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CONDENSATION FROM A LARGE HCDA VAPOR-GAS BUBBLE ONTO STRUCTURES*

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A mechanistic assessment of the consequences of a Hypothetical Core Disruptive Accident (HCDA) for a sodium-cooled breeder reactor will require analyses that determine the quantity of fuel released from the primary containment. This release is due to fuel melting, vaporization, and movement through the sodium pool and leakage through the assumed damaged vessel head closure. According to some views[1], this fuel may move through the cooler sodium pool as a large fuel vapor bubble containing non-condensable fission gases. There is potential for removal of the radionuclide source during this transport by condensation onto structural material (i.e., instrument carriers, control rod drives, support structures, etc.) as well as at the bubble interface.

Previous analyses[2–4] have estimated the condensation rates at the bubble interface. The present work extends the model in reference [4] to condensation on structural surfaces in the bubble path.

The transient heat conduction equations for thick structures, assuming that the solid can be treated as a semi-infinite medium during a short exposure time, are

$$\frac{\partial^2 T_s}{\partial z^2} = \frac{1}{\alpha_s} \frac{\partial T_s(z,t)}{\partial t} \qquad \text{in } z > o,\ t > o \qquad (1a)$$

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$$-k_s \frac{\partial T_s}{\partial z} = q_s(t) \qquad \text{at } z = o,\ t > o \tag{1b}$$

$$T_s(z,t) = T_{s\infty} \qquad \text{as } z \to \infty,\ t > o \tag{1c}$$

$$T_s(z,t) = T_{s\infty} \qquad \text{for } t = o,\ z > o \tag{1d}$$

where T_s is the structure temperature, $T_{s\infty}$ is the initial temperature of the structure taken as the sodium pool temperature, z is the coordinate measured inside the structure perpendicular to the surface, α_s is the thermal diffusivity and $q_s(t)$ is the heat flux at the surface resulting from condensation. The condensate layer build-up on the structure surface is neglected because the thickness of the layer was determined to be very small.

The energy balance at the liquid-vapor interface is given by

$$\frac{H_v M_v P_v}{R\, T_{v\infty}} |V_w| = q_s(t) \tag{2}$$

where H_v is the latent heat of condensation, M_v is the molecular weight of the condensing vapor, R is the gas constant, P_v is the vapor pressure, $T_{v\infty}$ is the bulk vapor temperature and V_w is the normal velocity of the condensing vapor at the surface given by

$$|V_w| = - \frac{D}{X_{go}} \frac{\partial X_g(y,t)}{\partial y} \bigg|_{y = o} \tag{3}$$

where X_{go} and $X_g(y,t)$ are the molar concentration of the noncondensable gas at the structure surface and at location y in the vapor space, y is the coordinate measured inside the bubble perpendicular to the surface, and D is the molecular diffusion coefficient. The equations governing the conservation of noncondensable gas inside the bubble are as given in [4].

The mathematical formulation becomes complete with the requirement that the partial pressure of the vapor at the surface should be equal to the saturation vapor pressure at the interface temperature. It is found

that the partial pressure at the surface is sufficiently small so that changes in the surface temperature due to changes in heat transfer rates have negligible effects on the partial pressure at the surface.

The stated heat and mass diffusion problem is solved numerically by a finite difference scheme. Calculations were performed for a vapor bubble containing UO_2 vapor and noncondensable fission gas at 20 atm and 4462 K, passing over a steel structural material with initial temperature 838 K (i.e., the sodium pool temperature). A maximum time period of three seconds was used for the calculations which is the appropriate time scale for the bubble to move a distance equal to its diameter (i.e., $\sim$3 m).

For "thick" structural materials (i.e., thicker than about 1-1/2 cm for steel), the rise of surface temperature was 200°C for a noncondensable gas mole fraction of $X_{g\infty} = 0.01$ and much lower for higher mole fractions. This temperature rise is only a small fraction of the total difference between the bulk and vapor sodium temperatures.

Figure 1 shows the time integrated heat flow per unit area defined as

$$Q_{o\to t} = \int_o^t Q(t)\, dt \qquad [W\cdot sec/cm^2] \tag{4}$$

where $Q(t)$ is the surface heat flux for the case of thick steel structures. The amount of vapor condensed per unit area of the structure from t = o to t can be determined by dividing $Q_{o\to t}$ by the latent heat of condensation. The integrated heat transfer per unit area at the end of three seconds with $X_{g\infty} = 0.01$ for an estimated upper limit of internal circulation velocity parallel to the surface of $U_{V\infty} = 2000$ cm/sec is nearly four times that for the stagnant vapor.

