NAAREA'S XAMR® SAFETY APPROACH

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Abstract

NAAREA is a French startup currently designing a 80 MWth fast modular micro-reactor fueled with a molten chloride salt. No such reactor has been designed or operated in the past, the available experience feedback on molten salt reactors being limited to fluoride-fueled thermal reactors built at ORNL in the fifties and sixties. The current safety framework which has capitalized on several decades of PWR operation is not readily suited to molten salt reactors, and the solutions which were implemented in the sixties are not adequate today. Furthermore, molten salt reactor design is strongly versatile due to the very nature of the fuel used and the maturity of the various designs currently under development is not sufficient to outline a general safety approach.

Thus, this paper presents the approach chosen by NAAREA for its safety case, and especially:

• The main differences compared to the standard PWR safety approach.
• The design options selected to ensure decay heat removal, reactivity control and containment of radionuclides.
• The severe accident definition selected by NAAREA and its consequences on the reactor design.

1. INTRODUCTION

NAAREA is a French-startup currently developing a 80 MWth fast modulated micro-reactor fueled with plutonium-chloride, with the aim of supplying power to industrial sites or isolated locations. NAAREA aims at first building a prototype of its reactor for validation purposes before deploying an industrial fleet of reactors. If many MSR designs have been proposed over the decades since the operations of the MSRE and ARE in Oak Ridge fifty years ago, none has been built. Due to the high versatility of their fuel, MSRs come in a variety of designs of concepts which have been classified in a recent AIEA technical report [1].

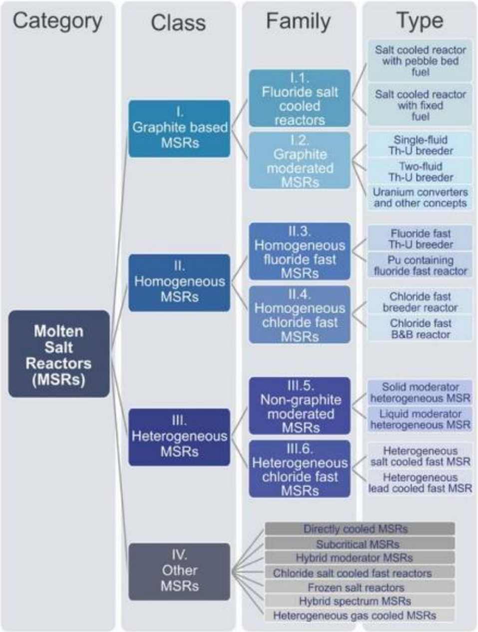

Figure 1 : Taxonomy of MSRs from [1]

This taxonomy approaches the question of MSRs design from the prism of core configuration and cooling but does not expand on the safety approach. This paper aims at proposing a similar approach but for safety functions for MSRs, along with a discussion on the severe accident that can be considered in their safety demonstration. It will be structured along the three main safety functions which are reactivity control, decay heat removal and containment of radionuclides, followed by severe accident considerations.

2. REACTIVITY AND CONTROL IN A MSR

Contrary to solid-fueled reactors in which either active mechanical control means (control rods or drums, movable reflector and/or fuel elements) or burnable neutron absorbers (either diluted such as boron in PWR or solid such as gadolinium), the fuel chemical composition can be altered during core operations to manage reactivity. Furthermore, the very high fuel density reactivity feedback coefficient of most MSR can be leveraged as a control mean to ensure a quick power decrease in case of loss-of-cooling, or to limit the total reactivity inserted in case of reactivity-initiated transients. A final way of controlling reactivity inside a molten salt reactor is to flush the fuel salt to drain-tanks which are designed to be subcritical.

The first molten salt reactor built, the Aircraft Reactor Experiment (ARE) used only shim rods as start-up and shutdown control means [2], with the core cooling system being used to control the core power without additional reactivity control. [3]. This arrangement is possible when the reactivity excess of the core is limited, which is achieved by controlling the fissile element concentration inside the fuel. The same design option was implemented for the Molten-Salt Reactor Experiment (MSRE) reactor, which also employed only shim rods [4]. Long-term operation of the MSRE was achieved by adding fissile element over the cycle to ensure a sufficient reactivity margin was available.

