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**Estimation of the mechanical consequences of a steam explosion with a local approach - Thermalhydraulic and mechanical linked computations**

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**Abstract**

In the frame of the PWR severe accident studies, hypothetical energetic steam explosions are considered if large amounts of molten corium fall into the reactor lower plenum. The mechanical consequences of an in-vessel steam explosion on a PWR lower plenum vessel are correlated to the explosion itself and to the whole premixing phase preceding the explosion. Therefore, taking into account precisely and locally the initial conditions of the explosion improves greatly the precision of the evaluations of the mechanical consequences of the explosion on the reactor pressure vessel.

As the french thermalhydraulic code MC3D is able to provide reliable assessments of the fragmentation of a corium jet issued from the core melting and as the french general fast dynamics code CASTEM-PLEXUS can perform computations of the steam explosion and of the vessel response, it was undertaken to initialize the steam explosion calculations of CASTEM-PLEXUS from the local data of the premixing phase computed by MC3D.

This paper presents the method used to link both codes. The main characteristics of the codes and of the linkage method are analyzed. An application concerning the computation of an in-vessel steam explosion resulting from a large central core degradation is also described.

## **1 Introduction**

Since the Three Mile Island accident (Libmann, 1996) on March 1979, steam explosion has been considered as a potential risk in the hypothesis of a severe accident occurring in a PWR nuclear power plant because it can lead to an early and massive containment failure, also called alpha-failure.

The subject is still broadly and wordly studied (Robbe<sup>a</sup>, 2000) (Robbe<sup>b</sup>, 2000) because of the increasing emphasis on the accident management in the existing nuclear plants and in the new designs of PWR (Van Goethem, 1997) (Van Goethem, 1999). The investigation is also motivated by the desire to understand better the phenomenon in order to estimate the safety margins.

A loss of coolant in the reactor may cause a degradation of the core and its melting. By falling down in the water remaining in the lower plenum, the hot corium transfers fastly its energy to the cold water which vaporizes. This phenomenon is called a vapor explosion.

Like (Berthoud, 1988) (Berthoud, 1994), 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 large drops whose characteristic size is 1 cm. The thermal exchanges are limited by the presence of a vapor film surrounding the corium drops. The drops are dispersed in the water by the steam generation.
- The second step is the explosion itself. The destabilization of the vapor film increases locally the thermal exchanges and thus the steaming. The movements of water and steam succeed in fragmenting locally the 1 cm corium drops into 100  $\mu\text{m}$  droplets. In turn, this fragmentation strongly increases the corium thermal exchange surface. As the energy transfers are much higher between liquid water and corium than between steam and corium, the corium fragmentation and the direct contact between water and corium cause the explosive vaporization of water. Then the propagation of the explosive wave fragments the corium drops in the vicinity, what allows the progression and the escalation of the explosion. This second step may be spontaneous or triggered off by a disturbing phenomenon.

The mechanical consequences of a hypothetical steam explosion are the possible failure of the reactor lower head or the acceleration of an upward-directed missile made of the intact part of the core. This missile may crush the upper internal structures, impact and maybe fail the upper head and then hit the containment (Krieg, 1995) (Jacobs<sup>a</sup>, 1993) (Robbe<sup>c</sup>, 2000).

From 1987, the CEA-Saclay and the CEA-Grenoble have been put in charge of the french investigation on steam explosion by the IPSN (Institute for Nuclear Protection and Safety). The CEA-Grenoble, specialized in the thermohydraulic studies, focused its work on the local understanding of the fragmentation and the dispersion of the corium jet into the water pool. The CEA-Saclay, known for its knowledge about mechanical behaviour of structures, dedicated to the evaluation of the reactor resistance to the explosion.

This paper is devoted to the presentation of a method, developed by both laboratories of the CEA, to assess the steam explosion consequences on the vessel lower head with a local approach. After a brief reflection about the classical methods in progress, the method adopted by both laboratories is described and an application on a case of in-vessel steam explosion is presented. According to the present evolution of the codes, future projects are evoked.

## 2 History of the methods used for assessing steam explosion

Steam explosion has been studied since the severe accident of Three Mile Island in 1979. Until 1987, the phenomenon was roughly described by global energetics consideration and rough analytical calculations. Theofanous summarized the knowledge at the time.

