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《Original》

An Evaluation of Cooling of Core Debris and Impact on Containment Transient Pressure under Severe Accident Conditions

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극심한 사고시 노심 냉각 및 격납용기 과도압력에 미치는 영향

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Abstract

An evaluation of containment transient pressure due to the particulate debris/water/concrete interaction under severe accident conditions is presented for a pressurized water reactor with a large dry containment building. A particulate debris/water/concrete model is developed and incorporated into the MARCH computer code. Comparisons with the existing MARCH molten debris/concrete model were performed for the TMLB' and S_2D sequences. The results yield a much slower concrete decomposition rate and release less gases into the containment atmosphere. Contrary to the molten debris model, the particulate debris model ekhibits a strong interaction with water and causes a higher containment pressure. The effect of gas influx on the debris bed heat transfer was found to be insignificant.

요 약

가압 경수로에서 극심한 사고시 Debris/Water/Concrete 상호작용에 의한 Debris Bed 냉각과 격납용기과도 압력 평가가 제시되었다. 이 논문에서 제시된 Debris/Water/Concrete 해석모델을 MARCH 전산코드에 도입시켜 TMLB'와 S_2D 사고분류에 따라 현존 용융 모델과 비교할 때 저속의 콘크리트 분해율과 소량의 개스 생성을 나타내는 반면 입자형 모델은 물과 상호작용이 지배적이며, 더 높은 격납용기 압력을 야기시켰다. 그 결과 Debris Bed의 열전달에 미치는 개스 유입효과는 중요하지 않음이 입증되었다.

Nomenclature

c	Specific heat
C_p	Specific heat at constant pressure
d	Average particulate diameter
E	Arrhenius activation energy
g	The acceleration of gravity
h_{fg}	Heat of vaporization
k	Thermal conductivity
K	Arrhenius frequency factor
L	Bed height
q	Total heat transfer
R	Universal gas constant
s	Effective Saturation
t	Time
T	Temperature
V	Superficial velocity
w	Inlet mass flux
x	Depth
β	Weight fraction
ρ	Density
μ	Dynamic viscosity
ε	Bed porosity
σ	Surface tension
θ	Contact angle between liquid and solid
α	Effective thermal diffusivity

Subscripts

av	Average
c	Concrete
d	Debris partcle
g	Gas
i	Interface between debris and concrete
I	Liquid
m	Gas-vapor mixtures
v	Vapor

1. Introduction

For a postulated core meltdown accident, predicting the containnment pressure and temperature histories resulting from steam overpressurization and hydrogen ignition is important for the development of severe accident mitigation feature[1] in the future. Furthermore, the thermal interactions of the core debris with water and concrete are of particular importance. The interaction of the core debris with water first occurs at the bottom of the reactor vessel, which could result in the complete evaporation of reactor vessel water, and then, the failure of the vessel. With the failure of the reactor vessel under severe accident conditions, large quantities of molten core dedris are released to the containment cavity. In the flooded cavity, the mixing of the molten debris with water may cause fragmentation of the core debris. If no steam explosion is triggered, the fragmented debris settles on the cavity basemat and forms a porous debris bed. The interactions of core debis with water and concrete in the cavity are the driving forces for the generation of steam and combustible gases. Recently, the analysis of the steam pressure spike due to the debris/water interaction evaluated by Yang and Pratt[2] was based on a porous debris bed located in the reactor cavity with adiabatic and nonpermeable boundary between its core debris and concrete. In the analysis, no heat and mass transfer between the debris bed and concrete were considered. Lee and Yang[3] presented a study of the particulate debris/water/ concrete interaction for pressurized water reactors under severe accident conditions. In the present paper, the previous work is extended to an evaluation of containment transient pressure for a typical 3,000 MWt PWR plant.

Most of the studies of core/concrete interaction are limited to core debris in the molten state [4,5]. There is only a few studies of the particulate dedris interacting with the concrete. Baker[6] and Tarbell[7] reported an experimental study of fragmented debris on concrete. The results indicated that the gas influxes generated by dehydration and decarboxylation reactions are smaller than those that would be produced by a molten overlying material. Using Tarbell's experimentally-measured gas flux, a dryout model by Gorham-Bergeron[8)] showed that the interaction of solid debris with gas flux has little effect on dryout heat flux of the dedris bed. In this study, Lipinski one-dimensional debris bed model[9)] is extended to include a steady gas influx from below. This model has not been applied to the transient containment conditions in which the gas fluxes are coupled with the cooling of core debris. For degraded core and full core meltdown accidents, Yang and pratt[2,10)] described that the hot core debris could be coolable and stay in the particulate form in the reactor cavity for hours. Since the interactions between core debris, water and concrete could take place for a long period of time, its coupled phenomena become an integral part of the containment transient.In this study, a treatment of particulate debris/water/concrete interaction was modeled and incorporated Into the MARCH code[11)] for an estimation of the coupled phenomena.

