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ENDURANCE

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

D1.1 Review of the EU MSR designs

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Executive Summary

The objective of this deliverable is to review the EU MSR designs of interest for the project, starting from the information available in open literature and refined with the shareable data of the design proposed by the partners of the project. Some of these designs will be more deeply studied in the work-packages 2 to 6 depending on the data available and the objectives of their different tasks. This review of EU MSR designs aims at gathering general information on each concept in preparation for the more detailed database of deliverable 1.3 and at identifying the data of interest that can be made available for the studies and calculations of the project.

Keywords

European Molten Salt Reactor Designs, MSR, system description, global database

Table Of Contents

1 Introduction

The objective of this deliverable is to review the EU MSR designs of interest for the ENDURANCE project, starting from the information available in open literature and refined with the shareable data of the design proposed by the partners of the project. Some of these designs will be more deeply studied in the work-packages 2 to 6 depending on the data available and the objectives of the various tasks.

The concepts summarized in Table 1 and listed by their alphabetic order will be detailed in the next sections.

Table 1: List of EU molten salt reactors identified

Concept	Fuel carrier	Moderator	Neutron spectrum	Fissile matter / Fuel cycle	Power [MW_{th}]	Use
ARAMIS-A (CEA + ISAC project)	Chloride	None	Fast	Pu + Am	300	Electricity production + Waste reduction
ARAMIS-P (CEA / Orano)	Chloride	None	Fast	Pu	300	Electricity production + Waste reduction
CMSR (Seaborg)	Fluoride	Graphite	Thermal	U-based	250	Electricity production
Copenhagen Atomics MSR	Fluoride	Heavy water	Thermal	Th-based	100	Heat production + Waste reduction
MSFR-F (CNRS + EU projects)	Fluoride	None	Fast	^{233}U – $^{enrich}U$ – Pu + MA / Th fuel cycle	3000	Electricity production
MSFR-Cl (CNRS + SAMOSAFER)	Chloride	None	Fast	Pu + MA / U fuel cycle	3000	Electricity production + Waste reduction
RAPTOr (CNRS/Orano)	Chloride	None	Fast	Pu + MA	300 / 500	Waste reduction + Electricity production
Stellarium (Stellaria)	Chloride	None	Fast	U-based or Pu-based	250	Energy + Waste reduction
Thorizon One (Thorizon)	Chloride	None	Fast	Th and Pu or U based	250	Electricity and possibly heat production + Waste reduction
XAMR (Naarea)	Chloride	None	Fast	Pu-based	80	Electricity and/or heat production + Waste reduction

2 ARAMIS-P and ARAMIS-A

2.1 *Presentation and development status*

The ARAMIS (Advanced Reactor for Actinides Management In Salt) concept has been developed initially through a collaboration between CEA and ORANO to convert plutonium in the first version called ARAMIS-P [Pascal et al. 2025]. Its derived and more recent version, ARAMIS-A, aims at converting americium and plutonium and is studied in the ISAC (Innovative System for Actinides Conversion) French national project led by CEA with CNRS, EDF, Framatome and ORANO as partners.

The ISAC project (2022-2026), supported by the French Investment Plan “France 2030”, addresses the whole integrated system consisting of the reactor and the fuel cycle. The proposal to use a molten salt reactor is based on the one hand on the favorable neutronics of the MSR, with chloride salt in fast spectrum, in terms of actinide conversion performance and on the other hand on the potential simplification of the fuel manufacturing and reprocessing operations. However, the feasibility has not been demonstrated yet: reactors or experimental facilities using chloride salt, or a fast spectrum, or with a high content of minor actinides have not yet been built. The ISAC project therefore aims to characterize the feasibility of this integrated solution and to propose R&D, including experiments, on the main hurdles: chemistry, corrosion, materials. It has been decided to focus on Americium transmutation at first [Chenaud et al., 2024].

2.2 *System description*

The ARAMIS concept is a 300 MW_{th} fast-spectrum molten salt reactor. Its purpose is to burn actinides for inventory management. A chloride salt was selected thanks to a higher solubility of plutonium than in fluoride salts, a harder neutron spectrum and the solubility of chloride salts in water, which would make the concept compatible with hydrometallurgical treatment and separation processes already used in France.

The ARAMIS-P design was focused on the flexibility of plutonium burning service which has to accommodate a wide range of plutonium quality. The ARAMIS-P design has been used afterwards as the basis design of the ARAMIS-A concept dedicated to the opportunity assessment of the MSR to convert americium in order to reduce the amount of LLHL waste and deep geological repositories footprint.

The following sections give information on both designs.

2.2.1 **Fuel circuit / core description**

The chosen architecture for the fuel circuit (for ARAMIS-P and ARAMIS-A) is a loop design as shown in Figure 1 and Figure 2.

The fuel circuit is composed of six loops; each fuel loop is made of one pump connected to an expansion tank, one heat exchanger (IHX for Intermediate Heat eXchanger) and pipes.

The core internal tank, where the fission reaction occurs, is surrounded by neutron protection (in MgO), which acts both as neutron reflector and neutron protection to lower the flux in the out-core components.

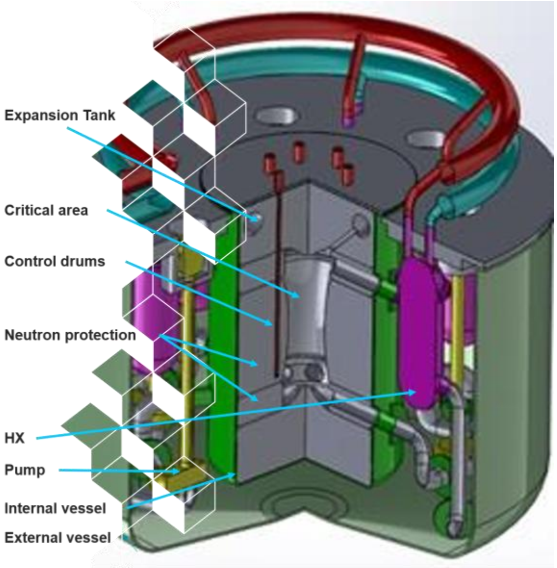


Figure 1: ARAMIS-P – Sketch Integration @CEA

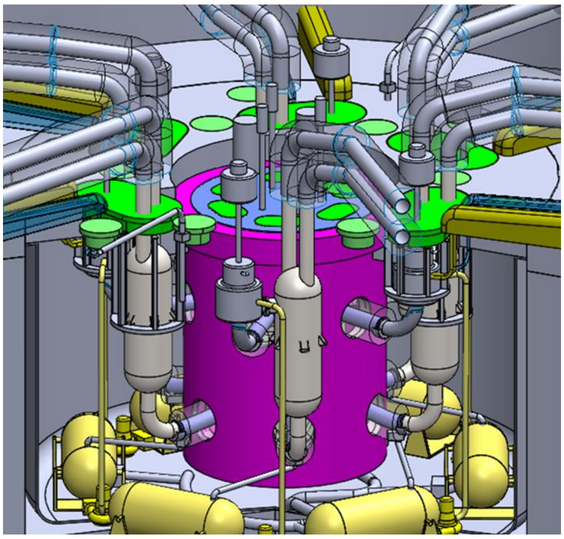


Figure 2: ARAMIS -A – Sketch Integration @Framatome

The reactor is designed to operate with NaCl-$MgCl_2$-$PuCl_3$ as fuel salt, NaCl-$MgCl_2$ as intermediate salt for chemical compatibility in case of breach in the IHX.

The chlorine fuel salt is enriched in ^{37}Cl.

Table 2 summarizes the main characteristics of the ARAMIS-P [Martin-Lopez et al., 2023] and ARAMIS-A fuel circuit [Chenaud et al., 2024].

2.2.2 **Other circuits and systems (intermediate, conversion, RHR, etc)**

The intermediate circuit, composed of three loops, transfers the heat generated by fission to a Power Conversion System (PCS), via three Energy Conversion Heat Exchangers (ECHX). The PCS converts heat to electricity with a Brayton cycle. Gaseous nitrogen (N_2) is considered as the working fluid for the PCS.

Table 2: Main characteristics of the ARAMIS-P and ARAMIS-A fuel circuit

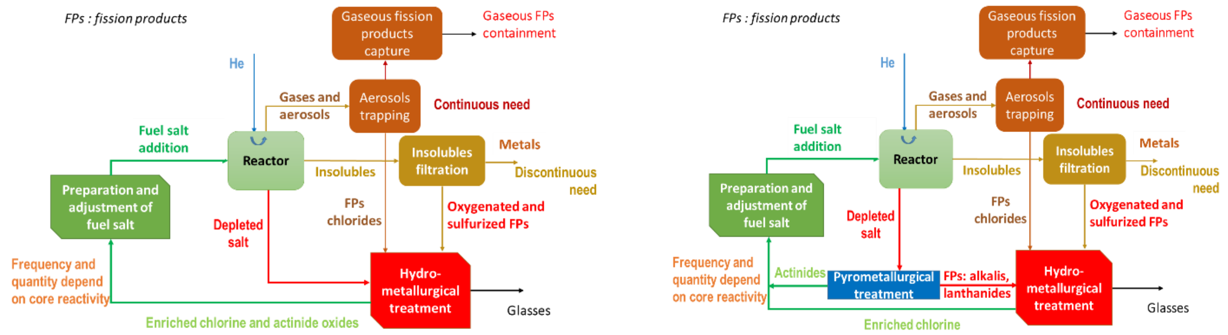
	ARAMIS-P	ARAMIS-A
Power	300 MW_{th}	
Fuel salt composition	$NaCl-MgCl_2-PuCl_3$	$NaCl-MgCl_2$- (Pu, Am)Cl_3
Core Volumic power	250 W/cm^3	250 W/cm^3
Core volume (critical zone)	1.2 m^3	1.2 m^3 (=23% of the fuel salt total volume)
Core diameter and height	0.91 m / 1.82 m	0.91 m / 1.82 m
Conversion target	130 kg/TWhe Pu	80 kg/TWhe Am
Flexibility of Pu vector	Yes	Yes
Initial mas of Pu / Am	1.4 t (BOL[*])	2827 kg / 3485 kg
Pu recharge/year	250 kg/an	250 kg/an
Cycle duration / reactivity loss	~ 6 months	~ 6 months / 650 pcm
Core inlet / outlet temperatures	570°C / 650°C	570°C / 650°C
Architecture	Loop-type	Loop-type
Loops	6	6
Heat exchangers type and power density	Shell & Tubes ~200 W/cm^3	Shell & Tubes ~200 W/cm^3
Pumps	Rotodynamic	Rotodynamic
Cooling fluid	$NaCl-MgCl_2$	$NaCl-MgCl_2$
Internal diameter vessel	< 3 m	< 3 m
External diameter vessel	< 5 m	< 5 m
Vessel Height	~ 5 m	~ 5 m

(*) BOL = Beginning Of Life

2.2.3 **Fuel characteristics and processing**

Considered actinides isotopic compositions are representative of the French fleet's spent fuel.

Waste salts are treated by hydrometallurgical processes; the introduction of a pyrometallurgical processing step will be studied as a possible optimization to separate actinides closer to the reactor and return only fission products and lanthanides in the La Hague processes.



Exclusive hydrometallurgical treatment — Pyrometallurgical and hydrometallurgical treatment

Figure 3: Options for the ARAMIS salt treatment

The depleted salt requires treatment that aims to recover actinides, recycle chlorine and synthesize a new salt free of fission products that is re-injected into the reactor.

In the hydrometallurgical option (Figure 3, left), the depleted salt is sent to the process unit (for example at la Hague). Chlorine and actinide oxides are separated in the hydrometallurgical process unit and sent back to the reactor unit of preparation of fresh fuel.

In the pyrometallurgical option (Figure 3, right), the depleted salt is first treated in the pyrometallurgical process unit where actinides are separated. The pre-treated salt is then sent to the hydrometallurgical process unit where chlorine is separated from fission products and sent back to the reactor unit of preparation of fresh fuel that also retrieve actinides from the pyrometallurgical process unit.

2.3 Elements on reactor operation and safety

Operation of such reactors is studied in [Mascaron et al., 2024] and some safety transients calculations results are presented in [Mascaron et al., 2023].

2.4 Summary and adequation of the available data with the work in ENDURANCE

The design of the ARAMIS-P reactor is sufficiently advanced to be able to provide a coherent set of data for work in other WPs.

If required in other WPs, for example for WP4 system code benchmark, CEA can provide fuel salt composition, geometry description, constitutive materials and operating conditions.

3 Compact Molten Salt Reactor (CMSR)

Note: The present description has been prepared for [IAEA SMR catalogue, 2024] and had been updated for this deliverable.

3.1 Presentation and development status

The Seaborg CMSR is an advanced, small and modular molten salt reactor characterized by using a liquid fluoride molten salt fuel in direct contact with graphite moderator.

The CMSR has a thermal power capacity of 250 MW_{th} which is transformed into more than 100 MW_e. It operates on standard LEU with enrichment below 5% U-235, making use of high-frequency online refuelling to achieve its operating lifetime of 12 years while maintaining low excess reactivity and minimizing control rod movement. To facilitate inspection and maintenance, the CMSR is being designed as a loop-type reactor implementing a single fuel salt circulation loop.

Due to its very high boiling temperature, the CMSR needs no pressurization above what is needed to circulate the fuel salt which together with the avoidance of phase changing material in close proximity to the fuel salt circuit yields important and unique inherent safety benefits.

The CMSR is deployed on modular and standardized non-self-propelled CMSR Power Barges, scalable from 200 MW_e to 800 MW_e containing one to four so-called Power Modules, each equipped with two concurrently operating CMSRs, yielding a total plant operating life of 24 years.

3.2 System description

3.2.1 Plant overview

The main characteristics of the CMSR are listed in Table 3 below and views of the system are presented in Figure 4.

