Molten salt reactor

Main characteristics of the system

Molten salt reactor (MSR) concepts have been studied since the early 1950s, but with only one test reactor operated at the Oak Ridge National Laboratory (ORNL, United States) in the 1960s. For the past 15 years, there has been a renewal of interest in this reactor technology, in particular for its acknowledged inherent reactor safety and its flexibility.

MSR uses molten salts as fuel and/or coolant. When a fluoride salt is the coolant alone, the concept is called a fluoride salt-cooled high-temperature reactor (FHR). Today, in the GIF pSSC MSR, most, if not to say all, the studied concepts are actual MSRs with liquid fuel.

The MSR is a concept and not a technology. Indeed, the MSR generic name covers thermal and fast reactors, operated with a U/Pu or a Th/233U fuel cycle, or as trans-uranium (TRU) burners, with a fluoride or a fluoride carrier salt. An illustration of the most studied concept is provided in Figure MSR-1 below.

Depending on the fuel cycle, MSRs can re-use fissile and fertile materials from LWRs, or they can use uranium, or burn plutonium or minor actinides. They have an increased power conversion efficiency (the fission directly occurs in the carrier salt, which transfers its heat to the coolant salt in the heat exchangers). MSRs are operated under low pressure, slightly above atmospheric pressure. They can be deployed as large power reactors or as small modular reactors (SMRs). Their deployment is today limited by technological challenges, such as high temperatures, structural materials, and corrosion.

The MSR pSSC today includes seven full members (Australia, Canada, Euratom, France, Russia, Switzerland and the United States) and three observers (China, Japan and Korea) and is moving towards a system arrangement. The mission of the MSR pSSC is to support the development of future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts.

R&D objectives

The common objective of MSR projects is to propose a conceptual design with the best system configuration – resulting from physical, chemical and material studies – for the reactor core, the reprocessing unit and wastes conditioning. Mastering of the technically challenging MSR technology will require concerted, long-term international R&D efforts, namely:

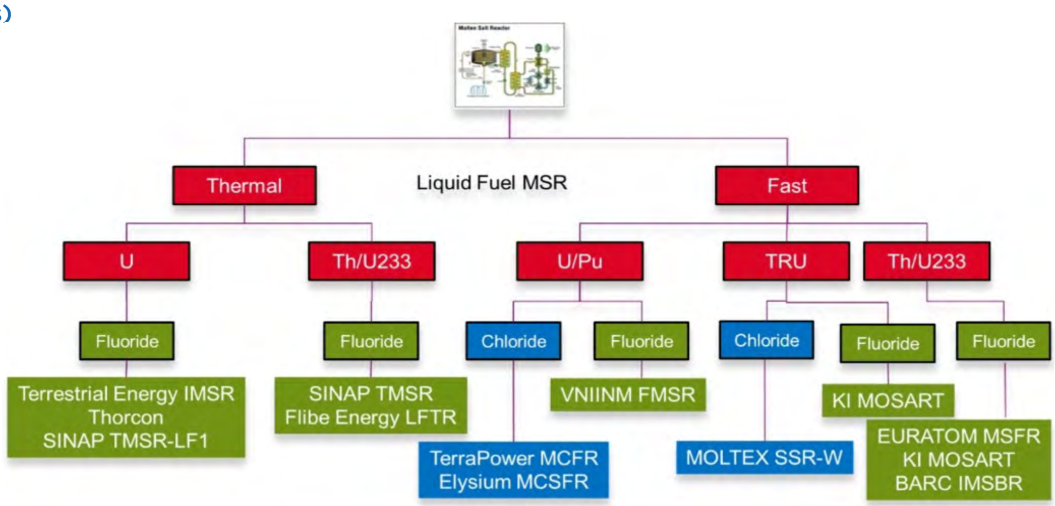
- the study of salt chemical and thermo-dynamic properties;
- for the system design, development of advanced neutronic and thermal-hydraulic coupling models;
- the study of materials compatibility with molten salt;
- salt Redox control technologies to master corrosion of the primary fuel circuit and other components;
- development of efficient techniques for the extraction of gaseous fission products from the coolant through He bubbling;
- for salt reprocessing, reductive extraction tests (actinide-lanthanide separation);
- development of a safety approach dedicated to liquid-fuelled reactors.

