



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

D3.1 Specification requirements for
experimental infrastructures



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D3.1 Specification requirements for experimental infrastructures	1/57
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Executive Summary

Task 3.4 of the ENDURANCE project addresses the specification requirements for large test and qualification experimental infrastructures supporting the development, safety assessment and licensing of Molten Salt Reactors (MSRs) in Europe. The objective is to identify generic requirements for experimental facilities capable of generating high-quality data for the validation of Scientific Computing Tools, while also enabling the qualification of materials, components and systems under MSR-representative conditions. Particular attention is given to experiments where reduced-scale testing may introduce significant distortions and to testing activities that can provide evidence for safety assessment and licensing.

The work combines an overview of the experimental programmes of the two industrial partners, Saltfoss and Thorizon, with a questionnaire addressing the needs of the wider ENDURANCE community. The questionnaire considers the definition of large-scale testing, physical phenomena that are difficult to scale, component qualification, nuclear qualification, criticality experiments, the fuel lifecycle, integrated-effects testing, decommissioning and severe-accident testing. At the current stage, responses have been received from Saltfoss and Thorizon.

The two responses demonstrate substantial convergence on the need for large-scale experimentation in several important areas. In particular, natural circulation and heat transfer with internal heat generation, salt freezing and remelting, multiphase flow, corrosion and mass transfer, deposition and fouling, fission-product transport and volatile release are identified as phenomena for which reduced-scale experiments may not adequately reproduce the relevant physical interactions. Large-scale testing is therefore considered important both for reducing experimental uncertainty and for providing representative data for validation of system codes, CFD models and other Scientific Computing Tools. Material compatibility and the qualification of safety-relevant components and systems are also identified as important elements of a future European MSR technology demonstration and licensing roadmap.

The analysis also demonstrates that MSR experimental requirements are strongly dependent on reactor concept. Differences in fuel chemistry, neutron spectrum, reactor architecture, deployment strategy and safety concept result in different priorities for component qualification, integrated-effects testing, nuclear experiments and severe-accident testing. For example, the responses differ regarding the prioritization of components, the interpretation of the scalability of certain phenomena, and the potential value of a solid-salt criticality experiment. These differences indicate that a single experimental facility or uniform testing program is unlikely to satisfy the requirements of all European MSR concepts.

Based on the current assessment, a European MSR experimental program should therefore be structured as a **portfolio of complementary and, where possible, flexible experimental infrastructures**. Three principal areas emerge:

1. **Large-scale facilities for phenomena that cannot be adequately scaled down.** These facilities should reproduce relevant thermal-hydraulic and multiphysics conditions sufficiently well to provide experimental data for model validation and to demonstrate safety functions and operational procedures.



2. **Shared facilities for materials and component qualification.** Such facilities should enable long-duration testing of materials and representative components under relevant combinations of temperature, pressure, salt chemistry, flow, mechanical loading and, where required, irradiation. The infrastructure should ideally be sufficiently flexible to serve multiple MSR concepts. Given the fundamental differences between fluoride-fueled thermal-spectrum and chloride-fueled fast-spectrum concepts, separate or adaptable testing capabilities may be required for these two technology families.
3. **Shared infrastructure for fuel-related activities.** Common European capabilities could address fuel synthesis, purification, qualification, handling, storage, reprocessing and waste conditioning. Again, the significant differences between fluoride and chloride fuel salts may justify dedicated or separately configurable experimental tracks.

An important conclusion is that the value of large experimental infrastructure extends beyond demonstrating the operation of individual components. Experiments should be designed from the outset according to their intended use in the development and licensing process. Test conditions, instrumentation, measurement uncertainty, data quality and experimental procedures should therefore be defined with the subsequent use of the data for model validation, component qualification and safety assessment in mind. Flexible facilities and standardized approaches to data generation and uncertainty quantification could increase the reusability of experimental results across different MSR concepts.

The current results provide a first basis for a European roadmap for MSR experimental infrastructure. They indicate significant potential for coordinated investment in shared facilities while recognizing that design-specific experimental capabilities will remain necessary. The proposed approach would allow European MSR developers and research organizations to share infrastructure where requirements are common, while retaining sufficient flexibility to address concept-specific safety and licensing challenges.

Keywords

Saltfoss, Thorizon, Large facilities, testing, experimental, salt, qualification, MSR



Table Of Contents

Executive Summary.....	3
Table Of Contents.....	5
1 Introduction.....	6
2 Overview of industrial experimental programmes for the development of MSRs	6
2.1 Saltfoss	6
2.2 Thorizon.....	8
2.2.1 Thorizon-1 reactor concept	8
2.2.2 Demonstration plan for the development and licensing of the Thorizon-1	9
3 Questionnaire on Large Scale Testing Needs.....	13
3.1 Purpose and structure of questionnaire	13
3.2 Analysis of the responses obtained	14
4 Conclusion and Discussion.....	17
References	19
Annex A Questionnaire	20
Annex B Questionnaire – Response Saltfoss	31
Annex C Questionnaire – Response Thorizon	42



1 Introduction

This deliverable marks the completion of task 3.4 on “Specification requirements for large test and qualification experimental infrastructures”, due M24 of the Endurance project. The key responsables for this task are Thorizon and Saltfoss. The aim of this activity is to provide generic requirements for large experimental tests aimed at qualifying materials and components under MSR representative conditions, and to validate or provide experimental input to simulation codes and analysis tools, with focus on supporting licensing.

Since the task emphasizes the specification for *large scale* tests, small scale tests (like lab-scale chemistry experiments or determination of material properties, or salt micro loops) are excluded from the scope of this deliverable. Instead this task focuses on:

- Large scale molten salt loops (or other setups) for validating codes for MSR design and safety assessment.
- Experimental setups for the qualification of MSR components.
- Integral testing.
- Severe accident testing.
- Experimental facilities for molten salt fuel production, storage, reprocessing and handling of waste.
- Tests for decommissioning of MSR reactors.

The main outcome of this task is the identification of the shared needs for large scale experimental tests for the different Molten Salt Reactor Designs amongst the European MSR community, with a corresponding list of activities. As such, this task could be the starting point for discussions concerning a joint testing program between the different European nuclear research institutes and industrial partners.

2 Overview of industrial experimental programmes for the development of MSRs

The two industrial partners within the Endurance project involved in this study are Saltfoss and Thorizon. Here, a brief overview of the respective testing programs is discussed for advancing the design and licensing of the seaMSR-100 and Thorizon-1 reactors respectively.

2.1 Saltfoss

Saltfoss Energy is developing the seaMSR-100, a liquid-fuelled molten salt reactor intended for maritime deployment as a floating nuclear power plant – the Molten Salt Power Barge. The seaMSR-100 reactor is designed to deliver 100 MWe/250 MWth, with multiple reactors potentially combined on a single plant. The MSR operating temperature is ~650 °C at near-atmospheric pressure. The fuel is dissolved in a fluoride-based molten salt (FUNaK), and the reactor uses a thermal neutron spectrum with graphite moderation and low-enriched uranium (LEU) fuel.

D3.1 Specification requirements for experimental infrastructures		6/57
Security: PUBLIC		GA 101165896



For the development and licensing of the seaMSR-100, experimental activities are required in several areas. Saltfoss has identified materials science, fuel-salt development, experimental thermal hydraulics and testing and demonstration as important parts of the current development programme.

The experimental programme address both individual phenomena (separate effects testing) and integrated system behaviour (integral effects). Of particular importance are the interaction between fluoride salt chemistry and structural materials, thermal-hydraulic behaviour of the primary system, component performance at elevated temperature, and the behaviour of systems and components during normal, transient and accident conditions.

A particular challenge for the seaMSR-100 is the long-term compatibility of structural materials with the fuel salt – not least considering the long service life of 24 years. While laboratory experiments have proven feasibility, large scale testing is needed on several aspects. Large-scale testing should be capable of exposing representative materials and components to controlled molten-salt conditions for sufficiently long durations to assess degradation mechanisms, material compatibility and component lifetime. Where relevant, testing should include representative thermal gradients, flow conditions, mechanical loading and salt chemistry rather than considering corrosion as an isolated material-property question.

The development of the fuel-salt technology also creates a need for experimental infrastructure covering salt preparation and conditioning, fuel manufacture and characterization, and handling of fuel salt. In September 2026, Saltfoss announced an agreement with the Korea Atomic Energy Research Institute (KAERI) covering fuel-salt development and material corrosion evaluation. The programme includes pretreatment of fluoride molten salt, fabrication and characterization, construction and operation of a natural-circulation molten-salt test loop, and corrosion evaluation of candidate reactor structural materials under high-temperature molten-salt conditions. This provides a concrete example of the type of infrastructure and testing activities relevant to the seaMSR-100 development programme.

For thermal-hydraulic development, large-scale experimental facilities are relevant where phenomena depend strongly on system geometry, flow configuration or coupled heat transfer.

The reactor primary circuit and passive draining of fuel salt into dedicated tanks are important aspects of the safety concept and aspects hereof are foreseen to require large scale experimental setups for validation.

Experimental programmes should ultimately address not only steady-state heat transfer and circulation, but also relevant transients and passive safety functions. The experimental facilities should provide sufficient instrumentation to generate data suitable for validation of system and CFD models, including temperatures, flow rates, pressures and, where relevant, spatially resolved measurements.

From the Saltfoss perspective, the principal purpose of large-scale experimental infrastructure is therefore not simply to demonstrate that an individual component or phenomenon can operate. In addition, the experiments should generate evidence that can be used to support design decisions, qualification of materials and components, validation of modelling tools and,



ultimately, the safety case and licensing process. This requires experimental conditions, instrumentation, test procedures and data quality to be defined from the intended use of the results.

Saltfoss programme for large scale testing include:

- long-duration molten-salt loops for materials and component qualification.
- thermal-hydraulic facilities for forced and natural circulation and heat-transfer phenomena.
- representative component test rigs for pumps, valves, heat exchangers, seals and other salt-wetted components.
- facilities for salt preparation, conditioning and fuel handling.
- integrated experiments addressing interactions between chemistry, thermal hydraulics and component behaviour.
- experiments addressing relevant transient and passive safety functions.

Where possible, such facilities should be designed as flexible test platforms rather than single-purpose installations. This would allow different materials, component designs and operating conditions to be investigated using a common infrastructure.

2.2 Thorizon

2.2.1 Thorizon-1 reactor concept

The Thorizon-1 reactor is a Gen IV fast-spectrum Molten Salt Reactor (MSR) concept with a target electrical power output between 50 and 300 MW_e, and the capability to produce steam at approximately 550 °C. The primary fuel salt (NaCl-KCl-PuCl₃-UCl₃) transfers heat from each cartridge to a secondary molten salt circuit, which is transferred to a tertiary molten salt circuit and subsequently to a conventional steam cycle. Contrary to other MSR technologies, Thorizon One doesn't contain all of the molten salt nuclear fuel in a single vessel, but in a set of 19 cartridges (arranged in a hexagonal layout with 1 central cartridge, 6 cartridges in the first ring, and 12 cartridges in the second ring), placed together in a reactor cavity. Each cartridge forms an independent module with a pump, a core section (where the power is generated) and a heat exchanger. The cartridges are replaceable and transportable while ensuring confinement of the fuel salts.

