STUDY OF CORIUM RADIAL SPREADING BETWEEN FUEL RODS IN A PWR CORE

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Abstract

In the framework of severe accident studies for PWR like Three Mile Island Unit 2 (TMI-2), the reactor core essentially constituted of fuel rods begins to heat and then to melt. During the early degradation phase, a melt (essentially UO2 and ZrO2) that constitutes the corium flows first along the rods, and after a blockage formation, may radially propagate towards the core periphery.

A simplified model has been elaborated to study the corium freezing phenomena during its crossflow between the fuel rods. The corium spreads on an horizontal support made, of either a corium crust, or a grid assembly.

The model solves numerically the interface energy balance equation at the solid-liquid corium interface and the monodimensionnal heat balance equation in transient process with convective terms and heat source (residual power). "Zukauskas" correlations are used to calculate heat transfer coefficients.

The model can be integrated in severe accident codes like ICARE II (IPSN) describing the in-vessel degradation scenarios.

1. INTRODUCTION

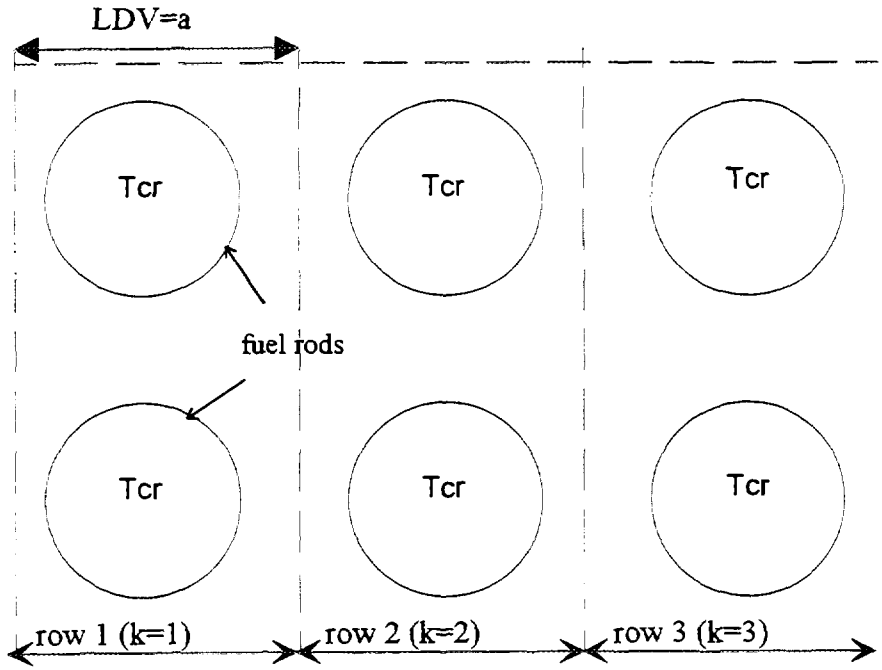
We have to solve a corium phase-change liquid-solid problem during corium spreading between the fuel rods. The fuel rods are considered as smooth tubes and they are arranged in an in-line tube bank (see Fig.1). The first row represents the corium inlet in the tube bank. The fuel rods stay at a constant temperature less than the corium melting temperature. A simplified model has been elaborated to study the corium freezing phenomena during its crossflow between the fuel rods. The model solves numerically two equations : the interface energy balance equation at the solid-liquid corium interface and the monodimensionnal heat balance equation in transient process with convective terms and heat source (residual power). The first equation determines the corium crust thickness which forms around the fuel rods. The second equation calculates the temperature evolution of the corium which flows between the fuel rods in the direction of the flow.