At present, MARCH is the principal code available for analyzing meltdown accidents in the light water reactors. In the MARCH code, only the molten debris/concrete interaction is computed in the subroutine INTER; no particulate dedris/water/concrete interaction is considered. The interaction of molten dedris/concrete modeled in the MARCH code represents the situation in which the core debris uncoolable and vigorous attack of the concrete takes place. The particulate debris/water/concrete model developed in this report represents another limiting situation in which the core debris is coolable and no vigorus attack of concrete is expected.

2. Theoretical Analysis

2. 1. Gas Generation Model

The characteristics of the attack of the core debris on the concrete below the reactor cavity are important since it involves the final line of defence against violation of the containment An experimental study of transient heat transfer in concrete was reported by Baker[6)] for evaluating LMFBR molten core debris with concrete. In this model of transient heat transfer in concrete, the heating of the concrete is approximated by heat conduction in semi-infinite medium with heat sink and step-change of temperature at the debris/concrete interface. This is extended in Reference 3 to include the effect of concrete decomposition on transient cencrete temperature distribution. In developing the model below, it is assumed that the interaction between the hot core debris and concrete causes the decomposition of the concrete only. No melting of the transient temperature distribution of the concrete as a function of depth (x) is given as follows[6,12)]:

$$T=T_c+(T_i-T_c)\ [\mathrm{erfc}\ Y+g(\mathrm{ierfc}\ Y-i^2\mathrm{erfc}\ Y)] \tag{1}$$

whree

$$Y=\frac{X}{2\sqrt{\alpha t}}$$

$$g=-2\left[\frac{1-\sqrt{\alpha_i/\alpha_{av}}}{0.134}+\frac{\sum a_k f_k \Delta H_k \sqrt{k/\alpha_{av}}}{0.0756\, C_p(T_i-T_c)}\right]\Big/(1+3.616\sqrt{\alpha_i/\alpha_{av}})$$

Here, α_i is the thermal diffusivity of concrete at temperature T_i ΔH_k and f_k are the reaction heat and the propagation constant of ***k*,*th*** speies, respectively. a_k is the mole fraction of the ***k-th*** species per unit mass of concrete.The interface temperature between core debris and concrete is approximated by

$$T_i=\frac{T_D\sqrt{(k\rho C)_d}+T_C\sqrt{(k\rho C)_c}}{\sqrt{(k\rho c)_d}+\sqrt{(k\rho c)_c}} \tag{2}$$

Knowing the the concrete temperature, the decomposition rectionss in the concrete can be computed. Powers[13] has shown that there are three events of thermal deccmposition involved in the calcarous aggregate and basaltic aggregate types of concrete. These events are,

(a) loss of evaporable water at temperature of 293 to 473°K,

(b) loss of chemically costituted water at temperature of 473 to 673°K, and

(c) loss of carbon dioxide at temperature of 870°K.

The kinetic equations of the above events[13] has been empirically described by the first-order rate laws:

$$\frac{\partial \beta_d}{\partial t}=K_j(1-\beta_j)\ \exp\ (-E_j/RT) \tag{3}$$

where $j=1, 2, 3$ are for the evaporable water, chemically bounded water, and carbon dioxide, respectively. The empirical constants, K_j and E_j, are reported in the reference[13].

