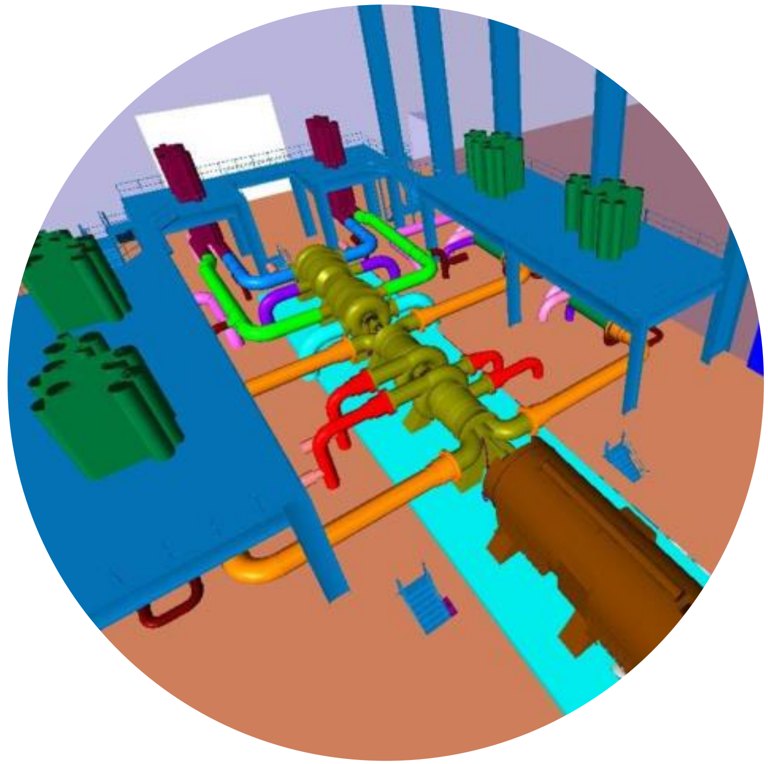
DE LA RECHERCHE À L'INDUSTRIE

COLD STORAGE SYSTEM FOR SODIUM FAST REACTOR FLEXIBILITY



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Heat Storage Workshop | Idaho Falls | July 23-24, 2019

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CONTENTS

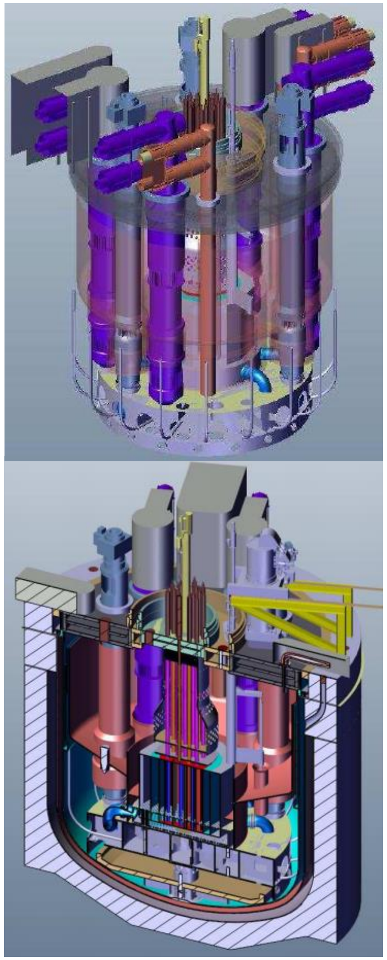
CONTEXT

Advanced Sodium Technological Reactor for Industrial Demonstration

- Pool type 1500 MW – 600 MWe sodium-cooled fast reactor

- Main layout choices
  - Conical inner vessel
  - 3 primary pumps
  - 4 intermediate heat exchangers
  - 4 secondary sodium circuits set in motion by electromagnetic pumps

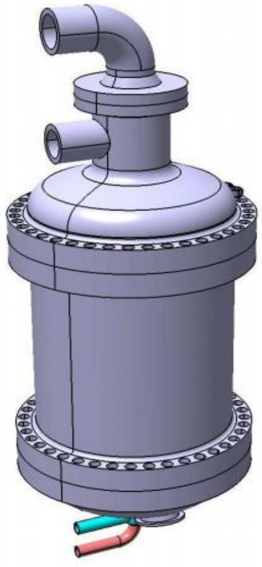
- Innovative options are investigated
  - A low void effect core (CFV)
  - An in-vessel core catcher for corium
  - **<u>A Gas Power Conversion System (PCS)</u>**



ASTRID POWER CONVERSION SYSTEM (1/2)

Two PCS are investigated for ASTRID [1]

- Steam PCS (Rankine cycle) versus **Gas PCS (Brayton cycle):**
  - Safety: Sodium Water Reaction (SWR & SWAR), decay heat removal [2]
  - Technology maturity : turbomachinery, exchangers (SGHE), operability
  - Technical-economics: plant efficiency, investment cost

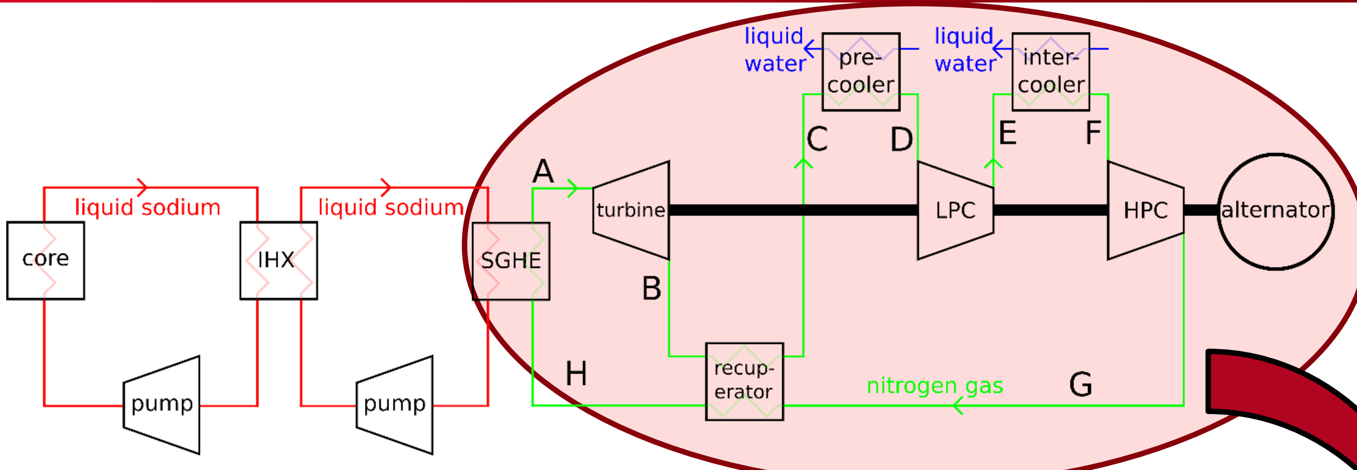


Sodium Gas Heat Exchanger (CEA/DTN)

