SNETP

Sustainable Nuclear Energy Technology Platform

Strategic Research Agenda - Annex

January 2012

Molten Salt Reactor Systems

www.SNETP.eu

Table of contents

Molten Salt Reactor Systems

1 - Introduction

New and demanding goals have been assigned to the reactors of the future. They must use the natural resources more efficiently while offering options for a better management of the nuclear waste. In this context, there is currently a renewed interest in molten salt reactors. This is due to recent conceptual developments on fast neutron spectrum molten salt reactors (MSFRs) using fluoride salts. These open promising possibilities to exploit the 232Th-233U cycle. On the other hand, they can also contribute to significantly diminish the radiotoxic inventory from present-reactors spent fuels in particular by lowering the masses of transuranian elements (TRU).

These MSFRs have large negative temperature and void reactivity coefficients, a unique safety characteristic not found in solid-fuel fast reactors. Compared with solid-fuelled reactors, MSFR systems have lower fissile inventories, no radiation damage constraint on attainable fuel burn-up, no spent nuclear fuel, no requirement to fabricate and handle solid fuel, and a homogeneous isotopic composition of fuel in the reactor. These and other characteristics give MSFRs potentially unique capabilities and competitive economics for actinide burning and extending fuel resources.

Finally the development of high temperature salts as fuel and coolant may open new nuclear and non-nuclear applications.

2 - Present Concept

The reference Molten Salt Fast Reactor or MSFR is a 3000 MWth reactor with a total fuel salt volume of 18 m^3, with a mean operation temperature of 700°C.

In order to initiate work and discussions on possible ranges for physical and chemical parameters, basic drawings have been done in relation to calculations. The Fig.1 describes ones of the possible geometrical configurations (height/diameter ratio = 1). The core consists of a compact cylinder where the liquid fluoride fuel salt is flowing freely from bottom to the top of the central part without any solid moderator. The back circulation of the salt (from the top to bottom) is divided into 16 groups of pumps and heat exchangers located around the core. A fertile salt blanket (Th loaded liquid fertile salt) in red in Fig.1 is placed between the central canal and the surrounding heat exchangers/pumps groups.

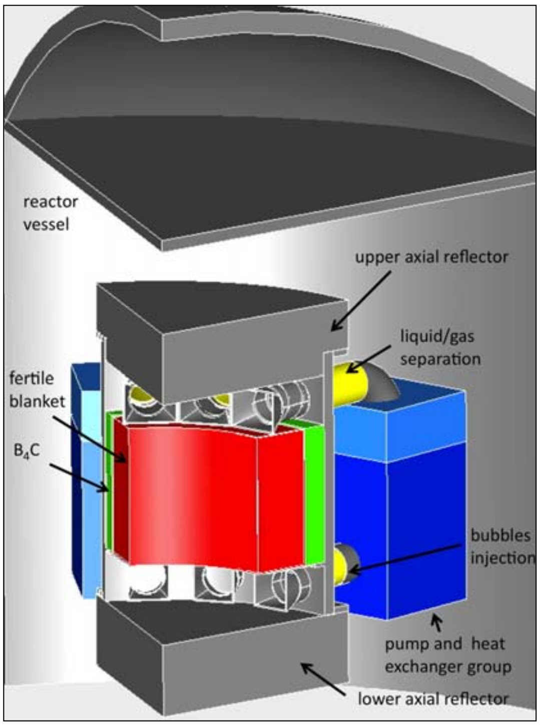

Fig. 1 Schematic view of the MSFR general concept

Salt cleaning involves two processes. One is performed in line. It involves the mechanical extraction of rare gases and some noble metals via on-line bubbling process. Removing other fission products from the salt is done in batches on small quantities (typical rate ~10-20l/day) taken from the fuel flow and processed at an on site facility close to the reactor.

The fuel salt is a binary fluoride salt, composed of LiF enriched in 7Li to 99.995 % and a heavy nuclei (HN) mixture initially composed of fertile thorium and fissile matter, either 233U, enriched U and/or Pu+MA[1]. The (HN)F4 proportion is set at 22.5 mole % (eutectic point), corresponding to a melting temperature of 565°C. This salt composition leads to a fast neutron spectrum in the core, as shown in Fig.2 where the fast neutron spectrum of the simulated reference MSFR is compared to the spectra of 2 solid-fuel reactors: a Na-cooled Fast Neutron Reactor (FNR-Na) and a thermal Pressurized Water Reactor (PWR).

