

QUENCH COOLING OF SUPERHEATED DEBRIS BEDS IN CONTAINMENT  
DURING LWR CORE MELTDOWN ACCIDENTS

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T. Glasberg

J. C. Chen

**MASTER**

Brockhaven National Laboratory  
Department of Nuclear Energy  
Upton, New York 11973

Lehigh University  
Department of Chemical Engineering  
Bethlehem, Pennsylvania 18015

ABSTRACT

Light water reactor core meltdown accident sequence studies suggest that superheated debris beds may settle on the concrete floor beneath the reactor vessel. A model for the heat transfer processes during quench of superheated debris beds cooled by an overlying pool of water has been presented in a prior paper. This paper discusses the coolability of decay-heated debris beds from the standpoint of their transient quench characteristics. It is shown that even though a debris bed configuration may be coolable from the point of view of steady-state decay heat removal, the quench behavior from an initially elevated temperature may lead to bed melting prior to quench of the debris.

INTRODUCTION

Core meltdown accident sequence studies in light-water reactors suggest that reactor vessel failure would occur as molten core material (corium) thermally attacks the lower vessel dome. In many important sequences water would be available in the region beneath the vessel. As indicated schematically in Fig. 1, melt would be ejected from the reactor vessel upon failure and some degree of corium-water mixing would occur, accompanied by rapid steam generation, and possibly steam explosions. The melt would be partially quenched by the water and would eventually settle to the concrete floor beneath the reactor vessel ("quench" implies reduction of debris temperature to water saturation temperature). Much uncertainty exists as to the state and configuration of the melt at this point. The corium may be in the form of a partially quenched solid debris bed or in the form of a molten pool, which is both attacking the concrete and transferring heat to the overlying coolant layer. The lack of convincing evidence from large scale tests regarding the nature of the debris following arrival to the concrete floor necessitates consideration of the impact of two scenarios on the accident progression: (i) the quench of solid debris beds by overlying pools of water and their coolability, and (ii) the cooling behavior of molten pools which attack the concrete and are cooled by overlying pools of water. This paper considers the quench cooling of superheated debris beds in containment during core melt accidents.

Debris bed quench heat transfer has in the past been computed using a single lumped-parameter energy equation for the debris bed, together with steady-state debris bed heat removal formulations [1]. As a consequence of this assumption, the debris temperature would be predicted to decrease monotonically with time if the bed were coolable based upon steady-state debris coolability considerations [2]. Experimental results suggest that steady

state heat removal concepts can, indeed, be used to predict the debris bed heat removal rate under transient quench conditions [3,4]. The data, however, indicate that the bed quench is a complex, multi-dimensional process that cannot be treated using a single-volume energy equation method of analysis. Models have been developed [5,6] to characterize the transient debris bed quench process. Early results [5] suggested that remelting of the debris is possible under some circumstances, dependent on bed parameters and initial conditions. The objective of this paper is to discuss the coolability of superheated debris beds under conditions of transient quench cooling. Coolability limits are discussed for decay-heated debris beds.

## BED QUENCH MODEL AND ITS BASIS

Figure 2 presents a conceptualized view of a superheated debris bed under transient quench conditions. Experimental data [3-5] 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. It was estimated [3] 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 is conceptualized consisting of three regions. The uppermost partially quenched region (as represented in Fig. 2) consists of wetted channels of particles which are quenched to the saturation temperature and channels of unquenched particles close to their initial temperature. A 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 experimental measurements further show that the steam flow rate was nearly constant for the entire duration of the quench process, inclusive of both frontal progression periods [7]. 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 indicate that the bed-to-water heat transfer rate is well-approximated using the Lipinski [2] model for steady-state heat removal from debris beds. The evidence suggests, therefore, that the rate of quenching of a superheated debris bed is limited by the hydrodynamics of countercurrent two-phase flow within the bed.

