CFX CODE APPLICATION TO THE FRENCH REACTOR FOR INHERENT BORON DILUTION SAFETY ISSUE

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Abstract

Inherent boron dilution can occur in case of a small Break LOCA when low borated water is accumulated in the U-legs due to reflux boiling in the Steam Generator tubes after the loss of natural circulation. The restart of the natural circulation may lead to criticality because of the injection of these low borated slugs towards the core. To evaluate this potential risk, the boron concentration at the core inlet has to be known which makes necessary to estimate the mixing phenomena in the cold leg, in the downcomer and in the lower plenum: CFD calculations are required.

First of all the validation of CFX5 CFD code on the relevant phenomena of inherent boron dilution has been established (UPTF TRAM C3 test). Then, an application to the 900 MW French Pressurized Water Reactor series has been performed.

Introduction

In case of small Break LOCA on a Pressurized Water Reactor (PWR), the loss of primary water could induce, under specific conditions, the accumulation and the transport of a low borated water slug at the core inlet: that's the inhomogeneous inherent boron dilution. The consequence of this accident is a potential return to criticality and a power excursion with fuel damage. The conditions to obtain such scenario are:

- The loss of natural circulation, which is characterized by the interruption of the liquid flow at the top of steam generators (SG) tubes (pumps off) ;
- The condensation of the low borated steam coming from the core (reflux boiling) in the SG tubes, which induces the generation of low borated slugs ;
- The restart of the natural circulation (in one or all primary loops) due to the ECC (Emergency Core Cooling) injection leading to the injection of low borated slugs into the core.

The description of three-dimensional turbulent mixing and buoyant flow phenomena in complex reactor geometries is inadequate with the 1D system codes, and in spite of the uncertainties of the turbulence and numerical models, the risk evaluation of a boron dilution scenario in PWR requires the support of CFD calculations.

Methodology

To performed boron dilution calculation for a French PWR, IRSN has developed a methodology which focuses on the qualification of the CFX5 code on UPTF facility in accordance with the Best Practices Guidelines and the limitations induced by the full scale reactor (Figure 1). Then, the application on the French reactor is allowed by the establishment of boundary and initial conditions obtained by system code results and preliminary CFD calculations on a limited model. Finally, the results of the extrapolation UPTF model to the full scale French PWR should be validated, if the same relevant phenomena are obtained.

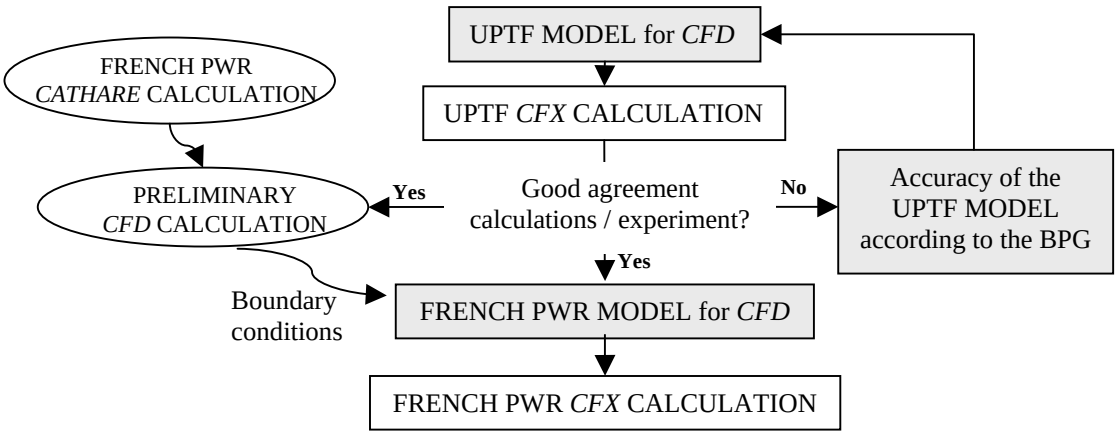

Figure 1: Flow sheet to ensure a consistent modelling of the reactor application as well as of the qualification calculations.

Qualification of the code CFX5 on the UPTF experiment

The UPTF test TRAM C3 has been selected by IRSN in order to qualify CFX5 for inherent boron dilution. The aim of those tests was to investigate the mixing of low borated condensate slugs with the surrounding highly borated water during the time period related to the restart of natural convection along the cold leg, the downcomer and in the lower plenum. The TRAM-C3 test series analyze the single-phase mixing of hot and cold water in the Reactor Pressure Vessel (RPV) under accidental conditions. The test 12b of these series, which is presented here, is dedicated to the formation of a thermal stratification (or mixing) in the RPV when the natural circulation restarts after the successful reflood of the primary circuit.