Main activities and outcomes

MSR pSSC activity

In 2019, the key activity was the preparation of the system arrangements (SAs) with the definition of three potential projects arrangements, which would allow the community to contribute broadly. These PAs are therefore quite transversal, and not concept-dependent, but they can support the development of any concept (see Figure MSR-2).

Figure MSR-1. The most studied MSR concepts, with key players (research & technology organization or vendors)



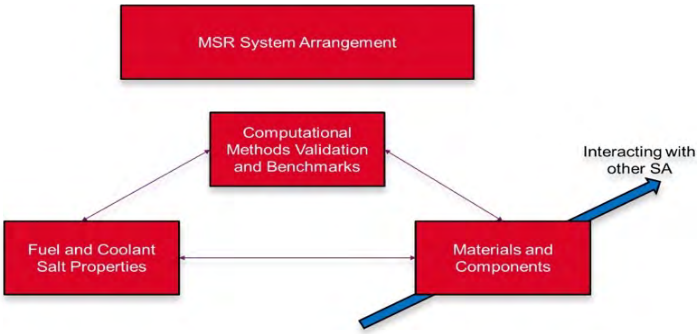


Figure MSR-2. Foreseen structure of the MSR SA, including three PAs

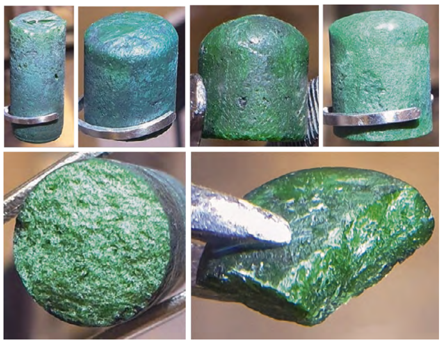


Figure MSR-3. Fuel salt ingots fabricated at JRC Karlsruhe for the SALIENT-03 irradiation experiment

They address the salt behavior, materials properties and system integration. The SA should enter into force in 2021.

Euratom

European SAMOSAFER project:

On 1 October 2019, the new Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors (SAMOSAFER) project started with the aim of developing new simulation models and tools, and designing new safety barriers for the MSR. The goal of this new project is to develop and demonstrate new safety barriers for more controlled behavior of MSRs in severe accidents, based on new simulation models and tools validated with experiments. The overall objective is to ensure that the MSR can comply with all expected regulations in 30 years' time. After successful completion of this project, the simulation models and tools can be used by the nuclear industry, and the innovative safety barriers can be implemented in new MSR designs. This will lead to increased safety margins in future Gen-IV MSRs to ensure that they comply with the latest and future safety standards. SAMOSAFER is co-ordinated by TU Delft and will run until 2023.

In 2020, SAMOSAFER partners focused, inter alia, on the continuation of the design of the MSR, the distribution of radionuclides in the fuel treatment unit, the risk identification (list of post-irradiation examinations [PIEs]) in the Fuel Treatment µUnit (FTU) as input for the safety analysis using the failure modes and effects analysis (FMEA) method, the development of new algorithms and the design and construction of experimental setups for validation of these, as well as the generation of physico-chemical data of various molten salts to extend the JRC Karlsruhe database.

In the Netherlands, the Salient-01 irradiations in the Petten high-flux reactor were finalized. The samples are currently being investigated in the framework of SAMOSAFER in the NRG and JRC Karlsruhe laboratories. Follow-up irradiations (Salient-03), containing five fuel salt samples encapsulated in nickel-based alloys, are under preparation.

