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► **To cite this version:**

Serguei Potapov, Marie-France Robbe, François Téphany. Hydrodynamic consequences of a LOCA in a 4-loop PWR. European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2000), Sep 2000, Barcelona, Spain. cea-04177324

HAL Id: cea-04177324

<https://cea.hal.science/cea-04177324v1>

Submitted on 4 Aug 2023

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HYDRODYNAMIC CONSEQUENCES OF A LOCA IN A 4-LOOP PWR

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Key words: LOCA, Hydrodynamic loads, PWR, Two-phase flow, Nuclear reactor.

Abstract. *This paper presents a numerical simulation with CASTEM-PLEXUS fast dynamics code of the hydrodynamic behaviour of the pressurised primary piping system belonging to a 4-loop nuclear PWR under a sudden pipe break known as a Loss-Of-Coolant-Accident (LOCA). To calculate unsteady pressure and velocity fields a hydrodynamic model of the primary fluid was developed. The fluid behaviour in the whole piping is approximated by Euler equations with a homogeneous equilibrated two-phase flow model. In the broken zone a more precise Moody's non-equilibrated model is used taking into account the sliding between liquid and steam phases. Under an assumption of plane waves, a finite element discretization of all fluid volumes of the primary circuit is performed using pipe elements of CASTEM-PLEXUS code. An assumption of perfectly rigid structures is used which is justified because anti-whipping devices are used to limit displacements of the primary circuit piping. Using the above hydrodynamic model, the nominal flow rate in the undamaged circuit is first calculated. The stabilisation of nominal rate computation for main variables close to initial conditions proves the coherence of the numerical hydrodynamic model and allows using it for the LOCA computation. The nominal computation was carried out until 1000 ms of physical time. Then, a sudden break of a U-leg of one of the primary-circuit loops is simulated. It generates a strong decompression wave running through the circuit. A LOCA computation is performed for 500 ms more. The curves of evolution of main variables allow understanding the chronology of the blowdown from the rupture time.*

1 INTRODUCTION

The components of the primary circuit pipe system of Pressurised Water nuclear Reactors (PWR) are originally dimensioned in the way to support the consequences of a hypothetical pipe break (blowdown), known as Loss-Of-Coolant-Accident (LOCA) in the safety analysis. During first hundreds of milliseconds of LOCA, a depressurization wave propagates through the whole primary circuit. The passing of a strong pressure drop excites violently the piping and structural components, namely fuel assemblies and core structures. Consequently, the pressure distribution and its history must be assessed during the LOCA.

This paper presents a numerical simulation of the hydrodynamic behaviour of the pressurised primary piping system belonging to a 4-loop nuclear reactor under a sudden pipe break. For this purpose we use a general explicit fast dynamics code CASTEM-PLEXUS which has been developed by CEA-DMT since 1978^{1,2}. CASTEM-PLEXUS is devoted to simulations of fast transients problems (impacts, explosions, pipe circuits, hydrodynamics) as well as to the mechanical analysis of accidental situations involving fluids and structures with and without coupling. Different formulations of motion can be used : Lagrangian, Eulerian and ALE (Arbitrary Lagrangian Eulerian). Material and geometric non-linearities can be considered.

In this paper we first give a brief description of a hydrodynamic pipe model of the 4-loop primary circuit. Then, nominal rating calculations are presented to show the coherence of numerical model. Finally, LOCA calculations are exposed and their results are discussed.

2 HYDRODYNAMIC MODEL

To calculate time dependent pressure and velocity fields due to the pipe system break and a fast loss of coolant, a hydrodynamic model of the fluid contained in the Main Primary Circuit (MPC) was developed³. In this model we suppose that all structural components of the MPC are perfectly rigid and fixed during the blowdown because several anti-whipping devices are used to limit displacements of the MPC piping. Furthermore, we assume that the fluid flow is mono-directional. Thus, the hydraulic circuit containing four symmetrically disposed loops and a reactor (Fig. 1) is represented with a pipe model respecting 3D component volumes (piping, steam generators, pumps, reactor) and average distances covered by the coolant water (Fig. 2). Using pipe elements of CASTEM-PLEXUS code a finite element discretization of all fluid volumes of the MPC is performed.

