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Thème « Nucléaire Energie » - Session Réacteurs à sels fondus

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1. Summary

There is a growing consensus among energy experts that the goal of limiting global warming to 2°C cannot be achieved without the use of nuclear power. In such a context, proposing an innovative nuclear solution as an essential component of the energy system becomes a key to growth by limiting CO_2 emissions, provided that the technologies proposed are acceptable to the public in terms of safety, waste management and cost. The so-called molten salt reactors (MSRs) offer potential advantages in all three aspects, due to their completely different design from the solid fuel-based reactors currently in operation or under construction. The molten salt reactors have as main characteristic to have a fuel in liquid form, a fluoride or chloride molten salt, this fuel also playing the role of coolant which brings very interesting advantages at the level of safety and nuclear waste incineration. MSRs being very different from the current industrial nuclear solid-fueled reactors, they correspond to a breakthrough innovation and thus require human resources and financial investments substantial enough to ensure the long-term durability of the project, to validate it and to bring it to fruition. They were seen maybe as too innovative for classic R&D developments and to be understood and approved by safety authorities, and their study has been limited during the golden age of deployment of the present fleet of pressurized water reactors (PWRs).

In France, CNRS has been involved in molten salt reactors since 1997, initially through the legal obligation imposed at CNRS to have research activities on systems able to reduce the wastes of the nuclear industry (loi Bataille of 1991 extended by the law of June 28, 2006). The Thorium fuel cycle, as for MSRs, was also seen as too immature industrially and not necessary

compared to the classic U/Pu fuel cycle already in place in PWRs. But since only two fuel cycles exist on Earth (only two fertile materials being naturally available: ^{232}Th and ^{238}U), researchers at CNRS/IN2P3 decided also to work on this topic. CNRS/IN2P3 became a recognized expert and leader on Thorium MSR in France, in Europe and more largely in the world.

An innovative concept called Molten Salt Fast Reactor (MSFR) initially based on the Thorium fuel cycle was proposed by CNRS/IN2P3, resulting from extensive parametric studies in which various core arrangements, reprocessing performances, and salt compositions were first investigated to adapt the reactor in the framework of the deployment of a reactor fleet based on thorium on a worldwide scale. The primary feature of the MSFR concept is the removal of the graphite moderator from the core, resulting in a breeder reactor with a fast neutron spectrum and operated in the thorium fuel cycle. This "reference MSFR" (large power reactor of 3 thermal GW operated in the Th fuel cycle and using a fluoride salt) is listed as "CNRS reactor" in the official ARIS (Advanced Reactors Information System) database of IAEA and has been internationally recognized as an alternative for the long term to fast neutron systems with solid fuel, and with unique potential (such as negative reactivity coefficients, smaller fissile inventory, possible in-service inspection, and simplified fuel cycle). Accordingly, it was selected for further studies by the Generation 4 International Forum in 2008. A safety analysis methodology for such a reactor with circulating liquid fuel has been developed in collaboration with IRSN, Framatome and POLITO in the SAMOFAR and then the SAMOSAFER European projects of the H2020 program, including now also CEA and Politecnico di Milano.

The IN2P3 research activities described in this document are supported by the development of innovative simulation codes and by experimental facilities (see FEST document and presentation and the 2016 IN2P3 scientific council dedicated to chemistry), both dedicated to MSR technology. The research activities cover reactor physics including neutronics, physics coupling and transient calculations, experimental molten salt chemistry, risk analysis and evaluation, decay heat calculation, structural material corrosion, plant design, and experimental technology for molten salt. New studies are being conducted at CNRS/IN2P3 on other kinds of molten salt reactors, for example as a small modular reactor (SMR) or even as a micro-reactor (see the XSMR concept of the NAAREA start-up) of reduced power, or operated in the U/Pu fuel cycle, or as an actinide burner, or a combination of these characteristics. These research activities are done in collaboration with an increasing number of French partners (Orano, CEA, Framatome, IRSN, EDF), which reflects a growing national interest for MSR technology during recent years in France and also in the world. In this new context of high interest for MSRs, the CNRS/IN2P3 expertise acquired over the last 20 years is very useful, recognized and much in demand. This is combined with the present possibility of moving towards concrete realization of such reactors up to a demonstrator in the coming years, CNRS/IN2P3 being of course involved (see new collaborations with NAAREA, Orano, Thorizon).

Our academic approach is complementary to the R&D approach of the industry or the semi-industrial one of the CEA, starting from the knowledge of the elementary phenomena in physics and chemistry, from an analysis of the evaluated databases and the new needs, based on systematic studies of the various observables related to these phenomena, and carried by traditional approaches of the fundamental research (Monte-Carlo simulation codes, Green functions, genetic algorithms, correlated samplings, analytical resolution...).

The previous IN2P3 scientific council dedicated to nuclear energy was hold in 2013.

2. Scientific issues and IN2P3 achievements in the MSR thematic

2.1 Context and scientific issues

There is a growing consensus among energy experts that the goal of limiting global warming to 2°C cannot be achieved without the use of nuclear power. To achieve this, global nuclear power capacity should increase by at least 60% by 2045. Regarding the current landscape of the global nuclear industry, about two thirds of the reactors under construction are located in Asia, where there is a steady evolution of some countries towards a more intense future use of nuclear power. In OECD countries, nuclear power development is stagnating due to depressed electricity markets following the fall in commodity prices, despite difficulties in controlling carbon emissions. Finally, in nuclearized countries, the social acceptability of this energy is based on the safety of the installations and the management of nuclear waste, with a strategic interest, notably for France, in closing its fuel cycle. A part of the reactor fleet in France and in the world is also reaching the end of its life and will have to be renewed, and it is therefore necessary to reflect on future deployment strategies.

In such a context, proposing an innovative nuclear solution as an essential component of the energy system becomes a key to growth while limiting CO_2 emissions, provided that the technologies proposed are acceptable to the public in terms of safety, waste management and cost. In this context, the nuclear industry is recently analyzing innovative systems that are being studied around the world, particularly in the academic world. These systems must meet a number of new requirements:

- Improve nuclear safety
- Offer greater operating flexibility, particularly in terms of load following, in order to adapt to the demands of electrical networks that integrate an increasing share of intermittent and renewable energy sources
- If possible, facilitate the use as nuclear fuel of actinides (produced in current reactors and classified as nuclear waste).
- Improve the social acceptability of nuclear power.

The so-called molten salt reactors (MSRs) offer advantages in all four aspects, due to their completely different design from the solid fuel-based reactors currently in operation or under construction. The molten salt reactors have as main characteristic to have a fuel in liquid form, a fluoride or chloride molten salt, this fuel also playing the role of coolant which brings very interesting advantages at the level of safety and nuclear waste incineration. Their liquid fuel confers significant potential advantages to molten salt reactors:

- The homogeneity of the fuel allows a uniform combustion, which avoids loading plans and thus greatly simplifies the operation of the reactor.
- The feedback coefficients necessary for the self-stabilization of the reactor are excellent, in particular thanks to the expansion of the fuel, which takes it partially out of the core zone (where it is critical by geometry). This improves the safety of the reactor and makes it very flexible in operation, the load following being carried out directly by the extracted power without requiring a control rod. This flexibility is further facilitated by the fact that the fuel also acts as a coolant, and the nuclear power is thus directly produced in the coolant (no heat transfer delay).
- Reprocessing and preparation of the fuel can be done without changing its state, there is no need to manufacture pellets and then assemblies. This also facilitates the use of actinides (reprocessing of current waste) which can be simply dissolved in the liquid fuel.

- The reprocessing of the fuel can be done in line or by mini-batch and thus without requiring the shutdown of the reactor. This means that the reactivity reserve is reduced, and a part of the radioactive fission products are extracted out of the core which reduces the amount of radioactive matter that may be released in the environment in case of accident.
- Finally, in case of emergency, the fuel can be drained rapidly by gravity flow into tanks designed to passively evacuate the residual power and ensure long-term subcriticality without any intervention.

As early as the 1950s, some liquid fuel reactors were studied either as homogeneous reactors (the compound containing the fuel element is soluble or suspended in water), or as molten salt reactors circulating in a beryllium or graphite matrix to moderate the neutron spectrum (the compound containing the fuel element is soluble in molten salts). Historical studies have also shown the ease of piloting this type of reactor without the help of control rods or command rods thanks to excellent counter-reaction coefficients. The experimental molten salt reactors ARE (Aircraft Reactor Experiment) and MSRE (Molten Salt Reactor Experiment) of the Oak-Ridge laboratory in the USA have shown the possibility of operating without pressure at high temperatures (typically 600°C) [1]. However, these historical reactors, based on a large graphite matrix with channels for the circulation of fuel, had safety defaults and required irradiated graphite processing.

In 2006, the CNRS, under the impulse of the MSFR team of the LPSC Grenoble, following collaborations with EdF within the framework of co-funded theses, proposed a new concept of molten salt reactor using a fast neutron spectrum which combines the advantages of homogeneous reactors (controllability) with those of molten salt reactors (operation without pressure at high temperature) while completely correcting the defects of the historical American concepts. This new concept was officially adopted at the international level by the GEN IV International Forum (acronym GIF - see section 5 for more details) in 2008 under the name of MSFR (Molten Salt Fast Reactor, see figure 1) [2,3]. The use of a fast neutron spectrum allows, in addition, access to actinide burning and a strong reduction in neutron capture by fission products, which makes fuel reprocessing very light (reprocessing of less than 0.1% of the total volume of fuel each day).

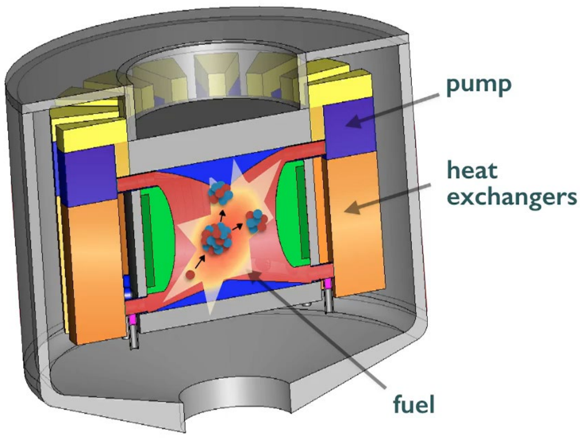

Figure 1. Conceptual view of the MSFR fuel circuit

2.2 IN2P3 achievements on MSR in reactor physics, design and safety

For more than 20 years, CNRS and mainly IN2P3, with national and European partners, has carried out scientific developments on the molten salt reactor concept called the Molten Salt

Fast Reactor (MSFR). The policy group of the Generation IV International Forum (GIF) launched by the DOE selected in 2008 the French MSFR (representative of reactor with molten salt as fuel and coolant) and the American AHTR (representative of reactor with molten salt as coolant only) due to their promising safety and design characteristics [4,5]. The so-called 'reference MSFR' design is a 3000 thermal MW reactor based on a fluoride fuel salt volume of 18 m^3 and operated at a mean fuel salt temperature of 700°C. The IN2P3 contributions are detailed in the next sub-sections 2.2.1 to 2.2.7, with a focus on the activities since the last IN2P3 scientific council on nuclear energy in 2013.

As presented in section 3, new research activities started in 2018 also on small modular versions of the MSFR (s-MSFR), to be operated as a breeder in the U/Pu fuel cycle or as an actinide burner and thus using a chloride salt. These research activities are currently expanded with a growing national interest in France to assess the ability of these MSFR systems to satisfy the objectives of Generation IV reactors in terms of sustainability, resource saving (closed fuel cycle, no uranium enrichment), safety, waste management (actinide burner) and non-proliferation. The expected advantages of Small Modular Reactors (SMR) include the simplicity of design, enhanced safety features, the economics and quality afforded by factory production, and more flexibility compared to larger nuclear power plants. Additional modules can be added incrementally as demand for energy increases.

