Thermal Behavior of Cohesive Debris Beds in a Degraded Nuclear Reactor

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EGG-M--88444

DE90 010934

1990

ABSTRACT

During a severe core damage accident in a nuclear light water reactor, the process of melting and solidification of core material results in a cohesive debris bed. This paper determines (a) the initial equilibrium thickness of the lower crust of the bed, which serves as a receptacle for subsequently melted material, (b) the formation of the upper crust of the bed, which, together with the lower crust, forms the boundary of the bed, (c) the heatup of the interior of the bed, and (d) the erosion of the crusts by the enclosed material as the latter is heated above its melting point. The results show that the upper crust tends to be relatively thin and is likely to fail under stress, as it did during the TMI-2 accident.

INTRODUCTION

The aim of the paper is to determine the evolution of the thermal behavior of a cohesive debris bed formed in the core of a nuclear light water reactor during a severe core damage accident. A cohesive debris bed can be formed when part of the core melts, relocates to the cooler, lower region of the core, and freezes. This initial relocation and freezing give rise to a lower crust, which serves as a receptacle for subsequently relocated molten material which adds to the growth of the cohesive debris bed. If cooling water is introduced before the complete melt of the core, as in the TMI-2 accident, a crust will form at the upper surface of the bed.[1] This upper crust, together with the lower crust, defines the boundary of the cohesive debris bed. The complete melting of the interior of the bed and its heatup lead to the erosion of the enclosing crusts.

First, a scenario of the development of a cohesive debris bed is given. This scenario forms the basis for the analysis presented later. The analysis starts with the heatup of the interior of the cohesive debris bed. The results are used in the calculation of the erosion of the crusts. The analysis gives the growth history of the upper crust and its erosion by the enclosed molten pool; it determines the equilibrium thickness of the lower crust before the formation of the upper crust and also the erosion of the lower crust by the enclosed molten material. The paper concludes with some observations of the evolution of cohesive debris beds.

SCENARIO OF THE DEVELOPMENT OF A COHESIVE DEBRIS BED

After core dryout in a loss of coolant accident in a nuclear light water reactor, the zircaloy cladding of the fuel rods melts and partially dissolves the uranium dioxide fuel pellets. Upon cladding breach, the liquid flows downwards and solidifies in the cooler, lower region of the core to form the lower crust of a developing cohesive debris bed. Because of lower power density and more cooling toward the radial periphery of the core, the lower crust tends to take on the form of a crucible.

Because cooling is negligible on the inside surface of the lower crust, the relocating material eventually stops to freeze and settles around the fuel pellets. If the temperature of the outer surface of the lower crust is constant, an equilibrium thickness of the lower crust is attained when its inner surface reaches its melting point. This equilibrium thickness is determined by the power density inside the crust and the thermal conductivity of the crust, as analyzed in the section on the evolution of the lower crust.

The heatup of the molten material contained by the lower crust is accompanied by a slow dissolution of the submerged fuel pellets and a corresponding slumping of the rod segments above the partially molten pool. During this stage, the partially molten pool is at a temperature near the melting point of the material. Any appreciable temperature increase in the liquid above its melting point (hereafter referred to as "superheat") will be dissipated in dissolving or melting the fuel pellets.

If water is introduced into the core before the completion of fuel rod slumping, as it happened during the TMI-2 accident, the surface of the partially molten pool could be cooled below its melting point and solidification of the surface would proceed to form an upper crust. With the formation of an upper crust, the partially molten pool contained by the lower crust is closed off from the rest of the core and the slumping of fuel rod segments or rubble in the upper core region ceases. As long as there is an appreciable amount of fuel pellets inside the pool, most of the decay heat generation in the enclosed core material is dissipated in melting the pellets and the pool temperature remains slightly above the melting point of the material. When all the fuel pellets inside the pool melts, the pool superheats, natural convection sets in, and heat is transferred to the crusts. Such heat transfer ablates the inner surfaces of the crusts until all the heat transferred to the crust is conducted to their outer surfaces. If the outer surfaces of the crusts are at constant temperatures, an equilibrium state can be reached. The equilibrium state is characterized by some superheat in the molten pool and constant thicknesses of the crusts. The analysis that follows determines such an equilibrium state.