The above observations were applied to development of a model characterizing the quench of a superheated debris bed of uniform-size particles and uniform porosity with decay heat generation  $Q'''$ . The analytical model, presented in an earlier paper [5], considers that a decay-heated, superheated debris bed is cooled in the two-stage quench front propagation process represented schematically in Fig. 2. Coolant is assumed to initially penetrate the bed, leaving dry regions of particles which continue to heat under decay heating. Upon arrival of the downward front to the base of the bed, a final upward-directed front propagates up the bed, removing the remaining stored energy. The bed cooling rate is modeled using the Lipinski formulation [2], modified to account for transient liquid storage within the bed which takes place during the quench process. The quench fronts are assumed to propagate at a rate limited by the rate of liquid supply to the front. 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 and steam superheating are neglected.

The complete formulation of the model includes: (i) a coolant mass conservation equation, (ii) a pair of momentum equations, one for liquid and the other for vapor, (iii) a quench front propagation equation and (iv) an energy equation for the unquenched particles. The reader is referred to the Appendix for details of the model.

### CALCULATIONAL RESULTS

Calculations were performed for the range of conditions shown in Table 1. Figures 3 and 4, which are representative results, present the downward- and upward-frontal positions as a function of time for uniform beds of 6-mm particles, of depth 0.5 and 1.0 m, respectively. It was assumed in these calculations that 40% of the bed cross-sectional area is quenched during the downward propagation period. The remaining energy is removed during the upward frontal propagation time. The effect of initial bed temperature is shown on each figure. The temperature rise of the unquenched debris is shown in Fig. 5 for each initial temperature condition. It is noted that since the effect of steam superheating is not considered, the temperature rise rate is simply proportional to the decay-heating rate.

Table 1. Debris Bed Characteristics

Debris Density	8000 kg/m <sup>3</sup>
Debris Specific Heat	600 J/kg K
Bed Porosity	0.4
System Pressure	0.5 MPa
Debris Particle Diameter	1-, 3-, 6-, 12-mm
Initial Bed Temperature	1000 K-3000 K
Bed Height	to 1.0 m
Decay Heat Generation (per volume bed)	1.5 MW/m <sup>3</sup>
Coolant	Water
$f_d$	0.4

Referring to Figs. 3 and 4, the quench process begins with the progression of the downward front from the top of the bed, and is represented as the lines with the negative slope. This front reaches the bottom of the bed, at which time the upward-directed front begins its progression, refilling the bed during the process. The quench process is complete when the front reaches the top of the bed. During the entire quench process, the dry unquenched channels are assumed to continue to heat, as represented by the heating curves of Fig. 5. If the quench process is complete before the bed melting temperature is reached, then the bed is considered coolable. In comparing Figs. 3 and 5, for example, one observes that beds of 6-mm particles with 0.5 m height are coolable at initial temperatures up to nearly 3000 K. On the other hand, a comparison of Figs. 4 and 5 suggests that beds of 1-m height are quench coolable only if their initial temperature is relatively low, i.e., in the range of 1000 K.

Figure 6 presents the steady-state debris bed heat flux, based on the Liptack [2] model as a function of particle size, along with the maximum coolable bed height computed on the basis of the heat flux. These results indicate, based upon steady-state heat removal from uniform debris beds, that beds of

6-mm particles up to 1.5 m in height are coolable from the standpoint of decay heat removal. It is thus clear, based upon the model assumptions characterized above, that debris beds which are coolable based upon steady state, decay heat removal calculations are not necessarily coolable from the standpoint of transient quench heat removal. Bed melting may occur prior to transition to the decay heat removal mode of bed cooling.

Calculations similar to those described above were used to construct debris bed quench coolability maps for the conditions and particle diameters represented in Table 1. As discussed above, a bed was judged to be coolable if the quench process was completed prior to fuel remelting in the unquenched vapor channels. The results of these calculations are shown in Figs. 7-10. The range of bed initial conditions leading to a coolable final state are presented for each of the particle diameters considered.

The results presented in Figs. 7-10 clearly demonstrate that debris quenching imposes an additional constraint on establishment of conditions for bed coolability.

#### SUMMARY AND CONCLUSIONS

A model for the heat transfer processes during quench of superheated debris beds cooled by an overlying pool of water is used to discuss the coolability of decay-heated beds from the standpoint of their transient quench characteristics. The analytical model is based on observations made during experimental simulations of the quench process using beds of spherical particles of uniform diameter.

