Experimental facilities grouped under the name of FEST for “Fluid Experiment and simulations in Temperature”

These works are in close collaboration with what is exposed by Pablo Rubiolo in the part on “The Multi-Physics couplings”.

1. ABSTRACT

The studies of complex systems involving nuclear reactions in a fluid or solid medium with energy and mass transfers, phase changes and chemical reactions, rely on two components:

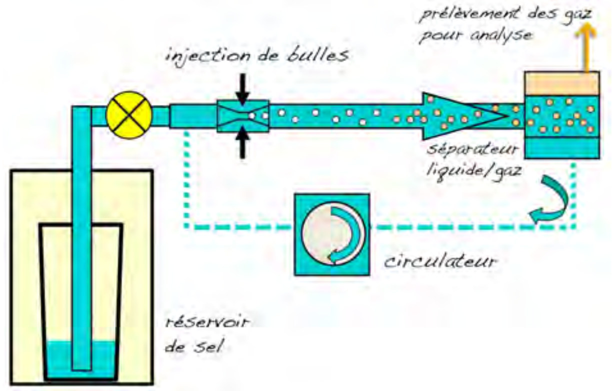
- numerical developments, the only ones able to take into account all the physical phenomena
- experimental developments designed to validate separately some aspects of the numerical models (turbulence models, thermal radiation effects...)

The activities related to these points and usable in several types of applications (nuclear reactors, neutron or isotope production targets, etc.) are grouped under the acronym FEST. They are based on the experience and feedback of the previous FFFER project and on the working structure set up in the framework of the SWATH project (WP3 - European project SAMOFAR). The objective is to take advantage of a rather exceptional situation allowing coupling the experimental and numerical aspects at all stages of the studies. The experimental aspects concerning heat exchange with molten salts are maintained (European contract SAMOSAFER) and an activity of development of liquid metal target for neutron production is developed in parallel within the framework of the application to the BNCT (Boron Neutron Capture Therapy).

2. Genesis of the work

Since 1998, the “Physique des Réacteurs” team has been interested in Molten Salt Reactors (MSR) in the thorium cycle. In the years 2008-2010, the preoccupation focused on the necessity to look at the on-line salt purification systems and the question of the possibility of the technical control of the necessary experiments. A major project was launched at that time with the construction of a fluoride molten salt loop at LPSC, the FFFER (Forced Fluoride Flow for Experimental Research) project, a project based on the IN2P3-molten salt PCR then in operation on the IN2P3 side and the Carnot Institute of Grenoble on the other. The scientific objective of the construction of the loop was the implementation of in-line bubbling as an extraction process for a certain number of fission products present in the state of gas, particles or aggregates. This project was a real challenge and allowed us to create a real technical background on the subject. Background that we are currently the only ones to have in France.

The final tests were carried out in 2017 after a large number of difficulties that allowed us to acquire our current know-how. The salt used was eutectic mixture LiF-NaF-KF (Flinak as familiar name) with a melting temperature of 452°C, the final acceptable operating range of the installation was 500°-650°C. The installation included a large number of elements, each of which gave rise to technical developments.



Schematic diagram of the plant

Photograph taken during the assembly stage

The work, which was very interdisciplinary, covers all fields from the design of the various components and the circuit, to the purely experimental development on hydraulic models, including the creation of control instrumentation and the characterization of certain materials after use. A beginning of effort in the direction of thermal-hydraulic numerical simulations is envisaged at this time to develop the liquid/gas separator, but not developed for lack of competences and human and financial means. After this period and the separation from the people who founded a separate group (MSFR group, see part "molten salt reactors", Elsa Merle) and the arrival of Pablo Rubiolo we worked in such a way as to systematically associate numerical simulations and experimentation, both during the design and the analysis of the results. Since then, all the developments undertaken within the framework of the successive European projects, Samofar and then Samosafer, have been based on the same type of approach, which we explain in the following paragraph. Most of the experimental developments developed in the framework of FEST are related to molten salt reactors. In parallel, an activity related to the design of targets for the generation of intense neutron fields is also carried out in collaboration with Daniel Santos, from the LPSC Mimac group. The type of target considered uses lithium in the liquid state. These works, different in their approach more focused on direct application and prototype design, are nevertheless integrated without difficulty in the FEST platform (management of heat transfer fluid at high temperature, reactive liquids, problem of choice of materials, thermal-hydraulic simulation ... etc).

3. Scientific Challenges and type of approach now used for MSR studies

The first step that we address before we start designing any experiment was to identify the key phenomena that are relevant to the MSR concept and require experimental data to asses the accuracy of the thermal models. This task was somehow subjective and required carrying-out a qualitatively review of the different thermal hydraulic phenomena that are believed to occur in the reactor. The following qualitatively criteria were adopted in the analysis:

a) Importance of the phenomenon for the MSFR design and safety studies,

b) Knowledge level and/or accuracy that could be achieved on the numeric modeling of the phenomenon,

c) Feasibility for designing an experiment with sufficient precision to investigate the phenomenon.

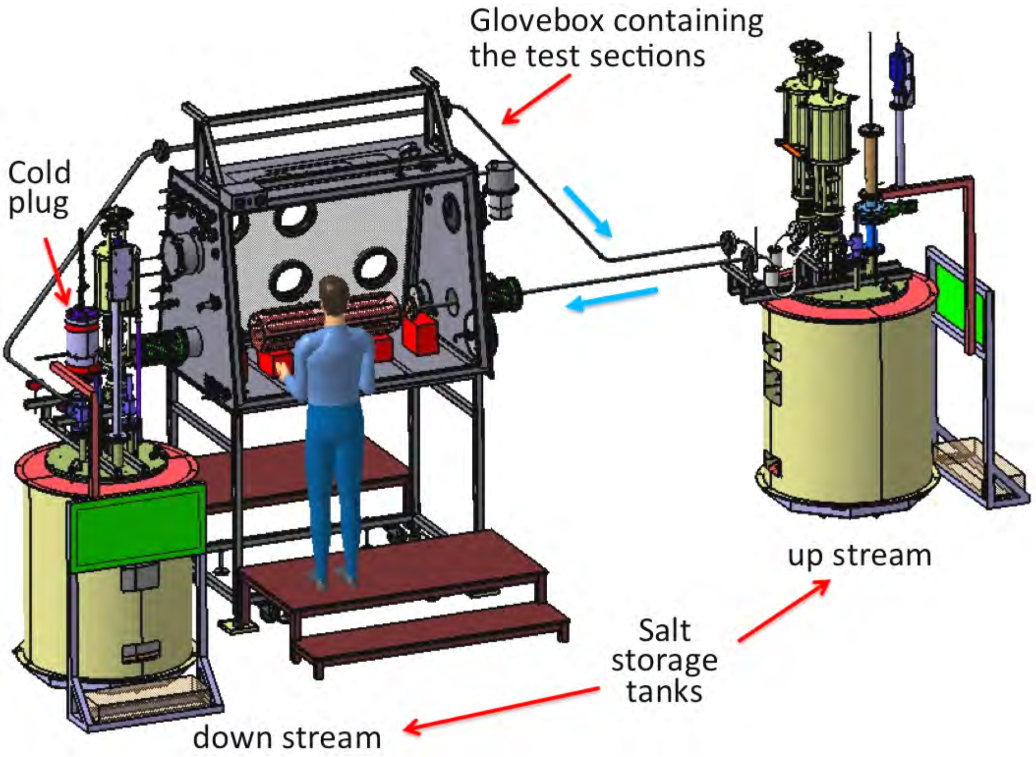
In the Samofar European project context, Phenomena Identification and Ranking Table (PIRT) was therefore developed based on the MSFR phenomena that are expected to happen and follow these three criteria. Particular attention was given to some critical reactor processes, such as the fuel draining process. The PIRT analysis led to identify the following priority phenomena:

- Heat transfer in very simple geometries,
- Evolution of the salt solidification interface with and without forced convection,
- Solidification along a cold wall after successive molten salt flows (lava flow like),
- Flow structure characteristics (flow rate, film thickness, etc.) in an open channel,
- Turbulence effects on the flow velocity field,
- Radiation heat transfer in the salt.

Performing experiments with a molten salt involves in general high temperatures and the risk of chemical reactions. These particular conditions make hydraulics measurements such as flow rate, liquid level, pressure or flow visualization quite challenging. To overcome some of these challenges a strategy using two separate facilities was adopted.