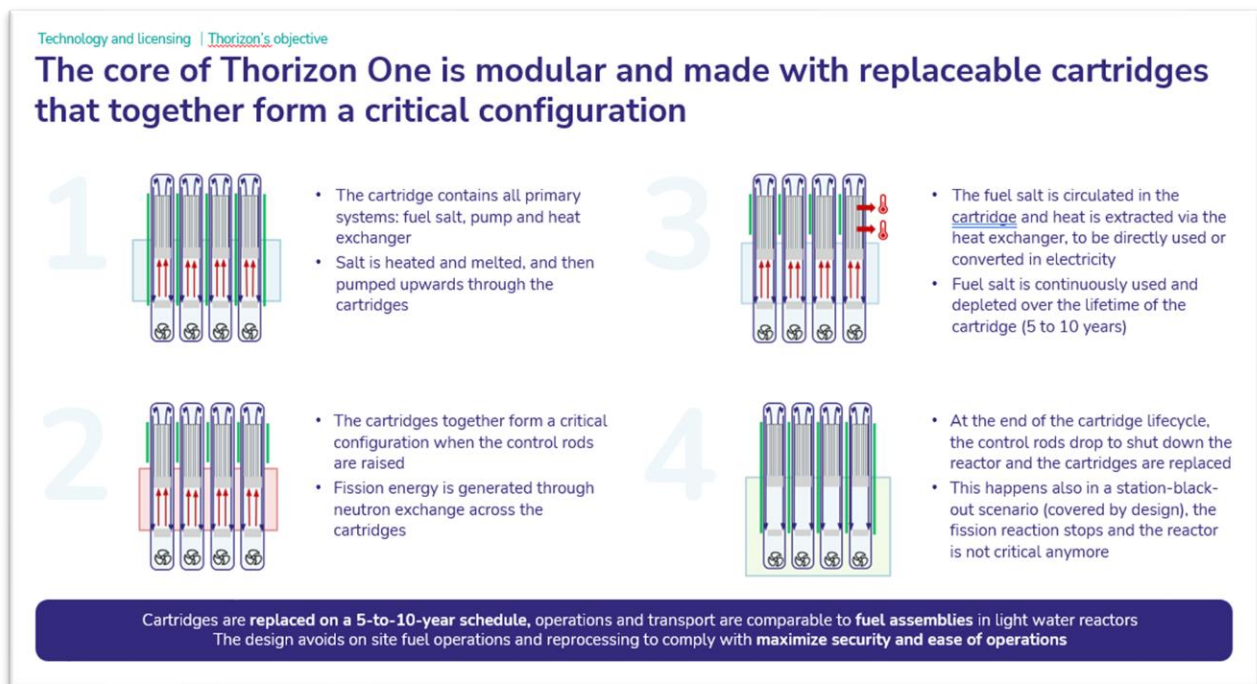


Figure 1 Illustration of the Thorizon MSR concept

2.2.2 Demonstration plan for the development and licensing of the Thorizon-1

The main (technical) challenges associated with the Thorizon-1 project are as follows:

- Molten chloride salt fuel:
 - Behaviour: thermal physical properties, evolution of composition throughout reactor operation.
 - Production: no existing supply chain for molten salt fuel. Thorizon is collaborating with Orano to this end.
 - Management of spent fuel salt: there is no industrial-scale process for reprocessing spent fuel salt. Thorizon is collaborating with Orano to this end.
- Cartridge design and development:
 - Forced convection: innovative pump to be developed and qualified.
 - Heat removal: heat exchanger with proven technology but to be qualified for the conditions of use.
 - Materials to be qualified for conditions of use/aging (salt-material interaction under harsh irradiation, temperature, and pressure conditions): primary containment, primary containment connections, secondary containment fabrication and assembly.
 - Manufacturability to be demonstrated.
 - Conditions of use, both for normal operations and for accidental scenarios. This is mainly associated with the identification of relevant phenomena (PIRT), and the demonstration of the scientific computing tool's capability to adequately represent these phenomena (validation), within the intended scope of use.
- Core cavity and severe accidents.
- Cartridge transport and transport cask, to and from the plant.



These challenges are addressed within Thorizon’s Development And Prototyping program (DAP). The DAP follows a step-by-step validation approach (see Figure 2) where the aspects of each discipline are addressed individually, and the coupling between disciplines are addressed by dedicated experiments or by demonstrating decoupling using conservative hypotheses. This enables a sufficient understanding and validation of the phenomena and mechanisms at play in the reactor system, where the remaining uncertainties are managed by appropriate safety margins in the design and operating procedures. A brief overview of the fundamental development stage and the PILOT and the PIONEER projects is given below.

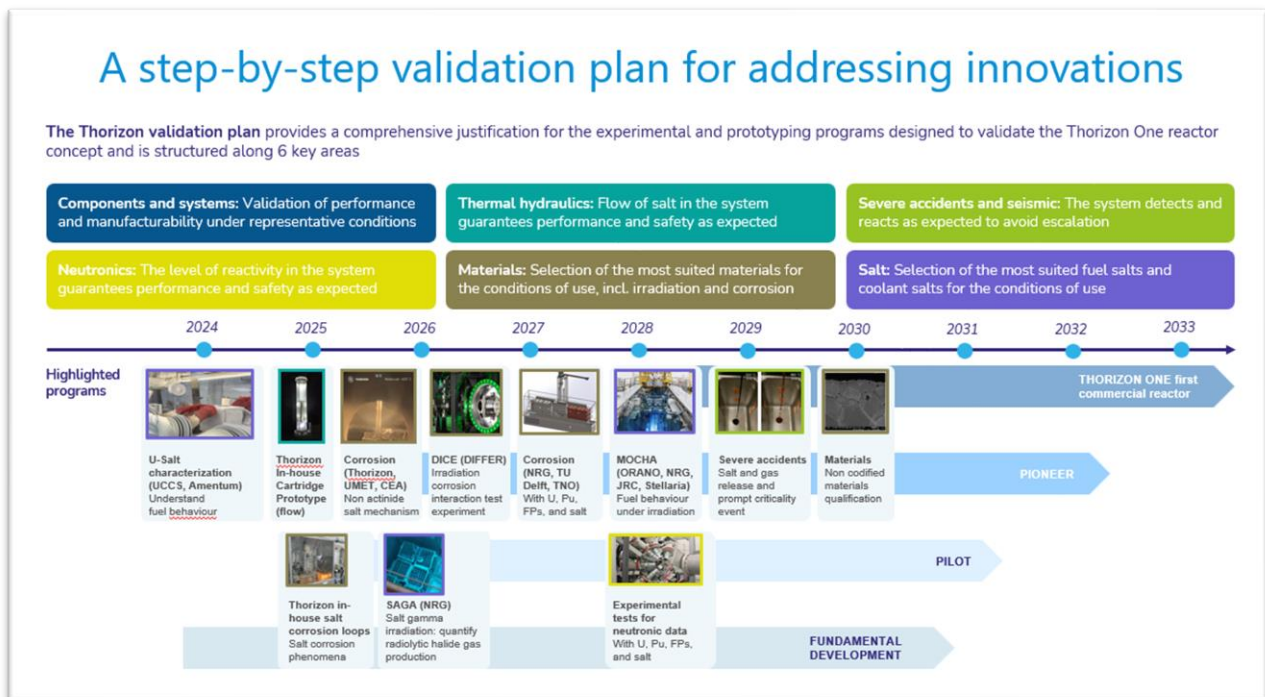


Figure 2 Step-by-step validation approach of Thorizon.

Fundamental development

Fundamental development is needed to advance Molten Salt Reactor technology and to realize Thorizon’s First-Of-A-Kind (FOAK) Thorizon-1 reactor. Some of the main knowledge gaps are related to the behavior of the fuel salt (including the production of fuel salt, the fuel handling, and the reprocessing of the spent fuel), the performance of materials in a molten salt reactor environment, and severe accidents. To this end, Thorizon is collaborating with associated industrial partners, research institutes and partner institutes across Europe. Thorizon also participates in international research projects, such as ENDURANCE and MIMOSA, to advance on general MSR related topics.

Examples of ongoing activities are:

- Characterization of the fuel salt, together with Université de Lille and Amentum.
- Quantification of halide gas production due to salt radiolysis (SAGA, together with NRG).
- Behavior of the fuel salt under irradiation (MOCHA, together with ORANO, NRG, JRC and Stellaris).
- Combined corrosion – irradiation testing (DICE, together with DIFFER).



- Thorizon collaborates with Orano on key topics related to the front-end and the back-end of the fuel cycle, such as the production of chlorine fuel salt, the transport of the fuel salt within the cartridges, and the reprocessing of the fuel salt.

Thorizon is also working on in-house experiments and prototypes within its lab in Amsterdam, related to:

- Salt purification.
- Corrosion, including both static corrosion setups and mini forced convection molten salt loops for studying dynamic corrosion effects.
- Prototypes, such as a plexiglass mockup of the Thorizon cartridge for studying the hydraulic behavior.

PILOT

The aim of Thorizon's PILOT program is to derisk innovative aspects of the Thorizon-1 cartridge design through the prototyping and testing of components. All tests within the PILOT program are non-nuclear, i.e. executed using surrogate salt (or another surrogate fluid) and electrically heated. The scope of the PILOT program is on the development of systems and components (pump, primary heat exchanger etcetera), on the validation of scientific computing tools (with the main emphasis on corrosion and the thermal hydraulic behavior within the Thorizon-1 cartridge), and a demonstration of manufacturability (including establishment of the supply chain for the different components within the cartridge).

The Pilot project includes (but is not limited to) the following activities:

- Salt purification tests, at both the lab and the batch scale. This is needed to produce the high purity surrogate salt grades which are required by the rest of the program.
- Mini molten salt loops for conducting corrosion tests under representative conditions (turbulent forced flow, with a temperature difference between the hot and cold-leg).
- Hydraulic mockup of the cartridge, for studying the flow behaviour and validating hydraulic models.
- Thermal loop for simulating the decay heat removal.
- Test of gas venting system.
- Prototyping and testing of components (primary heat exchanger, primary pump, reflector. / absorber, cartridge connections).
- Manufacturing of containment + establishment of material qualification roadmap.

The PILOT project will culminate in a full-scale non-nuclear prototype of the Thorizon-1 cartridge.

PIONEER

The Pioneer is a fast spectrum, molten chloride fuel salt nuclear demonstrator. The key characteristics of the Pioneer are: low power (200 kW_{th}), NaCl-PuCl₃ fuel salt, a primary containment made from Inconel-625, an operating temperature between 540 °C and 545 °C and a gas cooling system. Construction is foreseen to commence in 2028 and operation in 2030. The main objectives of the Pioneer are to:

- Build credibility and stakeholder confidence.
- Generate fundamental and operational data to validate models and derisk the FOAK.
- Simplify and accelerate licensing and technology adoption of molten salt reactors.
- Unlock and secure the nuclear supply chain (for the FOAK).

D3.1 Specification requirements for experimental infrastructures		11/57
Security: PUBLIC		GA 101165896

- Enable learning and operational understanding of molten salt reactors.

A representation of Pioneer is shown in Figure 3.

