SAMOFAR Stakeholders bulletin

January 2018

Content

Message from the coordinator

Since the start of the SAMOFAR project two years ago, the global Molten Salt Reactor community has gained enormous momentum. We experience this every day by the increasing number of requests we receive for cooperation and information exchange by companies and research institutions and the invitations for presentations at meetings for politicians and policy makers. It's a clear sign that the world is ready for a new form of nuclear energy that has the potential to generate in a cheap and safe way electricity and medium-range process heat, and that has the potential to operate synergistically with intermittent energy sources like renewables. Together with renewables, nuclear energy can contribute to a CO2 free world that we urgently need.

Many reactor concepts are being investigated world-wide ranging from thermal to fast spectrum reactors, and from burner to breeder reactors. Depending on these choices one would like to opt for a fluoride or a chloride based fuel salt. This shows that there is no consensus about which MSR design is most suitable because each country has its own needs.

The SAMOFAR project is now midway and we just successfully finalized the mid-term review meeting by the EC. In conjunction with this event we organized an MSR summer school with more than 90 enthusiastic participants from over 30 countries. This shows how international the community is, but fortunately we all speak the same language, namely that of enthusiasm and cooperation.

In this newsletter you can read more about the progress made in the activities of our project, and we hope you want to connect to our project and become part of this world wide exciting movement.

SAMOFAR
The way forward to the ultimate safe nuclear reactor

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The SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor) project is one of the major projects in the Horizon 2020 Euratom research and innovation programme. The grand objective of SAMOFAR is to deliver a breakthrough in nuclear safety and waste management to make nuclear energy truly safe and sustainable. To this end, a new type of nuclear reactor, the Molten Salt Fast Reactor (MSFR), has been developed, whose key safety features will be demonstrated in the project.

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MSR Summer School great success!

SAMOFAR aims at educating as much students as possible. To this purpose we organized an MSR summer school with focus on the scientific fundamentals of fluid fuel reactors. The school was held at the premises of POLIMI along the Como lake in Italy from 2-4 July, 2017.

86 master students, PhD students and young professionals in the Thorium-MSR field from all over the world participated.

Presentations and lecture videos are available on the SAMOFAR website.

The jury of the MSR Summer School awarded the Best Poster Prize to Delphine GERARDIN for her poster entitled ‘Design and safety studies of the MSFR draining system‘.

Best Poster Prize winner
Delphine GERARDIN

SAMOFAR has its own YouTube channel!

A **SAMOFAR youtube channel** was launched in February 2017 containing four educational videos with the following topics: 1. Greenhouse gas emission and climate change, 2. Principles of nuclear fission, 3. The nuclear fuel cycle, 4. The MSFR and the Generation-IV initiative . The videos were prepared and recorded at TU Delft by an exchange student from Phelma - School of Grenoble Institute of Technology, showing the cooperation and exchange between parties. By letting the student present the movies we hope to reach young people in Europe and beyond.

In addition to these four movies, also two other movies from the GENTLE project were uploaded on the SAMOFAR channel, explaining the principles of nuclear reactors (light-water cooled reactors and fast reactors) and the principles of a molten salt reactor. In the channel description a link is given to the other movies of the Massive Open Online Course (MOOC) prepared in the framework of the GENTLE project for visitors interested to learn more about nuclear energy or for visitors interested to follow the MOOC.

Please feel free and have a look at the online videos.

SAMOFAR at TechNet 2017

On October 7, 2017, the SAMOFAR project presented the simulation challenges in the field of Molten Salt Reactors at the bi-annual TechNet Alliance Fall Meeting in Bilbao. The combined calculation of the power density distribution, the molten salt fluid flow carrying the heat and the neutron precursors, and the calculation of the temperature field of the fuel salt and structural materials impose a real challenge for which specialized code packages are being developed within SAMOFAR.

The presentation gave an overview of nuclear energy operation principles and on the molten salt reactors through history starting with the Molten Salt Reactor Experiment and ending with the Molten Salt Fast Reactor. Also the differences in calculation needs between thermal reactors with coolant channels and fast reactors with free fluid flow has been explained. Finally the advanced physics needed to simulate freezing and melting phenomena (e.g. in freeze plugs) and the skills needed to experimentally validate the calculation codes has been shown.

The Technet Alliance is a global network of Computer Aided Engineering (CAE) experts focussing on ANSYS as their main calculation tool.

