Molten Salt Fast Reactor transient analyses with the COUPLE code

Brovchenko[1] M., Merle-Lucotte[1] E., Heuer[1] D., Rineiski[2] A.

[1]*Laboratoire de Physique Subatomique et de Cosmologie – IN2P3 – CNRS / Grenoble INP / UJF,* 53*, rue des Martyrs 38026 Grenoble, France*

[2]*Institute for Nuclear and Energy Technologies, Karlsruhe Institute of Technology, P.O.B.3640, D-76021 Karlsruhe, Germany*

Email Address: brovchenko@lpsc.in2p3.fr, merle@lpsc.in2p3.fr,

INTRODUCTION

The recent development of the particular molten salt reactor concept called Molten Salt Fast Reactor (MSFR) [1] seems very promising. The reference MSFR combines the generic assets of fast neutron reactors (reduced absorptions in the fission products, waste minimization) with those related to liquid fuel (low pressure, high boiling temperature, optical transparency, efficient use of fissile material thanks to the reprocessing). It is one of the reference reactors of the Generation IV International Forum , for those a higher level of safety insurance is requested. The molten salt reactors are liquid-fuelled reactors and thus they present other interesting safety features: no reactivity reserve, inherent stability of the reactor, power control thanks to the cooling system, draining the liquid fuel towards a passive cooling system by gravity.

MOLTEN SALT FAST REACTOR

Since 2004, the National Centre for Scientific Research (CNRS, Grenoble-France) has focused its R&D efforts on the development of a new fast-spectrum reactor based on the molten salt reactor concept. This resulted in an innovative breeder concept: the Molten Salt Fast Reactor, which precise design has to be defined. This work is motivated by the safety-by-design approach. The design of MSFR is thus developed in order to minimize the severity and the frequency of the accidents. The results of accidental calculations, like the one discussed in this paper, will lead to the specification of the main components: fuel salt pumps and heat exchangers, draining system, materials.

The reference MSFR design is a 3000 MWth reactor with three different loops: the fuel loop, the intermediate loop and the power conversion system. The MSFR fuel salt loop is a binary fluoride salt, composed of LiF enriched in ^{7}Li and a heavy nuclei (HN) fluoride mixture initially composed of fertile thorium and fissile matter (^{233}U, or ^{enriched}U and/or Pu and minor actinides). The $(HN)F_4$ proportion is set at 22.5 mole % (eutectic point), corresponding to a melting temperature of 565°C. The total fuel salt volume (18m^3) is distributed half (9m^3) in the core and half (9m^3) in the recirculation loop. As presented in figure 1, the recirculation loop (outlet pipes, salt-bubble separator, heat exchanger, pump, inlet pipes and other pipes) is broken up in 16 identical modules distributed around the core, outside the fertile blanket and within the reactor vessel. The fuel salt flows upward in the active core until it reaches the outlet pipes. And then the salt flows downward in the pumps and the fuel salt heat exchangers before finally re-entering the bottom of the core through the inlet pipes.

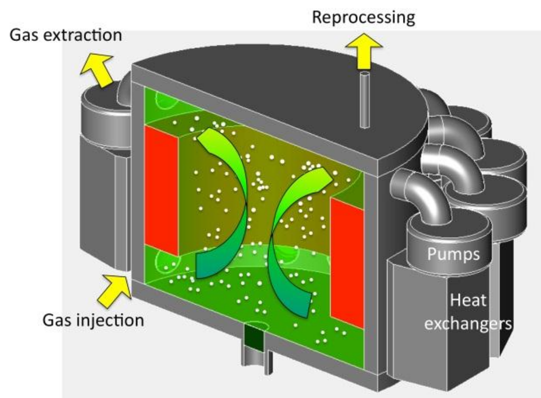

Fig. 1. A simplified schematic of the MSFR system including the fertile blanket (red) and the fuel salt (transparent green) circulating in the core, pumps and heat exchangers.

The MSFR is proposed as the reference design in the EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor System) project in the European 7th framework program. Furthermore, benchmarks calculations for such a MSFR are set up, where the reactor geometry, fuel salt composition, structure materials etc. are described in detail. The studies presented in this paper will be based on the configuration of the system described in the neutronic benchmark.

The geometry of the neutronic benchmark is presented in figure 2. From the thermo-hydraulic point of view this geometry is not optimized due to the important recirculation which takes place near the fertile blanket. The optimized geometry is currently studied in the thermo-hydraulic benchmark of the EVOL project. We will use a simplified cylindrical geometry of the neutronic benchmark and bypass the problem of recirculation by adding an injection profile on the fuel salt entering the core.