MOLTEN POOL HEATUP

A large molten pool with internal heat generation and in natural convection can be characterized by a uniform temperature above its melting point throughout most of the pool and a sharp temperature drop to its melting point across a thin layer near a solid boundary. The analysis assumes that the molten pool enclosed by the upper and lower crusts is at a uniform temperature, receives energy from the decay of radioactive material, and transfers energy to the crusts. The excess of energy generation over energy transfer results in heatup of the molten pool.

The equation for the temperature of the molten pool is given by

$$\rho c_p V \frac{dT_p}{dt} = q V - \sum_i A_i h_i (T_p - T_m) \qquad (1)$$

where the summation is over the surfaces of the crusts enclosing the molten pool. (Notation is given at the end of the paper.)

For constant coefficients, the solution of the above equation is given by

$$T_p - T_m = \frac{q\bar{V}}{\sum_i A_i h_i} \left\{ 1 - \exp\left[- \frac{1}{\rho C_p \bar{V}} \sum_i A_i h_i (t - t_0) \right] \right\} . \qquad (2)$$

Maximum superheat is obtained when thermal equilibrium is reached such that all the heat generated in the pool is transferred to the crusts. The maximum superheat is

$$\Delta T_{max} = max\,(T_p - T_m) = \frac{q\bar{V}}{\sum_i A_i h_i} , \qquad (3)$$

and the time constant for achieving equilibrium is

$$\tau = \frac{\rho C_p \bar{V}}{\sum_i A_i h_i} . \qquad (4)$$

Calculations were performed for the heatup of hemispherical pools with radii of 0.5 m, 0.85 m, and 1.2 m, respectively. Two heat transfer coefficients were used, one for the flat top of the hemispherical pool and one for the hemisphere. These are[2,3]

$$h_u = 0.345 \left(\frac{g\beta q R^5}{\alpha \nu k} \right)^{0.226} \frac{k}{R} , \text{ for the upper crust} \qquad (5)$$

$$h_l = 0.55 \left(\frac{g\beta q R^5}{\alpha \nu k} \right)^{0.2} \frac{k}{R} , \text{ for the lower crust} . \qquad (6)$$

Physical and thermal properties of a mixture of molten zircaloy and uranium dioxide are not well known. As illustrations, the mixture was assumed to be 82 % UO_2 and 18 % zircaloy by mass, and the properties of the mixture (specific heat, volumetric coefficient of thermal expansion), or their reciprocals (density, thermal conductivity, kinematic viscosity) were obtained as mass weighted averages of the properties of the constituents. In computing the the power density, a core average decay heat from the nonvolatile radioisotopes (volatile fission products were assumed to have released ffrom the fuel) between three and four hours after reactor shutdown was assumed. The parameters used in the calculations were

$\rho = 8200\ kg/m^3$, $C_p = 470\ J/kg\text{-}K$, $k = 36\ W/m\text{-}K$,

$\beta = 1.4 \times 10^{-4}\ K^{-1}$, $\alpha = 9.3 \times 10^{-7}\ m^2/s$, $\nu = 4 \times 10^{-7}\ m^2/s$.

It was assumed in the calculations that erosion of the crusts did not increase the size of the pool. For the first 10 minutes, the pool was assumed to be two-thirds molten and that decay heat caused the fuel pellets to melt, but did not raise the pool temperature. The results of the calculations are shown in Figure 1. These results were used in the crust erosion calculations.

EVOLUTION OF THE UPPER CRUST

The one-dimensional heat conduction equation governing heat transfer within the crust, assuming a constant thermal conductivity, is given by

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \qquad (7)$$

At time t, the crust occupies the region, $0 \leq z \leq \delta(t)$, with the following boundary conditions

$T = T_i$ at $z = 0$ and $T = T_m$ at $z = \delta$ for all t;

$T = T_m$ at $t = 0$ for all $z > 0$, and

$$-k\left(\frac{\partial T}{\partial z}\right)_{\delta^-} + h\,(T_p - T_m) = -\rho \Delta H \frac{d\delta}{dt} \qquad (8)$$

The last boundary condition is a mathematical statement that the net heat transferred to the boundary, $z = \delta$, results either in melting of the crust or in freezing of the molten material onto the crust. This is the equation for the erosion or the growth of the crust.

