



EU kNowleDge hUb foR enAbling MolteN Salt ReaCtor safety development and dEployment

D4.1 -PIRT for modelling needs





Grant agreement No	101165896
Project name	ENDURANCE
Project full title	EU kNowleDge hUb foR enAbling MolteN Salt ReaCtor safety development and dEPloyment
Topic	EURATOM-2023-NRT-01-03 Nuclear Research and Training
Start of project	1 st October 2024
End of project	30 th September 2028
Project website	https://www.endurance-msr-project.eu/
Project officer	Mykola DZUBINSKY European Commission
Project coordinator	Stefano Lorenzi – Energy Department - Politecnico di Milano
Deliverable Title	PIRT for modelling needs
Deliverable ID	D4.1/WP4/T4.1
Responsible partner	CEA
Authors	Barbara Forno, Elena Martin Lopez, Frédéric Bertrand
Nature	Report
Dissemination Level	PU (Public)
File name	ENDURANCE_D4.1_PIRT_v1.docx
Revision	V1
Due date of deliverable	31 st March 2026
Actual submission date	30 th May 2026

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Status / Issue:		1.0
Date Last Change:	30/05/2026 18:54:00	



Document History:	
17/03/2026	First Version
25/05/2026	Final revised version

Approvals

Date	Name and organisation	Role
20/04/2026	Nathalie Girault (ASNR)	Reviewer and WP4 leader
25/05/2026	Stefano Lorenzi (POLIMI)	Reviewer and Scientific Coordinator



Executive Summary

Within the framework of the ENDURANCE Project, a Phenomena Identification and Ranking Table (PIRT) exercise was conducted to support R&D efforts prioritization in order to improve scientific knowledge and safety studies during the design process for molten salt reactor (MSR) technologies. Moreover, the insights from this PIRT will feed scientific topics to be tackled in other tasks of ENDURANCE Project WP4.

The objective of the PIRT was to identify the main physical phenomena governing the reactor behavior especially during accidental conditions, and to rank them according to their importance in the sequence of events during the accident and their level of knowledge or uncertainty. This structured approach allows the identification of knowledge gaps that may affect safety studies and provides guidance for future research activities.

The PIRT exercise was performed by an expert panel from ASNR (L'Autorité de sûreté nucléaire et de radioprotection), CEA (Commissariat à l'énergie atomique et aux énergies alternatives), POLIMI (Politecnico di Milano), POLITO (Politecnico di Torino) and PSI (Paul Scherrer Institut).

The exercise was carried out for the ARAMIS-P reactor developed within the ISAC project focused on three main relevant accidental transients: the Unprotected Transient Over Power (UTOP), the Station Black-OUT (SBOUT) and the Loss Of Fuel-Coolant Accident (LOFCA).

The analysis relied on a structured methodology based on two tools: the Generic Event Tree (GETs) and the Phenomena Evaluation Chart (PECs). GETs describe the possible evolutions of accident sequences from the initiating event to the final reactor state, depending on the impact of key physical effects or system actions (e.g., effectiveness of reactivity feedbacks or actuation of safety systems). PECs complement this analysis by describing the accident progression in terms of the underlying physical phenomena. These tools enable the systematic identification of the relevant phenomena governing the considered transients, including their associated time and spatial scales, and the definition of related Figures of Merit (FoM) that serve as evaluation criteria to assess the safety importance of each phenomenon and to support the subsequent ranking process. The scope of the PIRT covers phenomena that may occur up to the failure of the second confinement barrier (guard vessel and emergency storage tank).

Based on these analyses, PIRT tables were constructed and discussed within the expert panel in order to assign rankings of all the identified phenomena regarding both their importance and knowledge level. The results support the identification of priority research areas such as future experimental programs and will support the upcoming developments of computational tools and calculations methodologies in support of MSR safety analyses and technological deployment.

For the UTOP transient, the highest-priority phenomena are mainly associated with pressure-wave effects, compressible multiphase flow, salt density increase and radionuclide/species transport. In particular, fuel density increase induced by wave compression and salt packing due to bubble removal from the core region are directly linked to the local evolution of salt density and void fraction, and therefore to the reactivity evolution during the UTOP sequence. Other



important phenomena, such as multiphase flow through the off-gas line, migration of salt species to bubbles, and actinide precipitation on cold surfaces of the Emergency Storage Tank (EST), are relevant to pressure management, salt composition evolution, source-term assessment and confinement performance.

For the SBOUT transient, the main priority phenomena are associated with passive decay heat removal, salt thermal behaviour, corrosion mechanisms, salt chemistry, phase changes and long-term salt management in the EST. The results highlight the importance of freezing in the DHR loop pipes, corrosion increase driven by redox and radiolysis potential evolution, multiphase flow through the off-gas line, actinide precipitation on cold surfaces of the EST, salt mass solidification, species precipitation including actinides, redox-driven phase changes and air ingress in the EST. These phenomena may affect salt coolability, salt composition evolution, local distribution of fissile material, subcriticality margins in the EST, source-term assessment and confinement integrity.

For the LOFCA transient, fewer phenomena exceed the selected priority threshold compared with UTOP and SBOUT. Nevertheless, the identified high-priority issue is critical for confinement assessment. The main priority is the breakthrough of the guard vessel with downward relocation of the fuel salt. Salt and compound vaporization and radionuclide release due to excessive pressure in the guard vessel remain closely connected to this issue, as they may contribute to pressure build-up, source-term mobilization, thermal and chemical loading of the guard vessel, and potential loss of confinement.

Only 3 phenomena with discrepant votes among partners (measured as the difference between the maximum and the minimum vote larger than 6) were identified and they have an average ranking lower than 6, thus showing that for the most important and uncertain phenomena partners agreed on the scores. The highest scores were recorded for UTOP, followed by SBOUT and then LOFCA. The order between SBOUT and LOFCA was unexpected. The uncertainties for UTOP and SBOUT are comparable and higher than those associated with LOFCA phenomena. In the future, it would be valuable to extend this exercise to different MSR concepts for a broader applicability of the PIRT.

A major outcome of this work is the prioritization of FoMs and associated phenomena to guide future R&D planning. The main priority areas include fast reactivity-feedback and compressible multiphase phenomena, salt relocation and venting, radionuclide/species transport, salt chemistry and actinide precipitation in the EST, passive decay heat removal and phase change, corrosion and chemical behaviour, and guard vessel integrity during late-phase salt relocation. These priorities should guide the development and validation of calculation tools and the planning of dedicated experimental programmes.

Finally, the PIRT exercise was conducted specifically for the ARAMIS-P concept. The description of the accident sequences and the associated phenomena is therefore inherently linked to this design. Extending the methodology to other MSR concepts would help assess the robustness and broader applicability of the conclusions obtained here, distinguish concept-specific phenomena



from more generic MSR safety issues, and support the development of a broader R&D roadmap for MSR deployment.



Acronyms

DHR	Decay Heat Removal
DHX	Decay Heat Exchanger
EST	Emergency Storage Tank
FoM	Figures of Merit
GET	Generic Event Tree
IHX	Intermediate Heat Exchanger
LOFCA	Loss Of Fuel and Coolant Accident
PEC	Phenomenological Event Chart
SBOU	Station Black-OUT
UTOP	Unprotected Transient Over Power

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1. Introduction

In the ENDURANCE project, the main objective of Task 4.1 is to develop a PIRT tailored and oriented to typical MSR transient scenarios to identify and rank all safety-related phenomena and processes that should be simulated and taken into account in the safety related design process for MSR systems. The PIRT was done in about one year with the objective to feed R&D performed in other work packages. Moreover, considering the early design stage of MSRs, it was dedicated to three emblematic transient families and limited to sequence events taking place inside the two first confinement barriers of the ARAMIS-P reactor.

An expert panel study was organized to identify phenomena of interest in order to address issues in the field of neutron physics, thermal hydraulics, chemistry and mechanics. However, aspects related to molten salt chemistry and the behavior of fission product radionuclides were included but not addressed in detail. Indeed, addressing them comprehensively would require a dedicated exercise and a panel of experts specializing in this field. Some transverse design and safety experts were also associated and have led the PIRT. While traditional PIRTs are dependent in some ways on the reactor design, the present analysis is aimed at identifying major phenomena playing a role in accident sequence of events and assessing the modelling and experimental needs to better understand and describe accident scenario consequences for reactor safety.

The methodology consists thus in identifying elementary phenomena that are crucial to accident progression, highly relevant for safety, and associated with a high level of uncertainties due to lack of knowledge in the field. Within this framework, this exercise aims to outline the phenomena and related parameters that must be adequately represented in analytical tools and computational chains, in order to improve the reliability and robustness of safety analyses. It also helps identify areas requiring further experimental characterization and would help for the organization of dedicated experimental programs.

The ARAMIS-P reactor was selected for the exercise. The extrapolability of the exercise to other concepts is a perspective of this work. ARAMIS is a 300MWth chloride-fueled, loop-type fast reactor with a homogeneous core currently under development within the French ISAC project [1]. Three representative accidental transients have been analyzed within this PIRT task: Unprotected Transient Overpower (UTOP), Station-Black Out Transient (SBOUT), and Loss of Fuel Coolant Accident (LOFCA).

The exercise was carried out in several phases. First, CEA provided PIRT tables of macroscopic events with associated Figures of Merit (FoM). The PIRT tables have been discussed among partners in a dedicated meeting and some revisions were agreed. In a second phase of the work, each partner has individually voted for the importance and uncertainties of each phenomenon. The results were collected, analyzed, and synthesized. Then they were discussed in a dedicated meeting, particularly where discrepancies in the partners' votes arose. The detailed methodology followed during the work is described in the next paragraph.

1.1 Description of the general methodology

Molten salt reactors exhibit specific characteristics that require adaptation of the standard safety considerations applied to other types of reactors. In summary, this type of reactor is relatively new, and there is limited operational experience available. A key distinguishing feature is the composition of the fuel salt, which requires specific control during reactor operation and is subject to significant uncertainties. The salt can be refueled online, meaning its composition may change over time; this aspect must also be taken into account under accident conditions. Furthermore, molten salt reactors are characterized by a salt



chemistry that differs substantially from that of solid-fueled reactors, involving the behavior of a hot, corrosive, and radioactive fluid. They also exhibit strong neutronic–thermal coupling. Finally, the fuel is distributed across multiple locations rather than confined solely to the core region. Even in accidental scenarios, it is necessary to address the voluntary or spurious drainage of the liquid fuel, its relocation, its cooling and the prevention of recriticality.

When applied to selected accidental sequences of interest for Molten Salt Reactors (MSRs), the PIRT methodology aims specifically at identifying phenomena that combine high safety significance with a high degree of uncertainty [2]. These phenomena represent priority areas for research and development. The analysis of PIRT results should foster a broad expert consensus on safety-related phenomena where substantial uncertainties remain, with the following objectives:

- Improve the reliability of accidental sequence analyses by reducing uncertainties,
- Provide a structured framework for defining and prioritizing the R&D program required to reduce these uncertainties.

Therefore, PIRT analysis helps to identify which accident sequences and associated phenomena require additional efforts to decrease uncertainties, especially in situations where coupled phenomena and/or successive stage of events must be considered. It also provides guidance for structuring research activities aimed at improving modelling capabilities and reducing knowledge gaps.

To support the construction of PIRT tables elaborated within this task, similar approach as the one presented in [3] has been applied, where structured analytical tools such as the Phenomenological Event Tree (PET or PEC) and the Generic Event Tree (GET) have been used. Their scope is the following:

- **The Phenomenological Event Tree (PEC)** focuses on the sequence of physico-chemical phenomena following a generic initiating event. It emphasizes the physical behavior of the reactor and related phenomena of the studied accidental sequence
- **The Generic Event Tree (GET)**, in contrast, describes both the progression of the main physical phenomena taking into account safety systems, thereby illustrating the general evolution of accident scenarios and their potential consequences.

In practice, PECs detail the relationships among key physical phenomena within each branch of the GET. Together, they are particularly useful for characterizing the physical response of the reactor within the evolution of the accidental sequence, with relevant reactor states described in the GETs, which are characterized by macro phenomena and their interactions with safety systems. These states are structured through “headings,” which act as branching points in the GET and can be analyzed in detail using PECs, which provide a deeper insight of phenomena evolution.

In the present work, for each accidental transient considered, dedicated PECs and GETs were developed to describe both the physical behavior of the reactor and the response of its safety systems throughout the sequence. The PIRT tables were therefore constructed based on these analyses. Each phenomenon was identified from the decomposition of the accident sequence into successive time periods. This temporal segmentation allowed grouping phenomena into macrophenomenon that are consistent in terms of time scale, space scale. Figures of Merit (FoM) were then associated with each macro-phenomenon. These last act as an evaluation criterion and can be defined as a physical quantity relevant for assessing the impact of various phenomena in the accidental sequence.



Subsequently, each partner independently assessed and voted on the importance and uncertainty level of each identified phenomenon within the elaborated PIRT tables for each selected transient. The final stage consisted of consolidating and analysing the results to establish a ranked list of the most important and most uncertain phenomena.

Regarding the ranking of phenomena according to their importance, the following general criteria apply:

- **High-importance phenomena:** These have a strong impact on safety and on the accidental sequence (i.e., associated with high risk, combining high consequence and high probability). They must therefore be modelled with high accuracy in computational tools and investigated through dedicated experimental programs.
- **Medium-importance phenomena:** These have a moderate safety impact. Experimental investigations and analytical modelling remain necessary, though with lower priority.
- **Low-importance phenomena:** These have limited or negligible safety impact. Simplified or approximate modelling is generally sufficient.

Concerning the ranking of knowledge levels, the literature [6] generally distinguishes:

- **Well-known phenomena (little uncertainty):** Calculation tools are validated against an extensive experimental database, and associated uncertainties are low.
- **Moderately known phenomena (moderate uncertainty):** The basic physical mechanisms are understood, but knowledge is incomplete in certain parameter ranges, with significant uncertainties when extrapolating to reactor-scale conditions.
- **Poorly known phenomena (high uncertainty):** Very limited experimental data exist, and no fully validated models are available. These phenomena typically represent priority areas for future research, especially if associated with high importance ranking.

Overall, the PIRT methodology provides a transparent, structured, and consensus-driven framework for identifying safety-relevant knowledge gaps and prioritizing research efforts. This approach is particularly valuable for emerging technologies such as MSRs, as it supports the development of robust safety designs and strengthens the foundation for safety assessment.

1.2 Context and presentation of the ARAMIS-P reactor

Within the scope of strengthening the credibility and maturity of MSR technology, CEA and Orano launched in 2020 a dedicated R&D program focusing on the fuel cycle and transuranic actinide management in Molten Salt Reactors. This initiative led to the development of the ARAMIS-P design [7], a loop-type MSR concept specifically dedicated to plutonium management. ISAC brings together five major French stakeholders - CEA, CNRS, EDF, Framatome and Orano - combining complementary expertise in reactor design, operation and fuel management. The project aims to evaluate both the potential benefits and the associated risks of MSR technology; to characterize the feasibility of this integrated solution and to propose R&D, including experiments, on the main hurdles: chemistry, corrosion, materials.

ARAMIS-P is a 300 MWth fast-spectrum MSR focused on the flexibility of plutonium burning service. The selected fuel salt is $\text{NaCl-MgCl}_2\text{-PuCl}_3$. Chloride salts provide harder neutron spectrum compared to fluoride salts, making them more suitable for plutonium conversion. From a chemical point of view, chloride salts also offer favorable plutonium solubility compared with fluoride salts. The selected

intermediate salt is NaCl-MgCl_2 , primarily for chemical compatibility considerations with the fuel salt. Regarding reactor architecture, ARAMIS-P adopts a loop-type fuel circuit configuration. The system is composed of six fuel loops. Each loop includes a shell-and-tube heat exchanger able of removing at least $50 \text{ MW}_{\text{th}}$, and primary pump to ensure fuel salt circulation. Finally, three intermediate loops transfer the thermal power generated in the fuel loops to the power conversion system. Figure 1.1 shows a detailed scheme of the architecture of ARAMIS-P with main components.

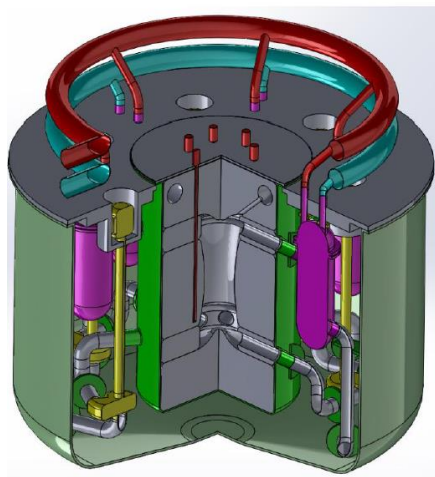


Figure 1.1 : ARAMIS-P architecture scheme with main components

Table 1.1 sums-up main data concerning the nominal conditions of ARAMIS-P reactor.

Table 1.1: Nominal conditions of ARAMIS-P reactor

Conditions	Unit	Value
Nominal Power	MW_{th}	300
Core power density	W/cm^3	250
Conversion target	$\text{Kg}/\text{TWhe Pu}$	130
Core inlet temperature	$^{\circ}\text{C}$	570
Core outlet temperature	$^{\circ}\text{C}$	650
Fuel loops number	-	6
Heat exchangers type	-	Shell and tubes
Pumps type	-	Rotodynamic

2. Presentation of accident sequences studied in the PIRT

Several elements are first provided in this section in order to explain the rationale of the accident sequence choice for the PIRT. First, the following section is aimed at providing a general description of the event sequence associated with each accident family. This description will be illustrated by generic event trees (GETs) and phenomenological event chart (PECs), in order to visualize the sequence evolution and its various phases [3].

As introduced in previous section, the GETs enables to describe the various possible evolutions of the accident sequences starting from the initiating event and leading to the final state of the reactor. This



evolution is determined by the success or failure corresponding to the headings of the trees. For instance, one of the headings is the efficiency of the reactivity feedbacks (physical effect) but it could be as well, the efficiency of the reactor shutdown system (system action).

The PECs describe the interrelation between physical phenomena involved during the accident and their related consequences on its subsequent evolution. Among other things, considering a molten salt reactor, it describes the interrelation between the salt temperature/pressure/density evolution and the reactivity feedbacks. Most of the phenomena of the PECs should be tackled by modelling them in calculation tools. Finally, together with safety systems they govern the bifurcation of the accident sequences represented in GETs.

2.1 Accident sequence selection

The PIRT analysis has been performed to prioritize R&D needs by evaluating the importance and uncertainty of phenomena with respect to selected FoM. Considering the pre-conceptual design stage of a reactor, like that of the ARAMIS-P working horse, it is not necessary to describe too much in detail accident sequences. For instance, the progressivity of their evolution or system actions are not yet decided at this stage of the design and would be too specific to be studied compared to still unknown physic basics of such a reactor.

Therefore, only representative families of accidents have been retained:

- Reactivity insertions (transient overpower, TOP) because this family induces reactivity effects, very important to take into account in the design of a fast reactor;
- The total loss of active systems (station blackout accident, SBO) that enables to assess the capability of a reactor design to remove decay heat without any active system and to assess the reactor cooling issues;
- The loss of fuel and of coolant accident (LOFCA) that enables to tackle the specificity of molten salt reactors in terms of confinement. Actually, in case of breach in the fuel circuit, among other things, depending on the boundary conditions (thermal, chemical), the chemical composition of the spilled molten salt may change, potentially leading to the subsequent radiological releases.

2.2 (U)TOP (unprotected transient overpower)

GETs and PECs describing the evolution of reactivity insertions are presented in this section. UTOP stands for unprotected transient overpower, meaning that the reactor shutdown has failed, has been actuated too late or has been inefficient. The reactivity insertion is postulated and does not refer to any specific initiating event. Nevertheless, a large diversity of reactivity ramps is implicitly considered in order to be able to tackle various accident dynamics in the accident analysis proposed in the PIRT.

The GET dedicated to UTOP is presented in Figure 2.1 below. The boxes located at the top of the GET correspond to a mix of system actions and of physical phenomena. The last column of the GET deals with the reactor final state obtained at the end of each possible accident sequence of events.