The first facility called SWATH-W (for Salt at Wall- Thermal ExcHanges) uses water as working fluid to study hydraulics aspects while the second one called SWATH-S uses a molten fluoride salt to study heat transfer, both have been built during and built during the first two years of the Samofar project. The operation of both SWATH facilities is based on a discontinuous working principle in which the flow is established in a channel section (for example a circular close channel) by regulating the pressure difference between two tanks. This solution was better suitable for the project constraints (time and cost) than the alternative one that would be developing a pump for the experiment, because the circulator used in the previous loop (FFFER) was not adapted to the flow rates and conditions we were looking for in SWATH. The measurement of the salt flow is also a problem resolved by the used of the discontinuous concept. The pressure control system is designed to maintain a stable flow during the operation of the loop by regulating opening and closing of a set of tanks valves connected to a pressurized argon tank and the atmosphere. This control system uses information related to the flow rate such as the salt level in the tanks or the pressure drop at a specific component of the circuit. During the experiment, the salt mass flow rate is calculated from the variation of the tank levels measured by two independent methods: a laser beam system and electrical contactors system.

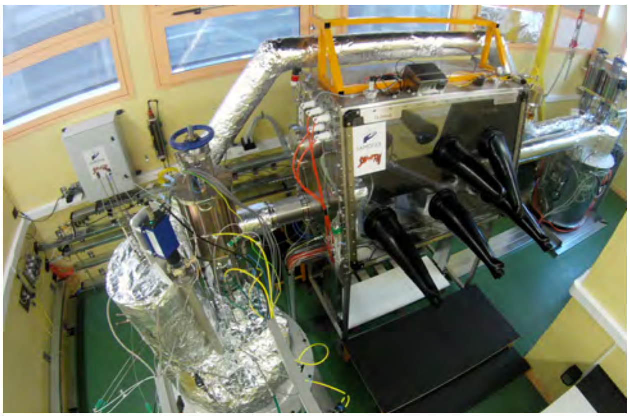
Following figure shows a layout of the SWATH-S facility which is composed by the two salt storage tanks, the circuit pipes with the heating system and the thermal insulation (not shown in the figure), automatic valves, cold plug, glovebox, pressure control system and instrumentation. The glovebox is required to host the test section and allows for manipulation in a chemically inert argon atmosphere. The return of the salt from the downstream tank to the upstream tank is done through the conduit passing above the glove box.



Layout of the SWATH-S facility

Fluid	FLINAK Service temperature: 500°C to 700°C
Tank volume	60 liters
Tank material	304 L Stainless Steel
Tank dimension	Diameter: 440 mm (in)/456 mm(out) Inner height: 938 mm
Design Pressure	1 bar at 600°c
Piping	Inner/Outer diameter : 20 mm/25 mm Material : SS 304L (seamless tube)
Flow rate	1 l/min to 8 l/min

Main characteristics of SWATH-S



SWATH-S after completion

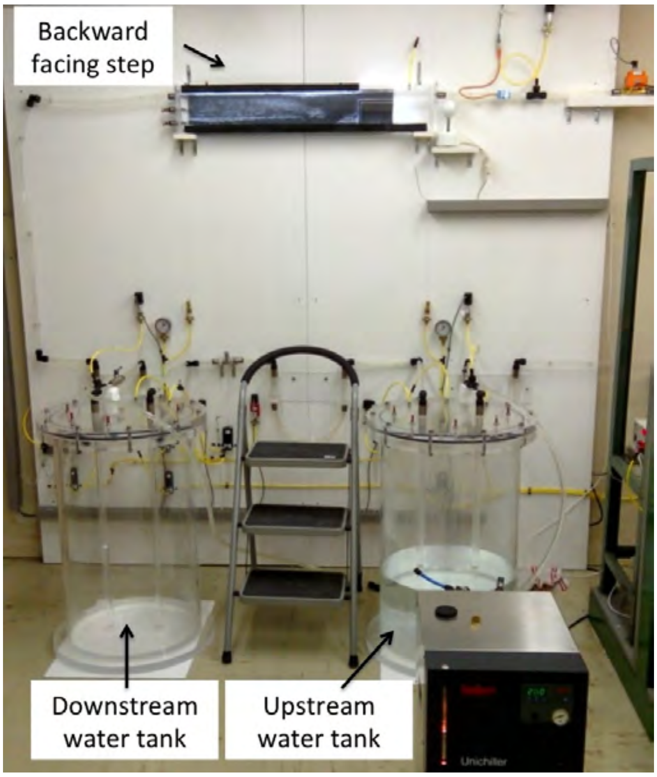
The SWATH-W facility uses water at nearly room temperature conditions. The main purposes of SWATH-W are:

(1) Perform purely hydraulic measurements,

(2) Technical support for the experiment design of SWATH-S and the test sections (e.g. confirm adequate flow stability is obtained or verify the accuracy of the flow rate measurement instruments),

(3) Technical support to the definition of the experiment procedures and control implemented in SWATH-S.

Following the same working principle, the SWATH-W set-up is composed of two tanks, the mechanical valves, the flow instrumentation (pressure and flow rate measurements) and can host different test sections to be studied. Different flow measurements can be made: volumetric rate, pressure at selected locations, water level in the tanks and the detailed velocity flow field in the experimental section. The latter is performed using a Particle Image Velocimetry method (PIV), a nonintrusive measurement technique allowing measuring the two components of the velocity field in a flow over a plane.



The SWATH-W facility in operation with the backward facing step

The back step geometry has not been used in SWATH-S Facility.

Other channel Close, open channels and other type of simple geometries were selected for study in SWATH-S and also tested in the same set-up in place of the backward facing step section shown in this figure.

4. Some achievements

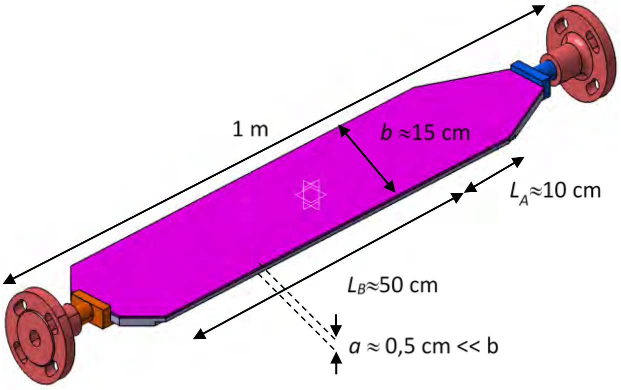
Several experimental campaigns have been achieved using SAWTH-S facility, using section inside gloves box or on a specific component placed above the reception tanks, the cold plug. We briefly describe these studies in the following paragraphs, 4-1 and 4-2.

The experimental tools grouped under the name “FEST” are not limited to the SWATH facility but also include all the possibilities introduced by the existence of our glove box line, which was originally dedicated to the manufacture of salt ingots but which can be advantageously used for small-scale experiments (see paragraph 4-3). Some information will also be given in paragraph 4-4 on the development work of the liquid lithium target for neutron production.

In all case, experimental work is associated with numerical and scientific analysis described in more detail in the report by Pablo Rubiolo on Multi-physic developments.

4-1: Flat channel section:

The flat channel geometry of the following figure is adopted for the experiment because of the relative simplicity of the resulting thermal boundary layers and velocity profiles. This is important not only for the experiments but also for minimizing the numerical modeling uncertainties. In such a configuration, “numerically” changing the gap between walls will change the heat input per flow section. This help to deal with the limits on the maximal electrical thermal heaters power input to the experimental section. The gap between walls can also be used to manage the global optical properties of the channel and thus partially accommodate the uncertainties on the salt/wall optical properties. The local temperatures in one wall have to be precisely measured and the flat wall geometry allows better accessibility and localization for thermocouples instrumentation. Laminar flow conditions are in general to be adopted during the tests to decrease the effect of the convective heat transfer mechanisms.

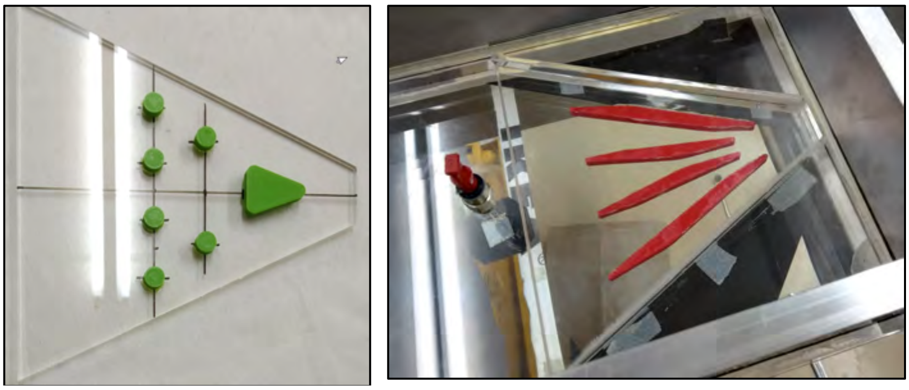


Approximate sketch of the flat close channel.

