Analysis of the Heat and Mass Transfer Processes of a UO_2 Bubble in Sodium for the Fuel Aerosol Simulant Test (FAST)

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MASTER

OAK RIDGE NATIONAL LABORATORY
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SYMBOLS

A	Bubble area, m^2
D_{eq}	Diameter of a sphere whose volume is equal to that of the bubble, m
D_{cap}	Diameter of the cap bubble, m (Fig. 3.1)
u	Bubble velocity, m/sec
g	Gravitational acceleration, 9.8 m/sec^2
$h_c(t)$	Condensation heat transfer coefficient at time t , $W/K\text{-}m^2$; $h_c(0)$, $h_c(\infty)$ are values of $h_c(t)$ at zero and "infinite" time, respectively
t	Time, sec
V	Bubble volume, m^3
θ	Bubble cap angle, about 100° (Fig. 3.1)
h	Height of bubble cap, m (Fig. 3.1)
a	Radius of sphere of which the bubble is the cap, m (Fig. 3.1)
σ	Stefan-Boltzmann Constant, $5.67032 \times 10^{-8} \text{ W/m}^2\text{-K}^4$
ϵ	Emissivity
ϵ_g	Bubble emissivity
ϵ_{Na}	Sodium emissivity
N_{in}	kg-moles of inert gas (xenon)
N_{UO_2}	kg-moles of UO_2
R	Gas constant, $8314.2 \text{ J/(kg-mole}\cdot\text{K)}$
T_g	Bubble temperature, K
T_x	Radiation sink temperature, K; either T_w or T_{sat}
T_w	Temperature at sodium-vapor interface, K
T_{sat}	Saturation temperature of UO_2 vapor at a given pressure, K
P	Total pressure, Pa

h_{rad}	Radiation "heat transfer coefficient," (a computed quantity) $\text{W/m}^2\text{-K}$
h_{gas}	Coefficient of heat transfer from a hot noncondensing gas to a cooler surface, $\text{W/m}^2\text{-K}$. (The value of 5.7 was used in all cases.)
Q_c	Heat transfer by condensation at bubble-sodium interface, W [Eq. (4b)]
Q_{gas}	Rate of heat transfer from a noncondensing gas to a cooler surface, W
Q_{rad}	Rate of heat transfer by radiation, W
Q_{in}	W, defined by Eqs. (10) and (10a)
T_ℓ	Temperature of liquid sodium at an "infinite" distance from the interface
TGRAD	The temperature gradient in the sodium at the bubble-sodium interface, K/m
k_L	Thermal conductivity of sodium, W/m-K
Q_{con}	Heat transfer rate due to condensation of UO_2 from the gas phase, W
$\chi(t)$	Mol fraction of inert gas in the gas phase, $N_{\text{in}}/(N_{\text{in}} + N_{\text{UO}_2})$, at time t
ρ_L	Liquid density, kg/m^3 , at T_ℓ
α_L	Thermal diffusivity of sodium at the interface temperature, T_w , m^2/sec
f	Function defined by Eq. (14a)
C_{p,UO_2}	Heat capacity of UO_2 vapor, J/kg-K
$C_{p,\text{in}}$	Molar heat capacity of inert gas, $2.5 R$, $\text{J/kg-mole}\cdot\text{K}$
W_g	Weight of UO_2 in the bubble, kg
H	Latent heat of vaporization of UO_2 , J/kg
M_{UO_2}	Molecular weight of uranium dioxide, 270 kg/kg mole
P_{UO_2}	Pressure of saturated UO_2 vapor, Pa
T	Temperature, K

V_g	Specific volume of UO_2 vapor, m^3/kg
ρ_{UO_2}	Density of liquid UO_2 , kg/m^3
ρ_{Na}	Density of liquid sodium, kg/m^3
$C(T)$	Heat capacity of liquid sodium at temperature T in $cal/g\text{-mol}\cdot K$
$T(x,t)$	Temperature in a medium at position x and time t
P_{cg}	Cover gas pressure, Pa

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SUMMARY

An overall analysis is presented of the heat and mass transfer processes expected to occur during the rise of a uranium dioxide bubble during the course of an under-sodium experiment in the Fuel Aerosol Simulant Test (FAST) Facility. Simple models of the various complex physical processes are used and parametric calculations are carried out to determine the relative importance of the mechanisms. The calculations were performed using the Continuous System Modeling Program (CSMP) coding package.

The calculations show that special attention needs to be given to the effects of noncondensable gas on the condensation process in the bubble and to radiation losses. Radiation losses are potentially of as large a significance as heat transfer by condensation at the vapor-sodium interface, but this can only be determined by more elaborate studies. The heat removal process on the sodium side appears to be so rapid that relatively crude models should provide enough information to determine the interface temperature, given the rate of heat liberated at the surface.

In addition to the above, the effects of cover gas pressure, depth of bubble release, initial bubble temperature, and amount vaporized are discussed.

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ABSTRACT

The anticipated behavior of uranium oxide vapor bubbles produced by the capacitor discharge vaporization (CDV) method in the Fuel Aerosol Simulant Test (FAST) Facility is discussed on the basis of relatively simple physical models. Results of calculations for the rate of bubble rise and for heat and mass transfer rates are presented. Parametric studies indicate that future analysis efforts should emphasize the diffusion condensation process and the loss of heat from the bubble by radiation. Transfer of heat in the surrounding sodium is rapid enough that simplified models should be adequate. No important effects were noted in connection with bubble depth, initial quantity of UO₂, or initial superheat.

1. INTRODUCTION

The purpose of this report is to discuss certain aspects of the motion and heat and mass transfer in a UO₂ bubble generated by the capacitor discharge vaporization (CDV) method under liquid in the Fuel Aerosol Simulant Test (FAST) Facility.¹ Predictive calculations are described for bubble behavior in the range of pressure, temperature, and depth believed likely to exist in the experiments. The scope of the studies in this document is restricted to under-sodium experiments. Underwater experiments are to be conducted also and will be analyzed later.

The analysis of the FAST UO₂ bubbles presents a variety of difficult technical problems, each of which can require quite a significant amount of effort to solve. Some of the more important physical phenomena that might be considered are

1. heat transfer processes in the region outside the bubble,
2. condensation heat transfer inside the bubble of high-temperature vapor in the presence of a noncondensable gas,

3. radiation heat transfer from the hot vapor to the surrounding liquid,
4. the dynamics of the motion of the bubble as a whole in the liquid,
5. entrainment and precipitation of vapor droplets formed in the course of condensation,
6. the nature and stability of the bubble surface shape and the integrity of bubbles of particular sizes,
7. vaporization of coolant and thermal exchanges with entrained liquid.

The present study deals with the relative significance of the first four items. [The area of heat and mass transfer from a bubble passing through structures could also be mentioned. While this is certainly appropriate to the consideration of a hypothetical core-disruptive accident (HCDA), we restrict ourselves here to the relatively simpler conditions of the FAST experiment.]

