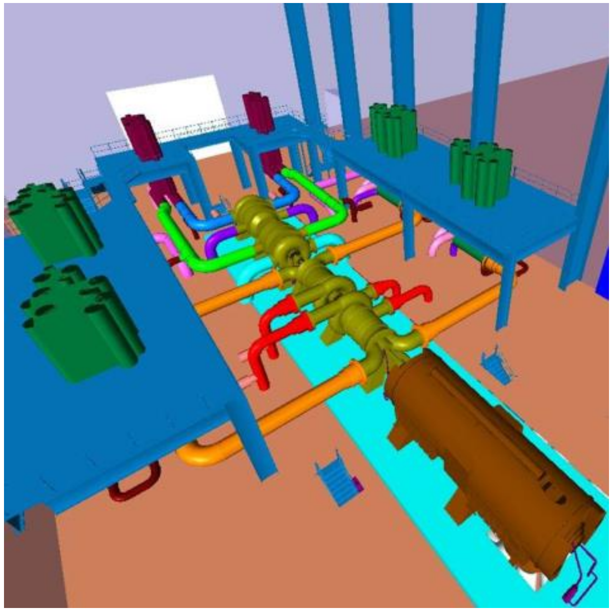
DE LA RECHERCHE À L'INDUSTRIE

SPECIFIC MODELS IN CATHARE 2 & 3 FOR GAS SYSTEM APPLICATIONS



Gédéon Mauger

CATHARE Gas Seminar - ALLEGRO
January 25, 2018

CONTENTS

2000'S GAS CONTEXT IN CEA

Gas Cooled Reactors

Main Transients & Physical Phenomena

GAS COOLED REACTORS (1/2)

Generation IV International Forum

- Between 2000 and 2010 CEA has been performing a large number of thermal hydraulics studies for different Gas Cooled Reactor (GCR) concepts including Very High Temperature Reactors (VHTR) and Gas Fast Reactors (GFR)
- Main efforts on the GFR concept aiming to combine the benefits of fast spectrum and high temperature
- A rather large thermal core power of 2400MWth was selected to enhance core performance and for economic competitiveness (economy of scale)

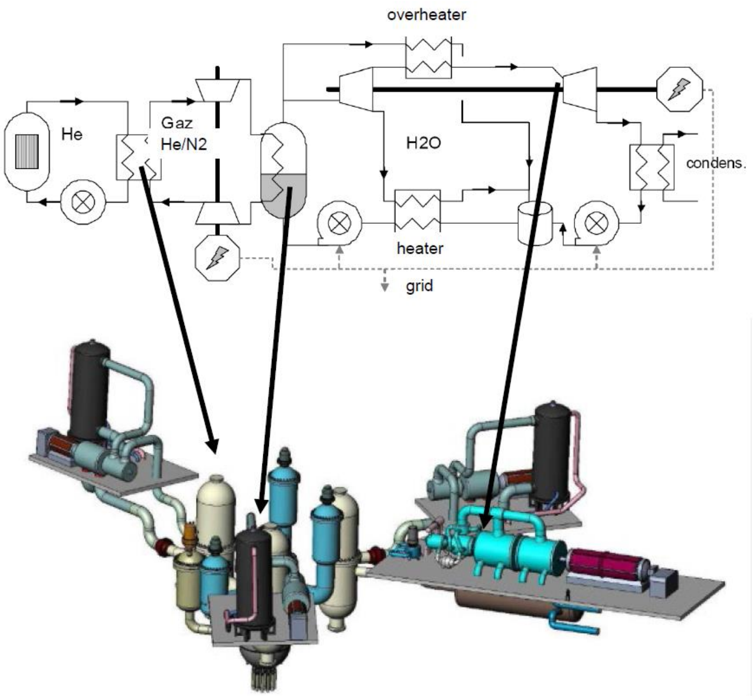
- The thermal hydraulic behavior of the GFR2400 is a key issue for, among other things, the design of the core, the assessment of thermal stresses, and the design of decay heat removal systems
- These studies therefore require efficient and reliable simulation tools capable of modelling the whole reactor, including the core, the core vessel, piping, heat exchangers and turbo machines.
- CATHARE 2 has been used during the design phase in order to develop the reactor concept and also for safety analysis

