# Two-tanks heat storage for variable electricity production in SFR: preliminary architecture and transient results

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## Abstract

The prospective energy mix scenarii generally imply a large contribution of renewable energy. The increasing use of solar and wind energies, which are intrinsically intermittent, actually constitutes a source of uncertainties and fragilities for the electrical grid. As nuclear energy produces heat before being converted into electricity, a step of heat storage prior to the heat conversion step might be effective to remedy this intermittence in order to ensure the grid reliability and flexibility without involving large variations of the nuclear core power. Depending on the daily scenarii, the nuclear core could even stay at its maximal power all day long. Following this approach, a smaller core is then able to cope with the same peaks of demand than a larger one without heat storage systems.

In this paper, a preliminary heat storage architecture coupled to a Sodium Fast Reactor is proposed in order to highlight the benefits of such a storage technology. The technical design based on two tanks respectively containing hot and cold fluids is inspired by current solar power technologies. The sizing of this system is carried out with a Thermodynamic Cycle Optimization tool (CYCLOP) and preliminary transients are simulated with the system thermal-hydraulics code CATHARE3.

Even if some architecture improvements are still necessary, especially for safety related reasons, this study enables to draw the main benefits of such an electricity production strategy. In particular, it is shown that a variable electricity production while operating the reactor at base load is possible in load following conditions, thus enabling to optimize the plant profitability. As the impact on the primary circuit is shown to be negligible in terms of temperature evolutions, thermomechanical loading constraints in the vessel may also be drastically relaxed.

## 1- Introduction

The production of energy currently faces two major evolutions: we live in a more and more carbon-constrained world, and the global energy mix at local and international scale is increasingly based on renewable energies. In particular, the use of solar and wind energies, which are intrinsically intermittent, actually constitutes a source of uncertainties and fragilities for the electrical grid. As nuclear energy produces a carbon-free electricity, it is a good candidate to remedy this intermittence through variable electrical productions in order to ensure the grid reliability. The current nuclear technologies however suffer from their limited ability to perform large and repeated power variations for thermomechanical reasons. This is why the design of processes aiming at improving the flexibility of nuclear energy production is a major challenge regarding the current world energy transition.

As mentioned in [1], this problem may be tackled through different ways. Instead of producing a variable amount of heat energy in the core, solutions involving a variable electricity power production without affecting the primary circuit are foreseen: energy storage before the Power Conversion System, energy storage in the Power Conversion System (PCS) and hybrid systems (*cf.* Figure 1).
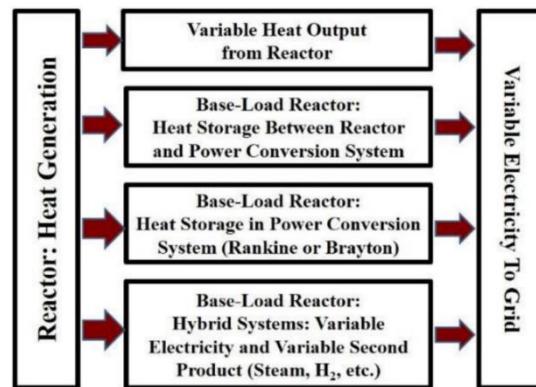
Figure 1 – Design options for a variable electricity production with a nuclear power plant [1]

By maintaining the core at constant power, these technologies could offer many advantages:
- The thermomechanical loadings are drastically reduced in the core and in the primary circuit structures;
- The variable electricity output can maximize revenue (through selling when prices are high and storing when prices are low) while operating the reactor at base load to minimize costs;
- If adequately designed, the system may reduce the production response time in order to better accommodate the grid to an unexpected intermittent production.

Moreover, when applied to the Sodium Fast Reactor case, such a storage system can make impossible by design the occurrence of the dreaded sodium-water interaction if the storage fluid is correctly chosen.