The research activities led at CNRS rely on simulations/safety/design/chemistry in three laboratories (LPSC, IJC Lab, Subatech) and are related to the following topics:

- Neutronic calculations of material composition, nuclei evolution, and burnup associated with MSRs: development and validation of the REM neutronic evolution code and in perspective of an adapted version of the Serpent code for MSR; studies and optimization of different kinds of MSRs (fluoride and chlorides salts, fast and thermal spectrum, a fuel cycle based on Th/^{233}U or on ^{238}U/Pu, and MSR versions for burning actinides) (LPSC and Subatech) – See sub-section 2.2.1
- Nuclear data related to decay heat and neutron cross sections, uncertainty propagation and assimilation based on Monte Carlo approach (Subatech) – see sub-section 2.2.2
- Simulation studies during normal and accident conditions: development of two simulation tools for MSRs that account for the delayed neutron precursor motion in a circulating liquid fuel and developed by IN2P3 at LPSC, namely, the TFM-OpenFOAM code coupling high fidelity neutron kinetics to Computational Fluid Dynamics (CFD) thermal hydraulic code for transient analysis (see sub-section 2.2.3); and the LiCore power plant simulator for real time simulation under development by CNRS and CORYS (see sub-section 2.2.4)
- Safety analyses of molten salt reactors (LPSC and Subatech): Safety evaluation of the 'reference' MSFR (a 3,000 MW(t) MSFR based on the Th-U cycle) to achieve safety-by-design for a large MSFR, with the plan to apply the same approach for a small MSFR (S-MSFR) in the coming years – see sub-section 2.2.5
- Core and systems design studies (LPSC) – see sub-section 2.2.6
- Chemical experimental studies of molten salts (IJCLab) – Activities already presented and evaluated by the SC of IN2P3 in 2016, not detailed in this document
- Experimental facilities FFFER and SWATH (LPSC) – See the dedicated FEST presentation/report during this IN2P3 SC.

2.2.1 Neutronic calculations

The MSFR team based at the CNRS/LPSC laboratory of Grenoble is developing, updating and validating the REM neutronic code for more than 20 years [6,7]. REM is a code of evolution under constraints which can be used to simulate the composition evolution of the materials under neutron irradiation in any kind of nuclear system, including molten salt reactors where the fuel cleaning (fission product extraction) and feeding (addition of fertile or fissile matter) is done during the reactor operation. This code remains quite unique in the world in its neutron-chemistry coupling capabilities and also the only one to allow the setting of several parameters during the evolution (reactivity, power, proportion of given elements). The REM code has been used to perform various MSR studies and optimizations of the MSFR concept based on the evolution of material composition during irradiation or in storage, including burnup studies of different kinds of MSFR (fluoride and chlorides salts, fast to thermal spectrum, and versions of MSRs as breeders and actinide burners using a cycle based on Th-^{233}U [8] and based on ^{238}U-Pu).

A neutronic benchmark [9] has been carried out in the frame of the EVOL European project. These burnup calculations have been used for applications such as proliferation evaluations [10,11] and radioprotection issues in the frame of the work-package 5 of the SAMOFAR project between IPN Orsay, LPSC and CEA/IRFU.

Finally, a new neutronic benchmark is under working in the frame of the current SAMOSAFER, led by CNRS/Subatech with contributions of Paul Scherrer Institut, Politecnico di Milano, CEA, LPSC and Subatech, and aiming at providing the term source (amount of all radioisotopes that can be released in the environment by the reactor in case of severe accident).

2.2.2 Nuclear data related to decay heat calculation and neutron cross sections: uncertainty propagation and assimilation based on Monte Carlo approach

Cooling the fuel in all places at any time and the control of the chain reaction are two of the three fundamental safety functions. Both phenomena are major issues for safety studies and are directly linked to the current knowledge in the databases. Propagating the corresponding uncertainty impacts the design of the reactor systems, and when possible improving the databases is an important element.

Some dedicated studies were performed at CNRS/Subatech to evaluate the decay heat produced by a MSFR and to assess the potential needs of new nuclear data for such a Generation IV concept. The decay heat, corresponding to the heat that has to be extracted after the reactor shutdown due to radioactive decay of the materials present in the reactor, is calculated by combining reactor simulations to estimate the fuel inventory with nuclear data (decay properties of fission products and actinides, cross sections and fission yields) as inputs. The codes currently used are mainly validated for boiling water reactors (BWRs)/pressurized water reactors (PWRs) in the U/Pu cycle, but they are not yet validated for Generation IV reactor concepts. Moreover, some fission products in the decay data libraries have decay schemes biased due to the Pandemonium effect. This Pandemonium effect comes from the low efficiency of Germanium detectors at high energy, resulting in an overestimation of the β- contribution and an underestimation of the γ contribution in the decay heat. The SERPENT2 code was used to carry out a simulation of the MSFR reactor core operated with a fluoride salt, based on the ^{232}Th-^{233}U cycle. The aim was to identify the main nuclei contributors to decay heat for different cooling times and to see if some important fission products are also biased by the Pandemonium effect and need to be re-measured with an alternative experimental technique based on the Total Absorption Spectroscopy method. A preliminary list of 10 potential Pandemonium nuclei was established [12], and will be extended/compared to cases with chloride salts and the ^{238}U-^{239}Pu cycle, before being discussed with the TAS collaboration (Subatech, Univ. of Surrey, IFIC Valencia) for a potential experimental proposal on an ISOL (Isotope Separation On-Line) facility.

In addition, some work just started (2020-2024) in uncertainty calculations of the MSFR's decay heat, especially to determine the impact of nuclear decay data by using an approach based on the Total-Monte Carlo (TMC) method with the development of the Cocodrilo code coupled to the SERPENT code, which may be used for different concepts – see more details in the report/presentation on reactor physics modelling (Xavier Doligez). Another new code named Coconust focuses on the neutron cross section sampling for uncertainty propagation and assimilation as studied in [22].

2.2.3 Simulation studies during normal and accident conditions and the TFM-OpenFOAM code

The MSFR, as a reactor with circulating liquid fuel, requires a new definition of its safety and operating procedures. The intrinsic core stability is guaranteed by its excellent negative feedback coefficients. Thanks to this stability, the power production may be driven only by the heat extraction, resulting in a very interesting flexibility to follow the electric grid's load; control rods in the core may then not be required, which suppresses a classic accident initiator. Since the heat is produced directly in the salt that circulates in the fuel circuit, the negative feedback coefficients act very rapidly to stabilize the core, unlike reactors with solid fuel. The fuel salt itself is cooled in the heat exchangers. Due to theses specificities, dedicated tools are being developed to simulate the reactor's behavior for normal (e.g. start-up, load following) and accident (e.g. reactivity insertion) conditions, to develop, optimize and assess the MSFR operation procedures. The reactor modelling requires specific treatment to consider the phenomena associated with the liquid fuel circulation as detailed next.

The study of MSR cores in such conditions requires a code coupling the neutronic and thermohydraulic evolutions. Classical codes used in reactor physics cannot be used as they do not allow for the key features of the MSFR. The special features of the MSFR include the movement of precursors with the moving fuel, the strong coupling between the neutronic and the thermohydraulic aspects due to the use of liquid fuel, the internal heat generation and the shape of the core having no fuel pins as a repeated structure. These features cause a variety of phenomena occurring during transients that are particular to the MSFR (and to any MSR where the fuel is circulating and acts as the coolant) for which dedicated tools are required. Accordingly, two tools for transient simulation have been developed at CNRS: the TFM-OpenFOAM 3D-coupled code, and a simulator of an MSR power plant based on the LiCore core model (see next sub-section).

Important aspects of such systems regarding the coupling are the delayed neutron precursor convection and a complex flow pattern in the core cavity. Thus a multiphysics tool, that is more generic than those existing for reactors with solid fuel, has been developed by coupling CFD thermalhydraulics and an innovative green function neutronic approach based on Monte Carlo calculations called Transient Fission Matrix (TFM) [13,14] invented at CNRS/IN2P3 by Axel Laureau initially during his PhD thesis and developed since then. The CFD modelling allows to solve the Reynolds Average Navier Stokes (RANS) equation and provides a 3D flow description in the core. The TFM approach is a time-dependent version of the fission matrices characterizing the transport of a neutron from its birth position to its death/fission position. This includes the prompt as well as the delayed neutrons whatever their location in the fuel circuit is (in the critical zone or in the recirculation/cooling sectors). Then, using a technique of power iteration, all the generations of prompt neutrons are reconstructed, and finally the reactor fission distribution, that accounts for the precursor transport, is obtained. The description of the TFM neutronics approach and this approach's coupling to the OpenFOAM is available in references [14,15].

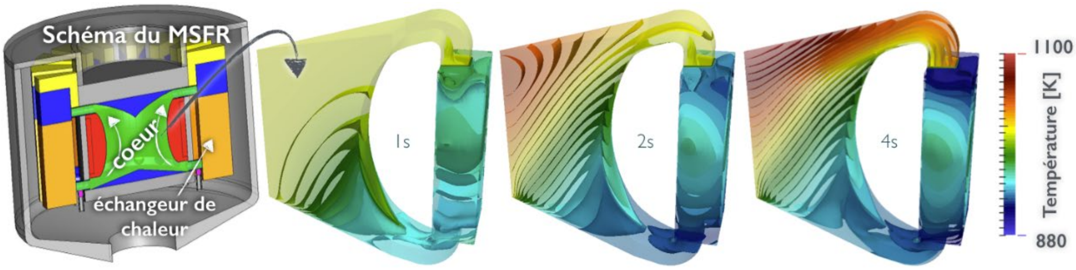

Figure 2. Temperature evolution during an instantaneous overcooling transient of the MSFR reactor: entry of cold fuel salt from the exchanger (1s), inducing an increase of the power and thus of the core temperature (2-4s)

The TFM- OpenFOAM code may be used to calculate various normal (start-up and load following procedures) and abnormal transients (reactivity insertion, loss of fuel flow, loss of heat sink, low power overcooling accident). Depending on the calculation options and mainly the refinement of the meshing, the calculation time for a given transient varies from several seconds (real time calculation) to one week. Finally, the TFM- OpenFOAM code developed initially for MSFR studies was also used for PWR calculations [14], and recently was extended to perform transient calculations of sodium fast reactors [16,17,18,19] or of research reactors [20].

Various MSFR transient studies have already been calculated with the TFM-OF code, including parametric studies of overcooling (see figure 2) and reactivity insertion transients. A parametric study of an overcooling transient is illustrated in figure 3 [15].

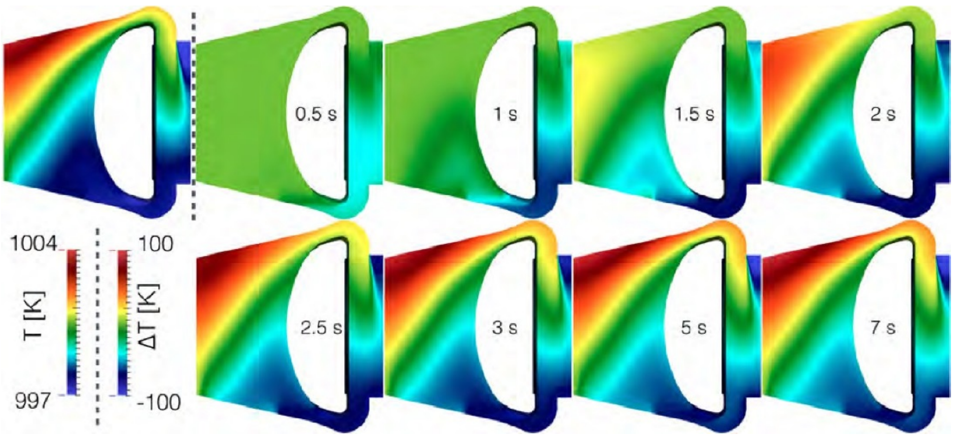

Figure 3. Distribution of the fuel salt temperature at t = 0 (left), and its time variation T(t) − T(0) for a 100 MW to 3 GW overcooling transient.