- It has been adapted to the specific needs of GFR applications (improvement of existing potentialities, development of specific components, and introduction of specific physical laws…) → **current presentation**
- At the same time, a strategy for validating CATHARE 2 for GCR applications has been developed → **next presentation**

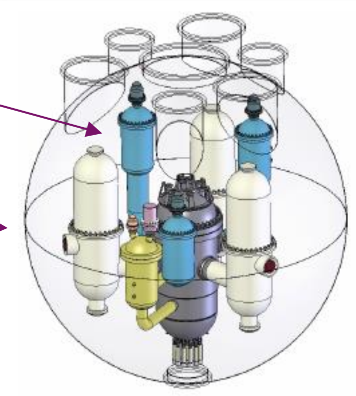
GAS COOLED REACTORS (2/2)

Main GFR2400 characteristics

- 2400MWth core based on ceramic pin type fuel elements
- inlet temperature of 400°C and an outlet temperature of 800°C
- power conversion system is based on an indirect combined cycle with helium for the primary circuit; a Brayton cycle with a mixture of nitrogen and helium for the secondary circuit and a steam cycle for the tertiary circuit



- In accidental situations, the use of the gas coolant circulation as the main way to remove the decay heat has been selected
- A specific DHR system has been designed: it consists in three loops in extension of the pressure vessel, equipped with heat exchangers and blowers
- This strategy requires a medium back-up pressure always higher than 4.25 bar This back-up pressure is ensured by a stand-alone metallic guard containment disposed around the primary circuit



- The whole plant is modelled with CATHARE 2 using 1800 meshes

MAIN TRANSIENTS & PHYSICAL PHENOMENA

Main transients

- Normal conditions
  - Start-up
  - Stop
  - Load following
- Accidental transients which may be protected (SCRAM actuated) or unprotected :
  - Loss of flow
  - Blackout
  - Loss of coolant
- Aggravating events may be taken into account such as the unexpected closure or aperture of a valve in the primary circuit (core bypass)

Main physical phenomena

- Turbomachine (blower, TM) performances (head and torque) far from nominal state and quick dynamics (start-up, stop, possible reverse flow, blocked rotor head loss, possible mixing of gases, motor behavior, shaft equation, gearbox, alternator)
- Core kinetic behavior from sub-critic to super-critical regime, from null to nominal power
- Fuel thermal modelling (gap, cladding, fuel) + thermo-mechanical modelling due to fuel dilatation (unprotected transients)
- Hydraulics and heat transfer in exchangers (IHX, SG, DHR) and piping including possible reverse flow (from natural convection to nominal flow)
- DHR pools (from natural convection to boiling conditions at low pressure)
- Operation of the Helium Service System (HSS)
- Operation of (DHR & TM) valves (sonic flow calculation)
- Break flow rate (sonic flow calculation, pressure losses for internal breaks) + water ingress from DHR loops
- Close containment behavior (balance pressure, mixing of helium and nitrogen which could re-enter in the primary circuit)
- Asymmetry between the PCS or the DHR loops

2000'S GAS MODELS AVAILABLE IN CATHARE 2 & 3

Fluid

Turbomachinery

Heat Exchangers

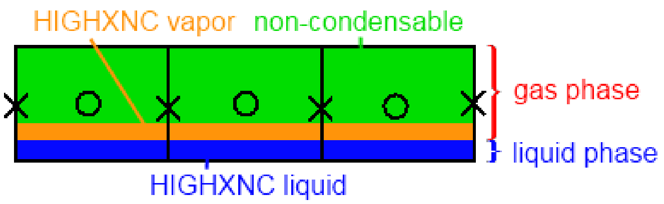
Core

Breaks

FLUID (1/2)

