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**SCOPING CALCULATIONS OF AN IN-VESSEL STEAM EXPLOSION.
CASTEM-PLEXUS COMPUTATIONS**

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Keywords

PWR, steam explosion, fuel-coolant interaction, lower head mechanical behaviour, CASTEM-PLEXUS, fluid-structure coupling

Abstract

Steam explosion is considered as a potential risk for PWR nuclear power plants in case of a severe accident. The loss of coolant can cause 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.

This paper presents parametrical computations of an in-vessel steam explosion, regarding the possible lower head vessel ruin resulting from a large central core degradation. The mechanical consequences of the steam explosion on the lower head are foreseen by the CASTEM-PLEXUS fast dynamic software, estimating approximately the thermodynamic data.

A 2D-axisymmetric representation is adopted because of the vessel symmetry. The vessel lower head is considered as an elastoplastic hemispheric shell without penetrations and coupled with coolant. Four parameters are examined: the corium location, the energy transferred from the corium to the water, the energy transfer kinetics and the water constitutive law.

During the explosion, we observe the propagation of a pressure wave from the corium zone towards the vessel and the core. The wave reflects against the vessel and the core support plate and then is sent again to the corium zone. After the wave passing, the water vaporizes massively and escapes in the free space in the core centre.

1 Introduction

Since the Three Miles Island accident (Libmann, 1996) on the 28th march 1979 and the publication of

the Rasmussen report known as WASH 1400, steam explosion has been considered as a potential risk for PWR nuclear power plants.

Among the hypothetical severe accidents induced by a core melting, steam explosion has been intensely studied (Theofanous, 1987) (Abolfadl, 1987) (Amarasooriya, 1987) (Lucas, 1987) (Jacobs, 1993) (Theofanous (a), 1995) (Theofanous (b), 1995) (Cenerino, 1996) (Turland, 1995) (Van Goethem, 1997) (Robbe, 1997) (Vivien, 1997) (Robbe, 2000) because it might lead to potentially catastrophic environmental consequences caused by an early and massive containment failure.

We assume that a loss of coolant caused a 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 (Berthoud, 1988). Steam explosion can damage either the reactor lower head because of the direct pressure rise, or the upper head by accelerating an upward-directed missile, or both (Krieg, 1995).

In France, the CEA-Saclay has been put in charge of assessing the mechanical consequences of a steam explosion on the reactor vessel. As the french premixing software MC3D (Berthoud, 1993) is not devoted to the coupled simulation of the explosion with the reactor pressure vessel response, the mechanical consequences of a steam explosion on the lower head are assessed by the general fast dynamic software CASTEM-PLEXUS, estimating approximately the thermodynamic data.

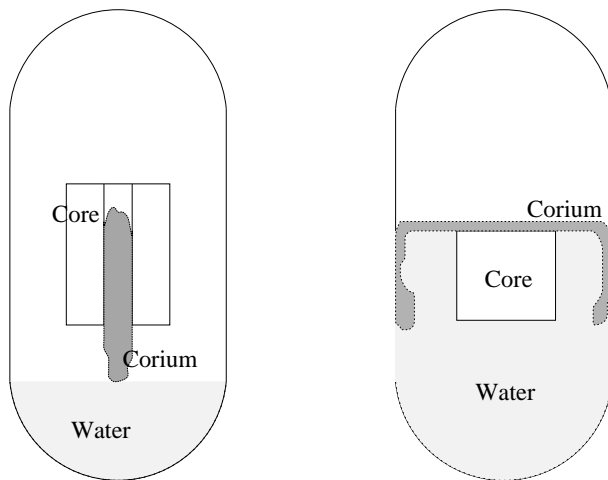
This paper presents a synthesis of the French work regarding the possible lower head vessel ruin. In order to weigh up the sensibility of the lower head response to the accident scenario, a parametric study is realised. The considered parameters are the corium location, the corium amount interacting during the explosion, the steam explosion numerical model and the water constitutive law. This presentation is focused on our parametric study.

2 The accident scenario

The hypothetical accident scenario must be chosen as close as possible as an envelope scenario for the estimation of the mechanical consequences on the reactor pressure vessel lower head. Therefore the most pessimistic hypotheses have to be considered.

The accident scenario supposes an in-vessel steam explosion resulting from a core degradation. The level of the water cooling the core went down. Thus part of the core has molten down and is draining into the lower plenum. By contact with the water remaining in the lower plenum, the corium fragments and the water vaporizes. Most probably, the explosion starts by contact on a plate or on the bottom of the lower head, what destabilizes the steam film around the corium pieces.

For the corium draining into the water pool, there are two probable scenarios (Figure 1): either a large central core degradation with the corium falling vertically or an upper core degradation with the corium falling laterally by the downcomer. We chose the central core degradation scenario because it is more dangerous for the lower head safety. We suppose that the corium drains into the lower plenum through a 1 m diameter opening.



Central core degradation

Upper core degradation

Figure 1: Accident scenarios

We suppose too that the intact part of the core support plate remains rigid during the explosion and that the cylindrical canal between the core and the vessel (downcomer) is blocked up by molten corium or debris. Both hypotheses are very conservative. The intact part of the core is not represented whereas the central hole is modelled.

We suppose that the initial pressure in the vessel is 10 bar and the water is initially saturated. Below the core support plate, we take a water level of 1.6 m above the bottom and a steam blanket of 0.2 m above the water. The central hole is filled with steam.

A 2D-axisymmetric representation is adopted because of the vessel symmetry. The vessel lower head is considered as an elastoplastic hemispheric shell without penetrations and coupled with coolant. The top limit in contact with the intact part of the core is blocked up vertically. The central hole cannot expand laterally and its extremity is provided with an absorbing material in order to prevent numerical pressure wave reflections (Figure 2).

