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Safety Analysis and Assessment of Molten Salt Reactors

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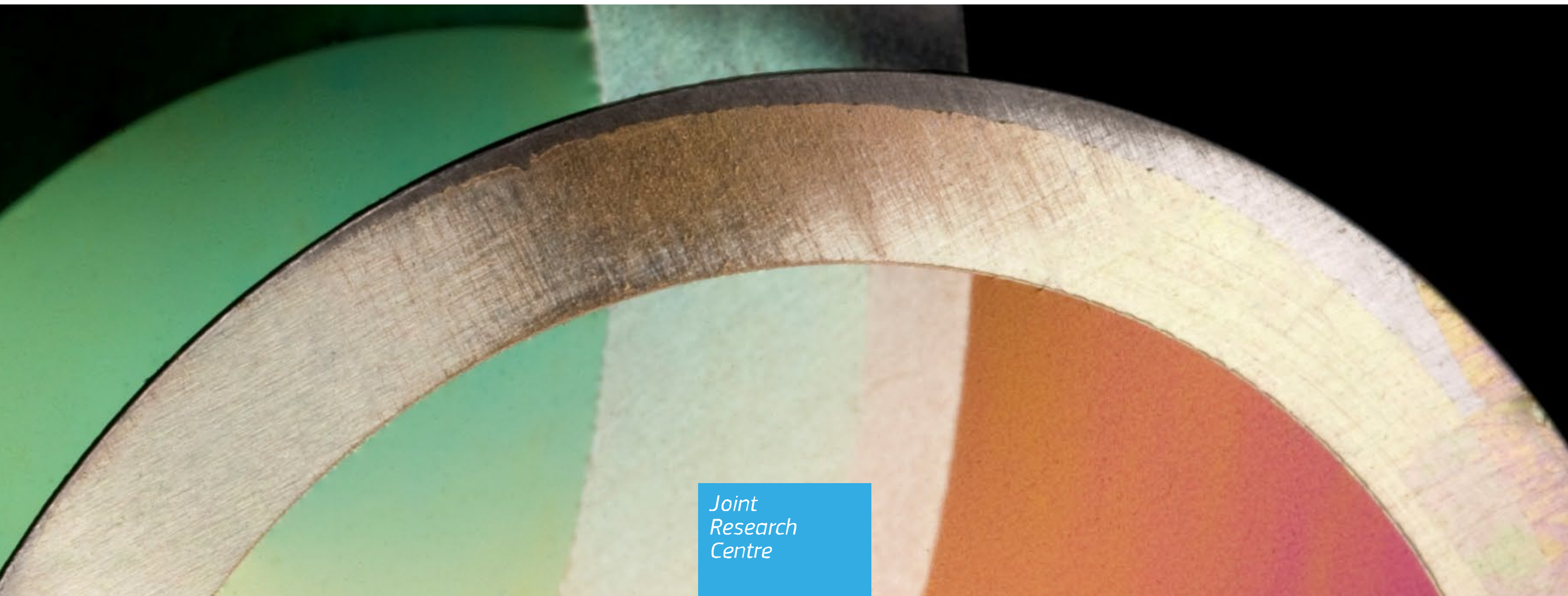

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Contents

Abstract

Molten Salt Reactors (MSR) constitute one of the most promising designs seemingly able to solve the most challenging issues related to the use of nuclear energy for power generation: possibility of large radionuclide releases, nuclear waste and nuclear safeguards.

However, MSRs also present a large set of novel features when compared to most of the nuclear reactors in operation whose technology is based on encapsulated solid fuel and water as coolant and moderator. Such large technology differences make the risk of non-compliance with the nuclear safety licensing framework increase. Bearing this aspect in mind, a careful, comprehensive safety evaluation parallel to the development of the design becomes key.

This report presents the fundamentals of a safety-by-design approach to Molten Salt Reactors consisting of the integration of safety from the first steps of the design. Such integration is conducted through a dedicated methodology that starts by identifying and prioritizing the safety-related activities by means of a Safety Activity Ranking Table (SART) and planning through Safety Work Plan. Once the activities have been ordered upon dedicated importance criteria, each of them is analysed via Evaluation-Model Phenomena Identification Ranking Table (EM-PIRT) out of which safety is assessed and feedback to the design provided.

Executive Summary

Comprehensive assessment of nuclear reactors exceeds the limited context of efficiency and safety in energy production, falling under a wider perspective whose cornerstones fit well with the Generation IV International Forum (GIF) goals of reliability, safety, security and safeguards, sustainability and economics [OECD, 2021].

Among the promising future technologies for nuclear energy production, significant efforts worldwide focus on Molten Salt Reactors (MSR), which constitute a family of nuclear reactors featuring molten salt as fuel, coolant or both.

The European Commission Directorate Joint Research Centre G.I.4 Unit has launched a dedicated MSR Task Force (MSRTF) on MSR safety with the goal of contributing to the implementation of the ***safety-by-design*** concept, namely the integration of safety-related activities in such a way that not only design informs safety but also safety informs design. In other words, safety in design decision-making is not applied a posteriori as an external artefact over the design, but safety is embedded from the early stages of R&D and design, i.e. safety is intrinsic to design.

The MRSTF will greatly benefit from the unique and long experience of the Joint Research Centre G.I.2 Unit, which has already more than two decades in the field of MSR safety studies, especially on molten salt reactor fuel and coolant salts.

The MSRTF vision is the harmonization, coordination and hands-on contribution at EU level of identified open issues / gaps for MSR deployment related to safety. This vision implies the MSRTF acting as MSR safety hub with the aim of optimizing resources and avoiding overlapping, unifying safety (in form, i.e. approach, and content, i.e. requirements and objectives), and sharing expertise and operating experience in the field of safety MSRs. Such harmonized coordination leads to the convergence of efforts into a single path in order to boost MSR deployment at EU level through detailed specifications of design safety requirements and resource planning. Such convergence requires creating a stable, coordination reference centre at EU level, role that should be taken by the MSRTF.

The MSRTF mission is the contribution to research and development efforts in MSR safety and design, and to assess compliance with the most demanding up-to-date safety requirements as issued by international organizations (e.g. IAEA, OECD, EU). Such long-term goal needs first to pave the way through safety gap identification and layout of a safety work plan on one hand, and tasks prioritization suited with MSRTF resources onto the other; and second, detailed analysis of selected open issues among the identified safety gaps.

The MSRTF mission is accomplished through the development of a so-called *safety roadmap* and application to MSR technologies. The report sets up the basis of a systematic approach to safety integrated into the design and includes a preliminary, top-level application of the very first milestone, so-called Safety Activities Ranking Table, based on the analysis of all relevant safety areas in the area of the GIF goals[1] of safety, operability, security and safeguards and on a comparative assessment of MSRs against reference Water Cooled Reactors (WCR).

Molten salt adopted functions and configurations vary widely among MSRs: it can work as coolant and fuel-coolant mixture; it can be encapsulated within rigid rods or freely circulate as primary system; MSRs can feature thermal or fast neutron spectrum, large or small size, rely on active or passive safety systems, involve reprocessing or once-through fuel performance.

Each of these aspects optimize a specific set of safety and sustainability goals but no design seems to optimize all of them. This is why no MSR design can be *the* optimal solution. For instance, safety challenges of TRISO fuel with molten salt as coolant may be currently limited compared to homogeneous solutions (fuel-coolant mixtures); conversely, thermal spectrums characterising TRISO fuel configurations do not provide solution for major actinides and waste management as homogeneous reactor do. Additionally, some MSR

[1] GIF goals dealing with sustainability and economics are out of scope. As regards sustainability, maximization of fuel burnup and minimization of long-lived radioactive waste are key pillars towards achieving high levels of sustainability according to GIF sustainability goals 1 ("*Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production*") and 2 ("*Generation IV nuclear energy systems will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment*").

designs are far more advanced than others, and hence their licensing process should be less demanding, since their design features depart less from existing, already licensed Water Coolant Reactors (WCR).

Consequently, the selection of the plant design within the spectrum of MSR designs should result from either a balanced trade-off of the full list of safety and sustainability goals, or through prioritization of one goal in particular above the others.

MSR is the reactor concept departing the most from existing reactors among the selected alternatives by GIF, resulting in a large list of safety and operational knowledge gaps –even at fundamental level– that may in some cases prevent a current accurate assessment in terms of compliance with the GIF goals.

The current report aims at the identification of safety-related gaps where MSRTF may provide added value to MSR safety consolidation. Such identification grounds on the layout of a safety work plan.

The safety work plan is the direct result of a ***Safety Activity Ranking Table*** (SART) applied to MSR technology. The SART is a safety gap analysis where each item is identified and assessed against a so-called ***suitability index***. The application of this index provides a chronologically-ordered list of safety-related activities, namely the safety work plan.

In order to identify the MSR safety gaps, a first top-level analysis of MSR technologies against existing nuclear reactors is performed at GIF goal level of (1) reliability, (2) safety and (3) security and safeguards. This comparative assessment, even if MSR-technology-neutral, provides, on one hand, a clear overall picture of the MSR 3S (safety, security and safeguards) state of the art, and onto the other, the identification of the activities suiting well with the MSRTF capabilities.

This report has therefore two main outputs: the comparative assessment of MSR designs against existing WCRs, and a top-level, generic SART.

As for the comparative assessment of MSRs against reference WCRs[2], it allows (1) **strengthening justification of the current needed investment R&D efforts** focused on MSRs, (2) **assessing the efficiency** in meeting with each analysed GIF goal according to the current design objectives and, most important, (3) the **identification of SART safety activities** allowing us pinpointing less robust aspects of the design thereby opening the door for changes along the design process in order to improve the achievement of the pursued goal. In fact, MSR current maturity level in terms of reliability, safety, security and safeguards, brings an opportunity to select optimal solutions for each of the open issues at this pre-conceptual stage of the design.

According to the analysis shown in the current report, the list of open issues in the three fields of activities is substantial and places MSR at a very early step of the design. Fundamental knowledge such as material properties, fission product releases, operational performance limits or status of safety barriers in accidental conditions is partly lacking, in most of the cases preventing an accurate analysis of MSR design and quantitative assessment against reference WCRs. Conversely, MSR is one of the most promising solutions provided the GIF sustainability goal is prioritized, as it potentially allows getting rid of the majority of the actinides stock and reducing the amount of long-lived waste significantly –provided MSR design objectives are met–, letting alone its very high flexibility achieved through fuel online adjustment in the fuel coolant mixture, and the excellent inherent response against large and / or early radioactive releases.

As for the comparative assessment, the European-designed Molten Salt Fast Reactor (MSFR) [Merle, 2017] is taken as generic MSR reference since it features major deviations from existing WCRs at fundamental reactor-system levels: the fuel is dissolved into the molten salt, acting hence as both fuel and coolant, fast spectrum, breeder with online reprocessing and High Enrichment Uranium (HEU), all these characteristics departing from existing, reference WCRs. Even if the MSFR has been taken as MSR reference, no specific design aspects have been taken into account for the comparison assessment in the top-level SART application. The adoption of MSFR as MSR design in the current analysis prevents neither the further analysis of alternative MSR designs nor the orientation of MSRTF efforts in other directions different from the MSFR. The comparative assessment at GIF level is made qualitatively for all aspects identified, and only quantitative for those where detailed information does exist because of a more mature state of the art.

[2] Reference plant in this report stands for existing plants belong to 3rd Generation Nuclear Power Plants, comprising PWRs, BWRs, CANDUs and gas-cooled reactors.

The most relevant output of the top-level comparative assessment of MSRs against existing WCRs is the SART, whose identified open issues are ranked according to the suitability index.

The suitability index is developed to contain all aspects related to the safety-relevance of each identified issue plus the analysis of the matching against the MSRTF capabilities and expertise:

- **Priority**: the earlier in the safety work plan, the higher the impact;
- **Critical**: the more relevant the open issue as hold point, green light or potential showstopper for triggering other open issues, the higher the impact;
- **State of the art**: the lower the knowledge, the higher the impact;
- **Fitness**: The higher the matching between MSRTF capacities and the open issue, the higher the impact.

The suitability index takes an efficiency-like shape ranging between 0% and 100%.

According to the SART results[3], the open issues with the highest suitability index are the followings:

1. Top Safety Requirements.
2. Structural material behaviour under normal operating conditions.
3. Last-confinement boundary conditions.

Figures 3 and 4 show the suitability index ranking for all identified open issues using two different quantification methods, whereas Figure 5 presents the results as an arithmetic average of the two suitability index calculations methods. Table 3 shows the open issues main features together with the scores assigned to the criteria underlying the suitability index quantification.

Table 4 shows the safety work plan resulting from a top-level SART application to MSR technologies. This safety work plan allows i) the identification of dependencies between safety-related activities, ii) how prompt each of them should be addressed by looking at their chronological arrangement, and iii) an estimate in the allocation of resources necessary to close the open safety issue.

[3] This first SART application included in the report features a broader scope beyond safety, also including security and safeguards, and also reliability in operation.

1 Introduction, Goal and Scope

MSR is not a specific nuclear reactor design but a family of designs sharing a single yet sound common feature: the use of molten salt as fuel, coolant or both. The family of MSR designs is referred to as 'MSR conceptual design' in the current report, or simply as 'MSR'.

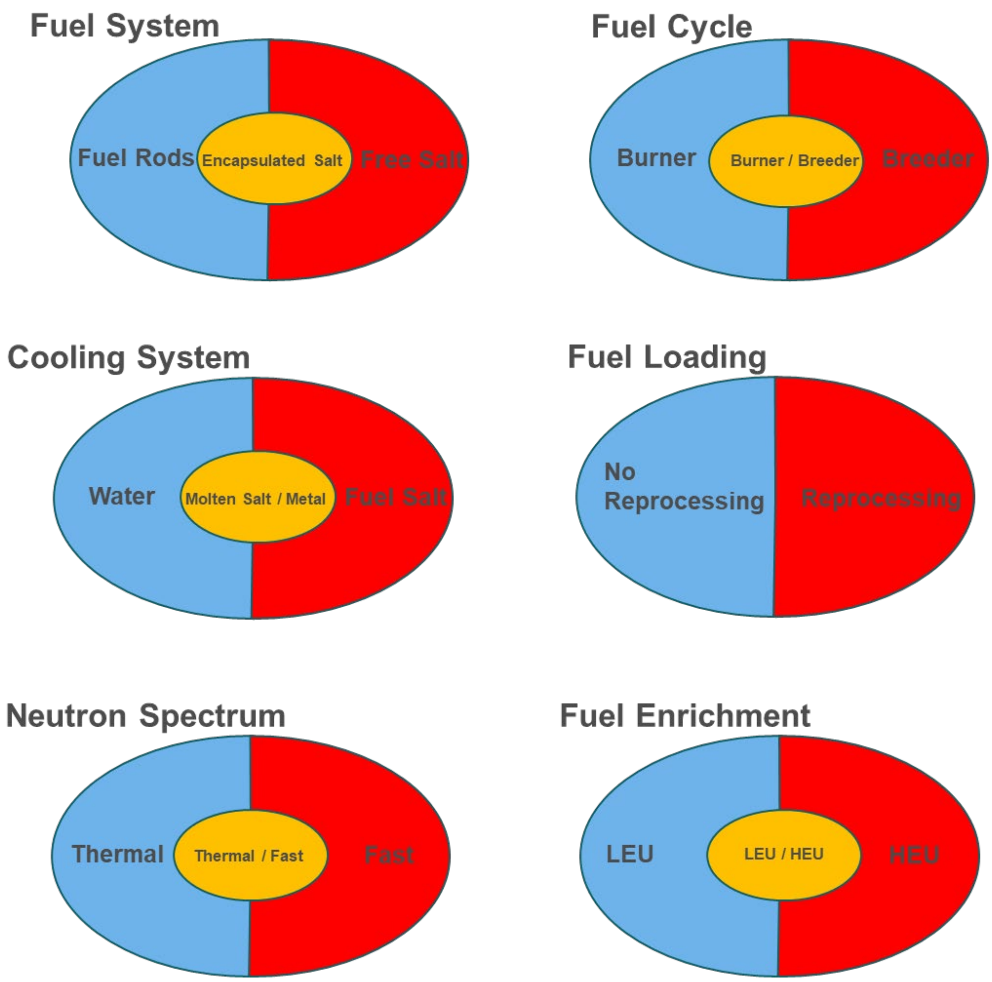
In order to categorize MSR designs, the following fundamental design informing criteria are used:

- Fuel system:
  - Existing plants make use of encapsulated solid fuel rods.
  - MSR plants feature:
    - Encapsulated fuel molten salt in fuel rods
    - Fuel salt in fuel-coolant fluid –so-called free salt
- Cooling system:
  - Existing plants make use of water or gas as coolant
  - MSR plants feature:
    - Molten salt or liquid metal
    - Fuel-coolant fluid
- Neutron spectrum:
  - The majority of existing plants feature thermal spectrum
  - MSR plants feature:
    - Thermal or epithermal spectrum
    - Fast spectrum
- Fuel cycle:
  - Existing plants work like burner
  - MSR plants work as:
    - Burner
    - Breeder
- Fuel loading:
  - Existing plants work in closed fuel arrangements (no online reprocessing)
  - MSR plants work as:
    - Closed fuel
    - Online reprocessing loops
- Fuel enrichment:
  - Existing plants work with LEU enrichments
  - MSR plants:
    - Can accommodate LEU / HEU fuels
    - Only HEU

Figure 1 arranges these criteria graphically in order to capture the extent that each of them depart from existing NPPs:

- Blue colour indicates the implemented design option for existing or the majority of existing plants
- Orange colour indicates a limited degree of departure from the selected option for existing plants
- Red colour indicates full departure from the selected option for existing plants

Figure 1. Molten Salt Reactor Concept Design Criteria



Source: JRC

The combination of these criteria lead to some of the most promising MSR designs:

- **Molten Salt Fast Reactor** (MSFR, [Merle, 2017]): homogenous / fast spectrum / breeder reactor / online reprocessing / high enrichment / large reactor
- **Terrestrial Energy Integrated Molten Salt Reactor** [IAEA, 2020]: homogeneous / thermal spectrum / burner reactor / no reprocessing / low enrichment / SMR
- **Stable Salt** [IAEA, 2020]: heterogeneous (encapsulated vented fuel molten salt separated from molten salt as coolant, i.e. stable salt type) / fast or thermal spectrum / breeder or burner reactor / no reprocessing / different fuel and coolant salts of different enrichments / SMR
- **Dual Fluid** [Wang, 2017]: heterogeneous (fuel molten salt and liquid metal as coolant) / fast spectrum / breeder reactor / online reprocessing / high enrichment (25% U + Pu) / large reactor
- **Kairos Power** [IAEA, 2020]: hybrid (solid fuel and molten salt as coolant) / thermal spectrum / burner reactor / no reprocessing / TRISO particles as fuel-moderator / large reactor
- **CMSR** [Seaborg, 2023]: homogeneous / thermal spectrum / burner reactor / online reprocessing / low enrichment / SMR

The goal of the report is the presentation of the fundamentals of a *Safety Roadmap* ultimately leading to a *preliminary safety work plan*: a list of safety-related activities chronologically ordered upon their urgency and degree of mutual dependency, with an assigned estimate on the relative needed resources to address each activity.

The safety work plan draws from two fundamental and interacting inputs of different nature: safety activities and safety phenomena.

Ultimate safety compliance stands for meeting with a set of predetermined safety goals: radiological safety objectives linked to a certain frequency of occurrence.

For underdevelopment technologies, it is not possible to ensure ultimate safety compliance since all the necessary tools to calculate the performance results constituting the safety demonstration, i.e. collection of modelling capabilities and experimental evidence applied to the design, are not yet there. In order to bridge this gap, the technology safety performance is decomposed into a set of **key contributors to the ultimate safety compliance and open safety issues**, namely open gaps that need to be addressed along the R&D and design phases so ensure ultimate safety compliance. Each of these contributors is called **safety activity**. Each of these activities is assessed against a standard reference, which is the expected result that can take the form of a value, criterion, of performance condition. If all the activities –i.e. all the steps– are satisfactorily met, there is a very high degree of confidence of ultimate safety compliance. Therefore, **safety activities** are the key performance and design driving safety features needed to assess to ensure ultimate safety compliance.

Activities falling short their standard reference may rely upon intrinsic or extrinsic reasons. If the latter, noncompliance can be solved by changing the design accordingly. This is the main idea of the concept of safety-by-design. Therefore, the **implementation of the safety-by-design concept to the MSR from the conceptual stage of the design is the outcome of the safety roadmap**.

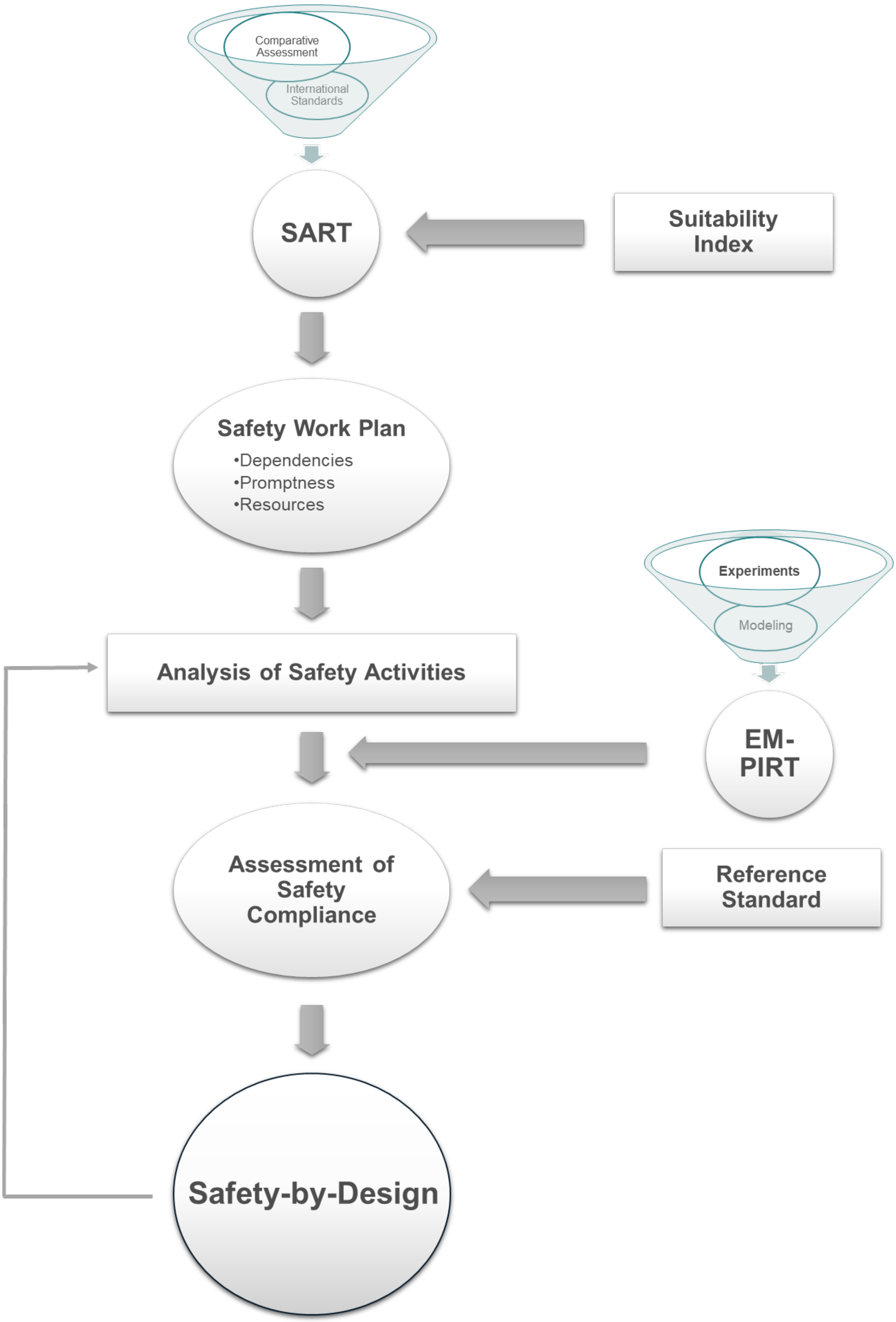
Assessment of compliance at safety activity level depends on the nature of the corresponding standard reference, some of which have to do with physicochemical phenomena. An Evaluation Matrix coupled with a Phenomena Identification Ranking Table (EM-PIRT) supports the compliance assessment. The EM-PIRT provides the list of key phenomena whose knowledge is necessary to perform the compliance assessment of the safety activities indicated in the SART.

The key steps of the whole safety roadmap ultimately looking at the application of a safety-by-design approach follow:

1. SART development
    a. Identification of safety activities
        i. Comparative assessment against existing WCRs
        ii. Applicable international standards
    b. Safety activities ranking
        i. Development and application of a suitability index
2. Development of safety work plan
3. Analysis of safety activities
    a. Development of Evaluation Matrix
    b. Development of PIRT
4. Assessment of safety compliance at activity level
    a. Identification of standard reference
    b. Closure of phenomena gaps (experiments and modelling)
    c. Assessment against the standard reference
5. Safety-by-design application
    a. Identification of non-compliance activities
    b. Conceptual design modifications

The complete methodological process for the application of the safety-by-design concept is illustrated in Figure 2. The comprehensive application of the safety roadmap requires a certain degree of design development without which an accurate safety activities identification, assessment, and closure of phenomena gaps, are not feasible.

Figure 2. Sketch of Full Safety Roadmap



Source: JRC

The scope of the report is the development of a preliminary, top-level generic SART, i.e. without looking at one MSR design solution in particular. The ranking comes from the application of a so-called suitability index, as further on explained in Section 8. The safety activities identification is performed via analysis of the main features brought by MSRs in the area of the GIF goals of safety, operability, security and safeguards. Where enough information is available, such analysis will be further complemented by a comparative assessment against existing plants[4]. Additional sources for a solid and comprehensive SART should be used, such as applicable international standards. However, due to the limited scope of the report and the preliminary nature of the SART, no further reference will be taken into account.

This top-level analysis in the area of safety, operability, security and safeguards, additionally aims to orient R&D efforts in identifying and arranging activities necessary to address and close the path towards a safe MSR deployment.

Table 1 reflects the criteria behind the most promising MSR designs as listed above, where the colour reflects the departure from the reference plant: blue 'no departure'; red 'significant departure'; and orange somewhere in the middle –hence using the same colour code than in Figure 1.

Table 1. Main MSR designs per design criteria

MSR Design	Fuel Salt	Fuel Configuration	Coolant	Spectrum	Breeding	Reprocessing	Enrichment
MSFR	LiF-ThF4-UF4-(TRU)F3	Fuel Salt	Fuel Salt	Fast	Breeder	Yes	HEU
Terrestrial	UF4 + F-based salts	Fuel Salt	Fuel Salt	Thermal	Burner	No	LEU
Stable Salt	45% KCl+ 25% Pu/minor actinide Cl3 + 30% UCl3 + LaCl3	Encapsulated Salt	Molten Salt	Thermal / Fast	Burner / Breeder	No	LEU / HEU
Dual Fluid	Cl-U/Pu	Fuel Salt	Metal	Fast	Breeder	Yes	HEU
Kairos	N/A	Fuel Rods	Molten Salt	Thermal	Burner	No	LEU
CMSR	Unknown	Fuel Salt	Fuel Salt	Thermal	Burner / Breeder	Yes	LEU / HEU
ORANO - Terra Power	NaCl-PuCl3	Fuel Salt	Fuel Salt	Fast	Breeder	Yes	HEU

Source: JRC

As shown in Table 1, MSFR features all the novel aspects brought by the MSR concept against reference plants. This is why the analysis of the MSFR covers the full-scope analysis of the MSR concept in such a way that, specific features of one specific MSR design different from the MSFR and shared with reference plants, e.g. no reprocessing in Terrestrial, does not deserve a specific analysis in this report. Therefore, MSFR will be taken as MSR reference design for a top-level analysis and assessment in the current report[5].

[4] Existing plants are taken as complying with the latest safety standards –such as 3rd Generation NPPs. Existing plants for comparison's sake are hereafter named 'reference plants'.

[5] It is noted that the validity of this top-level analysis and assessment applied to MSFR, as representative of the entire MSR conceptual design, does not suit subsequent broken-down, in-depth specific analysis at particular issue level.

2 Analysis of Safety Areas in GIF Goals and Preliminary Top-Level Comparison of MSRs against current WCRs

Comparative assessment against reference plants attempts to measure the **gap distance** between the desired goal and two MSFR *positions*, actual and potential:

- **Actual distance** between the current status of the design and the postulated goal;
- **Potential distance** between the final design according to the design expectations and the postulated goal.

Actual distances need **gap analysis** whereas potential distances make in addition use of **benefit analysis**. Gap analysis is based on the identification of open issues whereas benefit analysis on the improvements provided by the design. Both issues and improvements are measured against a set of postulated goals.

Current position + gap analysis: Open issues → actual distance
Final design position + gap and benefit analysis: Improvements → potential distance

'Open issue' means any activity whose current status does not satisfy i) the minimum documentation in terms of operation and safety and / or ii) lacks of the necessary knowledge and tools for safety demonstration. The path to close the open issue is known in the former category (and hence the results can be anticipated or are not critical to the project viability), while for the latter the path is also lacking. Both open issues require dedicated work, but the former category does not need R&D efforts –while the second does. The former is coined '**resource-based gap**' while the latter is coined '**R&D-based gap**'. Resource-based gaps are not critical in such a way that the results do not affect the project viability while R&D-based gaps are.

'Benefit' represents the MSR performance against each predefined goal assuming that the design is finalized and meet the objectives fixed as design requirements. Potential distances inform on the improvements provided by the MSR in fulfilling the GIF goal pillars. If the result is not satisfactory, it means that the design solution should be changed in order for the MSR to better meet the objective.

In terms of individual scores, for issue where enough information is available so that a quantitative comparison is reasonable, the range is 0 – 3. The reference plant scores 2. Lower values stand for better performance compared to reference plants –and the other way around.

Each GIF safety, operability and security and safeguards goal is broken down into pillars at independent hazard source level, e.g. reactor, reprocessing units, etc. Depending on the pillar's complexity and maturity of the design, it might be further broken down into events and each event expressed through factors, namely contributors to the occurrence of the event (by definition, factors are independent one another). For each pillar, source and event, factor scores are multiplied to get the event distance –actual on one hand, and potential onto the other. Each event within each hazard source has an assigned weighting factor, whereas factors do not, since they are independent elements of a chain of failures –thus they are all equally important. The source distance is the sum of the events distance, and the pillar distance is the sum of the sources distances:

$$d_G = \sum_{i=1}^{i=n_P} d_{P_i} = \sum_{i=1}^{i=n_P} \sum_{j=1}^{j=n_S} d_{S_{i,j}} = \sum_{i=1}^{i=n_P} \sum_{j=1}^{j=n_S} \sum_{k=1}^{k=n_E} d_{E_{i,j,k}} = \sum_{i=1}^{i=n_P} \sum_{j=1}^{j=n_S} \sum_{k=1}^{k=n_E} \prod_{l=1}^{l=n_F} \bar{\omega}_{j,k} \cdot f_{i,j,k,l}$$

Where the weighting factors of event *k* of hazard source *j*, $\bar{\omega}_{j,k}$ have been normalized. Being *2* the assigned score for the reference plant, the goal average scores used as reference are calculated as:

$$d_{event,avg} = \bar{\omega}_E \cdot 2^{n_F}$$

$$d_{source,avg} = \sum_{k=1}^{k=n_E} \bar{\omega}_k \cdot 2^{n_F} = 2^{n_F}$$

$$d_{pillar,avg} = n_S \cdot 2^{n_F}$$

$$d_{goal,avg} = n_P \cdot n_S \cdot 2^{n_F}$$

For each goal:

1) Identification of pillars / sources / events / factors;
2) Analysis of pillars / events / factors;
3) Identification of open issues and benefits;
4) Weighting of events;
5) Quantification of factors.