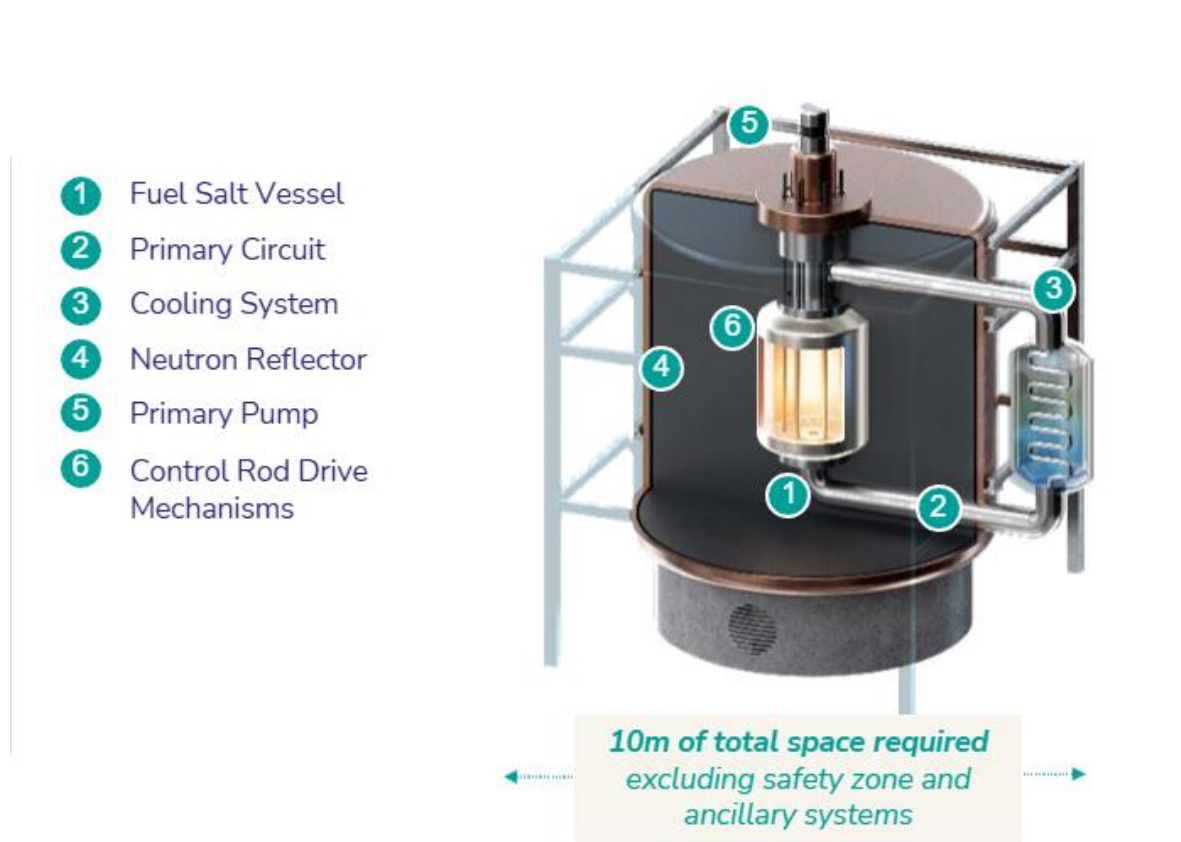


Figure 3 Pioneer nuclear demonstrator.

Pioneer will serve as a unique experimental platform for reactor physics and reactor dynamics studies, generating essential experimental and operational data for fast-spectrum molten chloride fuel salt reactors. The following list of experiments has been planned:

- Approach to criticality (at relevant fuel salt temperature).
- Determination of reaction rates of fissionable materials.
- Determination of the neutron spectrum.
- Gamma deposition inside neutron reflector.
- Differential and integral control rod worth with no forced flow.
- Determination of the dynamic reactivity response during pump startup.
- Determination of the dynamic reactivity response during pump coast-down.
- Isothermal temperature coefficient.
- β_{eff} determination with no forced flow.
- β_{eff} determination at different flow rates.
- Kinetics measurements using alpha (prompt neutron decay constant) measurement techniques or noise analysis.
- Periodic perturbations for stability analysis.
- Dynamic reactivity response to reactivity insertions due to heat removal changes or reflector characteristic changes.



- Dynamic reactivity response during pump startup and coast-down with thermal feedback.
- Dynamic reactivity experiments via rapid step control element insertions.
- Unprotected loss of forced flow (from different initial flow rates at different power levels).

3 Questionnaire on Large Scale Testing Needs

3.1 Purpose and structure of questionnaire

To obtain the feedback from the European MSR community on their vision, and their needs / requirements for a large-scale testing program, a questionnaire was developed [1] and sent out to the partners in the Endurance project. The questionnaire is included as an appendix within this deliverable report (see Annex A Questionnaire).

The questionnaire is structured into multiple sections to address the following different topics:

- What do we define by ‘large-scale’? What are the relevant scales for large experimental facilities?
- Which phenomena cannot be scaled down without resulting in (unacceptable) distortions? Here, a selection of phenomena was made based on Deliverable 4.1 on the ‘PIRT for Modelling Needs’ [2]. Some of these phenomena have been grouped into container terms to reduce the effort on behalf of the respondents.
- Relevant MSR components to be tested, types of tests needed for component qualification, and the relevant scales for component testing. This may be design dependent / specific, however an effort will be made to extract the common elements when performing the analysis of the responses obtained.
- Need for performing criticality experiments prior to building a demonstrator reactor.
- Fuel lifecycle, including production, transport / storage, fuel handling within the reactor itself (including refueling), and handling of spent fuel / waste (including reprocessing).
- Integrated effects testing. We foresee that the exact form of the integrated effects test will be highly design specific, but we hope to extract enough common elements to enable the specification of general high level requirements and recommendations on best practices.
- Decommissioning. This topic has been included since so far it has not received a lot of attention (compared to MSR Multiphysics for instance or the reprocessing of fuel). However, no regulatory body will grant a license for MSR construction without a plan for decommissioning. Due to the innovative nature of the MSR designs and the expected challenges in the decontamination and disassembly of salt wetted components, we believe decommissioning should be included within the vision for a MSR testing program.
- Severe accident testing (and the relevant scales).

Through the responses to the questions raised for each of these topics, we aim to obtain (as much as possible) the different pieces of the puzzle. By analyzing the different responses based on their common elements (and their differences) we strive to put together the puzzle and present a common vision / outlook for a technological roadmap towards the commercialization of European Molten Salt Reactors.



3.2 Analysis of the responses obtained

The questionnaire developed under Task 3.4 was intended to collect the views of the ENDURANCE partners on the requirements for a European large-scale MSR testing programme. The questionnaire addresses the definition of large-scale testing, scaling requirements, phenomena that cannot readily be scaled down, component qualification, criticality experiments, the fuel lifecycle, integrated-effects testing, decommissioning and severe-accident testing [1].

The analysis of the responses is intended to identify both common requirements and design-specific requirements. This distinction is important because some experimental questions can potentially be addressed through shared European infrastructure, whereas others depend strongly on the reactor architecture, fuel salt, materials or safety concept of an individual MSR design.

Two responses were obtained to the questionnaire, from Saltfoss and Thorizon respectively (see Annex B Questionnaire – Response Saltfoss and Annex C Questionnaire – Response Thorizon). Additional responses from other Endurance partners may be incorporated into an updated version of the deliverable.

The responses from Saltfoss and Thorizon are largely compatible, and demonstrate substantial agreement on the phenomena for which reduced-scale testing may introduce non-negligible distortions. Nevertheless, differences remain concerning the required test scales, the interpretation of specific phenomena, design specific aspects (such as component testing and nuclear qualification) and the views on certain topics such as the need for a solid salt criticality experiment. A comparison between the responses is provided below, for each tab of the questionnaire:

1_LargeScale:

Both Saltfoss and Thorizon arrive at ~100 kg/s, a thermal power of 1 MW, a pipe diameter of ~ 100 mm and 5 m height as indicators of large scale. The main discrepancy is salt inventory. Thorizon considers a large scale test to have more than 300 kg of salt, whereas this is 1000 kg for Saltfoss. It should also be noted that scale is multidimensional (for instance a test may have high flow but modest power, or vice versa) and duration of the test is not necessarily linked to geometry.

2_ScalingPhenomena:

Both organizations consider the following phenomena to only be partially scalable:

- Natural convection heat transfer with internal heat generation
- Two-phase flow
- Salt freezing and melting
- Corrosion (+ redox control)
- Deposition and fouling

D3.1 Specification requirements for experimental infrastructures	14/57
Security: PUBLIC	GA 101165896



- Fission-product transport
- Volatile release / source-term behavior

Testing these phenomena at 1:1 scale thus provides additional value (in terms of validation). Both companies agree that single, relatively decoupled phenomena can often be studied at small scale (such as forced-convection heat transfer with internal heat generation, or irradiation effects). The main disagreement is on ‘compressible flow’. This disagreement may be (partially) attributed to a difference in scope. Thorizon considers compressible flow to only be partially scalable, due to the influence of void fraction and the difficulty in replicating the conditions in which compressible flow becomes important at a smaller scale. On the other hand, Saltfoss appears to consider fuel salt compressibility as a relatively isolated phenomenon.

Other differences concern thermal stratification, which Thorizon considers partially scalable and Saltfoss considers not scalable, and heat transfer to structures, which Saltfoss considers scalable using representative surrogate conditions and Thorizon only considers partially scalable due to its coupling to the scaling of internally heated flow. Finally, Saltfoss also includes large motions, such as earthquakes or maritime motion, as a phenomenon to be investigated. Saltfoss classifies large motions as partially scalable.

3_ ComponentTesting

Thorizon identifies pumps, heat exchangers, decay-heat-removal systems, instrumentation and freeze valves as the top 5 components to test. Thorizon’s rationale is balanced between operational performance (pumps, heat exchangers and freeze valves), availability of measurements (needed for operation but also for tests in molten salt) and safety (decay-heat-removal system). Saltfoss identifies drain/storage tanks, decay heat removal systems, off-gas systems, and reactivity-control systems as the highest priority components / systems to test. Saltfoss’s rationale is that these systems directly relate to the fundamental safety functions and should therefore have the highest priority.

4_ NuclearQualification

Both Saltfoss and Thorizon include corrosion testing and case-by-case seismic qualification and irradiation testing as part of nuclear qualification. Saltfoss comments that seismic qualification may be very different for land-based versus maritime, and for fast versus thermal spectrum reactors. Saltfoss also adds the fuel salt itself as a subject for nuclear qualification.

5_ CriticalityExperiment

Thorizon considers a static-salt criticality experiment useful for reactor-physics validation (but not necessarily mandatory). Thorizon proposes irradiation of a sample of solid fuel salt (at least a few kg) as a first step, the data from this experiment would then be used to evaluate the necessity of a larger-scale zero-power frozen salt reactor experiment. The proposed measurements include criticality, neutron spectrum and reaction rates, and the reactivity worths. However, the limitations are the absence of thermal-hydraulic feedback or representative fission product behavior. Saltfoss does not believe such an experiment is required. Its proposed path is a

D3.1 Specification requirements for experimental infrastructures		15/57
Security: PUBLIC		GA 101165896



restricted license for the first-of-a-kind reactor, followed by a gradual relaxation of restrictions as technology and performance are demonstrated.

6_FuelLifeCycle

Thorizon recommends tests in the 100 to 1000 kg range to industrialize fuel production (synthesis+purification) and fuel handling (transport, storage tests, refueling and waste conditioning). Certain operations (such as salt sampling) may be addressed using smaller salt inventories. Saltfoss did not assess the required test scales in this section; consequently, no shared position can yet be identified.

7_IntegratedEffectsTests

Thorizon proposed a scope for integrated-effects testing which covers representative primary-system components (such as the pump and primary heat exchanger), expansion volume (and off-gas system if this interacts with normal plant operation), decay-heat removal and selected emergency functions. Thorizon does not include systems which are not part of the TH1 cartridge design (such as a drain tank or online salt purification / sampling systems) within its integral effects testing scope. Thorizon does not believe a non-nuclear integral effects test with surrogate salt can reproduce the handling of the actual fuel salt. Thorizon recommends to include both normal operations (including initial salt loading, pre-heating, start-up and power ramp-up, with maintenance and decontamination considered to be optional / nice-to-haves) and selected transients (loss of flow response, loss of heat sink response, salt freezing response and salt remelting procedure) within the testing matrix. Thorizon believes operations such as chemistry monitoring and control, salt sampling (if relevant to the specific reactor design) and loss of leak tightness response can be tested separately using simpler facilities.