2.2 Gas Flux Dryout Model

This model is similar to that presented by Gorham-Bergeron, which is based on Lipinski's one-dimensional model[9]. A modified analysis has been presented by Lee and Yang[3], who updated the Lipinski modl[14] to include gas influx at the bottom of the bed. The conservation equations for two-phase fluid counterflow through porous media with capillary effect are:

$$\frac{1.75(1-\varepsilon)\rho_m V_m^2}{d\varepsilon^3(1-s)^3}+\frac{150(1-\varepsilon)^2\mu_m V_m}{d^2\varepsilon^3(1-s)^3}+\frac{\Delta P_m}{L}+\rho_m g=0 \tag{4}$$

$$\frac{1.75(1-\varepsilon)P_1 V_1|V_1|}{d\varepsilon^3 s^3}+\frac{150(1-\varepsilon)\mu_1 V_1}{d^2\varepsilon^3\delta^3}+\frac{\Delta P_1}{L}+\rho_1 g=0 \tag{5}$$

$$\rho_1 V_1+\rho_v V_v=w \tag{6}$$

$$\rho_m V_m=\rho_v V_v+\rho_g V_g \tag{7}$$

$$\rho_1 V_1=w-\frac{q}{h_{fg}} \text{ and } |\rho_1 V_1|=\delta\left(w-\frac{q}{h_{fg}}\right) \tag{8}$$

$$\rho_v V_v h_{fg}=q \tag{9}$$

where W is the inlet gas flow rate through the bed. The total capillary pressure drop is given by

$$\Delta P_1-\Delta P_m=\frac{6\sigma(1-\varepsilon)\mathrm{Cos}\theta}{\varepsilon d}$$

By combining Eqs (4) through (9), a single algebraic equation can be obtained as follows:

$$\begin{aligned}&\frac{1.75(1-\varepsilon)}{d\varepsilon^3}\left[\frac{1}{\rho_m(1-s)^3}-\frac{\delta}{\rho_1 s^3}\right]\frac{q^2}{h_{fg}^2}+\frac{150(1-\varepsilon)^2}{d^2\varepsilon^3}\left[\frac{\mu_1}{\rho_1 s^3}+\frac{\mu_m}{\rho_m(1-s)^3}\right]\frac{q}{h_{fg}}\\&+\frac{1.75(1-\varepsilon)}{d\varepsilon^3}\left[\frac{2V_g\rho_g}{\rho_m(1-s)^3}+\frac{2\delta w}{\rho_1 s^3}\right]\frac{q}{h_{fg}}+\frac{1.75(1-\varepsilon)}{d\varepsilon^3}\left[\frac{V_g^2\rho_g^2}{\rho_m(1-s)^3}-\frac{\delta w^2}{\rho_1 s^3}\right]\\&+\frac{150(1-\varepsilon)^2}{d^2 s^3}\left[\frac{\mu_m\rho_g V_g}{\rho_m(1-s)^3}-\frac{\mu_1 w}{\rho_1 s^3}\right]-\frac{6\sigma(1-\varepsilon)\mathrm{Cos}\theta}{\varepsilon dL}-(\rho_1-\rho_m)g=0\end{aligned} \tag{10}$$

where δ detemines the direction of liquid flow. δ equals 1 for $w>\frac{q}{h_{hg}}$ and -1 for $w<\frac{q}{h_{fg}}$.

The term, q represents the total heat transfer to water for steam generation and is also given by

$$q=q_d+q_g \tag{11}$$

where q_d and q_g are the heat transfer from the debris particles and the inflowing gases, respectively. It is assumed that the gases released from the concrete, mix with water vapor and are cooled to the saturation temperature of the two-phase flow in the bed:

$$q_g=\int_{T_s}^{T_\varepsilon}\rho_g C_{pg} V_g dT \tag{12}$$

After water in the reactor cavity boils off, the rate of heat loss from debris to gas may be obtained from this formula:

$$q_{dg}=\int_{T_\varepsilon}^{T_{max}} C_{pg}\rho_g V_g dT \tag{13}$$

where, q_{dg} is the heat loss from debris to gas during degassing below the debris. T_{max} can be approximated as the debris temperature. This term is used only when the debris is in the solid state. Equation (10) is used to evaluate the total heat flux (q) in terms of the saturation (s). This is done by maximizing q with respect to variations in s. As suggested by Lipinski[14], this procedure determines the onset of dryout in the debris bed. According to Equation (10), the effect of the inflowing gases is to reduce the downward liquid flow and, hence the heat flux from the bed. However, based on the gas flow rate generated from the concrete, no significant effect on the heat flux was computed as will be shown in the next section.

