Some Aspects of Fuel-Pin Failure Propagation in Sodium-Cooled Fast Reactors

In a recent paper, Fauske[1] has discussed the potential for pin-to-pin failure propagation in sodium-cooled reactors for three accident conditions, namely: (a) fission-gas release from a defective pin causing subsequent flow dilution, (b) a local blockage leading to sodium boiling, and (c) release of small amounts of molten fuel. Considering each of these aspects separately, it was concluded that none of them can lead to a rapid failure propagation. The paper did not consider the possible effects of any combination of these phenomena. At least in the case of a molten fuel release, a combination of these phenomena appears to be a realistic possibility. For example, noncondensable gases in the form of interstitial, bond, and fission gases are always present in a fuel pin. The effects of the release of noncondensable gases with the molten fuel need to be addressed. The purpose of this Letter is to discuss the possible effects of the presence of noncondensable gases in the fuel-coolant interaction region.

If a substantial amount of the noncondensable gases is ejected into the coolant before the release of any molten fuel, the fuel will be ejected in a voided volume. Then the fragmentation of the molten fuel will not be extensive. (In the absence of direct UO_2/liquid sodium contact, fragmentation takes place only due to hydrodynamic instabilities.) This was evident in a recent overpower pin failure experiment in the TREAT reactor.[2] If the molten fuel is released in the form of a jet, the failure of at least an adjacent pin cannot be precluded.[3] It may be that the failure will be self-limiting; that is, only one adjacent pin fails; however, this is yet to be demonstrated. More significantly, as the fuel tends to remain in large solidified particles, the possibility of forming a heat-generating local blockage should be investigated.

When the internal gas is essentially released with the molten fuel and intermittent UO_2-liquid sodium contact does occur, extensive fragmentation will take place. The development of an interaction zone that contains liquid sodium, vapor sodium, noncondensable gases, and fragmented fuel can then be realized. In Fauske's model, the effects of noncondensable gases on the fuel-coolant interactions have been ignored. Because the noncondensable gases tend to accumulate at condensing surfaces, the condensation rate will be drastically reduced, thereby affecting the pin dry out and the vapor heat transfer dynamics. This has been illustrated by various analyses including that of Theofanous and Fauske.[4] This leads to a larger radius and longer lifetime for the bubbles generated because of the release of the hot molten fuel.

To illustrate the importance of the presence of noncondensables, we have calculated the condensation rate in the presence of different amounts of the noncondensables as compared to the condensation rate in the absence of noncondensables from vapor bubbles. In these calculations the effect of the noncondensable gases is realized by assuming a linear temperature profile across an equivalent thin layer of gas adhering to the condensing surface. The inert gas is assumed to have a temperature-independent thermal conductivity, K_g. The condensation rate is taken to be proportional to $T_S - T_L$, where T_S is the bubble/liquid interface temperature and T_L is the liquid bulk temperature. In the absence of noncondensable gases $T_S = T_V$, where T_V is the vapor temperature. The effects of the presence of a noncondensable gas on the condensation rate is shown in Fig. 1 for various values of the condensation coefficient, h. A value 1.5 cal/(sec cm^2 °C) for h was used by Fauske.[1] The results indicate that for practical values of condensation coefficients, the presence of small quantities of noncondensable gases in vapor bubbles reduces the condensation rate by significant amounts. For the bubble size discussed by Fauske, $\delta = 10^{-4}$ cm corresponds to about 0.01% by volume of gas on the surface compared to the total vapor

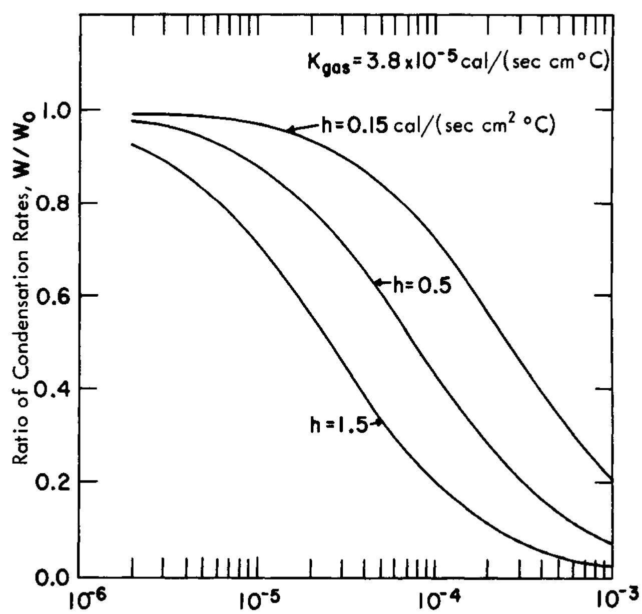

Fig. 1. The ratio of the condensation rate in the presence of noncondensable gases to that in the absence of gases, W/W_0, is shown as a function of the equivalent gas film thickness for various condensation coefficients.

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[1]H. K. FAUSKE, *Nucl. Sci. Eng.*, **54**, 10 (1974)

[2]R. C. DOERNER and A. DeVOLPI, *Trans. Am. Nucl. Soc.*, **18**, 212 (1974).

[3]A. B. ROTHMAN et al., *Trans. Am. Nucl. Soc.*, **16**, 181 (1973).

[4]T. G. THEOFANOUS and H. K. FAUSKE, *Nucl. Technol.*, **19**, 132 (1973).

volume. The volume of the noncondensable gases in a single fuel pin is about 20 cm^3. The pin internal pressure may be between 1 and 60 atm. Therefore, the existence of a thin layer of gas at the condensing surfaces in the fuel/sodium interaction region is a distinct possibility.

