Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

# Crust instability effect on the vessel thermomechanical behaviour during a PWR severe accident

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ABSTRACT:

Within the framework of the study of vessel behaviour during a PWR severe accident, we propose an analysis of the crust instability effect on the vessel thermomechanical behaviour.
We propose a numerical and an analytical approach.
We show that if the crust frequency rupture reaches a limit, then there is an effect on the vessel residual thickness. In spite of this residual thickness reduction, we conclude that the effects on the vessel mechanical behaviour are weak.
In this study we have taken very conservative hypotheses, whose the main are: local vessel ablation (hot spot), pulling out of the crust and after each crust instability the hot corium comes in contact with the steel vessel.
Nevertheless, we do not take into account, in the mechanical analysis, the discontinuity geometry effects due to the local vessel ablation.

## 1 INTRODUCTION

Within the framework of PWR severe accident studies, scenarios leading to partial or whole core melting are studied. In this case, a molten mixture, called «corium» and essentially composed of high refractory materials ($UO_2$, $ZrO_2$) and metals (Fe, Zr) can flow down towards the lower head (as during the TMI2 accident [1]) and if there is no intervention, melt-through the vessel and spread into the reactor pit.
In the case where an efficient external vessel cooling is kept, we observe a thermal ablation of the vessel up to a steady state. At this time, the knowledge of the vessel thermomechanical behaviour is important to know if the in-vessel corium retention is possible. For that we have to study the vessel thermomecanical behaviour and the influence of the crust growing between the molten pool and the vessel.
In this paper, we propose rough evaluations with very pessimistic hypotheses to show that in the most severe situations the vessel integrity is maintained, if of course a sufficient vessel cooling is kept.
We propose two simplified approaches, analytical and numerical.
In the first part we analyse the thermomecanical behaviour of the vessel, in the steady state and without taking into account the mechanical instability of the crust.
In the second part, we present the main hypotheses and the analytical approach.
In the third part, we present the numerical approach with the CRUST code. This code allowds to simulate the corium/vessel system behaviour, taking into account the conduction phenomena and the crust mechanical behaviour.

Afterwards we compare the two approaches and we finish with the vessel mechanical behaviour at steady state, taking into account the rupture crust effect.

## 2. BEHAVIOUR OF THE CORIUM/VESSEL SYSTEM

When the corium flows down into the lower head, different scenarios are possible: debris bed formation, molten pool formation with or without focusing effect, melt-through with a corium jet. In our study we consider the molten pool situation. The flux repartition versus the height of the vessel is not uniform because of the natural convection phenomena. We can estimate that the mean flux varies between: 0.5 to 2 $MW/m^2$ [2]. With this flux, noted $\varphi_{pool}$, we can estimate the vessel residual thickness by the following relation:

$$e = \frac{\lambda_s \Delta T}{\varphi_{pool}} \qquad (1)$$

with: $\Delta T = T_i - T_e$ the difference between the internal and external vessel temperature,
$\lambda_s$ the steel vessel thermal conductivity.

With this thickness (1) and considering an internal pressure (P = 20 bars) and a radius of the vessel (R = 2.5 m), we obtain the following hoop stress:

$$\sigma = \frac{P.R}{2.e} = \frac{P.R}{2.\lambda_s.\Delta T}.\varphi_{pool} \qquad (2)$$

We can analyze two types of failure: immediate plastic failure and creep rupture.
We have $T_e = 373$ K and $T_i = 1658$ K, in this case we have an exterior elastic non creeping structure. Then we make the hypothesis that all stresses relax in the hot creeping zone. Then we have only to analyze the immediate plastic failure on the cold zone with: $T'_{mean} = 800$ K (we consider that if $T_{mean} < 800$ K there is no creep), and

$$e' = e.\frac{2.(T'_{mean} - T_e)}{\Delta T}$$

We obtain the following results:

| $\varphi_{pool}$ ($MW/m^2$) | $\sigma$ (MPa) |
|---|---|
| 0.5 | 59 |
| 1 | 118 |
| 2 | 236 |

For these temperature values we have $\sigma_{rupture} = 309$ MPa (for SA 533 B steel). Then, with this very simplified analysis, we see that the vessel keeps its integrity.

## 3. INFUENCE OF THE CRUST INSTABILITY

We take the following assumptions:

- We consider a hot spot (radius b) with a local ablation of the vessel. The corium comes in contact with the vessel after each crust instability.
- The temperature between the molten pool and the crust stays constant and equal to the corium melting temperature.
- The mean flux transmitted by the molten pool towards the crust is constant, noted $\varphi_{pool}$.

- The crust can be considered as an embedded plate submitted to the vessel internal pressure.
- There is a ductile/brittle transition temperature for the crust [3].
- Only the crust ductile part is considered in the mechanical analyses.