The benchmark configuration has the characteristics described in this paragraph. As shown in Fig.1 and 2, the radial reflector is a fertile blanket filled with 7.3m^3 of a fertile salt LiF-ThF_4 with molar 22.5% of ^{232}Th. This fertile blanket improves the global breeding ratio of the reactor due to the extraction of ^{233}U corresponding to a reprocessing rate of 40 liters per day. This fertile blanket is surrounded by a 20cm thick neutronic protection of B_4C which absorbs the remaining neutrons and protects the heat exchangers.

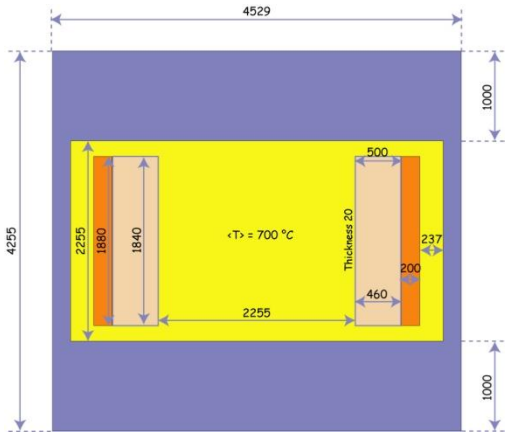

Fig. 2. MSFR configuration of the EVOL neutronic Benchmark (dimensions given in mm) with fuel salt (yellow), the fertile salt (pink) the B4C protection (orange) and the reflectors and the 20mm thick walls in Ni-based alloy (blue).

The calculations of the feedback coefficient were performed with a probabilistic neutronics code (MCNP) and the results are presented in Table I. Different compositions of the fuel salt were studied: initial composition of ^{233}U started MSFR and transuranic elements (TRU)-started MSFR. After 100 years of operation the composition of the fuel salt is almost the same for both initial compositions. Its feedback coefficient calculations are also presented in the Table I called “Steady State” composition.

In pcm/K	**Void**	**Doppler**	**Total**	**+/- Δ**
^{233}U-started	-3.26	-3.74	-6.67	-0.19
TRU-started	-2.73	-1.79	-3.76	-0.18
Steady State (100 yrs)	-2.98	-2.34	-5.07	-0.19

TABLE I. Void coefficient, Doppler coefficient and the total feedback coefficient for three compositions: beginning of life of a ^{233}U-started MSFR, a TRU-started MSFR and the steady state composition.

Both contributions of the feedback coefficient: Doppler and void (salt thermal expansion) coefficient were calculated to be negative for all studied compositions (see Table I). It is an important advantage from the safety point of view that will be discussed in the next paragraph.

SAFETY

MSFR, as a liquid-fuelled reactor, needs a good understanding of all safety issues. Some important safety issues will be discussed in this paragraph. The negative feedback coefficient, as presented in the Table I, allows intrinsic stability of the reactor. Unlike in the solid fuel reactors, the negative feedback coefficient acts very rapidly since the fuel salt itself is directly cooled in the heat exchanger. This behavior can be observed for the different transients studied in this paper. Besides the accidental transients, some power control transients will be presented in the results. Indeed, the MSFR has a very interesting advantage to allow a fast load following.

For this type of reactor no reactivity reserve is needed, thanks to the fast neutron spectrum and the reprocessing during the operation of the reactor. The criticality is controlled at short term by the temperature and at long term by controlling the salt composition using the reprocessing unit, whose effect is very slow. Thus a control rod would represent a large reactivity reserve, while being not mandatory to drive the reactor (see below), as also already stated for homogeneous reactors [2]. Consequently, there is no control rod in this design.

Due to the excellent feedback coefficient, a reactivity accident will lead to an intrinsic stabilization of the mean fuel salt temperature. Combined to the small reactivity reserve, it seems not to be the more important accident for this type of reactor.

The strong coupling between the thermal hydraulics and the neutronics (due to the feedback coefficient) lead us to consider all transients that effect the circulation and the temperature of the fuel salt. In other words the pumps and the heat exchangers have a crucial role for the accidental transient study. In this paper we will present the results of heat sink loss transients. The cooling of the fuel salt may be lost due to a fuel salt circulation loss or due to a heat sink loss coming from the intermediate circuit. These two types of transients have similar behaviors. Their only difference is in the contribution of the delayed neutrons. If the fuel salt circulation is maintained, the created precursors of the delayed neutrons may decay outside the core and do not contribute to the chain reaction. If the fuel salt circulation is not maintained all the created precursors will decay in the core and thus contribute to the chain reaction. From the practical point of view, a circulation loss of the fuel salt leads to a cooling loss that requires a detailed heat exchanger simulation which cannot currently be performed with the code COUPLE, used in this paper. For this reason, only the loss of heat sink transients will be presented in this paper.