Webinar on MSR

23 May 2017, Prof. Elsa Merle, CNRS, France

Liquid-fuelled reactors exhibit unusual and interesting properties in terms of operation and safety compared to solid-fuelled reactors requesting a revision of some well-known design and safety rules. In the webinar, such characteristics of Molten Salt Reactors (MSRs) were presented, together with the past and current R&D activities. The concepts studied in the frame work of the Generation-IV international collaboration was described, after which the presentation focused on the concept of the Molten Salt Fast Reactor (MSFR), a fast spectrum reactor that has been studied since almost a decade by calculations and experiments, initially at CNRS in France, but now also by other partners in the EU. In the webinar the main design choices and characteristics of this MSFR concept were explained and discussed including transient simulations, chemistry and material issues, safety analysis, research roadmap and laboratory scale experiments.

You can watch the free Gen IV webcast via this link.

Cooperation between SAMOFAR and NuStem

Molten Salt Reactor Technologies are gaining considerable momentum in the United States. After granting research and development awards to industry and research institutions to develop a Molten Chloride-Salt Reactor (MCSR), the Department of Energy (DOE) has now funded the Nuclear Science, Technology and Education for Molten Salt Reactors (NuSTEM). This project is part of the Nuclear Energy University Program of DOE to support nuclear energy research at US universities. The NuSTEM project is coordinated by Texas A&M University with the University of California at Berkeley and the University of Wisconsin at Madison as main collaborators. The NuSTEM project will (1) contribute to the development of enabling technologies for molten salt reactor concepts and (2) educate young professionals in molten salt reactor technologies. The technical scope of NuSTEM is embodied in five thrusts: material and corrosion science, sensor development, modeling and simulation, thermal-hydraulics, and nuclear data evaluation. The educational thrust will include collaborations with SAMOFAR.

Under the auspices of SAMOFAR, education of students and young engineers will be an important pillar for dissemination of our knowledge and to enlarge the community of stakeholders. The success of our summer school in Lecco-Italy (see the article in this newsletter) and the e-learning tools and video’s on the SAMOFAR YouTube channel is evident.

NuSTEM and SAMOFAR have agreed to collaborate in the next two years by establishing exchanges for students and principal investigators. Students will have the opportunity to seek internships in US and European institutions, while the NuSTEM-SAMOFAR collaboration will create a platform for scientists to exchange ideas and information during workshops and to give invited talks and seminars at the participating institutions and universities. The collaboration will also organize special sessions and roundtable discussions at large international conferences and prepare a special issue of a peer-reviewed journal focusing on MSRs both with liquid and static fuel arrangements.

Research highlights

In work package one we focus on the integral safety assessment of the MSFR. The strong involvement of the technical support organisation and the nuclear industry lays a sound basis for the exploitation and dissemination of the safety methodology and for the acceptance of the safety methodology by the nuclear safety authorities.

The safety and optimization studies performed in previous projects and in SAMOFAR has led to the initial design of the liquid fuel circuit and the emergency drain system of the MSFR (see Figure 1). These systems are now being optimized in terms of safety in the technical work packages of SAMOFAR.

This initial design of the fuel circuit and emergency drain system, has been evaluated and approved by international experts during the SAMOFAR progress meeting in June 2016 and is continuously being improved to take into account the results obtained in the SAMOFAR project.

In August 2017, the first version of the basic plant simulator was released. This system code has been developed conjointly by CNRS (primary fuel circuit) and POLIMI (intermediate and conversion circuits) and is under validation. This will be done by comparing the results to those of well-known system codes. Afterwards the code will be used to define the operation procedures of the MSFR including the identification of safety issues. Preliminary calculations with the LiCore code developed at CNRS (primary fuel circuit) show the excellent behavior of the MSFR to load follow variations (figure 2). Doubling the power from 1.5 to 3 GW leads to a fuel salt temperature change of only a few tens of degrees. Figure 3 shows an example of the thermal behaviour of the heat exchangers during transients in the intermediate circuit. This has been calculated with the Modelica code developed at POLIMI.