In the figure 1 we can see the studied system.

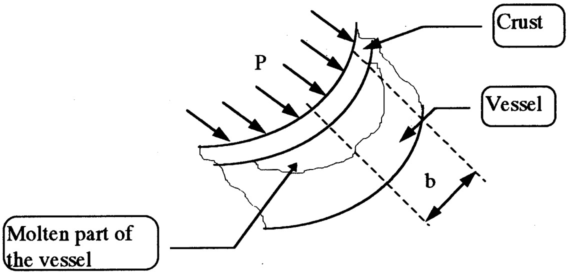


Figure 1: Hot spot modelling with local ablation of the vessel

To study this system, we propose two approaches: analytical and numerical.

## 4. ANALYTICAL APPROACH

In this approach we consider a succession of crust formation and rupture. In this case, the vessel is submitted to a succession of thermal shocks (see figure 2). We can write the flux $\varphi_T$ by mean the contact theory between two bodies:

$$\varphi_T = \frac{2.b_S.(Tit - Tms)}{\sqrt{\pi.\tau_r}} \qquad (3)$$

with $b_s$ the steel effusivity ($b_s = \sqrt{\lambda.\rho.Cp}$), $\tau_r$ the rupture time, Tit the interface temperature and Tms the molten steel temperature.
The interface temperature can be estimated by the following expression:

$$Tit = \frac{b_S.Tms + b_c Tmc}{b_S + b_c} \qquad (4)$$

$b_c$ and Tmc are the effusivity and the molten temperature of the corium respectively.

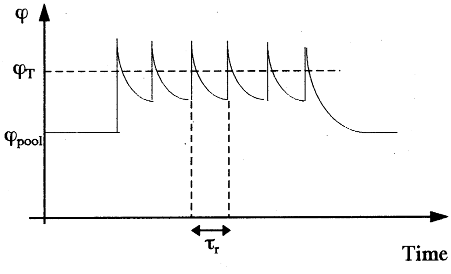


Figure 2: flux evolution

To validate this appoach we have to verify that:

$$\varphi_T > \varphi_{pool}$$

and then with (3)

$$\tau_r < \frac{1}{\pi}.\left(\frac{2.b_s.(Tit - Tms)}{\varphi_{pool}}\right)^2 \qquad (5)$$

moreover, we can estimate the rupture time with mechanical considerations. The crust is considered as an embedded plate submitted to the in-vessel pressure. Mechanically we have two possible situations: first, the vessel thickness ablation is weak, the crust stays in contact with the vessel, submitted to a stress P and an imposed displacement, second, the vessel thickness ablation is high enough to get a crust submitted to a bending stress. The limit between these two cases, is given by:

$$e_m = \frac{\alpha.P.b^4}{E.e_{cr}^3} \qquad (6)$$

$\alpha = 0.1706$ if the hot spot is assumed to be circular.

This equation (6) means that the deflection of the bending crust is equal to the molten thickness ($e_m$) of the vessel.

If we put: $e_m = \sqrt{2.\alpha_s.\tau_r}$ (7) and $e_{cr} = \sqrt{2.\alpha_c.\tau_r}$ (8), with $\alpha_s$ and $\alpha_c$ the thermal diffusivity of the steel vessel and the corium respectively, we obtain with the equation (6) the following expression for the rupture time:

$$\tau_r = b^2.\sqrt{\frac{\alpha.P}{E.(2.\alpha_c)^{3/2}.(2.\alpha_s)^{1/2}}} \qquad (9)$$

With equations (4) and (9), the mean flux due to the thermal shock $\varphi_T$ (equation (3)) can be calculated. Then we can estimate the vessel residual thickness and the interface temperature between the crust and the vessel at the steady state by:

$$e_{res} = \frac{\lambda_s.(Tms - Te)}{\varphi_T} \qquad (10)$$

$$Ti = \frac{e_{res}.\varphi_{pool}}{\lambda_s} + Te \qquad (11)$$

Numerical application:

We take: $b_s = 1.0943.10^4$ IS, $b_c = 3.6638.10^3$ IS, Tms = 1658 K, Tmc = 3000 K,
$\alpha_s = 5.2.10^{-6}$ m$^2$/s, $\alpha_c = 4.7.10^{-7}$ m$^2$/s, E= $10^{11}$ Pa, Te = 373 K,
P = $2.10^6$ Pa

If we assume that $\varphi_{pool} = 0.5$ MW/m$^2$ we find with (3) and (9):

$$\varphi_T = \frac{4.2.10^6}{\sqrt{\tau_r}}$$

and

$$\tau_r = 1.1.10^3.b^2$$

The inequation (5) shows that this approach is justified if: $\tau_r < 70$ s and then the maximun radius is: b = 25 cm.
In the following table we propose a parametric study on the radius of the hot spot (b).