HIGHXNC FLUID

- A specific fluid (thermodynamic properties and closure laws) to represent high fraction of non-condensable gas
- Prandtl number is calculated (while it is set to 1 with standard FLUID WATER)



MONOPHASE DIRECTIVE

- A specific directive which allows the user to simulate a single gas phase flow computation by degenerating the 3 liquid balance equations into :

$$\alpha = \alpha_{max}$$

$$v_L = v_G$$

$$T_L = T_{sat}(P_V)$$

- No liquid mass, energy and momentum balances are computed for the corresponding elements
- The volume levels are set to their residual value 10^{-3}
- The directive can be used several times for a same element or for different elements during a transient calculation. For instance, it can be disabled in order to take into account water injection

FLUID (2/2)

GAS MIXTURE MODELS FOR NONCOND OPERATOR

- Treatment of non-condensable gases has been extended to deal with binary mixtures (helium-nitrogen, helium-air)
- This affects in particular the calculation of mixture viscosity according the Wilke's laws (Wilke, 1950)

$$\mu_G = \sum_i \frac{y_i \mu_i}{\sum_j y_j \Phi_{ij}} \quad \text{where} \quad \Phi_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}}$$

- And the calculation of thermal conductivity according the Mason-Saxena's laws (Mason, 1958)

$$\lambda_G = \sum_i \frac{y_i \lambda_i}{\sum_j y_j \Phi_{ij}} \quad \text{where} \quad \Phi_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}}$$

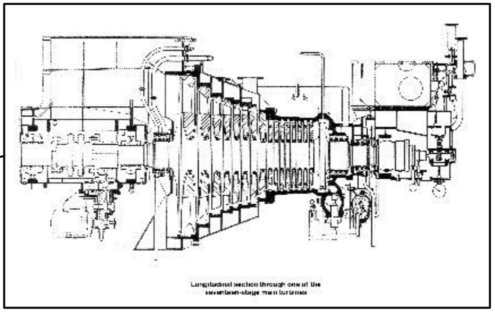
- Standard model is based on an arithmetic mean of the thermodynamic properties (weighted by molar fractions)
- Users can also specify their own weighting coefficient as a function of mass (or molar) fractions

POLYNCPT OPTION FOR NONCOND OPERATOR

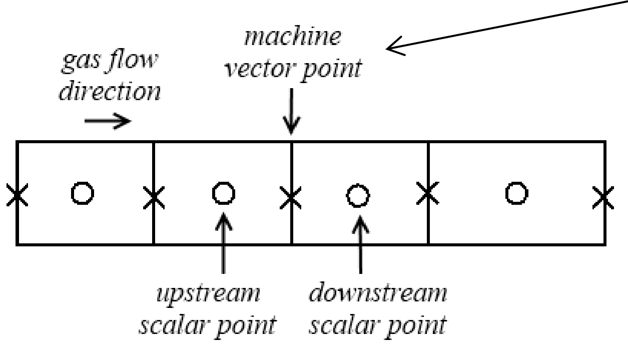
- A specific option for the non-condensable gas to describe the heat capacity $C_P(T)$ as a polynomial function of the temperature (especially for nitrogen or air)

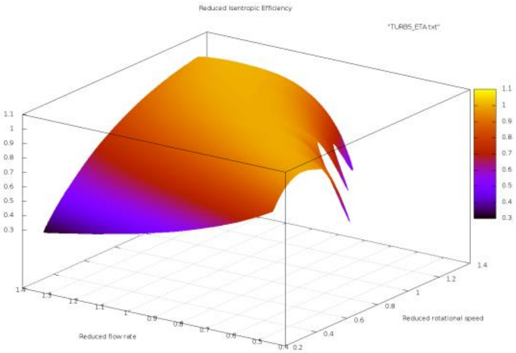
TURBOMACHINERY (1/3)