For constant thermal diffusivity, α, a solution of Equation (1), satisfying the boundary conditions, is

$$T = T_i + \frac{T_m - T_i}{\mathrm{erf}\left(\frac{\delta}{2\sqrt{\alpha t}}\right)} \mathrm{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right), \quad 0 \le z \le \delta . \tag{9}$$

The solution is exact if the thickness of the crust, δ, varies as the square root of time; it is approximately correct if the thickness divided by the square root of time is a slowly varying function of time. Moreover, because the solution satisfies the boundary condition at $z = \delta$, the solution is approximately correct near $z = \delta$, where melting of the crust or solidification of molten material takes place. As to be seen later, the thickness of the crust derived from Equation (9) asymptotically approaches the equilibrium thickness.

Substitution of the solution given by Equation (9) into the crust growth (erosion) equation yields

$$\rho \Delta H \frac{d\delta}{dt} = \frac{k(T_m - T_i)}{\sqrt{\pi \alpha t}} \frac{\exp\left(-\frac{\delta^2}{4\alpha t}\right)}{\mathrm{erf}\left(\frac{\delta}{2\sqrt{\alpha t}}\right)} - h(T_p - T_m) . \tag{10}$$

With no convective heat transfer and constant density and heat of fusion, Equation (10) gives a solution δ that varies as the square root of time, and so the solution is exact, as remarked earlier. To obtain an approximate solution for the case when convective heat transfer is present at the boundary, a new variable, λ, is introduced:

$$\delta = 2\lambda\sqrt{\alpha t} \tag{11}$$

A solution for λ as a function of time can be considered as a correction factor in calculating the crust thickness for variable thermal properties and time dependent convective heat transfer at the crust boundary.

The equation for λ is

$$\frac{d\lambda}{dt} = \frac{1}{2\rho \Delta H \alpha t}\left[\frac{1}{\sqrt{\pi}} \frac{k(T_m - T_i)}{\mathrm{erf}(\lambda)} e^{-\lambda^2} - h\sqrt{\alpha t}\,(T_p - T_m) - \rho \Delta H \alpha \lambda\right]. \tag{12}$$

For constant ρ and ΔH, and for $h = 0$, λ is the growth constant and is given by the solution of the transcendental equation

$$k(T_m - T_i)\, e^{-\lambda^2} = \sqrt{\pi}\, \rho \Delta H \alpha \lambda \, \mathrm{erf}(\lambda). \qquad (13)$$

For large t and constant heat flux, the crust thickness should approach a finite value, and so λ must vary as $t^{-1/2}$. With the approximation $\mathrm{erf}(\lambda) \simeq \frac{2}{\sqrt{\pi}} \lambda e^{-\lambda^2}$ for small λ, the right-hand side of Equation (12) gives

$$k\, \frac{T_m - T_i}{2\lambda} \simeq h\sqrt{\alpha t}\,(T_p - T_m). \qquad (14)$$

Thus, using the definition of λ,

$$\delta_\infty \equiv \lim_{t \to \infty} (2\lambda\sqrt{\alpha t}) = \frac{k(T_m - T_i)}{h(T_p - T_m)}. \qquad (15)$$

This is the equilibrium thickness of the crust under the condition when a constant amount of heat per unit time is transferred to the crust from the molten pool and when the boundary temperatures of the crust are constant. This agrees with the solution oabtained by considering equilibrium heat balance in the crust.

Numerical integration of Equation (12) was carried out with variable heat flux at the inner boundary of the crust as given in the section on molten pool heatup. For the first 10 min of the calculation, the convective heat flux was assumed to be zero, but the melt fraction in the partially molten pool increased linearly, giving a slightly variable volumetric heat of fusion at the solidification surface. The thermal conductivity of the crust was assumed to be 5 W/m-K, and the thermal diffusivity, 1.2×10^{-6} m^2/s, appropriate for a ceramic material with a slight metallic content. The inner and outer boundary temperatures, T_m and T_i, are assumed to be 2800 K and 1500 K respectively. The results for the three cases corresponding to those given in the section on molten pool heatup (hemispherical pools with radii 0.5 m, 0.85 m, and 1.2 m, respectively) are shown in Figure 2.