In MSFR, a loss of cooling leads to a temperature increase of the fuel salt and, thanks to the negative feedback coefficient, to the reactor shut down (chain reaction stop). As for a solid fuelled reactor, the radioactive matters (actinides and fission products) represent a heat source even after the reactor shut down. The extraction of this residual heat is a crucial safety issue. The decay heat for the MSFR has been previously evaluated in [3]. These data will be used in all transient calculations. In the case when the fuel salt cannot be sufficiently cooled down in the fuel circuit, the fuel salt will be passively drained by gravity towards the draining storage system that includes a passive cooling system currently under study.

TOOL DESCRIPTION

The COUPLE code is developed at the IKET/TRANS group, Karlsruhe Institute of Technology, for the neutronics and thermal hydraulics coupled calculation of liquid-fuelled reactors. The code is described in detail in reference [4].

RESULTS

The MSFR model is implemented in the COUPLE code, using the neutronic benchmark data (see above). The reactor (core, fertile blanket, neutronic protection, heat exchanger) is simulated in COUPLE, following a mesh of 112/130 cells in the R/Z directions. To simulate respectively the pumps and heat exchangers, we have used the pump model (fixed velocity) and the heat exchanger model (fixed negative heat source) of COUPLE. First, a steady state calculation was performed with COUPLE.

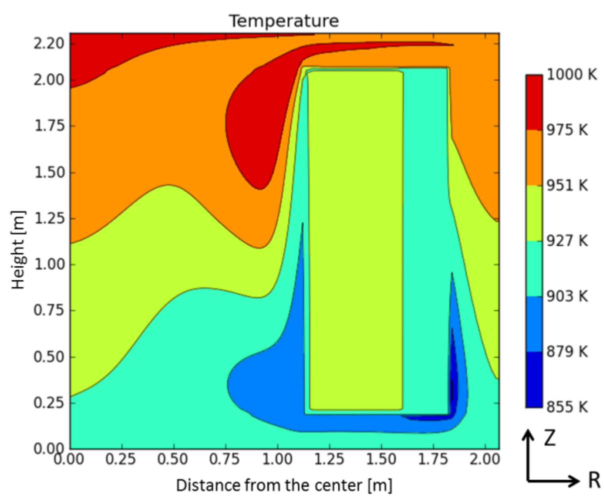

Fig. 3. Temperature distribution in the half MSFR core model calculated with COUPLE. The fuel salt circulates upwards in the core (on the left) and downwards in the heat exchanger (on the right). In between is the fertile blanket with the neutronic protection.

The resulting temperature distribution is presented in figure 3. As already mentioned above, an adapted injection profile is used to avoid recirculation. This state was used as the initial state for the calculated transients. Different types of transient have been studied, corresponding to normal operation and to incidental/accidental scenarios.

First, the transients of load following are presented. The circulation of the fuel salt is fixed at the operational conditions throughout the transient while the extracted heat in the heat exchanger decreases as shown in figure 4 (crosses). At the beginning of the transient the extracted heat is equal to 100% (nominal power) and then it decreases exponentially stepwise towards chosen final value. Different final values of the power are studied: 50% (red curves), 25% (blue curves) and 4% (black curves). The characteristic time of the exponential decrease is equal to 100s. The 4% of the nominal power represents the hot shutdown: no more fission occurs, only decay heat is to be extracted.

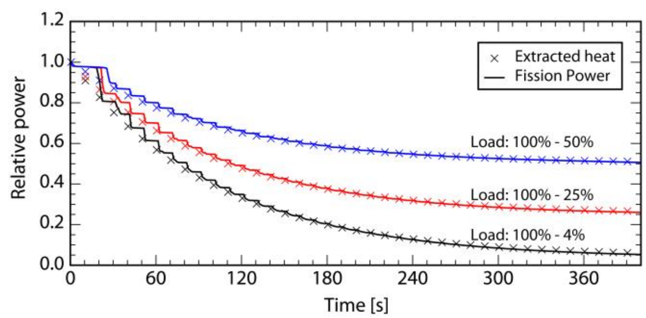

Fig. 4. Fission power with the extracted heat relative to nominal power for different load followings: 100%-50%, 100% - 25% and 100% - 4%.

Thanks to the negative feedback coefficient, the fission power produced in the core follows the extracted power (solid lines). Thereby the mean temperature of the fuel salt stays almost constant. This behavior shows well that driven the MSFR core by the extracted power is possible, even for an important load following in a short time.