2. DETERMINATION OF THE CORIUM CRUST THICKNESS

The corium is a mixture of different components (UO2, ZrO2, Steel, ...). In the present study, the corium is considered like a pure material. The phase change takes place at a discrete temperature T_f , and the solid and liquid phases are separated by a sharp moving interface. The requirement on the continuity of temperature at the solid liquid interface is given by :

$$T_s(r,t) = T_l(r,t) = T_f$$

where $T_s(r,t)$ et $T_l(r,t)$ are respectively the temperatures of the solid and the liquid phases, and T_f is the melting (or solidification) temperature. The energy equation at the solid-liquid interface for the



$$t'(1)=\frac{LDV}{U_{max}^{n'}} \qquad t'(2)=\frac{LDV}{U_{max}^{n'}} \qquad t'(3)=\frac{LDV}{U_{max}^{n'}}$$

Fig.1 Cross-sectional view of fuel rods arranged in an in-line tube bank

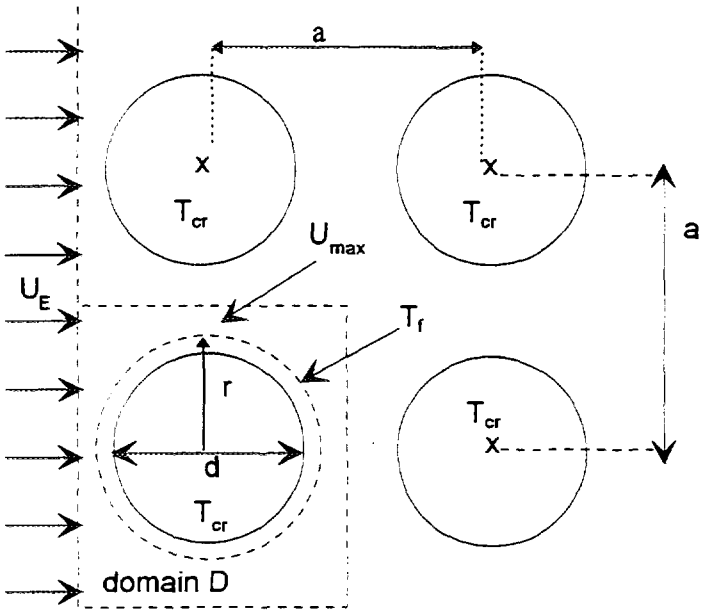


Fig. 2. Interface energy balance equation solved in the domain D

solidification problem [1] can be stated as :

$$\varphi_l - \varphi_s = \rho_s L \frac{dr}{dt} \qquad (1)$$

where φ_l et φ_s are the heat fluxes (in W/m^2), L is the latent heat of melting per unit mass of the material (in J/kg) and ρ is the density (in kg/m^3). If the heat transfer on the liquid side is controlled by convection characterized by a heat transfer coefficient h_m, and on the solid side by conduction, the equation (1) can be written :

$$\lambda_s \frac{\partial T_s}{\partial r} - h_m \left(T_M - T_f\right) = \rho_s L \frac{dr}{dt} \qquad (2)$$

where T_M is the inlet temperature of the liquid corium in every row. By considering the conduction phenomenon has reached the steady state in the solid phase, the term $\lambda_s \frac{\partial T_s}{\partial r}$ can be written in cylindrical coordinates :

$$\lambda_s \frac{\partial T_s}{\partial r} = \lambda_s \frac{\left(T_f - T_{cr}\right)}{r \ln\left(2r / d\right)}$$

Equation (2) can be stated as :

$$\lambda_s \frac{\left(T_f - T_{cr}\right)}{r \ln\left(2r / d\right)} - h_m \left(T_M - T_f\right) = \rho_s L \frac{dr}{dt} \qquad (3)$$

This energy balance equation is solved in a domain D. It is indicated by a dotted-lined square on figure 2. The maximum radius r_{max} cannot exceed the value a/2.

2.1 Assumptions

- The corium crust is concentric with the fuel rod.
- The fuel rod temperature is constant.
- The corium density does not change with phase change.
- The inlet temperature T_M represents the inlet temperature of the liquid corium in every row. This temperature changes with the time step except for the first row where T_M is considered constant. T_M is defined in the paragraph 4.