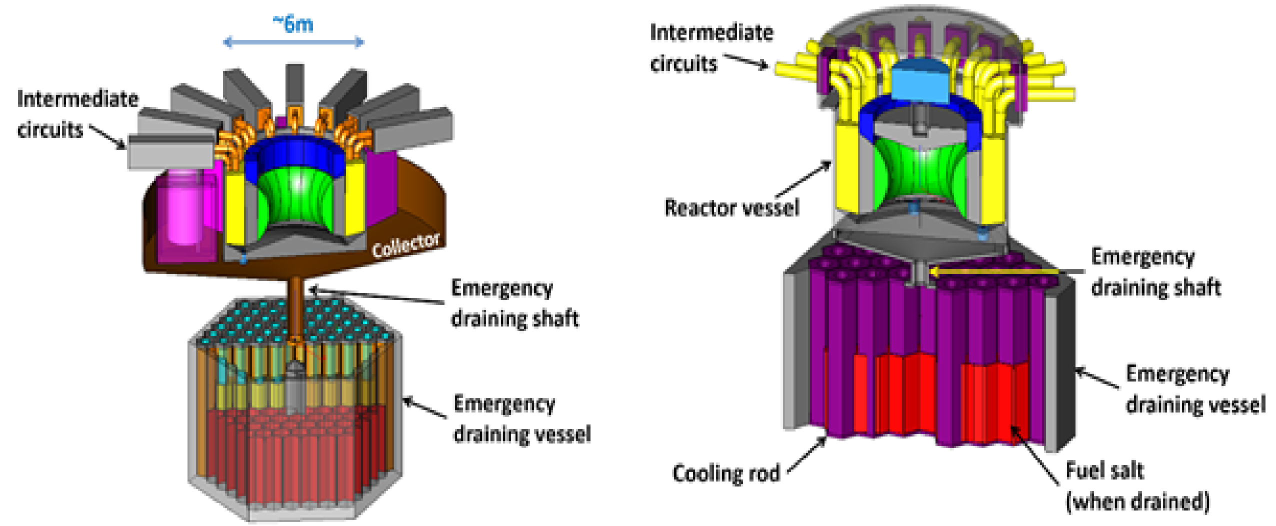

Figure 1: Overviews of the MSFR system (left) for two possible designs, including the fuel circuit and the Emergency draining system (EDS)

A study of the start-up procedure of the MSFR is under development, including the criticality approach and the multiphysics simulations of possible incidents during this step. A safety approach dedicated to liquid-fuel fast reactors has been developed by IRSN based on the ISAM methodology of GIF as well as other safety methodologies and guidelines. The definition of its application procedure and of the required tools will become available soon. Various safety assessment tools are being applied, like the Functional Failure Mode and Effects Analysis (FFMEA) and the Master Logical Diagram and the Line of Defense approach.

The application of defense in depth principles led to several proposals for the confinement barriers of the MSFR. This study has also helped to establish a list of design key-points that are relevant for safety and that should be further defined, such as the type of pumps used for the fuel circulation, the definition of the decay heat removal system or the components of the fission product removal systems. It has also highlighted the need to further define the operation and accidental procedures. Finally a list of Postulated Initiated Events is being defined and will be released soon.

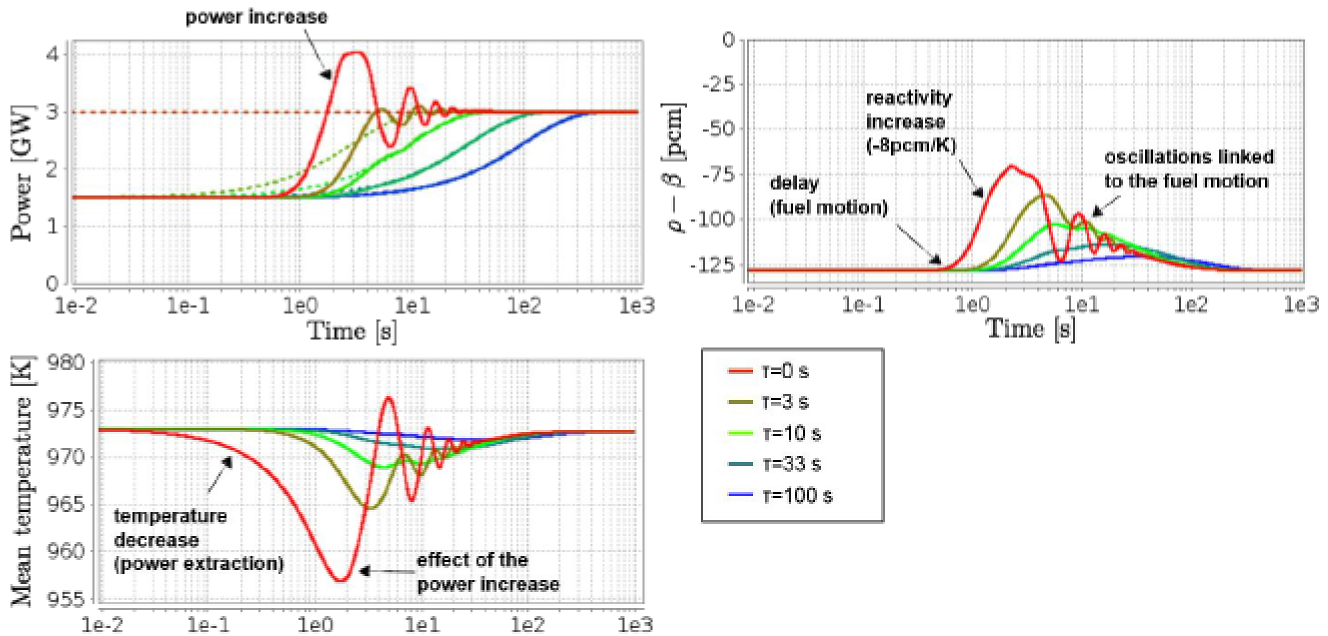

Figure 2: Load following transients from 1.5 to 3 GW simulated with the LiCore code by varying the power extracted in the heat exchangers

