

TRANSIENT ANALYSIS OF THE ASTRID DEMONSTRATOR INCLUDING A GAS NITROGEN POWER CONVERSION SYSTEM WITH THE CATHARE2 CODE

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ABSTRACT

The present paper is dedicated to preliminary transient studies carried out for the analysis of the overall system behavior of the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) demonstrator developed in France by CEA and its industrial partners. ASTRID is foreseen to demonstrate the progress made in SFR technology at an industrial scale by qualifying innovative options, some of which still remain open in the areas requiring improvements, especially safety and operability. Among the options investigated, two various power conversion systems (PCS) are studied. On the one hand, a classical water/steam Rankine cycle has been considered, on the other hand, a gas Brayton cycle has also been preliminarily designed in order to assess its figure of merits in terms of safety. In this latter innovative PCS, the working gas is nitrogen whose flow rate delivers power to a turbine driving with the same shaft two compressors (low and high pressure) separated by an intercooler. The other part of the work delivered by the gas is used to drive the alternator that produces electricity. The main objective of such a PCS consists in avoiding physically the possibility of a sodium/water reaction with the secondary circuit but the impact of this PCS on the control of the accidents is still under assessment. The main purpose of the studies presented in the paper is to assess the dynamic behavior of ASTRID including a gas PCS with the CATHARE2 code for typical transients.

Two families of initiating events affecting the PCS are investigated: a loss of power supply and the spurious opening of the turbine by-pass valve. Regarding this last transient, sensitivity studies have shown that an adequate design of the turbomachine by-pass lines allow a control of the event without shutdown. Moreover, regulating actions following the scram are also investigated in order to take benefit of the PCS in order to remove the decay heat.

KEYWORDS

ASTRID, CATHARE2, Transient analysis, gas PCS

1. INTRODUCTION

After a brief presentation of the ASTRID reactor main design options, the stress is put on the presentation of the power conversion system (PCS). In this gas innovative PCS designed by ALSTOM, the working gas is nitrogen whose flow rate delivers power to a turbine driving with the same shaft two compressors (low and high pressure) separated by an intercooler. The other part of the work delivered by the gas is used to drive the alternator that produces electricity. Moreover, a recuperator enables to pre-

heat the gas flow entering the gas/sodium heat exchanger with the gas exhausting from the turbine. The main objective of such a PCS consists in physically avoiding the possibility of a sodium/water reaction at the interface between the secondary and the ternary circuit. In the following part of the paper, the main features of the CATHARE2 modelling of nitrogen cycle currently envisaged for ASTRID is detailed as well as the system actions simulated in the CATHARE2 input deck for transient calculations. Finally, the calculation results are presented and the consequences on the reactor (thermal shock, long term behaviour and heat removal process) of the various transients simulated are assessed.

2. OVERVIEW OF ASTRID REACTOR DESIGN

ASTRID, standing for Advanced Sodium Technological Reactor for Industrial Demonstration consists in a 1500 MWth SFR pool type reactor of about 600 MWe that is an integrated technological demonstrator designed for industrial-scale demonstration of 4th generation sodium-cooled fast reactor (SFR) safety and operation [1]. The main objective of ASTRID is to test advances on an industrial scale in dedicated areas (in particular safety, operability and in service inspection and repair). ASTRID will also be designed to perform waste transmutation in order to demonstrate the industrial feasibility of this technique for reducing volume of end waste and lifetime of ultimate waste. Additionally, ASTRID is being designed to fulfil the GENIV criteria in terms of safety, sustainability, economy and proliferation [2]. Various innovative options have been investigated during the first stage of the conceptual design carried out in 2011 and 2012 in order to improve safety on the following points:

- prevention of core degradation and mitigation of its effects (innovative CFV¹ core design with a low total voiding effect has been retained);
- elimination of the possibility of sodium/water reaction at the interface between secondary loops and ternary circuit (investigation on the feasibility of a gas PCS whose transient behaviour is presented in this paper);
- enhancement of the efficiency, redundancy and diversification of the DHR systems has been promoted (diversification of heat sink and way to cool the primary sodium inventory).

2.1. Core design

The so-called CFV concept (version 1) featured by a low global Na voiding effect has been designed by CEA in order to increase the margin up to sodium boiling in case of unprotected transient [3] and also to reduce the severity of a primary power excursion should it occur in case of a severe accident [4]. This core is an axial heterogeneous core (Fig. 1). The low voiding effect of this core results mainly from the presence of a sodium plenum above the fissile zones [5] combined to the presence of a fertile plate in the inner zone of the core (Fig. 1). The height of the outer fissile zone enables the void reactivity effect to be lowered as well. All these effects lead to a reactivity decrease when the upper part of the core (plenum in particular) experiences a sodium thermal expansion or sodium boiling. Finally the overall voiding effect for this version of the core is equal to -0,5 \$ at the end of cycle (one Dollar being the delayed neutron fraction) [3].

¹ CFV stands for « cœur à faible effet de vidange » that means core with low sodium worth effect.