2.2 Zukauskas correlations [2]

Zukauskas has established correlations which determine the mean Nusselt number of a crossflow in an in-lined or staggered tube bank. Heat transfer in the first row of tube bank is generally different compared to the heat transfer in the inner rows. It principally depends on the Reynolds number value, the tube bank arrangement and the intertubular spacing. Above a Reynolds number of 10^3, the flow turbulence in intertubular spacing of the tube bank increases and heat transfer in inner rows becomes more intensive than in the first row. Turbulence is generated by the first rows of tubes and affects heat transfer in inner rows. Thus, for the first row of in-line tube banks, the mean Nusselt number Nu_m is given by Zukauskas as follows :

- If $1 \leq Re_{max} \leq 10^2$ then $Nu_m = 1.02 \cdot Re_{max}^{0.36} \cdot Pr_l^{0.36} \cdot \left(\frac{Pr_l}{Pr_s}\right)^{0.25}$
- If $10^2 \leq Re_{max} \leq 1.5.10^3$ then $Nu_m = 0.7 \cdot Re_{max}^{0.45} \cdot Pr_l^{0.36} \cdot \left(\frac{Pr_l}{Pr_s}\right)^{0.25}$

For the inner rows, the mean Nusselt number Nu_m is given as follows :

- If $1 \leq Re_{max} \leq 10^2$ then $Nu_m = 0.9 . Re_{max}^{0.4} . Pr_l^{0.36} . \left(\frac{Pr_l}{Pr_s}\right)^{0.25}$
- If $10^2 \leq Re_{max} \leq 10^3$ then $Nu_m = 0.52 . Re_{max}^{0.5} . Pr_l^{0.36} . \left(\frac{Pr_l}{Pr_s}\right)^{0.25}$
- If $10^3 \leq Re_{max} \leq 2.10^5$ then $Nu_m = 0.27 . Re_{max}^{0.63} . Pr_l^{0.36} . \left(\frac{Pr_l}{Pr_s}\right)^{0.25}$

The heat transfer coefficients h_m are determined by the expression : $h_m = \lambda_l . Nu_m / d$. In these correlations, the Reynolds number Re_{max} is defined by the maximum corium velocity between the neighboring tubes, U_{max}. This velocity is determined as follows :

$$U_{max} = U_E \frac{a}{a - 2r}$$

where U_E is the inlet velocity of the corium in the tube bank. U_{max} is obtained by the balance flow rate equation in the tube bank [3]. The velocity U_{max} has a finite value : in the present study, when the Reynolds number Re_{max} exceeds the value 2.10^5, the velocity stops to change. The pressure losses are not considered.

2.3 Discretization of equation (3)

$$r^{n+1} = r^n + \frac{\lambda_S . \Delta t}{\rho_S . L} \cdot \frac{(T_f - T_{cr})}{r^n . \ln(2r^n / d)} - \frac{h_m . \Delta t}{\rho_S . L} (T_M^n(k) - T_f \qquad (4)$$

The inlet temperature $T_M^n(k)$ of the liquid corium changes with the time step and with the row. This evolution is determined by the solution of a second equation, the heat balance equation.

3. DETERMINATION OF THE TEMPERATURE EVOLUTION OF THE LIQUID CORIUM

The heat balance equation determines the temperature evolution of the corium which flows between the fuel rods in the x direction of the flow.

3.1 Study domain

The heat balance equation is solved in the domain V shown by the dotted line rectangle in figure 3. The domain V represents the liquid corium crossing between the tubes. The domain decreases widthwise when the crust appears around the tubes, the crust growth being determined by equation (4). The temperature of the longitudinal wall of the domain V is equal to the melting temperature of the corium T_f. The length of the domain V (LDV) is equal to the tube bank pitch (a). The heat balance equation can be stated as :

$$\frac{\partial T}{\partial t} + U_{max} \frac{\partial T}{\partial x} = \frac{h_m (T_f - T)}{e . \rho . Cp} + \frac{q}{\rho . Cp} \qquad (5)$$

The conduction terms are neglected because the Peclet number is more than 10.