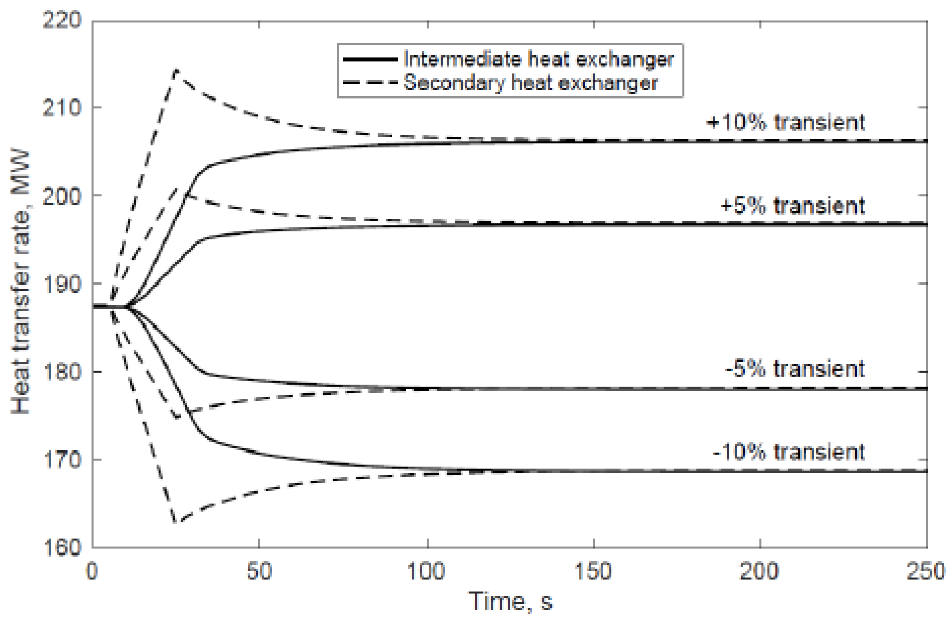

Figure 3: Evolution of the heat transfer rates in the heat exchangers for gas mass flow rate transients in the intermediate circuit (POLIMI Modelica code)

In work package two we develop new experimental methods and new instruments to measure the safety-related data of the fuel salt .

Recently at JRC Karlsruhe, the synthesis of pure PuF_3 has been achieved and the first experimental results on systems containing PuF_3 have been obtained, extending the knowledge of the LiF-PuF_3 phase diagram as shown in Figure 1.

Another highlight was the experimental demonstration of the retention capacity of caesium in the MSFR fuel solvent using a Knudsen effusion mass spectrometry, a unique device to measure volatility of nuclear materials. The results of this campaign are summarized in Figure 2, indicating reduction of CsF volatility of nominal concentration of 1 mol% by more than 2 orders of magnitude due to the fact that it is dissolved in the fuel. This effect reduces the source term in case of an accidental release of fuel salt. Using calorimetric facilities, the melting temperature of the uranium-based MSFR fuel salt has been determined and the influence of caesium and iodine on the fuel salt melting point has been investigated showing no major effect with respect to reactor operation. To complement the study of the caesium behaviour in the MSFR fuel the full thermodynamic assessment of the ternary CsF-ThF_4-LiF system has been made requiring the assessment of the CsF-ThF_4 sub-system (LiF-ThF_4 and LiF-CsF have already been implemented in the JRC molten salt database) which has been studied using various techniques, including differential scanning calorimetry for the determination of equilibrium data, Knudsen effusion mass spectrometry for the determination of activity coefficients, and X-ray diffraction measurements to reveal the structure and stability of various intermediate compounds. Using this novel information the CsF-ThF_4 system has been assessed and is shown, together with the measured equilibrium points, in Figure 3. To understand the fuel behaviour under accidental scenarios, the vaporization behaviour of the uranium-based fuel salt has been investigated at elevated temperatures, providing fundamental thermodynamic data on partial vapour pressures of gaseous species which are in equilibrium with the molten fuel salt. These data were used for the extrapolation of the vaporization behaviour up to the boiling point of the fuel salt.

In order to study the methods for the MSR fuel salt clean-up, a facility for the synthesis of pure fluoride actinides and for electrochemical measurements of actinides in molten fluorides has been designed and put into operation. The syntheses of pure UF_4, ThF_4 and PuF_3 have been established and the purity of the products has been verified experimentally. The electrochemical studies of selected actinides in molten fluoride salt media are still ongoing.

