Screening calculations on the vessel lower head behaviour due to an in-vessel steam explosion

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ABSTRACT

The mechanical consequences of a steam explosion on a PWR lower plenum vessel are estimated through a parametric study regarding the corium location, the kinetics to transfer the corium energy to the water and the water constitutive law.

1 INTRODUCTION

Since the Three Miles Island accident on the 28^{th} march 1979 and the publication of Rasmussen's report known as WASH 1400, steam explosion has been considered as a potential risk for PWR nuclear power plants in case of a severe accident. The loss of coolant can provoke 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.

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. This paper presents the synthesis of the French work from 1987 to 1995, regarding the possible lower head vessel ruin.

Up to 1987, the mechanical consequences of the explosion were essentially estimated thanks to rough analytical calculations. T.G. Theofanous summarized the knowledge at the time and presented first finite element calculations in [1].

As the development of the French premixing softwares was not sufficient at the time to simulate the explosion, the mechanical consequences of a steam explosion on the lower head could be foreseen by a fast dynamic software, estimating approximately the thermodynamic data. Moreover, these calculations could weigh up the sensibility of the lower head response to various parameters. This presentation is focused on our parametric study.

2 THE ACCIDENT SCENARIO

The hypothetical accident scenario (cf figure 1) considers an in-vessel steam explosion resulting from a large central core degradation. The core central part is molten and is draining into the lower plenum through a 1 m diameter opening (like in [1]). The cylindrical canal between the core and the vessel (down-comer) is blocked up.

The initial pressure in the vessel is 10 bar and the water is initially saturated. The water level is 1.6 m above the bottom. The height of the steam blanket above the water is 0.2 m. 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.

3 SCREENED PARAMETERS

CASTEM-PLEXUS [2] is a general finite element software devoted to 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.

In CASTEM-PLEXUS, the corium interacting with water during the explosion is not modelled. The corium is represented by a zone containing only water and where energy is injected.

The water constitutive laws include vaporization but the models are homogeneous. That means that the two phases are assumed to have the same pressure and no phase sliding.

The parameters studied in the screening calculations can be shared in three sets [3] :
- the location and the shape of the corium zone,
- the energy injection kinetics modelling the thermal transfer from corium to water,
- the water constitutive laws.

3.1 The location and the shape of the corium zone

Assuming a central core collapse after melting, two kinds of steam explosion have been studied. In the first set of calculations, steam explosion is supposed to occur before corium reaches the vessel bottom. In this case, the corium zone is represented by a 0.52 m^3 "**SPHERE**" located in the centre of the water (cf figure 2).

In other calculations, steam explosion is supposed to occur when the corium reaches 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 (cf figure 3).

3.2 The kinetics modelling the thermal transfer from corium to water

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 (like in [1]).

Supposing that the corium mass is M_c = 8000 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

$$E_a = \eta * M_c * E_{th} = 1000 \text{ MJ}$$

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.

The "**SIMULTANEOUS INJECTION**" is a stepwise energy injection. The available energy is calculated at every 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 $m_{corium} = \rho_{corium}\; V_{water}\; Prop_{corium/water} \;= 1066$ kg/m^3. $\rho_{corium} = 8200$ 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 (cf figure 4). 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 energy injection stops when the average water density in a mesh reaches 10 or 33 % of the initial density, so only a part E_{inj} of the available energy E_a is injected. This arbitrary criterion takes partially into account the heat transfer drop due to the steam creation during the explosion.

Like [4], 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 spheres of corium to the liquid water. The initial temperature of the virtual marbles is 2273 K and their diameter is 1 mm. The energy $E_{inj}(t)$ transferred from the marbles to the water is calculated at every step by:

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

where ρ is the water density, $c_p = 600$ J kg^{-1} 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 $\lambda = 3$ W m^{-1} 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 quasi-infinite (10^6 W m^{-2} 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.