Figure 4: The CMSR Power Barge(left) and the primary salt circuit(right) including the following major components: reactor core, fuel salt drain tanks, heat exchanger and pump

Table 3: Main design parameters of the CMSR

Parameter	Value
Technology developer, country of origin	Seaborg Technologies ApS, Denmark
Reactor Type	Molten Salt Reactor/thermal spectrum
Neutron spectrum	Thermal
Coolant / moderator	Fluoride fuel salt / graphite
Thermal/electric capacity	$250MW_t/110MW_e$ per CMSR
Operating Pressure (MPa) (primary/secondary/NSSS)	0.45/1.05/18
Fuel type/assembly	LEU/Molten Salt fuel
Power conversion process	Superheated steam driven turbine (Rankine cycle)
Fuel enrichment	Approx. 2%
Refueling cycle	144 months once through Online addition of fuel (approx. 5%)
Core Discharge Burnup	Approx. 6 GWd/tU
Reactivity control mechanism	Negative temp. coef. Regulating and safety rods, fuel salt draining
Approach to safety systems	Automatic shutdown, Passive decay heat removal
Design life (target)	12y per CMSR/ 24y per Power Barge
Plant footprint	200 – $800MW_e$: 5000 – $14000m^2$
RPV(*) height/diameter	5.5/6.0m
RPV Weight	138 metric ton
Seismic design (SSE)	Not applicable
Fuel cycle requirements / approach	LEU with online refueling Off-site reprocessing
Distinguishing features	CMSR integrated into a floating non-self-propelled Power Barge; new CMSR units installed after 12 years. CMSR Power Barge operates for 24 years. Modular nature provides output from 200-800 MW_e Liquid fuel acts as primary coolant
Design status	Conceptual design

(*) RPV = reactor pressure vessel

3.2.2 **Fuel circuit / core description**

Reactor Core

The CMSR reactor core consists of several hundred graphite blocks arranged into columns in a central active core region and a periphery reflector region. In total, the graphite core measures approximately 5.5 m in diameter and 5 m in height. The fuel salt flows through fuel channels in the graphite core configuration and transports heat deposited into the fuel salt, graphite, and structural materials. At certain positions in the core, metallic control rod guide tubes extend down from the top of the core, providing an unobstructed path for inserting the control rods.

Reactivity Control

The CMSRs credits two main methods for reactivity control: control rods and fuel salt draining, which are relatively fast and slow acting, respectively. The control rods are subdivided into regulating rods for compensating short-term reactivity changes during operation, and safety rods for extinguishing the nuclear chain reaction promptly when needed. The draining of the fuel salt is initiated by opening one of several fuel salt drain valves that are redundant, independent, and diverse. Inherent reactivity control means include negative temperature coefficients and the geometrical configuration of the fuel salt drain tanks.

Reactor Vessel and Internals

The CMSR reactor vessel measures approximately 6 m in diameter, accommodating the graphite active core and reflector regions followed by a fuel salt channel which cools the reactor vessel during power operation. Due to its relatively low operating pressure, the vessel will be welded rather than forged. It has upper and lower plena that sit above and below the graphite core, respectively, which guide and distribute the fuel salt flow through the core. On the top of the vessel are penetrations for the control rod guide tubes and inspection channels. The reactor vessel internals include the control rod guide tubes, structural supports that keep the graphite in place, and equipment for material surveillance.

3.2.3 **Other circuits and systems (intermediate, conversion, RHR, etc)**

Each CMSR molten salt fuel loop transfers heat generated in the core to a secondary liquid heat-transfer fluoride salt via the primary heat exchanger. The secondary circuit then transfers heat to a tertiary salt circuit which circulates solar salt from the secondary heat exchanger and into the steam generator, using technology from concentrated solar power plants. The Power Conversion System receives heat in the form of superheated steam from two concurrently operating CMSRs, at pressures and temperatures up to 18 MPa and 565ºC. The steam produced from the two steam generators drives a single conventional condensing steam turbine with exhaust positioned axially into the seawater-cooled condenser. Electrical output from the connected generators allows delivery of 200 MWe net from each Power Module through a common electrical interface to the high-voltage onshore electrical transmission grid. Through this arrangement, a CMSR Power Barge can provide between 200 and 800 MWe net to the grid depending on the number of modules installed.

3.2.4 **Fuel characteristics and processing**

The fuel consists of NaF, KF and UF_4, with partial reduction of UF4 to UF3 to limit degradation of the structural materials and graphite. The uranium enrichment differs through the fuel cycle, with the initial fuel loading at approximately 2% and subsequent online refuelling at approximately 5%. Most fission products form soluble fluoride species which are retained in the fuel (no online reprocessing envisioned). The volatile species that bubble out are collected and passed to an off-gas system that delays and conditions the gases, effectively removing them as a source term in postulated reactor accidents.

3.3 Elements on reactor operation and safety

Engineered Safety System Approach and Configuration

The CMSR and CMSR Power Barge design implements a tailored approach to defence in depth with a top-down focus on the three fundamental safety functions, taking into account the inherent safety features of the CMSR in a risk-informed and performance-based manner. The inherent safety features include:

• For control of reactivity: negative temperature coefficients; use of draining to reach a subcritical configuration; low excess reactivity due to online refuelling.

• For cooling of fuel and waste stores: high boiling point and large margin to boiling; volumetric heat capacity of fuel and graphite; low decay heat power density.

• For confinement: retention of fission products in fuel; low-pressure operation; no material that can phase change, burn or explode in proximity of the fuel.

The engineered safety systems include:

• For control of reactivity: regulating and safety rods.

• For cooling of fuel and waste: a combination of active and passive decay heat removal systems.

• For confinement: a number of independent and isolatable containment barriers provided around different sources of radioactivity, with the number and leak-tightness requirements based on risk-informed and performance-based principles.

Decay Heat Removal System

The CMSR implements a decay heat removal system that removes heat from the fuel salt drain tanks. During normal operation and hot standby, heat is removed through the salt and turbine circuits. By opening one out of several redundant, independent and diverse fuel salt drain valves, the fuel salt is drained by gravity to the fuel salt drain tanks. There decay heat is transported to the decay heat removal system through radiative heat transfer, and the heat can subsequently be dissipated in the ultimate heat sink through either active or passive means. The passive decay heat removal system relies on the natural convection of water, and ultimately rejects the heat to the atmosphere. It is dimensioned for at least 72 hours of decay heat removal without operator interaction.

Emergency Core Cooling System

The CMSR does not implement a traditional emergency core cooling system. Due to the low-pressure operation, high thermal inertia, passive fuel salt draining, and passive capabilities of the decay heat removal system, the omission of an emergency core cooling system is thought to be acceptable following the risk-informed and performance-based safety approach.

Containment System

Radioactive sources onboard the CMSR Power Barge are located in different compartments and separated from the environment by a number of physical containment barriers. The leak-tightness requirements of and number of containment barriers surrounding a compartment are commensurate with its risk importance. Penetrations through containment barriers are equipped with means of isolation that actuate in accident conditions.

3.4 Summary and adequation of the available data with the work in ENDURANCE / Interest of the designers in the frame of ENDURANCE

Any data relating to fluorides is of interest – in particular FUNaK. While Seaborg is carrying out its own research on e.g. thermophysical properties of the salt over its operational lifetime, independent verification is valuable.

In addition to thermophysical properties other areas of interest include, but are not limited to: performance under irradiation, fission production retention as well as safety related characteristics, such as salt spill experiments or properties and fission product retention at beyond design temperatures.

Seaborg also has an interest in salt interfacing with structural materials (e.g. corrosion in steels) or graphite – and, in particular to irradiation induced effects, which are difficult to assess theoretically as well as in laboratories.

Moreover, Seaborg is generally interested in code development. Several features of MSR modelling needs significant development and in particular experimental validation. Seaborg is keen to contribute to this, as well as to obtain early access to software tools under active development.

It is the generally the intention of Seaborg to share data within the consortium to the extent possible.

4 Copenhagen Atomics Waste Burner

4.1 Presentation and development status

The detailed description of the Copenhagen Atomics Waste Burner can be found in [IAEA SMR catalogue, 2024].

4.2 Summary and adequation of the available data with the work in ENDURANCE

The main characteristics of the Copenhagen Atomics Waste Burner are summarized in Table 4.

Table 4: Characteristics of the Copenhagen Atomics Waste Burner [IAEA SMR catalogue, 2024]

Parameter	Value
Technology developer, country	Copenhagen Atomics, Denmark
Thermal/electrical capacity, MW(t)/MW(e)	100 / (not defined)
Fuel circuit circulation	Forced circulation
NSSS Operating Pressure (fuel/intermediate), MPa	0.05-0.25 / 0.1-0.25
Fuel type	^{7}LiF-UF_4 or ^{7}LiF-ThF_4-$(TRU)F_3$
Initial fissile inventory	LEU or TRU/RGPu
Core Inlet/Outlet Coolant Temperature (°C)	600 / 650 - 700
Online reprocessing	Vacuum spraying
Moderator	Heavy water
Power conversion process	Heat source
Core Discharge Burnup (GWd/ton)	900-1000
Refuelling Cycle (months)	Continuous operation / fuel salt as needed
Reactivity control mechanism	Heavy water level adjustment
Approach to safety systems	Passive
Design life (years)	5 years for the reactor vessel, minimum 50 years for the surrounding building, and unlimited lifetime for the salts and heavy water
Plant footprint (m^2)	50 000 per 2.5GW_{th} plant
RPV height/diameter (m)	12 / 2.55
Fuel cycle requirements / Approach	LEU or transuranic initiated / conversion to Th-U cycle
Distinguishing features	Liquid moderator, Low fissile inventory, and Potential for breeding
Operation	Firmware, no human operators
Design status	Detailed design / Equipment manufacturing in progress

Data availability for WP2 to WP6 will not be easy since Copenhagen Atomics is not partner of ENDURANCE and no open data except reference [IAEA SMR catalogue, 2024] are available on the project.

5 Molten Salt Fast Reactor (MSFR)

5.1 *Presentation and development status*

Since 2004, the National Centre for Scientific Research (CNRS, France) has focused R&D efforts on the development of a new MSR concept called the Molten Salt Fast Reactor (MSFR) supported by the successive Euratom's projects: EVOL (Evaluation and Viability Of Liquid fuel fast reactor systems, 2009-2013), SAMOFAR (Safety Assessment of MOlten salt FAst Reactor, 2015-2019) and SAMOSAFER (Severe Accident MOdeling and Safety Assessment for Fluid-fuel Energy Reactors, 2019-2023) Euratom projects of respectively the Framework Program 7 [Brovchenko et al., 2014a; Dulla et al., 2014, Merle et al., 2018] and the Horizon2020 program [Gerardin et al., 2017].

The MSFR does not employ any solid moderator (no graphite lifespan issues) which results in a fast spectrum breeder reactor with a large negative power coefficient. The initial version of the MSFR, named "reference MSFR" or MSFR-F, based on a fluoride LiF salt, can be operated in a Thorium fuel cycle. A new version named MSFR-Cl [Pitois 2022] has been developed in the SAMOSAFER project, based on a chloride NaCl salt, can be operated in the Uranium fuel cycle. Other advantages of an MSR as the MSFR include homogeneous fuel irradiation and the possibility of fuel reload and processing on-line or in batch mode, without requiring reactor shut-down and involving the transfer of small volumes of fuel. GIF forum selected the MSFR concept in 2008 as one of the GEN IV reference reactors. The MSFR concept is at a conceptual design phase (see descriptions below).

The design studies on the MSFR have to be seen as a basis for interdisciplinary studies and not some plans to build a reactor directly. CNRS being not a vendor, the goal of the MSFR development and optimization is to identify the possible viable configurations of homogeneous breeder MSRs regarding physics, chemistry and material sciences and to propose a realistic working horse for various R&D studies and training of the European community.

The MSFR design has been also used to study some alternative versions:

- a burner version named RAPTOr [Mesthiviers et al., 2022] studied in collaboration between CNRS and ORANO in the frame of the PhD thesis of Laura Mesthiviers [Mesthiviers, 2022]. The optimized RAPTOr version is a 250 MW_{th} reactor without any fertile blanket, based on a NaCl-$MgCl_2$ salt and using Pu and/or minor actinides as heavy nuclei.
- Scaling effects of the MSFR-Cl have been studied in the frame of the PhD thesis of Thomas Sornay [Sornay, 2024] in collaboration between CNRS and Framatome, by varying the fuel salt volume and the number of circulation/cooling loops, with a particular focus on smaller and lower-power reactors, akin to Small Modular Reactor (SMR) designs. These studies involved coupled neutronic thermal-hydraulic calculations and multicriteria design optimization. CAD drawings of these alternative SMR versions may be shared in the ENDURANCE project.

5.2 *System description*

5.2.1 **Plant overview**

The system includes three circuits: the fuel circuit, the intermediate circuit and the power conversion circuit as illustrated in Figure 5.

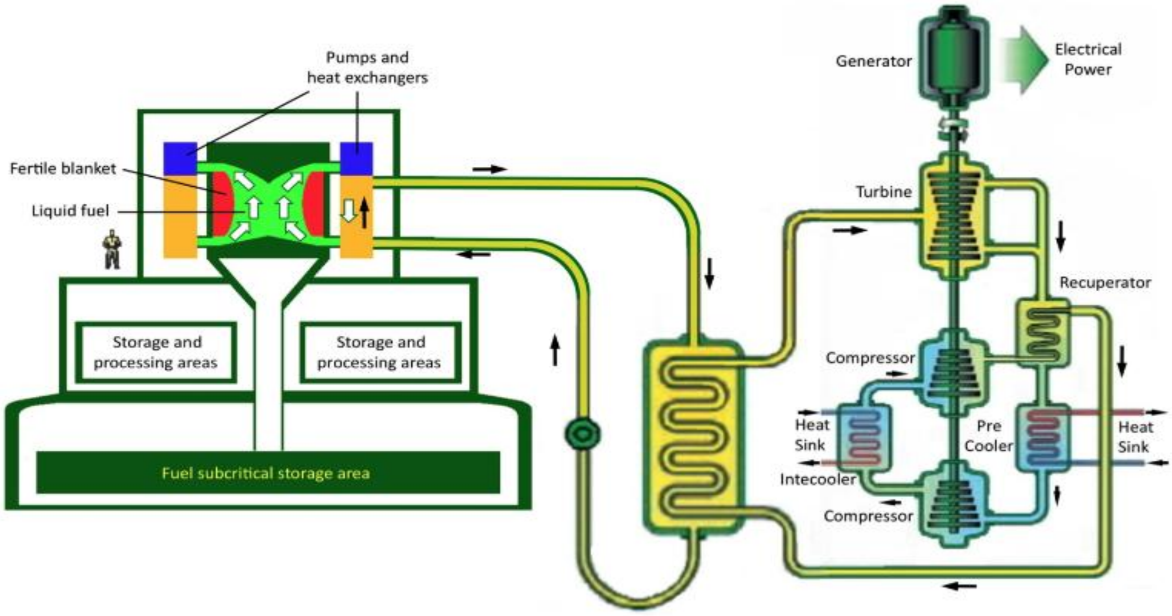


Figure 5: overview of the MSFR concept

Both MSFR versions are 3 GW_{th} breeder reactors. The reference MSFR or MSFR-F, based on fluoride salts and the $Th/^{233}U$ fuel cycle, has with a total fuel salt volume of 18 m^3, operated at a max fuel salt temperature of 750 °C (Mathieu et al., 2009; Merle-Lucotte et al., 2012; Brovchenko et al., 2019). The MSFR-Cl version, based on chloride salts and the U/Pu fuel cycle, has a total fuel salt volume of 45 m^3.