Debris bed quench coolability maps were constructed for beds of spherical particles of 1- to 12-mm diameter, up to 1 m in height. Initial bed temperatures in the range 1000 K-3000 K were considered. A bed was considered coolable if the quench process was completed prior to fuel remelting in the unquenched vapor channels. The coolability maps so constructed were compared with coolability considerations based on steady state, decay-heated particle bed analysis. The Lipinski two-phase countercurrent hydrodynamics treatment for the bed heat flux was used in the transient quench formulation (modified to account for the transient liquid bed refill mechanism) and also in the steady-state coolability calculations.

The results demonstrate that debris bed quenching imposes an additional constraint on establishment of conditions for bed coolability. Even though a debris bed configuration may be coolable from the point of view of steady-state decay heat removal, the quench behavior from an initially elevated temperature may lead to bed melting prior to quench of the debris. The question of steady-state, decay heat removal debris coolability is moot unless one can first demonstrate that conditions are favorable for debris quench to the coolant saturation temperature. These results point to the need for more detailed examination of debris bed initial conditions and of the physical mechanisms which lead to bed formation.

The analysis presented here may be overly conservative in that it was postulated that particles in the dry, unquenched regions of the superheated particle bed continue to increase in temperature despite the presence of flowing steam in these regions. The questions of heat transfer from the particles to the steam and superheating of the steam will be addressed in future work.

## 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
$T_0$	Initial bed temperature
$T_p$	Particle temperature
$T_{SAT}$	Water saturation temperature
$u_{go}$	Velocity of steam exiting bed
$u_{lo}$	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
$c$	Bed porosity
$\rho_g$	Steam density
$\rho_l$	Liquid density
$\rho_p$	Particle density

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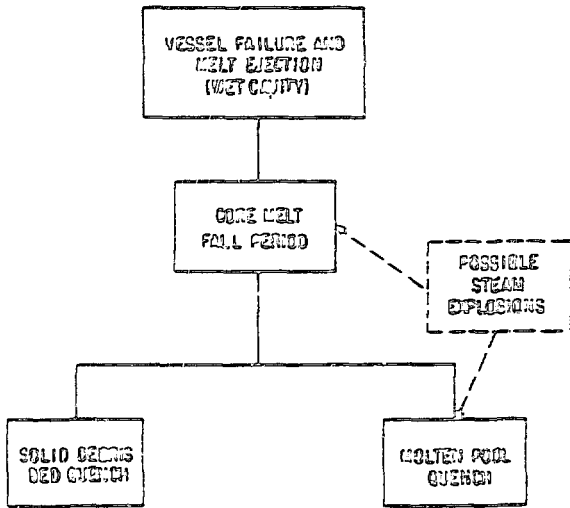