From the above considerations, we conclude that in the analysis of the consequences of releasing small amounts of molten fuel to the coolant in liquid-metal fast breeder reactors, it is necessary that the effects of noncondensable gases be considered.

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Reply to "Comments on Fuel-Pin-Failure Propagation"

The effect of noncondensables has been shown in a recent paper by Theofanous and Fauske[1] to seriously retard the condensation process, in the case the bulk concentration of noncondensables is assumed to remain constant with time. A simple extension of this analysis, accounting for depletion of noncondensables as additional vapor is produced and new condensing surface area is uncovered, indicates that in the case of fresh fuel (this is the case treated in the fuel failure propagation paper[2]) the presence of bond gases has little effect upon the rate of vapor bubble growth. In fact, the value of 1.5 cal/(sec cm^2 °C) used for the condensing coefficient may be on the low side. It is important to recognize that in the present application the condensing surface area is rapidly varying with time, and that the small amounts of noncondensables present initially (at time equals zero the fuel is assumed fully fragmented) is rapidly being depleted as a result of being absorbed on surface areas created early in the bubble lifetime. The condensing analysis presented by Majumdar and Kazimi[3] would not appear to be applicable in this case since their treatment assumes a uniform layer of noncondensables adhering to the total available condensing surface.

In the case of highly irradiated fuel, the release of molten fuel is likely to be preceded by fission gas release as indicated by Majumdar and Kazimi. The question in this case is not the potential for large pressure generation and bulk flow starvation, but rather the potential for creating a blockage (as a result of freezing and plugging) or for adding to the blockage that may have caused the fuel release in the first place; i.e., *blockage propagation* rather than *rapid* fuel failure propagation is the main concern in this case. In the concluding remarks of my paper, it was stated that the magnitudes of the pressure generation and the void growth appear insufficient to cause *rapid* failure propagation. It should be added that slow propagation (blockage propagation) cannot be ruled out at this time. However, note that detection by means of fission product monitoring systems is possible even for a single failed fuel pin, within a time period of tens of seconds. It is, therefore, important to clearly distinguish, on the one extreme, rapid pin-to-pin failure propagation, postulated to take place on a time scale too short to enable detection of the phenomenon and shutdown of the reactor prior to involvement of the entire subassembly, and, on the other extreme, self-limiting and/or slow failure propagation (blockage propagation), occurring on a time scale long enough to allow ample time for detection and corrective action if necessary. Major safety testing needs in the area of fuel pin failure propagation, therefore, appear to be the study of long term behavior following molten fuel release (both fresh and old fuel), including measurements of the rate of blockage propagation if it should occur and the related signals associated with fuel sweepout (delayed neutron detection) and boiling noise. Both out-of-pile and in-pile experiments are in progress to provide information in the above areas.

[1]T. G. THEOFANOUS and H. K. FAUSKE, *Nucl. Technol.*, **19**, 132 (1973).
[2]H. K. FAUSKE, *Nucl. Sci. Eng.*, **54**, 10 (1974).
[3]D. MAJUMDAR and M. G. KAZIMI, *Nucl. Sci. Eng.*, **55**, 481 (1974).

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The Influence of Neutron Poisons on High-Concentration Plutonium Solutions

The criticality of plutonium nitrate solutions poisoned by borosilicate glass raschig rings was discussed by Lloyd et al.[1] I wish to comment on one of their conclusions which could have dangerous consequences if applied to a typical process plant situation and could result in a nuclearly unsafe condition. They state on p. 133 of Ref. 1 that: ". . . the calculations indicate that (the reactivity effect of) neutron poisoning is nil in the high, 391-g Pu/liter, concentration solution. The small reactivity effects . . . observed in this relatively undermoderated system appear to be entirely due to the density reduction caused by the rings displacing solution." These statements are true because of the small size of the experimental vessel used. Assuming their validity for larger vessels could lead a design agency to reduce costs by substituting a less expensive material for the boron-loaded glass. Their sole criterion would be that 19.27% of the tank's volume be consumed by the substitute material, as was the case in Ref. 1.

The vessel used by Lloyd et al. measured only 61 cm in diameter, and the critical 391-g Pu/liter solution height was 25.5 cm when 0.5 wt% boron-loaded rings occupied 19.27% of the volume. Using the KENO (Ref. 2) code and GAMTEC-II (Ref. 3) cross sections, they calculated k_{eff} = 1.012 ± 0.006, treating the raschig rings as parallel vertical tubes displacing the same solution as rings. Their conclusion apparently is based on the result of a second calculation in which the geometry and materials used in the first were retained except that the borosilicate glass material was replaced by a void. This result (k_{eff} = 1.010 ± 0.006) was not significantly different from the calculation including ring material and, hence, their conclusion.

At Rocky Flats, similar experiments involving heterogeneous poisoning of uranyl nitrate solutions have been performed.[4-6] The most recent experiment measured

[1]R. C. LLOYD, S. R. BIERMAN, and E. D. CLAYTON, *Nucl. Sci. Eng.*, **50**, 127 (1973).
[2]G. E. WHITESIDES and N. F. CROSS, "KENO, A Multigroup Monte Carlo Criticality Program," CTC-5, Computing Technology Center, Union Carbide Corp., Nuclear Division (1969).
[3]L. L. CARTER, C. R. RICHEY, and C. E. HUGHEY, "GAMTEC-II—A Code for Generating Consistent Multigroup Constants Utilized in Diffusion and Transport Theory Calculations," BNWL-35, Battelle-Pacific Northwest Laboratories (1965).