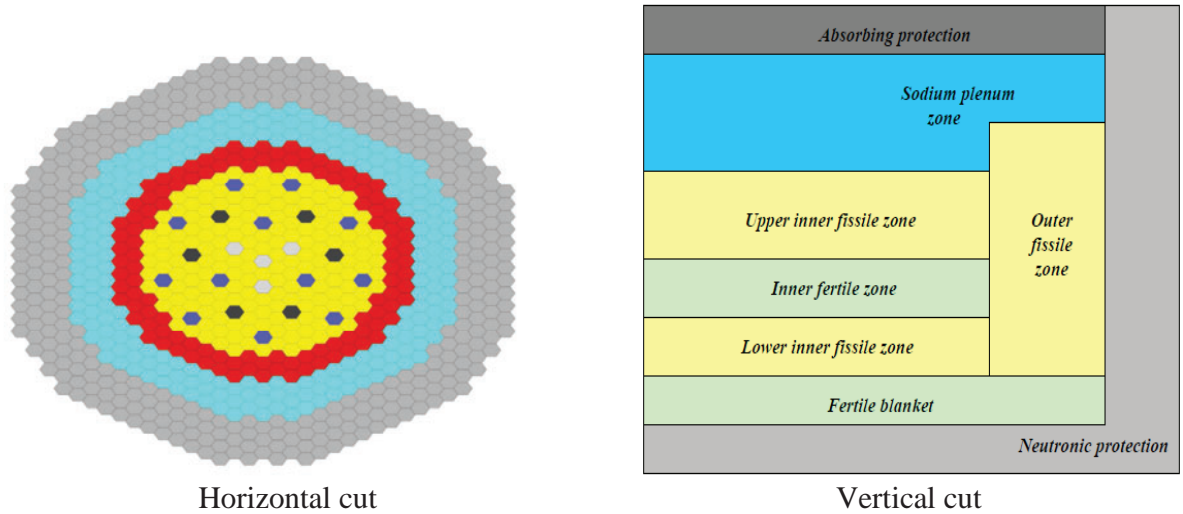


Figure 1. CFV core design

2.2. Primary and secondary systems overview

The ASTRID pool type primary circuit includes 3 primary pumps and 4 intermediate heat exchangers (IHX) immersed in the reactor vessel (Fig. 2). Each of the 4 secondary loops delivers a fourth of the core power (375 MWth) to 3 modular sodium/gas heat exchangers (SGHX); the modularity enables the impact of an event in a SGHX to be reduced. Those loops also insure the decay heat removal (DHR) during the first hours after shutdown when they are available. The preliminary design modelled in this paper includes a mechanical pump located at a low elevation within the loop and is equipped with one sodium dump vessel used to store the sodium and to collect leaks [1]. Actually, the reference retained of the secondary circuit deals with electro-magnetic pumps during the current stage of the project. Finally, an argon covered expansion vessel is foreseen in order to protect the loop against an accidental pressure wave.

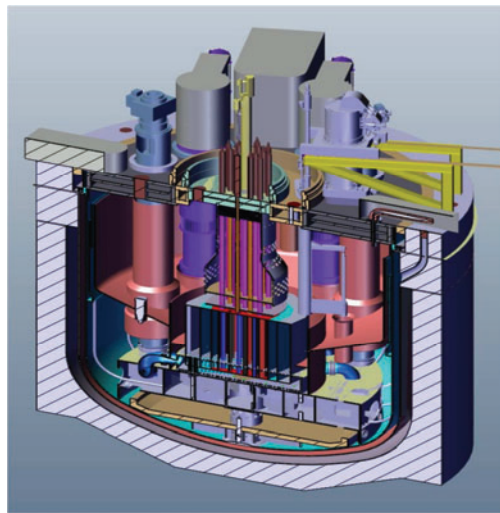


Figure 2. Primary system arrangement for ASTRID

The main features of the reactor operating point are provided in Table 1 for the primary and secondary circuits.

Table 1. Nominal operating point of the secondary and primary circuits

Primary Circuit	
Core flow rate (kg/s)	7900
Fraction of the flow for vessel cooling (kg/s)	600
Primary flow rate (kg/s)	8500
Core inlet/outlet temperature (°C)	400/550
Core inlet/outlet pressure (bar)	4.5/1.9
Secondary Circuit	
Secondary flow rate (kg/s)	6370
IHX inlet/outlet temperature (°C)	345/530
Pump inlet/outlet pressure (bar)	1.9/7.1

2.3. Power conversion system (PCS)

The power conversion system using nitrogen as a working gas is presented on Figure 3 with its associated operating point [6] [7]. The choice of the PCS gas has been performed by taking into account heat transfer, compression work, pressure level and its simplicity of operation. Consideration of all these criteria led to the nitrogen at 180 bars (turbine inlet) as the reference coolant. A Brayton cycle, which has never been implemented in any sodium reactor but has been investigated for High Temperature Reactors (HTR) has been chosen. This kind of cycle provides the best efficiency. The PCS flow rate is about 7170 kg/s and a by-pass line (preliminarily located in red in Fig. 3) enables to stop or to regulate the TM speed by reducing the outlet/inlet pressure ratio, the by-pass opening consisting in an aerodynamic brake.

Basically, the PCS includes a turbine driving two compressors located on the same shaft². Since the realization of the calculations presented in the present paper, the design of the PCS has evolved and is made now of two shaft-lines, each one including two symmetric turbines arranged in parallel, a low pressure compressor and a high pressure compressor plus an alternator. The efficiency of the whole gas compression is improved by means of a pre-cooler and an intercooler separating the 2 compression stages; these heat exchangers (HX) are cooled by the heat sink of the reactor.