| Radius (m) | Rupture time (s) | $\varphi_T$ (Mw/m$^2$) | Residual thickness (cm) | Interface temperature (K) |
|---|---|---|---|---|
| 0.05 | 3 | 2.4 | 1.3 | 633 |
| 0.1 | 11 | 1.3 | 2.5 | 873 |
| 0.15 | 24 | 0.9 | 3.6 | 1093 |
| 0.2 | 43 | 0.6 | 5.3 | 1443 |

We have two principal unknowns: the residual thickness and the interface temperature. From equations (3), (4), (9), (10), (11), we can deduce that:

$$\text{If} \quad \tau_r < \frac{1}{\pi}.\left(\frac{2.b_s.(Ti - Tms)}{\varphi_{pool}}\right)^2 \quad \text{Then} \quad e_{res} \propto b.\sqrt[4]{\frac{P}{E}}$$

$$Ti \propto \varphi_{pool}.b.\sqrt[4]{\frac{P}{E}}$$

(Notation: ∞ means proportional to)

## 5 NUMERICAL APPROACH (CRUST code [4])

To simulate locally the transient behaviour of the corium/vessel system, we use the one dimensional modelling. The studied system and the limit conditions are presented figure 3.

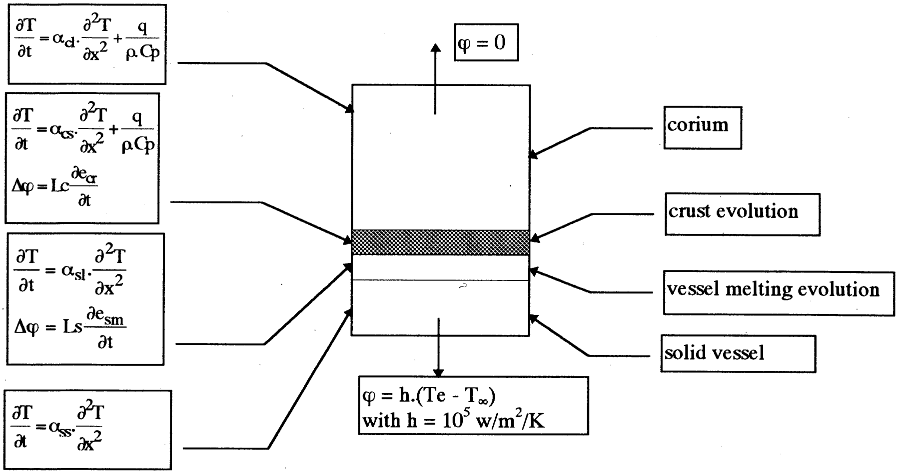


Figure 3: corium/vessel modelling (CRUST)

With: Lc and Ls the latent heat of corium and steel,
$e_{cr}$ and $e_{ms}$ the crust and molten vessel thickness,
$\alpha_{cl}$ and $\alpha_{cs}$ the liquid and solid corium diffusivity
$\alpha_{sl}$ and $\alpha_{ss}$ the liquid and solid steel diffusivity

In order to simulate the natural convection in the molten pool we use a high value for the liquid corium conductivity.

The numerical method used is the Tacke method [5], which allows a correct survey of the melt front evolution.

In this modelling, at every step time, we calculate the stress and strain of the crust, which can be considered as an embedded plate submitted to the internal pressure and corium weight. We consider three criteria for crust rupture:

-immediate plastic failure,

- delayed plastic failure (creep) with Bohaboy model [6],

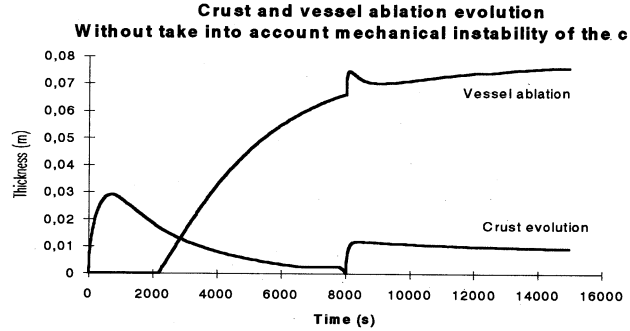
- melting of the crust resistant thickness.

After each mechanical instability, we consider two cases:

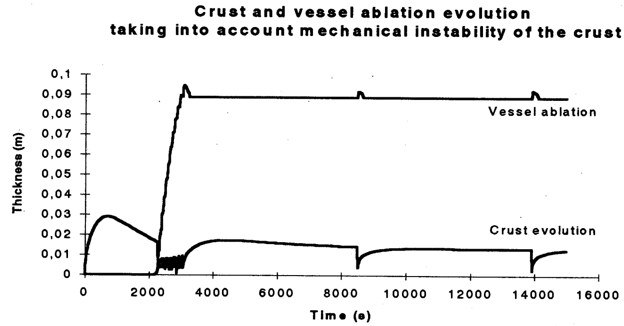
- the pulling out of the crust and instantaneous mixture of the liquid steel with the corium,

- the crust stays in contact with the vessel and continues to keep a thermal resistance.