5.2.2 Fuel circuit / core description and optimization

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 (16 in the MSFR-F and 24 in the MSFR-Cl), which are mainly comprised by the inlet and outlet pipes, pumps, and fuel heat exchangers.

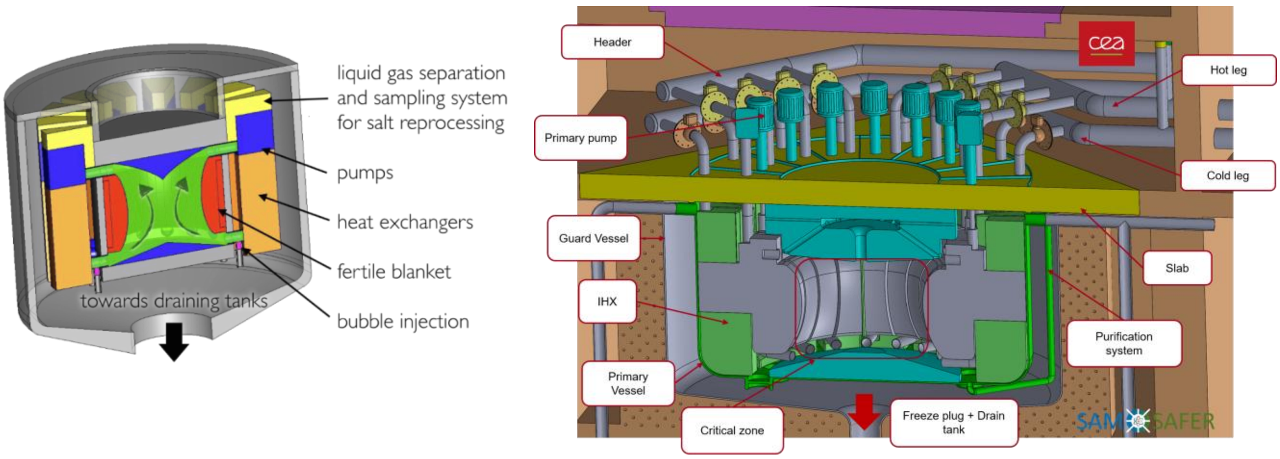


Figure 6: Schematic representation (left – CNRS studies) and CAD drawings (right – SAMOSAFER project) of the reference MSFR fuel circuit

The fuel circuit is connected to a salt draining system which can be used for a planned shut down or in case of any incident/accident resulting in an excessive temperature being reached in the core. In such situations the fuel salt geometry can be passively reconfigured by gravity driven draining of the fuel salt into tanks located under the reactor and where a passive cooling and adequate reactivity margin can be implemented.

Concerning the reference MSFR (MSFR-F), the characteristics of its fuel circuit are listed in Table 5. The external core structures and the fuel heat exchangers are protected by thick reflectors made of nickel-based alloys, which are designed to absorb more than 99% of the escaping neutron flux. These reflectors are themselves surrounded by a 20cm thick layer of B_4C, which provides protection from the remaining neutrons. The radial reflector includes a fertile blanket (50 cm thick - red area in Figure 6 left) to increase the breeding ratio. This blanket is filled with a LiF-based fertile salt with initially 22.5mol % 232ThF4. Due to the neutron inelastic scattering on fluorine nuclei, the MSFR spectrum is a bit less fast than that of solid-fueled fast reactors. This fact, combined to the absence of solid material in the core, results in reduced irradiation damages of the materials surrounding the core.

Table 5: Characteristics of the reference MSFR fuel circuit

Parameter	Value
Thermal/electric power	3000 MW_{th} / 1300 MW_e
Fuel salt temperature rise in the core (K)	100
Fuel molten salt - Initial composition	LiF-ThF_4-(^{233}U or ^{enr}U)F_4 or LiF-ThF_4-(Pu-MA)F_3 with 77.5 mol% LiF
Fuel salt melting point (°C)	565
Mean fuel salt temperature (°C)	700
Fuel salt density (g/cm^3)	4.1
Fuel salt dilation coefficient ($g.cm^{-3}/K$)	$8.82 * 10^{-4}$
Fertile blanket salt - Initial composition (mol%)	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient (pcm/K)	-5
Core dimensions (m)	Radius: 1.1275 Height: 2.255
Fuel salt volume (m^3)	18
Total fuel salt cycle in the fuel circuit	3.9 s

As shown in the sketch of Figure 6, the fuel salt flows from the bottom to the top of the core cavity (note the absence of in core solid matter). In preliminary designs developed in relation to calculations, the core of the MSFR is a single compact cylinder (2.25 m high per 2.25 m diameter for the MSFR-F version), where the nuclear reactions occur within the liquid salt acting both as fuel and as coolant.

Following the very preliminary safety studies done on the MSFR-F [Brovchenko et al., 2013] during the EVOL project, an integrated design of the fuel circuit has been developed to avoid the loss of liquid fuel (LOLF) accident.

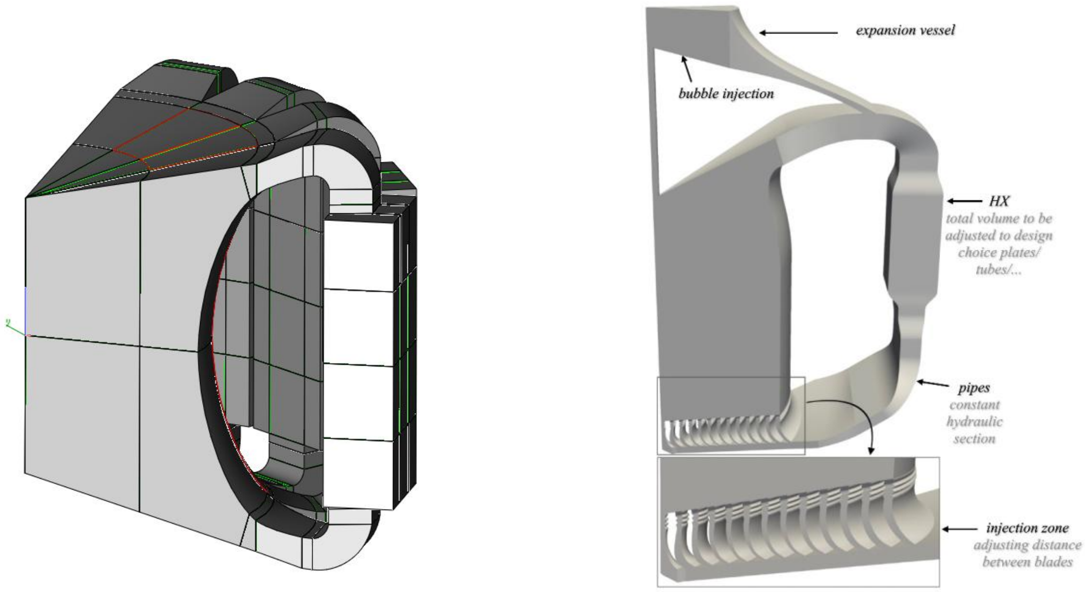


Figure 7: MSFR fuel circuit geometries optimized through CFD RANS modelling ('EVOL shape' – left) and CFD DES modelling ('optimized shape' – right)

Thermal-hydraulic studies using RANS modeling performed in the frame of the EVOL project have shown that a torus shaped core (see Figure 7 on the left) improves thermal flow [Laureau et al., 2013; Rouch et al., 2014], while more recent optimization studies based on DES CFD calculations led to a new optimized core geometry to reduce temperature and thus power fluctuations (Figure 7 right).

5.2.3 **Other circuits and systems (intermediate, conversion, RHR, EDS)**

Studies on the intermediate and conversion circuits, based on the development of system codes, have been led in the frame of the SAMOFAR project, led by PoliMi, and in parallel in a CNRS/CORYS collaboration.

Regarding the energy conversion systems, PoliMi identified a Helium Joule-Brayton cycle as a potential candidate to take advantage from the high temperatures of the MSFR concept while complying with the potential risk of salt freezing in the intermediate circuit [Di Ronco et al., 2020]. Supercritical steam cycle options may offer higher efficiency but can be more prone to salt freezing in the conversion heat exchanger.

The general layout is depicted in Figure 8. The optimization of the layout led to consider three intercooling stages and three reheating stages. The static optimization has been implemented in a Modelica-based model of the Energy conversion system (Figure 9). Table 6 provides the main parameters of the cycle while additional details can be found in [Di Ronco et al., 2020].

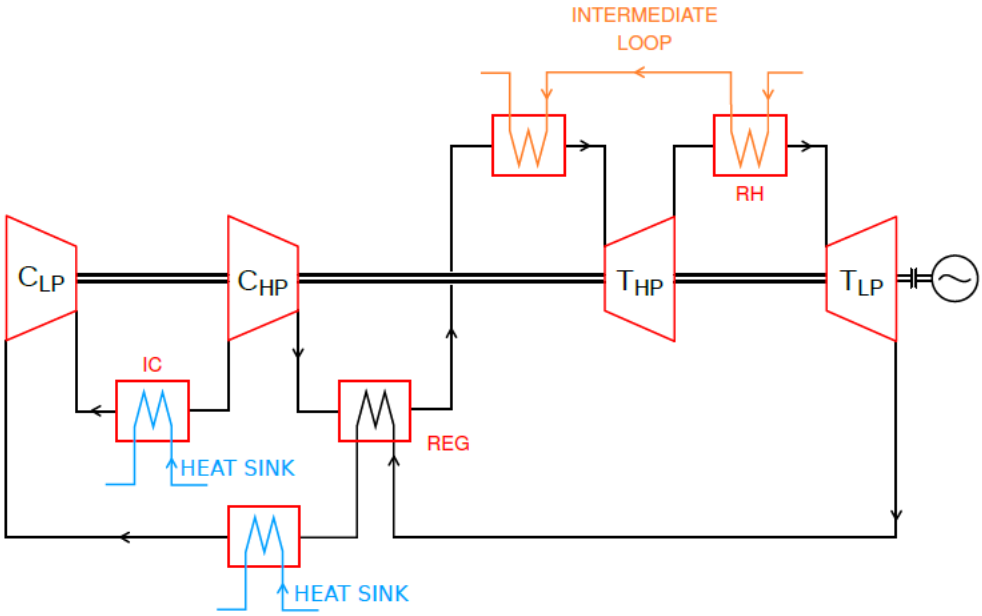


Figure 8: Simplified scheme of a closed gas cycle plant: RH = reheater, IC = intercooler, REG =regenerator, HP/LP = high/low pressure [Di Ronco et al., 2020].

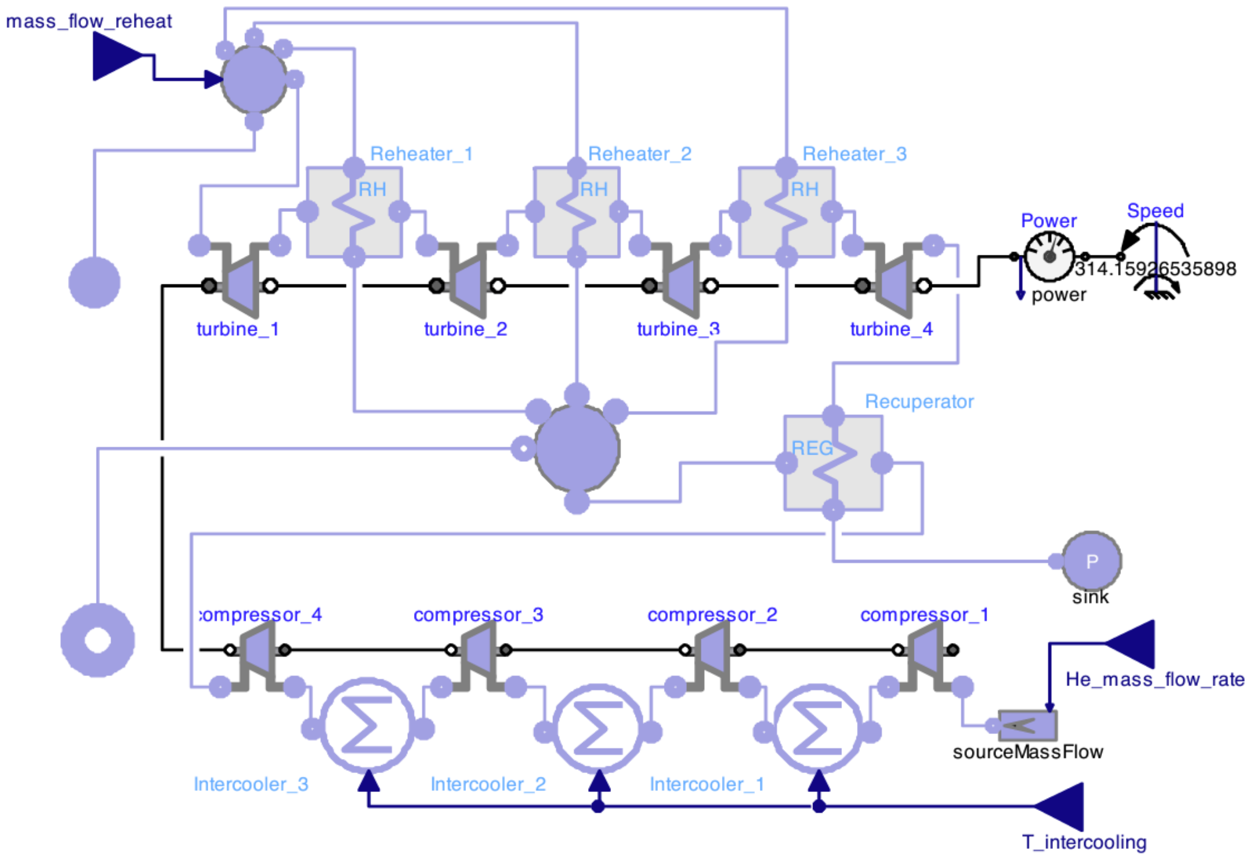


Figure 9: Energy conversion system (Helium Joule-Brayton cycle) model developed in Modelica [Tripodo et al., 2019].

Table 6: Main parameters of the Energy conversion system (He Joule-Brayton cycle).

Parameter	Value
Outlet He gas temperature	625 °C
Inlet He gas temperature	462 °C
Cycle efficiency	~40%
Gas mass flow rate (total mass flow rate for 3000 MW MSFR)	1211 kg/s

CNRS (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. This integrated version allows to study the whole MSFR plant (see Figure 10), thus helping to define the operating procedures of the reactor. The more recent steps for developing this power plant simulator have been the addition of control-command devices and the improvement of the modelling of the components, such as the turbine.