It has to noticed that an important investigation (experiment and CFX calculations) of the major buoyancy effects on mixing, during natural convection, in the downcomer of a 1:5 scaled model of a German PWR was analyzed at the Rossendorf Coolant Mixing test facility ROCOM, see Th. Höhne [3], [4] and [5].

UPTF test facility

The UPTF test facility consists in a four loops reactor model (Figure 2) scale 1:1 with the main components. The core is simulated by 17 internals which are not injected vapor in this test. The vessel is a model of the Grafenrheinfeld vessel reactor. The pumps and the SG are replaced by simulators.

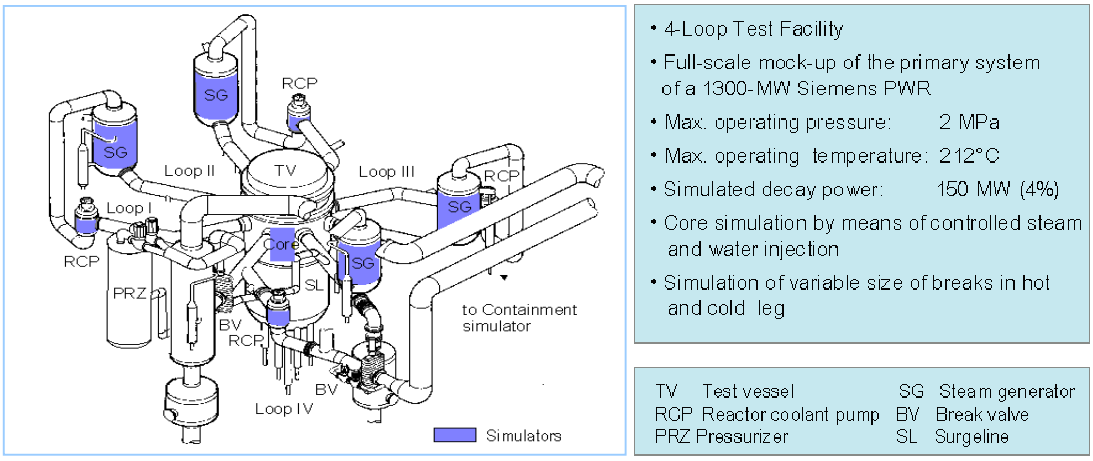

Figure 2: Scheme of the UPTF facility

The inflow boundary conditions of the test (see also Figure 3) are the following:

- Natural convection (simulated by hot water injection) is reestablished in three of the four primary loops ;
- The condensate slug (low borated water) is characterized by hot water injected in these three loops ;
- Highly borated water is characterized by the cold Emergency Core Cooling water flow injected in the loop n°2 ;
- Loop n°4 has no injection flow (dead loop)

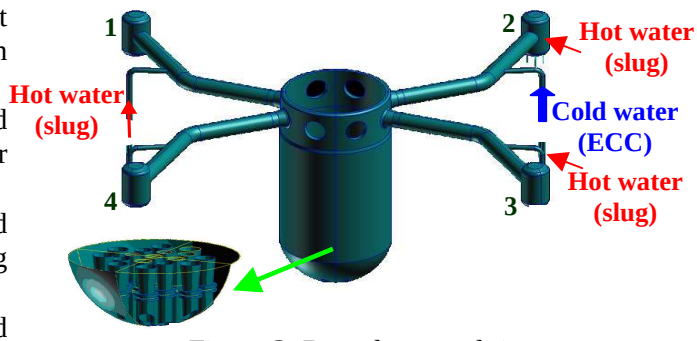

Figure 3: Boundary conditions

Instrumentation

The temperature distribution in the facility was measured by probes [2] in and along the cold leg n°2 and in the downcomer (Figure 4) in order to identify a mixing or stratification.