JRC Karlsruhe:

Among experimental studies on basic thermo-chemical properties, JRC is extensively involved in the synthesis and fabrication of the fluoride fuel salt for the planned irradiation experiment, SALIENT-03, in the high-flux reactor (HFR) at Petten via this major collaboration with NRG. Four batches of fuel salts were synthesized, having the following compositions (mol. %): 757LiF-18.7ThF4-6.0UF4-0.3PuF3 (28.02 g), 757LiF-18.7ThF4-5.7UF4-0.3UF3-0.3PuF3 (15.02 g), 757LiF-18.6ThF4-6.0UF4-0.4CrF3-0.3PuF3 (7.01 g) and 75LiF-23.0ThF4-2.0UF4-0.1UF3 (50.12 g). The first three salts will be irradiated, while the latter will serve for out-of-pile electro-chemical tests at NRG. The end members, 7LiF, ThF4, UF4 and PuF3, were synthesized and their purity verified using methods developed and published previously by JRC Karlsruhe. The method for synthesis of UF3, based on reduction of UF4 through gaseous hydrogen at 800°C, was developed specifically for the project. The fuels for irradiation were prepared in a form of solid ingots of the quenched salts exactly fitting into the irradiation capsules. The salt mixtures were melted in liners made of the same materials as the irradiation capsules (Hastelloy-N and GH3535) under a flow of pure HF gas, which was found necessary for further purification. All obtained ingots have the required shape and mass and an excellent purity, as proven by the combination of XRD, DSC, ICP-MS and oxygen analysis through Knudsen effusion mass spectrometry (KEMS) methods. The selected ingots are shown in Figure MSR-3, including a cross-section demonstrating sufficient homogeneity and purity.

With the increasing demand for reliable measurements of density for MSR fuels, significant effort has been expended in 2020 to design and test the novel densitometer at JRC Karlsruhe. The selected method of measurement is based on the Archimedean buoyancy effect, and entire set up was designed such that it fits the current glove boxes that are kept under protective argon atmosphere, and which are licensed to handle nuclear materials. Furthermore, the spherical bob that is immersed into the molten salt during measurement is made of nickel to avoid corrosions at high temperatures. The first high-temperature measurements were undertaken using the LiCl-KCl eutectic salt, and were successfully tested up to 650°C. The results obtained are shown in Figure MSR-4 below, which indicates high reliability of the method. The experimental set up is designed such that it provides data for both fluoride and chloride based MSR fuels. The figure also shows the roadmap of the densitometer development, indicating very rapid development. In early 2021, further tests are planned with a few more fluoride and chloride inactive salt mixtures, with successive installation of the final design in a hot glove box for measurement of actinide containing fuels.

Further development of the Joint Research Centre Molten Salt Database (JRCMSD) continued with the addition of BeF2-ZrF4, KF-ThF4 binary systems. With increasing worldwide demand for the use of chloride salts as fuels for certain MSR designs, the database is being extended to relevant chloride systems.

Research Centre Řež:

In addition to the activities carried out within the SAMOSAFER project, the Research Centre Řež, together with other Czech companies, has also continued the national MSR technology development program. The program is focused on the theoretical and experimental development of selected areas of MSR technology. In 2020, the main task of the program was to fully finalize all preparatory phases and stages for the measurement of neutronic characteristics of the molten fluoride salt, FLIBE, in the working temperature range of MSRs using the method of "hot inserted FLIBE zone" in the LR-0 experimental reactor. For this purpose, the core of the LR-0 reactor was completely reconstructed so that a set of the "hot inserted FLIBE zones" could be placed at its centre. Before the end of 2020, a set of inserted zones was completed, the location in the LR-0 reactor was verified and all so-called "cold" non-active experiments were successfully completed. The inserted zone occupies the space of seven fuel assemblies in the middle of the LR-0 reactor core. Hot experiments-measurements of the neutronic characteristics of the FLIBE melt in the range of MSR operating temperatures (550-750°C) will start in the first half of 2021.

In addition to hot inserted zone experiments, the R&D program in the area of materials research, development and verification of components and equipment for fluoride melt media, and the study of electro-chemical separation methods, along with methods of fused salt volatilization suitable for online MSR liquid fuel reprocessing technology, also continued.

