Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Numerical modelization of the corium/substratum system

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1. INTRODUCTION

To study severe accident scenarios, the formation and evolution phenomenum of the corium throught the core is very important. Corium is a mixture of different components (UO2, ZrO2, steel, ...) at very high temperature. A corium crust may appear at contact on a cold surface (vessel, plane surface of a core-catcher, ...) or at the free level of a corium pool or accumulation. Crust stability is a difficult problem, because a mixture of mechanic, thermic, hydrodynamic and chimistry fields. In order to simplify the problem, in this paper, we try to study the behaviour of the corium/substratum system in one dimension, the substratum being made up of two layers (see figure 1). The CRUST code solves the heat equation in every layer and at every step-time by the explicit enthalpy method proposed by TACKE [1]. We calculate the stress and strain in crust with simple analytic formulation [3]. Finally we show an application of the corium behaviour on two different substrata made up with a ZrO2 layer and concrete layer for the first and one steel layer for the second. In these examples we study the corium coolability as a function of the crust ultimate stress.

2. PRESENTATION OF THE NUMERICAL METHOD

The studied bodies can be liquid or solid, then we define the enthalpy by the following equations:

$$H = C_{ps}.(T - Tf) \text{ if } T \le Tf$$

$$H = C_{pl}.(T - Tf) + Lf \text{ if } T > Tf$$

C_{ps} and C_{pl} being the specific heat of the solid body and liquid body.

Tf is the melting temperature and Lf the latent heat of melting.

Knowing enthalpy of the body we can calculate its temperature by:

$$T = Tf + \frac{H}{C_{ps}} \text{ if } H < 0$$

$$T = Tf \quad \text{ if } 0 \le H \le Lf$$

$$T = Tf + \frac{H - Lf}{C_{ps}} \text{ if } H > Lf$$

If we write the heat equation with an explicit formulation we obtain the following classical equation:

$$H_i^{(t+\delta t)} = H_i^{(t)} + \frac{\lambda_i}{\rho}.\frac{\delta t}{\delta x^2}.(T_{i-1} - 2.T_i + T_{i+1}) + \frac{q}{\rho}.\delta t$$

with δx the size of the mesh, δt the step time and q the volume power.

Usually, in order to assess the phase front position, we determine the mesh where occurs the body changes of phase (the mesh i0 where $0 < H_{i0} < Lf$) and we calculate an approximation of the solid fraction in this mesh by:

$$Fs = 1 - \frac{H_{i0}}{Lf}$$

With this method we find a front evolution by plateaus and temperatures fluctuation. However in our problem we need good representation of the melting and solidification front evolution to study the crust stability and then we use the Tacke's method to get this good representation.

In Tacke's method, we assume that the temperature profile is linear on both sides of the front in one mesh (see fig 2). With this hypothesis we find that the solid fraction (ξ) in the mesh is solution of the following degre 3 equation:

$$\xi^3.(4 + 2.St_{i0+1} + 2.St_{i0-1}) - \xi^2.(4 + 3.St_{i0+1} + 3.St_{i0-1} + 4.Fs) + \xi.(4.Fs - 3) + St_{i0+1} + 3.Fs = 0$$

with:

$$St_{i0+1} = \frac{C_{pl}.(T_{i0+1} - Tf)}{Lf}$$

$$St_{i0-1} = \frac{C_{pl}.(Tf - T_{i0-1})}{Lf}$$

In this method we get a problem to go from one mesh to another (fig 3).

If $\xi^{t+\delta t} > 1$ then the solidification front goes up.

If $\xi^{t+\delta t} < 0$ then the melting front goes down.

Let us take for example the solidification case.

When the solidification front goes from the mesh $i0^t$ to the mesh $i0^{t+\delta t} = i0^t + 1$, $H_{i0}^{(t+\delta t)}$ and $H_{i0+1}^{(t+\delta t)}$ are not estimated correctly. Let $H_{i0}^{(t+\delta t)*}$ be the correct enthalpy and let $r.\delta t$ be the time to fill the mesh (see fig 3).

