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A MODEL FOR SUPERHEATED DEBRIS-BED QUENCH FOR SEVERE-ACCIDENT CONTAINMENT CALCULATIONS*

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1. INTRODUCTION

Core meltdown accidents are being analyzed to develop an understanding of the risk associated with such postulated accidents and to evaluate the impact of possible mitigating engineering safety equipment [1-3]. An integral feature of these analyses is the determination of containment building pressurization as a result of loadings imposed by the energy stored in the molten core debris. A major source of containment pressurization would result from the ex-vessel thermal interaction between molten core debris and water available beneath the reactor vessel. It has been suggested [4] that the thermal interaction would occur in two stages: (i) the melt fall period during which the melt mixes with water, breaks up and transfers energy to the coolant, and (ii) the debris bed or molten pool quench period during which the core debris rests on the concrete beneath the vessel and is cooled by an overlying pool of water. This paper is directed towards development of models to predict the thermal-hydraulic characteristics of superheated beds of solidified core debris which are cooled by water supplied by an overlying pool of water.

Containment pressurization resulting from the ex-vessel thermal interaction between core debris and water has been modeled using variations of two

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limiting heat transfer models: (i) a single-particle heat transfer model [5] and (ii) a debris-bed limited dryout heat flux model [6]. Steady-state debris bed models have been applied to the transient bed quench calculations with no supporting evidence. Recent data [7,8] suggest that the steady-state models provide a reasonable characterization of the transient bed quench steam generation rate. The data, however, suggest that the bed quench is a complex and multi-dimensional process. A model presented earlier [7] to characterize the bed quench process has been extended to include the effect of decay heating on the quench behavior. This model is presented and calculational results are discussed. Emphasis is placed on quench front propagation and on its effect on bed temperature.

2. ANALYTICAL FORMULATION

2.1 Experimental Basis of Model

Figure 1 presents a schematic view of a superheated packed bed of debris under transient quench conditions. The experimental data [7] suggest that packed beds of superheated particles (with no internal heating), which were cooled by water supplied from overlying pools of water, were quenched in a two-stage cooling process. Water initially penetrated the beds during the initial downward frontal progression. This process was irregular and left channels or pockets of dry particles. This observation agrees with those of Armstrong, et al. [8]. It is estimated that approximately 30-40% of the initial stored energy was transferred to the water during this time period. During the initial frontal progression the bed consists of three regions. The uppermost partially quenched region (as represented in Fig. 1) consists of wetted channels of particles which are quenched to the saturation temperature and channels of