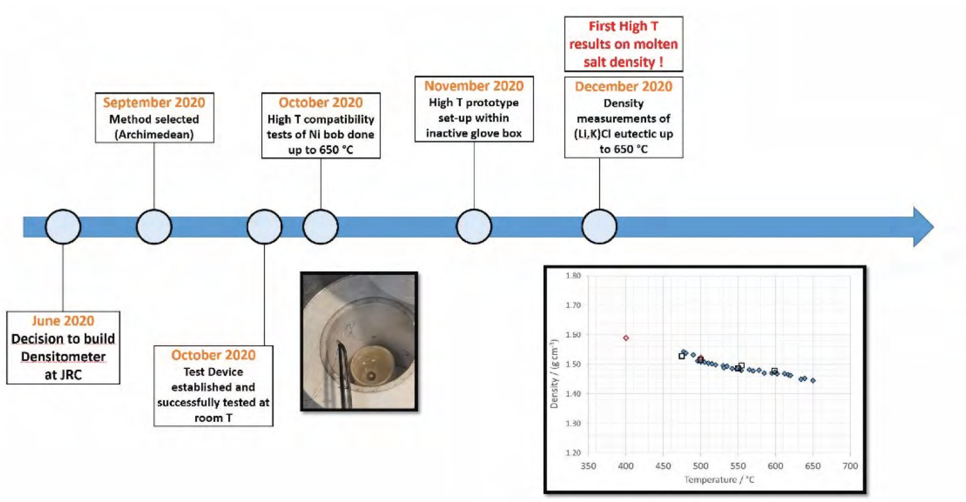
France

Since the beginning of 2020, the CEA has been carrying out its a research program oriented around defining a sketch of a molten salt reactor. Three options are being considered, all in a fast spectrum and in molten chloride: isogenerator, Pu burner, and minor-actinide transmutor.

Studies cover the reactor system (i.e. neutronics, materials, components) and the associated fuel cycle (i.e. salt behavior, corrosion, salt polishing). Multi-physics and chemistry modelling and simulation are also part of the scope. This program, involving the three research institutes of the CEA (IRESNE at Cadarache, ISEC at Marcoule and ISAS at Saclay[1]), is carried out in collaboration with the CNRS (Grenoble, Orsay), with the support of Orano. JRC Karlsruhe is also contributing.

In 2020, work focused on the definition of the plutonium burner option with the study of different

Figure MSR-4. Roadmap of densitometer development at JRC for measurement of MSR fuels



Note: the graph first shows the successful results on the (li,K)Cl eutectic salt – blue: data obtained during heating; red: data obtained during successive cooling; black: data obtained during repeated measurement.

1. IRESNE : Institut de recherche sur les systèmes nucléaires pour la production d'énergie bas carbone; ISEC : Institut pour les Sciences et Technologies pour une Économie Circulaire des Énergies bas carbone, ISAS : Institut des Sciences Appliquées et de la Simulation pour les énergies bas carbone.

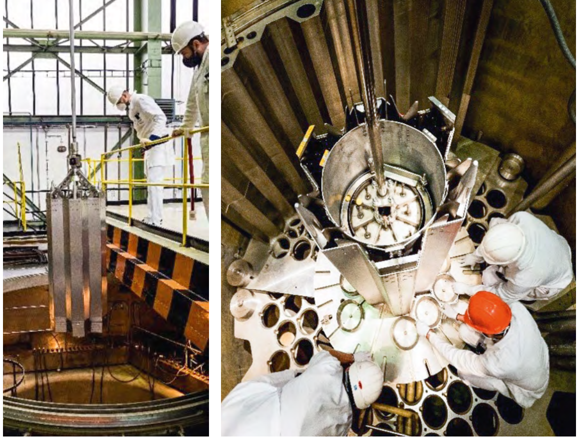
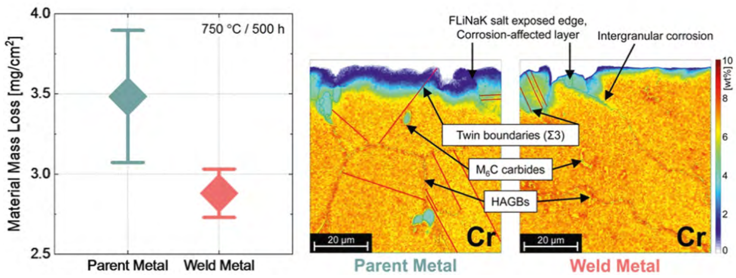