Finally, a so-called recuperator HX permits to pre-heat the gas flow before entering the SGHX and to cool it before entering the pre-cooler. The net efficiency of the reactor considering this PCS option would be about 37.5 % according to preliminary assessments [6]. A multiple pipe design in parallel has been adopted in order to limit the gas velocity in the pipes (minimization of pressure drop) and in the same time to limit the maximum pipe diameter at about 1 m for mechanical and manufacturing reasons. By the way, a sensitivity study on the cycle parameters has shown that the turbomachine performance and the pressure losses are the most influent parameters in terms of efficiency. The main operating parameters of the PCS are presented in Table 2.

² Actually, in order to better balance the forces on the shaft, a double-body turbine is now used in order to reduce the thrust on it. However, a simple line turbine is modelled in this version of the CATHARE2 input deck.

Table 2. Main features of the PCS operating point

Generator power	580 MWe
Pre-cooler power	570 MWth
Intercooler power	340 MWth
Ternary flow rate	7170 kg/s
Inlet temperature of SGHX	330°C
outlet temperature of SGHX	515°C
Turbine pressure (inlet/outlet)	180 bar/73 bar
Low pressure compressor (inlet/outlet)	72 bar/112 bar
High pressure compressor (inlet/outlet)	111 bar/ 181 bar

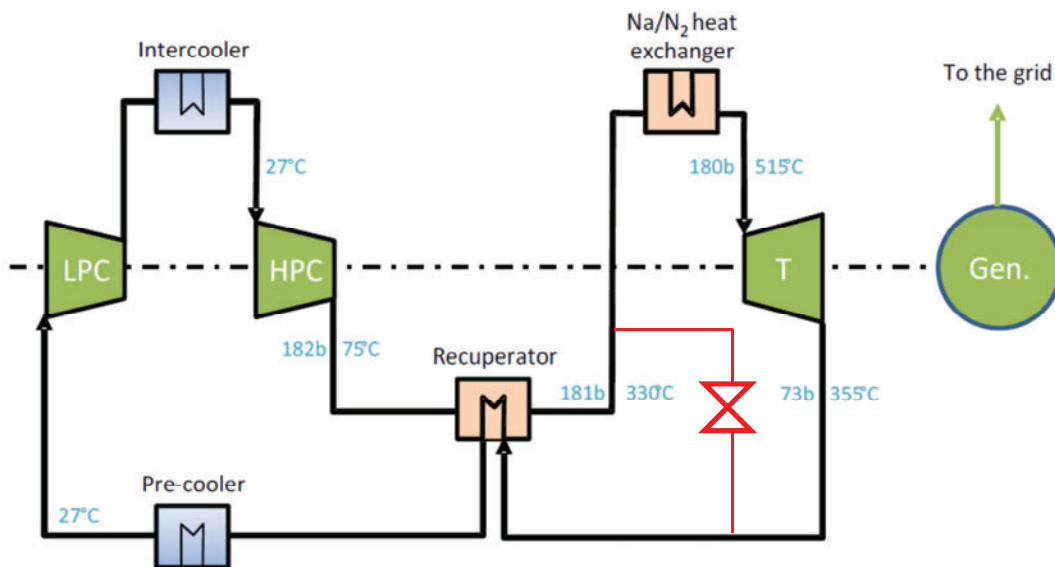


Figure 3. Sketch of the gas PCS [6]

3. BRIEF PRESENTATION OF THE CATHARE2 MODELLING OF THE SYSTEM

3.1. Primary and secondary circuits

The whole system has been modelled partly by CEA and partly by AREVA and the calculations have been run with CATHARE2 v25_3 mod2.1 [8]. The CATHARE2 code is a 6-equations thermalhydraulic system code. Properties of sodium have been implemented in the code but the form of the friction and heat transfer correlations are the same as in the water standard version [8]. The 291 sub-assemblies of the core (SAs) core are represented by 7 weighted CATHARE2 channels considering the 2 enrichment levels of the core (23,5 % for the internal core (177 SAs) and 20 % for the external one (114 SAs)). The following neutronic effects are modelled: Doppler, sodium density, cladding expansion, fuel expansion, hexcan (HC) expansion, diagrid expansion and finally the reactivity feedback resulting from relative location of control rods within the core (the vessel expansion is not taken into account in these calculations but will be in future studies). All these reactivity coefficients are included in the point kinetics of neutron physics of CATHARE2 including 8 groups of delayed neutrons and 4 groups of fission products to model the decay heat. The core channels, the IHX, the fraction of the primary flow

cooling the vessel and the inlet/outlet region of the pumps are modelled thanks to 1-D CATHARE2 axial elements. The flow distribution within the cold and hot collectors is modelled thanks to a dedicated volume decomposition in several volumes whose flow-path has been assessed with CFD calculations performed in nominal regime. The secondary circuit is modelled with a single loop representing the 4 loops, connected to the primary system by means of a single IHX representing the 4 IHXs. A secondary pump is modelled and enables the loss and variation of flow to be simulated.