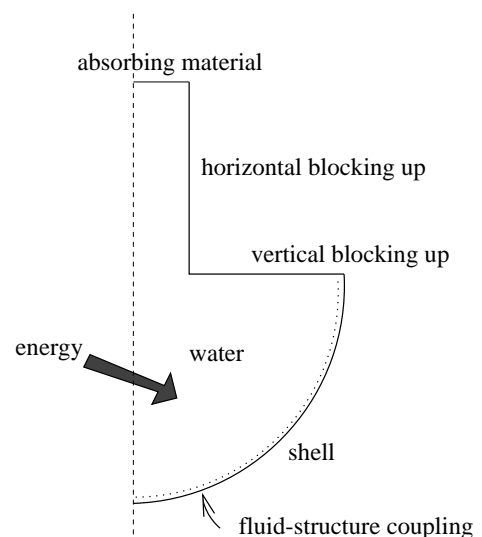


Figure 2: Geometrical model

3 Representation of the steam explosion with CASTEM-PLEXUS

CASTEM-PLEXUS (Hoffmann, 1984) is a general finite element software devoted to the analysis of fast transients. It can provide 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, explosions, circuits, hydrodynamics (Robbe, 1999).

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 uses the mass and energy conservation laws to calculate mass and energy flows between contiguous elements and it solves the momentum equation.

CASTEM-PLEXUS is not a code devoted to the premixing study. It does not allow to solve the three conservation equations for each constituent. The liquid water and steam are described by a single water constitutive law including vaporization but supposing a homogeneous mixture. That means that the two phases are assumed to have the same pressure and no phase sliding.

As the corium is finely splitted up at the beginning of the explosion, it is closely mixed with water and cannot be meshed. To take into account the corium interacting with water during the explosion without modelling it, the corium is represented by a zone containing only water and where energy is injected. It is described through its thermal exchanges with water.

The energy-giving loading for CASTEM-PLEXUS corresponds to the thermal energy of the corium fraction participating in the explosion: W_{water} (Figure 3).

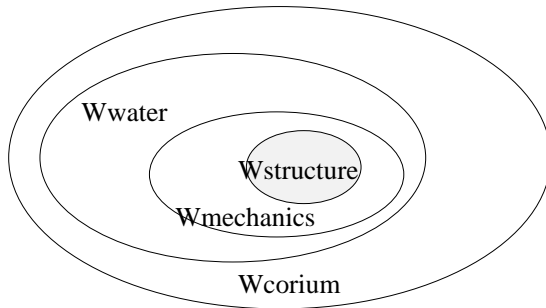


Figure 3: Energies in CASTEM-PLEXUS

The table 1 summarizes the different kinds of energy used in the litterature and in the code with their definition.

| | |
|-----------------|--|
| $W_{structure}$ | Energy stored in the structure (vessel) in the form of elastic and plastic strains |
| $W_{mechanics}$ | Work of the pressure forces on the vessel = $W_{structure}$ + Kinetic energy |
| W_{water} | Energy transmitted from corium to water = $W_{mechanics}$ + Heat transmitted to water for rising its temperature and for vaporization |
| W_{corium} | Corium available energy = W_{water} + Energy wasted in irreversible phenomena |

$$W_{structure} < W_{mechanics} < W_{water} < W_{corium}$$

Table 1: Description of the different energies

As CASTEM-PLEXUS is not a thermohydraulic software, the loading has to be previously assessed. Initially, there was no premixing software to evaluate corium parameters. So complementary hypotheses were needed :

- shape and distribution of corium,

- amount of energy transferred from corium to water,
- history of loading (Figure 4).

In order to assess the influence of these parameters on the lower head response, we carried out a large set of parametric studies concerning:

- the location and the shape of the corium zone,
- the energy injection kinetics modelling the thermal transfer from corium to water,
- the amount of transferred energy,
- the water constitutive law.

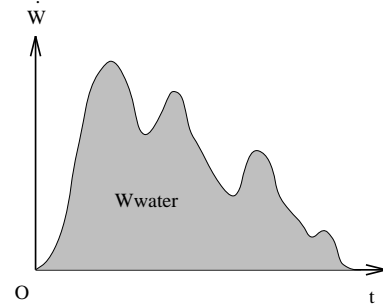


Figure 4: History of loading

4 Description of the parametric study

4.1 The location and the shape of the corium zone

Assuming a central core collapse after melting, three kinds of steam explosion were studied. In screening calculations, we supposed first that the corium was fully scattered in the water pool (Figure 5). As the results showed that this representation had no chance to damage the pressure vessel, we ruled it out from the parametric studies.

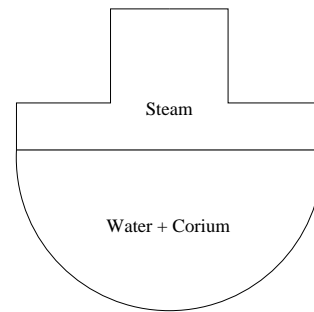


Figure 5: Corium scattered in the water

So, in the parametric studies presented hereby, we examined a first set of calculations where steam explosion is supposed to occur before corium reaches the vessel bottom, for instance when the corium cloud hits a plate halfway up the lower head . In this case, the corium zone is represented by a 0.52 m^3

”**SPHERE**” located in the centre of the water (Figure 6).

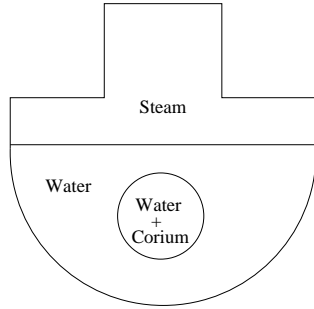


Figure 6: Corium in a central sphere

A second set of calculations was performed where steam explosion is supposed to occur when the corium contacts the vessel bottom. In that case, the corium zone is represented by an elliptic zone of 0.52 m^3 located at the ”**BOTTOM**” of the lower head (Figure 7).