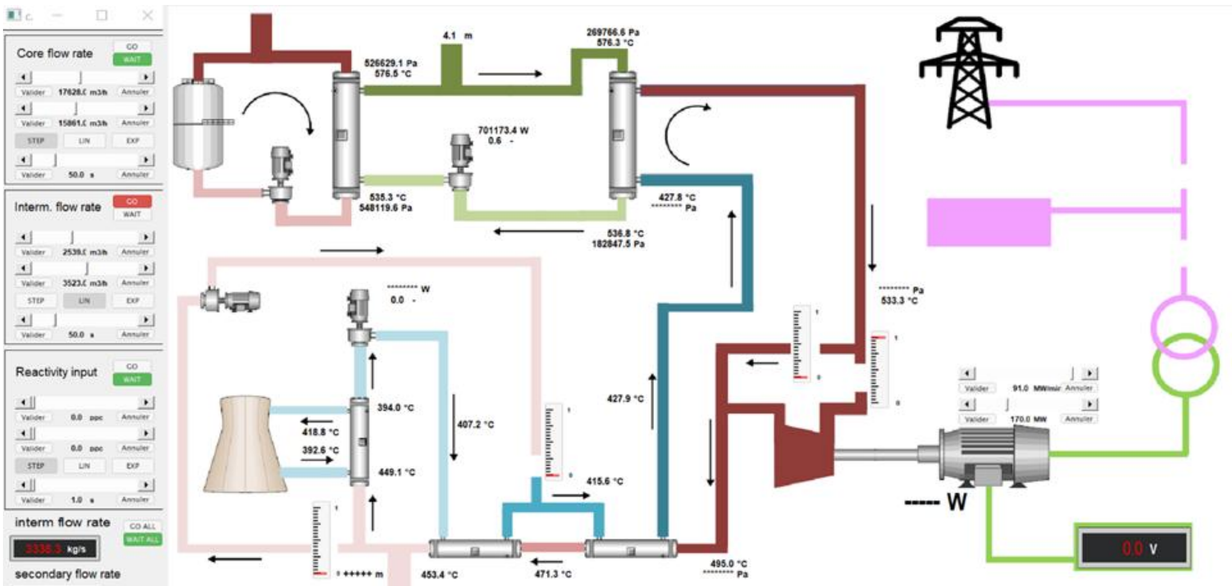


Figure 10 : Main screen of the LiCore-ALICES power plant simulator for the MSFR

Some first design studies of the systems dedicated to the extraction of the decay heat have been led during the SAMOSAFER project by CNRS and Framatome, as presented in Figure 11 with a schematic of the Residual Heat Removal system on the left and a CAD drawing from the SAMOSAFER project studies on the right. Finally, an emergency draining system (EDS) has been designed for the MSFR-F version (see also Figure 11) first at CNRS and then in the SAMOFAR and SAMOSAFER projects.

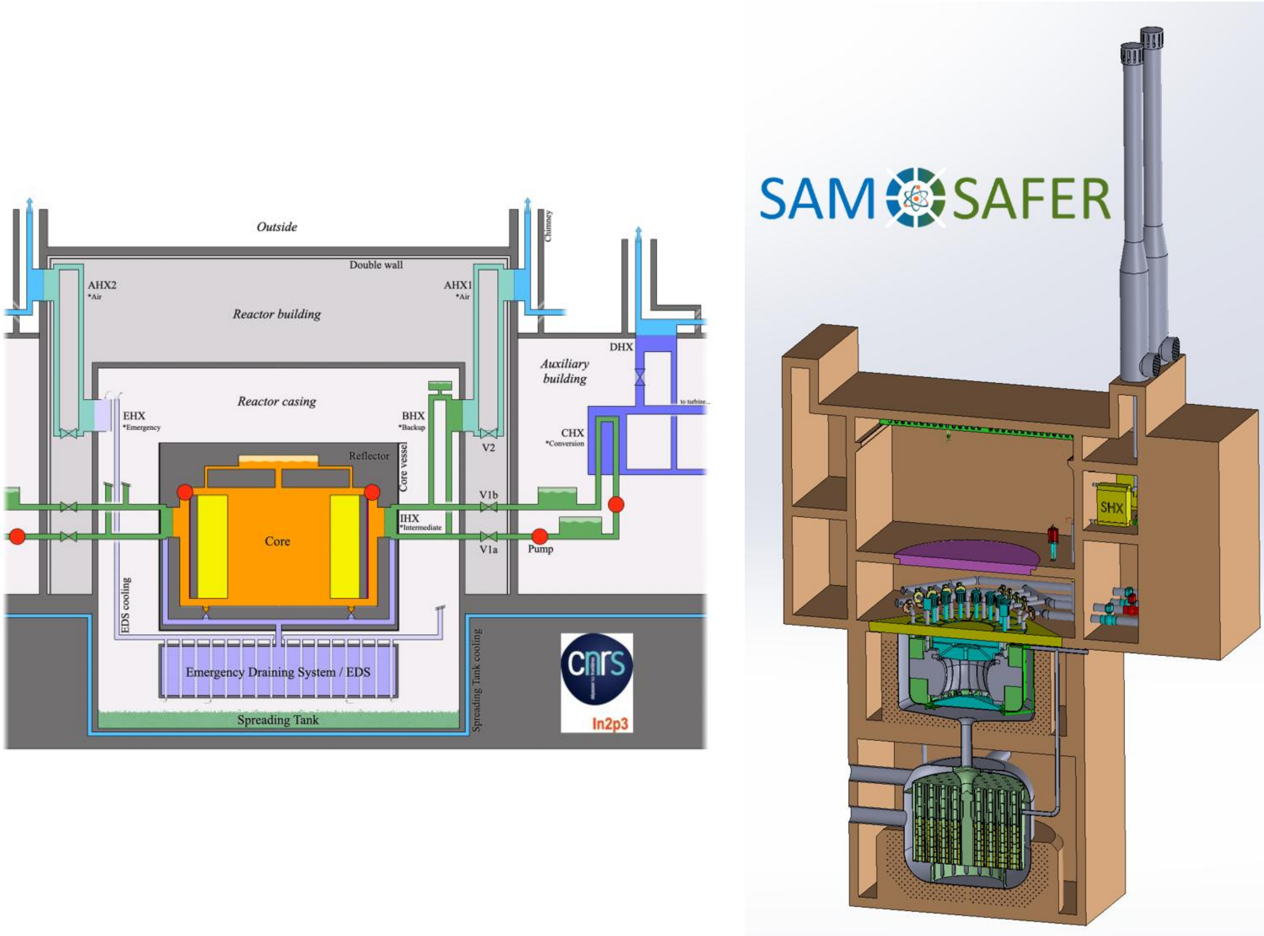


Figure 11 : Residual Heat Removal (RHR) system of the MSFR-F – On the left: Components related to the heat extraction in the MSFR system, with the fuel circuit in yellow, the intermediate circuit in green and a part of the energy conversion circuit in purple (from left to right) – On the right: CAD drawing

5.2.4 Fuel characteristics and processing

The fuel salt undergoes two types of treatment: on-line neutral gas bubbling in the core and delayed mini-batch on-site reprocessing (Delpech et al., 2009). This is displayed in Figure 12 for the MSFR-F and in Figure 14 for the MSFR-Cl. These salt treatments aim at removing most of the fission products without stopping the reactor and thus securing a rather small fissile inventory outside the core compared to present day LWRs. The reprocessing rate itself is assumed equivalent to the present LWR rate, although it could be possible to reprocess the fuel salt every ten years but to the detriment of economical yield.

The gas bubbling has two objectives: removing metallic particles by capillarity (floating) and extracting gaseous fission product before their decay in the salt. The second part of the processing is a semi-continuous salt reprocessing at a rate of some tens (10-40) liters per day for the MSFR-F, in order to limit the lanthanide and Zr concentration in the fuel salt. The salt sample is returned to the reactor after purification and after addition of ^{233}U and Th as needed to adjust the fuel composition and the redox potential of the salt by controlling the U^{4+} to U^{3+} ratio.

These two processes aim at keeping the liquid fuel salt in an efficient physical and chemical state for long time periods (decades).

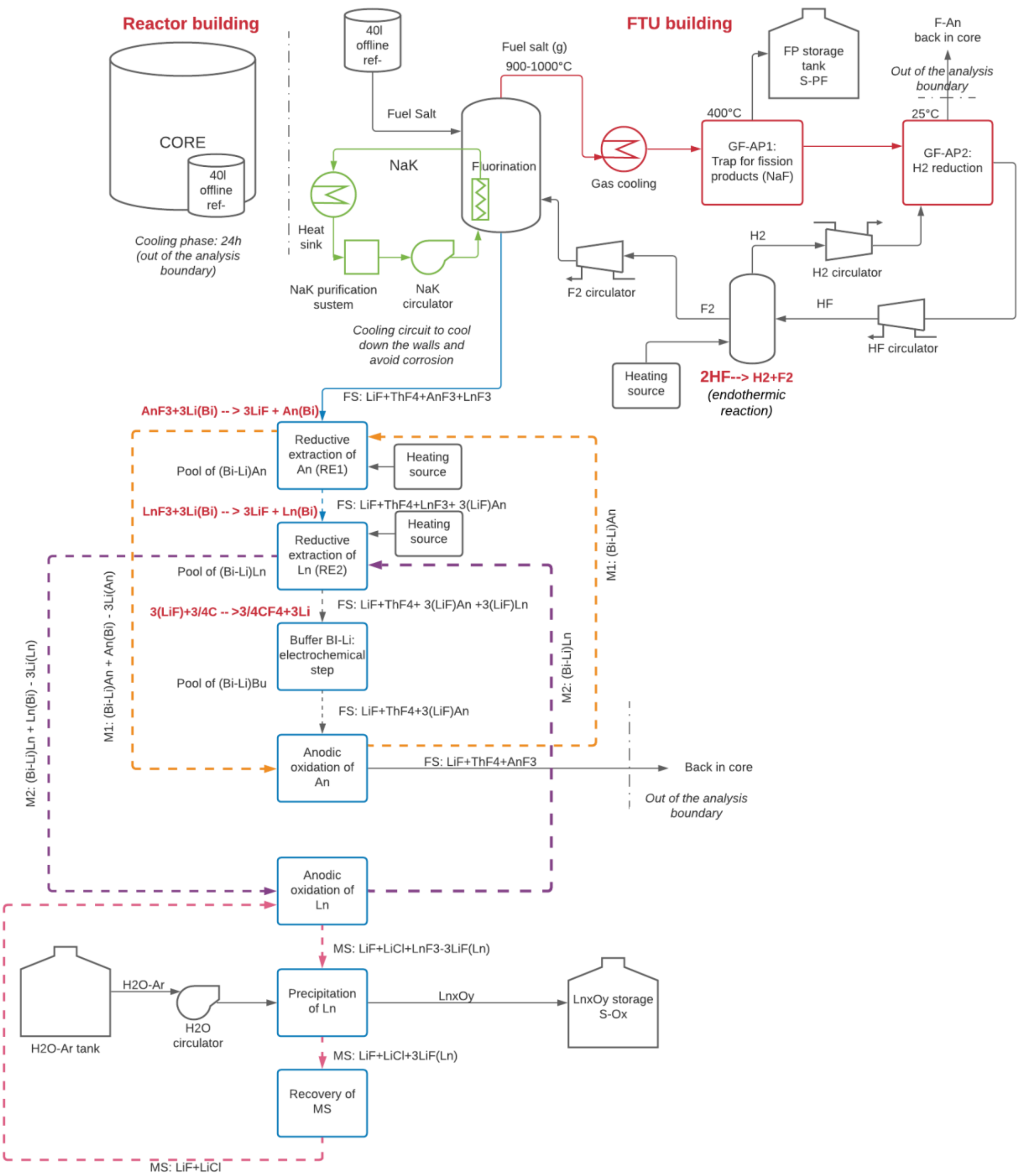


Figure 12 : Schematic representation of the fuel salt treatment units of the MSFR-F [SAMOSAFER D1.3, 2023]

The impact of the batch pyro processing rate is shown in Figure 13. Note that with the reactor configuration used for the calculation, the core is under-breeder. The addition of a fertile blanket secures breeding, up to a reprocessing time of the total fuel salt volume as large as 4000 days.

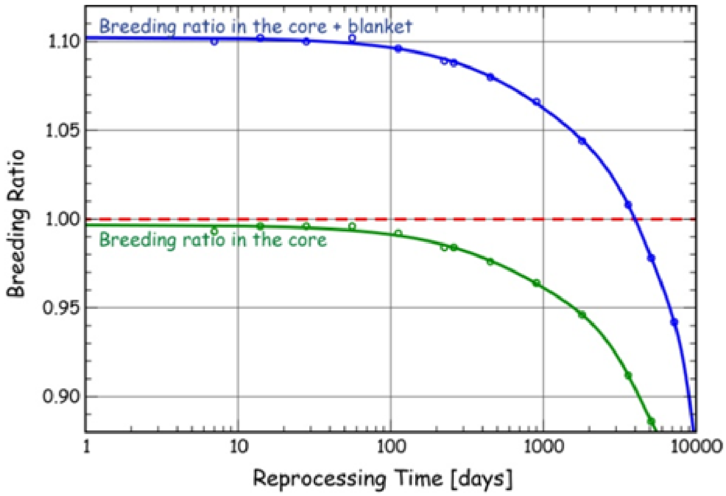


Figure 13 : Influence of the batch reprocessing rate on the breeding ratio in the core and in the whole MSFR system (core + fertile blanket) [Handbook Gen4 MSR chapter, 2020]

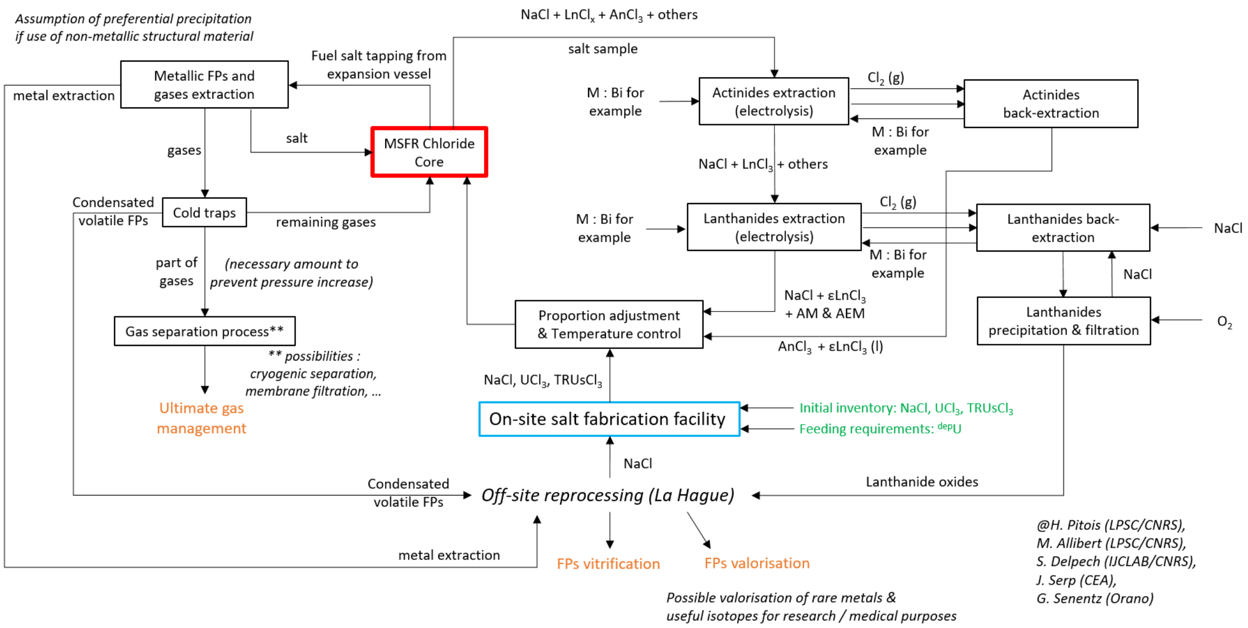


Figure 14 : Principle diagram for the MSFR-Cl reprocessing scheme [Pitois et al., 2023]

Concerning the MSFR-Cl version, the principle diagram of the reprocessing scheme is presented in Figure 14 [Pitois et al., 2023]. The main steps are the following:

- Gas swipe and fuel tapping are performed in the expansion vessel in order to avoid in-core gas injection.
- Gases and volatile species are first sent towards cold traps to isolate the latter, then a part of the formers is processed with advanced techniques.
- Metallic particles are adsorbed on solid metallic traps. It is possible assuming that the fuel circuit is coated in a non-metallic material. Otherwise they are likely to be adsorbed in heat exchangers that present a significant area, ultimately leading to clogging and/or damages.
- Lanthanides can be extracted by electrolysis with separate compartments, but actinides must be extracted first because of the respective electrochemical potentials. Formers are then oxidized, they precipitate and are filtrated out. The latters are reinjected in the core.