Each of these four phenomena has been examined in the light of simple models in which crucial parameters have been allowed to vary to obtain a relative assessment of the significance of each problem. This approach has already been presented in part in considerations of reactor-size bubbles.² In this way it is hoped that future efforts in the areas of concern will be made more efficiently with appropriate regard to the significance of the results both to the FAST experiment and to those reactor accident phenomena it is intended to model.

The rest of the report is structured as follows. Section 2 describes those dimensions and conditions in the FAST under-sodium tests that were modeled in the calculations, and Sect. 3 describes the computational methods employed and the underlying assumptions. Section 4, starting with a listing of the parameters covered, discusses the results obtained from examining each of several effects: cover gas pressure, depth of bubble release, initial bubble temperature, initial amount of UO₂ vaporized, value of the condensation coefficient and its dependence on the quality of inert gas present, and radiation heat loss. The report ends with a discussion of conclusions and recommendations for future work.

2. FAST EXPERIMENT DIMENSIONS AND CONDITIONS MODELED IN CALCULATIONS

Figure 2.1 shows the dimensions used in the calculations to model the FAST experiment. The sample position is denoted by S and two possible sodium level positions by A and B. Level A is 1067 mm (42 in.) above the specimen with a 254-mm (10-in.) argon cover gas space. Level B is 711 mm (28 in.) above the specimen with a 610-mm (24-in.) cover gas space. The vessel is 610 mm in internal diameter. Figure 2.2 shows those CDV specimen dimensions that bear upon the inert gas content of the bubble. The specimen is expected to be loaded with xenon gas at 2 atm* and 2000 K

* It will be necessary to load the xenon at higher pressures for higher pressure tests, but this consideration was not included in the present calculations.

Fig. 2.1. Schematic diagram of FAST experiment, with A and B denoting liquid levels and S the specimen position.

Fig. 2.2. Capacitor discharge vaporization specimen dimensions assumed for inert gas gap.

in the indicated cylindrical gap region 100 mm long and 1.3 mm (0.05 in.) wide, corresponding to a nominal internal diameter of 17 mm ID (0.67 in.) and 19.6 mm OD (0.77 in.).

Calculations were performed for cover gas pressures of 1 and 20 atm, for specimen depths of 28 and 42 in., and for initial bubble temperatures of 4000 and 5000 K.

3. COMPUTATIONAL METHOD EMPLOYED AND ASSUMPTIONS IN PHYSICAL MODEL

3.1 General Comments

The calculations consider the parallel problems of heat transfer from the bubble and of the rise of the bubble through the liquid. The bubble is assumed to start at a given depth composed of an assumed amount of UO_2 vapor and inert gas at a given temperature and pressure, rising through a sodium pool whose temperature at a "long" distance from the bubble is fixed. As the bubble rises, heat is transferred from the bubble by the following mechanisms:

1. condensation of vapor at the vapor-sodium interface,
2. radiation from the bubble producing cooling, but no condensation before the bubble reaches saturation temperatures,
3. cooling of the inert gas by gas-to-liquid heat transfer once all the condensable material has been removed,
4. transferring heat on the sodium side as if in an infinite medium by conduction only.

In the present calculation it is assumed that all condensation processes result in immediate removal of the UO_2 from the bubble and that the bubble contains no sodium by either vaporization or mechanical entrainment.

The calculations have been carried out using the Continuous System Modeling Program (CSMP),³ which enables the user to construct a model of complex time-dependent processes, linear or nonlinear, using FORTRAN-type coding. The basic mathematical tool is a fourth-order Runge-Kutta variable step procedure. While other integration formulas are available, use of this method as programmed frees the user in most cases from many awkward details, such as increasing or decreasing the time step used. In addition, the program provides plots produced on the line printer that are readily invoked by the user. For the present study, cases run very rapidly, with most of them providing complete output in less than 20 sec of IBM 360/91 time.

3.2 Equations Used

All quantities are computed in kg-m-s (SI) units.

$$A = 5.3155 D_{eq}^2 \quad (1)$$

$$D_{cap} = 1.74658 D_{eq} \quad (2)$$

$$v = 0.712 \sqrt{g D_{eq}} \quad (3)$$

$$h_c(t) = [h_c(0) - h_c(\infty)]/(1 + t) + h_c(\infty) \quad (4a)$$

$$Q_c = h_c A (T_g - T_w) \quad (4b)$$

$$Q_{rad} = \sigma \epsilon (T_g^4 - T_x^4) A \quad (5a)$$

$$h_{rad} = \sigma \epsilon (T_g^2 + T_x^2) (T_g + T_x) \quad (5b)$$

$$\epsilon = 1/(\epsilon_{gas}^{-1} + \epsilon_{Na}^{-1} - 1) \quad (6)$$

$$V = (N_{in} + N_{UO_2}) RT_g / P \quad (7)$$

$$Q_{gas} = h_{gas} A (T_g - T_x) \quad (8)$$

$$T_w = \frac{2.0k_L T_\ell + (Q_{in}/A + h_c T_g) \sqrt{h_c \alpha_L t}}{h_c \sqrt{h_c \alpha_L t} + 2.0k_L} \quad (9)$$

$$Q_{in} = Q_{gas} + Q_{rad} \quad (10)$$

$$TGRAD = \frac{(T_w - T_g) h_c - Q_{in}/A}{k_L}, \quad t = 0 \quad (11a)$$

$$TGRAD = \frac{2(T_\ell - T_w)}{\sqrt{h_c \alpha_L t}}, \quad t > 0 \quad (11b)$$

$$Q_{\text{con}} = Q_c; T_g > T_{\text{sat}} \quad (12a)$$

$$Q_{\text{con}} = Q_c + Q_{\text{rad}}; T_g = T_{\text{sat}} \quad (12b)$$

$$\frac{dP_{\text{UO}_2}}{dt} = \left[-P \frac{Q_{\text{con}} \chi}{H(N_{\text{in}} + N_{\text{UO}_2})M_{\text{UO}_2}} - (1 - \chi)\rho_L u \right] \quad (13)$$

$$\frac{dT_g}{dt} = \frac{dP_{\text{UO}_2}}{dt} \times \frac{1}{P(1 - \chi)} \times \frac{1}{f}; N_{\text{UO}_2} > 0, T_g = T_{\text{sat}}^* \quad (14)$$

$$f = -\frac{4.34}{T_g} + \frac{7.68 \times 10^4}{T_g^2} \quad (14a)$$

$$\frac{dT_g}{dt} = -\frac{Q_{\text{rad}} + Q_{\text{gas}}}{W_g C_{p, \text{UO}_2} + N_{\text{in}} C_{p, \text{in}}} T_g > T_{\text{sat}} \text{ or when } W_g = 0 \quad (15)$$

$$\frac{dV}{dt} = -\frac{Q_{\text{con}} RT_{\text{UO}_2}}{HPM_{\text{UO}_2}} + \frac{\rho_L u V}{P} + \frac{(N_{\text{UO}_2} + N_{\text{in}})R}{P} \frac{dT_g}{dt} \quad (16)$$

3.3 Discussion of Equations

3.3.1 Bubble area, diameter, and speed of rise [Eqs. (1) through (3)]

These equations refer to the dimensions of the bubble cap shown in Fig. 3.1. As discussed by Zimmerman,⁴ these equations are based on the observations of Davies and Taylor.⁵ The spherical cap model is appropriate to bubbles larger than 8×10^{-3} m; all of the cases considered here involved bubbles considerably larger than this.