References:

[1] C.J. Barton, R.A. Strehlow, J. Inorg. Nucl. Chem. 18 (1961) 143-147.

[2] R. Thoma, T. Carlton, J. Inorg. Nucl. Chem. 17 (1961) 88–97.

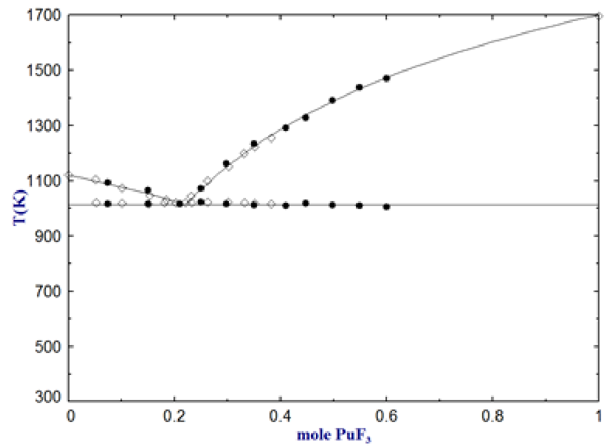

Figure 1: The assessed LiF-PuF_3 phase diagram; solid symbols: data measures at JRC Karlsruhe; open symbols: data measured by ORNL [1].

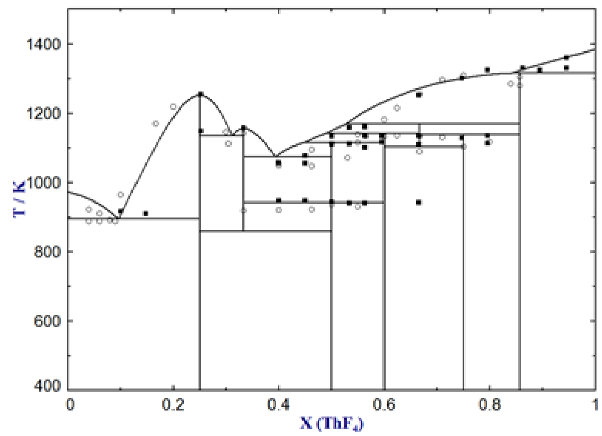

Figure 2: The assessed CsF-ThF_4 system; solid symbols: data measures at JRC Karlsruhe; open symbols: data measured by ORNL [2].

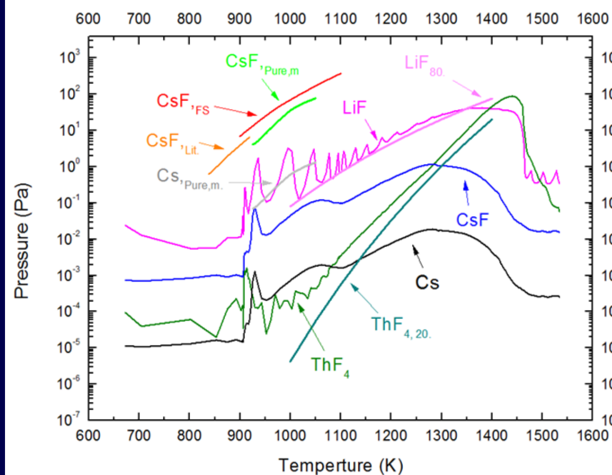

Figure 3: The vapour pressure of 1 mol% CsF in a eutectic mixture of LiF-ThF_4.

In work package three we investigate the natural circulation dynamics of the fuel salt in the primary vessel and in the drain tanks, and the behavior of the salt in the freeze plugs during transients.

At POLIMI the DYNASTY loop (see Figure 1) and the data acquisition system have been developed. Some preliminary experiments have been carried out with water. Also the salt that will be used in the facility at the next stage has been characterized. The facility will be used to study the dynamics behaviour of natural circulation systems subject to distributed heating. Experimental campaigns have already started to support the validation of analytical and numerical simulation tools developed by PoliMi, EDF, and TU Delft. Among others, the experimental results show the impact of the thermal inertia on the behaviour of natural circulation systems. The dynamic instabilities in the form of periodic oscillations and pulsed flow behavior will be studied soon. The extension for the experimental simulation of the passive Decay Heat Removal (DHR) system has been designed and commissioned. This extension aims at investigating the coupled dynamics of the primary loop and the passive DHR system.

The SWATH-W (Water) and SWATH-S (Salt) facilities have been built at CNRS to investigate various heat transfer and phase-change phenomena of molten salts. In SWATH-W (Figure 2), Particle Image Velocimetry (PIV) is being applied to determine the velocity field of a backward facing step (BFS). This allows the study of hydraulic phenomena along with the optimization of RANS CFD modelling. Comparisons of the flow velocity fields obtained by PIV measurements at different flow rates using both the pressure control system and pumps have been made. Results show that adequate flow stability can be obtained.