1 - Minor Actinides

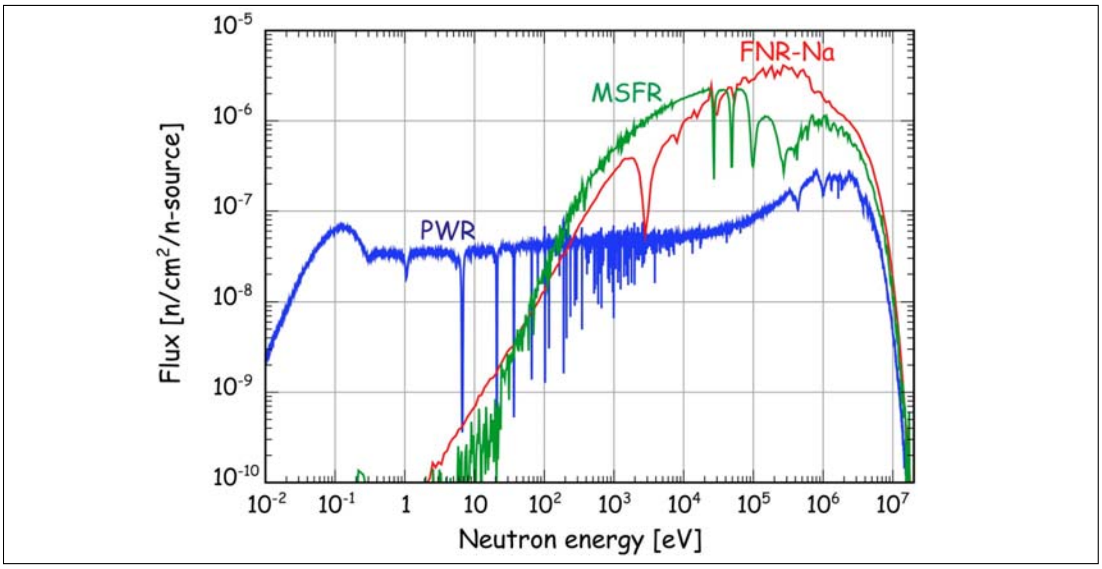

Fig. 2 Fast neutron spectra of the MSFR and of a Na-cooled fast neutron reactor (FNR-Na) compared to the thermalized spectrum of a pressurized water reactor (PWR).

The large Na capture cross-section appears clearly on the red curve at 2.8 keV, while the inelastic cross-section of fluorine is characteristic of the green curve between 0.1 and 1 MeV.

The evaluation of the potential of such a reactor is shown on the Fig.3, when operated either in the 232Th/233U cycle (solid lines) or when started with the Pu+MA (TRU) isotopic composition that can be extracted from used Uox fuel discharged from LWR reactors. The initial heavy nuclei inventory per GWe comprises only 3.5 tons of 233U and 26 tons of 232Th.