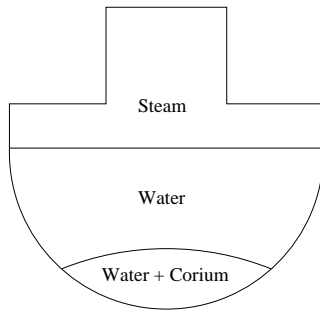


Figure 7: Corium at the bottom

The meshes used for the ”**SPHERE**” and ”**BOTTOM**” computations are displayed on figures 8 and 9.

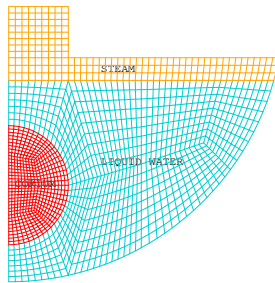


Figure 8: The ”**SPHERE**” mesh

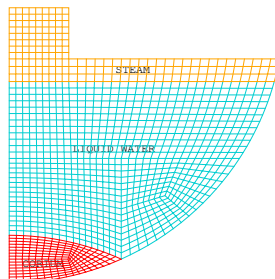


Figure 9: The ”**BOTTOM**” mesh

4.2 The energy injection kinetics

The corium is described by an energy, ”available” for the explosion, and injected in the water of the corium zone. This energy corresponds to the fraction of the corium which participates in the explosion. This fraction is obtained by applying an explosion yield to the corium (Vivien, 1997).

Supposing that the corium mass is $M_c = 8000 \text{ kg}$, that the explosion yield η is 10 % and that the thermal energy E_{th} of the fragmented corium is approximately 1.25 MJ per kg of corium, the ”available” energy is estimated at

$E_a = \eta * M_c * E_{th} = 1000 \text{ MJ}$ This value also corresponds to the Ideal yield energy recommended by Theofanous.

The energy injection is described by an energy source term in the energy balance equation of the water in the corium zone. Three types of kinetics were proved.

4.2.1 Simultaneous injection

The ”simultaneous injection” is a stepwise energy injection (Figure 10). It is a basic way to model the heat transfer between corium and water. Without any precise information about the kinetics of the transfer and the corium spreading, we inject a global amount of energy simultaneously in the whole zone containing corium.

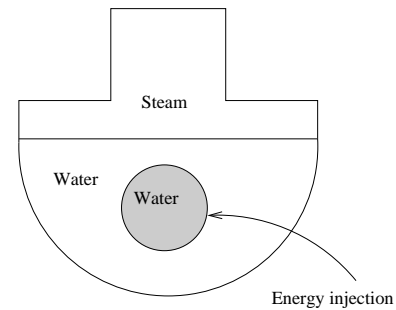


Figure 10: Simultaneous injection

The available energy is calculated at each step by

$$E_a(t) = P_m(t) m_{corium} \frac{m_{water}(t)}{m_{water}(t_0)} dt$$

where $P_m(t)$ is the corium massic power, m_{corium} the corium mass in the mesh (constant), $m_{water}(t)$ the current water mass, $m_{water}(t_0)$ the initial water mass and dt the time increment.

The corium mass is

$$\begin{aligned} m_{corium} &= \rho_{corium} V_{water} Prop_{corium/water} \\ &= 1066 \text{ kg/m}^3. \end{aligned}$$

$\rho_{corium} = 8200 \text{ kg/m}^3$ is the corium density.

V_{water} is the volume of the injection zone.

$Prop_{corium/water} = 0.25$ is the volumic proportion of corium in a mesh.

The massic power is a time dependent function (Figure 11). We suppose the injection is uniform and constant for a given duration $\Delta t = 2.5$ ms. So the maximum power is $P_{max} = 375$ MJ/kg of corium.

The ratio $m_{water}(t)/m_{water}(t_0)$ accounts for the heat transfer coefficient decrease between corium and water when the steam amount increases. As the heat transfer with steam is very low, compared with the water one, the energy injection is slowed down proportionally to the steam generation.

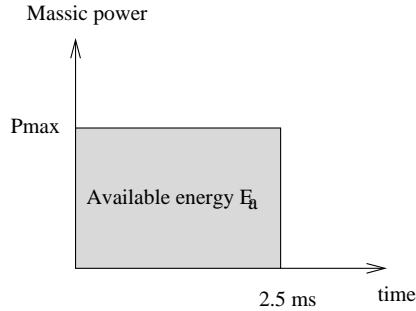


Figure 11: Massic power

For the corium scattered in the whole water pool, the chosen kinetics is different. The corium volume is 17.3 m^3 . The massic power is 3.82 MJ/kg of corium. The injection duration is 17 ms . These data lead to an available energy of 1125 MJ .

Finally the energy injection stops when the average water density in a mesh reaches 10 or 33 % of the initial density. That means the injection is stopped when the local steam rate is very high. Thus only a part E_{inj} of the available energy E_a is injected.

This arbitrary criterion takes into account the heat transfer drastic drop when the water is almost fully steamed. It is justified by the fact that the explosion naturally stops when the water is fully vaporized. Moreover, this criterion avoids numerical difficulties due to the emptying of meshes containing only steam and whose density is close to zero. A similar criterion was also used in the CULDESAC code for a void fraction of 70 % (Fletcher, 1993).

The "simultaneous injection" is a conservative model for the heat transfer kinetics because it supposes that the explosion starts simultaneously and uniformly in the whole zone containing corium. So the injected energy is maximizes at the beginning, just when the external confining by the surrounding water is also maximum. This model allows to inject a high quantity of energy in a given duration.

4.2.2 Marble injection

We suppose that, before steam explosion happens, the jet of corium has fragmented into small

drops. The "marble injection" simulates the heat transfer from solid identical spheres of corium to the liquid water (Figure 12). The droplet temperature is much greater than the water temperature. Thus the energy released by the corium marbles is injected into the water in a heat flux form, guided by diffusion laws.