The total distance –either actual or potential– will be calculated as a weighted average value of the goals' distance:

$$d_{total} = \sum_{i} \alpha_i \cdot d_{G_i}$$

3 Analysed Goals

3.1 GIF Operability Goals

GIF Safety and Reliability 1 goal states:

"*Generation IV nuclear energy systems operations will excel in safety and reliability.*"

Excellence in operation. This ideal feature is broken down into two pillars: reliability –on one hand– and flexibility –onto the other:

- **Reliability** is proportional to the operational experience, number of supporting systems, operating human actions and system complexity (number of devices and complexity of devices and interfaces).
- **Flexibility** stands for the easiness of nuclear operating device to quickly accommodate the needs of the energy market. Flexibility in operation is quantified by means of expert judgement based on the existence of operating the plant at different powers, e.g. through buffer devices such as large heat storages, etc.

3.2 GIF Safety Goals

GIF Safety and Reliability 2 goal states:

"*Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.*"

GIF Safety and Reliability 3 goal states:

"*Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*"

These two goals are very much related one another and can be summarized and quantified through the following two pillars:

- **Accident**. This pillar looks at the full spectrum of accidents both from a deterministic and probabilistic side. First, accidents are taken as leading to offsite radioactive / toxic releases[6]. The ideal feature consists of a nuclear plant where radioactive releases are physically impossible, i.e. based on laws of nature.
- **Worst-case** offsite radiological / toxic releases. No matter the accident frequency or accident spectrum, risk is very high and unacceptable if there is the chance for an accident with significant consequences to occur. In order to reflect this additional factor on the entire nuclear risk, namely consequences independent on its frequency (rather than operating directly with the synthesized parameter of risk as the final product of frequency times consequences), a deterministic approach to risk will complete the safety assessment. This factor is quantified by looking at the worst-case scenario, i.e. maximum releases in case of extreme accident conditions.

3.3 GIF Security and Safeguards Goal

GIF Proliferation Resistance and Physical Protection goal states:

"*Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*"

This goal is broken down into two pillars:

[6] Accidents leading to consequences limited onsite are not considered because of the perception of risk by society, furthermore since onsite consequences are common in every industry. Instead, offsite consequences –hence beyond restricted specific areas– constitutes the inherent nuclear risk as perceived by society.

- **Security**. This pillar measures the MSR design higher or lower exposure, on one hand, and higher or lower consequences, onto the other, to malicious attacks.
- **Safeguards**. This pillar measures the MSR design exposure for nuclear weapon-grade material to be stolen. This pillar depends on three factors: weapon-grade enrichment reached in the plant on permanent basis, temporarily or never, in one location or multiple locations onsite; weapon-grade enrichment material is easily transported, e.g. it has high or low irradiation; weapon-grade material accountability is easy, e.g. solid or liquid material, encapsulated or not, etc.

4 Safety Goal

4.1 Accident Pillar

4.1.1 Open Issues / Benefits

4.1.1.1 Open Issues

4.1.1.1.1 Operational and Accidental Performance

Description

Neutronic, thermal-hydraulic and physicochemical phenomena are strongly linked in homogeneous MSRs. Fuel salt chemical compositions are continuously changing throughout the fuel cycle. Indeed, the meaning of fuel cycle, as elapsed time between BOL and EOL for standard nuclear reactors, needs redefinition for homogeneous MSRs with online reprocessing and quasi-continuous fuel adjustment.

The current status of the design shows deficiencies as regards plant performance and plant response against accidental situations. Such deficiencies are both resource-based and R&D-based gaps, the latter requiring experimental and analytical efforts.

In terms of compliance with the critical safety function of protection of workers against radiation exposure, the harder the neutron spectrum, the more challenging the radiation protection. This means that radiation maps need accurate 3D predictions to ensure that actual dose rates allow performing operation, surveillance and maintenance activities. Otherwise remote handling is necessary.

Activities under fuel handling, i.e. the set of activities having to do with fuel since the arrival onsite to the final disposal, comprising unpacking, storage, input and output of the reactor, shall be identified and bounded in terms of hazard, main PIEs, safety provisions, accountability, etc.

Tritium handling per se requires dedicated considerable efforts in terms of handling equipment and application of safety principles, mainly due to its highly radioactive and diffusive nature, making it especially sensitive to uncontrolled leaks. Furthermore, tritium processing requires state-of-the-art dedicated systems for capturing, recycling, filtering and safe release to the outside environment in normal operating conditions.

Knowledge Gaps

Several coupling modelling activities have already been carried out in different countries such as Germany or France, and at international level, e.g. SAMOFAR EU project [SAMOFAR, 2019]. Nevertheless, a systematic and comprehensive approach for the entire set of scenarios for all operating and accidental conditions is lacking, especially dealing with the following aspects:

- MSRs as a FFOAK, i.e. Full First-Of-A-Kind design: No other GIV designs departs as much as the MSR from existing technologies. Operating experience on MSRs mainly comes from ORNL MSRE [Chisholm, 2020], which in addition may depart significantly from other MSR designs such as MSFR: MSRE featured thermal spectrum and its fuel salt chemical composition was also very different compared to the ones currently under consideration.
- Knowledge gaps are not related (only) to low frequency scenarios, yet also to normal operating conditions and high frequency accidents, where uncertainties need be kept to a minimum (unless very high, sometimes unbearable safety margins are applied, which is not desirable and would go in detriment of MSRs against other GIV alternative designs).
- Extensive validation of neutron-thermal-hydraulic-physicochemical coupling analytical simulations through experimental tests is necessary to provide with safety demonstration.
- Characterization of tritium –and other volatile FPs and gases– at all stages along the plant lifecycle and operation modes.
- Characterization of in-confinement source term and in-confinement aerosol retention / deposition mechanisms is crucial to understand the offsite consequences of the MSFR.
- Radioactive and toxicities carried out by the different streams in and out the vessel and reprocessing / storage systems must be quantified / bounded. To this aim, a realistic and accurate calculation of the operational performance in all operating modes is necessary, i.e. all inlet and

outlet flows, transport, physicochemical evolution and storage of radiative materials, uncontrolled leakages, etc.

Suggested Solutions

- Dealing with the reactor itself:
    - Full 3D-3C (3-dimension, 3-field-coupling, i.e. neutronic, thermal-hydraulic and physicochemical) analysis for all operating modes and accident categories: chemical, radiative, thermodynamic, thermal-hydraulic, inlet / outlet streams, uncontrolled leakages (see, e.g. [Pettersen, 2016]).
    - Uncertainty analysis for the identification of appropriate engineering safety margins (pressure, temperature, corrosion, FP handling, off-gas handling, etc.).
    - Characterization of in-confinement source term and confinement retention by deposition mechanisms; barrier surface able for the aerosols to adsorb and deposit (see, e.g. [NRC, 1995]).
    - Influence of re-volatilization. Characterization of severe-accident phase evolution.
- Dealing with the reprocessing units:
    - Characterization of tritium (in particular) and FPs (in general) cycles: generation and handling. Adequate safety provisions, i.e. safety barriers architecture, safety systems for capture, filtering, storage and release for all operating modes, principal PIEs, accident evolution and bounding analysis of dose consequences.
- Dealing with both:
    - Keep updating the work already started in [Allibert, 2019]:
        - Cliff-edge effects are not properly and exhaustively addressed, for instance:
            - Scenarios characterised by sustained LUHS should be better analysed through a top-down approach since they can lead to FP volatilization – which is one of the two strongest features of MSRs.
            - Scenarios characterised by the impossibility of fluid expansion should be better analysed through a top-down approach since they can lead to a loss of negative reactivity –which is one of the two strongest positive features of MSR.
        - Potential energetic events, e.g. explosions with tritium, hydrogen generation through radiolysis, water-salt interaction, etc., should be analysed in detail with a conservative approach.
        - IAEA SSR-2/1, requirement 13 [IAEA, 2016]: *"Criteria shall be assigned to each plant state, such that frequently occurring plant states shall have no, or only minor, radiological consequences and **plant states that could give rise to serious consequences shall have a very low frequency of occurrence**"*.

4.1.1.1.2 Complexity of Safety Barriers Boundaries

Description

If fuel needs reprocessing, physical safety barriers exceed the reactor vessel and becomes highly complex because of the presence of radiative and toxic sources in different places. Even the general strategy for confinement can drastically change, e.g. because of tritium as new radioactive hazard source to handle. Coupling with such reprocessing units can turn out in displacing the risk off the reactor but not reducing it when analysed globally. In addition, leakages from the reactor can also occur, among which confinement barrier bypass, e.g. through the intermediate cooling circuit. Fuel molten salts can also heat up and challenge structure materials.

Knowledge Gaps

In-vessel hazard source evolution for all possible accident scenarios needs to be completed and refined with a higher degree of accuracy.

Hazard sources outside the reactor vessel that are not fully identified can contribute to nuclear risk even more than the reactor itself, if not in terms of worst-case, during normal operating conditions or less-severe, more-frequent accident scenarios.

It is highlighted here once again the special attention that tritium deserves due to its very high diffusion and radiation damage.

Suggested Solutions

- Accident identification and qualitative / quantitative analysis of risk (frequency and consequences). This activity should be addressed through both deterministic studies plus probabilistic tool application, e.g. Master Logic, HAZOP, FMEA, PRA, etc.
- Determination of passive safety barriers: geometrical configuration, pressurization (analysis of confinement versus containment, i.e. depression better than only relying on hermetic compartmentalization, i.e. high leak-tightness?), neutron shielding, physicochemical performance (ultimate pressure failure, chemical reaction, etc.), etc.
- Determination of active safety barriers: independent safety systems for each passive safety barrier accounting for the outcomes of the previous suggested solutions and the previous activities under this particular item. In fact, this is a feedback activity on the previous tasks aimed at plant characterization (pressure, temperature, corrosion, FP handling, off-gas handling, etc.).
- Safety barriers applied to FP and tritium carrier and storage components.

4.1.1.2 Benefits

In terms of accident frequency, MSRs, and in particular MSFRs, claim a set of novel benefits departing from the reference plant:

- Reactivity control drops from the standard three key safety functions due to the strong natural negative feedback based on lower densities leading to lower fuel material in the core.

- Fuel salt can retain an important fraction of FPs within the salt itself, indeed coolant fuel salt showing very low volatility at working pressures. This means that there is a significant difference between the hazard inventory and the mobilized hazard inventory, much in favour of MSFRs against reference plants.

- Inherent flexibility of fuel in liquid state can make it easier to handle and guide it wherever needed to be cooled down by the implemented safety systems, rather than struggling in certain situations to bring the coolant system to the solid, in-position fuel rods. This important feature deserves special attention since it can turn out to be a paradigm shift in meeting with what has been proven the most challenging critical safety function of fuel cooling.

4.1.2 Analysis and Assessment

<u>Hazard sources</u> are the followings:

- Reactor;
- Reprocessing units including off-gas treatment and fertile material units;
- Spent fuel pool.

<u>Events</u> are initiating events triggering challenging scenarios. Events are analysed at family level, and families taken at key safety function level:

- Reactivity control;
- Heat removal;
- Confinement.

Accidents leading to radioactive / toxic releases take place when confinement safety function is lost. Loss of other nuclear safety functions, i.e. criticality and heat removal, will not be considered accidents per se but key contributors to accidents treated as families of precursors potentially leading to the loss of confinement safety function.

<u>Factors</u> are the followings:

- Number of initiating events potentially leading to the total loss of confinement. This means the disposition of the plant to propagate a specific triggering event as challenging scenario dealing with a specific key safety function potentially leading to loss of confinement.

- Safety barrier *length*: number of existing levels of defence in depth between the hazard and the offsite environment –hence barrier as the integral barrier or sum of all existing barriers / levels of defence in depth– that can be jeopardized because of the loss of one specific safety function. This is the K_{SF} value in the equation below.

- Safety barrier w*idth*: the robustness of a safety barrier can be quantified inversely to the total failure probability of the barrier. Such probability can be measured through the sum of Minimum Cut Sets (MCS) if probabilistic risk assessment is available, otherwise through assigned generic values.

  Safety barrier stands for the collection of safety arrangements, e.g. SSCs, active or passive, static or dynamic, human actions or system actions, contributing to stop the threat jeopardizing one specific confinement level of defence in depth assigned to that safety barrier and because of the loss of one specific key safety function. This factor can be measured as follows:

$$Total\_Width_{SF} = \sum_{K=1}^{K=length} Width_{K_{SF}} := \sum_{K_{SF}=1}^{K_{SF}=length} \sum_{i=MCS_{k,1}}^{i=MCS_{k,N}} \prod_{j=1}^{j=N_i} R_{k,ij}$$

  Where $R_{k,ij}$ stands for reliability of component *j* of MCS *i* of barrier K threatened by the loss of safety function SF. Safety barrier width is an overall measure of the single safety barrier reliability. The total width of a safety function is therefore the sum of the single barrier widths for all the safety functions.

- Mobilized stored hazard within the barriers. Total loss of confinement needs the source not only to be exposed to the sensitive environment, but also the source to be released. Therefore, the figure of merit does not comprise the entire existing radioactive / toxic inventory, but only the part subject to mobilization. Mobilized hazard for each hazard source is the same no matter the event, hence it will get the same score at hazard source level.

4.1.2.1 Reactor Hazard Source

The mobilized hazard factor is common for all events for the reactor hazard, as just stated above. This is why it is analysed here globally.

One of the major advantages of homogenous MSRs is the retention of FPs as well as the near-continuous segregation of FPs, e.g. noble gases, metals and actinides. Even in the event of a total loss of confinement, still the release potential should be lower than the reference plant. Still, the current knowledge of retention of FPs by the salt under irradiation conditions needs to be significantly increased. This is why the actual score is 2 but the potential score is 1. This analysis and resulting score applies for all events under the reactor hazard source.

Continuous recycling and purification of generated FPs avoid full storage of the hazard source in the reactor. Such diversification of the hazard inventory turns into lower hazard source in the reactor but it creates a new source of hazard in the processing / storage rooms. As a result, risk is more evenly spread into different sources instead of being centralized in a single one: the total accident frequency increases compared to the reference plant (due to the fact of having new sources of risk in the processing rooms), but each source has a lower source term. This can be simplified as follows:

Before splitting the source into several lower sources, total risk comes from the reactor (assuming here no risk in the SFP):

$$R1 \; \alpha \; F1 \cdot C1$$

After that splitting:

$$R2 \; \alpha \; (F1 \cdot C11 + F2 \cdot C12 + F3 \cdot C13), \text{ where } C1 \approx C11 + C12 + C13$$

Where F1 stands for the accident frequency of the reactor vessel, F2 for one processing unit, etc. C1 represents the single initial radioactive inventory whereas C1i the hazard inventory located in each hazard source.

This last assumption of the total radioactive inventory continuity is very conservative, first, since radionuclides will decay once outside the criticality area, and second, because retention mechanisms by the fuel salt are not taken into account.

Please note that the accident frequency is independent on the stored source term.

Overall risk decreases if R2<R1:

$$F1 \cdot C11 + F2 \cdot C12 + F3 \cdot C13 < F1 \cdot C1 = F1 \cdot (C11 + C12 + C13) \rightarrow$$

$$R2 < R1 \rightarrow F2 \cdot C12 + F3 \cdot C13 < F1 \cdot (C12 + C13) \rightarrow$$

$$(F1 - F2) \cdot C12 + (F1 - F3) \cdot C13 > 0$$

Since C12 and C13 are positive:

$$If\ F1 > F2\ and\ F1 > F3, then: R2 < R1$$

This inequality can be generalized in as many hazard sources the reference hazard source is split into. If the reactor overall accident frequency is higher than that of the processing and storage rooms, the distribution of the source term should be beneficial in terms of total risk.