The hydraulic effects of flow restrictions due to grids, perforated plates, cross section changes are taken into account in the model by local pressure losses⁴. Distributed pressure losses are applied to different parts of the model to represent flow-piping friction phenomenon. The pressure loss coefficients established for normal operation are used also in the LOCA calculation. Other hydraulic peculiarities such as multi-pipe links, pumps, the break are taken into account by additional constitutive laws and boundary conditions. Namely, BIFURCATION elements of CASTEM-PLEXUS are used to join two or more pipes with different diameters, CL1D elements for local boundary conditions (local pressure drops, pumps, break). Special WATER and FRICTION constitutive laws are used respectively to de-

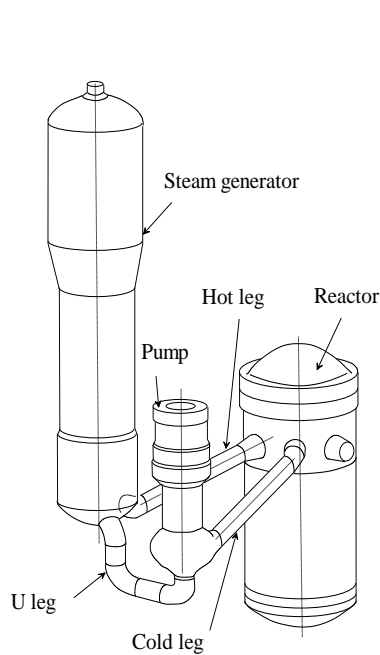


Figure 1 : A primary circuit loop

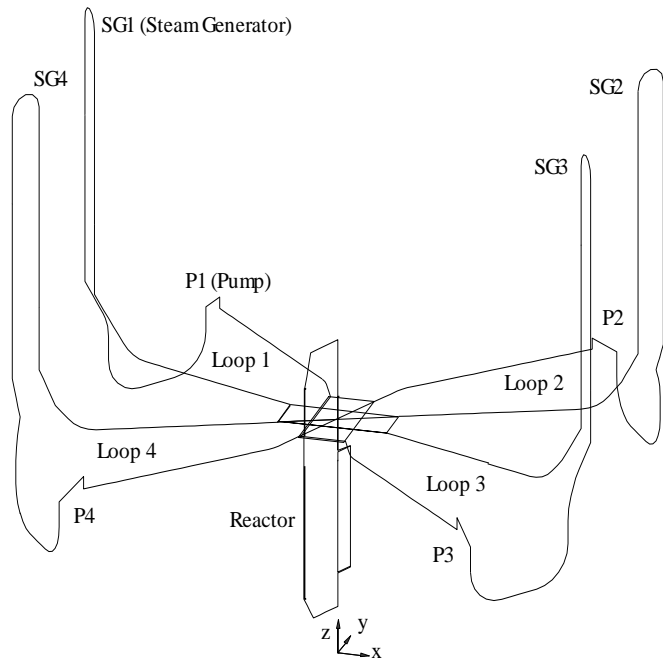


Figure 2 : Pipe model of 4-loop primary circuit

scribe the coolant fluid behaviour and distributed pressure losses.

The behaviour of PWR coolant fluid is described by Euler equations with a homogeneous equilibrated two-phase flow model⁵ (same pressure, same temperature, same velocity for steam and liquid phases). From the mixture density and enthalpy within each finite element of the model, other thermal hydraulic parameters such as pressure, temperature, void fraction are obtained from steam tables⁶. Since the depressurization process in the MPC is very dependent on the thermal hydraulic conditions at the opening, we use in the broken zone a more precise Moody's non-equilibrated flow model⁷ which allows us to take into account the sliding between liquid and steam phases.

3 NOMINAL CALCULATION

Using the above hydrodynamic model, the normal operation regime in the undamaged circuit is first simulated. The calculations are initialised with nominal flow rate values given by PWR specifications at different parts of MPC. The initial pressure is about 15.5 MPa. The average temperature of the circuit is equal to 311° C. The corresponding values of water density and sound speed are respectively 702 kg/m³ and 950 m/s. The nominal computation was carried out until 1000 ms of physical time.