EVOLUTION OF THE LOWER CRUST

The lower crust of a cohesive debris bed is expected to be thicker than the upper crust because of its higher thermal conductivity and a smaller amount of heat transfer from the molten pool it contains. The higher thermal conductivity comes from its higher content of zircaloy, and the smaller amount of heat transfer can be deduced from the correlations given in Equations (5) and (6) when appropriate values are substituted for the parameters. For these reasons, the one-dimensional, heat conduction equation with a distributed heat source is used in calculating the crust thickness. The equation is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{q}{\rho c_p} \tag{16}$$

The thermal diffusivity and the term containing the power generation are assumed to be constants. The boundary conditions are

$T = T_i$ at $z = 0$ and $T = T_m$ at $z = \delta$ for all t, and

$$-k\left(\frac{\partial T}{\partial z}\right)_{\delta^-} + h(T_p - T_m) = \rho \Delta H \frac{d\delta}{dt} . \tag{17}$$

If time zero refers to the time when the molten pool starts to superheat, and for time less than zero the crust is in thermal equilibrium, the temperature profile across the crust at time zero is the solution of the time independent conduction equation and is given by

$$T = -\frac{q}{2k} z^2 + \frac{q\delta}{k} z + T_i \tag{18}$$

We seek a solution for the time dependent conduction equation as a superposition of the solution of the time independent equation and a solution of the homogeneous part of the time dependent equation. The solution can be written as

$$T = -\frac{q}{2k} z^2 + \frac{q\delta}{k} z + T_i + \left(T_m - T_i - \frac{q\delta^2}{2k}\right) \cdot \frac{\mathrm{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right)}{\mathrm{erf}\left(\frac{\delta}{2\sqrt{\alpha t}}\right)} . \tag{19}$$

The solution satisfies the boundary conditions but the temperature given by the solution is only approximately correct in the interior of the crust when the crust thickness does not vary as the square root of time. Since we are only interested in the erosion of the crust, which is determined by the boundary condition given by Equation (17), we shall use Equation (19) to calculate the crust thickness.

Substituting the derivative of the temperature at z = δ, as given by Equation (19), into Equation (17), we obatin the crust erosion equation

$$\rho \Delta H \frac{d\delta}{dt} = \frac{k(T_m - T_i - q\delta^2/2k)}{\sqrt{\pi \alpha t}} \cdot \frac{\exp(-\frac{\delta^2}{4\alpha t})}{\mathrm{erf}(\frac{\delta}{2\sqrt{\alpha t}})} - h(T_p - T_m) \quad (20)$$

To solve Equation (20), we subtitute

$$\delta = \delta_0 - 2\lambda\sqrt{\alpha t} \quad (21)$$

where δ_0 is the crust thickness at time zero (equilibrium crust thickness before the molten pool is superheated). The equation for λ is

$$-\frac{d\lambda}{dt} = \frac{1}{2\rho\Delta H \alpha t}\left[\frac{k(T_m - T_i - q\delta^2/2k)}{\sqrt{\pi}} \cdot \frac{\exp(-\frac{\delta^2}{4\alpha t})}{\mathrm{erf}(\frac{\delta}{2\sqrt{\alpha t}})} - h\sqrt{\alpha t}(T_p - T_m) + \rho\Delta H \alpha \lambda\right]. \quad (22)$$

As $t \to \infty$, λ is asymptotically proportional to the reciprocal of the square root of time, and the first two terms on the right-hand side of Equation (22) approaches each other. Consequently, the crust thickness approaches a constant is is given by

$$\delta_\infty = \frac{-h(T_p - T_m) + \sqrt{h^2(T_p - T_m)^2 + 2kq(T_m - T_i)}}{q}. \quad (23)$$

This agrees with the solution of the crust thickness in steady-state when the heat transferred (at a constant rate) by the molten pool to the crust and the heat generated inside the crust are all transferred to the outer surface of the crust.

