Hydrodynamic Loads on a PWR Primary Circuit due to a LOCA - Pipe Computations with the CASTEM-PLEXUS Code

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Abstract

The hydrodynamic loads due to a LOCA are computed with the CASTEM-PLEXUS code for a PWR primary circuit. An hydraulic model of the complete circuit (pipes, pumps, steam generators and reactor) is performed here assuming rigid pipes. CASTEM-PLEXUS being able to carry out FSI, the future work will take into account this effect.

1 Introduction

For the PWR safety, it is necessary to analyse the consequences of a hypothetical rupture of a primary pipe. From the opening time, the blowdown causes the propagation of an acoustic wave through the whole primary circuit, pipe whipping, component recoil and internal structure moving. Then the circuit empties progressively with a diphasic regime.

During the 70s, pipe whipping [1] and split [2], pipe impact on bumpers [4] and the recoil force on the vessel [3] were studied with the AQUITAINE II test-facility and the TEDEL [3], TRICO and TITUS [5] codes. The acoustic response was assessed by a mono-dimensionnal modal analysis [6] [7] with the monophasic fluid represented with an added mass. The transfert function of the circuit was computed with the VIBRAPHONE code [8] and the circuit response with the TRANSIT code. Both codes had been qualified [9] on the WHAM blowdown test-facility [10].

During the 80s, by using an improved modal approach [11] [12] taking into account the fluid-structure interaction, the effects of the LOCA acoustic phase on the reactor internal structures [13] [14] were calculated with a set of three codes: TEDEL for the pipes, AQUAMODE for the axisymmetrical vessel with the internal structures and fluid, and TRISTANA for the connections.

Now, a single code dedicated to Fast Dynamic Analysis is sufficient to carry out hydrodynamic calculations involving acoustic transients and fluid mass transfers. After the validation of the CASTEM-PLEXUS code [15] [16] for pipe circuits [17] [18] on test-facilities [19], first calculations were performed on a HDR reactor [20] [21] [22] with water initially at rest and described by a simplified diphasic constitutive law.

This paper presents a CASTEM-PLEXUS calculation of the hydrodynamic loads due to a LOCA on a complete PWR primary circuit. The geometrical and hydraulic models, the initial conditions and the calculation are successively described. The results concern the propagation of the depressurization acoustic wave, coupled with the transient fluid flow, along the circuit and their effects on the reactor internal structures.

2 Geometrical model

A PWR primary circuit is composed of a reactor cooled by three identical loops. Each loop is made up of a steam generator, a pump and three pipes: a hot leg, a U leg and a cold leg (fig. 1).

We assume that the structures are fixed and infinitely rigid during the blowdown. The hydraulic circuit is represented with a pipe model respecting the 3D component capacities and the average distances covered by the water. Specific laws complete the description for geometrical peculiarities.

The three loops are schematized the same way. The internal fluid of the legs is easily represented with pipes. For the steam generator, the pipe bundle is considered as a unique pipe with the total pipe set cross-section and the average bundle length. The thick pipe simulating the fluid volume of each water chamber goes from the nozzle to the middle of the flow distribution baffle.

The pump is described by a thin pipe for the water guide and the diffuser and by a thick short pipe for the casing. The volume of both pipes is equal to the primary water volume running inside the pump, neglecting the upward flow towards the controlled-leakage shaft seals. The pipe length corresponds to the shortest water path between the pump entrance and the exit, supposing a vortex absence in the casing.

The reactor is split up into seven fluid zones. We represented only the space taken by water, substracting the internal structure volume to the global reactor one.

- The downcomer is contained between the reactor vessel and the core barrel. Its capacity is calculated by removing those of the outlet nozzles, the thermal shields, the irradiation specimens...
- The structures enclosed in the lower plenum are plates, columns and instrumentation tubes.
- The main internal structures of the core lower volume are the core support plate, the lower core plate and the down part of fuel assemblies.
- The core cross-section is the free space around the fuel assemblies, the instrumentation tubes and the RCC guide tubes.

• The core bypass is the area between the core barrel and the baffle assembly.
• The higher plenum comes roughly from the upper core plate to the upper core support plate. The metallic part of the RCC guide tubes is removed but the water between the inner face of the RCC guide tubes and the control rods is taken into account.
• The top volume below the closure head contains mainly RCC guide tubes.

The pipe length is calculated using the average water route inside each zone (fig. 2): halfway between the vertical downcomer walls, midway down the lower plenum and in the middle of the core lower volume, the core and the higher plenum and then going out directly by the outlet nozzle.

The flow restrictions due to grids or perforated plates are not modelled geometrically but their hydraulic effects are taken into account thanks to pressure losses. The mesh of the complete circuit is presented on figure 3.