Figures 3 shows the evolution of volumic flow and pressure fields in some points of MPC during the nominal simulation. Strong oscillations observed on different curves at the beginning of calculation are due to locally non-equilibrated initialisation of main variables. These oscillations are rapidly dumped by pressure losses, and the numerical solution

converges to the normal operation regime values. This artificial procedure of dynamic relaxation allows us to obtain the stationary solution using an explicit numerical scheme of CASTEM-PLEXUS code.

The stabilisation of the nominal rating computations for pressures, volumic flows and pump working conditions close to the initial conditions proves the coherence of the developed numerical hydrodynamic model and allows us to use it for the LOCA computation.

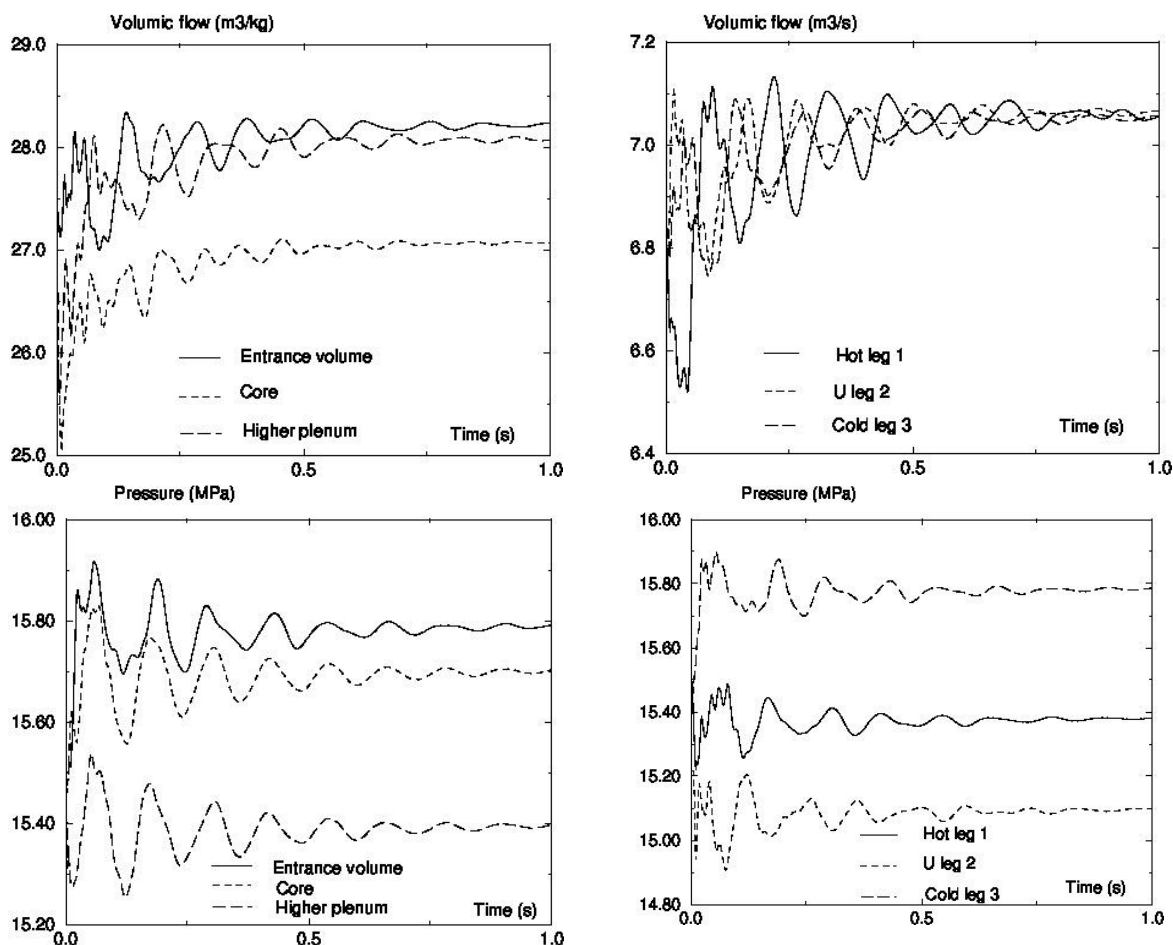


Figure 3 : Nominal calculation

4 LOCA CALCULATION

Previous CASTEM-PLEXUS simulations of LOCA regime for the 3-loop PWR⁸ were carried out in assumption that the initial conditions imposed to the MPC at the beginning of LOCA computation were sufficiently close to the real stationary solution corresponding to the nominal operation conditions. A first computation in nominal conditions was necessary to verify the model consistency (no mass loss, correct pump working, correct initialisations) and

to check that the computations converged around the initial nominal conditions. Then a second computation was carried out from the same initial conditions as in the nominal regime computation. There was no possibility to use the final solution of the nominal regime simulation to start the LOCA calculation. This way to cope with the problem had two drawbacks. The hydrodynamic models used in nominal and accidental simulations were slightly different : the first model was “undamaged” whereas the second one was “broken” and contained additional elements modelling the piping break. Besides, the initialisation of the LOCA computation was not very precise because the initial conditions were imposed locally by the user and there was no global agreement between the local data.

Since the 3-loop PWR simulations, the modelling capacities of CASTEM-PLEXUS have been improved. In this paper we perform both nominal and LOCA calculations with the same hydrodynamic model. Actually, it is now possible to introduce the break element into undamaged circuit and activate (“open”) it at a specified time during the simulation.