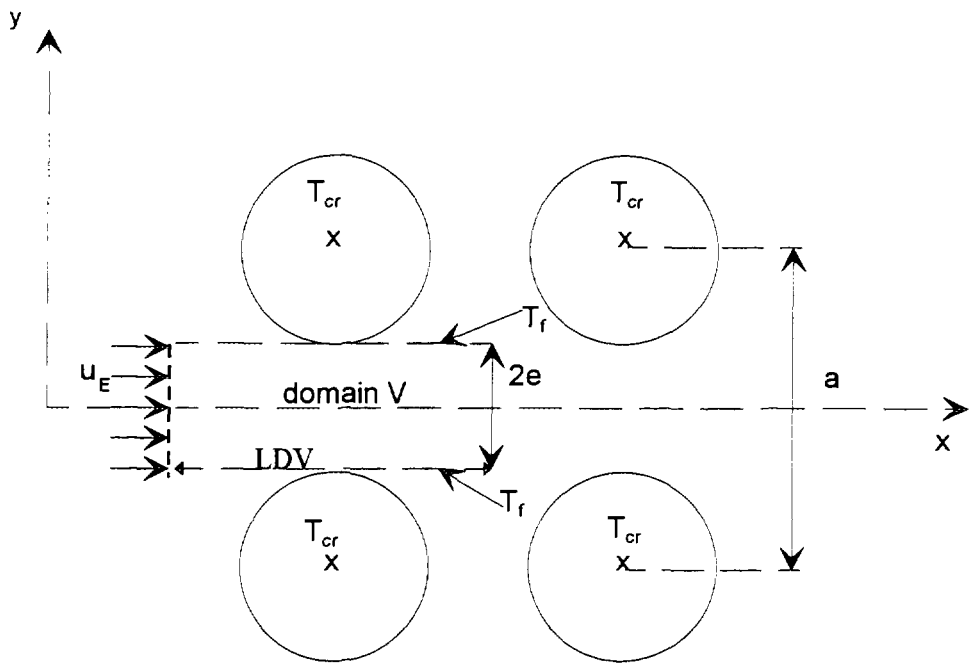


Fig. 3. Heat balance equation solved in the domain V

3.2 Discretization of the equation

The equation is discretized with an explicit finite difference scheme. We use an upwind scheme [4] to avoid the possible instability due to a centered discretization :

$$T_i^{n+1}(k) = \frac{U_{max}^n . \Delta t}{\Delta x} . T_{i-1}^n(k) + \left[1 - \frac{U_{max}^n . \Delta t}{\Delta x} - \frac{h_m^n . \Delta t}{e^n . \rho . Cp} \right] . T_i^n(k) + \frac{\Delta t}{\rho . Cp} \left[q + \frac{h_m^n}{e^n} T_f \right] \qquad (6)$$

with :

$$U_{max}^n = U_E \frac{a}{a - 2r^n} \qquad e^n = (a - 2r^n)/2 \qquad h_m^n = \lambda_s . Nu_m^n / d$$

The upwind scheme of equation (6) is stable if the time step Δt is less than the rate $\frac{\Delta x}{U_{max}}$.

4. THE HEAT BALANCE EQUATION COUPLING WITH THE INTERFACE ENERGY BALANCE EQUATION

The corium crust thickness which forms around the fuel rods is calculated by equation (4). However, the corium temperature is decreasing as and when the corium penetrates in the banks. This temperature can be obtained by equation (6) which determines the liquid corium temperature evolution according to corium spreading in the tube bank. Each temperature $T_i^n(k)$ is calculated in each row of the tube bank during a local time $t_{lo}(k)$. $T_i^n(k)$ depends on the local time $t_{lo}(k)$ defined by $t_{lo}(k) = t_g - \Sigma t'$. $\Sigma t'$ is the sum of the time t' necessary for the corium to cross the $(k-1)^{th}$ precedent rows. t_g is the global time in the bank (see Fig.1). The time t' necessary for the corium to cross the row k (domain V) is defined by the following expression :

$$t'(k) = \frac{LDV}{U_{max}^{n'}}$$

The domain V only varies in width, its length stays constant and equal to LDV. The global time t_g is the time of corium spreading in the tube bank. For example, in the $(k+1)^{th}$ row, t_g is equal to the sum of the time t' necessary for the corium to cross the first k rows plus the local time $t_{lo}(k+1)$ of the $(k+1)^{th}$ row.