The SWATH-S facility operates with a fluoride salt (LiF-NaF-KF eutectic) to study radiative heat transfer and solidification phenomena and to demonstrate the phenomena during operation of the freeze plug. The experimental sections are located in a glove box to avoid any contact with ambient air (Figure 3). The tanks have been filled with fluoride salt, and the first experiments on cold plug formation and melting have been carried out, as well as solidification experiments on a cold rotating wall to validate CFD models.

Figure 1: DYNASTY facility at PoliMi labs.

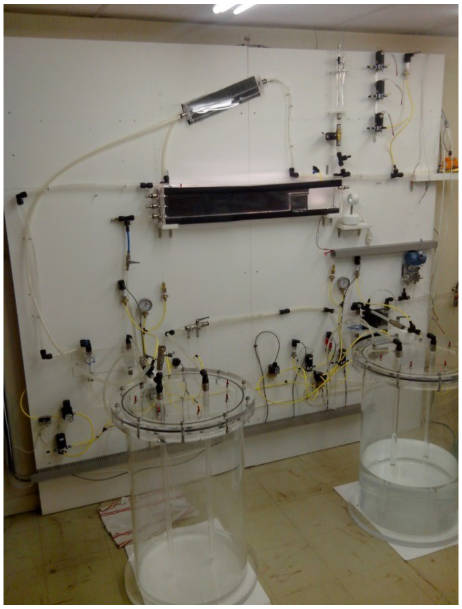

Figure 2: SWATH-W facility at CNRS labs.

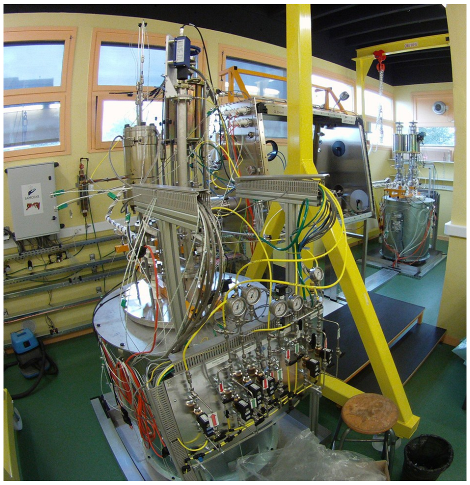

Figure 3: SWATH-S solidification experiment at CNRS labs.

In work package four we assess numerically the accident scenarios identified in work package one. These include both the normal operation transients and the off-normal accident scenarios.

During the first two years of the project the code systems of the SAMOFAR partners have been extended to include the unique aspects of the molten salt reactor that exclude the possibility to employ standard reactor physics code packages for its simulation. These simulation packages include OpenFoam based tools at POLIMI and PSI based on neutronics diffusion theory. The CNRS code package constitutes a coupling between OpenFoam and the Monte Carlo code Serpent using the transient fission matrix approach. KIT and EdF have further extended the SIMMER code to include the correct thermodynamics properties of the salt. At TU Delft the code coupling consists of a discrete ordinates code coupled to a new discontinuous Galerkin finite element flow code.

The correctness of these codes has been assessed through a benchmark study between the partners. This benchmark has been defined by CNRS and is specifically devised for the multi-physics processes in the molten salt reactor and takes as approach a gradual increase in complexity of the physics to be modeled making identification of possible errors an easier task. The results showed very good agreement between partners. At the same time the benchmark did its work in initially highlighting code problems that were solved along the way. An example result of the benchmark is shown in Figure 1. The code systems are now in good shape to proceed with multi-physics transient analyses.