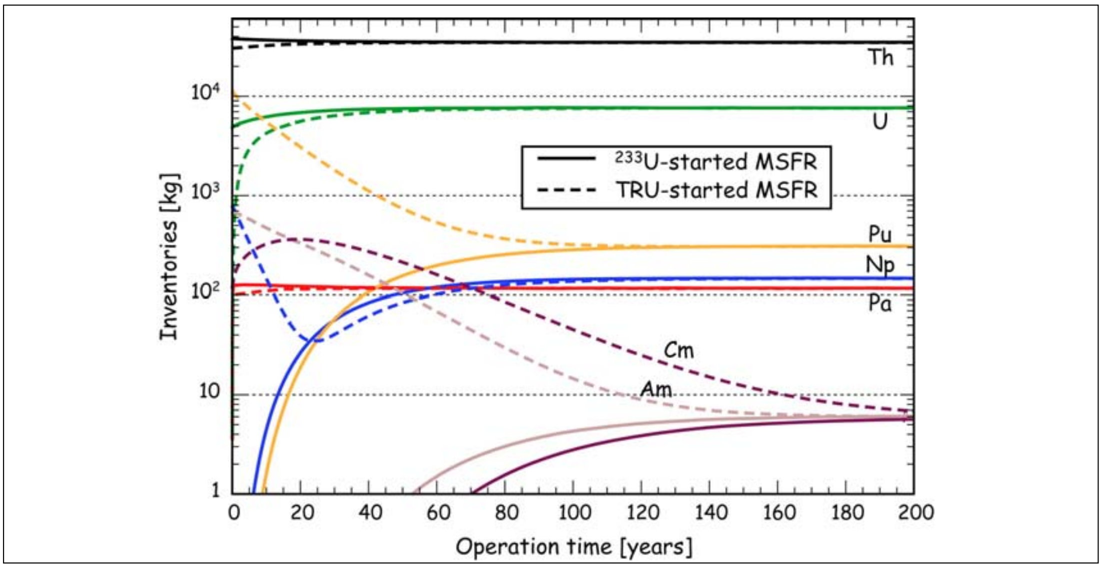

Fig. 3 Evolution of MSFR core composition (kg/GWth). Solid lines correspond to a reactor started with 233U as fissile element while dash lines correspond to the case when the fissile elements are obtained from the TRU extracted from the waste of present LWR

The proportion of minor actinides in the salt remains low: around one percent at equilibrium. It is seen that because of the absence of moderation, a transition can be performed from the waste of the LWR U/Pu cycle to the Th/U cycle. The time scale for an almost complete transition is approximately one century.

An expansion of nuclear electricity generation might require breeding beyond isogeneration. The MSFR would be then asked to prepare 233U material for other reactors.

It is known that in a fast neutron spectrum the breeding potential of the Th/U cycle is less than that of the U/Pu cycle. However, for a MSFR, part of this disadvantage is compensated by its low initial fissile load and by the fact that a new reactor can be started when only one load of fissile material (instead of around 2 cores for a solid fuel reactor) has been produced.

3 - R&D Challenges

The potential of MSFR for breeding and actinide burning has been well assessed. Nevertheless, specific technological challenges must still be addressed and the safety approach established. As a consequence, the present main R&D topics are:

- Structural Materials
- Fuel salt chemistry and properties
- Fuel salt clean-up
- System design, operation and safety

3.1 Structural Materials

The structural materials of the MSFR are located between the fertile blanket and the pump/heat exchanger groups core and at the top and bottom parts. They have to bear the constraints generated by the neutron flux together with the fluoride salts. The former constraint (neutron irradiation) is not in itself much more exacting than for other systems. For instance, the maximum irradiation impact only affects a small slice in the center of the upper axial reflector. It does not exceed 10 dpa per year. Chemical corrosion and abrasion phenomena in moving high temperature salts loaded with fission products, phenomena with still many unknowns today may provide a much greater challenge.

The Oak Ridge program on the molten salt reactor experiment led to the development of the Hastelloy N alloy, essentially a Nickel ternary alloy incorporating 8wt% of Cr and 12wt% of Mo. The composition of the alloy was optimized for corrosion resistance (both in a low oxygen gas atmosphere and in molten fluorides), irradiation resistance and high temperature mechanical properties. The behaviour of this alloy proved satisfactory up to 750°C. However, higher in-service temperatures are desirable in order to reach optimal performances of the present designs of MSFR. It is not clear that the evolving microstructure of Hastelloy N as temperature increases, would allow it to maintain required mechanical and corrosion properties.

Replacing molybdenum by tungsten in the alloy (Ni-W-Cr ternary alloy) may yield the desired improvements. Laboratory scale processing of Ni-W-Cr alloys has been demonstrated recently. These alloys have recently been produced (by A&D, France) in quantities at the level of several hundreds kg. They have been shown to display acceptable workability and welding properties as well as very good high temperature hardness. The full potentialities of these kinds of materials as well as Hastelloy N have yet to be tested and characterized over the full range of temperatures and in presence of the fluoride salts.

3.2 Fuel salt chemistry and properties

Possible salt systems have been critically reviewed and reference compositions proposed or confirmed, in particular within the European ALISIA SSA of the 6th Framework Program. Complementary data have been measured in the ISTC-1606 project conducted in Russia. These studies have led to the selection of the LiF –ThF4 salt loaded with fractions of fissile material (either 233UF4 or [TRU]F3). The heavy nuclei (Th, 233U and transuranian elements) proportion is set at 22.5 mole % (eutectic point), corresponding to a melting temperature of 565°C.