Saltfoss considers the requirements for an integrated-effects facility to be strongly design dependent and was therefore not comfortable with sharing this information. Therefore, no comparison between the responses of Saltfoss and Thorizon could be made.

8_Decommissioning

Thorizon believes tests dedicated tests are potentially required for topics related to residual-salt removal, decontamination and dismantling of salt wetted components, waste characterization and conditioning, remote handling where relevant, management of fumes and volatile species and retention of fission products.

Saltfoss did not provide a response to this section. Therefore, no comparison between the responses of Saltfoss and Thorizon could be made.

9_SevereAccident

For severe accidents, Saltfoss identifies salt-water interaction as the principal severe-accident phenomenon requiring testing. It does not propose a dedicated large-scale salt-spill experiment, but indicates that salt-air interaction could be addressed through smaller-scale spill testing. Thorizon proposes salt-spill testing at an intermediate or engineering scale of at least 50 kg and considers the appropriate scale for salt-water, salt-air and salt-concrete interactions to be scenario dependent.

D3.1 Specification requirements for experimental infrastructures		16/57
Security: PUBLIC		GA 101165896



Overall assessment

Overall, the two responses indicate a substantial common basis for a European large-scale MSR experimental programme. The strongest areas of convergence are thermal-hydraulic testing (such as natural circulation and heat removal, freezing and remelting), corrosion and material compatibility, and the qualification of safety-relevant components.

At the same time, the responses demonstrate that a single shared experimental programme is unlikely to satisfy all MSR testing needs. The required infrastructure depends on the fuel chemistry, neutron spectrum, reactor architecture, safety functions and licensing strategy. A European programme should therefore combine shared, flexible experimental platforms with dedicated facilities for design-specific questions.

A potentially effective approach is consequently to establish a portfolio of experimental infrastructures rather than a single large facility. Shared facilities could address generic thermal-hydraulic phenomena, materials and component qualification, measurement and modelling validation, while dedicated installations could address fuel-specific chemistry, nuclear experiments, fuel-cycle processes and reactor-specific integrated effects. Flexible experimental design and standardised approaches to instrumentation, data quality, uncertainty quantification and model validation would increase the value and reusability of the resulting experimental data across different MSR concepts.

The responses therefore provide a basis for defining a European testing roadmap in which common infrastructure needs are separated from design-specific needs and in which experimental priorities are linked explicitly to safety functions, modelling uncertainties and licensing requirements.

4 Conclusion and Discussion

The objective of Task 3.4 was to identify the requirements for large-scale experimental and qualification infrastructures that can support the development and licensing of molten salt reactors in Europe, by generating relevant experimental data for the validation of Scientific Computing Tools and enabling the qualification of materials and components under representative conditions. To this end, a questionnaire was distributed to the ENDURANCE partners, focusing on the definition of large-scale testing (particularly with respect to the question of what is considered to be ‘large scale’), scaling requirements for relevant physical phenomena, qualification of components, the need for (solid-fuel) criticality tests, the required scale of tests for fuel synthesis, fuel handling and spent fuel processing, integrated-effects testing, tests needed to develop the strategy for decommissioning and severe-accident testing. Two responses were obtained to the questionnaire, from Thorizon and Saltfoss respectively. Additional responses from other Endurance partners may be incorporated into an updated version of the deliverable. The responses obtained from Saltfoss and Thorizon were analyzed to identify common requirements and areas where the needs remain design dependent.

The responses from Saltfoss and Thorizon were found to be largely compatible. This indicates a common basis for a European experimental programme, although additional responses are needed to further confirm the shared needs. Both organizations recognize the importance of large-scale testing for phenomena that are difficult to scale since these rely on multiple mechanisms that scale independently with geometry. As such, the relevant scales for each of

D3.1 Specification requirements for experimental infrastructures	17/57
Security: PUBLIC	GA 101165896



these mechanisms cannot be simultaneously preserved in a reduced scale facility. Examples are natural circulation, freezing and remelting, multiphase flow and corrosion. Both also identify material compatibility and qualification of safety-relevant systems as important elements of a future technology demonstration roadmap.

At the same time, the responses show that a common European testing program is unlikely to simultaneously satisfy all testing needs of the different European MSR developers and European research institutes. The required infrastructure depends on reactor architecture, fuel chemistry, neutron spectrum, deployment strategy and safety concept. Differences were observed in the prioritization of systems for qualification, the interpretation of some physical phenomena (and their relevant scales), and the perceived need for specific activities such as solid-salt criticality experiments. These differences reflect the diversity of MSR concepts currently under development in Europe.

A shared European testing program could be structured around three complementary pillars:

1. Large scale facilities for selected phenomena where scaling leads to inevitable distortions. These facilities shall provide representative experimental data to validate system codes, CFD models or other Scientific Computing Tools, and support the demonstration of (passive) safety functions and operational procedures.
2. Shared facilities for material and component qualification under MSR representative conditions. These facilities should be enveloping of the different MSR prototypes (in terms of operating pressure, temperature range and fuel compositions). Potentially, two different facilities would be needed to cater to the needs of both the thermal spectrum with fluoride salt concepts and the fast spectrum with chloride salt concepts.
3. Shared facilities for topics on the nuclear fuel where there is a common interest (for instance fuel synthesis, fuel qualification, fuel handling and fuel reprocessing). Again, two dedicated tracks may be needed for fluoride and chloride based salt compositions.

Such an approach would maximize the use of shared infrastructure while retaining sufficient flexibility to enable each of the MSR developers to pursue their unique concepts (and address related design-specific challenges) without favouring one concept over the other.

The present analysis is based on a limited number of responses and should therefore be regarded as an initial step toward defining a European roadmap for molten-salt-reactor experimentation. Additional input from Endurance partners would further strengthen the conclusions and help refine priorities for future infrastructure investments. Nevertheless, the responses obtained already provide a valuable foundation for identifying common experimental needs and for guiding discussions on coordinated European testing and qualification activities supporting the deployment of molten salt reactors.

A second issue of this report may be issued once more responses have been received. In addition, the questionnaire and their responses may be updated to reflect new insights and growing



experience amongst the European MSR community. Such updates would also be reflected in new issues of this deliverable report.

References

- [1] B. Kaaks and S. Berquand, *ENDURANCE_Task_3_4_Questionnaire*, 2026.
- [2] B. Forno, E. M. Lopez and F. Bertrand, "D4.1 - PIRT for modelling needs," Endurance, 2026.



Annex A Questionnaire

ENDURANCE Task 3.4 – Focused Questionnaire

The objective of task 3.4 is to define generic requirements and best-practice recommendations for large experimental infrastructures aimed at the generation of experimental data for modelling, simulation code validation, safety assessment and licensing. These infrastructures should also support the qualification of materials, components and systems under MSR-representative conditions.

The attached questionnaire is intended to gather the input from the community on the necessity of large scale tests (for which physical phenomena or components is this needed?) and on what is considered to be 'large scale'. We kindly ask each partner to complete the sections relevant to their expertise and facilities. Therefore, it is not necessary to complete all sections. Partial answers are welcome: the objective is not to obtain a fully harmonised view at this stage, but to identify converging needs, gaps and priorities across the consortium.

For every section, there is a comment section where you can leave your remaining thoughts and remarks. In particular, we would be interested in hearing the thoughts of the community on the difference in testing needs between fluoride (thermal spectrum) and chloride salt (fast spectrum) compositions or any other design-specific test requirements.

Field	Response / guidance
Organisation	
Name of respondent(s)	
Area(s) of expertise (remove the ones which are not relevant)	Core Physics/Thermal-hydraulics / Salt chemistry / Materials / Nuclear safety / System design & engineering / Other
Use of answers (remove the ones which are not relevant)	With organisation name / Anonymised / Internal consortium use only / To be discussed
Date	

Sheet	Question covered
1_LargeScale	What do you understand by large scale? Include thresholds for salt inventory and loop parameters.
2_ScalingPhenomena	Which important MSR phenomena cannot be scaled down without unacceptable distortions?
3_ComponentTesting	Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?
4_NuclearQualification	Which type of tests do you believe necessary for a nuclear qualification program of MSR components?



5_CriticalityExperiment	Assess whether a solid-salt criticality experiment would be useful or necessary as an intermediate step before building a nuclear demonstrator.
6_FuelLifecycle	Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts.
7_IntegratedEffectsTest	Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.
8-Decommissioning	Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.
9_SevereAccident	Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

1. Definition of 'large scale'

What do you understand by large scale? Include thresholds for salt inventory and loop parameters.

Criterion	Small-scale range	Intermediate scale	Large-scale threshold
Salt inventory (kg)			
Mass flow rate (kg/s) or volumetric flow rate (m3/s)			
Thermal/heating power (kW)			
Test duration (h)			
Piping internal diameter (mm)			
Loop height (m)			
Loop length (m)			
Other (please add lines as needed)			

Comments

2. Physical phenomena that cannot be properly scaled

Which important MSR phenomena cannot be scaled down without unacceptable distortions? Phenomena identification has already been done in D4.1 / PIRT.

Phenomenon	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Natural convection heat transfer with IHG (Internal Heat Generation)			
Forced convection heat transfer with IHG			
Compressible flow			



Two-phase flow (molten salt - gas)			
Thermal stratification			
Salt freezing / melting			
Heat transfer to structures			
Corrosion / mass transfer			
Deposition / fouling			
Fission product transport			
Volatile release / source term			
Redox control			
Irradiation effects			
Other (please add lines as needed)			

Top 3 phenomena requiring large-scale testing	Rationale
1	
2	
3	

Comments

3. Priority components for testing and appropriate scale.



Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?

Component / equipment	Which key performance indicators do we want to measure?	Priority 1-5	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Pumps					
Heat exchangers					
(Freeze) Valves					
Instrumentation					
Salt sampling systems					
Salt purification systems					
Off-gas systems					
Piping and fittings					
Welds and joints					
Seals and gaskets					
Drain tank / storage tank					
Decay heat removal components					
Fuel handling equipment					
Other (please add lines as needed)					

Top 5 components to test first	Rationale
1	
2	
3	



4	
5	

Comments

4. Tests needed for the nuclear qualification of components

Which type of tests do you believe necessary for a nuclear qualification program of MSR components? Please include any thoughts on design-specific requirements within the comment section.

Test type	Required? Yes/No/Case-by-case	Relevant components	Test objective
Functional testing			
Endurance testing			
Thermal cycling			
Corrosion exposure			
Mechanical loading			
Vibration testing			
Seismic qualification			
Irradiation testing			
Leak-tightness testing			
Failure mode testing			
Accelerated ageing tests			
Maintenance / inspection			
Decontamination test			



Other (please add lines as needed)			
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Comments

5. Criticality experiment with solid salt

Assess whether a solid-salt criticality experiment would be useful or necessary before building a nuclear demonstrator with molten salt fuel.

Question	Answers
Would such an experiment be useful / necessary before building a nuclear demonstrator with molten salt fuel? What would be the expected impact on code validation and licensing?	
What would be the scale of this experiment?Please specify the preferred choice between the introduction of a (big) sample of salt within an existing nuclear test reactor or the construction of a cold zero power reactor with a solid nuclear salt core.	
What would be the main experimental objectives? Which nuclear data would it improve?	
Should it focus on chloride salts, fluoride salts, or both? Which salt composition(s) should be considered?	
What are the limitations of a solid fuel test compared to a nuclear test with flowing, liquid fuel?	
What are possible alternative nuclear experiments or benchmarks which could support the licensing of molten salt reactors? For instance, a dedicated experiment for prompt criticality conditions in molten salt?	