3 Hydraulic model

The PWR coolant fluid is described by a classical diphasic water constitutive law [23]. During the vaporization phase, liquid water and steam are supposed to be at the same pressure, the same temperature and to have the same velocity, except at the break. From the mixture density and enthalpy within an element, the pressure, temperature, void fraction and other thermodynamic parameters are given by steam tables [24].

The hydraulic peculiarities are the pumps, the pressure losses and the break. The pump characteristic gives the pressure increment. In normal operation, the fluid is accelerated. But in accidental operation, the pump is considered out of order if the flow is out of the characteristic range.

Distributed pressure losses [25] are applied to the legs, the steam generators (SG), the downcomer and the core. In the legs, the pressure losses come from friction against the inner pipe surface, flow direction changes in the elbows and section changes in the cones at the SG and reactor inlets. The pressure loss coefficients for normal operation are kept for the accidental one.

As the SG pressure losses are globally measured between inlet and outlet, a distributed drop is applied even if it could be separated into a distributed one along the bundle and local ones due to the flow distribution baffle and the cross section changes at the water chamber nozzles. The pressure losses in the downcomer and the core come mainly from friction respectively against the walls and the fuel assemblies.

Local pressure drops [25] are applied:
• at the reactor inlet and outlet owing to the 1D-3D flow changes between the pipes and the reactor,
• at the bottom of the core lower volume because of the core support plate.

A guillotine rupture is applied to one of the cold legs, just downstream the pump. The break conditions govern the dynamic mass transfers of the pressurized internal fluid. The initial liquid water vaporizes almost instantaneously and its speed is limited by the diphasic critical flow rate.

The CASTEM-PLEXUS available break models suppose a monodimensionnal annular flow, steady-state operating conditions, a pressure equilibrium between both phases, an isentropic flow and the total energy conservation according to Moody and Fauske hypothesises [26]. Among these models, we used a homogeneous one (no phase slide).

For the core bypass and the top volume, as the cross section restrictions at inlet and outlet are not geometrically represented, the flow rate is imposed thanks to local pressure drops.

In the CASTEM-PLEXUS code, the mesh is realised with TUBE elements for pipes, BIFURCATION elements to join two or more pipes with a different diameter and CL1D elements for local boundary conditions (local pressure drops, pumps, break). WATER and FRICTION constitutive laws are used for the coolant fluid and the distributed pressure losses. Specific IMPEDANCE constitutive laws describe the boundary conditions.

4 Initial conditions

The calculations are initialized at the reactor nominal rating. The initial pressure is 155 bar. The average temperature of the circuit is around 300°C. Thus, according to [24], the water density is 727 kg/m^3 and the sound velocity is 932 m/s.

The full flow is 6.3 m^3/s per loop, what means 18.9 m^3/s at the reactor inlet and outlet. The top volume flow rate is 2 % of the reactor inlet flow rate with the cold dome configuration. The core bypass flow rate is 1 % of the core one.

A conventionnal double ended break is represented. The outside pressure is 1 bar and the tear lasts 1 ms.

5 Computations

CASTEM-PLEXUS is a general fast dynamic analysis software developped by the CEA-DMT. It uses the finite element method and an explicit time resolution. It is devoted to the mechanical analysis of accidental situations in one, two or three dimensions, involving structures and fluids with or without coupling. Its main applications are impacts, explosions, piping transients and hydrodynamics.

A first calculation is carried out at the nominal rating for 1 s. The break is replaced by a connection between both pipe ends. The calculation aim consists in validating the numerical model. From the approximate initial data and the imposed pressure drops provided by the user, CASTEM-PLEXUS computes the local pressures, densities, velocities... along the circuit. If the results converge quickly on the nominal values, then the model is correct.

The LOCA calculation is performed from the initial data during 1 s but the interesting results concern only the first 100 ms.

6 Results

In the LOCA calculation, we observe a pressure drop (fig. 4) with three phases:

- from 0 to 5 ms: a pressure drop at the break,
- from 5 to 100 ms: a general pressure loss in the whole circuit around 80 bar,
- after 100 ms: a slower diphasic pressure decrease in the primary circuit.

We observe high velocity variations (fig. 5) in the primary circuit for the first 100 ms because of the high pressure gradients due to the break opening. Then the velocities vary slowlier while the circuit pressures come closer.

6.1 At the break

We observe at the break a pressure drop from 155 bar to around 70 bar for the first 5 ms after the rupture. When it gets up to the saturation pressure (86 bar at 300^{o}C), the water vaporizes. As the pressure gap between the reactor and outside is very high, the flow rate increases until the critical flow rate. The flow towards the downcomer changes direction (fig. 6). After an initial peak at 35 T/s, the total massic flow rate at the break stabilizes around 20 T/s. Almost 6 tons of water are lost for the first 200 ms, and 23 tons after 1 s.

