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LOS ALAMOS EXPERIMENTS AND THEIR IMPACTS ON FAST REACTOR SAFETY

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ABSTRACT

Results of two sets of recent Los Alamos transition-phase experiments are reported herein. The two sets of experiments addressed two different behaviors of boiling pools of molten fuel, molten steel and steel vapor, in the transition phase of a core-disruptive accident (CDA) in a liquid-metal fast breeder reactor (LMFBR). The transient boilup experiments simulated the recriticality-induced motions of a boiling pool within a single subassembly during the subassembly-pool subphase of the transition phase. The melting wall experiments simulated the melting and entrainment of subassembly duct wall steel into a boiling pool during the same subphase. From the results of the transient boilup experiment we identified behaviors and phenomena that argue against an energetic disassembly from the subassembly-pool subphase. From the melting wall experiments we determined that a stable boiling pool is unlikely by showing that significant amounts of wall steel would likely be rapidly entrained and lead to pool collapse.

INTRODUCTION

The transition phase of a core-disruptive accident (CDA) in a liquid-metal fast breeder reactor (LMFBR) is the phase or time period of the accident during which the reactor core is changing from a mostly intact geometry to a mostly molten state. During the transition phase, that phase of the CDA between the initiating phase and the termination phase, boiling of molten core debris and recriticalities are possible and of concern. CDAs are generally grouped into three categories, the loss of flow (LOF), the transient overpower (TOP) and the loss of heat sink (LOHS). In addition, CDAs are usually unprotected, that is, they include a failure to scram although in some cases severe core disruption can still occur after a reactor scram. The transition phase starts at the onset of subassembly duct wall melting. By this time limited fuel and steel have melted in a few subassemblies. As the transition phase progresses, more molten fuel is formed and as the molten inventory in the core region grows and becomes more mobile, the reactor can return to a neutronically critical state. The transition phase ends when further recriticalities can not occur. The events that can stop further recriticalities are fissile fuel core-region inventory reduction, core-region fissile fuel dilution with fertile fuel, or an energetic disassembly (a very severe recriticality). The behavior of pools of molten fuel, molten steel and steel vapor, formed in the transition phase, can strongly influence the character of the transition phase, and of the entire accident. Los Alamos transition-phase experiments simulated the behaviors of these pools.

The transition phase progresses through three fairly distinct subphases, the subassembly-pool subphase, the regional-pool subphase and the whole-core-pool subphase. In the subassembly-pool subphase, pools of molten fuel, molten steel and steel vapor, are confined to several scattered high-powered subassemblies and display predominantly one-dimensional axial fluid motions. The transient boilup experiments addressed this subphase, and simulated the motion of a subassembly pool following a recriticality-induced power burst. The melting wall experiments addressed this subassembly subphase also, and simulated the entrainment of melting steel from the duct wall into the subassembly pool. In the regional pool subphase, slightly larger but still separated pools exist, made up of the molten remains of clusters of subassemblies. In the whole-core-pool subphase, the regional pools are linked, coalesced into one large pool that can