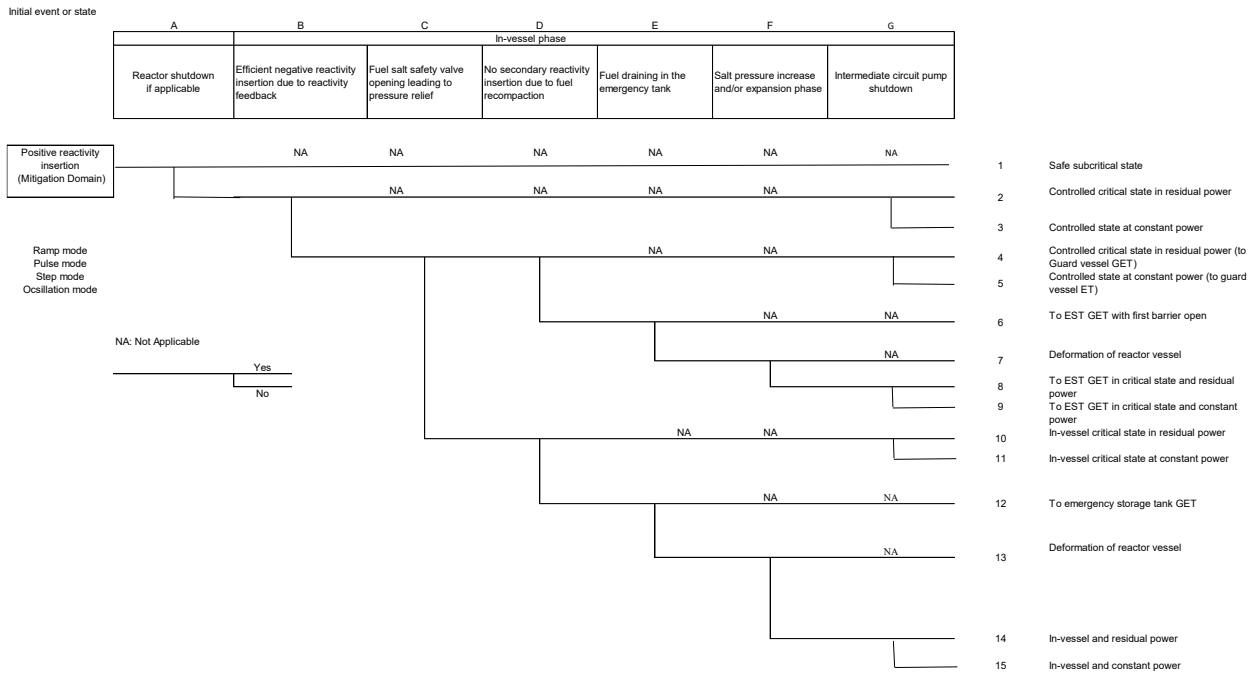


Figure 2.1: GET for UTOP (the guard vessel GET is developed in the LOFCA GET for uncollected leak case)

Heading A, related to the first event of the sequence, is applicable for the ARAMIS-P reactor studied in this PIRT but it could not be applicable if the reactor is not equipped with control drums or control rods. Headings B and D correspond to the overall effect of reactivity feedbacks with the temperature, the density, the pressure and the salt geometry evolution. Finally, headings C and E are related to safety actions accomplished to mitigate the accident, either by releasing the pressure in the reactor or by relocating the salt in order to make it sub-critical.

As far as the final states of the reactor are concerned, the safe state can be reached when the decay heat is extracted and the subcriticality is ensured. Only a controlled state can be achieved when there are no control rods (or control rod malfunction) or emergency storage tank able to make the salt sub-critical. Depending on whether the intermediate circuit is operating or not, the salt power can be only residual power (critical core but negligible fission power) or a constant power equal to that extracted by the power conversion system if the intermediate circuit pump is still working.

Finally, regarding the radiological confinement, depending on fuel pressure and temperature, there are 3 possibilities: either the fuel salt stays in the reactor vessel without any pressure relief through, either some radiological releases occurs through the safety valve into the guard vessel either the fuel salt is drained towards the emergency storage tank (EST), or either both. The sequence evolution in the guard vessel or in the emergency storage tank is described via other GETs. Finally, some sequences can lead to the deformation of the reactor vessel if the overpressure induced by the UTOP cannot be mitigated. Figure 2.2 shows a scheme of the draining system of ARAMIS-A reactor, that is taken as reference for this PIRT exercise.

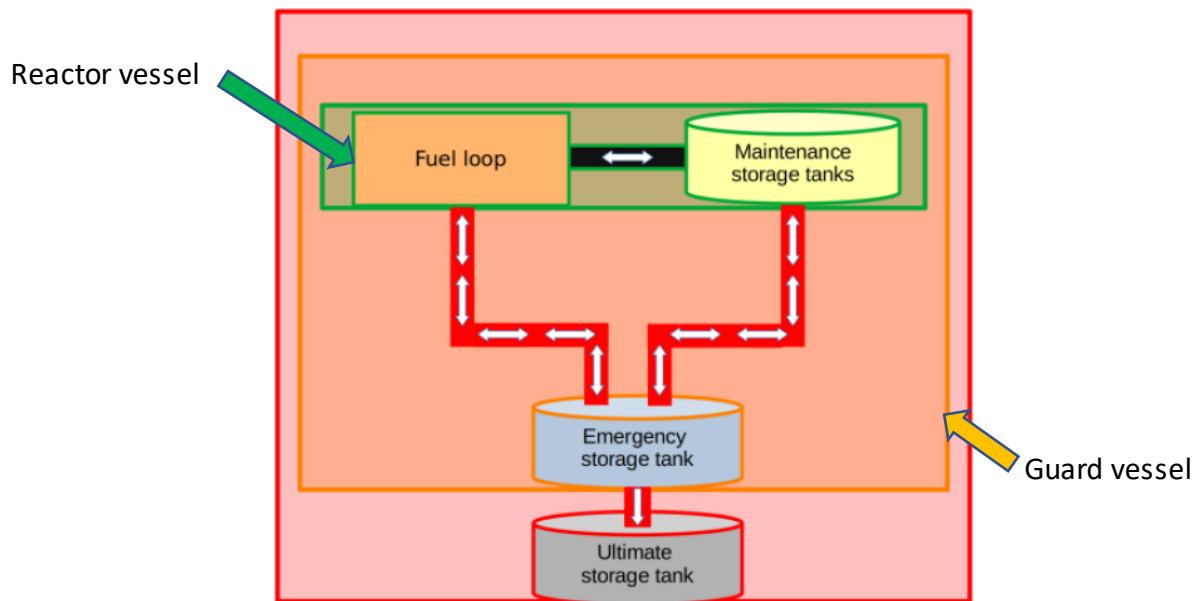


Figure 2.2: ARAMIS-A proposed fuel salt location configuration [8]

The PECs related to the UTOP sequence events are presented in Figure 2.3 and Figure 2.4. PEC of Figure 2.3 explains the logic chaining of successive physical phenomena that have an impact on the reactivity evolution with positive (leading to phenomena escalation) or negative reactivity feedback effects (leading to stabilisation). Depending on the relative importance of the various phenomena, two extreme situations can be reached: either a coolable state at stabilized power with the salt remaining in the fuel vessel either a mechanical loading, leading to a strain of the reactor vessel. An intermediate state leads to the PEC of Figure 2.4, providing an unbalanced reactor state requiring mitigation actions. The overall structure of this PEC represents the competition between the compressibility effects (large reactivity ramp) in the salt and the feedback effects due to the fuel density change and thermal expansion. These latter can enter into play as soon as an acoustic/shock wave forms and propagates to the fuel salt free surface and a subsequent expansion wave propagated back to the fuel core region.

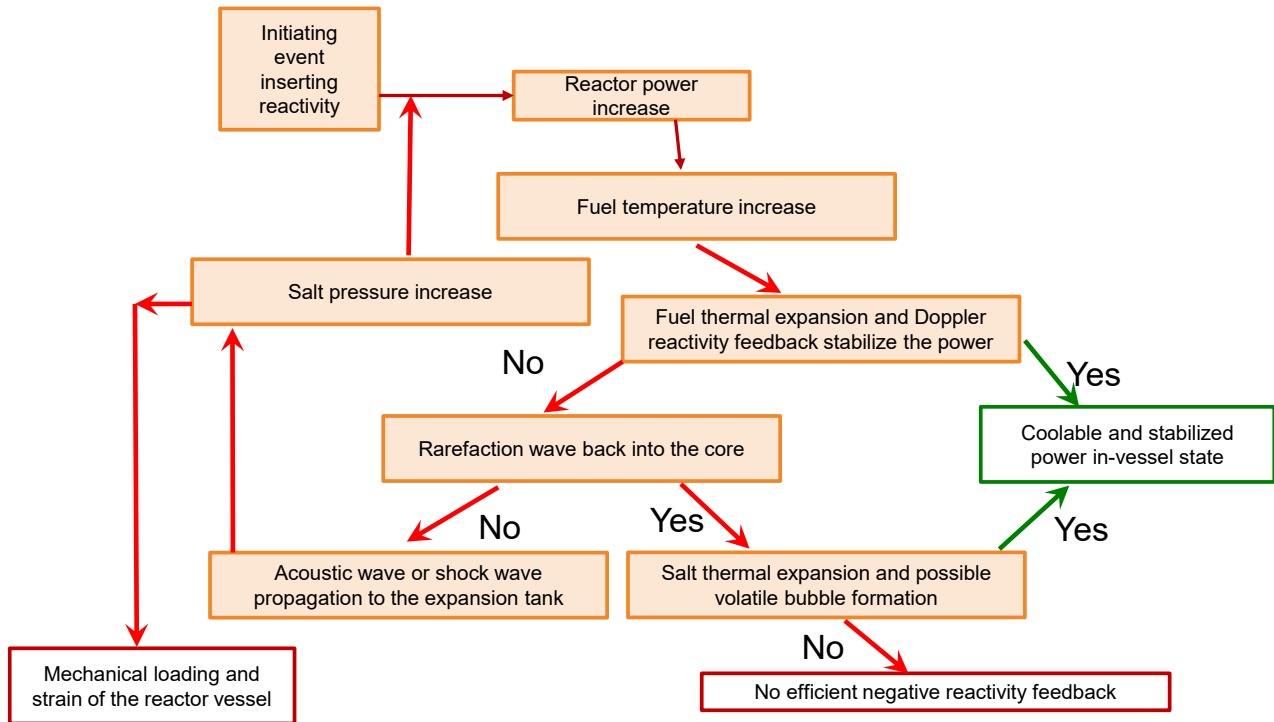


Figure 2.3: UTOP PEC, short-term reactivity feedbacks

PEC presented in Figure 2.4 is aimed at assessing the reactivity evolution and its balance in case of fuel circuit venting or/and fuel draining in the EST. The gas and vapour draining induces first a swelling of the salt and then its compaction when gas and vapor bubbles are vented. The swelling decreases the reactivity whereas the subsequent compaction increases it. The reactor net reactivity varies during a venting transient with at the end the possibility for the salt to be drained down to the EST. In the right part of the chart, either the salt fission power can be stabilized in the reactor vessel, either it is drained in order to make it sub-critical. As in the PEC of Figure 2.3, if the reactor power still increases, without any efficiency of mitigation actions, fuel vessel strains may occur due to mechanical loadings.

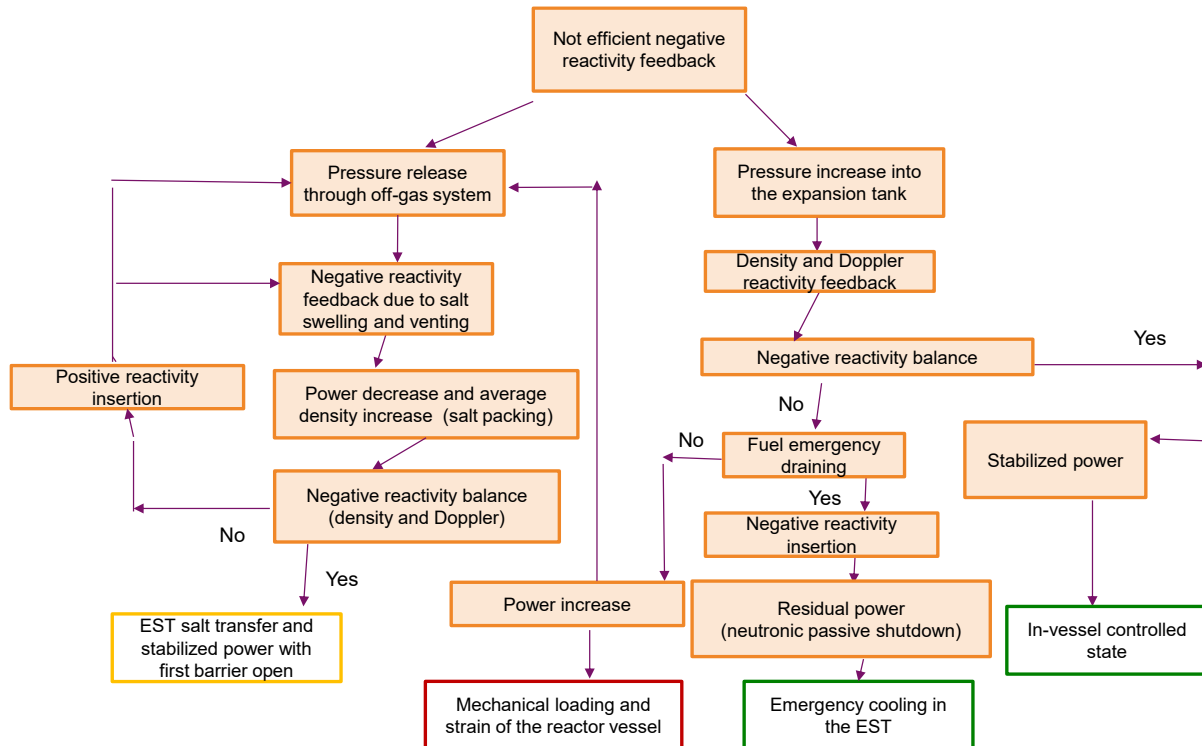
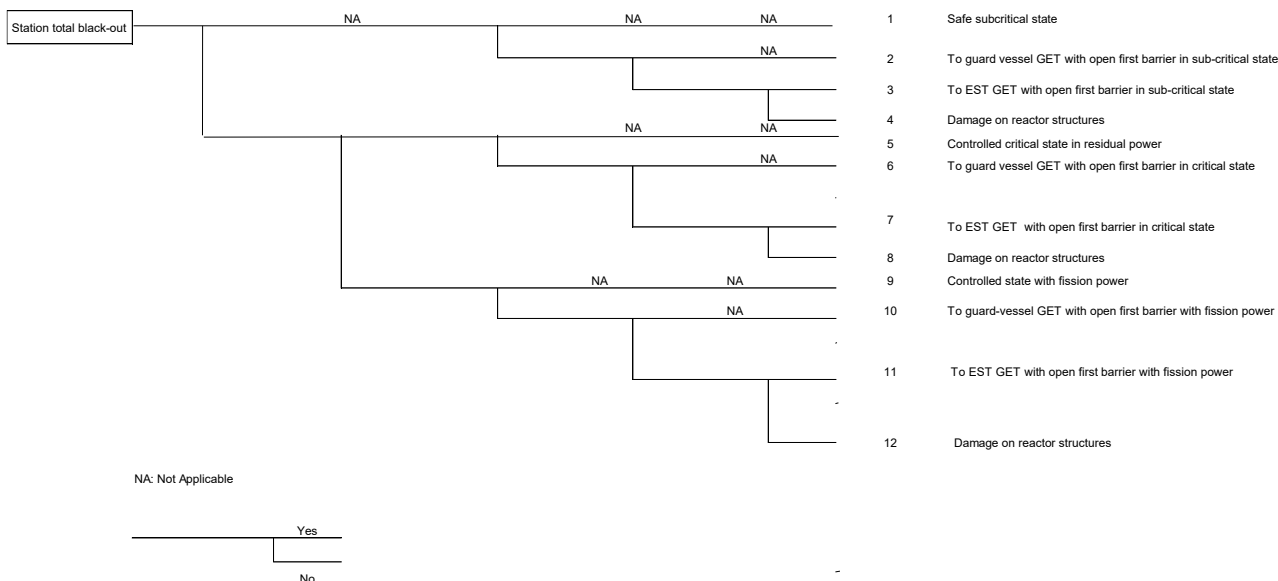


Figure 2.4: UTOP PEC, longer term reactivity feedbacks coupled with mitigating actions

2.3 SBOUT (station black-out)

This accident family starts with the unavailability of all systems needing electrical supply since it is assumed that the back-up supply also fails. In other terms, the fuel salt pumps, the intermediate circuit pumps and the power conversion system become unavailable at the accident initiation. The first heading of the event sequence (A) deals with the success/failure of the reactor shutdown if the reactor concept has a shutdown system. Heading B is related to the efficiency of the reactivity feedback to drive the core power to zero fission power despite being critical yet. Heading C corresponds to the success/failure of decay heat removal into the fuel vessel. If not, the safety valve (heading D) or the salt draining (heading E) need to be actuated.

The final states are all featured by a low fission power because the intermediate side is stopped and does not remove power anymore. Moreover, the passive DHR system extracts the salt power and finally neutronic passive shutdown should be reached at the residual power level. Different final states can be obtained depending on the fuel salt location (in the fuel vessel, in the guard vessel and in the EST) and on whether the reactor vessel structures are damaged or not (possible loadings are thermal and static pressure loadings).