Using this new functionality, the nominal computation of 4-loop PWR was first carried out with an undamaged circuit with a closed break element. Then, a sudden break (in 1 ms) of the piping at the outlet of one of steam generators (in U-branch) is simulated by opening the break element (Fig. 4). This opening generates two strong decompression waves running through the circuit from the ruptured zone. A LOCA computation is performed for 500 ms more of physical time.

The results are scrutinised thanks to local curves showing the evolution of main variables versus time at different points of circuit (Fig. 5, 6). These curves allow the understanding of the blowdown wave propagation chronology from the rupture time. The analysis deals with pressures, velocities, densities and void fractions in the complete circuit as well as with local pressure differences in the reactor.

From the break extremities of the U-branch two depressurization waves propagate in opposite directions through the whole primary circuit. Both waves superimpose at the higher plenum and in the steam generators of the non broken loops. The wave passing is characterised by a pressure fall until the saturation pressure at 9.5 MPa. During the propagation through the circuit, the spatial profile of these waves spreads progressively due to the expansion nature of rarefaction waves. Starting from 1 ms which corresponds to the time of circuit opening, their profiles spread on 100 ms at inlet nozzles of the reactor. The wave passing causes the liquid water vaporisation and the flow increase until the diphasic critical flow rate, about 220 m³/s from 300 ms after the break. After the first wave passing a slower diphasic pressure decrease is observed due to progressive emptying of the primary circuit.

In the broken loop the flow increases on the hot side near the break point from 7 m³/s until 20 m³/s around 80 ms after the rupture, then it progressively decreases (see curves marked on figures with number 1). In the counterpart, in the cold side of the break the flow rapidly slows down, stops and changes direction to discharge through the opening (Fig. 5).

Pressure and density gradients set up between the break and the reactor nozzles. At the end of the simulation, the pressure varies from 3.5 MPa at the break to 9.5 MPa next to the reactor. On the same way, the water near the reactor nozzles only starts to become diphasic 100 ms after the rupture whereas it is almost immediately diphasic at the break.