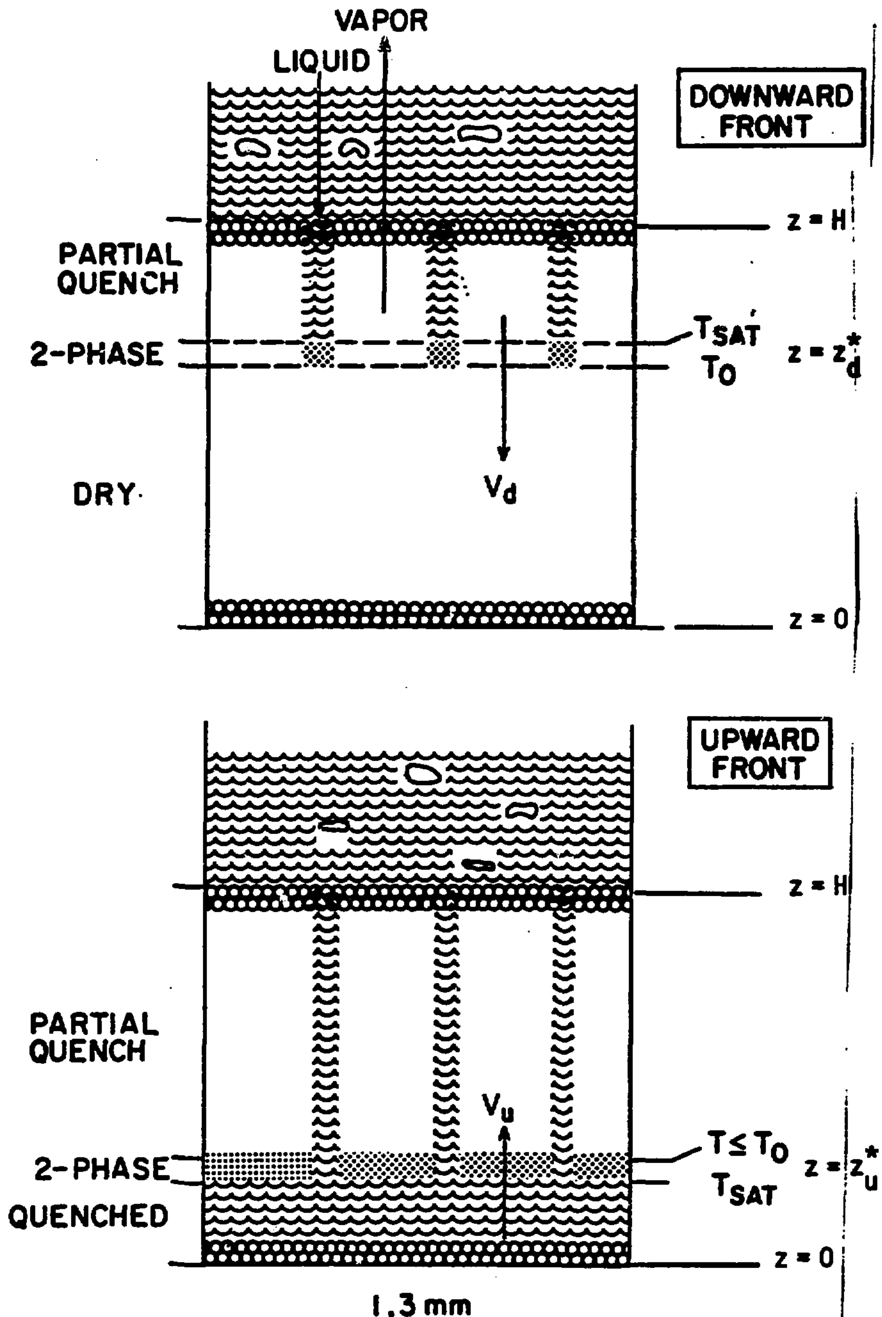

Fig. 1 Schematic Behavior of Superheated Packed Bed Quench Process

unquenched particles close to their initial temperature. A thin two-phase region follows below. The particles in the wetted channels in this region are not yet quenched to the saturation temperature and the surrounding fluid is composed of steam and water. The bottom-most region is completely dry. No liquid has yet penetrated to the particles in this region. The speed of the downward-progressing cooling front is v_d. A final upward-progressing front, moving at speed v_u, began its traverse subsequent to completion of the downward process. During this final upward frontal progression, the remaining stored energy was removed from the particles and the bed was completely quenched and filled with water.

The results further indicate [7] that the rate of heat transfer from the particle bed to water is independent of the mass of particles and initial particle bed temperature. The time required to quench the bed, however, increases with particle mass and initial particle temperature. The speeds of the two cooling fronts decrease with increasing initial particle temperature. The initial water penetration rate, v_d, is greater than the speed of the upward final quench front. Finally, experimental measurements show that the steam flow rate was nearly constant for the entire duration of the quench process, inclusive of both frontal progression periods. This is taken to imply that the rate of heat transfer from the bed to the water was limited by processes common to both frontal periods. The steam flow rate data [9] further indicate that the bed-to-water heat transfer rate lies between that calculated using the Lipinski [10] and Ostensen [11] models for steady-state heat removal from debris beds.

2.2 Model Assumptions

The above observations are applied to quench of a superheated debris bed of uniform-size particles and uniform porosity with decay heat generation Q'''. It is assumed that the liquid penetrates the bed and removes stored energy in the vicinity of the two-phase frontal region. Particles which have been quenched to the saturation temperature are assumed to remain at steady temperature by transfer of energy to the coolant by vaporization. The rate of heat transfer with liquid supplied from an overlying pool is assumed to be limited by the maximum rate at which vapor can be removed from the bed under conditions of countercurrent two-phase, vapor-liquid flow in or to the packed bed.

It is assumed that the bed is initially dry and at temperature T_0. Both frontal processes are treated one-dimensionally (averaged radially). The downward-moving front penetrates axially at speed v_d, while at the same time leaving pockets or channels of unquenched particles. It is assumed that a fraction f_d of the particle bed is quenched, i.e., its temperature is reduced to T_{SAT}, during passage of this initial front.

The final upward frontal period is also treated one-dimensionally. The region beneath the front is uniformly at temperature T_{SAT}. The speed of the front is v_u and the remaining fraction of the bed, $1-f_d$, is quenched during this time period.

Particles in the unquenched region of the bed are assumed to increase in temperature due to the internal heat source. Steam cooling of the debris is assumed negligible.

2.3 Formulation of Basic Equations

The analysis presented below focuses on the calculation of the frontal propagation speeds and on the particle temperatures.