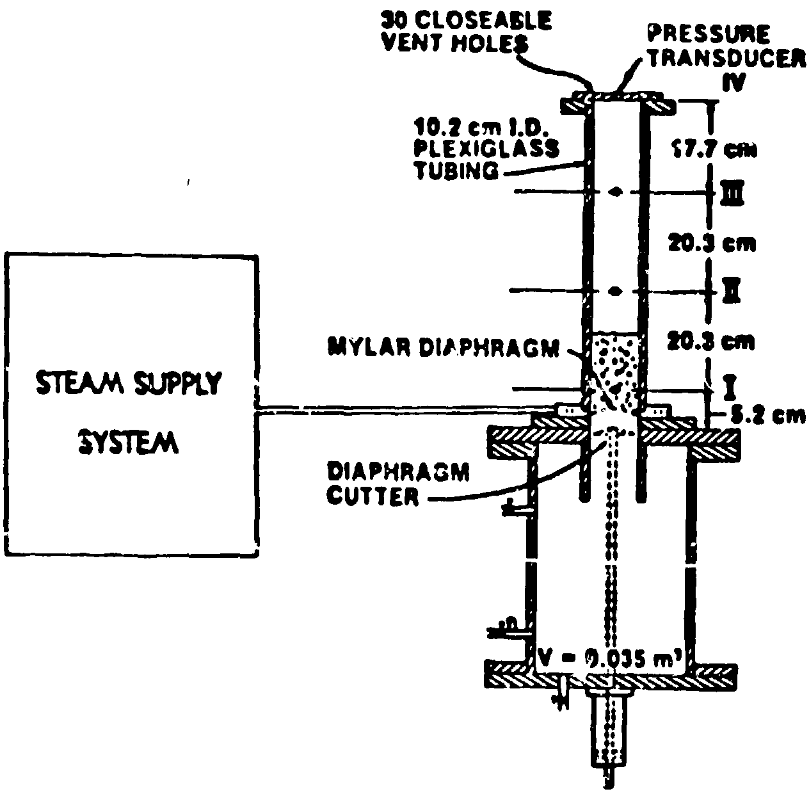


Fig. 1.
Transient boilup experiment apparatus.

now display large radial, as well as axial fluid motions.

TRANSIENT BOILUP EXPERIMENTS

The transient boilup experiments (1-4) simulated the power-burst-induced transient motion of a boiling pool of molten fuel, molten steel and steel vapor, within a subassembly duct in the subassembly-pool subphase. With probable steel blockages at the top and bottom, and intact subassembly duct walls, the molten fuel-steel mixture is effectively "bottled up," and material motions are predominantly one-dimensional in the axial direction. Additional steel enters the pool by the melting and entrainment of subassembly duct walls, cladding remnants and pieces of wire wrap. As steel is vaporized in the pool, it leaves the pool and travels upward in the subassembly to where cooler temperatures provide a condensation sink. This pool, "boiled up" by steel vapor, is not static. When a recriticality and power burst occur, fuel-vapor generation near the pool midplane accelerates the top half of the pool upward. After the upward motion stops, the elevated fuel-steel mixture descends, generating the reactivity ramp rate for the next recriticality. The mixture may drain back, rain back or fall back as a slug, at various speeds to rejoin the bottom half of the subassembly pool (5). Thus, the severity of the next recriticality and the energy from the associated power burst are very strongly dependent on the collapse mode and descent rate of the elevated top half of the pool. During the subassembly-pool subphase, recriticalities and their associated power bursts cause an increasing amount of fissile fuel to move up and down in subassemblies in a more coherent manner. This process stops and the subassembly-pool subphase ends when one of three things occurs. They are: 1) subassembly duct wall melting, introducing the regional-pool subphase, 2) fissile fuel inventory reduction that stops further recriticalities, and 3) energetic disassembly due to coherent fuel collapse. It is this last scenario that the experiments address, for it is the acceleration up and the collapse down that determine the reactivity ramp rate for the next recriticality and power burst. The ramp rate is a function of the initial fuel distribution as collapse begins, the rate of collapse or reassembly, and the collapse mode. Estimates indicated that slug fallback produces ramp rates ten times those for drainback and that rainback produces ramp rates three times those for drainback (5). The Los Alamos transient boil up experiments simulated the acceleration up and collapse down of the top half of a subassembly pool and provide information for establishing a defensible ramp-rate range or limit for this subphase.