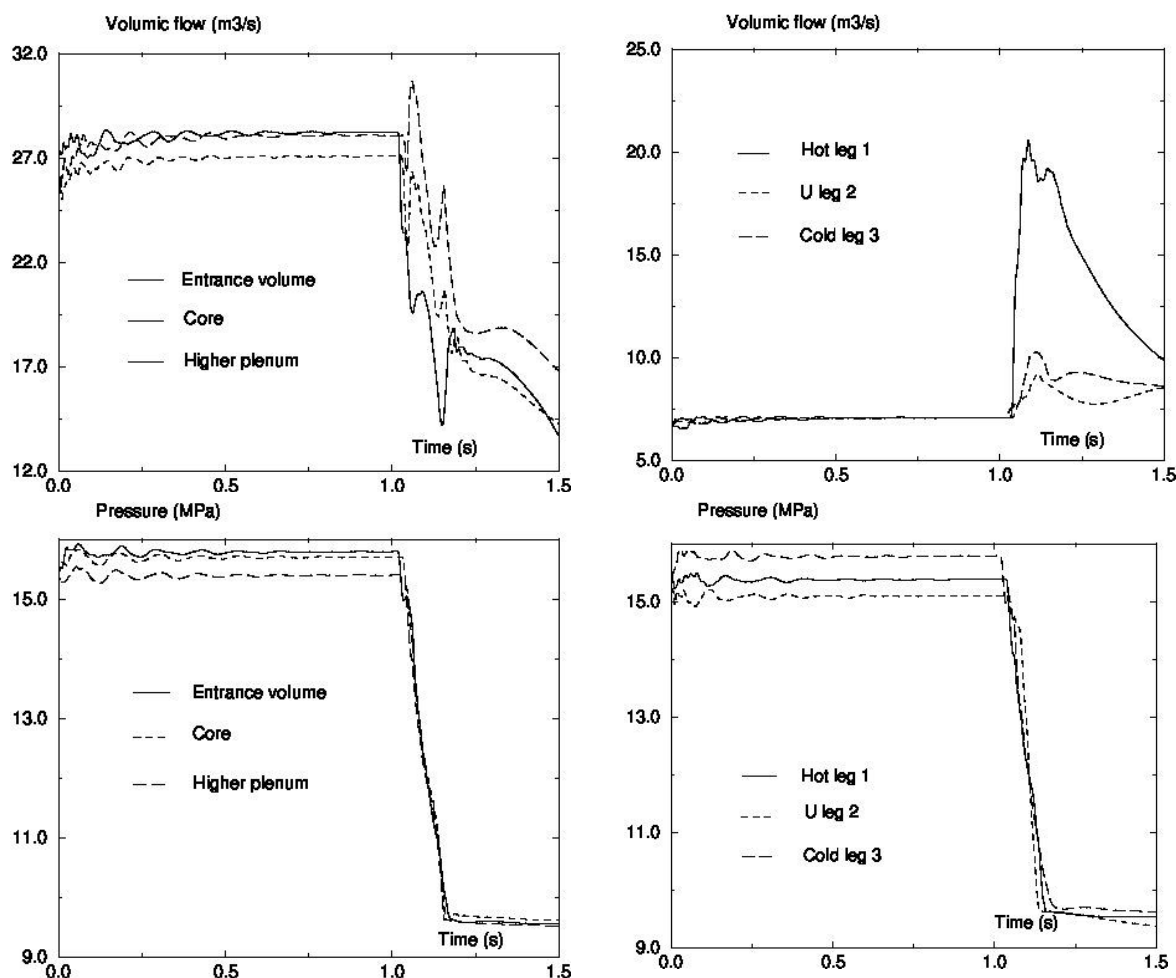


Figure 4 : Transition phase

The three non-broken loops (indexed by number 2 on figures) behave the same during the LOCA because the model does not allow 3D dissymmetry. Actually, the four tubes which model the inlet (outlet) reactor nozzles are interconnected in our model.

In the non-broken loops the fluid flow continues in the same direction. However, the water speed decreases on the hot side of the loops whereas it increases on the cold side. The change between both behaviours occurs more or less half-way the loops (that means in the steam generators). At the reactor outlet, the water is attracted by the broken loop rather than the hot legs of the non-broken loops because of the higher pressure gap with the break. On the contrary, the pumps push more in the cold legs to feed the cold leg of the broken loop whose flow is oriented outwards. From 150 ms after the rupture, the pressure falls around 9.5 MPa in the whole non-broken loops. The density decreases much more in the U legs than near the reactor : the reactor feeds the hot legs but less than at nominal rating, the pumps empty the middle of the loops to feed the broken loop cold leg and the reactor entrance volume.