In the frame of prospective studies for the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project, the objective of this paper is to design a heat storage system enabling to perform load following and frequency regulation while maintaining a 1500 MWth Sodium Fast Reactor at base load. Among the solutions listed previously, the two-tank energy storage before the PCS is adopted for preliminary feasibility reasons. Such a configuration has indeed been significantly studied and applied by the past, for instance in solar thermal systems. In ANDASOL (Spain) [2], a system based on two tanks of 14000 $m^3$ each filled with molten salt (Figure 2) already enables a Thermal Energy Storage (TES) of more than 1000 MW.h. In the USA, both Solar Two [3] (Figure 3, left side) and Solana (Figure 3, right side) have demonstrated this process feasibility, respectively enabling a 100 and a 4000 MW.h TES. As discussed below, the TES foreseen for our project is of the same order of magnitude; this is why this two-tank technology is firstly studied in this paper.
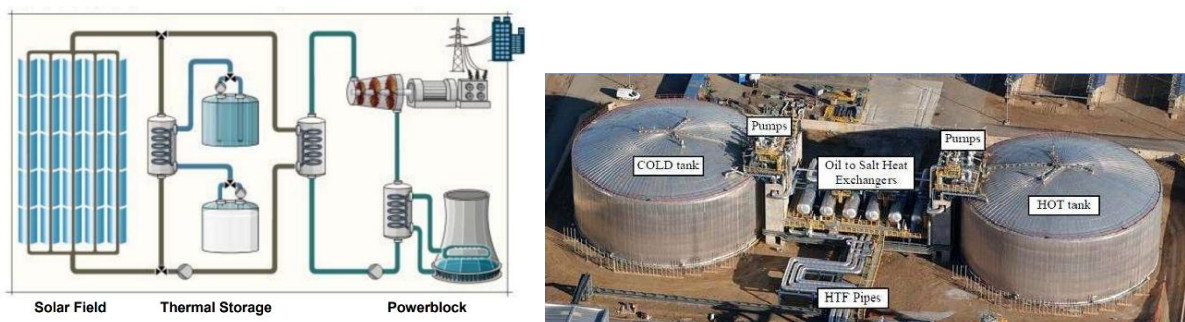


Figure 2 – ANDASOL power plant configuration (left) and storage installation (right) [2]
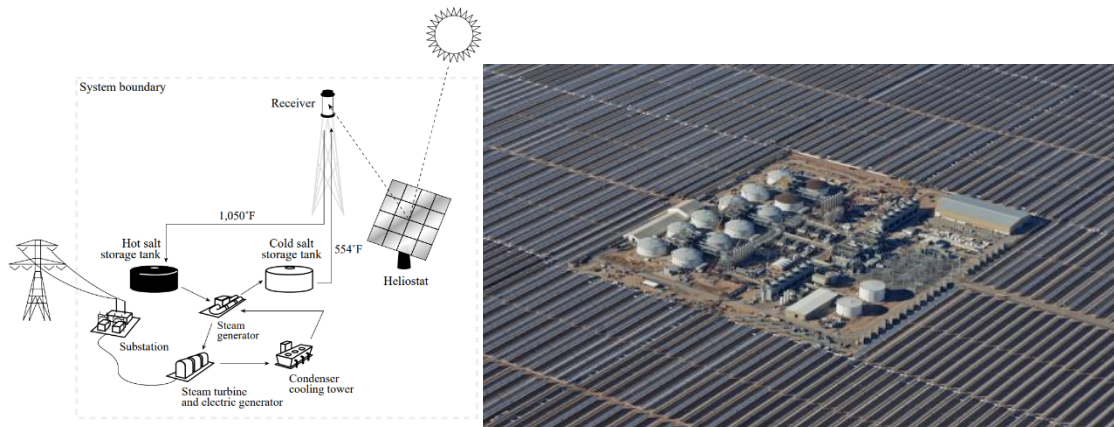
**Figure 3 - Solar Two power system configuration [3] (left) and Solana site photography [4] (right)**

## 2- Global system architecture and design

### Reactor Design

The reactor chosen for this preliminary application study is the Sodium Fast Reactor proposed by the French GenIV research program ASTRID [5] [6]. It is an integrated pool-type reactor delivering a 1500 MWth thermal power to four secondary sodium loops. The latter are connected to a Power Conversion System that may be based on a Water-Rankine or on a Gas-Brayton thermodynamical cycle [7]. In this paper, the Rankine option is considered, resulting in a global effiency around 42 %. In nominal operating conditions and without storage system, this power plant thus produces around 620 MW of electricity (MWe).