Making an enthalpy balance we have:

$$H_{i0}^{(t+\delta t)*} = H_{i0}^{(t+\delta t)} + \alpha.(\phi_{io+1} - \phi_{io})$$

$$H_{i0+1}^{(t+\delta t)*} = H_{i0+1}^{(t+\delta t)} - \alpha.(\phi_{io+1} - \phi_{io})$$

with: $\alpha = \frac{(1-r).\delta t}{\rho.\delta x}$

Assuming that on the interval $[\, t\, ,\, t + \delta t\,]$ the velocity phase change is linear, we obtain:

$$r = \frac{1 - \xi^t}{\xi^{t+\delta t} - \xi^t}$$

3. BOUNDARY CONDITIONS

We have considered three kinds of boundary conditions:

- Convective exchange with the external atmosphere: $\phi = \dfrac{T_N - T_\infty}{\dfrac{1}{h} + \dfrac{\delta x}{2.\lambda}}$
- Radiant exchange: $\phi = \varepsilon.\sigma.(T_i^4 - T_\infty^4)$

T_i is the interface temperature calculated with the solution of the following degre 4 equation:

$$\varepsilon.\sigma.T_i^4 + \left(h + \frac{2.\lambda}{\delta x}\right).T_i - h.T_\infty - \frac{2.\lambda}{\delta x}.T_N - \varepsilon.\sigma.T_\infty^4 = 0$$

- Contact with another body (see fig 3): $\phi_{N+1}^{(1)} = \phi_1^{(2)} = \dfrac{T_N^{(1)} - T_\infty^{(2)}}{\dfrac{\delta x1}{2.\lambda 1} + \dfrac{\delta x2}{2.\lambda 2} + R}$

R being the thermic contact resistance

4. NATURAL CONVECTION IN THE LIQUID

The natural convection is modelised by a modification of the liquid conductivity versus time. The conductivity evolution law is shown in figure 4. Parameters λ_{max} maximum conductivity, t_b and t_e the beginning time and end time of transition phase, are given by the user.

5. ASSESSMENT OF THE CRUST STABILITY

- Hypothesis 1

There is a ductile/brittle transition temperature (1600 K for UO2) [2]

- Hypothesis 2

The brittle part is wholly cracked. There is a large thermic gradient along the crust thickness.

- Hypothesis 3

The ductile part is submitted to the following mechanical loadings:

- pressure ΔP (hydrostatic, degassing of the substratum...)
- shear stress τ (natural or/and forced convection)

- Hypothesis 4

We consider three criteria for the crust failure:

- immediate plastic fracture: $\sigma > \sigma_{max}$
- delayed plastic fracture (creep): $\varepsilon > \varepsilon_{max}$
- melting of the crust resistant thickness

With these hypotheses we can compute the stress and strain in different configurations [4]. After the first unstability, we assume that the crust vanishes and the liquid corium make contact with substratum and then another crust can appear and disappear successively. Other scenarios may be envisages, for example the crust becomes porous and stays in contact with substratum.

6. APPLICATION

We use the CRUST code to study the cooling of a corium accumulation, with volume power, on a substratum. We consider two substrata, the first with two layers (ZrO2 and concrete) to simulate the core-catcher ablation and the second with one steel layer to simulate the vessel ablation. The physical characteristics of different components are in the table 1.

6.1 Application 1

We study the coolability of 40 cm of corium in contact with a substratum made of one ZrO2 layer (20 cm) and one concrete layer (1 m). In figure 5 we can see the evolution of different fronts like the upper crust (curve C), the lower crust (curve B) and the ZrO2 melting front (curve A). Concrete does not melt before 1000 seconds in this case. The crust failure occurs by melting of its resistant thickness at about 400 seconds after the corium arrival.

6.1 Application 2

We study the coolability of 1 m of corium in contact with a steel substratum (14 cm). In figures 6 and 7 we can see the evolutions of lower crust (curve B) and ablation of substratum (curve A) in two cases, $\sigma_r = 50\,MPa$ and $\sigma_r = 5\,MPa$. In the first case, we get the delayed plastic fracture (creep) at 580 secondes. In the second case, we get an instantaneous plastic fracture at about 500 secondes.