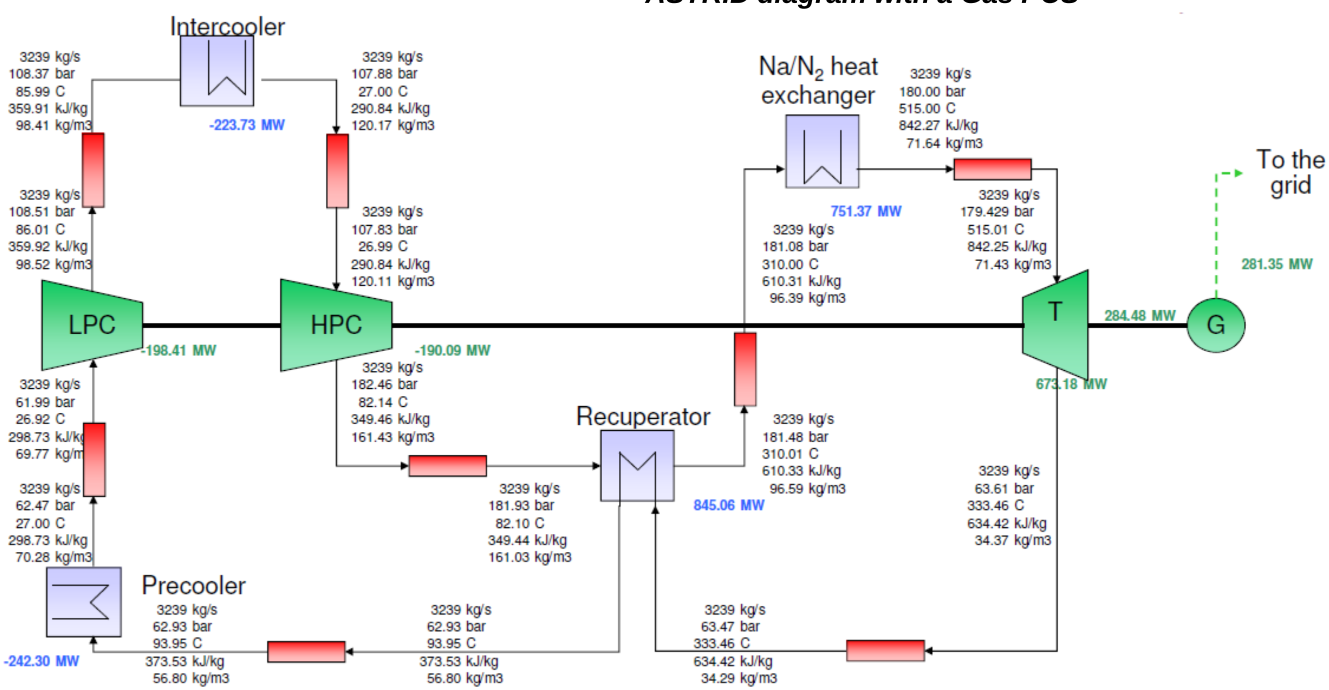
ArabelleTM steam turbine (General Electric, from 700 to 1900 MWe)

GT26 gas turbine (General Electric, 345 MWe)

ASTRID POWER CONVERSION SYSTEM (2/2)



ASTRID diagram with a Gas PCS



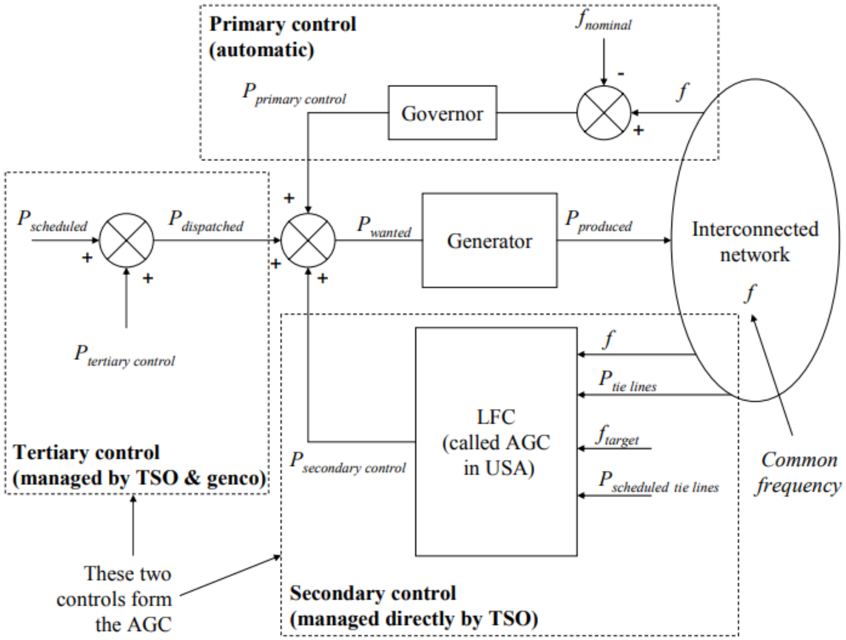
Gas PCS heat balance diagram

RESERVE SERVICES FOR FREQUENCY CONTROL

- To maintain the security and the quality of the supply of electricity, the frequency of an electrical grid must be controlled:
  - Primary control: local automatic control which delivers reserve power in opposition to any frequency change;
  - Secondary control: centralized automatic control which delivers reserve power in order to bring back the frequency to its target value;
  - Tertiary control: manual change in the dispatching and unit commitment in order to restore the secondary control reserve and to manage eventual congestions.

- For each control level some dedicated power is kept in reserve to be able to re-establish the balance between load and generation at any time. In addition, the requirements of each reserve are different, especially in terms of power quantity and timing. For example, we considered for ASTRID:
  - Primary reserve: 2.5% of nominal power available in 30 seconds (half of which in 15 seconds);
  - Secondary reserve: 4.5% of nominal power available in 133 seconds.

- In this study we considered as a sizing transient (in terms of storage and dynamics) a step of 7% of nominal power available in 133 seconds.



COLD STORAGE SYSTEM AND CATHARE MODEL

COLD STORAGE SYSTEM (1/2)

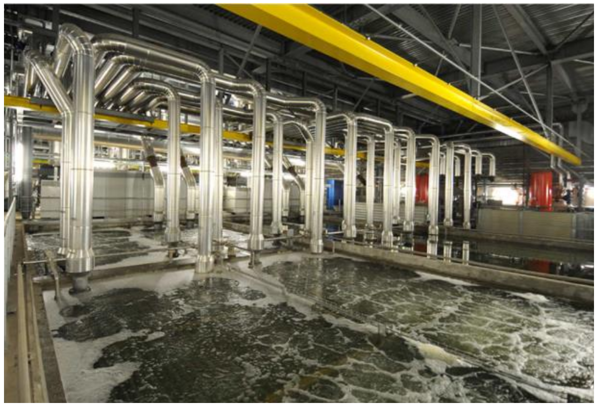
- In nuclear reactors, frequency control is performed either with boron dilution (PWR) or with the use of control rods (ASTRID):
  - They must operate at 93.5% of nominal electrical power to ensure a reserve of +7%;
  - For ASTRID this means an operating point at 98% of nominal core power (because of efficiency degradation);
  - It creates thermomechanical loads at the core and hot collector structures.

- The initial idea is that lowering the cold temperature increases the efficiency of the Brayton cycle with recovery:

$$\eta_{th} = 1 - \frac{\left(P^{+}/P^{-}\right)^{\frac{\gamma-1}{\gamma}}}{T^{+}/T^{-}}$$

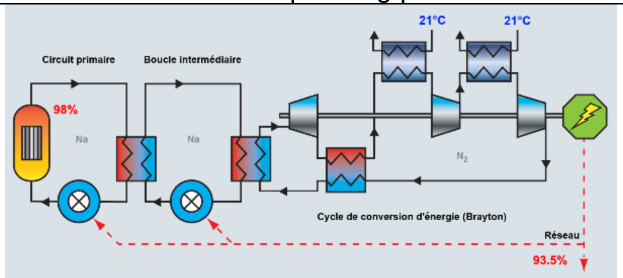
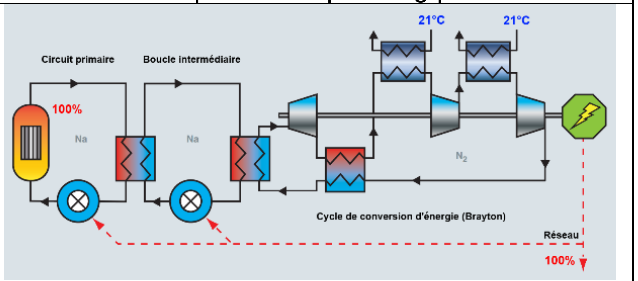
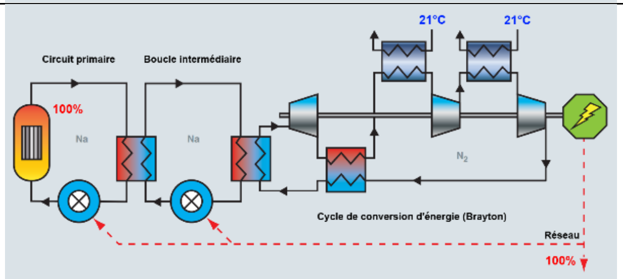
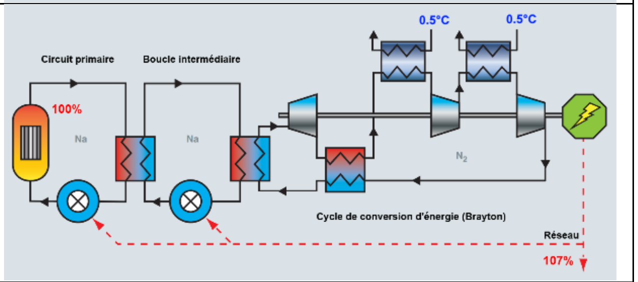
- A cold water storage (0.5°C in this study) is used to carry out the frequency control (Patent FR3060190 - 2018-06-15 - BOPI 2018-24) [3,4,5]. The use of water with glycol or salt or ice-based storage can be considered to achieve even lower temperatures.