Fig. 1 Accident Progression Following Vessel Failure

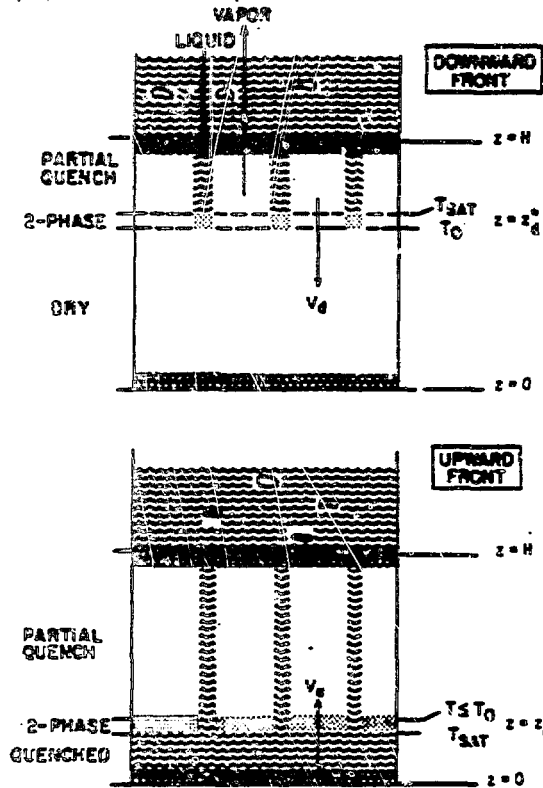


Fig. 2 Schematic of Superheated Debris Bed Quench Front Propagation

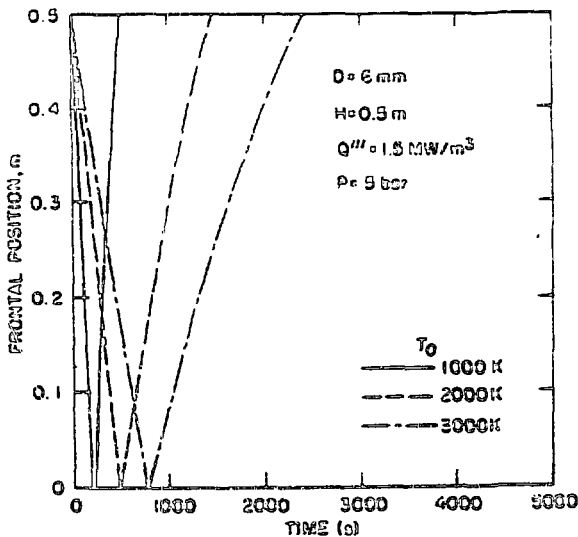


Fig. 3 Quench Front Propagation for 0.5 m Height Bed

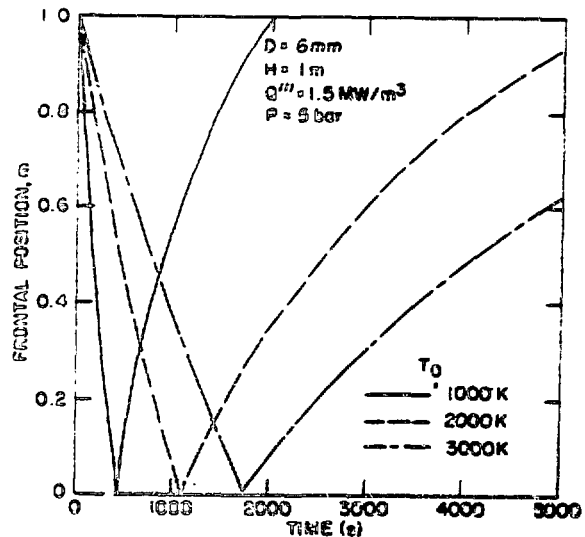


Fig. 4 Quench Front Propagation for 1.0 m Height Bed

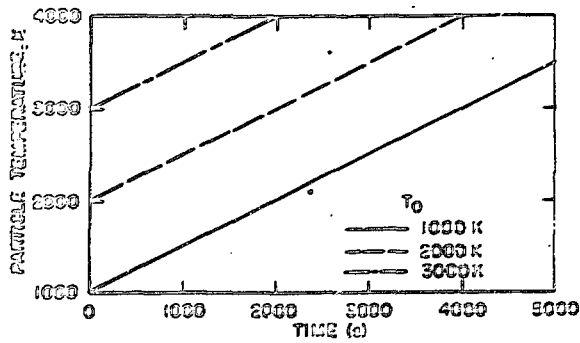


Fig. 5 Particle Temperature Results as Function of Initial Temperature

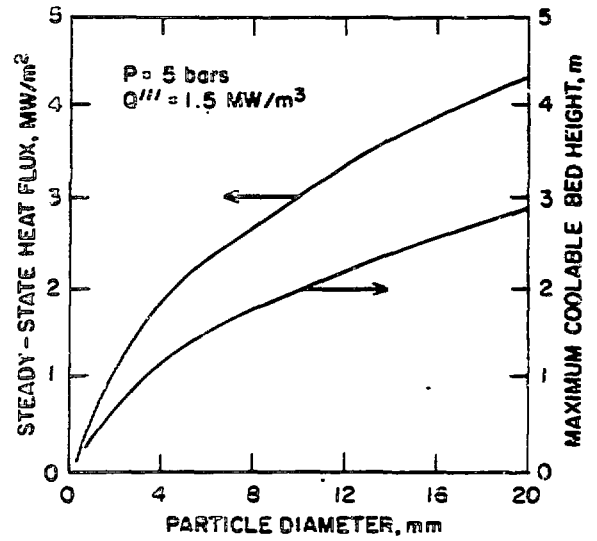


Fig. 6 Steady-State Coolability Map for Beds of Spherical Particles

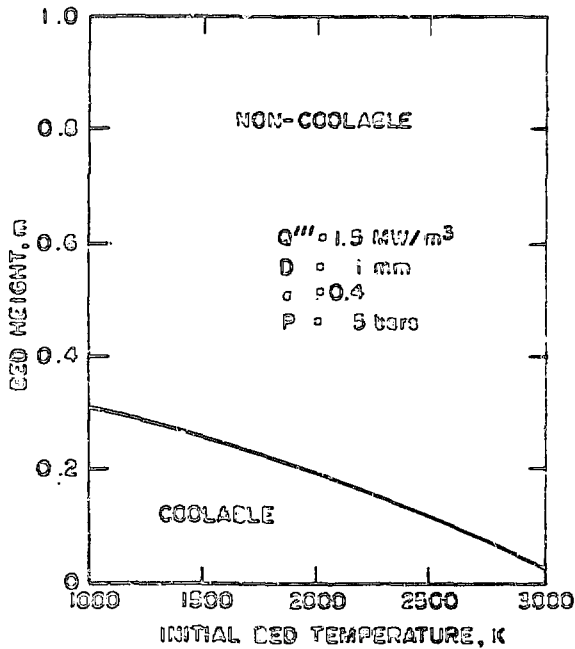


Fig. 7 Quench Coolability Map:  $D = 1 \text{ mm}$

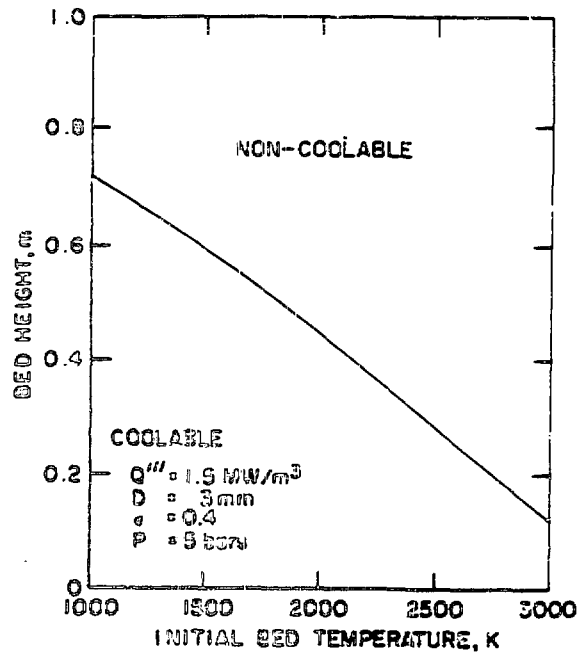


Fig. 8 Quench Coolability Map:  $D = 3 \text{ mm}$

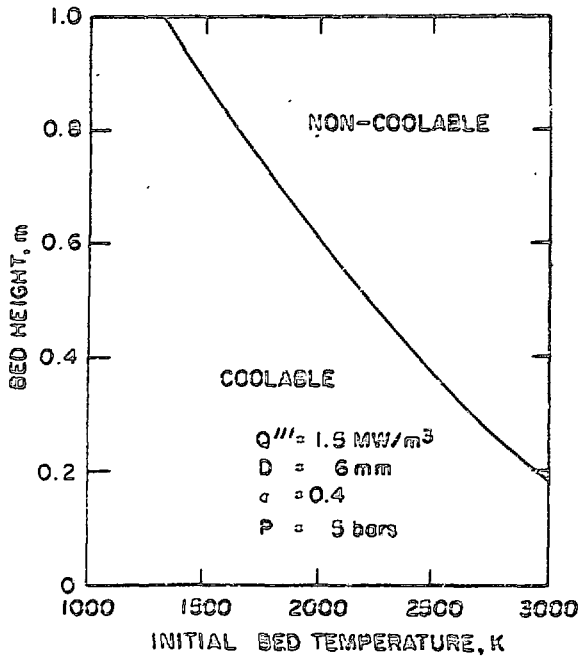


Fig. 9 Quench Coolability Map:  
 $D = 6 \text{ mm}$

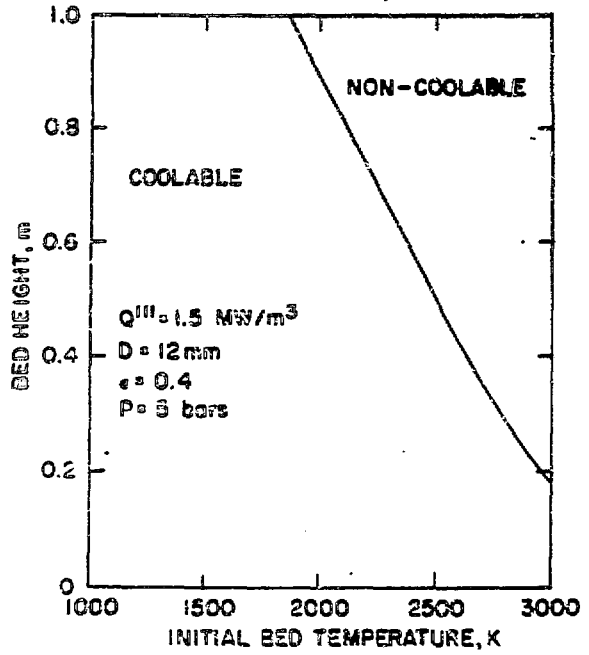


Fig. 10 Quench Coolability Map:  
 $D = 12 \text{ mm}$

APPENDIX: 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 flow 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. 2. During the downward front propagation period