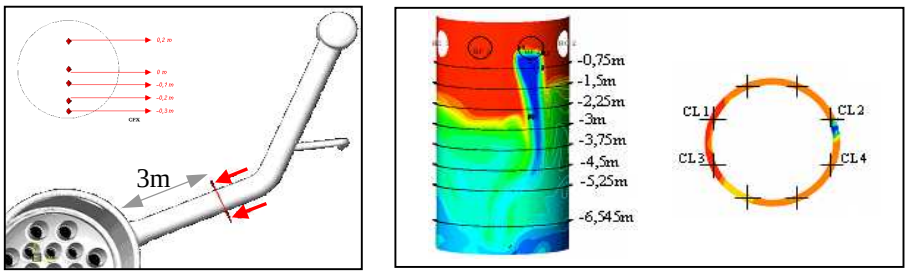

Figure 4: Probes positions in the cold leg (3m upstream of the vessel entrance) and in the downcomer

Computational modelling of the UPTF facility

The identification of each numerical error and its effect due to the grid density, the time step size, the discretization order and the convergence error is complex in CFD. Nevertheless, if the uncertainties should not be quantified yet, the computational modelling has to be based on sensitivity analyses like recommended in the Best Practice Guidelines. For mixing studies which supported reactor safety analyses, IRSN performed calculations with CFX5, and followed the requirements of the ERCOFTAC Best Practices Guidelines [6] and the ECORA [7].

In order to reduce the discretization errors, higher-order discretization methods, smaller time step size (0,25s), sufficient convergence criterion (Root Mean Square = 1.10^{-4}) and refiner grids were finally selected according to the hardware limitations, and to the constraints of the size of the full scale reactor model. In spite of the limitations of the k-ε turbulences model like anisotropies of the Reynolds Stress not resolved and weak laminar areas not modeled, due to the transient duration this "cheaper" model is in a first time chosen.

Unstructured grid generation

An exact and exhaustive representation of the geometric details of the RPV was modeled. The full model contains four cold legs with their pumps and inlet nozzles and the vessel with the lower plenum and its internals. No additional physical model as Porous media or Body forces was used. Two 3D meshes were generated with CFX5-BUILD software, according to the Courant Friedrich Levy criteria.

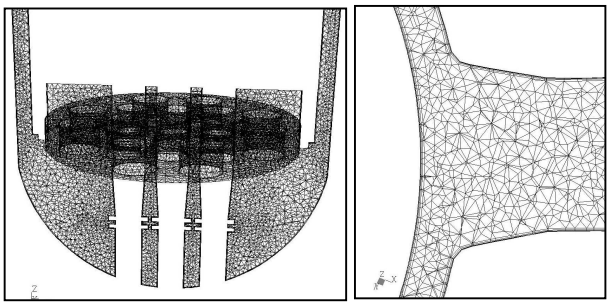

Figure 5 : Local refinement of the meshing in the lower plenum and the cold leg

The refiners was finally kept and consisted of 2.7 millions hybrid elements, the characteristic size of mesh is two times smaller and the limit layer is modeled. The grids present local mesh refinement in particular at the impinging area and in the lower plenum, but the limit layer modeled is necessary reduced to four meshes therefore the requirement of ten meshes by the Best Practices Guidelines.

Boundary conditions

Dirichlet boundary conditions for the temperature are specified at the inlet of the pump of the cold leg n°2 and at the nozzle of the cold legs n°1, 2 and 3 (see Table 1). A uniform velocity profile was also imposed at the inlets and a constant static pressure was specified at the support core plate outlet. In order to model the bypass flow between the downcomer and the hot legs, an outlet mass flow

rate is specified at each hot leg. A no slip boundary condition with logarithmic wall functions was used at all solid adiabatic walls. The fluid is assumed to be incompressible and the thermal effects in the Navier-Stokes equations are considered by the Boussinesq approximation.

	Fluid domain		$BF_{1,3}$		BF_2		$BC_{1,2,3,4}$	$ECC_{,2}$		
test	*T (°C)*	*P (bar)*	*Q ($kg.s^{-1}$)*	*T (°C)*	*Q ($kg.s^{-1}$)*	*T (°C)*	Q_{BP}^{*} *($kg.s^{-1}$)*	*Q ($kg.s^{-1}$)*	*T (°C)*	*Time (s)*
12b	100	15	134	167	267	102	37,5	133	37	≈ 600

(*) Q_{BP}: *bypass flow rate*

Table 1: Boundary conditions of the scenario

Results

The experiment has shown a perfect mixing in the cold leg n°2 with both primary loop inventory and ECC cold water (Figure 6), and the ECC water by density effects falls as a plume (Figure 7) and reaches the lower plenum.