### Storage System Architecture

As mentioned in the introduction, the solution consisting in installing a heat storage system in a dedicated loop, between the reactor and the power cycle, is hereafter chosen for a preliminary feasibility study. This so-called Storage Loop is located in a third circuit as illustrated in Figure 4. As it can be seen on this scheme, the storage loop architecture mainly relies on four main components:
-   A secondary intermediate heat exchanger (SIHX) connecting the sodium secondary loops with the storage loop;
-   The steam generator (SG) connecting the storage loop with the Rankine PCS;
-   A hot tank whose free level varies according to the heat storage or release;
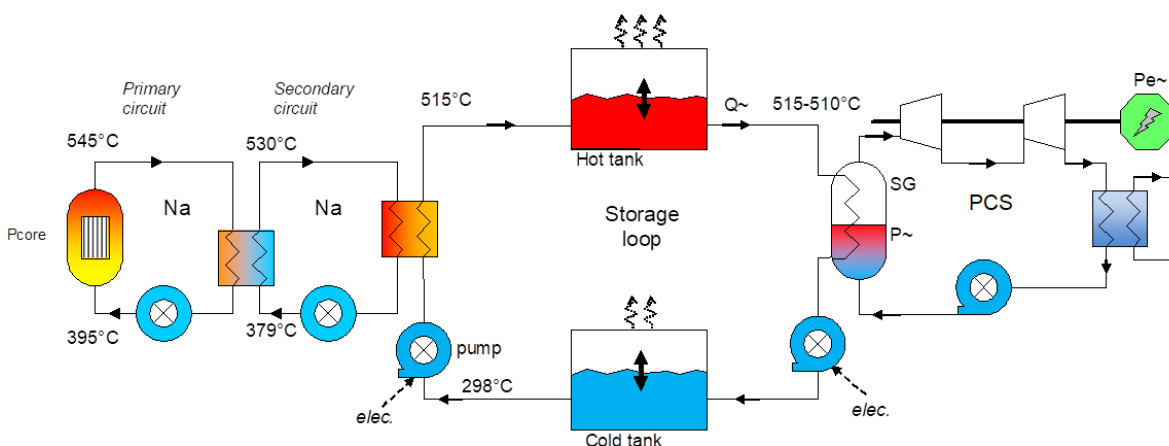-   A cold tank whose free level also varies.



**Figure 4 – Illustration of the two-tank heat storage configuration associated with a SFR heat production and a Rankine PCS**

**Operating mode**

In order to store a various amount of heat in the tanks, the storage loop also includes two pumps, respectively located upstream and downstream of both tanks. The pump located on the SIHX side operates at full power at any time, in order to extract always the same nominal power from the core that operates at base load. Conversely, the pump located on the SG side is characterized by a variable power, resulting in a variable mass flow rate in the SG and thus in a variable power transmitted to the PCS. Regarding this architecture, the two following operating modes are identified and illustrated in Figure 5:

-   The so-called "day mode" relying on heat release: the SG side pump delivers a higher mass flow rate than the SIHX side one, the free level in the hot tank goes down while it goes up in the cold one;
-   The so-called "night mode" relying on heat storage: the SG side pump delivers a lower mass flow rate than the SIHX side one, etc.
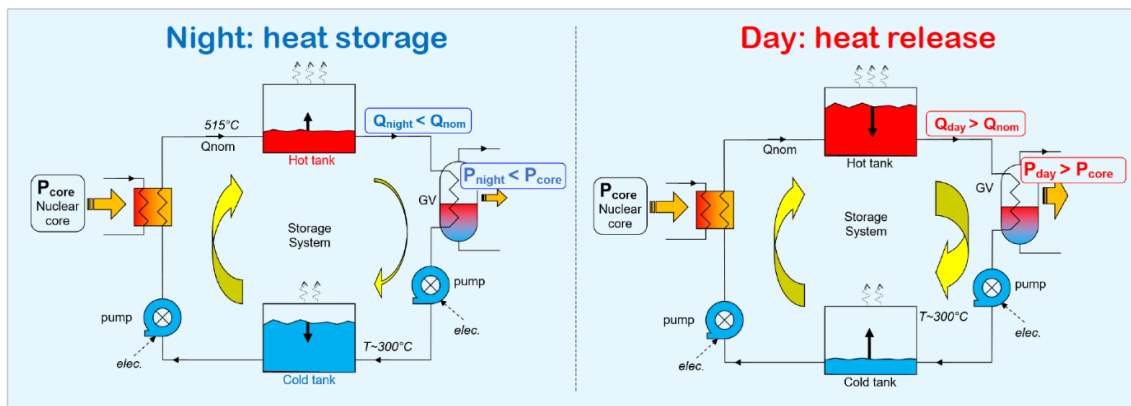