4.1.2.1.1 Reactivity Control

Changes in reactivity may lead to pressure and temperature excursions threatening confinement barriers but per se not necessarily leading to loss of confinement safety function.

As for the <u>initiating event</u> factor, given the absence of reactivity control systems, the list of triggering events is significantly reduced to changes in heat removal, e.g. ATWS or control rod withdrawal events are naturally eliminated. Such reduction lead to a score equal to one.

It is worth noting that the contribution of reactivity-driven accidents in reference plants to core damage and accidental radioactive releases is extremely low, and most of the cases it is even screened out in terms of offsite releases. Therefore, even if recognizing the actual benefit of removing one key safety function out of the NPP safety functions, still the other two safety functions contribute to almost all accidental releases when it comes to the spectrum of accidents not screened out by frequency.

As for the <u>barrier width</u> factor, reactivity control happens inherent to the fuel salt through salt expansion leading to low fuel material subject to fission in the critical part of the reactor. In order for this lower density to occur, fuel salt must be free to expand outside the core area by means of an expansion volume type of device. Should this volume fail to perform, reactivity could increase contrary to the expectations. This means that reactivity control still relies on the good performance of safety systems, even if such system is extremely simple and hence its reliability is very high. It is not clear how the SFC safety principle will apply: through the connection of the primary system (fuel salt) to two independent expansion volumes, perhaps at different set points? Etc. Even if easy to implement, existing uncertainties and potential cliff-edge effects on this matter aggravates the score in one point and makes it become two for the actual distance and one for the potential distance.

As for the <u>barrier length</u> factor, fluid expansion will naturally occur in case of loss of first confinement barrier, leading to an inherent negative reactivity. This is why this phenomenon will not specifically contribute further to the total loss of confinement and gets the minimum score in both distances.

4.1.2.1.2 Heat Removal

As for the <u>initiating event</u> factor, the current MSFR design features an additional intermediate coolant circuit compared to a reference PWR plant in normal operating conditions. In addition, potential clogging due to fuel salt crystallization is still unclear. On the contrary, MSRs should simplify the design and make a step further towards intrinsic safety rather than engineering-based safety. This is why initiating triggering events on loss of heat removal score two in actual distance and one in potential distance.

As for the <u>barrier width</u> factor, the current MSFR heat removal function is not inherent to the system and relies on active and passive systems. The double coolant circuit makes its reliability decrease compared to the reference plant. On the other hand, in case of loss of heat removal, the disk-rupture type of valves should be designed in such a way to evacuate the fuel coolant to a safe deposit. However, there are still significant uncertainties dealing with the performance of these valves, which are frequently identified as one weak point in the design. Protection against loss of heat removal with intact reactor needs prompt reaction by draining the fuel coolant to the core catcher. During that time interval until full draining occurs, the fuel salt heats up and transfers the heat towards the structures, with the possibility of challenging the vessel integrity. If safety demonstration is provided showing that confinement is not loss due to reaching high temperatures along the entire transient, the barriers against loss of heat removal, clearly simpler against a reference plant, will also be more robust. In addition, being the fuel in liquid state, the number of design solutions for the safety systems able to cool the fuel down should be significantly higher than the reference plant with its fixed, rigid fuel rods. The fact that the fuel is in liquid state implies that it will not stay at a specific position. This turns into a drastic change in the fundamental approach to the heat-sink-fuel interaction: instead of designing the layout of the reactor in order to bring safety cooling systems to the fuel material, it is actually the fuel material the one that must be conducted to the safety cooling system. This **change in paradigm in plant safety response** in such fundamental aspect of the whole reactor safety should be very beneficial compared to reference plants and its consequences should be deeply investigated to take the most out of it. However, nowadays uncertainties are still high to confirm this point. This is why it scores 3 in actual distance and 1 in potential distance.

As for the barrier length factor, protection against loss of heat removal with intact reactor depends on two different mechanisms, namely an auxiliary cooling system plus backup consisting of draining plus subcritical fuel casing, while reference plants usually rely on two independent mechanisms, namely emergency feed water and feed & bleed. Both distances score two since it is unclear whether the total barrier length against loss of heat removal improves with MSFRs compared to reference plants.

4.1.2.1.3 Confinement

As for the initiating event factor, it benefits from integral reactor advantages in reducing the part of the system placed outside the vessel. Direct breaks affecting the vessel might then come from intermediate circuit breaks and primary pumps. In addition, routine draining or emergency draining can inadvertently open, but if opened, the primary barrier is still not lost. This is why the number of initiating events leading to loss of confinement scores 1 compared to reference plants.

As for the barrier width factor, loss of confinement has not been thoroughly analysed so far, where analytical efforts have focused on isolation configurations such as LUHS. Loss of confinement scenarios represent pros and cons compared to reference plants:

- In case of a break in the primary casing, the fuel coolant will leak to the reactor vessel and it should be drained downwards towards the subcritical fuel casing area. However, it is unclear how very small leakages will evolve and how small high-radiation hot spots will behave locally.
- Management of loss of confinement events in the MSFR seems to only deal with decreasing the temperature of the fuel salt whereas overpressure should not be a problem. Furthermore, reference plants need also to submerge the fuel in the coolant, which does not apply in the MSFR, hence much simpler management in preventing further losses of confinement barriers.
- Due to the fact that the primary coolant is mixed with fuel, FPs and gases, these accidents may evolve in a more complex manner compared to reference plants.
- Reference barriers, both static and dynamic, are very simple whereas MSFR features more complex configurations and subsystems underneath.
- Reference plants will only leak the primary coolant to containment whereas any FP (except for VLBLOCAs with fuel rod damage) will be kept stored inside the primary barrier. Instead, MSFR loss of primary confinement will directly put in contact FPs with the vessel, in addition, the fuel being in liquid state. This is why confinement barriers will need very high leak-tightness levels in order to prevent any leakage directly coming from the fuel material and releasing through subsequent barriers in case of DBA.
- Fuel in liquid state, when located next to a penetration, can easily migrate through it and release to the subsequent confinement barrier.

Loss of confinement events therefore represent some advantages and disadvantages over existing reference plants. If open issues dealing with the management of fuel coolant salts outside the fuel primary casing are solved successfully by providing robust safety demonstration of independent safety systems able to keep the integrity of the remaining barriers, confinement would be better achieved compared to existing plants. However, uncertainties are for the time being quite significant. This is why it gets 2.5 and 1.5 in actual and potential distance scores.

As for the barrier length factor, reference plants can make use of a long myriad of systems and barriers, i.e. dynamic and static, to tackle the challenge to the remaining barriers. These barriers look at reducing the pressure and temperature of the different environments and keeping the core submerged in the coolant. On the other hand, MSFR barriers compliance with the SFC needs to be further analyzed. For instance, what would it happen if the fuel coolant cannot be drained down to the subcritical fuel casing? Fans are senseless, spray function is unclear, etc. As a result, it scores 3 and 3 in both distances.

4.1.2.2 Processing / Storage Units

MSFR includes several in-parallel online reprocessing systems: off-gas, FPs and noble metals, and fissile material through breeding. It seems clear that MSR weakest point has to do with the fact that radioactive/ toxic sources are not kept only in the reactor but circulating beyond. According to the current design, it seems that all processing rooms are contained within the reactor vessel. It is unclear though how this can be the case considering the size of the entire processing rooms as well as the potential need for human actions, e.g. surveillance.

4.1.2.2.1 Reactivity Control

Some of the processing rooms carry and store fissile material subject to criticality. With the appropriate implemented measures, risk of criticality may be very low, but still it is an additional source of risk not present at reference plants.

As for the initiating event factor, the expected quantities of fissile material handled and stored should be sufficiently low –well below the critical mass. Due to the lack of information, it is not possible to assess if this risk can be precluded or not; nonetheless, it can be taken as safety objective that **the final design will prevent any criticality risk by inherent safety design**. If this is the case, then scores of 3 and 0 are assigned.

As for the barrier width and barrier length factors, the same reasoning applies: due to the lack of uncertainties and current risk, the score for the actual distance is 3, whereas prevention by natural means of any criticality risk will eliminate the need of safety barriers, hence the scores being 3 and 0.

As for the mobilized hazard factor, FPs are not processed in the reference plant, and this risk cannot disappear from the final MSFR design. This is why it scores 3 for both distances –applying for the three families of events.

4.1.2.2.2 Heat Removal

Just like prevention of criticality, **the risk of heat removal jeopardizing confinement barriers in processing rooms shall be avoided by inherent design**. This means, for instance, through high-reliability passive safety means with very high safety margins. Otherwise, the risk of confinement loss due to loss of heat removal in processing rooms will eliminate any advantage in nuclear safety at reactor level brought by MSRs.

Just like for reactivity control in the processing rooms, no initiating event shall lead to loss of confinement. If this is the case, the whole loss of heat removal event does not apply. Since this is not the case in the current situation, the actual distance is 3.

4.1.2.2.3 Confinement

Even if criticality cannot be reached and loss of heat removal shall not lead to loss of confinement, risk of loss of confinement itself cannot be screened out.

In terms of score of the different factors, namely initiating events, barriers width and length, the design of the processing units is not mature enough to proceed with the evaluation. Being clear that such risk is higher than the reference plant for the obvious reason that reference plants feature no reprocessing, a score of 3 for all families of events applies for both actual and potential distance.

4.1.2.3 Spent Fuel Pool

MSFRs shift the risk from the spent fuel pool of reference plants to the risk in processing rooms. As for the spent fuel pool, either it does not exist or its risk is much lower due to the much lower stored inventory.

No analysis at event level is needed since no SFP is considered in MSFRs in this report.

4.1.3 Assessment Results

Table 2 shows the results of the accident frequency pillar. Particular assigned assessments have already been discussed along previous chapters. Some general observations in light of the results follow:

- Significant differences between actual and potential distances –around 4 times lower the latter– are consequence of current large uncertainties in many fields of the MSFR.
- Potential distances are positive, which means that even if crediting the goals claimed by MSFR, still it is unclear whether the accident pillar will be more favourable when compared to reference plants.
- SFP as source of risk is eliminated in MSFR[7] but risk from reprocessing units shows up compared to reference plants.
- Quantitative assessment is inherently and purposely biased against MSFRs due to the exponential increase of X^y with X. In fact, 3^n grows faster than 2^n and $1^n=1$. Such bias turns out in aggravating MSFR in the increase in distances for the reprocessing units (3^4 against 2^4, inexistent for reference plants) compared to the decrease in distances for the SFP (inexistent for MSFR), turning into 406.25% positive against 93.75% negative for reprocessing units and SFP respectively for the actual distances.
- Quantification does not assign weights to the hazard sources, which means that it is assigning the same level of risk for the reactor, reprocessing units and SFP, whereas the SFP hazard source is much bigger than the reactor's, which in turn is much bigger than the reprocessing units, which is the most penalizing hazard source of MSFRs. If weights were assigned to $d_{S_{i,j}}$ accordingly, the results would obviously differ from the ones shown in Table 2.
- The accident pillar does not contain all the information regarding accident consequences. In fact, most aggravating consequences from most extreme accidents are linearly offset by their lower frequencies of occurrence. One could even say that lower frequencies somehow *hide* the impact of the extreme accidents in the concept of risk. This is the reason why a second pillar, dedicated only to looking into the worst-case conditions, have been taken out of the accident pillar and treated separately. And it is precisely the elimination of such worst-case releases one of the clear benefits that MSRs should bring compared to reference plants.

Table 2. Assessment of the MSFR Accident Pillar

Accident Pillar														
			FACTORS											
HAZARD SOURCE	EVENTS	WF	Initiating events		Barrier Width		Barrier Length		Mobilized hazard		Total Distance			
			A-Score	P-Score	A-Score	P-Score	A-Score	P-Score	A-Score	P-Score	Total A-Score	Total P-Score		
Reactor	Reactivity Control	0.1	1	1	2	1	1	1			4	1	A-Score	P-Score
	Heat Removal	0.5	2	1	3	1	2	2	2	1	24	2	18.4	2.9
	Confinement	0.4	1	1	2.5	1.5	3	3			15	4.5	15.00%	-81.88%
Reprocessing / Storage Units	Reactivity Control	0.1	3	2	3	2	3	2			81	24	A-Score	P-Score
	Heat Removal	0.2	3	2	3	2	3	2	3	3	81	24	81	63.9
	Confinement	0.7	3	3	3	3	3	3			81	81	406.25%	192.50%
Spent Fuel Pool	Reactivity Control	0.1	1	1	1	1	1	1			1	1	A-Score	P-Score
	Heat Removal	0.5	1	1	1	1	1	1	1	1	1	1	1	1
	Confinement	0.4	1	1	1	1	1	1			1	1	-93.75%	-93.75%
											100.4	67.8		
											109.17%	41.25%		

Source: JRC

[7] It is unclear for the time being the characterization of MSR SFPs, strongly depending on the MSR specific design in terms of neutron spectrum, breeder / burner type and open / closed cycle. For homogeneous MSRs with reprocessing, it is expected that SFPs become much smaller than current SFPs, since wasted U-238 that constitutes more than 90% of the SFP, should be "re-enriched" and back to the fuel coolant.

4.2 Worst-Case Offsite Releases Pillar

4.2.1 Open Issues / Benefits

4.2.1.1 Open Issues

4.2.1.1.1 Last-confinement source term

Description

Standard approaches for the calculation of offsite radioactive releases may rely in the first place on a generic approach consisting on the identification of a bounding representative generic scenario for core releases to the primary system and containment, complemented in the second place with the application of plant-specific boundary conditions. This generic source term released to the last-confinement barrier is called in-confinement source term. If such input information is known, e.g. via existing models for radionuclide release from the core material such as CORSOR or CORSOR-M [NRC, 1985], offsite radioactive releases can then be calculated by means of relatively simple equations in charge of accounting for any retention and transport mechanism, together with the chemistry activity specific of some radionuclides, such as iodine radioisotopes. Coupling this modelling with boundary conditions such as break size, filtering system, venting behaviour, etc., offsite releases can be predicted with acceptable accuracy.

Knowledge Gaps

- Accurate characterization of FPs –including gases and noble metals–: interaction with the salt fuel coolant, retention, dilution, precipitation and vapour pressure for the different species, –including ACPs–, location, flow rates, etc.
- Rough conservative estimates for the processing and storage units and rooms, together with a conceptual design for the management and safety barriers.

Suggested Solutions

- Identification and characterization of worst-case scenarios for each hazard source.
- Calculation of last-confinement source term via FP releases, transport and retention for each hazard source.
- Calculation of FP releases to the outside environment for each hazard source.
- Behaviour of fuel coolant salts in extreme conditions, i.e. long-term LUHS, and in different configurations. Behaviour of fuel coolant salt if there is a break –even small– in the subcritical area interface with the coolant salt.
- Identification of the entire spectrum of fuel salt configurations in direct or indirect (via LUHS) loss-of-confinement accidents. Analysis of thermal attack in the entire spectrum of configurations by the fuel coolant salt.

4.2.1.2 Benefits

Fuel coolant salt retention and continuous recycling of FPs including gases and noble metals is the most relevant benefit brought by MSRs dealing with the last-confinement source term. Such recycling avoids full storage of FP and noble gases within the reactor vessel, thereby diversifying the hazard source into smaller source terms. According to the impact that splitting the initial radioactive inventory into different sources has on the total risk as seen above, it is likely that such diversification is beneficial for the total plant risk.

4.2.2 Analysis and Assessment

Three variables drive radiological / toxic releases to the outside environment:

- **Last-Confinement Overpressure** (LCO). Without this driving force, only natural-driven convection and diffusion releases mainly by high temperature will take place at lower rate.
- **Last-Confinement Source Term** (LCST). This is the maximum credible radiological / toxic hazard located within the last two confinement barriers. Bounding last-confinement source term will mainly come from the reactor hazard source but also other sources should be analysed as well. The LCST should only account for the mobilized hazard source, which is a fraction of the LCST subject to be released, where the complementary fraction stays inside the last

confinement barrier due to deposition mechanisms and retention within the salt itself. Each hazard source, namely reactor and the different reprocessing units including fertile material modules, should have a representative, bounding LCST.