Modern MSR designers are left with various options to ensure reactivity control of their reactors. The first one pertains to achieving the required cycle length. Three main solutions are available to ensure year-long operations:

- The first one is to implement the historical approach of adding fissile material in the salt to compensate for depletion. This can be achieved either by “topping off” the fuel salt with carrier salt containing new fissile nuclei and thus increase the overall salt inventory inside the fuel salt loop or treat the used salt either on-line or after removal and add fresh fuel inside the salt. This approach can be used in conjunction with breeding blankets with adequate mixing of the blankets and the fuel to achieve the required fuel composition.
- The second one is to implement traditional active reactivity control means such as control rods or control drums and load the core with enough initial reactivity excess to ensure that the required cycle length can be achieved. It should be noted here that, contrary to fast reactors in which this approach is used, the large amount of reactivity stored inside these reactivity control means would be not create significant additional risks thanks to the strong fuel expansion reactivity coefficient. Burnable absorbers may also be used.
- The third one is to design a reactor large enough to ensure that the reactivity loss is small enough for the initial reactivity excess to be limited and for the change of reactivity due to fuel depletion to be compensated by a modification of the reactor operating point.

The first approach has the drawback of requiring a constant stream and/or inventory of fresh fissile material on the site of the reactor and requires the adequate sampling/addition system on the fuel loop. The second one is similar to the way reactivity is controlled in fast or research reactors and adds complexity to the reactor design and safety studies. The third one is limited to large reactors and is hampered by the remaining uncertainties associated with MSR design. These three approaches are summarized in Figure 2.

As NAAREA aims at deploying small reactors with site constraints being as limited as possible, the design choice made by NAAREA is to implement control drums inside the XAMR reflector to compensate for the initial excess reactivity. The choice of control drums has been done to limit the axial deformation of the flux profile at the beginning of operation. This solution allows the XAMR up to 4 years of operation on a single batch of fuel.

If you need to subdivide the sections of your paper, use the headings shown below. You can use second and third level paper headings. To subdivide further, please use lists numbered (a), (b), and so on, but this is usually not necessary in a paper of normal length.

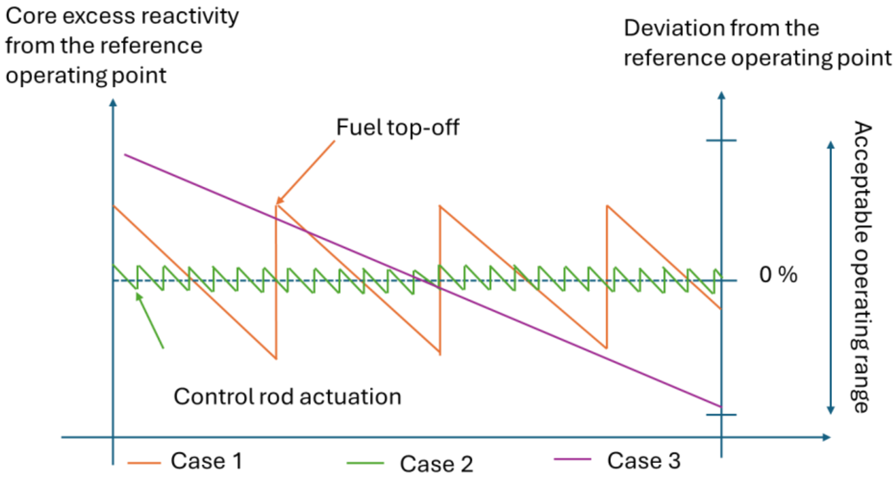

Figure 2: Illustration of the reactivity management options for a MSR

It is also necessary to ensure that adequate shutdown of the reactor can be achieved in any core conditions. As mentioned previously, historical reactors used a combination of shim rods to quickly stop the chain reaction followed by flushing of the fuel salt to sub-critical drain tanks. NAAREA has also chosen this approach for its prototype reactor, as the associated safety case is expected to be readily acceptable by safety authorities.

Nevertheless, other options are available to ensure safe shutdown of a MSR:

- Flushing of the fuel salt to drain tanks may not be necessary if adequate margins can be achieved during salt cooling down. This implies both that the shutdown system of the reactor is able to compensate for the entirety of the reactivity added by salt cooling and contracting and that the core geometrical configuration and mechanical design allows efficient melting of the solidified salt.
- Use of shim rods may also not be necessary as the salt strong thermal expansion will lead to a rapid decrease of the core power (down to the level of the core heat losses) along with an associated increase in the salt temperature. If a limited decay heat removal system is available (e.g., a system able to prevent salt overheating but not solidifying it), a stable configuration in which the core is critical but only produces enough power to remain in a liquid state can be reached.