In the first row, the boundary conditions are :

$$T_M^n(1) = T_E \quad T_i^0(1) = T_I \qquad T_0^{n>0}(1) = T_E$$

From the second row, we have :

$$T_M^n(k+1) = T_{LDV}^{n+n'}(k)$$
$$T_0^n(k+1) = T_{LDV}^{n+n'}(k)$$
$$T_i^0(k+1) = T_{LDV}^{n'}(k)$$

where : $T_{LDV}^{n'}(k)$: temperature at the end of the k^{th} row at the time t'(k).

$T_M^n(k+1)$: inlet temperature of the $(k+1)^{th}$ row at the time $t_{lo}(k+1)$.

The maximum corium spreading in the tube bank (blocking) is reached when the liquid corium temperature $T_i^n(k)$ in the domain V is equal to the solidification temperature of the corium.

5. APPLICATION

5.1 Physical characteristics and parameters

The fuel rods are arranged in an in-line tube bank with a pitch equal to 12.6 mm. The fuel rod diameter is equal to 9.5 mm, the intertubular spacing is then equal to 3.1 mm. The dimensions and arrangement of the tube bank correspond to the fuel rod assembly in a PWR core. In the present numerical example, the inlet velocity of the corium is chosen equal to 5.10^{-2} m/s. This value is generally used in computer codes describing invessel degradation scenarios to represent the corium spreading velocity in the core. The melting temperature is set at 2800 K, the inlet temperature of the bank T_E is equal to 3000 K, the fuel rod temperature takes the value 2000 K. The physical characteristics of the corium used in the numerical application are :

$\rho = 8.10^3$ kg/m^3 $\quad \lambda = 3$ W/m.K $\quad Cp = 5.10^2$ J/kg.K

$\mu = 5.10^{-3}$ kg/m.s $\quad L = 3.10^5$ J/kg $\quad q = 2.10^6$ W/m^3.

The minimum Reynolds number for the corium flowing is equal to 760.

5.2 Results

Figures 4 to 9 show the evolution of the corium crust thickness as a function of the global time t_g and the location of the fuel rod in the bank. There is a time lag between the successive rows about the start of crust formation to take into account the necessary time for the corium to cross a row. From a time t_{lo}, the crust thickness in a row does not progress and the steady-state is reached. When the corium penetrates into the tube bank, the maximum crust thickens more and more. At the 20^{th} row, the corium spreading stops, the corium crust entirely fills the intratubular spacing. The corium has crossed twenty rows : this corresponds to the crossing of a fuel rod assembly in a PWR core (17 rows) plus three rows in a neighboring assembly. Figure 10 shows the variation of the liquid corium temperature with the corium penetration into the tube bank. This variation is determined when the corium crust has reached its maximum thickness in every row. We can notice that the residual power q included in the source term given in the equation (5) has no influence. This term is negligible compared with the convection term.

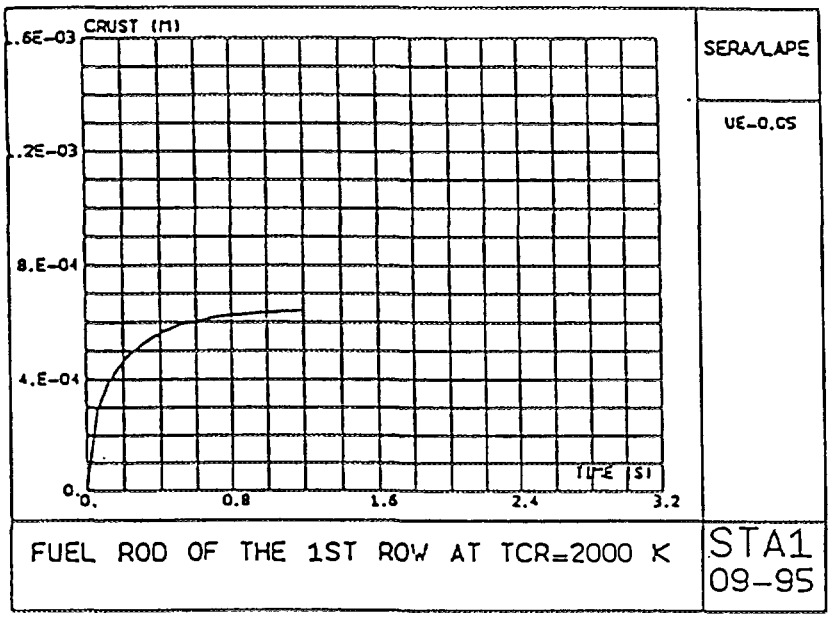


Fig. 4: Evolution of the corium crust thickness with the global time t, (I st row).