Finally, the loss of heat sink transients, corresponding to an accidental situation will be presented, for different inertia of the system. Similarly to the load following transients, we fix the circulation of the fuel salt all along the transient while the extracted heat decreases from nominal conditions (100%) to 0. The loss of the heat sink is exponential and stepwise with a characteristic time τ as shown in figure 5 a) (dashed lines). Different values of this characteristic time τ represent different inertias of the system.

Figure 5 a) presents the fission power in the core in solid lines. It is interesting to point out that the reactor behavior for a heat sink loss with τ=1s (red curves) and τ=0.1s (green curves) and also for the lower values of τ is almost the same. It represents the "limit"; the fission power cannot decrease more quickly. This limit comes from the circulation time of the fuel salt: it is the time period necessary for the fuel salt to go from the output of the heat exchanges to the core.

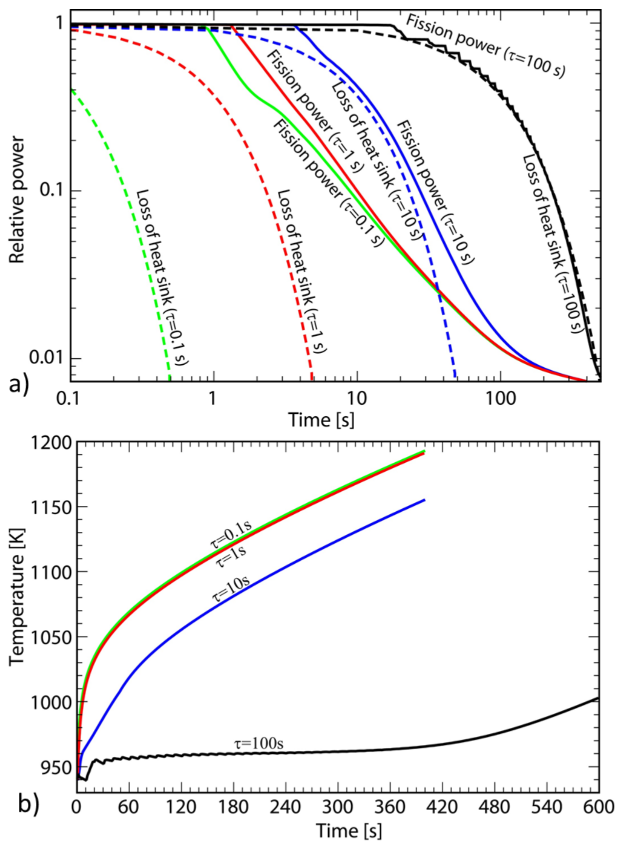

Fig. 5. a) Evolution of the fission power and the extracted heat relative to nominal power as a function of the time since the beginning of the transient; b) Evolution of the mean fuel salt temperature in the core during the transient. Four transients considered: with an exponential heat sink loss with τ=0.1s (green curves), 1s (red curves), 10s (blue curves) and 100s (black curves).

For a heat sink loss with a characteristic time τ=10s (blue curves) or τ=10s (black curves), the fission power and the extracted power are very close in shape and value. Nevertheless 100s after the transient begins, the three solid curves for τ=10s, 1s and 0.1s converge towards almost the same value. That is due to the delayed neutron precursors with a long lifetime (typically $T_{1/2}$~50s) which were mainly created before the beginning of the transient. Thus their amount is very similar for these three transients. The loss of heat sink with τ=100s is sufficiently slow, so that the reactor is stabilized at each step (black solid line). For this reason the fission power is lower than the extracted heat, when its value is on the same order as the decay heat (~4%).

The evolution of the fuel salt temperature during the described transients is presented in figure 5 b). Additionally to the fission power that heats up the fuel salt, the decay heat is also taken into account in these transients. For this reason, the temperature still increases even when there is almost no more fissions. In particular for loss of heat sink with τ=100s, the temperature starts to increase when the fissions stops (after some 500s). As it was observed for the fission power, there is almost no difference between a heat sink loss with τ=0.1s and 1s regarding the temperature of the fuel salt. Thereby for a larger inertia (τ=10s) the temperature increase is much slower at the beginning of the transient. For longer term, the fuel salt must be cooled down in the draining system including a passive cooling system that will extract the produced decay heat to keep the fuel salt temperature at acceptable levels.

These results obtained with the code COUPLE, even if still preliminary, confirm the satisfactory behavior of the MSFR for safety issues, as already noticed while using a more simple approach based on the kinetic-point model. This coupled code, simple but easy to run, will allow quick transient analyses, on the way to safety calculations and optimizations of the MSFR concept.

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