Adopting such a strategy for the reactivity control of MSR would not preclude the need for one or more drain tanks for normal operations, but the draining function would not be a part of the safety case, which would significantly decrease the overall complexity of the reactor design. Furthermore, the removal of shim rods would also have a positive impact on reactor complexity and remove many initiating events from the safety case.

Safety-wise, it is interesting to compare the above discussions with the approach proposed for MSR safety in the recently published standard proposed by the American Nuclear Society (ANS) [5]. This standard was produced with the intent of adapting the currently available Code of Federal Regulations (CFR) Title 10, “Energy,” Part 50, “Domestic Licensing of Production and Utilization Facilities,” Appendix A, “General Design Criteria for Nuclear Power Plants,” requirements to MSR plants.

Most notably, criterion 26 of this document proposes that MSR should be equipped with two reactivity control systems with sufficient margin to ensure containment integrity during normal operation as well as anticipated operational occurrences (AOOs), and that a safe shutdown condition can be reached and maintained during a postulated accident. Considering the discussions above, it appears that the inclusion of the salt thermal expansion capability as a “reactivity control system” should be considered in future safety related discussions, as it is theoretically possible to design a MSR with only shim rods or drain tank and fulfill the reactivity control requirements proposed in [5].

3. DECAY HEAT REMOVAL IN A MSR

Decay heat removal (DHR) must be available in any nuclear reactor to ensure that the containment barriers are not mechanically stressed by an unwanted temperature or pressure increase. This is also true for a MSR and the historical approach to DHR in a MSR was to add DHR systems in the drain tanks of the reactor. For the ARE, since core operation did not exceed 3 days at up to a few MW, DHR was achieved by natural convection of the drain tank cell atmosphere through a tube lattice containing the fuel salt. In the MSRE, decay heat removal was carried out by bayonet tubes immersed inside the fuel salt, which allowed for passive heat removal. Most notably, no provisions were made for safety-related in-core DHR systems. Such an approach could be reconducted in modern MSRs but would require the demonstration that the reliability of the drain function of the reactor is high enough to ensure that it is always possible to drain the core. NAAREA chose to pursue this approach, with stringent requirements put on the drain function and dedicated DHR removal systems located inside the drain tanks with adequate redundancy.

Two interesting notes should be made here about DHR inside an MSR. Firstly, because a significant fraction of fission products may leave the salt due to their chemical behavior, the off-gas system of the reactor may require a significant heat removal capacity to ensure that it does not exceed its operational limits. For instance, it is estimated by NAAREA that between 20 and 40 % of the fission products produced by its reactor will be removed from the salt and be extracted by the off-gas system. Consequently, in normal operation, a few hundred kilowatts of power (for a typical reactor power of 100 MW) must be removed from this stream to prevent any hazardous temperature rise inside the structures of the off-gas system. This system will concentrate the off-gassed fission products and accumulate a few tens of kilowatts of decay power during the reactor cycle. Adequate provisions are thus taken to ensure that the components of this system do not lose their containment properties.

A second point which must be made here is the fact that it is possible to implement DHR in a MSR by keeping the salt inside the core and cooling it down using dedicated means. This approach is similar to the one implemented in solid fuel reactors. However, due to the strong thermal expansion coefficient of the salt, significant core cooling may lead to unwanted criticality if the core shims rods are not adequately designed. In the event where the choice of maintaining the fuel salt liquid using fission power in case of AOOs, care should thus be taken not to excessively oversize the DHR system.

Overall, the main takeaway of this cursory analysis is that reactivity control and decay heat removal are heavily linked inside a MSR, and some configurations are mutually exclusive unless significant modifications of the internationally acknowledged safety approach are considered. For instance,

- Designing a MSR without drain tanks and shim rods would require that a critical core with a power level equal to the heat losses of the core can be considered as a controlled or a safe “shutdown” state.
- Requiring a MSR to have in-core decay heat removal systems would necessarily generate a requirement for shim rods to ensure that the core cannot become critical due to severe overcooling of the salt, and this in turns obviates the need for drain tanks and severely constrains the design space of MSRs.

4. SEVERE ACCIDENTS AND CONTAINEMENT IN A MSR

The containment safety function is treated in conjunction with the severe accident case, as it will be shown further on that for MSR, this function is heavily linked with severe accident definition. Defense-in-depth recommends that an adequate number of independent redundant layers of defense are implemented to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. NAAREA’s prototype design follows the defense-in-depth principles and considers 3 containment layers for its reactor.

