NEWSLETTER
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MIMOSA

MULTI-RECYCLING STRATEGIES OF LWR SNF FOCUSING ON MOLTEN SALT TECHNOLOGY

IN THIS ISSUE

MIMOSA General Assembly at TU Delft in May 2024

A few words from the Coordination

By Isabelle Morlaes | Project Coordinator | Sr. VP MSR Initiatives - Orano

I am very pleased, on behalf of all the MIMOSA partners, to present a new issue of our project newsletter!

The high level of attendance to our recent Summer School on Molten Salt Reactors (MSR) held at TU Delft clearly reflects the growing interest in molten salt technology in Europe - not only in the reactor concept itself, but also in its capacity to breed or burn actinides, offering multiple options in terms of fuel cycle applications, including multi-recycling strategies of Light Water Reactors (LWRs) spent nuclear fuels (SNF).

The race to develop such advanced nuclear technology is accelerating worldwide, with actors like Russia, China, South Korea, the United States and Canada leading the way… The MIMOSA consortium, as one of the first European ecosystems to gather state-of-the-art competences on MSRs and recycling technologies, lays the foundation for a European ambition towards such chloride MSRs deployment, transforming the European Union into a credible contender in this international race.

We are focusing on MSR technology because, among the various multi-recycling options, fast MSRs are probably the least mature and least studied advanced technology, yet one of the most promising and worthwhile of attention. We are simulating European fleets, with LWRs as baseload completed with fast spectrum reactors, specifically chloride MSRs, to ensure long-term sustainability by recycling Uranium, Plutonoium and ultimately minor actinides.

Rather than dispersing resources across a large number of topics, we focus on a few key issues:

- global analysis of strategies for multi-recycling of SNFs from LWRs in the EU, based on LWRs and fast chloride MSRs capabilities,
- assessment of chloride salt properties to support studies of reactor performance and safety,
- simulations of chloride salt composition evolution in the reactor,
- demonstration of several key aspects of technical feasibility of chloride MSRs,
- study of chloride salt recycling and back-end options, particularly in synergy with La Hague plant,
- evaluation of the capacity of MSRs to produce valuable isotopes for other applications, and the way to extract, separate and purify them.

Our strategy within MIMOSA is to be highly relevant to nuclear stakeholders aiming to develop molten salt technologies, paving the way of fast chloride MSRs development in Europe. Therefore, disseminating the project results is essential for the success of MIMOSA. We are keen to share our first results and lessons learned…

To be clear: MIMOSA is a small piece of a big puzzle, but we hope our collective efforts contribute to accelerating the maturity of MSR technology, and to making it better understood and better perceived as a potential game changer in the nuclear energy landscape, contributing to a significant improvement in social acceptance of nuclear energy in general.

Multi-recycling scenario analysis and roadmapping

By Luc Van Den Durpel | Founding Partner - Nuclear-21

A first round of EU27 nuclear energy system scenarios has been undertaken providing a comprehensive view on the future prospects for nuclear energy in Europe and providing the projected inventories of Spent Nuclear Fuel (SNF) and fuel cycle service needs for the decades to come. This first round is largely based on 'evolutionary' scenarios with light-water reactor (LWR) technology and gradually some LWR-technology Small Modular Reactors (SMRs) and Fast Reactors (FRs) though not yet introducing molten salt reactors (MSRs) as such.

The outcome of these scenarios, with an example of such reactor-per-reactor/country-per-country evolution in figure 1, are the projected SNF amounts, separated nuclear materials and waste arisings, including also the isotopic compositions for all these materials for the decades to come.

The projected transuranics (TRU) that would be separated and destined for vitrification though amenable to be send to MSRs, have been analysed including their isotopic compositions.

The scenarios are still lacking the implementation of MSRs because the modelling of MSRs with such varying TRU-isotopic compositions as input does require more verification from a reactor physics modelling perspective. Indeed, a first round of simulations with a first version of MSR Reduced Order Model has been performed and lead to results requiring further analysis. A different ROM-model approach has been decided upon in June 2024 aimed at providing more reliable results, expected to be issued during Q3/2024, in time to perform the second round of scenario simulations, including the various modes of introducing MSRs in these European nuclear energy system scenarios.