Comments

6. Large-scale tests for the fuel lifecycle

Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts (in comment section).



Fuel lifecycle step	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Fuel salt synthesis				
Fuel salt purification				
Fuel transport				
Fresh fuel storage				
Reactor (re) fueling				
Fuel sampling				
Spent fuel unloading				
Spent fuel storage				
Reprocessing / treatment				
Waste conditioning				
Other (please add lines as needed)				

Comments

7. Integrated effects test

Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.



Primary loop		
Pump		
Heat exchanger		
Drain tank		
Expansion volume / cover gas system		
Off-gas system		
Salt purification system		
Salt sampling system		
Instrumentation and control		
Decay heat removal system		
Fuel handling / salt transfer system		
Containment / retention system		
Emergency systems		
Other (please add lines as needed)		

Operational procedures to be tested		
Operational procedure	Include? Yes/No/Optional	Main objective
Initial salt loading		
Pre-heating		
Start-up		
Power ramp-up / thermal ramp-up		
Normal operation		
Chemistry monitoring and control		
Salt sampling		



Controlled shutdown		
(Emergency) draining		
Loss of flow response		
Loss of heat sink response		
Loss of leak tightness response		
Salt freezing response		
Salt (re) melting procedure		
Maintenance / replacement operation		
Decontamination		
Other (please add lines as needed)		

Comments

8. Decommissioning testing programme

Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.

Tests potentially required for decommissioning			
Test type	Needed? Yes/No/Case-by-case	Objective	Specific challenges for MSRs
D3.1 Specification requirements for experimental infrastructures		28/57	
Security: PUBLIC		GA 101165896	



Removal of residual fuel salt			
Decontamination and dismantling of salt-wetted components			
Remote handling			
Waste characterisation			
Waste conditioning			
Management of fumes & vapours during dismantling			
Fission product retention during decommissioning			
Other (please add lines as needed)			

Comments

9. Severe accident testing programme

Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

Test type	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Salt spill testing				



Salt-water interaction				
Salt-air interaction				
Salt-concrete interaction				
Other (please add lines as needed)				

Comments



Annex B Questionnaire – Response Saltfoss

ENDURANCE Task 3.4 – Focused Questionnaire

The objective of task 3.4 is to define generic requirements and best-practice recommendations for large experimental infrastructures aimed at the generation of experimental data for modelling, simulation code validation, safety assessment and licensing. These infrastructures should also support the qualification of materials, components and systems under MSR-representative conditions.

The attached questionnaire is intended to gather the input from the community on the necessity of large scale tests (for which physical phenomena or components is this needed?) and on what is considered to be 'large scale'. We kindly ask each partner to complete the sections relevant to their expertise and facilities. Therefore, it is not necessary to complete all sections. Partial answers are welcome: the objective is not to obtain a fully harmonised view at this stage, but to identify converging needs, gaps and priorities across the consortium.

For every section, there is a comment section where you can leave your remaining thoughts and remarks. In particular, we would be interested in hearing the thoughts of the community on the difference in testing needs between fluoride (thermal spectrum) and chloride salt (fast spectrum) compositions or any other design-specific test requirements.

Field	Response / guidance
Organisation	Saltfoss
Name of respondent(s)	Esben Klinkby, Per Nilsson
Area(s) of expertise (remove the ones which are not relevant)	Core Physics/Thermal-hydraulics / Salt chemistry / Materials / Nuclear safety / System design & engineering / Other . Expertise in the bolded areas. Some knowledge in others
Use of answers (remove the ones which are not relevant)	To be discussed
Date	11-Sep-26

Sheet	Question covered
1_LargeScale	What do you understand by large scale? Include thresholds for salt inventory and loop parameters.
2_ScalingPhenomena	Which important MSR phenomena cannot be scaled down without unacceptable distortions?
3_ComponentTesting	Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?
4_NuclearQualification	Which type of tests do you believe necessary for a nuclear qualification program of MSR components?
5_CriticalityExperiment	Assess whether a solid-salt criticality experiment would be useful or necessary as an intermediate step before building a nuclear demonstrator.



6_FuelLifecycle	Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts.
7_IntegratedEffectsTest	Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.
8-Decommissioning	Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.
9_SevereAccident	Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

1. Definition of 'large scale'

What do you understand by large scale? Include thresholds for salt inventory and loop parameters.

Criterion	Small-scale range	Intermediate scale	Large-scale threshold
Salt inventory (kg)	< 1 kg < 1 kg/s < 10 kW		> 1000 kg
Mass flow rate (kg/s) or volumetric flow rate (m3/s)			> 100 kg/s
Thermal/heating power (kW)			> 1000 kW
Test duration (h)			
Piping internal diameter (mm)	< 25 mm		> 100 mm
Loop height (m)	< 2 m		> 5 m
Loop length (m)			
Other (please add lines as needed)			

Comments
Intermediate: anything between small and large

2. Physical phenomena that cannot be properly scaled



Which important MSR phenomena cannot be scaled down without unacceptable distortions? Phenomena identification has already been done in D4.1 / PIRT.

Phenomenon	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Natural convection heat transfer with IHG (Internal Heat Generation)	Partially	Natural convection scales strongly with height.	Incorrect heat transfer and temperature predictions.
Forced convection heat transfer with IHG	Yes	Turbulence and forced convection heat transfer can be scaled, e.g. using surrogates.	Incorrect heat transfer and temperature predictions.
Compressible flow	Yes	With compressibility as a density changes, the effects are comparably small. If it concerned sonic flow, it would be harder.	Incorrect flow rate or pressure predictions.
Two-phase flow (molten salt - gas)	Partially	In some situations, it may be hard to maintain both the flow regime and two-phase regime at scaling, even with surrogates.	Incorrect flow rate or pressure predictions.
Thermal stratification	No	As natural convection scales strongly with height.	Incorrect heat transfer and temperature predictions.
Salt freezing / melting	Partially	As the some involved phenomena are hard to model, scaling is uncertain.	Unpredictable operation.
Heat transfer to structures	Yes	The phenomena can be scaled with surrogates.	Incorrect heat transfer and temperature predictions.
Corrosion / mass transfer	Partially	The phenomena can occur in interaction between a range of local conditions, which are hard to obtain at the same time in a small experiment.	Incorrect corrosion and contamination predictions.
Deposition / fouling	Partially	The phenomena can occur in interaction between a range of local conditions, which are hard to obtain at the same time in a small experiment.	Incorrect flow, heat transfer and contamination predictions.
Fission product transport	Partially	The phenomena can occur in interaction between a range of local conditions, which are hard to obtain at the same time in a small experiment.	Incorrect heat transfer and contamination predictions.
Volatile release / source term	Partially	The phenomena can occur in interaction between a range of local conditions, which are hard to obtain at the same time in a small experiment.	Incorrect reactivity, flow, heat transfer and contamination predictions.
Redox control	Partially	The phenomena can occur in interaction between a range of local conditions, which are hard to obtain at the same time in a small experiment.	Incorrect corrosion and contamination predictions.
Irradiation effects	Yes	Specific conditions can be obtained in lab scale. (Like the above, it may be difficult to cover ranges in a small scale.)	Incorrect strength and integrity predictions.
Large motions, like earthquake or maritime.	Partially	Liquid / gas surfaces, may be hard to mimic both in flow regime and two-phase regime at scaling, even with surrogates.	Unpredictable operation and incorrect integrity predictions.
Thermal radiation	Yes	The phenomena are established.	Incorrect heat transfer and temperature predictions.



Top 3 phenomena requiring large-scale testing			
1			
2			
3			

Comments
skip

3. Priority components for testing and appropriate scale.

Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?

Component / equipment	Which key performance indicators do we want to measure?	Priority 1-5	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Pumps					
Heat exchangers					
(Freeze) Valves					
Instrumentation					
Salt sampling systems					
Salt purification systems					
Off-gas systems					
Piping and fittings					
Welds and joints					
Seals and gaskets					
Drain tank / storage tank					



Decay heat removal components					
Fuel handling equipment					
Other (please add lines as needed)					

Top 5 components to test first	Rationale
Drain tank / storage tank	systems listed here relate directly to the fundament safety functions
Decay heat removal components	
Off-gas systems	
reactivity control system	
5	

Comments
less mature

4. Tests needed for the nuclear qualification of components

Which type of tests do you believe necessary for a nuclear qualification program of MSR components? Please include any thoughts on design-specific requirements within the comment section.

Test type	Required? Yes/No/Case-by-case	Relevant components	Test objective
Functional testing			
Endurance testing			
Thermal cycling			
Corrosion exposure	Yes	salt facing materials	ensure component lifetime. Depending on safety function, testing may not be required from qualification perspective, but purely from asset protection
Mechanical loading			
Vibration testing			



Seismic qualification	Case-by-case	primary circuit	very different for land based vs maritime. And fast vs. thermae
Irradiation testing	Case-by-case	all components subject to radiation	where exposure exceeds conditions of exisiting knowledge, the structural entegrity / performance might require irradiation testing
Leak-tightness testing			
Failure mode testing			
Accelerated ageing tests			
Maintenance / inspection			
Decontamination test			
Fuel salt	Yes	thermophysical properties over it's lifetime.	ensure that the salt fulfill its safety function in both normal operations and accident conditions
Other (please add lines as needed)			

Comments

5. Criticality experiment with solid salt

Assess whether a solid-salt criticality experiment would be useful or necessary before building a nuclear demonstrator with molten salt fuel.

Question	Answers
Would such an experiment be useful / necessary before building a nuclear demonstrator with molten salt fuel? What would be the expected impact on code validation and licensing?	
What would be the scale of this experiment?Please specify the preferred choice between the introduction of a (big) sample of salt within an existing nuclear test reactor or the construction of a cold zero power reactor with a solid nuclear salt core.	
What would be the main experimental objectives? Which nuclear data would it improve?	
Should it focus on chloride salts, fluoride salts, or both? Which salt composition(s) should be considered?	
What are the limitations of a solid fuel test compared to a nuclear test with flowing, liquid fuel?	



What are possible alternative nuclear experiments or benchmarks which could support the licensing of molten salt reactors? For instance, a dedicated experiment for prompt criticality conditions in molten salt?

Comments

At Salfoss we do not believe we need such experiment. Instead we do anticipate restricted license for FOAK and that restrictions are eventually lifted, as the technology and performance is demonstrated

6. Large-scale tests for the fuel lifecycle

Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts (in comment section).

Fuel lifecycle step	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Fuel salt synthesis				
Fuel salt purification				
Fuel transport				
Fresh fuel storage				
Reactor (re) fueling				
Fuel sampling				
Spent fuel unloading				
Spent fuel storage				
Reprocessing / treatment				
Waste conditioning				
Other (please add lines as needed)				

Comments

The scales of testing needed for these aspects have not been assessed



7. Integrated effects test

Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.

SSC	Include? Yes/No/Optional	Why?
Primary loop		
Pump		
Heat exchanger		
Drain tank		
Expansion volume / cover gas system		
Off-gas system		
Salt purification system		
Salt sampling system		
Instrumentation and control		
Decay heat removal system		
Fuel handling / salt transfer system		
Containment / retention system		
Emergency systems		
Other (please add lines as needed)		

Operational procedures to be tested

Operational procedure	Include? Yes/No/Optional	Main objective
Initial salt loading		
Pre-heating		
Start-up		



Power ramp-up / thermal ramp-up		
Normal operation		
Chemistry monitoring and control		
Salt sampling		
Controlled shutdown		
(Emergency) draining		
Loss of flow response		
Loss of heat sink response		
Loss of leak tightness response		
Salt freezing response		
Salt (re) melting procedure		
Maintenance / replacement operation		
Decontamination		
Other (please add lines as needed)		

Comments
not comfortable sharing

8. Decommissioning testing programme

Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.