TCOMCHAR OPERATOR



- Used to describe either a turbine, a compressor, or a blower
- Located at a vector node of a 1-D module





- Performances are given as 2-D performance maps (flow rate, rotational speed)
  - Either in head and specific torque
  - Or in pressure ratio and isentropic efficiency
- Based on similarity theory and application of Buckingham's π theorem to turbomachine performance
- Interpolation method compute performances for any couple of flow rate and rotational speed
- Compute head and specific torque and contribute to balance equations :
  - Head source term (ΑρΗ) is added to the momentum equation at the machine vector point
  - Specific torque source term (ρτω) is added to the energy equation at the scalar downstream point

TURBOMACHINERY (2/3)

- Fluid viscous and thermal models have been developed to take into account a gas mixture

- Models require the reference specific gas constant r_{ref} and the reference ratio of specific heats γ_{ref} to calculate the complete expressions of reduced generalized flow rate and rotational speed :

$$Q^* = \frac{\frac{Q}{\sqrt{\gamma \cdot r \cdot T}}}{\frac{Q_{ref}}{\sqrt{\gamma_{ref} \cdot r_{ref} \cdot T_{ref}}}} \text{ and } \Omega^* = \frac{\frac{\Omega}{\sqrt{\gamma \cdot r \cdot T}}}{\frac{\Omega_{ref}}{\sqrt{\gamma_{ref} \cdot r_{ref} \cdot T_{ref}}}}$$

- Influence of the specific heat capacity ratio on the isentropic efficiency is given by the following Robert's correlation

$$\eta = 1 + \left(\frac{\gamma}{\gamma_{ref}}\right)^{0.8} (\eta_0 - 1)$$

- Influence of the specific heat capacity ratio on the pressure ratio is given by the following Robert's correlation

$$\Pi = \left(1 + \frac{\eta}{\eta_0}\left(\frac{\gamma - 1}{\gamma_{ref} - 1}\right)\left[\Pi_0^{\left(\frac{\gamma_{ref}-1}{\gamma_{ref}}\right)} - 1\right]\right)^{\frac{\gamma}{\gamma-1}}$$

- If the optional reference pressure P_{ref} is given (implicitly the reference dynamic viscosity μ_{ref} should also be given), the influence of the Reynolds number on the isentropic efficiency is given by the following Wiesner correlation

$$\eta = 1 + \left[\frac{1}{2} + \frac{1}{2}\left(\frac{Re}{Re_{ref}}\right)^{-0.1}\right](\eta_0 - 1) \text{ , with } Re = \frac{P\sqrt{\gamma}}{\mu\sqrt{rT}} \text{ and } Re_{ref} = \frac{P_{ref}\sqrt{\gamma_{ref}}}{\mu_{ref}\sqrt{r_{ref}T_{ref}}}$$

- In this case, the influence of the specific heat capacity ratio on the isentropic efficiency is no longer considered but still considered for the pressure ratio correction

TURBOMACHINERY (3/3)

BLOWER OPTION

$$\Pi = \left(1+\frac{\eta}{\eta_0}\left(\frac{\gamma-1}{\gamma_{ref}-1}\right)\left[\Pi_0^{\left(\frac{\gamma_{ref}-1}{\gamma_{ref}}\right)}-1\right]\right)^{\frac{\gamma}{\gamma-1}}$$

- This specific adaptation is only used for head and torque input data when the fluid viscous and thermal corrections are used ; in all other cases blower models are identical to compressors one
- It enables to model the start-up because when Ω equals 0, π equals 1 and so η_0 equals 0

$$\eta_0 = \frac{Q}{\Omega}\cdot\frac{\gamma_{ref}}{\gamma_{ref}-1}\cdot\frac{r_{ref}T_{ref}}{t_{ref}}\cdot\frac{1}{t^*}\cdot\left[\Pi_0^{\left(\frac{\gamma_{ref}-1}{\gamma_{ref}}\right)}-1\right]$$