Considerations pertaining to severe accidents are inherently part of the reactor design process, as they constitute the threshold between design basis conditions (DBC) and design extended conditions (DEC) for the designers. In France and for PWRs, a severe accident is defined as the melting of a significant fraction of the fuel rods constituting the core. This definition obviously does not apply to a MSR and requires adaptation. Earlier discussions [6] proposed to consider the classical criticality accident and inability to remove decay heat in the safety approach of a MSR.

More recently, the French Institute for Nuclear Safety and Radioprotection proposed a broader definition for GEN IV systems [7] (in French) which can be translated as : "*In a nuclear reactor, an accident is considered "severe" when the confinement function designed to prevent or mitigate the release of radioactive elements from the nuclear fuel is significantly degraded, whether the fuel is in the reactor, being handled or in a storage area.*". The notion of "large and early release" is also used to characterize severe accidents [8]. Reference [9] further considers that postulated severe accidents scenarios start with the failure of the containment boundary of the fuel salt system or the off-gas system layout.

Leaving aside the case of criticality accidents, which will be discussed further on, it seems acceptable to consider that for a MSR, a severe accident can be defined as the loss of the containment function and the early release of a large inventory of radionuclides to the public. The probability of such an event must thus be very small, as can be represented on the Farmer diagram of Figure 3 . The probabilities reported in this diagram are the ones considered in the frame of French nuclear safety.

The modern MSR designer is thus left with various options for its safety approach. The first one could be to demonstrate that in no case whatsoever will the fuel boundary leak or release radionuclides outside of the reactor facility. Given the remaining uncertainties on corrosion issues and fission products behavior, this approach can hardly be considered as feasible at the time.

Another option would be to add another containment boundary around the fuel loop and to demonstrate that the probability of failure of the salt fuel boundary is small enough so that its failure constitutes a severe accident. In that case, the role of this additional containment boundary, which could be a guard vessel, or the reactor building would be to contain the radionuclides and prevent a large and early release of radioactivity to the environment.

This approach appears feasible but requires the developer to be able to demonstrate that the first containment boundary (e.g. the fuel boundary) has a very small probability of failure. This can arguably be considered an acceptable approach for fluoride-fueled MSRs, which can rely on the experience feedback from the ORNL program, but NAAREA considers that the data available both on chloride salts and corrosion mechanisms in chloride-based salts are not sufficient to be able to demonstrate such a low probability of failure.