- There are already high-capacity cold storage systems in the fields of air conditioning (shopping centers, offices), refrigeration (ice rinks), etc.

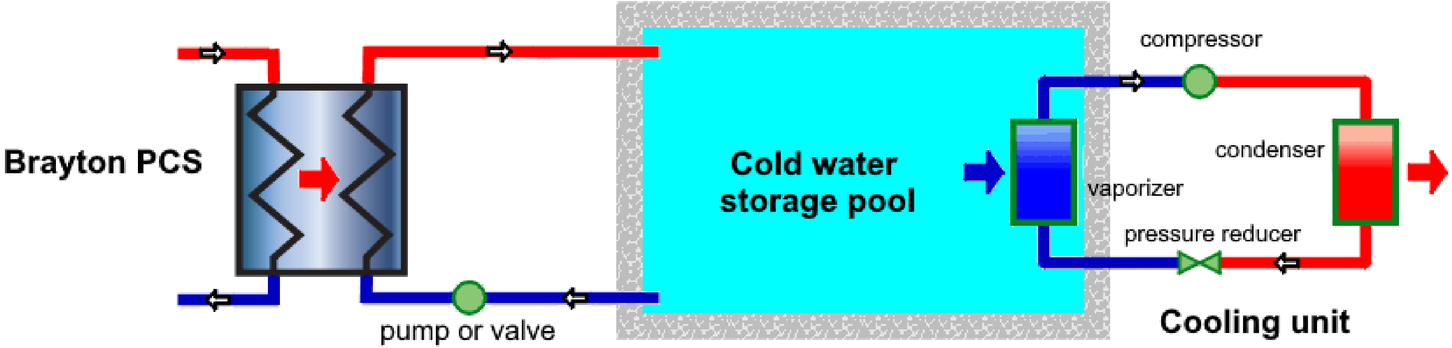


240 MW.h ice storage for air conditioning (Enertherm, Paris)

COLD STORAGE SYSTEM (2/2)

	Nominal operating point	Over-powered operating point
Without cold storage system		
With cold storage system		

- Several design for the interface between the Brayton cycle and the cold storage have been studied:
  - By using existing cycle coolers or **dedicated coolers**;
  - By recycling or not the water that exits the first exchanger.

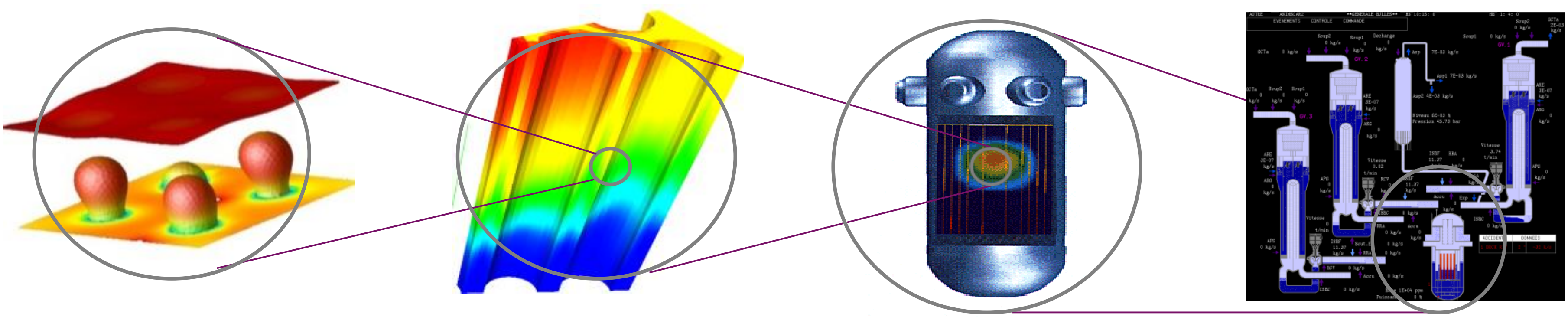


THE CATHARE SYSTEM CODE (1/2)

CATHARE : **C**ode for **A**nalysis of **TH**ermalhydraulics during **A**ccident and for **R**eactor safety **E**valuation

The CATHARE code is a thermo-hydraulic safety code developed since 1979 by joint effort of FRAMATOME, EDF, IRSN and CEA [6].

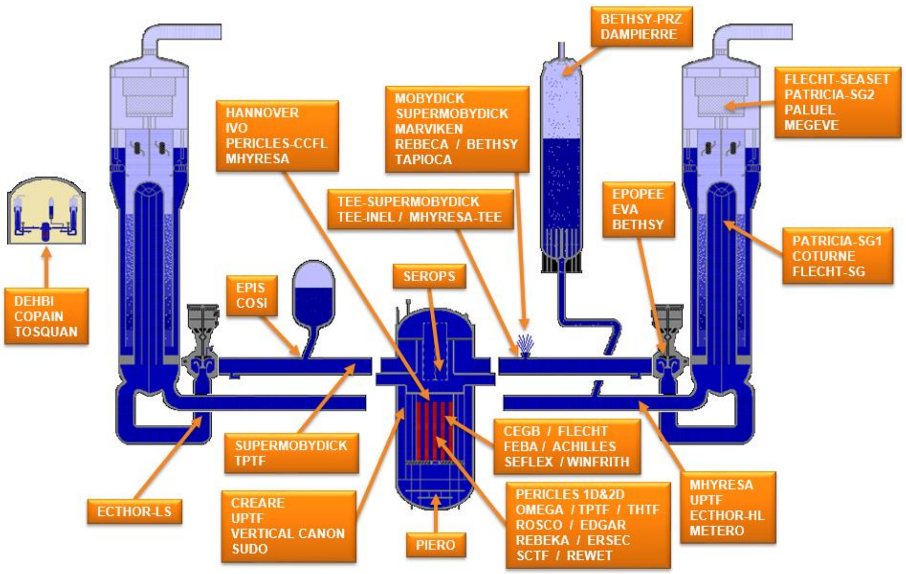
Used to calculate at a system scale the thermo-hydraulic of a reactor in various operating states for various incidental or accidental sequences



Instant local scale $\sim 1\mu m$ | Local scale $\sim 1mm$ | Component scale $\sim 1cm$ | System scale $\sim 10cm$

THE CATHARE SYSTEM CODE (2/2)

- Modelling of large type of experiments and reactors [7] based on:
  - A modular topological and technical description of the facility;
  - A generic set of equations based on the 6 equations 2 phase flow model (allowing thermal and momentum non equilibrium between the 2 phases);
  - A dedicated fluid description including equation of state and closure laws for mass, momentum and energy equations.
- Main uses:
  - Safety Analysis;
  - Design purposes (plant or component);
  - Quantify the conservative analysis margins;
  - Define and verify emergency procedures;
  - Reference code for real plant simulator.
- Some applications:
  - Standard light water reactors;
  - New Gen III concepts;
  - Gen IV concepts: SFR [8,9] and GCR [10,11,12,13];
  - Power conversion systems [14];
  - Experimental reactors;
  - Naval propulsion;
  - Other reactors : BWR, RBMK, LFR, SCLR;
  - Cryogenic rocket engines (ARIANE GROUP).

