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A steam explosion assessment by thermalhydraulic and mechanical linked computations

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Abstract

The mechanical consequences on a PWR lower plenum vessel are evaluated by initializing fast dynamic calculations of steam explosion with local data issued from a thermal-hydraulic code.

1 Introduction

Steam explosion is still considered as a potential risk in the hypothesis of a severe accident occuring in a PWR nuclear power plant. The loss of coolant provokes the degradation of the core and its melting. By falling down in the water remaining in the lower plenum, the corium transfers fastly its energy to the water which vaporizes.

Like [1], we suppose that steam explosion happens in two steps.

• The first step is the premixing of the corium with the water. The jet of corium fragments under the action of hydrodynamic forces in small drops whose characteristic size is 1 cm. The thermal exchanges are limited by the presence of a vapor film surrounding the corium drops.

• The second step is the explosion itself. The destabilization of the vapor film or a local interaction causes a fine fragmentation of the 1 cm drops into 100 μm droplets. This fragmentation strongly increases the corium thermal exchange surface and allows the explosive vaporization of the water due to the energy transfers between corium and water. The second step has to be triggered off by a disturbing phenomenon.

2 Steam explosion assessments

Up to now, the thermalhydraulic softwares have only described the premixing phase and have been unable to perform calculations of the explosion. In order to evaluate the mechanical consequences of the explosion on the lower plenum vessel, a method was needed to quantify the energy delivered by the explosion with the results of the premixing phase.

Theofanous [2] and Turland [3] considered that the premixing phase provided an available corium mass, from which they calculated an explosion energy, applying an explosion yield. Even if the premixing phase was carried out with a local approach, the explosion was calculated with a semi-global method. This method is unprecise because it does not take into account the spatial distribution of the corium (and then of the energy).

In France, a method has been proposed to represent the corium interacting during the explosion as an energy injection into the water, without modelling the corium.

Screening calculations [4] were performed up to 1995 with a fast dynamic finite element code. They were aimed at evaluating the mechanical consequences of the explosion on the vessel, using simplified loads to simulate the energy transfers between corium and water (rough corium locations, several methods to inject a parametric global amount of energy with various shapes into the water, two constitutive water laws).

These calculations have shown that, among the different parameters studied, only two of them had a significant influence on the vessel response. These parameters were the corium location in the lower plenum water before the explosion took place, and the energy transferred from the corium to the water, during the fine fragmentation of the drops.

The current thermalhydraulic codes are now able to describe correctly the premixing phase. As we know accurately the location and the thermodynamic characteristics of the corium and the water at the end of the premixing phase, we can calculate more precisely the explosion mechanical effects on the vessel by injecting with a local distribution the available corium energy in the remaining water. The main difference with other approaches is that the mechanical effects of the explosion are dealt with local data.

3 Description of the linkage method

The thermalhydraulic code MC3D and the general fast dynamic mechanics code CASTEM-PLEXUS are available for steam explosion studies.

MC3D [5] is a transient three-dimensional thermalhydraulic software, dealing with the premixing of the corium falling down in the water. Knowing the total mass of the initial corium, the amount of the remaining water in the lower plenum, and the initial conditions of pressure and temperatures, the whole phase of premixing can be evaluated versus time. MC3D provides all the thermodynamic characteristics of corium, steam and water in a structured grid. Among them, we only use the corium presence fraction and the corium temperature.

CASTEM-PLEXUS [6] [7] is a general software of dynamic mechanical calculations of structures in one, two or three dimensions. Structures may be either solids or fluids, with a possibility of coupling. The fields dealt with are impacts, explosions, circuits, hydrodynamics.

	MC3D	CASTEM-PLEXUS
Method	finite volume	finite element
Mesh	structured (rectangles)	non-structured (quadrangles)
Problem representation	axisymmetric	axisymmetric
Water model	triphasic model: 3 continuity equations, 3 momentum equations, 3 energy equations (water, steam, corium)	homogeneous model: same temperature, same pressure, same velocity for liquid water and steam
Corium model		internal source of energy in water

In CASTEM-PLEXUS, the corium presence is described as an energy injection. Liquid water and steam are treated as a unique material.