Figure MSR-5. Test insertion of the complete FLIBE insertion zone assembly into LR-0 and verification its location in the centre of the reactor core



Source: Danon, A. E. et al. (2020)

Figure MSR-6. Corrosion rate and microstructural differences in a GH3535 weldment a corrosion tested in FLiNaK molten salt at 750°C

concepts for the reactor, and for different salt composition. In parallel, a tool calculating the evolution of the composition of the salt under irradiation was built (MOSARELA). This tool will contribute to the definition of the reactor operation conditions and the salt treatment strategy.

Australia

The molten salt technology is becoming increasingly important in a wide range of low-carbon energy production and storage systems. Successful deployment requires the development and qualification of materials and components capable of withstanding the challenging operation conditions. Australia's Nuclear Science and Technology Organisation (ANSTO) continues to collaborate with GIF partners to understand corrosion in FLiNaK of candidate stainless steels and nickel-based alloys, as well as how advanced manufacturing techniques may be used to decrease their time to deployment in advanced reactors.

Highlights include a recent investigation of the corrosion performance of the welded Ni-Mo-Cr (GH3535) alloy, where it was shown that the weld, while having a very similar composition, had a superior corrosion resistance to the parent metal. The difference is attributed to the differences in microstructure and in particular, a significantly lower density of high-angle grain boundaries (HAGBs) in the weld metal and the large M6C carbides present in the parent metal.

Russia

During the year 2020, Rosatom continued to provide support to preliminary design development for: 1) test 10-megawatt thermal (MWt) Lithium, Beryllium, Actinides/Fluorine MSR with homogeneous core; and 2) its fuel salt clean-up unit at the site of the Mining and Chemical Combine (Zheleznogorsk) in order to demonstrate the control of the reactor and fuel salt management with different long-lived actinide loadings, drain-out, shut down, etc.

Two main objectives of the MSR project for the period up to year 2024 include:

- development and demonstration of key technological solutions for a MSR with circulating fuel for the transmutation of long-lived actinides;
- development of a preliminary design for the test MSR and required materials to obtain a license for its placement.

During the year 2020, the main R&D efforts were focused on the following issues:

- optimization of neutron and the thermal-hydraulic characteristics of the core and fuel circuit;
- development of analytical methods to measure the impurities in the fuel salt and intermediate coolant;
- development of an advanced high nickel alloy with enhanced corrosion and radiation resistance properties for the fuel circuit;
- construction of experimental units for materials tests with fuel and coolant salts in laboratory and reactor conditions.

United States

The US government continues to foster US MSR industry development through a number of cost-sharing R&D programs. The US Department of Energy (DOE) in particular is supporting both university and national laboratory activities at a limited scale to overcome the remaining technical hurdles to MSR deployment.

In 2020, MIT received a DOE award to build an in-reactor molten salt test loop.[2] This facility will provide researchers with an understanding of by-products in an MSR and test instrumentation. It will also serve as a prototype for other university loop studies and DOE test reactors. The research will use both a non-irradiated and irradiated flowing salt loop to examine the behavior of fission by-products, especially ones that do not stay dissolved in the salt. These by-products in particular will deposit themselves on surfaces

2. https://nrl.mit.edu/announcements/2020/nrl-receives-four-doe-project-awards.