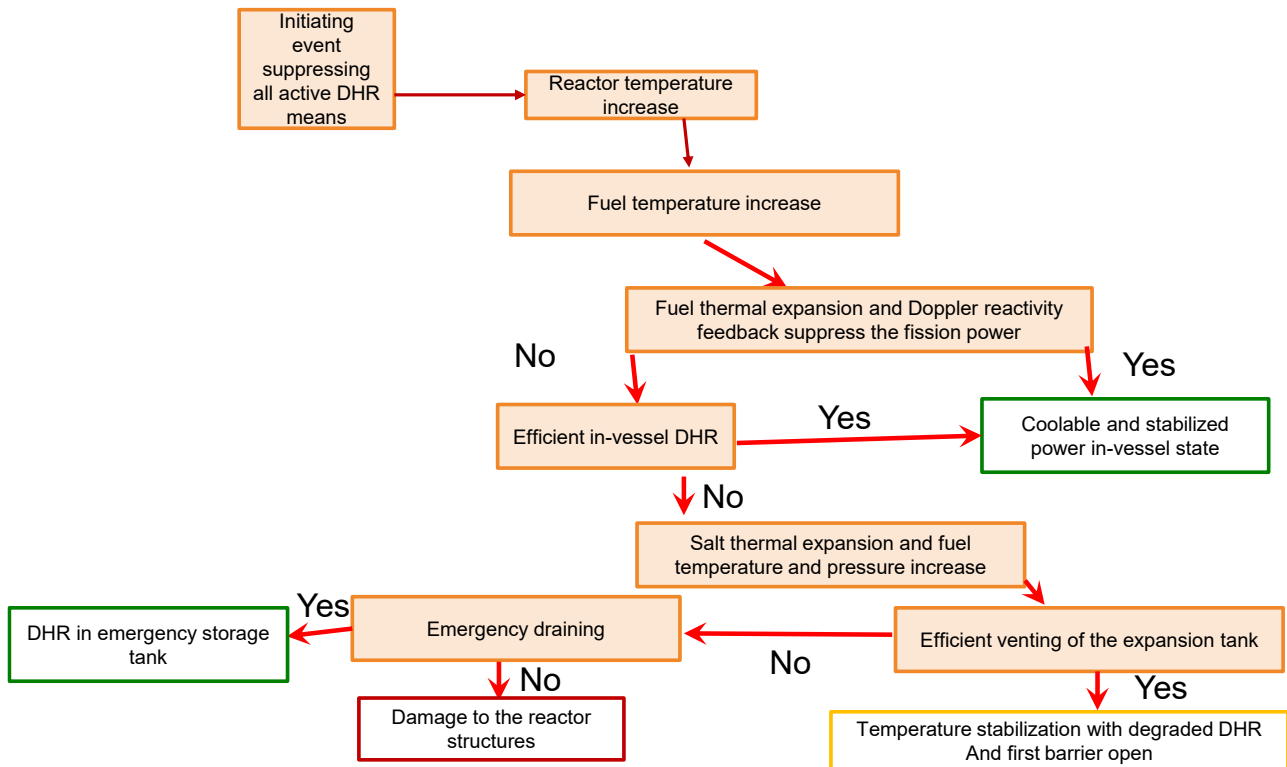


Figure 2.6: PEC related to SBOUT with the salt in the reactor vessel

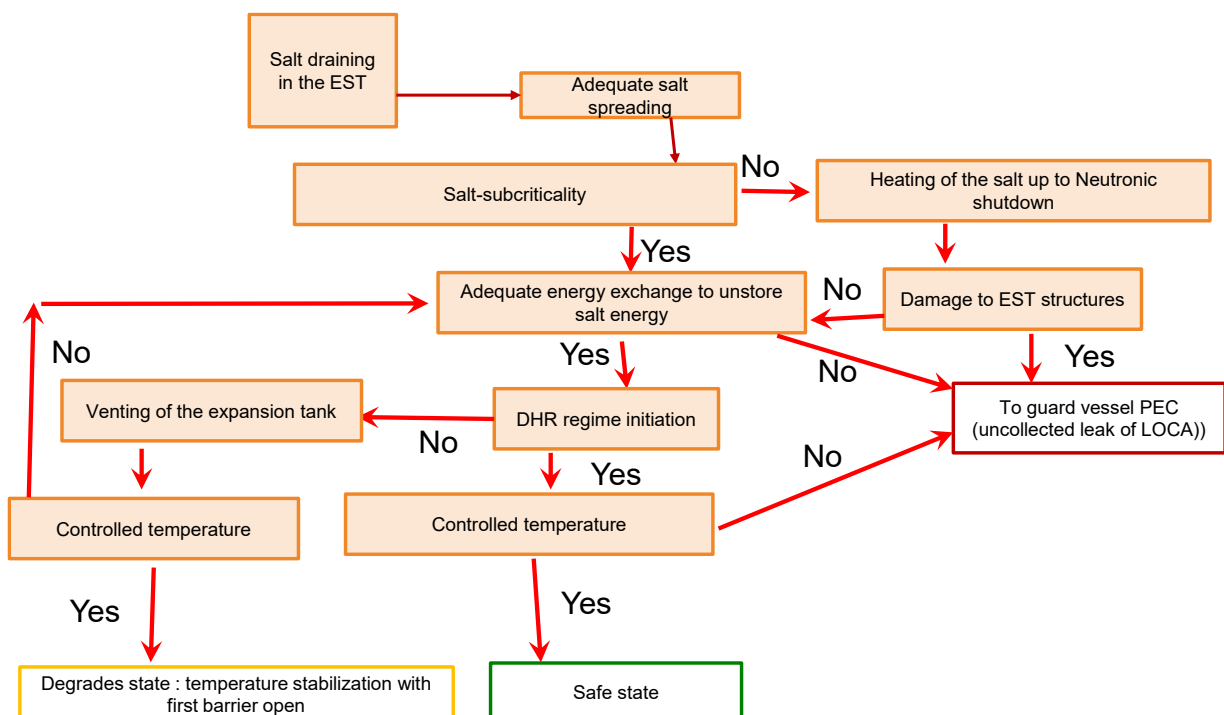


Figure 2.7: PEC related to SBOUT with the salt in the EST



Initial event or state

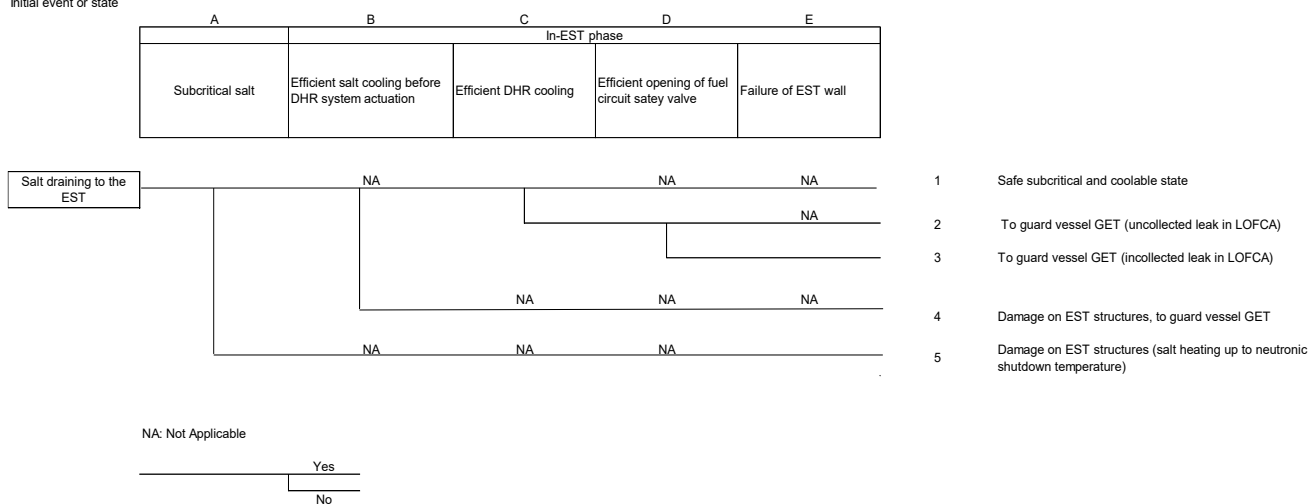


Figure 2.8: GET for salt drained in the emergency storage tank (EST)

2.4 LOFCA (loss of fuel and coolant accident)

The accident evolution is represented in the GET of Figure 2.9 and in the PEC of Figure 2.10. Since the phenomena induced in case of salt relocation into the EST being the same as in the SBOUT accident, the GET and PEC describing this part of the sequence are not displayed again in this section.

The GET describes the possible relocation of the fuel salt in the guard vessel and the evolution of the salt (criticality, cooling, location) after the occurrence of a breach in the fuel circuit. The first event that discriminates the event sequence evolution is the location of the breach (heading A in Figure 2.9). If it occurs in a location that enables the salt collection, it is relocated in the EST. In this case, the evolution of the sequence is described in the EST GET. However, depending on the break location, the spilling of the salt could take place in an uncollected area. In this case, the fuel would be relocated in the guard vessel and therefore it would lose any controlled geometry. As a result, the first (heading B) possible event is a recriticality of the salt leading to salt boiling and to damages to the guard vessel if no peripheral crust is forming. Such a crust stops the fuel salt spreading (upper face crust) and isolate the guard vessel wall from the salt (lower face crust). In this latter situation and a fortiori in the absence of stable crust, due to high heat flux and chemical attack, the guard vessel wall could still be eroded. It has been considered that if no recriticality happens and if the fuel salt crust is formed, a controlled state can be reached without damaging the guard vessel.

Finally, the presented PEC in Figure 2.10 provides some details on physico-chemical phenomena that could lead to damages of the guard vessel walls, like chemical attack and overpressure. On the contrary, the possible mitigating effect of the pressure increase induced by vapour condensation is specified in this PEC. The final states are featured by:

- either a safe state with a coolable salt partially relocated in the EST;
- either a safe state with a coolable salt partially relocated in the guard vessel but surrounded by a crust;
- or a final state with the salt partially relocated in a no more leak tight guard vessel.

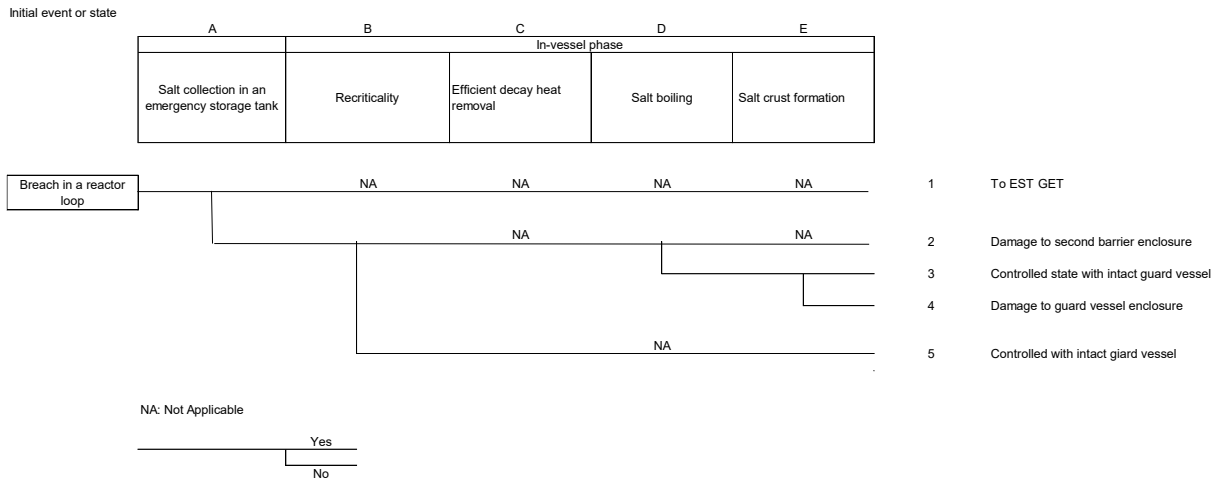


Figure 2.9: GET for LOFCA

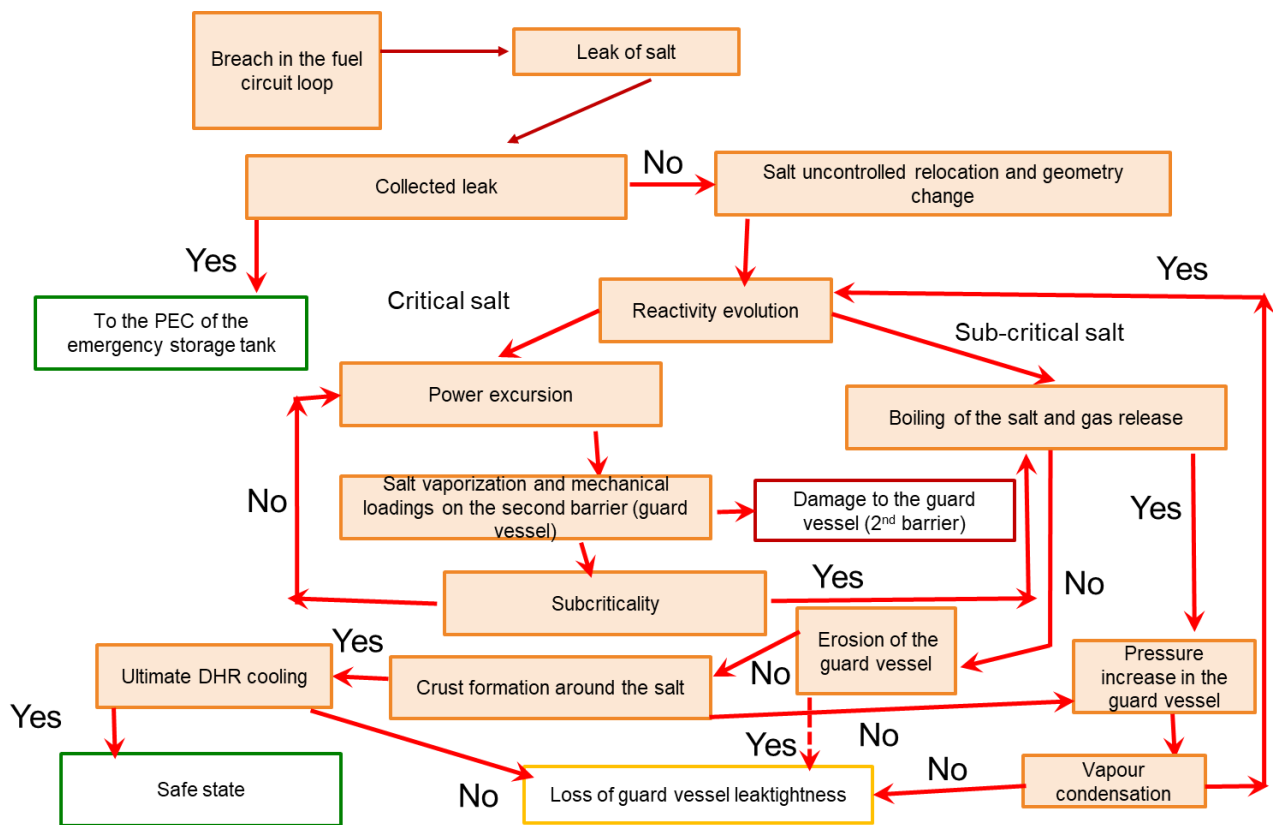


Figure 2.10: PEC for a LOFCA



3. Results on Phenomena Identification and Ranking Table and discrepancy analysis

The PIRT exercise has been conducted in four phases:

1. The PIRT tables have been edited for each considered transient sequence and discussed among partners in a dedicated meeting. The results are shown in Annex 1.
2. Each partner individually assigned a vote for the importance and uncertainty of each phenomenon listed in the tables, in accordance with the rules described below.
3. The overall votes have been summarized and analyzed to draw attention to the phenomena that receive the largest global vote and therefore are of high importance and high associated uncertainty. This analysis is described in the next section 3.1.
4. The phenomena with votes that showed largest disagreement between partners have been discussed in a dedicated meeting. Some partners either change their vote or justify it. The final results on discrepancy analysis are shown in the section 3.2.

The voting rules have led to rank the phenomena according to their importance and uncertainty. One score is assigned to each criterion, and the product of these two values is referred to as the global vote. The importance was ranked from 1 (low importance phenomena) to 3 (high importance phenomena). The uncertainty was ranked from 1 (phenomena with good knowledge) to 3 (poor knowledge of phenomena).

The interpretation of the PIRT results provides guidance for identifying phenomena that should be addressed with priority in future R&D activities. These activities may include further analysis, simulation studies, and dedicated experimental investigations aimed at reducing the main knowledge gaps. The detailed assessment of suitable calculation tools, modelling assumptions and validation databases should be performed in subsequent WP4 activities.

3.1 PIRT results analysis

Three levels of evaluation are carried out for each transient. First, the PIRT tables have been edited, for each transient. Second, after the partners voting, the individual votes from each partner are examined, and conclusions are drawn highlighting the most important or uncertain vote provided by each partner. Third, the global votes are analyzed to identify the phenomena that exhibit the highest levels of importance and uncertainty according to all the partners. In the whole analysis of this section, each phenomenon is referenced using the numbering shown in the PIRT tables.

3.1.1 UTOP

In the Annex the PIRT of the UTOP transient is shown. After the voting of each partner, the individual votes are analyzed and this section highlights the main conclusions from this initial analysis.

Figure 3.1 shows the **ASNR** votes for each phenomenon.

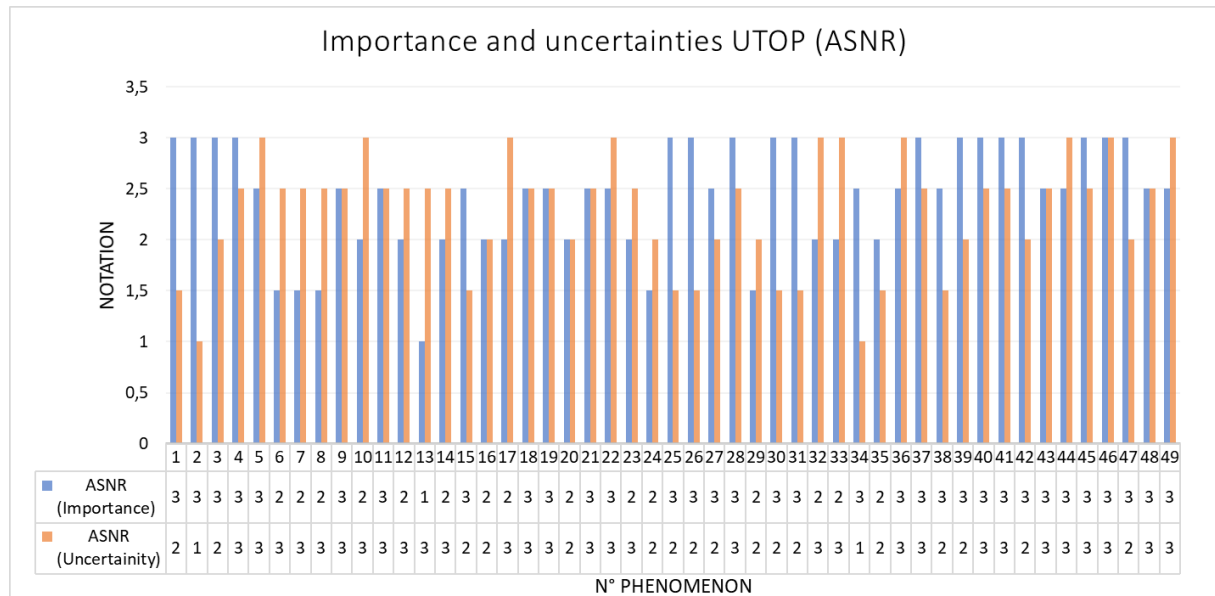


Figure 3.1: ASNR votes for UTOP phenomena.

ASNR voted for 17 phenomena out of 49 with high importance (vote 3) related to:

- Reactivity insertion and reactivity feedbacks;
- Dynamic vessel loading;
- Salt relocation/venting;
- Radionuclide bubble transport.

On the other hand, 10 phenomena out of 49 were considered highly uncertain (vote 3). They are related to:

- The fuel thermal expansion and the density reactivity feedback related to the shock wave formation.
- The salt relocation in the EST (in particular the pressure venting through the off-gas line, the migration of gas species into bubbles and the actinides precipitation).

Figure 3.2 shows the **CEA** votes for each phenomenon.

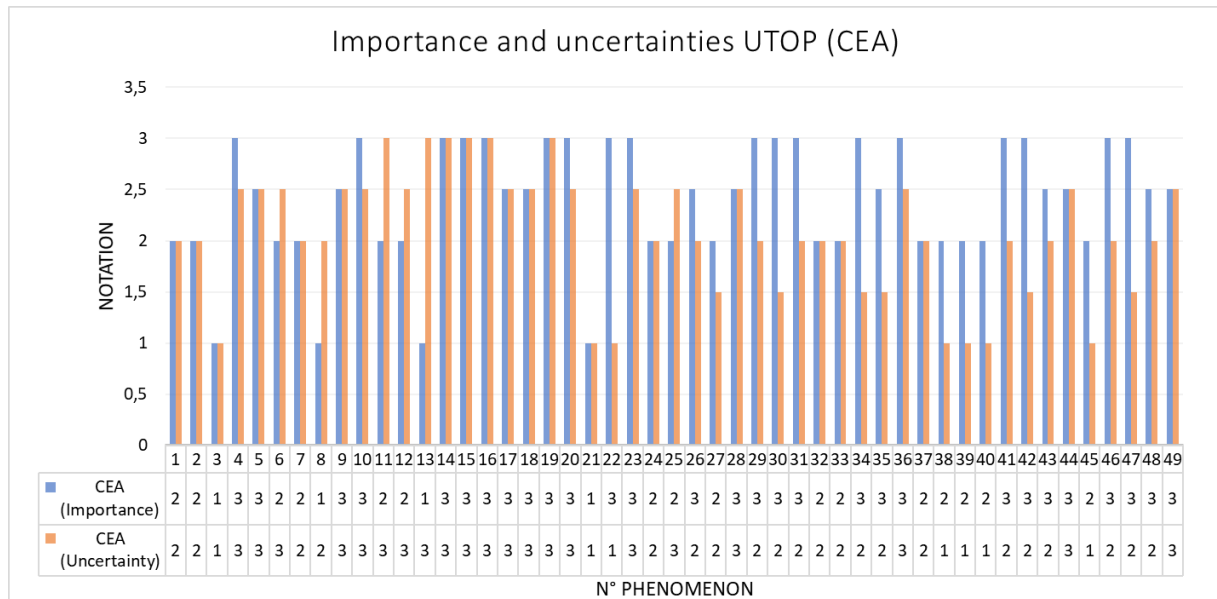


Figure 3.2: CEA votes for UTOP phenomena.