Tests potentially required for decommissioning			
Test type	Needed? Yes/No/Case-by-case	Objective	Specific challenges for MSRs
Removal of residual fuel salt			
Decontamination and dismantling of salt-wetted components			
Remote handling			
Waste characterisation			
Waste conditioning			
Management of fumes & vapours during dismantling			
Fission product retention during decommissioning			
Other (please add lines as needed)			

Comments

9. Severe accident testing programme

Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

Test type	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Salt spill testing	No			
Salt-water interaction	Yes			
Salt-air interaction				
Salt-concrete interaction	No			
Other (please add lines as needed)				

Comments



small scale

salt-air should be covered by salt spill



Annex C Questionnaire – Response Thorizon

ENDURANCE Task 3.4 – Focused Questionnaire

The objective of task 3.4 is to define generic requirements and best-practice recommendations for large experimental infrastructures aimed at the generation of experimental data for modelling, simulation code validation, safety assessment and licensing. These infrastructures should also support the qualification of materials, components and systems under MSR-representative conditions.

The attached questionnaire is intended to gather the input from the community on the necessity of large scale tests (for which physical phenomena or components is this needed?) and on what is considered to be 'large scale'. We kindly ask each partner to complete the sections relevant to their expertise and facilities. Therefore, it is not necessary to complete all sections. Partial answers are welcome: the objective is not to obtain a fully harmonised view at this stage, but to identify converging needs, gaps and priorities across the consortium.

For every section, there is a comment section where you can leave your remaining thoughts and remarks. In particular, we would be interested in hearing the thoughts of the community on the difference in testing needs between fluoride (thermal spectrum) and chloride salt (fast spectrum) compositions or any other design-specific test requirements.

Field	Response / guidance
Organisation	Thorizon
Name of respondent(s)	Bouke Kaaks, Damien Becat-Mateu, Fabio Alcaro, Sébastien Fleureau, Giulia Russo, Mees Wortelboer, Jop Schilder, Lolita Hilaire
Area(s) of expertise (remove the ones which are not relevant)	Core Physics/Thermal-hydraulics / Salt chemistry / Materials / Nuclear safety / System design & engineering / Other
Use of answers (remove the ones which are not relevant)	With organisation name
Date	

Sheet	Question covered
1_LargeScale	What do you understand by large scale? Include thresholds for salt inventory and loop parameters.
2_ScalingPhenomena	Which important MSR phenomena cannot be scaled down without unacceptable distortions?
3_ComponentTesting	Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?
4_NuclearQualification	Which type of tests do you believe necessary for a nuclear qualification program of MSR components?
5_CriticalityExperiment	Assess whether a solid-salt criticality experiment would be useful or necessary as an intermediate step before building a nuclear demonstrator.



6_FuelLifecycle	Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts.
7_IntegratedEffectsTest	Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.
8-Decommissioning	Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.
9_SevereAccident	Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

1. Definition of 'large scale'

What do you understand by large scale? Include thresholds for salt inventory and loop parameters.

Criterion	Small-scale range	Intermediate scale	Large-scale threshold
Salt inventory (kg)	< 10 kg	10 kg - 300 kg	> 300 kg
Mass flow rate (kg/s) or volumetric flow rate (m3/s)	< 1 kg/s	1 - 100 kg/s	> 100 kg/s
Thermal/heating power (kW)	< 20 kW	20 kW -1000 kW	>1000 kW
Test duration (h)	2000 h -4000 h	2000 h - 4000 h	>8000 h
Piping internal diameter (mm)	<DN10	DN10-DN100	>DN100
Loop height (m)	<2 m	2 m - 5 m	>5 m
Loop length (m)	<2 m	2 m - 25 m	>25 m
Other (please add lines as needed)			

Comments
Difficult to clearly distinguish intermediate scale from large-scale. For one test, the mass flow rate may be high whereas another test has high heat input. Test duration is not really dependent on scale.

2. Physical phenomena that cannot be properly scaled



Which important MSR phenomena cannot be scaled down without unacceptable distortions? Phenomena identification has already been done in D4.1 / PIRT.

Phenomenon	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Natural convection heat transfer with IHG (Internal Heat Generation)	Partially	It will be difficult to design a representative small scale experiment due to the coupling between the power density (internal heat generation), the buoyancy forces driving the flow, and the pressure losses opposing the flow -> achieving the same ratio between power density, buoyancy and pressure losses whilst also achieving the same flow characteristics (Reynolds number) will be very difficult	The experiment cannot be fully transposed to the reactor system -> consequently the heat transfer coefficient (for natural convection with IHG) needs to be penalized. This will negatively impact the (predicted) performance of the reactor during a passive decay heat removal scenario, and hence impose additional constraints on the reactor design.
Forced convection heat transfer with IHG	Yes	Scaling depends on Reynolds number, temperature of the cold structure, and power density of the salt. These parameters can be modified independently, with limited cross-over / mutual influence. In addition, research has shown that the impact of IHG on the forced convection heat transfer can be modelled by a simple correction within the heat transfer coefficient.	None, since experiment can be scaled. Potentially, high fidelity CFD can be used to confirm the scaling and exclude the presence of coupled phenomena leading to (significant) distortion.
Compressible flow	Partially	The speed of sound of the salt is significantly impacted by the void fraction. Two-phase flow are difficult to scale. In addition, it is difficult to replicate the conditions under which compressible flow becomes relevant (i.e. fast and high reactivity-initiated accidents).	Penalization needs to be applied to ensure the fuel salt compressibility is conservatively predicted. Additional design provisions would need to be put in place to limit the possible reactivity injection (amplitude and speed).
Two-phase flow (molten salt - gas)	Partially	The bubble size distribution and flow regime are influenced by both geometry (dimensions), salt and gas properties, and flow regime. As such, multiphase flow is difficult to scale without resulting in distortions	Scaling will inevitably lead to distortions, which will have consequences for the design and safety assessment of the reactor (depending on the location of the cover gas plenum and whether helium bubbling is used or not).
Thermal stratification	Partially	Thermal stratification occurs when the buoyancy forces are stronger than the convective mixing. Since the buoyancy forces and convective mixing are coupled (and each are influenced by geometric scale), scaling will inevitably lead to distortion. Also see part on natural convection in IHG	To compensate for the uncertainty, penalization needs to be applied (of the heat transfer coefficient, or of the pressure losses in the flow). Also see part on natural convection in IHG



Salt freezing / melting	Partially	Priority here is to determine the mechanical loading during the freezing and (re) melting and to determine the impact of the partial flow blockage during freezing, + the conditions that can lead to a full blockage. The melting and freezing behavior of the salt will be affected by the natural convection inside the fuel salt (assuming no forced flow). See 'natural convection with IHG + 'thermal stratification'. In addition, it will be difficult to accurately assess the resulting mechanical loads in a scaled-down experiment (although valuable information may be obtained on the general phenomenogy of the melting and freezing process contributing to the material stresses).	Nneed to penalize the freezing rate and melting rate in the evaluation models used (through the melting point, the cold wall temperature, and the mechanical loads
Heat transfer to structures	Partially	See natural or forced convection heat transfer with IHG. There is also surface-to-surface radiation of structures + thermal conduction within the structures, however these can be scaled without distortion.	See natural convection with IHG and forced convection heat transfer with IHG. We may also include additional safety margins within the evaluation models, with respect to the material temperature limits.
Corrosion / mass transfer	Partially	Determined by electrochemical potential of material and the salt, presence of impurities, temperature gradient and flow regime. Impact of geometry scale mainly due to coupling to other physics (erosion, galvanic coupling, stress corrosion etc)	Use of additional corrosion allowance during design. However, this cannot compensate for localized effects (such as corrosion of welds, pitting corrosion etc). As such, failure to conduct corrosion tests at representative scale may lead to underestimation of component / reactor lifetime.
Deposition / fouling	Partially	This depends on the solubility of the particles and salt, but also by the flow characteristics (mixing and shear due to turbulence) and the particle characteristics (size, concentration, adhesion to walls) which are also affected by scale	Penalization of heat transfer coefficients and pressure losses in the reactor system evaluation models -> extra margins needed during design.



Fission product transport	Partially	Fission products will either be solid (metal, particles), dissolved in the molten salt or gaseous (see two-phase flow). As stated earlier, multi-phase flow phenomena are difficult to scale without distortion. This applies to both gas-liquid and solid-liquid	Penalties need to be applied for the void fraction (+ bubble distribution) in the fuel salt and associated reactivity effects 9+ impact on heat transfer), as well as for the particle concentration and associated impact on material lifetime (erosion) and on deposition / fouling and erosion. Finally, an incorrect prediction of fission product transport will propagate to an incorrect prediction of the radioactive source term distribution, and hence the source term release (see below)
Volatile release / source term	Partially	Fuel salt volatility itself may be studied at small scale. It depends on the scenario (and associated couplings with other phenomena) whether the source term release may be studied at small scale or whether a large / intermediate scale is needed (e.g. release of volatiles during a salt spill)	Incorrect prediction of radioactive source term release -> penalization needed in severe accident analysis.
Redox control	Partially	Depends on the approach taken. If a sacrificial material is being used, this should be tested at scale to determine the interaction with the rest of the system	Incorrect prediction of corrosion (and therefore of material lifetime)
Irradiation effects	Yes	No need to be tested at scale. What matters is that the neutron spectrum is sufficiently representative, and the time tested is sufficiently long.	Incorrect prediction of material lifetime. However, impact is expected to be limited, since experiment can be scaled (although separate tests are needed to demonstrate that irradiation can be decoupled from other material ageing mechanisms such as corrosion and erosion)
Erosion	Partially	Erosion depends on shear rate of the fuel salt (which can be scaled), but mainly on the presence of gas bubbles and solid particles (which impact the surface). Two phase flow (either molten-salt gas or molten-salt solid particles) cannot be scaled without distortion (see two-phase flow molten-salt gas). Therefore erosion can also only be scaled partially.	Failure to conduct corrosion tests at representative scale (and with a representative salt composition including gas bubbles and particles) may lead to underestimation of component / reactor lifetime.
Other (please add lines as needed)			

Top 3 phenomena requiring large-scale testing	Rationale
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1 Two-phase flow molten salt gas	Major implications for safety (and succes of helium bubbling strategy depending on the design), scaling will inevitably lead to distortions
2 Natural convection IHG	This phenomenon is essential for passive DHR. For most designs, scaling is expected to lead to distortions. However, designing a large scale experiment that accurately simulates IHG with sufficient power will be difficult
3 Compressible flow	Fuel salt compressibility in relation to density reactivity feedback remains one of the most challenging aspects of MSR multi physics. Designing a representative test may be difficult however, a graduated approach is preferable than doing a full scale integral experiment.

Comments
Most of these phenomena should be studied at a smaller scale first, and will automatically be included in a large-scale test. Large-scale molten salt loops will large likely be focused on gaining engineering and operational experience and will automatically included phenomena related to multiphase flow (since there needs to be an expansion vessel), heat transfer, salt freezing etc.

3. Priority components for testing and appropriate scale.
Which type of components do you consider to be the highest priority for testing / prototyping? What is the appropriate scale of the test?

