ATTENUATION OF RADIOLOGICAL CONSEQUENCES
FROM CDA'S BY RADIATION

Progress report

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1. "A preliminary assessment of the attenuation of HCDA radiological consequences by thermal radiation," American Nuclear Society Transactions, 24, p. 253 (1976).
2. "Effect of radiative cooling on HCDA radiological consequences during buoyancy period," to be presented at ANS Summer Annual Meeting, New York, June (1977).

ABSTRACT

This technical progress report summarizes the research work accomplished during the first six months of the investigation on the significance of radiation heat transfer in attenuating the radiological consequences from LMFBR core disruptive accidents. Considerable progress has been made in modeling and computing the effects of radiative cooling on a rising HCDA bubble buoyant through a sodium pool. Our results reveal that most of the fuel vapor within the bubble can be effectively condensed out by radiating cooling. The finding has a profound implication as it could lead to a substantial reduction in subsequent aerosol releases.

NOMENCLATURE

A	surface area
C_l	specific heat of a liquid fuel
C_p, C_v	specific heats of a vapor
E	internal energy
h	enthalpy
k	conductivity
L	latent heat of vaporization
m_f	fuel mass (liquid and vapor)
P	pressure
Q	heat input
R	gas constant
T	temperature
t	time
Δt_c	contact time of a liquid sodium with bubble
V	volume
x	fuel vapor quality
$\alpha_{i,st}$	steel absorptance
$\alpha_{i,Na}$	sodium absorptance
α_{Na}	sodium thermal diffusivity
ϵ	emissivity of bubble mixture
σ	Stefan-Boltzmann constant

SUBSCRIPTS

b	boiling
f	fuel
g	gas
i	interface
l	liquid
o	initial condition
st	steel
Na	sodium

I. INTRODUCTION

Consider a HCDA bubble resulting from a mechanical disassembly of a voided core. The bubble originated in the core travels through the gas plenum section of fuel pins and emerges into the sodium pool above the core. As the bubble emerges into the pool, the cover gas above the sodium liquid experiences an adiabatic compression. The expansion of the bubble is halted when their pressures reach equilibrium. The bubble then rises to the top by buoyancy and stays in the cover gas region until it leaks out of the reactor vessels.

The two-phase mixture in the bubble contains primarily fuel vapor and liquid fuel, with fission gases and steel vapor as minor constituents. In spite of high temperature of the mixture, radiative heat transfer has been neglected in the current analyses of HCDA bubbles, whereby an ultraconservative approach is adopted by assuming an adiabatic process during its buoyancy through the sodium pool.¹ Our objective is to examine the significance of radiative heat transfer in attenuating radiological consequences from HCDA bubble after it surfaces to the sodium pool.

II. SIMPLE MODEL FOR BUBBLE RISE

The purpose here is to devise a simple mathematical model to study isolated effects of radiation during bubble rise through the sodium pool. The model has the capability to predict radiation heat transfer effects over the full range of initial bubble conditions and of radiation property uncertainty. The simple model

includes the following idealizations:

- A. No sodium evaporation, all radiant heat deposited on sodium interface is conducted into sodium.
- B. Bubble emits as a black body.
- C. Bubble pressure is approximated by fuel pressure (i.e., neglect sodium and noncondensable gas pressures).
- D. Fuel vapor and fuel liquid in thermal equilibrium.
- E. Bubble volume and surface area remain constant.
- F. Neglect conductive and convective heat transfer from within the bubble to the bubble interface.
- G. Fuel vapor behaves as a perfect gas.

Those idealizations will be relaxed in the improved model.

With them, three equations can be set up and an analytical solution can be obtained.