**Figure 5 – Description of the heat storage operating modes [8]**

**Choice of the storage fluid**

The choice of the storage fluid for this preliminary study has been inspired by the study exhaustively described in [9], which was dedicated to the fluid selection in the intermediate loop of a SFR. A group of experts firstly selected six fluids considered as promising, and a multi-criteria analysis has been performed to evaluate these fluids according to several criteria (thermal properties, interaction with structures and fluids, chemistry control, etc.). According to the results synthetized in [9], three best promising fluids were identified: Na-Ni, Pb-Bi and NaOH-KOH. Specific results concerning these fluids are displayed in Figure 6. Regarding this analysis, the eutectic alloy Pb-Bi seems the most promising fluid for intermediate loops between the core and the PCS. Thus, further evaluation of the heat storage impact on the electrical production will be applied on a Pb-Bi storage loop. Sodium has been by default excluded in this study owing to the water-sodium interaction that may occur in a SFR connected to a Water-Rankine cycle. Molten salt (such as HITEC or Solar Salt) were also excluded for chemical interaction reasons, but they would be good candidates for further studies applied to Pressurized Water Reactors.
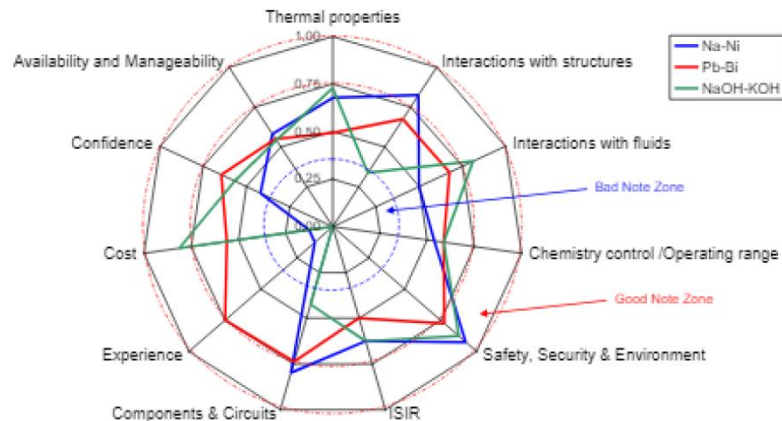
Figure 6 – Synthesis of the 3 promising fluids performances [9]

**Tanks design**

The design of the storage system depends on the energy storage objective. As this system is expected to enable a load following on the grid, it should store energy during the night-time (min: 8h) and release it to produce electricity during the day-time (max: 16h). Let's note that seasonal or annual energy storage are not addressed in this paper. According to these objectives, the system should store a TES around 5.700 MW.h. Considering the SFR core temperatures (inlet: 400°C, outlet: 550°C) and the Rankine cycle configuration, the hot tank fluid temperature is preliminary considered around 515°C, and the cold one is around 300°C. In these conditions and due to the Pb-Bi thermo-physical properties, the storage tanks should contain 63.000 tons of fluid: storage tanks characterized by a diameter of 74 m and a 14 m height each are thus suitable. Such tanks design seems feasible in the light of already existing two-tank storage programs as mentioned in the introduction.

### 3-  Overall cycle efficiency assessment

In order to assess the whole installation thermodynamical cycle performance, the CYCLOP tool developed by CEA has been used. This is a tool dedicated to the elaboration and optimization of such thermodynamical cycles [10]. The illustration of the modelling including the primary circuit, the intermediate sodium loops, the storage loop filled with Pb-Bi and the Rankine-PCS is displayed in Figure 7 for the day-time production. It appears that, whereas the global efficiency of such an installation without storage system is around 42 %, it reaches 52 %[1] in daytime production (*i.e.* when the demand is higher) if a storage system is implemented. In return, the efficiency during night-time is lowered to 17 % to enable the thermal energy storage.