Numerical integration of Equation (22) was carried out with variable heat flux at the inner boundary of the crust as given in the section on molten pool heatup. The thermal conductivity of the crust was assumed to be 8 W/m-K, the thermal diffusivity, 1.9×10^{-6} m^2/s, and the power density, 8×10^5 W/m^3. The inner surface of the crust was assumed to be at 2800 K and the outer surface at 1000 K. The results for the three cases corresponding to those given in the section on molten pool heatup (hemispherical pool with radii 0.5 m, 0.85 m, and 1.2 m, respectively) are shown in Figure 3. The time axis has been shifted such that erosion of the crust starts at 10 min, so as to be consistent with Figures 1 and 2.

CONCLUSION

We have analyzed the thermal behavior of three cohesive debris bed that could be formed in a degraded nuclear reactor, covering a range from a small (0.5 m in diameter) to a large enough bed (1.2 m in diameter) that would almost extend over the entire reactor core. Based on the scenario of the formation and the evolution of the crusts of the bed, the calculations show that the lower crust is relatively thick because of its higher thermal conductivity and less heat transfer from the molten pool it contains. The lower crust may achieve and maintain a steady-state thickness of approximately 200 mm for quite some time when the pool it contains is only partially molten. If coolant is introduced into the core before its upper part is completley melted, an upper crust may form at the top surface of the partially molten pool. Approximately 10 min after the crusts have completely enclosed the cohesive region, its interior begins to superheat and erosion of the crusts occur. The upper crust first attains a maximum transient thickness of approximately 50 mm, and then is eroded by the molten pool to less than 20 mm. The lower crust, while similarly eroded by the molten pool, is calculated to maintain a thickness of more than 100 mm, even in the case of the largest cohesive debris bed. These calculated final thicknesses of the upper and lower crusts agree quite well with the corresponding thicknesses of the crusts retrieved from the damaged TMI-2 reactor.

It has been deduced from the response of on-line instruments that molten core material relocated suddenly to the lower plenum during the

TMI-2 accident.[1] During defueling of the reactor, it was discovered that relocation path started at the top of a cohesive debris bed in the core, indicating that the upper crust of the bed failed and the rubble on top of the crust may have forced out molten material in the interior of the bed through the break in the upper crust. The calculations presented here show that the upper crust would have been 12 times thinner than the lower crust within one-half hour of the formation of the upper crust (corresponding to the case of a 1.2 m-diameter hemespherical cohesive debris bed). The latest formation time of the upper crust in the TMI-2 accident was at 200 min after accident initiation when emergency cooling water was introduced into the core and the crust was believed to have failed at 224 min. It is, therefore, not surprising that the lower crust remained intact while the upper crust could have failed under the weight of the rubble it supported.

ACKNOWLEGMENT

This work was performed as part of the reserach of the TMI-2 Accident Evaluation Program, supported by the Office of Nuclear Energy, the U.S. Department of Energy under DOE Contract No. DE-AC07-76ID01570.

NOTATION

Roman Letters

A = surface element
C_p = specific heat
g = gravitational acceleration
ΔH = heat of fusion per unit mass
h = heat transfer coefficient
k = thermal conductivity
q = volumetric heat generation rate
T = temeprature
T_i = temperature of outer surface of lower crust
T_m = melting point of molten pool
T_p = molten pool bulk temperature
t = time variable
z = spatial variable

Greek Letters

α = thermal diffusivity
β = volumetric coefficient of thermal expansion
δ = crust thickness
λ = growth "constant"
ν = kinematic viscosity
ρ = density