The studies were separated into four parts:

- a probabilistic approach considering global energies to estimate the possible failure of the reactor lower head, of the upper head and of the containment (Theofanous, 1987),
- the first results relative to the premixing of the corium within the water (Abolfadl, 1987),
- steam explosion with its expansion through the lower plenum and the possible propulsion of an upward-directed missile (Amarasooriya, 1987),
- impact of a slug on the containment after it crushed and failed all the internal structures and the reactor upper head (Lucas, 1987).

For the evaluation of the consequences of the steam explosion, Theofanous considered that the premixing phase provided an available corium mass, from which he 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 was unprecise

because it did not take into account the spatial distribution of the corium (and then of the energy).

Nevertheless, this synthesis is always considered as a master piece of the research about steam explosion and the current investigation is still compared and making reference to the work of Theofanous.

In France, the first research program concerning steam explosion started around 1987. The IPSN asked the CEA to evaluate the risk brought upon the reactor safety and the vessel possible ruin. From this time, a broad research program was undertaken. It has been based on the main steps defined by Theofanous and its principal hypotheses and results were taken into account at the beginning.

On the one hand, the CEA-Saclay tried to answer quickly to the problem of the nuclear safety by dealing with the possible mechanical consequences of a steam explosion on the reactor vessel. Analytical conservative calculations were realised with simplified laws to represent the pressure peak due to a global steam explosion hitting simultaneously the whole reactor lower head (Combescure, 1995) (Lepareux, 1996).

In parallel, computations (Robbe, 1997) (Robbe<sup>d</sup>, 2000) were carried out with the general fast dynamics code CASTEM-PLEXUS, developed by the CEA-Saclay. This computations aimed at evaluating the mechanical consequences of the explosion on the vessel, using simplified loads to simulate the energy transfers between corium and water. In particular, a method was proposed to represent the corium interacting during the explosion as an energy injection into the water, without modelling the corium (Cénérino, 1996).

Sensibility studies were carried out to understand the influence of the parameters on the vessel response: rough corium locations, several methods to inject a global amount of energy with various shapes into the water and two constitutive water laws. These calculations showed that, among the different parameters studied, 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 amount of energy available for the explosion.

On the other hand, the CEA-Grenoble concentrated its efforts on the local aspects of the steam explosion: fragmentation of a corium jet and dispersion of the corium drops into the water, local generation of steam, explosibility of the corium-liquid water-steam mixture and finally the escalation of the explosion.

In order to deepen the understanding of the dispersion of the corium drops into water, a 2D-analytical experiment was settled. The BILLEAU test-facility consisted in pouring into water hundreds of cold or hot solid spheres stacked into tubes. The volume fractions of the three fields (solid, water and vapor), the sphere velocities, the free level swell and the final distribution of the spheres were measured (Duplat<sup>a</sup>, 1998) (Duplat<sup>b</sup>, 1998).

On the same time, a computer code was especially developed. MC3D is devoted to the analysis and the prediction of the fragmentation of the corium jet, to the local steam generation and the escalation of the steam explosion. Its models of corium fragmentation and steam generation were validated on the experiments BILLEAU and FARO (Berthoud<sup>a</sup>, 1997) (Berthoud<sup>b</sup>, 1997) (Berthoud<sup>c</sup>, 1997).

Until 1995, the development and the validation of the premixing phase preceding the explosion were in progress in the European thermalhydraulic codes: MC3D in France, IVA (Jacobs<sup>b</sup>, 1993) in Germany, CHYMES (Hall, 1993) (Fletcher, 1993) in England, COMETA (Annunziato, 1994) (Annunziato, 1997) at the European Center JRC. At that time, the knowledge was sufficient to provide reliable predictions of the premixing but the codes were not yet performing calculations of the explosion.

The french code MC3D could predict accurately the location and the thermodynamic characteristics of the corium and water all along the premixing phase. But the development of the explosion phase was just starting. 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.

Therefore it was imagined to link the code MC3D computing the premixing, to the code CASTEM-PLEXUS able to compute the steam explosion (Vivien, 1997). For a given accident scenario, the falling down of the corium jet into the water pool, the jet fragmentation and the premixing of the corium drops could be computed with MC3D. At the instant corresponding to the most probable configuration for the explosion to start, the results of MC3D could be transferred into CASTEM-PLEXUS to initialise the computation of the explosion.

This method allows to 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 previous approaches is that the mechanical effects of the explosion are dealt with local data.

### 3 Description of the codes

MC3D is a multidimensional multicomponent code designed to solve various thermohydraulics problems. It is based on an eulerian description of the flows, a staggered grid configuration for variable location, a finite volume integration method and a semi-implicit method for time integration.