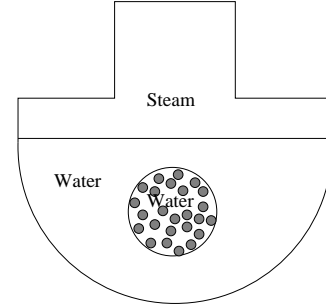


Figure 12: Marble injection

The initial temperature of the virtual marbles is 2273 K and their diameter is 1 mm . The energy $E_{inj}(t)$ transferred from one marble to the water is calculated at every step by :

$$E_{inj}(t) = \rho c_p (\theta_i^e - \theta_f^e) V_{cor}$$

where ρ is the water density,

$c_p = 600 \text{ J kg}^{-1} \text{ K}^{-1}$ the heat capacity of the corium,

θ_i^e and θ_f^e the external temperature of the marbles at the beginning and the end of the step,

V_{cor} the corium volume.

The final temperature θ_f^e is obtained by solving the heat equation inside the marbles :

$$\int_V \left(\rho c_p \frac{\partial \theta}{\partial t} - \lambda \Delta \theta \right) dV = \int_S H (T_{water} - \theta) dS$$

where $\lambda = 3 \text{ W m}^{-1} \text{ K}^{-1}$ is the corium conductivity, H the exchange coefficient and T_{water} the average water temperature next to the marbles.

The value of the exchange coefficient H is supposed quasi-infinite ($10^6 \text{ W m}^{-2} \text{ K}^{-1}$) when the water is liquid. It decreases linearly as the void fraction increases. The energy injection stops when the void fraction reaches 0.99 (Figure 13).

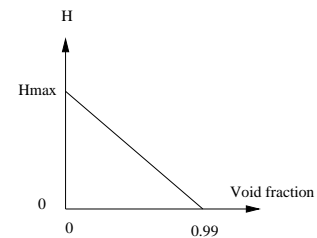


Figure 13: Heat exchange coefficient

The quasi-infinite value of H was chosen in order to have the maximum thermal exchange in the shortest time. As there is a delay before the water is ejected from the premixing zone by the pressure

accumulated in the zone, this process allows the explosion to be more violent. A constant value in the range 10^5 to 10^6 was also used for the steam explosion calculations computed with the CULDESAC code (Fletcher, 1993).

The last parameter of the study consists in the number of marbles. As this parameter will allow to perform a specific investigation about the amount of transferred energy, a special chapter will be devoted to it.

This way to calculate the kinetics of the energy transfer is closer to the reality and less conservative. Especially it accounts for the local differences of temperature and steam rate in the corium zone as the heat transfer is not identical in the whole zone. However, as the thermal exchange coefficient is very high, the virtual corium marbles are cooled very soon what leads to overestimate the explosion strength. The main difficulty of this model is the assessment of the parameter set used to calculate the heat transfer.

4.2.3 Injection with propagation

According to (Berthoud, 1988), the explosion starts when the corium drops fragment into small droplets. This process strongly increases the corium thermal exchange surface and allows the explosive vaporization of the water due to the energy transfers between corium and water. This stage is either spontaneous or it has to be triggered off by a disturbing phenomenon. The trigger may be the violent overpressure caused by a neighbouring previous steam explosion.

Therefore the explosion may be triggered at a certain point of the corium zone by contact with the vessel or the internal structures of the lower head. Then the propagation of the pressure wave due to the initial explosion would fragment finely the large corium drops at the proximity and thus create successive and delayed explosions.

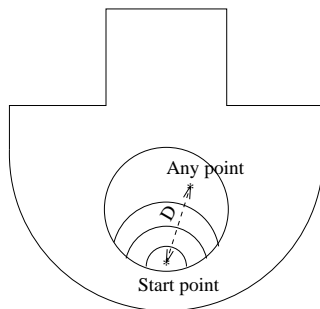


Figure 14: Injection with propagation

The "injection with propagation" supposes that the energy injection is not simultaneous in the whole corium zone but spreads from a starting point (the initial explosion) through the corium zone at a constant velocity (Figure 14).

The explosion, simulated by an energy injection such as the "simultaneous injection", begins, at each point of the corium zone, with a delay $t_d = D/v$. D is the distance between the current point and the starting point. The propagation velocity $v = 500$ m/s corresponds to an experimental value.

The starting point was chosen as the lowest point of the corium zone because it coincides with the first contact between the corium and the bottom of the reactor vessel or with lower plates.

4.3 The amount of transferred energy

In the "simultaneous injection" and the "injection with propagation", the amount of transferred energy is only known at the end of the computation. Even if an initial wished value $E_{inj} = 1000 MJ$ is imposed, the real injected energy is lower than planned because of the ratio on the water mass and because of the the injection stop when there is too much steam in a mesh.

Thus a parametric study about the transferred energy is difficult to pilot with these models. Consequently, the "marble model", easier to use, was preferred. Physically, a variation of the transferred energy consists in a variation of the amount of corium which interacts with water. This can be represented by a parametric study about the marble number in the corium zone.

We chose to present computations with marble rates of 1, 5, 10, 15, 20 and 25 % in the corium zone. We assessed that the marble number could not exceed 25 %.

Mathematically, the highest rate of marbles in a volume is 65 %, supposing that all the marbles are in contact with each other. As no thermal exchange can exist if there is no space for water between the marbles, a minimum free space is necessary between the marbles. Besides, if the free space is too narrow, the water vaporizes instantaneously and there is no possible steam explosion. That is the reason why we limited the marble rate to 25 %.

4.4 The water constitutive law

The water behaviour is governed by a specific constitutive law. This law computes the pressure and temperature variations and the vaporization from the energy source term in the corium zone and from the mass and energy flows between meshes.