CEA voted for 18 phenomena out of 49 with high importance (vote 3) related to:

- Compressible effects;
- Salt swelling/compaction;
- Dynamic vessel loading;
- Salt relocation/venting;
- Radionuclide bubble transport.

On the other hand, 6 phenomena out of 49, relating to compressible multiphase flow, are considered highly uncertain (vote 3).

Figure 3.3 shows the **POLIMI** votes for each phenomenon.

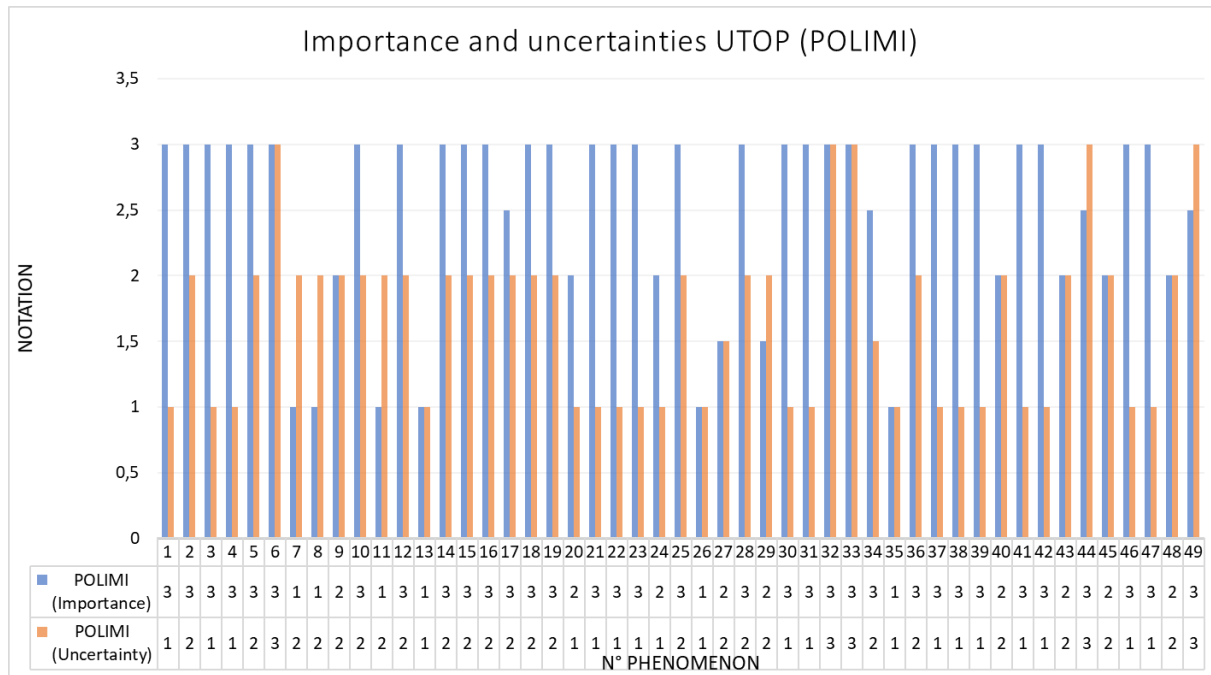


Figure 3.3: POLIMI votes for UTOP phenomena.

POLIMI voted for quite a number of phenomena with high importance (30 out of 49), which therefore concern most phenomena.

On the other hand, 5 phenomena out of 49 are classified as uncertain (vote 3) and they concern:

- The bubble collapse in the bubbling system;
- The gas transfer and actinide precipitation in the EST.

Figure 3.4 shows the **POLITO** votes for each phenomenon.

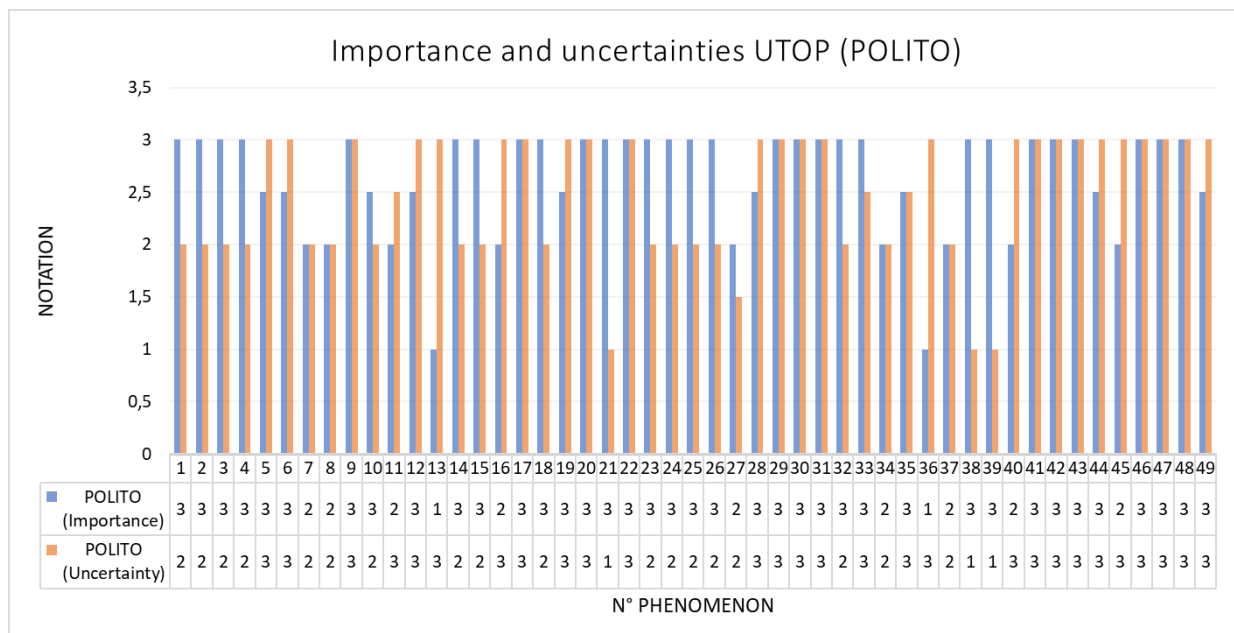


Figure 3.4: POLITO votes for UTOP phenomena.



POLITO voted for quite a number of phenomena with high importance (29 out of 49), which therefore concern most phenomena.

On the other hand, 25 phenomena out of 49 are classified as uncertain (vote 3) and they concern:

- The compressible multiphase flow;
- The salt and radionuclide transport and relocation.

Figure 3.5 shows the **PSI** votes for each phenomenon.

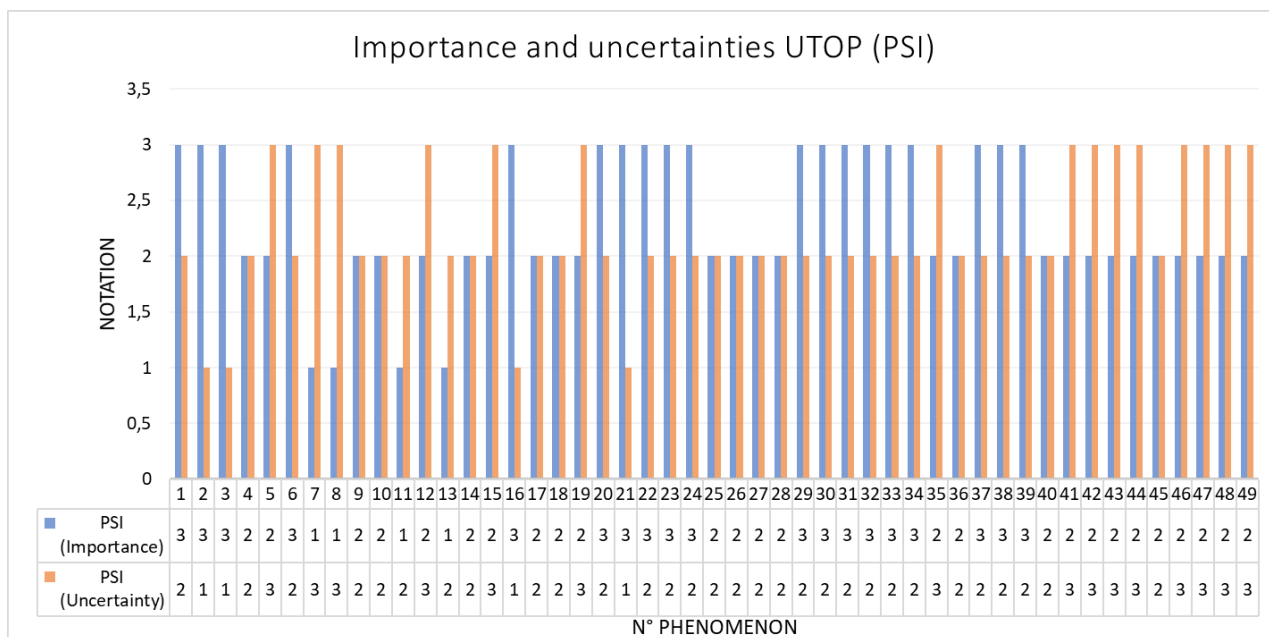


Figure 3.5: PSI votes for UTOP phenomena.

PSI voted for 19 phenomena out of 49 with high importance (vote 3) related to:

- Reactivity insertion / Doppler;
- Bubble collapse and growth;
- Compressible effects;
- Radionuclide bubble transport;
- Actinide precipitation.

On the other hand, 15 phenomena out of 49 were considered highly uncertain (vote 3). They are related to:

- The salt radionuclide transport and relocation;
- The salt pressure evolution in compressible stage.

Thereafter, for each phenomenon and each partner, the product (Importance × Uncertainty) was analyzed. This product is referred here as global score and range from 1 to 9. Low overall scores indicate low importance and good knowledge of the phenomenon. Conversely, high overall scores indicate high importance and high uncertainty, and therefore identify the phenomena to be studied as a priority.

Figure 3.6 summarizes the global vote of each partner for each phenomenon. In the figure, the scores of each partner are represented by different markers, and the phenomena are indicated on the horizontal axis by their corresponding numbers in the PIRT tables. In addition, each column is colored according to a scale ranging from white to red, representing the mean score, from 1 to 9 - white corresponds to the lowest mean value and dark red to the highest.

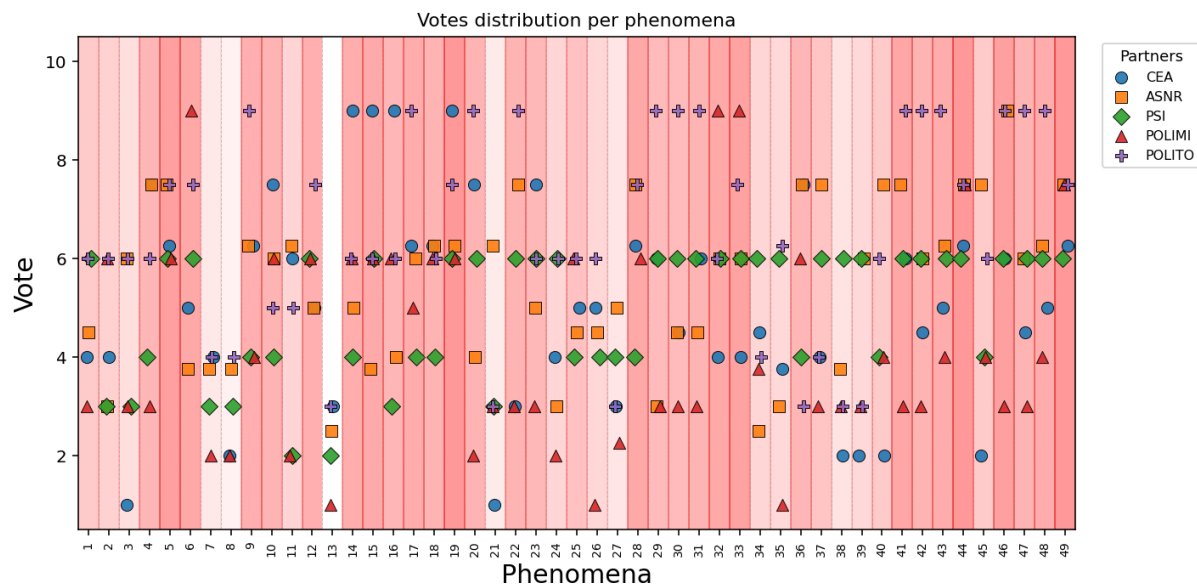


Figure 3.6 – Global votes (Importance x Uncertainty) for each partner – UTOP transient.

From the analysis of this graph, it appears that:

- ASNR votes are more or less uniformly distributed. Votes exceeding 8 were attributed only to one phenomenon.
- CEA votes are more or less uniformly distributed. Phenomena considered important and uncertain (global vote 9) are 4 out of 49.
- POLIMI votes are rather located in the low-importance and low-uncertainty region, 42 out of 49 phenomena obtain a global score less than or equal to 6. Moreover, 3 phenomena received the vote of 9.
- POLITICO votes are more or less uniformly distributed. Out of 49 total votes, 13 assigned the maximum score of 9.
- PSI assigned an overall score of 6 to a large number of phenomena (28 out of 49) and no phenomenon received the vote of 9.

In the Figure 3.7, for each phenomenon, the mean of the global scores among all the partner's votes are shown, with the associated standard deviation. Vote results with a mean value greater than 6 are considered the most significant. Indeed, they correspond to phenomena that have the greatest impact on the accident sequence and exhibit the largest knowledge gaps. Consequently, these phenomena should be addressed in priority (in particular, those for which the standard deviation is lower) in safety analysis and be the subject of experimental studies in order to fill the identified knowledge gaps and allows analytical modelling improvements.



In this figure, the standard deviation provides qualitative information about the level of agreement or disagreement among partners: the greater the agreement, the smaller the standard deviation. A more detailed analysis of the votes with large disagreement is presented in Section 3.2.

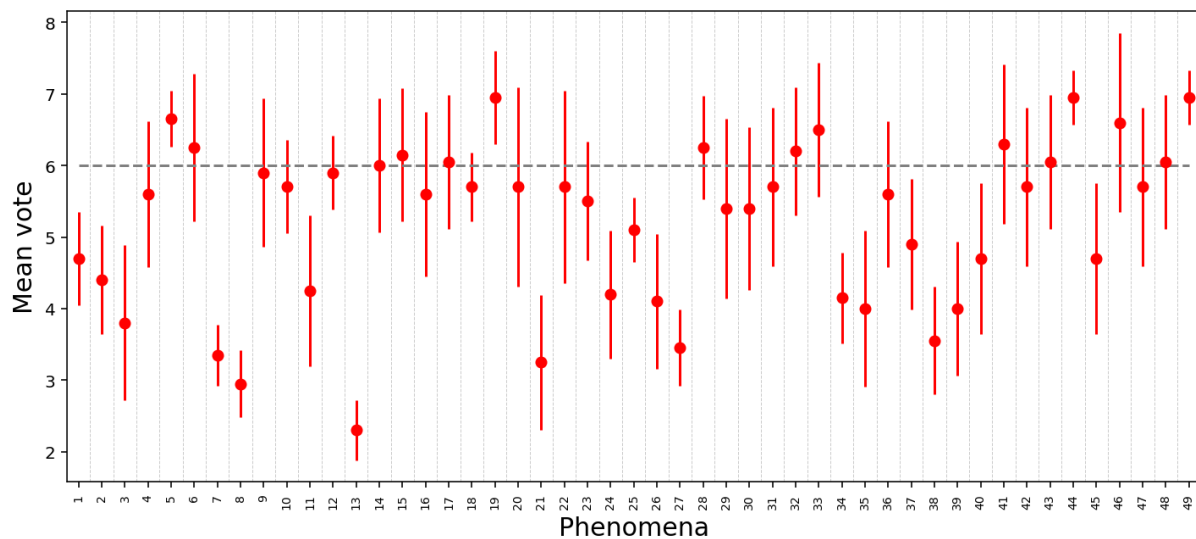


Figure 3.7 – Mean vote and standard deviation of the partners’ votes – UTOP transient.

The phenomena with an average global score larger than 6 are listed in the following Table 3.1. The lines corresponding to the phenomena with higher value (6.95) are highlighted.

In conclusion, the UTOP PIRT results show that the most important and uncertain phenomena are mainly associated with pressure-wave effects, compressible multiphase flow and radionuclide/species transport. Considering the highest-ranked phenomena, the main priorities are associated with fuel density increase induced by wave compression, salt packing due to bubble removal from the core region, multiphase flow through the off-gas line, migration of salt species to bubbles, and actinide precipitation on cold surfaces of the EST. These phenomena affect key FoMs related to reactivity feedback, stored energy, maximum salt temperature, maximum fuel circuit pressure, and vessel mechanical loading. In particular, wave-induced density changes and salt packing are directly linked to the local evolution of salt density and void fraction in the core region, and therefore to the reactivity evolution during the UTOP sequence. In parallel, actinide precipitation on cold surfaces of the EST is directly linked to the redistribution of actinides and salt species during the salt relocation and venting phase. It may therefore affect salt composition evolution, local fissile inventory distribution and source-term assessment.

**Table 3.1 – Phenomena with global score larger than 6 – UTOP transient.**

Accident phase	FoM	Phenomena	IxU (Average)
Salt behavior in the fuel circuit	Reactivity feedback and power evolution	5 - Fuel density increase by wave compression	6.65
Salt behavior in the fuel circuit	Reactivity feedback and power evolution	6 - Bubble collapse (if bubbling system)	6.25
Fuel salt behavior in the fuel circuit	Fuel salt behavior before thermal expansion	15 - Pressure wave refraction to the free surface	6.15
Salt behavior in the fuel circuit	Fuel salt behavior during thermal expansion	17 - Fuel pressure decrease and possible bubble formation in superheated zones	6.05
Salt behavior in the fuel circuit	Fuel salt behavior during thermal expansion	19 - Salt packing due to bubble exhaust from the core region	6.95
Fuel vessel wall loading	Dynamic loading	28 - Fuel pressure increase (by wave compression)	6.25
Salt relocation and venting	Pressure venting	32 - Vapor and gas phase exhaust through the off-gas line	6.20
Salt relocation and venting	Pressure venting	33 - Multiphase flow through the off-gas line	6.50
Salt relocation and venting	Salt draining in the EST	41 - Migration of salt species to bubble (if bubbling transport)	6.30
Salt relocation and venting	Salt draining in the EST	43 - Bubble formation due to salt heating (fission gas and volatile species)	6.05
Salt relocation and venting	Salt draining in the EST	44 - Actinide precipitation on cold surfaces of the emergency storage tank	6.95
Salt relocation and venting	Radionuclide transport	46 - Migration of salt species to bubble (if bubbling transport)	6.60
Salt relocation and venting	Radionuclide transport	48 - Bubble formation due to salt heating (fission gas and volatile species)	6.05
Salt relocation and venting	Radionuclide transport	49 - Actinide precipitation on cold surfaces of the emergency storage tank	6.95



3.1.2 SBOUT

In the Annex the PIRT of the SBOUT transient is shown. As before, also for the SBOUT transient, the individual votes of each partner are analyzed at first; this section highlights the main conclusions from this initial analysis.

Figure 3.8 shows the **ASNR** votes for each phenomenon.