MC3D is based on a common kernel (including inputs and outputs, a balance and transport equation solver, time step management,...) and on several applications. Each application is characterized by a different number of balance equations (mass, momentum and energy), closure laws and transport equations.

The "premixing" application describes the behaviour of water, steam and fuel droplets with three continuity equations, three momentum equations and three internal energy equations. Each field can exchange momentum and energy with the other fields, the exchange of mass being limited between water and steam, and between corium jet and droplets. The corium droplet population undergoes fragmentation; this is described through an interfacial area transport. The mathematical description of the code is given by (Berthoud, 1993) (Berthoud, 1994).

Knowing the total mass of the corium falling down from the core, the amount of the water remaining in the lower plenum and the initial conditions of pressure and temperatures, the whole phase of premixing can be evaluated versus time by MC3D. This code provides all the thermodynamic characteristics of corium, steam and water in a structured grid.

CASTEM-PLEXUS (Hoffman, 1984) is a general finite element computer code for fast dynamics mechanical calculations of structures in one, two or three dimensions. Structures may be either solids or fluids, with a possibility of coupling. The main fields dealt with are impacts (Robbe, 1999), explosions, circuits (Lepareux, 1985), hydrodynamics and robots.

The formulation can be Lagrangian, Eulerian or A.L.E. (Arbitrary Lagrangian Eulerian Method) according to the kind of problem to be solved. The time integration is done with an explicit Newmark algorithm. CASTEM-PLEXUS disposes of three balance equations: mass, momentum and total energy.

The mass and total energy equations are computed by balancing the flows between contiguous elements:

Mass conservation

$$M^{(n+1)} = M^{(n)} + \Delta M^{(n \rightarrow n+1)}$$

$$\text{with } \Delta M^{(n \rightarrow n+1)} = - \int_{t^{(n)}}^{t^{(n+1)}} \oint_A \rho \vec{n} \cdot \vec{v} dA dt + \int_{t^{(n)}}^{t^{(n+1)}} \int_V M_{ext} dV dt$$

Total energy conservation

$$E^{(n+1)} = E^{(n)} + \Delta E^{(n \rightarrow n+1)}$$

$$\text{with } \Delta E^{(n \rightarrow n+1)} = - \int_{t^{(n)}}^{t^{(n+1)}} \oint_A \rho \left( H + \frac{1}{2} \vec{v} \cdot \vec{v} \right) \vec{n} \cdot \vec{v} dA dt + \int_{t^{(n)}}^{t^{(n+1)}} \int_V E_{ext} dV dt$$

CASTEM-PLEXUS solves the weak formulation of the momentum equation:

$$\int_{t^{(n)}}^{t^{(n+1)}} \int_V \vec{U}^* \cdot \rho \frac{\partial \vec{v}}{\partial t} + \vec{U}^* \cdot (\rho \vec{v} \cdot \vec{\epsilon}) + \vec{\epsilon}^* : \vec{\sigma} dV dt - \int_{t^{(n)}}^{t^{(n+1)}} \oint_A \vec{n} \cdot (\vec{U}^* \cdot \vec{\sigma}) dA dt = \int_{t^{(n)}}^{t^{(n+1)}} \int_V \vec{F}_{ext} dV dt$$

with

A	surface	t	time
E	total energy	$\vec{U}^*$	arbitrary displacement
$E_{ext}$	external energy source	V	volume
$\vec{F}_{ext}$	external force	$\vec{v}$	velocity
H	total enthalpy	$\vec{\epsilon}^*$	strain
M	mass	$\dot{\vec{\epsilon}}$	strain velocity
$M_{ext}$	external mass source	$\rho$	density
n	time step	$\vec{\sigma}$	stress
$\vec{n}$	normal vector		

In our case, the liquid water and steam are described by a diphasic water constitutive law including vaporization but supposing a homogeneous mixture (Papon, 1990). Both phases are assumed to be at thermal and mechanical equilibrium and no phase sliding is allowed. Liquid water and steam are treated as a unique material. From the mass and enthalpy increments (provided by the mass and energy equations) and the steam tables (Haar, 1984), the code computes all the thermodynamic variables.

In CASTEM-PLEXUS, the corium is not meshed; it is represented by the energy source term in the total energy equation. The different models available to describe the corium presence are described in (Robbe<sup>d</sup>, 2000). The vessel is represented by an elastoplastic shell, coupled with the water.