All the thermodynamic parameters necessary to the evaluation of the water behaviour changes (enthalpy, entropy, density, pressure, temperature, heat capacity, steam rate, velocity, sound speed...) are computed at each time step. Apart from the pressure and the velocities which are supposed identical for liquid water and steam, the other variables are calculated independently from the "Steam tables"

(Haar, 1984) and an average value weighted up versus the steam rate is assessed.

Two different constitutive laws were proved. There are identical when the water is fully liquid or fully steam. Their differences come from the gestion of the diphasic states.

4.4.1 The "equilibrium" law

The "equilibrium" constitutive law assumes that, for the diphasic states, liquid water and steam are instantaneously in thermal and mechanical equilibrium in each mesh, that means:

$P_{steam} = P_{water}$ and $T_{steam} = T_{water}$. The vaporization is calculated with a classical thermodynamic formulation.

4.4.2 The metastable law

In an explosion, the pressure equilibrium is generally instantaneous but the thermal phenomena are very slow compared to the very short time of a steam explosion propagation (< 30 ms). This absence of equilibrium is particularly noticeable at the beginning of the vaporization.

In the "metastable" constitutive law, the phases are allowed to have different temperatures in a mesh, but they remain in mechanical equilibrium and there is still no phase sliding.

The metastability means that, when the corium falls down into the water (causing a violent energy transfer), the thermal equilibrium between both phases has no time enough to be realised (Papon, 1990). The constitutive law considers that (Figure 15):

$P_{steam} = P_{water}$ but $T_{water} \geq T_{steam} = T_{saturation}$

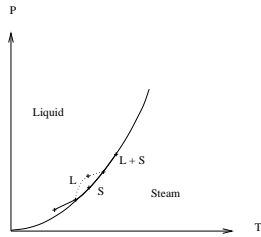


Figure 15: Metastable water law

Because of the better liquid thermal exchange coefficient, the energy is transferred with priority to the liquid rather than to the steam. The liquid becomes overheated. The thermal equilibrium occurs when the amount of steam is sufficient. This process should slow down the steam creation.

The steam creation happens in 2 steps (Plesset, 1954). The nucleation is a very short step. It corresponds to the bubble creation and its fast initial growth, controlled by inertial effects. The bubble growth lasts a longer time. It is driven by the Rayleigh conduction equations.

Whereas the "equilibrium" water constitutive law was developed and used in CASTEM-PLEXUS for a lot of applications concerning water, the metastable water constitutive law was especially implemented in the code for the steam explosion application.

The CASTEM-PLEXUS metastable law is focused on the bubble growth pilotage. It does not take into account the nucleation step. The Plesset and Zwik conditions represent the growth of spherical identical vapor bubbles within a uniformly overheated liquid. The metastability is only considered during the vaporization phases but not during the condensation ones. At the beginning of the vaporization, the metastability appears. When the thermal equilibrium is reached, the "equilibrium law" is used in place of the "metastable law". Thus the metastability is employed only for a short period at the beginning of the steaming.

5 Results

We performed a complete set of calculations with all the models previously described. Except for the scenario with the corium scattered everywhere in the water pool which was computed only once with the "simultaneous injection" and "equilibrium" water law, the scenarios "sphere" and "bottom" were computed once for the "simultaneous injection", once for the "injection with propagation" and six times with the "marble injection". Some of the computations were duplicated for both "equilibrium" and "metastable" water laws.

The steam explosions were generally computed until 20 or 30 ms, according to the models. CASTEM-PLEXUS can provide either local information versus time or general information at precise time.

For the scenario with the corium scattered, the results are very different from the other scenarios because of the absence of confinement of the pre-mixing zone by the water. The energy really injected after 17 ms reaches 1039 MJ because the density drop is not sufficient to limit the energy injection. However, the effects of the explosion remain very weak. The steaming is low. The pressure only raises until about 20 bar in the whole lower head with a maximum of 25 bar at the bottom, near the vessel. The shell displacements are inferior to 0.5 mm and the stress remains inferior to the elastic limit. Therefore this case was not calculated for the other models.

All the results of the computations are summarized in the table 2. This table presents the maximum pressures P_1 at the bottom and P_2 in the corner during the two peaks, the radial and axial displacements u_r and u_a , the maximum Von Mises

stresses σ , the maximum plastic strains ϵ^p and the injected energies E_{inj} .

5.1 Pressure

For all the pressure curves versus time, we observe instantaneously a first pressure peak at the bottom in the centre, on the symmetry axis (Figure 16).

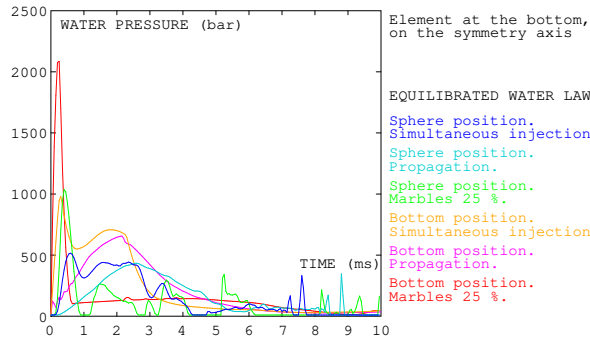


Figure 16: Pressure at the bottom

For the "bottom" case, the amplitude and duration of the peak are :

- around 1000 bar and 2.5 ms in the "simultaneous injection" case,
- about 600 bar and 5 ms in the "injection with propagation" case,
- comprised between 80 and 2100 bar, and less than 1 ms in the "marble injection" cases.

For the "sphere" case, these values are :

- around 500 bar and 2.8 ms in the "simultaneous injection" case,
- about 450 bar and 5 ms in the "injection with propagation" case,
- comprised between 90 and 1000 bar, and less than 1 ms in the "marble injection" cases.

We can remark that the pressure calculated for the "simultaneous injection" cases displays a kind of crenel during about 2.5 ms. This crenel corresponds to the duration of the energy injection. That means that the pressure decreases as soon as the energy injection stops.