The energy injection describing the corium presence is calculated as following:

$$P(t) = \frac{m_{water}(t)}{m_{water}(t=0)}\, m_{corium}\; E_m\; f(t)$$

where m_{water} is the water mass, m_{corium} the corium mass, E_m the available energy per kg of corium to be injected, $f(t)$ a normalized function representing the shape of the injection versus time.

If the water contained in a cell was initially liquid and has vaporized, the water ratio prevents from injecting energy in the vapor zone. The corium mass is kept constant in each cell during the calculation. The normalized function enables the injection energy to be spread out versus time, to represent better the phenomenon. Any shape for this function can be chosen by the user.

The available energy E_m is given by:

$$E_m = \eta\; [H_{liquidus} +\; c_p\,(T_{corium} - T_{liquidus})] \quad \text{if } T_{corium} \geq T_{liquidus}$$

where η is the explosion efficiency, $H_{liquidus}$ the "liquidus" enthalpy of the corium, c_p the heat capacity of the liquid corium, T_{corium} the corium temperature and $T_{liquidus}$ the "liquidus" temperature. This formula is classical for a pure body. Because of the uncertainties on the corium composition, it was difficult to use a more precise law.

We have assumed that there was no injected energy if the corium temperature was below the "liquidus" temperature. That means that, below this temperature, the solid fraction of the corium constitutes a crust which isolates the liquid corium from the coolant. In those conditions, the fine fragmentation cannot occur if the corium is solid. As the exchange surface is small, compared with fine fragments, the energy transferred from the large drops to the water is assumed as negligible.

The explosion efficiency renders two facts:

- In a real case, only a part of the corium in the water takes effectively part in the explosion.
- The mixture is not only composed of fine droplets and it is not a perfect thermodynamic mixture between phases.

Even if our method reduces the number of parameters, and specially regarding the corium and energy injection location, some parameters remain because no accurate information exists on these subjects.

As MC3D uses a structured mesh and CASTEM-PLEXUS a non-structured one, a MC3D cell does not coincide with a CASTEM-PLEXUS one. So the data cannot be directly transferred from one code to the other. For a given CASTEM-PLEXUS cell, the contribution of the MC3D cells is obtained by a superposition of both cells. When there is a common volume, the variables calculated by MC3D are transmitted to CASTEM-PLEXUS, balanced by their common volume (cf figure 1).

From the two variables (corium presence fraction and corium temperature) provided by MC3D, the local energy is injected in the water during the CASTEM-PLEXUS computations. CASTEM-PLEXUS calculates, in the lower plenum vessel, the evolution of the pressure, water temperature and steam quality due to the vaporization. Thanks to a fluid-structure coupling, the code determines the stresses and strains in the vessel. It also provides the internal energy of the water and the shell, the kinetic energy of the water and the mechanical energy received by the shell.

4 Application

The chosen scenario (cf figures 2 and 3) is an in-vessel steam explosion resulting from a large central core degradation, like in [4]. It is assumed that 100 tons of molten core, with an initial temperature of 3073 K, are falling down in the lower plenum water. The pressure in the vessel is 50 bar and the water is initially saturated. The energy injection zone only contains liquid water. The water level is 2 m above the bottom, and the central hole diameter, from where is arriving the corium, is 1.2 m. The height of the vapor blanket above the water is 0.85 m.

At the end of the premixing phase, a trigger is necessary to start the fine fragmentation. Such an information cannot be calculated by a code, and must be determined by an expert judgement. The instant of the trigger is chosen as the instant of the first contact between the corium and the bottom of the reactor pressure vessel. This corresponds to the situation where the amount of corium in the bath is maximum with a large dispersion and no accumulation.

Figures 4 to 7 present some of the linkage data viewed on the MC3D mesh and on the CASTEM-PLEXUS mesh. Figures 8 to 11 represent the pressure during the explosion. Figures 12 to 15 show the void fraction. Figures 16 and 17 represent the deformed shape of the shell and the plastic strains versus time.

5 Prospects

The initial spatial balance of steam and water in the injection zone is evaluated by MC3D and can be taken into account by CASTEM-PLEXUS. This will probably further reduce the conservatism of the present calculations.