The fissile isotope 233U of the thorium cycle does not exist in nature. Reactor core calculations have nevertheless demonstrated the possibility to achieve its production by first deploying a generation of MSFR using Plutonium and minor actinides of PWR wastes as fissile fuel. Then core criticality is reached for amounts of plutonium close to 5mol %. Under such conditions the fast neutron spectrum makes possible the concept both a burner (minor actinide consumer) and a breeder (producer of 233U). One has to notice that, the amount of data on plutonium chemistry in the fuel salt is limited. In particular, it is not presently known if plutonium can be dissolved in the fuel salt at the desired concentration. Plutonium chemistry in LiF-ThF4 molten salt needs to be studied to determine solubility coefficients and to determine which fissile mixture best fulfils chemical and neutronic criteria.

Liquid-salt chemistry plays a major role in the viability demonstration, with such essential R&D issues as: i) the physico-chemical behaviour of coolant and fuel salts, in the presence of fission products and tritium; ii) the compatibility of salts with structural materials for fuel and coolant circuits, as well as fuel-processing material development; iii) the maintenance, instrumentation and control of liquid-salt chemistry and iiii) safety aspects, including interaction of liquid salts with various elements.

3.3 Fuel salt clean-up

The progress made in core design in the last years has allowed the definition of a workable fuel salt clean-up scheme with a realistic rate (few tens liters per day) and minimized losses to wastes. It is a major achievement since the value of the clean-up flux is almost two orders of magnitude smaller than that of the reference scheme of the MSBR project of Oak-Ridge. Under this new scheme, the treatment of the salt is performed in two ways.

First, there is an on-line gaseous extraction using helium bubbling process which removes continuously gaseous fission products (Xe and Kr) and noble metals particles. The present knowledge on the bubbling salt cleaning is mostly based on the experimental feedback from the reactor MSRE of Oak-Ridge. The second way is an on-site off-line reprocessing line in which some ten litres per day of fuel salt have to be cleaned by pyrochemistry to extract the lanthanides. The actinides are sent back into the core fuel. The respective efficiency for each of both treatments has to be thoroughly assessed for the specific salt selected for the MSFR. Thanks to its fast neutron spectrum, the neutronic characteristics of the reactor are only slightly sensitive to the reprocessing rate. This is illustrated in Fig.4 where the safety coefficients of the MSFR show no noticeable variation with the reprocessing capacities provided the whole fuel salt volume is reprocessed in less than 10000 days.

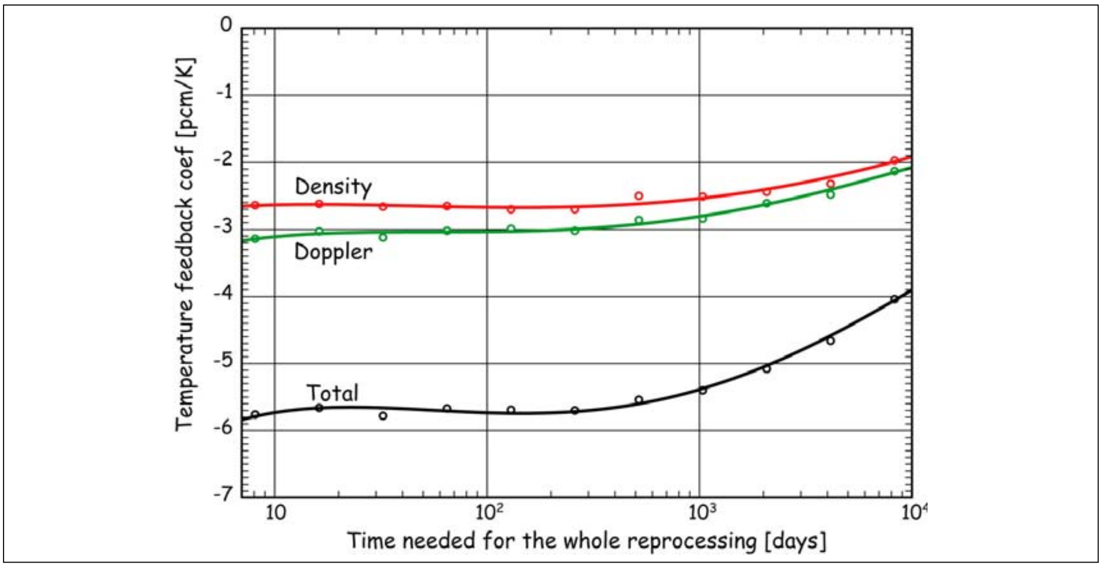

Fig. 4 **Feedback coefficients as a function of the reprocessing rate**

Steps of salt treatments are sketched on the Fig.5. The thick line follows the progress of salt along the cleaning processes using standard convention for blood (from dark blue to "clean" red). As mentioned earlier, extraction of rare gases and some noble metals is performed on line within the reactor building via the bubbling process. Stage 1 has already been tested at Oak-Ridge. Stage 2 and 3 are presently investigated in France, ITU and Russia.