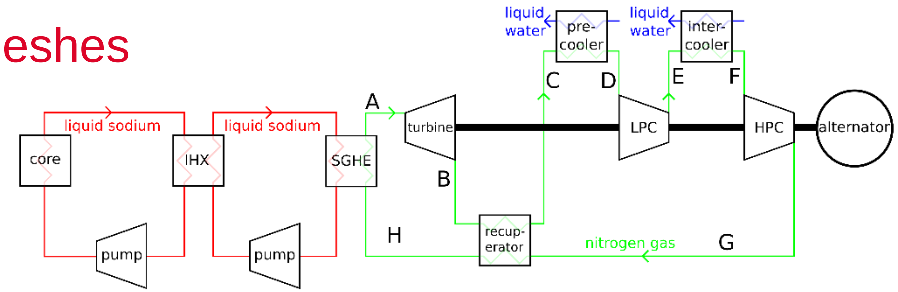


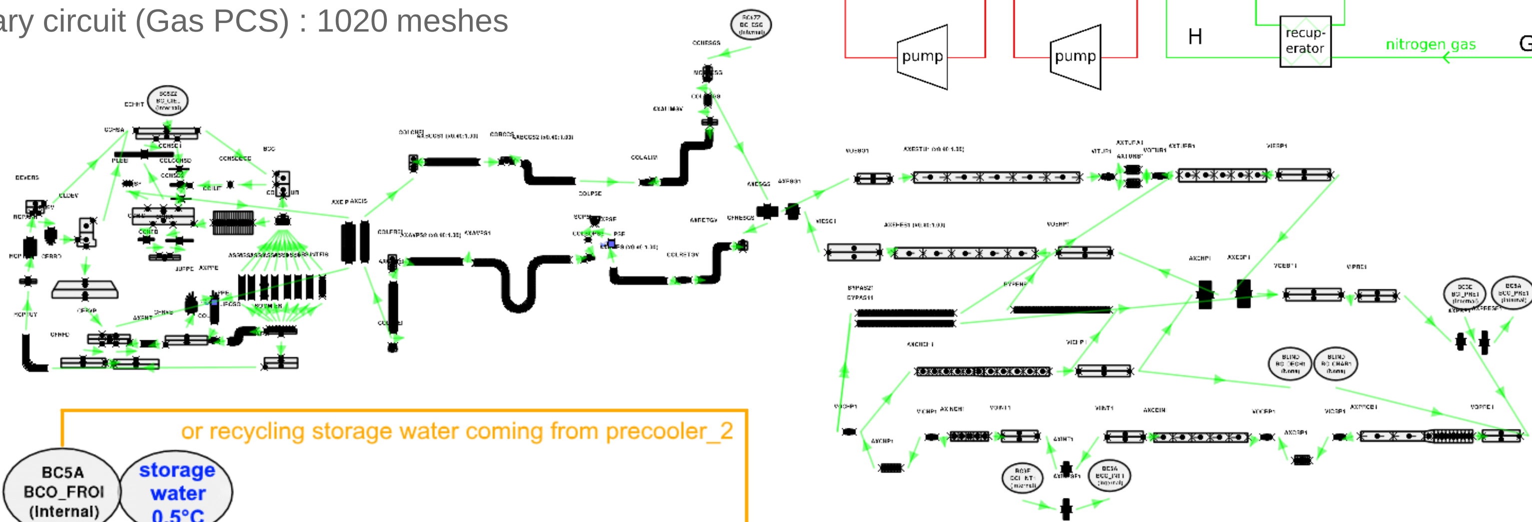
CATHARE validation tests for PWR application

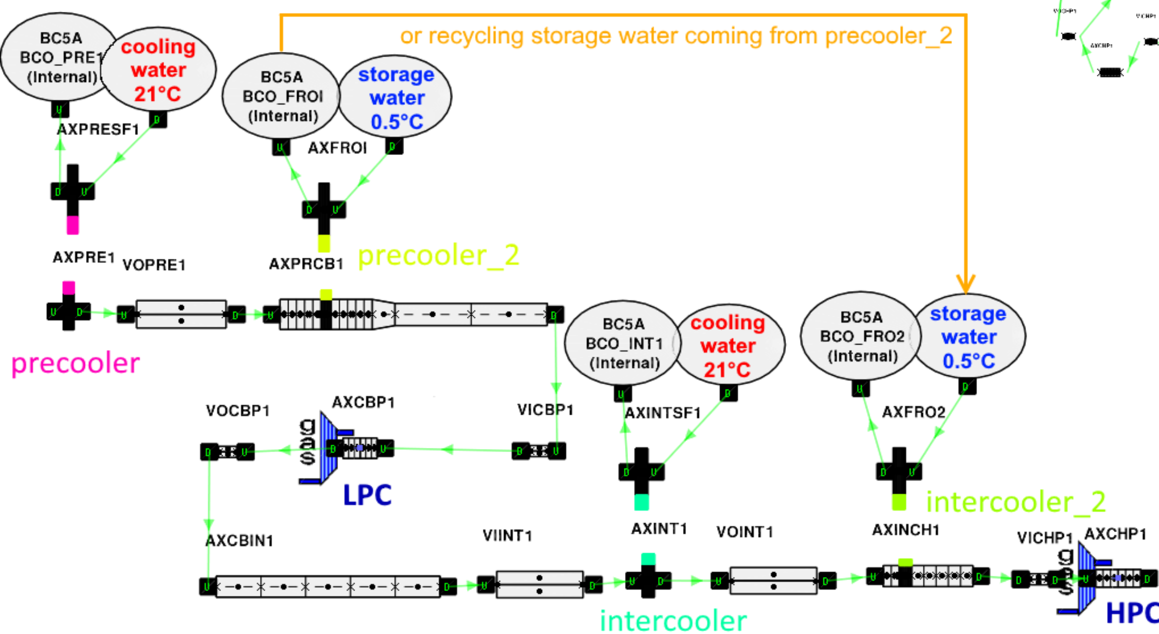
CATHARE MODELLING OF THE COLD STORAGE SYSTEM

Whole Reactor : 3335 CATHARE meshes

- Primary circuit : 1375 meshes
- Secondary circuit : 940 meshes
- Tertiary circuit (Gas PCS) : 1020 meshes







Dedicated exchangers precooler_2 and intercooler_2 are modelled

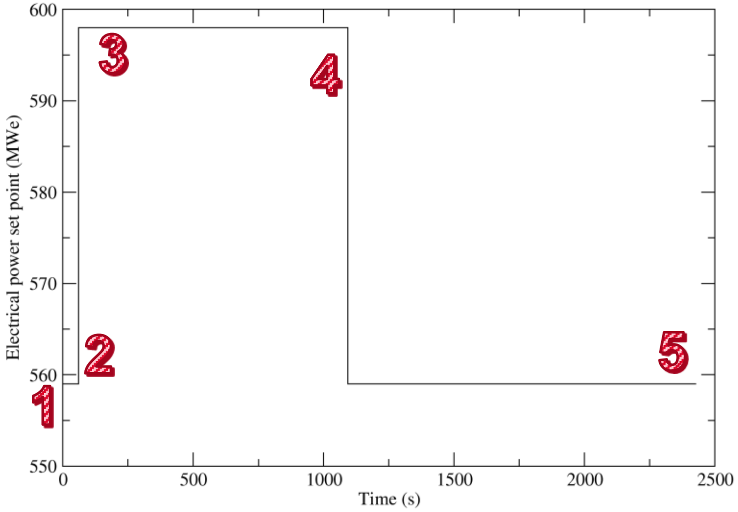
COLD STORAGE SIZING AND SYSTEM DYNAMICS

TRANSIENT SCENARIO

- During the transient, two PID controllers are used:
  - control of electrical power by the water flow rate coming from the cold storage (0.5°C). Actuators are not modelled but could be either valves (gravity system) or pumps with a total opening/closing time of 2 minutes.
  - control of pressure of the Brayton cycle by adding/removing nitrogen. If not activated, the pressure decreases by about 1 bar (due to overcooling), which slightly reduces the system efficiency.