The energy balance of the bubble yields

$$dE = dQ - p dv \rightarrow 0$$

or

$$m_f [c_l dT + L_f dx - R_f d(Tx)] = -\alpha_{i,Na} A_{Na} \sigma T^4 dt \quad (1)$$

where $\alpha_{i,Na}$ is the absorptance at the bubble-sodium interface. A_{Na} , x and m_f designate bubble surface area, fuel vapor fraction and total fuel mass, respectively. The constant volume condition implies

$$dV = 0 = m_f d[V_l (1-x) + V_g x]$$

or

$$-V_l dx + d(R_g Tx/P) = 0 \quad (2)$$

Finally, the equilibrium assumption links fuel vapor pressure to bubble temperature by

$$p_f = \exp \left(69.979 - \frac{76800}{T} - 4.34 \ln T \right) / 1013250 \quad (3)$$

Given a set of initial conditions, the three unknowns (x , T and p_f) can be solved from the three equations as a function of time. The transient bubble temperature can be solved approximately to yield,

$$T/T_0 = [1 + (3A_{Na} \sigma T_0^3 \alpha_{i,Na} / m_f C_l) t]^{-1/3}$$

from which we can find

$$p_f = f(\alpha_{i,Na}, t, T_0, m_f, A_{Na})$$

and

$$x_f = f(\alpha_{i,Na}, t, T_0, m_f, A_{Na}).$$

For example, consider a HCDA bubble having the following initial condition as it emerges from the core into the sodium pool: 4640°K (solid line in Figure 1) or 3640°K (dotted line); fuel vapor mass fraction = 7.66%; fuel mass = 2647 kg; bubble surface area = $2.94 \times 10^5 \text{ cm}^2$ and mole fraction of noncondensable gases less than 10%. Figure 1 shows two separate calculations ($T_0 = 4640^\circ\text{K}$ and 3640°K) for the amount of fuel vapor left at the end of 2 seconds when the bubble reaches the cover gas space. It is noted that the final conditions are plotted versus interface absorptance because of a widely uncertain range of absorptance values as discussed in the first publication of this work.² The uncertainty ranges from 0.014 to 0.52 for pure interface and from 0.3 to 0.8 for contaminated interface. The latter was estimated from our recent study on surface radiation properties of reactor materials.³

From the results of the simple model, we can draw two important conclusions. First, the fuel vapor remaining in the bubble is strongly governed by the interface absorptance. Secondly, within

Fig 1. Simple Model

the possible range of absorptance value, radiative cooling can attenuate the fuel vapor fraction by an order of magnitude.

III. IMPROVED MODEL FOR BUBBLE RISE

The simple model developed above is improved to include the following considerations:

- A. Sodium evaporation
- B. Nondensable gas effects
- C. Nonblack emission from bubble
- D. Variable bubble size due to evaporation of sodium and condensation of fuel vapor
- E. Conductive and convective heat transfer from bubble mixture to interface
- F. Non-equilibrium fuel vapor and liquid
- G. Bubble-sodium interface temperature changes due to fuel vapor condensation and sodium vaporization
- H. Bubble-sodium interface absorptivity changes due to fuel vapor condensation and sodium vaporization.

A reconsideration of the energy balance of the bubble yields

$$\dot{m}_{Na} h_{Na,b} + \dot{m}_{st} h_{st,b} = (A_{Na} \alpha_{i,Na} + A_{st} \alpha_{i,st}) \epsilon_b \sigma T_b^4 + dE/dt$$

where the left hand side accounts for the possible sodium evaporation from the bubble-sodium interface and steel evaporation from the steel structures exposed within the bubble as sketched in Figure 2. Those upper in-vessel structures provide additional heat sink surfaces which have been accounted for. With some deliberation, we find that the steel evaporation is unlikely within their contact time and the energy equation becomes

$$\begin{aligned} \dot{m}_{Na}(t) [C_{p,Na} T_{Na,b} - C_{v,Na} T_f] - (A_{Na} \alpha_{i,Na} + A_{st} \alpha_{i,st}) \epsilon \sigma T_f^4 \\ = \frac{dT_f}{dt} [m_f (c_{f,l} - R_f x_f) + m_{Na}(t) C_{v,Na}] \end{aligned} \quad (4)$$

The sodium evaporation rate can be calculated from

$$\dot{m}_{Na}(t) = \begin{cases} 0 & \text{if } t \leq t_1 \end{cases} \quad (5a)$$

$$\dot{m}_{Na}(t) = \begin{cases} \frac{A_{Na}}{L_{Na}} [\alpha_{i,Na} \epsilon \sigma T_f^4 - \frac{2K_{Na}(T_{Na,b} - T_{Na,0})}{(\pi \alpha_{Na} \Delta t_c)^{1/2}}] \end{cases} \quad (5b)$$

and the total sodium content in the bubble from

$$m_{Na}(t) = \int_{t_1}^t \dot{m}_{Na}(t) dt \quad (6)$$

Equation (5a) indicates no sodium evaporation prior to time t_1 , the warm-up time for the initially subcooled sodium,

$$t_1 = \frac{\pi}{\alpha_{Na}} [k_{Na} (T_{Na,b} - T_{Na,0}) / 2 \alpha_{i,Na} \epsilon \sigma T^4]^2.$$