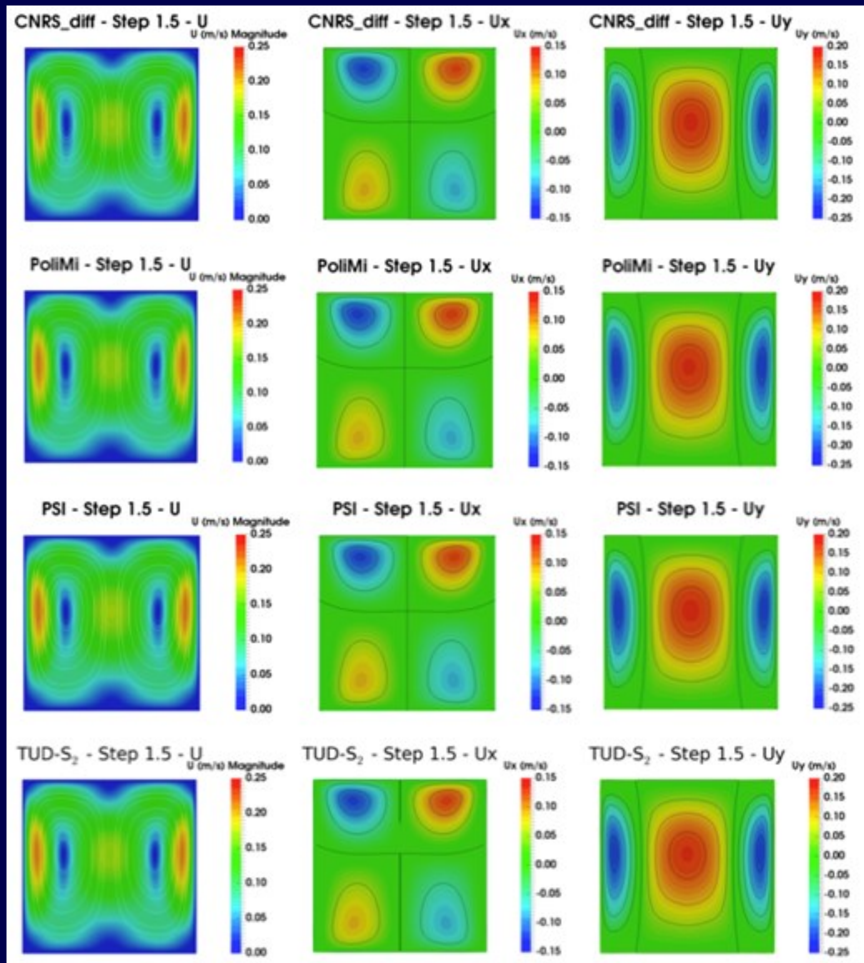

Figure 1: Results of different partners for steady-state coupling between neutronics and CFD. (Left) velocity magnitude, (middle) x-component of velocity with isolines, (right) y-component with isolines.

A set of transients has been selected that are considered most important to study the safety of the MSFR. Examples of the selected set are Unprotected Loss of Heat Sink (ULOHS) transient, Unprotected Loss of Fuel Flow (ULOFF), and blockage of fuel salt in the draining system to name a few.

Some of the partners have already started modeling transient scenarios. Notably KIT and EdF have investigated the speed of draining of the salt from the core . As an example Figure 2 show the dependency of the draining time on the draining tube diameter. Fundamental studies of plug melting are also being performed that precede the draining process.

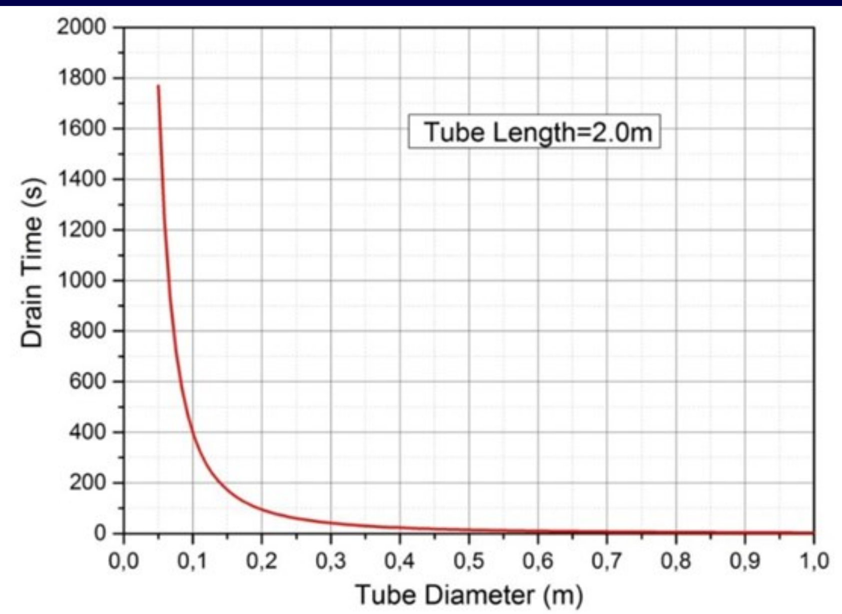

Figure 2: Core draining time obtained by KIT as function of the draining tube diameter.

In work package five we will provide a complete analysis of the nuclear and chemical safety aspects of the chemical plant in interaction with the nuclear reactor.

Recently CINVESTAV, the Mexican partner in SAMOFAR, has delivered the first Yttria Stabilized Zirconia (YSZ) samples for the corrosion studies at CNRS in LiF-ThF_4 (77-23 %mol) molten salt. Yttria Stabilized Zirconia samples with different compositions have been prepared in the form of pellets (8, 11.3, 17 and 20 %mol Y_2O_3) and Hastelloy coatings (17 %mol Y_2O_3 and 17 %mol Y_2O_3 + 10 %mol C). All pellets have been sintered at 1300°C in air.