6.2 In the broken loop

From the break ends, two acoustic waves propagate. The one coming from the reactor side end arrives at the reactor inlet in 5 ms. The other goes all over the loop from the pump side end and arrives at the reactor outlet in 45 ms. Between the break and the reactor inlet, the flow reverses. Whereas the break proximity becomes almost instantaneously diphasic, the steam generator and the reactor inlet remain monophasic until 700 ms because of the water poured out by the loops and the reactor.

6.3 In the reactor

A first acoustic wave coming from the reactor inlet propagates from the downcomer all along the reactor. It crosses the downcomer at 5 ms and the higher plenum at 25 ms. This wave causes a fluid velocity decreasing in the reactor. A second wave coming from the pump side end goes in the reactor from 45 ms; its influence on the fluid flow is rather low. Except in the top volume, there is no flow direction reversing in the reactor. The void fraction starts increasing after 100 ms in the core and the higher plenum and only after 200 ms in the downcomer and the lower plenum.

6.4 In the other loops

The first acoustic wave coming from the reactor inlet at 5 ms propagates all along the loops in the direction "pump towards steam generator". When this same wave has crossed the reactor at 25 ms, it propagates along the loops a second time in the opposite direction. The vaporization begins at about 100 ms. The flow remain in the same direction because the pumps are still going on.

7 Conclusion

The hydrodynamic loads due to a LOCA were computed successfully with the CASTEM-PLEXUS code, by means of an hydraulic model of the complete primary circuit and the reactor. The code deals with coupled computations of the acoustic transients and the fluid mass transfers. The work in progress concerns 3D calculations and FSI effects.

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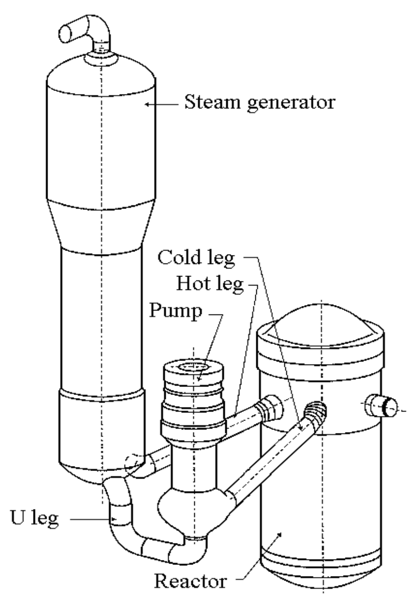