The choices described above correspond to favorable numerical conditions but they also had to be compatible with the experimental possibilities. In particular, some key experiment design challenges that have been addressed during the design and construction of the experimental test section were:

- Inlet flow diffusor design: obtaining adequate flow inlet conditions: a fully developed flow with uniform temperature as to be present in the study area,
- Test section thermal regulation systems: obtaining pseudo-adiabatic conditions in one wall while temperature it is fixed on the other one,
- Test operation: obtaining adequate steady conditions in the section (thermal inertia of the section, avoiding presence of bubbles, etc.),
- Experimental uncertainties: molten salt properties, inlet temperature and circuit flow rate.

The transition between the circular salt inlet (20 mm in diameter tube) to the flat rectangular section (150 x 5 mm) has been designed so as not to create flow disturbances that would propagate in the measurement area of the close channel. CFD numerical studies shown that a simple smooth transition in the shape of the channel is not enough to guarantee this condition. The development of an inlet flow diffusor to allow obtaining approximated developed flow conditions at the measurement area of the close channel was therefore needed. Several different flow diffusor designs have been developed and evaluated in order to identify the designs that allow obtaining a nearly fully developed laminar flow at the outlet of the expansion. As an example, two of these designs are presented below.

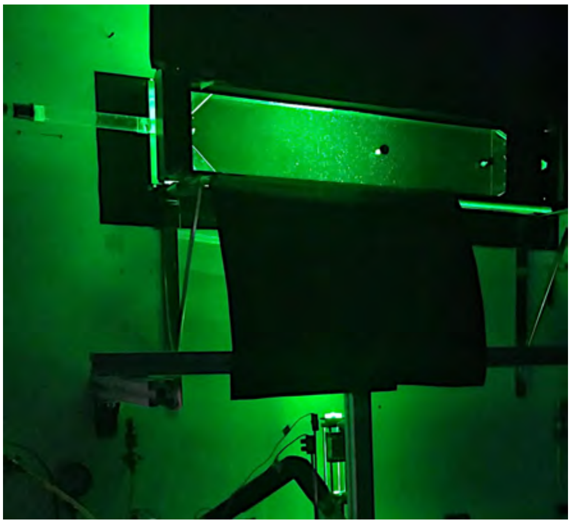


Two flow diffusors designs (D1 and D3 respectively) studied in SWATH-W.

The flow fields developed inside the PEXIGLASS flat rectangular channel experimental test section were measured in SWATH-W at various flow rates and considering three configurations:

- No flow diffusor installed inside the transition zone
- Using flow diffusor D1
- Using flow diffusor D3

The flow fields were measured in September 2020 at the LPSC using a Particle Image Velocimetry (PIV) technique. All the tests and calculations allowed us to choose the design D1 as the more efficient flow diffuser. This design was therefore used to build the metallic version of the flat rectangular channel that will be tested in SWATH-S.

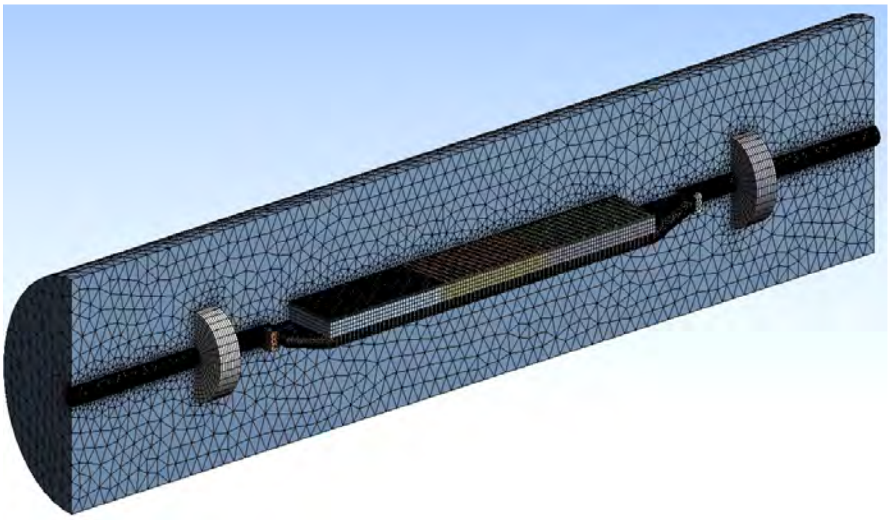


Experimental setup used during the PIV measurements on the rectangular flat channel.

A detailed thermal model of the flat rectangular channel section has been developed to:

- Design the thermal heating resistances
- Determine the position of the thermocouples used to measure the temperature profile
- Design the thermal insulation system
- Confirm the overall performance and operating parameters of the experiment

This detailed model includes the molten salt flow, the flow diffusor, the parallel plates, the connection flanges, the thermal heating resistances and the thermal insulation.

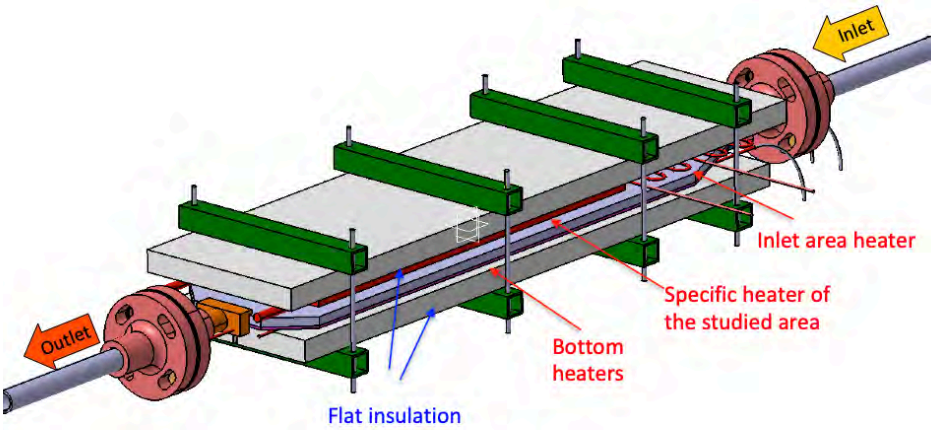


Full thermal model of the experimental test section: The simulations include fluid flow (FLINAK Salt) and coupling heat transfer with fluid and solid (Stainless steel 304L section and insulation). Heating systems are included in the simulation by distributed power or imposed temperature methods.

As discussed in the previous section, the plates have different boundary conditions. On the upper plate (upper wall of the channel) the electric power of the heating resistances has to be set such as to compensate the heat losses in the thermal insulation (so quasi-adiabatic conditions). On the lower plate (lower wall of the channel) two different zones exist: (a) heated zone with fixed temperature (3000 W heating system, 150 mm x 400 mm) and (b) zone with quasi-adiabatic conditions. In all cases, the heating resistances shall withstanding a temperature of 700°C with a sufficient lifetime.

The flat rectangular channel was built from two pieces of 304L Stainless Steel (SS) that were fully welded to form the close channel. The flow diffuser (D1) components (vertical cylinders) and the flat flowing area were cut in on the metal pieces. Following figures illustrates one of the later stages of the test section construction when the bottom wall electric heaters were attached and the thermocouples fixed to the bottom wall. All the electric heating elements and the rigid thermal insulation plates are maintained by a mechanical holding system.

Positioning of the electric heaters and the thermocouples on the bottom wall of the flat channel.



Mechanical setup used to maintain the heaters and flat rigid thermal insulation attached to the flat channel walls.

The flat rectangular channel section was installed in the glove box of SWATH-S after dismantling the previous circular channel section owing to certain flexibility for connection of the section flanges to the SWATH box inlet/outlet pipes. The flat section sitting in place in the box, before thermal insulation completion is shown on the following figure.

Two tests campaigns had to be carried out because the first set-up did not give complete satisfaction as regard the results and did not allow a clearly significant interpretation of the phenomena. The assembly had to be heated and insulated differently.

Flat section in place in the SWATH glove box of SWATH-S before completion of the external thermal isolation.