- Reactor's primary and secondary circuits evolve naturally without any controller (only reactivity feedbacks are considered)

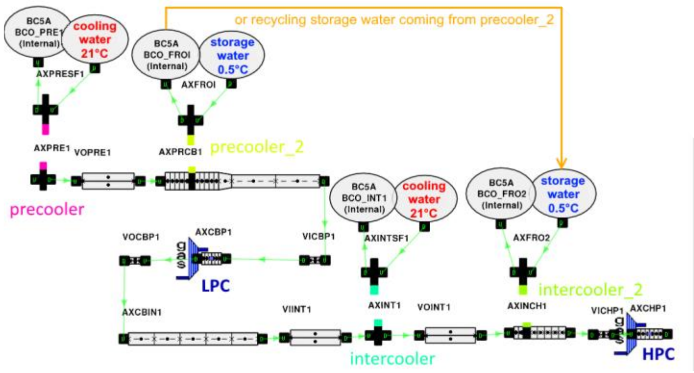
- Transient carried out with the CATHARE code:
  - 1 t_1=0s : beginning of the calculation, reactor at nominal power;
  - 2 t_2=t_1+60s: the electrical power set point is subject to a step from 559 MWe to 598 MWe (+7%);
  - 3 t_3=t_2+133=193s : electrical power is expected to have reached the new set point (598 MWe);
  - 4 t_4=t_3+15*60=1093s : after 15 minutes of over-power, the set point returns to its nominal value (559 MWe);
  - 5 t_5=t_4+133+20*60=2426s : after 20 minutes at nominal power the calculation is stopped.

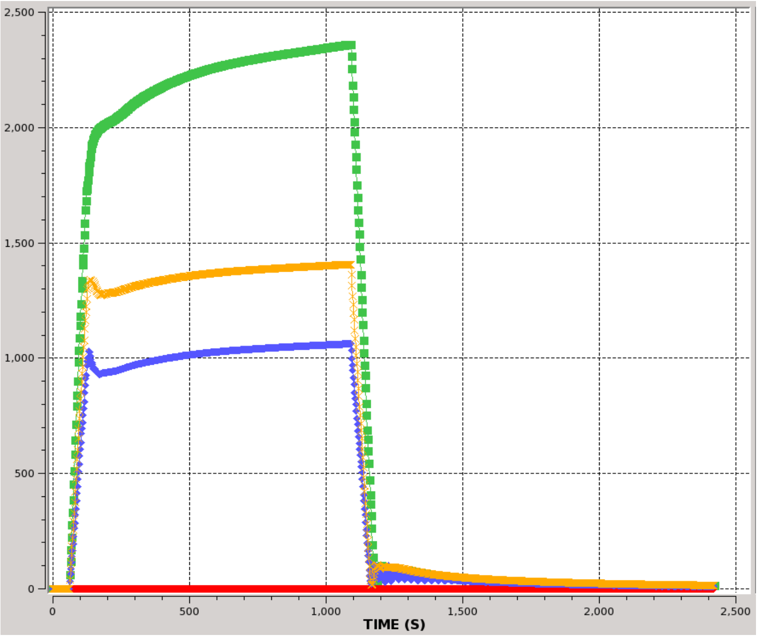


- During the calculation we are interested in:
  - the amount of cold water from the storage required to complete the transient;
  - the dynamics of the electrical power increase;
  - the impact on the primary circuit.

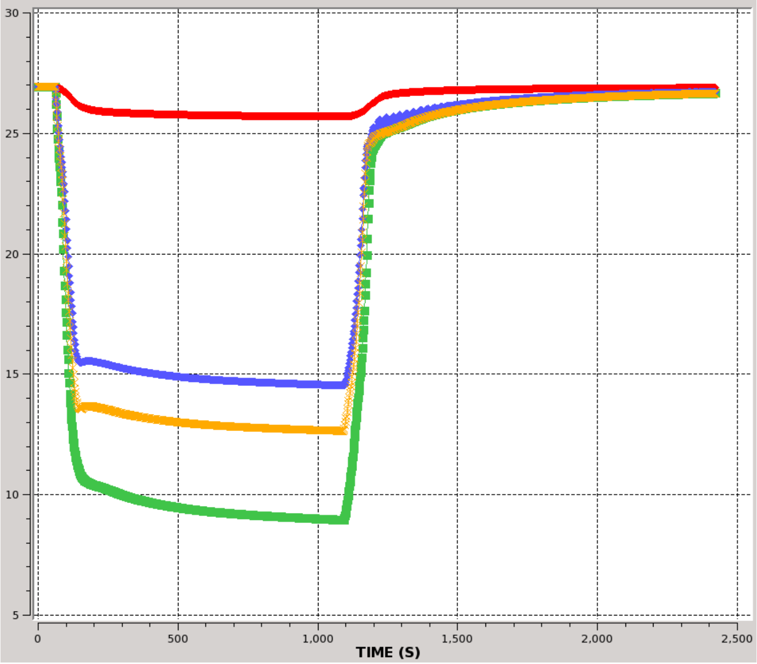
RESULTS (1/4)

- Four interfaces between the Brayton cycle and the cold storage are compared:
  - Green curves : only precooler_2 is used with water from the storage;
  - Red curves : only intercooler_2 is used with water from the storage;
  - Blue curves : both precooler_2 and intercooler_2 are used with water from the storage;
  - Orange curves : precooler_2 is used with water from the storage and intercooler_2 with water that exits precooler_2 as it is colder (about 14°C) than the cold source (21°C).