We chosed to present computations with 10 and 25 % of marbles in the water, in order to compare the effects of the released energy amount. We assess that the marble number cannot physically exceed 25 % because the highest possible marble rate with all the marbles in contact is 65 % and the water does not vanish when the corium is falling down.

According to [4], a fine fragmentation of the corium drops into droplets 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 has to be triggered off by a disturbing phenomenon. The trigger may be the violent overpressure caused by a neighbouring previous steam explosion. The "**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.

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 is 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.

3.3 The water constitutive laws

The "**EQUILIBRIUM**" constitutive law assumes that, for the diphasic states, liquid water and steam are in thermal and mechanical equilibrium in each mesh ($P_{steam} = P_{water}$ and $T_{steam} = T_{water}$). The vaporization is calculated with a classical thermodynamic formulation.

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 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 not time enough to be realised [5]. 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. The constitutive law considers that : $P_{steam} = P_{water}$ but $T_{water} \geq T_{steam} = T_{saturation}$.

The steam creation happens in 2 steps. The nucleation is a very short step. It corresponds to the bubble creation and their fast initial growth, controlled by inertial effects. The bubble growth lasts a longer time. It is driven by the Rayleigh conduction equations. Our constitutive law does not take into account the nucleation step. The Plesset and Zwik [6] conditions represent the growth of spherical identical vapor bubbles within a uniformly overheated liquid.

4 RESULTS

The calculated steam explosions generally last between 20 and 30 ms, according to the models. CASTEM-PLEXUS can provide either local information versus time or general information at precise time.

For all the pressure curves versus time, we observe instantaneously a first pressure peak at the bottom in the centre (on the symmetry axis). Its amplitude and its duration are:
- around 1000 bar and 3 ms in the "simultaneous injection" case,
- about 600 bar and 5 ms in the "injection with propagation" case,
- comprised between 840 and 2400 bar, and less than 1 ms in the "marble injection" case.

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 18 ms for the low energy cases ("10 % of marbles") and around 7 or 8 ms for all the others. These very pessimistic results come from the pessimistic down-comer blocking up hypothesis.

The water density decreases from 892 kg/m^3 to about 15 kg/m^3 into approximately 5 ms for the high energy injections ("simultaneous", "with propagation", "25 % of marbles"). 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 maximum radial displacement of the shell is observed at the two third level from the bottom. It is included between 2 and 20 mm. The maximum axial displacement takes place at the bottom in the centre and is comprised between 7 and 90 mm.

The maximum Von Mises stress is situated at the bottom in the centre for all the cases and it reaches 340 to 440 MPa according to the cases. The maximum plastic strain is observed again at the bottom in the centre for all the cases. The strains corresponding to the "sphere" location vary from 1.3 to 4.1 % and those for the "bottom" location from 3.05 to 6.5 %.

The amount of energy transferred from the corium to the water pertains to the range 240 - 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: it is unrealistic to go on transferring thermal energy when water is become steam because the thermal exchanges with steam are very low. For the "marble injection" calculations, the liberated energy is limited by the marble proportion.

The figures 5 to 8 present the pressure and the water density for the calculation "Sphere, 25% of Marbles, Equilibrium".

The following table presents the maximum pressures P_1 and P_2 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}.

Calculations			P_1 (bar)	P_2 (bar)	u_r (mm)	u_a (mm)	σ (MPa)	ϵ^p (%)	E_{inj} (MJ)
Bottom	Simultaneous $\rho_{lim} = 0.33\ \rho_0$	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 10 %	Equilibrium	850	1150	3.3	10.5	390	3.05	280
		Metastable	840	1200	3.3	11	390	3.15	280
	Marbles 25 %	Equilibrium	2100	2050	16.5	48	430	4.7	540
		Metastable	2000	1900	16.5	47	420	4.7	540
Sphere	Simultaneous $\rho_{lim} = 0.10\ \rho_0$	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 10 %	Equilibrium	1000	840	1.7	6.5	340	1.3	240
		Metastable	1000	850	1.7	6.5	340	1.3	240
	Marbles 25 %	Equilibrium	2400	1800	7.5	20	410	4.1	460
		Metastable	2400	1750	7.5	20	410	4.1	460