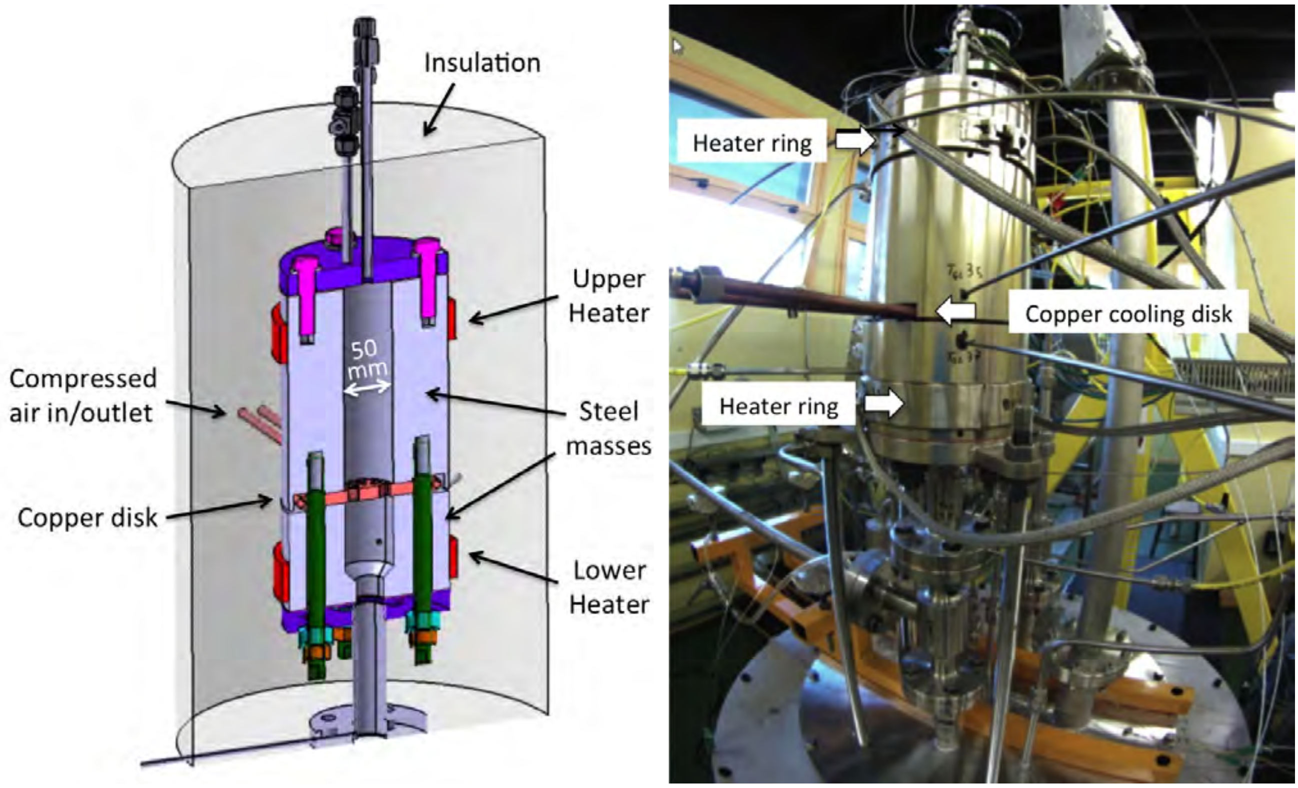
4-2: Cold plug test:

One of the objectives of SWATH-S experiments was the demonstration of the working principles of the cold plug device, which is a key component of the MSFR fuel salt draining system. The design of a cold plug device in which the onset of the melting process depends only on the increase of the molten salt temperature in the core cavity seems not enough efficient to avoid an excessive increase of the fuel salt temperature (and thus avoiding damage in the core structures). In comparison, the cold plug device based on the control of the heat transfer balance inside the device seems to be more efficient, faster and robust at the price of losing some degree of passive safety in some accidental scenarios. The heat balance inside the cold plug determines if the salt in the plug region solidifies or melts: when cooling disk is stopped (e.g. due to a loss of electrical power), the thermal energy stored in the steel mass is transferred by conduction to the cooling disk causing the solidified salt region melt. The objective of experiments with cold plug device in SWATH-S was to improve the understanding on the mechanisms regulation the operation of the cold plug in order to investigate the possibility of scaling-up the cold plug design to a size that could be used in the reactor and thus provide recommendations for a future design.

In the proposed design, it is the heat balance established between the heater and the cooler inside the cold plug that determines whether the salt in the plug region solidifies or melts. The cold plug is basically made of two cylinders of stainless steel (160 mm outer diameter). The massive cylinders are used to store the energy needed for an autonomous cold plug opening. Copper disk is inserted between the stainless steel cylinders. This copper disk has a cooling pipe brazed to outer diameter. The particular design “flower petal” of copper disk center was developed to minimize the closing and opening time of the cold plug. The two heaters rings and the cooling of the copper disk, drive the global thermal balancing of the cold plug. The position of the heaters is visible on the left photo of taken before putting insolation (right).

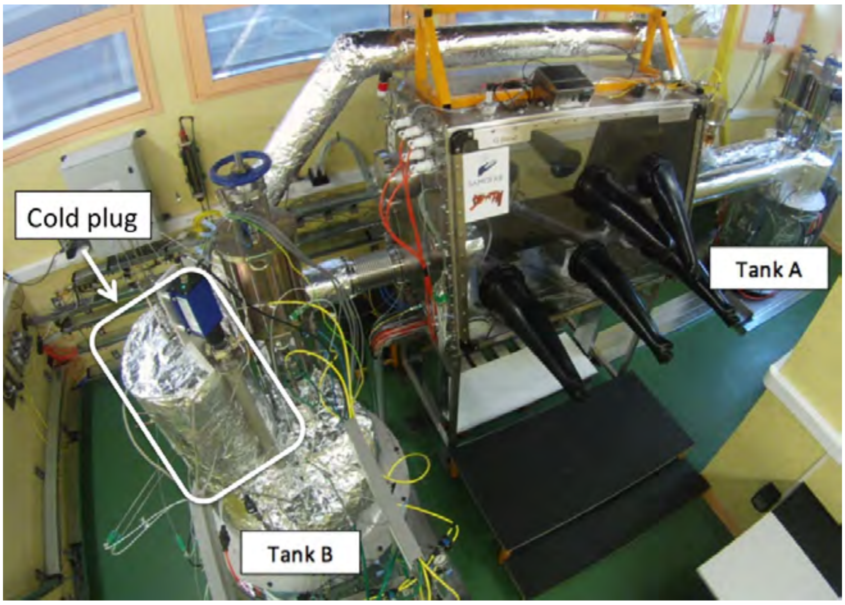
This vertical cold plug geometry is expected to allow for a better control and measurements of the solidification/melting processes that take place during the cold plug operation. In SWATH, the cold plug device is studied alone, with no external salt flow to have a better control of the heat balance in the device. This arrangement simplifies the data collection, the experiment operation and also provides a simpler access to the upper part of the solidified area. The effect of an external flow, for instance the one cause by the fuel salt in the core cavity, should therefore be investigated in the future. Nevertheless, increasing the distance between the cold plug pipe and the reactor cavity can reduce this effect.

The cold plug SWATH experiments were performed with Flinak salt and the cold plug internal pipe diameter was set equal to 50 mm. The system included two massive cylinders of stainless steel (160 mm outer diameter) used to store the energy needed for an autonomous cold plug opening.



Design of the SWATH cold plug experiment (left) and cold plug experiment fully assembled on the downstream tank of SWATH-S (right)

The cold Plug set-up is located above the downstream tank B. During the cold plug experiments, no flow circulation is established between the tanks but rather the cold plug system is filled using the molten salt from Tank B. To reach the necessary salt level above the cold copper plate used as cooling disk implies the presence of salt in the salt return pipe too. This pipe is compulsorily heated during these experiments.



Swath-S experiment: cold plug location

Each cold plug experiment was carried-out in SWATH-S according to the procedure including the stages implemented in the order given below. In all cases, the main parameters of the "cold plug" component remain however the temperature of the up-stream and downstream heaters and the cooling flow rate in the cooling disk:

a- Thermal equilibrium of the steel masses at about melting temperature of the salt

b- Filling of the cold plug area

c- Maintenance of static conditions for the liquid during the closing of the plug

