[illegible]

[illegible] and [illegible]

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[illegible]

In an HCDA, [illegible] materials are in contact with the metal [illegible]. A mathematical model [illegible] has been developed [illegible] in the concrete. [illegible] water and [illegible] of the [illegible] of the model [illegible] experimental results [illegible].

[illegible]

In the event of a hypothetical [illegible] current generation of fast reactors, the [illegible] of concrete and other construction materials must be [illegible]. In an HCDA the high temperature liquid metal core debris [illegible] materials are contained by a structure predominantly composed of concrete. A mathematical model describing the heat and mass transfer in the concrete for the anticipated high temperature and heat flux conditions has been developed and a computer program has been written.

The major phenomena treated include 1) conductive energy transport, 2) chemical decomposition of concrete, 3) two phase-three component heat and mass transport of the decomposition products: steam, liquid water, carbon dioxide, and 4) ablation of the heated surface. Another unique part of the model is the provision for the porosity to increase as the water and CO_2 is formed from the concrete.

Upon heating the concrete decomposes with a resulting increase of porosity and release of evaporable water, chemically constituted water and carbon dioxide. The evolved gases pressurize the pore spaces of the concrete thus providing a driving force for flow of the fluids through the porous medium. Energy is transported through the concrete both by conduction and convection. Local thermal equilibrium between the mobile decompo-

[illegible] fluid and [illegible] approximation [illegible] possible [illegible] partly [illegible] primarily [illegible] but [illegible] the partial pressure of water [illegible] whereas [illegible] pressure [illegible] formation [illegible]

[illegible] equations [illegible] not [illegible] be obtained. [illegible] and [illegible] properties [illegible] variation [illegible] temperature [illegible]

A distinguishing feature of the present treatment [illegible] chemical rate equations are [illegible] the [illegible] of water and carbon dioxide [illegible] concrete [illegible] analysis appears to have [illegible] this aspect; [illegible] have [illegible] of [illegible] the wet [illegible] have not [illegible].

The rate equations for decomposition are identical in both the wet and dry regions. [illegible] [1] found that the [illegible] were well approximated by first order reaction rate equations of the form

$$[illegible] \qquad (1)$$

where α_i is the fraction of reactant decomposed, T is the [illegible] temperature, [illegible] E_i [illegible] are the empirical [illegible] respectively [illegible] experimentally [illegible] An exact solution for the above equations is used for a given time step assuming that the temperature varies linearly with time during the interval. Higher order reactions can be handled in the same manner.

[illegible]

The energy and fluid flow equations in the dry region are given below.

The energy equation is

$$\overline{\rho c_p}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - (\rho_1 c_{p1} + \rho_2 c_{p2}) u_m \frac{\partial T}{\partial x} + [illegible] \qquad (2)$$

where the subscripts (s,g,m,1,2) are respectively solid, [illegible], gas mixture, steam, and CO_2. The second term on the right accounts for convective transfer of energy due to [illegible]. [illegible]

$$\overline{\rho c}_{pm} = \rho_{c} \; \text{[illegible]} + \rho \; \text{[illegible]}$$

where ρ_c is the initial concrete density [illegible] source term, [illegible] from [illegible] the first three terms [illegible]. The [illegible] equation for water vapor is

$$\frac{\partial(\rho_1 \, \text{[illegible]})}{\partial t} = -\frac{\partial}{\partial x} \; \text{[illegible]}$$

and the continuity equation for [illegible] is

$$\frac{\partial(\rho_2 \, \text{[illegible]})}{\partial t} = -\frac{\partial \, \text{[illegible]}}{\partial x} \; \text{[illegible]}$$

The mass source terms, $\dot{S}_1$ and $\dot{r}_2$, are [illegible] Arrhenius rate equations for concrete decomposition. [illegible] both the wet and dry regions, we write

$$\dot{S}_1 = \omega_{1'}^{o} \frac{\partial \, \text{[illegible]}}{\partial t} + \omega_{1''}^{o} \frac{\partial \, \text{[illegible]}}{\partial t}$$

and

$$\dot{r}_2 = \omega_2^{o} \frac{\partial \, \text{[illegible]}_2}{\partial t}$$

where $\omega_{1'}^{o}$, $\omega_{1''}^{o}$ and ω_2^{o} are the total masses of original concrete per unit volume of original concrete that can be lost [illegible] water, chemically constituted water and carbon dioxide respectively. The [illegible] of the concrete is assumed to increase linearly with [illegible] and [illegible] in both the wet and dry regions.