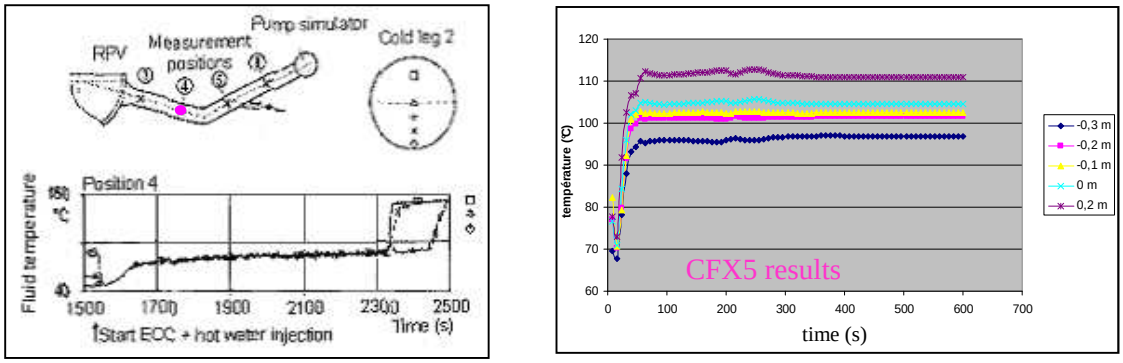

Figure 6: Perfect mixing in the cold leg n°2, good agreement experiment / calculation

The experimental and numerical values of temperature show that the main mixing takes place in the downcomer three meters below the cold legs.

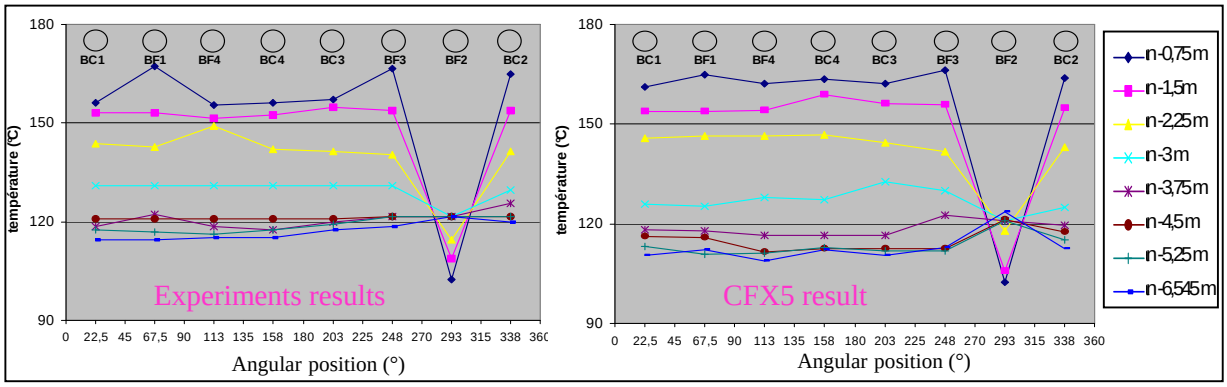

Figure 7: Comparison of the temperature profiles in the downcomer at 300s

The calculations recover the experiment behaviour (Figure 8) in particular good mixing between the ECC water mixes almost ideally and the ambient hot water (condensate slug) in the cold leg. In the downcomer, the flow which is coming from the cold leg n°2 falls down and participates in the mixing process. At the mid-downcomer elevation, an almost ideal mixing establishes.

The CFX5 calculations show a good agreement with the experiment data. The CFX5 computational on French pressurized water reactor should be performed with the main hypotheses of this UPTF-TRAM C3 qualification test; nevertheless a particular attention will be paid on the differences on the geometric, the boundary conditions and key parameters of the main physical phenomena.