The top half of the pool of molten fuel, molten steel and steel vapor, was simulated by a two-phase saturated steam-water mixture resting at the bottom of a 0.64-m-high, 102-mm diameter vertical transparent acrylic tube (Fig. 1). In all cases, the unvoided liquid height was 150 mm. Steam above the mixture simulated steel vapor above the subassembly pool. In a previous set of Los Alamos experiments, nitrogen, a noncondensible, was used instead of steam for apparatus development and to simulate fission gas above the pool (2). The use of steam, a condensible, was a significant achievement, because the experiment with condensible material more closely approximated the expected in-reactor conditions. The two-phase mixture rested on a thin Mylar diaphragm, below which was a nitrogen reservoir at elevated pressure. The nitrogen below the diaphragm simulated fuel vapor generated near the center of the subassembly pool by a power burst. At the start of the experiment, the Mylar diaphragm was rapidly cut and the pressurized nitrogen began to accelerate the mixture upward in the tube, or column. This simulated the upward acceleration of the top half of the subassembly pool caused by fuel-vapor generation at the pool midplane. The mixture then traveled up the column, stopped, sometimes by impacting the top plate, and came back down the column. Five important pieces of data were collected, a high-speed movie and four pressure traces. The two principal parameters varied in the experiments were the initial pressure difference (Δp) between the tube and the nitrogen reservoir below, and the initial vapor volume fraction in the two-phase mixture.

High-Void-Fraction Cases

Experimental results for the steam-voided series and the nitrogen-voided series were very similar, even though the void fractions used were 40% and 50%, respectively (not quite the same). Figure 2 shows comparison plots for the steam-voided and nitrogen-voided transient boilup experiment series.

The low initial Δp cases [34 kPa (5 psig)] for both the steam-voided and nitrogen-voided series produced a slowly rising pressure at the top of the column without a pressure spike (Fig. 2a). In both series the nitrogen driver gas percolated through the two-phase mixture, entraining it, and dragging it up the column. The water was dispersed fairly uniformly over the height of the column, but by the time the water started to fall most of the water was in the upper quarter of the column. Experimental pressure traces at the top of the column for the two series were close. The movie results for the two series are close as well, and we conclude that condensation did not play a significant role.

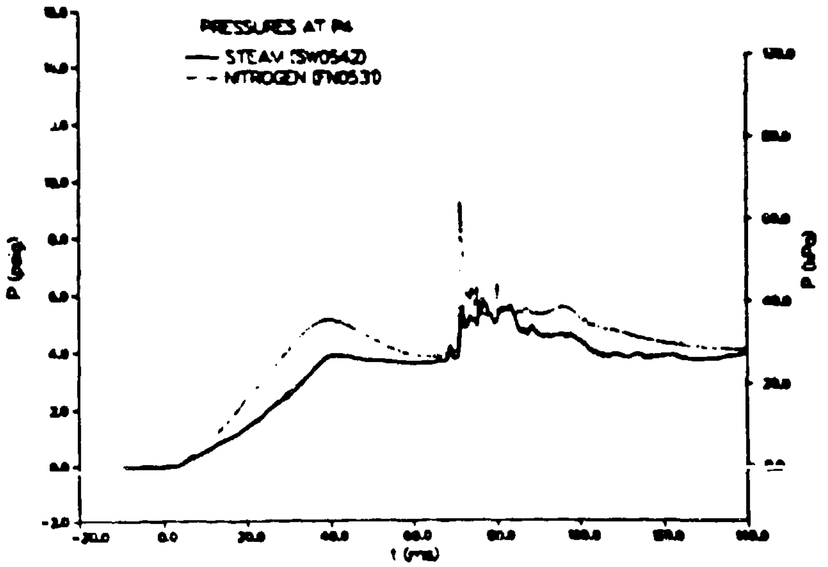
The high initial Δp cases [310 kPa (45 psig)] both the condensible and noncondensible series produced very similar results, (Fig. 2b). Although the high initial Δp case is faster and more violent, the general behavior was similar to that in the low initial Δp case. In both series the nitrogen gas percolated through the two-phase mixture and entrained it upward in the column. The water was dispersed fairly uniformly over the height of the column; additionally, when the water started to fall it was still dispersed rather than concentrated in any part of the column. For both the steam-voided and nitrogen-voided series, the pressure at the top of the column peaked rapidly and quickly damped to a steady final pressure. So, at high void fractions (40% to 50%) and at low and high initial Δp [34 kPa (5 psig) and 310 kPa (45 psig)], for both the steam-voided and nitrogen-voided series of experiments, the experimental results were very close. Therefore, we conclude that condensation was not significant in these high-initial-void-fraction experiments.