7) CONCLUSION

The CRUST code was developed to study thermal evolution of corium on a substratum. This code resolves the heat equation with change of phase using Tacke method. This method allows to follow with a good precision the crust evolution. At each step time, the code gives an assessment of the stress and strain in the crust, allowing a study of its stability.

With this code, we can study the relative influence between the different parameters like cooling mode, depth of corium, substratum characteristics, ultimate stress of the crust, and so on. We have given two examples of application with two different substrata to show the capabilities of CRUST code.

8) REFERENCES

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table 1

material	Cp $J/Kg/^0C$	λ $W/m/^0C$	ρ Kg/m^3	Tf ^0C	L J/Kg
corium	565	2.88	8020	2850	$3.39.10^5$
ZrO2	670	2.08	6000	2800	$3.39.10^5$
concrete	1100	2.3	2400	1600	$2.47.10^6$
steel	632	37.5	7890	1385	$2.47.10^5$

figure 1

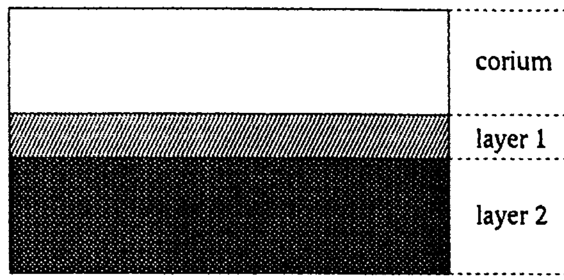


figure 2

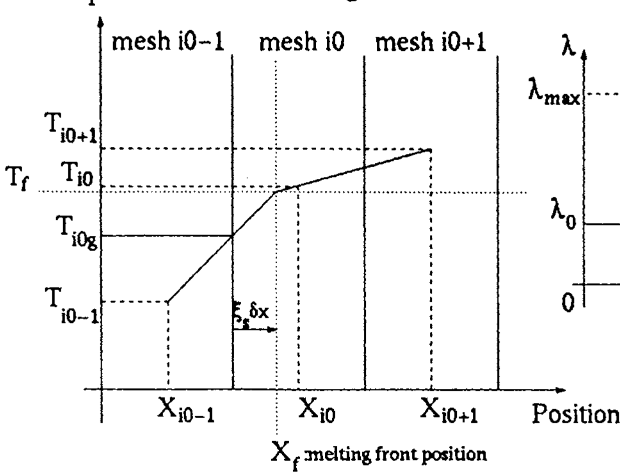


figure 4

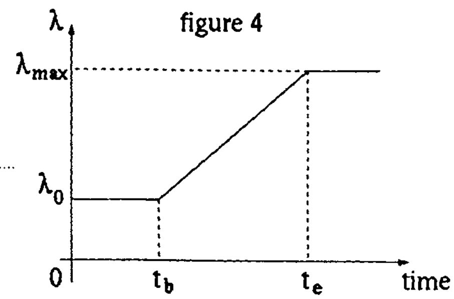
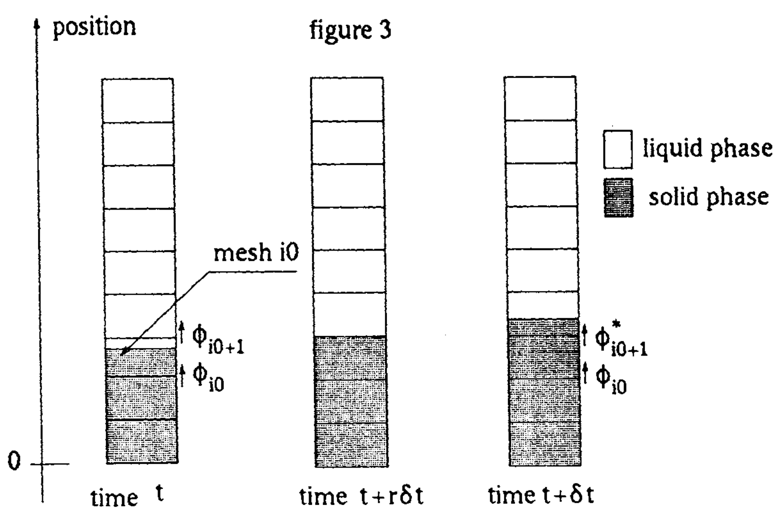