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[1] Taking into account auxilliary services consumption.
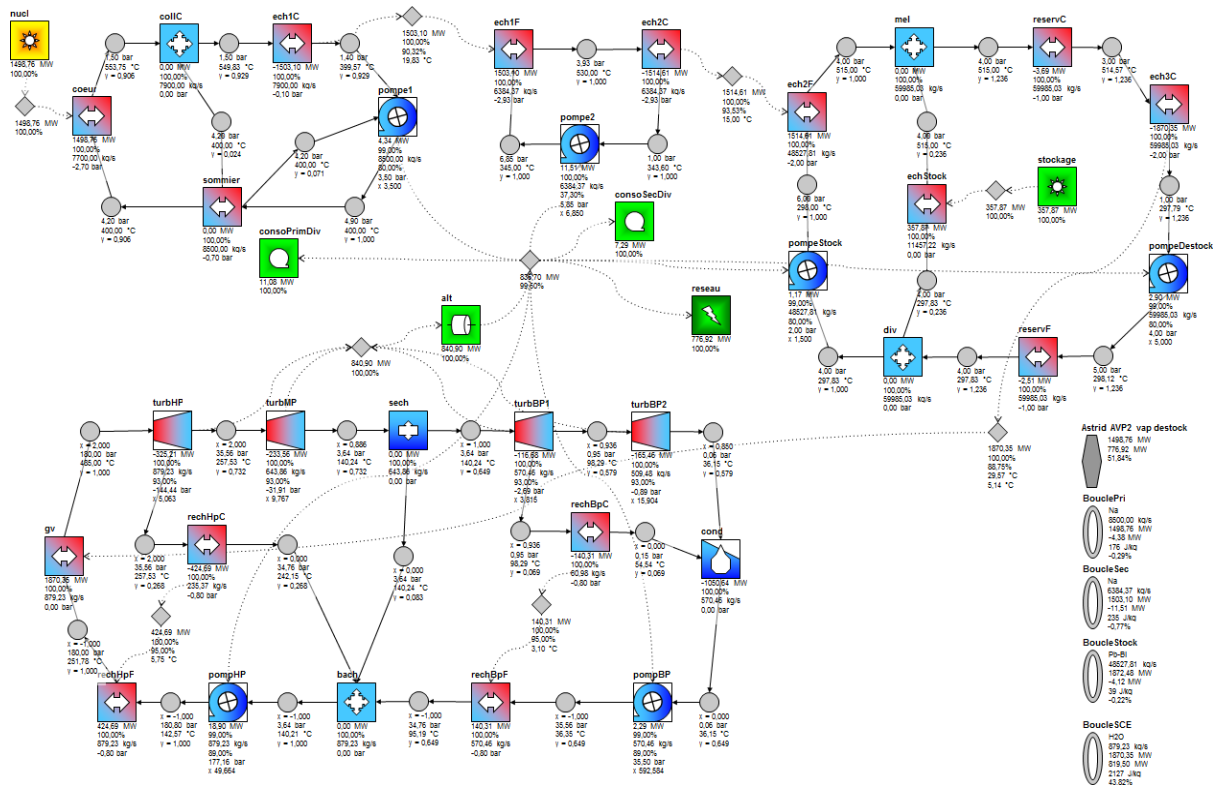
**Figure 7 – CYCLOP modeling of the storage installation coupled to a SFR heat production and a Rankine Power Conversion System – Day mode with a 1500 MWth reactor**

This first approach highlights the ability of such a system to increase the electricity production when a peak of demand is observed in the day-time. Another way to highlight the interest of this technology consist of designing a smaller (and cheaper) core that can produce the same daily electric production than a larger core without storage systems. This study has also been performed with CYCLOP. It showed that a core power lowered to 1150 MWth with a storage system enables to produce the same electrical production (600 MWe) during the day-time than a larger 1500 MWth core without storage system.