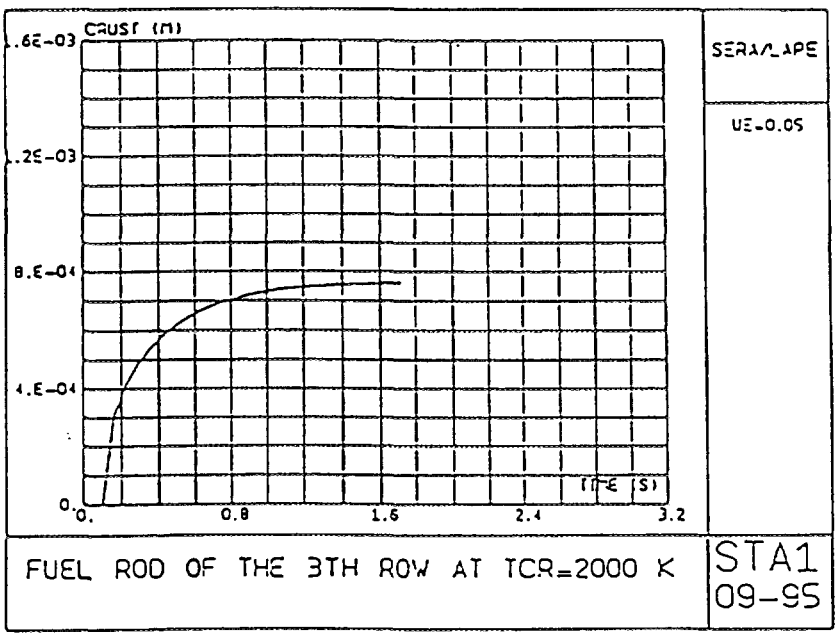


Fig. 5: Evolution of the corium crust thickness with the global time t, (3th row).

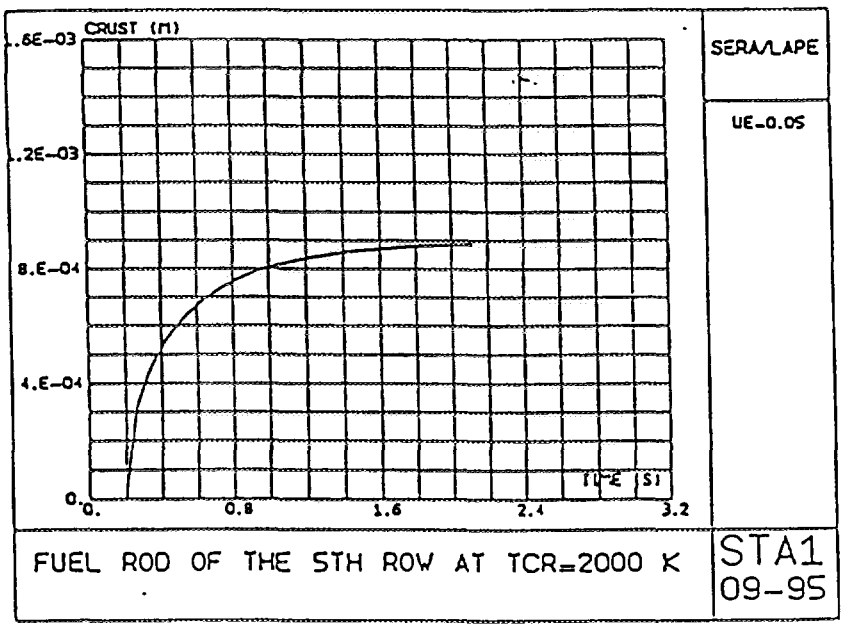


Fig. 6: Evolution of the corium crust thickness with the global time t, (5th row).