The velocity of rise as calculated by Eq. (3) corresponds to Davies and Taylor's observations for freely rising bubbles in a quiescent pool. This situation is, of course, not the same as the circumstances of either the FAST experiment or the hypothetical reactor accident. The relatively unstable initial period lasting perhaps a few msec, which was studied in

* T_g is permitted to fall slightly below T_{sat} at times to prevent numerical instabilities. (See Sect. 3.3.6.)

$$v = \frac{\pi}{3} h^2 (3a - h) = \frac{\pi}{3} a^3 \left(1 - \cos \frac{\theta}{2}\right)^2 \left(2 + \cos \frac{\theta}{2}\right)$$

Fig. 3.1. Principal dimensions of a cap bubble.

the Grenoble "EXCOBULLE" experiments,⁶ has been neglected here. The photographic record of these expansions of hot water vapor in a colder pool shows surface instabilities and a downward bubble motion caused by interaction with the free and rigid surfaces.

3.3.2 Condensation coefficient, h_c [Eq. (4a)] and condensation heat flux Q_c [Eq. (4b)]

Özisik and Kress⁷ calculated condensation heat transfer rates and derived coefficients of heat transfer as functions of time for various initial inert gas fractions and assumed circulation velocities for the bubbles of UO_2 vapor mixed with noncondensable gas rising in sodium. (Results were also reported for mixtures of sodium vapor and noncondensables.) The computed curves are easily fitted by hyperbolas and the representation of Eq. (4) was used parametrically in the present study, taking $h_c(\infty)$ as $0.1 h_c(0)$. The heat flux was based on the temperature difference between the vapor and the interface as given by Eq. (4b). A computational scheme that employed the mass transfer concepts of the Özisik-Kress model directly would have worked better; however, this would

have led to a far more complex computer program without necessarily providing much more physical insight at this stage of the study. It was assumed that condensate was removed from the bubble. Heat transfer due to subcooling of condensate, UO_2 fusion, or cooling of solid UO_2 was neglected.

3.3.3 Radiation heat transfer [Eqs. (5a), (5b), and (6)]

The rate of radiation heat transfer from the bubble to the sodium is expressed by the familiar 4th power formula, Eq. (5a). By the rearrangement $Q_{\text{rad}} = h_{\text{rad}} A (T_g - T_x)$, an expression for a "radiation heat transfer coefficient," h_{rad} , may be defined as in Eq. (5b) for comparison with other heat transfer coefficients.

To complete this model of radiation heat transfer, the emissivity ϵ and the sink temperature T_x need to be defined. The radiation transfer is approximated by treating the bubble as if it were an opaque body at a uniform temperature T_g , radiating with emissivity ϵ_{gas} to a surface at temperature T_x whose emissivity is ϵ_{Na} . In all the calculations, ϵ_{Na} was taken as 0.2 while ϵ_{gas} was varied from 0.01 to 1.0. The emissivity of the gas-sodium system ϵ was taken from the well-known formula Eq. (6). This is the limiting form for radiation between two concentric spheres⁸ as the area of the inner sphere A_1 approaches that of the outer sphere A_2 :

$$\epsilon = \frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right). \quad (17)$$

This same formulation was employed by Huang,⁹ who took $\epsilon_1 = 1$ and varied ϵ_2 parametrically. Huang, quoting Chan and Cho,¹⁰ notes that the sodium emissivity may vary between 0.01 and 0.8, depending on the degree of contamination of the surface. In our calculations, the value of 0.2 has been taken as a rough mean for this quantity.

The other emissivity quantity, ϵ_{gas} , was varied to correspond to the following physical picture. The bubble may be considered as hot gas in which droplets of UO_2 are nucleating to a greater or lesser extent in the main body of the bubble and probably as a fog or mist in the neighborhood of the sodium. The droplets may be thought of as

sources of thermal radiation and, at the same time, scatterers of radiation that slow down the rate of heat transfer. The attenuation properties of the bubble, like those of any other gas volume, depend on its size and shape.¹¹ They would therefore be functions of time, changing as the bubble rose. Clearly, such concepts would require an elaborate analysis necessarily based upon an uncertain knowledge of the optical properties of the medium. This difficult problem has been bypassed, therefore, by varying ϵ_g over a "reasonable" range in order to obtain an idea of the relative importance of the radiation problem.

The question of the sink temperature is also part of the physical picture. Two extremes were chosen in the calculations. T_x was taken first at the saturation temperature of the vapor as if the vapor could not "see" the sodium surface but was radiating to a thin film of fog there. Alternatively, the sink temperature was taken as the sodium surface temperature. In the first case, radiation continues as long as the bubble is above the saturation temperature and stops thereafter until all the vapor has condensed. When T_x is taken as T_w , radiation heat loss continues throughout the cooling process.

In the present study it was assumed that radiation cooling produced no condensation as long as $T_g > T_{\text{sat}}$ and that it could contribute to condensation thereafter (if $T_x = T_w$). As with condensation by the diffusion process calculated using h_c , the condensate was assumed to be removed from the bubble; provision was made to account for entrainment, but it has not been used.

3.3.4 Ideal gas assumption [Eq. (7)]

The bubble gas was treated as an ideal gas mixture of a monoatomic inert gas and UO_2 . The molar heat capacity of the inert gas was taken at $5/2 R$, the classical value for C_p . As pointed out by Karow,¹² saturated UO_2 vapor behaves like a perfect gas up to 5000 K. Appendix B shows the good agreement of results obtained using the saturation pressure and specific volume relations of Appendix A with the ideal gas law.

3.3.5 Calculation of temperature and heat balance at sodium-vapor interface [Eqs. (9) through (12)]

3.3.5.1 Interface temperature. One of the most important quantities to be determined is the sodium temperature at the interface. It is determined by a heat balance at the interface that equates the rate at which heat enters the sodium from the bubble and the rate at which it flows into the sodium.

1. Heat deposition on the gas side is calculated as the sum of the radiation term Q_{rad} [Eq. (5)], the gas cooling term Q_{gas} [Eq. (8)]. To these terms is added the heating due to condensation, $h_c A(T_g - T_w)$.