- Advanced processing of fission products can be performed off-site, using aqueous chemistry. On-site chemical treatment can only use pyrochemical processes due to the high temperature and radiolysis risks for compounds at low temperature

5.3 Elements on reactor operation and safety

In the frame of the previous European projects on MSR – the SAMOSAFER, SAMOFAR and EVOL Euratom projects – design, operation and safety studies of the Molten Salt Fast Reactor (MSFR) system have been led [Beils et al., 2019; Gerardin et al., 2019; Uggenti et al., 2017; Gerardin, 2018; Brovchenko et al., 2014b].

5.3.1 **Reactor operation**

A first identification of the following normal operational states of the MSFR power plant has been performed in the SAMOSAFER project: Reactor in Power (RP), Normal Shutdown (NS) on CHX + DHX, Maintenance Shutdown (MS), Maintenance Cold Shutdown (MCS), and Start-up of the reactor. Each step has been described with the corresponding pieces of equipment [SAMOSAFER Milestone 15, 2021]. Here CHX stands for Conversion Heat Exchangers and DHX for Dumping Heat Exchanger (see Figure 11).

The definition and assessment of MSFR operation procedures requires dedicated tools to simulate the reactor's behavior and assess its flexibility during normal (e.g. load-following or start-up) or incidental (e.g. pump failure or overcooling) transients. The reactor modelling requires specific treatments to take into account the phenomena associated to the liquid fuel circulation. Two kinds of approaches have been developed: multiphysics codes coupling CFD thermohydraulics and neutronics for precise calculations of the core behavior during normal and abnormal transients, and a power plant simulator containing simplified modeling of the neutronics and the thermohydraulics of the core but representative of the core behavior while allowing real-time calculations and including models for the whole circuits from the core to the turbine. In the first category, one can mention the TFM-OpenFOAM code developed at CNRS [Laureau, 2015; Laureau et al, 2017; Laureau et al, 2022] or its adaptation TFM-Star based on the StartCCM+ code used by Framatome [Sornay, 2024].

5.3.2 **Safety and risk assessment**

In the frame of the SAMOFAR project, the development of the safety approach has been driven by IRSN with the support of Framatome, CNRS and POLITO. The objective of this work was to define a risk assessment methodology which could be applied from the earliest stages of design to licensing, operation and decommissioning. This methodology had to take into account the Generation-IV safety requirements, the international safety standards, the available return of experience and the peculiarities of this kind of reactor with the help of available risk analysis tools, with the idea to achieve a safety which is "built-in" and not "added-on" providing with a detailed understanding of safety related design vulnerabilities, and resulting contributions to risk. As such, new safety provisions or design improvements as well as R&D needs could be identified, developed, and implemented relatively early. The MSFR technology being at its first stages of design will benefit from such an approach. The methodology is based on the Integrated Safety Assessment Methodology (ISAM) developed in the framework of the GIF. ISAM is best thought of as a tool kit of useful analysis tools for Gen IV systems. Some of these tools are primarily qualitative, others quantitative. Some are primarily probabilistic, others deterministic. Some focus on high-level issues such as systemic response to various phenomena, others focus on more detailed issues. This diversity helps to provide a robust guidance based on a good understanding of risk and safety issues.

The ISAM tools have been reviewed, completed and adapted, when needed, to better reflect the European standards/rules, the available return of experience on MSRs and to better fit the scope of the SAMOFAR project. In addition, the usual risk analysis methods have been reviewed and their integration within the ISAM framework studied (see Figure 13). This adapted method has then been declined to be applied to the MSFR technology. A focus has also placed on the safety-related subjects to be examined as a priority at the basic design stage and on the depth of their analysis.

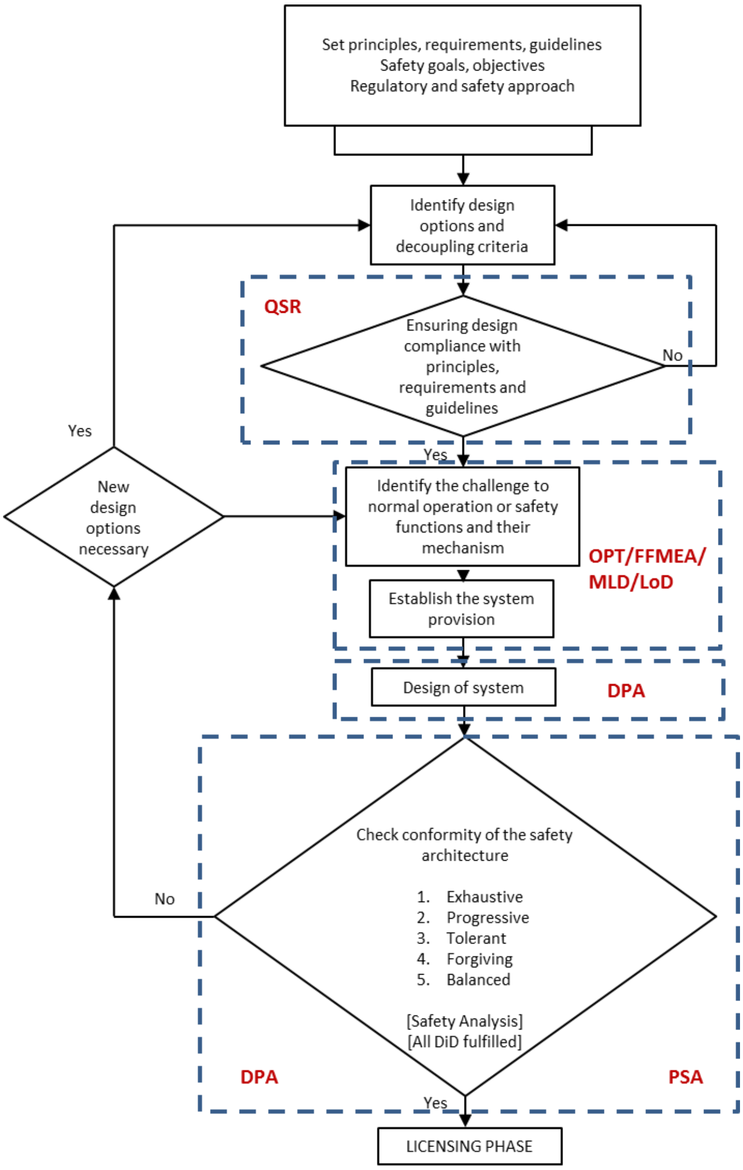


Figure 15: Flowchart of the MSFR design/safety assessment and relevance of the different tools

A preliminary list of accident initiators has resulted from the analysis performed during the EVOL European project. This first step of a safety evaluation was completed during the SAMOFAR project with the application of the safety analysis methodology described in the previous section and the related recommendations on the MSFR for the normal conditions of power production. The identification of the accident initiators has been performed using both bottom-up and top-down approaches. The Functional Failure Mode and Effects Analysis (FFMEA), bottom-up approach, has been performed by CIRTEN/POLITO and CNRS/LPSC and the Master Logical Diagram (MLD), top-down approach, has been performed by CNRS/LPSC and Framatome for the plant state corresponding to the power production of the MSFR. This has led to the identification of the Postulated Initiating Events (PIEs) of the Molten Salt Fast Reactor [Gerardin et al., 2019; Uggenti et al., 2017]. The families of events identified for the MSFR are currently:

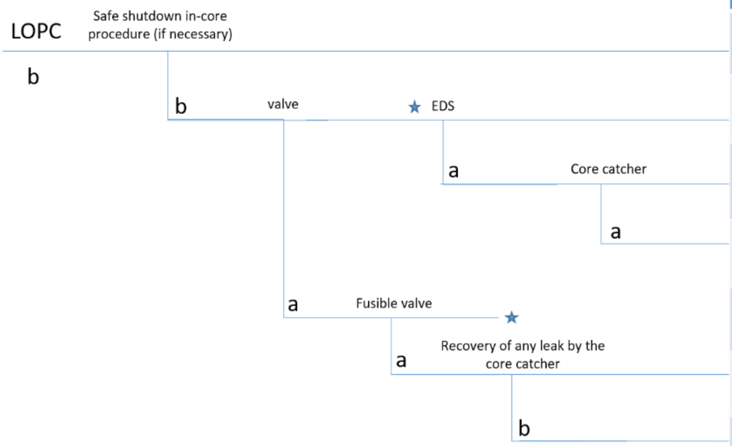
- Reactivity insertion
- Loss of fuel flow
- Increase of heat extraction/over-cooling
- Decrease of heat extraction
- Loss of fuel circuit tightness
- Loss of fuel composition/chemistry control
- Fuel circuit structures over-heating
- Loss of cooling of other systems containing radioactive materials
- Loss of containment of radioactive materials in other systems
- Mechanical degradation of the fuel circuit
- Loss of pressure control in fuel circuit
- Conversion circuit leak
- Loss of electric power supply

This list will be updated with the progress of the MSFR safety analysis if other phenomena are identified.

The method of the Lines of Defense (LoD) has been applied for the MSFR during nominal power production [Beils et al., 2019]. The following rules have been proposed for a preliminary allocation of the LoD:

- Sequences or situations which could significantly impair the reactor availability or which could lead to limited radiological releases should at least be prevented by one medium line of defense;
- Sequences or situations which could significantly impair the reactor investment (or which could lead to significant radiological releases (with no need for off-site confinement measures) should at least be prevented by one strong line of defense;
- Sequences or situations which could threaten safety (with the loss of one of the three safety function or the occurrence of a severe accident situation if any is identified for the MSFR), with potentially important radiological releases should at least be prevented by two strong and one medium lines of defense.

An example of the LoD analysis of the Loss of Pressure Control event for the MSFR is given in Figure 15.



Number and quality of LODs	Consequences
b	Safe shutdown
2b (b required)	availability
a+2b (a required)	Investment (to be confirmed)
2a+2b (2a +b required)	Safety ? (to be assessed)
2a+2b (a required)	Investment (to be confirmed)
2a+3b (2a +b required)	Safety ? (to be assessed)

Figure 16: Line of Defense analysis of the Loss of Pressure Control event for the MSFR-F

In addition to the risk analysis performed up to now, coupled to multiphysics calculations are done to evaluate each identified scenario, using among others the codes TFM-OpenFOAM and TFM-Star mentioned in section 5.3.1 [Laureau, 2015; Laureau et al, 2017; Sornay, 2024].

In addition to the above-mentioned risk analysis studies, work on safety paradigms and their application to MSRs, based on the case of the MSFR, has been started within the framework of an IAEA working group on the safety of non-PWR reactors [Merle et al, 2022].

5.4 Summary and adequation of the available data with the work in ENDURANCE

The MSFR-F has been used as working horse in the previous EU MSR projects (EVOL, SAMOFAR, SAMOSAFER) while the MSFR-Cl has been developed in the frame of the SAMOSAFER project, and the RAPTOr concept is used as working horse in the MIMOSA EU project. All the data obtained by CNRS and the ENDURANCE partners working on MSFR may thus be made available for the project depending on the need of WP 2 to 6.

6 Stellarium

6.1 Presentation and development status

Stellaria is a French startup founded by experts from the Commissariat à l'Énergie Atomique (CEA) and Schneider Electric. The company is developing the Stellarium reactor, a molten chloride salt fast breeder reactor. Two designs are being considered: a 250 MW_{th} version and a scalable concept capable of delivering up to 500 MW_{th}. These reactors are designed to provide both electricity and high-temperature steam, with applications to energy-intensive industries like data centers or heavy industries.

The reactor utilizes natural convection in the fuel vessel to carry heat from the core to the primary heat exchanger, reducing mechanical complexity and enhancing reliability. The core achieves iso-reactivity, maintaining a stable reactivity balance over time due to in-core breeding and burning processes. This allows for long operational cycles of up to 20 years without refueling. The fuel salt contains a mixture of uranium, plutonium, thorium and optionally minor actinides, supporting a closed fuel cycle that minimizes waste.

The Stellarium reactor operates at low pressure, which, combined with passive safety features like a strong negative temperature reactivity coefficient, ensures a good behavior under transient conditions like reactivity insertions or loss of flow.

The conceptual design phase was completed at the end of 2024: it encompasses the entire reactor building, including all critical components and systems. This includes the reactor core, the fuel-to-primary heat exchanger, the primary-to-intermediate heat exchanger, and essential systems such as fission gas management, draining tanks, and circuits for both the fuel salt and primary coolant.

6.2 System description

6.2.1 Plant overview

A schematic view of the reactor building is presented in Figure 17 and Figure 18. Each reactor cell houses a Stellarium fuel vessel, connected to a molten chloride primary circuit via a plate heat exchanger located at the top of the fuel vessel.