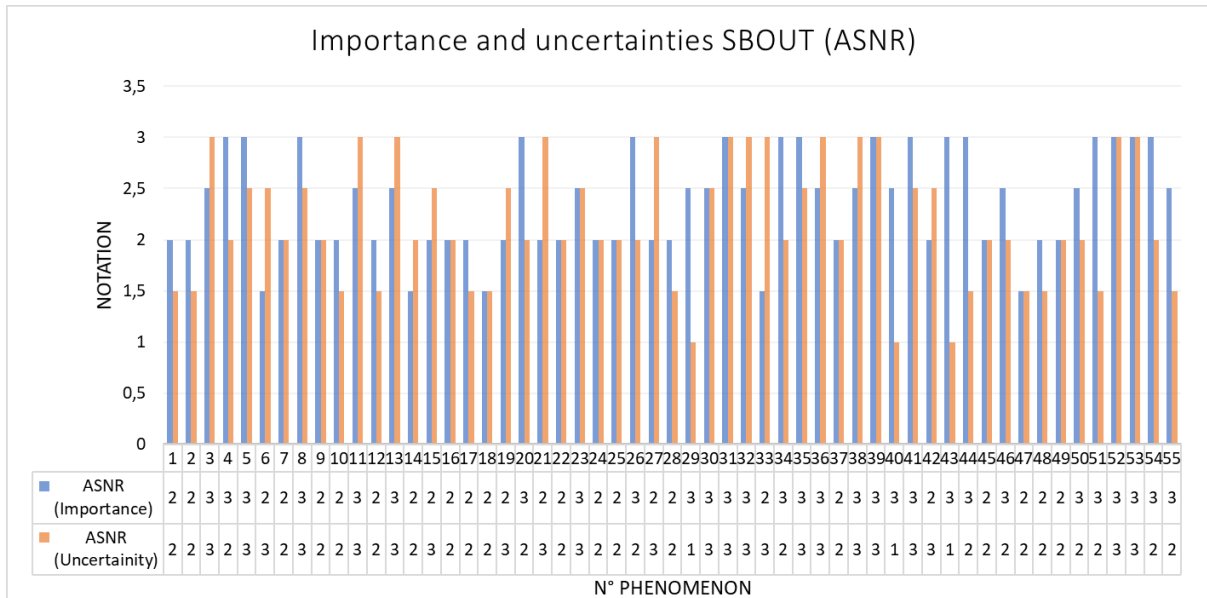


Figure 3.8: ASNR votes for SBOUT phenomena

ASNR voted for 16 phenomena out of 55 with high importance (vote 3) mainly related to:

- Salt heating and freezing;
- Salt draining in the emergency storage tank;
- Salt managing in the EST.

On the other hand, 13 phenomena out of 55 were considered highly uncertain (vote 3). A significant number of them deal with the salt draining in the emergency storage tank and radionuclide transport.

Figure 3.9 shows the **CEA** votes for each phenomenon.

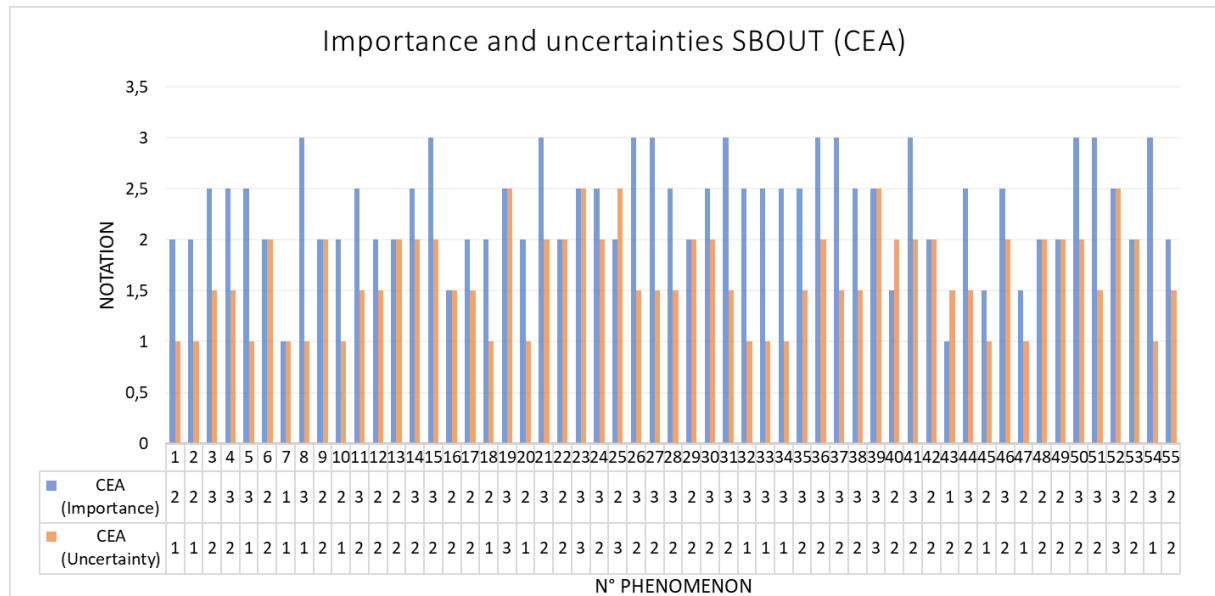


Figure 3.9: CEA votes for SBOUT phenomena

CEA voted for 12 phenomena out of 55 with high importance (vote 3) related to:

- Pressure venting related phenomena;
- Salt phase change;
- Radionuclide bubble transport.

On the other hand, none of the phenomena were considered as highly uncertain (vote 3).

Figure 3.10 shows the **POLIMI** votes for each phenomenon.

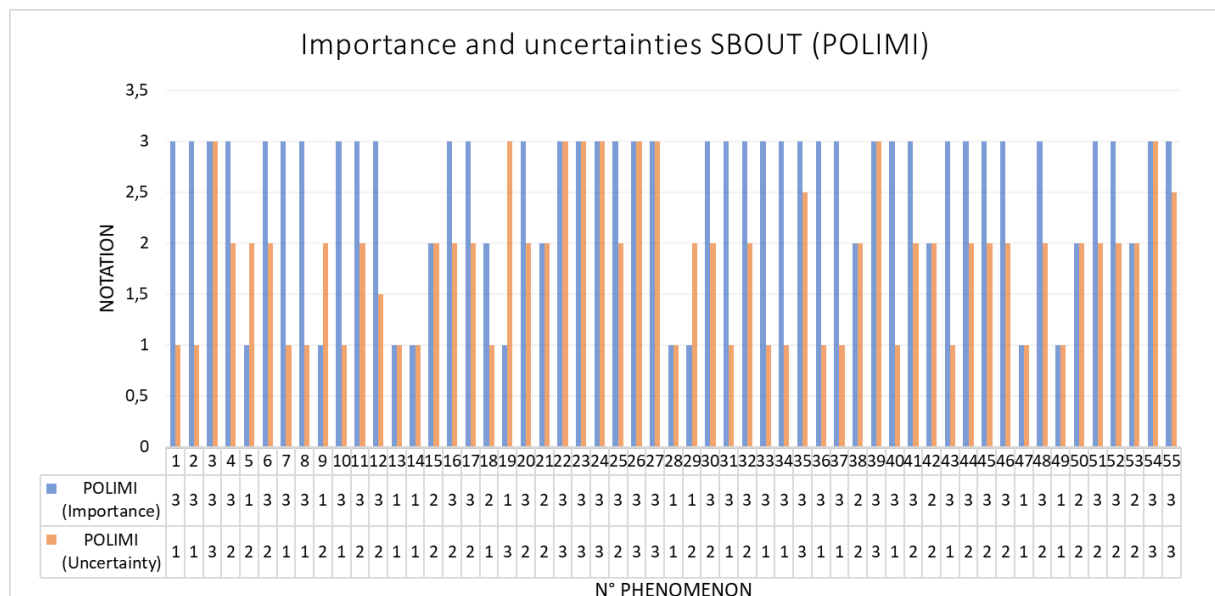


Figure 3.10: POLIMI votes for SBOUT phenomena

POLIMI voted for quite a number of phenomena with high importance (39 out of 55), which therefore concern most phenomena.

On the other hand, 9 phenomena out of 55 are classified as uncertain (vote 3) and they concern:



- Salt freezing;
- Corrosion and thermal creep on the vessel walls;
- Pressure venting and gas management in EST;
- Actinide precipitation in the EST;
- Air ingress in the EST.

Figure 3.11 shows the **POLITO** votes for each phenomenon.

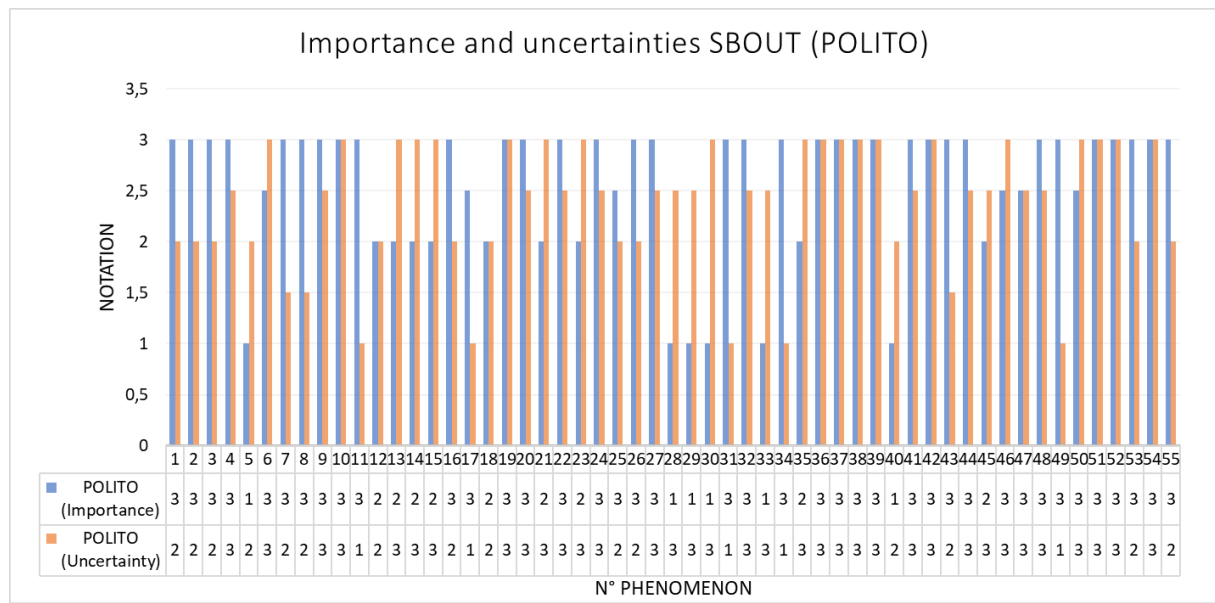


Figure 3.11: POLITO votes for SBOUT phenomena

POLITO voted for quite a number of phenomena with high importance (34 out of 55), which therefore concern most phenomena.

On the other hand, 20 phenomena out of 55 are classified as uncertain (vote 3), thus corresponding to a large part of phenomena except for the ones related to neutronics, heat transfer and draining phenomena.

Figure 3.12 shows the **PSI** votes for each phenomenon.

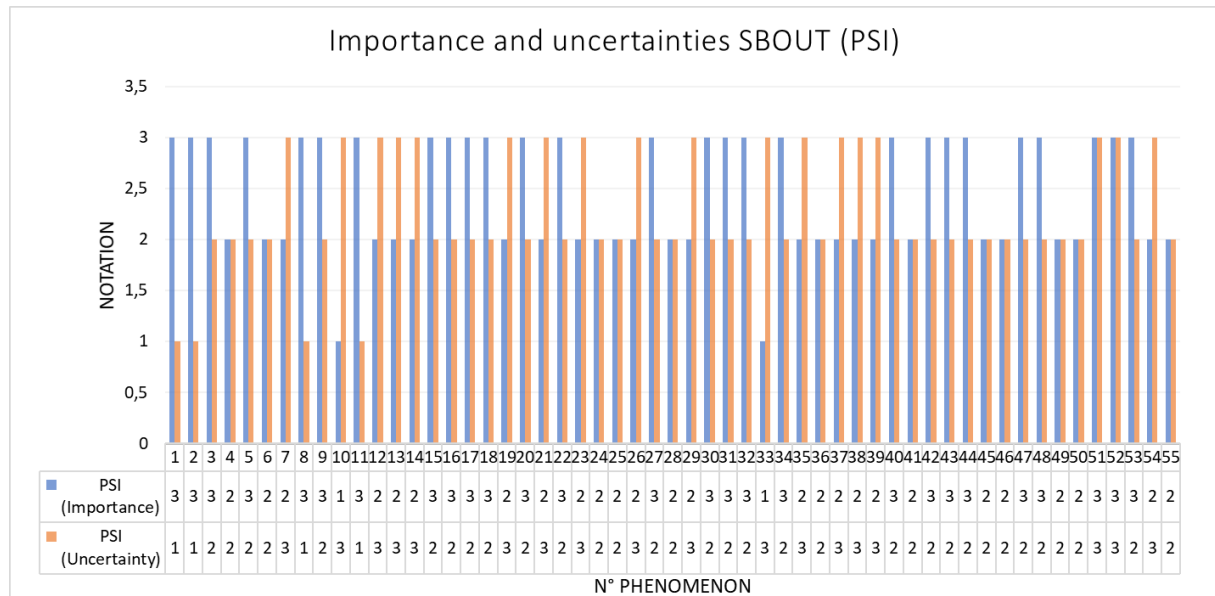


Figure 3.12: PSI votes for SBOU phenomena

PSI voted for quite a number of phenomena with high importance (27 out of 55), mostly associated with salt power, temperature and pressure evolution.

On the other hand, 18 phenomena out of 55 were considered highly uncertain (vote 3). They are related to:

- Reactivity feedback;
- Transport of species from salt to cover gas;
- Long term salt behaviour.

Thereafter, for each phenomenon and each partner, the global vote, corresponding to the product (Importance × Uncertainty), was analyzed. Figure 3.13 summarizes the global vote of each partner for each phenomenon. In the figure, the scores of each partner are represented by different markers, and the phenomena are indicated on the horizontal axis by their corresponding numbers of the PIRT tables. In addition, each column is colored according to a scale ranging from white to red, representing the mean score, from 1 to 9 - white corresponds to the lowest mean value and dark red to the highest.

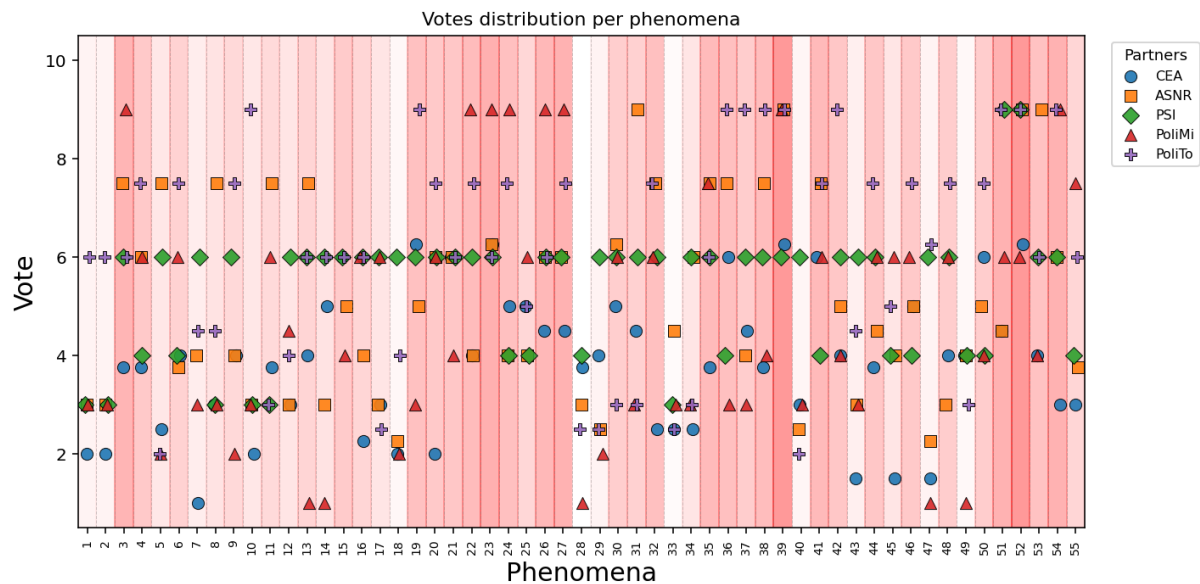


Figure 3.13 - Global votes (Importance x Uncertainty) for each partner – SBOUT transient.

From the analysis of this graph, it emerges that:

- ASNR votes are more or less uniformly distributed. Phenomena considered important and uncertain (global vote 9) are 4 out of 55.
- CEA votes are all inferior or equal to 6.25.
- POLIMI votes are more or less uniformly distributed. Phenomena considered important and uncertain (global vote 9) are 8 out of 55.
- POLITO votes are more or less uniformly distributed. Phenomena considered as important and uncertain (global vote 9) are 10 out of 55.
- PSI assigned an overall score of 6 to a large number of phenomena (35 out of 55). Phenomena considered as important and uncertain (global vote 9) are 2 out of 55.

In the Figure 3.14, for each phenomenon, the mean of the global scores among all the partner's votes are shown, with the associated standard deviation. As for UTOP, the attention is focused on the phenomena with global vote larger than 6.

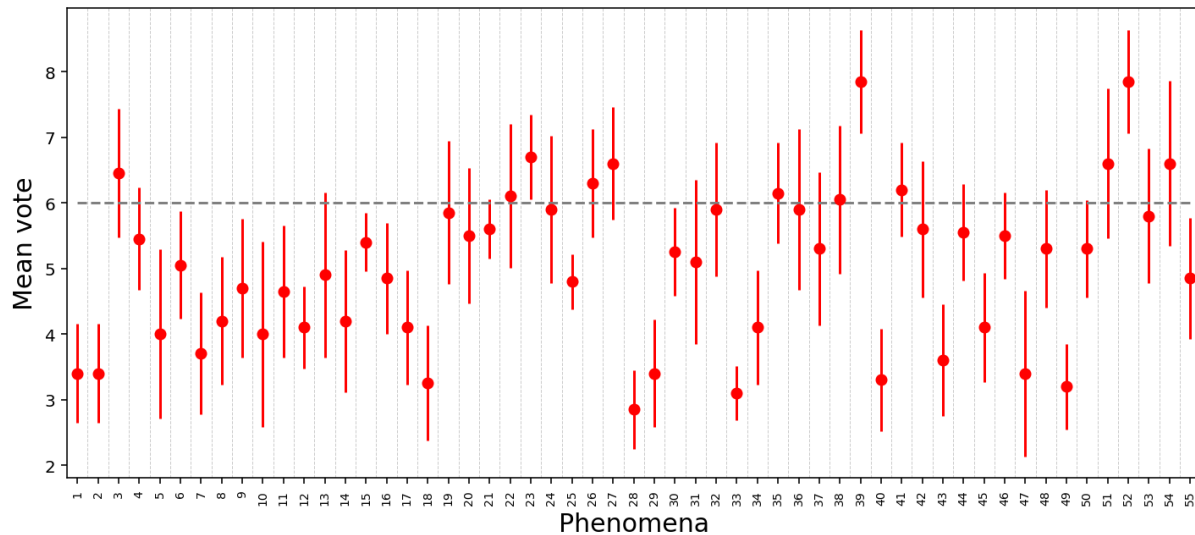


Figure 3.14 - Mean vote and standard deviation of the partners' votes – SBOUT transient.

The phenomena with an average global score larger than 6 are listed in the following Table 3.2. The lines corresponding to the phenomena with higher value (7.85) are highlighted.

In conclusion, the SBOUT PIRT results show that the most important and uncertain phenomena are mainly associated with salt thermal behaviour, corrosion mechanisms, and salt management in the EST. Considering the highest-ranked phenomena, the main priorities are associated with freezing in the DHR loop pipes, corrosion increase due to redox and radiolysis potential evolution with salt temperature, vapour and gas phase exhaust through the off-gas line, multiphase flow through the off-gas line, actinide precipitation on cold surfaces of the EST, salt mass solidification, species precipitation including actinides, phase changes due to redox potential changes, and air ingress in the EST. These phenomena affect key FoMs related to maximum and minimum salt temperature, salt pressure evolution, and decay heat removal capability.

In particular, freezing in the DHR loop pipes and salt mass solidification are directly linked to the long-term coolability of the fuel salt and to the effectiveness of passive decay heat removal during the SBOUT sequence. In parallel, actinide precipitation on cold EST surfaces and species precipitation including actinides are directly linked to the redistribution of fissile and radioactive species during salt relocation and long-term salt management in the EST. These phenomena may therefore affect salt composition evolution, local distribution of fissile material, subcriticality margins in the EST, source-term assessment, and confinement performance. Corrosion driven by redox and radiolysis potential evolution, as well as air ingress in the EST, also appears as a priority issue because these phenomena may challenge the integrity of structures involved in confinement.