Component / equipment	Which key performance indicators do we want to measure?	Priority 1-5	Can it be scaled? Yes/No/Partially	Why?	Consequence if not tested at relevant scale
Pumps	Flow-head curve; efficiency; required inlet pressure / cavitation margin; gas ingestion tolerance; vibration; bearing and shaft temperatures; leakage; start-up, coast-down and trip response.	5	Partially	Affinity laws support preliminary scaling, but molten-salt density and viscosity, inlet geometry, free-surface effects, gas entrainment, Reynolds number and thermal expansion affect real pump behaviour.	Pump head, cavitation or gas-ingestion margin, coast-down flow and vibration may be mispredicted. This can invalidate normal-operation and transient flow assumptions.
Heat exchangers	Heat duty; overall heat-transfer coefficient (UA); primary and secondary pressure drop; flow distribution; approach temperature; thermal expansion, mechanical integrity; wall temperature; freeze margin; transient response; corrosion/erosion/fouling behaviour.	5	Partially	Local heat transfer can be correlated, but full-channel distribution, bypass flow, headers, buoyancy, thermal deformation and coupled primary/secondary transients are strongly geometry dependent.	Heat-removal capability and pressure loss may be wrong. Local freezing or hotspots, flow maldistribution or thermal stresses may only appear near relevant geometry and power.
(Freeze) valves	Opening and closing time; leak tightness; freeze/melt-front location; required heater/cooler power; repeatability; fail-safe behaviour; thermal cycling endurance; pressure drop when open.	5	Partially	Freeze-front conduction can be studied at small scale, but plug length, pipe diameter, gravity, thermal inertia, insulation and heat losses determine full-device actuation and reliability.	A valve may fail to open, close, or remain leak-tight within the credited time. Required heater power and freeze margin can be underestimated.
Instrumentation	Accuracy; precision; response time; drift; calibration stability; range; availability; survivability; plugging/fouling; flow-measurement bias; level and pressure measurement performance.	5	Partially	Individual sensors can be bench-qualified, but installation geometry, electromagnetic environment, cross-talk, long heated lines, flow profile, bubbles and temperature gradients create system-level measurement errors.	Control, protection and test conclusions may rely on biased or delayed signals. Unmodelled drift or installation effects can mask unsafe or unstable conditions.



Salt sampling systems	Sample representativeness; sample mass; acquisition time; line hold-up; temperature loss; plugging frequency; cross-contamination; recovery fraction; worker/remote-handling steps.	4	Partially	Sampling chemistry can be tested locally, but representative withdrawal depends on full-loop mixing, residence time, line length, temperature control and local solids or bubbles.	Samples may not represent the bulk salt. Chemistry-control or material-accountancy decisions could then be based on biased composition measurements.
Salt purification systems	Impurity-removal efficiency; throughput; redox-control capability; pressure drop; filter or sorbent loading; regeneration interval; salt loss; chemistry stability after treatment.	4	Partially	Reaction and sorption data scale reasonably, but bed hydraulics, residence time, inventory, gas-salt contact, filter loading and continuous operation depend on realistic throughput and geometry.	Plant purification capacity, consumable lifetime and chemistry-control response can be overstated. Corrosion or plugging rates may then differ from predictions.
Off-gas systems	Gas removal rate; species-specific capture efficiency; aerosol capture, generation and transport efficiency; pressure drop; residence and hold-up time; gas inventory; leak tightness; bed temperature; decay-heat removal; transient response.	5	Partially	Component efficiencies can be measured separately, but coupled gas generation, bubbles, aerosols, daughter products, transport delays and staged treatment depend on realistic flow and inventory.	Source-term retention, pressure control and component sizing may be non-conservative. Hot spots, excessive pressure drop or unexpected radionuclide transport can be missed.
Piping and fittings	Pressure drop; flow distribution; heat loss; surface temperature; thermal expansion; displacement; vibration; stratification; freeze margin; corrosion/erosion/fouling locations; drainability and residual salt inventory after draining.	5	Partially	Straight-pipe friction is scalable, but elbows, tees, long runs, elevation changes, mixed convection, heat tracing, structural restraint and expansion accumulate as system size increases.	System resistance, natural-circulation paths, thermal movements, freeze locations and local loads can be wrong, affecting pump sizing and transient predictions.
Welds and joints	Leak rate; dimensional stability; creep-fatigue response; corrosion at weld metal and heat-affected zones; thermal-cycle endurance; inspection detectability; residual deformation.	4	Partially	Representative weld coupons are useful, but section thickness, restraint, residual stress, joint geometry and thermal gradients should match the intended fabrication as closely as practical.	Small specimens may miss full-joint distortion, local corrosion, crack initiation or inspection limitations. Leak-before-break and lifetime assumptions could be unsupported.
Seals and gaskets	Leak rate; preload retention; relaxation; thermal-cycle endurance; chemical compatibility; permeation; recoverability after maintenance; tolerance to misalignment.	4	Yes	Performance is mainly local. A bench rig can reproduce actual seal geometry, contact load, temperature, pressure and chemistry without reproducing the complete loop.	If only reduced or substitute seals are tested, leakage and preload loss can be underestimated. Actual-size representative hardware should still be qualified.
Drain tank / storage tank	Drain time; residual salt inventory; level indication; mixing/stratification; peak wall and salt temperatures; natural-cooling heat removal; freeze/thaw behaviour; gas displacement; structural movement.	5	Partially	Drain hydraulics and heat transfer can be scaled, but tank aspect ratio, inlet jets, inventory, buoyancy, radiative losses, structural mass and natural-circulation patterns matter.	Credited drain time, decay-heat temperatures and residual inventory may be wrong. Unseen stratification or freezing can challenge safe storage and restart.
Decay heat removal components	Passive heat-removal capacity; natural-circulation flow; start-up time; stability; peak temperatures; heat-sink performance; freeze margin; response after loss of forced flow or power.	5	Partially	Natural circulation requires simultaneous similarity in buoyancy, friction, geometry and thermal inertia. Those constraints are difficult to preserve in strongly reduced facilities.	A passive system can appear adequate at small scale yet fail to establish stable flow, remove the required heat, or avoid freezing at plant-relevant geometry.



Fuel handling equipment	Transfer rate; transferred mass accuracy; residual hold-up; leak tightness; line temperature; plugging; inventory tracking; remote operation; recovery from interrupted transfer.	4	Partially	Hydraulic and mechanical operations can use non-fissile salt, but radiation, decay heat, fissile accountability, volatile species and remote-maintenance constraints are not reproduced by simple surrogates.	Transfer reliability and inventory uncertainty can be understated. Recovery procedures and safeguards assumptions may not be demonstrated under representative conditions.
Heat tracing, heaters and insulation	Warm-up time; steady heat loss; minimum wall temperature; power demand; temperature uniformity; freeze margin; failed-zone tolerance; restart after a freeze event.	5	Partially	Local heater performance is testable, but total heat loss scales with surface area, supports, penetrations, insulation joints, ambient conditions and long piping runs.	Installed heater power or zoning may be inadequate. Local cold spots can cause salt freezing, blocked lines or excessive restart time.

Top 5 components to test first	Rationale
Pumps	The pump directly determines system flow, heat removal performance, and transient behaviour during start-up, shutdown, and loss-of-power events. Full-scale testing is important because gas ingestion, cavitation margin, coast-down behaviour, and vibration can differ significantly from scaled predictions.
Heat exchangers	Heat exchangers are critical for transferring heat while maintaining acceptable pressure losses and thermal margins. Their performance depends strongly on flow distribution, buoyancy effects, thermal deformation, and coupled transients that cannot be fully captured in reduced-scale testing.
Decay heat removal systems	Passive decay heat removal is one of the most safety-significant functions in an MSR and relies on natural circulation, which is inherently difficult to scale. Large-scale testing is needed to demonstrate that sufficient heat can be removed without freezing, flow instabilities, or loss of cooling capability.
Instrumentation	Reliable experimental data and safe operation depend on accurate measurements under representative conditions. Installation effects, temperature gradients, bubbles, long heated lines, and electromagnetic interference can introduce errors that are not visible in laboratory-scale sensor qualification.
Freez valves	Freeze valves are a unique MSR technology that often performs essential operational and safety functions such as isolation and draining. Their reliability depends on freeze-front formation, thermal inertia, and heater performance, all of which are strongly geometry dependent.

Comments
5 is the highest priority

4. Tests needed for the nuclear qualification of components



Which type of tests do you believe necessary for a nuclear qualification program of MSR components? Please include any thoughts on design-specific requirements within the comment section.

Test type	Required? Yes/No/Case-by-case	Relevant components	Test objective
Functional testing	Yes	Heat exchanger, pump, connections/valves, containment, instrumentation, fuel handling, off-gas	Demonstrate that the component performs its required function across the specified operating envelope.
Endurance testing	Yes	Same	Demonstrate acceptable performance over the required number of operating cycles and operating hours.
Thermal cycling	Yes	Heat exchanger, pump, connections/valves, containment, piping, welds, seals, supports, instrumentation penetrations	Demonstrate resistance to fatigue, creep, distortion, loss of preload, cracking and functional degradation caused by heating and cooling.
Corrosion behaviour	Yes	Heat exchanger, pump, connections/valves, containment, piping, welds, seals,	Establish corrosion rate, localized attack, mass transfer, material compatibility, effects on mechanical integrity, solid particles in salt (their size, hardness and concentration).
Mechanical loading	Yes	Heat exchanger, pump, piping, supports, valves, flanges, joints	Demonstrate integrity under pressure, dead weight, thermal loads, nozzle loads and other design loads.
Vibration testing	Yes	Heat exchanger, pump, piping, supports, valves, instrumentation	Demonstrate that flow-induced and machinery-induced vibration does not cause malfunction, fatigue or measurement degradation.
Seismic qualification	Yes	Safety-classified pumps, valves, instrumentation, tanks, piping, electrical equipment, supports	Demonstrate required safety functions and structural integrity during and after the design-basis seismic event.
Irradiation testing	Case-by-case	Fuel system internal, in-core instrumentations, components close to the core, polymers/electronics exposed to significant dose	Demonstrate that neutron and gamma exposure does not invalidate mechanical, electrical or functional performance.
Leak-tightness testing	Yes	Salt boundary, cover-gas boundary, heat exchangers, valves, flanges, welds, tanks, off-gas equipment	Demonstrate confinement of salt, cover gas and radioactive material.



Failure mode testing	Yes	All	Verify predicted failure behaviour and demonstrate safe response to credible single failures.
Accelerated ageing tests	Yes	Seals, electrical insulation and connectors, cables, electronics, actuators, bearings, coatings and selected instrumentation	Establish qualified lifetime and identify age-related degradation before loss of required function.
Maintenance / inspection	Yes	In-service inspection techniques and systems, in-core inspection techniques and systems	Demonstrate that required inspection, replacement and maintenance can actually be performed and can identify relevant degradation.
Decontamination test	Case-by-case	Fuel System (external surfaces), internal volume (draining, waste segratation)	Demonstrate that contamination can be reduced enough for maintenance, replacement, transport or disposal.
Other (please add lines as needed)			

Comments

5. Criticality experiment with solid salt

Assess whether a solid-salt criticality experiment would be useful or necessary before building a nuclear demonstrator with molten salt fuel.