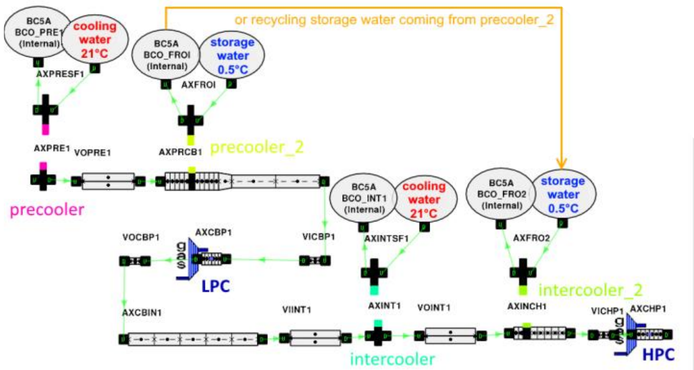
Cold water flowrate in precooler_2

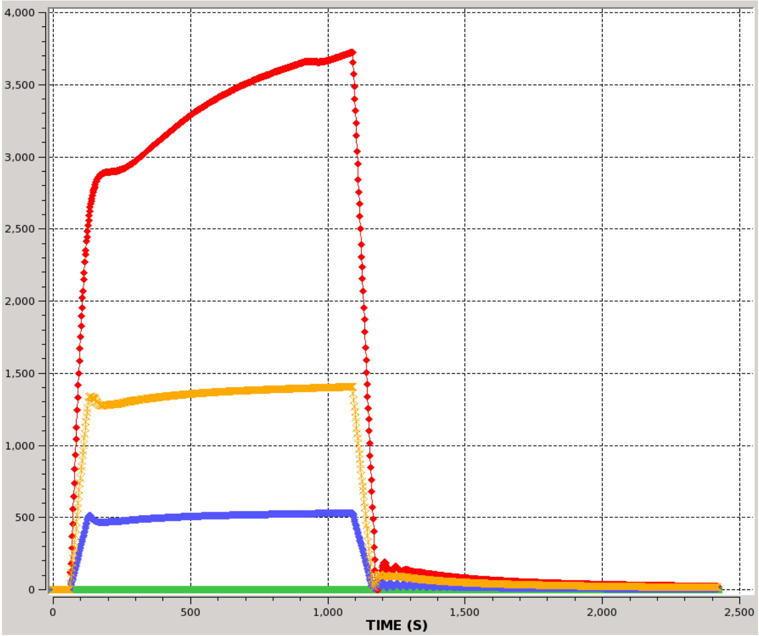


Nitrogen temperature at LPC inlet

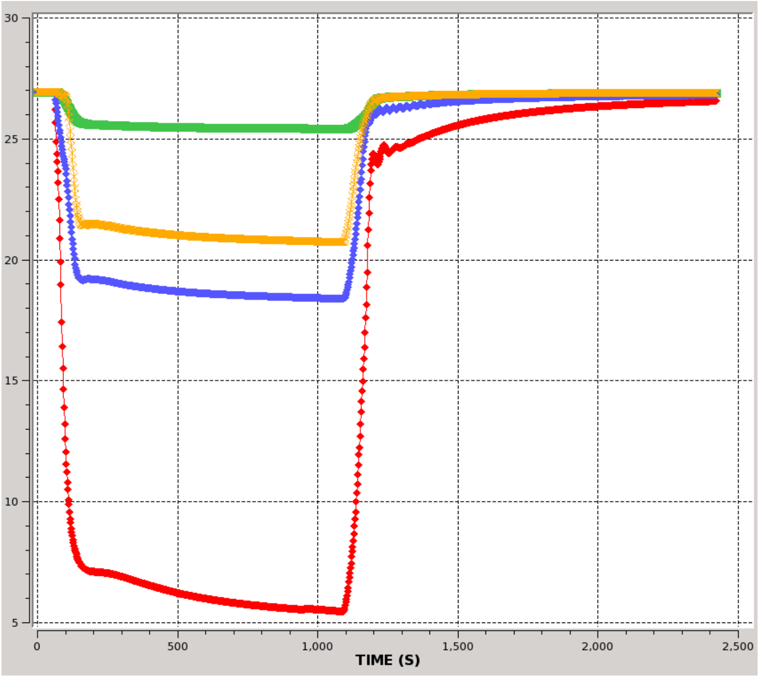
RESULTS (2/4)

- Four interfaces between the Brayton cycle and the cold storage are compared:
  - Green curves : only precooler_2 is used with water from the storage;
  - Red curves : only intercooler_2 is used with water from the storage;
  - Blue curves : both precooler_2 and intercooler_2 are used with water from the storage;
  - Orange curves : precooler_2 is used with water from the storage and intercooler_2 with water that exits precooler_2 as it is colder (about 14°C) than the cold source (21°C).





Cold water flowrate in intercooler_2



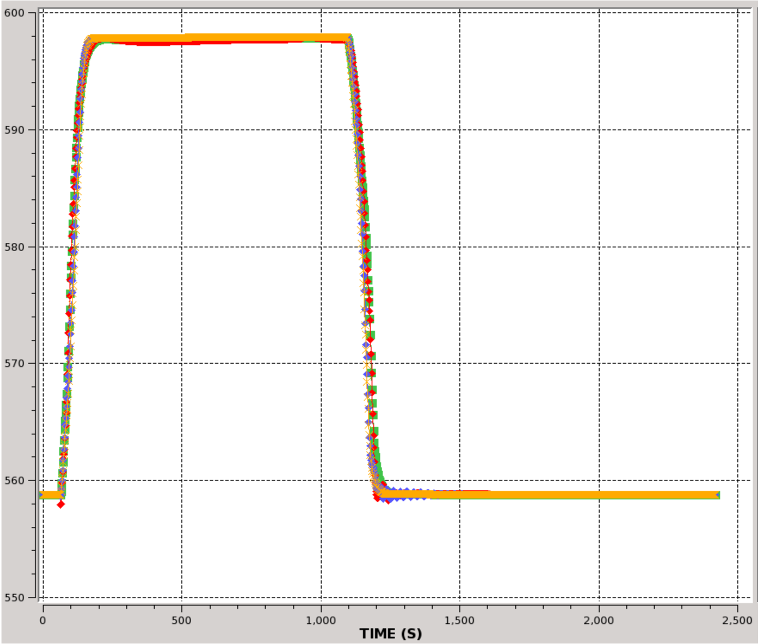
Nitrogen temperature at HPC inlet

RESULTS (3/4)

- In all cases, the electrical power step respects the criteria of the secondary reserve:
  - +7% of electrical power reached in 133 seconds;
  - maintaining overpower for 15 minutes.

- About 1500 m^3 of cold water at 0.5°C are needed in the storage to achieve this transient. The use of water with glycol or salt or ice-based storage could be considered to reduce the storage size which is already reasonable.

- The efficiency of the system calculated by CATHARE is about 3: 120 MW of cold are needed to increase the electrical power by 40 MWe



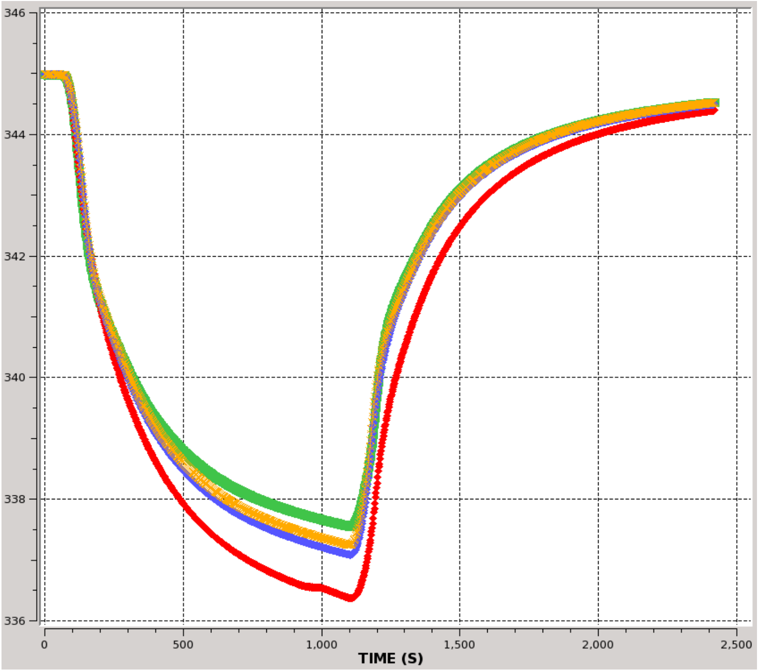
Electrical power delivered by the alternator

Cycle/storage interface	Total amount of cold water (in m^3)
Only precooler_2	2403
Only intercooler_2	3557
Precooler_2 + Intercooler_2	1656
Precooler_2 + Intercooler_2 (with recycled water)	1462

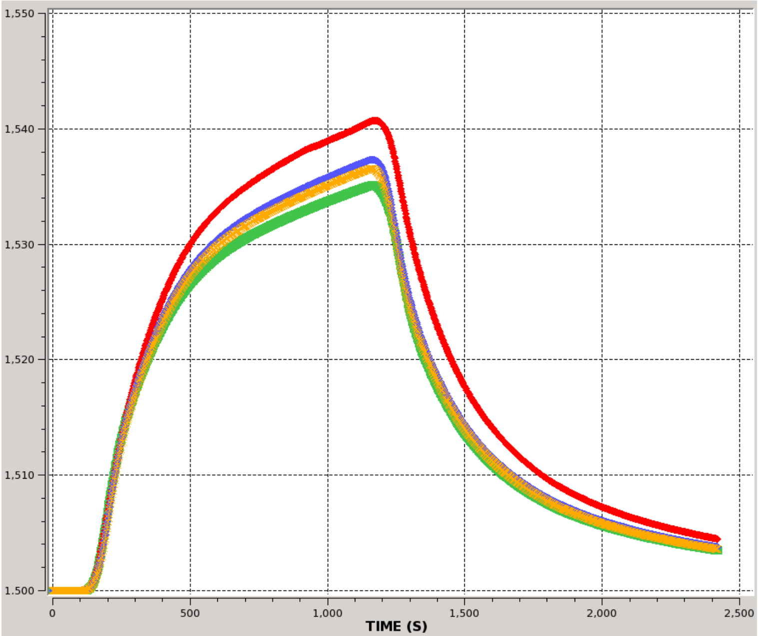
Olympic-size swimming pool contains about 3000 m^3 of water