3.2. Nitrogen PCS

The PCS system is fully modelled in the CATHARE2 input deck. This modelling includes a comprehensive TM module whose performance maps are derived from CEA gas fast reactor (GFR2400) performance maps [9] but adapted to a nitrogen circuit. The parameters of the heat transfer correlation (Dittus-Boelter form) for plate type Na/gas exchangers used in CATHARE2 have been derived from CFD calculations [7]. The next step of modelling will be to include the performance maps elaborated by ALSTOM in order to have a more realistic design and its associated modelling. The SGHX modules are associated to a weight³ equal to 12 and the recuperator to a weight of 18 in order to cope with the pre-design of the PCS. The pre-cooler and intercooler are respectively divided in 72 and 60 modules represented by a single HX in CATHARE2 associated to their weight. The whole nitrogen inventory of the circuit is around 560 tons. The rotating mass equation is solved on the TM shaft including the turbine, the compressors and the resisting torque of the alternator.

4. SYSTEM ACTIONS AND REGULATIONS FOR TRANSIENT CALCULATIONS

This section is devoted to the transient analysis of ASTRID equipped with a gas PCS. In a first general part, the system actions are presented (actions triggered via the input deck after the transient initiation) and further on, the analysis of the reactor behaviour when facing specific transients of the gas PCS are presented. Additionally, the capability to remove decay heat from the system with the gas PCS is also preliminarily investigated. Finally a sensitivity study to the design of the TM by-pass line is also provided, the aim of this design alternative being to improve the capability of the reactor to withstand the transient without scram.

4.1. Reactor trip system modelling and other system actions

The transient input deck includes several trip parameters enabling the reactor scram to be actuated and the PCS to be protected (Table 3). Moreover, in case of reactor trip, the rotation speed of the primary pumps is decreased to 25% of its nominal value in 30s and the rotation speed of the secondary pumps is reduced to 15% of its nominal value in 9s.

³ A weight equal to 12 means that only one representative axial pipe is modelled in order to represent a component including 12 pipes. So, in such a case, the overall flow rate of the component is obtained by multiplying the flow rate of the single pipe by 12.

Table 3. Reactor trip parameters and ternary system protection actions

Parameter (N stands for nominal conditions)	Threshold	Action
Core power (P)	$P/P_N > 1.08$	Scram
Core power/Flow rate (P/Q)	$(P/Q)/(P_N/Q_N) > 1.35$	Scram
Core outlet temperature, T_{co} (°C)	$T_{co} > 583$	Scram
Core inlet temperature, T_{ci} (°C)	$T_{ci} > 420$	Scram
Core Delta T ratio	$(T_{co}-T_{ci})/(T_{co_N}-T_{ci_N}) > 1.09$	Scram
Alternator electrical power ratio	$Pelec/Pelec_N > 1.15$	Alternator disconnection
Alternator electrical power ratio	$Pelec/Pelec_N < 0.1$	Alternator disconnection
Turbomachinery speed (ω)	$\omega/\omega_N > 1.1$	By-pass opening, scram

4.2. System regulation

Several regulation actions are implemented in the input deck in order to be able to remove the decay heat and to maintain all the circuit in acceptable conditions. In the frame of those exploratory studies, some regulations have been settled in order to control the power extracted by the ternary circuit (Table 4).

Table 4: regulation system in order to control the power extracted by the ternary circuit (the regulations implemented depend on the calculated transient)

Variable to regulate	Targeted value	Action
Cooler flow rate	20 % of Q_{nom}	Boundary condition
Turbomachine speed	3000 rpm	By-pass valve opening
Turbomachine pressure inlet	12 bars	Surge valve of NSS opening

5. TRANSIENT CALCULATIONS

The transient investigated in this paper are focused on situations with PCS under pressure. Depressurized transient calculations (breach transients) have been already presented in [10]. Among the pressurized transients, the black-out transient, the loss of off-site power (LOOP) and the spurious opening of by-pass valves of the TM have been simulated. The dedicated DHR loops plugged on the primary circuit of the reactor are not used during the transient but the TM speed is kept as long as possible at 3000 rpm by means of a regulated opening of its by-pass valve (Tab. 4).

5.1. Black-out

This transient results from the total loss of electrical supply: there is no back-up flow rate delivered by means of emergency electrical supply and the water feeding of the coolers is no more available as well. The reactor trip is actuated at the beginning of the transient. The pump run-down is governed by their inertia. The power balance between the core and the reactor circuits and the temperature evolution across the core and on the interface between the secondary and ternary circuits are presented on Figure 4. A cold shock affects all the circuits because of the heat extraction by the ternary circuit thanks to a substantial

flow rate that remains in this circuit thanks to the TM operation and to the gas expansion in it (Fig. 5). This can be observed on Fig. 4 because the nitrogen temperature at the inlet of the SGHX decreases to 300°C because only the decay heat is transferred to the PCS and yet, its flow rate remains very high as long as the TM is under rotation.