It is assumed that the quench front is propagated at a speed limited by the rate of liquid supplied to the quench front, and that the thickness of the two-phase front is negligible. The front is assumed located at $z = z^*(t)$, as shown in Fig. 1. During the downward front propagation period

liquid available for vaporization = liquid flow to front - liquid flow to fill voids in quenched region

An energy balance across the quench front then yields

$$(1-\varepsilon)\; f_d \rho_p c_p \; (T_p - T_{SAT}) \frac{dz_d^*}{dt} = \left[\varepsilon\, f_d u_\ell^* \rho_\ell - \varepsilon\, f_d v_d \rho_\ell\right] h_{fg} \quad . \tag{1}$$

A mass balance on the liquid phase yields

$$f_d \rho_\ell \varepsilon \frac{du_\ell}{dz} = - \frac{Q''' f_d}{h_{fg}} \quad , \tag{2}$$

which when integrated from z^* to H yields

$$u_\ell^* = u_{\ell o} - \frac{Q''' (H - z_d^*)}{\rho_\ell h_{fg} \varepsilon} \quad . \tag{3}$$

Combining Eqs. (1) and (3), with $v_d = dz_d^*/dt$ gives

$$\frac{dz_d^*}{dt} = \frac{(1-\varepsilon)\,\rho_\ell h_{fg}}{\varepsilon \rho_p c_p \Delta T + (1-\varepsilon)\rho_\ell h_{fg}} \left[u_{\ell o} - \frac{Q''' (H - z_d^*)}{h_{fg} \rho_\ell \varepsilon}\right] , \tag{4}$$

where $\Delta T = T_p - T_{SAT}$.

A similar set of equations can be written for the time period of the upward-progressing front. During this time period, liquid supplied from the pool is used to remove decay heat from the debris which is already quenched, including those for which $z < z^*$. The resulting frontal propagation equation is

$$-\frac{dz_u^*}{dt} = \frac{\varepsilon f_d \rho_\ell u_\ell^* h_{fg} - Q''' z_u^*}{(1-\varepsilon)(1-f_d)\rho_p c_p \Delta T + \varepsilon (1-f_d)\rho_\ell h_{fg}} \quad . \tag{5}$$

The energy equation for the unquenched particles is

$$\rho_p c_p (1-\varepsilon) \frac{dT_p}{dt} = Q''' \quad , \tag{6}$$

while for the quenched particles $T_p = T_{SAT}$. The effect of steam cooling has been neglected.

The overall coolant conservation equations are

$$\begin{aligned} u_{\ell o} f_d \rho_\ell + u_{go}(1-f_d)\rho_g &= f_d v_d (\rho_\ell - \rho_g) && \text{down-front} \\ &= (1-f_d) v_u (\rho_\ell - \rho_g) && \text{up-front} \end{aligned} \tag{7}$$

where $u_{\ell o}$ and u_{go} are the liquid and vapor velocities at the top of the bed.

The above set of equations can be solved once u_{go} and $u_{\ell o}$ are related. This is accomplished by assuming, as discussed above, that the heat transfer from the debris bed to water is limited by countercurrent two-phase flow conditions near the top of the bed. Debris bed heat removal models [9,10] which bracket the quench heat transfer data are used to characterize the flow-limited heat transfer mechanism. These models supply the additional required relationship between $u_{\ell o}$ and u_{go}.

Equations (4)-(7), together with the formulations for the bed heat removal, were solved simultaneously using Gear's method of integration. Two sets of results are presented in Section 2.4, one based upon Lipinski's model [9], the other on Ostensen's model [10], for the debris bed hydrodynamically-limited flow characteristics.

3. CALCULATIONAL RESULTS

Table 1 presents the debris bed and coolant initial condition parameters. Calculation results are shown in Figs. 2 and 3 for the case of negligible steam cooling of the debris. The positions of the two fronts vs. time are presented as consecutive line segments. The downward partial quench front is characterized by the negative slope; the upward final quench front has the positive slope. Results shown are for a 1-m deep bed of 3-mm particles which transfers heat to water at 5 bars. The initial sphere temperature is assumed to be 1723 K. The Lipinski [10] [Fig. 2] and Ostensen [11] [Fig. 3] models were used in two separate calculations to represent the countercurrent flow limiting heat flux from the bed. Results are presented parametrically as a function of particle internal heat generation rate. Note that the bed decay heat is approximately 1-2 MW/m^3 (per unit volume of bed) at 1% of steady-state power for a 1000 MWe power plant.

The effect of decay heat is to reduce the speeds of the quench fronts. The reduction in quench front speeds is attributable to two factors. First, the liquid supplied to the bed is required to both remove sensible heat (thereby advancing the quench fronts) and to remove decay heat. Second, the unquenched

TABLE 1

Debris Bed Characteristics

Debris Density	8000 kg/m^3
Debris Specific Heat	600 J/kg K
Bed Porosity	0.4
Initial Bed Temperature	1723 K
System Pressure	0.5 MPa
Bed Height	1.0 m
f_d	0.4