RESULTS (4/4)

- The impact on primary circuit (which evolves in a natural way) is limited to variations of the order of %
- The decrease in the nitrogen temperatures induces a slight decrease in sodium temperatures in the primary and secondary circuits, which causes an increase in core power (reactivity feedback effect)
- It would be interesting to repeat these calculations with the controllers of the primary and secondary circuits to assess the impact on the dynamics and on the cold water requirement



Sodium temperature at SGHE outlet



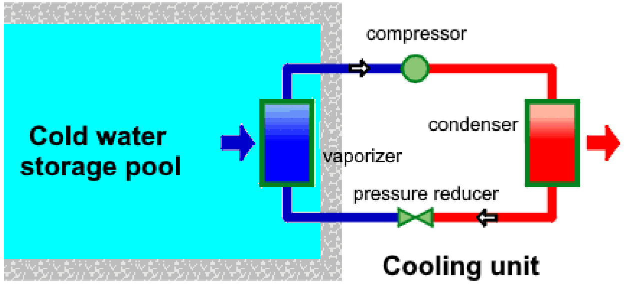
Core power (MW)

ENERGY BALANCE AND RECHARGING STRATEGIES

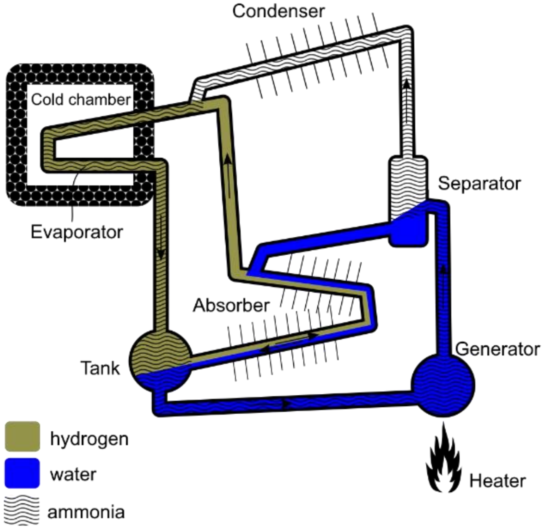
- The cold storage can be restored in two ways:
  - Intermittently during base load operation (implies operating in load-following mode) → - storage size + efficiency
  - Continuously during nominal load operation → + storage size - efficiency

- Energy balance of the cooling system over 1 hour is made:
  - Cold thermal energy used for frequency control (system efficiency is taken to 4 → 4 MW to produce 1 MWe);
  - Cold thermal energy produced by the cooling unit (efficiency is taken to 2.5 → 1 MWe to produce 2.5 MW);
  - Heat losses are estimated at 30% of the cold thermal energy used.

- Note that an absorption refrigerator could use the waste heat from the coolers (466 MW at 90°C) to provide the energy needed to drive the cooling process.



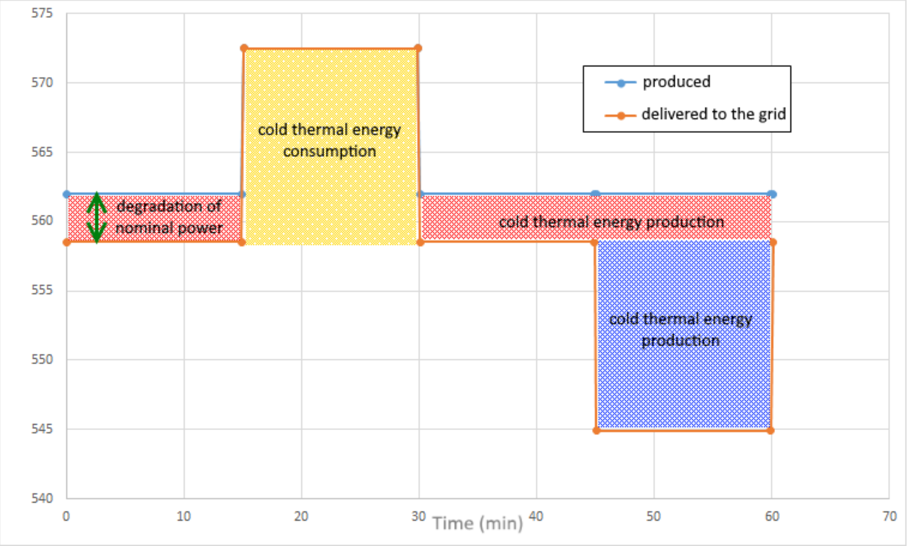
Principle of vapor-compression refrigeration



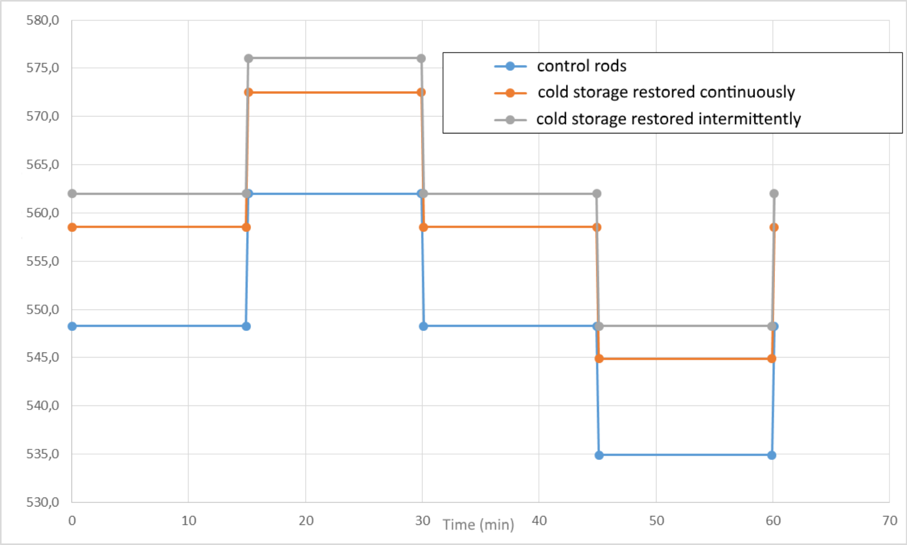
Principle of the absorption refrigerator

- During this hour of study we considered:
  - For primary control a +2.5% call and a -2.5% call for electrical power of 15 min each once an hour;
  - For secondary control a +4.5% call (in addition to a primary call) and a -4.5% call of 15 min each once a week i.e. 5.4 sec per hour.

RESULTS (1/2): CONSIDERING ONLY THE PRIMARY RESERVE



1-hour plan of the electrical powers produced by the alternator and delivered to the grid with continuous recharging option

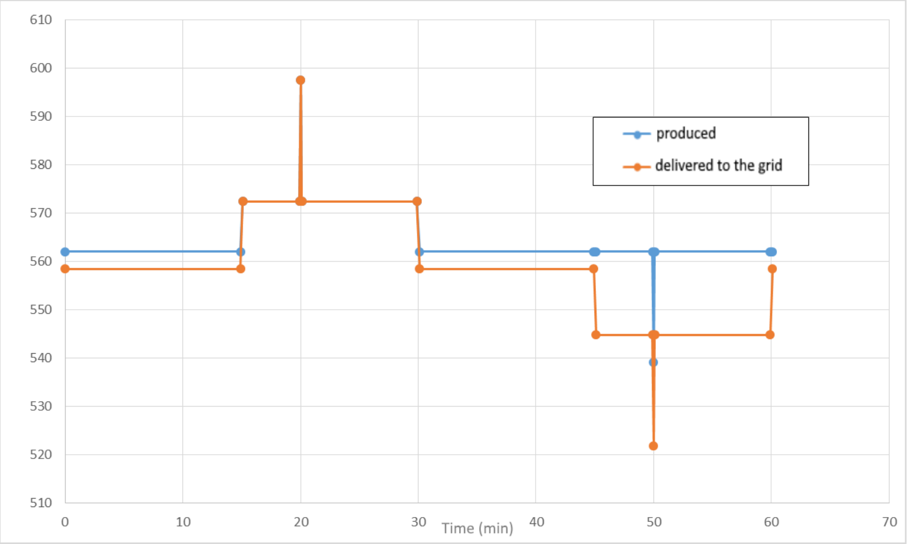


1-hour plan of the electrical powers delivered to the grid: comparison of the 3 options