- **Last-Confinement Boundary Conditions** (LCBC). Offsite releases depend on the status of the last confinement barrier, which partly depends on the fuel salt configuration and interaction with the last confinement barrier.

4.2.2.1 Reactor Hazard Source

As regards the LCO factor, if non-condensable gases or vapours are not present, the pressure inside the confinement barriers should be low. However, the worst-case accident may come from a break in the subcritical fuel casing area so that the coolant fluid is mixed with the fuel coolant salt and the overall fluid mixture heats up and pressurizes the system. It is unclear if the mixing salt will reach the boiling point. Since there is no large containment space for the expansion of the fluid, high-pressure values might be reached. Due to the high uncertainties and lack of maturity in the design, assessment against reference plants is useless.

As regards the LCST factor, retention of FPs in the salt should make it lower than the reference plant. However, it is unclear how the fuel salt would behave in case of long-term LUHS. Furthermore, the absence of large containment drastically reduces the available surfaces for aerosol deposition while increasing the bulk temperature, so re-evaporation might occur. Due to the high uncertainties, assessment against reference plants is useless.

As regards the LCBC factor, it is unclear to know if the thermal attack would be enough to jeopardize the confinement barrier if the coolant in the subcritical area is lost. Due to the high uncertainties, assessment against reference plants is useless.

The worst-case scenario might therefore be taken as a primary loss-of-confinement with failure of the drainage valves, or loss-of-confinement combined with break caused by hot-spot temperatures in the subcritical area in such a way that the secondary coolant salt is eventually mixed with the fuel salt.

Due to the high uncertainties, analysis and subsequent assessment against reference plants is unfeasible at this stage.

4.2.2.2 Processing / Storage Units

Due to the high uncertainties, analysis and subsequent assessment against reference plants is unfeasible at this stage.

4.2.2.3 Spent Fuel Pool

No SFP is considered for MSFRs in this report.

4.2.3 Assessment Results

The lack of knowledge prevents performing a useful assessment. Nonetheless, based on the fundamental rationale behind MSRs, i.e. retention of FPs within the fuel coolant and continuous separation and reprocessing outside the reactor vessel, any worst-case scenario should lead to radioactive releases significantly much lower compared to reference plants.

5 Operability Goal

5.1 Reliability Pillar

5.1.1 Open Issues / Benefits

5.1.1.1 Open Issues

5.1.1.1.1 Characterization of Materials: Fuel Salt, Reprocessing Units and Structures

Description

NPPs' behaviour can be arranged twofold:

- At working performance level as a set of system layouts each of which characterized by a specific set of working conditions, called 'operating modes'.
- At accident level as a set of system layouts each of which representing a deviation from a specific set of boundary conditions dealing with safety variables, called 'plant states' or 'design basis conditions' (DBC). Each plant state is characterized by a maximum frequency of occurrence and linked to bounding limits regarding safety parameters –such as integrity of safety barriers or radiological consequences. In order to keep risk under a certain threshold, the higher the frequency, the lower the acceptable consequences.

Knowledge gaps are traditionally overcome through application of safety margins –or uncertainty quantification. Knowledge gaps must however be kept below a certain level compared to state-of-the-art knowledge for one particular subject. Otherwise safety demonstration is not feasible and the nuclear system cannot be operated according to the minimum safety standards. More severe accident scenarios against which there are no safety provisions to prevent fuel damage, categorized as DBC-4 or DEC-B [EUR, 2016], compensate the lack of knowledge with very low frequencies of occurrence. This is the residual risk accepted in the operation of reference nuclear systems. However, high-frequency scenarios cannot afford significant knowledge gaps, since otherwise it would not be possible to provide safety demonstration given that the residual risk would be such that radiological safety objectives exceed acceptable thresholds.

Thermodynamic and physicochemical properties of materials and interaction between fluids and structural materials are among the fundamental pieces of knowledge dealing with the design of any engineering system. They are part of any operating mode belonging to all DBCs –including DBC-1. This is why knowledge gaps are only acceptable in materials behaviour when limited to extreme conditions, such as creep failure by very high temperature, molten core porosity to surrounding fluids or thermal attack by dumped corium into the reactor lower plenum.

In conclusion:

- Knowledge gaps dealing with materials behaviour in normal operating conditions, i.e. DBC-1, belong to the field of plant reliability and not safety.
- Knowledge gaps dealing with materials behaviour in normal operating conditions, i.e. DBC-1, shall be extremely low compared to the state-of-the-art knowledge in this field.

Knowledge Gaps

Even though significant improvements have been made during the last 20 years, there are still important gaps in the full characterization of the fuel salt behaviour before irradiation and after irradiation –when FPs are present in the system. Moreover, MSRs usually include in-parallel online reprocessing for different systems: off-gas, FPs and noble metals, and fissile material through breeding. Each of these radiative and toxic streams needs to be accurately characterized as they constitute clear sources of risk. Furthermore, structural materials might significantly suffer from inherent problems brought by using molten salt, e.g. corrosion.

Suggested Solutions

- Full dynamic physicochemical and thermodynamic characterization of fuel salts through experimental tests with and without FPs.

- Chemical characterization of all processes carried out in the reactor including determination of uncertainty for all reprocessing modules.
- Assessment of existing information on structure materials under realistic conditions. If needed, additional experimental tests should be performed.

5.1.1.2 Benefits

No clear benefit dealing with reliability of MSFRs: operating experience is negligible, the number of supporting systems and human actions is unclear, and there are no reasons to assume that the complexity of the systems involved in operation is lower than reference plants'.

5.1.2 Analysis and Assessment

Reliability levels in reference plants are already very high to the extent that there is no need to improve them, so that there is no reason justifying the significant qualitative conceptual jump of the MSFR against reference plants in this particular GIF goal. Due to that, there is no need to break this pillar down into factors.

5.1.3 Assessment Results

MSFRs score 2 in the reliability pillar.

5.2 Flexibility Pillar

5.2.1 Open Issues / Benefits

5.2.1.1 Open Issues

No open issues identified.

5.2.1.2 Benefits

If the fuel content can be continuously adjusted, the system inertia to cope with the demand load is lower, which results in an easier, more flexible capacity for the electricity grid. Moreover, MSRs might also be coupled with *thermal buffers*, i.e. large salt repositories to store energy as thermal energy, whenever there is a decrease in the demand.

5.2.2 Analysis and Assessment

There is no need to break this pillar down into events, sources or factors, since MSFRs can be equal or more flexible than reference plants'.

5.2.3 Assessment Results

MSFRs score 1 in the flexibility pillar.

6 Security and Safeguards Goal

6.1 Security Pillar

6.1.1 Open Issues / Benefits

6.1.1.1 Open Issues

MSFRs distribute the hazard source into several locations, namely reactor vessel, processing rooms, storage rooms and fertile material. The existence of additional sources of radiological material makes the whole site more vulnerable for malicious acts.

6.1.1.2 Benefits

Just like with safety-related scenarios, the distribution of a single hazard source into many sources and locations make the consequences of security-related accidents less severe.

6.1.2 Analysis and Assessment

Two factors (not at event level) are considered: accident frequency and consequences.

Applying the same reasoning than for safety scenarios:

$$If\ F1 > F2\ and\ F1 > F3, then: R2 < R1$$

If security accidents are less frequent in processing rooms and storage rooms, and any other room different than the RPV containing radioactive / toxic material, then security-related accidents will present lower security concerns compared to reference plants.

6.1.3 Assessment Results

It is not possible to proceed with a realistic, useful assessment without clear information dealing with security aspects of MSFRs. Therefore, no assessment applies for this pillar.

6.2 Safeguards Pillar

6.2.1 Open Issues / Benefits

6.2.1.1 Open Issues

Contrary to reference plants, and as any fast reactor, MSFRs need high-enrichment fuel, which turns into a new matter of concern dealing with weapon-grade material.

Furthermore, MSFRs use reprocessed fuel embedded in salt initially in solid state and liquid for / during operation, rather than encapsulated in solid state without opening for recycling / handling activities. Therefore, accountability in this situation becomes more complex compared to reference plants.

6.2.1.2 Benefits

Being the fuel chemically bonded with salt, it can be beneficial from a safeguards standpoint since the resulting fissile density may decrease compared to the reference fuel rods. If looking at used material, then perhaps a fuel liquid irradiated and without any rigid confinement barrier such as the fuel rod itself, may become an added burden compared to reference plants.

Suggested Solutions

Analysis of safeguards of MSFR plants: identification / characterization of available sources aimed at / able to reach / or already featuring weapon-grade material; identification / characterisation of natural (e.g. high radiation), salt as fuel solvent / static (glovebox, walls, rooms, buildings, etc.) / administrative / natural barriers, i.e. high irradiation, to steal weapon-grade-sensitive sources; preliminary identification of postulated scenarios leading to steal weapon-grade-sensitive sources; design / management solutions.

6.2.2 Analysis and Assessment

There are three main factors driving the safeguards pillar:

- Weapon-grade material easiness for accountability, e.g. solid or liquid material, encapsulated or not, etc.
- Weapon-grade enrichment reached in the plant on permanent basis, temporarily or never, in one location or multiple locations onsite;
- Weapon-grade enrichment material easiness for transportation, e.g. it has high or low irradiation.

6.2.3 Assessment Results

There is not enough information to make an accurate, useful assessment on this goal. Only generic statements at this stage can be given, such that security issues should not be higher than reference plants, whereas safeguards is likely to be a weak point of MSFRs compared to reference plants.

7 Preliminary Top-Level SART

Table 3 shows a preliminary, top-level, MSR-generic SART where the safety activities have been derived from the analysis and comparative assessment shown in the previous sections.

As it has been already mentioned, this first SART application goes beyond safety, comprising the other two *S*, namely security and safeguards, and also reliability in operation –even if only at a high level without entering into an in-depth analysis.

Suitability on the open issues is measured as an efficiency at issue level. It is noted that each issue comprises a set of specific open issues.

The suitability efficiency is quantified via four factors:

1. **State of the art**. The lower the SOA, the higher the need to focus on the issue. SOA is quantified from 0.1 (very low knowledge) to 1 (full knowledge).
2. **Priority**. Open issues are related one another. The assigned priority applies to each open issue as a family of issues of the same type. Even if an open issue depends on other issues as inputs, there can be specific open issues within the open issue that might be launched without the need of waiting until all inputs are fully closed. Priority looks at ranking how prompt the issue must be addressed and closed within the whole safety work plan. Priority is quantified between 1 and 10, where lower values stand for issues requiring higher number of open issues as inputs and / or not requiring immediate action. Open issues are further marked in two different colours upon whether they are inputs (green) or outputs (blue) of the safety design: inputs are imposed design criteria, on one hand, and initial and boundary conditions, onto the other, whereas outputs are figures of merit or results of the design. Since inputs and outputs are related one another, the degree of dependence –which is indicated quantitatively by the priority value– turns the colour code within the green and blue class into a scale of colours of higher and lower intensity. Figure 3 shows the colour coding assigned to the priority factor and its correspondence with numbers.
3. **Fitness**. This factor assesses MSRTF capabilities in addressing the necessary tasks for the issue. MSRTF main core of expertise are analytical dealing with calculations and system codes in the field of safety, and also on structural materials. In addition, analytical activities are easy to address due to the fact that no extra budget is needed, with the potential exception of the licensing fees of simulation software tools. Fitness ranges between 1 and 10.
4. **Criticality**. An open issue is critical if it constitutes a showstopper or green light for triggering other open issues, or if a certain outcome constitutes a necessary condition for the design (otherwise the design should be modified or even rejected). The higher the critical the open issue, the higher the impact. Critical factor ranges between 1 and 10. The score comes from assuming that critical open issues can be modified at this stage of the design (otherwise this factor would be binary and get either 1 or 10), so that if the results do not meet with the expectations, still there is room for MSR viability. The higher the critical factor, the lower the flexibility to accommodate the design.

7.1 The critical factor as a necessary condition for the design

Many open issues can be solved by applying different solutions. These solutions are not vital for the MSR design: they have just to be applied to close the issue.

However, there are issues that need compliance with certain imposed conditions, e.g. top safety requirements. Such issue is not closed by merely finding a solution to the issue, but a specific solution matching with the imposed condition. Such condition is indeed a top safety requirement of the MSR design.

For instance, characterization of accident scenarios per se is not critical: the evolution must be known in advance as part of the design, but the outcomes are flexible as long as they meet with the safety limits. Conversely, a certain degree of system inertia to inherently not exceed safety limits is a condition to the design, for instance, a minimum grace period in terms of necessary human actions and perhaps also safety system actuation. If such grace period is less than a certain threshold, the design is not accepted or must be drastically modified. Another example may be the worst-case source term: it must be proved –even at conceptual stage– that this source term is well below reference source terms with high confidence.

7.2 Suitability Index Results

The suitability index is calculated as follows:

$$SI_1[\%] = \frac{\left(P \cdot F \cdot (1 - SOA)\right)^{\frac{C}{10}}}{90} \cdot 100$$

This way, giving more importance to the critical factor over the others.

In order to make this assessment robust, the suitability index is calculated in a different way:

$$SI_2[\%] = \frac{(P \cdot F \cdot C)/_{SOA}}{10^4} \cdot 100$$

Table 3 shows the results of the suitability efficiency for the two simple indexes and the averaged one at family of open issues level, including the type of gap and the score of the factors influencing the index.

Suitability indexes are therefore figures of merit resulting from different weighting techniques of the relevant factors affecting the importance of each open issue and the added value brought by MSRTF to close the open issue.

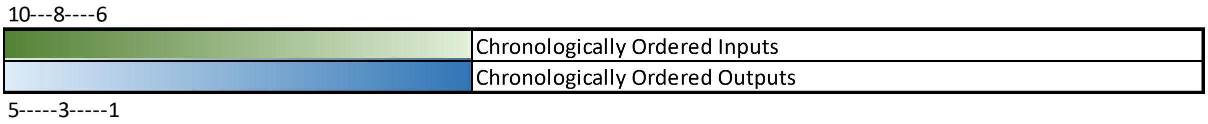
As it is shown in Figures 4 and 5, both algebraic expressions lead to quite similar suitability indexes, which increases the robustness of the results. Exceptions of issues not ranking high in both SI_1 and SI_2 should not be addressed with priority.

When taking the arithmetic average of SI_1 and SI_2, see Figure 6, the three families of open issues ranking the highest are the followings:

1. **Top safety requirements** is the first task to be addressed by MSRTF. Such ranking is driven by the key importance that top safety requirements have in driving the whole plant design, but also on MSRTF capabilities, expertise and easiness (not experimental tests are necessary) in carrying out the task. In fact, clear top safety requirements are key in informing plant design, even more since MSRs belong to GIV and as such, safety requirements are more challenging than for reference plants. Requirements may comprise different aspects of nuclear performance and design such as grace periods, number of safety barriers, safety principles, maximum allowable radioactive releases, etc.
2. **Characterization of structural materials under (normal) operational conditions** ranks high because this is basic knowledge and critical as showstopper for the entire SMR design: structural materials need to meet with top-level safety requirements as they are key constituents of the safety barriers.
3. Identification of **last-confinement boundary conditions** to be coupled with the in-confinement source term in order to compute the radioactive releases to the offsite environment. This task is sensitive since one of the most challenging safety requirements imposes no significant dose consequences beyond the site boundary. But at the same time, this task depends on accurate information on structural materials and fuel salt behaviour and therefore it cannot be addressed at first even if critical. MSRTF may contribute with long expertise in the field of severe accidents and calculation of source term and radioactive releases, even more since no experimental testing for this open issue is foreseen, which makes it easier to close.