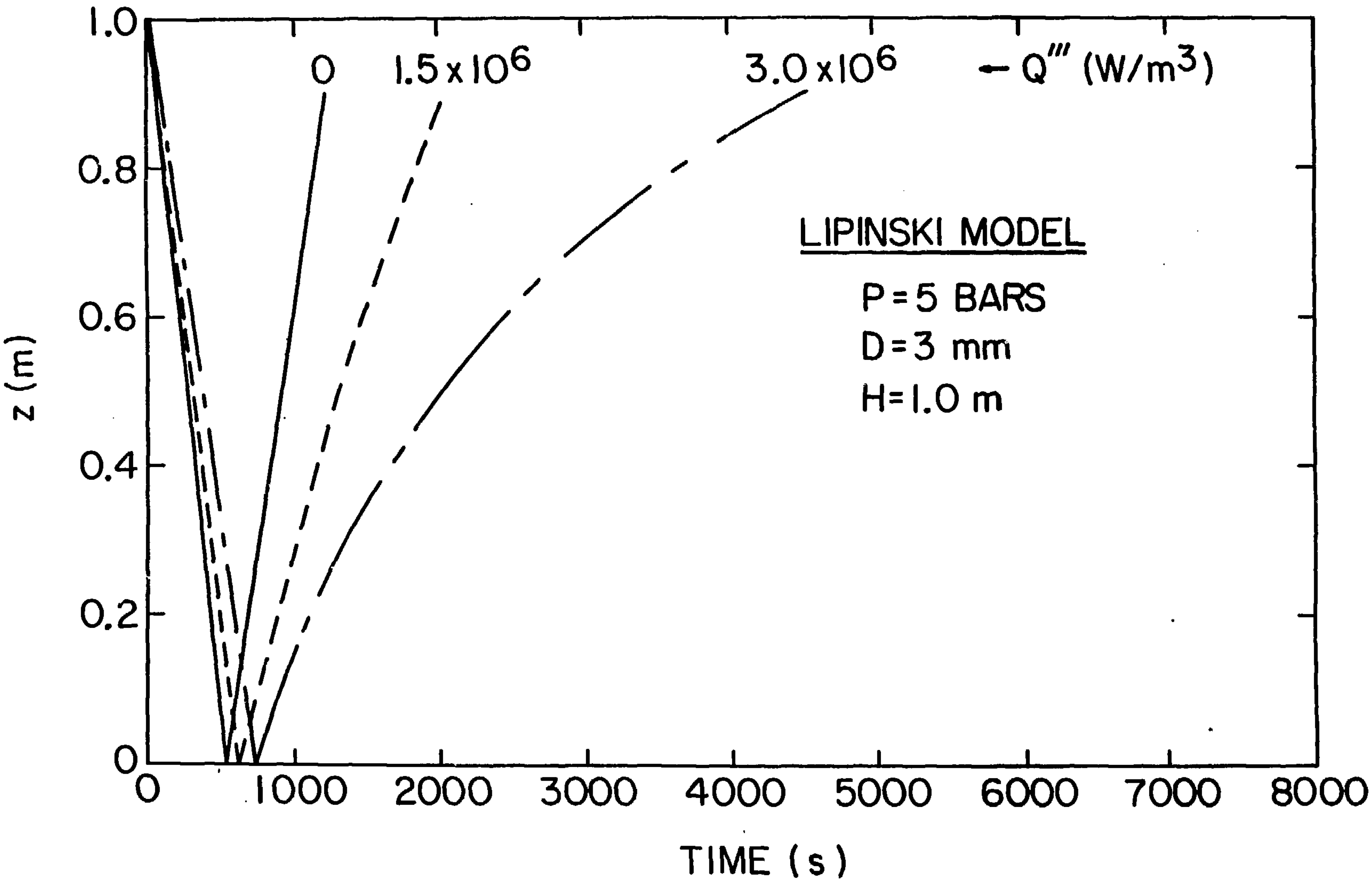

Fig. 2 Quench Front Location Vs. Time as Function of
Q'''-Based on Lipinski Heat Flux