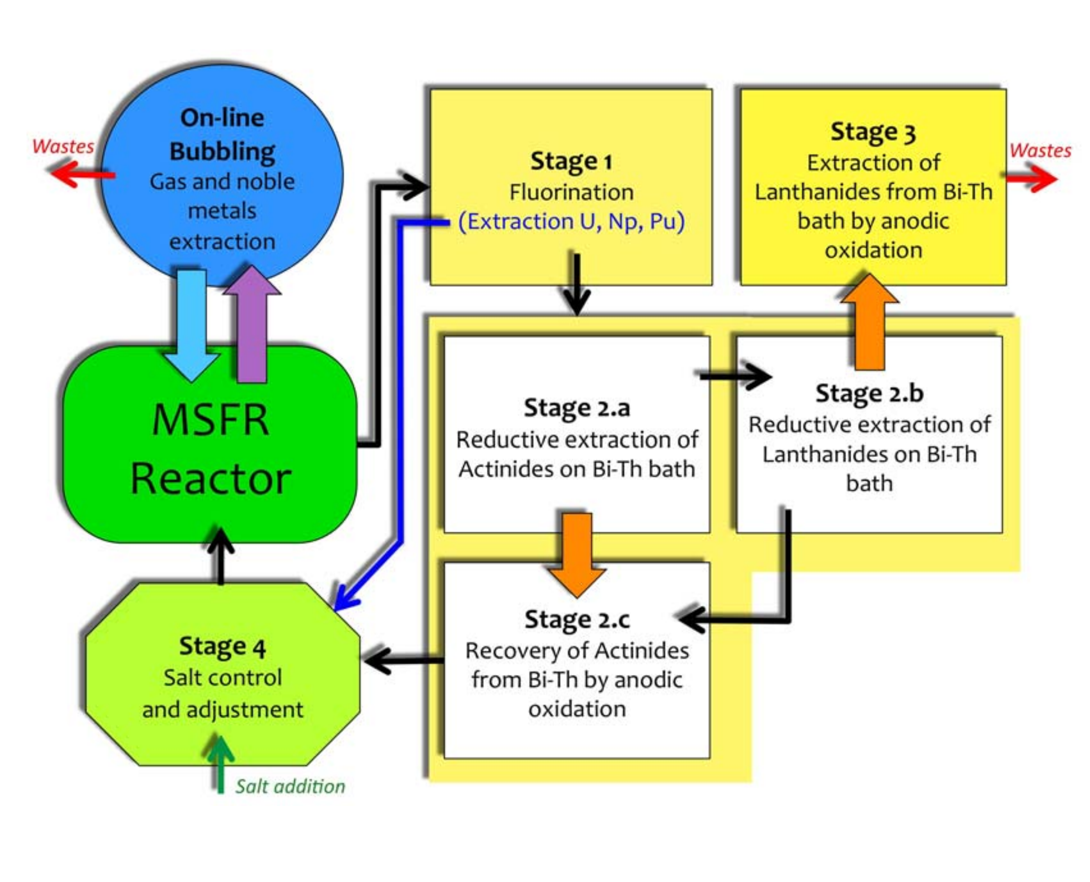

Fig.5 **Salt reprocessing scheme under investigation. Black or blue arrows indicate salt route, broad orange arrows point out transfers through lead-bismuth bath and broad blue/violet arrows transfers through gas**

3.4 System design, operation and safety

The results of the R&D studies sketched in the first three sections will lead to scientific and technological choices impacting the final design of the MSFR system. The remaining R&D challenges are thus related to the design and the safety analysis of the MSFR. They involve:

- Defining a safety approach specific to MSFR, taking into account a fuel in a liquid form within the coolant and the safety aspects of the chemistry-controlled phenomena.
- The influence of the reprocessing during reactor operation on the decay heat is significant and leads to a low decay heat in the core and the fuel loops (3.5% compared to 6% in a PWR). An important part of the decay heat (around 2% of nominal power) is located in the reprocessing units, mainly in the gas reprocessing unit, so that its safety assessment should be studied separately.
- In case of any accidental deviation from nominal conditions, as for example a loss of heat sink, the fuel salt will be evacuated by gravity into a draining storage system located under the reactor, whose design will ensure passive cooling.
- Improving the design of the MSFR core via a coupled neutronic and thermal-hydraulic studies;
- Fully assessing the transmutation capabilities, dynamics and safety related parameters;
- Implementing of passive safety systems (frozen valve, natural convection heat removal) and checking their efficiency;
- Dimensioning an integrated primary circuit, including heat exchangers leading to the design of a first MSFR demonstrator.