A constitutive equation usually used for pressure driven flow in porous media is Darcy's law. The form of Darcy's law used for velocity of the gas mixture is

$$u_m = -\frac{k_{rm}}{\mu_m} K \frac{\partial}{\partial x}(p_{g1} + p_{g2})$$

where K is the permeability of the medium, k_{rm} is the relative permeability of the gas mixture and μ_m is the viscosity of the mixture. The permeability is a function of temperature. The relative permeability is a function of void fraction and pore pressure, and the viscosity is a function of temperature.

The [illegible] of [illegible] water [illegible] law,

$$[illegible]$$

Dalton's law for the total pressure [illegible]

$$p = p_{[illegible]} + p_{a}$$

[illegible]

The corresponding equation in the wet region [illegible] the energy equation,

$$\overline{\rho c}_{[illegible]} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) - \sum_{j=1} [illegible]$$

where the additional convective term accounts for [illegible] transport due to water flow. The source, [illegible] to j=2, now includes terms due to change of phase of water,

$$[illegible]$$

$$\dot{S}_2 = -\frac{\partial}{\partial t}\left[[illegible]\right] - \frac{\partial [illegible]}{\partial x}$$

In which q_v is the heat of [illegible] of water [illegible] fraction of [illegible] and ρ_l is the density of water. The [illegible] water and chemically-bound water.

The continuity equation for water (both liquid [illegible]) is,

$$\frac{\partial(\rho_{g1} [illegible])}{\partial t} + \frac{\partial [illegible]}{\partial y} + \left[\frac{\partial}{\partial t} \rho_{l}(1-\theta) + [illegible]\right] = [illegible]$$

The source, $\dot{S}_1$, is given by eq. [illegible]. The continuity equation for carbon dioxide given by eq. (5) and the source term, eq. [illegible], are valid in both the wet and dry regions.

Darcy's law in the forms for flow of the gas mixture and of the liquid water are

[illegible]

[illegible]

plus the Clausius-Clapeyron equation,

[illegible] (7)

and the perfect gas law, the partial pressure of water [illegible] can be directly computed as a function of temperature. In addition to the equations listed above for the wet region, the ideal gas law and Dalton's law are utilized.

METHOD OF SOLUTION

In the dry region these equations are combined to yield three equations in the variables T, ρ_{g1} and ρ_{g2}. The dependent variables in the wet region are T, ρ_{g2}, and [illegible]. The resulting equations are solved by an implidict finite difference scheme that is a generalization of the Crank-Nicholson algorithm. This method permits considerably larger time steps than the usual explicit methods.

Comparison with Experimental Data

An earlier version of the model has been compared [2] with radiant heat flux experiments [3] performed at Sandia Laboratories. The time to onset of concrete ablation, the ablation rate and the temperature profile in the concrete were predicted well by the code. Pressure and water release were not measured in the experiment.

Recently, the model has been set up to predict results from Hanford Engineering Development Laboratory's water release demonstration test no. 1 [4]. Since these tests do not involve high temperatures, the melt and ablation sections in the code were not used. The temperature is predicted well as a function of both space and time. A sample time history comparison at the thermocouple located at .0351 m depth below heated surface is given in Figure 1. Comparison of the predicted and measured water release rate as a function of time is given in Figure 2. The pressure histories at .0351 m depth are compared in Figure 3. Although this result is not as pleasing as the previous ones, it falls well within the repeatability of the experiments. For example compare the HEDL demonstration tests no. 1 and no. 2 in reference 4.

Input parameters in the code include material properties for concrete and for each fluid species, reaction rate coefficients for each decomposition product, and Darcy coefficients for gas and fluid flow rates. To obtain the degree of agreement with experimental [illegible] the concrete conductivity and the Darcy coefficients [illegible] more detailed description of the model and its [illegible] Reference 5.

[illegible]

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