- A Taylor series is used to get an expression of the head independent of the pressure ratio and the isentropic efficiency

SHAFT OPERATOR

- Used to slave several turbines and/or compressors sub-modules
- The transient behavior of the turbomachinery requires the rotating mass equation to be solved at each time step

$$I\frac{\partial\Omega}{\partial t} = C_{hydr} - C_{mech} - C_{elec}$$

- An ALTERNATOR can optionally be added to the SHAFT operator which calculates an additional torque on the shaft

$$C_{elec} = \frac{co\cdot max(sin\phi,0)}{max(\Omega,4.2\cdot10^{-4})}\cdot load$$

  - Either connected to a large electric network (imposed rotation speed and variable power). The swing angle Φ is calculated from :

$$\frac{\partial\phi}{\partial t} = \Omega - \Omega_s$$

  - Or in house load operation (imposed power and variable rotational speed). The swing angle Φ is constant.

COMPONEN OPERATOR (TECHDATA IN C3)

- Enables the user to define technical data describing specific hydraulic (friction) and thermal (heat exchange) components like fuel assemblies and heat exchangers
- Some correlations are already implemented in the code and derived from literature or from experimental data :
  - the tube side of a heat exchanger
  - the shell side of a heat exchanger
  - the finned side of a heat exchanger
  - the bundle side of a helicoid tube bundle heat exchanger
  - both sides of a Printed Circuit Heat eXchanger (PCHX)
  - the plate-type hydraulic core (wall friction only)
  - the pinned-type hydraulic core

HUWSCHEM Cathare Computation Variables (CCV)

- The high temperature gradients encountered in case of Counter-current Gas/Gas Heat Exchangers have to be well taken into account by the code
- Recommended to use the 2nd order donor-cell scheme to smooth mesh by mesh the variation of temperature
- This option must be applied element by element

CORE (1/2)

HTR FUELPLAQ OPERATOR

- All walls in a GCR core should be defined using the FUELPLAQ directive with the keyword HTR, if they should be able to receive fission power, and/or contribute a thermal anti-reactivity to the core neutronics
- Two advanced fuel concepts have been studied : a plate-type fuel and a pin-type fuel concept
- Several specific pressure drop and heat exchange correlations have been implemented (see COMPONEN)
- The thermal modelling takes into account the cladding, the gap, the fuel

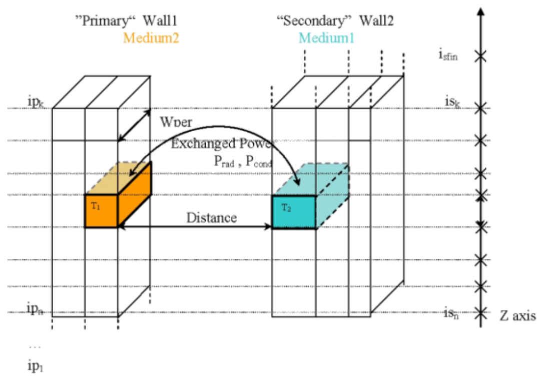
HTR CORE OPERATOR

- The HTR FUELPLAQ walls should be used together with a CORE object, also with the keyword HTR
- CATHARE already features a point neutron kinetics module with 6 delayed neutron groups and 11 heat decay groups
- The point kinetics module collects anti-reactivities from all elements of the core to compute a global core reactivity
- For a HTR application the way to compute the global feedback reactivity is different than the standard model
- The core reactivity is the sum of the external reactivity (control-rods) and the reactivity based on changes in the core fuel temperature (doppler effect), in the graphite moderator temperature (moderator effect), in the wall structures temperature (reflector effect) but also on changes of the coolant density (void effect)

$$\delta_{fdbk}\rho(t) = \delta\rho_{dop-T}(t) + \delta\rho_{mod-T}(t) + \delta\rho_{mod-\alpha}(t) + \delta\rho_{ref-T}(t)$$