These transient calculations have highlighted the excellent stability of the MSFR core even in the case of a violent and quick perturbation. Parametric transient studies (such as the overcooling event at low power level illustrated above) performed up to prompt critical regime [15] have also demonstrated that no cliff-edge effect occurs when this regime is reached, that is, no sudden violent behavior is observed for the MSFR. This behavior is very important regarding safety considerations and analyses.

As detailed in the perspectives (see section 3), a collaboration started with Framatome in 2020 through three master theses to implement the TFM neutronic model in their StarCCM+ thermalhydraulic code to develop the TFM-Star code that will be used in parallel to the TFM-OpenFOAM code in the future ISAC project and in the PhD thesis of Thomas Sornay (funding LPSC/Framatome, started in November 2021). Among the perspectives on this subject, the addition of a more refined thermalhydraulic modeling LES (Large Eddy Simulation) is under development in the frame of the SAMOSAFER European project to allow an evaluation of power fluctuations in the reactor core.

2.2.4 Power plant simulator and the LiCore code

As mentioned above, molten salt reactors whose fuel is in liquid form are indeed flexible in terms of operation (such as the capability to follow the grid's load) and design choices (such as fuel composition, power level…), and they are very different in terms of design, operation and safety approach compared to reactors with solid fuel. Such reactors require a new definition of their operating procedures.

Dedicated developments and studies have been performed in the frame of the European SAMOFAR project of Horizon2020 and in parallel in France involving CNRS, CORYS and Framatome on the code called LiCore. This code is a power plant simulator based on basic principles and adapted for MSRs.

The MSFR plant is composed of three circuits: the fuel circuit, the intermediate circuit, and the power conversion circuit. The fuel circuit, defined as the circuit that contains the fuel salt during power generation, includes the core cavity and the recirculation–cooling loops or sectors, which are mainly comprised by the inlet and outlet pipes, pumps, and fuel heat exchangers. The neutronic model LiCore, at the center of the simulator, corresponds to an improved model of point kinetics to account for the specificities of an MSR, notably the circulation of the delayed neutron precursors out of the core. Coupled to a piston model for the fuel motion in the core, this code can perform calculations faster than real time to simulate the behavior of the fuel circuit. A simplified model of the intermediate circuit allows to run parametric studies of the MSFR fuel circuit during normal and accident conditions. Consistency of the results provided by LiCore code with the 3D coupled neutronic thermohydraulic TFM-OpenFOAM code has been checked [14,21].

Finally, LPSC (developing the LiCore simulator) is collaborating since 2017 with the CORYS company, which is a subsidiary company of Framatome that develops simulators for trains and nuclear power plants (NPPs). The LiCore code has been integrated successfully in ALICES, the integrated simulation toolset designed by CORYS for the development, maintenance, and operation of major simulators, such as power plant simulators. Additional modules are being added to fully simulate the intermediate and energy conversion circuits. The idea is to add a simulation of the intermediate and energy conversion circuits. This integrated version allows to study the whole MSFR plant (see figure 4), thus helping to define the operating procedures of the reactor. The next steps for developing this power plant simulator will be the addition of control-command devices and the improvement of the modelling of the components, such as the turbine.

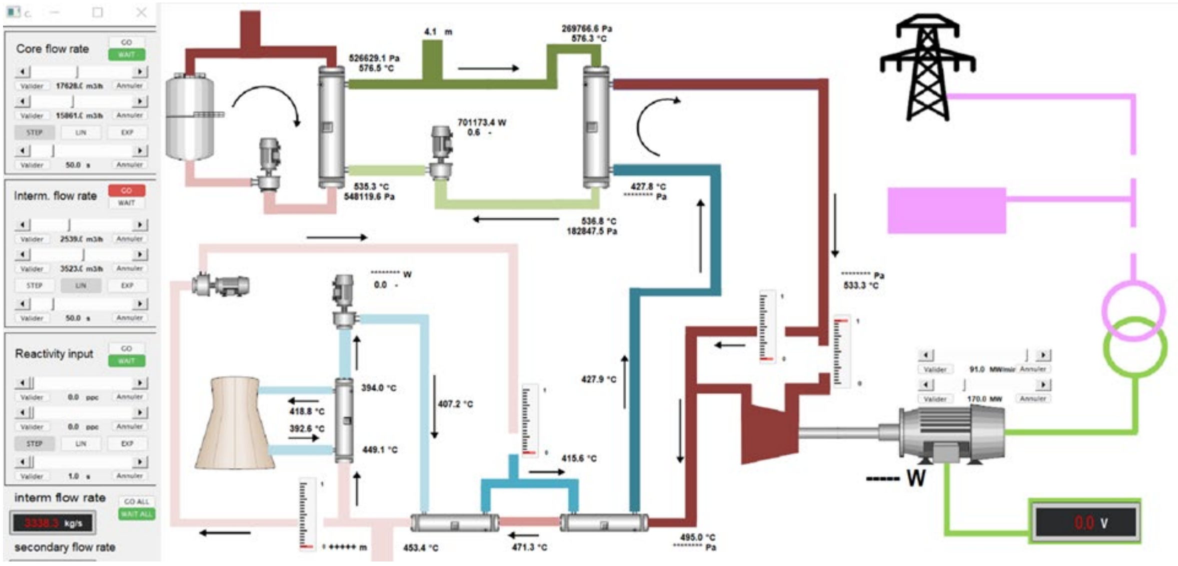

Figure 4. Main screen of the LiCore-ALICES power plant simulator for the MSFR

Studies have been performed with the LiCore and the TFM- OpenFOAM codes, together with expert judgement, to propose some operation procedures such as the startup [22] and the procedures for following the electric load [15]. This procedure definition continues in the frame of the SAMOSAFER European Project [23].

2.2.5 Safety approach and risk analysis

A safety approach dedicated to the MSFR or more comprehensively for reactors with fuel that is circulating in liquid state is being developed. Some preliminary steps have been studied in the frame of the EVOL project as well as in Mariya Brovchenko's PhD thesis [24]. The approach for this development has been defined in the SAMOFAR project in a task led by the IRSN (France), and involving mainly the CNRS (France), Framatome (France) and Politecnico di Torino (POLITO, Italy). This assessment methodology aims at reaching a safety that is "built-in" and not "added-on" by applying it at the earliest stages of design. The approach is based on the Integrated Safety Assessment Methodology (ISAM) developed by the Risk and Safety Working Group of the Generation IV International Forum [25], coupled to usual risk analysis methods such as functional method analysis, master logic diagram, and line of defense method [26,27].

Based on the new integrated design of the MSFR plant, abnormal situations of the fuel circuit and the emergency draining system have been identified and classified according to their initiating event (i.e., according to the phenomena involved), based on the following sources:

- The analysis of the accident types identified for currently operating pressurized water reactors (PWRs);
- Deterministic calculations, such as criticality and thermal studies [22,28], and calculations of transient and accident scenarios using multiphysics calculation tools [14,15];
- Preliminary risk analyses considering design optimizations, together with the identification of the associated initiating events [29,30,31].

The application of the assessment methodology combining deterministic and probabilistic tools has been launched during the SAMOFAR European project and in the PhD thesis of Delphine Gérardin [28], for example, to identify a reference severe accident of the MSFR, and to propose and evaluate possible confinement barriers and lines of defense. This work continues in the frame of the SAMOSAFER European project (2019-2023).

Finally, a safety exercise is under working in a national level since 2021: the MSR PIRT project of the NEEDS interdisciplinary program. This project is led by CNRS/IN2P3 and by CEA/DES (Direction des Energies) and gathers experts from CEA, CNRS, Framatome, EDF, IRSN and Orano. Through a PIRT (Phenomena Identification Ranking Table), the objective is to identify and prioritize in terms of importance and knowledge all the physical and chemical phenomena that underlie the behavior of molten salt reactors in case of accident. During the two first technical meetings in July and October 2021, the MSR concepts on which the analysis will be applied have been selected (the reference MSFR concept of CNRS and the ARAMIS concept of CEA) and two accident scenarios have been defined, together with the associated figures of merit. At the end of the MSR PIRT project, the phenomena identified as being both important and relatively little known will subsequently be labelled as research and R&D actions in order to improve knowledge as next steps of a possible national research roadmap.

2.2.6 MSR system design optimization and pre-conceptual design studies

The static system SONGe (System OptimizatioN by Genetics / Système d'Optimisation Numérique par algorithme Génetique) code developed at LPSC is focused on the MSFR’s fuel circuit and connected to genetic algorithms. This code allows optimization studies of this circuit. The objective is to obtain a globally optimized geometry of the fuel circuit by setting different parameters and constraints, instead of separately optimizing the various components (such as heat exchangers and pipes). This is mandatory since some constraints cover several components (for example, the fuel salt–coolant volume). A configuration that best satisfies these constraints can then be sought by adjusting a list of variable design parameters.

This code thus describes the system as an assembly of components, each component having specific properties (physical properties) or parameters (such as length, hydraulic diameter, and power). It sets a set of constraints on each parameter (minimum and maximum values) with a contribution to the figure of merit of the system. Then, a genetic algorithm optimizes the global figure of merit of the system by changing the parameters. An example of application is the optimization of the fuel circuit with a competition for the total fuel salt volume to be reduced to lower the fissile inventory but to keep it large enough to reduce the pressure drops in the pipes and heat exchangers. The results are the geometric parameters of the heat exchangers (plate heat exchangers are better than channel heat exchangers) and that the main risk is due to the lowest fuel temperature (freezing). Applications include the main temperatures (criticality temperature and wall temperatures) and hydraulic characteristics as functions of the core specific power, ranging from 50 to 600 MW/m^3.

In the frame of the EVOL, SAMOFAR and SAMOSAFER European projects and in collaboration with Framatome and now also CEA, pre-conceptual design activities are also carried out at CNRS/IN2P3 on the MSFR concept, based on the functions to be performed by the components with no precise drawings. Several simplified designs of the 3 GWth reference MSFR were proposed during the EVOL and SAMOFAR European projects in order to integrate qualitative and quantitative studies related to safety analysis. Safety analysis of the functional design of the fuel circuit was conducted, and the results were used to propose changes to eliminate or reduce the consequences of accidents for each design option. This continuous process is ongoing to achieve safety-by-design and its advancement depends on the sophistication of the available numerical modelling.

A set of passive or partly active decay heat removal devices has been selected and studied. Two emergency draining containers were proposed: An Emergency Draining System (relatively frequent draining events are expected because this design allows for reversible draining of the fuel salt), and a Core Catcher (not reversible, in case of failure of the Emergency Draining System). Both are passively cooled by gas through the second (core casing) and third (reactor casing) barriers. This cooling remains to be studied in more detail to assess its reliability because of the possibility of common cause failure.

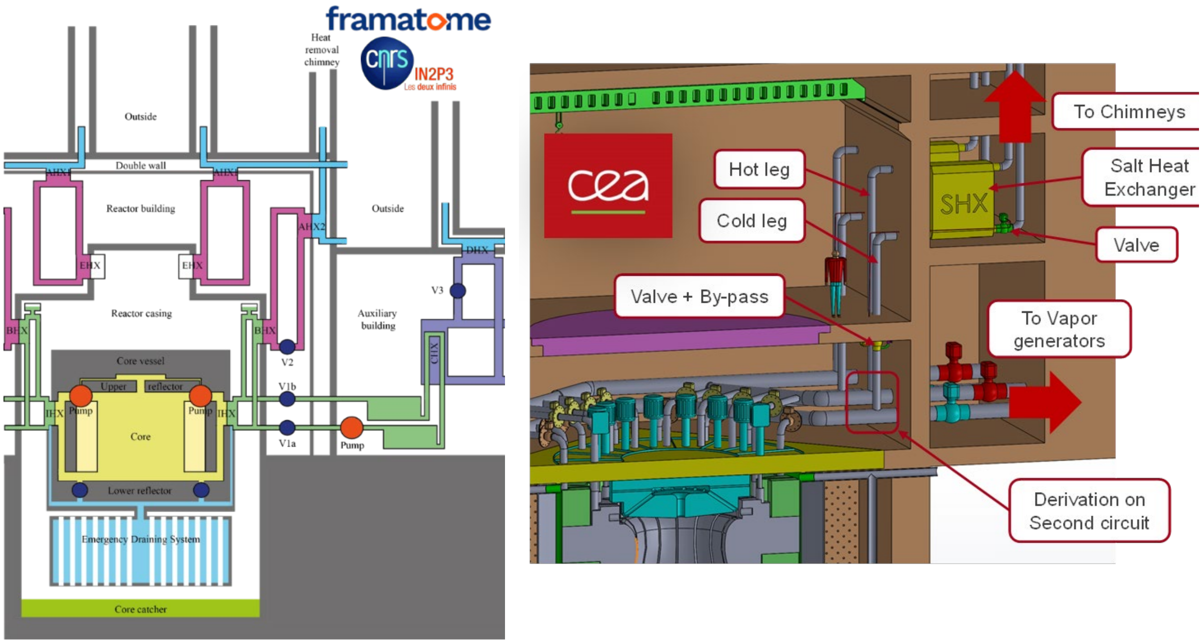

Figure 5. Arrangement of the decay heat extraction systems of the MSFR, principle scheme by CNRS and Framatome (left) and corresponding CAO drawings by CEA (right)

As perspective, we start working on the decay heat removal system arrangement proposed by LPSC in the SAMOSAFER project, also in collaboration with CEA for the corresponding plant drawings as shown in Figure 5. This is based on the SONGe code and with natural convection studies started in the master thesis of H. Pitois (2020).