d- Draining of the liquid salt in the downstream part

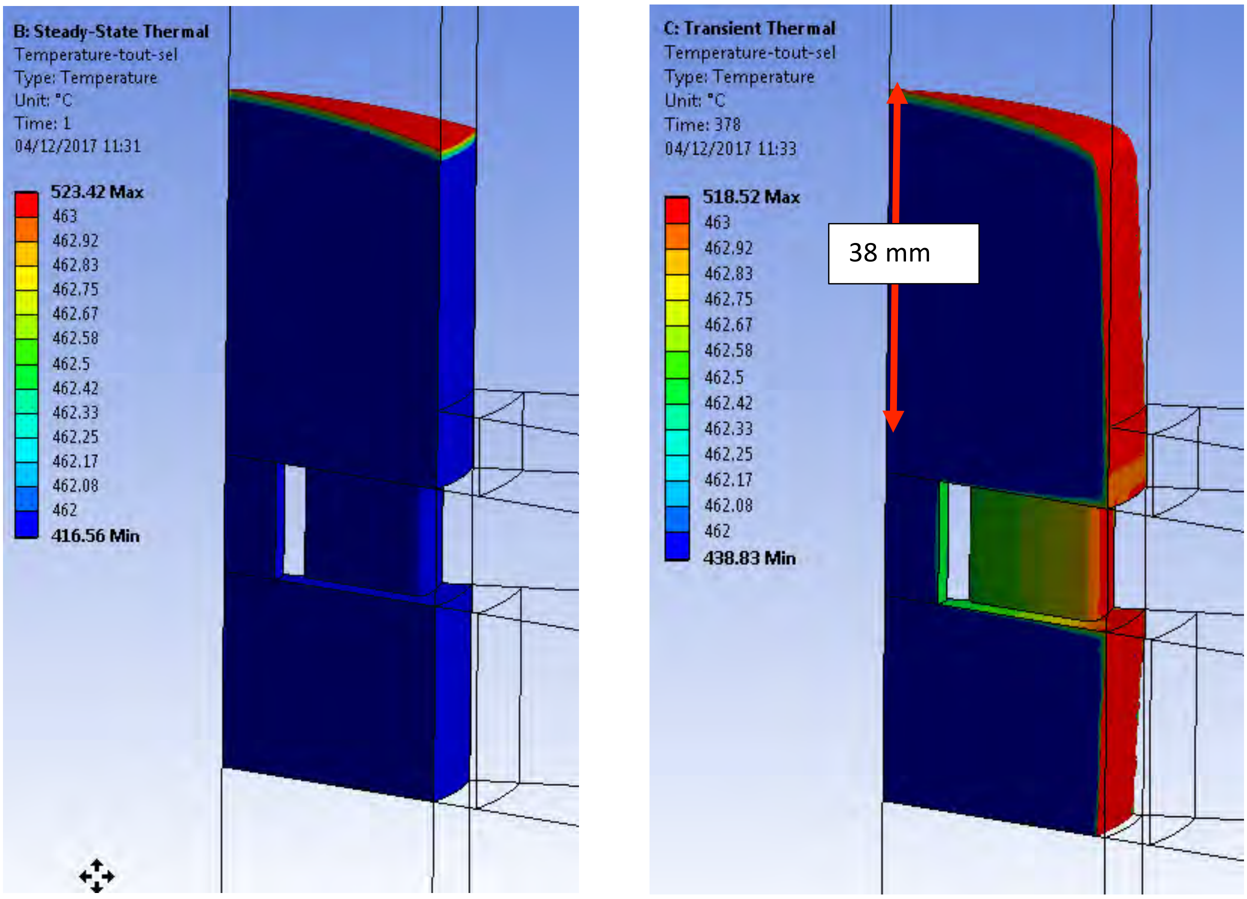
d- Stabilization time for the normal operation conditions

Some key remarks from these experiments were that the choice of temperatures of the heaters and of the cooling flow rate influences the time required to obtain the cold plug, which corresponds to a steady state configuration. In the experiment, this time is important (about five hours) due to thermal inertia of the system. The normal operation setting (heater temperature and air cooling flow rate) determines the size of the frozen salt and has a direct influence on the cold plug opening time. The experiments showed that the parameters determined for a reliable normal operation condition depend slightly on the cooling disk air flow rate imposed.

Cold plug thermal simulation was performed with ANSYS mechanical (Finite Element Method), the example of the BF11 cold plug experiment is shown in the following figure. The enthalpy curve is used to take into account the phase change energy in the numerical model employed in the transient simulation of cold plug opening step. Only the salt represented with a fine color scale varying with temperature is shown. Accordingly, the blue color corresponds to the solid salt region and the molten salt region is displayed in red. The numerical simulation results presented on the following figure correspond to the instant considered as the "opening time". This is the moment when the liquid salt finds a flow path along the steel and copper walls. At this stage, only a very small part of the plug is melted, but as long as the temperature of the upstream liquid salt is sufficient, wider opening of the plug can occur. The total energy required to completely open the plug is not provided by the device itself but by the flow of the upstream salt. Since the trigger phenomenon of the opening takes place at the lateral interfaces, the total volume of the normal crystallized plug is not a relevant condition for cold plug melting. On the other hand, in the stage of the cold plug formation, the size of the crystallized volume is an important factor conditioning the time needed for completed solidification and the cooling power.

Accordingly the blue color corresponds to the solid salt region and the molten salt region is displayed in red. The simulation of step 2 (left) corresponds to the instant of the "opening time", 378 s. This is the moment when the liquid salt finds a flow path along the steel and copper walls.

There is a good agreement between the height of the simulated BF11 cold plug and the experimental height measured after salt graining. The quantity of liquid salt stored in upper part of the device at the beginning of the experiment is not sufficient to induce the complete melting of the plug, then, we have access to the salt thickness above the copper plate. For this case, the cold plug solid part resulting from the numerical simulation is 38 mm. The experimental cold plug solid part height measured 39.5 mm. In the same way, the shape of the residual solid has been verified by introduction of a small camera after cooling of the whole assembly.



Step 1: Cold plug normal operation *Step 2: transient after 378 second*

Result of the numerical simulation for the BF11 cold plug

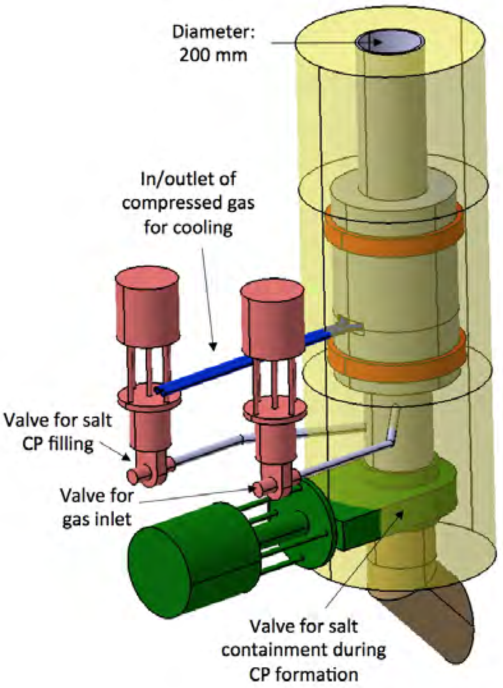
In order to verify the possibility of extrapolating the results obtained with Flinak salt in simplified conditions we perform numerical calculations with LiF-ThF$_4$ salt and relevant structural materials. From thermal properties point of view, 304L stainless steel and Hastelloy N have close behaviours. At 600°C (≈ temperature of normal running of a closed cold plug) thermal conductivity of molybdenum is 2.6 times lower than that of molybdenum (following Table). Design of a reactor cold plug has to be defined with the most important parameters:

- Diameter of the plug. It can be slightly narrower of the up-stream and down-stream pipes but this throttling will created pressure drop and complications in flow profiles. We have chosen to keep the same diameter in the pipe and in the plug. The diameter depends of the number of system to be included for draining the core and the maximal authorized duration,
- Position of the plug systems against the reactor core,

	Swath Cold plug studies	Reactor Plug
Inner diameter (mm)	50	200
Outer diameter (mm)	160	400
Thermal bloc height (mm)	312	630
Thermal bloc material	SS304L	Hastelloy N
Thermal bloc conductivity (W.m-1.K-1) (600°c)	22.2	20.3
Cold plate thicnkess (mm)	12	30
Cold plate material	Copper CuC1	Molybdenum
Thermal cold plate conductivity (W.m-1.K-1) (600°c)	330	126
Salt	FLINAK	LiF ThF4

Materials properties used for Swath experiments and reactor plug numerical simulations.

Based on a fuel inventory of de 18 m^3 of salt to be drained (reactor core + pipes + thermal exchangers) and the draining pipe geometry (presented in SAMOFAR D3.1 report) sixteen draining pipes with an internal diameter of 200 mm have been considered. The numerical simulations of the core cavity draining have shown (see SAMOFAR D3.1 report) that this geometry allows obtaining acceptable results even if only one cold plug opens. The following figure presents a detailed view of the components of the cold plug with a 200 mm in diameter; there is a factor of four on diameter used in SWATH cold plug experiments.



Main required components of a reactor cold plug.

During the SWATH cold plug studies, the plug formation did not require a downstream valve because the salt level was maintained by the tank pressure control system but in reactor liquid salt has to be introduced and kept in the system during solidification. Then we add a valve (green part in the figure 4) to block the molten salt after its filling. This valve will likely have a large size in order to decrease the pressure drop during draining. The valve for filling can be a smaller one. In the same way, the gas valve for emptying of the downstream part of the plug after solidification.

