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Experiments GAP-3 and GAP-4[1] were performed at ANL to investigate the ability of molten fuel to penetrate downward through the narrow channels separating adjacent subassemblies during an LMFBR hypothetical core disruptive accident. Molten fuel-metal mixtures (81% UO_2, 19% Mo) at an initial temperature of 3470 K generated by a thermite reaction were injected downward into 1 m long rectangular test sections (gap thickness = 0.43 cm, channel width = 20.3 cm) initially at 1170 K simulating the nominal Clinch River Breeder Reactor intersubassembly gap. In the GAP-3 test, a prolonged reaction time of ~ 15 s resulted in segregation of the metallic Mo and oxidic UO_2 constituents within the reaction vessel prior to injection. Consequently, Mo entered the test section first and froze, forming a complete plug at a penetration distance of 0.18 m. In GAP-4, the reaction time was reduced to ~ 3 s and the constituents remained well mixed upon injection with the result that the leading edge penetration distance increased to 0.35 m. Posttest examination of the cut-open test sections has revealed the existence of stable insulating crusts upon the underlying steel walls with melting and ablation of the walls only very localized. In light of the preponderance of stable crust formation observed in the experiments, analysis of the tests has been undertaken with computer code calculations assuming that molten material penetration is limited only by the growth of stable crusts upon the channel walls

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(i.e., the stable crust growth/conduction model[2] of freezing and plugging). Presented here are the results of the calculations together with discussion of the differences between prediction and experiment.

The calculations were performed with a coupled fluid dynamics/conduction heat transfer computer code. The injected fuel is modeled as a one-dimensional, growing length of incompressible liquid flowing downward through a rectangular steel channel possessing dimensions which vary in space and time to reflect the growth and remelting of fuel crust. Behind the molten fuel leading edge, crust formation and conduction heat transfer are modeled normal to the flow and assuming a slab geometry. The one-dimensional calculations of the simultaneous growth of crust and the heating of the surrounding steel walls combine a continuous tracking of the fluid-crust interface together with a refined integral heat balance[3] formulation of conduction heat transfer within the crust and wall. Calculations are continued until either: (a) the crust grows to completely occlude the flow channel at some location, (b) the fluid leading edge transcends the full channel length, or (c) the available fluid mass is completely deposited as a crust on the channel boundaries leaving a partially plugged channel.

Because of the significant segregation of metallic and oxidic components in GAP-3, an assessment of conduction theory versus experiment was carried out by calculating the penetration of pure molybdenum under the test conditions. It is assumed that 1.08 kg (the actual injected mass) of fully dense Mo initially at 3470 K is injected at a constant driving pressure drop of 0.045 MPa (the measured pressure differential at the onset of injection). The calculation predicts that all of the available mass of Mo is deposited as a thin crust on the channel walls leaving behind only a partially plugged channel. The Mo penetrates a maximum distance of 0.92 m into the test section over a time interval of 0.13 s. The crust is thickest at 0.14 m into the test section where 25% of the initial gap channel cross-section is occluded. Decreasing the driving pressure drop to zero (i.e., a pure gravity drainage) reduces the penetration distance to 0.42 m over a longer interval of 0.41 s while increasing the maximum channel occlusion to 56% at 0.08 m.

For GAP-4, the injected thermite mixture is modeled using thermophysical properties for UO_2 with the thermal conductivity and viscosity increased to account for the presence of the metallic phase as small spheres of Mo dispersed throughout a UO_2 continuum. A mass of 2.38 kg of molten thermite at 3470 K is assumed injected in response to a constant 0.048 MPa pressure drop. The injected fuel is predicted to drain the entire 1 m test section length in 0.25 s to form a 0.20 m deep pool at the bottom of the test section leaving behind a thin crust on the steel channel walls. The crust thickness is greatest at 0.29 m into the test section where 15% of the gap channel is occluded. For the case of a pure gravity drainage, the fuel leading edge transcends the test section length in 0.66 s and the maximum occlusion is increased to 28% at the test section inlet. Reducing the initial fuel temperature to the UO_2 liquidus (3138 K) does not preclude the complete penetration of the gap channel, although the maximum occlusion is increased to 25% for a pressure drop of 0.048 MPa and 51% for a gravity drainage.

Conclusions

Conduction theory predicts that the injected mass of thermite will drain over most or all of the test section length leaving behind a crust which only partially occludes the flow channel. Furthermore, the results are qualitatively unchanged when either the driving pressure drop or initial fuel temperature are decreased below their nominal values. In contrast, the experiments are suggestive of complete plugging in a bulk mode at the fuel leading edge at significantly shorter penetration distances.

The conduction model considers only one mode of freezing: crust formation on the channel boundaries. This model has been highly successful in describing the freezing of flowing simulant materials. However, for the high temperature reactor materials employed in the gap penetration experiments, it is possible to envision processes for solidification which may be operative concurrently with crust growth and which would tend to promote freezing and plugging in a bulk manner. An example of such an additional process might be thermal radiation from "fingers" of advancing fuel at the leading edge to the relatively cold steel walls between adjacent fingers. Irrespective of the stability of fuel crusts, such an additional freezing mechanism would probably give rise to the formation of solid particulate within the flow field. The particles would lead to an enhanced frictional resistance and possibly jamming together of particles to create a mechanical blockage resulting in reduced penetration distances. The wide disparity between conduction theory calculations and the results of the GAP experiments suggests that the consideration of such an additional freezing process may be a necessity in the prediction of fuel immobilization.

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