within the loop, or separate from the liquid salt as gaseous by-products. Understanding how these by-products affect the loops will give valuable insights into the MSR design. Natura Resources LLC also granted Abilene Christian University (ACU) USD 21.5 million[3] over the next three years as part of a USD 30.5 million effort to design and license a research reactor in collaboration with three major universities: Georgia Institute of Technology, Texas A&M University, and The University of Texas at Austin. Launched in spring 2019, the consortium's goal is to design, license and commission the first university-based molten salt research reactor, which ACU will host and own. The deal represents the largest sponsored research agreement in the university's history. Recent national laboratory activities related to MSRs include developing a molten salt thermal properties database based on molten salt thermo-physical and thermo-chemical property measurement and engineering evaluation of off-gas system technology.

In parallel, the Nuclear Regulatory Commission (NRC) is making progress on the process of modernizing its licensing requirements to better reflect the safety characteristics of advanced reactors. MSR features and phenomena are being incorporated into accident progression evaluation tools. Progress in being made in developing methodologies for qualifying liquid fuel salts, as well as non-power reactor review guidance.

Vendors such as Kairos Power and Terrestrial Energy USA have also filed multiple topical reports and white papers to the NRC in 2020 in order to support the licensing process of their MSR concepts.

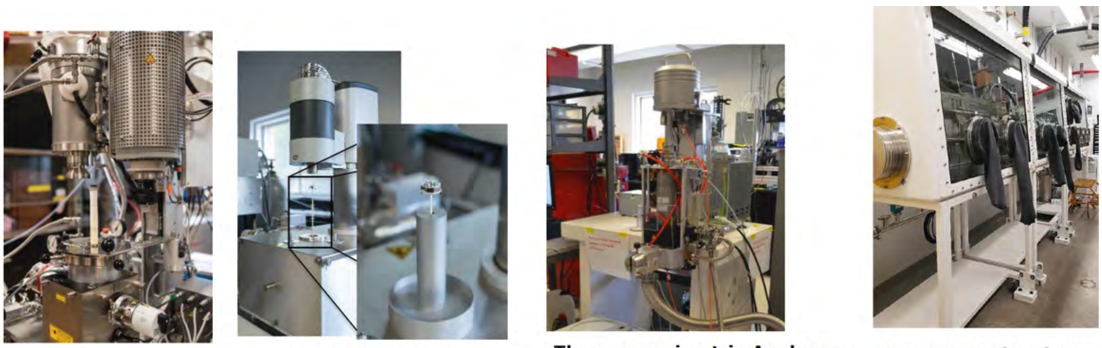
Canada

In 2020, Canadian Nuclear Laboratories (CNL) continued to develop expertise and capabilities in support of SMRs. The CNL executed multiple projects for SMR vendors under a new cost-sharing R&D program called the Canadian Nuclear Research Initiative (CNRI). The CNRI program was established by the CNL to accelerate the deployment of SMRs in Canada, enabling research and development and connecting the SMR industry with facilities and expertise within Canada's national nuclear laboratories. Among the many benefits of the program, participants are able to optimize resources, share technical knowledge and gain access to CNL expertise so as to help advance the commercialization of SMR technologies. Among the first to take part in this new program, three MSR vendors worked with the CNL on a diverse program of work, including electro-chemical separation methods, tritium management, reactor physics, thermal-hydraulics and safeguards studies.

Under the auspices of the Canadian Federal Nuclear Science and Technology Programme, the CNL continued to develop molten salt capabilities across a wide range of areas including:

- development of actinide molten salt fuel synthesis using no gaseous reagents;
- fission product retention in molten salt experiments; evaluation of passive cooling during a station blackout with experiments on coupled natural circulation heat transfer between water and molten salt loops, and evaluation of molten salt plug melting in accident conditions;
- corrosion loop development for measuring the corrosion of structural materials;
- modelling and simulation of MSR designs, including evaluation of the codes for an advanced reactor coupled transient simulation toolset against ORNL MSRE: Physics (SERPENT, Rattlesnake); TH (RELAP5-3D, ARIANT); CFD (STAR-CCM+) and atomistic simulations to predict molten salt properties.