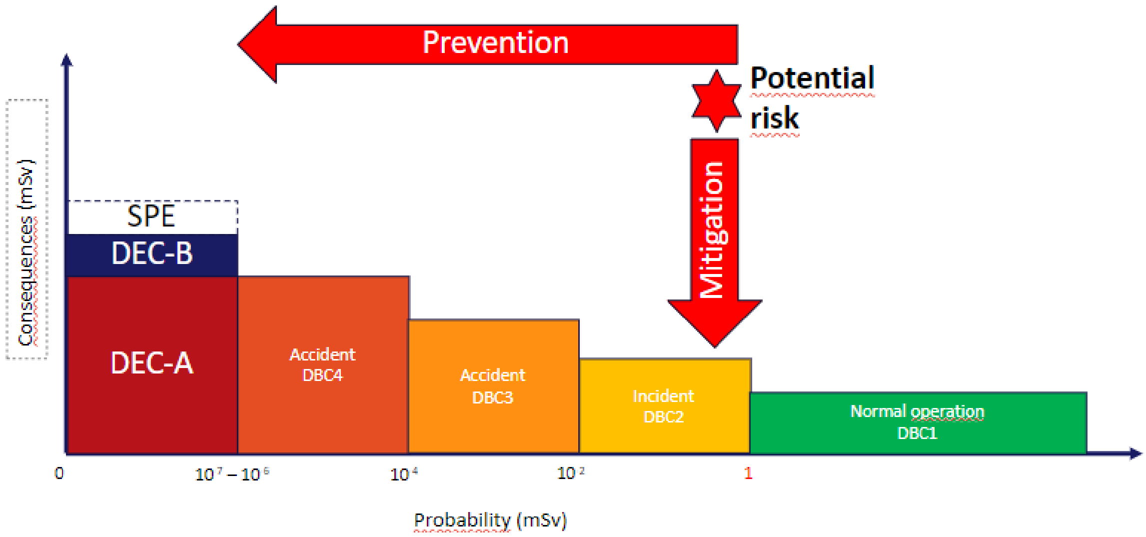

Figure 3 : Risk-Probability diagram in nuclear safety

Consequently, NAAREA considers, <u>for its prototype reactor</u>, that a severe accident is characterized as an accident likely to lead to the loss of the first two containments boundaries inside the facilities if no mitigation actions are taken. The salt fuel loop of the XAMR is enclosed inside a guard vessel which can collect and redirect leaks to a drain tank able to ensure sub-criticality and decay heat removal, and it is thus the failure of this second barrier which constitutes a severe accident. Considering this, NAAREA's prototype will be equipped with a third barrier in the shape of a reactor building with similar provisions to what can be found in solid-fuel nuclear reactors. The ventilation system of this building will be designed to delay and prevent the release of large amounts of radionuclides to the environment in a severe accident scenario. The phenomenology of such type of accidents has been extensively described in [9].

It may be possible in the future acquire enough data on corrosion and salt behavior be able to demonstrate that the probability of failure of the first fuel barrier is small enough to adopt an approach in which the severe accident can be considered as the failure of the first fuel containment barrier and to demonstrate that the second barrier is sufficient to prevent large and early releases.

It should be noted that the radionuclides contained in the off-gas system of the reactor can also lead to a large and early release risk, more so if a large inventory of ^{85}Kr, which is the main gaseous long-lived radionuclide, is stored onsite. Similar conclusions can be drawn for this system: if the probability of failure of the first containment layer can be demonstrated to be small enough, then its rupture is considered as the limiting severe accident. NAAREA currently considers a second boundary layer for its off-gas system and that a severe accident is defined as the consecutive loss of the two layers, with the third barrier providing the containment function.

Regarding the criticality accident, which should be excluded out of the core by design, various scenarios could lead to a criticality accident:

- Salt freezing in an unfavorable geometry may lead to a criticality excursion, which would either melt the salt and allow its flowing or mechanically alter the critical geometry and allow salt to leak outside. Such occurrences can be prevented by design or by ensuring that the salt circuits are subcritical in any possible configuration and that leaks are properly drained and redirected to an adequate drain tank.
- Salt leaks outside the primary salt loop, which would be treated by draining and redirecting the flow to adequate tanks. Design quirks may also lead to critical geometries in which a liquid salt collects and boils off during “slow cook-off” in a manner similar to criticality accidents in aqueous media. In the “cook-off” case, care should be taken to ensure that the salt evaporation would lead to a decrease in fissile content in the salt rather than an enrichment of the liquid phase in fissile material.

In NAAREA’s case, a leakage from the first boundary layer is caught and redirected to a drain tank by the second layer. In the case of severe accidents, an uncharacterized spill of salt to the cell floor will occur. NAAREA has the objective to achieve subcritical salt spreading on the cell floor while maintaining the containment performances of the reactor building. It should be noted that this specific case mainly concerns fast MSR with high fissile content in the salt, as thermal reactors with a small fraction of fissile material inside the salt are less sensitive to out-of-core criticality issues.

5. CONCLUSIONS

This paper presented a rapid overview of the main peculiarities of the safety approach for MSR. A significant amount of literature has been produced in the past decade on the topic of MSR safety, which culminated in the US with the publication of the requirements for MSR safety by ANS/ANSI in 2023 [5]. As shown above, decay heat and reactivity control in a MSR are strongly linked and two main strategies can be proposed to address these fundamental safety functions. The first one is a “one vessel” approach in which the fuel salt stays in the core area throughout its entire lifetime, no drain tank is provided and thus shim rods or adequate absorbers are added to the design to maintain subcriticality when the reactor is not operating. In this configuration, decay heat removal is carried out directly in the core. The second one is a “two vessels” approach, in which the reactor is provided with one or more drain tanks which are subcritical by design and allows for DHR. This strategy heavily relies on the effectiveness of the core flushing function. NAAREA has selected the second strategy, which is considered to yield a better overall reactor safety by leveraging the specificities of MSR.

Concerning the containment function, it is assumed that a severe accident inside a MSR is a situation in which containment failure leads to a large and early release of radionuclides. A direct transposition of the PWR doctrine would thus lead the MSR designer to consider that a breach of the salt fuel loop should be considered as a severe accident. The design direction taken by NAAREA has been to surround the fuel loop of its prototype reactor with a guard vessel and to consider the failure of both the fuel loop and the guard vessel as a severe accident, with salt spilling on the cell floor. Thus, the building housing the reactor is considered as the third layer of containment for this reactor design.

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