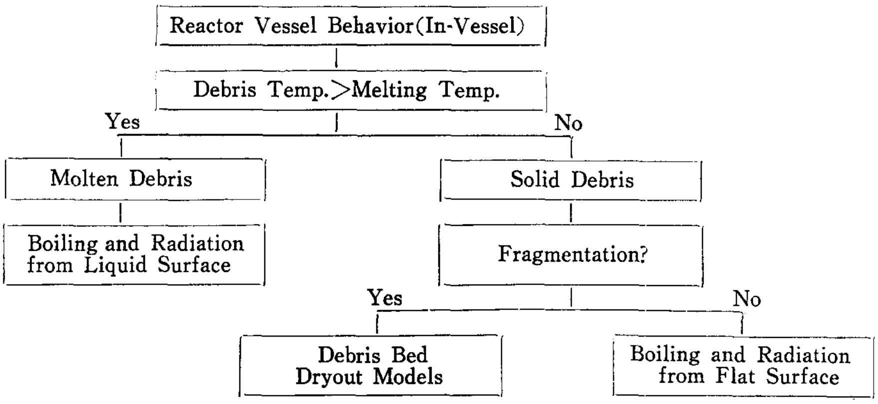

Fig. 1a Computation Logic for Debris/Water Interaction (In-Vessel Analysis)

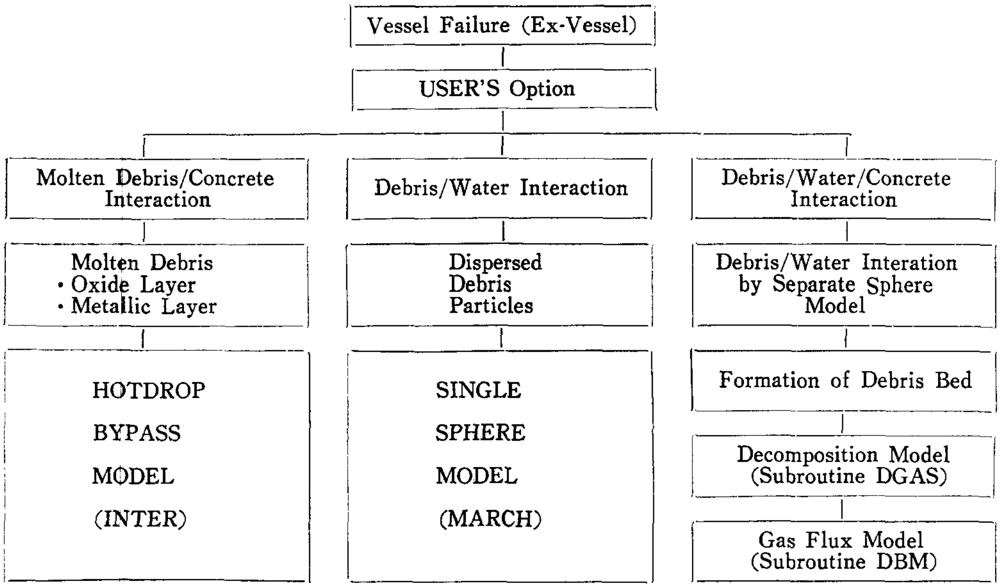

Fig. 1b Computation Logic for Debris/Water/Concrete Interation (Ex-Vessel Analsis)

2.3 Application

The computation logic for the interaction of debris, water, and/or concrete is shown in Figures 1a and 1b. The in-vessel and ex-vessel analyses were performed according to the general structure of the MARCH code and the modifications reported in the references(2, 3). The melting temperature of the core debris is strongly affected by its interfacing species. When the core debris is in the molten state, the heat transfer is determined by Berenson's film boiling or Zuber's critical heat flux correlation. If the computed temperature of core debris is below its melting temperature, it is then assumed that the debris may form a packed debris bed and the heat transfer is controlled by the dryout heat flux of the dedris bed. For the ex-vessel case, the initial stage of debris/water interaction is approximated by the separated sphere model in which film boiling and radiation from single sphere are computed. After forming a packed bed, the dryout heat flux in the conditions, in which the maximum possible vapor volume flux can flow through the debris bed, is used to cempute the cooling of the debris particles and the boiling rate. When water in the reactor cavity remains, the heat loss from gas to water is computed by the dryout heat flux model with gas flow. If water boils off, the debris will reheat. Until the debris temperature reaches the limiting temperature (1, 700°k) which is assumed in the MARCH model, Heat loss from debris to gas is computed by this model. Two new subroutines were developed. The effect of gas flux on the debris bed is computed in the subroutine DBM and the concrete decomposition in the subroutine DGAS.