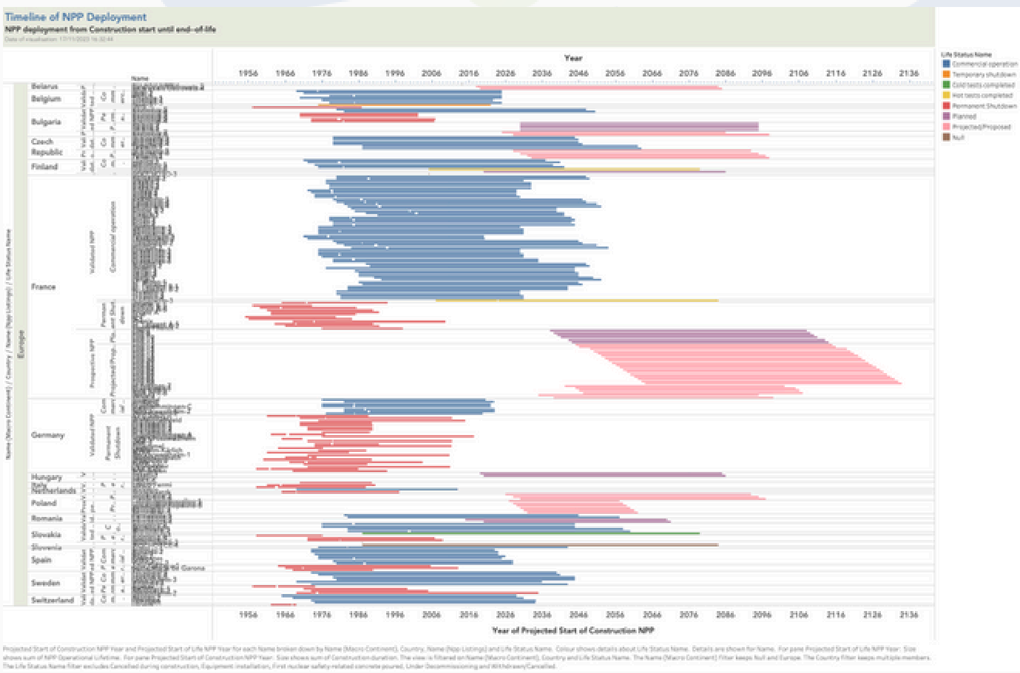

Figure 1: Example of reactor-per-reactor/country-per-country evolution

Molten salt properties

By Anna Smith | Associate Professor - TU Delft

The safe and optimal performance of a molten salt reactor design is directly related to the properties of the fuel salt mixture. WP2 aims to gain knowledge on some of the key properties for the reactor operation, namely melting temperature, heat capacity, vapour pressure, density, viscosity and thermal conductivity. Two fuel salt mixtures have been selected in the MIMOSA project in the NaCl-MgCl2-PuCl3 and NaCl-ThCl4-PuCl3 systems.

After selection of some specific compositions in the first year of the project, based on melting temperatures and neutronics, synthesis and preparation of the relevant mixtures have taken place in the second year of the project. The synthesis procedure for PuCl3 has been verified and reproducibility confirmed at JRC, leading to a product with high purity. Enough material was prepared to cover the needs of the MIMOSA project across the various work packages. The synthesis procedure for ThCl4 has been successfully implemented at the TU Delft, leading again to a high purity product, and scaling-up of the process is on-going. Several kilograms of NaCl and MgCl2 salts were also purified at CV Rez for neutronic measurements performed in work package 3.

Measurements of the thermochemical and thermophysical properties of salt mixtures are underway, both at JRC and TU Delft. The melting and transition temperatures of several compositions in the NaCl-MgCl2-PuCl3 system have been measured at JRC and used as input for the re-assessment of the thermodynamic model of this fuel system. Density of the selected NaCl-MgCl2-PuCl3 composition was also collected using a Archimedean method.