2. Heat removal on the sodium side was treated assuming that only conduction heat transmission exists in the sodium and that the temperature gradient could be obtained by a plane surface solution, as follows.¹³ Given a semi-infinite slab of diffusivity κ ($\equiv k/c\rho$) originally at zero temperature, let the temperature of the free surface vary as $k_1 t$ where k_1 is a constant. The temperature in the slab will take the form

$$T(x,t) = k_1 t \left[\left(1 + \frac{x^2}{2\kappa t} \right) \text{erfc} \left(\frac{x}{2\sqrt{\kappa t}} \right) - \frac{x}{\sqrt{\pi\kappa t}} e^{-x^2/4\kappa t} \right], \quad (18)$$

at distance x from the surface and at time t . To adapt this solution to the present circumstances, we make the substitution

$$v = T(x,t) - T_\ell, \quad (19)$$

and

$$k_1 t = T_w - T_\ell. \quad (20)$$

Differentiating to find $[\partial T(x,t)]/\partial x$ and finding its value at $x = 0$ yields

$$\left. \frac{\partial T}{\partial x} \right|_{x=0} \equiv \text{TGRAD} = - \frac{(2)(T_w - T_\ell)}{\sqrt{\pi\kappa t}}; \quad t > 0, \quad (21)$$

which is the result given earlier in Eq. (11b). This is just twice the

expression obtained for the gradient if a fixed T_w is used as in Zimmerman's work. (Note that TGRAD is negative.) At $t = 0$, the right side of Eq. (21) becomes indeterminate, and Eq. (11a) is used in the code instead. The heat removal rate then becomes

$$-k_L \left. \frac{\partial T}{\partial X} \right|_{x=0} A = -k_L (\text{TGRAD}) A . \quad (22)$$

We now have a simple formula for the heat flow on the sodium side derived on the basis that the surface temperature will be rising linearly and that conduction is the only heat removal mechanism. The reasonableness of these assumptions is borne out by the nature of the results obtained for the interface temperature. It is found that the temperature rise at the wall is initially roughly linear; further, the temperature changes are found to be small. This approximation seems suitable for a high-conductivity material like sodium but would not be appropriate for water, for which alternative formulations would have to be sought.*

Equating the heat removal rate indicated in Eq. (22) to $Q_{\text{rad}} + Q_{\text{gas}} + h_c A (T_g - T_w)$ and solving for T_w yields Eq. (9). Note that Q_{rad} contains T_w ; checks, however, have shown that the cyclic nature of the CSMP computing procedure and the fact that $T_g^4 - T_w^4 \cong T_g$ in the calculations make the error from this source negligible.

3.3.5.2 Condensation rate [Eqs. (12a) and (12b)]. As the gas cools from the initial temperature to the saturation temperature, condensation is assumed to occur entirely at the vapor-liquid interface, corresponding to the heat transfer rate Q_c . When the saturation temperature is reached, Eq. (12b) is used, in which the heat lost by radiation now contributes to condensation. [Q_{rad} will be zero if T_x in Eq. (5a) is taken as T_{sat} rather than T_x .]

*The alternative approach might be to use solutions involving the heat flux at the surface;¹⁴ for example, the temperature in a semi-infinite slab initially at zero temperature with heat flux $f(t)$ at $x = 0$ is given by

$$T(x,t) = (\sqrt{k}/k\sqrt{\pi}) \int_0^t \tau^{-1/2} f(t-\tau) \exp(-x^2/4k\tau) d\tau .$$

The numerical accuracy of the code has been checked by comparing Q_{con} calculated by the following relationships, which are equivalent to Eqs. (12a) and (12b):

$$Q_{\text{con}} = -k_L A(T_{\text{GRAD}}) - Q_{\text{gas}} - Q_{\text{rad}} , T_g > T_{\text{sat}} , \quad (24a)$$

and

$$Q_{\text{con}} = -k_L A(T_{\text{GRAD}}) , T_g = T_{\text{sat}} . \quad (24b)$$

3.3.6 Calculation of UO_2 removal rate and changes in bubble volume [Eqs. (13) through (16)]

Bubble volume controls the rate of rise, as calculated by Eq. (3). It is affected by pressure and temperature and its quantity of vapor.

Starting with the general gas law for the mixture of inert gas and UO_2 as expressed by Eq. (7), we have

$$PV = (N_{\text{in}} + N_{\text{UO}_2})RT . \quad (25)$$

Differentiating with respect to time,

$$V \frac{dP}{dt} = -V \frac{dP}{dt} + \frac{dN_{\text{UO}_2}}{dt} RT_g + (N_{\text{in}} + N_{\text{UO}_2})R \frac{dT_g}{dt} , \quad (26)$$

and

$$\frac{dV}{dt} = -\frac{V}{P} \frac{dP}{dt} + \frac{dN_{\text{UO}_2}}{dt} \frac{RT_g}{P} + (N_{\text{in}} + N_{\text{UO}_2}) \frac{R}{P} \frac{dT_g}{dt} . \quad (27)$$

Since

$$P = \text{depth} \times \rho_L g + P_{\text{cg}} , \quad (28)$$

we have

$$\frac{dP}{dt} = -v \rho_L g . \quad (29)$$

The time rate of change of the molar quantity of UO_2 is simply determined

from the mass rate of condensation

$$\frac{dN_{\text{UO}_2}}{dt} = \frac{Q_{\text{con}}}{HM_{\text{UO}_2}} . \quad (30)$$

Substitution of Eqs. (29) and (30) into Eq. (27) gives Eq. (16).

The code, using the CSMP method, calculates the volume of the bubble by the numerical integration of the expression

$$V(t) = V(t = 0) + \int_0^t \frac{dV}{dt} dt . \quad (31)$$

The one remaining quantity needed to calculate dV/dt is dT_g/dt . When $T_g > T_{\text{sat}}$, Eq. (15) is used, assuming that the bubble is at a uniform temperature and losing heat by radiation and conduction; heat lost by condensation at the sodium surface is assumed to remove only the heat of vaporization of the quantity of vapor condensed. When the vapor cools to saturation conditions, the temperature changes more slowly, being a function of the partial pressure of the UO_2 in the inert gas- UO_2 vapor mixture. The value of dT_g/dt is a function of the rate of bubble rise and of the rate of condensation. At saturation conditions, the pressure of UO_2 is related to the temperature by the vapor pressure Eq. (A.2), which, slightly rearranged, is

$$\log_e P_{\text{UO}_2} = -4.34 \log_e T_g - \frac{7.68 \times 10^4}{T_g^2} + 67.676 . \quad (32)$$

Differentiating with respect to time and solving for dT_g/dt gives

$$\frac{dT_g}{dt} = \frac{1}{f} \frac{1}{P_{\text{UO}_2}} \frac{dP_{\text{UO}_2}}{dt} , \quad (33)$$

where f is defined by Eq. (14a). We note that $P_{\text{UO}_2} = (1 - \chi)P$, thus producing Eq. (14). Differentiation of P_{UO_2} gives

$$\frac{dP_{\text{UO}_2}}{dt} = -P \frac{d\chi}{dt} + (1 - \chi) \frac{dP}{dt} . \quad (34)$$

To obtain $d\chi/dt$, the expression defining

$$N_{in} = \chi(N_{UO_2} + N_{in}) \quad (35)$$

is differentiated with respect to time also, giving

$$0 = \frac{d\chi}{dt} (N_{UO_2} + N_{in}) + \chi \frac{dN_{UO_2}}{dt} . \quad (36)$$

Using Eq. (30) in Eq. (36) and rearranging gives

$$\frac{d\chi}{dt} = - \frac{\chi}{N_{UO_2} + N_{in}} \frac{Q_{con}}{HM_{UO_2}} , \quad (37)$$

and using Eq. (29) for dP/dt gives Eq. (34), as

$$\frac{dP_{UO_2}}{dt} = \frac{P_x}{N_{UO_2} + N_{in}} \frac{Q_{con}}{HM_{UO_2}} - (1 - \chi)u\rho_L ,$$

which is Eq. (13), completing the calculation of dT_g/dt at saturation conditions.