Up to now, calculations are performed assuming that the injection begins simultaneously in the whole corium zone. By simulating a propagation wave for the beginning of the injection from a trigger cell to the whole lower plenum, the conservatism can also be reduced.

To appreciate the benefit of coupled calculations in relation to our present linked calculations, it was necessary to assess the influence of the mechanics on the thermalhydraulics. So two explosion calculations were carried out with the same initial conditions and the vessel represented either by a rigid shell or by an elastoplastic one assuming the fluid-structure coupling. The overpressure observed along the rigid shell was weak enough to consider that coupled calculations might not send significant improvements.

A future application could be to deal at the same time with the coupled problems of slug impact and steam explosion. In that case, the reactor would be completely modelled and the slug would be a heavy fluid.

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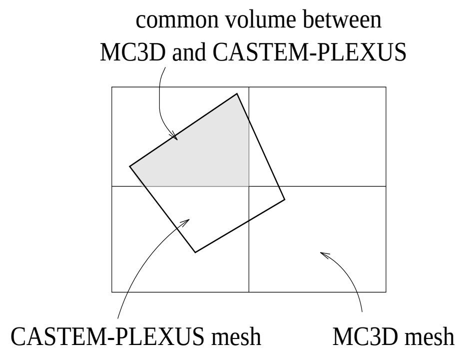