Measurements of vapour pressures are on-going. Moreover, experimental set-ups for the measurement of heat capacity, viscosity, and thermal conductivity are still under development. Benchmarking on inactive salts is already underway. At the TU Delft, preliminary measurements of the phase equilibria in the NaCl-ThCl4 system have been performed, complemented by molecular dynamics simulations of thermo-physical properties (e.g. density, heat capacity, mixing enthalpy).

During irradiation, numerous fission products will be generated, which will affect the fuel salt properties. In view of licensing of the MSR technology, it will be essential to perform thermo-physical property measurements on irradiated fuel salt, which is a challenging task due to the high radiotoxicity of these materials. As part of the project, a plan will be made for the measurements of key properties on irradiated salts coming from an irradiation campaign in a research reactor such as the HFR in Petten (Netherlands), and the identification of suitable techniques. In the second year of the project, information was collected from the project partners on salt irradiated samples characteristics as well as availability and suitability of measurement techniques.

Figure 2: Synthesis facilities at TU Delft

Molten salt composition evolution in reactor

By Dirk Visser | Consultant in Fluid Dynamics - NRG

Within MIMOSA's Work Package 3, experiments and advanced computer calculations are developed and employed to simulate the evolution of the chloride molten salt composition in the reactor. These simulations support fuel cycle calculations, safety evaluation and the analysis of valuable isotopes extraction options.

In WP3 Task 3.1, depletion calculations have been performed with the CNRS REM code for four MSR evolution scenarios (two power reactors and two supplied salt vectors), providing relevant depleted fuel compositions to WP5 to study reprocessing options for these irradiated salts. The preliminary processing scheme developed in collaboration with IJCLab was also used. Figure 3 shows results for a 300 MWth reactor and NaCl-MgCl2-PuCl3 fuel (enriched chlorine) associated with different actinides provenance: Scenario 2 (supply with Pu ex-MOX, solid line) and Scenario 2bis (supply with Pu ex-MOX and Minor Actinides, dashed line).

In parallel, CV Rez has started the experimental work in WP3 Task 3.2, studying the neutronic properties of chloride salts in the LR-0 reactor in Czech Republic, and using the 252Cf radionuclide source.

In the LR-0 reactor, two types of critical experiments were conducted, in which the NaCl salt acted either as an inserted zone in the thermal reactor or as a salt-reflected core. Preliminary results show that the salt acts as a strong absorber in the thermal reactor. These experiments provide valuable data to validate the nuclear data used for MSR modelling. Models of the experimental reactor assemblies are shown in Figure 4. The experiments with 252Cf source focused on validation of prompt gamma ray production, which could impact tracing/dosimetry of the irradiated salts. The spherical tank filled with NaCl solution shown in Figure 5 was used for this experiment.

Finally, a simple MSR loop system is devised in WP3 Task 3.3, which will be applied for code verification and numerical parameter studies.

Figure 3: First results of depletion calculations performed with the CNRS REM code related to scenario 2 (solid Line) and scenario 2 bis (dashed line). This work is part of L. Clot's PhD (CNRS-LPSC/ORANO). **Figure 4:** LR-0 core with NaCl insertion (left) and core with NaCl reflector (right).
Figure 5: Configuration for the prompt gamma radiation measurement, schematic view (left) real configuration (right).