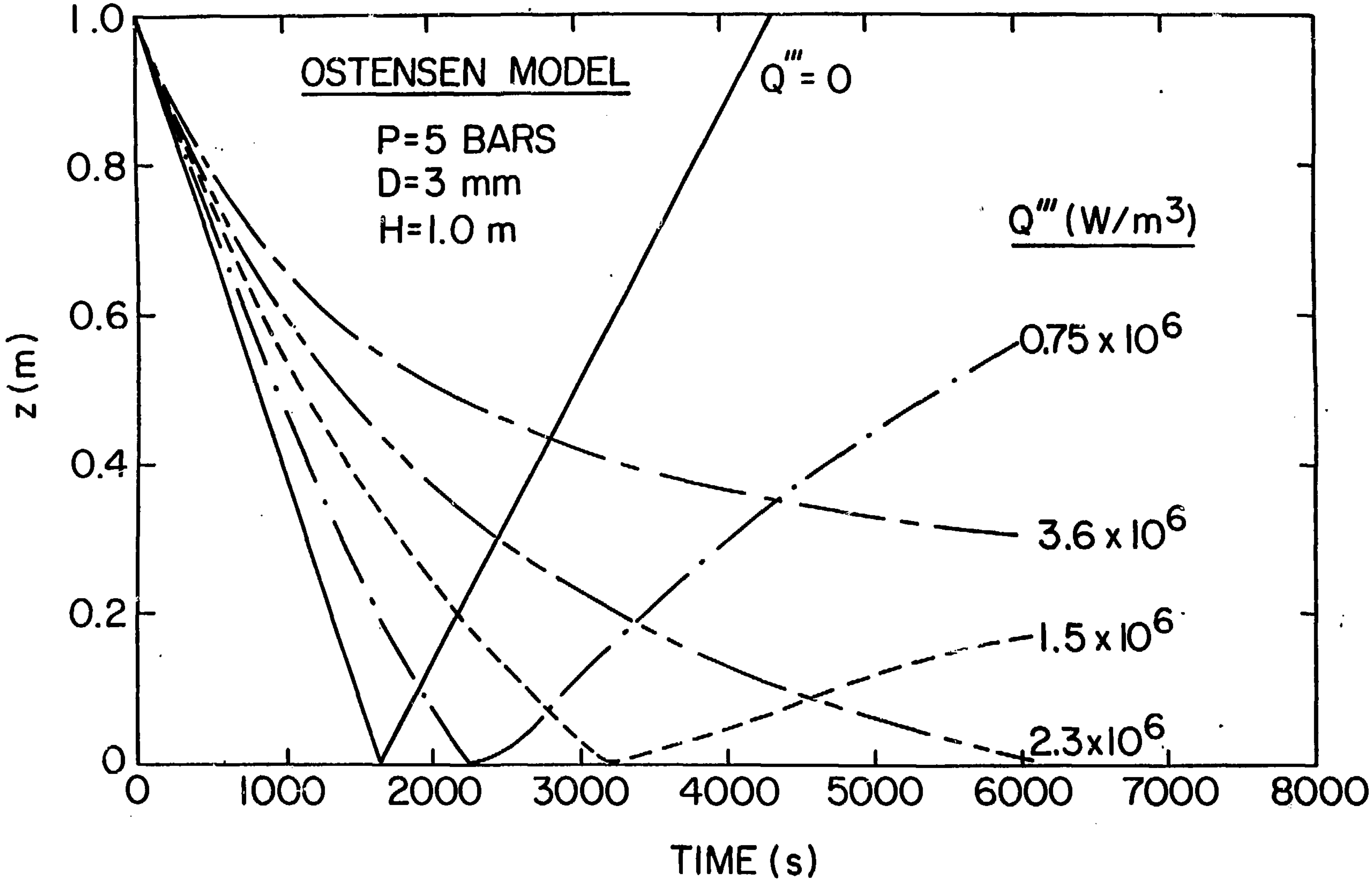

Fig. 3 Quench Front Location Vs. Time as Function of Q'''-Based on Ostensen Heat Flux

particle temperatures increase with time, and subsequently require more time to cool upon arrival of liquid. The magnitude of the effect depends on the overall bed cooling rate. Using the Lipinski model, the bed cooling rate is approximately 3.1 MW/m^2 (per unit bed area) while the Ostensen model predicts approximately 0.91 MW/m^2. The effect of decay heating is much more pronounced based upon the Ostensen correlation. Use of both the Lipinski and Ostensen models leads to prediction of substantial delay times before water reaches the base of the bed, at least 500 s and 1600 s, respectively, for the two calculations. During this time period, the unquenched portion of the bed would continue to heat and this region of the bed would transfer heat to the concrete basemat beneath the bed. If the particle temperature were high enough, then concrete decomposition and melting would have to be considered.

Figures 4 and 5 present the quench front propagation results based upon the Lipinski and Ostensen debris bed heat transfer models, respectively, for beds of particles of diameters 1-, 3- and 6-mm. The decay heat generation rate is assumed here to be $Q''' = 1.5$ MW/m^3. Significant differences in quench times are observed based upon the two models, attributable to the difference in predicted bed heat flux. For 3-mm particles, for example, the calculation using the Lipinski model predicts that the downward quench front reaches the base of the bed at approximately 600 s, while the Ostensen calculation predicts approximately 3500 s. Similarly, the upward-directed front for the 3-mm particles advances extremely slowly based upon the Ostensen heat flux prediction as compared with the Lipinski prediction. This large difference in results is attributable partially to the smaller heat flux predicted by the Ostensen model, which leads to a longer bed quench time. The longer quench time, in turn, leads