**Table 3.2 - Phenomena with global score larger than 6 – SBOUT transient.**

Accident phase	FoM	Phenomena	IxU (Average)
Salt behavior in the fuel circuit	Salt heating/freezing	3 - Freezing in DHR loop pipes	6.45
Corrosion and loading of fuel vessel walls	Thermal and chemical loading (vessel)	23 - Corrosion increase due to redox and radiolysis potential evolution with salt temperature evolution	6.88
Corrosion and loading of fuel vessel walls	Pressure venting	26 - Vapor and gas phase exhaust through the off-gas line	6.30
Corrosion and loading of fuel vessel walls	Pressure venting	27 - Multiphase flow through the off-gas line	6.60
Salt relocation and venting	Salt draining in the emergency storage tank	35 - Gas transfer from the emergency tank to manage pressure balance in fuel circuit	6.15
Salt relocation and venting	Radionuclide transport	39 - Actinide precipitation on cold surfaces of the emergency storage tank	7.85
Salt management in the emergency storage tank	Salt power evolution	41 - Decay heat evolution in the salt	6.20
Salt management in the emergency storage tank	Salt pressure evolution	51 - Salt mass solidification	6.60
Salt management in the emergency storage tank	Salt pressure evolution	52 - Species precipitation including actinide	7.85
Salt management in the emergency storage tank	Salt pressure evolution	53 - Phase changes due to redox potential change	6.33
Salt management in the emergency storage tank	Salt pressure evolution	54 - Air ingress in the EST	6.60



3.1.3 LOFCA

In the Annex the PIRT of the LOFCA transient is shown. As before, also for the LOFCA transient, the individual votes of each partner are analyzed at first. The detailed results, presented as graphs, are summarized in Annex, while this section highlights the main conclusions from this initial analysis.

Figure 3.15 shows the **ASNR** votes for each phenomenon.

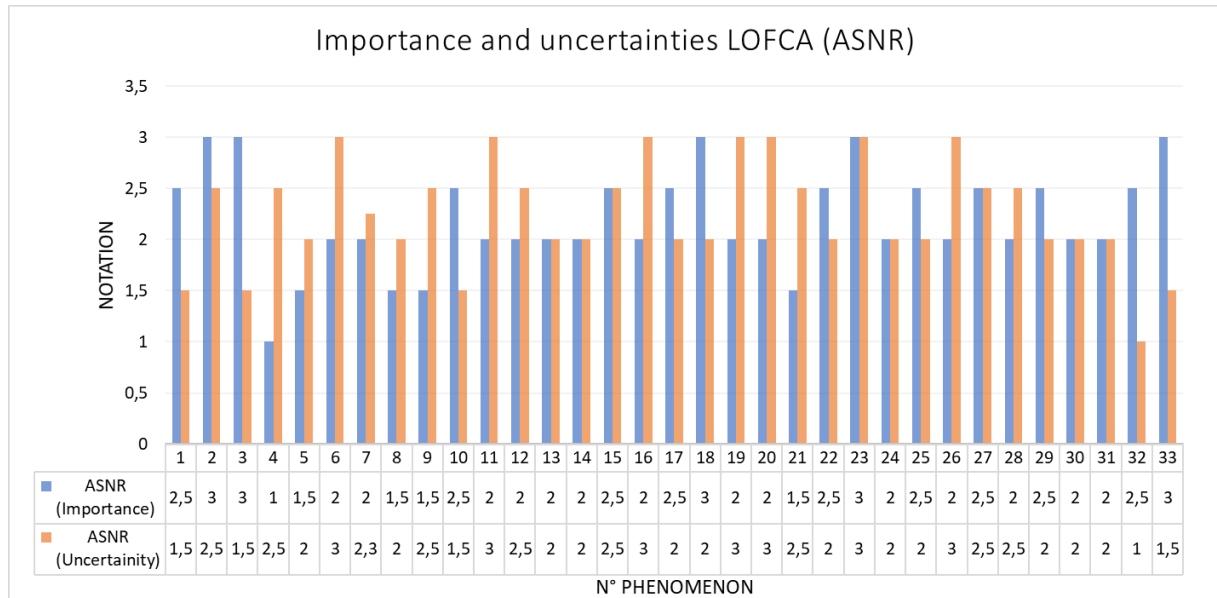


Figure 3.15: ASNR votes for LOFCA phenomena

ASNR voted for 5 phenomena out of 33 with high importance (vote 3) mainly related to:

- Draining to the EST;
- Actinides precipitation and recriticality risk;
- Breakthrough the guard vessel.

While 7 phenomena out of 33 were considered highly uncertain (vote 3) and they concern:

- Salt accumulation during discharge;
- Decay heat;
- Salt thermal hydraulic and chemical behavior.

Figure 3.16 shows the **CEA** votes for each phenomenon.

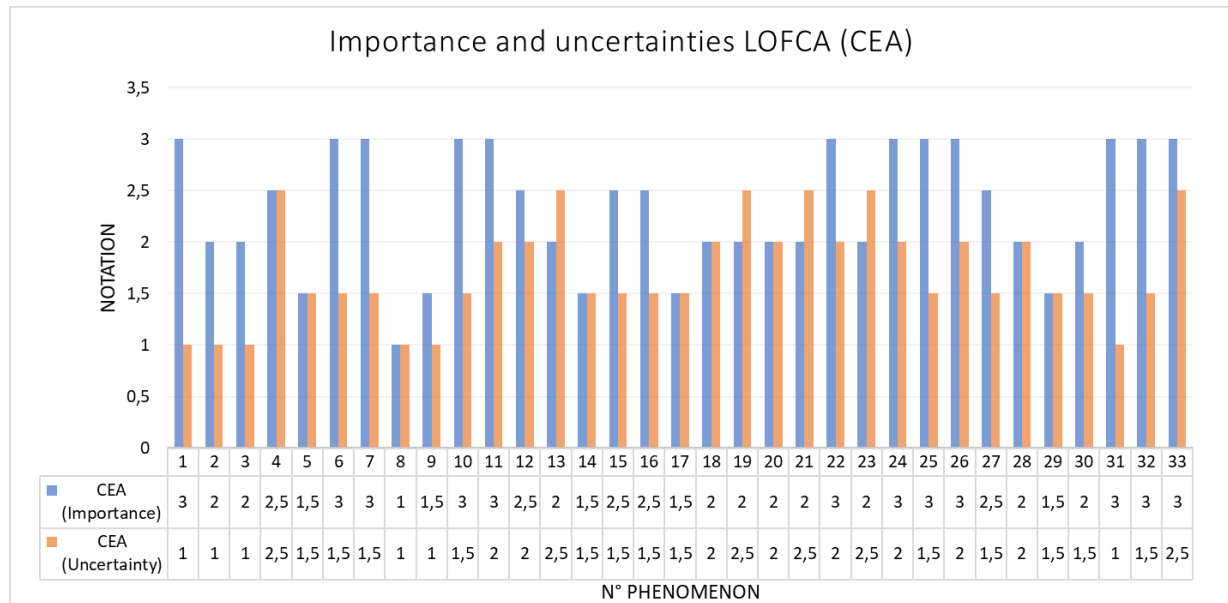


Figure 3.16: CEA votes for LOFCA phenomena

CEA voted for 12 phenomena out of 33 with high importance (vote 3) related to:

- Salt spilling and relocation;
- Decay heat;
- Salt containment.

While none of the phenomena were considered highly uncertain (vote 3).

Figure 3.17 shows the **POLIMI** votes for each phenomenon.

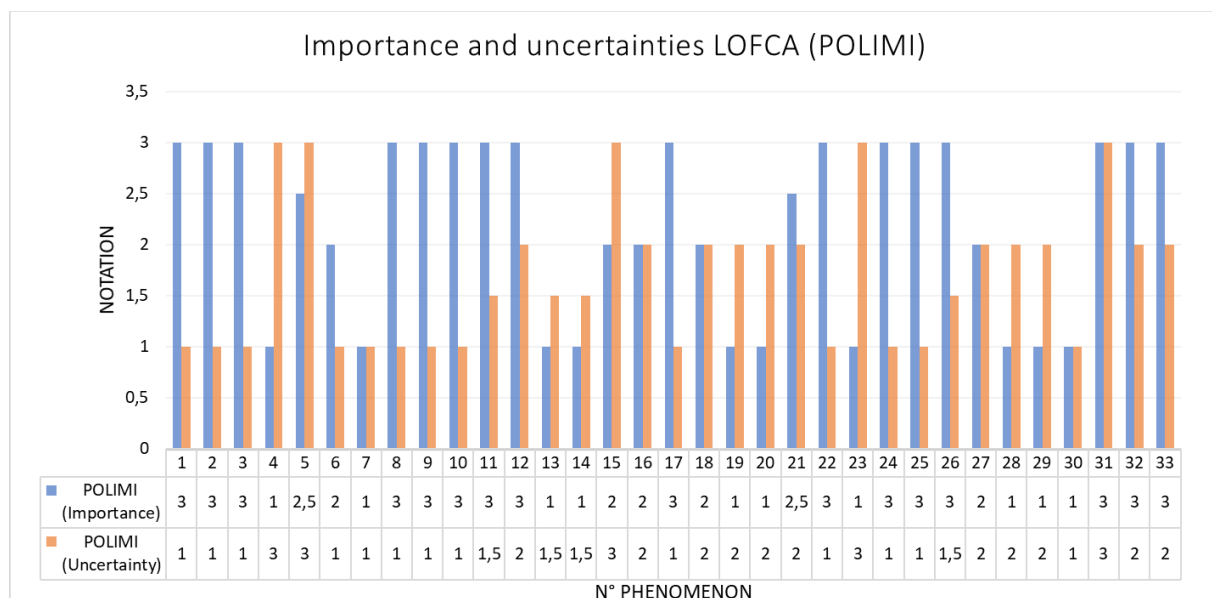


Figure 3.17: POLIMI votes for LOFCA phenomena

POLIMI voted for quite a number of phenomena with high importance (16 out of 33) which therefore concern most phenomena except those linked to salt thermal exchanges, phase changing, vessel erosion, and missile effect.



On the other hand, 5 phenomena out of 33 are classified as uncertain (vote 3) and they concern:

- Missile effect;
- Salt phase change;
- Salt long term confinement.

Figure 3.18 shows the **POLITO** votes for each phenomenon.

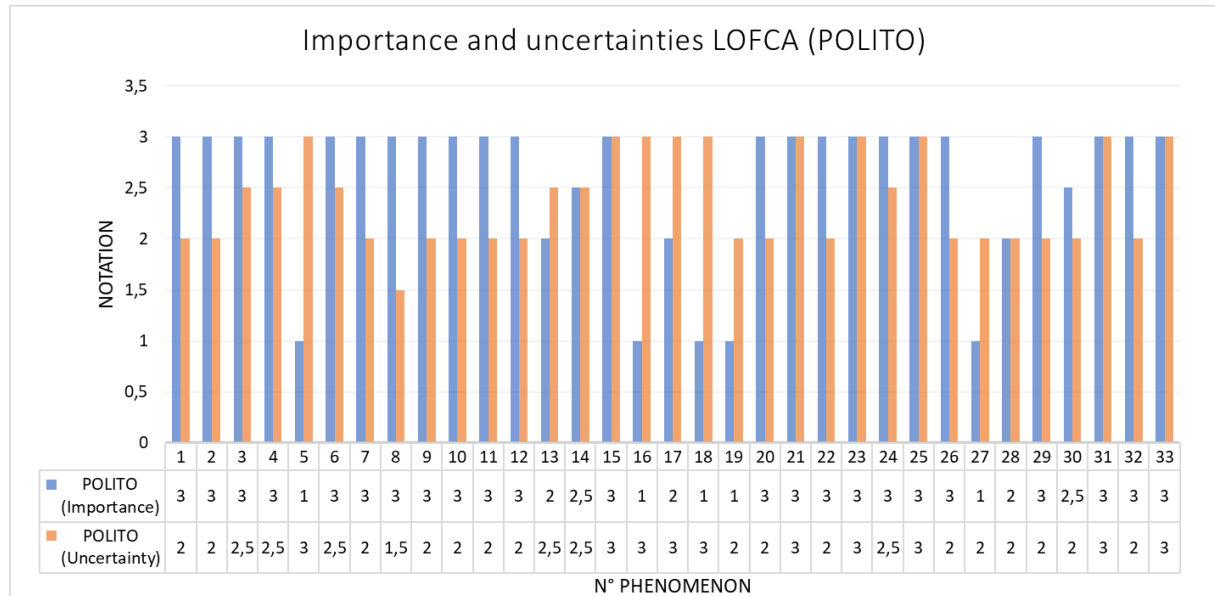


Figure 3.18: POLITO votes for LOFCA phenomena

POLITO voted for quite a number of phenomena with high importance (23 out of 33), which therefore concern most phenomena.

On the other hand, 10 phenomena out of 33 are classified as uncertain (vote 3) and they concern:

- Missile effect;
- Salt thermal hydraulic and chemical behavior;
- Salt long term confinement.

Figure 3.19 shows the **PSI** votes for each phenomenon.

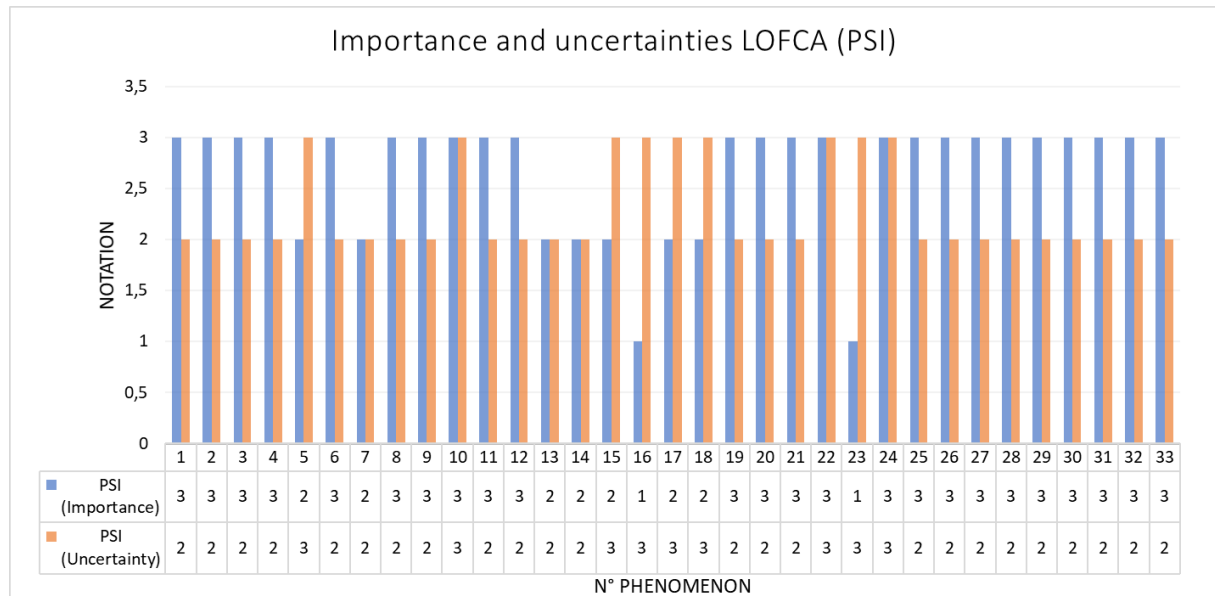


Figure 3.19: PSI votes for LOFCA phenomena

PSI voted for quite a number of phenomena with high importance (24 out of 33) which therefore concern most phenomena except mostly the salt thermal hydraulic and chemical behavior.

On the other hand, 9 phenomena out of 33 were considered highly uncertain (vote 3). They are related to:

- Salt geometry and spreading;
- Salt phase change decomposition;
- Power evolution.

Thereafter, for each phenomenon and each partner, the global vote, corresponding to the product (Importance × Uncertainty), was analyzed. Figure 3.20 summarizes the global vote of each partner for each phenomenon. In the figure, the scores of each partner are represented by different markers, and the phenomena are indicated on the horizontal axis by their corresponding numbers of the PIRT tables. In addition, each column is colored according to a scale ranging from white to red, representing the mean score, from 1 to 9 - white corresponds to the lowest mean value and dark red to the highest.

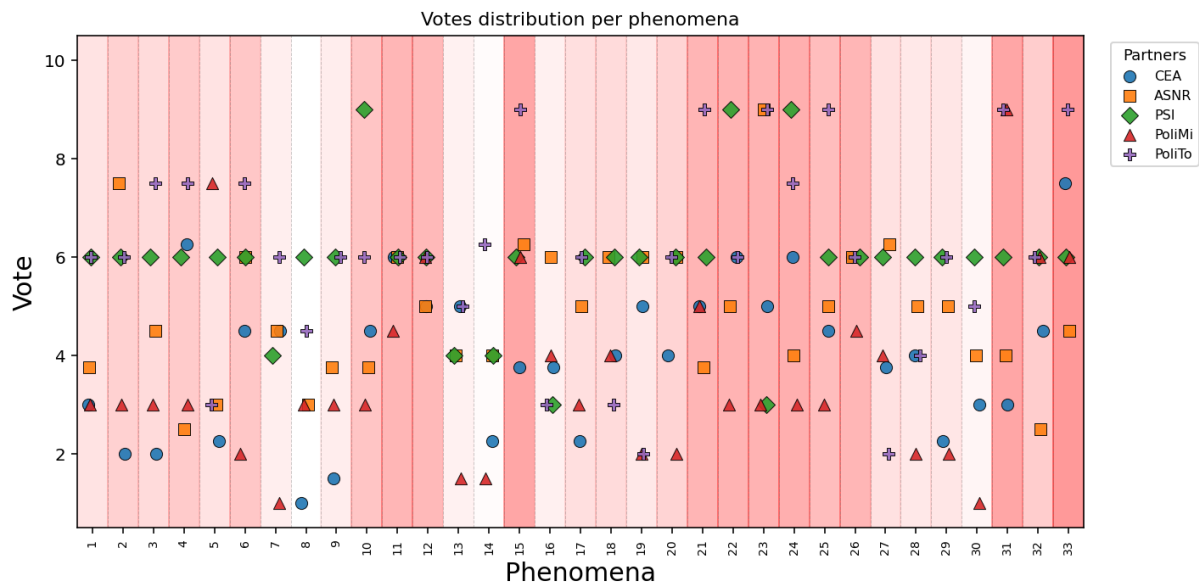


Figure 3.20 - Global votes (Importance x Uncertainty) for each partner – LOFCA transient.

From the analysis of this graph, it emerges that:

- The majority of the votes have a value equal to or lower than 6. For ASNR they are 29, for CEA 31, for POLIMI 31, for POLITO 22 and for PSI 30 out of 33.
- For ASNR and POLIMI only one phenomenon received the vote of 9.
- CEA votes are all inferior or equal to 7.5.
- POLITO voted for 6 out of 33 phenomena important and uncertain (global vote 9).
- PSI assigned an overall score of 6 to a large number of phenomena (25 out of 33), except for 3 phenomena that received an overall score of 9.

In Figure 3.21, for each phenomenon, the mean of the global scores among all the partner's votes are shown, with the associated standard deviation. As for SBOU, the attention is focused on the phenomena with global vote larger than 6.