Δt_c in eq. (5b) is the contact time of a sodium sails around the bubble surface. By combining the equation of state with the Clausius-Clapeyron equation for saturated fuel, we have

$$\frac{dx_f}{dt} = \frac{V_b}{R_f} \frac{P_f}{m_f T_f^2} \left(\frac{76800}{T_f} - 5.34 \right) \frac{dT_f}{dt}. \quad (7)$$

To solve for x_f , T_f , $\dot{m}_{Na}$ and m_{Na} , the information about the emissivity of the bubble mixture must be provided. When a hot fuel vapor is brought in contact with a cool liquid sodium, rapid radiative cooling from the vapor will induce fog formation.⁴ In addition to altering the radiative properties, the fog formation process itself offers a temperature-sustaining mechanism. By virtue of the high heat effects of condensation relative to sensible heat effects, a temperature will be maintained at high levels even

under conditions of rapid radiative heat removal, which in turn is supportive of the radiation heat transport mechanisms. The emissivity can be inferred from Ref. 4.

Similar to simple model, consider a HCDA bubble having the following conditions: 2445 kg of liquid fuel, 202 kg of fuel vapor, surface area = $2.94 \times 10^5 \text{ cm}^2$, temperature 4640°K and pressure, 21.4 atm (19.26 atm. of fuel vapor and 2.14 atm of noncondensable gases). No sedimentation of liquid fuel is assumed. Taking fuel droplet size as 1 mm, the bubble emissivity is estimated to be close to unity. The final conditions when the bubble reaches the cover gas space are presented in Figure 3. We examine another case with the same initial conditions except no liquid fuel is present. This would simulate the extreme case where all liquid fuel droplets have already been removed by imparting into liquid sodium or by sedimentation. The bubble emissivity decreases to about 0.8 and the results of calculations are plotted in Figure 4. They should provide the upper and lower bounds for the actual situation in which some fuel drops are presented initially.

From Figures 3 and 4, we see that the final total pressure decreases for low absorptivity values but increases for higher values due to sodium evaporation. However, the final fuel vapor pressure and the fuel mass fraction decrease rapidly with increasing values of absorptivity. As an example, if we assume the interface being contaminated by fuel condensate, the interface absorptivity could be $0.8^{2,3}$. Either no vapor (Figure 4) or at most 37 kg (Figure 3, solid lines, $x_f = 0.014$) of 202 kg could reach the cover gas region. Thus, the potential aerosol source is greatly

FIG. 3. BUBBLE WITH LONG SURF.

FIG 4 BUBBLE WITHOUT LIQUID FUEL

reduced. Furthermore, if the radiative heat loss to the steel structure is considered, the radiative cooling effect is found to be even more pronounced as shown by the dotted lines in both figures. In the calculations, the steel surface was taken as $4 \times 10^5 \text{ cm}^2$ and absorptivity as 0.3.

Considerations are now extended to include the effects due to variable bubble sizes, conductive and convective heat losses from bubble mixtures as well as the non-equilibrium effects. Those studies are expected to be completed by the end of this fiscal year.

IV. COVER GAS MODEL DEVELOPMENT

A model is currently being developed to determine bubble behavior after it has surfaced into the cover gas space. We have identified the key heat transfer processes which include

- A. Mixing of bubble gases with cover gases
- B. Radiative cooling to sodium and structures
- C. Conduction and convective heat losses.

Taking the output from the bubble rise calculations as input parameters for the cover gas model, parametric calculations will be performed in the next six months to determine the bubble temperature, pressure and fuel vapor condensation in the cover gas region.

V. REFERENCES

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2. S.H. Chan and D. Cho, "A preliminary assessment of the attenuation of HCDA radiological consequences by thermal radiation," American Nuclear Society Transactions, 24, p. 253 (1976).

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