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Thermal-Mechanical Behaviour of the Reactor Pressure Vessel and Corium Molten Pool in a Severe Accident with Core Melt Down

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ABSTRACT

The thermal and mechanical behaviour of a PWR vessel in consequence of a severe accident with core melt down and flooding of the reactor pit has been investigated by refined finite element analyses of the vessel and of the corium. Although the large corium mass and high residual power, the external water cooling avoids complete melt of the vessel but a deep thermal attack is observed in the inner part of the wall with a residual thickness of few centimetres. The high temperature gradients that establish through this thickness cause a high stress level and plastic deformations are observed in a large region of the vessel.

1. INTRODUCTION

In a severe accident in a PWR with core melt down, flooding of the reactor pit is a way to prevent melt through of the lower head but could induce very strong temperature gradients in the vessel wall. When large amounts of core mass with a high residual power ($20 \approx 25MW$) are relocated in the lower head, complete melt of the vessel may be avoided by an efficient debris cooling. Pit flooding is a promising accident management strategy that assures a very efficient external cooling of the vessel if the conditions of nucleate boiling exist at the external vessel surface. In this case the steam generated in the cooling water by the high heat fluxes forms bubbles that are rapidly removed and the external wall remains always wetted. The turbulence generated by the moving bubbles assures an efficient heat removal, the temperature drop at the vessel-water interface is low and the external vessel temperature is kept close to the water temperature. Furthermore, as can be shown by simple computations of heat conduction, the high heat fluxes imply high temperatures of the inner vessel side and sometimes even partial melting. As a result high temperature gradients, that could reach even 1000 Kelvin over some centimetres, establish through the vessel wall.
This induces high thermal-mechanical stresses that add to those originated by the in-vessel pressure and by the lower head and corium weight. Furthermore, because of the lower head partial melting, the primary loads are reacted by a reduced section of the vessel a part of which is at temperatures close to the melting point. Therefore, also for situations where the thermal analysis excludes complete melt, the capability of the vessel to withstand the accidental condition must be assessed by refined stress analyses that account for high temperatures, plastic behaviour and large strains. Of course the knowledge of the temperature field is of crucial importance for the identification of the thermal load, of the residual

thickness and for the mechanical properties of the vessel. In this paper we present a complete analysis of an accidental condition in a PWR with corium relocation and pit flooding. The thermal field has been computed by refined thermal–hydraulic analyses of the corium and of the vessel. These data have been then used for a finite element mechanical assessment of the vessel. The analyses here presented are an exercise finalised to investigate the mechanical behaviour of a vessel under realistic accidental conditions (for large relocated mass and external vessel cooling) and to improve the computation methodology.

2. SCENARIO

Although the aim of this research was not to investigate the consequences of an accident in a particular reactor but rather to draw a general advice on the potential of external cooling as accident management strategy, this exercise has considered realistic reactor characteristics close to those of an EPR. The analysis refers to a large break LOCA occurred in the hot leg of the primary cooling system. Flooding of the reactor pit is provided during the accident. The data on amount and composition of the relocated mass, residual power in the debris and in-vessel pressure have been deduced from computations carried out using the MAAP4 code. The analyses here presented correspond to the late phase of the accident when the relocation is completed and the debris assumes a molten pool configuration. The geometric characteristics of the vessel are given in table 1. A total mass of 280 t of debris is relocated in the lower head. Because of density differences the debris forms a stratified molten pool with an upper metal layer and a lower oxide layer. The residual power, initially 30 MW, is uniformly distributed in the oxide layer and decreases linearly with the time with a rate of 1MW/h. The data on the debris are given in table 2. In the early stage of the accident the reactor pit is flooded and the presence of water is assured during the cooling transient. The water in the pit is in boiling condition (because of the high heat fluxes from the vessel) at the saturated vapour temperature corresponding to the containment pressure of 0.30 MPa. The pressure in-vessel is 0.55 Mpa.