Figure 1: Superposition of the meshes

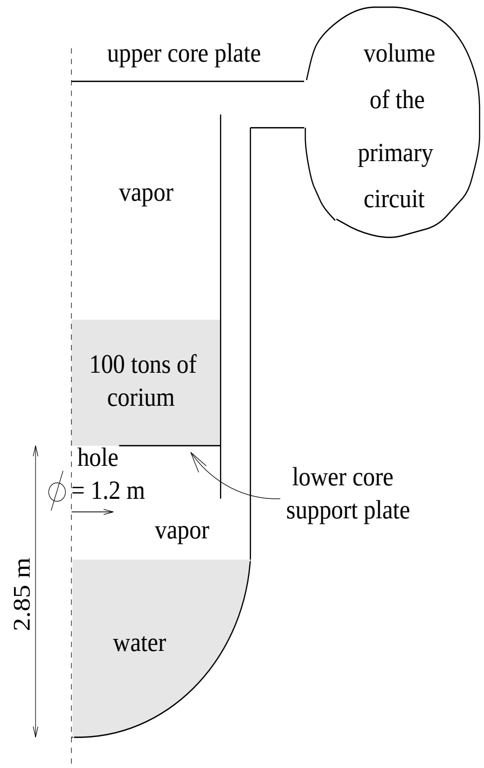

Figure 2: Geometry and boundary conditions of MC3D

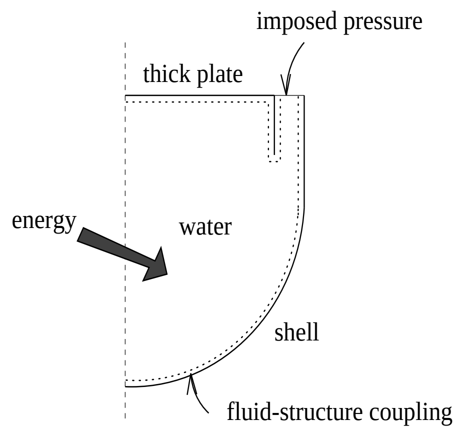

Figure 3: Geometry and boundary conditions of CASTEM-PLEXUS

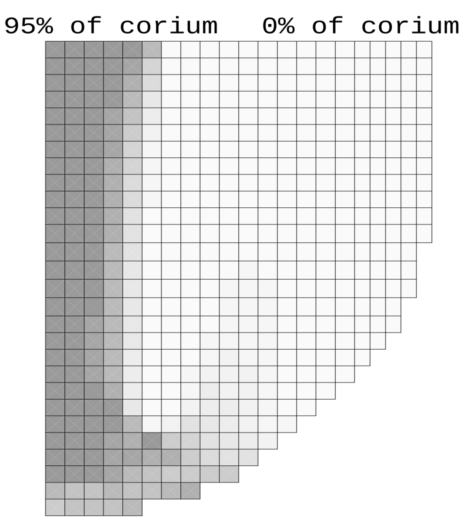

Figure 4: Presence fraction of the corium with MC3D

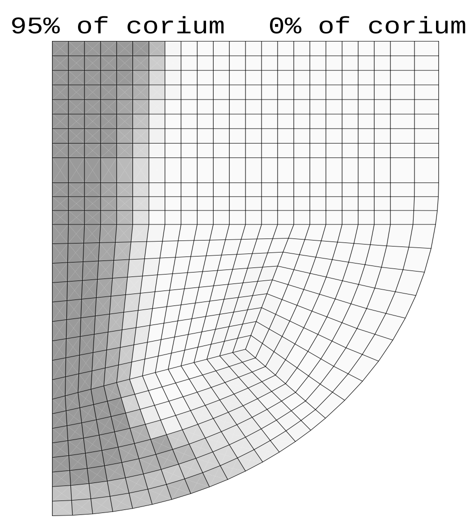

Figure 5: Presence fraction of the corium with CASTEM-PLEXUS

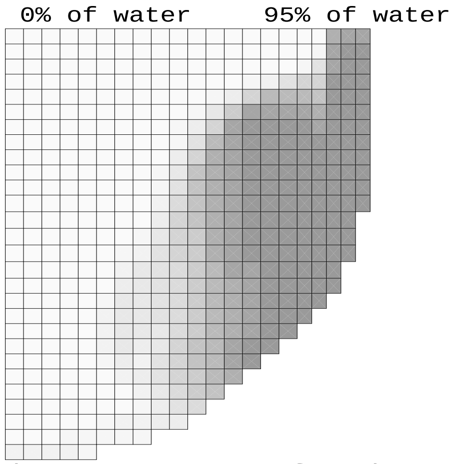

Figure 6: Presence fraction of the liquid water with MC3D

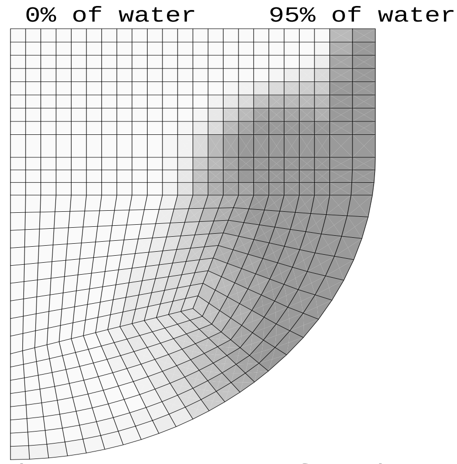

Figure 7: Presence fraction of the liquid water with CASTEM-PLEXUS

Figure 8: Pressure - Time = 0.6 ms