Figure 1: A primary circuit loop

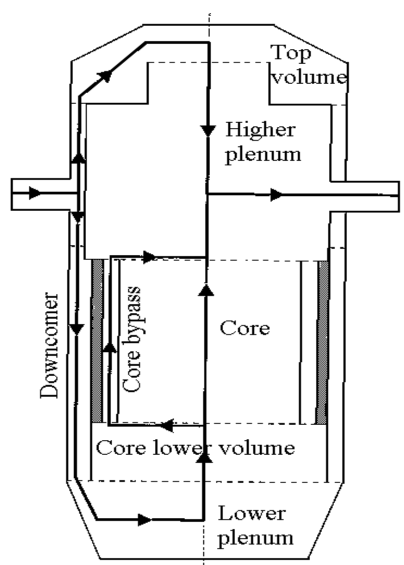

Figure 2: The pipe model for the reactor

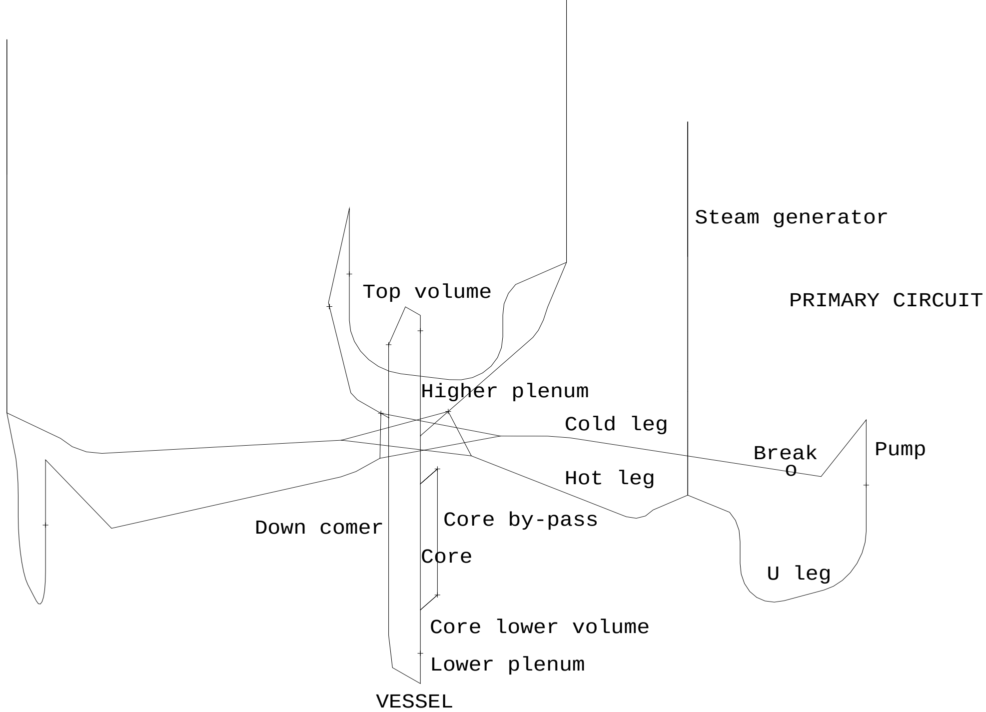

Figure 3: Pipe model of the PWR

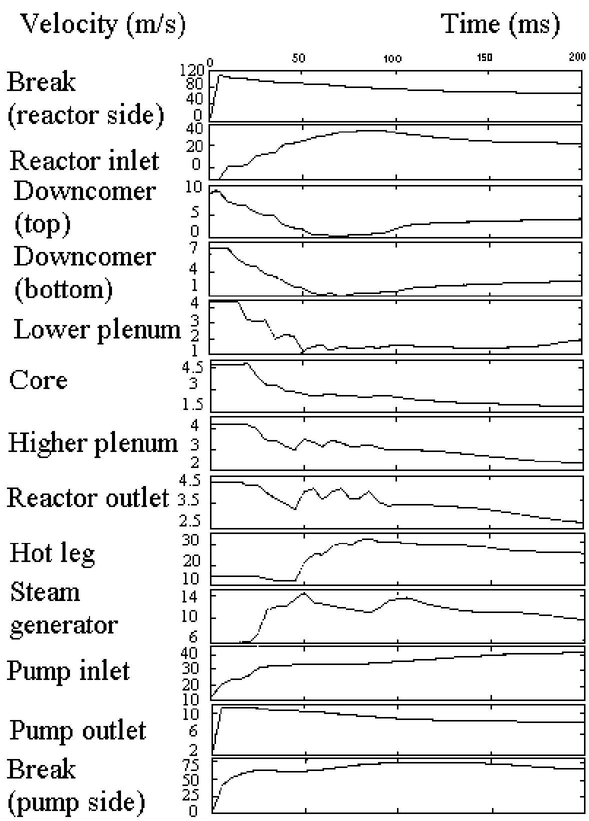

Figure 5: Velocities versus time in the reactor and the broken loop

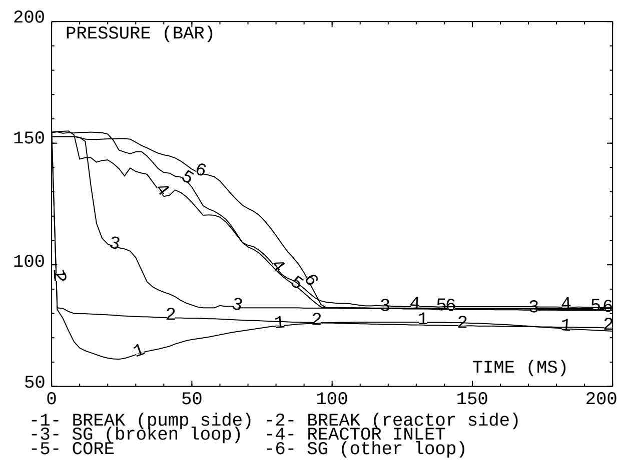

Figure 4: Pressures in the circuit

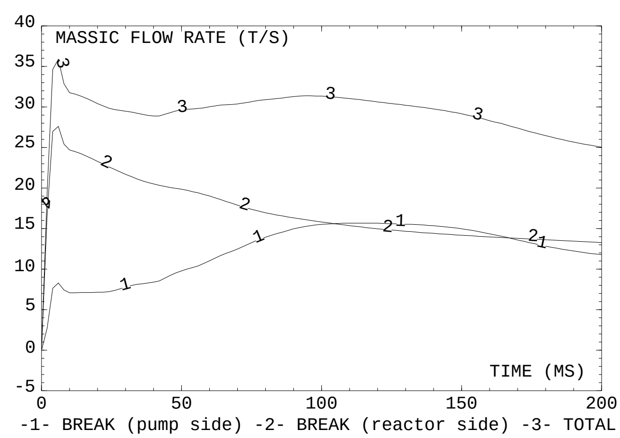

Figure 6: Massic flow rates at the break