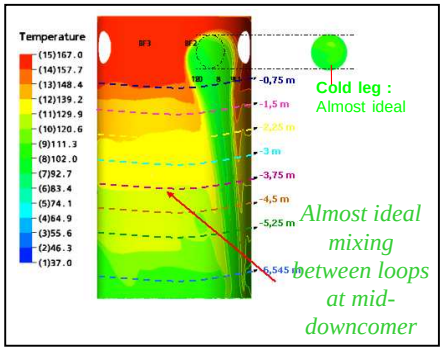

Figure 8: Mixing in the downcomer

The limitation of the qualification towards the phenomenology

The application of qualification mixing test related problems of two different temperatures fluids requires a similitude of the mixing phenomena between prototype and full scale model. This phenomena are correlated by equating ratios of inertial and buoyancy forces. The most characteristic numbers are the Froude number and the Richardson number [8]. The first one governs the stratification in the cold leg, when it is less than 1. The second one governs the stratification in the downcomer. In fact, the Richardson number permits to predict the type of convection (natural or forced). It is the ratio of the Grashoff number to the Reynolds number square.

$$Fr = \frac{V_{in}}{\sqrt{g.L.\frac{\rho_{in} - \rho_a}{\rho_{in}}}}$$

$$Ri = \frac{g.L.(\rho_{in} - \rho_a)}{\sqrt{\rho^2{}_{in}.V^2{}_{in}}}$$

V_{in} is the velocity at the reactor inlet (convection and ECC flow),
g is the gravitational acceleration,
L is the length of the downcomer,
ρ_{in} is the density of the incoming flow (convection and ECC flow),
ρ_a is the density of the ambient water.

In the UPTF TRAM C3 test, the mixing in the cold leg is quite perfect, the momentum effects dominates. In fact, for this case the Froude number is quite superior to one. In the UPTF TRAM C3 test, the slug entrances in a hot vessel, and a mixing takes place under the mid downcomer. The Richardson number is quite inferior to one and the approach of mixing is more relevant of a forced convection where the density effects are negligible.

In the full scale PWR scenario, as it is shown after, there is stratification in the cold leg, the density effects dominates. The density differences suppress the propagation of the ECC water in the circumferential direction, a density dominated flow is established, and a segregated plume expands in the downcomer in a no mixing flow. In fact, for this case the Froude number is less than one and the Richardson number is quite superior to one.

So, the main phenomena in the downcomer are quite different. This difference is mainly due to the gap between thermal hydraulics properties, and the characterized length (hydraulic diameter). As a consequence, the stratification has been validated for other boundary conditions on the UPTF model, in accordance of the characteristic Froude and Richardson Numbers of the PWR scenario.

Application to the French reactor for inherent boron dilution safety issue

In fact, the objective of this study is to analyse the potential risk of return to criticality resulting from a LOCA scenario.

The scenario was established thanks to CATHARE system code calculations (a restricted intermediate leg domain has also been calculated with the CFX5 code to estimate the boundary conditions in term of boron concentration).

In accordance with the UPTF analysis, the calculation of the boron concentration in the RPV, including sensitivity studies to the initial and boundary conditions (resulting from CATHARE calculations) to point out the relevant phenomena of inherent boron dilution, was performed with CFX5.

System thermal hydraulic transient

The search of a penalizing case is based on the objective of minimizing the boron concentration at the core inlet. Thus, the aim of the CATHARE calculations is to provide the maximal low boron water slug in the steam generators, water boxes or U-leg, taking into accounts the key parameters of the transient [9]. Two of them are the break size and the ECC water and accumulators mass flow rate. Those first calculations permitted to define the initial and boundary conditions (temperature, pressure, boron concentration, mass flow rate) for the CFX5 scenario performed.

Preliminary CFD transient

In order to quantify the volume and the concentration of the slug, a preliminary CFX5 calculation was performed on a limited model. It permitted to identify the thermal and boric mixing in the U-leg, between the pump seal water injection, the condensates from the steam generators and the potential ECC back flow injected in cold leg.

Unstructured Grid generated

The domain covers the U-leg (inlet of the domain), the pump and a part of the cold leg (outlet of the domain). A hybrid 3D grid was generated with CFX5-BUILD software in accordance of the UPTF model and the next PWR model to be build. It consists in 6.4 10^5 elements, including 2.10^5 structure elements that will be to add to a first model to analyze by comparison the sensitivity of the wall conduction.

Boundary conditions

The initial and boundary conditions are obtained by CATHARE results. Dirichlet boundary conditions for the temperature and the boron concentration (passive scalar) are specified at the inlet of the top of the pump volute, at the ECC nozzle, and at the entrance of the U-leg at the downstream side of the steam generators water boxes. A uniform velocity profile was also imposed at the inlets, and a constant static pressure was specified at the outlet (see Figure 9).