From an initial distribution of the corium, liquid water and steam, CASTEM-PLEXUS computes the steam explosion (escalation and propagation of the pressure wave through the lower plenum) and its mechanical effects on the reactor vessel.

The table 1 presents the main characteristics and differences between the codes to link.

## 4 Description of the linkage method

MC3D provides the spatial distribution and the thermodynamic information (pressure, temperature, volumic presence fraction) versus time for each constituent of the triphasic mixture composed of liquid water, steam and corium. Among them, we transfer to CASTEM-PLEXUS the average pressure, the average water temperature, the corium presence fraction and the corium temperature.

An expert judgement selects the configuration most probable for the triggering of the explosion. In CASTEM-PLEXUS, the corium is described by an energy injection in an element containing only water.

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

$$\int_{t^{(n)}}^{t^{(n+1)}} \int_V E_{ext} dV dt = \int_{t^{(n)}}^{t^{(n+1)}} \int_V \frac{M_{water}(t)}{M_{water}(t=0)} M_{corium} E_a dV f(t) dt$$

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

The corium mass and the water mass are obtained respectively by:

$$M_{corium} = \tau_{corium} \rho_{corium} \quad \text{and} \quad M_{water} = \tau_{liquid\ water} \rho_{liquid\ water} + \tau_{steam} \rho_{steam}$$

where  $\tau$  is the volumic presence fraction and  $\rho$  the volumic mass.

The corium mass is kept constant in each cell during the calculation. The water ratio prevents from injecting energy in the vapor zone after the water initially liquid in the cell vaporized. 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  $E_a$  is given by :

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

where  $\eta$  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 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 local method reduces the number of parameters compared to a global method (especially regarding the corium and energy injection location), some parameters remain because no accurate information exists on these subjects (corium characteristics, simulation of the heat transfer between corium and water during the explosion).

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 (Fig. 1).

To initiate the CASTEM-PLEXUS computations, the data necessary to describe the water state are: pressure, saturation temperature and void fraction. The code supposes that both phases have the same temperature and the same pressure. The massic void fraction is calculated by:

$$Void\ fraction = \frac{\tau_{liquid\ water} \rho_{liquid\ water}}{\tau_{liquid\ water} \rho_{liquid\ water} + \tau_{steam} \rho_{steam}}$$

From the two variables (corium presence fraction and corium temperature) provided by MC3D, the local energy is calculated and injected step by step 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.

## 5 Application

The chosen scenario (Fig. 2) is an in-vessel steam explosion resulting from a large central core degradation, like in (Robbe<sup>d</sup>, 2000). It is assumed that 100 tons of molten core, with an initial temperature of 3073 K, are falling down in the water of the lower plenum. The central hole diameter, from where is arriving the corium, is 1.2 m.

Part of the lower core support plate is considered still intact, as well as the vertical cylindrical wall separating the core from the downcomer. The bottom of the downcomer is supposed not obstructed by debris, on the contrary of the previous models used in (Robbe, 1997) (Robbe<sup>d</sup>, 2000). This representation of the accident (with the free canal near the vessel) should avoid the unrealistic pressure peaks observed in the previous models during the CASTEM-PLEXUS computations.

The pressure in the vessel is 50 bar and the water is initially saturated. The water level is 2 m above the bottom and the height of the vapor blanket above the water is 0.85 m. The same global geometry is adopted for the computations with MC3D and CASTEM-PLEXUS. For MC3D, the three components are represented. For CASTEM-PLEXUS, the vessel contains only water and steam; the interaction zone is represented by liquid water in which energy is injected.

In MC3D, the reactor is represented from the lower plenum up to the upper core plate. The volume of the empty primary circuit is also included in the model. Because of the finite volume integration method, the reactor is described by rectangular cells. Therefore the vessel shape is approximated by a succession of steps. The lower core support plate and the cylindrical canal wall are described by fixed grids. No mechanical effect is taken into account.

For CASTEM-PLEXUS, the vessel is represented by an elastoplastic shell (Fig. 3) coupled with the water contained inside the lower plenum. The lower core support plate and the cylindrical canal wall are supposed to be thick plates, also coupled with the inner fluid. The downcomer is limited by an imposed pressure of 50 bar in order to represent the pressure of the vapor in the upper part of the reactor.

MC3D computes the corium draining away from the central hole in the core support plate and going down through a steam blanket before it gets to the liquid water. The code also calculates the corium jet fragmentation, its progression through the water-steam mixture and the steaming due to the passing of the corium jet.