3. Results

The particulate debris/water/concrete interaction is studied for a typical 3, 000MWt PWR dry containment plant. It is assumed that substantial quantities of water are present in the containment cavity prior to pressure vessel failure and that a continuous supply of condensed water to the cavity may be maintained after the pressure vessel is breached. The concrete of cavity is of limestone type and is characterized by high calcium carbonate(80% $CaCO_3$) content. The first case considered is the TMLB' sequence(extended loss of total ac power coupled with failure of the auxiliary feedwater system)[15]. According to the MARCH calculation, the pressure vessel fails at 303 minutes after the accident is initiated and the core debris falls directly into the cavity which contains 2.18×10^5Kg of subcooled water. Initially, the core debris temperature (2, 379°K) is above the assumed melting temperature of the corium (2, 080°K). The initial mixing of the debris

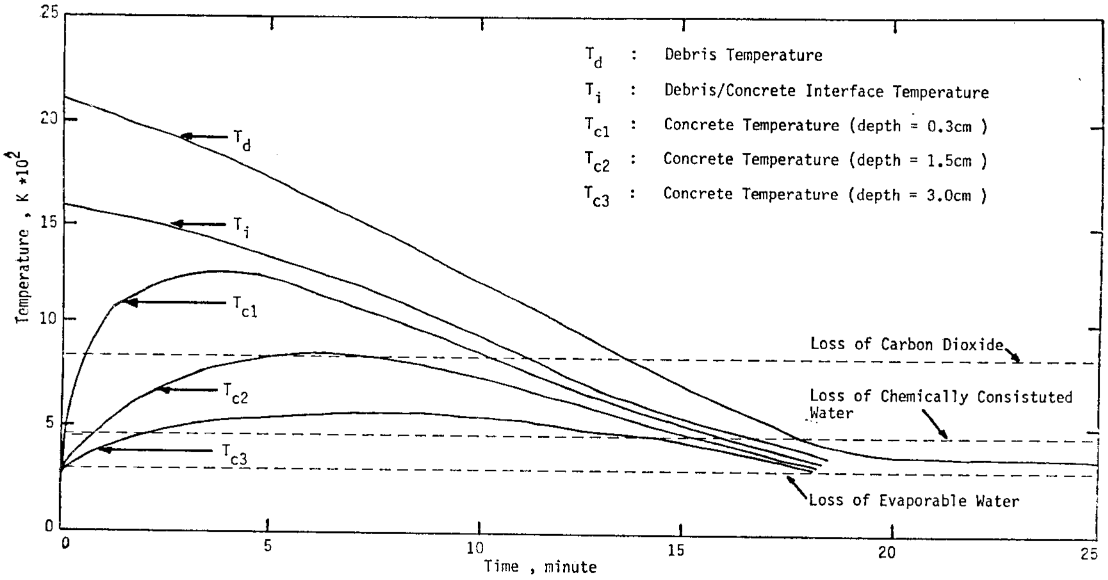

Fig. 2. Calculated Temperature Profiles for TMLB' Sequence (flooded cavity case)

with water results in a rapid cooling and fragmentation of the debris. Corradini[16] has estimated that the particle size could vary from 6mm to 25mm based on the balance of steam generation rate and fluidization velocity. On this paper, the particle size is assumed to be 10mm in diameter based on the parametric study of the particle size[3,16]. The MARCH computation shows that interaction with concrete starts immediately after the failure of pressure vessel. Because of the rapid cooling of the core debris, the interaction only affects a narrow layer of the concrete as illustrated in Figure 2. According to the predicted concrete temperatures, carbon dioxide is released from a layer 1.5cm in depth, and no chemically constituted water is released below the depth of about 3~4cm. The interaction between the particulate debris and concrete continues for only about 15 minutes. During this period, 221Kg of CO_2 and 314 Kg of water vapor are released. Figure 3 shows the amount of gases released in comparison with that released by using the existing INTER model. The INTER model simulates the event in which the debris is assumed to be uncooled and stays at the molten state. As seen in Figure 3, the particulate debris/concrete interaction is much weaker in comparison with the molten debris/concrete interaction. The effect of debris/concrete interaction on containment pressure is illustrated in Figure 4. The containment is subjected to a pressure rise (AB in Figure 4) at the pressure vessel failure due to the sudden release of high pressure gases into the containment. In one situation (curve 1 in Figure 4), the rapid cooling and fragmentation of core debris in the flooded cavity generate a large amount of steam which causes an increase in pressure. At point C, the debris is quenched, i.e., the sensible heat associated with the hot debris particulates has been removed. Further increase of pressure is the result of continuous generation of steam by the decay heat. In contrast curve 2 represents a different situation which assumes that the core debris cannot be cooled immediately by water in the cavity and