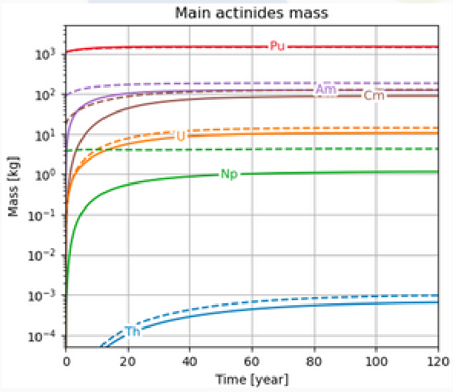

Figure 3

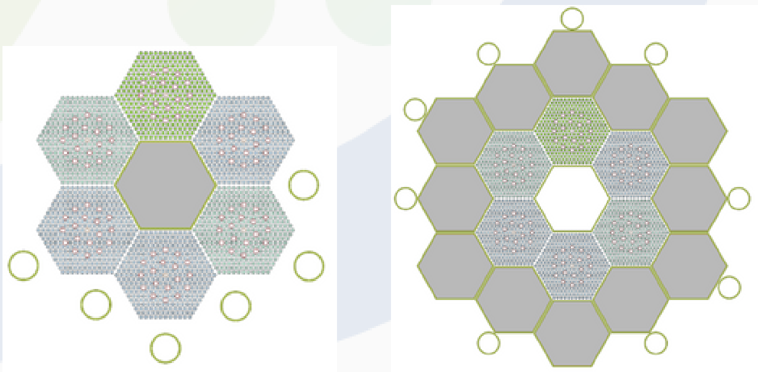

Figure 4

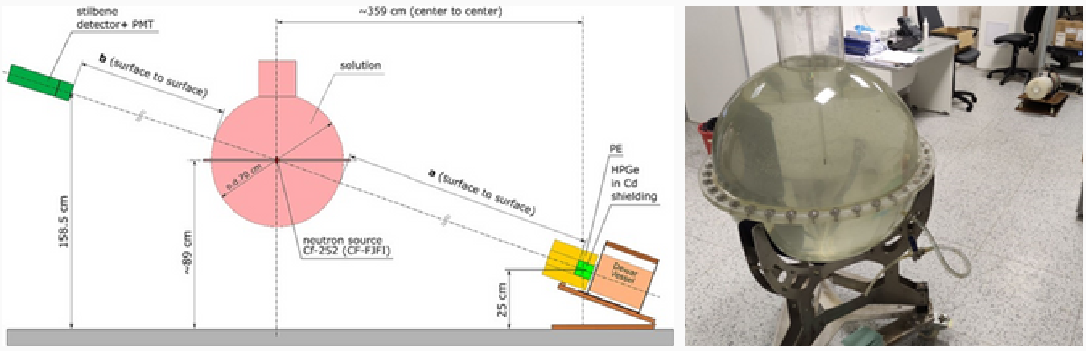

Figure 5

MSR key technologies

By Jaén Ocadiz | Chemical Lead - Thorizon

In the previous newsletter we reported that the test matrix for the corrosion studies had been completed, with three phases of increasing complexity and duration. By now, the simplest stage -- the so-called 'phase 0' – consisting of a short duration, high throughput exploration of the sample space, has covered all the selected metallic materials (TU Delft). A critical analysis of the results will inform the decision on which of these materials to take further to the next battery of tests. To gain a better understanding of the corrosion chemistry, novel measurements of the binary systems between NdCl3 (as a surrogate for PuCl3) and relevant transition metal chlorides are being performed.

Meanwhile, our partners at Schunk Carbon Technology have been working hard to manufacture a variety of silicon carbide samples, paying special attention to the porosity of the finished material. Porosity and free silicon content are two important parameters which may affect the corrosion resistance of these kinds of materials in molten salt environments.

The samples have been delivered to TU Delft to also undergo phase 0. At the Nuclear Research and Consultancy Group, NRG, larger specimens have also been delivered to undergo mechanical testing. The mechanical properties before and after salt immersion will then be compared.

At JRC-Karlsruhe there have also been developments on static corrosion tests (see Fig. 6). These involve phase 1: an immersion of longer duration having discarded some materials following phase 0. A new crucible designed at the institute allows the immersion of small coupons in small amounts of salt, such that the salt-to-volume ratio recommended by ASTM corrosion standards is fulfilled. Such a design will enable immersion tests with actinide-bearing salts which are difficult to manufacture and handle in large amounts.