EXWALINK OPERATOR

- Used to create an EXplicit WAll to wall LINK between two walls (WALL or FUELPLAQ)
- The heat exchanged can be computed using a thermal resistance model (conduction), a simplified radiation model, or a combination of both
- Modelling of radial heat transfer between blocks of the core, taking into account the presence of block gaps, coolant channels, …



AXICOND DIRECTIVE

- Enables the axial conduction computation within a WALL (1D or 3D) or a FUELPLAQ
- AXICOND model is explicit and so the time step is strongly limited by Fourier condition

$$dt < \frac{\rho C_P \cdot dz^2}{\lambda}$$

- It is recommended to use AXICOND with wall on which the thermal conductivity vary slowly along the axial direction
- It is also recommended to have radial meshing with a slight axial variation so that cells coincide at the most

BREAKS

- Generally modelled with an axial module with a refined meshing and low time steps
- PIKBREK, PIQREV and RUPTURE 0-D operators have been developed to reduce the CPU cost

EXHYLINK OPERATOR

- Used to create an EXplicit HYdraulic LINK between two hydraulics objects (BC, PIKBREK, PIQREV, RUPTURE, etc) exchanging mass and energy
- One of the main aims of this link is to simulate a rupture between the main system of a plant and the reactor containment

WATER INGRESS

- In this kind of transient 3 main issues are concerned :
  - kinetics: the presence of water in the core will lead to a moderator effect which will modify the core power (some specific anti-reactivity can be taken into account but require specific data given by a kinetics code)
  - chemistry: interaction between water and the cladding can lead to strong chemical reactions (not in the scope of CATHARE)
  - decay heat removal: a sufficient mass flow rate have to be maintained in the core to remove decay heat (main issues are the properties of the mixture of helium, water and steam and the behavior of DHR blowers)
- A common phenomenon concerns all these 3 issues: the calculation of the amount of water entering in the primary circuit
  - break calculation: 1^{st} He → H2O (water vaporization) and then counter-courant flow entering the primary circuit
  - 2-phase flow calculation in the 2 circuits with occurrence of water, steam and very high fraction of helium
- The main issue is the numerical behavior of the code (first draft but not finalized)

CURRENT GAS CONTEXT IN CEA

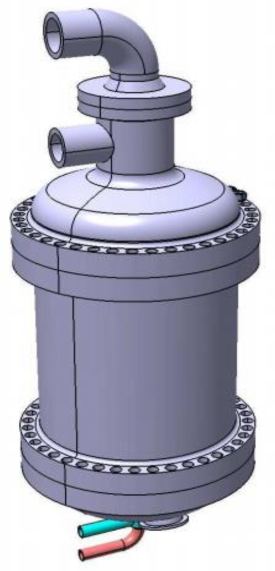
ASTRID Gas PCS

Main Transients & Physical Phenomena

ASTRID GAS POWER CONVERSION SYSTEM (1/2)

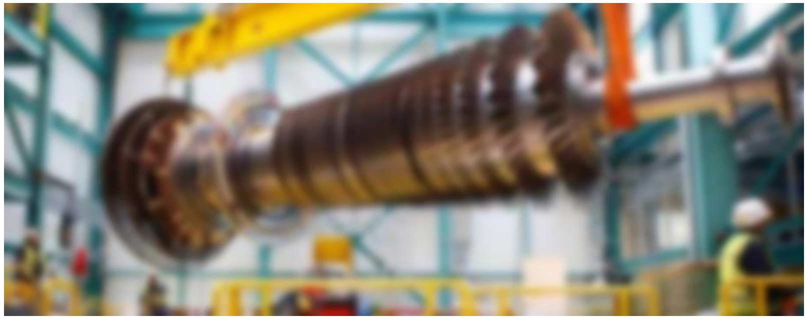
Two PCS are investigated for ASTRID (1500MWth SFR)