### 4- Preliminary transient calculations

In section 3-, the loop architecture has been shown to be able to store enough energy in static conditions. In order to study its capacity to restitute enough energy in transient conditions, some calculations were carried out using the system thermal-hydraulic tool CATHARE3 which has already been used for many ASTRID PCS calculations [11] [12]. The objective is to conclude about the feasibility of operating the system in load following and frequency regulation conditions without affecting the operating conditions of the primary circuit in terms of temperatures and power.

**Main assumptions**
For this preliminary transient study, the following assumptions are made:
- The storage fluid is not Pb-Bi as expected in the light of previous paragraphs but sodium for practical reasons. The sodium thermophysical properties are indeed already implemented in CATHARE3 whereas the Pb-Bi fluid would require further investigations. Nevertheless, sodium is characterized by good thermal properties and thus it is a good candidate for a preliminary feasibility study as expected in this paper. Due to this consideration, the tanks size has been fitted in order to store the same energy than Pb-Bi tanks;

- The electrical power delivered by the alternator is considered instantly proportional to the power transmitted to water in the SG. The considered input deck does not include the description of the PCS, except in the SG part. This assumption, which is valid for small power variations, will require further ongoing developments for large power amplitude variations;
- Heat losses are not taken into account for this preliminary feasibility work. A dedicated study will enable to assess these thermal losses in such cylindrical tanks in 2019.

The input deck also includes control loops (based on PID controllers) dedicated to the global system regulation. As listed in Figure 8:
- The power extracted from the primary circuit in the second intermediate heat exchanger is controlled via the rotating speed of the pump located downstream of the hot tank;
- The power transmitted to the PCS in the SG is controlled via the rotating speed of the pump located downstream of the cold tank;
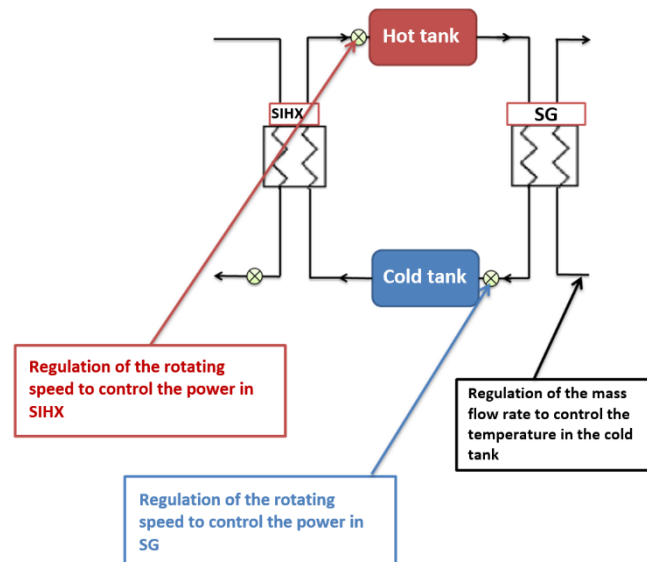- The storage fluid temperature in the cold tank is controlled via the water mass flow rate in the SG (PCS side).



Figure 8 – Description of the control loops (PID controllers) implemented in the input deck

**Load following transient**

The considered load following transient is defined as below:
- During the day (16 h), while demand is high, the electric power should be at its maximal possible value;
- During the night (8 h), the electric power should be lowered to 30 % of this maximal value.

In other words, while the core is always at 1500 MWth, the day electric production should vary from 840 MWe during 16 h (day) to 250 MWe (*i.e.* 30 % of the day electric power) during 8h to enable heat storage during night. Moreover, the primary circuit should not be impacted to preserve structures from repeated thermomechanical loadings.

Results of the CATHARE3 simulation are illustrated in Figure 9. This figure firstly shows that the heat storage/release cycle is correctly ensured by the variation of the free levels in both hot and cold tanks. As this process enables to modify the mass flow rate in the SG, the power transmitted to the Rankine PCS also varies as illustrated in the middle of this figure. The small power variation ob-