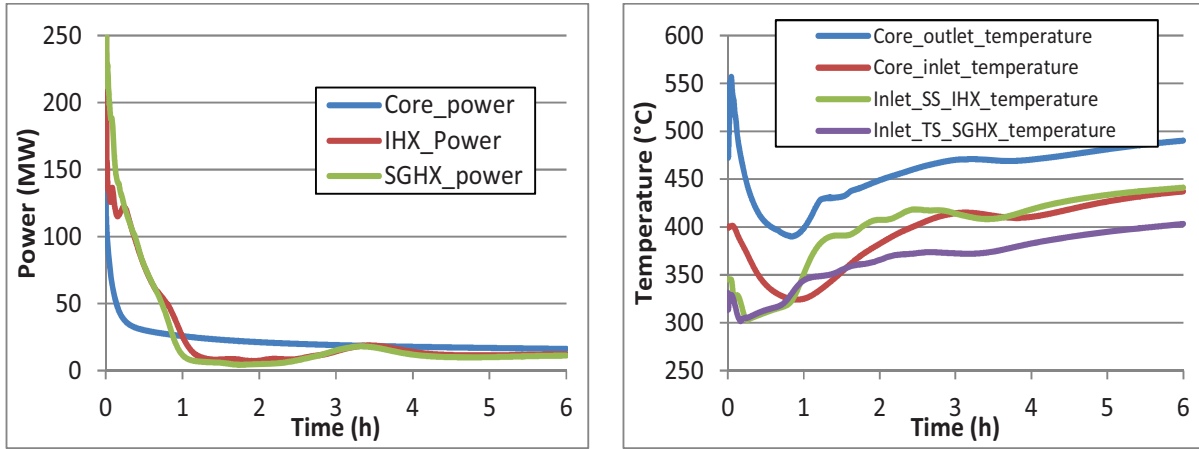


Figure 4. Power balance and temperature evolutions during the black-out transient

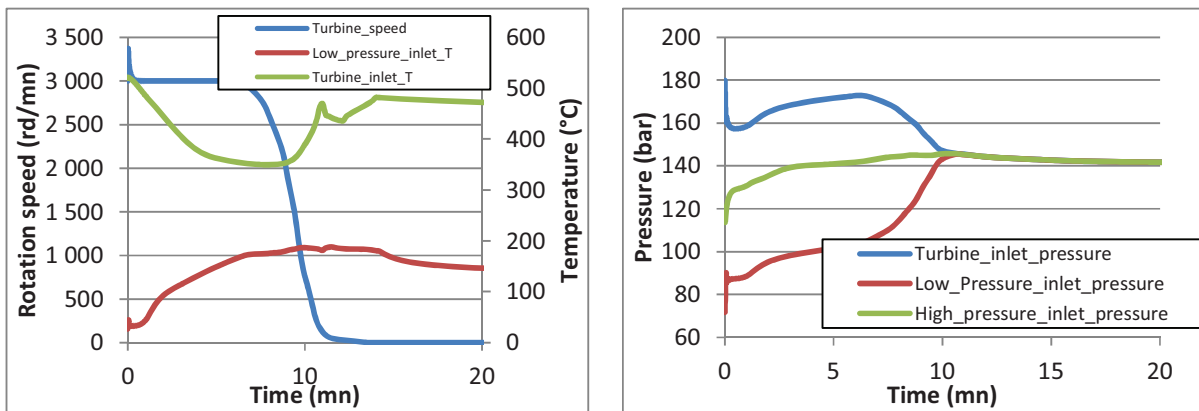


Figure 5. Rotation speed, temperature and pressure evolution across the turbomachine

After 10 minutes, the balance between the heat transferred to the PCS from the core and the heat released by the coolers leads to the TM rundown (Fig. 5). As a consequence, at this time, the PCS pressure is balanced around 140 (Fig. 5) bars and the secondary and ternary side temperatures begin to increase. At 1 h, a thermal and power balance is reached and the heat removed by the ternary side becomes lower than the decay heat and the primary sodium temperature begins to increase. Actually, even after the primary and secondary pumps shutdown and the TM rundown, natural circulation flows in each circuit drive the whole reactor cooling. However, this result should be to confirm considering the uncertainty on the natural circulation regime calculation (pressure head of the stopped pumps, performance maps of the TM and circuit elevation are not assessed adequately). Nevertheless, this result indicates that the heating rate of the whole system is very low and that thanks to the Brayton cycle and of the inertia of the reactor cooling circuits, the PCS enables the decay heat to be removed more than 6 hours without reaching the temperature level of the nominal state of the reactor.

5.2. LOOP (Loss Of Off-site Power)

In this transient, the initiating event is the same as in the black-out, but emergency electrical supply is available to deliver a back-up flow rate to the primary and secondary pumps (see section 4.1) as well as to the water-feeding system of the coolers. The aim of this sub-section is to present the sensitivity of the system behaviour to back-up flow rate of the coolers⁴. Figure 6 shows that as soon as a back-up flow rate is available (even only 5 % of the nominal flow rate), the core inlet temperature decreases of at least 150°C in one hour. The 0 % cooler flow rate corresponds to the transient presented in sub-section 5.1. It is interesting to observe that the minimum flow rate tested (5%) is enough to keep the TM under operation. Therefore, the ternary flow rate and the cold source is enough to cool the core adequately, thus providing a substantial additional delay before switching the decay heat removal to the dedicated in-vessel loops. Moreover, the rotation of the TM enables to reduce the hot shock on the primary vessel by compensating the heating due to the loss of flow on the primary and secondary circuits (+ 20°C at the IHX outlet instead of + 75°C when the TM is stopped). Finally, the TM stops after approximately 1 h whatever the flow rate of the coolers.