2.2.7 Deployment scenario studies

Finally, the ISF (Innovative Scenarios for the Future) code has been developed at LPSC in parallel to the REM code to study nuclear deployment scenarios including molten salt reactors. ISF is a simulation program for the deployment of electro-nuclear energy developed in the DALI environment in the context of the study of molten salt reactors. The DALI code development environment is a toolbox in C language developed by Daniel Heuer for more than 20 years. These tools are grouped in the form of DALI modules, one of which is the ISF code and another one is the REM (neutronic evolving under constraints) code. A scenario is defined by its start and end dates, a monitoring step for the evolution of the reactor fleet (generally taken as one year), a list of reactor types classified by decreasing order of priority at start-up with their enrichment and/or reprocessing units, reserves or stocks of certain materials shared by the reactors that can be modified by these units, and energy objectives by monitoring step. A type of reactor is defined by a name, a power, an initial commissioning date for the concerned reactor, a load factor, a lifetime, and the materials consumed and produced. These consumed and produced materials are put in the form of objects called evomats designed to follow the evolution of a given material (each one characterized by a name, for example "Pu produced in PWR", an isotopic vector, its type of evolution which can be linear or exponential or entered via a file in absolute or relative date of the reactor, and a delay on the availability of the material for example due to a cooling or reprocessing time). Examples of applications of the ISF code are available in references [8,30].

An internship student (L. Clot) has worked in Spring and Summer 2021 with the ISF code to do preliminary comparisons between the deployment capacities of fluoride versus chloride molten salt reactors. The perspectives are to use this code ISF in the frame of the ISAC French project (accepted in January 2022) and in the Mimosa European project if funded (answer in February 2022) by including also burner versions of molten salt reactors to study the fuel cycle closure with MSRs. This work will be done with partners both in a national frame (among which Orano with a new collaborative PhD thesis starting in Fall 2022) and CEA, and in a European frame in a dedicated work-package led by Nuclear21.

3. Project and perspectives

Given the interest aroused by MSR in the world, the needs of nuclear energy and the possible collaborations, new studies are underway as mentioned above around other applications and versions of the reference "MSFR" studied for about fifteen years as a high power reactor and regenerator in the Thorium fuel cycle: notably as a low power Small Modular Reactor (SMR), using one of the two fuel cycles $^{238}U/Pu$ or $Th/^{233}U$, for power generation, or transuranics for nuclear waste incineration.

The results of our previous studies based on various disciplines such as reactor physics, chemistry, nuclear data, material and engineering sciences, safety and risk analysis, motivate the deepening of this research in progress and in the years to come, in order to prove the feasibility of such a reactor. Since 2017, new collaborations have been set up both nationally (CEA, Framatome and ORANO) and internationally (Canada, Turkey...). This has led to several PhD theses co-funded between CNRS/IN2P3/LPSC and Orano (beginning in November 2019), CEA (two theses starting in October 2019 and December 2020) and Framatome (beginning in November 2021), see more details on these PhD theses also in section 6.

Our academic approach is complementary to the R&D approach of the industry or the semi-industrial one of CEA, starting from the knowledge of the elementary phenomena in physics and chemistry, from an analysis of the evaluated databases and the new needs, based on systematic studies of the various observables related to these phenomena, and carried by traditional approaches of the fundamental research (Monte-Carlo simulation codes, Green functions, genetic algorithms, correlated samplings, analytical resolution...).

Details on the current and future research activities at IN2P3 are given in sub-section 3.2, after a short reminder of the MSR concepts studied and of the simulation tools available at IN2P3 (section 3.1).

3.1 Overview of the MSR project and expertise of the associated IN2P3 teams

3.1.1 Overview of the codes developed/maintained at CNRS/IN2P3 for MSR modelling

As detailed in section 2, the following codes dedicated/adapted to the study and optimization of molten salt reactors are developed at CNRS/IN2P3:

- Coupled code neutronics chemistry REM for burn-up calculations (@D. Heuer, X. Doligez, A. Nuttin)
- ISF code for nuclear scenario studies with MSRs (@D. Heuer)
- 3D code coupling neutronics « Transient Fission Matrix » and CFD thermal-hydraulics (@A. Laureau)
- Power plant simulator: LiCore MSR core code (@A. Laureau) coupled to the ALICES platform of CORYS/Framatome
- Multicriteria system optimization code SONGe based on genetic algorithm (@D. Heuer)
- Cocodrilo and Coconust codes for nuclear data uncertainties propagation and assimilation respectively due to decay heat data and to neutron cross sections using a Monte Carlo approach (@ L. Giot and A. Laureau).

Some of these codes (REM, TFM-OpenFOAM, LiCore-ALICES) are quite unique in the world, simulating MSRs requiring usually codes more generic and can be applied on solid fuel reactors. Moreover, these codes have been validated since years by code-to-code comparisons and also on experimental data for the TFM code.

The TFM code is now also available and used at Framatome, CEA and EPFL, while the LiCore code is currently under development with the CORYS company in its whole power plant simulator version. CEA is also developing an equivalent of the REM code, with interactions with the LPSC/MSFR team, and an adaptation of the COSI scenario code of CEA is foreseen in the coming years to include MSRs in the frame of the ISAC project (see sub-section 3.2.2).

3.1.2 MSR concepts currently studied at CNRS/IN2P3

When selecting a liquid that can be used in a nuclear reactor to contain the fuel matter and to act as coolant, with the corresponding specifications (transparent to neutrons, solubility issues, thermal and hydraulic properties, high boiling and low melting temperature, no problematic radioisotope production…), only two solutions arise, both being molten salts: the fluoride salts (based on LiF) and the chloride salts (based on NaCl, our kitchen salt). This explains that liquid-fueled reactors are called molten salt reactors. Dedicated studies led at CNRS showed that the Thorium fuel cycle is more compatible with a fluoride salt, while using plutonium and minor actinides as fuel leads to a chloride salt mainly due to solubility issues. This explains why the main studies performed at CNRS/IN2P3 and focused on the Thorium fuel cycle were on fluoride reactors (as the 'reference MSFR'), and the new developments to design reactors able to burn nuclear wastes are now more oriented on chloride reactors. We are thus working today on the following MSR concepts:

- The « reference MSFR » concept (breeder in Th/^{233}U cycle with fluoride salt, fast neutron spectrum, large power of 3 thermal GW equivalent to an EPR to identify all the viable configurations regarding physics and chemical considerations): studied and optimized for 15 years at CNRS/IN2P3 and in the EVOL, SAMOFAR, SAMOSAFER European projects, also selected by GIF and IAEA. It has a toroidal core of around 2.3mx2.3m with 18m^3 of fuel salt.

- A new MSFR concept equivalent to the reference MSFR in terms of power (3 GWth), neutron spectrum (fast) and objective (breeder reactor producing electricity), but studied in the U/Pu fuel cycle and so with a chloride NaCl salt): optimization studies done in the frame of the SAMOSAFER project through the PhD thesis of Hugo Pitois (funded by Samosafer)
- An alternative MSR version considered this time as convertor/burner to use plutonium and current nuclear wastes (minor actinides) as fuel, based on a chloride salt NaCl+MgCl2 and designed to be placed in a glove box thus with a reduced size (Small Modular Reactor): these studies, initially launched by an expertise contract asked by Orano in 2019, are led in the PhD thesis of Laura Mesthiviers in a CNRS-LPSC/Orano collaboration.

3.2 Perspectives and future projects and collaborations

Concerning the prospects of these IN2P3 research activities and as already mentioned, the objective is to capitalize on the expertise, knowledge and codes available at IN2P3 and to move towards concrete achievements. A part of the future work will be a continuation of the present projects as detailed in sub-section 3.2.1. This concerns both the reference MSFR concept developed since more than 10 years (see SAMOSAFER project), and other studies started since 2019 on alternative versions of the MSFR based on a chloride salt and designed as breeders in the U/Pu fuel cycle or as actinide burners (see collaboration with Orano). The second part of the future project, presented in sub-section 3.2.2, relies on new topics and new collaborations related to the ISAC national project and the Mimosa European project, and to the NAAREA start-up. Some of these alternative versions are small modular reactors (SMRs). All these versions (the reference and alternative ones) are characterized by an integrated design for the fuel circuit. These activities are done in the frame of national collaborations between academic (CNRS, Grenoble Institute of Technology, IMT Atlantique) and industrial (Framatome, Orano, CORYS, EDF) partners, together with CEA and IRSN.

3.2.1 Continuation of the present projects

SAMOSAFER project

The contributions of CNRS/IN2P3 in the SAMOSAFER project continue in the five following subjects:

- The neutronic benchmark, led by IN2P3/Subatech and already described in sub-section 2.2.1. The work to be done corresponds to the last steps of the defined benchmark, up to the final calculation of the source term for the reference MSFR concept. Then a neutronic benchmark will be done also on a chloride version of the MSFR under definition and optimization in the PhD thesis of Hugo Pitois (see next item).
- The optimization of a chloride version of the MSFR based on the U/Pu fuel cycle (see sub-section 3.1.2), part of the PhD thesis of Hugo Pitois (PhD funded by SAMOSAFER). This alternative version of the MSFR will also be used in a task led by IN2P3 aiming at defining the scope of applicability of the results, methods, codes and analyses of safety developed for the reference MSFR during the SAMOSAFER project, to check what is technology neutral or not.
- Another contribution of IN2P3 in SAMOSAFER is to evaluate the impact of turbulent in-core temperature fluctuations on the fission power distribution during normal operation. For

this, the TFM-OpenFOAM code has to be completed with a more precise LES thermalhydraulics modelling (see end of sub-section 2.2.3). We also collaborate with CEA on this topic, for the development of their simulation coupled code (PhD thesis of François Martin).

- We are also working with Framatome, EDF and Italian partners to define the MSFR normal operational domain. IN2P3 already submitted in June 2021 a milestone on the identification of the operational states of the reactor, the work is now led by Framatome on the normal operating modes for the reactor and the main plant parameters.
- Finally, as already mentioned, we are working with CEA (in charge of the CAO) on precise drawings of the MSFR power plant (see sub-section 2.2.6), and on study of accidental transients through the PhD thesis of Thibault Le Meute (see sub-section 3.1.1).

Nuclear data for decay heat evaluation and cross section uncertainty management

The research activities on the data for the residual power calculations and the associated uncertainties propagation, essential as explained in sub-section 2.2.2 for the safety evaluation of MSR concepts and to define the safety margins of such reactors, will continue through the PhD thesis of Yohannes Molla (started in October 2021 at Subatech and funded by IMT Atlantique and Nantes University) with the development by L. Giot of the Cocodrilo code associated to the Coconuts code developed by A. Laureau for quantifying the uncertainties of nuclear data for the MSFR concept.