In the following figures, we can follow the behaviour of the crust and the vessel in both cases.



**Crust and vessel ablation evolution**
**Without take into account mechanical instability of the crust**



**Crust and vessel ablation evolution**
**taking into account mechanical instability of the crust**

In the first graphic, we can see the growth of the crust followed by the vessel ablation. At 8000 seconds we can observe the crust melting and the thermal shock effect on the vessel.

In the second graphic, we can also see the growth of the crust followed by its rupture and a fast vessel ablation up to the steady state.

The steady state is more rapidly reached when we take into account mechanical instability of the crust.

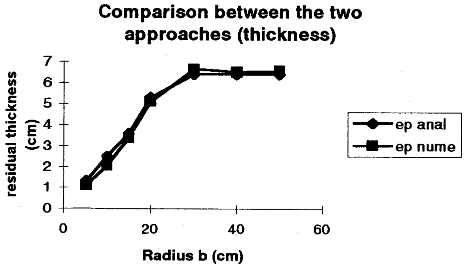
In the following table, we can see the results of different simulations with different hot spot radii.

| Radius b (m) | vessel residual thickness (cm) | Interface temperature crust/vessel (K) |
|---|---|---|
| 0.05 | 1.12 | 578 |
| 0.1 | 2.05 | 839 |
| 0.15 | 3.39 | 1086 |
| 0.2 | 5.11 | 1368 |
| 0.3 | 6.64 | 1688 |
| 0.4 | 6.51 | 1686 |
| 0.5 | 6.56 | 1687 |

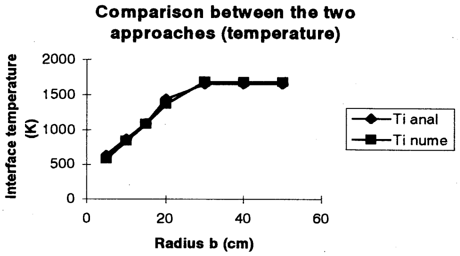
In the analytical theory we have seen that for a radius greater than 25 cm there is no thermal shock effect. This is verified by the numerical simulation.

## 6 COMPARISON BETWEEN THE TWO APPROACHES

If we compare the residual thickness and the interface temperature calculated by the two approaches, we obtain the following graphics:



**Comparison between the two approaches (thickness)**



**Comparison between the two approaches (temperature)**

## 7 VESSEL MECHANICAL ANALYSIS

We assume that the stress can be written as: $\sigma = \dfrac{P.R}{2.e_{res}}$

$e_{res}$ being the residual thickness of the vessel reached at the steady state. If we take a pressure of 20 bars and a radius of 2.5 m we obtain the following results:

| radius b (cm) | $e_{res}$ (cm) | $\sigma$ (MPa) | $T_{mean}$ (K) | $\Delta T$ (K) | $\sigma_{rupture}$ (K) |
|---|---|---|---|---|---|
| 5 | 1.1 | 227 | 475 | 205 | 500 |
| 10 | 2. | 125 | 606 | 466 | 465 |
| 15 | 3.4 | 74 | 729 | 713 | 400 |
| 20 | 5.1 | 49 | 870 | 995 | 275 |
| >20 | 6.6 | 38 | 1015 | 1285 | 230 |

If we compare $\sigma_{rupture}$ and $\sigma$ we obtain that $\sigma < \sigma_{rupture}/2$ and then we have not immediate plastic failure.

For the creep analysis, we have not problem for mean temperatures lower than 800K. For the temperatures greater than 800 K, the stresses are small enough to keep the vessel integrity.

## 8 CONCLUSION

We have studied the behaviour of the crust/vessel system, taking into account the mechanical crust instability. For this analysis, we took very pessimistic hypotheses: there is a local hot spot, the crust instability is local and frequent. We showed that there is a frequency limit of crust rupture, beyond which an effect on the residual thickness can be obtained. For instance, for a flux of 0.5 $MW/m^2$ we need one rupture every 70 s (at least) to obtain an effect. In spite of thickness reduction of the vessel due to this effect, and if we assume that the values of the mean pool flux stays constant, the mean temperature and the gradient decrease, and then the conclusion is that the mechanical stability of the vessel is maintained.
Nevertheless, we did not take into account the discontinuity geometry influence due to the local vessel ablation on the mechanical analysis of the vessel. This last point can be evaluated only by an accurate analysis (by Finite Element) of the problem.

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