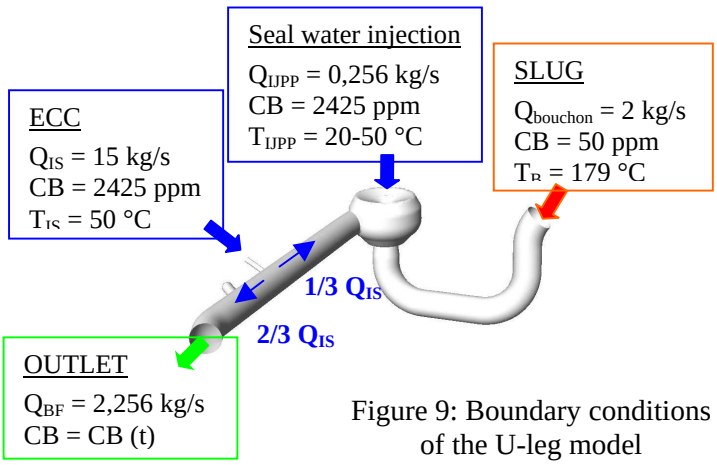

Figure 9: Boundary conditions of the U-leg model

A no slip boundary condition with logarithmic wall functions was used at all solid walls. The fluid is assumed to be incompressible and the thermal effects in the Navier-Stokes equations are considered by the Boussinesq approximation.

Results

This preliminary study on a reduced model allows in first approximation to provide the concentration of the slug entering into the cold leg after mixing in the U-leg, without considering the wall conduction.

Thus, the clear slug entering into the cold leg is composed successively of two parts:

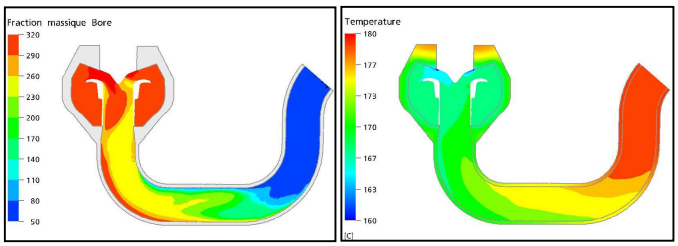

Figure 10: Boron concentration and temperature profiles in the U-leg

- 2,7 tons at 320 ppm, which fills a mid U-leg and the volute of the pump (≈3.06 m^3)
- 5,6 tons at 50 ppm, which fills the other mid U-leg (1,84 m^3) and the water boxes (4,5 m^3).

Computational modelling of the full scale French PWR

Due to the assessment of the relevant phenomena of the boron dilution (jet, mixing, plume), the application of the qualification requirements and the extrapolation to the French reactor are allowed.

According to the Best Practices Guidelines and in suitability of the computers limits, the CFX5 calculation of the full scale three loops French PWR was performed and finally the sensitivity of the input data on the results was analyzed, to determine the minimal boron concentration which is compared to the critical boron concentration.

Unstructured grid generation

Special attention was given to geometrical details of the reactor pressurized vessel, which may significantly influence the velocity field, like the curvature radius of the inner wall at the junction with the reactor pressure vessel, the detail of the inlet nozzles and the specific internals of the lower plenum (Figure 11).

The full model contains three cold legs with their pumps and inlet nozzles, the vessel with the thermal screen, the lower plenum and its internals. Different positions of the inlet nozzles on the three legs are modeled, which characterized the different real configurations on French PWR series, and permit also a comparison of the impinging jet.

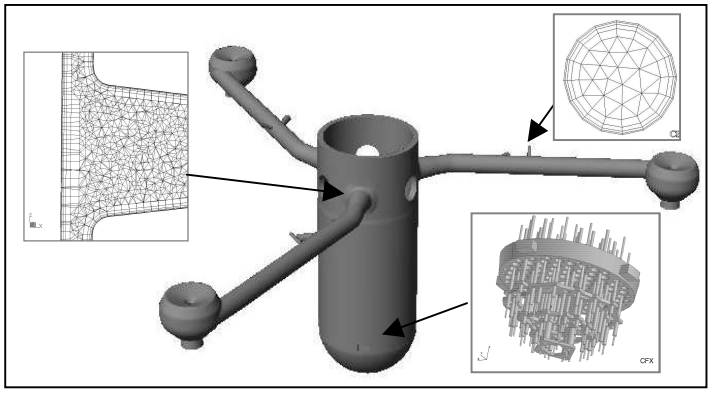

Figure 11: Geometrical details of the mesh

The 3D mesh was generated with CFX5-BUILD software, according to the Courant Friedrich Levy criteria and consisted of near 4 millions hybrid elements with the limit layer modeled. The grid contains local mesh refinement in particular at the impinging area and in the lower plenum, and the

limit layer modeled is necessary reduced to five meshes in spite of the requirement of ten meshes of the BPG. In accordance to the application of the validation UPTF test, the time step is reduced to 0,1s.