Low Void-Fraction Cases

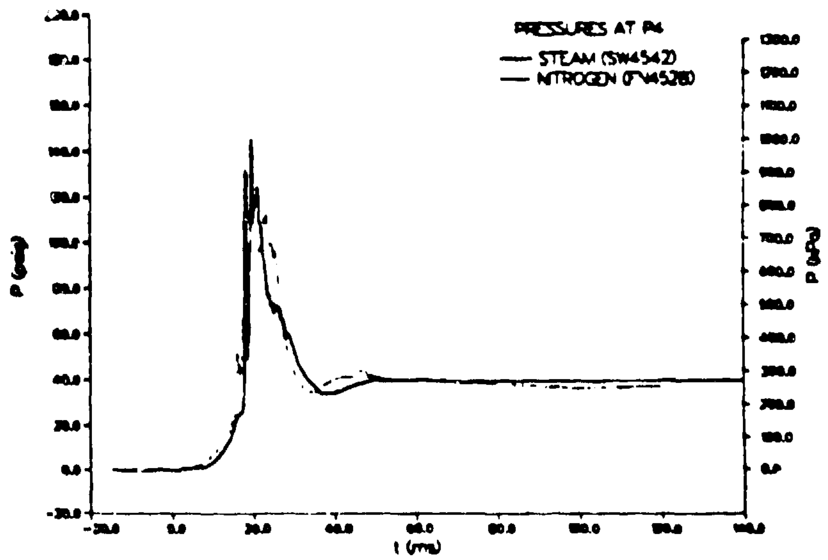
At the low initial void fraction (10%) the steam-voided and nitrogen-voided experiment series have similarities and differences. In the steam-voided series the steam voids quickly collapsed after the initial pressure pulse; obviously this did not occur in the nitrogen-voided series.

At the high initial Δp [310 kPa (45 psig)] the behavior and pressure traces for the two series were similar (Fig. 2d). The pressures at top of the column peaked at about the same magnitude and time, and displayed a characteristic damped piston-like behavior. In the noncondensible series the plug remained a two-phase mixture as it rose in the column. In contrast, in the condensible series, in which the steam-voids had quickly collapsed, the slug remained single-phase as it rose in the column. In both series the pressurized nitrogen below broke through the slug as it approached the top of the column and dispersed the water. For both series, descent began with the mixture dispersed throughout the tube.

At the low initial Δp [34 kPa (5 psig)] the largest difference between the steam-voided and nitrogen-voided series emerges (Fig. 2c). As at the high initial Δp, in the nitrogen-voided series the slug remained a two-phase mixture while ascending, and the nitrogen above the slug, compressed by the slug's upward travel, vents downward through the slug and disperses the liquid, as the slug approaches the top of the column. In the steam-voided series, the steam, compressed above the slug, experiences some condensation and possibly vents down through the partially broken but essentially single-phase water without significant dispersion of the liquid. The single-phase slug reaches the top plate and more water accumulates there (from the wall film and droplets entrained in the wake) until it resembles a glass of water turned quickly upside-down before any draining. The water in the steam-voided series drained down the sides of the column and some globules fell down the middle. In the nitrogen-voided series the broken-up two-phase mixture does not accumulate at the top plate and descends as a dispersed mass of droplets. Yet even though the two series produced quite different behaviors, the pressure traces are quite similar. In fact for the two series the pressures at the top plate are the same except that for the condensible series the peak is slightly reduced. So, only for the low void, low pressure case does condensation have a noticeable effect. Condensation does appear to affect the collapse