An important aspect of the numerical process used in the CSMP III Program was that it is impossible to obtain a material balance between the sum of condensed UO_2 plus the weight of UO_2 in the bubbles vs the original amount of UO_2 if the requirement that T_g could not be less than T_{sat} were explicitly imposed. The procedure ran an order of magnitude more rapidly without this restraint; in every case where comparison was possible, results were practically identical to those where the restriction was imposed.

4. RESULTS OBTAINED

4.1 Calculation Parameters

The calculations were run for various (but not all) combinations of the parameters shown in Table 1.

Table 1. Nominal values of parameters used in calculations

Parameter	Nominal value
Depth of CDV specimen, in. ^a	28, 42
Temperature of bubble, K	4000, 5000
h_c (condensation heat transfer coefficient initial value), W/m^2-K	10, 100
Pressure of cover gas, atm ^b	1, 20
ϵ_g (bubble emissivity)	0.01, 0.1, 0.5, 1.0
Initial quantity of UO_2 , kg	2, 5
T_x (temperature used as radiation sink)	T_{sat} , T_w
h_{gas} (gas heat transfer coefficient), W/m^2-K	5.7

^a711 and 1067 mm.

^b 1.0135×10^5 and 2.027×10^6 Pa.

4.2 Effect of Cover Gas Pressure

Table 2 shows the results of several cases to test pressure effects, and the behavior is quite monotonic in all respects, with more rapid condensation occurring as the pressure is lowered. As can be seen from the listed values of bubble surface area, the initial area of the bubble is ten times greater at 0.5 atm than at 20 atm. While the saturation temperature at 20 atm is about 20% higher, this does not change the temperature difference enough to compensate.

The increase in bubble velocity due to lowering the pressure does not compensate either. The diameter soon shrinks because of the more rapid condensation rate, and the velocity advantage is rapidly lost.

Table 2. Effect of pressure on bubble rise^a

	Case No.			
	1	2	3	4
Cover gas pressure, atm	0.5	1.0	10.0	20.0
Time to condense, sec				
50% UO ₂	0.05	0.05	0.20	0.27
90%	0.11	0.16	0.54	0.74
98%	0.16	0.22	0.71	0.96
100%	0.19	0.26	0.79	1.061
Distance risen to condense 100% UO ₂ , m	0.133	0.171	0.400	0.504
Maximum wall temperature, K	848	850	857	859
Initial bubble area, m ²	0.24608	0.163	0.038	0.025
T _{sat} (t = 0)	3639.1	3778.4	4389.1	4613.2
Initial velocity, m/sec	1.034	0.933	0.649	0.584

^aParameters common to these cases: $h_c(0) = 100 \text{ W/m}^2\text{-K}$; initial mass of UO₂ vapor = 2 g; original bubble depth = 1.067 m (42 in.); $\epsilon_g = 0.5$; $T_v(t = 0) = 5000 \text{ K}$; radiation sink temperature = T_{sat} .

A series of cases was run based on case 1 of Table 2 to examine how small a condensation coefficient was needed to permit the rise of the bubble in the 0.5-atm case to exceed that of the 20-atm case. The results are shown in Table 3, in which the initial value of h_c varied between 10 and 100 W/m²-K. The bubble rise matches that at 20 atm if the value of h_c is 30, that is, the bubble rises to about 0.5 m (18.7 in.) in both cases before all of the UO₂ condenses. A further reduction of the value of h_c to 16 (case not shown) will just permit the bubble to rise the full 42 in. before 100% condensation of the UO₂. Note that in all of these cases, the sink temperature for radiative heat transfer is the saturation temperature, so that radiation ceases to be a heat flow mechanism very early in the rise.

Table 3. Effect of varying initial condensation coefficient at a pressure of 0.5 atm^a

	Case No.				
	1	2	3	4	5
$h_c(t = 0)$	100	50	30	20	10
Time to condense, sec					
50% UO ₂	0.05	0.10	0.16	0.22	0.50
90%	0.11	0.24	0.42	0.66	82% condensed ^b
98%	0.16	0.32	0.58	0.96	
100%	0.19	0.40	0.73	1.22	
Distance to condense 100% UO ₂ , m	0.133	0.284	0.514	0.849	
Maximum wall temperature, K	848	845	843	841	840

^aParameters common to these cases: $T_{v,ip}(t = 0) = 5000$ K; $\epsilon_{gas} = 0.5$; initial depth = 1.067 m (42 in.); initial UO₂ vapor mass = 2 g; radiation sink temperature = T_{sat} .

^bBubble reached surface.

4.3 Effect of Original Depth

The behavior of the bubble showed practically no difference with starting depth and other conditions being alike. (See Sect. 4, however, for a brief comment on wall effects.)

4.4 Effect of Starting Temperature

Over the range of heat transfer parameters used, the initial temperature assumed for the bubble proved to be of no importance. For all assumptions used for heat transfer coefficients, radiation emissivity, or sink temperature, the bubble cooled to the saturation temperature corresponding to the pressure in a few hundredths of a second whether the initial temperature was 4000 or 5000 K. A direct comparison between these temperatures was available only at an ϵ_g of 0.5, but inspection of cases at lower emissivities showed no different behavior.* It can

*This remark refers to "reasonable" emissivities. If radiation is suppressed, superheat in the vapor is retained for a significant portion of the rise.

therefore be concluded that the vapor bubble ought to be considered as saturated at the outset for analysis purposes.