Boundary conditions

Dirichlet boundary conditions (temperature and boric concentration) are specified at the inlet of the pumps of the three cold legs and at the ECC nozzles (Table 2). A uniform velocity profile was also imposed at the inlets, and a constant static pressure was specified at the outlet: one meter above the inlet of the core. A no slip boundary condition with logarithmic wall functions was used at all solid adiabatic walls. The fluid is assumed to be incompressible and the thermal effects in the Navier-Stokes equations (k-ε turbulence model) are considered by the Boussinesq approximation. The boron is transported with the flow as passive scalar (one for each cold leg) without any feedback on the momentum equations. The boron density is actually not considered.

	Loop 1	**Loop 2**	**Loop 3**
Mass flow rate of the natural convection flow *($kg.s^{-1}$)*	135	135	135
Mass flow rate of safety injection (ECC) *($kg.s^{-1}$)*	15	15	15
Temperature of the natural convection flow *(°C)*	179	179	179
Temperature of safety injection *(°C)*	7	7	7
Boron concentration before and after the slug *(ppm)*	2425	2425	2425
Boron concentration of safety injection	2425	2425	2425
Boron concentration of the slug *(ppm) (here in the CL2)*	2425	320 for 2,7 t 50 for 5,6 t	2425

Table 2: Thermal hydraulic conditions of the scenario

The scenario consists in the onset of the natural circulation (time = 0s) in the last loop (loop number 2) with the departure of the slug (same mass flow rate), whereas the natural circulation was going on in the both other loops. The duration of the transient which is performed is 300 s, which is a sufficient duration to obtain the lowest boron concentration at the core inlet.

Results

Due to buoyancy effects, stratification develops, the ECC cold water swaps at the bottom of the cold leg, and the slug, as the ambient coolant inventory propagates above, at the top of the tube. The cold leg flow transports the ECC water towards the reactor vessel, there is a weak mixing.

The nozzle locations influence the injected jet and its partly mixing with the hot slug. The position of the ECC nozzle in the cold leg n°1 allows the "best" mixing at the entrance of the vessel (Figure 12).

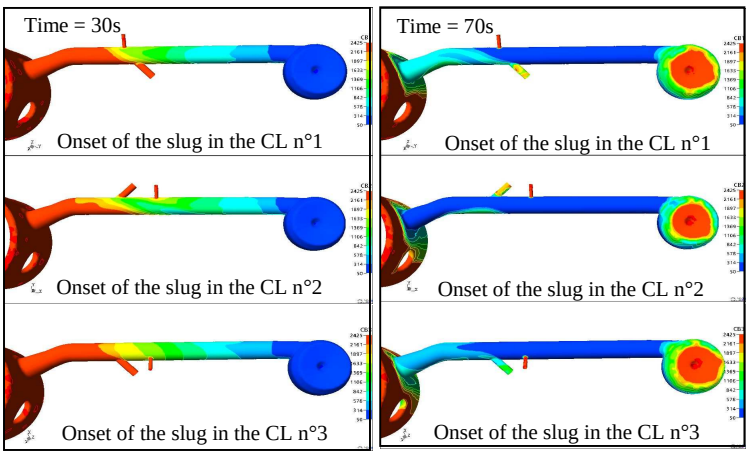

Figure 12: Influence of the ECC nozzle location on the boron mixing in the cold leg

At the inlet of the vessel on the top of the full thermal screen, the flow is divided into two jets in the downcomer. The low borated slug follows the flow of the ECC cold water which falls down in an almost straight line and reaches the lower downcomer.

The mainly part of both falls in front of the thermal screen. The loop which initiates the slug has a little influence of the circumferential propagation of the slug in the downcomer.

In the downcomer (Figure 13), because of the density difference between the ECC water and the ambient coolant, the density dominated flow is established. The downward ECC flow doesn't mixed with the ambient coolant, and the slug streaks towards the lower plenum as a plume. Except the segregated plume, the azimuthally boron concentration distribution in the downcomer is rather homogeneous and not diluted.