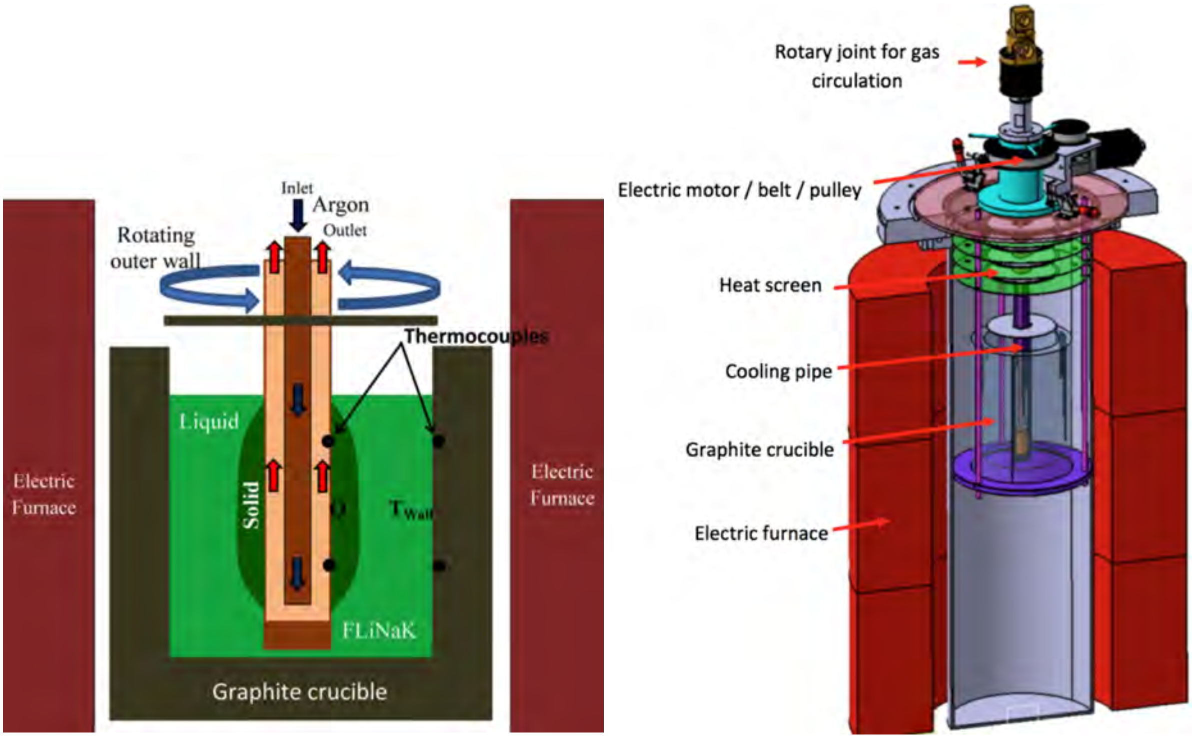
Of course the chosen components (salts valves and gas valve with their actuators) have been taken only for example to illustrate the occupied volume and the complexity of the system. Other type of valves can be used but a significant reduction of the volume and complexity should not be expected.

4-3: Solidification on rotating

One of the main objectives of the phase change experiments in SWTAH was to validate the two numerical models being developed for the solidification of the ternary system LiF-KF-NaF (FlinaK):

- MASOFOAM (MAcro-scale SOlification Foam): implements a solidification-convection coupled solver based on a mixture model
- MUSOFOAM (MUlti-scale SOlification Foam) improves the accuracy of the previous model by solving the species diffusion equation with a length adaptable phase field model

It is expected that during normal and accidental conditions the solidification (or melting) can occur in presence of flow convection and since this condition will have a noticeable effect on the shape of the solidification front, SWATH experiments consider two conditions: (a) Natural convection and (b) forced convection. Moreover to decrease the uncertainties associated with the numerical modeling of flow velocity field conditions, a relatively simple geometry has been adopted in the experiment. As can be seen in the following figure at the left. The solidification experiment employs a rotating tube inside an annular cavity filled with molten salt. The rotating tube contains an inner tube that allows for the circulation of a gas coolant (argon) to decrease the temperature of the external wall of the outer tube below the FLiNaK melting point and thus initiating the solidification process. The tube rotation generates a relative simple forced convection velocity field in the fluid. The inner wall temperature of the graphite crucible is maintained at a constant temperature (above the melting point) by regulating the electric furnace power. The rotating tube and the crucible walls are instrumented with thermocouples.



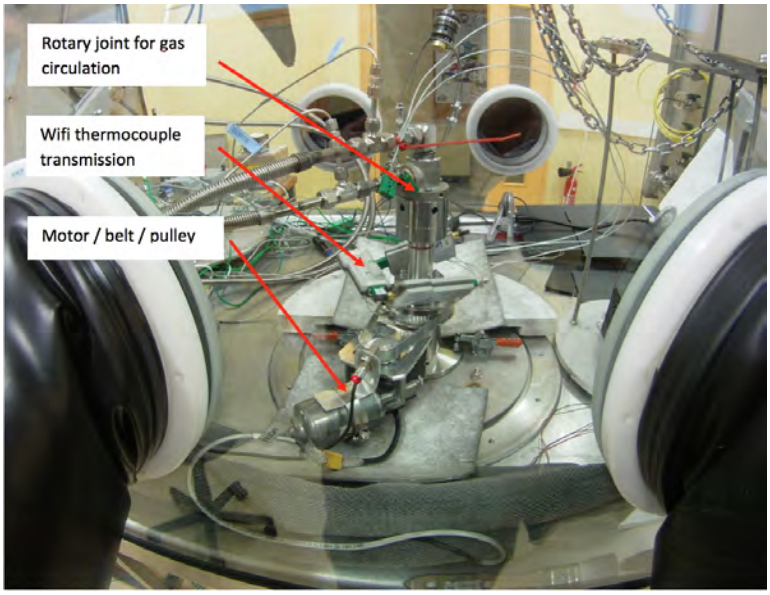
Simplified (left) and detailed (right) layout of the SWATH-S solidification experiment

The configuration shown in this sketch has several interesting points:

- The solidification front can be measured at any time by extracting the rotating tube from the molten salt bath and measuring the dimensions of the solidified salt by a mechanic or a visual method
- Flow field established in the cavity is relatively simple although flow instabilities may appear (Taylor-Couette instability) depending on the rotation speed and also a small natural convection effect will exist. Setting the rotation speed can change force convection in the fluid.
- Heat extracted from the tube can me approximated measured by performing the enthalpy balance on the argon flow based on the inlet/outlet temperatures and the flow rate.
- Boundaries conditions on the molten salt cavity such as the crucible and tube walls temperatures can be better controlled or at least measured
- Experiment instrumentation using with thermocouple is relatively simple. Although the use of a rotating tube requires the use of thermocouples connected to a WIFI system to avoid wires

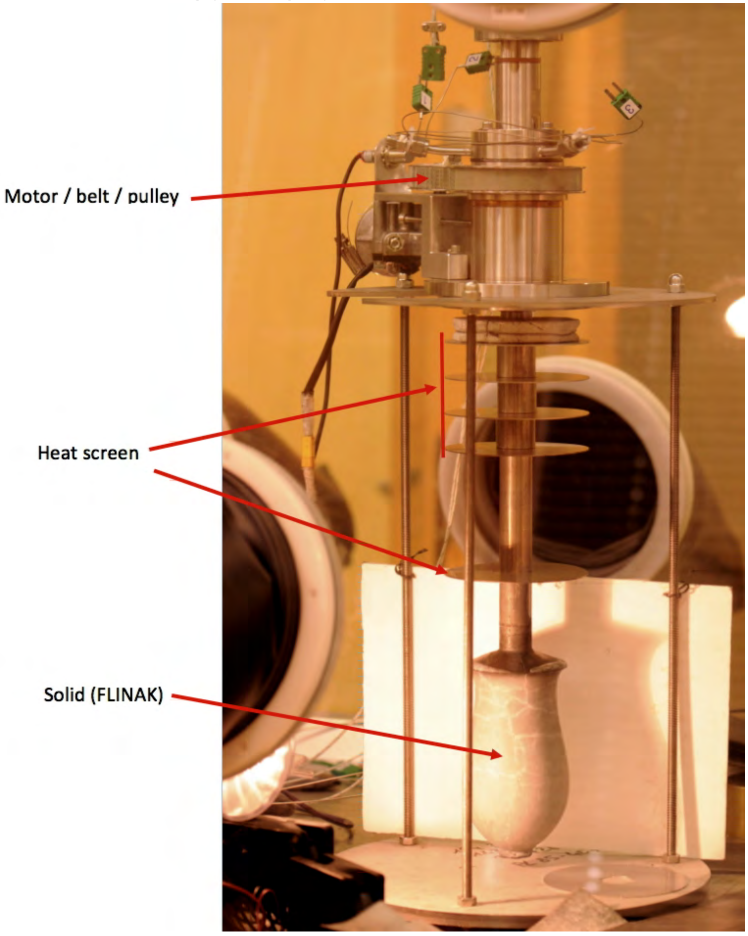
Although the geometry is relatively simple, the experiment is still complex and requires to be installed inside a glove box with an inert atmosphere. Special attention has to be given to the design of the thermal radiation shielding (heat scream) above the molten salt cavity to avoid excessive heating on the upper structure and also a too high thermal radiation losses on the surface of the molten salt bath, as can be seen in the detailed drawing presented in the previous figure at the right side. In addition, a rotary tightness joint to allow for the argon gas circulation inside the tube. The right drawing shows the set up when inserted in the furnace and the following photograph shows the whole system in working condition in the glove box furnace.