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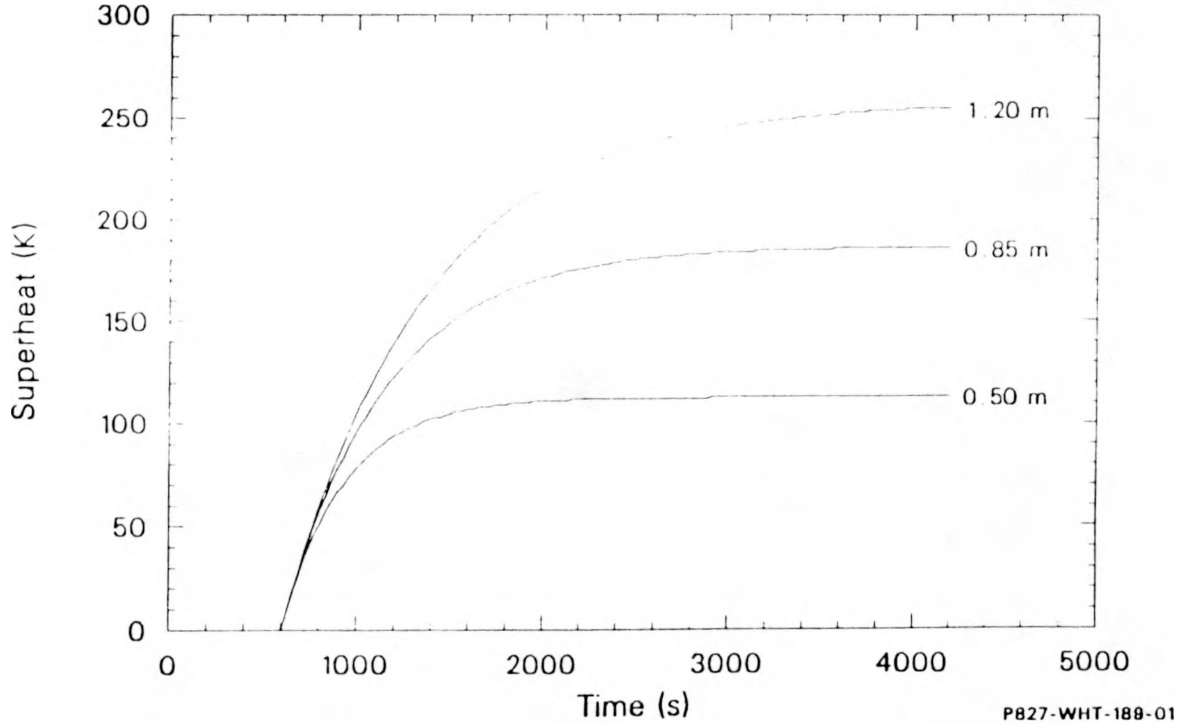

Figure 1. Superheat temperature of molten pool for pools of hemispherical shape and radii 0.50 m, 0.85 m, and 1.20 m, respectively. Pools are partially molten before 600 s.