served around 16h30 in Figure 9 (middle figure) would require a better PID corrector implementation. However, these results demonstrate the ability of the system to perform load following for several day/night cycles. The evolution of the sodium cold temperature in the secondary loop is finally displayed in order to check the impact of this transient in the secondary loops (and a fortiori on the primary circuit). The maximum observed variation is only around 1°C, highlighting that this load following process based on two-tanks storage has a negligible impact on the core power, and more generally on the primary circuit.
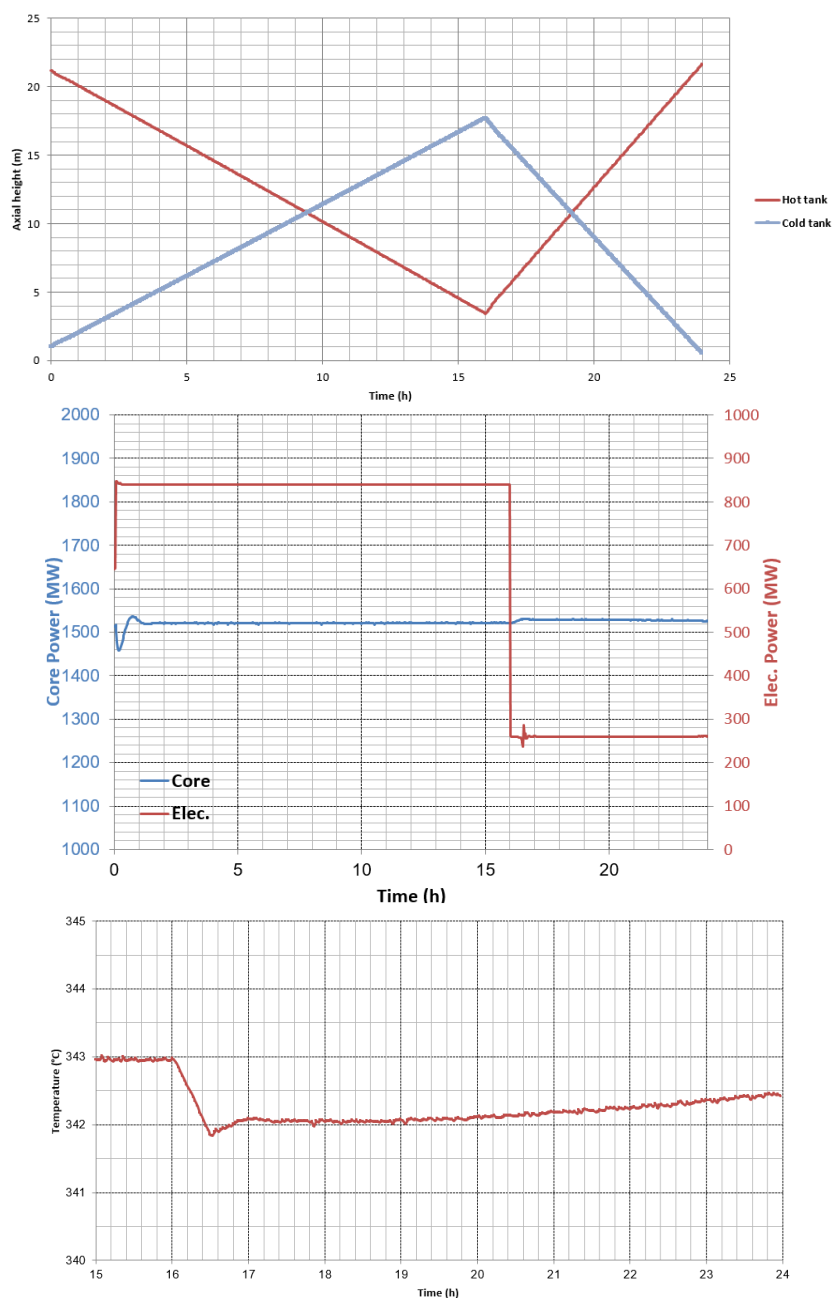


**Figure 9 – Load following simulation: evolution of the free levels in the hot and cold tanks (up), of the core and electrical power (middle) and of the sodium temperature in the cold leg of the secondary loops (down)**

**Frequency regulation transient**

The same study has been carried out on a more dynamic case: a frequency regulation transient. The regulation authorities require that the reactor should be able to vary the electrical production from 100 % of its maximal power to 91 % in a maximum 133 s. The objective of this study is to check if the storage system is able to produce such a variation without involving a core temperatures variation.