The figure 4 shows the shape of the fragmented and dispersed corium when it arrives near the bottom of the lower plenum. The corium is concentrated in the centre of the lower plenum, under the central hole. The corium has the shape of a long column which stretches out from the top to the bottom of the lower plenum because the corium has drained out progressively from the core support plate.

The figure 6 shows the presence fraction of the liquid water. The remaining liquid water is confined near the vessel because the central part of the lower plenum is filled in with corium which pushed away the mixture of water and steam and an intermediary vertical layer is formed of the steam vaporized by contact of the initial liquid water with the corium.

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. The presence fractions are transferred from the structured MC3D mesh to the non-structured CASTEM-PLEXUS mesh.

Figures 8 to 11 represent the pressure during the explosion. The explosion starts on the bottom, on the symmetry axis and near the vessel because it is the most confined part of the corium zone. Then the pressure zone propagates diametrically. After 3 ms, the pressure wave has almost completely crossed the lower head.

Figures 12 to 15 show the void fraction. A vapor zone creates first on the symmetry axis, near the bottom, in the middle of the pressurised zone. The vapor zone expands diametrically and then vertically. Finally, the vapor zone has the same shape as the initial corium zone: a vertical column with a larger base.

The figure 16 represents the deformed shape of the shell at different times. Due to the starting of the explosion on the bottom, the first part to deform is the lowest part of the shell, near the symmetry axis. As the pressure wave expands, the upper parts of the vessel are in demand and deform progressively. Finally a large bulk is created near the bottom of the downcomer. The vessel does not deform much above the downcomer bottom because of the imposed pressure at the top limit of the downcomer.

The figure 17 shows the plastic strains versus time. Plastic strains first appear at the bottom since 1.3 ms, increases until 4.5 ms, remain constant until 7 ms before they increase again a little. The plastic level on the plateau is limited to 4 %. The plastic strains observed after 7 ms may be due to some wave reflection and their level depends very much on the reactor model and boundary conditions.

Plasticity starts only after 3 ms in the upper part of the lower head vessel. It reaches a plateau from 7 ms. The plastic strains are higher in the upper part than on the bottom: more than 5 %. We can observe that the vessel part most in demand is the upper part of the lower plenum in this computation. The level of plastic strains reached here is high enough to consider a possible failure of the lower head in case of steam explosion.

## 6 Discussion

This method, dealing with linked computations between the thermalhydraulics code MC3D and the fast dynamics code CASTEM-PLEXUS, was used by the IPSN for the prediction and assessment of the mechanical consequences of a steam explosion on a PWR lower head from 1997. Parametrical computations were carried out with several accident scenarios to determine which scenarios could be able to fail the vessel, how much energy was needed to cause a probable rupture and the most likely vessel failure modes in case of high energy accident.

First, the calculations were performed assuming that the injection began simultaneously in the whole corium zone. This method constitutes a progress, compared with the previous global very conservative computations realised until 1997, because of the introduction of local data for initiating the steam explosion calculation.

Besides, the conservatism was a little reduced later by simulating the progressive fragmentation of the corium drops under the influence of the propagating pressure wave. Locally, the beginning of the energy injection (corresponding to the corium fine fragmentation and to the beginning of the high heat transfers between corium and liquid water) was delayed until the passing of the pressure wave coming from the trigger cell and crossing the lower plenum.

To appreciate the benefit of coupled calculations in relation to our present linked calculations, we tried 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 was 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 of this linked computations 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. The steam explosion would deform the lower head and throw up the liquid slug simultaneously. This kind of computations is already possible thanks to the current capacities of the code CASTEM-PLEXUS.

Since 1997, the development of the code MC3D has been extended to the computation of the explosion. MC3D is now able to model the fine fragmentation phase and the pressure escalation. The code can take into account the subcritical and supercritical pressures and the problem is decomposed into four fields (liquid coolant, vapor, fuel drops and fuel fragments after the fine fragmentation). The explosion is completely dealt with local information.

The equations (mass, momentum and energy balance equations) and the models (fragmentation, heat transfers and friction laws) are described in (Brayer<sup>a</sup>, 1997). The code validation and qualification on experimental results started with comparisons with results issued from the code CULDESAC and from the KROTOS test-facility (Brayer<sup>b</sup>, 1997).