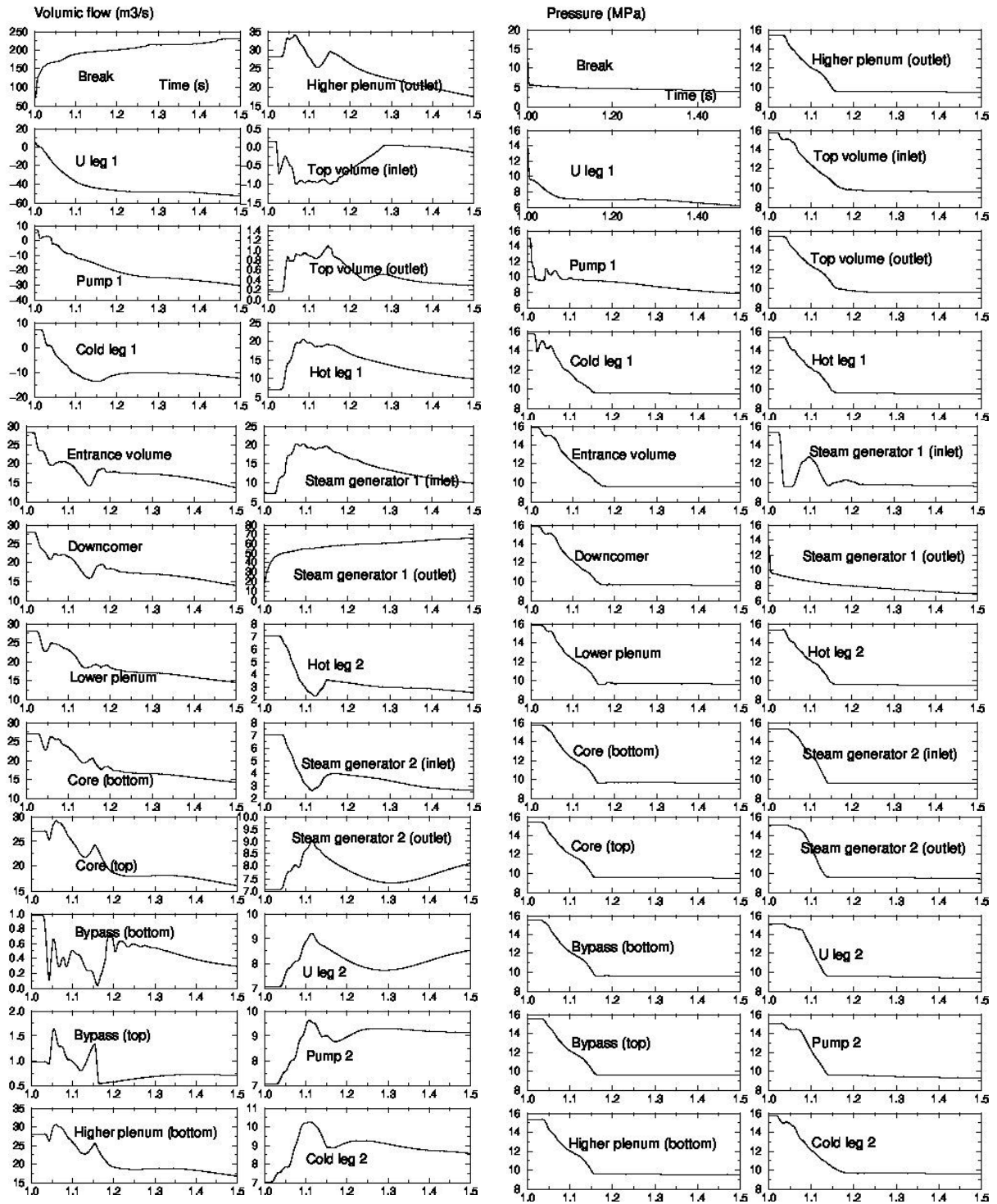


Figure 5 : LOCA simulation, volumic flow and pressure evolution

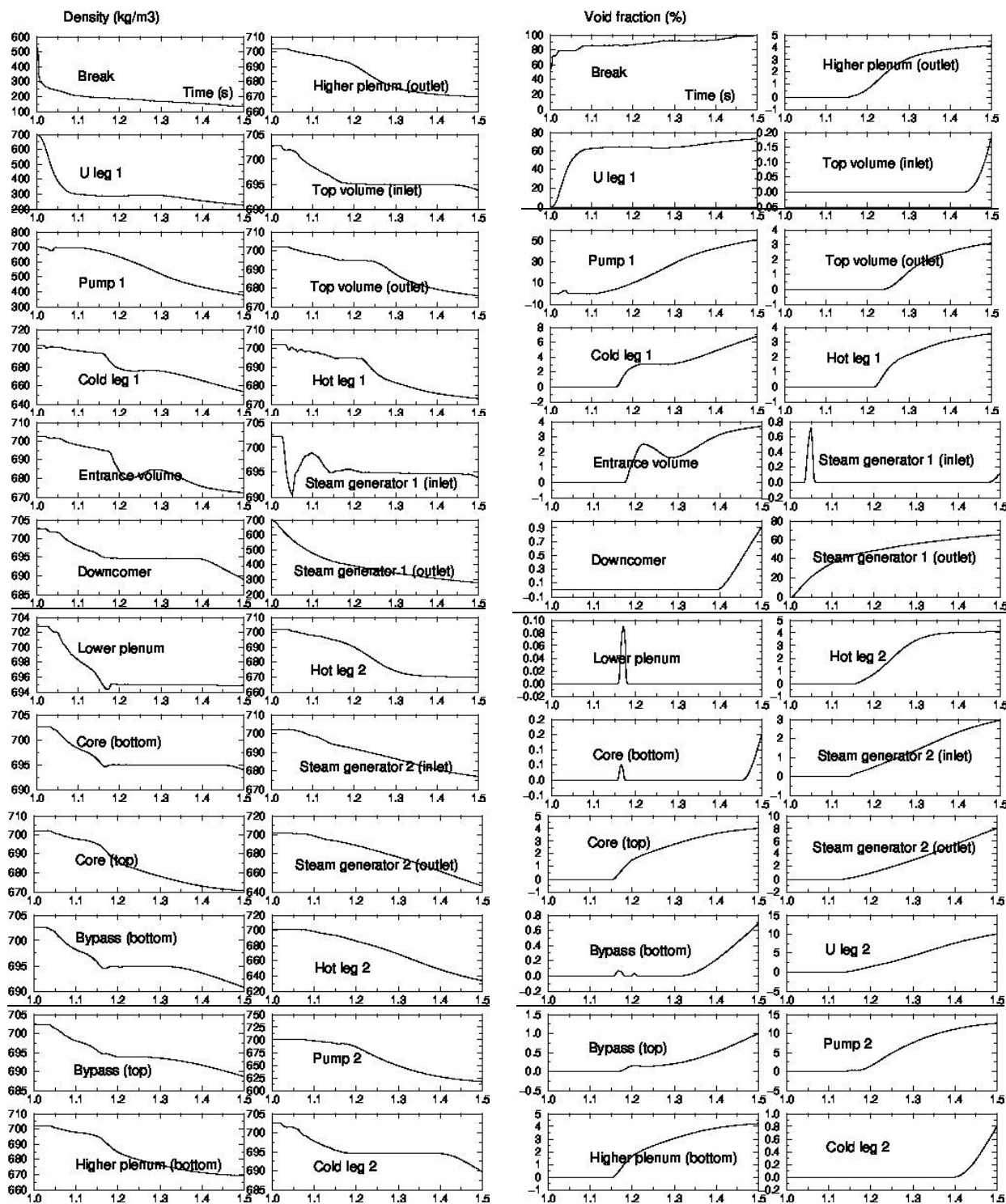


Figure 6 : LOCA simulation, density and void fraction evolution

As in the non-broken loops, there are two characteristic zones of flow variations in the reactor. The flow decreases in the reactor volumes near the reactor inlet nozzles (entrance volume, down-comer, lower plenum, bottom of the core and the core bypass, inlet of the top volume). Because of the 1D representation of the circuit, the four loops and the reactor entrance volume inlet are directly interconnected. Thus the non-broken loops directly feed the broken loop rather than the reactor. In the rest of the reactor, the flow starts increasing : the reactor empties to feed the broken loop hot leg. The flow decreases later.