Figure MSR-7. Sample encapsulation and measurement technique development at CNL



Laser Flash (LFA)
Thermal diffusivity

Differential Scanning Calorimeter (DSC)
- Liquidus/solidus temperatures
- Specific heat capacity
- Phase diagrams

Thermogravimetric Analyser (TGA/STA)
Mass change with temperature to verify thermal stability of molten salt mixtures

Dry, Inert Gloveboxes
Commissioned and authorized to be used for preparation of salt fuels, including plutonium-bearing salts

3. https://techtransfercentral.com/2020/08/04/abilene-christian-u-with-21-million-from-natura-resources-to-build-research-reactor-as-part-of-consortium/.

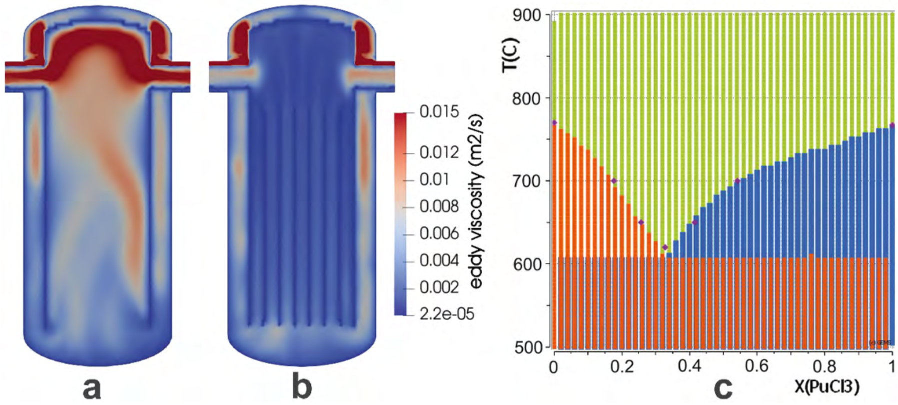


Figure MSR-8. Conceptual layout of the MCFR core vessel a) without and b) with baffles. Phase diagram of the ThCl-PuCl3 system c).

Finally, significant efforts have continued in further developing nuclear qualified measurement techniques for the thermo-physical properties of molten salts.

Terrestrial Energy: Terrestrial Energy Inc. (TEI) is a privately funded reactor vendor developing the integral MSR (IMSR). A 195 MWe, graphite-moderated design employing standard assay low-enriched uranium (LEU) for near- term deployment in the late 2020's. TEI is sourcing R&D services worldwide in order to develop its IMSR concept. In 2020, NRG was contracted for a major multi-year irradiation program in the Petten reactor of multiple commercial graphite grades suitable for MSR use (sub-micron pore diameter). The first specimens were introduced in the reactors in October 2020 with similar protocols to the INNOGRAPH study for gas-cooled graphite candidates. Argonne National Laboratory will provide services for various fuel salt property verifications with the high standards needed for the regulator process.

In terms of commercialization milestones achieved in 2020, the IMSR concept has been short-listed by Ontario Power Generation as one of three technologies developed for potential commercialization, after extensive commercial due diligence. TEI has also been awarded CAD 20 million from the Canadian federal government's Strategic Innovation Fund.

Switzerland

Swiss MSR research continued in 2020 at the Paul Scherrer Institute (PSI) with a major aim of monitoring the technology, education of new experts, and development of knowledge and simulation capabilities in: fuel cycle, system behavior, and thermo-dynamics areas of molten salt research. A big part of PSI activities represent contributions to the EU Horizon 2020 project, SAMOSAFER, and therefore these belong to the EU progress report.

In the area of fuel cycle assessment, the PSI continued to develop a dedicated benchmark for the respective simulation tools with partners from the SAMOSAFER project. The breed-and-burn fuel cycle in the molten chloride fast reactor (MCFR) was further assessed, and the Serpent 2-based procedure, EQL0D, was applied to several additional fuel cycle configurations. The in-depth knowledge of this reactor and fuel cycle type, together with past Swiss research in this area, was used for preparation of an MCFR chapter for Elsevier's *Encyclopedia of Nuclear Energy* (to be published in 2021). For the same encyclopedia, a series of three chapters dedicated to self-sustained breeding in advanced reactors was prepared based on the extensive knowledge of actinide behavior during irradiation in numerous MSR concepts and other advanced reactors.