The next step concerning the evaluation of the mechanical consequences of a steam explosion should consist in developing a new link between the codes MC3D and CASTEM-PLEXUS at the end of the explosion. The explosion could be entirely computed with MC3D, using only local data. Then the pressures, next to the vessel limit and during the complete steam explosion process, could be transferred to CASTEM-PLEXUS through another procedure. And CASTEM-PLEXUS would predict the mechanical effects of the explosion on the vessel (displacements, deformations and stresses) versus time by modeling the vessel alone.

## 7 Conclusion

This paper presents an assessment of the mechanical consequences of an hypothetical steam explosion on the reactor lower head by means of thermalhydraulic and mechanical linked computations with two specialized computer codes. Compared with the previous analytical or computer calculations using global approaches to represent the explosion parameters, the main advantage of this method consists in making use of local data to initiate the explosion escalation and propagation. Consequently, the precision of the mechanical results is greatly improved.

The specificities of the thermallyhydraulic code MC3D and the fast dynamic code CASTEM-PLEXUS are explained and the linkage method is fully described. An application is presented; it concerns a PWR central core degradation involving 100 kg of corium. The thermallyhydraulic results are described at the end of the premixing, just before the explosion triggering. The data transfer is also showed. The progression of the explosion and the mechanical results are finally presented.

Thanks to the current progress in the modeling of the explosion by MC3D, the next step may consist in a new linkage between both codes with the explosion computed by MC3D and the mechanical effects by CASTEM-PLEXUS.

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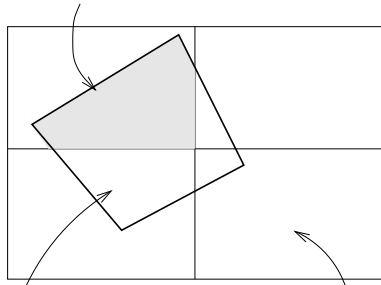
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	MC3D	CASTEM-PLEXUS
Method	finite volume	finite element
Mesh	structured (rectangles)	non-structured (quadrangles)
Problem representation	axisymmetric	axisymmetric
Water model	triphasic model: 3 continuity equations, 3 momentum equations, 3 energy equations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

Table 1: Characteristics of the codes MC3D and CASTEM-PLEXUS

common volume between  
MC3D and CASTEM-PLEXUS



CASTEM-PLEXUS mesh MC3D mesh  
Fig. 1: Superposition of the meshes imposed pressure