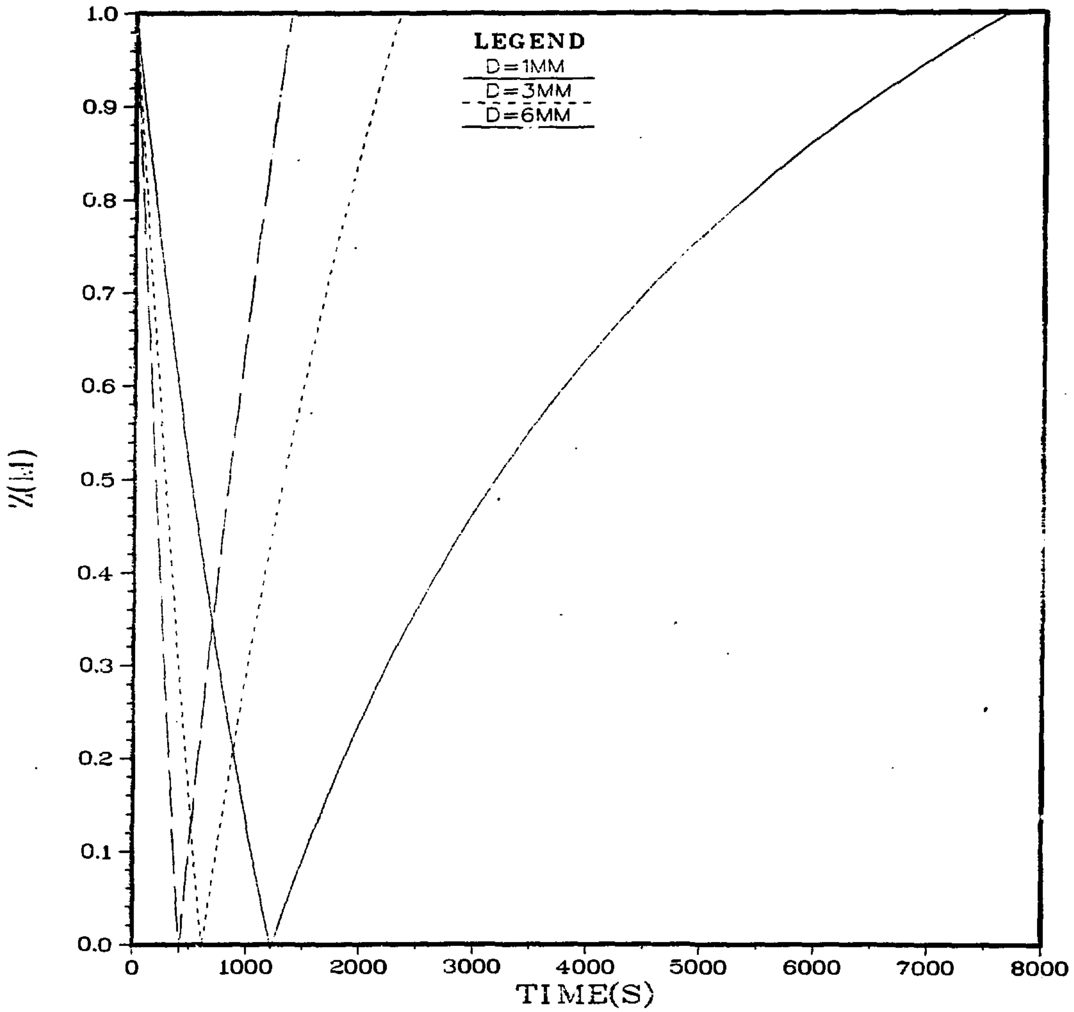

Fig. 4 Quench Front Location Vs. Time Based on Lipinski Debris Bed Heat Flux; Q''' = 1.5 MW/m^3