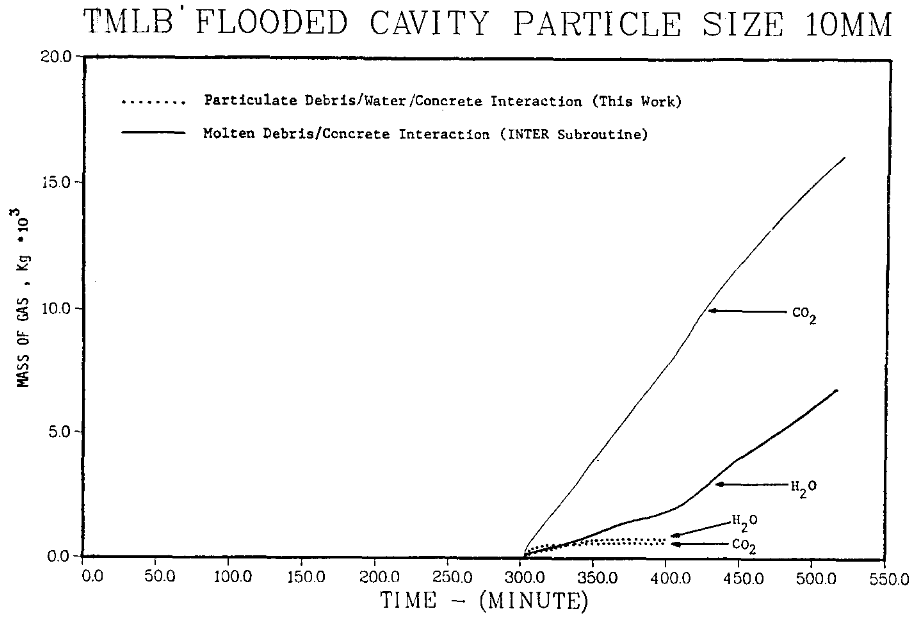

Fig. 3. Comarison of Mass of Gasses Generated from Concrete for TMLB' Sequence (flooded cavity case)

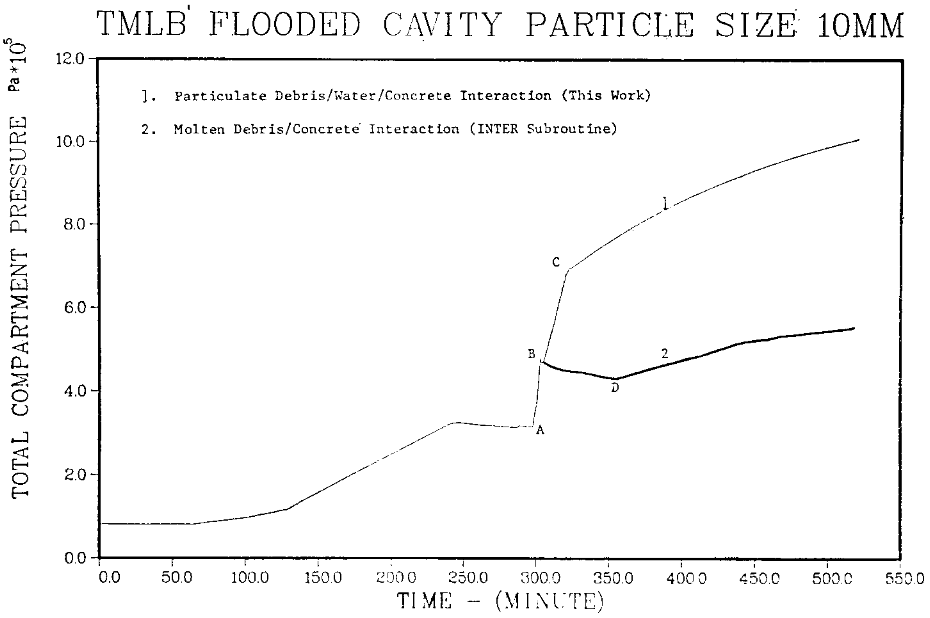

Fig. 4. Comparision of Containment Transient Pressure for TMLB' Sequence (flooded cavity case)