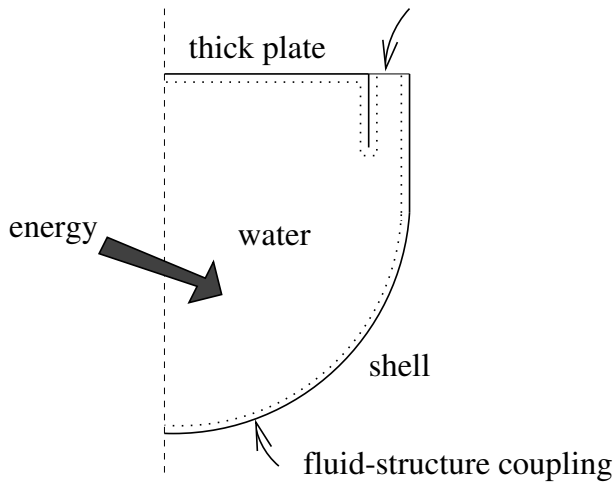


Fig. 3: Geometry and boundary conditions of CASTEM-PLEXUS

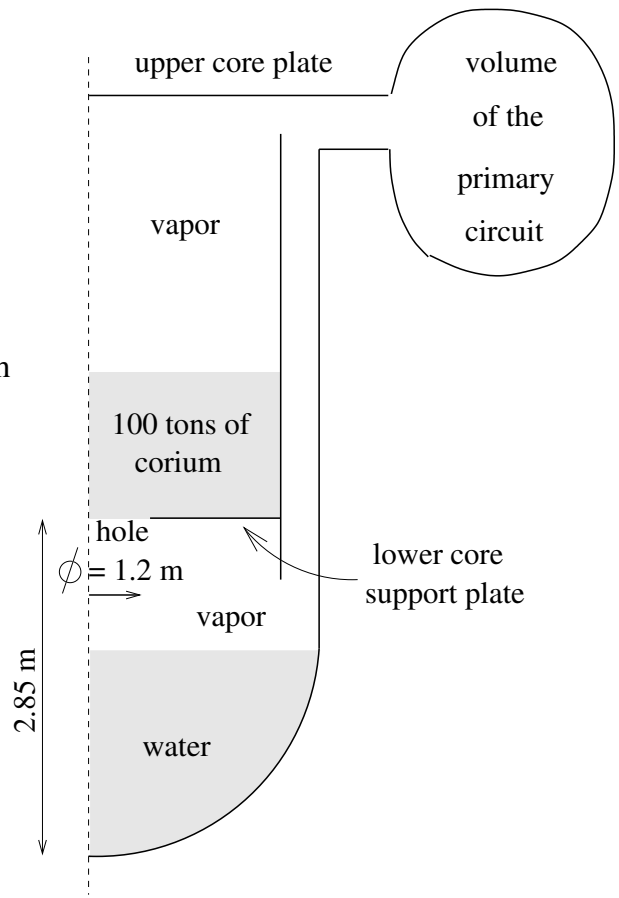


Fig. 2: Geometry and boundary conditions of MC3D

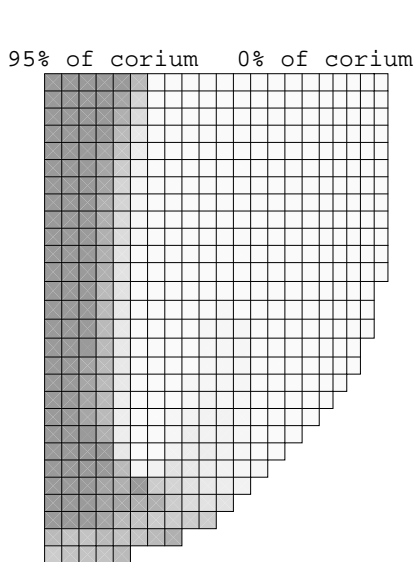


Fig. 4: Presence fraction of the corium with MC3D

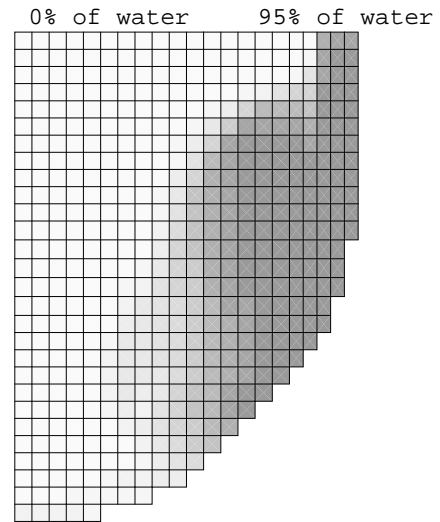


Fig. 6: Presence fraction of the liquid water with MC3D

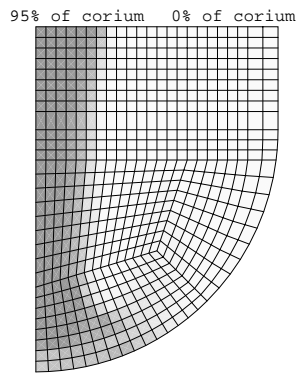


Fig. 5: Presence fraction of the corium with CASTEM-PLEXUS

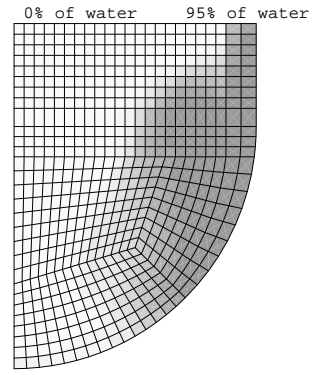


Fig. 7: Presence fraction of the liquid water with CASTEM-PLEXUS

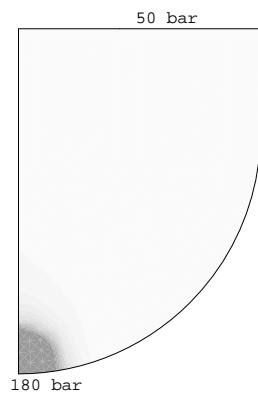


Fig. 8: Pressure at time 0.6 ms

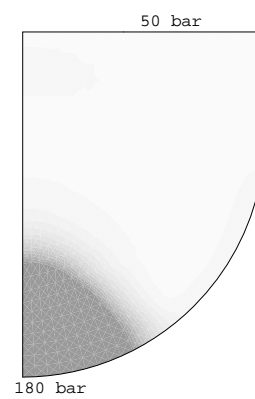