At CNRS a preliminary study of the chemical and electrochemical behavior of zirconium (introduced in the molten salt as ZrF_4) has been performed in LiF-NaF-KF (46.5-11.5-42 %mol) molten salt at a temperature of 550°C. A complex electrochemical response of zirconium was observed on the tungsten and molybdenum electrodes. Several reduction and oxidation processes have been identified. The role of oxide ions has been studied as well. Complementary studies are necessary for a better knowledge of the zirconium behavior and its interaction with oxide ions. Later, the same system will be evaluated in LiF-ThF_4 molten salt.

An extensive study of the chemical behavior of iodide has been accomplished at the CNRS. This study was executed in two different fluoride molten salts, LiF-NaF-KF (500°C) and LiF-ThF4 (650°C). Through voltammetry techniques three oxidation processes have been identified in the two molten salts: oxygen evolution, iodine evolution and metallic gold oxidation. A redox potential inversion has clearly been observed among the I2(g)/I- and O2(g)/O2- redox systems present in LiF-NaF-KF and LiF-ThF4 (see Figure 3). The redox potential shift of O2(g)/O2- redox system to more anodic potentials shows a high stabilization of the oxide ions in LiF-ThF4 molten salt, which was attributed to the formation of a stable and soluble thorium oxyfluoride specie (ThOF2) in the salt. In LiF-ThF4 salt, the presence of a more oxidant redox system than I2(g)/I- lead to a spontaneous oxidation of iodide ions, see Figure 4. This chemical reaction is related to the presence of oxygen (2ppm) in the inert gas. The fluorination extraction was electrochemically simulated in LiF-ThF4 molten salt. A yield extraction of iodide higher to 95% was obtained.

Figure1. *YSZ Samples (CINESTAV)*

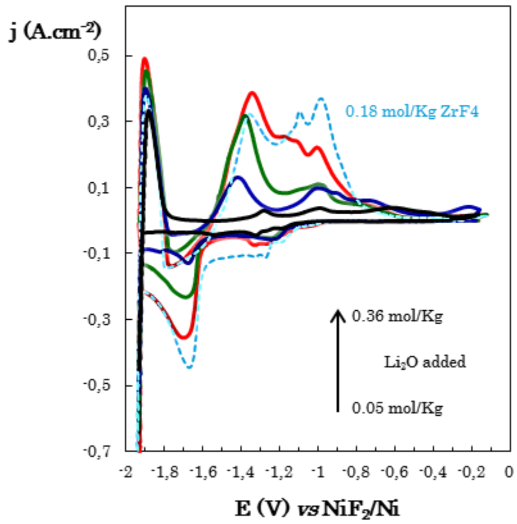

Figure 2. *Zirconium behavior in LiF-NaF-KF molten salt at 550 °C with and without oxide ions*

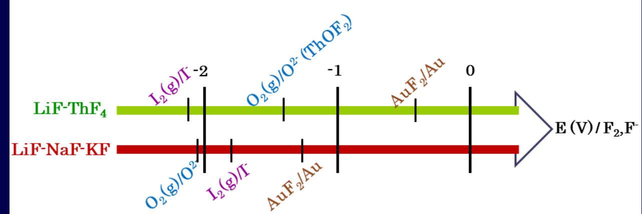

Figure 3. *Potential scale representing the several redox system and the potential measured in LiF-NaF-KF (500 °C) et LiF-ThF₄ (650 °C) molten salt with KI.*

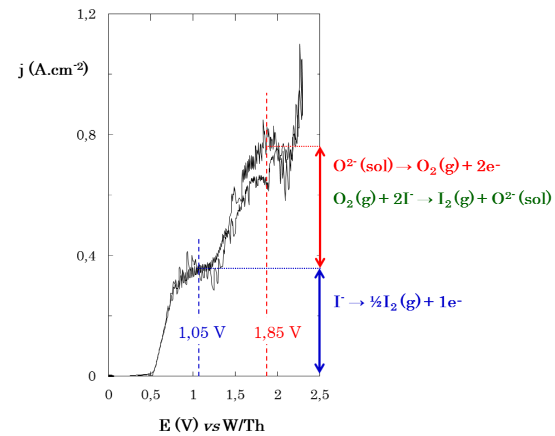

Figure 4. *Potassium iodide behavior in LiF-ThF₄ at 650 °C on a gold electrode. Scan speed 100mV/s*

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SAMOFAR

The way forward to the ultimate safe nuclear reactor

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