Each reactor cell incorporates the following equipment:

- The fuel vessel serves as the first barrier, containing the molten salt fuel.
- A secondary vessel, surrounding the fuel vessel and connected to dedicated drain tanks, serves as the second barrier in the event of fuel vessel leakage.
- The secondary vessel contains a fission gas management system above the fuel vessel to handle radioactive gases.
- A lead neutron reflector is employed to scatter neutrons back into the core while preserving a fast neutron spectrum. Additionally, a neutron shield minimizes neutron leakage and activation of surrounding structures, allowing for safe operator access to the reactor cell shortly after shutdown.
- The reactor cell is sealed with a steel liner, forming the third barrier.

The reactor building itself serves as the fourth and final containment barrier.

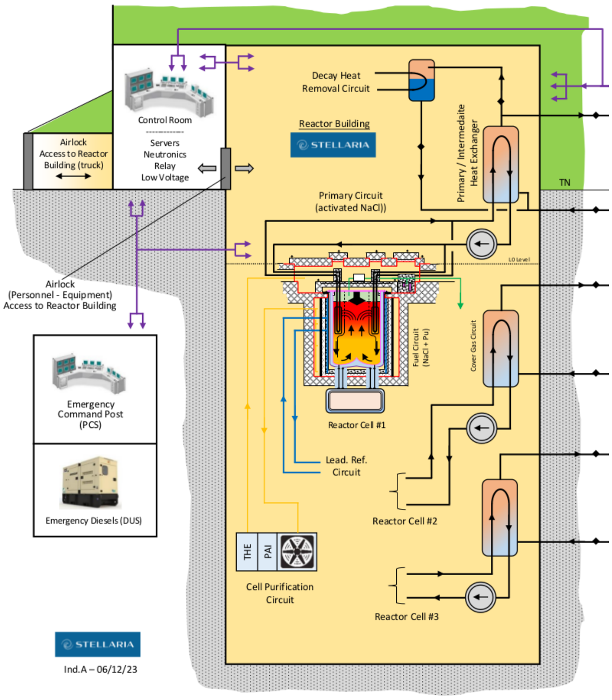


Figure 17 : Reactor building layout

The activated primary circuit remains entirely within the reactor, while the non-activated intermediate circuit, which transports heat to the conventional island, exits the reactor building for power conversion processes.

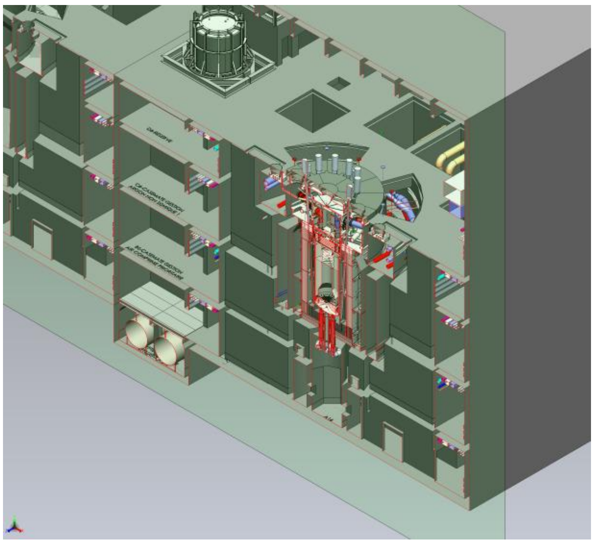


Figure 18 : 3D view of the reactor building

6.2.2 Fuel circuit / core description

The fuel salt in the Stellarium reactor is a molten mixture of sodium chloride containing fissile material (plutonium or enriched uranium) and fertile material (depleted uranium and thorium).

Thorium serves a dual purpose: as a fertile material for breeding and to reduce the melting temperature of the salt.

The reactor vessel, made of Inconel-625, is filled with this fuel salt. A plate heat exchanger is positioned at the top, around the periphery of the vessel, to transfer heat from the fuel salt to the primary circuit, which also operates with molten salt. The chimney inside the vessel serves two purposes:

- Separate the hot leg and the cold leg, guiding the upward flow at the center, and the downward flow at the periphery,
- center the neutron flux distribution on the lower part of the vessel. Indeed, the upper part of the chimney contains neutron-absorbing material ensuring that the neutron flux remains concentrated in the active core region, increasing height difference between the core and the heat exchanger and reducing structural activation in the heat exchanger and the upper part of the reactor.

The height difference between the core (the hot point) and the heat exchanger (the cold point), and the low pressure drop of the heat exchanger, allows natural convection to drive the fuel flow. This natural circulation eliminates the need for pumps within the vessel.

In operation, the fuel salt is heated to approximately 700°C in the core due to fission reactions. The heated salt rises to the top, where it passes through the heat exchanger and transfers thermal energy to the primary coolant. The salt then cools to around 500°C and descends back to the core.

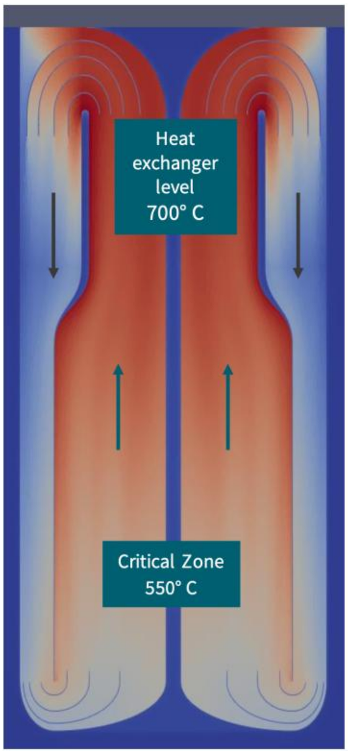


Figure 19: Temperature field of the fuel salt

The design ensures iso-reactivity, a significant advantage over traditional solid-fuel breeder reactors. In solid-fuel systems, fissile material depletes in the core and accumulates at the periphery, reducing reactivity over time. In contrast, the homogenous mixture of fissile and fertile materials in the fuel salt, combined with its continuous circulation, keeps the fissile concentration uniform throughout the core. This results in nearly constant reactivity over the fuel cycle, allowing for long operational periods of up to 20 years without refueling.

Iso-reactivity also reduces the need for reactivity control equipment. The reactor relies on inherent neutronic stability due to its strong negative temperature feedback. Any temperature increase reduces reactivity, leading to rapid, self-regulating behavior. This feedback mechanism eliminates the need for emergency control rods. Instead, the reactor includes slow-acting control rods, primarily used to maintain subcriticality during shutdowns and to compensate for small reactivity variations over time.

6.2.3 Other circuits and systems (intermediate, conversion, RHR, etc)

The scope of Stellaria's design is focused on the reactor building, which includes the reactor core, the primary circuit up to the primary-to-intermediate heat exchanger, and all associated safety systems such as fission gas management and drain tanks.

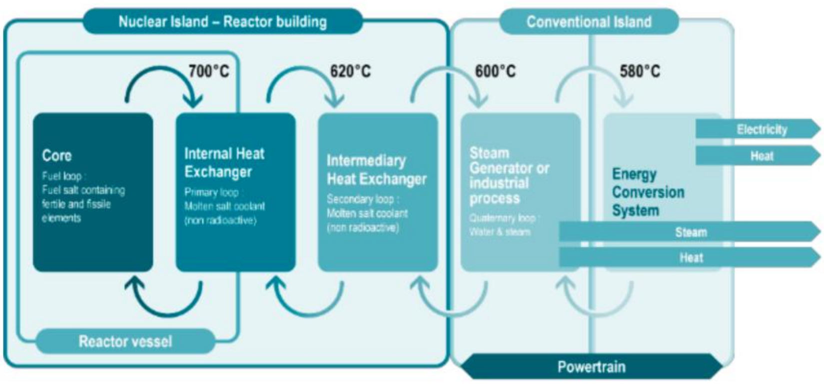


Figure 20: Sketch of the main circuits

The primary circuit, which is activated due to its direct connection to the reactor core, remains entirely within the reactor building to ensure containment of radiological hazards. It operates with $NaCl$-$MgCl_2$ eutectic. The intermediate circuit, carrying non-activated molten salt, exits the reactor building and connects to the conventional island, where it drives the steam generator and power conversion systems.

6.2.4 Fuel characteristics and processing

The Stellarium reactor uses a molten salt fuel composed of sodium chloride ($NaCl$) as the primary carrier salt, combined with thorium chloride ($ThCl_4$), uranium chloride (UCl_3), and plutonium chloride ($PuCl_3$) in the following proportions:

- $NaCl$: 55.0 mol%
- $ThCl_4$: 5.0 mol%
- UCl_3: 32.0 mol%
- $PuCl_3$: 8.0 mol%

This mixture is designed to support the reactor's breeding and burning processes while maintaining favorable thermophysical properties, such as a reduced melting point due to the presence of thorium.

Chlorine in enriched to 99% in ^{37}Cl, Uranium is primarily ^{238}U and Plutonium is derived from spent MOX fuel.

The reactor incorporates a system for managing fission gases and volatile chlorides generated by fissions. The system involves weekly degassing of the reactor plenum, where the gas pressure increases by approximately 0.1 bar per week. The degassed materials pass through:

1. Cold Traps (60°C): In order to deposit volatile chlorides (the design is still ongoing).
2. Buffer Reservoirs (0.2 m³): Rare gases undergo decay over one month within the second containment barrier, utilizing four parallel circuits (one per week).

After initial decay, gases are transferred to a secondary system outside the second barrier, which includes:

- Iodine Traps and High-Efficiency Filters: To capture volatile and radioactive isotopes like iodine.
- Storage Reservoirs (2 m³): For a total decay period of 12 months (6 months of filling and 6 months of decay).

The processed gases are then safely released, with emissions limited to levels below 1 µSv, primarily consisting of ^{85}Kr.

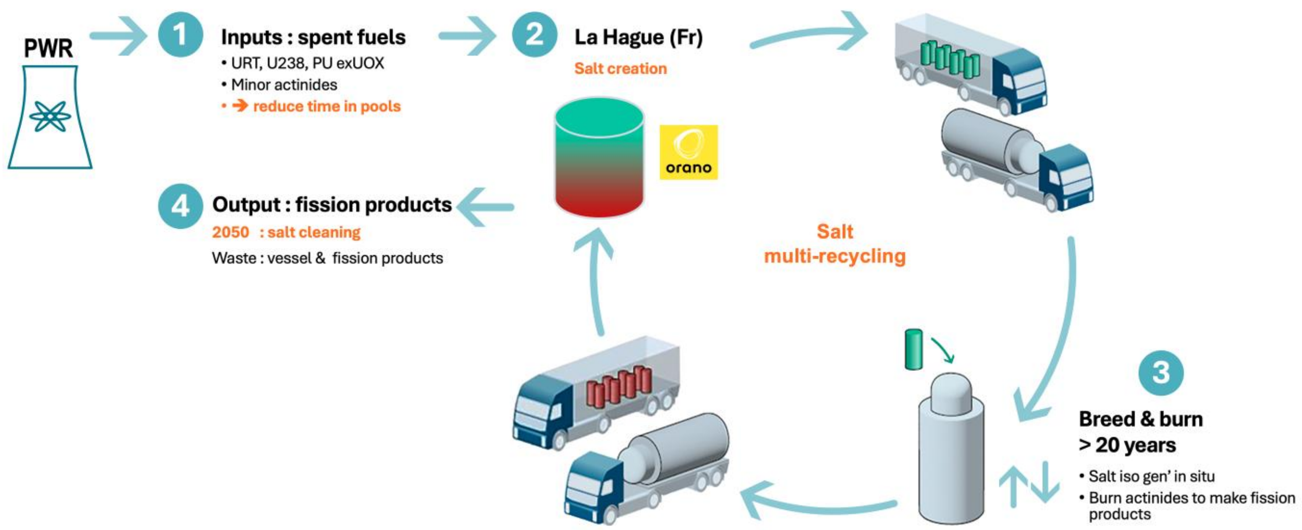


Figure 21: Fuel cycle

While the fuel can be used for at least 20 years, the reactor vessel is planned to be replaced every 10 years. During vessel replacement, the fuel salt is drained into storage tanks and put back in the vessel at the end of the maintenance. At the end of the 20-year fuel cycle, the spent fuel salt is sent to the La Hague reprocessing plant in transport casks.

6.3 Elements on reactor operation and safety

The power output of the reactor is directly governed by the extracted power at the turbine, allowing for rapid load-following capability. This feature makes the reactor highly adaptable to varying power demands, a key requirement for integration with industrial processes or grid systems with renewables. One can see in Figure 22 a simulated load following on a 500MWth Stellarium. The scenario is as follows:

1. Nominal state
2. 100% to 50% primary flow rate in 10s
3. Keep 50% primary flow rate during 100s
4. Back to 100% primary flow rate in 10s

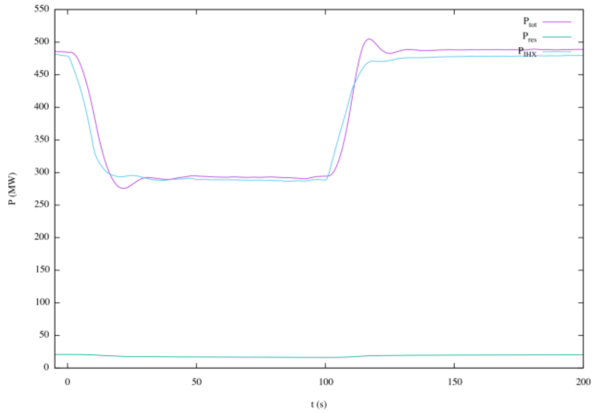


Figure 22: Generated and extracted power during a load following transient

Decay heat

Decay heat is passively removed through radiation from the reactor vessel to the surrounding reflector. The reflector is cooled using a system of boiling water tanks connected by natural convection. This passive cooling mechanism ensures effective heat removal without relying on active components such as pumps, enhancing the system's reliability during both normal operation and transients.

Safety

Unlike traditional reactors where severe accidents may require countermeasures for the public, the Stellarium reactor is designed to eliminate any off-site consequences under all scenarios. This is critical for public acceptance, especially since the reactor is intended for deployment near cities or industrial sites. The safety design ensures that radiation exposure at the site boundary remains below 1 mSv, even in the most severe events.

The reactor achieves this high level of safety through several inherent and engineered features:

- Strong neutronic feedback: the reactor exhibits strong negative temperature coefficients, ensuring self-regulation during temperature excursions.
- Absence of pressure: operating at near-atmospheric pressure reduces the risk of pressure-induced failures.

- Pump-free design: natural convection drives fuel salt circulation, eliminating mechanical failure risks associated with pumps.
- Iso-reactivity: the homogeneous mixing of fissile and fertile materials ensures stable reactivity over time, reducing the need of reactivity compensation equipment, minimizing the risk of reactivity-driven transients.