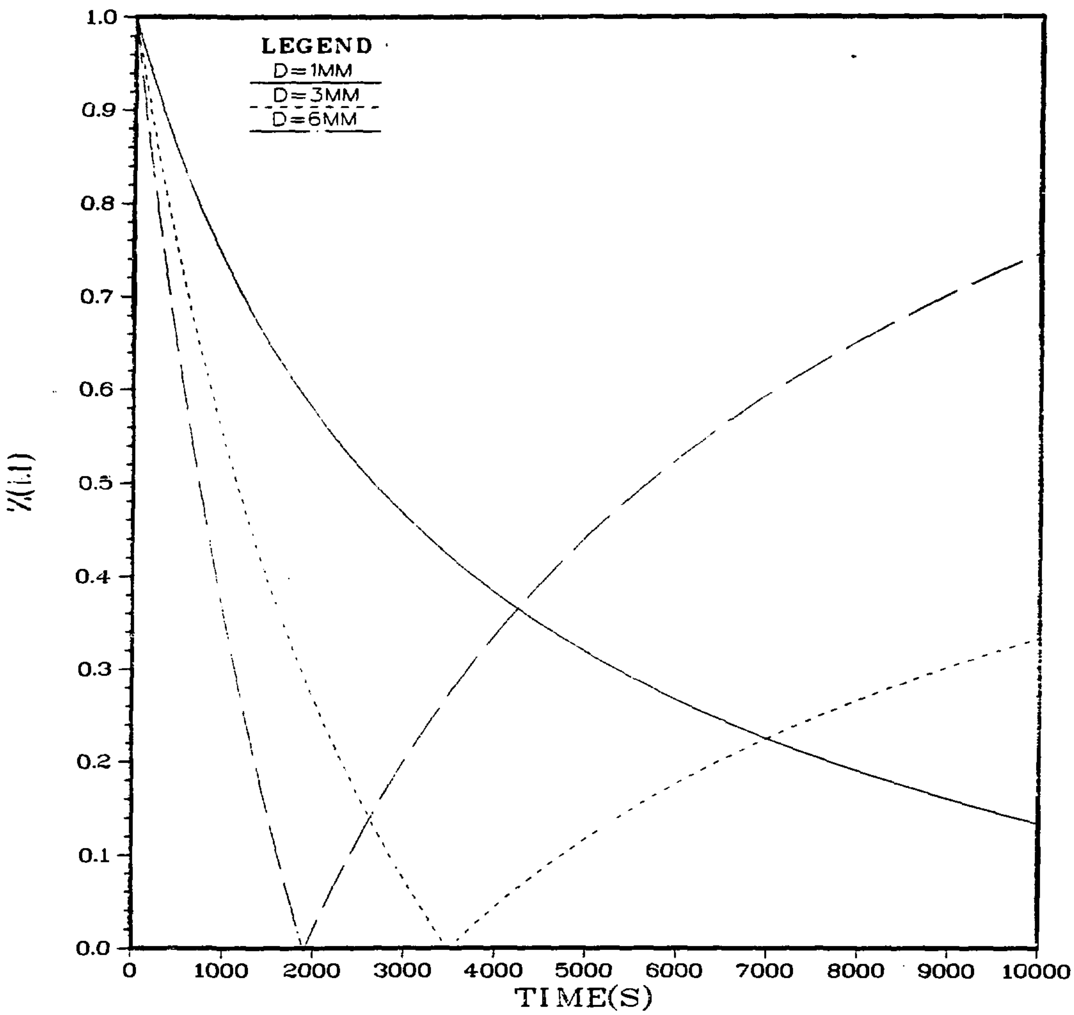

Fig. 5 Quench Front Location Vs. Time Based on Ostensen Debris Bed Heat Flux; Q''' = 1.5 MW/m^3

to increased stored energy due to decay heat generation which then feeds back to slow the bed quench. The temperature-time history of the unquenched particles within the bed is shown in Figure 6. Note that the adiabatic temperature rise rate of the debris is 0.52 K/s. It is apparent, therefore, from Figs. 4 and 5 that quench times on the order of 1000 s can have significant impact on the debris bed stored energy.

The results suggest that remelting of the debris is possible during the quench process in the yet-unquenched regions of the bed. This possibility is strongly dependent on particle size, on the limiting bed heat flux, and on the decay heat generation rate. Remelting would also depend on the initial debris temperature.

4. SUMMARY AND CONCLUSIONS

A model for the transient quench behavior of superheated packed beds of heat-generating core debris is presented. The debris is assumed supplied with coolant from an overlying pool of water. The model, based upon bed quench experiments with no internal heating, considers that a superheated debris bed is cooled in a two-stage quench front propagation process. Coolant is assumed to penetrate the bed, leaving dry pockets or channels of particles which continue to heat under decay heating. Following arrival of the downward front to the base of the bed, a final upward-directed front propagates up the bed, removing the remaining particle stored energy. Calculations based upon the model are presented and discussed.

The results indicate that the debris bed quench can be delayed significantly due to the effect of decay heating. The delay of the quench process is also strongly dependent on the particle diameter and is likely dependent on the