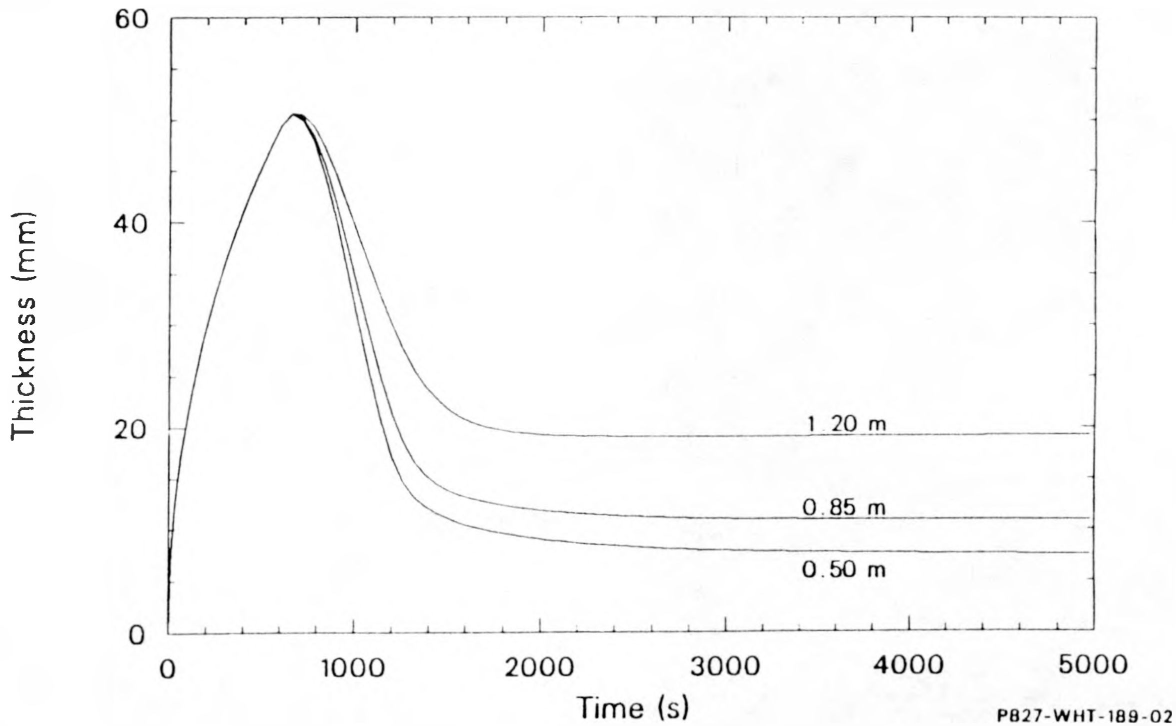

Figure 2. History of upper crust growth and erosion after cooling of top surface of partially molten pools of radii 0.50 m, 0.85 m, and 1.20 m, respectively.

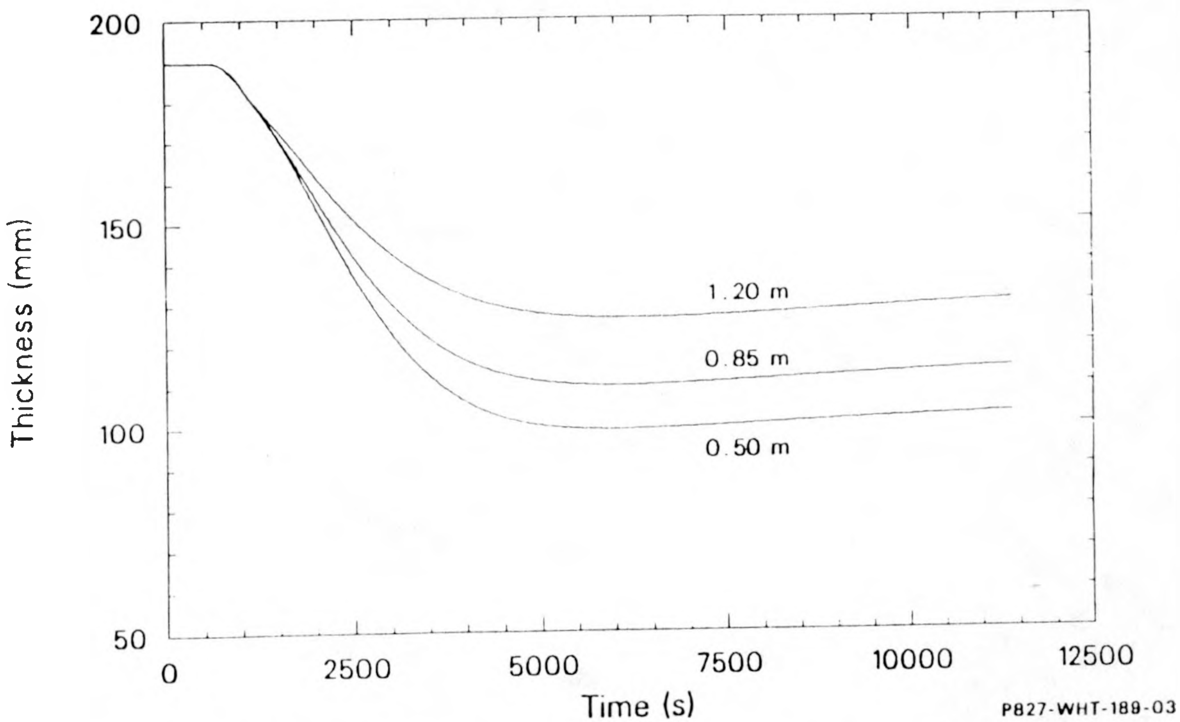

Figure 3. History of erosion of lower crust containing molten pools of radii 0.50 m, 0.85 m, and 1.20 m, respectively. Erosion starts when pool is completely melted at 600 s.