- Steam PCS (Rankine cycle) versus **Gas PCS (Brayton cycle)**
  - Sodium Water Reaction (SWR & SWAR)
  - Technology maturity : turbomachinery (TM), exchangers (SGHE), operability
  - Plant efficiency



Sodium Gas Heat Exchanger (CEA/DTN)

Arabelle^{TM} steam turbine (ALSTOM, from 700 to 1900 MWe)

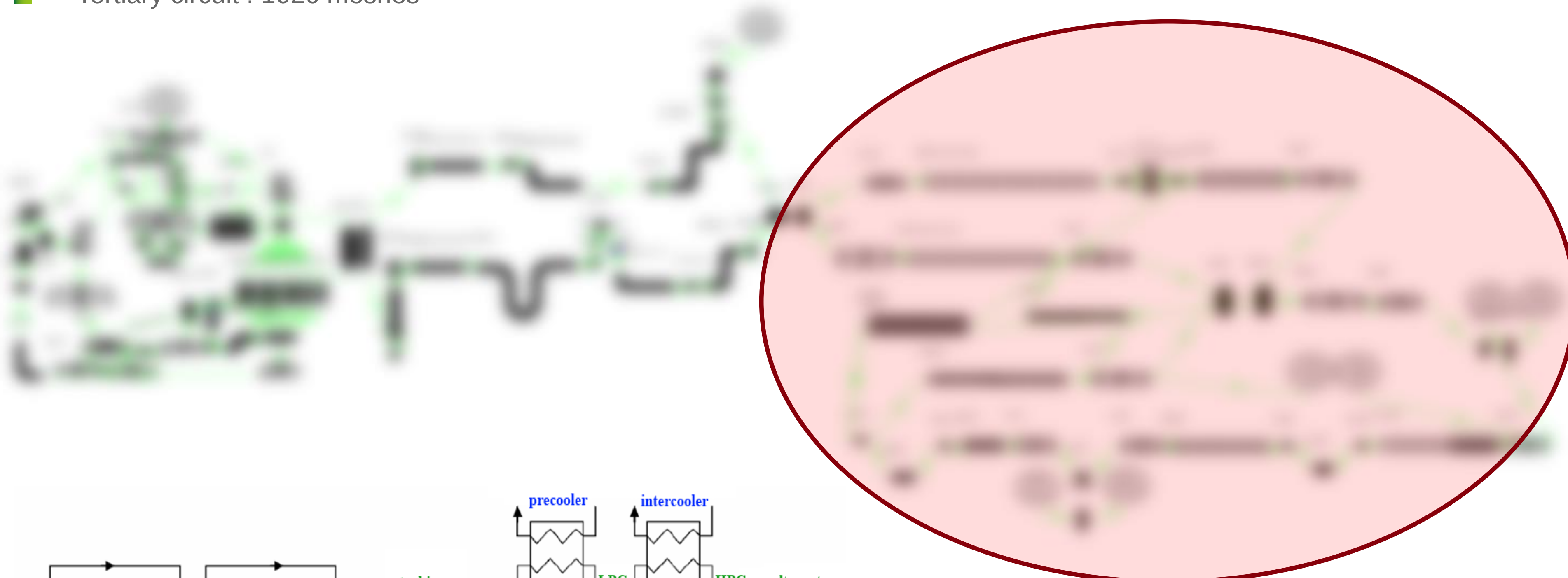


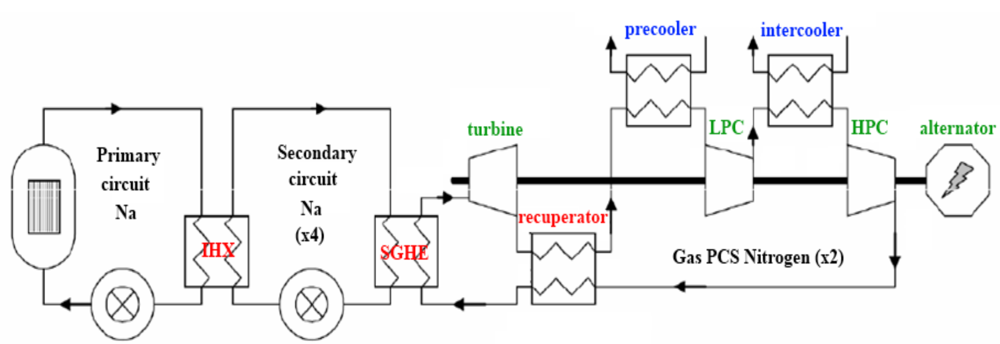
GT26 gas turbine (ALSTOM, 345 MWe)

ASTRID GAS POWER CONVERSION SYSTEM (2/2)

Whole ASTRID Reactor : 3335 meshes

- Primary circuit : 1375 meshes
- Secondary circuit : 940 meshes
- Tertiary circuit : 1020 meshes



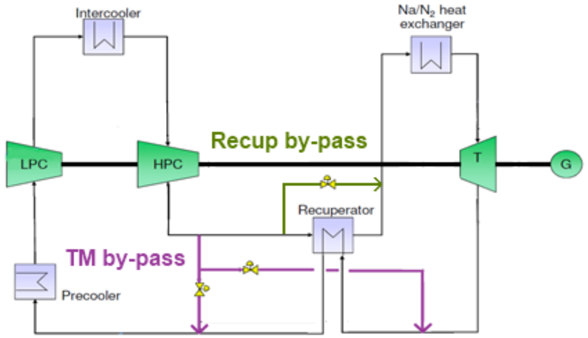


MAIN TRANSIENTS & PHYSICAL PHENOMENA

Main transients

- Normal conditions
  - Start-up
  - Shutdown (normal, quick & automatic)
  - Load following
  - House load operation

- Accidental transients
  - Loss of load (turbine trip)
  - Loss of heat sink
  - Break in main piping (including doubled-ended)
  - Spurious opening of TM by-pass valve



Main physical phenomena

- Turbomachine (TM) performances far from nominal state and quick dynamics
- TM starter engine or alternator in motor operation
- TM over speed and slowdown on inertia → rotating mass equation calculation

- Alternator grid coupling and disconnection
- Alternator switch from grid operation to house load operation

- Operation of TM and recuperator by-pass lines and valve flow rate (sonic flow calculation)
- Operation of the nitrogen filling/draining system (NSS)