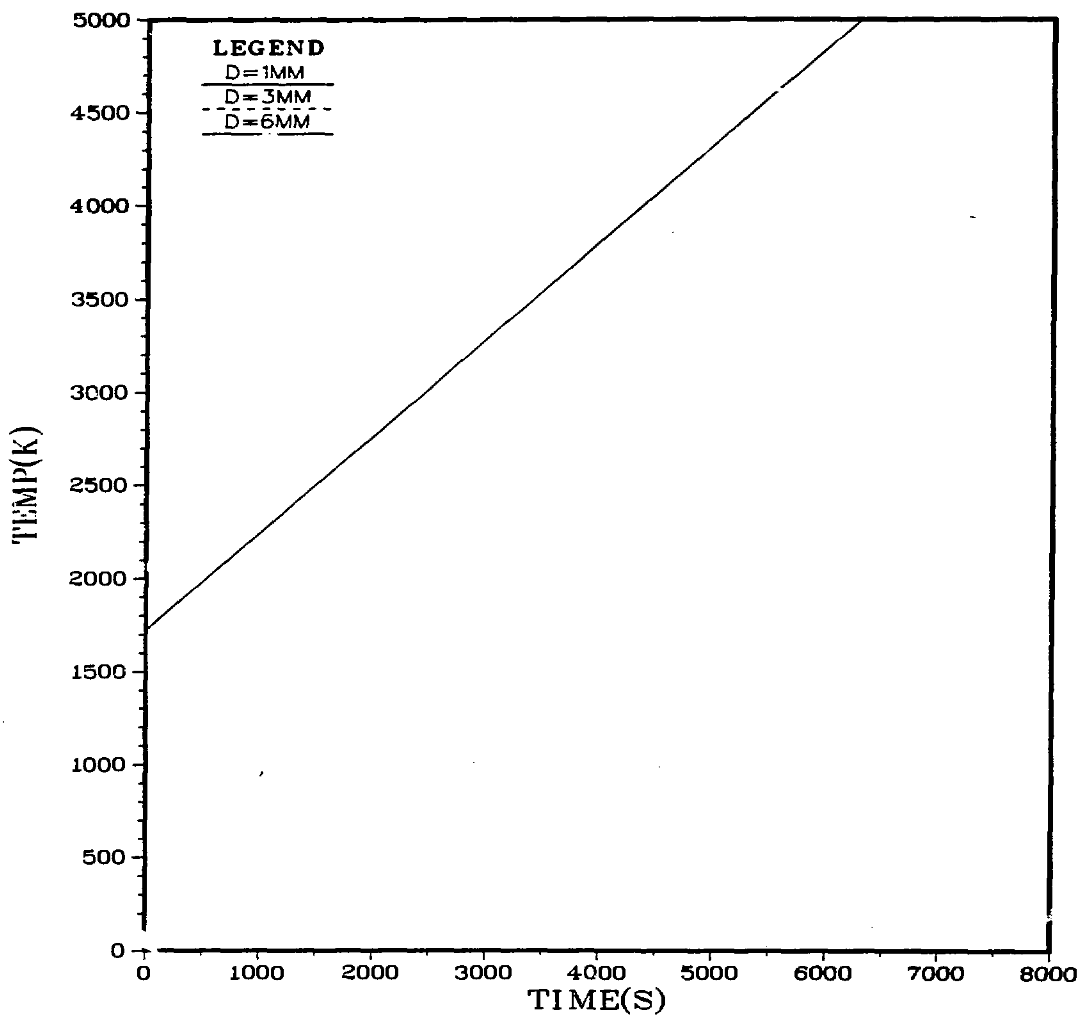

Fig. 6 Unquenched Particle Temperature Vs. Time;
$Q''' = 1.5\ MW/m^3$

initial debris bed temperature. The predicted time scale of the quench process is strongly dependent on the model used to represent the debris bed heat flux. The lower heat flux prediction couples with the consequent increase in stored energy with time in the unquenched region of the bed and leads to very slow quench of the debris bed. This process is not as obvious using the Lipinski representation for the bed heat flux for beds of particles with diameter greater than 3 mm. For 1-mm particles, however, the bed quench time becomes extremely long.

The results suggest that the possibility of debris bed remelting must be considered. The unquenched portion of the debris bed would continue to heat under decay heating conditions. Since the model does not allow for steam cooling of the unquenched debris in the dry channels of the bed, delays of 1000 s before quenching are predicted to lead to significant temperature rise, even for 6-mm debris. The possibility of remelting must be considered as a function of the initial debris temperature.

The model presented and discussed here does not include a number of potentially important physical mechanisms, including steam cooling of the debris, hydrogen generation from metal oxidation reaction, the effect of hydrogen on the bed heat flux and hydrodynamics and steam superheating. Work is under way to incorporate these phenomena in a more generalized treatment of the superheated debris bed quench phenomenon.

Nomenclature

c_p	Specific heat of debris
f_d	Fraction of bed quenched during downward front period
h_{fg}	Latent heat of vaporization of water
H	Bed height
Q'''	Volumetric heat generation rate (per unit bed volume)
t	Time
T_o	Initial bed temperature
T_p	Particle temperature
T_{SAT}	Water saturation temperature
u_{go}	Velocity of steam exiting bed
$u_{\ell o}$	Velocity of liquid entering bed
u_ℓ^*	Velocity of liquid at quench front
v_d	Speed of downward front
v_u	Speed of upward front
z	Axial position in debris bed
z_d^*	Position of downward front
z_u^*	Position of upward front
ε	Bed porosity
ρ_g	Steam density
ρ_ℓ	Liquid density
ρ_p	Particle density

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