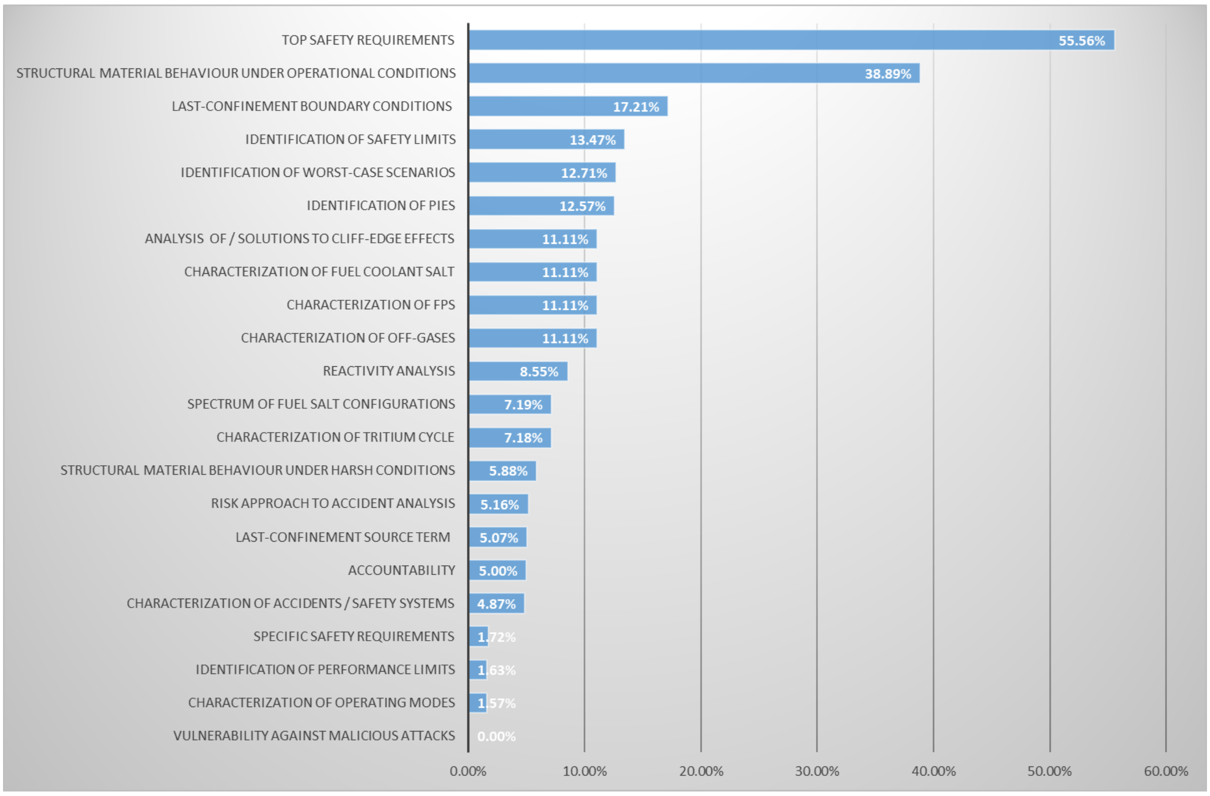
Appendix 1 shows the rationale supporting the suitability index assigned to each open issue.

Figure 3. Input / Output classification of Open Issues



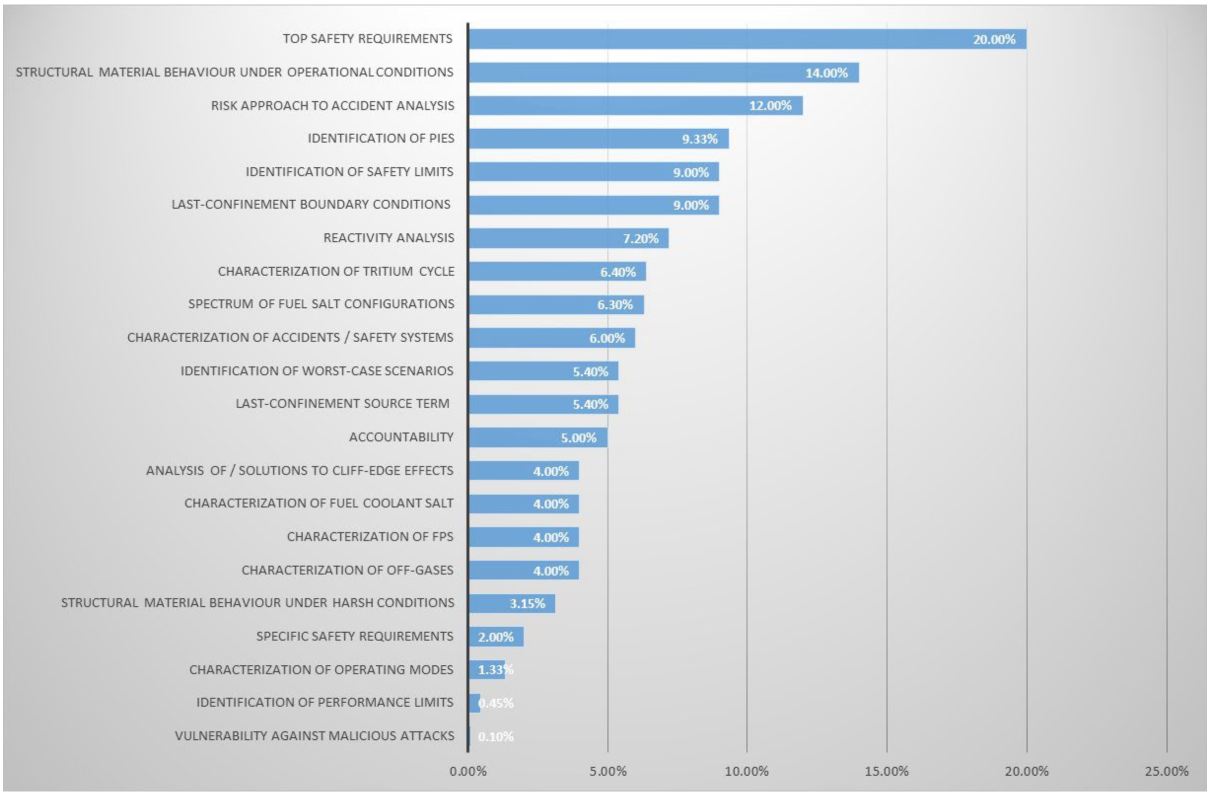
Source: JRC

Figure 4. Open Issue Suitability Index arranged per SI1



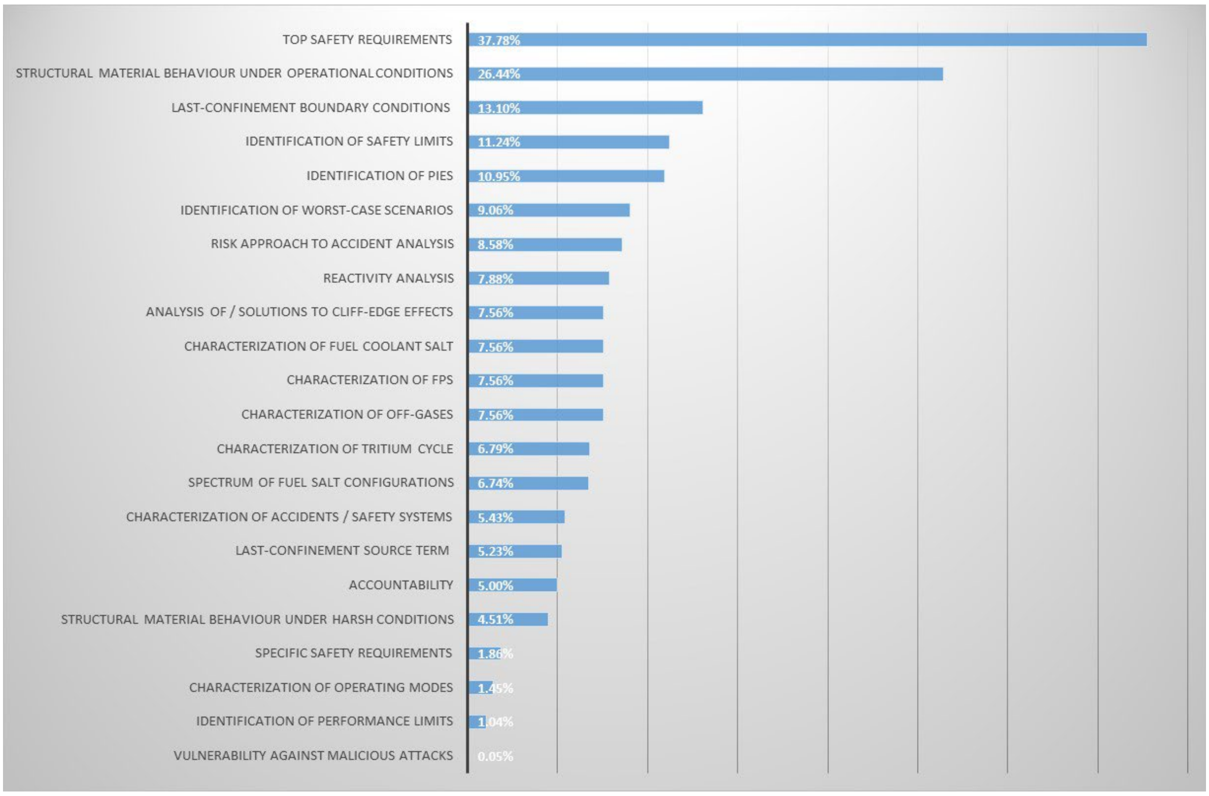
Source: JRC

Figure 5. Open Issue Suitability Index arranged per SI2



Source: JRC

Figure 6. Arithmetic average of Open Issue Suitability Index SI1 and SI2



Source: JRC

7.3 Safety Work Plan

Table 4 shows the safety work plan, with a rough estimate of allocated needed resources for each open issue, distinguishing between formal development and preliminary / updating activities for each task with filled and diagonal strip patterns. This safety work plan shows also the dependency between the open issues in their chronological arrangement. The work plan arranges safety activities chronologically upon the criticality and priority factors, hence not directly from the suitability index.

It is noted that the allocation of resources (as converted in time duration) is done at relative and not absolute level, i.e. each cell does not account for a certain time; it just gives an indication of the expected resources between open issues.

Issues needed of experimental testing have been directly allocated a minimum of four cells whereas the allocated time of the analytical issues have relied upon the expected efforts.

8 Conclusions and Future Steps

MSR is a revolutionary technology concept for energy production and storage based on nuclear energy. According to the design, which is nowadays at a very preliminary stage, it may solve two out of the most significant long-standing problems associated with nuclear energy: nuclear waste and risk of severe offsite contamination.

The EC-JRC G.I.4 Unit has launched a dedicated task force on MSRs (abbreviated as MSRTF) with the aim of becoming a coordination reference centre at EU level on harmonizing safety, coordinating safety-related activities and sharing experience and knowledge. Convergence of efforts at EU level into a single road –rather than multiple roads in parallel– is key to speed up MSR deployment for energy production and storage. JRC G.I.4 will build their knowledge and capabilities upon the unique and long experience of more than two decades gained by JRC G.I.2 Unit.

The very first activities of the MSRTF consist of developing a safety work plan through the identification of open issues and gaps related to MSR safety. Such analysis will allow, on one hand, to have a clear overall picture of the MSR safety state of the art and how they relate one another and arrange them in time, and onto the other, to identify which activities fit the best with the MSRTF capabilities.

A list of open issues and gaps is developed together with a safety work plan for the arrangement in time, placing the tasks in relation one another and showing the expected resources needed to close each of them. According to Table 3 and Figure 6, the open issues deserving prompt action from MSRTF are the top safety requirements and structural material behaviour under operational conditions.

As for the former, this open issue scores 10 in priority, 10 in critical, 10 in fitness and 0.5 in SOA. The main goal is twofold:

a) Comprehensive analysis of internationally agreed safety frameworks to identify those applying to MSRs. The highest standards on safety shall drive the MSR design and operational performance. Identification of safety approach for MSR licensing activities dealing with safety.
b) Specification to the maximum extent possible, even qualitative-to-quantitative conversion whenever feasible, of the safety requirements.

As for the latter, this open issue scores 10 in priority, 10 in critical, 7 in fitness and 0.5 in SOA. The main goal is the analysis of the long-term interaction with molten salts and high-energy neutrons at high temperature in normal operating conditions.

As already reflected in the MSRTF vision, namely (i) safety harmonization –both in approach and content–, (ii) activities coordination –both analytical and experimental–, and (iii) sharing of MSR R&D activities, run transversal to all activities carried out by MSRTF. This is why the selected open issues –outcomes of the current report, as well as for any other open issue in the future–, will include a dedicated section on networking and dissemination so that the following two objectives are met all the way:

1) Identification of the best tools ensuring harmonization, coordination and sharing as previously stated;
2) Agreement in the efforts made and achieved results with the MSR stakeholders EU-wide.

The subsequent actions will consist of addressing the open issues upon their position in the suitability index ranking, and developing a project plan for each of them starting from the first ones, i.e. top safety requirements and structural material behaviour under operational conditions. The outcomes of the project plan are a list of detailed activities, type and estimate of MSRTF allocated resources. Any development performed by the MSRTF will keep in mind the driving framework concepts of safety harmonization, activities coordination and knowledge sharing at EU level.

After agreement on the safety gap analysis and safety work plan, the subsequent actions will consist of addressing the open issues upon their position in the suitability index ranking, and developing a project plan for each of them starting from the first ones. The outcomes of the project plan are a list of detailed activities, type and estimate of MSRTF allocated resources. Any development performed by the MSRTF will keep in mind the driving framework concepts of safety harmonization, activities coordination and knowledge sharing at EU level.