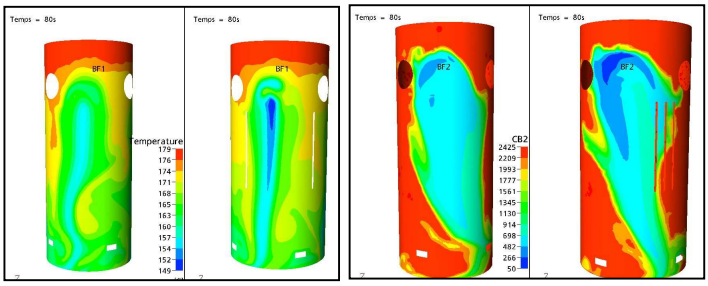

Figure 13: Temperature profile and un-borated slug (from CL n°2) in back and in front of the thermal screen

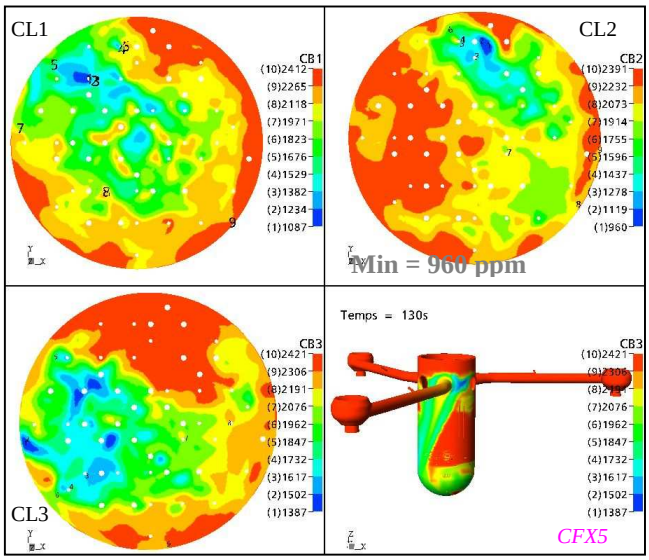

Figure 14: Boron concentration at the core inlet and in the downcomer for each case of cold leg coming from the slug

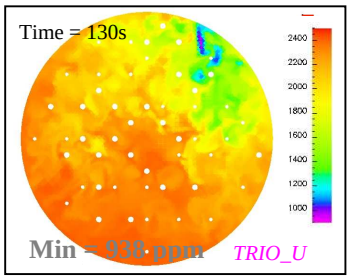

Figure 15: TRIO_U: Boron concentration at the core inlet for the slug from CL n°2

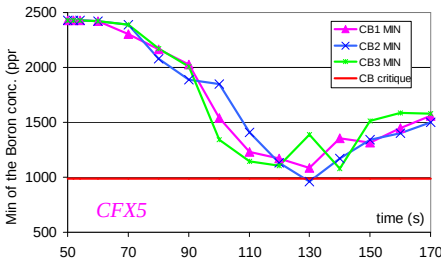

Figure 16: Minimum of the boron concentration profile at the core inlet

The slug reaches the lower plenum, rebounds on the centering pins, slips under the internals and appears in a large place at the core inlet in the direction of the opposite side of the leg where it comes from. The minimum of boron concentration at the core inlet is observed around 130 s after the onset of the slug in the pump, for the slug which is started in the cold leg n°2 (Figure14), probably because of the position of the ECC nozzle and the location of the centering pins. The same observation was obtained (Figure15) by the TRIO_U results [10], for the same scenario. After 130 s, the low borated plume which enters in the core disappears gradually (Figure 16).
The value of the critically boron concentration of 1000 ppm is reaches and it appears that a potential return to criticality might not be excluded in this realistic scenario.

Conclusion

Despite the hardware limitations and prohibitive calculations, the application of the Best Practices Guidelines allowed to perform predictive CFX5 calculations on the qualitative and quantitative UPTF TRAM C3 experiment. The relevant phenomena of a boron dilution as impinging jet, mixing/stratification, plume are observed and should encouraged, in spite of the geometrical evident differences, the transposition of the modeling choices to a full scale PWR computational. The calculation of a boron dilution PWR scenario shows for any boundary conditions on the slug, that a thermal and boron stratification takes place in the cold leg and enters into the vessel as a segregated plume, where no mixing appears in the downcomer. One of the objectives of this calculation is to identify the risk of an inhomogeneous boron dilution at the core inlet. The CFD results of a realistic scenario of a boron dilution in case of small break LOCA predict there is a potential return to criticality.

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