The system behavior study with Open-FOAM based solver, ATARI, continued in 2020 covering three different aspects: 1) simulation of the SAMOSAFER project reference concept MSFR; 2) assessment of freezing phenomena in printed circuit heat exchangers; and 3) conceptual design of an MCFR core with tube-in-tube and baffles options. The impact of baffles on eddy viscosity is illustrated in Figure MSR-8 a and b.

The thermo-dynamics simulation of molten salts continued with the GEMS TM code, focusing on further refinement of the database and major fluoride and chloride salt components. The adjusted database was applied to phase diagram calculations (see Figure MSR-8 c) and to the cGEMS code for the estimation of evaporation behavior.

China

In 2020, the Shanghai Institute of Applied Physics and the Chinese Academy of Sciences (SINAP-CAS) have been steadily promoting the related work of the thorium molten salt reactor (TMSR). This 2 MWth molten salt test reactor (TMSR-LF1) was approved with a construction license. Construction of the plant structure for the experimental reactor was started and completed in 2020, and the equipment was delivered for installation. The application for an operation license (including the final safety analysis report [FSAR] and other relevant attachments) was submitted, and the first stage review was completed. Key equipment has entered the final stage of manufacturing and will be delivered to the project site in succession. At present, installation of the main equipment has started.

A number of experiments have been completed on the scaled experimental device (TMSR-SF0), including: the thermal-hydraulic performance experiment of key equipment and the steady-state and transient characteristic experiment on the salt system. The experimental program will continue in 2021.

The conceptual design of the flowsheet for TMSR fuels has been finished, and validation of the flowsheet for thorium fuel reprocessing is in progress. Fundamental studies on the structure and reaction of actinide and fission product fluorides in molten salt have been carried out.

Significant progress has been achieved on MSR material research. It was proven that GH3535 alloys maintain good creep properties in FLiNaK molten salts. Experiments on molten salt erosion of nuclear graphite at elevated temperatures were carried out, which provided data support for the further application of nuclear graphite in MSRs. In addition, the neutron-radiation-induced defect evolution of nickel-based alloy has been studied using the newly developed rate theory method.

Japan

In Japan, the International Thorium Molten Salt Forum (ITMSF) was established in 2008 for the basic study of MSR technology, such as conceptual designs and safety analysis for MSR-FUJI. The ITMSF has been an observer in the GIF-MSR System Steering Committee from the beginning of the committee. In 2010, Thorium Tech Solution Inc. (TTS) was established for the business application of the MSR-FUJI. In addition to these activities, several universities have been carrying out basic studies in the recent decade.

The Japanese government began supporting the development of MSR technology in 2019, and continued to do so until the beginning of 2021. Three MSR companies were selected: two (the Thermal Transient Test Facility for Structures [TTS] and MOSTECH) are promoting MSRs with fluoride salt moderated by graphite, and one is promoting a fast spectrum MSR with chloride salt, on which universities (Tokyo Institute of Technology [TIT], Fukui, Doshisha) and the Central Research Institute of Electric Power Industry (CRIEPI) are working together.

Figure MSR-9. FLiNaK molten salt loop at the National Institute for Fusion Science

MOSTECH is planning to construct a molten salt loop at Kyushu University and is also preparing freeze valve tests for a fusion blanket loop system of molten salt, together with Kyushu University and the University of Electro Communications (UEC), as shown below. This loop system (Oroshhi-2: described by A. Sagara et al. in Fusion Science and Technology in 2015), was built in the National Institute for Fusion Science (NIFS) using FLiNaK.

Stéphane Bourg
Chair of the MSR SSC, with contributions from MSR members