Table 3. MSFR List and Classification of Open Issues

GOAL	PILLAR	NO.	ISSUE	DESCRIPTION	APPROACH	TOOLS	INPUT	OUTCOMES	GAP	PRIORITY	CRITICAL	SOA	FITNESS	EFFICIENCY 1	EFFICIENCY 2	AVG EFFICIENCY
Safety	Accident	1	Identification of PIEs	Identification of full-scope Postulated Initiating Events at conceptual design stage, with emphasis on internal events and all modes of operation	Analytical	Literature survey, FMEA, HAZOP, PRA, Master Logic, etc.	White Paper MSRE, literature	Preliminary full-scope list of PIEs: all PIE hazards for all hazard sources and all operational modes	+ Resource - R&D	8	7	0.6	10	12.57%	9.33%	10.95%
		2	Identification of Safety Limits	Identification and quantification of thresholds beyond which safety is challenged (e.g. equivalent to US NRC 10 CFR 50.46)	Analytical / Experimental	Analysis / Operating Experience / Testing	SAMOFAR 15, 16, 17, 18	List of safety figures of merit and quantification (equivalent to PCT, CET, cladding oxidation limit, etc., for existing NPPs)	- Resource + R&D	5	9	0.2	4	13.47%	9.00%	11.24%
		3	Characterization of Accidents / Safety Systems	Iterative process of analysis of accident evolution and plant response (identification of safety systems and performance)	Analytical / Experimental	Deterministic Simulations / Testing	White Paper 1, 2, 6, 7, 10, 15, 16, 17, 20	Accident evolution including plant response below the safety limits	- Resource + R&D	3	5	0.2	8	4.87%	6.00%	5.43%
		4	Risk Approach to Accident Analysis	Conceptual quantification of full-scope risk for all PIE hazards and hazard sources	Analytical	FMEA, PRA, Fault Trees	White Paper 3	Preliminary estimate of accident frequencies	Resource	3	5	0.1	8	5.16%	12.00%	8.58%
		5	Top Safety Requirements	Identification of / compliance with high-level informing safety requirements	Analytical	Expert Judgement	White Paper	Fundamental Safety Principles	Resource	10	10	0.5	10	55.56%	20.00%	37.78%
		6	Spectrum of Fuel Salt Configurations	Identification of fuel salt geometrical layouts in accident conditions	Analytical / Experimental	Simulation / Testing	10, 17, 20	Fuel salt configurations and interaction with confinement barriers	R&D	3	7	0.2	6	7.19%	6.30%	6.74%
		7	Characterization of tritium cycle	Generation and handling; safety barriers; throughputs, location, etc.	Analytical	Calculation Literature Review and OE	Tritium generation in fast reactors; Processing rooms conceptual design of MSFR 15	Maximum tritium limits, conceptual design throughputs, conceptual design of tritium safety approach (static / dynamic barriers, safety response, filtering, programmed and non-programmed releases, etc.)	Resource R&D	8	6	0.3	4	7.18%	6.40%	6.79%
		8	Specific Safety Requirements	Identification of specific safety requirements	Analytical	Expert Judgement	White Paper 3, 5	Specific Safety Requirements	Resource	1	2	0.1	10	1.72%	2.00%	1.86%
		9	Reactivity Analysis	Analysis of reactivity of the chosen molten salt against controlled and beyond-controlled events	Analytical	Neutronic software tools coupling with T-H	Design Literature 17	Reactivity coefficients (void, T, etc.)	R&D	6	6	0.5	10	8.55%	7.20%	7.88%
		10	Structural material behaviour under Harsh Conditions	Short-term (performance under harsh conditions) interaction with molten salts during DEC-B accidents, e.g. high temperature, loss of safety systems, etc.	Experimental	Testing	SAMOFAR, work done by JRC-Karlsruhe 17, 20	Status of confinement barriers, pressure and temperature evolution, interaction with working fluids including heat sinks	R&D	6	7	0.4	3	5.88%	3.15%	4.51%
	Worst-Case	11	Identification of Worst-Case Scenarios	Identification of source term bounding accident(s)	Analytical	Expert Judgement	White Paper 3, 5, 10	Selection of worst-case scenario (or scenarios)	+R&D - Resource	3	9	0.5	10	12.71%	5.40%	9.06%
		12	Last-Confinement Source Term	Maximum credible radiological / toxic hazard located within the last two confinement barriers	Analytical / Experimental	Simulation / Testing	11, 13	Phase-wise FP group releases for each hazard source (reactor, process rooms, storage rooms, fertile material)	- Resource + R&D	1	9	0.1	6	5.07%	5.40%	5.23%
		13	Last-Confinement Boundary Conditions	Status of last confinement barrier depending on fuel salt configuration and interaction with last confinement barrier	Analytical	Calculations Expert Judgement	Plant design 6, 11	Boundary conditions dealing with the status of the confinement barriers, filtering, uncontrolled / controlled leakages, pressure differences, etc.	- Resource + R&D	3	9	0.3	10	17.21%	9.00%	13.10%
		14	Analysis of / Solutions to Cliff-Edge Effects	Energetic phenomena, large / early releases, practically eliminated condition phenomena, e.g. Q2 explosion, salt interaction, etc.	Analytical / Experimental	Simulation / Testing	SAMOFAR 5, 15, 16, 17, 18	Equivalent 'practically eliminated conditions' phenomena are identified and screened out by intrinsic mechanisms	- Resource + R&D	5	10	0.5	4	11.11%	4.00%	7.56%
Reliability	Hazard Sources	15	Characterization of off-gases	Generation and handling; safety barriers; throughputs, location, etc.	Analytical / Experimental	Simulation / Testing	SAMOFAR Other related projects	Flowrates, stored quantities and evolution at radionuclide level	R&D	10	10	0.5	2	11.11%	4.00%	7.56%
		16	Characterization of FPs	Generation and handling of all FPs except gases (including actinides); safety barriers; throughputs, location, etc.	Analytical / Experimental	Simulation / Testing	SAMOFAR Other related projects	Flowrates, stored quantities and evolution at radionuclide level	R&D	10	10	0.5	2	11.11%	4.00%	7.56%
		17	Characterization of fuel coolant salt	Full knowledge of physicochemical (thermodynamic, thermalhydraulic, precipitation, solubility, etc.) and nuclear properties	Experimental	Testing iteratively fed by HAZOP	Work done by JRC Karlsruhe	Basic data to model the operation in all operating modes	R&D	10	10	0.5	2	11.11%	4.00%	7.56%
		18	Characterization of Operating Modes	Identification and characterization at conceptual design stage of all modes of operation and definition of safe state	Analytical	Literature / Expert Judgement	Design concept Oerating Experience	Set of variables and configurations characterizing each Operational Mode together with the definition of safe state	Resource	10	1	0.6	8	1.57%	1.33%	1.45%
		19	Identification of Performance Limits	Identification of Operating Conditions and Limiting Conditions for Operation (T, P, rates, head losses, etc.)	Analytical	Calculation / Expert Judgement	Work done by JRC Karlsruhe 3, 15-18	E.g. maximum pressures, leakages, tritium limit per room / facility, etc. to trigger control / protection actions	R&D	3	3	0.4	2	1.63%	0.45%	1.04%
	Materials	20	Structural material behaviour under Operational Conditions	Long-term (normal operating conditions) interaction with molten salts and high-energy neutrons at high temperature	Experimental	Testing	SAMOFAR Work done by JRC Karlsruhe	Basic data to model the operation in all operating modes	R&D	10	10	0.5	7	38.89%	14.00%	26.44%
Security & Safeguards	Security	21	Vulnerability against malicious attacks	Analysis of security-related scenarios	Analytical	Simulation	Operating Experience Design concept	Analysis of accident scenarios and consequences dealing with malicious attacks	Resource R&D	1	1	0.1	1	0.00%	0.10%	0.05%
	Safeguards	22	Accountability	Weapon-grade material accountability in view of the hazard source diversity in terms of location, handling, solid / liquid state; facilty for transportation, etc.	Analytical	Calculation Event Tree	16	Hazard Inventories Analysis of malicious events	Resource R&D	5	10	0.1	1	5.00%	5.00%	5.00%

Source: JRC

Table 4. Safety Work Plan

OPEN ISSUE	NO.	PRIORITY	CRITICAL	APPROACH	INPUT	SAFETY WORK PLAN
Top Safety Requirements	5	10	10	Analytical	White Paper	
Characterization of off-gases	15	10	10	Analytical / Experimental	SAMOFAR Other related projects	
Characterization of FPs	16	10	10	Analytical / Experimental	SAMOFAR Other related projects	
Characterization of fuel coolant salt	17	10	10	Experimental	Work done by JRC Karlsruhe	
Characterization of Operating Modes	18	10	1	Analytical	Design concept Oerating Experience	
Structural material behaviour under Operational Conditions	20	10	10	Experimental	SAMOFAR Work done by JRC Karlsruhe	
Identification of PIEs	1	8	7	Analytical	White Paper MSRE, literature	
Characterization of tritium cycle	7	8	6	Analytical	Tritium generation in fast reactors; Processing rooms conceptual	
Reactivity Analysis	9	6	6	Analytical	Design Literature	
Structural material behaviour under Harsh Conditions	10	6	7	Experimental	SAMOFAR, work done by JRC-Karlsruhe	
Identification of Safety Limits	2	5	9	Experimental	SAMOFAR 15, 16, 17, 18	
Analysis of / Solutions to Cliff-Edge Effects	14	5	10	Analytical / Experimental	SAMOFAR 5, 15, 16, 17, 18	
Accountability	22	5	10	Analytical	16	
Characterization of Accidents / Safety Systems	3	3	5	Analytical / Experimental	White Paper 1, 2, 6, 7, 10, 15, 16, 17, 20	
Risk Approach to Accident Analysis	4	3	5	Analytical	White Paper 3	
Spectrum of Fuel Salt Configurations	6	3	7	Analytical / Experimental	10, 17, 20	
Identification of Worst-Case Scenarios	11	3	9	Analytical	White Paper 3, 5, 10	
Last-Confinement Boundary Conditions	13	3	9	Analytical	Plant design 6, 11	
Identification of Performance Limits	19	3	3	Analytical	Work done by JRC Karlsruhe 3, 15-18	
Specific Safety Requirements	8	1	2	Analytical	White Paper 3, 5	
Last-Confinement Source Term	12	1	9	Analytical / Experimental	11, 13	
Vulnerability against malicious attacks	21	1	1	Analytical	Operating Experience Design concept	

Source: JRC

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Abbreviations

BOL	Beginning of Life
C_{ij}	Radioactive / toxic inventory *i* split into *j* sources
EOL	End of Life
F_i	Accident frequency associated to source *i*
FMEA	Failure Modes and Effects Analysis
FP	Fission Product
GIF	Generation IV International Forum
HAZOP	Hazard and Operability S
HEU	Highly Enriched Uranium
ICO	In-confinement overpressure
LCBC	– Last-confinement boundary conditions
LCST	Last-confinement source term
LEU	Low Enriched Uranium
LoERF	Large or Early Release Frequency
LUHS	Loss of Ultimate Heat Sink
MSFR	Molten Salt Fast Reactor
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
MSRTF	Molten Salt Reactor Task Force
NPP	Nuclear Power Plant
PIE	Postulated Initiating Event
PRA	Probabilistic Risk Assessment
R_i	Risk related to radioactive / toxic source
RPV	Reactor Pressure Vessel
SI	Suitability Index
SFP	Spent Fuel Pool
SSC	Structure, System and Component

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Appendix 1 Synthesis of Open Issues and Suitability Index

1. Identification of PIEs

1.1 Synthesis

FIELD	CONTENT
No.	1
Description	Identification of full-scope Postulated Initiating Events at conceptual design stage, with emphasis on internal events and all modes of operation
Approach	Analytical
Tools	Literature survey, FMEA, HAZOP, PRA, Master Logic, etc.
Gap	Mostly resource-based but also R&D-based to complete technology-dependent PIEs, e.g. stemming from fuel coolant salt behaviour not applicable in reference plants
Input	White Paper, SAMOFAR, literature
Outcomes	Preliminary full-scope list of PIEs: all PIE hazards for all hazard sources and all operational modes

1.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	8	Identification of PIEs is an input activity at preliminary stage. Nonetheless, new PIEs can be identified, or former PIEs can be readjusted, as knowledge increases
Critical	7	Even if at conceptual stage, PIEs inform the design and orient R&D efforts to pinpoint potential weaknesses that might need design modifications or further investigation
SOA	0.6	Most of the efforts towards PIEs identification have been done in SAMOFAR project and the White Paper
Fitness	10	Long expertise in this field; no need of allocating budget, only desktop activities

2. Identification of Safety Limits

2.1 Synthesis

FIELD	CONTENT
No.	2
Description	Identification and quantification of thresholds beyond which safety is challenged (e.g. equivalent to US NRC 10 CFR 50.46)
Approach	Analytical and Experimental
Tools	Operating Experience, Analysis and Testing
Gap	Mostly R&D-based since many aspects dealing with the physicochemical behaviour of molten salts and structural materials are unknown. Also resource-based since some of the safety limits might already be derived from accumulated knowledge in the literature
Input	SAMOFAR 15, 16, 17, 18
Outcomes	List of safety figures of merit and quantification (equivalent to PCT, CET, cladding oxidation limit, etc., for existing NPPs)

2.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	5	This family of open issues needs several inputs
Critical	9	Safety limits, safety margins, and control and operation margins, need to feature a certain flexibility and relatively wide distances between the working region and the challenging region. Knowledge of these aspects is critical to inform the design and it can even become a showstopper for the design if margins are too narrow
SOA	0.2	Long Operating Experience and high expertise in the fields of nuclear physics and thermal-hydraulics have led to the establishment of solid safety margins with due conservatisms implemented. However, fuel molten salts introduce a new field of phenomena to the other two aforementioned ones, namely chemistry through precipitation, solubility, interaction with structural materials, etc. This is why existing, robust safety limits, such as PCT, local or integral cladding oxidation limits, or even core damage figures of merit, lose their meaning when applied to MSRs.
Fitness	4	Identification of deterministic safety limits fall under the field of safety analysis where strong and long expertise within MSRTF is found. However, allocated budget for new experiments is needed. Furthermore, the type of experiments necessary to determine the safety limits are more challenging than those necessary to characterize the system behaviour under normal operating conditions.

3. Characterization of Accidents / Safety Systems

3.1 Synthesis

FIELD	CONTENT
No.	3
Description	Iterative process of analysis of accident evolution and plant response (identification of safety systems and performance)
Approach	Analytical / Experimental
Tools	Deterministic Simulations / Testing
Gap	Same rationale than for open issue 2, namely R&D efforts mostly needed even if some material is already available
Input	White Paper 1, 2, 6, 7, 10, 15, 16, 17, 20
Outcomes	Accident evolution including plant response below the safety limits

3.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	This task needs to be fed by many other open issues
Critical	5	This task looks at a full characterization of accidental operation conditions including plant response and design improvement through feedback process. The results are not critical to the MSR design feasibility since boundary values and margins are fixed by other open issues, namely worst-case related issues and identification of safety limits respectively
SOA	0.2	Significant developments have been done, however, the current knowledge is still not enough even for a conceptual / preliminary stage of the design
Fitness	8	This task needs deterministic safety analysis through software tools, where high expertise in MSRTF is gathered, together with testing (about which, comments on the previous issue applies)

4 Risk Approach to Accident Analysis

4.1 Synthesis

FIELD	CONTENT
No.	4
Description	Conceptual quantification of full-scope risk for all PIE hazards and hazard sources
Approach	Analytical
Tools	FMEA, PRA, Fault Tree
Gap	Full resource-based gap. This task is not intended to perform a full, in-depth level PRA, but to assess frequencies at a more conceptual level, where assignments of generic frequencies is also possible. This approach therefore does not need to perform experimental testing for equipment failure probability quantification.
Input	White Paper 3
Outcomes	Preliminary estimate of accident frequencies

4.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	This task needs to be fed by open issue 3 which in turn needs be fed by many others
Critical	5	Not a critical task: it supports design informed by risk through unveiling weak points in the design
SOA	0.1	No probabilistic analysis performed so far
Fitness	8	Expertise in applying probabilistic tools is high within MSRTF

5 Top Safety Requirements

5.1 Synthesis

FIELD	CONTENT
No.	5
Description	Identification of / compliance with high-level informing safety requirements
Approach	Analytical
Tools	Expert Judgement
Gap	Full resource-based gap.
Input	White Paper
Outcomes	Fundamental Safety Principles

5.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	This is a full input type of open issue: it does not rely on other open issues but the other way around
Critical	10	MSRs are GIV reactors. As such, they need to align with the latest plant safety response requirements on inherent safety, passive safety, grace periods, portable equipment, safety objectives, etc. This means that top-level safety requirements shall guide the design and not the other way around, i.e. they do not have to be derived from de-facto design and safety features. For instance, decay heat removal is very likely the most challenging safety aspect faced by any NPP. MSRs, as any other GIV design, must necessarily rely on an extremely highly reliable plant response. Such high confidence in the response is addressed by so-called inherent safety or passive safety, meaning plant response with none or very low dependence on any system or human action. This top-level requirement on safety strongly drives (and limits) the reactor design in such a way that any design must meet with it, with no room for flexibility. Furthermore, and as it has already been pointed out in the report, MSRs represent a huge jump from reference plants, and that is clearly a trade-off that should be justified by improvements in other fields, one of which is sustainability, the other one being safety. So safety should be addressed just in line with the maximum standards in safety as achieved in other 3rd-plus generation plants and GIV plants. The same goes for statements on the "practically eliminated conditions", Emergency Planning Zones, etc.
SOA	0.5	The *white paper* has already made significant efforts here, but still more determination in clearly specifying the requirements is needed to reflect the statements made in the rationale of the critical factor. Moreover, it should also be clear that such top safety requirements are not derived, or even are not dependent on the MSR design but independent from them and before them.
Fitness	10	MSRTF gathers long and strong expertise in this field.