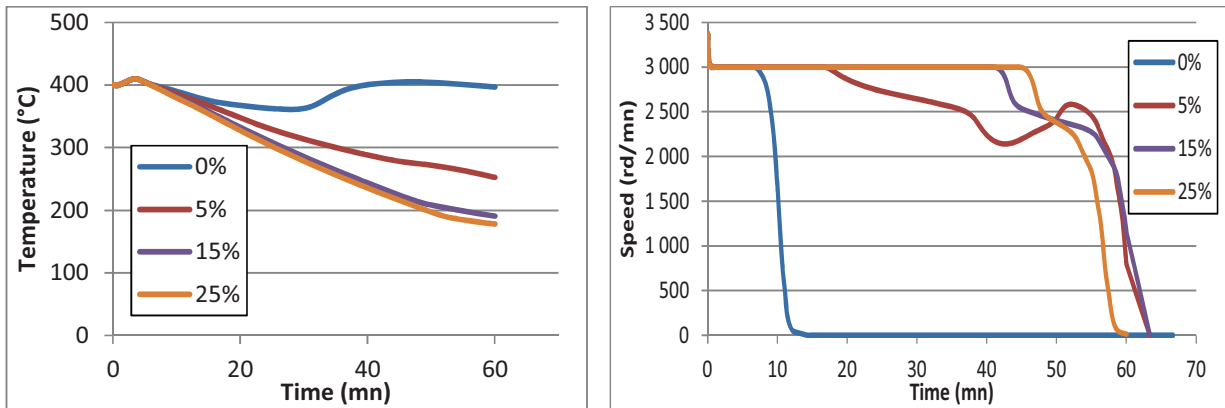


Figure 6. Core inlet temperature and turbomachine rotation speed for various back-up flow rates of the coolers (from 0 to 25 %)

5.3. Reaching of the cold back-up state after a LOOP (Loss Of Off-site Power)

In this transient, the targeted value of the TM speed and the back-up flow rate in all circuits are kept constant (cf. Tab. 4 for the regulated variables). Considering this set of regulation enabling the reactor to be withdrawn after a spurious scram for instance, the cooling transient is presented on Figure 7. The possibility to decrease the pressure at the turbine inlet allows operating the TM during the whole transient because, basically, the pressure decrease in the ternary circuit should follow the decrease of the decay heat of the reactor in order to keep the thermodynamic cycle operational. After a first cold shock in the primary circuit of about 71°C in the first tenth of minutes, the cooling rate of the system is limited to 21°C/h after 1 h of transient (Fig. 7). During this stage of the transient, the heat removed by the ternary side is about 40 MW, allowing the cooling of the whole system because this value is higher than the core decay heat.

⁴ This study is only performed in order to assess the behaviour of the system no matter what the decisions will be taken regarding the systems rescued: in particular, at that time, it is not foreseen to have an emergency electrical supply for the coolers.

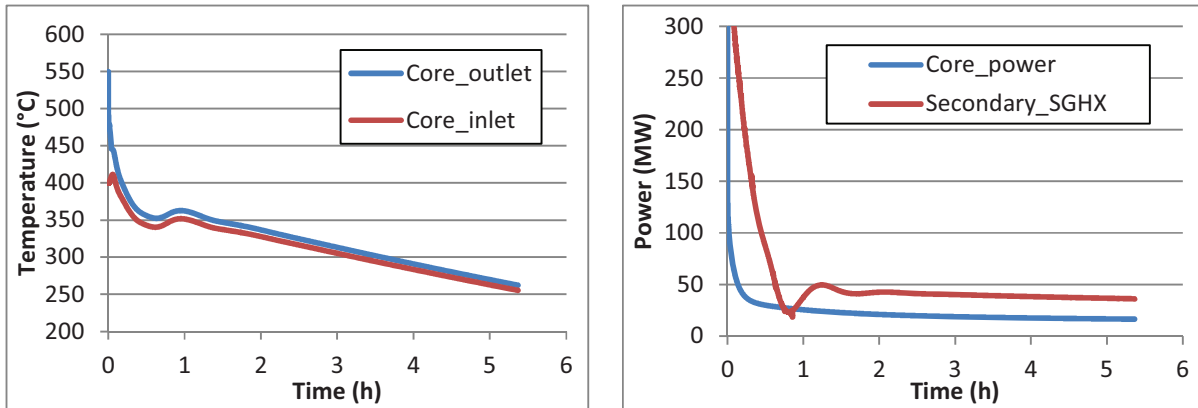


Figure 7. Core inlet/outlet temperature and primary/secondary side power evolution

5.4. Spurious opening of by-pass valves

Various flow paths are possible (Fig. 8) in order to by-pass the turbine and practically, a mix of gas taken in the cold leg (opening of by-pass2) and of gas taken in the hot leg (opening of by-pass1) is injected in the exhaust pipe of the turbine (opening of by-pass4). The transients calculated in this paper deal respectively with the spurious opening of the lines by-pass1 + by-pass4 (called BYP1) and of the spurious opening of the lines by-pass2 + by-pass4 (called BYP2). The spurious opening of the valves is realized in 3 s. The line by-pass 4 is open before the transient and the lines by-pass1 and by-pass2 are respectively made of 2 pipes of 60 cm diameter and when the transient occurs, 1 over 2 lines are open. The flow rate redistribution in the ternary circuit is plotted on Figure 9. The temperature of the gas is colder in the branch BYPASS1 than in the branch BYPASS2 (Fig. 8). Therefore, the flow rate is much more larger in the case “BYP2” (Fig. 9) because of the larger density of the gas.