Table 1: Geometric data [m] of the vessel

Lower Head	Inner radius	2.685
	Thickness	0.147
	Inner Height	1.590
Cylinder	Inner radius	2.440
	Thickness	0.250
	Height	9.92

Table 2: Molten pool data

	Composition	Mass [t]	Height [m]	Initial debris power [MW]	Debris power decrease rate [MW/h]
Metal layer	Fe, Cr, Ni, others	110	0.80	----	----
Oxide layer	UO_2, Zr, ZrO_2, others	170	1.67	30	1
Total	----	280	2.47	30	1

3. MODELLING

The computations are based on a finite element method and have been carried out using CASTEM2000 [1] that is a code with potentiality for thermal-hydraulic and structural analyses. Both the thermal and mechanical computations have assumed axial symmetry. The thermal load on the vessel has been computed by a coupled thermal-hydraulic analysis of the corium and of the vessel. The model accounts for phase changes and describes the corium solidification (corium crust) and vessel melting. The convection has been considered in the whole liquid region included the melted vessel. A heat source accounts for the residual power. Thermal radiation has been considered from the upper surface of the pool. The presence of water in the reactor pit has been modelled by a thermal boundary condition at the external vessel surface. This condition, based on experimental correlation [2], accounts for nucleate boiling. The existence of nucleate boiling has been verified comparing at each time step the local heat flux with the local Critical Heat Flux (CHF) [3] [4]. The gap between vessel and corium crust has not been considered and perfect thermal contact has been assumed. The temperature field so computed has been used as thermal load for the mechanical assessment of the vessel. The structural analysis has been carried out under the hypothesis of large displacements and large strains. Two material models have been used depending on the vessel temperature. The vessel region with temperatures below 800 K has been modelled as elastic-plastic with isotropic hardening. For the region with temperatures above 800 K a viscous elastic behaviour has been considered. Here the creep has been modelled using a Norton-Bailey law. To overcome the difficulties related with the vessel melting and the consequent variation of the geometrical configuration, the melted zone of the vessel has been considered in the structural analysis with artificially poor material properties. The steel properties have been taken from experiences carried out at CEA on a 16MND5 steel and cover the range 400-1600 K.

4. THERMAL BEHAVIOUR

The thermal behaviour of the vessel is strictly related with the natural convection inside the molten corium and with the external water cooling. The metal layer convection is characterised by a large eddy flowing downward close to the vessel and upward in the central region of the pool. This eddy, normally well developed, is sometime broken by instabilities that give rise to the formation of smaller eddies that coalesce together in short time.

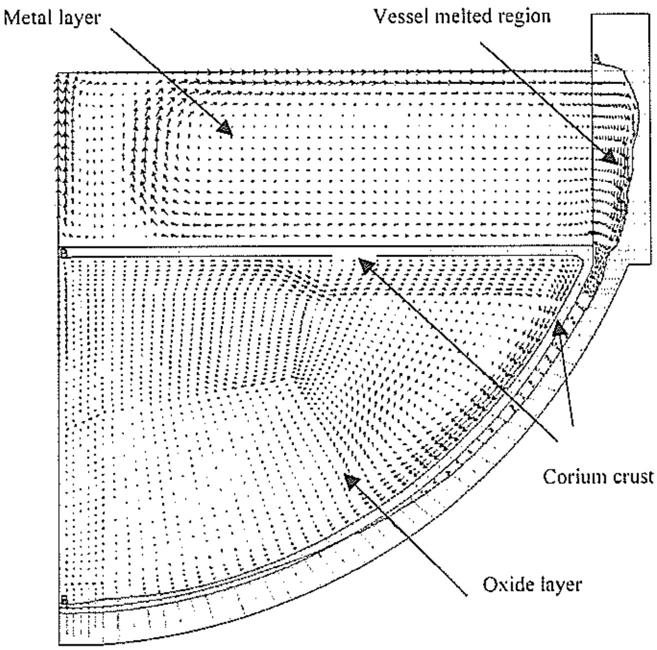

Figure 1 : Velocity field in the corium and in the melted region of the vessel

Despite thermal radiation the upper surface of the metal layer does not solidify. The convection in the oxide layer shows instabilities with the formation of several small eddies overlapping the main eddy that flows downward close to the vessel wall. The oxide pool is bounded by a crust that avoids direct contact between the molten oxide and the vessel. The typical velocity field is shown in figure 1. The heat flux from the vessel to the cooling water is high but remains always lower than the local CHF and the nucleate boiling conditions persist during the whole transient. The thermal attack of the vessel begins in the hemispherical region close to the oxide layer but extends rapidly toward the cylindrical part