In the CATHARE3 simulation, as for the load following case, these variations are ensured by the rapid increase or decrease of the pumps located between the SG and the cold tank. Results in terms of power evolution are available in Figure 10, where two frequency regulation cycles are plotted. It can be seen that the targeted power is reached in less than 130 s. Despite a slight overshoot of the target, these results are in accordance with the requirements. Moreover, the influence on the secondary and primary circuits is still negligible as also indicated in terms of temperature evolution in Figure 10. This figure shows that, in the secondary loops, the cold sodium temperature oscillations amplitude is indeed lower than 0.5°C for this frequency regulation transient. Further studies dealing with the same frequency regulation transient but for other core power regimes are still under way.
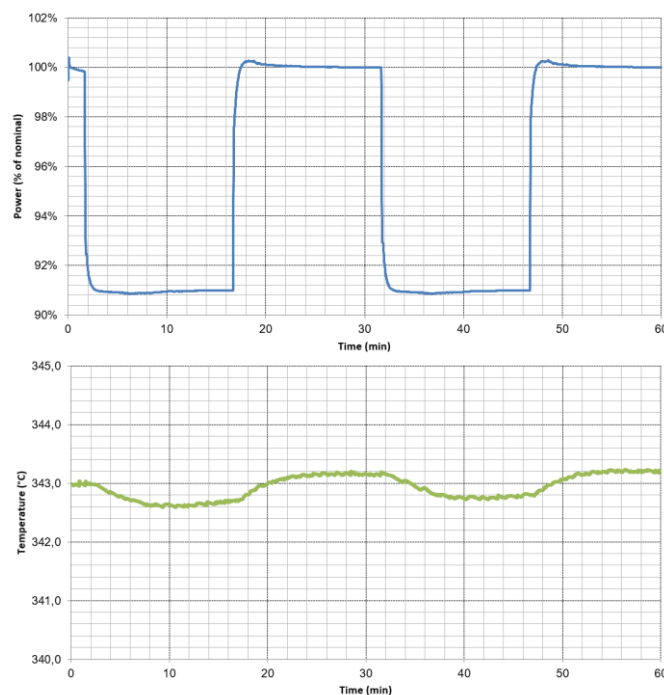


**Figure 10 – Frequency regulation simulation: evolution of the electrical power (up) and of the sodium temperature in the cold leg of the secondary loops (down)**

## 5- Conclusions and prospects

In the frame of the design of technologies aiming at improving the flexibility of the nuclear energy production, the two-tank heat storage solution is investigated in this paper. A preliminary storage loop architecture coupled to a SFR heat production with a Water-Rankine PCS is proposed in order to highlight the benefits of this technology. The Pb-Bi selection for the storage fluid has been made according to a multicriteria analysis performed by a group of experts. This choice resulted in a two-tank design of 63.000 m$^3$ each implemented in a loop also including two pumps. The latter are respectively in charge of the heat extraction from the core and of the heat transmission to the PCS,

the difference being stored through thermal energy in both tanks.

The overall sizing of the system has been carried out with the thermodynamic cycle optimization tool CYCLOP. On the one hand, it revealed that the efficiency of the installation can reach 52 % during the day (*i.e.* when the price of electricity is high) instead of 42 % thanks to the thermal energy restitution. On the other, it showed that a 1150 MWth core can produce the same daily electric power than a 1500 MWth one if coupled to such a storage system.

Transient preliminary simulations were performed with the system thermal-hydraulic tool CATHARE3. Although the storage fluid was sodium and not Pb-Bi for these first calculations, they enabled to draw the main benefits of such a storage strategy. In particular, the possibility to vary the electricity production while operating the reactor at base load is demonstrated. As the impact in the primary circuit is shown to be negligible in terms of temperature evolutions; thermomechanical loading constraints on the primary circuit structures are also drastically relaxed.

This work is paving the way to design more flexible and more profitable nuclear production units. However, this preliminary approach would need further investigations, in particular dealing with more suitable architecture design possibilities, in terms of minimizing the storage fluid amount as in order to make impossible by design the Water-Sodium reaction. Technologies involving a fourth loop in parallel to the third one are for instance under study. A single tank storage strategy based on a thermocline heat storage may also be a suitable solution. Finally, the CATHARE3 simulation should be improved by adding heat losses considerations, and the impact of the off-design transient on the PCS performance should also be investigated through further studies.

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