- Quick pressure balance between HP and LP parts of the circuit
- Hydraulics in exchangers and piping including possible reverse flow
- Break flow rate (sonic flow calculation)
- Asymmetry between the two power conversion systems (PCS)

CONCLUSION

CONCLUSION

- The development of CATHARE for gas applications has been undertaken since 2000 and is still under progress

- Specific models and functionalities have been developed for Gas Cooled Reactors, especially for GFR concept

- New gas models are under development in CATHARE 3 code, especially for real gas Brayton cycles (ASTRID Gas PCS)
  - Fluid
  - Turbomachinery
  - Breaks
  - Friction models

- However, in the frame of ASTRID Gas PCS, some important GCR issues are not studied anymore :
  - Core issues (but partially studied in the frame of ASTRID SFR core)
  - Natural convection (but partially studied in the frame of ASTRID SFR pool concept)
  - Containment behavior (but partially studied in the frame of PWR application)
  - Water ingress → only issue which is really not under study

- At the same time, a strategy for validating CATHARE 2 & 3 codes for gas applications has been developed → **next presentation**

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 88 01

Direction de l'Energie Nucléaire
Direction déléguée aux Activités Nucléaires de Saclay
Département de Modélisation des Systèmes et Structures
Service de Thermo-hydraulique et de Mécanique des Fluides
Laboratoire de Modélisation et de simulation à l'Echelle Système