$$\begin{array}{l} \text{liquid available} \\ \text{for} \\ \text{vaporization} \end{array} = \begin{array}{l} \text{liquid flow} \\ \text{to} \\ \text{front} \end{array} - \begin{array}{l} \text{liquid flow to} \\ \text{fill voids in} \\ \text{quenched region} \end{array}$$

An energy balance across the quench front then yields

$$(1-\epsilon)f_d \rho_p c_p (T_p - T_{SAT}) \frac{dz_d^*}{dt} = [\epsilon f_d u_l^* \rho_l - \epsilon f_d v_d \rho_l] h_{fg} \quad (1)$$

A mass balance on the liquid phase yields

$$f_d \rho_l \epsilon \frac{du_l}{dz} = - \frac{Q''' f_d}{h_{fg}} \quad (2)$$

which when integrated from  $z^*$  to H yields

$$u_l^* = u_{lo} - \frac{Q''' (H - z_d^*)}{\rho_l h_{fg} \epsilon} \quad (3)$$

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

$$\frac{dz_d^*}{dt} = \frac{(1-\epsilon)\rho_l h_{fg}}{(1-\epsilon)\rho_p c_p \Delta T + \epsilon \rho_l h_{fg}} \times \left[ u_{lo} - \frac{Q''' (H - z_d^*)}{h_{fg} \rho_l \epsilon} \right] \quad (4)$$

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  $z < z_u^*$ . The resulting frontal propagation equation is

$$\frac{dz_u^*}{dt} = \frac{\epsilon f_d \rho_l u_l^* h_{fg} - Q''' z_u^*}{(1-\epsilon)(1-f_d)\rho_p c_p \Delta T + \epsilon(1-f_d)\rho_l h_{fg}} \quad (5)$$

The energy equation for the unquenched particles is

$$\rho_p c_p (1-\epsilon) \frac{dT}{dt} = Q''' \quad (6)$$

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

The overall coolant conservation equations are

$$\begin{aligned} u_{l0} f_d \rho_l + u_{g0} (1-f_d) \rho_g &= f_d v_d (\rho_l - \rho_g) && \text{down-front} \\ &= (1-f_d) v_u (\rho_l - \rho_g) && \text{up-front} \end{aligned} \quad (7)$$

where  $u_{l0}$  and  $u_{g0}$  are the liquid and vapor velocities at the top of the bed.

The above set of equations can be solved once  $u_{g0}$  and  $u_{l0}$  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. The Lipinski model supplies the additional required relationship between  $u_{l0}$  and  $u_{g0}$ .

Equations (4)-(7), together with the formulations for the bed heat removal, were solved simultaneously using Gear's method of integration.

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