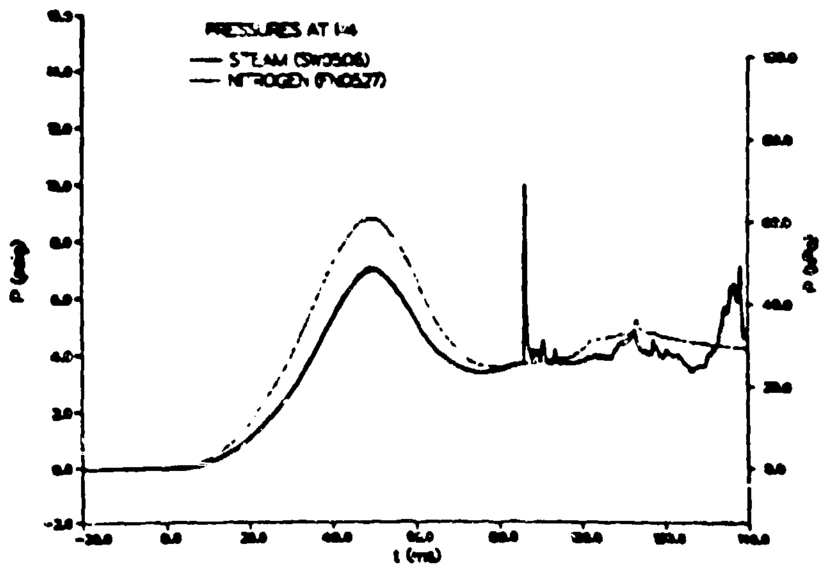


(a) Pressure traces for a 40% voided column with a 5-psi pressure pulse.

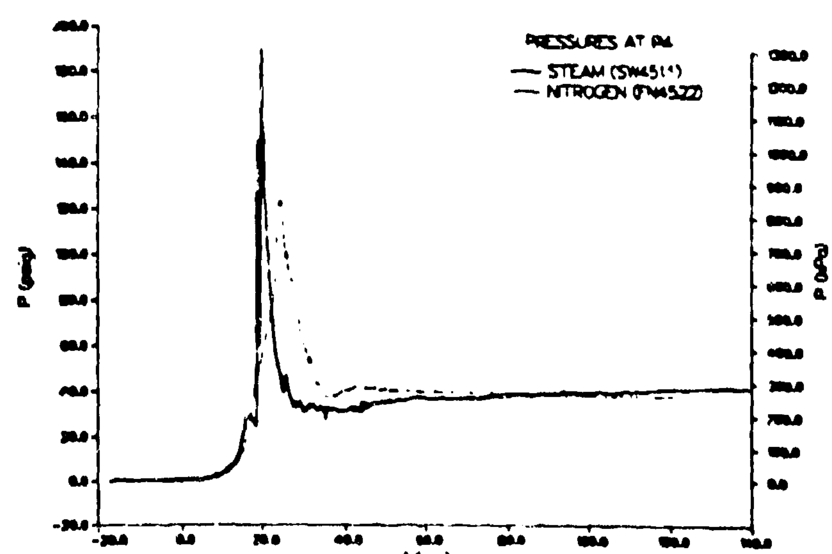


(b) Pressure traces for a 40% voided column with a 45 psi pressure pulse.

Fig. 2.
Comparisons of top-plate pressure histories for steam-voided and nitrogen-voided transient boilup experiments.



(c) Pressure traces for a 10% voided column with a 5-psi pressure pulse.



(d) Pressure traces for a 10% voided column with a 45-psi pressure pulse.

Fig. 2.
Comparisons of top-plate pressure histories for steam-voided and nitrogen-voided transient boilup experiments.

mode, while the pressures in the column are only affected slightly. For both series, descent began when the mixture was concentrated in the upper quarter of the tube.