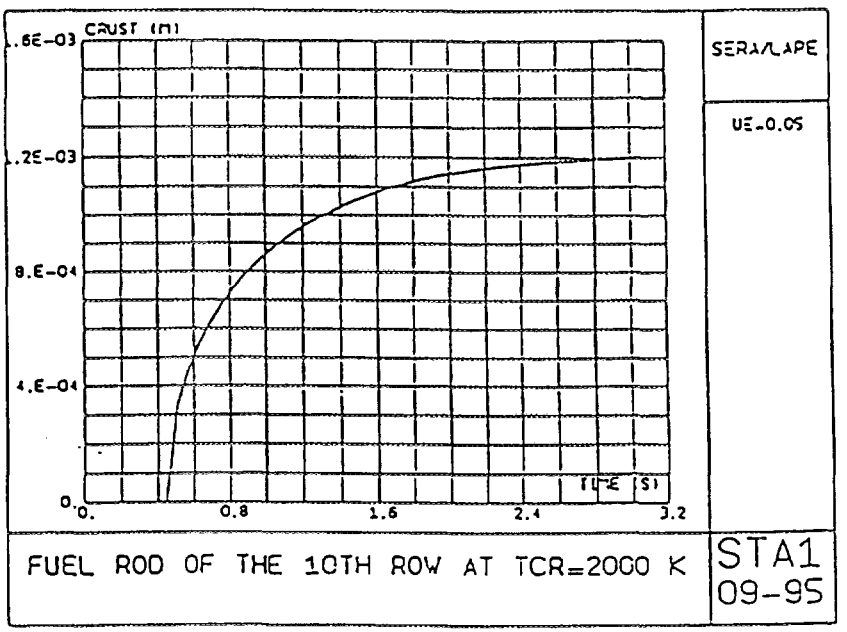


Fig. 7: Evolution of the corium crust thickness with the global time t, (10th row).

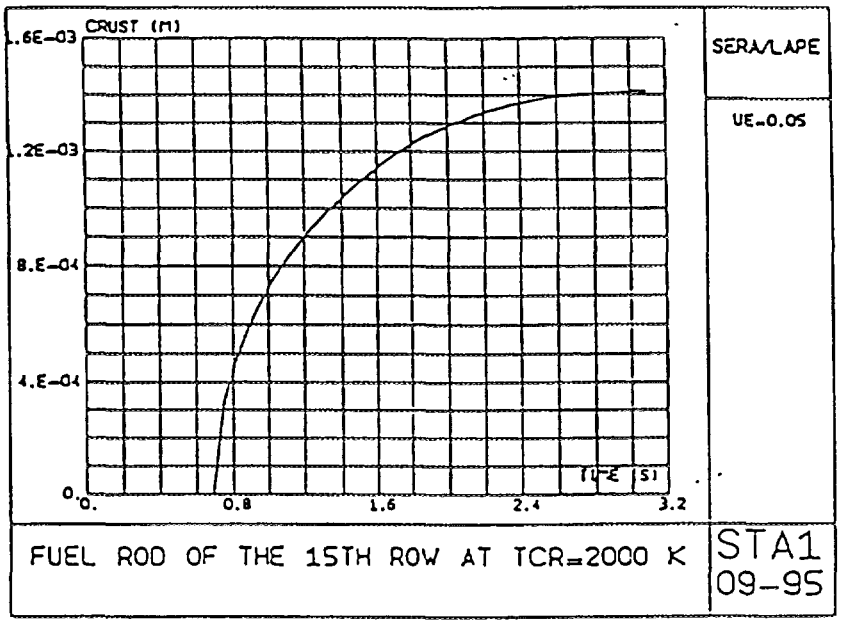


Fig. 8: Evolution of the corium crust thickness with the global time t, (I 5th row).