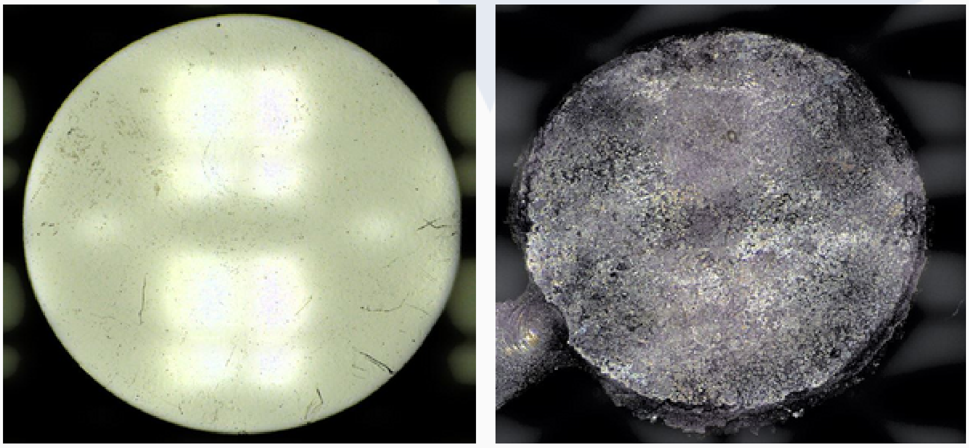

Figure 6: Small coupon immersion at JRC-Karlsruhe. Left: before exposure. Right: After exposure to a chloride salt bath for 500 h.

Molten salt recycling and back end

By Elisa Capelli | R&D Engineer - Orano

Work Package 5 (WP5) is progressing in developing innovative methods for treating spent fuel salt, with objectives aimed at enhancing the sustainability and efficiency of nuclear waste management. The primary goals include studying the integration of spent fuel salt treatment with the La Hague reprocessing scheme, exploring alternative pyrochemical treatments, converting chloride waste into glass, and analyzing these treatment options to recommend the optimal route.

Led by Orano with contributions from JRC-Karlsruhe, Task 5.1 focuses on assessing the compatibility of chloride fuel with the La Hague reprocessing facility. Orano is conducting a comprehensive technical study to integrate chloride fuel into La Hague's processes, addressing challenges such as minimizing chlorine inventory to prevent equipment corrosion and understanding the impact of unconventional fission product concentrations. In collaboration with CNRS (WP3), the work has also involved defining eight reference scenarios, with the evolution of the associated fuel compositions being calculated. The scenarios identified are based on some strategic choices and on some hypothesis on the salts and on the reactor designs, e.g., Mg-based salts vs Th-based salts, FOAK reactor vs reactor fleet, different predicted technological maturity. Concurrently, a parallel effort is underway focusing on the study of the dissolution process and the recovery of chlorides in nitric acid.

Within Task 5.2, CNRS is investigating pyrochemical processes to remove neutron poisons and minor actinides from spent fuel salt.

Experiments have identified the most effective liquid metals for extraction, showing promising results for the reductive extraction of lanthanides and actinides (see Figure 7). These efforts are crucial in developing a method that efficiently removes these elements from the salt, thereby improving the overall treatment process.

NRG is focused on converting chloride waste into glass, with initial experiments conducted on representative chloride salt compositions. The goal is to establish a robust vitrification method, with ongoing experiments aimed at refining this process. Future tests will focus on actual chloride waste, with the aim of ensuring that the vitrified waste meets all necessary standards for safe storage and disposal.

Starting soon, Task 5.4 led by CVR will compare the various salt treatment methods studied to recommend the most efficient and effective route. This analysis will synthesize the findings from the previous tasks to provide a comprehensive strategy for treating spent fuel salt, ensuring optimal safety, efficiency, and environmental protection.

These efforts under WP5 are crucial in advancing sustainable and safe methods for treating chloride spent fuel salt, contributing to the broader goals of efficient nuclear waste management and environmental protection. Stay tuned for more updates as the project progresses!