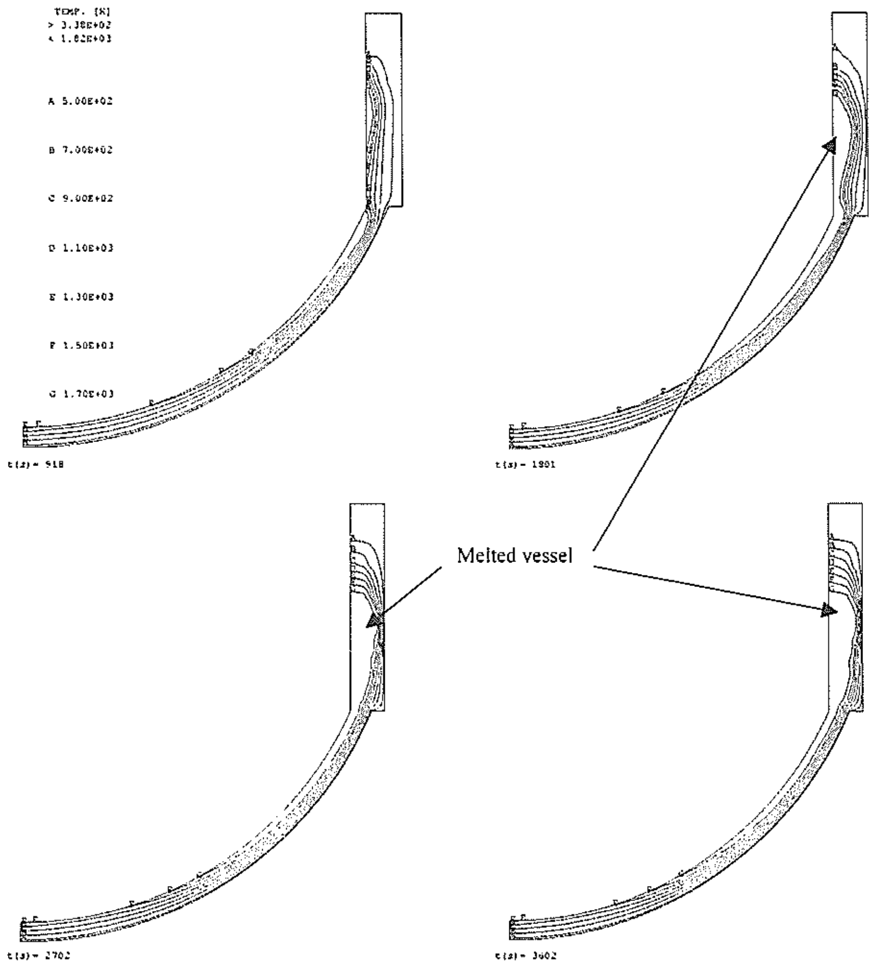

Figure 2: Evolution of the vessel temperature [K]

(see figure 2).
A partial re-solidification is observed in the lower head after 1/2 hour from the beginning of the transient. Roughly in one hour the vessel reaches a stable thermal situation with minor changes during the rest of the transient. Although the metal layer has no residual power the deepest thermal attack of the vessel is observed in the region close to it. This is probably due

to the corium crust that, because of its low thermal conductivity, limits the heat flux from the oxide layer toward the vessel. The residual thickness is $\approx 90mm$ (roughly 3/5 of the initial) in the hemispherical part and $\approx 60mm$ in the cylindrical (1/4 of the initial).
The external surface of the vessel, cooled by water in nucleate boiling conditions, is always kept at low temperature. The worst thermal loading condition is observed along sections in the cylindrical part of the vessel close to the metal layer (figure 3). Here some section in particular shows a thermal gradient of $\approx 1300K$ over the residual thickness of $\approx 60mm$. Part of this residual thickness has a temperature close to the melting point. An external shell, whose thickness is in some point less than 15 mm, has however a temperature below 800K and can be considered free from a creep behaviour.