The solidification experiments begin with the immersion of the cooling system in molten salt. Once thermal equilibrium has been reached (thermocouple temperatures do not change), the argon cooling is started. The solidification experiment can be performed with or without rotation.



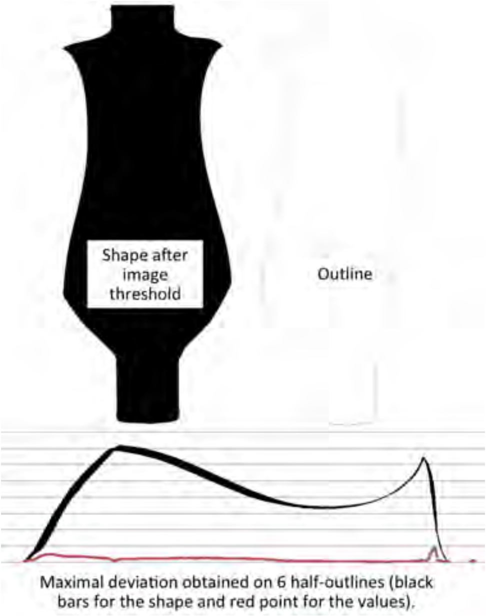
Rotating solidification system in working condition inside the glove box

The experiment duration is one of the experiment variables and once it has been reached, then the cooling system is extracted from the bath (to stop the solid growth). The cooling system is then placed inside the glove box and left to slow cooling. Once the temperatures are low enough, the formed salt ingot can be measured. An example of the cooling system and the solidification ingot after a typical experiment is showed in the following photograph.



Rotating system after extraction and cooling with the solid salt formed on the cooled diver

The salt ingot formed by solidification over the tube is measured by two methods. Firstly from picture recording and secondly by mechanically measuring the diameter (perpendicular to the axe of rotation) at three characteristic positions given by the shape of the ingot: (a) The bump maximal diameter, (b) The neck minimal diameter and (c) The “hat” diameter). For each solid ingot, three pictures are taken at 120° apart. Threshold is applied to solid shape pictures and finally 6 half-outline are obtained. Solid are not always perfectly symmetrical and the deviation is evaluated with calculation of the maximal gap between each half-outline. The comparisons with simulated cross sections are based on the average of the 6 half outlines.



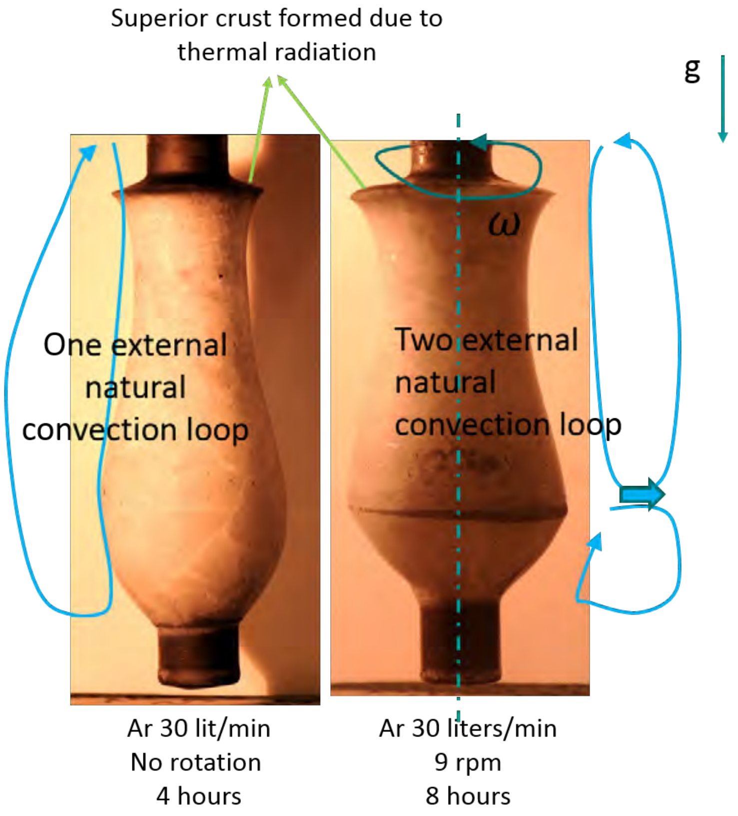
Various stages of the image process used to determine the solid salt ingot profile.

Changing the argon flow rate, the rotation speed or the salt temperature at the external wall has performed more than forty different solidification transient experiments. Re-melting transients were also investigated. The following Table summarizes selected solidification experiments, which used different durations at different argon cooling flow rates (15 L/min, 30 L/Min and 60 L/min) and with or without rotation (9 rpm).

Cooling Flow Rate **Duration**	**15 L/min**		**30 L/min**		**60 L/min**	
1			X	X	X	X
2	X	X	X	X	X	X
3				X	X	X
4	X	X	X	X	X	X
8	X	X	X	X		
24			X			
Rotation	**0 rpm**	**9 rpm**	**0 rpm**	**9 rpm**	**0 rpm**	**9 rpm**

Main solidification experiments

Typical difference between salt ingot shapes is shown on the following figure. On the left side of the figure, an example of the solid ingot obtained after four hours of experiment without rotation of the cooling tube. On the left side the solid ingot was obtained after eight hours of experiment and using a rotation speed of the cooling tube of 9 RPM.



Flinak ingots obtained in the solidification experiments without cooling system rotation (left) and with cooling system rotation (right)

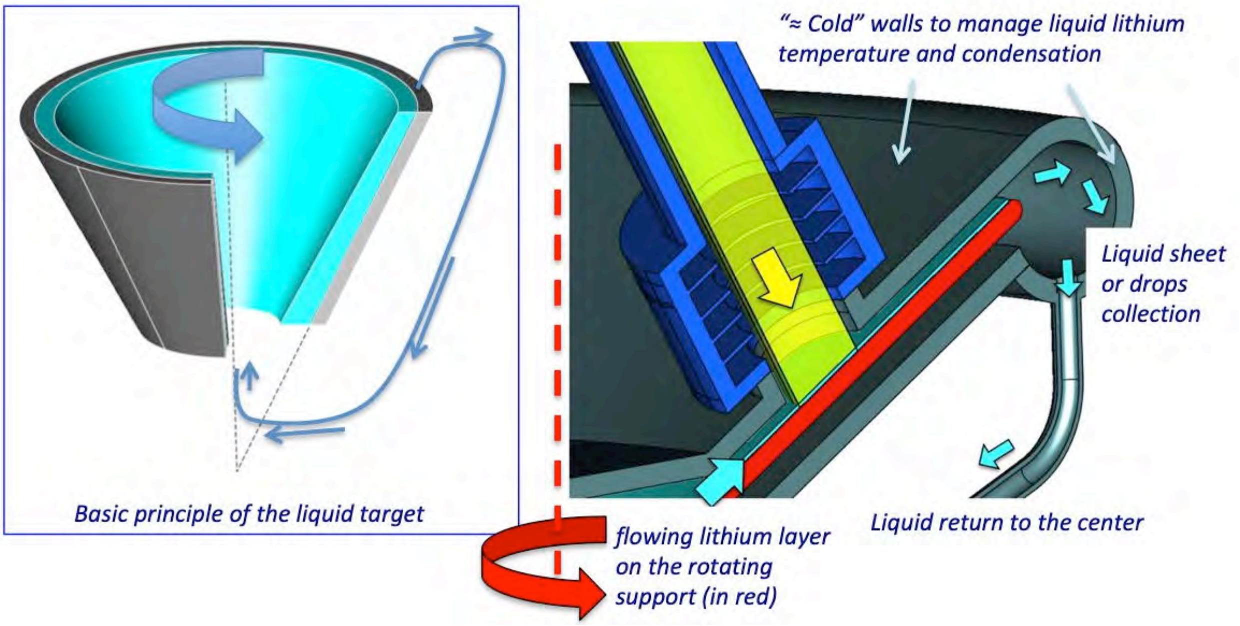
The differences observed in the shapes of the solids formed are a result of the flow circulation patterns in the molten FLiNaK mold and with the boundary conditions. In the solidification experiment without rotation, as the molten salt is cooled by the internal cooling system, the temperature of the molten salt next to the cooling device in the center of the mold will be lower than the one next to the lateral wall of the mold. Hence, a natural convection circulation loop is established, in which the molten salt rises next to the exterior wall of the mold and descends next to the interior cooling device. As the molten salt descends in the interior tube, it is gradually cooled down and, hence, the solidification is preferentially produced in the inferior part of the cooling device. However, when the interior cooling device rotates, a shear flow is produced between the interior cooling device and the mold walls ($\partial p/\partial r \neq 0$), causing a pumping of molten salt from the interior tube to the walls of the mold. The magnitude of the pumping effect is dependent on the tangential velocity of the inner rotating device ($\partial p/\partial r \approx -\rho V_T^2/r$). Hence, the larger the amount of solid form, the larger the tangential velocity and the larger the pumping effect. When the solid grows far enough, the secondary pressure gradients in the vertical direction produced by the radial flow becomes larger than the pressure gradients produced by the temperature differences. Hence, a split-up of the flow is produced, producing two convection cells.