5 INTERPRETATION OF THE RESULTS

The "bottom" corium location is more dangerous, for the vessel lower head behaviour, than the "sphere" location because the injected energies and the plastic strains are higher. For the "bottom" location, the vessel proximity provides a better confinement, so the water displacements due to the propagation of the pressure wave are delayed and the pressure can increase more.

The "simultaneous injection" is the most penalizing energy kinetics because it allows the highest energy injection. But this kinetics is not very realistic because it is unlikely the whole corium to explode at the same time. The "injection with propagation" describes better the explosive phenomenon. Moreover, for an injected energy a bit lower than for the simultaneous case, the maximum plastic strain is hardly different. The "injection with 25 % of marbles" is a little softer. The efficiency of the "marble injection" depends on the proportion of marbles.

Both water constitutive laws provide the same results. The "metastable" modelling is unefficient because the energy supply is so high that the water pressure raises at once above the critical point one ($P_{crit} = 221$ bar) as the water remains liquid. As the metastability takes place only during the diphasic states, the model is quite never used during the energy injection duration.

6 CONCLUSIONS

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. With plastic strains reaching 6 %, the lower head vessel ruin is probable.

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. In the "bottom" location, the confinement due to the vessel proximity and the water above strongly worsens the damages, compared with the "sphere" location. The stresses and the plastic strains observed depend very much on the injected energy (cf figure 9).

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. From these conclusions, we have developped a new calculation method [7] allowing to know precisely the corium location.

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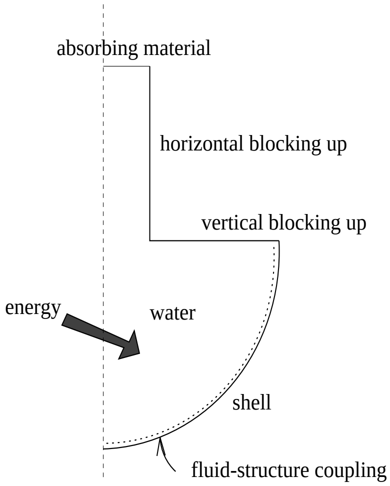