4 - R&D Milestones

The R&D program aims at establishing the viability of the Molten Salt Fast Reactor by 2018 and at optimizing its design features as well as its operating parameters by 2030.

The scoping and screening phase (up to 2016), prior to the viability and performance phases, 2017-2022 and 2023-2030 respectively. The main milestones for the demonstration phase (final design, construction and operation of prototypes) have also been fixed, with a view to building a MSFR prototype by 2040 (Fig. 6).

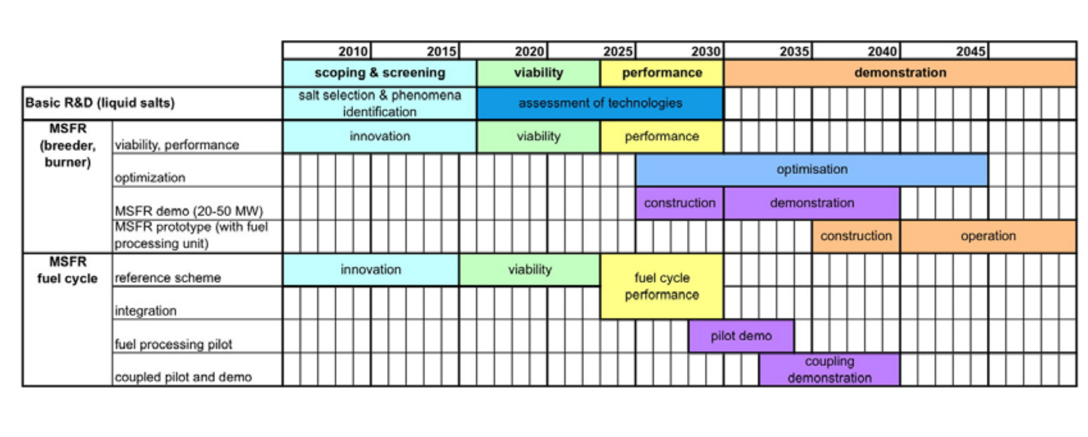

Fig. 6 Generation IV MSFR Master plan

The R&D developments for the short and medium terms in the forthcoming MSR projects are described in the following sections. The R&D issues for the longer term depending on the results obtained. They are taken into account in the definition of the Euratom EVOL project (acronym for Evaluation and Viability of Liquid Fuel Fast Reactor Systems) of the 7th Framework Program and Rosatom MARS (acronym for Minor Actinides Recycling in Molten Salt) projects and in other international research programs.

4.1 Structural Materials

The R&D developments will focus on experimental studies of the properties of Ni-W-Cr alloys proposed as structural materials for the MSFR system. Following the laboratory scale and first pre-industrial fabrication of Ni-W-Cr alloys, the next step will consist to study and to improve their characteristics (control of the microstructure, purity and high temperature hardness).

A number of key properties need also to be determined: the industrialization of Ni-W-Cr processing and welding, mechanical properties assessment and corrosion resistance in the temperature range of the MSFR (700-900°C). Long term corrosion tests have to be performed in relevant dynamic and well controlled chemical conditions. Finally irradiation damages will be quantified, specially the Helium implantation and diffusion.

4.2 Fuel salt chemistry and properties

Missing or inaccurate data for molten salt mixtures containing transuranian elements have been identified (melting points, TRU solubility, thermal conductivity, expansivity) and need to be acquired.

One of the R&D objectives in the short term will also be to develop a method to measure the redox potential of the fuel salt and to control it through the addition of a reductive species such as metallic thorium.

A substantial effort will be made to understand the properties of the molten salt at a fundamental level by studying the characteristics of the fuel bearing molten salt not only at the macroscopic level but also at the microscopic/atomistic level. This knowledge will be validated via numerical simulations.

4.3 Fuel salt clean-up

Critical steps of the two main stages (helium bubbling in the primary salt loop; on-site fuel processing) of the new fuel clean-up scheme will be addressed for experimental assessment at new facilities.