4.5 Effect of Initial Amount Vaporized

Table 4 compares results for corresponding cases for which 2 and 5 g of UO_2 vapor were assumed. The pair of cases 1 and 2 show much the same changes due to initial mass difference as do 3 and 4, for which conditions were quite different with respect to pressure, emissivity, and condensation coefficients. The difference in quantity results in

Table 4. Comparison of cases for 2 and 5 g initial UO_2 vapor

	Case No.			
	1	2	3	4
Initial depth, in.	42	42	28	28
ϵ_g	0.5	0.5	0.1	0.1
$h_c(t = 0)$	100	100	10.0	10.0
Initial UO_2 , g	2	5	2	5
Pressure, atm	10	20	1	1
Initial vapor temperature, K	5000	5000	4000	4000
Maximum T_w , K	858	860	840	840
Total rise, m	0.48 ^a	1.00 ^a	0.72	0.72
Time, sec	1.00	1.92	0.86	0.72
Initial volume, m ³	1.69×10^{-4}	3.96×10^{-4}	2.32×10^{-3}	5.76×10^{-3}
Initial area, m ²	2.51×10^{-2}	4.42×10^{-2}	0.143	0.263
Time to condense, sec				
1 g UO_2	0.27	0.13	0.72	0.30
2 g UO_2	1.00	0.29		
50%	0.27	0.40	0.72	<i>b</i>
90%	0.73	1.23	<i>c</i>	
98%	0.92	1.70		
100%	1.00	1.92		
UO_2 present at 28-in. rise, %		9.6	44	61
Time to rise 28 in., sec		1.26	0.86	0.72

^aCalculation ended at 100% UO_2 condensed.

^bReaches surface with 39% condensed at 0.72 sec.

^cReaches surface with 56% condensed at 0.86 sec.

a larger surface area, which increases the rate of condensation; however, the percentage loss of mass per unit time is slower from the larger bubble. In case 4 (5 g UO_2) the bubble reaches the surface with 61% of the initial UO_2 vapor, while the 2-g case carries 44%. Qualitatively similar results are seen in comparing cases 1 and 2 with each other.

A comparison of the 5-g cases 2 and 4 shows that, while the bubble for case 2 would have reached the surface if released at a 28-in. depth, it would have held <10% of the original vapor, far less than for case 4. The higher condensation coefficient and emissivity used in case 2 account for this.

In the context of the simple bubble rise model used, effects that might be ascribable to the free surface and rigid container, such as those observed in EXCOBULLE,⁶ were neglected.

4.6 Effect of Condensation Coefficient

The condensation coefficient h_c is one of the strongest determinants of calculated bubble behavior. This is exhibited in Table 5, where use of values of h_c of 10 and 100 $\text{W/m}^2\text{-K}$ (1.8 and 18 $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$) is compared. The values are typical of what might be expected in condensation heat transfer where diffusion through an inert gas is a major factor. The results for the rather modest higher value indicate that if, in fact, the condensation coefficient is that large, all the UO_2 will condense; therefore, it can only enter the cover gas region by being carried along with the inert gas. The calculated interface temperature rises are not very large, reflecting the idea expressed elsewhere that heat removal by the sodium is so efficient that great emphasis should not be placed on its analysis. By contrast, knowledge of the probable value of condensation coefficient is of vital importance to the experimental design. Further work should therefore emphasize as exact a calculation as possible, such as incorporating a diffusion mass transfer calculation for condensation in the presence of an inert gas along the lines of the Özisik-Kress model.⁷

Table 5. Comparison of behavior for condensation coefficients of 10 and 100 W/m²-K^a

	Case 1, $h_c(t = 0) = 10$	Case 2, $h_c(t = 0) = 100$
Total rise, m	0.71	0.17
Time, sec	0.85	0.17
Maximum wall temperature, K	839.7	850.3
Time to condense, sec		
50% of UO ₂	0.72	0.06
90%	^b	0.16
100%		0.17
Condensation coefficient range, W/m ² -K	5.9-10	82-100

^aParameters common to these cases: initial depth = 0.711 m (28 in.); $\epsilon_g = 0.1$; initial UO₂ mass = 2 g; cover gas pressure = 1 atm; initial vapor temperature = 4000 K; initial sodium temperature = 838 K.

^bBubble reaches surface with 55% of UO₂ condensed.

4.7 Effect of Assumed Dependence of Condensation Heat Transfer Coefficient on Mol Fraction of Inert Gas vs Assumed Variation with Time

The effect of the assumption used for the condensation heat transfer coefficient can be quite strong. Two cases were compared, one of which assumed a variation with time and the other with the mol fraction of inert gas. Time variation was

$$h_c = \frac{h_c(0) - h_c(\infty)}{t + 1} + h_c(\infty) , \quad (38)$$

while the variation with mol fraction was

$$h_c = [h_c(0) - h_c(\infty)] \left[\frac{\chi(0)}{\chi(t)} \right] \left[\frac{1 - \chi(t)}{1 - \chi(0)} \right] + h_c(\infty) . \quad (39)$$

In both formulas, the variation is hyperbolic in character. In the time variation, the condensation coefficient starts out at $h_c(0) = 100$ W/m²-K and asymptotically reaches a value of 10 at infinite time. Assuming a

mol fraction variation, h_c again starts at 100 and falls off to $10 \text{ W/m}^2\text{-K}$, as $\chi(t)$ approaches 1.0 (i.e., when all the UO_2 has condensed). For comparison, results were also obtained for $h_c(\infty) = 5.7$, which is the h_{gas} value used.

In these cases the original depth was 1.07 m (42 in.), and the bubble temperature was 5000 K at 1 atm cover gas pressure. The initial UO_2 content of the bubble was 2 g, with a gas emissivity of 0.5. It was assumed that radiation heat flow was based on the difference between the vapor temperature and the saturation temperature, so that this heat loss process ceased very early.

Table 6 compares the results obtained, showing that condensation when time dependence is assumed is much more rapid (case 1) than when the corresponding mol fraction variation is assumed (case 3). The condensation process is over in about one-fourth the time and the rise attained (0.171 m) is correspondingly lower. If the mol fraction dependence is based on the gas coefficient, h_{gas} , of 5.7, the bubble rises to 0.789 m before all the UO_2 is gone. Radiation plays only a limited role for cases 1-3, because the sink temperature is based on the vapor saturation temperature. As t_{rad} shows, the radiation heat flux is cut off very early in the rise. If, however, as in cases 4 and 5, the radiation sink temperature is assumed to be the wall temperature, hardly any difference is seen between the results obtained by the two condensation assumptions. The heat transfer coefficient for radiation is many times greater than the condensation coefficient h_c , completely masking any such effects.

4.8 Heat Loss by Radiation

Heat loss by radiation is potentially the most important heat transfer mechanism, even more important than the convective condensation process previously discussed. This is because the driving force depends on the difference of fourth powers of the absolute temperature, for which an equivalent heat transfer coefficient can be defined as

$$h_{\text{rad}} = \sigma \epsilon (T_g^2 + T_x^2) (T_g + T_x) , \quad (5b)$$

Table 6. Comparison of bubble behavior for different condensation coefficient assumptions

	Case No.				
	1 (time dependence)	2 (mol fraction dependence)	3 (mol fraction dependence)	4 (time dependence)	5 (mol fraction dependence) ^a
Maximum interface temperature, K	850	843	843	876	873
Time to condense					
50% UO ₂ , sec	0.06	0.08	0.08	0.0088	0.0088
90%	0.16	0.44	0.36	0.021	0.021
98%	0.22	0.88	0.72	0.028	0.029
100%	0.26	1.43	1.04	0.0325	0.0325
$h_c(t = 0)$	100	100	100	100	100
$h_c(\text{final})$	10	5.7	10	10	10
Range of h_c	81-100	5.7-100	10-100	97-100	10.6-100
Radiation sink temperature	T_{sat}	T_{sat}	T_{sat}	T_w	T_w
Range of h_{rad}^b	2000-3258 ^c	2000-3258 ^c	2000-3258 ^c	360-1418	591-1418
t_{rad} , sec ^b	<0.02	<0.04	<0.04	0.0325	0.0325
Height at 100% condensation, m	0.171	0.789	0.595	0.022	0.022

^aCase terminated at 99.4% condensation.