Figure 1: Accident scenario

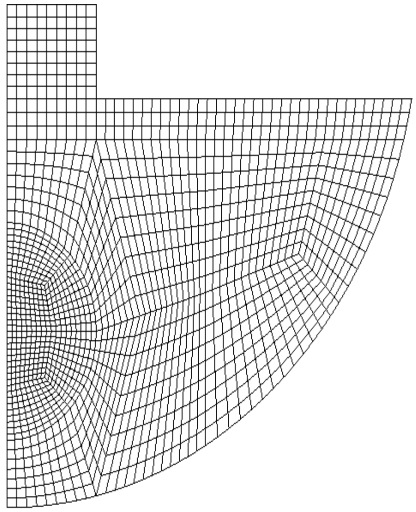


Figure 2: Sphere location

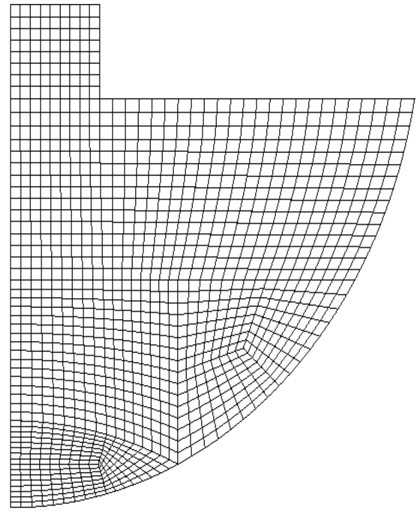


Figure 3: Bottom location

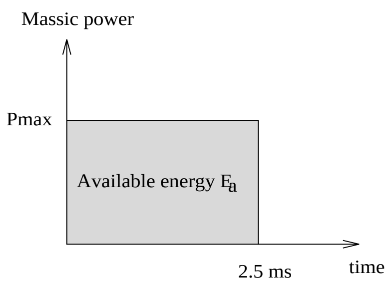
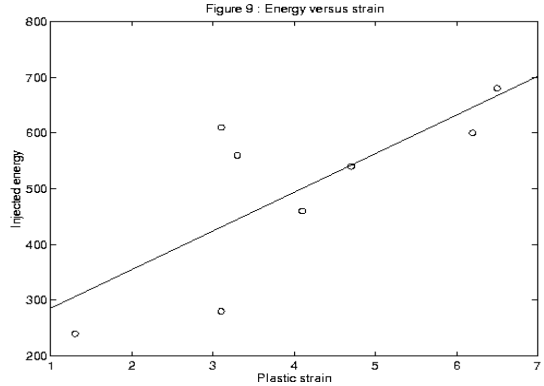


Figure 4: The massic power versus time

Figure 9 : Energy versus strain



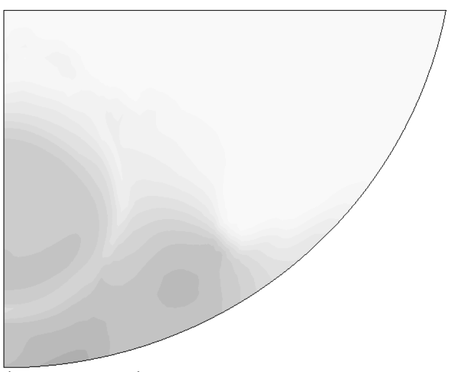


Figure 5: Time = 2 ms - Pressure

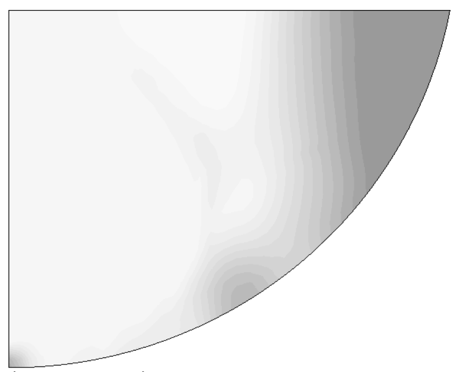


Figure 6: Time = 10 ms - Pressure

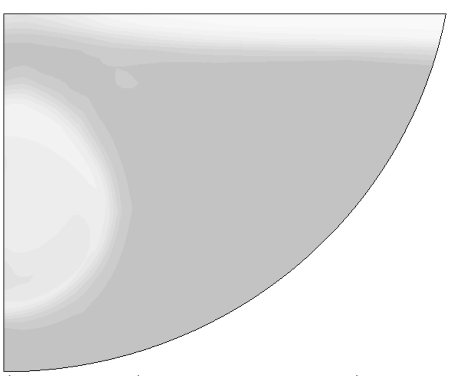


Figure 7: Time = 2 ms - Density

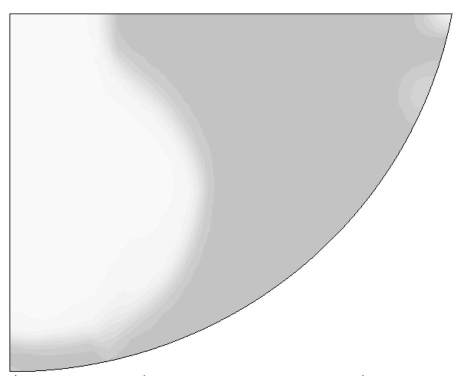


Figure 8: Time = 8 ms - Density