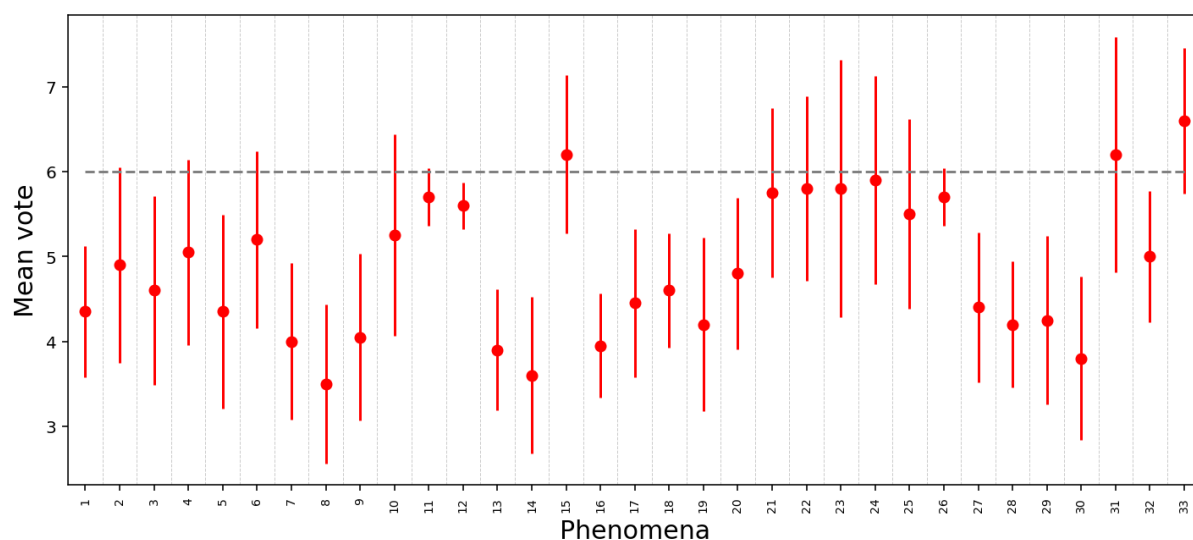


Figure 3.21 - Mean vote and standard deviation of the partners' votes – LOFCA transient.

Only 3 phenomena obtain a global score larger than 6, they are listed in the following Table 3.3. The lines corresponding to the phenomena with higher value (6.60) are highlighted.

Table 3.3 - Phenomena with global score larger than 6 – LOFCA transient.

Accident phase	FoM	Phenomena	IxU (Average)
Salt behavior in the guard vessel	Salt thermalhydraulic and chemical behavior	15 - Salt and its compound vaporization	6.20
Salt behavior in the guard vessel	Guard vessel loadings	31 - Radionuclide release because of a too large pressure in the guard vessel	6.20
Salt behavior in the guard vessel	Guard vessel loadings	33 - Breakthrough of the guard vessel with salt downward relocation	6.60

In conclusion, the LOFCA PIRT results show that the most important and uncertain phenomena are mainly associated with salt vaporization, pressure build-up, radionuclide release, and guard vessel integrity. Compared with UTOP and SBOU, fewer LOFCA phenomena exceed the selected priority threshold. Considering the highest-ranked phenomenon, the main priority is the breakthrough of the guard vessel with downward relocation of the fuel salt. Salt and compound vaporization and radionuclide release due to excessive pressure in the guard vessel remain closely connected to this high-priority issue. These phenomena may contribute to pressure increase, source-term mobilization, thermal and chemical loading of the guard vessel, and ultimately to loss of confinement. In particular, guard vessel breakthrough is directly linked to the late-phase evolution of the relocated salt inventory, including its thermal state, pressure conditions, interaction with surrounding structures, and possible downward relocation path. It may therefore affect confinement integrity, source-term assessment, salt retention capability, and the definition of mitigation strategies for LOFCA scenarios.



3.2 PIRT discrepancy analysis

A second stage in the development of the PIRT involved analyzing discrepancies in the partners' votes. For the same phenomenon, significant differences in voting could indicate disagreement or misunderstanding among the partners.

After an initial round of independent voting, the discrepancy in votes for each phenomenon was calculated. Specifically, it was measured as the difference between the maximum and minimum values of the global score (importance $\times$ uncertainty). The phenomena characterized by a discrepancy larger than 6 have been discussed among partners in a dedicated meeting. Phenomena with a discrepancy greater than 6 were reviewed during a dedicated meeting among the partners, with the aim of understanding the reasons for disagreement and providing clarification. Following the discussion, some partners revised their votes, and additional comments or explanations have been included where necessary.

After the discussion between partners, some of them reconsidered their votes which reduced considerably the number of phenomena with discrepancy larger than 6. In the first round of voting, there were 25 phenomena identified with a discrepancy larger than 6 among all transients; after reconsideration of the votes, this number was reduced to 3.

Moreover, after the second round of voting, the large discrepancies do not concern anymore any of the phenomena with mean vote larger than 6, meaning that partners are in agreement on the phenomena with the largest importance and uncertainty.

The votes reported in this document are the most recent and up-to-date ones. As it will be shown below, some discrepancies still remain, and the comments discussed during the meeting are provided in this note to explain and understand them. As before, in the whole analysis of this section, each phenomenon is referenced using the numbering shown in the PIRT tables in Annex 1.

Figure 3.22 refers to the UTOP transient and shows the mean scores on the horizontal axis, with votes having a discrepancy greater than 6 highlighted in red.

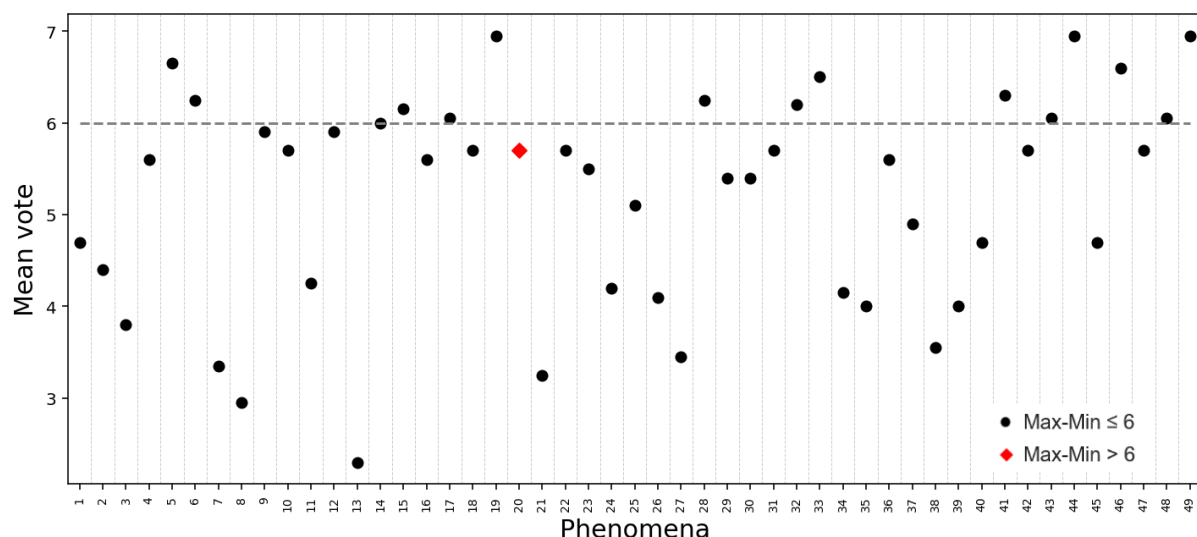


Figure 3.22 – Discrepancy analysis for the votes of UTOP transient.

The UTOP transient presents only one phenomenon with a vote discrepancy greater than 6. It corresponds to the phenomenon of pressurization of the fuel circuit (numbered 20), related to the figure of merit of



fuel salt behavior during the thermal expansion stage (incompressible stage). This phenomenon results in a discrepancy of votes of 7 and it corresponds to an average vote of 5.7, meaning importance and uncertainty quite important. This discrepancy results from a disagreement between POLITO that voted both high (vote 3) importance and uncertainty counter to POLIMI that attributes middle importance (vote 2) and low uncertainty (vote 1). The pressurization of the fuel circuit is a phenomenon that can be produced in the sequence of both the UTOP and SBOU. The global vote in UTOP is expected to be larger than in SBOU. POLIMI stated that they focused mainly on the different dynamics characterizing the two scenarios, in particular, the effect of a general pressure variation in the circuit versus the oscillations induced by a pressure wave. A possible misunderstanding between partners may be behind this divergent analysis. Further discussion between CEA and POLIMI could be valuable to reach a common understanding of the pressurization phenomenon mentioned here, which is caused by the bubble exhaust from the core region to the cover gas region, and leads to fuel salt packing.

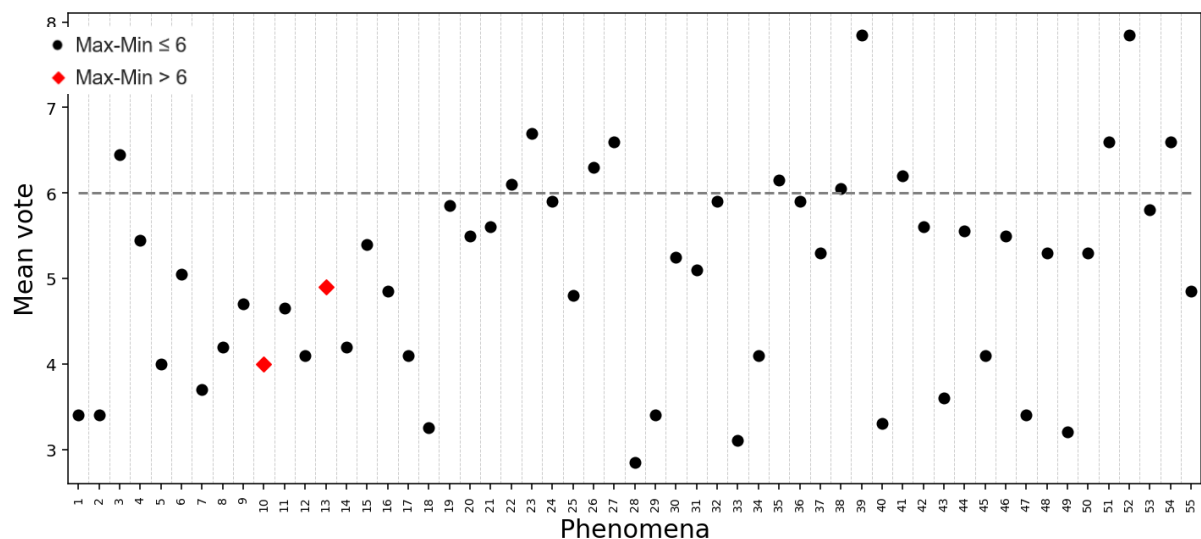


Figure 3.23 - Discrepancy analysis for the votes of SBOU transient.

Figure 3.23 refers to the SBOU transient and shows the mean scores on the horizontal axis, with votes having a discrepancy greater than 6 highlighted in red. This transient presents two phenomena with a vote discrepancy greater than 6. Both are linked to the FoM of reactivity feedback and power evolution. The first is the moderating effect, with a discrepancy of 7 (CEA voted 2 and POLITO voted 9) and an average vote of 4. The second is the effect of migration of salt species to bubble (if bubbling transport), with a discrepancy of 6.5 (ASNR voted 7.5 and POLIMI voted 1) and an average vote of 4.6. It is worth noting that the discrepancy between these two cases is associated with phenomena whose global vote is below 5, indicating that their importance and the uncertainty surrounding them are considered relatively low.

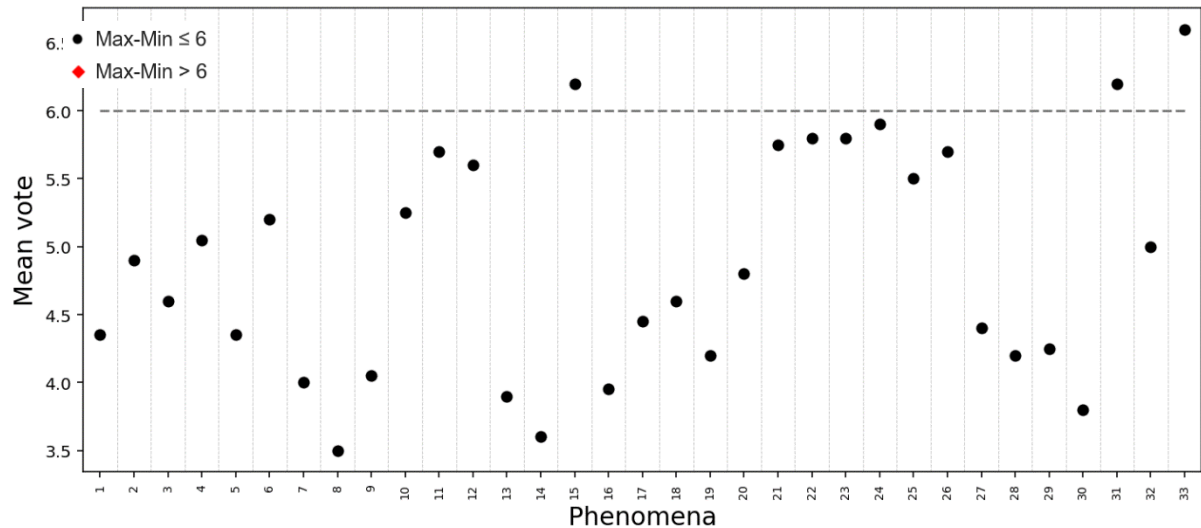


Figure 3.24 - Discrepancy analysis for the votes of LOFCA transient.

Figure 3.24 refers to the LOFCA transient and shows no phenomena with a vote discrepancy greater than 6. After the discussion and the revoting phase, all the partners reached an agreement and the discrepancy was reduced below or equal to 6.

In this paragraph the importance of discussion between partners is highlighted after a first phase of independent voting. Discussion helped reduce the discrepancies in the votes and to provide comment on phenomenon.

4. Conclusions and perspectives

The Task 4.1 of the ENDURANCE project consisted of a PIRT exercise tailored to typical MSR accident sequences based on the ARAMIS-P concept. The objective of this work is to identify and rank all safety-related phenomena that should be simulated or experimentally studied and taken into account in a safety assessment process for MSR systems at an early design stage depending on their importance and uncertainty. Thanks to the PIRT results some priority R&D topics should be identified. The work has been carried out for three different accidental transients: the reactivity insertions or Transient OverPower (TOP), the total loss of active systems or Station Black-Out accident (SBO) and the Loss of Fuel and of Coolant Accident (LOFCA). The PIRT exercise was performed by an expert panel from ASNR (L'Autorité de sûreté nucléaire et de radioprotection), CEA (Commissariat à l'énergie atomique et aux énergies alternatives), POLIMI (Politecnico di Milano), POLITO (Politecnico di Torino) and PSI (Paul Scherrer Institut).

The construction of the PIRT tables was supported by two structured analytical tools: the Phenomenological Event Chart (PEC) and the Generic Event Tree (GET). Each phenomenon was identified from the decomposition of the accident sequence into successive time periods. This temporal segmentation allowed grouping phenomena that are consistent in terms of time and space scales in macrophenomena with their associated Figures of Merit (FoM) or evaluation criteria.

Subsequently, each partner independently assessed and voted on the importance and uncertainty level of each identified phenomenon within the elaborated PIRT tables for each selected transient. The final stage consisted of the consolidation, synthesis and analysis of the results in order to establish a ranked list of the most important and most uncertain phenomena.



The phase of discussion and revoting helped reduce significantly the discrepancy among the partners votes. At present it remains only 3 phenomena with discrepant votes among partners (measured as the difference between the maximum and the minimum vote larger than 6).

The UTOP transient is dominated by fast and strongly coupled phenomena affecting reactivity feedback, pressure-wave propagation, compressible multiphase flow, salt densification, and radionuclide/species transport. The SBOUT transient mainly highlights issues related to passive decay heat removal, salt freezing and solidification, salt chemistry, precipitation phenomena, redox/radiolysis effects, and long-term salt management in the Emergency Storage Tank (EST). The LOFCA transient involves fewer phenomena above the selected priority threshold, but the identified high-priority issues are critical for confinement assessment, in particular guard vessel integrity, salt vaporization, radionuclide release, and late-phase salt relocation.

Overall, the exercise shows that the most important knowledge gaps are not limited to global thermal-hydraulic behaviour. They also involve local and coupled phenomena, including salt density and void fraction evolution, multiphase venting, salt and actinide precipitation, redox-driven phase changes, radionuclide transport, and structural degradation under thermal, chemical, and pressure loading. These phenomena directly affect key safety functions, including reactivity control, decay heat removal, confinement, and source-term limitation.

Finally, the PIRT exercise was conducted to identify the key phenomena that could significantly influence both design choices and the safety assessment of MSRs. A major outcome of this work is the prioritization of the Figures of Merit (FoMs) identified in the PIRT tables and of the associated phenomena. This prioritization provides direct guidance for future R&D planning, as it helps identify which modelling developments, experimental programmes, and validation activities should be addressed first to support a robust safety demonstration and design justification. In parallel, a review of the available calculation tools and experimental databases used for their validation is required, since some of these tools and datasets still need further development or completion. The prioritization of such efforts should be guided by the parameters and phenomena that are essential for MSR safety assessment, particularly those involving strong coupling between neutronics, thermal-hydraulics, compressible flow, multiphase transport, salt chemistry, phase change, and structural response.

Multiple perspectives can be identified from this work. First, the remaining discrepancies should be further discussed among partners to clarify them and understand their origins (i.e., misunderstanding or actual difference of opinion requiring in that case a more thorough explanation).

In addition, this PIRT exercise was conducted specifically for the ARAMIS-P concept. The results as well as the description of the three accidental transients and the associated phenomena are inherently connected to this particular design. The PIRT methodology can be extended to other MSR concepts (such as pool concept, heterogenous core concept which are designs currently being considered by startups in Europe) to assess the robustness and broader applicability of the conclusions obtained for ARAMIS-P.