In the short term R&D will work to establish a viable fuel processing flow-sheet, with emphasis on the thorium-lanthanide and trivalent actinide-lanthanide separation. Scientific exchange and comparison with the experimental background of Russian researchers involving in the MARS project will be a key component of this part of the R&D programme.

A project dedicated to the technological handling and the study of the salt clean-up process by Helium bubbling is under progress in France (FFFER project - Forced Fluoride Flow for Experimental Research, Fig. 7). The foreseen planning for construction of the loop is 2009-2012. The scientific aim is the experimental determination of the bubbling process efficacy to remove the noble gases dissolved in the salt. Behaviour of noble metal particles in suspension within the liquid will be studied in a separate static set-up to first determine the particles aggregation behaviour. The forced convection loop (filled with LiF-NaF-KF mixture) will also allow the test of some components (cold plug, ball valve, ultrasonic measurement system, continuous level measurement system).

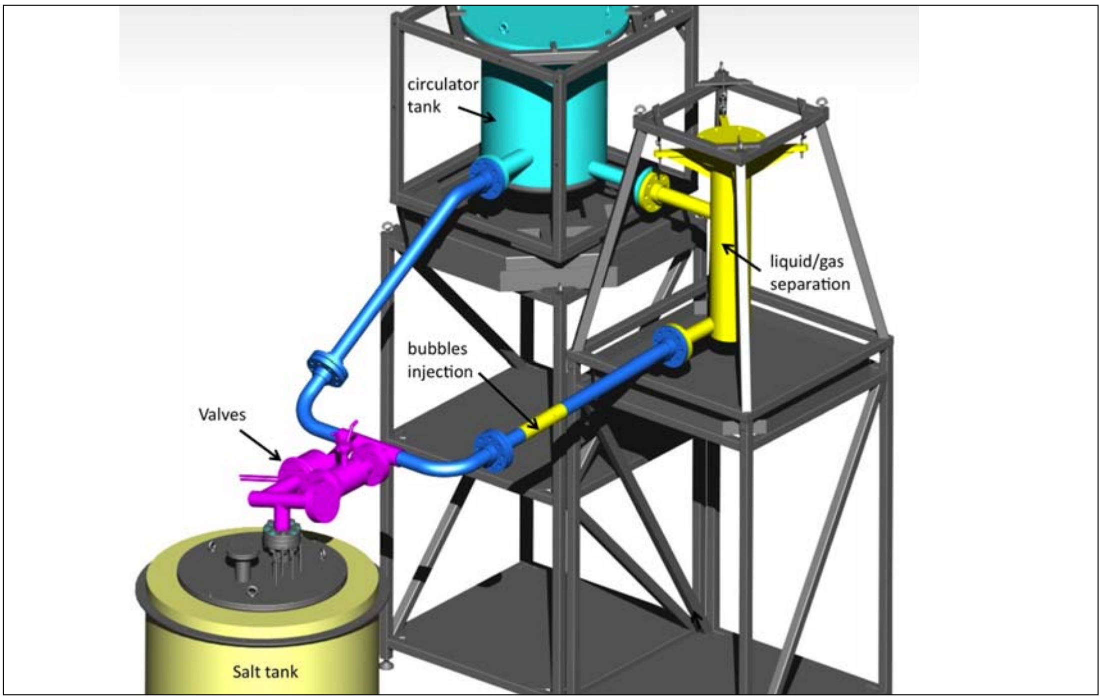

Fig. 7 **Simplified view of FFFER facility under construction (CNRS, France). The loop is dedicated to bubbling studies and will work with a LiF-KF-NaF salt**

4.4 System design, operation and safety

These R&D developments address the definition of the reactor configuration and a safety evaluation of the system and will lead to recommendations for a demonstrator of the MSFR concept.

The safety approach for the innovative MSFR system will also have to take into account today's regulations and requirements. Safety guidelines for assessing core and salt processing facility design options will be established. Computer codes will be adapted for performing safety analyses in fast spectrum MSRs. In particular the most important transients will be simulated. Synthesis of safety studies will provide preliminary conclusions on safety performance of the concept and underline issues requiring special attention in future design and safety assessment activities.

Realistic drawings showing the main MSFR components and their arrangement in the vessel have first to be performed, together with detailed 2D-3D thermal-hydraulics and neutronic simulations to evaluate the relevant range for operational parameters (temperature and pressure gradients, velocity distribution). Defining a design of heat exchanger adapted to salt coolant parameters (temperature, velocities) will be a major issue.