The pressure distribution is more or less the same in the whole reactor, about 9.5 MPa after 150 ms. A finer analysis would show pressure gaps between the different reactor zones.

The density goes down in the whole reactor but less than in the loops. The density decreases more in the volumes close to loops connection than in the reactor centre.

The void fraction climbs up very quickly near the opening. It reaches 80% about 20 ms after the break then continues to increase slowly and reaches 100% at about 500 ms of LOCA calculation. High quantities of steam remain localised in the neighbourhood of the break, namely in the broken U-leg (60% after 50 ms) and at the outlet of the nearest steam generator. Nevertheless, due to the initial flow little quantities of steam are transported through the circuit, and at about 400 ms after the break all reactor volumes contain from 0.01% to 4% of steam. At the end of the LOCA simulation the whole primary circuit is diphasic including non-broken loops.

The figure 7 shows the progressive emptying of the MPC by the opening. Although the primary fluid speed is very high at the break - of about 90 m/s compared with 14 m/s in nominal operation - the outgoing flow is limited by the diphasic critical flow rate. The water loss at the break reaches 17.5 tons at the end of the LOCA calculation.

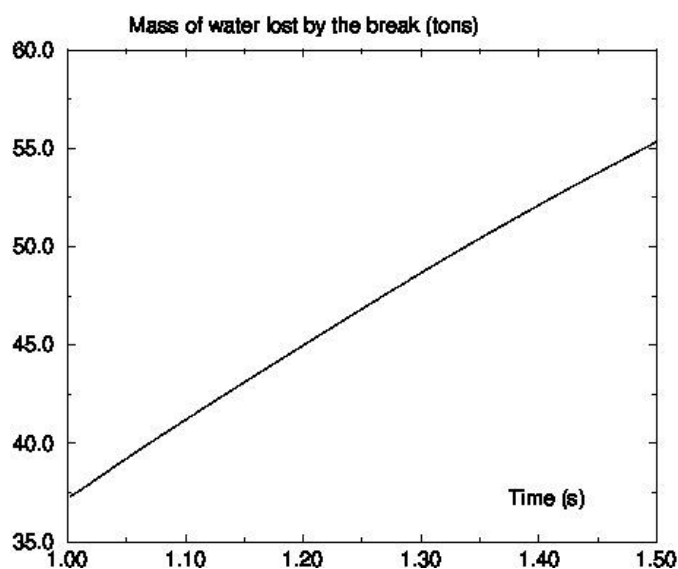


Figure 7 : Water mass loss at the break

5 CONCLUSIONS

In this paper, we have presented numerical simulation with fast dynamics code CASTEM-PLEXUS of the transient hydrodynamic behaviour of the 4-loop pressurised primary piping system subjected to LOCA. In this simulation a hydrodynamic pipe model of the whole primary circuit fluid has been used. The fluid behaviour is described using a homogenous two-phase flow law in the whole circuit, except at the break where a Moody's non-equilibrated flow model is used.

In order to verify a coherence of the hydrodynamic model, the nominal operation calculation with undamaged circuit was first performed. Then, a sudden break of a U-branch of one of the primary loops was simulated. Started from stabilised nominal rate values, a LOCA computation was performed for 500 ms more of physical time.

The results are scrutinised thanks to local curves showing the evolution of main variables versus time at different points of circuit. The analysis deals with pressures, velocities, densities and void fractions in the complete circuit.

The calculated transient pressure field was next applied to a piping structural model of the 4-loop PWR to compute its mechanical unsteady response and verify that there is no loss of integrity in other parts of the primary circuit⁹.

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