Collaboration with Orano

A study, under an expertise contract with ORANO on the topic of plutonium incineration in MSR, led to the establishment of the PhD thesis of Laura Mesthiviers on this topic between ORANO and the LPSC starting in November 2019. A new PhD thesis is foreseen for Fall 2022 in the continuation of Laura's thesis, also including new developments and studies on deployment and burning scenarios in the frame of the ISAC French project and of the MIMOSA European project (see sub-section 3.2.2).

We are also working, under request of Orano through an expertise contract, on an evaluation for Orano of the thermal MSR concept developed by the Thorizon start-up in the Netherlands.

MSR power plant simulator - collaboration with CORYS

As detailed in sub-section 2.2.4, the collaboration started four years ago, on the development of an MSFR power plant simulator, with the company CORYS (European leader in nuclear reactor simulators) continues. A first version is available since July 2019 and was presented during the final meeting of the SAMOFAR project. The developments continue through master theses co-funded and co-supervised at LPSC and CORYS each year.

Collaboration with CEA

A collaboration on the MSFR has been set up with the CEA in 2019. The PhD thesis of Thibault Le Meute began in October 2019, in collaboration and co-funded by CNRS/LPSC (own resources, overheads of the SAMOSAFER project) and the Service d'Etudes des Systèmes Innovants (SESI) of CEA Cadarache, on the study of MSFR behavior in severe accident situations.

This collaboration with CEA will continue in the frame of the PhD thesis of François Martin (started in December 2020 at CEA Saclay, funded by CEA and co-supervised by CNRS and CEA) on the development of CEA modelling codes for the MSFR and with the PhD thesis of Martin Mascaron (started in October 2021 at CEA Cadarache/SESI, funded by CEA and co-supervised by CEA and CNRS), dealing with a multi-criteria analysis of the control margins of a molten salt reactor.

Finally, as presented at the end of sub-section 2.2.5, we are also currently working on the MSR PIRT safety project of the NEEDS interdisciplinary program led by CNRS/IN2P3 and by CEA/DES (Direction des Energies).

3.2.2 New projects and collaborations

Thanks to the knowledge acquired during 20 years (see section 2) and in the projects in the continuity detailed in the previous sub-section, we have a broad view of the various types of MSR that can be imagined, and solid simulation tools to study them. We thus aim now at moving toward more practical achievements to see if and which MSRs may be build and operated and how. This is the objectives of our new projects and collaborations presented below in the present sub-section.

Collaboration with Framatome: The Small-MSFR (S-MSFR) concept

Following the memorandum of understanding (MoU) signed between IN2P3 and Framatome in October 2020 (on request from Framatome) and thanks to the links forged within the SAMOFAR and SAMOSAFER projects, a new collaboration started with the PhD thesis Framatome-Lyon/CNRS-LPSC of Thomas Sornay (started in 11/2021), dedicated to design and safety studies of a Small-MSFR (S-MSFR) in the U/Pu fuel cycle and with a chloride salt. The objective of this project is to define the simplifications of the MSFR concept gained by a reduced size (SMR) and allowed by safety, and to identify the steps to industrialization.

French ISAC project

We are involved in the new ISAC (Innovative System for Actinides Conversion) national project, submitted in November 2021 for funding to the French post-covid recovery plan and accepted by BPI in January 2022 for 4 years. The objective of ISAC is to check the feasibility of waste transmutation in fast chloride molten salt reactors, involving CEA (leader), CNRS, ORANO, EDF and Framatome. The project is centered on the CEA ARAMIS (Advanced Reactor for Actinide Management In Salt) concept of molten salt reactor, a small modular reactor that will be designed during ISAC to burn minor actinides.

IN2P3 is in charge of the ‘Operation and Safety’ workpackage and of the tasks ‘Nuclear data’ and ‘Normal operation and control’, we are also involved in the scenario workpackage.

1.5 PhD theses will be funded for IN2P3 in these topics: half a PhD thesis in collaboration with Orano (as mentioned in sub-section 3.2.1), and one PhD thesis in co-supervision and colocation between the Subatech Nantes and the LPSC Grenoble laboratories dedicated to neutronics calculations of the ARAMIS core (core and cycle performance, nuclear data sensitivity, decay heat) and safety studies (core behavior in accidental situations, and contribution to the risk analysis in collaboration with EDF and Framatome).

Just to mention that, in the frame of the ISAC project, CNRS is also involved in experimental facilities (see FEST report/presentation) and in chemistry (through IN2P3 and INC).

European MIMOSA project

We are partners of the new MIMOSA (MultI-recycling with MOlten SAlt technology) European project submitted of the last Euratom call of the H2020 program in October 2021. An answer will be given by the end of February 2022. MIMOSA, led by Orano, aims to develop an accessible and optimized multi-recycling strategy of spent nuclear fuel from LWR in the EU, which is based primarily on multi-recycling of Pu in PWRs, combined with one of the most promising advanced nuclear energy systems, i.e. the chloride MSR. Within the panorama of multi-recycling options, chloride MSRs are probably the less mature and less studied advanced technology, while one of the most promising and worthwhile to be analyzed. This is the reason why MIMOSA has chosen to focus more specifically on the demonstration of several key aspects of technical feasibility and performance, that would contribute to accelerate the deployment of this advanced technology, respectively on Pu and minor actinides conversion and on production of valuable isotopes for other applications. The goal is to bring this MSR concept from Technology readiness levels (TRLs) 1-2 to TRL3-4. The MSR concepts considered in the MIMOSA project will be MSR concepts developed at IN2P3 and the Thorizon MSR concept (see sub-section 3.2.1).

LPSC and Subatech laboratories are involved in two work-packages: "Multi-recycling scenarios analysis" and "1.2.4 Chloride molten salt composition evolution in reactor to support fuel cycle calculations and safety evaluation", with a small contribution to the "Dissemination, Exploitation, Communication, Training" workpackage. One can notice that on the chemistry side, IN2P3 is also leader of the workpackage "Production and recovery of valuable isotopes" (not evaluated here). A part of the PhD thesis in collaboration between Orano and CNRS, mentioned in sub-section 3.1.1, will take place in the MIMOSA project on scenario studies.

XSMR micro-reactor and collaboration with the Naarea start-up

The NAAREA start-up is developing the XSMR (eXtra Small Modular Reactor) for large-scale production of micro-generators of electrical energy from 1 MW to 40 MW. This reactor will minimize the natural resources by using fuel from nuclear and mining waste reserves (waste-to-energy concept). IN2P3/LPSC has performed some pre-conceptual evaluation of the XSMR concept through an expertise contract in 2021, leading to more collaborations between Naarea and IN2P3 on reactor physics, safety, modelling and chemistry. A framework contract between CNRS and Naarea is being prepared currently, to be signed in 2022. The goal is to participate to the development of the XSMR whose prototype is foreseen by less than 10 years and which may be supported by the French government in the frame of the "France 2030" investment plan.

4. Genesis and timeline

4.1 Genesis of the MSR project

The LPSC research team in reactor physics (separated in 2017 in the MSFR research team) starts working on molten salt reactors since more than 20 years, joined by the Subatech team since around three years.

4.1.1 National level

Concerning our national collaborations, their timeline is summarized in figure 6 (upper part), while the bottom part of the figure displays the European collaborations.

From 2009 to 2019, the public research on MSFR in France was mainly conducted by CNRS and French universities, with the participation of the Institute for Radiological Protection and Nuclear Safety (Institut de Radioprotection et de Sûreté Nucléaire (IRSN)) and industrial partners (CORYS, EdF, Framatome, Orano), and recently of CEA. It was supported by French research programs (PACEN, NEEDS, MSFR Master Project of CNRS/IN2P3) and European programs (EVOL (Evacuation and Viability of Molten Salt Rectors), SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor), and SAMOSAFER (Severe Accident Modelling and Safety Assessment for Fluid-fuel Energy Reactors)).

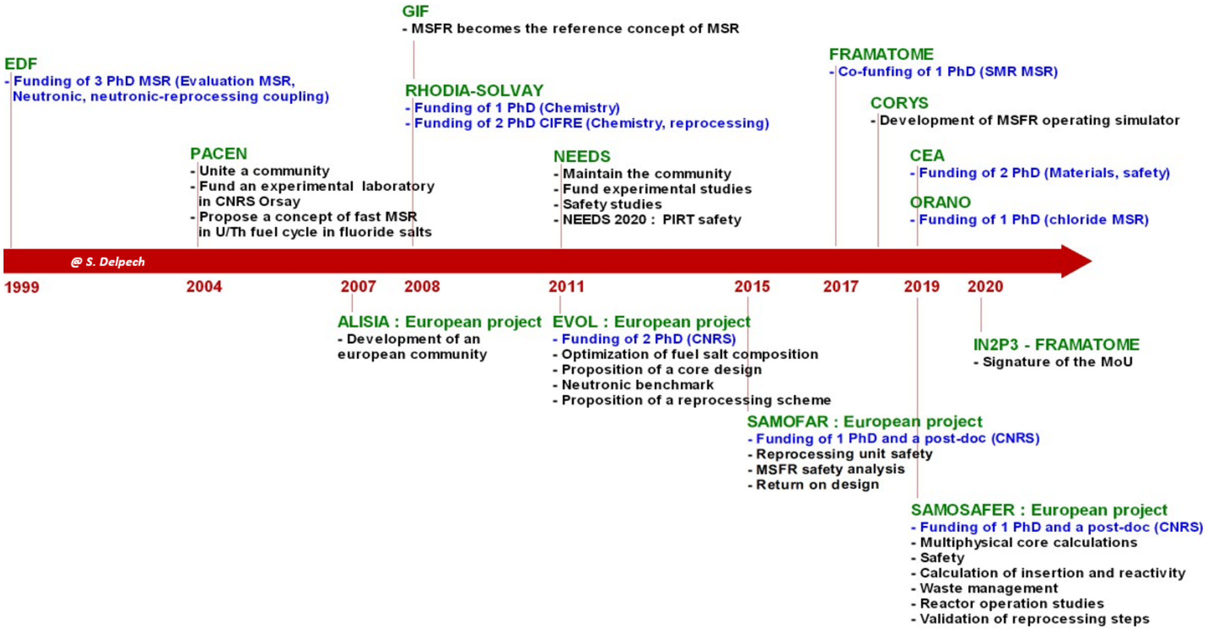

Figure 6: MSR national and European research frame and timeline

The CNRS budget allocated to MSR researches was substantial (around 1M€/year) during the PACEN program with a dedicated CNRS Concerted Research Program (PCR / programme concerté de recherche) named PCR-RSF. Nothing equivalent exists since then.

A "French MSR project" led by IN2P3 researchers and gathering the French MSR partners (initially CNRS, Framatome, IRSN and EDF, plus CEA since 2018) has been funded at the beginning of the NEEDS interdisciplinary program with a budget envelop of around 20-30 k€ up to 2019. The exploratory project "safety PIRT MSR" described at the end of section 2.2.5, with the same previous partners plus Orano, has been funded (15k€) in 2020 and 2021 with a delay due to the sanitary crisis (the funding being fully focused on travels and technical meetings organization). No call for new exploratory projects has been launched for 2022 in the NEEDS program and MSR has not been selected as NEEDS structural project (which was the objective of the initial exploratory project).

The MSR researches also participate to the Scinée research group (GDR Scinée) where we have been invited to present our work for fruitful discussions and which offers an interesting frame for our students (PhD and master theses) to have a broad view of the CNRS research activities in nuclear energy.

Our regular partnership with the major national industries in nuclear energy has been detailed in sections 2 and 3 (see also the list of PhD theses in our teams summarized in section 6.2, that reflects theses collaborations).

4.1.2 European level

The successive European projects on MSR are illustrated in Figure 7, while the IN2P3 participations to these projects are summarized at the bottom of Figure 6. The responsibilities of IN2P3 researchers in these projects are listed in sub-section 5.2.2.