6 Spectrum of Fuel Salt Configurations

6.1 Synthesis

FIELD	CONTENT
No.	6
Description	Identification of fuel salt geometrical layouts in accident conditions
Approach	Analytical / Experimental
Tools	Simulation / Testing
Gap	Full R&D gap
Input	10, 17, 20
Outcomes	Fuel salt configurations and interaction with confinement barriers

6.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	Closing of this open issue requires solid knowledge on fuel salt and structural materials behaviour under operating and accidental conditions, namely mild and harsh environments
Critical	7	This task is critical to inform the design. Fuel salts may lead to a change in paradigm dealing with solving the decay-heat-removal safety challenge: if the salt may be kept as liquid, it can be conducted to the coolant position rather than the other way around, which can at least provide an additional degree of flexibility to succeed in fulfilling this critical safety function. In turn, fuel salt configuration is also critical because it can jeopardize confinement barriers, because coolant is not separated from the fuel – hence being a coolant with generated internal heat– or it can adopt undesired configurations not suitable for decay heat removal, which makes this open issue key for safety and design optimization
SOA	0.2	Due to the high sensitivity of this phenomenon on the behaviour of fuel salts and structural materials, the achieved knowledge here is far from maturity
Fitness	6	MSRTF may contribute through safety analysis and testing by, e.g. postulating representative scenarios, and by supporting / performing lacking experimental tests

7 Characterization of tritium cycle

7.1 Synthesis

FIELD	CONTENT
No.	7
Description	Generation and handling; safety barriers; throughputs, location, etc.
Approach	Analytical
Tools	Calculation Literature Review and OE
Gap	R&D- and resource-based gap. Safety approach to tritium handling can benefit from cumulative experience in the field. However, analytical efforts for modelling tritium handling will be needed. Tritium control was identified as one of the main issues of the MSRE project [WASH-1222].
Outcomes	Maximum tritium limits, conceptual design throughputs, conceptual design of tritium safety approach (static / dynamic barriers, safety response, filtering, programmed and non-programmed releases, etc.)

7.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	8	Inputs to close this family of issues slightly depend on clarifying other issues, such as overall handling of off-gases
Critical	6	Even if it may drastically affect the design, tritium is not critical as design showstopper.
SOA	0.3	Examples in industry of tritium safety approach may be applied though to a certain extent, since in the case of MSRs, tritium will be first released directly in the molten salt and afterwards separated from other FPs and only then treated.
Fitness	4	Tritium handling requires highly specialized knowhow not featured by MSRTF. Conversely, safety approach to tritium still falls under safety assessment and as such, MSRTF can provide added value

8 Specific Safety Requirements

8.1 Synthesis

FIELD	CONTENT
No.	8
Description	Identification of specific safety requirements
Approach	Analytical
Tools	Expert Judgement
Gap	Full resource-based gap. This is the fundamental product of the extensive analysis performed through all the other activities. This activity therefore has a clear path whose results will not alter or impair the design at this stage.
Input	White Paper 3, 5
Outcomes	Specific Safety Requirements

8.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	1	Bottom-level safety requirements will only be specified after extensive analysis and knowledge is acquired, among others, on accident analysis and system properties
Critical	2	Bottom-level safety requirements do not guide the design so they do not require immediate resolution
SOA	0.1	The path ahead before this level of detail in the design can be achieved is very long
Fitness	10	MSRTF has long experience in safety approach and it can contribute in specifying bottom-level safety requirements

9 Reactivity Analysis

9.1 Synthesis

FIELD	CONTENT
No.	9
Description	Analysis of reactivity of the chosen molten salt against controlled and beyond-controlled events
Approach	Analytical
Tools	Transport software tools
Gap	R&D-based gap
Input	Design Literature 17
Outcomes	Reactivity coefficients (void, T, etc.)

9.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	5	It needs some inputs and it is also input for another open issues
Critical	6	It does not have to be promptly addressed; however, it is important for the salt selection and to accommodate one of the advantages of MSRs, namely inherent reactivity control
SOA	0.5	Some studies have been developed in academia, from which further analysis should be elaborated to close this issue
Fitness	10	Knowledge and expertise in the field of transport analysis makes this open issue fit well with MSRTF

10 Structural material behaviour under Harsh Conditions

10.1 Synthesis

FIELD	CONTENT
No.	10
Description	Short-term (performance under harsh conditions) interaction with molten salts during DEC-B accidents, e.g. high temperature, loss of safety systems, etc.
Approach	Experimental
Tools	Testing
Gap	R&D-based gap
Input	SAMOFAR (cf., e.g. [Benes, 2013] and [Benes, 2020]) 17, 20
Outcomes	Status of confinement barriers, pressure and temperature evolution, interaction with working fluids including heat sinks

10.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	5	This family of open issues depends on several resource-consuming inputs at basic level
Critical	7	Harsh conditions occur whenever first 3 levels of defence in depth fail. Harsh conditions are already extreme for reference plants in terms of structural materials. This is why, even if relevant, the behaviour of materials under extreme conditions do not guide the design at a preliminary stage or constitute a showstopper, as it is the case for less severe environment conditions
SOA	0.4	Structural materials under extreme conditions are partly known, e.g. bounding temperatures, overpressures, creep failure, thermal attack, dynamic events, etc. However, deep knowledge is lacking dealing with fuel molten salt interaction
Fitness	3	This open issue needs experimental tests to be solved. Experience in structural materials within MSRTF is valuable and can provide added value, even though dedicated experimental tests under extreme conditions may absorb significant resources and be extremely challenging

11 Identification of Worst-Case Scenarios

11.1 Synthesis

FIELD	CONTENT
No.	11
Description	Identification of source term bounding accident(s)
Approach	Analytical
Tools	Expert Judgement
Gap	R&D-based and resource-based gap, since most of the identification can be based on expert judgement but the analysis itself also needs R&D efforts
Input	White Paper 3, 5, 10
Outcomes	Selection of worst-case scenario (or scenarios)

11.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	Identification of worst-case scenarios builds on DBAs, which need therefore be addressed previously in open issue 3 complemented with open issue 10
Critical	9	This open issue is critical to make sure, since the first steps in the design, that the enveloping undesired consequences meet with the highest safety standards, and in particular with selected top-level safety requirements in open issue 5. If such enveloping scenario, equivalent to, e.g. NUREG-1465, already leads to LoERF, the design should not proceed or drastically modified
SOA	0.5	No study so far has addressed this matter in detail; however, dedicated efforts on DBAs help identify bounding scenarios
Fitness	10	Long experience field of severe accidents make this open issue fully in line with MSRTF capabilities

12 Last-Confinement Source Term

12.1 Synthesis

FIELD	CONTENT
No.	12
Description	Maximum credible radiological / toxic hazard located within the last two confinement barriers
Approach	Analytical / Experimental
Tools	Simulation / Testing
Gap	LCST needs major R&D efforts and cannot be extrapolated from reference plants
Input	11, 13
Outcomes	Phase-wise FP group releases for each hazard source (reactor, process rooms, storage rooms, fertile material)

12.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	1	This open issue requires other previous issue to be addressed first
Critical	9	This score follows the same reasoning than for the previous open issue
SOA	0.1	No
Fitness	6	Long experience field of severe accidents make this open issue fully in line with MSRTF capabilities as regards the analytical part. However, experimental testing in harsh conditions are likely needed, and such tests might be complex to address given the extreme conditions typical of a worst-case evolution, and especially related to FP releases

13 Last-Confinement Boundary Conditions

13.1 Synthesis

FIELD	CONTENT
No.	13
Description	Status of last confinement barrier depending on fuel salt configuration and interaction with last confinement barrier
Approach	Analytical
Tools	Calculations Expert Judgement
Gap	Mostly an R&D activity but also support on literature and expert judgement can play a role in imposing interfacing conditions dealing with the last confinement barrier
Input	Plant design 6, 11
Outcomes	Boundary conditions dealing with the status of the confinement barriers, filtering, uncontrolled / controlled leakages, pressure differences, etc.

13.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	This open issue is next to last open issue hence right at the very end of the safety work plan
Critical	9	This open issue is necessary to determine the boundary conditions for the calculation / implementation of the last-confinement source term, which is in turn key for MSR acceptance as viable GIV NPP solution
SOA	0.3	Significant knowledge gaps prevent making a reasonable estimate, even at this conceptual / preliminary stage, of the boundary conditions dealing with the worst-case scenario on radioactive releases
Fitness	10	If the necessary information is available, MSRTF expertise in the field of safety analysis and source term may significantly contribute in this open issue

14 Analysis of / Solutions to Cliff-Edge Effects

14.1 Synthesis

FIELD	CONTENT
No.	14
Description	Energetic phenomena, large / early releases, practically eliminated condition phenomena, e.g. Q2 explosion, salt interaction, etc.
Approach	Analytical / Experimental
Tools	Simulation / Testing
Gap	Mostly an R&D activity but also support on literature and expert judgement can play a role in analysing cliff-edge effects and come up with potential solutions
Input	SAMOFAR 5, 15, 16, 17, 18
Outcomes	Equivalent 'practically eliminated conditions' phenomena are identified and screened out by intrinsic mechanisms

14.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	5	This open issue is located around in the middle of the safety work plan
Critical	10	High-confidence results in avoiding energetic phenomena leading to extreme undesired consequences is a showstopper in the design or it can lead to drastic design modifications
SOA	0.5	Further elaboration on the acquired knowledge is necessary and shall be promptly addressed as soon as the necessary information is available following with the top-level safety requirements
Fitness	4	Long experience in the field of severe accidents within MSRTF makes it suitable to address this open issue. However, challenging experiments might be complex to develop since they involve potential energetic phenomena

15 Characterization of off-gases

15.1 Synthesis

FIELD	CONTENT
No.	15
Description	Generation and handling; safety barriers; throughputs, location, etc.
Approach	Analytical / Experimental
Tools	Simulation / Testing
Gap	Full R&D-based open issue
Input	SAMOFAR Other projects
Outcomes	Flowrates, stored quantities and evolution at radionuclide level

15.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	This is a full input of the safety work plan belonging to basic knowledge, i.e. the fundamental pieces the entire building of safety and design relies upon
Critical	10	It is necessary to characterize well the full cycle of off-gases to proceed with open issue 3 dealing with the set of accident scenarios related to this hazard source
SOA	0.5	Significant efforts made but still a long way before reaching sufficient knowledge
Fitness	2	The comprised tasks do not fit with MSRTF expertise

16 Characterization of Fission Products

16.1 Synthesis

FIELD	CONTENT
No.	16
Description	Generation and handling of all FPs except gases (including actinides); safety barriers; throughputs, location, etc., for all hazard sources (reactor vessel, reprocessing rooms, storage rooms, fertile material locations, etc.)
Approach	Experimental
Tools	Simulation / Testing
Gap	Full R&D-based open issue
Input	SAMOFAR Other related projects
Outcomes	Flowrates, stored quantities and evolution at radionuclide level

16.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	Same rationale than previous open issue
Critical	10	Same rationale than previous open issue
SOA	0.5	Same rationale than previous open issue
Fitness	2	Same rationale than previous open issue

17 Characterization of fuel coolant salt

17.1 Synthesis

FIELD	CONTENT
No.	17
Description	Full knowledge of physicochemical (thermodynamic, thermal-hydraulic, precipitation, solubility, etc.) and nuclear properties
Approach	Experimental
Tools	Testing iteratively fed by HAZOP
Gap	Full R&D-based open issue
Input	Work done by JRC G.I.2 Unit (former G.I.3)
Outcomes	Basic data to model the operation in all operating modes

17.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	Same rationale than previous open issue
Critical	10	Same rationale than previous open issue
SOA	0.5	Same rationale than previous open issue
Fitness	2	Same rationale than previous open issue

18 Characterization of Operating Modes

18.1 Synthesis

FIELD	CONTENT
No.	18
Description	Identification and characterization at conceptual design stage of all modes of operation and definition of safe state
Approach	Analytical
Tools	Literature / Expert Judgement
Gap	Full resource-based open issue since no calculation or operation is required
Input	Design concept Operating Experience
Outcomes	Set of variables and configurations characterizing each Operational Mode together with the definition of safe state

18.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	No other open issues as inputs
Critical	1	No need for prompt attention
SOA	0.6	Knowledge based on reference plants and conceptual design as inputs. However, the full reactor characterization including processing / storage rooms lacks of due analysis in terms of operating modes and safe state definition
Fitness	8	Expertise in safety analysis and assessment within MSRTF is the basis to address this task

19 Identification of Performance Limits

19.1 Synthesis

FIELD	CONTENT
No.	19
Description	Identification of Operating Conditions and Limiting Conditions for Operation (T, P, rates, head losses, etc.)
Approach	Analytical
Tools	Calculations / Expert Judgement
Gap	Full R&D-based open issue
Input	3, 15 – 18 (cf., e.g. [Benes, 2013] and [Benes, 2020])
Outcomes	E.g. maximum pressures, leakages, tritium limit per room / facility, etc. to trigger control / protection actions

19.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	3	This open issue is located towards the end in the safety work plan. It builds from accident safety analysis experimental testing in 15-18 open issues, but it should not need additional dedicated experiments (since all the information for the selection of the operating conditions and LCSs should be already present in the experiments
Critical	3	This open issue interfaces operation and safety and it is not critical to proceed with the design since the solutions are compatible with high standards of safety –contrary to safety limits, open issue 2
SOA	0.4	Some knowledge but still not sufficient to complete the LCOs. Given the key differences compared to reference plant, this open issue may need to allocate a significant number of resources
Fitness	2	Even if related to safety, LCOs should derive partly from the safety limits (on the safety side) and working conditions (on the operating, reliability side)

20 Structural material behaviour under Operational Conditions

20.1 Synthesis

FIELD	CONTENT
No.	20
Description	Long-term (normal operating conditions) interaction with molten salts and high-energy neutrons at high temperature
Approach	Experimental
Tools	Testing
Gap	Full R&D-based open issue
Input	SAMOFAR (cf., e.g. [Benes, 2013] and [Benes, 2020])
Outcomes	Basic data to model the operation in all operating mode

20.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	10	This open issue belong to the category of fundamental knowledge within which it is not possible to perform any reliable safety analysis and assessment
Critical	10	Structural material response on normal and abnormal and accident conditions must meet a minimum standards of safety and reliability. This is why this open issue may constitute a showstopper for the design and should be promptly addressed and closed
SOA	0.5	Some knowledge acquired but still significant efforts in R&D under realistic conditions, e.g. high neutron flux, interaction with FPs, tritium permeability, etc.
Fitness	7	This open issue may benefit from MSRTF expertise in structural materials. However, most of the activities would require performing complex, risk experimental tests

21 Vulnerability against malicious attacks

21.1 Synthesis

FIELD	CONTENT
No.	21
Description	Analysis of security-related scenarios
Approach	Analytical
Tools	Simulation
Gap	Resource-based and R&D-based open issue
Input	Operating Experience Design concept
Outcomes	Analysis of accident scenarios and consequences dealing with malicious attacks

21.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	1	Security scenarios are to be analysed at the very end of the safety work plan
Critical	1	Security scenarios are not guiding / informing / blocking the design
SOA	0.1	No analysis on security scenarios has been performed and made publicly available
Fitness	1	There are other teams especially looking at security issues but this issue is out of scope MSRTF's field of relevance

22 Accountability

22.1 Synthesis

FIELD	CONTENT
No.	22
Description	Weapon-grade material accountability in view of the hazard source diversity in terms of location, handling, solid / liquid state; ease of transport, etc.
Approach	Analytical
Tools	Calculation Event Tree
Gap	Resource-based and R&D-based open issue
Input	16
Outcomes	Hazard Inventories Analysis of malicious events

22.2 Suitability Index Factors

FACTOR	VALUE	RATIONALE
Priority	5	This open issue can be addressed upon basic knowledge on FPs and fuel
Critical	10	This open issue needs special treatment as it can be one of the weakest points of MSRs involving HEU fuel and reprocessing
SOA	0.1	No information is available for the time being
Fitness	1	There are other teams especially looking at security issues but this issue is out of scope MSRTF's field of relevance

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