The reactor’s response to various transients demonstrates its inherent safety as detailed below.

Reactivity Insertions: In scenarios involving reactivity insertions, the reactor responds with a controlled increase in salt temperature, avoiding damage to the main vessel or other critical components. This behavior will be confirmed in a 100 kW mockup. One can see in Figure 23 and Figure 24 the evolution of the power and maximum temperature in the 500 MW reactor during a 500 pcm reactivity insertion in 100 ms. Starting from a uniform 500°C state, the maximum temperature is less than 550°C at the end of the transient.

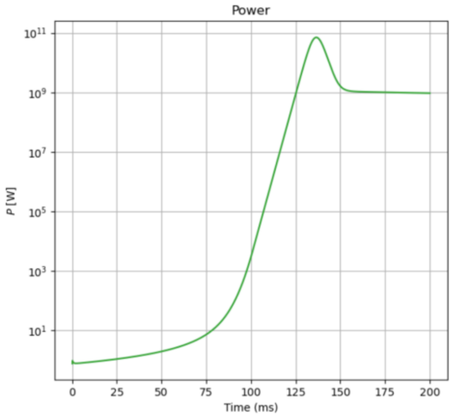


Figure 23: Generated power during a 500pcm reactivity insertion

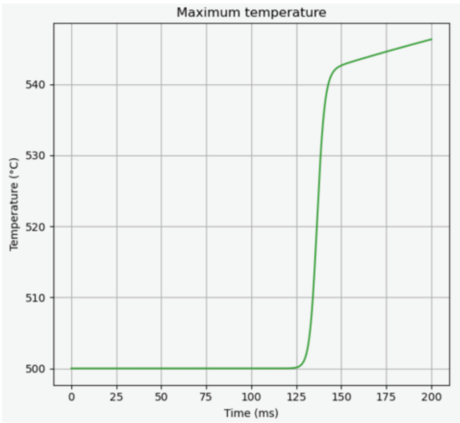


Figure 24: Maximum temperature evolution during a 500pcm reactivity insertion

Loss of Flow Transients: Even in unprotected loss-of-(primary)flow conditions, the temperature stabilizes at safe levels due to passive heat removal via radiation to the reflector, which is cooled by the boiling water system. In the short term, the power decreases rapidly, as shown in Figure 25, where the primary flow rate drops from 100% to 3% with a halving time of 5 seconds.

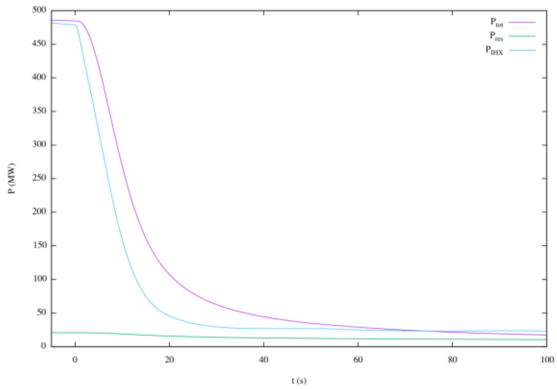


Figure 25: Generated power evolution during an unprotected loss of primary flow

Vessel Leak: In the event of a vessel leak, the salt would flow into the secondary containment vessel, which is connected to drain tanks. These tanks are designed to passively extract decay heat, ensuring safe containment and cooling of the salt.

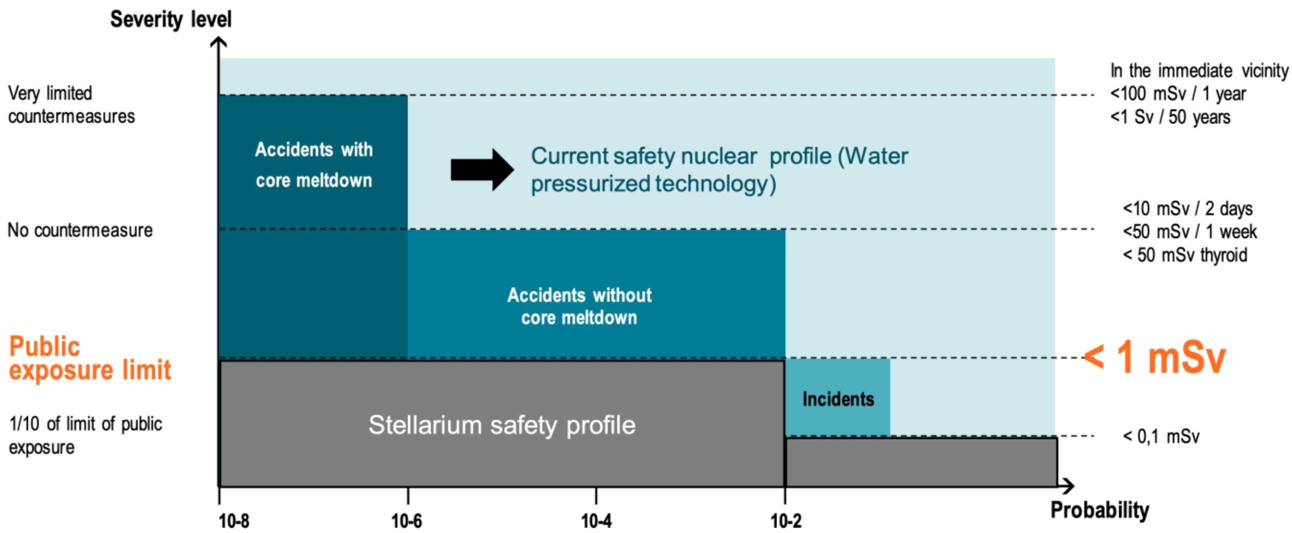


Figure 26: Farmer diagram for the Stellarium system

6.4 Summary and adequation of the available data with the work in ENDURANCE

As part of the ENDURANCE project, Stellaria will provide detailed data on the Stellarium reactor. This includes:

- Fuel Salt and Primary Salt Composition: comprehensive specifications of the chemical and isotopic composition of the fuel salt and the primary circuit salt will be provided, as well as the equation of state used in the design calculations.
- Geometry Description: detailed geometry descriptions of critical reactor components, including the core, reflector, neutron shield, and other key systems, will be supplied.
- Constitutive Materials: Stellaria will deliver precise information on the constitutive materials for each part of the design, including the reflector, neutron shield, reactor vessel and piping.

- Fuel Heat Exchanger: a principle description of the fuel heat exchanger will be provided, including sufficient data for nominal and transient simulation studies.
- Simulations: OpenMC simulations and coupled neutronics-thermalhydraulics simulations using the TRUST-NK code will be provided. TRUST-NK simulations will include steady-state conditions as well as transient scenarios, such as loss-of-flow events.

7 TMSR

7.1 *Presentation and development status*

The design of the Thorizon One molten-salt reactor is based on a modular core approach, in which the core consists of multiple individually contained replaceable modules, named cartridges. Each cartridge consists of a double-layer vessel where the chloride fuel salt circulates and the thermal power generated is exchanged with a secondary coolant salt. The ensemble of the cartridge makes up the core, which is of fast spectrum type. When the cartridges are removed, the reactor has no primary circuit and no primary circuit components. Additionally, the reactor has no fixed large pressure vessel. The technology basis is flexible and allows larger and smaller systems, either by larger or smaller modules, or by more or less modules. The technology offers fuel cycle flexibility, with first goal to burn LWR-plutonium and commercialize, which can be followed by advanced versions on the same technology basis in which U-breeding can be included, and fuel cycles can be closed.

Thorizon has finalized the conceptual design phase, has a positively evaluated patent, and successfully passed technical due diligences by third parties, and has secured the finances to enter the detailed design phase and execute a molten salt irradiation program.

7.2 *System description*

7.2.1 **Plant overview**

The plant layout consists of the nuclear island or reactor building and the conventional island or the power storage and conversion building. Other buildings are also part of the plant, as the office and staff building, the logistics building, the auxiliary building, etc. Figure 27 illustrates the main hydraulic systems of the plant: in the nuclear island the core (made of 19 cartridges) is located inside a reactor cavity. The power generated in the fuel salt is removed via a secondary salt cooling system which is transferred to a tertiary salt circulation system (outside the nuclear island), that is connected to the salt thermal storage tanks. Eventually, the thermal power is transferred to water in a conventional Rankine steam/water cycle system, for electricity generation.

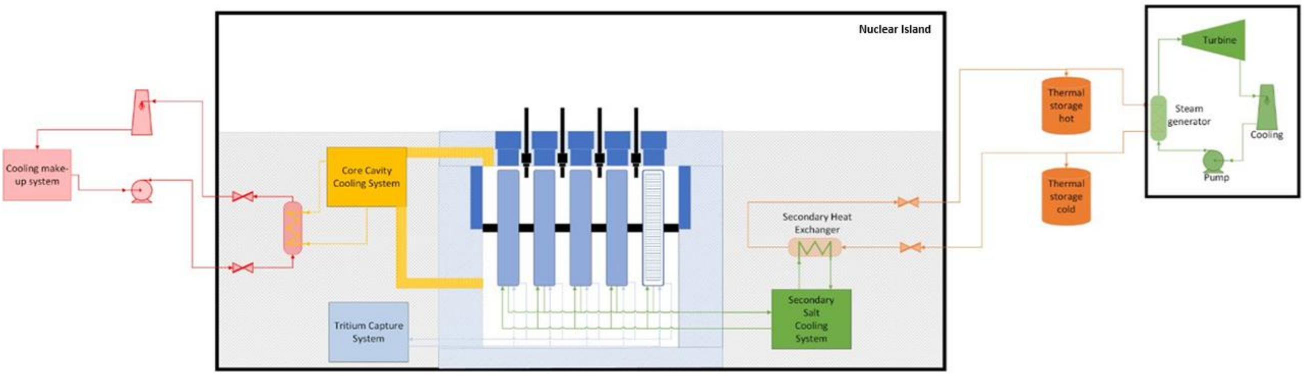


Figure 27: Schematic representation of the Thorizon One plant

7.2.2 **Fuel circuit / core description**

The core is composed of 19 cartridges that are placed inside a cylindrical reactor cavity region, filled with circulating gas (CO_2) for the cooling of the structural or core auxiliary elements as support structures, control rods, reflector blocks, etc. Each cartridge contains a centrifugal pump and a heat exchanger, located at the bottom end (see also Figure 28). Each cartridge contains a specific amount of fuel salt, a mixture of NaCl with U, Th and Pu chlorides, and a Helium gas pocket to accommodate for pressure build-up during operation. The nuclear power is generated in the fuel salt when it is circulated inside each cartridge. The arrangement of the radial and upper reflector structures in the reactor cavity, and the neutron reflecting and absorbing material inside each cartridge, is designed such that the criticality can be achieved in the upper part of the core only as long as the fuel salt is circulated by the pumps in all the cartridges. The gas pocket is relocated to a specifically designed plenum region in the middle of the cartridge when the pumps are operated (Figure 28, left picture). As soon as the pumps are stopped, the gas pocket rises at the top and the core becomes subcritical (Figure 28, right picture).

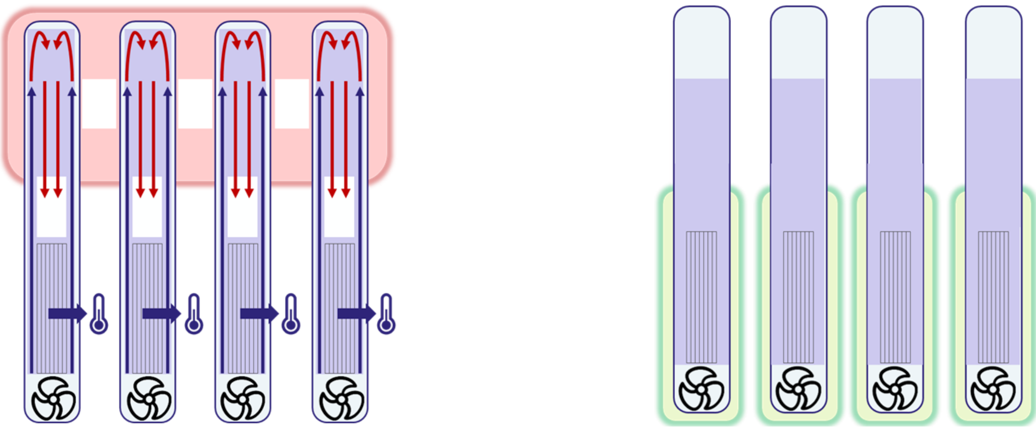


Figure 28 : Schematic representation of the reactor core operating principle – power mode when all cartridge pumps are active (left); shutdown mode when pumps are off (right)

The thermal power generated in the fuel salt is extracted via the primary heat exchanger by the secondary salt coolant. Such heat exchanger is manufactured inside each cartridge and is equipped with two pipes that extend through the lower dome of the cartridge, namely the hot and cold HX legs, that can be connected to the fixed part of the secondary salt circuit.

Control rods are used for normal start-up, shutdown and power operation as well as for any operation of the reactor foreseen in the technical specifications.

7.2.3 Other circuits and systems (intermediate, conversion, RHR, etc)

Each cartridge of the core contains a shell-tube type heat exchanger, with the fuel salt flowing in the shell side and the secondary cooling salt in the tubes. The tube sides of these primary heat exchangers are part of the secondary salt cooling system. Such system is designed to remove in normal operating conditions the nuclear thermal power generated in the fuel salt of the reactor core. The secondary salt is a low activating chloride salt with appropriate properties. The secondary salt cooling system is made up of different parallel loops and consists of a traditional pipe network which includes a circulation pump, a secondary heat exchanger between the secondary and tertiary salt heat transfer and auxiliary systems such as the salt purification system, the secondary salt drain tank, etc.

The tertiary salt cooling system represents the heat sink of the plant in normal conditions. A circulation pump drives the tertiary salt through a closed loop, extracting the thermal power from the secondary salt in the secondary heat exchangers and rejecting the heat in the steam generator of the conventional steam/water power conversion system (Rankine cycle), where eventually either high pressure steam or electricity is delivered to the final user. The tertiary salt cooling system is also connected to a couple of hot and cold salt tanks, respectively on the hot and cold legs of the circuit, that can be used for intraday thermal storage in order to tune the amount of power or steam to be produced to demand, while maximizing reactor uptime.

The core cavity cooling system represents the second cooling system of the Thorizon One reactor. It consists of a low-pressure CO_2 gas circulation system for the cooling, in normal operations, of the irradiated elements inside the reactor cavity, namely the radial and axial reflectors, the supporting structures, the outer containments of the cartridges, the control rods, etc. The power is rejected to the ultimate heat sink via a set of gas/water heat exchangers. During accidental scenarios, a dedicated system is adopted for the decay heat removal. This system can guarantee its functionality even in case of complete loss of electrical power, via natural circulation.