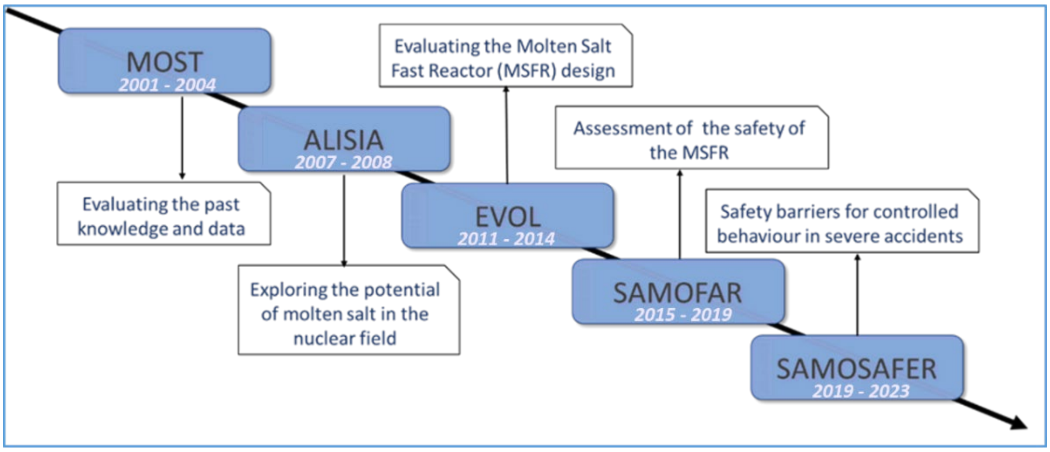

Figure 7: Time evolution of EU-projects on molten salt reactors

In the frame of the Euratom Research and Training program, a series of projects on MSR technology have thus been supported since 2004, as shown in Figure 7. These projects showed an evolution from research on the ORNL concepts (MOST project, FP6, 2001-2004), to a broader review of molten salt applications in nuclear technology, to a focus on the Molten Salt Fast Reactor (MSFR) design by the CNRS. Research within these projects is being carried out in various countries of the European Union (EU) in the framework of national research programs combined with European Framework R&D programs.

After completion of the MOST project, the ALISIA (Assessment of LIquid Salts for Innovative Applications) project was funded for one year (FP7, 2007-2008) and was dedicated to exploring the potential of MSR in the nuclear field. Furthermore, it aimed at the selection of the fuel salt and design choices for a European MSR.

The EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor System) project led by CNRS/IN2P3 (leader S. Delpech, FP7, 2011-2014) and focused on the integral evaluation of the MSFR design (which at that time utilized both core fuel and blanket salt that were rich in thorium to breed fissile uranium), including reactor and clean-up facility, and led to a build-up of necessary computational tools in Europe. It was performed in close collaboration with the sister Russian project MARS, which was sponsored by ROSATOM, in the frame of the EU-Russia collaboration in the field of nuclear energy.

In the SAMOFAR (Safety Assessment of the Molten Salt Fast Reactor) project (H2020, 2015-2019), the key safety features of the MSFR were analyzed in depth, based on substantial improvement of computational tools, particularly in the field of multi-physics analysis, and experimental studies.

The latest project of the European Community is SAMOSAFER (Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors), which is a logical follow up of the previous R&D projects funded by the EU. The SAMOSAFER project started in 2019 (project of 4 years ending in 2023) in the H2020 program, and is built upon the experience and knowledge from the previous projects with the aim to ensure that MSR technology (not only limited to the MSFR concept studied in the EU in the past) can fully comply with the more stringent safety requirements expected in the next 30 years. The chemistry and physics needed to increase the safety of the MSFR, and of an MSR in general, are also being modelled in SAMOSAFER.

Finally, we participated to the « SNETP/ESNII Workshop on MSR » in October 201 in tandem with the CEA for the presentation on “Molten Salt Reactor Research for Europe”. The objective of this workshop, that included industrial and academic presentations in Europe, was a demand to add Molten Salt Reactors as systems of the European Sustainable Nuclear Industrial Initiative (ESNII), the SNETP (Sustainable Nuclear Energy Technology Platform, R&D&I platform recognized by the European Commission) pillar for Generation 4 reactors.

4.2 Scientific production

The details of the scientific production on the MSR topic at IN2P3 are given in section 9 at the end of the document, corresponding to a total of 76 publications (29 peer-review articles and 47 proceedings), 6 book chapters, 21 deliverables and milestones of European projects and 3 other publications. We are regularly invited to give presentations, lectures and webinars in national and international frames, both for experts or general public (see details in section 9.1), and also in institutional auditions (OPECST, science academy, academy of technologies…).

5. State of the art and research frames

5.1 MSR research frame

Molten salt reactors (MSRs) are one of the six candidates selected by the Generation IV International Forum (GIF) as promising concepts for future nuclear reactors. In addition to the three initial partners (Euratom, France and the USA), three new countries (Russia, Switzerland and China) have announced that they will work on this type of reactors and have joined the MSR steering committee of this forum for the past years. As detailed in the previous sections, France, through the CNRS and more precisely the IN2P3, is interested in MSRs initially coupled to the Thorium fuel cycle since more than 15 years and also studied since 2019 MSRs based on the other existing fuel cycle (U/Pu cycle). The MSFR (molten salt fast reactor) concept is known as the "CNRS reactor" (see IAEA ARIS database https://aris.iaea.org/sites/MSR.html or GIF annual reports) and supported by the CNRS at the national, European and international (Generation 4 international forum, International Atomic Energy Agency) levels.

The table below gives an overview (maybe no more up to date since things are evolving very quickly presently) of the various and increasing research and R&D activities on MSR around the world.

	CA	CH	CN	FR	IN	EU	RU	TR	UK	US
Programs	-	-	X	?	-	X	?	?	-	X
Teams	X	X	-	X	X	-	X	-	-	-
Start-ups	X	-	-	X	-	-	-	-	X	X

China is building in the Gobi Desert a demonstrator of thermal MSR (a copy of the historical American Molten Salt Reactor Experiment initially operated in the 1970’s), and the preconception stage of a project of fast MSR, the Molten Chloride Salt Reactor, has been funded by the American DOE under the supervision of TerraPower. Orano is part of this American project through their knowledge in teleoperation. Several SMR concepts including MSRs are studied in Canada to produce heat and electricity in isolated places but no demonstrator has yet been chosen. The French NAAREA start-up (https://www.naarea.fr/) announced during the last World Nuclear Exhibition in December 2021 its objective to launch a molten salt micro-reactor (XSMR) with a first prototype in the coming years, aiming both at producing energy and burning wastes (see sub-section 3.2.2).

5.2 CNRS/IN2P3 place and responsibilities on MSR

As already written, the public research on molten salt reactors in France was mainly conducted by CNRS and French universities from 2009 to 2019, with the participation of the Institute for Radiological Protection and Nuclear Safety (Institut de Radioprotection et de Sûreté Nucléaire (IRSN)) and industrial partners (CORYS, EdF, Framatome, Orano), and recently of CEA. CNRS still has a major role of French scientific expert on this subject and is thus regularly solicited for example by IRSN, Orano, IAEA and more recently the NAAREA start-up and the academy of science. Also, many start-ups working on MSR came one day at CNRS/IN2P3 in Grenoble since more than 10 years to present their concept and have a free feedback on it.

5.2.1 National level

At the national level, an IN2P3 researcher is currently co-leading with a colleague from CEA (Paul Gauthé) since 2020 the Safety-MSFR project of the NEEDS interdisciplinary program carried by CNRS. We are also in charge of the 'Operation and Safety' workpackage of the new ISAC project starting in 2022 and led by CEA.

CNRS has co-organized with CEA in October 2021 during one week the first national MSR bootcamp gathering around 80 experts from the French nuclear field (see https://www.youtube.com/watch?v=8DNzzGAeWLU).

We are regularly asked by CEA and EDF to supervise PhD students not only on MSR but more largely in reactor physics (around 30 PhD thesis supervisions) and to participate to PhD and HDR committees (around 50 PhD committees without counting our PhD students and 10 HDR committees). We also do regular expertise of ANR, IDEX, Swiss National Science Foundation projects… An MSR IN2P3 researcher is also member of the programmatic group 3 "Nuclear Energies" of the national alliance ANCRE (Alliance Nationale de Coordination pour la Recherche sur l'Energie).

Finally, an IN2P3 researcher of the MSR project has been appointed member of the Scientific Council of IRSN (Institut de Radioprotection et de Sûreté Nucléaire) in 2021 (interministerial order of May 25, 2021, published in the Journal Officiel of May 30, 2021 - TREP2110051A).

5.2.2 European level

SAMOSAFER project "Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors" (2019-2023): Leader of task 3.1 'Source term distribution' (L. Giot) + in charge of the workpackage 6 'Reactor Operation and Safety Demonstration' (E. Merle)

SAMOFAR project “Safety Assessment of Molten Salt Fast Reactor” (2014-2019): in charge of workpackage 1 ‘Integral safety approach and system integration’ (E. Merle)

EVOL project “Evaluation and Viability of Liquid Fuel Fast Reactor” (2009-2013): project led by CNRS/IN2P3 (S. Delpech) + in charge of workpackage 2 “'Pre-conceptual Design and Safety” (E. Merle).

One has to notice that these three European projects are centered on the MSFR concept developed by CNRS/IN2P3.

5.2.3 International level

At the international level, we have been participating for 14 years in the international forum GEN4 within the MSR steering committee of this forum. The MSFR concept has been officially selected since 2008 by the GIF policy group. One of the objectives of this forum is first to establish the research program on the molten salt reactor concept for the next 10 to 15 years. The axes to be studied are the same as in the European network projects. Finally, we have also been in charge of the links between the MSR steering committee and the GIF's Risk and Safety Working Group (RSWG) and Proliferation Working Group (PR&PP).

Since 2019, one IN2P3 researcher is expert in the Technical Review Group for the International Assay Data of Spent Nuclear Fuel Database at the Nuclear Energy Agency (NEA).

We have been invited by the Canadian safety authority expert (Canadian National Laboratories, CNL) to be part of a panel of international experts who conducted in 2019 a PIRT (Phenomena Identification and Ranking Table) safety analysis on molten salt reactor projects.

Finally, we are regularly solicited by the International Atomic Energy Agency (IAEA) since 2016. We have been invited to participate as MSR experts and French representatives in the Technical Meeting on the Status of Molten Salt Reactors organized by the IAEA in 2016, 2019 and 2020 and to be contributors to the drafting of the IAEA Technical Research Series "IAEA Technical Reports Series on the Status of Molten Salt Reactor Technology" (see preprint https://preprint.iaea.org/search.aspx?orig_q=RN:52090830 released in November 2021), in charge of coordinating the chapter on French activities (2016-2021). We have also been invited to participate as MSR experts to an IAEA Small Modular Reactors symposium at the end of October 2018, and in August 2020 to give an invited webinar in pair with an American colleague in the "Webinar Series on Nuclear Technology Breakthroughs for the 21st Century" on "Molten Salt Reactors: A Game Changer in the Nuclear Industry". In December 2020 the IAEA invited two IN2P3 researchers to be part of a panel of experts to work on the issue of the safety approach of innovative modular reactors (Gen4 SMR concepts) via consultancy meetings that took place from January to June 2021, the final document of this work being under review before publication by the end of 2021.

6. Resources and means and PhD theses

6.1 Resources

Concerning the human resources, two IN2P3 laboratories are involved: the LPSC / MSFR team and the Subatech Nantes / SEN team with four permanent researchers and one volunteer: Lydie Giot (associate professor at IMT Atlantique, 25%), Daniel Heuer (CNRS research director, emeritus since January 2022, 100%), Axel Laureau (CNRS CRCN, 66% in 2022), Elsa Merle (professor at Grenoble INP, 50%) and Michel Allibert (retired CNRS research director and volunteer).

We have currently 5 PhD students working in the thematic in our IN2P3 laboratories (see details in the next sub-section): Laura Mesthiviers (100% on the MSR thematic), Thibault Le Meute (100%), Hugo Pitois (100%), Yohannes Molla (50%) and Thomas Sornay (100%).