This will lead to recommendations for the lay-out of the primary circuit and the definition of the main system components (reflector materials, blanket, pipes, pumps, reactor vessel, heat exchangers, and energy system conversion).

The current pre-design used for the MSFR concept studies is presented in Fig.8. Refined versions of this design will be obtained through an iterative design-by-safety approach.

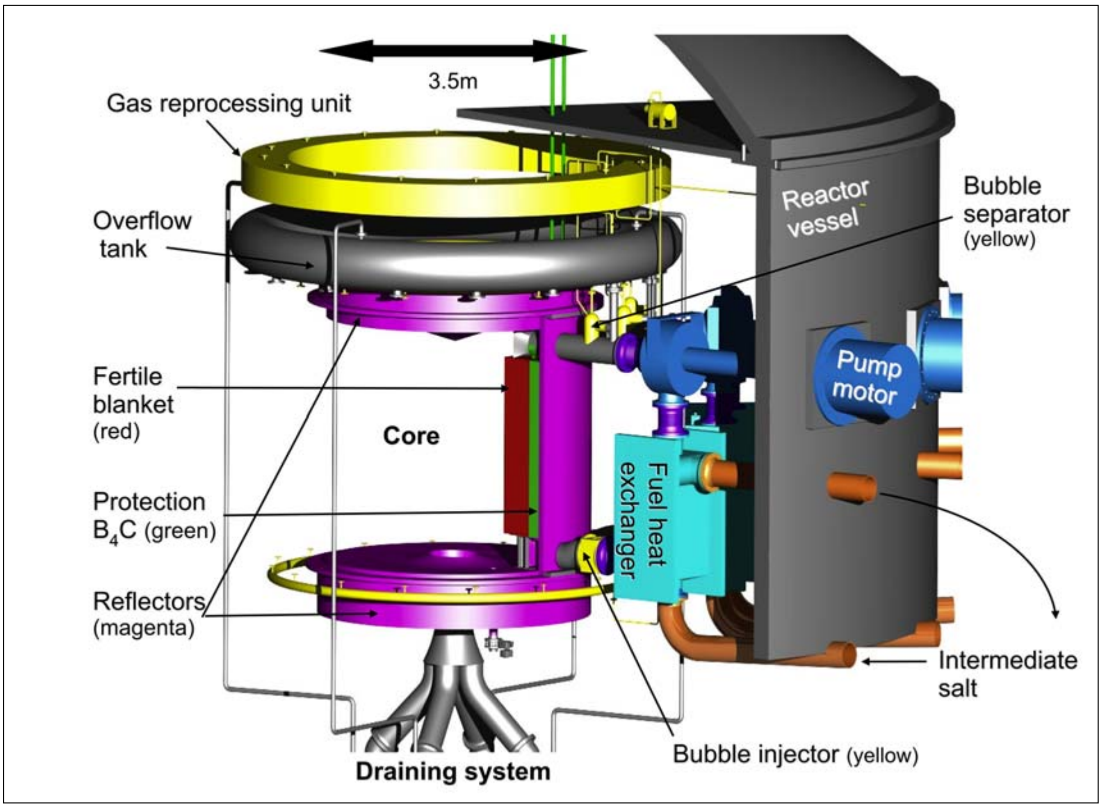

Fig. 8 Pre-design of the MSFR system

5 - Conclusions

In summary, the MSFR concept is endowed with several interesting properties. In particular it overcomes many of the drawbacks of the systems proposed in the decades 1960-1970.

- It combines simplified reactor core design (due to the absence of the moderation structure) with a high level of passive safety inherent to the use of a liquid fuel at atmospheric pressure.
- It is dedicated to the use of a thorium fuel cycle, which produces less transuranian wastes. As such it enlarges the horizon of nuclear fission due to the large global thorium resources.
- It uses on-site salt clean-up by pyrochemical techniques (in relatively small batches) simplifying the fuel cycle back-end from the point of view of logistics (transport) and fuel re-fabrication, leading to reduced proliferation risks and economic costs.

To conclude, the Molten Salt Fast-neutron Reactor (MSFR) is a promising long-term alternative to solid-fuelled fast neutron reactors. It offers very negative feedback coefficients and a simplified fuel cycle. Moreover, the MSFR is very well suited for an operation with the thorium fuel cycle. Presently it is the only system in the GENIV initiative which specifically addresses this issue.