Figure 9: Pressure - Time = 1.3 ms

Figure 10: Pressure - Time = 2 ms

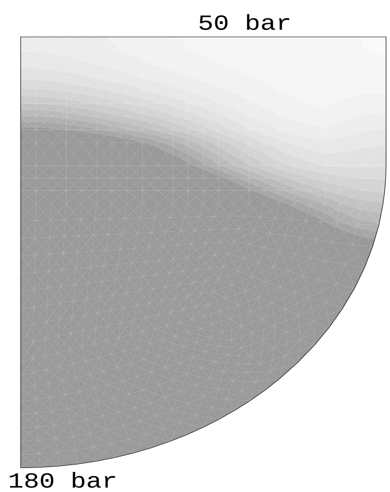

Figure 11: Pressure - Time = 2.7 ms

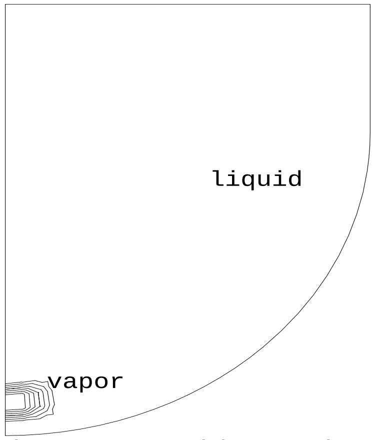

Figure 12: Void Fraction
Time = 1.3 ms

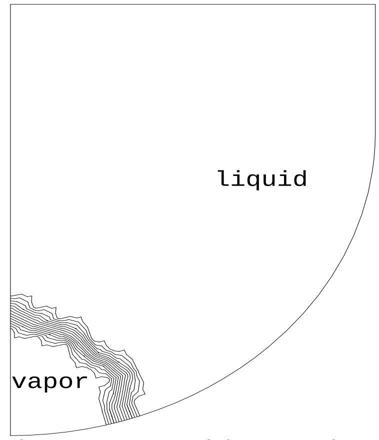

Figure 13: Void Fraction
Time = 2.1 ms

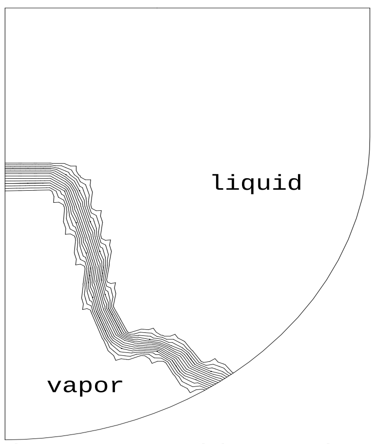

Figure 14: Void Fraction
Time = 4 ms

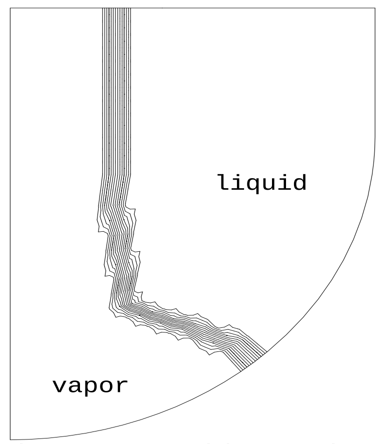

Figure 15: Void Fraction
Time = 7.2 ms

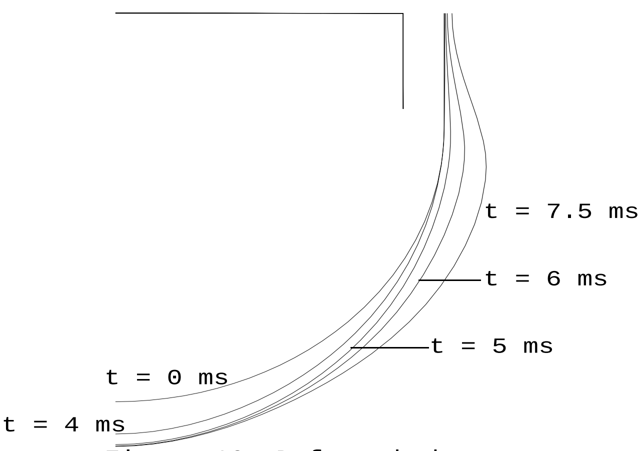

Figure 16: Deformed shape
of the shell
Amplification * 5

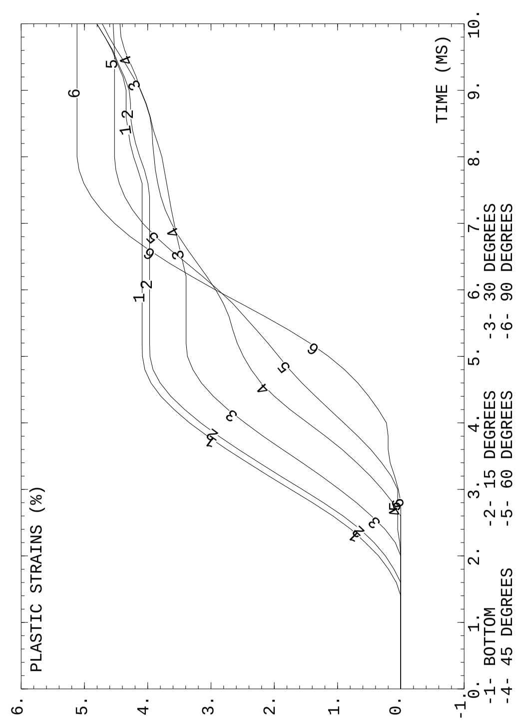

FIGURE 17: PLASTIC STRAINS ALONG THE SHELL, FROM THE BOTTOM