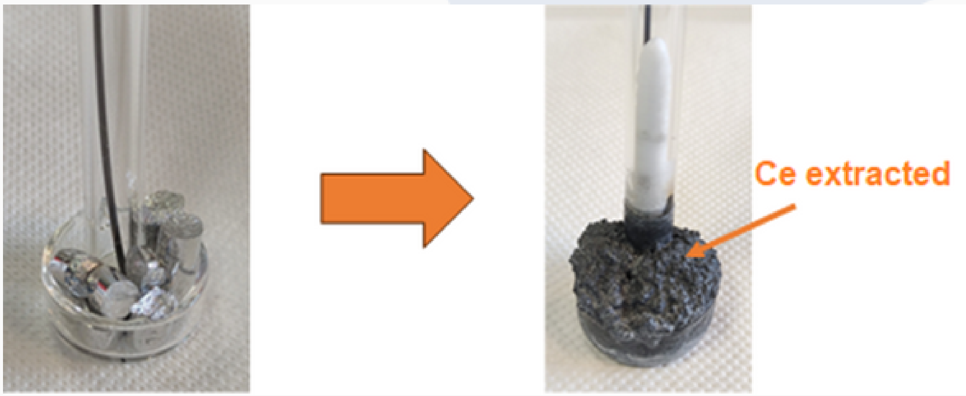

Figure 7: Experimental assembly used for the reductive extraction experiments of cerium on a metallic alloy.

Production and recovery of valuable isotopes

By Sylvie Delpech | Research Director - Centre National de la Recherche Scientifique (CNRS)

IWP6 is dedicated to evaluating the possibility of recovering some valuable isotopes produced in molten salt reactors (MSR). Due to its particularity of using a liquid fuel, MSR offer the possibility of recovering certain radionuclides just after their production in the core and, therefore, before their decay. This is the case for gaseous fission products and solid particles.
The last few months have been dedicated to establishing the list of elements that could be valued. Among them, we can cite: PGM (Platinum Group Metals) elements which are used in many applications (chemistry, CO2 conversion or hydrogen production), Xe133 and Mo99 for medical applications and Kr85 for EV batteries. PGM elements and Mo are fission products which are theoretically formed in the core as metallic particles. Xe and Kr are gaseous elements.

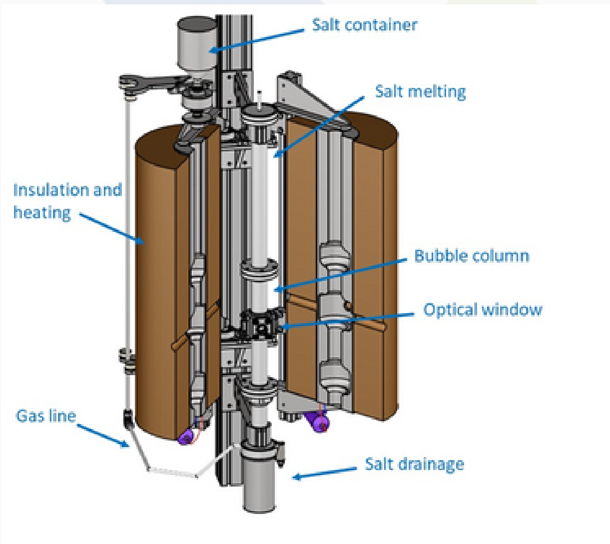

Figure 8: : Design of the molten salt bubble column with viewing ports, insulation, loading and drainage compartments and helium inlet.

One objective of WP6 consists of experimentally verifying the physical state of the fission products formed in the core fuel salt. Pd, Ru and Mo (elements of PGM group) were experimentally studied during this last period. A thermodynamic database of the main elements of the PGM group will be provided by the end of the project in order to explore the possibility of separating the platinoids elements by chlorination. In this context, the thermodynamic database of Mo and Nb have been already determined.

Obviously, the gaseous fission products formed in the fuel salt, because of their low solubility in the molten salt, will be naturally removed from the fuel salt and managed in a special gas management unit next to the reactor. As it was evidenced by the Oak Ridge National Laboratory during the Molten Salt Reactor Experiment (MSRE, based on a fluoride salt) operation, gas bubbles formed in the reactor carry through a flotation phenomenon the solid particles formed in the reactor. It is this particularity that we wish to exploit to recover gases and solids of interest at the same time and at the same place. In the frame of MIMOSA project, one objective is to experimentally verify the flotation process in a chloride molten salt. During the first period of the project, a device in aqueous solution was developed. Based on this first experimental feedback, a new device able to study the flotation in a molten salt is under construction in Delft (fig.8). Several parameters will be studied as the rate of gas flow in the column and the size of the solid particles on the extraction efficiency. Results will be available by the end of the project.