Fig. 9: Pressure at time 1.3 ms

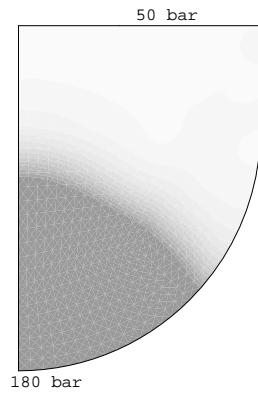


Fig. 10: Pressure at time 2 ms

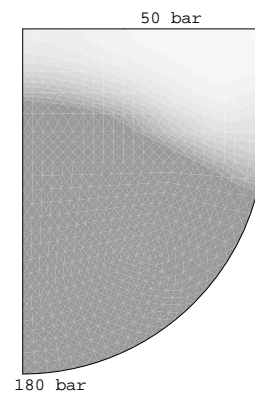


Fig. 11: Pressure at time 2.7 ms

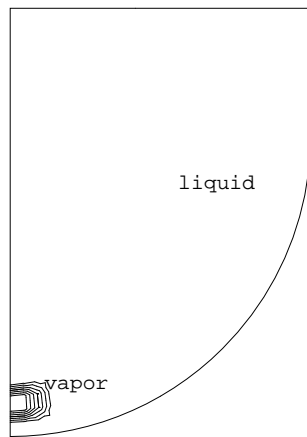


Fig. 12: Void fraction at time 1.3 ms

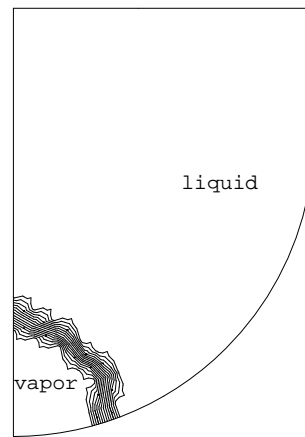


Fig. 13: Void fraction at time 2.1 ms

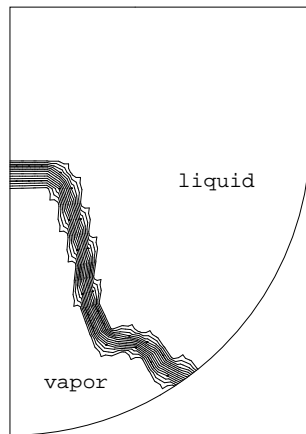


Fig. 14: Void fraction at time 4 ms

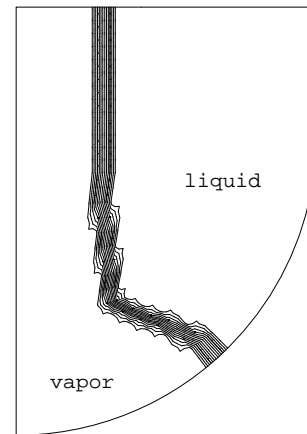


Fig. 15: Void fraction at time 7.2 ms

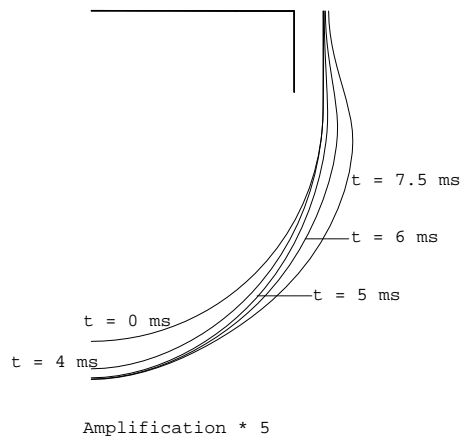


Fig. 16: Deformed shape of the shell **15**

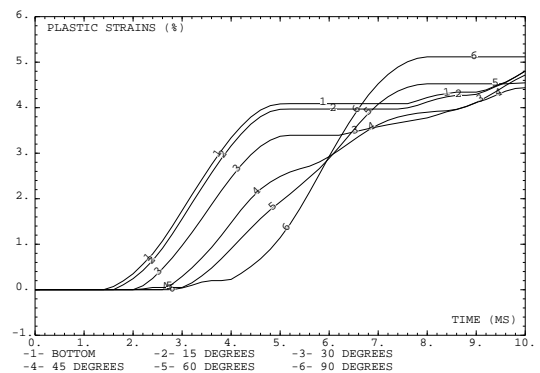


Fig. 17: Plastic strains along the shell, from the bottom to the top