As observed on Figure 10, the case “BYP2” leads to an earlier rundown of the TM due to the cold temperature of the gas in the cold leg, the flow rate by-passing the turbine being higher than in the case “BYP1”. As a result, the flow rate in the PCS is reduced faster in the case “BYP2” than in the case “BYP1” and the heating of the sodium at the core inlet occurs earlier. Moreover, in the case “BYP1”, the flow rate crossing the SGHX is enhanced after by-pass opening (up to 12000 kg/s according to Fig. 9) whereas in the case “BYP2” the ternary gas flow does not go anymore in the SGHX but through the line called BYPASS2. This effect of flow increase in the SGHX and its associated over-cooling is propagated through the secondary circuit up to the core inlet, resulting in a small and transitory decrease of the core inlet temperature approximately 5 min after the transient initiation (Fig. 10). The reference design option including 2 by-pass pipes for the parts of the circuit called BYPASS1 and BYPASS2 leads to an over-speed of the TM equal to 114 % of its nominal speed and to a fast reactor scram.

By keeping the same maximum over-speed, the BYPASS1 and BYPASS2 lines have been sub-divided into smaller pipes (6 pipes of 25 cm diameter) in order to limit the transient impact of the opening of one single line. In the case “BYP2” the reactor trip threshold are not reached and thus, the reactor is not scrammed, even after a long time. The electrical power delivered to the alternator remains higher than the minimum value. Therefore, the alternator remains connected and the core power is extracted. However, in the case “BYP1”, due a hotter gas intake in the recuperator, the core inlet temperature increases and reaches the trip level (Fig. 11) after 55 minutes. Nevertheless, this exploratory calculation has shown that by designing more modular by-pass lines, it is possible in the same time to limit adequately the turbine over-speed and to keep the reactor under operation.

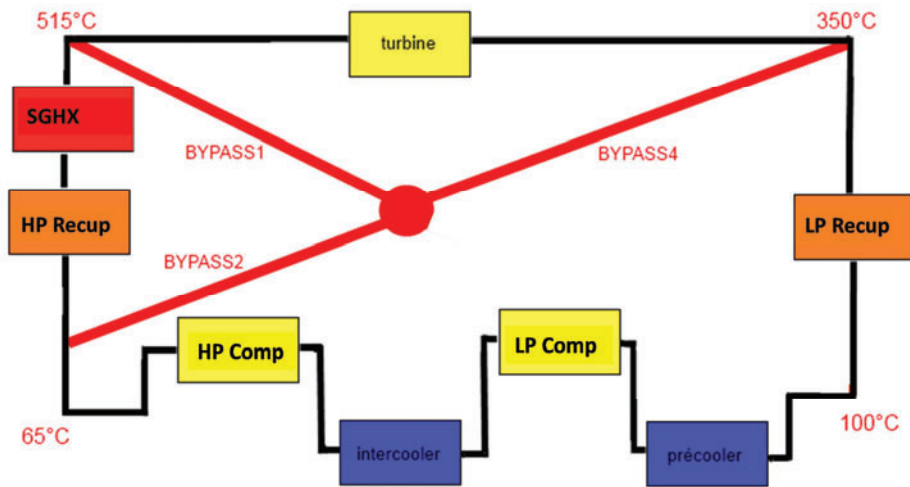


Figure 8. Sketch of the by-pass line system in the PCS (HP comp and LP comp : high pressure and low pressure compressors; HP recup and LP recup: high pressure and low pressure recuperator sides; SGHX: sodium gas heat exchanger)

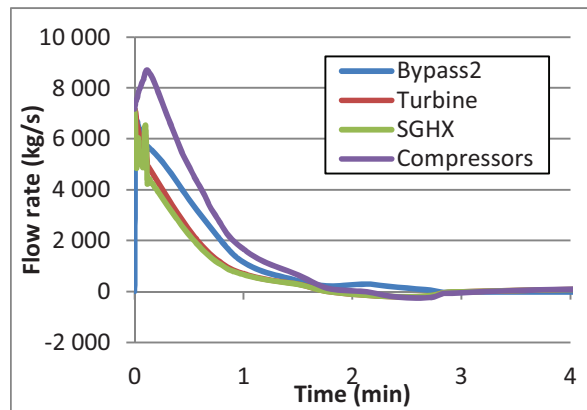
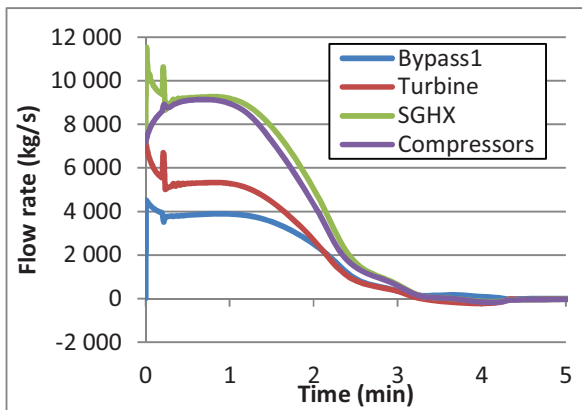