Concerning the financial resources, please find below the details for the 2 laboratories. One has to note that, since the disappearance some years ago of the interdisciplinary Master Projects (except for the master projects related to a European project but with no IN2P3 funding), the fundings allocated by IN2P3 to the interdisciplinary teams are calculated per researchers with rules varying each year. It was initially 3 k€ per permanent researcher and 1.5 k€ per teacher-researcher with no possibility to ask one year a different amount to support a given project. This is complicated for small research teams and/or for teams with PhD students (not counted in the endowment) and/or teams with important experimental activities.

Resources at LPSC: IN2P3 endowment of 4 to 5 k€/year (reduced by half in 2022 due the new emeritus status of D. Heuer no more counted as permanent researcher by IN2P3) + 1 master2 internship/year funded by LPSC + 1 conference per PhD student funded by LPSC + zero IN2P3 PhD thesis funding granted to the thematic since X. Doligez (2007-2010). See details on the PhD thesis fundings in the newt sub-section below. We had the funding of around one national MSR workshop per year by the NEEDS program up to 2020 (no funding foreseen for 2022 since no MSR thematic program has been accepted). The MSFR team of LPSC has some own resources thanks to the overheads of European programs (EVOL, SAMOFAR, SAMOSAFER) and some industrial contracts (expertise for IRSN in 2013, for Orano in 2019 and 2021, for Naarea in 2021).

Resources at Subatech: IN2P3 endowment of 1 to 1.5 k€/year while the MSFR Master Project was existing, nothing since its cancellation (SEN IN2P3 endowment for nuclear data activities). Current PhD thesis of Y. Molla (50% on MSR and 50% on nuclear data) funded by IMT Atlantique and Nantes University. The development of the Cocodrilo code has been paid through internship fundings from the SAMOSAFER and the NEEDS/SUDEC projects.

The expenses for these two teams are: PhD thesis grants (~65 k€ of half salary per thesis in collaboration/co-funding with a partner) + internship fundings (around 2 to 4 internships per year with a cost of 6k€ of salary/internship) + purchase of computing servers (16 k€/server) + conferences and workshops + travels to attend the various GIF and IAEA meetings (we are invited as experts but there is no funding at GIF as well as in IAEA, and no funding for this at CNRS/IN2P3) + travels to set up new collaborations.

6.2 PhD theses of the thematic at IN2P3/CNRS

- ***Sylvain DAVID*** : 'Capacités des réacteurs hybrides au plomb pour la production d'énergie et l'incinération avec multirecyclage des combustibles : évolution des paramètres physiques : radiotoxicités induites', encadrement D. Heuer, soutenance 1999 – Chercheur IN2P3 depuis 1999
- ***Alexis NUTTIN*** : 'Potentialités du concept de réacteur à sels fondus pour une production durable d'énergie nucléaire basée sur le cycle thorium en spectre épithermique', encadrement D. Heuer, soutenance 2002 – Financement ½ bourse IN2P3 et ½ bourse EDF – Postdoc à l'IPN Orsay puis maître de conférences à Grenoble INP / IN2P3-LPSC depuis 2003

- ***Ludovic MATHIEU*** : 'Cycle thorium et réacteurs à sel fondu : exploration du champ des paramètres et des contraintes définissant le Thorium Molten Salt Reactor', encadrement D. Heuer, soutenance 2005 – Financement ½ bourse IN2P3 et ½ bourse EDF – Postdoc puis chercheur CRCN CNRS/IN2P3
- ***Marie-Anne COGNET-CHEVALLIER*** : 'Mesure du rapport alpha de la section efficace moyenne de capture de l'Uranium 233 sur celle de fission, sur la plate-forme PEREN' (LPSC Grenoble), encadrement E. Merle et D. Heuer, soutenance le 20 décembre 2007 – Financement bourse ministère – Postdoc IRSN Cadarache sur l'installation Amande (2008-2009) puis CDI ingénieur-chercheur depuis 2009 à l'Institut de Radioprotection et de Sûreté Nucléaire en métrologie neutrons
- ***Xavier DOLIGEZ*** : 'Couplage de la neutronique et de l'unité de retraitement chimique du Thorium Molten Salt Reactor' (LPSC Grenoble), encadrement D. Heuer et E. Merle, soutenance le 15 octobre 2010 – Financement ½ bourse IN2P3 et ½ bourse EDF – Post-doc à l'IPN Orsay puis au SCK-CEN puis chercheur CNRS/IN2P3 CR2 (CRCN) à Orsay depuis 2012
- ***Mariya BROVCHENKO*** : 'Analyse préliminaire de sûreté du concept de Molten Salt Fast Reactor' (LPSC Grenoble), encadrement E. Merle et D. Heuer, soutenance le 25 octobre 2013 – Financement bourse ministère – CDI ingénieur-chercheur à l'Institut de Radioprotection et de Sûreté Nucléaire / service Neutronique Criticité depuis 2013
- ***Axel LAUREAU*** : 'Modélisation multi-physique d'un réacteur à sels fondus en cycle Thorium et à spectre neutronique rapide' (LPSC Grenoble), encadrement D. Heuer, E. Merle et P. Rubiolo, soutenance le 16 octobre 2015 – – Financement bourse ministère – Post-doctorant au CEA Cadarache (Service de Physique des Réacteurs et du Cycle) de 2015 à 2017 puis à l'EPFL en Suisse, et depuis 2020 chercheur CRCN au CNRS/IN2P3
- ***Delphine GERARDIN*** : 'Développement d'outils numériques pour l'étude et l'optimisation du pilotage et de la sûreté du Molten Salt Fast Reactor' (LPSC Grenoble), encadrement E. Merle et D. Heuer, soutenance le 16 octobre 2018 – Financement projet européen SAMOFAR – CDI ingénieure chercheure chez EdF R&D à Saclay sur des études de sûreté des réacteurs sodium depuis 11/2018
- **Thibault LE MEUTE** : 'Modélisation d'un scénario d'insertion de réactivité dans un réacteur à sels fondus de génération IV', (LPSC Grenoble et CEA Cadarache, DEN/DER/SESI/Laboratoire d'Etudes de Sûreté et de Maitrise des Risques – localisé 2 ans à Cadarache puis 1 an à Grenoble), encadrement F. Bertrand (CEA) et E. Merle, début octobre 2019 – Financement 2/3 CEA et 1/3 sur ressources propres de l'équipe MSFR du LPSC (demande de ½ bourse de thèse IN2P3 non acceptée en 2019)
- **Laura MESTHIVIERS** : 'Étude de la capacité de conversion des actinides dans un Réacteur à Sels Fondus' (collaboration LPSC Grenoble et entreprise Orano, localisée à Grenoble), encadrement D. Heuer, E. Merle et G. Senentz (Orano), début novembre 2019 – Financement salaire Orano et encadrement LPSC
- **Nicolas REY-TORNERO** : 'Etude et conception d'un réacteur spatial à sels fondus' (thèse CEA Saclay/SERMA), encadrement D. Heuer et G. Campioni, début novembre 2019 – Financement CEA
- **Hugo PITOIS** : 'Simulation et sûreté du réacteur à sels fondus MSFR dans le cadre du projet européen SAMOSAFER', (LPSC Grenoble), encadrement à 40% avec Daniel HEUER et Axel LAUREAU, début octobre 2020 – Financement projet européen SAMOSAFER
- **François MARTIN** : 'Modélisation avancée neutronique-thermohydraulique pour les MSR (Réacteurs à Sels Fondus) de type RNR à combustible liquide' (thèse CEA Saclay, DEN/Service d'Etudes des Réacteurs et de Math Appliquées), encadrement G. Campioni (CEA) et E. Merle, début décembre 2020 – Financement CEA
- **Martin MASCARON** : 'Analyse multicritère des marges de pilotage d'un réacteur à sel fondu' (thèse CEA Cadarache, DES/Service d'Etudes des Systèmes Innovants), encadrement V. Pascal, E. Merle et F. Bertrand, début octobre 2021 – Financement CEA
- **Yohannes MOLLA** : 'Quantification des incertitudes pour la puissance résiduelle, impact des données nucléaires', encadrement L. Giot, début octobre 2021 – Financement IMT Atlantique et université de Nantes

- **Thomas SORNAY** : ‘Etude des effets de seuil en termes de sûreté/fonctionnement, de conception et de gestion de la matière d’un réacteur à sels fondus de type SMR en cycle du combustible U/Pu’, thèse en collaboration/colocalisation LPSC-CNRS/Framatome Lyon, encadrement A. Laureau, E. Merle, T. Boisseau (Framatome) et F. Vaiana (Framatome), début 01/11/2021 – Financement ½ Framatome et ½ sur ressources propres de l’équipe MSFR du LPSC (demande de ½ bourse de thèse IN2P3 non acceptée en 2021)

7. SWOT self-analysis

The strengths of the project are based on the simulation and experimental means and methodologies developed, validated and mastered for more than fifteen years, on the recognition of the expertise of its members in the field, on the role of steering and responsibilities, on solid collaborations already existing in the academic world but also in the French industry as well as at the European and international levels, and finally on an important and continuous activity of publications and communications.

In the strengths and opportunities of the MSR project also, our research activities are done in collaboration with an increasing number of French partners (Orano, CEA, Framatome, IRSN, EDF), which reflects a growing national interest for MSR technology during recent years in France and also in the world. In this new context of high interest for MSRs, the CNRS/IN2P3 expertise acquired over the last 20 years is very useful, recognized and much in demand. This is combined with the present possibility of moving towards concrete realization of such reactors up to a demonstrator in the coming years, CNRS/IN2P3 being of course involved (see new collaborations with NAAREA, Orano, Thorizon…). This means that the time for concretization has arrived and we are at the first place and ready and invited to participate.

The main weakness is the low number of researchers working on the project. One has to mention the retirement at the end of 2021 of one of the two permanent members (more precisely the only CNRS researcher) of the LPSC MSFR team which leads the theme at CNRS and which works on reactor physics, design and safety, with no prospect of replacement for the moment, while the requests and proposals for collaborations are growing.

Even if the thematic is really recognized by IN2P3 with also a strong support of the two concerned laboratories LPSC and Subatech, the practical support from IN2P3 is quite small in terms of budget but also of PhD funding (no positive answer from IN2P3 since 2010 even if the PhD subjects were all in collaboration with partners with a guaranteed co-funding and with excellent master/engineer candidates) and of researcher positions (no position opened for the replacement of the colleague retired end of 2021, without dreaming of an additional research position on the thematic). The choice to suppress all the interdisciplinary master projects, where it was possible to ask for funds and which gathered the researchers of a given research thematic (as for the MSFR master project), also reduces the visibility of the project and the IN2P3 support.

In the threats, one has to mention that our activities related to waste management issues are directly linked to French institutions as the Parliamentary Office for Scientific and Technological Assessment (OPECST) and the CNE2 (commission nationale d'évaluation des recherches et études relatives à la gestion des matières et déchets radioactifs) where CNRS has a representative. But no information is transmitted from these institutions to the ‘basic’ CNRS researchers via this representative, we have some information thanks to our French industrial partners. And if we are sometimes auditioned to present our work (see section 9.1), it is only through direct invitations to our teams and never through CNRS.

The context is of course difficult at CNRS financially and for human resources. But the main threat is that the MSR thematic seems today clearly not a priority of IN2P3, with a continuous decrease of the support to the topic while other countries and institutions increase there fundings on the topic at the same time. This is a pity because IN2P3 has really a defined and capital role on the subject, with the associated skills.