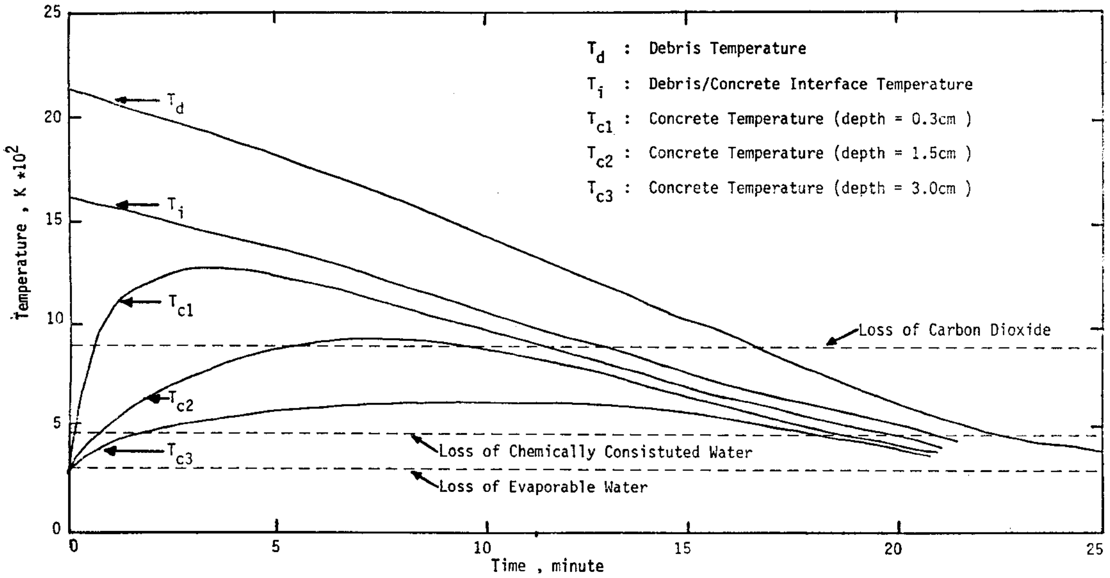

Fig. 5. Calculated Temperature Profiles for S_2D Sequence (flooded cavity case)

remains in the molten state. Apparently, the heat transfer from the molten debris to the water is much slower and no steam spike is predicted by the MARCH code. The interaction between the molten debris and concrete starts to release gases after the pressure vessel is breached. Initially, the containment pressure decreases due to condensation of steam up to about 353 minutes (point D in Figure 4). The effect of gas generation is represented by the slow pressurization of the containment building beyond the point D in Figure 4.

Another accident sequence of interest is the S_2D event. This event is characterized by a

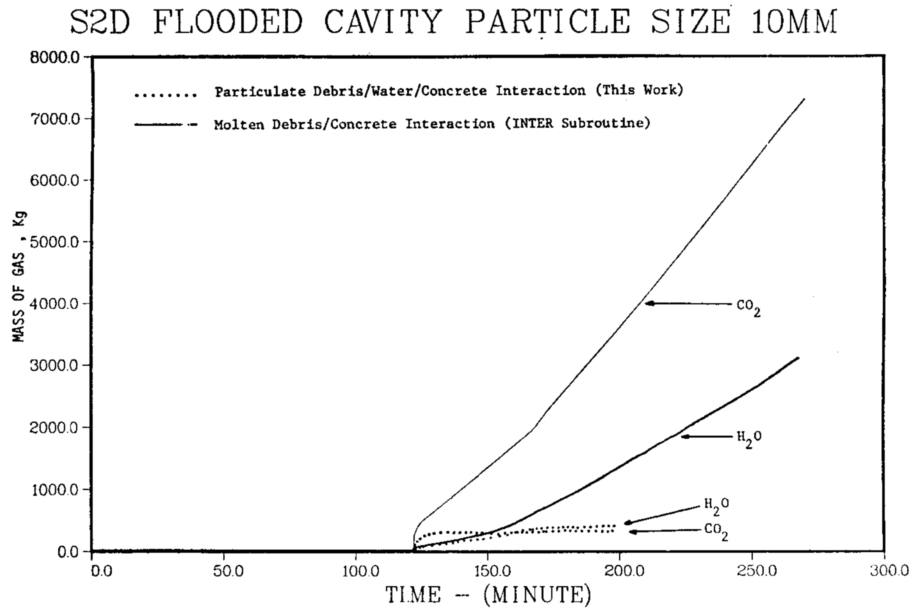

Fig. 6. Comparison of Mass of Gases Generated from Concrete for S_2D Sequence(flooded cavity case)