Question	Answers
Would such an experiment be useful / necessary before building a nuclear demonstrator with molten salt fuel? What would be the expected impact on code validation and licensing?	Useful for static reactor physics validation to reduce uncertainties. Not necessarily mandatory. Quantity of interests: -Criticality -Spatial fission-rate and reaction-rate distributions -Neutron spectrum and spectral indices -Control, shutdown and reflector worth -Leakage -Sensitivity to salt composition, chlorine enrichment and actinide vector -Surrogate density or void coefficients obtained by replacing or rearranging salt modules
What would be the scale of this experiment?Please specify the preferred choice between the introduction of a (big) sample of salt within an existing nuclear test reactor or the construction of a cold zero power reactor with a solid nuclear salt core.	Sample experiment: few kg necessary at least. Zero power reactor: from 100kg to several tons. Sample is prefered: first good cheaper step. Can evaluate after if full scale is necessary



What would be the main experimental objectives? Which nuclear data would it improve?	Criticality measure: -Critical salt loading or critical configuration -Sensitivity to fissile concentration -Sensitivity to isotopic composition -Reproducibility after disassembly and reassembly Spectrum and reaction rates: -Fission-rate distributions -Capture-to-fission ratios -Threshold-reaction spectral indices -Axial and radial flux profiles -Leakage-sensitive detector responses Reactivity worth: -Control and shutdown absorber worth -Reflector and structural-material worth -Salt sample worth -Replacement worth between carrier-only and fuel-bearing salt -Density and void surrogates using removable or lower-density modules For a fast chloride application, the leading priorities would normally include: -35Cl(n,p)35S -35Cl capture, elastic and inelastic scattering -37Cl scattering and capture -23Na elastic, inelastic and capture reactions -Solvent-dependent data such as Mg, K, Na, ... reactions -Reflector data: -235U capture, fission and neutron multiplicity; -238U capture and inelastic scattering -239Pu and 240Pu fission and capture where relevant -Fe, Cr and Ni reactions if structural material is present.
Should it focus on chloride salts, fluoride salts, or both? Which salt composition(s) should be considered?	Depends on the target application. Only help the other on the smallest commun denominator: commun isotopes and spectrum
What are the limitations of a solid fuel test compared to a nuclear test with flowing, liquid fuel?	Only test static reactor physics which are an input to flowing liquid fuel. Cannot test the loss of delayed neutrons through advection. No representative TH feedback. No representative FP behaviour
What are possible alternative nuclear experiments or benchmarks which could support the licensing of molten salt reactors? For instance, a dedicated experiment for prompt criticality conditions in molten salt?	Differential experiements (time of flight, neutron transmission, ...) of relevant isotopes at relevant energy range. Liquid fuel loop within a reactor for a slow transient. Full scale zero/low-power liquid fuel reactor for slow transients. Prompt criticality transient in aqueous reactors. Prompt criticality transient in solid driver core with a liquid sample. Prompt criticality transient in full scale molten salt reactors.

6. Large-scale tests for the fuel lifecycle



Identify large-scale tests for synthesis, handling, transport, storage, reprocessing and differences between fluoride/chloride salts (in comment section).

Fuel lifecycle step	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Fuel salt synthesis	Yes	1-10 kg TRU 100-1000kg Depleted U	Demonstrate conversion yield and production speed; control oxidation state and actinide valence; meet O, H ₂ O, oxide and metallic impurity specifications; verify homogeneity and batch repeatability; quantify reagent consumption, off-gas and secondary wastes; demonstrate remotely maintainable equipment	Strong halogenating reagents; exothermic reaction; HCl, Cl ₂ or other reactive off-gas; aerosol and volatile halide formation; incomplete conversion; oxyhalide formation; vessel corrosion; line plugging; criticality and material-accountancy constraints; reactive/pyrophoric metal formation
Fuel salt purification	Yes	10-100kg	Demonstrate purification efficiency and kinetics at relevant composition; establish impurity specification; validate purification equipment	HCl/Cl ₂ or other reactive gases used in the purification process; corrosion; aerosol formation; volatile species; reactive/pyrophoric metal formation
Fuel transport	Yes	100-1000kg	Demonstrate safe transport between salt synthesis facility and reactor site	Fuel freezing; leaks; loss of containment; moisture/oxygne ingress
Fresh fuel storage	Yes	100-1000kg	Validate storage facility design, draining and confinement	Freezing/remelting; thermal stress; corrosion; leakage; loss of containment; moisture/oxygen ingress
Reactor (re) fueling	Yes	100-1000kg	Demonstrate controlled addition/transfer of fuel salt under representative operating conditions	Flow control; thermal shocks; freezing; composition transients; gas entrainment; spills/leaks; moisture/oxygen ingress
Fuel sampling	Not necessarily	0.1-10kg loop inventory	Demonstrate representative, reproducible and contaminationfree-sampling, validate sampling devices and analytical chain	Sample representativeness; salt freezing; contamination; volatile species; aerosols; operator exposure; remote handling;
Spent fuel unloading	Yes	100-1000kg	Demonstrate draining under representative thermalhydraulic conditions; assess completeness of drainge and behaviour during abnormal conditions	Freezing; plugging; residual salt; decay heat; thermal stress; loss of power; gas formation; volatile species; criticality; oxygen/moisture ingress; contamination; operator exposure
Spent fuel storage	Yes	100-1000 kg	Demonstrate passive/active cooling, confinement, long-duration compatibility of materials, validate accident models, assess radiolysis effects	Decay heat; freezing/remlting; thermal gradients; corrosion; radiolysis; volatile fission products; criticality; confinement
Reprocessing / treatment	Not necessarily	0.1-100 kg	Demonstrate separation efficiency, process kinetics, equipment performance, demonstrate process scale-up	Precipitation; corrosion; redox control; volatile species; aerosols; accumulation of fissile material; radioactive waste



Waste conditioning	Yes	10-100kg	Demonstrate conversion of salt/process wastes into stable waste forms; establish waste activity and classification of wastes (short-lived, long-lived...), demonstrate confinement performance if needed	Heat generation; volatilisation: off-gas; phase separation; waste-form homogeneity; leaks; radioactivity
Other (please add lines as needed)				

Comments

7. Integrated effects test

Define which SSCs and operational procedures should be included in a (non-nuclear) integrated effects test.

SSC	Include? Yes/No/Optional	Why?
Primary loop	Yes	It represents the system where most physical phenomena of interest take place
Pump	Yes	It is part of the primary loop
Heat exchanger	Yes	It is part of the primary loop
Drain tank	No	Not present in the TH1 design
Expansion volume / cover gas system	Yes	It is part of the primary loop
Off-gas system	Optional	Include if gas stripping/off-gas operation interacts with normal plant operation.
Salt purification system	No	Not present in the TH1 design
Salt sampling system	No	Not present in the TH1 design
Instrumentation and control	No	Not needed (simpler facilities can accommodate I&C)
Decay heat removal system	Yes	It is directly related with the primary loop
Fuel handling / salt transfer system	No	Yes for salt transfer. Actual fissile handling cannot be reproduced.
Containment / retention system	No	Not present in the TH1 design



Emergency systems	Yes	It is directly related with the primary loop
Other (please add lines as needed)		

Operational procedures to be tested		
Operational procedure	Include? Yes/No/Optional	Main objective
Initial salt loading	Yes	Demonstrate safe transfer, inventory control, venting and filling. But out of core procedure for the TH1 design
Pre-heating	Yes	Verify uniform preheat and adequate margin above the salt melting point.
Start-up	Yes	Validate sequence, interlocks, pump start and establishment of stable circulation.
Power ramp-up / thermal ramp-up	Yes	Validate temperature control, thermal expansion and component response.
Normal operation	Yes	Demonstrate stable long-duration integrated operation.
Chemistry monitoring and control	No	Not needed (simpler facilities can accommodate the relevant phenomena)
Salt sampling	No	Not needed (simpler facilities can accommodate the relevant phenomena)
Controlled shutdown	No	Proven shutdown mecanism in TH1 design
(Emergency) draining	No	Not present in the TH1 design
Loss of flow response	Yes	Validate the physical phenomena of interest (e.g. natural circulation, heat rejection, ...)
Loss of heat sink response	Yes	Validate the physical phenomena of interest (e.g. natural circulation, heat rejection, ...)
Loss of leak tightness response	No	Not needed (simpler facilities can accommodate the relevant phenomena)
Salt freezing response	Yes	Validate the physical phenomena of interest (e.g. flow maldistribution, transport of solid salt debris, ...)
Salt (re) melting procedure	Yes	Demonstrate controlled recovery without overheating or damaging equipment.
Maintenance / replacement operation	Optional	Demonstrate accessibility and representative component isolation/removal where this is a facility objective.
Decontamination	Optional	Nuclear contamination cannot be reproduced, but salt-removal/cleaning procedures can be demonstrated.
Other (please add lines as needed)		

Comments



8. Decommissioning testing programme

Assess whether a dedicated testing programme for MSR decommissioning is needed and which tests should be included.

Tests potentially required for decommissioning			
Test type	Needed? Yes/No/Case-by-case	Objective	Specific challenges for MSRs
Removal of residual fuel salt	Yes	Demonstrate effective draining and recovery of residual fuel salt from vessels, piping and components.	Salt can freeze in low points and dead legs. Residual fissile inventory and decay heat must remain controlled. May require high temperature/pressure conditions or solvents that are (chemically) incompatible with the fuel salt
Decontamination and dismantling of salt-wetted components	Yes		Salt films, corrosion products and deposited fission products can strongly contaminate internal surfaces. Requirement of dedicated facilities on-site and special equipment.
Remote handling	Case-by-case	Demonstrate safe inspection, cutting, removal and packaging without direct worker access.	High dose rates, residual salt, restricted access and contaminated internal surfaces can make contact maintenance impractical.
Waste characterisation	Yes	Determine radionuclide inventory, chemical composition, dose rate and waste classification.	Uncertainties on chemical properties (composition of raw waste, water content, solubility, corrosiveness, combustibility, gas generation properties, chemical toxicity).
Waste conditioning	Yes	Demonstrate a stable waste form suitable for handling, transport, storage and disposal.	Salts may require conversion, immobilisation or separation before acceptance by a waste facility. May require ad-hoc techniques or adaptation of current ones for solidification/immobilization (cement-based, ceramic, polymer or bituminen) or for vitrification (stabilization with borosilicate glass)
Management of fumes & vapours during dismantling	Yes	Control airborne radioactive and chemically hazardous releases during heating, cutting or salt treatment.	Volatile fission products, aerosols and salt-derived fumes may be released when contaminated equipment is opened or heated.
Fission product retention during decommissioning	Yes	Demonstrate confinement of mobile or volatile radionuclides during draining, cleaning and dismantling.	Deposited and dissolved fission products can be remobilised when salt chemistry, temperature or atmosphere changes.
Other (please add lines as needed)			

Comments

9. Severe accident testing programme



Assess which tests are needed for MSR severe accident scenarios and the validation of associated codes (MELCOR, ASTEC).

Test type	Large-scale test needed?	Scale of the test [kg]	Main objectives	Key risks / phenomena
Salt spill testing	Yes	50+	Validate spreading, pool depth, cooling, crust formation, freezing and heat transfer to structures.	Fluid dynamics of liquid fuel salt (salt spreading), convective heat transfer in salt, solidification/melting at the structure-salt interfaces, crust formation/remelting at the free surface with the cavity gas, FP release by splashing salt droplets, aerosol dynamics
Salt-water interaction	Case-by-case	5-100	Quantify energetic reactions, steam generation, pressure rise and aerosol generation	Rapid vaporisation, chemical reactions, pressure loads and mobilisation of radionuclides. Needed only where credible water contact exists.
Salt-air interaction	Case-by-case	1-20	Measure oxidation/hydrolysis, evaporation and aerosol formation under accident atmospheres.	Volatile species, aerosols, salt chemistry changes and source-term release. Usually separate-effects tests are adequate.
Salt-concrete interaction	Case-by-case	20-200	Determine heat transfer, concrete ablation/dehydration, gas generation and salt chemistry changes.	Water and gas release, containment pressurisation, chemical reactions and radionuclide mobilisation.
Other (please add lines as needed)				

Comments

Interaction between fuel salt and other core structural materials (e.g., metal, control rods, etc.)
Entrainment of contaminated molten salt droplets in the gas flow
Vaporisation of fission products from the fuel salt from freezing/thawing cycles
Vaporisation/volatilisation of MA compounds