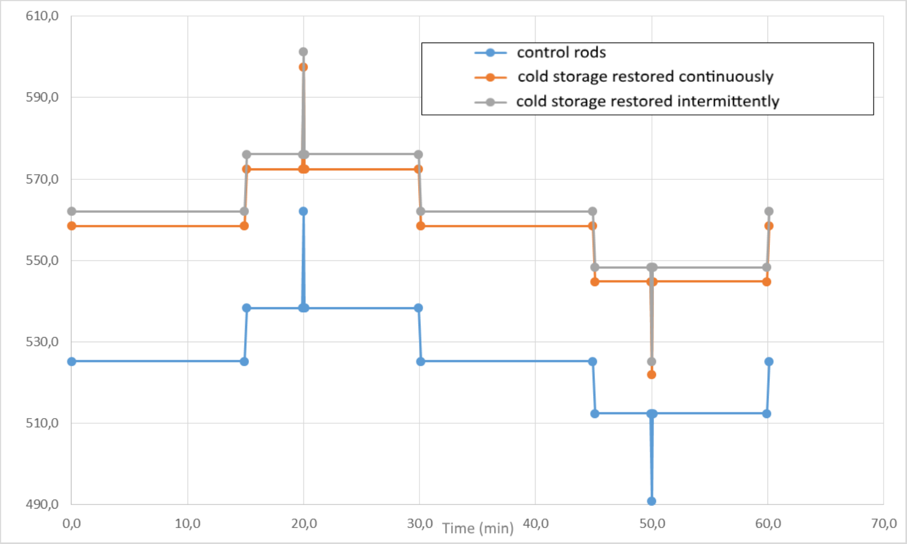
Option for frequency control	Nominal electrical power delivered to the grid (MWe)	Nominal gross reactor efficiency (%)
Control rods	548.3	36.55
Cold storage restored continuously	558.5	37.23
Cold storage restored intermittently	562	37.47

RESULTS (2/2): CONSIDERING ALSO THE SECONDARY RESERVE

- Insignificant for the cold storage solution because the amount of cold energy used by the secondary reserve is very low compared to the primary reserve due to the low occurrence of secondary power demands. However, this severely degrades the nominal power control rods solution for frequency control



1-hour plan of the electrical powers produced by the alternator and delivered to the grid with continuous recharging option



1-hour plan of the electrical powers delivered to the grid: comparison of the 3 options

Option for frequency control	Nominal electrical power delivered to the grid (MWe)	Nominal gross reactor efficiency (%)
Control rods	525.2 (548.3)	35.01 (36.55)
Cold storage restored continuously	558.4 (558.5)	37.23 (idem)
Cold storage restored intermittently	562 (idem)	37.47 (idem)

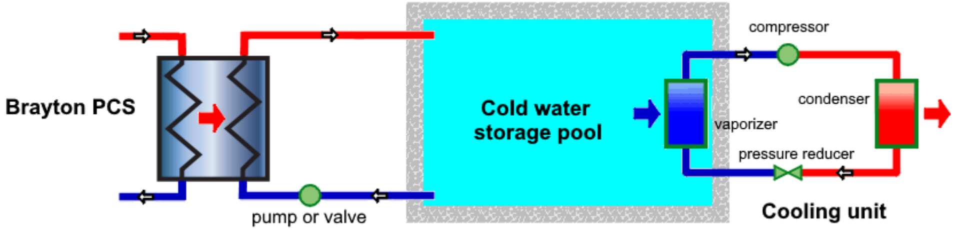
Considering a capacity factor of 80%, the same 600 MWe reactor produces 233 GWe.h more per year

CONCLUSION

CONCLUSION

- This quantitative study follows a more qualitative study on the processes that can be used for frequency control (nitrogen inventory, bypass, thermal or mechanical storages). Cold storage seemed to be the most promising option from an energy, technological maturity and size point of view.

- The architecture with dedicated coolers added in the Brayton cycle and recycled water is promising:
  - half of an olympic-size swimming pool (1500 m^3) of cold water (0.5 °C) is enough to perform a step from 559 MWe to 598 MWe (+7%) during 15 minutes (secondary reserve);
  - the regulatory dynamics of primary and secondary control are respected;
  - even with continuous recharging of the cold storage, the nominal electricity production is slightly degraded.



- Some items will require further studies:
  - the design, the cost and the pressure drop of the dedicated coolers;
  - the fast start and the consumption of the pump for cold water supply;
  - a two-part storage: cold at the top and “hot” at the bottom allowing a gravitational circulation of the water;
  - the feasibility of using Brayton coolers as an heat source for an absorption refrigerator cycle;
  - the impact of the primary and secondary circuits controllers on the system dynamics and efficiency;
  - the use of water with glycol or salt or ice-based storage to achieve lower temperatures;
  - A detailed economic analysis.

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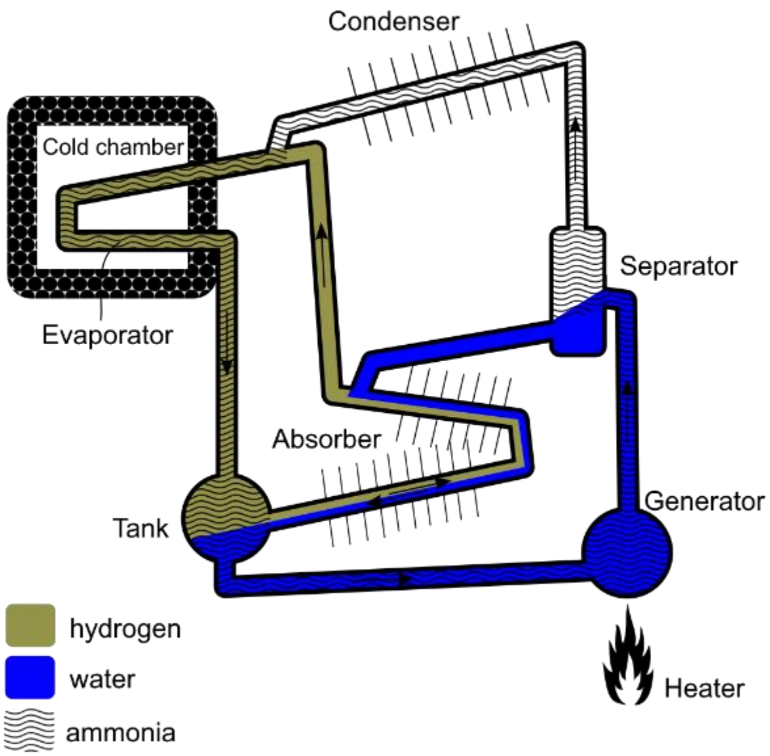
Service de Thermo-hydraulique et de Mécanique des Fluides
Laboratoire de Modélisation et de simulation à l’Echelle Système

ABSORPTION REFRIGERATOR

- Principle:
  - The absorption phenomenon creates the low pressure of the cycle
  - The heater creates the high pressure of the cycle

- Cycle description:
  - Ammonia evaporates in the cold chamber, thus extracting heat from its surroundings, at low temperature thanks to a low partial pressure environment (due to hydrogen)
  - Gaseous ammonia is absorbed by the ammonia at low concentration, forming a concentrated ammonia solution
  - This solution is heated in a boiler: the ammonia evaporates, its pressure and temperature increase
  - The water solution is depleted and regenerates the ammonia at low concentration in the separator
  - Gaseous ammonia passes through the condenser, transferring its heat outside the system and condenses



Principle of the absorption refrigerator