For the "marble injection", the pressure rises very fast and very strong during less than 1 ms. This narrow pressure peak is due to the almost infinite exchange coefficient.

The "injection with propagation" cases present smoother pressure curves. The pressure rises slower because of the space-delayed energy injection, but it decreases also later. As the local injection duration is constant, the injection is staggered. The maximum pressure is reached when the pressure

wave corresponding to the injection of energy in the whole corium zone arrives at the bottom.

We observe later a second peak in the top corner corresponding to the down-comer blocking up. This peak can reach 4100 bar. It lasts less than 2 ms and happens around 20 ms for the low energy cases and around 7 or 8 ms for all the others. These very pessimistic results come from the pessimistic down-comer blocking up hypothesis.

The figures 17 and 18 present the propagation of the pressure wave through the lower head for 25 % of marbles and the "bottom" and "sphere" locations.

For the "bottom" location, an over-pressure appears first at the bottom in the whole premixing zone. The pressure wave expands upwards spreading out laterally. After the wave passing, the pressure decreases again locally. Thus when the wave arrives near the top boundary, a low pressure zone has created at the bottom of the lower head. The wave hits the vessel laterally and then goes down along the vessel until the bottom. As the pressure wave has returned at the same place as at the beginning of the explosion, a new cycle starts again but with a lower value of the pressure.

For the "sphere" location, an over-pressure appears in the center of the corium zone located in the middle of the lower head. The pressure zone expands diametrically. Because of the corium zone location, the pressure wave contacts first the lower head at the bottom on the symmetry axis. Then the pressure wave expands laterally because the wave is blocked down by the vessel presence and because of the natural circumferential expansion of the initial sphere zone.

When both overpressure zones join next to the vessel halfway up from the bottom, a unique wave propagates downwards, in a reverse direction, following the vessel shape. Arrived at the bottom, the pressure wave splits into two pieces: the one propagates upwards laterally following the vessel shape, the other propagates upwards vertically starting a new cycle.

5.2 Density and void fraction

The water density decreases from 892 kg/m³ to about 15 kg/m³ into approximately 5 ms for the high energy injections ("simultaneous", "with propagation", "25 % of marbles"). For the low energy injections, the 15 kg/m³ density is reached after a longer time: for instance at 20 ms for 5 % of marbles. For the 1 % marble case, the phenomenon is so slow that the density is still equal to 300 kg/m³ after 30 ms.

The figures 19 and 20 present the void fraction generation in the lower head for 25 % of marbles and the "sphere" and "bottom" locations.

For the "bottom" location, a steam zone appears near the top of the corium zone because it is the less pressurized part of the corium zone. Progressively the whole corium zone vaporizes, except a narrow layer against the vessel. Then the steam zone expands upwards and laterally. Because of the presence of the hole due to the central part of the molten core, the steam goes away vertically. During the explosion, the initial steam blanket near the top limit is crushed and condenses.

For the "sphere" location, the central part and the top of the corium zone start steaming. Progressively the whole corium zone vaporizes, ending by the bottom of the zone. The steam zone takes successively an egg shape, then a pear shape before the steam escapes by the central top hole.

5.3 Temperature

The water temperature of the corium zone increases up to 813 K for the "simultaneous injection" and "injection with propagation" cases. The temperature rise is lower in the "marble injection" cases: the average temperature is in the range 470 K for 1 % of marbles up to 560 K for 25 % of marbles.

With the "metastable" water constitutive law, the temperature difference between the water and the steam increases from 0.7 to 13.3 K going from 1 to 20 % of marbles. For 25 % of marbles, the difference is only 3.7 K: the water becomes almost instantaneously supercritical because of the very high pressurization (Figure 21).

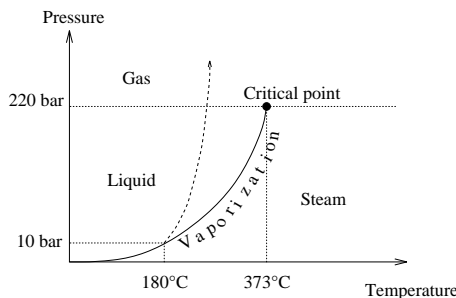


Figure 21: Suppression of the metastability

At the end of the computations, the marble temperature decreases until 800 K for 1 % of marbles and only until 1300 K for 25 % of marbles. For the fast and violent explosions, the corium cannot transfer all its energy to the water because the water vaporized and therefore the heat transfer coefficient is bad.

5.4 Displacements

The maximum radial displacement of the shell is observed at the two third level from the bottom. It

is included between 0.1 and 20 mm, according to the case (Figures 22 and 23). The maximum axial displacement takes place at the bottom on the symmetry axis and is comprised between 1 and 90 mm.

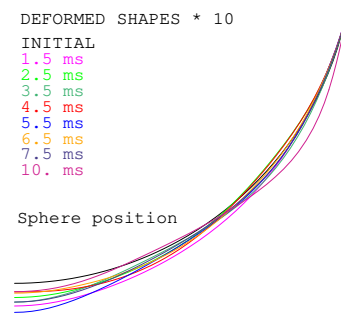


Figure 22: Deformed shape for the "SPHERE" case

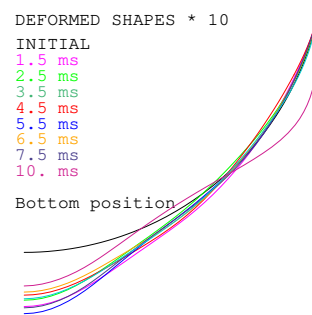


Figure 23: Deformed shape for the "BOTTOM" case

5.5 Stress and strain

The maximum Von Mises stress is located at the bottom on the symmetry axis for all the cases and it reaches 50 to 440 MPa according to the cases. The maximum plastic strain is observed again at the bottom in the centre for all the cases.

