-thermalhydraulic coupled code [6,7] and also system codes such as LiCore [7,8] and MIRACLS [9]. Some first studies already performed [6] show that no cliff-edge effect occurs while inserting reactivity even if the prompt criticality regime is reached. These studies are exploratory, reactivity insertions have been postulated without associating them with initiating events. The conclusions with the studies performed up to now are that, even for very severe ramps in velocity and amplitude, the temperature increases are limited and no case has been identified for which there is salt vaporization or any damaging phenomenon.

Simulation studies have also been performed on the MSFR power production including load-following with no control rods in the fuel circuit, driven by the heat extracted from the fuel in the intermediate heat exchangers. This is possible thanks to the excellent negative thermal feedback effects that stabilize the core to the required power level.

3.2.4. Accident analysis overall approach

In parallel a safety analysis is also led on the reference MSFR concept, to determine Postulated Initiating Events (PIEs) 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 into families and selecting, as representative, the most severe elementary failure of the group of events. The families of events identified for the MSFR are [10]:

- F1: Reactivity insertion
- F2: Loss of fuel flow
- F3: Increase of heat extraction/over-cooling
- F4: Decrease of heat extraction
- F5: Loss of fuel circuit tightness
- F6: Loss of fuel composition/chemistry control
- F7: Fuel circuit structures over-heating
- F8: Loss of cooling of other systems containing radioactive materials
- F9: Loss of containment of radioactive materials in other systems
- F10: Mechanical degradation of the fuel circuit
- F11: Loss of pressure control in fuel circuit
- F12: Conversion circuit leak
- F13: Loss of electric power supply

The following events are the assumed representative events from the list of Postulated Initiating Events related to family F1 “Reactivity insertion”:

- F1: Bulk precipitation of fissile matter
- F1: Accidental insertion of fuel
- F1: Important deformation of the fuel circuit possibly leading to a modification of the core configuration that may lead to an increased core volume
- F1: Fertile blanket loading with fuel salt
- F1 & F2: Fuel salt freezing scenario
- F1 & F6: Rupture/obstruction of reactivity bubble injector

One has to precise that these PIEs have been selected independently of their likelihood at this stage, to drive the analysis by the consideration of all phenomena of potential interest: some of them may be later found not to be relevant for the MSFR and thus to be withdrawn from the PIEs list.

4. CONCLUSIONS AND PERSPECTIVES

The options selected for MSFR reflect the new safety paradigm resulting from the characteristics of liquid fuel and fission gas extraction from the core. The MSFR concept is at its preconceptual design phase which is focused on the general architecture of the safety systems. The proposed options thus need to be confirmed by an exhaustive safety analysis and during the following steps of the design. In particular, the future studies aim at the following points:

- The architecture of the DHR systems must be confirmed. If needed additional redundant and diverse systems could need to be added in the different possible locations of the fuel salt in normal or accident conditions.
- The reliability of the transfer and draining functions must be assessed and the need of active and passive means must be defined.
- The abnormal concentration of fissile material likely to lead to unacceptable reactivity or heating effects must be analysed. This shall allow the definition of the required measures to prevent, detect and, if needed, mitigate this phenomenon.
- The confinement barriers for the fuel salt and the fission gases must be defined considering the loadings in accident conditions, and the possible locations of the radioactive materials.

These analyses shall be based on the defence-in-depth principle. Case-by-case, probabilistic assessments will be performed to confirm the adequate application of the defence-in-depth principle. Nevertheless, such probabilistic analyses shall take into account the available experience feedback on molten salt technologies, which is currently limited.

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