4-4: Liquid Lithium target

High neutrons flux, about 10^{13}n.cm^{-2}s^{-1}, are more and more required for many industrial and research domains such as isotopes production, non-destructive tests, neutrons radiography, sub-surface geophysical exploration or the promising cancer treatment called Boron Neutron Capture Therapy (BNCT). However, the production of such neutron field requires the development of specific targets able to stand a high power (~15-50 kW) on a small area (~10 cm²). These specific target designs, materials and supports, have to cope with extreme physical constraints. In this context, the LPSC team working on BNCT (related to MIMAC – D. Santos LPSC group) has conceived original targets with lithium or beryllium. The work in the framework of the FEST platform is particularly aimed at the target of liquid Lithium target using the ^{7}Li(p,n)^{7}Be reaction.

The nuclear reaction (^{7}Li(p (2.5 MeV) ,n))^{7}Be) is excellent from the neutron production point of view. It presents also the possibility to modify the maximum neutron energy produced as a function of the proton beam energy. It produces relatively low-energy neutrons (E_n < 765 keV with 2.5 MeV protons and E_n <30 keV with protons of 1.9 MeV) with a significant cross-section but the melting point of the metallic lithium (180°C) requires a sophisticated design and cooling devices to keep the specifications of the target.

The depth of penetration into the target material can vary according to the energies of the incident beams of particles employed. In the case of low energies (E < 2.5 MeV), which are the most suitable for the purpose of BNCT (minimized activation and simplified moderation), the penetration in the target material is low and the transfer of energy from the beam occurs at the subsurface, creating significant heating of the target material. With materials that have a low melting point, there is an advantage to use thin target materials in order to spread most of the heat supplied by the beam of incident particles into the backing-target material. Because solid thin layers have problems of stability and deterioration under the effect of the beam, their life is short and they have to be changed regularly. Then “liquid” targets represent an attractive solution for high current intensity beams (I > 1 mA). As a result, compared with a target based on solid lithium, the problems associated with the integrity of the layer, its adhesion to the support and keeping it at a very low temperature (< 180°C) could thus be solved. Several foreign target project based on liquid lithium involve a liquid lithium loop in closed ducting with, at the particle beam inlet, an open and curved zone on which the lithium forms a film ranging from several hundred microns up to 1.5 mm in thickness. The flow rate of lithium in the ducting is high enough to establish a high-speed flow of the thin film of liquid in the beam path (from 7 m/s to 30 m/s depending on current or past projects) so that the temperature of the film remains acceptable limiting the evaporation of liquid lithium. Our concept is not based on a circulation loop but on centrifugal phenomena (Left side of the following figure) and is currently at the stage of conceptual validation using computational fluid dynamics and water mock-up at true scale and has been the subject of a patent (FR3097401) and its extension to the international is currently in progress. The main parameters are the speed of rotation of the support and its radius and no longer a flow rate as in the case of lithium loops**.** This concept has the double advantage of using little liquid and of allowing the installation to be more compact. This last point makes it possible to minimize the radiation protection problems due to the ^{7}Be produced by the ^{7}Li(p,n)^{7}Be.

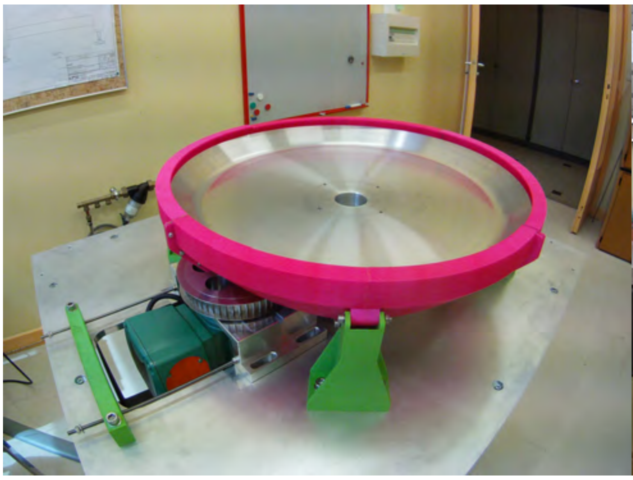


Principle of the rotating liquid target based on centrifugal effect to create a thin liquid film. The sketch on the right shows a possible configuration for the beam entrance area. After recovering drops, the liquid is redirected by gravity towards the center of the target.

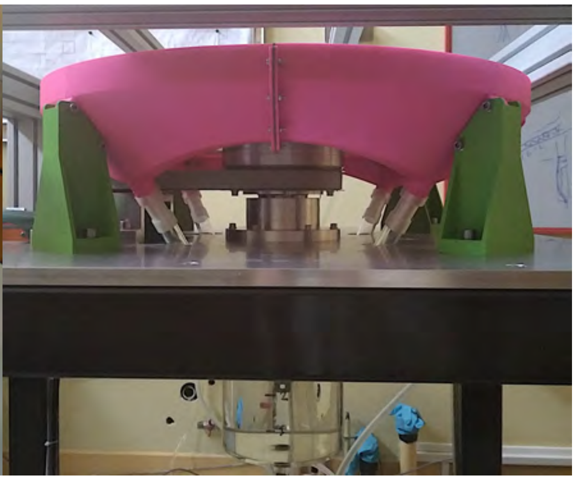
To determine the possible design of a prototype we need to guarantee two crucial points before testing it under conditions close to reality:

- the correct and continuous control of the evaporation/condensation phenomena that takes places respectively at the lithium film surface and the condensor surface. The circulating lithium quantity has to be kept constant. The evaporated lithium has to be recovered by condensation at the liquid state and reinjected in the circulation.
- the temperature reached on the beam impact area has to be low enough (< 300°C) to prevent any reactivity between lithium liquid and the supporting material and at the same time be compatible with the vacuum in the beam entrance area. At the same time, the temperature has not been lower than 180°C at any point of the condensing system preventing to create a local accumulation of solid lithium. The heat balance has to be precisely managed everywhere inside the system.

Work with lithium is currently out of reach and will require significant funding. As viscosity of lithium at 220°C ($1.06.10^{-6}$ m^2/s) is very close to that of water at 20°C ($1.02.10^{-6}$ m^2/s), the study on water model is relevant for the purely hydraulic aspects and has been undertaken at scale one. The following figure shows the water model.



The metal plate represents the surface where the fluid flows



Lower part of the model with the tank and the fluid return line

5. State of the art

On the side of the work concerning molten salts, our projects are favorably positioned in relation to European and International competition in terms of the ratio of results to human and financial resources allocated. However, we cannot claim to have the same influence or the same objectives as larger institutions. We will remain on a scale that allows us both to make relevant scientific studies and to transmit our knowledge to young scientists (Engineering students or PhD). The progress of the work on the target side is much more difficult, both because of the lack of human and financial resources and because of the lack of visibility and support.

6. Future Technical achievements

Further technical developments are foreseen within the framework of the end of the European Project Samosafer with the test of an open channel already designed and for which water tests are now beginning on one hand and the implementation of the PIA-ISACC French project, which will run from 2022 to 2026. This project is based on chloride salt reactor studies. The planned work will consist of building a new loop, smaller than FFFER, and partly included in a glove box to study in line bubbling and some other components.

7. Summary Auto-analysis SWOT

The major strength is the real know-how acquired over time on the technical implementation and the various problems that can arise and their mitigation by a well thought-out design. The weaknesses are related to the small number of people on which these works are based.