Figure 9. Flow rate distribution in the ternary circuit when opening by-pass 1 line (left hand side) and by-pass line 2 (right hand side)

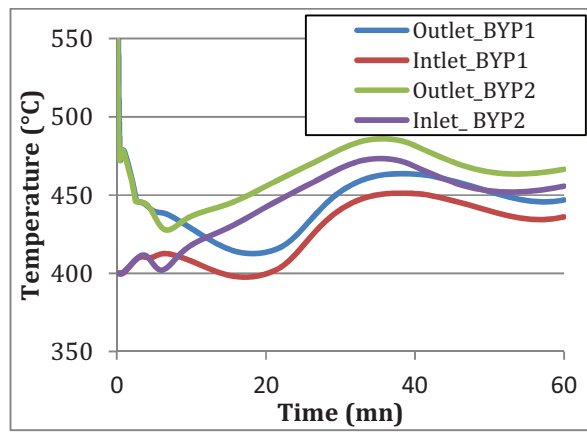
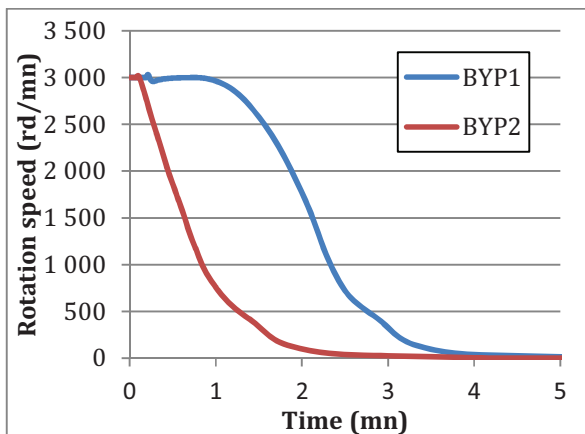


Figure 10. TM rotation speed and temperature across the core for by-pass valve opening transients

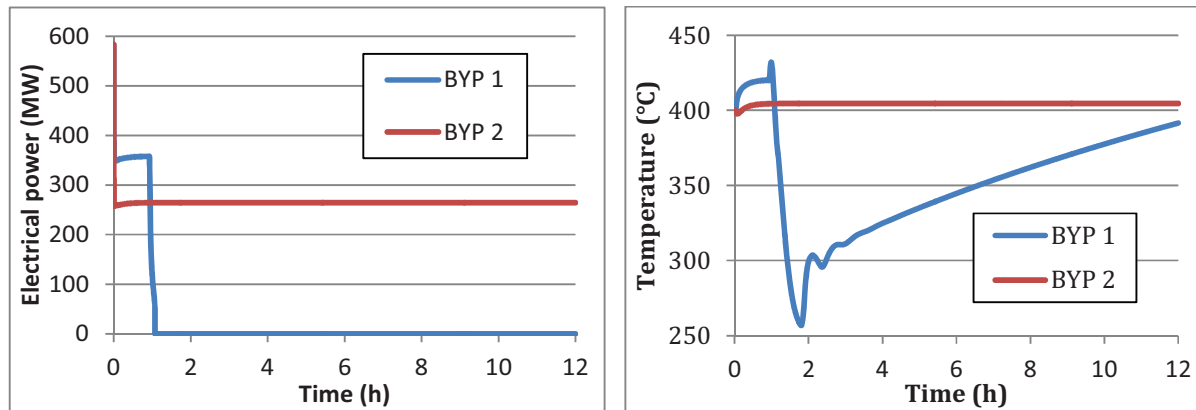


Figure 11. Alternator electrical power and core inlet temperature for by-pass valve opening transients, impact of design improvement

6. CONCLUSIONS AND PROSPECTS

Transient resulting from typical initiating events of a gas PCS have been investigated for ASTRID with the CATHARE2 code. The reactor design considered has been updated compared to that modelled in [10]: the CFV-v1 core and the PCS ALSTOM design are considered. First, the overall reactor behaviour when facing PCS transients does not exhibit any specific showstopper in terms of impact of the ternary circuit onto the primary and core temperature evolution compared to a water/steam PCS [10]. Several lessons learnt from the calculations could be used for the reactor design and piloting if necessary in order to consolidate the safety design of the reactor or to relax operation constraints on dedicated DHR systems. Regarding the design, the increase of the number of TM by-pass lines allowing the decrease of the flow rate in each line would enable the reactor to withstand a spurious opening of a single by-pass line without exceeding the thresholds of the reactor trip protection system. Such a design, when all the by-pass valves are open, enables the limitation of the TM over-speed as well as with the reference design. Another interesting conclusion of the study is the capability of the PCS to remove the decay heat during several hours providing that the TM is kept under operation at the beginning of the transient. This capability is even enhanced by feeding the cold side of the PCS coolers with only 5% of its nominal water flow rate. This could be done by a rescue of the feeding pumps at a low power level requiring only a small power supply from the emergency Diesel engines. Finally, with an adapted PCS operating, the reactor can reach a cold shutdown state with a cooling rate compatible with the reactor structure integrity.

Up to the end of the pre-conceptual design phase, additional calculations will be done with the twin turbines [7] and also with an input deck including the performance maps provided by ALSTOM. These new calculations as a complement to those already performed should allow to confirm the good behaviour of the gas PCS already observed in existing exploratory calculations as well as to validate new design options.

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