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.

Debaprasad Majumdar
Mujid S. Kazimi

Brookhaven National Laboratory
Upton, New York 11973

July 26, 1974

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.

H. K. Fauske

Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Illinois 60439

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[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).

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).

critical heights within a minimally reflected 106.6-cm-i.d. tank heterogeneously poisoned with vertical, parallel, evenly spaced stainless-steel plates containing 1 wt% natural boron. The system resembled Lloyd's except for size, details of the heterogeneous poison, and the use of uranium solution instead of plutonium solution. Qualitatively, the latter two differences are unimportant to this discussion, so an evaluation on the basis of size may be made. The specific example selected for comparison in the same fashion used in Ref. 1 was 450.8-g U/liter solution poisoned with 0.259-cm-thick plates spaced 1.46 cm. The calculated neutron reproduction factors for 60-cm solution height with boron stainless-steel material present and with the plate material replaced by a void are 1.004 ± 0.006 and 1.556 ± 0.005, respectively. (These values were calculated using Hansen-Roach[7] cross sections.) The plates occupied 17.78% of the critical volume—comparable to their 19.27%. The conclusion here is that the reactivity effect of neutron poisoning in a large tank is indeed very important for high concentration fissile solution. This is also consistent with one limiting case: A three-dimensionally infinite critical region of poisoned fissile solution would have a neutron reproduction factor equal to k_∞ for the fissile solution alone if all poison regions were replaced by voids. For both 391-g Pu/liter and 450.8-g U/liter solutions, k_∞ is something greater than 1.5.

To test further the contention that their conclusion depends upon tank size, a sequence of calculations in decreasingly smaller, unreflected, cuboidal tanks was performed. In each case, k_{eff} was calculated with the boron stainless-steel material present and with it replaced by a void. The number of plates was selected so that a reproduction factor near unity was obtained when the poison material was included. Table I shows the result of this program.

The diminishing influence of the poison material as the vessel decreases in size seems to support the present contention. A second limiting case lends further support: When the tank volume is so small that solution alone is critical, then k_{eff} will certainly remain unchanged if the poison material is replaced by a void for there is none.

Two factors influence the *magnitude* of the difference in reproduction factors calculated for poisons and voids as seen in Table I. The difference depends upon size for a given type of poison, because less is required in a smaller tank to achieve k_{eff} = 1.0 and its absence would be less important. In a given tank, however, the difference would be greater for poison elements having a high-boron content than for those of low-boron concentration. The authors of Ref. 1 hint at this in their final full paragraph on p. 133 when they give k_{eff} = 0.819 ± 0.005 for 4 wt% boron-loaded rings in place of the 0.5 wt% rings (1.012 ± 0.006).

TABLE I

KENO Calculated k_{eff} for 450.8-g U/liter Solution in Various Sized Cuboidal Tanks

Tank Dimensions L × W × H (cm)	Plate Spacing (cm)	k_{eff}	
		Plate Material Included	Plate Material Replaced by Void
106.6 × 106.6 × 130.7[a]	0.953	1.003 ± 0.006	1.621 ± 0.010
50.0 × 50.0 × 100.0	1.852	1.002 ± 0.006	1.395 ± 0.010
30.0 × 30.0 × 60.0	5.0	1.007 ± 0.010	1.092 ± 0.012
26.0 × 26.0 × 52.0	13.0	0.990 ± 0.013	1.028 ± 0.013
24.0 × 24.0 × 50.0	24.0	subcritical	

[a]Plates spanned only 119.7 cm of this height. Also, this calculation included some distant room reflection.

[4]C. L. SCHUSKE, *Chem. Eng. Prog. Symp. Ser.*, **61**, *60*, 18 (1965).

[5]R. E. ROTHE, *Nucl. Sci. Eng.*, **35**, 267 (1969).

[6]R. E. ROTHE, D. L. ALVAREZ, and H. E. CLARK, "The Criticality of Periodically Boron-Poisoned Enriched Uranium Solution Systems," submitted to *Nuclear Technology*.

[7]GORDON E. HANSEN and WILLIAM H. ROACH, "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies," LAMS-2543, Los Alamos Scientific Laboratory (1960).

Robert E. Rothe

Dow Chemical Company
Rocky Flats Division
P. O. Box 888
Golden, Colorado 80401

August 9, 1974

Response to "The Influence of Neutron Poisons on High-Concentration Plutonium Solutions"

We are pleased to comment on the Letter of R. E. Rothe, entitled, "The Influence of Neutron Poisons on High-Concentration Plutonium Solutions."[1] We wish to emphasize that the experimental data and our conclusions as given in Ref. 2 are correct as they stand for the *systems measured*. It is always possible for someone to misuse any data, but we would hope any such person applying these data to criticality problems would be sufficiently aware of the factors affecting criticality to understand that insertion of voids in an infinite system (a system with no neutron leakage) would affect neither neutron leakage nor k_∞ but that the neutron absorbing boron-containing glass raschig rings would, in any event, act to reduce k_∞.

The calculational comparisons shown in Table V, Ref. 2, were given to make the criticality safety engineer aware of the magnitude of the change in the effect of raschig rings with concentration. These data are for use in establishing criticality safety guidelines and for checking calculational models. Conclusions from finite systems should not be extrapolated to infinite systems (from small to large vessels, etc.) without consideration of the different conditions encountered, and of how these may affect criticality.

The vessel size used in the experiment was chosen not only from the practical view of the experiment, but to be of equivalent size to many process vessels and also to the common 55-gal drum. In any event, the final paragraph of Ref. 2, in the section entitled "Theory and Correlation," should clarify any misconceptions on the part of any reader:

> "As the boron content of the rings is increased, neutron absorption becomes the predominant mechanism by which the reactivity is decreased over the entire solution concentration range. This is illustrated in Table I where it is shown that the geometric buckling for the critical 391-g Pu/liter solution increases from 0.002 cm^{-2} to about 0.011 cm^{-2} when the boron content of the rings is decreased from 4 to 0.5 wt%. Although some variation in the volume of solution displaced by the two different rings was

[1]ROBERT E. ROTHE, *Nucl. Sci. Eng.*, **55**, 482 (1974).

[2]R. C. LLOYD, S. R. BIERMAN, and E. D. CLAYTON, *Nucl. Sci. Eng.*, **50**, 127 (1973).