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9. Detailed scientific production

9.1 Scientific communications since 2013

• **Audition CEA/CNRS lors du « SNETP/ESNII Workshop on MSR »** sur "Molten Salt Reactor Research for Europe" (octobre 2021)

• **Audition invitée devant le comité de prospective en énergie de l'Académie des Sciences** sur les réacteurs à sels fondus (mars 2021)

• **Présentation invitée grand public scientifique** lors de la journée « Le nucléaire et ses innovations au service d'une reprise durable en Europe ? » des Entretiens Européens (11/2020)

• **Présentation invitée à l'AIEA** dans le cadre des "Webinar Series on Nuclear Technology Breakthroughs for the 21st Century" sur "Molten Salt Reactors: A Game Changer in the Nuclear Industry" - plus de 230 auditeurs (août 2020)

• **Audition publique invitée** "Les réacteurs de 4ème génération à combustible liquide " devant **l'Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques (OPECST**) dans le cadre de « NOUVELLES TENDANCES DE LA RECHERCHE SUR L'ÉNERGIE : I - L'AVENIR DU NUCLÉAIRE », Assemblée Nationale, Paris, mai 2018

• **Talk expert invité**, "Molten Salt Fast Reactor as SMR: activities and perspectives" dans l'International Workshop on Design and Technology Status of Innovative (non-water cooled) SMRs for Near Term Deployment, Agence Internationale de l'Energie Atomique (**IAEA**), Vienne, Autriche (novembre 2018)

• **Webinaire invité** sur "Molten Salt Reactors (MSR)" du forum Generation 4 dans le cadre des Webinar series, GIF Education and Training Task Force, **Forum International Generation4** (https://www.gen-4.org/gif/jcms/c_82831/webinars (may 2017)

• **Audition** "Contribution du CNRS : Les MSFR, Réacteurs rapides à sels fondus" **devant le Comité d'Orientation et de Suivi des recherches pour les SYstèmes Nucléaires (COSSYN)** dans le cadre du bilan des recherches conduites sur le développement de réacteurs nucléaires de nouvelle génération et perspectives, mai 2013

• **Audition** "Thorium en combustible liquide : le concept MSFR (Molten Salt Fast Reactor)" devant la **Commission Nationale d'Evaluation (CNE)** des recherches et études relatives à la gestion des matières et déchets radioactifs, février 2013

• Organisation d'un **atelier national annuel sur les réacteurs à sels fondus** (RSF) - Lieux : IRSN Fontenay (10/2015), Areva Lyon (02/2017), LPSC Grenoble (10/2018)

• **SAMOSAFER Midterm Review Meeting**: « Progress Status of WP6: Reactor operation, Reactor control and Safety demonstration », 19/11/2021

• **SAMOSAFER Summer School 2021** – 4 interventions : Sylvie Delpech basic lecture « MSR thermo-chemistry », Elsa Merle basic lecture « Introduction to MSFR design », Axel Laureau and Elsa Merle basic lecture « Introduction to MSR Operation & Control », Hugo Pitois and Stefano Lorenzi and Axel Laureau interactive lecture « Use of CNRS and Polimi power plant simulator », September to November 2021

• **Bootcamp MSR** (co-organisation CEA/CNRS), Avignon, octobre 2021, plus de 80 participants – 3 cours+ateliers : Sylvie Delpech et Laure Martinelli « Introduction à la corrosion dans les sels fondus », Frédéric Bertrand et Elsa Merle « Design et sûreté de RSF », Yannick Gorsse et Axel Laureau « Couplage neutronique - thermohydraulique »

• **Projet européen Unite!** : E. Merle, « Generation IV Fission Reactors », session Sustainable Nuclear, mai 2021

• **Membre du conseil scientifique de l'école internationale FJOH** (Frédéric Joliot / Otto Hahn Summer School) (depuis 2020)

• **Présentation invitée à l'International Workshop on Design and Technology Status of Innovative (non water cooled) SMRs for Near Term Deployment**, de l'Agence Internationale de l'Energie

Atomique (IAEA) : « Molten Salt Fast Reactor as SMR: activities and perspectives », Vienne, Autriche, novembre 2018

• **3 présentations invitées au Molten Salt Reactor Technology Determination Workshop**, TUBITAK, Marmara Research Center, Gebze, Turquie, décembre 2017

• **Cours invité à la MSR Summer School**: "Integral safety analysis of the MSFR", Lecco, Italy, July 2017

• **Présentation invitée lors des Journées Techniques SFEN** "Place et Evolution de l'Energie Nucléaire dans le Futur", Paris, France, novembre 2017

• **Audition invitée à la Direction de l'Environnement, du Climat, de la Santé et de l'Energie (DCESE)** de la Région Rhône-Alpes Auvergne, Lyon, décembre 2016

• **Présentation invitée lors des Journées Techniques SFEN** " Contrôle de la réactivité et absorbants neutroniques " : A. Laureau, « Le cas particulier des réacteurs à sels fondus », Paris, France, novembre 2016

• **Workshop international 'SERPENT Code and Multiphysics Simulation for Nuclear Reactors'**, Grenoble, France: co-organisation et 3 présentations IN2P3 ('The TFM Approach using SERPENT – Application to Flattop experiment', 'Presentation of the MSFR reactor concept', 'Serpent-OpenFOAM coupling for criticality accidents modelling')

• Présentations régulières du **bilan officiel des activités françaises** (CNRS, CEA) depuis 2008 sur les thématiques des réacteurs à sels fondus lors des réunions du **comité de pilotage 'Molten Salt Reactor' du forum international GEN-IV**

• **Participation à des émissions de radio**, par exemple 'Continent Sciences' de France Culture, l'une sur la radioactivité (avril 2011) et l'autre sur les réacteurs à sels fondus avec J.L. Basdevant (avril 2013)

• Membre de **Commissions Locales d'Information (CLI)** dans la Drôme

• Nombreuses **conférences grand public** : D. Heuer (Club Mines Paris, Seyssins, Université de Normandie, Assosciences Midi-Pyrénées, Initiative des Étudiants pour l´Échange et la Solidarité, Rencontres Innovations et Sciences des Étudiants de l'ENSTA ParisTech, école ECOCLIM2018, Grenoble Europe Énergie…)

9.2 Editorial responsibilities

• Editeur invitée pour le numéro spécial « Molten Salt Reactors » d'European Physic Journal-N (10/2018-03/2019)

• Editeur associée du European Physical Journal – Nuclear Sciences & Technologies (EPJ-N) en 'Nuclear Reactor Physics', membre de l'éditorial board (depuis 2015)

• Editeur invitée pour le numéro spécial « Molten Salt Reactors » d'Annals of Nuclear Energy (2014)

• Membre de l'editorial board de l'International Journal of Nuclear Energy Science and Technology – Inderscience (depuis 2006)

• Reviews réguliers d'articles de revue (Annals of Nuclear Energy, Nuclear Engineering and Design, EPJ-N…) et de conférences internationales

9.3 Book chapters

- "**IAEA Technical Reports Series on the Status of Molten Salt Reactor Technology**", Technical Report Series (TRS no.489), International Atomic Energy Agency, Vienna (Austria) – preprint https://preprint.iaea.org/search.aspx?orig_q=RN:52090830 (2021)

- **Chapitre Worlwide Activities, "Molten Salt Reactors and Thorium Energy"**, Dolan T. J. (ed.), Woodhead Publishing (2017)

- E. Merle-Lucotte, M. Allibert, M. Brovchenko, D. Heuer, V. Ghetta, A. Laureau,P.Rubiolo, Chapitre **“Introduction to the Physics of Thorium Molten Salt Fast Reactor (MSFR) Concepts”**, Thorium Energy for the World, Springer International Publishing, Switzerland (2016)

- Michel Allibert, Manuele Aufiero, Mariya Brovchenko, Sylvie Delpech, Véronique Ghetta, Daniel Heuer, A. Laureau, Elsa Merle-Lucotte, **“Chapter 7 - Molten Salt Fast Reactors”**, Handbook of Generation IV Nuclear Reactors, Woodhead Publishing Series in Energy (2015) en cours de mise à jour avec une version 2021/2022

- E. Merle-Lucotte, chapitre **“La filière thorium”**, Collectif L’énergie à découvert, éditions CNRS (2013)

- D. Heuer et E. Merle-Lucotte, **“Un concept innovant : les réacteurs à sels fondus”**, Science au Présent 2009, complément annuel scientifique de l'Encyclopedia Universalis (2009)

9.4 Peer review publications

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S. Beils, D. Gerardin, A.C. Uggenti, A. Carpignano, S. Dulla, E. Merle, D. Heuer, M. Allibert, “Application of the lines of defence method to the molten salt fast reactor in the framework of the SAMOFAR project”, EPJ Nuclear Sci. Technol. 5, 18 (2019), https://doi.org/10.1051/epjn/2019031 (open access)

D. Gérardin, A.C. Uggenti, S. Beils, A. Carpignano, S. Dulla, E. Merle, D. Heuer, A. Laureau, M. Allibert, “Identification of the Postulated Initiating Events with MLD and FFMEA for the Molten Salt Fast Reactor”, Nuclear Engineering and Technology, 51(4), 1024-1031 (2019)

M. Brovchenko, J.L. Kloosterman, L. Luzzi, E. Merle et al., “Neutronic benchmark of the molten salt fast reactor in the frame of the EVOL and MARS collaborative projects”, EPJ Nuclear Sci. Technol. 5 (2019)

S. Wang, M. Massone, A. Rineiski, E. Merle-Lucotte, A. Laureau, D. Gérardin, D. Heuer, M. Allibert, “A passive decay heat removal system for emergency draining tanks of molten salt reactors”, Nuclear Engineering and Design, 2019, vol. 341, p. 423-431 (2019)

A. Laureau, D. Heuer, E. Merle-Lucotte, P. Rubiolo, M. Allibert, M. Aufiero, “Transient coupled calculations of the Molten Salt Fast Reactor using the Transient Fission Matrix approach”, Nuclear Engineering and Design, volume 316, p. 112–124 (2017)

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S. Delpech, E. Merle-Lucotte, D. Heuer, M. Allibert, V. Ghetta, C. Le-Brun, L. Mathieu, G. Picard, "Reactor physics and reprocessing scheme for innovative molten salt reactor system", J. of Fluorine Chemistry, 130 Issue 1, p. 11-17 (2009)

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E. Merle, M. Allibert, S. Beils, A. Cammi, B. Carluec, A. Carpignano, S. Delpech, A. Di Ronco, S. Dulla, Y. Flauw, D. Gerardin, A. Gerber, D. Heuer, A. Laureau, S. Lorenzi, M. Massone, A. Rineiski, V. Tiberi, A. C. Uggenti, “Design and Safety Studies of the Molten Salt Fast Reactor Concept in the Frame of the SAMOFAR H2020 Project”, Generation IV International Forum Symposium, Paris, France (2018)

M. Allibert, S. Beils, G. Campioni, B. Carluec, M. Delpech, S. Delpech, P. Gauthé, D. Gerardin, A. Gerschenfeld, Y. Gorsse, J. Guidez, D. Heuer, A. Laureau, J. Martinet, E. Merle, J. Serp, “Status of current knowledge and developments in France on Molten Salt Reactors”, Actes du Generation IV International Forum Symposium, Paris, France (2018)

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D. Heuer, A. Laureau, E. Merle-Lucotte, M. Allibert, D. Gerardin, "A starting procedure for the MSFR: approach to criticality and incident analysis", Acte de conférence de la conférence internationale ICAPP’2017, Kyoto, Japon (2017)

A. C. Uggenti, D. Gérardin, A. Carpignano1, S. Dulla, E. Merle, D. Heuer, A. Laureau, M. Allibert, “Preliminary functional safety assessment for molten salt fast reactors in the framework of the SAMOFAR project”, Actes de l’International Topical Meeting on Probabilistic Safety Assessment and Analysis PSA2017, Pittsburgh, USA (2017)

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D. Freynet, C. Coquelet-Pascal, R. Eschbach, G. Krivtchik, E. Merle-Lucotte, “Multiobjective Optimization for Nuclear Fleet Evolution Scenarios using the COSI Code”, Actes de la conference international GLOBAL’2015, Paris, France (2015)

E. Merle-Lucotte, D. Heuer, M. Allibert, M. Brovchenko, A. Laureau, V. Ghetta, P. Rubiolo, “Preliminary Design Studies of the Draining System for the Molten Salt Fast Reactor”, Actes de l’European Nuclear Conference, Marseille, France (2014)

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9.7 European project deliverables

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