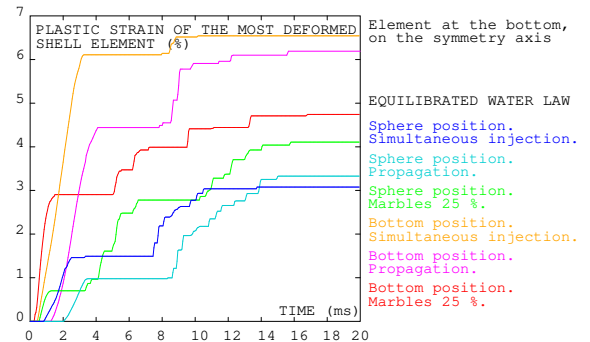


Figure 24: Maximum plastic strain

The plastic strain corresponding to the "sphere" location varies from 0 to 4.1 % and those for the "bottom" location from 0 to 6.5 % (Figure 24). For

the low energy cases, the vessel remains elastic.

5.6 Injected energy

The amount of energy transferred from the corium to the water pertains to the range 35 - 680 MJ. None of the released energies reach the wished 1000 MJ. Indeed, for the "simultaneous injection" and "injection with propagation" calculations, the energy injection is limited by the water density fall. For the "marble injection" calculations, the liberated energy is limited by the marble proportion.

The figure 25 shows the plastic strain versus the injected energy for the "marble injection". Globally, the strain is proportional to the energy.

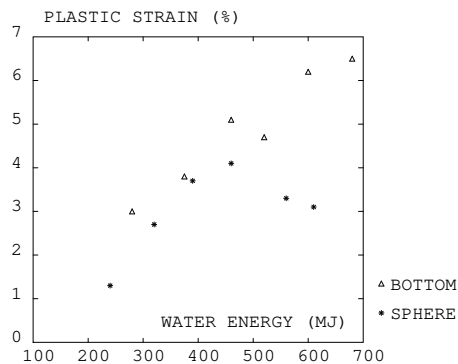


Figure 25: Plastic strain versus energy

6 Conclusion

We presented here general computations with the CASTEM-PLEXUS code to evaluate the effects of a steam explosion on the pressure vessel lower head of a PWR. A parametric study was carried out in order to provide a better understanding of the phenomenon and to weigh up the importance of the variables used to model the explosion.

The three energy injection kinetics "simultaneous injection", "injection with propagation" and "injection with 25 % of marbles" provide more or less the same results because the injected energy amount is very near. Consequently, the energy injection kinetics is not an important parameter. The two water constitutive laws "equilibrium" and "metastable" give the same results. So neither this parameter is an important one.

On the contrary, the results are very dependent on the corium location and on the amount of energy transferred from the corium to water. In the "bottom" location, the confinement due to the vessel proximity and the water above strongly worsens the damages, compared with the "sphere" location.

Generally speaking, taking into consideration the displacements, stresses and plastic strains, the best vessel part in demand is the lowest point of the shell located on the symmetry axis. The stresses and the plastic strains observed depend very much on the injected energy.

Therefore, the important parameters regarding steam explosion mechanical modelling are the corium location and the amount of energy transferred from the corium to the water. These conclusions were used to improve the precision of the computations by developing a method to link thermohydraulic and mechanical computations (Vivien, 1997).

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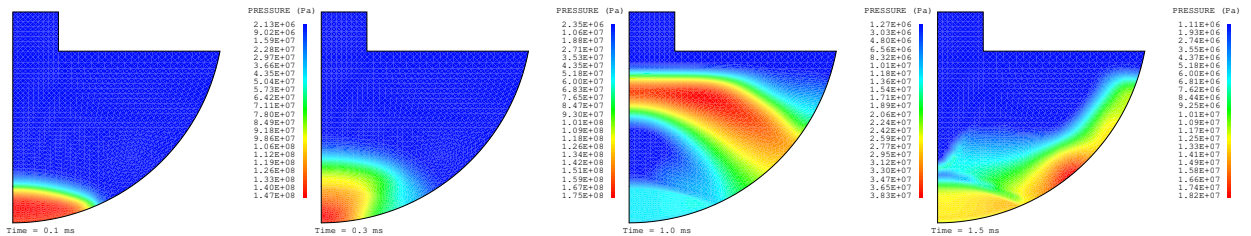