Training activities: MIMOSA Summer School on MSR

By Martin Rohde | Associate Professor and organiser of the MSR Summer School | TU Delft

In the week of July 8-12, 2024, TU Delft organised a summer school which was entirely dedicated to molten-salt reactor technology and the associated waste management. The programme covered both scientific and technical aspects, such as neutronics, thermal-hydraulics, salt synthesis and properties, structural materials, reprocessing/back-end of the fuel cycle and the recovery of valuable isotopes. 24 specialists and two startups provided lectures and practicals to 60 participants from all over Europe. These participants came from organisations both internal and external to the MIMOSA consortium. About 40% of participants came from the academic world and 60% from companies and research institutes.

Poster session and reactor tour

On Tuesday, 15 students, PhD students and post-doctoral researchers presented a poster on their research. Although there were many interesting posters, the jury chose the poster of Joelle Constantine (PhD student at the IJClab of the Université Paris-Saclay) as the winner! On Thursday, participants could have a look inside TU Delft's pool-type research reactor and admire the beautiful Cherenkov radiation. They were also shown around the many research facilities, such as the SESANS (spin-echo small-angle neutron scattering) and POSH, a highly intensive positron beam.

Political and regulatory landscape: EU Industrial Alliance for SMRs

By Elisabeth Guillaut | EU Affairs Manager - Orano

MIMOSA, one of the major Euratom projects supporting the development of SMRs in the EU, has closely followed the launch of the EU Industrial Alliance for SMRs.

This initiative, which brings together 277 members from industry, research, academia, national authorities, and NGOs, will dedicate key resources to developing and deploying the first SMR projects in Europe by the early 2030s.

During its first General Assembly, held in Brussels at the end of May, Commissioners Simson, Breton, and Ivanova expressed their full support for this initiative as a promising and efficient instrument to promote the development of SMRs and AMRs in Europe.

Various projects identified under this alliance, including Molten Salt Reactors (MSRs), will receive support from Technical Working Groups (TWGs) to find technological solutions and facilitate their development in the EU market. Among the eight different TWGs, one will be dedicated to research and development activities and another to fuel cycle and waste management.

The positive results already achieved by the MIMOSA project will make a key contribution to these discussions. The expertise and know-how of our consortium members will be crucial in overcoming the technological barriers of MSR projects. MIMOSA will thus participate in the annual stakeholder forum of this alliance.

Dissemination activities

Since the start of the project, we have presented our project at a number of nuclear research and industry events, including:

- **European Nuclear Education Network** (ENEN) event on training and education opportunities (Brussels, March 2023)
- **SNETP Coordinators' Hub Day** (Brussels, March 2023)
- **CEA/CNRS Bootcamp on MSRs** (Avignon, October 2022 & Nîmes, October 2023)
- **SNETP Forum** (Gothenburg, May 2023 & Rome, April 2024)
- **16th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (IEMPT/NEA) Conference** (Paris, October 2023)
- **NuFuel Conference** (Marseille, November 2023)
    - Experimental insight and modelling of the NaCl-ThCl4-PuCl3 fuel salt properties (Poster - TU Delft)
    - Irradiation test design for actinide-bearing chloride salts in the HFR (Presentation - NRG)
    - Corrosion behaviour of candidate MSR structural materials exposed to molten chloride salts (Presentation - TU Delft)
- **UK's Molten Salt Technology Platform** (January 2024)
- **Advanced MSR Workshop organised by Korean Advanced Institute of Technology and Hanyang University** (February 2024)

Just a few months after its launch, the MIMOSA project was labelled by the Sustainable Nuclear Energy Technology Platform (SNETP).

SNETP was established in September 2007 as a R&D&I platform to support and promote the safe, reliable and efficient operation of Generation II, III and IV civil nuclear systems. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The platform provides dissemination support and opportunities for research projects included in its portfolio.

Funded by
the European Union

Associated partner

Affiliated entities (CNRS)

Abbreviations

LWR: light-water reactor
MSR: molten-salt reactor
SNF: spent nuclear fuel