7.2.4 **Fuel characteristics and processing**

The fuel salt used is a quaternary mixture of NaCl with U, Pu and Th chlorides. The fuel salt is designed to consider a plutonium isotopic vector that is typical of the output of the reprocessing process of current LWRs, with enriched Uranium and Thorium chlorides fractions. Redox potential control in the fuel salt is obtained via the presence of sacrificial anode material inside the cartridge.

The cartridges making up the reactor core are closed systems, therefore no purification, bubbling or off-gas system is connected or present during reactor operations. The build-up of gaseous and highly volatile fission products, and the corresponding pressure build-up, are accommodated in the design of the cartridge by the presence of a gas plenum. The reactivity penalty due to the lack of FP purification is also accommodated in the design by salt composition and is limited due to the fast spectrum of the reactor.

The manufacturing of the fuel salt is performed outside of the reactor site. The salt is shipped to the reactor and cartridges are filled and sealed on site. The spent cartridges are stored after irradiation and transported to a dedicated reprocessing facility. The front and back end strategy of the fuel salt cycle is currently defined along with industrial partnerships, but not disclosable at present.

7.3 Elements on reactor operation and safety

The Thorizon One plant includes active safety control during operational transients and mostly passive safety features and engineered safety systems for design basis and design extension events. By design, the low pressure in the primary system (cartridges), which can be maintained as such under all credible circumstances, reduces the stresses on primary components and prevents from generating overly large energy release in case of hypothetical severe accidents.

The core is designed to maintain a negative void reactivity coefficient in all modes of operation. Control rods are used to control reactivity for all operational and design basis events, and for shutdown. Another shutdown system is established by gravity-driven passive drainage of the fuel salt in the cartridges, in case of station blackout and other hypothetical events.

Cooling of the fuel salt is assured by the secondary salt cooling system in normal operating conditions and some specific operational transients. The core cavity cooling system or the emergency core cavity cooling system are adopted for decay heat removal in some operational transients and design basis events. The emergency system can operate in natural circulation for the decay heat removal during design extension conditions and hypothetical accidents.

Defense-in-Depth is incorporated by adopting multiple barriers. Three barriers are foreseen by design for the core, fresh and spent fuel storage. Additional physical barriers are interposed between the core and the environment, although not explicitly considered as DiD safety barriers. Pressure escalation in the primary containment of the cartridges is limited by design, with a secondary containment to avoid release in case of primary containment failure. Passive safety features, passive reactivity control and external impact barriers, largely reduce core damage and release probability to very low levels. Station blackout scenario is managed by passive cooling as well, providing indefinite grace time.

7.4 Summary and adequation of the available data with the work in ENDURANCE

The main characteristics of the Thorizon One reactor are summarized in Table 8. The release of design sensible information for WP3, WP4 and WP6 will be provided to the extent possible in accordance with the company internal policy.

Table 7: Characteristics of the Thorizon One reactor.

Parameter	Value
Technology developer, country	Thorizon, France/Netherlands
Thermal/electrical capacity, MW(t)/MW(e)	250/100
Fuel circuit circulation	Forced circulation
Hydraulic Circuit Operating Pressure (fuel/intermediate), MPa	< 1.0/< 1.0
Fuel type	NaCl + (U,Th,Pu)Cl_x
Initial fissile inventory	TRU
Core Inlet/Outlet Coolant Temperature (ºC)	> 500/ < 700
Online reprocessing	None
Moderator	None
Power conversion process	Salt thermal storage + steam/water Rankine (Hirn) cycle
Core Discharge Burnup (GWd/ton)	*N/A*
Refuelling Cycle (months)	Continuous operation for at least 5 years, to be extended with new cartridge versions
Reactivity control mechanism	Control rods adjustment, temperature feedback
Approach to safety systems	Active and passive
Design life (years)	5-10 for each cartridge, 60 for the whole plant
Plant footprint (m^2)	*N/A*
RPV height/diameter (m)	*N/A*
Fuel cycle requirements / Approach	LWR spent fuel initially (burning), depleted U in future breeding scenario's
Distinguishing features	Modular and replaceable core, no fuel online reprocessing/purification, passive reactor shutdown
Operation	Human operators
Design status	Finalized conceptual design

8 XAMR

8.1 Presentation and development status

The XAMR (eXtra small Advanced Modular Reactor) is a small modular, molten chloride salt-fueled and -cooled fast neutron spectrum reactor with a reference nominal power of 80 MW_{th}. The XAMR aims to burn the excess plutonium and minor actinides from the existing UOX and MOX cycles. NAAREA is planning to build and test a first reactor in the late 2020's, before launching serial production.

The XAMR is intended as an industrial heat and/or electrical power source providing the most flexibility possible to an industrial customer. NAAREA will build, own and operate the reactor and sell power to its customer. To increase the flexibility even more, the fuel salt loop, the coolant salt loop, the off-gas system, and the fuel salt draining systems are built in a modular manner to replace components easily.

NAAREA is still exploring design ideas, through experiments and simulations.

8.2 System description

8.2.1 Plant overview

The XAMR is a fast-spectrum chloride-fueled and -cooled molten salt reactor with a Silicon carbide core (SiC) and three (fuel, secondary coolant, tertiary coolant) salt circuits.

8.2.2 Fuel circuit / core description

The core is a 130x110x60 cm plate heat exchanger designed with criticality and manufacturing limitations in mind and thus exchanging only part of the power generated in the fuel salt. The fuel salt volume is 395 l in core (46% volume fraction of the core) and 1635 L total, and the plate material volume fraction is 30%, the leftover 24% volume fraction represent coolant salts. The Silicon carbide is expected to contain approximately 1000 wppm Boron, which can be depleted in ^{10}B to improve performance.

Fuel circulation in the fuel circuit is established by forced convection using centrifugal pumps. The fuel circuit can be drained by a syphon system by introducing a slight pressure differential into two fuel drain tanks where residual heat is removed from the fuel by two circuits.

A 50 cm thick reflector surrounds the core to improve the neutron economy, both the core and its reflector are made of silicon carbide composite (SiC-SiC). NAAREA selected silicon carbide for its low neutron absorption rate as well as its high temperature and corrosion resistance.

Reactivity control mechanisms (rotating control drums and gravity-driven shutdown rods) composed of enriched Boron carbide (>90% ^{10}B) are inserted in the reflector.

8.2.3 Other circuits and systems (intermediate, conversion, RHR, etc.)

Each fuel salt loop heat exchanger is connected to a separate $NaCl-MgCl_2$ (58-42 mol%) coolant salt loop, making heat extraction robust to single failure. In addition, these coolant salt loops are slightly pressurized relative to the fuel salt loop to ensure radionuclide confinement in case of a leak.

The two secondary coolant salt loops are then linked to a tertiary coolant salt loop which either delivers heat to the customer or to a supercritical CO_2 power conversion system to make lower temperature industrial heat and/or electricity, respectively.

Residual heat removal from the fuel drain tanks is achieved by two independent systems: one active, one passive. The active system removes heat by circulating coolant salt in the drain tank through forced convection and rejecting heat into the atmosphere. The passive system uses heat pipes inserted in the drain tanks to transfer heat to a separate, natural convection loop which rejects heat to the atmosphere.

8.2.4 **Fuel characteristics and processing**

The fuel salt used is NaCl-(U,Pu)Cl_3 at the actinide trichloride fraction of the NaCl-PuCl_3 eutectic, i.e. 36%mol. The XAMR being designed for a variety of plutonium isotopic vectors, the UCl_3 fraction is adjusted to compensate for the reactivity of more favorable plutonium and chlorine isotopic vectors. A minimum fraction of 1 mol% UCl_3 is maintained for reasons of redox potential control in the fuel salt.

NAAREA plans to use ^{37}Cl-enriched chlorine in the fuel and secondary coolant salts to minimize the radioactive waste production and further improve the neutron economy of the reactor. The base salt would be recycled in the processing scheme to avoid losses of enriched chlorine in the waste stream.

Gaseous and volatile fission products are extracted at the expansion tank of the fuel circuit, which is situated in the pump bowl. No active He bubbling system is foreseen and the extraction rates are expected to be lower than those of historical MSR designs. The reactivity penalty can be tolerated due to the fast spectrum of the reactor.

Gases and volatile fission products are then handled by the off-gas system, which separates fission products from the gas stream depending on their physical (solid, liquid, gaseous) and chemical characteristics and the He carrier gas is recycled.

It is foreseen to recycle the plutonium at the end of cycle in a dedicated off-site facility. The salt would be refueled with plutonium actinides and shipped back to the reactor. A specific fuel processing scheme cannot be provided at this time.

8.2.5 **Power conversion system**

The heat generated in the fuel circuit is transferred to a tertiary fuel salt and can then be used for industrial heat applications and/or converted to electricity via a supercritical CO_2 turbine (see Figure 29 below) and associated components. The low-temperature waste heat can be recovered for simple industrial needs such as heating of buildings.

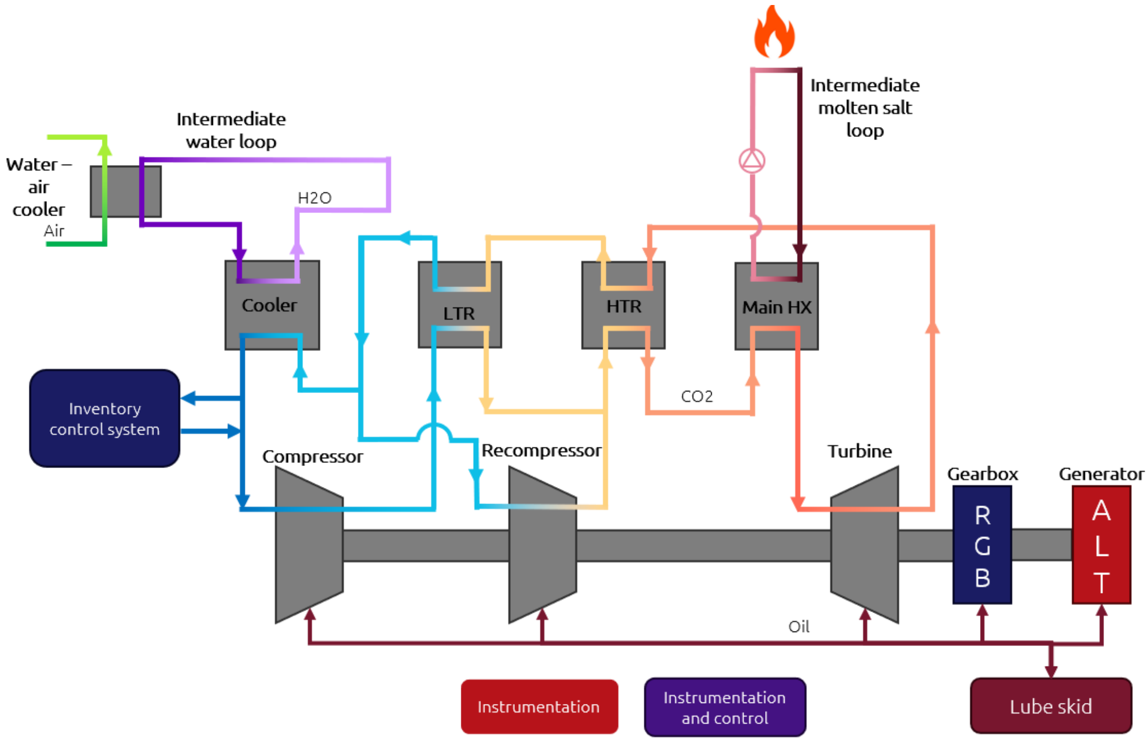


Figure 29: Layout of the sCO_2 power conversion system

8.3 Elements on reactor operation and safety

Power and fuel temperature are adjusted primarily using the control drums and coolant pump speeds. The fuel salt pump speed can be varied in some operating conditions.

Reactivity control is fulfilled by several independent redundant systems. Excess reactivity at beginning of cycle is controlled by slowly rotating control drums with a semi-circular boron carbide sector outwards during the cycle (the end of cycle being defined as zero reactivity with control drums fully rotated outwards). Normal shutdown can be achieved by rotating the control drums inwards. A separate reactivity control system is based on gravity-driven shutdown rods, which can be dropped in the reflector to rapidly shutdown the reactor. Finally, the fuel salt draining system can be actuated if shutdown margins are threatened during e.g. overcooling transients. The core is designed to maintain a negative void reactivity coefficient in all modes of operation.

Heat removal is obtained through the normal coolant loops in normal operation. The fuel salt can also be drained in case of loss of normal heat sink or coolant flow to remove residual heat through independent active and passive systems connected to the drain tanks.

The containment function is fulfilled by three barriers including the fuel circuit, the guard vessel in an Argon atmosphere around the reactor which is designed to redirect fuel salt leaks to the drain tanks, and the containment structure around the nuclear island.

8.4 Summary and adequation of the available data with the work in ENDURANCE

The main characteristics of the XAMR are summarized in Table 8.

Table 8 : Characteristics of the XAMR

Parameter	Value
Technology developer, country	NAAREA, France
Thermal/electrical capacity, MW(t)/MW(e)	80 / up to 40 MWe gross
Fuel circuit circulation	Forced circulation
NSSS Operating Pressure (fuel/intermediate), bars	1 + circuit head loss
Fuel type	NaCl-(U,Pu)Cl_3 (64-x-(36-x) mol%
Coolant type	NaCl-$MgCl_2$ (58-42 mol%)
Core Inlet/Outlet Coolant Inlet/Outlet Temperature (°C)	594 / 750 (fuel salt)– 550 / 682 (coolant salt)
Core dimensions (cm)	130x110x60 + 50 cm reflector on all sides
Core and reflector material	SiC/SiC composite (+1000 wppm Boron)
Fuel salt volume (in-core/total) (L)	395/1635
Power conversion process	Industrial heat (~650°C) and/or sCO2 power conversion system Low-temperature waste heat can be used if needed
Refueling Cycle	3.2 EFPY, single-batch
Reactivity control mechanism	Control drums and Shutdown rods
Approach to safety systems	Active + Passive
Fuel cycle requirements / Approach	Plutonium and minor actinides burning Fission products are extracted by pyroprocessing
Distinguishing features	Heat exchanger core (neutronically heterogeneous) and two coolant salt loops
Design status	Basic design

The salts used are standard for most chloride-fueled MSR designs. Thermophysical data is available from MD calculations which are partially validated on measurements. The core can be well approximated by smearing the materials in an homogeneous manner.

The following data will be shared in the ENDURANCE project:

- Core data for the reactor (operation point, fuel evolution, transient behavior)
- Loop operation data for a SiC natural convection loop

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List of Figures

List of Tables