small break LOCA followed by the failure of emergency core cooling system. To demonstrate the effect of debris/concrete interaction, a S_2D cenario is analyzed. A break in the primary system equivalent to 5 cm (2 inches) diameter is assumed. Again, the particle size is taken to be 10 mm and the cavity is flooded. The computed transient temperatures and gas released are shown in Figures 5 and 6, respectively. Similar to the TMLB' event, the particulate debris/concrete interaction is much slower than the molten debris/concrete interaction predicted by the INTER model. The transient containment pressure is illustrated in Figure 7. Because

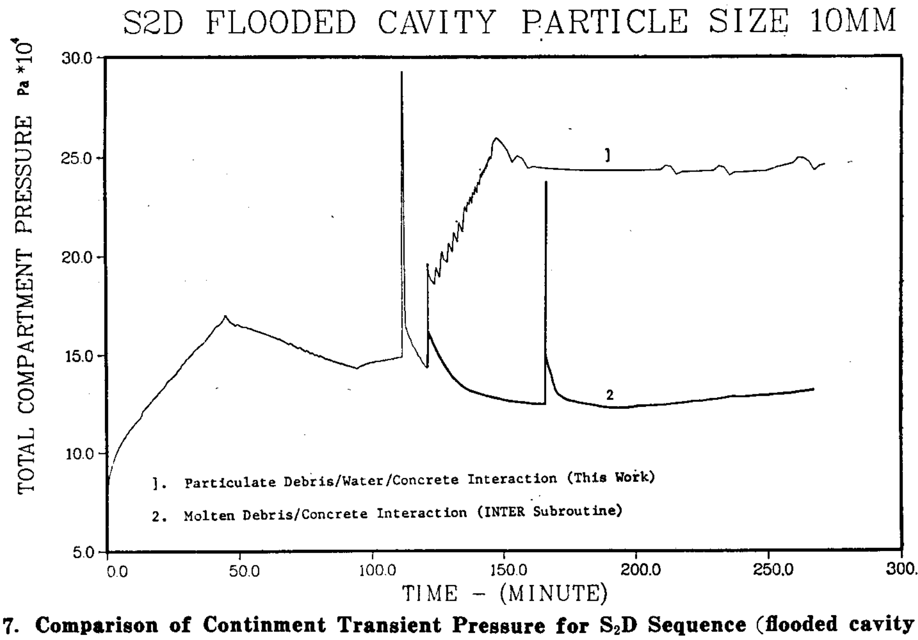

Fig. 7. Comparison of Continment Transient Pressure for S_2D Sequence (flooded cavity case)

of the depressurization of the primary system by the small break prior to reactor vessel failure, it it not expected to have a large pressure spike at the vessel failure. According to the MARCH prediction, a hydrogen ignition occurs at 111 minute and is followed by the reactor vessel failure at 121 minutes. The particulate debris model predicted a rapid rise of containment pressure by the production of steam from the particulate debris bed. The containment atmosphere is apparently inerted by the steam and no further hydrogen ignition is predicted. The molten debris model predicts, on the other hand, less steam productioon and lower containment pressure. With no sufficient steam to inert the containment atmosphere, a second hydrogen ignition at 167 minutes is predicted for the molten debris case. The peak containment pressure is less than the design pressure by both models.

4. Summary

A particulate debris/water/concrete model is developed and incorporated imto the MARCH computer code. The model can be used for cases in which a coolable debris bed is formed in a flooded cavity in the containment building. Applications to the TMLB' and S_2D sequences were made;the results were compared with predictions by the existing MARCH molten debris/concrete interaction model. Due to the rapid cooling of the debris particulates by the overlaying water, the interaction with concrete is much smaller in comparison with that of the molten debris case. The interaction with water, on the other hand, is much stronger and produces higher containment pressure.

Acknowledgments

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