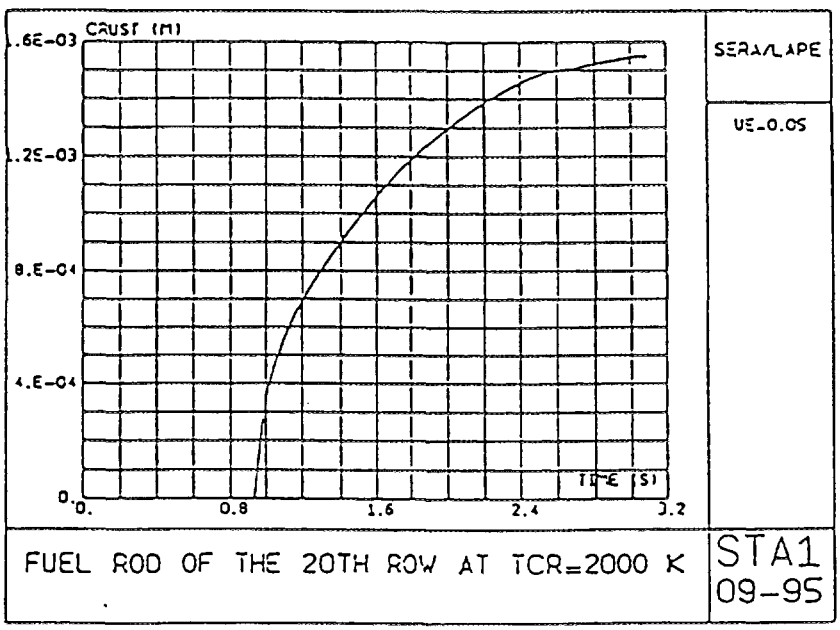


Fig. 9: Evolution of the corium crust thickness with the global time t, (20th row).

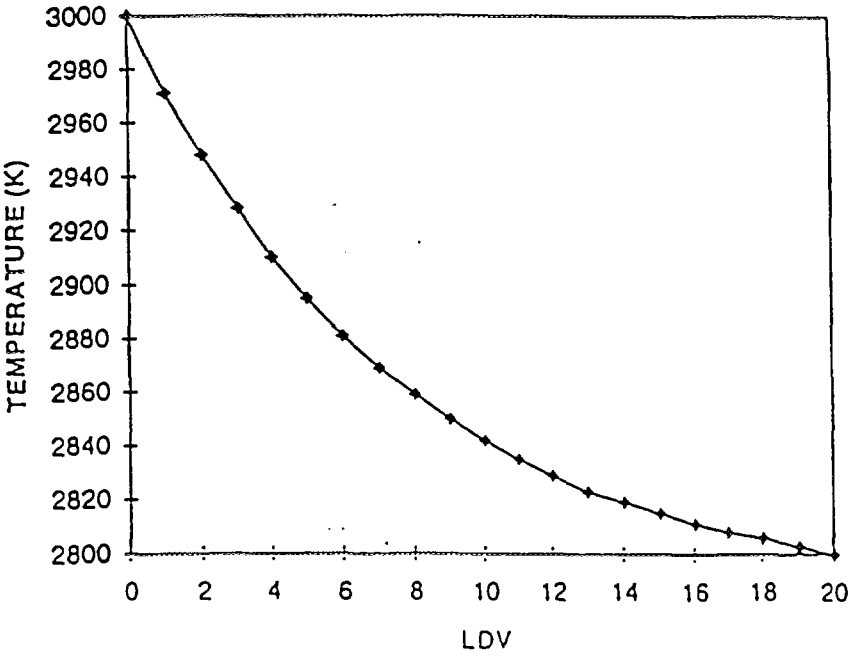


Fig. 10: Evolution of the liquid corium temperature with the corium penetration in the tube bank

6. CONCLUSION

A simplified model for the study of corium freezing phenomena during its crossflow between fuel rods has been elaborated. The model is based on two equations which are solved numerically : the interface energy balance equation and the heat balance equation. The model calculates the crust thickness which forms around the fuel rods. It also determines the liquid corium temperature which spreads between the fuel rods and the progression of the corium flowing in the tube bank till blockage. It should be noted that this model is in the process of being validated with the MARCUS code developed by IUSTI [5]. This code simulates numerically non-isothermal flows by a finite element method. After its validation, the model can be integrated in severe accident codes like ICARE II (IPSN) describing the in-vessel degradation scenarios.

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