For thin structures (i.e., Biot number less than about 0.1 or steel structure thinner than about 0.5 cm), equations (1) are simplified by the lumped system analysis to take into account the mean temperature rise of the solid. Sample calculations performed for thin structures show that for 0.1 cm thick steel, the mean temperature at the end of three seconds exceeded the melting temperature 1700 K for a noncondensable gas concentration of $X_{g\infty} = 0.01$, whereas it remained below the melting temperature for $X_{g\infty} = 0.2$.

The results of the present analysis show that the condensation model for thick steel structures yields similar results as the previous model for condensation on the bubble interface[4]. Due to the high thermal conductivities of both sodium and steel, the mass transfer on the vapor side becomes the controlling factor for condensation. In the case of thin steel structures, the interface temperature rise becomes significant (melting temperatures may be reached) due to the limited heat sink provided by the structure.

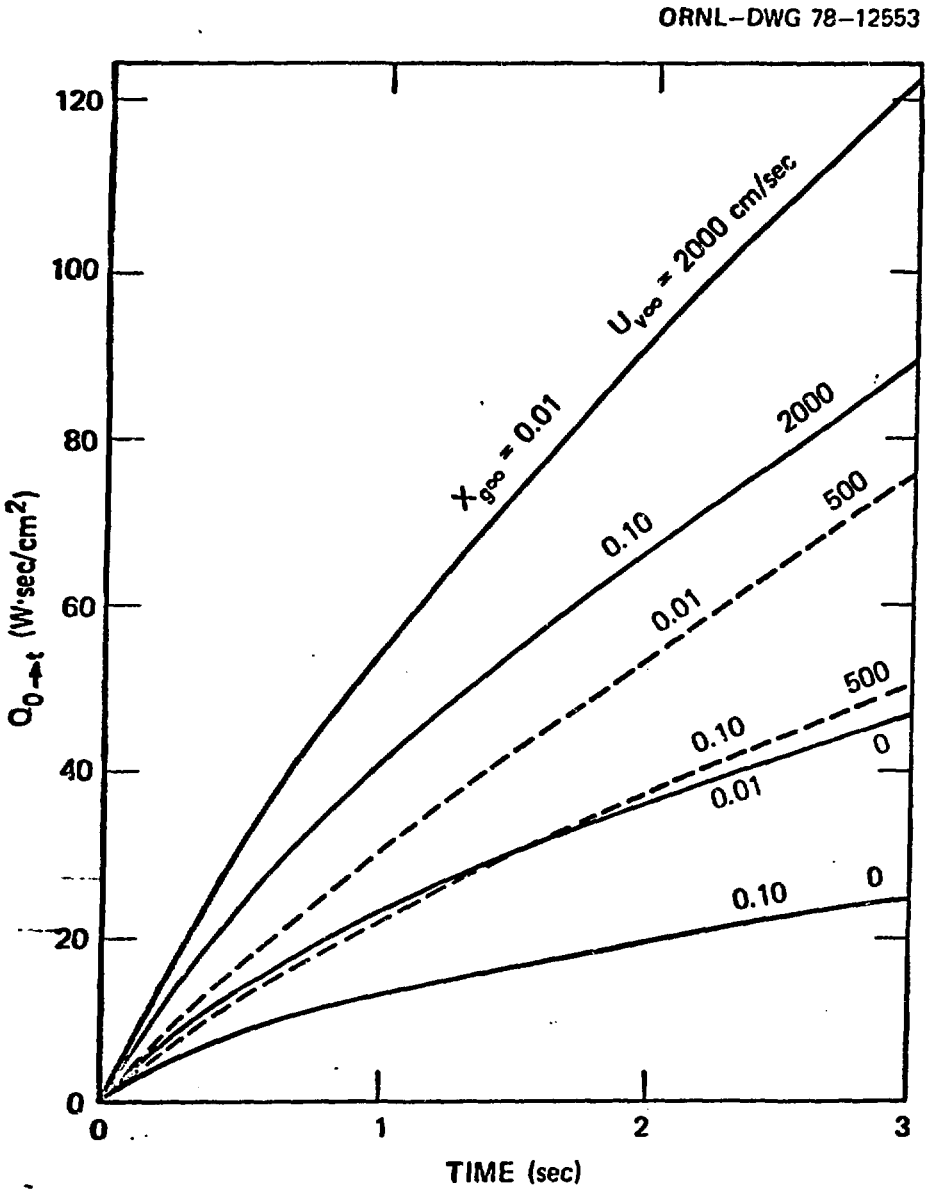

Fig. 1. The time integrated heat flow per unit area as a function of time for thick steel structure.

References

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