^b t_{rad} is period during which radiation heat transfer occurred. The range of h_{rad} given is for that time interval.

^cIf h_{rad} based on $T_g - T_w$ [Eq. (5d)], range would be 0-956 W/m²-K.

so that

$$Q_{\text{rad}} = \sigma \epsilon (T_g^4 - T_x^4) = h_{\text{rad}} A (T_g - T_x) . \quad (5a)$$

Alternatively, one may wish to base h_{rad} on the vapor-interface temperature difference, so that

$$Q_{\text{rad}} = h_{\text{rad}} A (T_g - T_w) , \quad (5c)$$

providing a direct comparison with h_c in Eq. (4b). Then h_{rad} could be defined as

$$h_{\text{rad}} = \frac{\sigma \epsilon (T_g^4 - T_x^4)}{T_g - T_w} . \quad (5d)$$

Equations (5b) and (5d) are identical if $T_x = T_w$. If $T_x = T_{\text{sat}}$, h_{rad} becomes zero when $T_g = T_{\text{sat}}$ by Eq. (5d) but not by (5b). The quantity h_{rad} often proves to be overwhelmingly greater than h_c , the condensation coefficient.

In passing, we note that the difference in radiation heat transfer coefficients between cases 1, 2, and 3 from those in 4 and 5 is due mainly to the difference in the temperature interval upon which the values shown are based. That is, if h_{rad} were computed by Eq. (5d), the h_{rad} range quoted for cases 1, 2, and 3 would be considerably reduced.

The calculated heat transfer rates will be strongly dependent on the selection of the sink temperature T_x and on the value for the emissivity ϵ . Figure 4.1 illustrates the mechanism adopted in these calculations for radiation heat transfer. The cap bubble is shown with a central gas region at a uniform temperature T_g , and the condensing UO_2 vapor forms a very thin fog region at the saturation temperature T_{sat} very close to the sodium interface. The radiation process occurs between the gas temperature T_g and some sink temperature T_x . The formulation of the heat transfer process represents the classical cases of concentric spheres or cylinders for which the emissivity is

$$\frac{1}{\epsilon} = \frac{1}{\epsilon_{\text{gas}}} + \frac{1}{\epsilon_{\text{Na}}} - 1 . \quad (6)$$

Fig. 4.1. Diagram illustrating radiation heat transfer process.

A fixed value of 0.2 was used in all cases for ϵ_{Na} , reasonably typical of what might be expected for a liquid metal surface under these circumstances. The value of ϵ_{gas} was varied between 0.01 and 1.0 to take into account both the unknown character of the emissivity of the central region and the strong possibility that a quite different physical picture may obtain: the fog as a result of the condensation process may be dispersed throughout the vapor region, forming a zone that both emits and scatters radiation. Calculations for such a model should be much more complex, resembling those for discrete ordinate or Monte Carlo calculation of neutron or gamma radiation through an absorbing scattering region. In contrast to the simple "concentric sphere" model we have used, it would be necessary to consider the temperature distribution through the bubble. The importance of this distribution is roughly indicated by the calculations done for different sink temperature values, T_x . If T_x is taken at one extreme, as the saturation temperature of the vapor, then radiation becomes an unimportant feature, for the vapor quickly cools to T_{sat} and $T_g - T_x$ becomes zero, cutting off radiation heat loss very early in the bubble rise. On the other hand, if the interface temperature T_w is used for T_x , then T_x^4 is negligible compared to T_g^4 , and condensation of the entire vapor mass quickly occurs. These points are illustrated in the following tabulations.

Table 7 shows results from a series of cases with the vapor initially at 5000 K and a cover gas pressure of 20 atm run with ϵ_g varying

Table 7. Calculation of bubble behavior for various values of vapor region emissivity (radiation sink temperature = T_{sat})^a

	Case No.			
	1	2	3	4
ϵ_g	1.0	0.5	0.1	0.01
Total rise, m	0.48	0.48	0.48	0.48
Time of rise, sec	1.0	1.0	1.0	1.0
Maximum interface temperature, K	858.1	858.1	858.4	859.0
Time to condense, sec				
50% of UO_2	0.27	0.27	0.27	0.26
90%	0.73	0.73	0.73	0.73
98%	0.93	0.92	0.93	0.92
100%	1.0	1.0	1.0	1.0
Time at which radiation stops, sec	<0.02	<0.02	<0.02	<0.02
Initial h_{rad} , $\text{W/m}^2\text{-K}$ [Eq. (5b)]	~5000	4205	1802	243
Initial h_{rad} , $\text{W/m}^2\text{-K}$ [Eq. (5d)]	469	391	168	22.5

^aParameters common to these cases: initial bubble depth = 1.067 m (42 in.); $h_c = 100 \text{ W/m}^2\text{-K}$; initial UO_2 vapor mass = 2 g; cover gas pressure = 20 atm; initial vapor temperature = 5000 K.

from 0.01 to 1.0. The radiation sink temperature is taken as the vapor saturation temperature. The influence of the variation of ϵ_g is negligible, for the vapor falls to saturation temperature in <0.02 sec of the total 1 sec time of rise. (While the vapor is superheated, no condensation due to radiation is assumed to occur.) The radiation heat transfer coefficients calculated by Eq. (5b) range from 243 for an ϵ_g of 0.01 to over 5000 for $\epsilon_g = 1$, or 2.4 to 50 times the value of 100 assumed for h_c . Those calculated by Eq. (5d), while much reduced (based as they are on the same temperature difference as h_c), still indicate the large radiation heat transfer contribution.

The situation depicted in Table 8 is entirely different, for here the interface temperature is taken as the sink temperature. (Note that

Table 8. Calculation of bubble behavior for various values of vapor region emissivity (radiation sink temperature = T_w)^a

	Case No.			
	1	2	3	4
ϵ_g	1.0	0.5	0.1	0.01
Total rise, m	0.036	0.031	0.068	0.25
Time of rise, sec	0.054	0.064	0.14	0.51
Maximum interface temperature, K	943.7	934.8	903.5	870.1
Time to condense, sec				
50% of UO ₂	0.02	0.02	0.04	0.16
90%	0.04	0.05	0.10	0.38
98%	0.05	0.06	0.13	0.47
100%	0.054	0.064	0.14	0.51
Range of h_{rad} , W/m ² -sec ^b	960-1367	794-1139	310-486	45-65
Initial h_{rad}	1700	1418	608	82
Time when $T_g = T_{sat}$, sec	<0.00125	<0.20125	<0.0175	<0.0175

^aParameters common to these cases: initial bubble depth = 1.067 m (42 in.); $h_c = 100$ W/m²-K; initial UO₂ vapor mass = 2 g; cover gas pressure = 20 atm; initial vapor temperature = 5000 K.