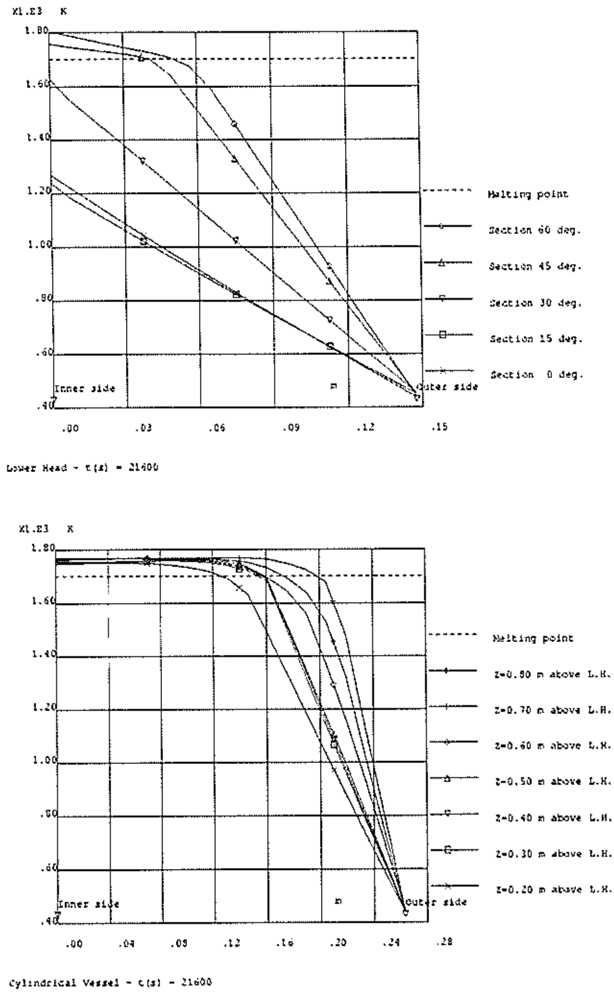

Figure 3: Temperature [K] along radial sections of the lower head (above) and horizontal sections of the cylindrical vessel (below)

5. MECHANICAL BEHAVIOUR

The primary loads (in-vessel pressure and corium weight) are essentially reacted by the most external shell of the vessel. The temperature gradient through the vessel thickness adds a supplementary stress level and the resulting Von Mises equivalent stress distribution is shown in figure 4. The highest stress level is reached in the region above the metal layer. This is probably due to the vertical temperature gradient along the cylindrical vessel generatrix.

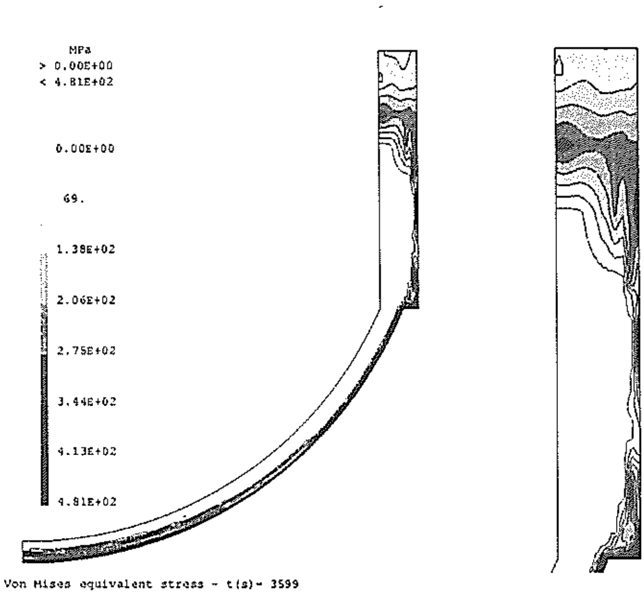

Figure 4 Von Mises equivalent stress

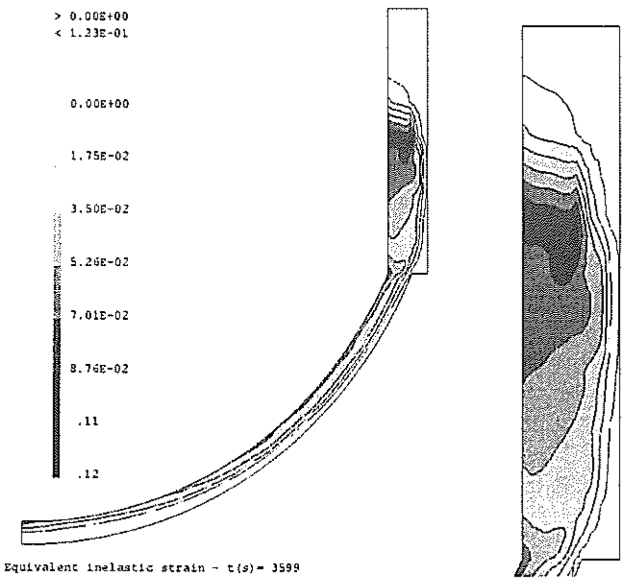

Figure 5 Equivalent inelastic strain. The higest values are reached in the melted region that has been modelled, in the structural analyses, with artificially poor mechanical properties.