Figure 17: Pressure with the "bottom" location

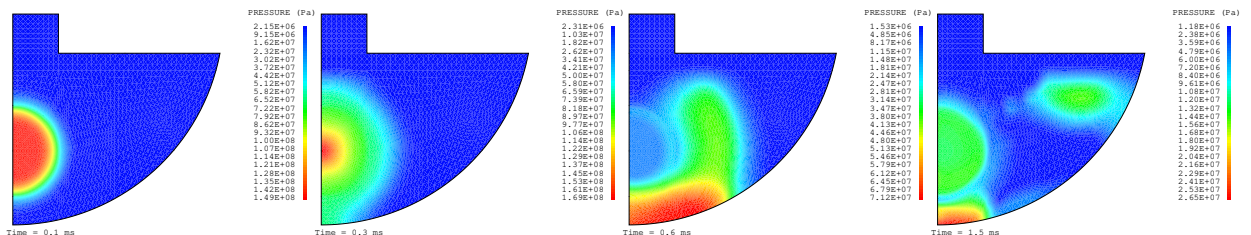


Figure 18: Pressure with the "sphere" location

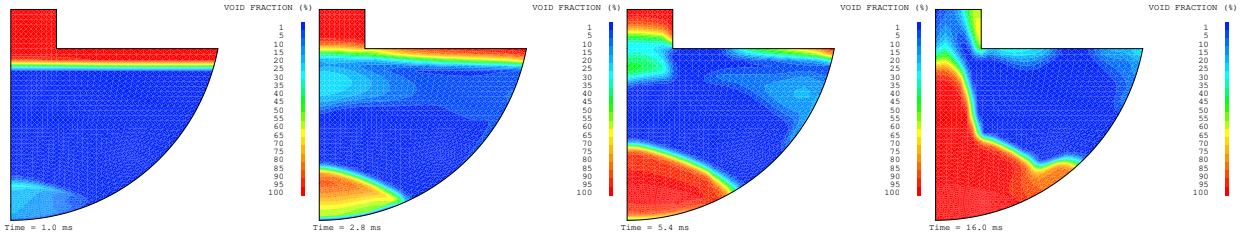


Figure 19: Void fraction with the "bottom" location

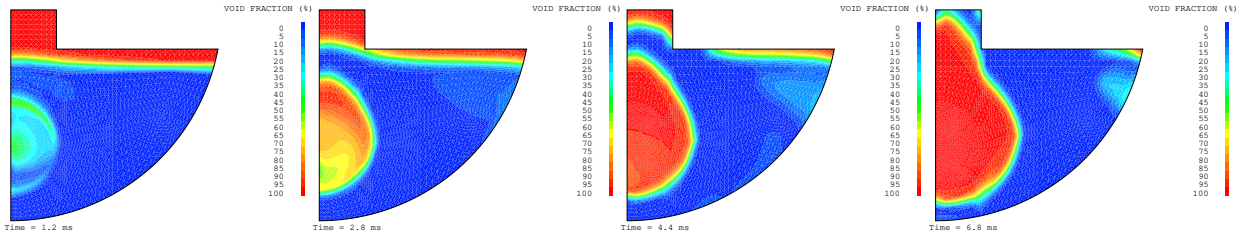


Figure 20: Void fraction with the "sphere" location

| Calculations | | | P_1 (bar) | P_2 (bar) | u_r (mm) | u_a (mm) | σ (MPa) | ϵ^p (%) | E_{inj} (MJ) |
|--------------|---|-------------|----------------|----------------|---------------|---------------|-------------------|---------------------|-------------------|
| Scattered | Simultaneous | Equilibrium | 24.5 | 14 | 0.13 | 0.44 | 27 | 0 | 1039 |
| Bottom | Simultaneous | Equilibrium | 980 | 4100 | 18.5 | 90 | 440 | 6.5 | 680 |
| | Propagation $\rho_{lim} = 0.33 \rho_0$ | Equilibrium | 660 | 3500 | 20.5 | 70 | 440 | 6.2 | 600 |
| | | Metastable | 660 | 2900 | 20.5 | 70 | 440 | 6.2 | 600 |
| | Marbles 1 % | Equilibrium | 79 | 230 | 0.14 | 0.77 | 46 | 0 | 35 |
| | | Metastable | 79 | 230 | 0.14 | 0.77 | 46 | 0 | 35 |
| | Marbles 5 % | Equilibrium | 368 | 255 | 1.51 | 3.6 | 200 | 0.6 | 164 |
| | | Metastable | 368 | 255 | 1.50 | 3.6 | 200 | 0.6 | 164 |
| | Marbles 10 % | Equilibrium | 750 | 800 | 3.3 | 10.5 | 325 | 3.1 | 280 |
| | | Metastable | 745 | 800 | 3.3 | 11 | 325 | 3.05 | 280 |
| | Marbles 15 % | Equilibrium | 1130 | 1650 | 6.5 | 14.5 | 340 | 3.6 | 360 |
| | | Metastable | 1130 | 1650 | 6.51 | 14.5 | 340 | 3.6 | 360 |
| | Marbles 20 % | Equilibrium | 1530 | 1900 | 10.1 | 28 | 373 | 4.2 | 444 |
| | | Metastable | 1520 | 1870 | 10.1 | 28 | 373 | 4.2 | 444 |
| | Marbles 25 % | Equilibrium | 2100 | 2050 | 16.5 | 48 | 430 | 4.7 | 540 |
| Metastable | | 2000 | 1900 | 16.5 | 47 | 420 | 4.7 | 540 | |
| Sphere | Simultaneous | Equilibrium | 1100 | 3350 | 14 | 24 | 440 | 3.1 | 610 |
| | Propagation $\rho_{lim} = 0.10 \rho_0$ | Equilibrium | 550 | 3200 | 14.5 | 17 | 390 | 3.3 | 560 |
| | | Metastable | 550 | 2700 | 14.5 | 17 | 390 | 3.3 | 560 |
| | Marbles 1 % | Equilibrium | 88 | 60 | 0.08 | 0.39 | 26 | 0 | 32 |
| | | Metastable | 88 | 60 | 0.08 | 0.39 | 26 | 0 | 32 |
| | Marbles 5 % | Equilibrium | 413 | 330 | 0.35 | 2.5 | 145 | 0.21 | 150 |
| | | Metastable | 413 | 330 | 0.35 | 2.5 | 145 | 0.2 | 150 |
| | Marbles 10 % | Equilibrium | 850 | 740 | 1.7 | 6.5 | 300 | 1.3 | 240 |
| | | Metastable | 840 | 740 | 1.7 | 6.5 | 300 | 1.3 | 240 |
| | Marbles 15 % | Equilibrium | 1290 | 1170 | 2.20 | 8.6 | 322 | 1.69 | 314 |
| | | Metastable | 1290 | 1200 | 2.21 | 8.6 | 322 | 1.68 | 314 |
| | Marbles 20 % | Equilibrium | 1750 | 1600 | 4.3 | 14.9 | 347 | 2.65 | 384 |
| | | Metastable | 1730 | 1570 | 4.3 | 14.9 | 347 | 2.65 | 384 |
| | Marbles 25 % | Equilibrium | 2400 | 1800 | 7.5 | 20 | 410 | 4.1 | 460 |
| Metastable | | 2400 | 1750 | 7.5 | 20 | 410 | 4.1 | 460 | |

Table 2: Results of the parametric study