^bCited range applies when $T_g \cong T_{sat}$.

for $T_g = 4000 - 5000$, $T_g^4 = 2.6 \times 10^{14} - 6.2 \times 10^{14}$, while $T_w^4 \sim 5 \times 10^{11} - 7.9 \times 10^{11}$ or a fraction of a percent of T_g^4 . One could assume, therefore, that radiation heat loss is a function of vapor temperature only.) Here the total rise is a very strong function of ϵ_g , as is the condensation rate. Also, there is a substantial rise in the interface temperature above the initial liquid temperature of 838 K, a phenomenon due to the size of the effective radiation heat transfer coefficients, which are of the order of 500 to 1000 W/m²-K (or 90 to 180 Btu/hr-ft²-°F) for ϵ_g between 0.1 and 1.0. In case 4, the results resemble those for the corresponding case 4 in Table 1, since the value of h_{rad} is about half of that for h_c . As in Table 1, a rapid initial cooling occurs until saturation is reached. From that point on, radiation is assumed to produce condensation of the UO₂, with effective removal of the condensate from the vapor.

Clearly, emphasis needs to be placed on radiation heat loss as a contributor to vapor condensation. The present crude analysis needs to be replaced by a more careful study. This will be difficult because of a lack of knowledge of the optical parameters involved and the fact that time-dependent effects will occur. By the latter, we mean that condensation due to radiation should occur in the body of the gas, rather than near the cold surface. The resultant fog should produce at least some variation in the heat loss; a related question will be how much precipitation of such a fog will occur. This will affect not only the heat loss but also the fraction of the vapor which reaches the cover gas region. Finally, we note that heating of the liquid by radiation in the case of sodium can produce a significant heating at the interface. In the case of FAST experiments with water, significant vaporization may occur, a feature that must be included in the analytical model.

5. CONCLUSIONS AND RECOMMENDATIONS

1. The sodium is efficient enough at removing heat that more elaborate analysis of coolant side heat transfer is of the lowest priority. The situation in water experiments may be quite different in this respect and will require appropriate treatment.

2. Heat loss by radiation is potentially the most important heat transfer process. Heat transfer coefficients calculated by this mechanism were usually found to be much greater than those calculated by the diffusion condensation process, but only more elaborate analysis will confirm whether the radiation temperature gradients and properties actually exist to produce these losses.

3. The other major heat transfer process, condensation in the presence of an inert gas, needs to be treated as an integral part of these calculations in order to receive proper accounting. Comparison between taking the heat transfer coefficient as a function of time vs taking it as a function of inert gas mol fraction shows that heat loss could be slowed down much more rapidly in the latter case, with a consequent increased possibility of carrying UO_2 to the surface.

4. No important effect was seen in calculations in which the bubble was released at a depth of 28 in. vs those results for a 42-in. original depth.

5. The effect of the original amount vaporized showed no unexpected results beyond some minor and obvious extensive effects. Finite vessel size effects on hydrodynamics were not included in the bubble rise model.

6. The starting temperature (in the sense of superheating) assumed was of practically no importance as the bubble quickly cooled to saturation temperature in all cases, due mainly to high initial radiation losses.

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APPENDICES

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Appendix A

PHYSICAL PROPERTY FORMULAS AND TABULATIONS

Thermal conductivity of Na at temperature T, K, in W/m-K

$$k_L = 93. - 0.0581(T - 273.) + 1.173 \times 10^{-5}(T - 273.)^2 \quad (A.1)$$

Pressure of saturated UO₂ vapor, Pa (Ref. 15)

$$P_{UO_2} = \exp (-4.34 \log_e T - 7.68 \times 10^4/T + 67.676) \quad (A.2)$$

Heat of vaporization of UO₂, J/kg

From the Clapeyron equation applied to the listed properties:

$$H = P_{UO_2} (V_g - 1/\rho_{UO_2}) \left(\frac{76,800}{T} - 4.34 \right) \quad (A.3)$$

Density of liquid sodium, kg/m³

$$\begin{aligned} \rho_{Na} = & 950.1 - 0.22976(T - 273.15) \\ & - 1.46 \times 10^{-5}(T - 273.15)^2 \\ & + 5.638 \times 10^{-9}(T - 273.15)^3 ; T < 1643 \text{ K} \end{aligned} \quad (A.4)$$

$$\rho_{Na} = 181.8[1 + 4.163(1 - T/2733)^{0.5885}] ; T > 1643 \text{ K} \quad (A.5)$$

Density of liquid UO₂, kg/m³ (Ref. 16)

$$\rho_{UO_2} = \frac{1 + \left(1 - \frac{T}{8000}\right)^{0.402581} (2.51373)}{3.3258 \times 10^{-4}} \quad (A.6)$$

Specific volume of saturated UO₂ vapor, m³/kg (Ref. 16)

$$V_g = BW \quad (A.7)$$

where

$$B \equiv 1 - 0.686424 \exp [(T - 8000)/200]$$

$$W \equiv 4.87833 \times 10^4 P_{UO_2}^{-0.92515}$$

Table A.1. Heat capacity of liquid sodium
(calories/mol-K) (Ref. 15)^a

Temperature (K)	C(T) ^b	Temperature (K)	C(T) ^b
400	7.53	1600	8.11
500	7.3	1700	8.38
600	7.12	1800	8.60
700	6.99	1900	8.88
800	6.92	2000	9.24
900	6.89	2100	9.72
1000	6.92	2200	10.4
1100	6.99	2300	11.4
1200	7.11	2400	13.1
1300	7.29	2500	16.3
1400	7.51	2600	25.1
1500	7.78	2700	135.0

^aHeat capacities at temperatures intermediate to these are obtained by the code using second degree curve fitting.

^bJ/kg-K = 182.1 C(T).

Appendix B

GENERAL GAS LAW APPLIED TO UO_2

Information in Table C-1, p. 98 of Ref. 17 (J. G. Refling's thesis) compared with ideal gas law estimates of specific volume

Temperature (K)	Saturation pressure (MPa) ^a	m ³ /kg ^b	Ideal gas (m ³ /kg) ^c
3800	0.1196	0.9786	0.9784
4000	0.2630	0.4721	0.4684
4500	1.332	0.1053	0.1040
5000	4.645	0.03313	0.03315
5500	12.41	0.01335	0.01365
6000	27.24	0.006451	0.006783

^aEquation (A.2), Appendix A.

^bEquation (A.7), Appendix A.

^c $V = 8.31441 \times 10^3 T / (270 \times P)$, where P is in pascals.

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