figure 3



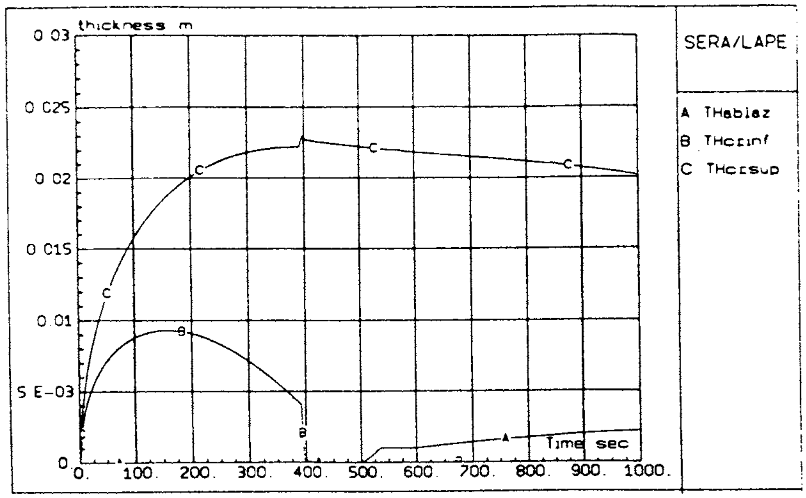


Figure 5

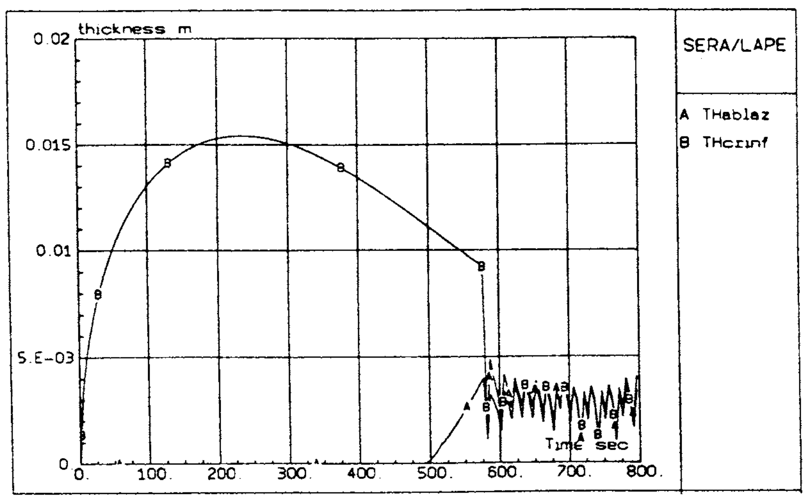


Figure 6

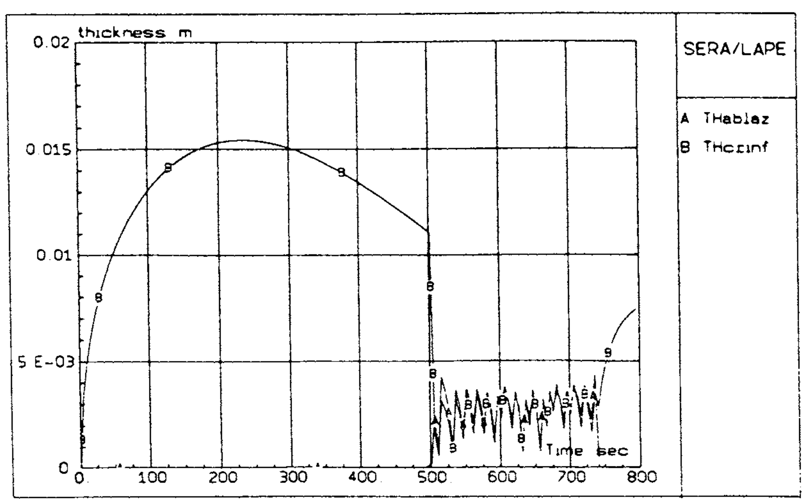


Figure 7