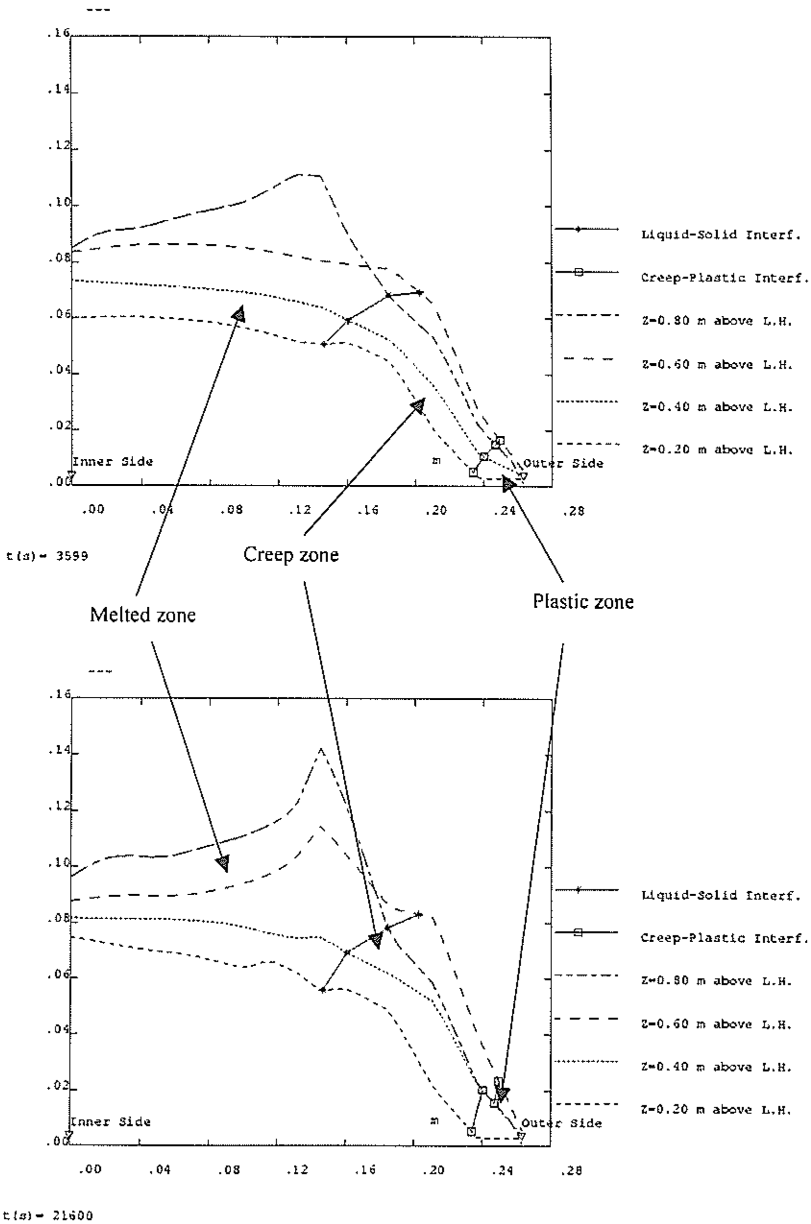

Figure 6 Equivalent inelastic strain along horizontal sections of the vessel after 1 hour (above) and 6 hours (below) from the beginning of the transient. The plastic, creep and melted zones are identified according to the vessel temperature. The melted zone has been considered in the structural analysis with artificially poor mechanical properties.

However as this region is at relatively low temperature it behaves elastically. The conditions of plastic deformations are reached in a large region of the wall close to the molten pool (figure 5). The level of plastic deformation is relatively low in the external part of the vessel. The equivalent inelastic strain distribution along horizontal sections of the cylindrical vessel (figure 6) shows clearly that in the region free from creep the inelastic strain does not exceed $\cong 2\%$. However there is an external shell where the inelastic strain is lower than 1%. In the cylindrical vessel close to the molten pool the most of the residual thickness undergoes creep. Here the inelastic strain reaches $\cong 8\%$ in 1 hours and is less than 10% after 6 hours. As this region is under compression, creep induces a stress relaxation and a reduction of the strain velocity is observed during the cooling transient. The stress and strain redistribution due to the creep deformation has limited consequences on the external part of the vessel.

6. CONCLUSIONS

Flooding of the reactor pit is a way to prevent complete melt of the vessel in case of severe accident with melt down of relevant core mass. However this accident management strategy cannot avoids a thermal attack with melting of the inner part of the vessel and high temperature gradients in the residual thickness. In this conditions also a relatively low in-vessel pressure may induce a high stress level and plastic deformation of the vessel. The external part of the wall remains however at low temperature with a high mechanical resistance. The capability of the vessel to withstand the accidental condition is essentially related with the level of plastic deformation induced in this layer. Creep behaviour, being limited to the inner part of the vessel, seems not to be a key point for the vessel resistance.

ACKNOWLEDGEMENT

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