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Annex A - PIRT table for the UTOP transient

Qualitative Figure of merit: Fuel salt boiling margin and to vapor formation (1), Fuel circuit wall loading (2), activity in the guard vessel (3), fuel salt mass distribution (4), power excursion (5)

Quantitative figure of merit: Maximum salt temperature (1) (2), Energy stored into the salt (5), Maximum fuel circuit pressure (2), mass salt inventory in guard vessel (3) (4), EST (4), and fuel circuit (4)

Numbers after FoMs provide the link between qualitative and quantitative FoMs

Scale: micro, meso (from 1 to several 10th of cm), large (typically of the meter order)

Time scale: short (~ 10 ms-1s), intermediate (~ 1-5 mn), long (~ 1 h-10 h)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Salt behavior in the fuel circuit (inside 1 st Barrier)	Reactivity insertion Stored energy Maximum salt temperature	1. Inserted reactivity			Meso scale, short time scale Design issue and accident assumption	Reactivity control
		2. Reactivity ramp			Meso scale, short time scale Design issue and accident assumption	Reactivity control
	Reactivity feedback and power evolution	3. Doppler			Micro scale, short time scale	Reactivity control
		4. Fuel expansion			Meso scale, short-intermediate time scale	Reactivity control



	Stored energy Maximum salt temperature Maximum fuel salt pressure	5. Fuel density increase (by wave compression)			Meso scale, short time scale	Reactivity control
		6. Bubble collapse (if bubbling system)			Meso scale, short time scale Likely to impact on the void reactivity coefficient	Reactivity control
	Fuel salt behavior before thermal expansion (compressible stage) Stored energy Maximum salt temperature Maximum fuel salt pressure	7. Migration of salt species to bubble (if bubbling transport)			Micro-meso scale, short time scale	Reactivity control
		8. Transport of species in the bubbles to the cover gas			Large scale, short time scale	Reactivity control
		9. Bubble formation due to salt heating (fission gas and volatile species)			Micro-meso scale, short time scale	Reactivity control
		10. Acoustic or shock wave formation due to fast salt heating and local volume increase			Meso scale, short time scale	Containment Reactivity control
		11. Heat exchanges increase by radiation towards cold structures			Large scale, short time scale	Cooling Confinement
		12. Salt pressure increase due to density increase behind shock wave			Meso scale, short time scale	Reactivity control
		13. Precursor drift (due to wave compression)			Micro scale, short time scale	Reactivity control



					Delayed Neutron Precursors could accumulate or spread due to the pressure wave constructive/destructive interference --> possible impact on the kinetics	
		14. Pressure wave propagation and reflection in the fuel circuit			Large scale, short time scale	Reactivity control
		15. Pressure wave refraction to the free surface			Meso scale, short time scale	Reactivity control
	Fuel salt behavior during thermal expansion stage (uncompressible stage)	16. Rarefaction wave travelling towards the fissile zone			Meso scale, short time scale	Reactivity control
		17. Fuel pressure decrease and possible bubble formation in superheated zones			Meso scale, short time scale	Reactivity control Confinement
		18. Bubble migration towards the salt free surface and void fraction evolution into the salt			Meso scale, intermediate time scale	Reactivity control
	Stored energy Maximum salt temperature Maximum fuel salt pressure	19. Salt packing due to bubble exhaust from the core region			Meso scale, short time scale	Reactivity control
		20. Pressurisation of the fuel circuit			Large scale, short-intermediate time scale	Confinement



	Reactivity feed-back and power evolution	21. Doppler			Micro scale, short time scale	Reactivity control
		22. Salt density effect			Meso-large scale, short time scale	Reactivity control
	Stored energy Maximum salt temperature	23. Salt bubble presence and migration (void fraction effect)			Micro-meso scale, intermediate time scale	Reactivity control



Qualitative Figure of merit: Fuel circuit structure loading (1)

Quantitative figure of merit: Maximum wall temperature (1), Maximum heating rate of the structures (1), Wall strain (1), Maximum static pressure (1), Impulse (1)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Fuel vessel wall loading during pressurization and salt draining transient	Static mechanical loading	24. Free surface elevation increase in the expansion tank			Meso scale, short-intermediate time scale	Confinement
	Maximum static pressure	25. Pressure evolution and associated mechanical loading			Large scale, short time scale	Confinement
	Maximum wall temperature	26. Loading on inner fuel circuit structures			Large scale, short time scale	Confinement
	Dynamic mechanical loading	27. Fuel expansion			Large scale, short time scale	Confinement
		28. Fuel pressure increase (by wave compression)			Meso scale, short time scale	Confinement
		29. Fission gas and volatile FP release because of a too large pressure in the fuel vessel			Large scale, intermediate time scale	Confinement
		30. Plastic deformation and loss of integrity of the fuel vessel			Large scale, short-intermediate time scale	Confinement
	Impulse, Wall strain					



	Fuel vessel loading Maximum wall temperature Wall strain	31. Breakthrough of the fuel vessel with salt relocation			Meso scale, short-intermediate time scale	Confinement
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Qualitative Figure of merit: amount of relocated fuel salt (1), fuel salt space distribution (3), salt composition and state evolution during relocation (2)

Quantitative figure of merit: salt temperature and pressure (2), salt mass in the fuel circuit (3), salt mass in EST (3), vented fuel mass (1), activity inside the second barrier (1)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Salt relocation and venting (inside 2nd Barrier)	Pressure venting Salt temperature and pressure Vented fuel mass and activity in the guard vessel	32. Vapour and gas phase exhaust through the off-gas line			Meso-large scale, intermediate time scale	Confinement
		33. Multiphase flow through the off-gas line			Micro-meso scale, intermediate time scale	Confinement
		34. Gas and salt (vapor and/or liquid) relief after safety valve opening to limit the pressure			Meso scale, intermediate time scale Design dependent	Confinement
		35. Sonic blockage in the safety valve			Meso scale, short time scale Design pressure dependent	Confinement
		36. Freezing in the off-gas line			Micro-meso scale, intermediate time scale	Confinement
	Salt draining in the emergency storage tank	37. Draining and relocation of the salt towards the EST			Large scale, intermediate time scale Depending on the design it could be passive or active	Confinement Reactivity control



	Salt mass in the fuel circuit, Salt mass in the emergency tank	38. Fuel salt active transfer			Large scale, intermediate time scale Pumping	Confinement Reactivity control
		39. Fuel salt draining by gravity			Large scale, intermediate time scale	Confinement Reactivity control
		40. Gas transfer from the EST to manage pressure balance in fuel circuit			Large scale, intermediate time scale	Confinement Reactivity control
		41. Migration of salt species to bubble (if bubbling transport)			Micro-meso scale, intermediate time scale	Confinement
		42. Transport of species in the bubbles to the cover gas			Meso scale, intermediate time scale	Confinement
		43. Bubble formation due to salt heating (fission gas and volatile species)			Meso scale, intermediate time scale	Confinement
		44. Actinide precipitation on cold surfaces of the emergency storage tank			Micro-meso scale, intermediate time scale	Confinement reactivity control
		45. Gas transfer from the EST to manage pressure balance in fuel circuit			Large scale, intermediate time scale	Confinement Reactivity control



	Radionuclide transport Activity inside the second barrier	46. Migration of salt species to bubble (if bubbling transport)			Micro-meso scale, intermediate time scale	Confinement
		47. Transport of species in the bubbles to the cover gas			Meso scale, intermediate time scale	Confinement
		48. Bubble formation due to salt heating (fission gas and volatile species)			Meso scale, intermediate time scale	Confinement
		49. Actinide precipitation on cold surfaces of the emergency storage tank			Micro-meso scale, intermediate time scale	Confinement reactivity control

Annex B - PIRT table for the SBOUT transient

Qualitative Figure of merit: Boiling margin (1) to vapour formation, fuel salt margin actinide precipitation (2), fuel salt criticality (3),

Quantitative figure of merit: Maximum (1) and minimum (2) salt temperature, Salt power (3), Maximum fuel circuit pressure (3), reactivity (3)

Number after FoM match the qualitative and quantitative FoMs

Scale: micro, meso (from 1 to several 10th of cm), large (typically of the meter order)

Time scale: short (~ 10 ms-1s), intermediate (~ 1-5 mn), long (~ 1 h-10 h)



Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Salt behavior in the fuel circuit (inside 1 st barrier)	Salt heating/freezing Maximum and minimal fuel temperature	1. Fuel salt flow rate coastdown			Large scale, intermediate time scale Design issue and accident assumption	Cooling
		2. Intermediate circuit flow rate coastdown			Large scale, intermediate time scale Design issue and accident assumption	Cooling
		3. Freezing in DHR loop pipes			Micro-meso scale, intermediate time scale Natural circulation in fuel, radiation impact on the fuel temperature	Cooling
		4. Natural circulation actuation in DHR loops			Large scale, intermediate time scale Change of flow pattern (flow instability)	Cooling
		5. Freezing in IHX			Micro-meso scale, intermediate time scale After scram or neutronic shutdown depending on residual cooling in IHX and DHX, the salt could freeze	Cooling
		6. Heat exchanges increase by radiation towards cold structures			Large scale, short time scale	Cooling
		7. Doppler effect reactivity feedback			Micro scale, short time scale	Reactivity control



	Reactivity feedback and power evolution Salt power reactivity	8. Salt density reactivity effect			Meso-large scale, short to intermediate time scale	Reactivity control
		9. Effect of structure shape variation on the reactivity			Meso-large scale, short to intermediate time scale	Reactivity control
		10. Moderating effect			Meso scale, short time scale Possibility to have moderator insertion in a degraded evolution of the sequence?	Reactivity control
		11. Decay heat evolution			Large scale, intermediate to long time scale In this evolution the inlet and outlet of decaying nuclei should be taken into account	Cooling
		12. Reactivity feedback due to precursors flow rate evolution			Large scale, intermediate time scale	Reactivity control
	Fuel salt behavior before possible draining or venting Maximum fuel pressure and temperature	13. Migration of salt species to bubble (if bubbling transport)			Micro scale, short-intermediate time scale	Cooling Reactivity control
		14. Transport of species in the bubbles to the cover gas			Meso-large scale, intermediate time scale (depends on salt composition)	Cooling Reactivity control
		15. Bubble formation due to salt heating (fission gas and volatile species)			Meso scale, short-intermediate time scale (depends on salt composition)	Cooling Reactivity control



		16. Heat exchanges by convection and conduction to the reactor structures			Meso scale, intermediate time scale	Cooling
		17. Salt pressure increase due to temperature increase and thermal expansion			Large scale, intermediate time scale (depends on salt composition)	Confinement



Qualitative Figure of merit: Fuel circuit structure loading (1), Fuel structure leak tightness (2)

Quantitative figure of merit: Maximum wall temperature (1), Maximum heating rate of the structures (1), Wall strain (2), Maximum static pressure (1), Wall thickness (2)

Scale: micro, meso (from 1 to several 10th of cm), large (typically of the meter order)

Time scale: short (~ 10 ms-1s), intermediate (~ 1-5 mn), long (~ 1 h-10 h)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety functions
Corrosion and loadings of fuel vessel wall (inside 1 st Barrier)	Fuel vessel wall loading Maximum salt pressure and temperature	18. Free surface elevation increase in the expansion tank			Meso scale, intermediate time scale	Confinement
		19. Salt saturation pressure evolution increase due to evaporation of volatile species			Micro to meso scale, intermediate time scale (depends on salt composition)	Confinement
		20. Thermomechanical loading of reactor vessel			Meso scale, intermediate time scale	Confinement
	Vessel wall strain	21. Plugging of off-gas system pipe due to salt species condensation and freezing			Meso scale, short to intermediate time scale Phase change due to melting and salt expansion (depends on salt composition)	Confinement
	Thermal and chemical loading (vessel)	22. Corrosion increase due to salt heating			Micro to meso scale, intermediate time scale Strongly dependent on the fission reaction	Confinement
	Maximum temperature	23. Corrosion increase due to redox and radiolysis potential evolution with salt temperature evolution			Micro scale, intermediate time scale Impact on precipitation, interconnexion with fission products speciation of the actinides and the	Confinement



	and heating rate, Eroded thickness (chemical attack)				FP components in the salt mixture. (Data for chloride-fluoride mixtures limited) (depends on salt composition)	
		24. Thermal creep of the reactor vessel wall			Large scale, intermediate-large time scale	Confinement
		25. Radiative heating of the reactor vessel wall			Large scale, short time scale	Confinement



Qualitative Figure of merit: amount of relocated fuel salt (1), fuel salt space distribution (1), salt composition and thermodynamic state evolution during relocation (2)

Quantitative figure of merit: salt temperature and pressure (2), mass of precipitated actinides (2), vented fuel mass (1), activity inside the second barrier (1)

Scale : micro, meso (from 1 to several 10th of cm), large (typically of the meter order)

Time scale : short (~ 10 ms-1s), intermediate (~ 1-5 mn), long (~ 1 h-10 h)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Compromised safety functions
Salt relocation and venting (inside 2 nd Barrier)	Pressure venting Salt pressure Vented fuel mass Activity in the guard vessel	26. Vapour and gas phase exhaust through the off-gas line			Meso scale, intermediate time scale	Confinement
		27. Multiphase flow through the off-gas line			Micro-meso scale, short to intermediate time scale	Confinement
		28. Pressure increase up to the opening of a safety valve			Large scale, intermediate time scale Design dependent	Confinement
		29. Sonic blockage in the safety valve			Meso scale, short time scale Design pressure dependent	Confinement
		30. Freezing in the off gas line			Micro-meso scale, intermediate time scale Dependent on the composition. Melting point known but phase diagrams for chloride salt fuel poorly known.	Confinement
		31. Actuation of the draining			Large scale, intermediate time scale	Confinement



	Salt draining in the emergency storage tank Drained fuel mass Fuel temperature Fuel pressure				Depending on the design it could be passive or active	
		32. Dynamic of salt draining			Large scale, intermediate time scale Power distribution between fuel vessel EST (possible mismatching with DHR design requirements)	Confinement
		33. Fuel salt active transfer			Large scale, intermediate time scale Pumping (not possible for black out)	Confinement
		34. Fuel salt draining by gravity			Large scale, intermediate time scale Reconfiguration of salt in the draining tank	Confinement
		35. Gas transfer from the emergency tank to manage pressure balance in fuel circuit			Large scale, intermediate time scale	Confinement
	Radionuclide transport Mass of precipitated/condensed fissile materials	36. Migration of salt species to bubble (if bubbling transport)			Micro-meso scale, intermediate time scale	Confinement
		37. Transport of species in the bubbles to the cover gas			Large scale, intermediate time scale Depends on the fluid dynamics in the liquid salt as well as vapor pressures of the species	Confinement
		38. Bubble formation due to salt heating (fission gas and volatile species)			Micro-meso scale, intermediate time scale Dependent on design and/or experiment. (depends on salt composition)	Confinement
		39. Actinide precipitation on cold surfaces of the emergency storage tank			Micro-meso scale, intermediate time scale	Confinement



(depends on salt composition)



Qualitative Figure of merit: Integrity of draining tanks (1), salt sub-criticality (2), salt coolability (3), draining tank leaktightness (4), draining tank loading (5)

Quantitative figure of merit: salt reactivity (2), salt temperature (3), draining tank pressure (1) (4), draining tank temperature (5), concentration of fissile materials after phase change (2)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety functions
Salt management In the emergency storage tank (inside second Barrier)	Salt power evolution Salt power	40. Reactivity evolution of the salt			Micro-meso scale, intermediate time scale Design dependent	Reactivity control
		41. Decay heat evolution in the salt			Large scale, intermediate to long time scale Dependent on the burnup of salt	Cooling
		42. Gaseous decaying nuclide extraction form the tank			Meso scale, intermediate to long time scale Design dependent	Cooling
	Salt temperature evolution Salt temperature	43. Conductive heat transfer between the salt and the tank wall			Micro-meso scale, intermediate time scale Design and event dependent.	Cooling
		44. Convective heat transfer between the tank wall and the DHR system coolant			Meso-large scale, intermediate time scale Pumping (not possible for black out)	Cooling
		45. Radiative heat transfer between the tank wall and the surrounding			Large scale, short time scale Dependent on the optical properties of the fuel salt	Cooling



		46. Phase change energy transfer between the salt and a dedicated material			Micro-meso scale, intermediate time scale Design dependent	Cooling
	Salt pressure evolution Salt pressure Condensed mass	47. Free level variation into the emergency tank			Meso scale, intermediate time scale	Confinement
		48. Salt pressure evolution with time and temperature			Large scale, intermediate time scale (depends on salt composition)	Confinement
		49. Vapour and gas formation due to radioactive decay			Micro-meso scale, intermediate time scale (depends on salt composition)	Cooling
		50. Vapour and gas condensation thanks to cooling system			Micro-meso scale, intermediate time scale	Confinement
	Salt state evolution concentration of fissile materials after phase change	51. Salt mass solidification			Micro-meso-large scale, intermediate time scale	Reactivity control Confinement
		52. Species precipitation including actinide			Micro-meso scale, intermediate time scale Dependent on deposition and on the burnup of salt (composition) → change of redox potential	Reactivity control Confinement
		53. Phase changes due to redox potential change			Micro-meso scale, intermediate time scale	Reactivity control Confinement



		54. Air ingress in the EST			Meso-large scale, intermediate time scale Salt precipitation risks	Reactivity control Confinement
		55. Salt crust formation at the tank wall			Micro-meso scale, intermediate time scale Corrosion issues and mechanical loading on the EST	Confinement



Annex C - PIRT table for the LOFCA transient

Qualitative Figure of merit: Fuel salt distribution (1), loadings on the guard vessel (2), fuel thermal and pressure evolution (3), criticality (4)

Quantitative figure of merit: Maximum salt temperature and pressure (3), Salt power (4), salt reactivity (4), guard vessel thermal erosion (2), leak flow rate (1), salt mass distribution (1), guard vessel temperature and pressure (2)

Numbers correspond to the link between qualitative and quantitative FoMs

Scale: micro, meso (from 1 to several 10th of cm), large (typically of the meter order)

Time scale: short (~ 10 ms-1s), intermediate (~ 1-5 mn), long (~ 1 h-10 h)

Category	Phenomenon FoM	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Salt leak and relocation	Salt discharge and spreading Salt leak flow rate Guard vessel thermal erosion	1. Fuel salt discharge regime (jet, spray,...)			Dynamics depends on the operating pressure and on the break size and geometry. <i>Intermediate scale</i>	Confinement
		2. Collection and draining to the emergency storage tank (Same table as for SBO when salt is relocated in the EST)			Design issue and accident assumption. <i>Large scale</i>	Confinement
		3. Flow to the emergency draining tank			Design issue if valve have to change their position. <i>Large scale</i>	Confinement
		4. Jet thermal loading of the guard vessel			<i>Meso scale, intermediate time scale</i>	Confinement



		5. “Missile” and jet mechanical loading of the guard vessel			Depending on the operating pressure and on the size and location of the break, both the salt jet and the fragment of the pipe can be projected causing mechanical damage to the surrounding structures. Meso scale, intermediate time scale	Confinement
		6. Salt accumulation during the discharge			Large scale, intermediate/long time scale. Position of relocation and resulting possible recriticality strongly dependent on design specifications (cf. later on)	Confinement
		7. Flow behaviour in the fuel circuit (pump head driven or driven by gravity)			Large scale, intermediate time scale	Confinement
	Reactivity feedback and power evolution Maximum salt temperature, Salt power	8. Doppler effect reactivity feedback			Micro scale, short time scale	Reactivity control
		9. Salt density reactivity effect			Intermediate scale, short-intermediate time scale	Reactivity control
		10. Salt geometry effect (accumulation/spreading/expansion)			Large scale, intermediate to long time scale	Reactivity control



					dependent on design specifications	
		11. Decay heat evolution			In this evolution the inlet and outlet of decaying nuclei in the pool should be taken into account. Large scale and long-time scale	Cooling

Qualitative Figure of merit: Fuel salt distribution (1), loadings on the guard vessel (2), criticality (3), guard vessel integrity (4)

Quantitative figure of merit: Maximum salt temperature (2), Salt power (3), Maximum guard vessel pressure (2), salt reactivity (3), guard vessel strain, eroded thickness (4), leaking rate (4), salt mass in various locations (1), activity outside the considered barrier (4)

Category	Phenomenon	Elementary phenomenon with dominant design/physical parameter	Ranking	Uncertainty	Note	Related safety function
Salt behavior in the guard vessel	Salt thermalhydraulic and chemical behaviour Maximum guard vessel pressure and temperature Maximum salt temperature Eroded thickness	12. Heat exchanges of the salt with the bottom part of the guard vessel			Large scale, intermediate time scale	Cooling
		13. Radiative heat exchanges between the salt free surface and surrounding structures (including guard vessel wall)			Large scale, short time scale	Cooling
		14. Convective heat exchanges with the salt free surface			Large scale, short time scale Design issue if valve have to change their position	Cooling
		15. Salt and its compound vaporization			Intermediate/large, short time scale (salt composition)	Confinement



		16. Salt and its compound condensation			Intermediate/large, intermediate time scale (salt composition)	Confinement
		17. Salt oxidation by air or water			Variable scales	Confinement
		18. Salt actinide precipitation			Variable scales (salt composition)	NA
		19. Chemical erosion of the vessel bottom			Variable scales	Confinement
		20. Thermal erosion of the vessel bottom			Variable scales	Confinement
		21. Gas or vapour release due to salt guard vessel interaction			Variable scales	Confinement
	Power evolution Salt reactivity And stored energy, Salt power	22. Power excursion due to recriticality during salt leakage (geometry effect)			Intermediate/large scale, short time scale (salt composition)	Reactivity control
		23. Recriticality due to actinide precipitation or temperature selective condensation			Intermediate, short time scale. Characteristics of precipitation depends on the burnup of the fuel	Reactivity control
		24. Fuel dispersion			Intermediate/large, short time scale. Design geometry impacts on results	Reactivity control Cooling



		25. Mixing with water (moderating effect)			Variable scales	Reactivity control
		26. Decay heat evolution			Large scale and long-time scale In this evolution the inlet and outlet of decaying nuclei should be taken into account	Cooling Confinement
	Guard vessel loadings Eroded thickness, Maximum guard vessel temperature And pressure Guard Vessel (GV) strain Leaking rate from the GV	27. Bubble formation due to salt heating (fission gas and volatile species)			Micro to intermediate scale, short to intermediate time scale (salt composition)	Confinement
		28. Heat exchanges increase by radiation towards cold structures			Large scale, short time scale	Cooling
		29. Heat exchanges by convection and conduction to the reactor structures			Large scale, intermediate time scale	Confinement Cooling
		30. Salt pressure increase due to temperature increase			Large scale, intermediate to long time scale (salt composition)	Confinement
		31. Radionuclide release because of a too large pressure in the guard vessel			Large scale, intermediate to long time scale	Confinement
		32. Plastic deformation and loss of integrity of the guard vessel			Intermediate scale, short time scale	Confinement
		33. Breakthrough the guard vessel with salt downward relocation			Intermediate scale, Intermediate time scale	Confinement