Interpretation

Our interpretation of the "transient boil-up" experiments leads to some conclusions about collapse modes and reactivity ramp rates. First, we did not observe coherent slug fallback of the liquid in any of the experiments. The experiments suggest that the fuel-steel mixture should not fallback as a coherent slug. This effectively limits the reactivity ramp-rate contribution of a single subassembly to that typical of the ra -back or drainback modes. Second, the severity of a recriticality is influenced by the severity of the preceeding recriticality. Upon descent, the more dispersed a mixture is, the less will be its positive reactivity effect during fallback. Our experiments suggest that high-power bursts should disperse mixtures more than low-power bursts. The positive reactivity contribution from a falling fuel-steel mixture within a subassembly should therefore be less following a high-power burst than following a low-power burst. Third, condensation should play a minor role in the transient behavior of boiling subassembly pool. The condensation effect we observed was at the lower-void-fraction and lower-pressure-pulse regime. In this case, the liquid formed into the configuration of an "upside-down glass of water" at the top of the tube. Even as such, the liquid did not fall back as a coherent slug. SIMMER-II (6) calculational results also indicated that condensation had little effect. Therefore, we conclude that condensation of steel vapor in the transient behavior of subassembly pools should not have a significant effect on reactivity ramp rates.

MELTING WALL EXPERIMENTS

A number of research scientists, more than a decade ago, asserted that stable boiling pools would keep fuel sufficiently dispersed to prevent recriticalities (7). The stability of a boiling pool experiencing decay power levels depends on a stable power level in balance with a stable steel vapor generation rate. The melting wall experiments simulated the melting and entrainment of subassembly duct wall steel into an agitated boiling pool of fuel and steel. The mass, droplet sizes, mixing and equilibration rate of the entrained steel affect the steel vapor generation rate, subsequent dynamic behavior of the pool and the overall accident characteristics. If the relatively cold steel from the walls slowly equilibrates with the boiling fuel-steel mixture, the boiling and associated dispersed state may be maintained for a number of seconds, thereby producing a quasistatic and slowly progressing character for the accident. On the other hand, if equilibration is rapid, boiling ceases and pool collpase may cause a recriticality. The accident character then becomes dominated by recriticalities with associated highly transient, accelerated disruption.

In the experiment, a rectangular column (152-mm long, 152-mm wide, 914-mm high) of freon-113, agitated by nitrogen injected at the base of the column, simulates the boiling mixture of fuel and steel (Fig. 3). Two opposite walls of the column are transparent for visual observations, one wall is metal for instrumentation support, and one wall is a porous flat plate. Injection of water through the porous plate into the freon pool simulates a melting subassembly duct wall. This apparatus allows us to study the hydrodynamic characteristics of thin buoyant films exposed to agitated pools without the added complications of thermal effects such as melting, freezing, and vaporization. Thermal effects such as these may be important. However, the melting wall experiment was intended to provide basic information pertaining to the stability and entrainment of immiscible liquid films exposed to agitated pools.

The results obtained from the melting wall experiment fall into two general categories. First, visual observations of the interaction between the agitated flow field of the freon pool and the thin film of water on the porous plate provide some qualitative results. Second, direct measurements of pool and film characteristics provide a quantitative description of how the pool and film interact, at least at low levels of agitation.

Visual observations of the pool and film have been made with differing water injection rates and differing levels of agitation. At the bottom of the porous plate, where the liquid film is just starting to grow and is very thin, the film is very smooth and free of waves. Further up the plate, the film is characterized by a wave pattern. The transition region between the smooth and wavy structures is characterized by intermittent formation and growth of waves. This general picture of the film remains unchanged for most operating conditions.

The behavior of the film is more sensitive to agitation than to the water injection rate. A simplified linear stability analysis for a thin film has been developed for the case in which there is no agitation. The observed location of the transition region and wavelength compare well with the predictions of the theory. However, the location of the transition region is very sensitive to the level of agitation. When a very small stream of nitrogen bubbles is admitted along the wall opposite the porous plate at the bottom of the pool, the transition region moves down to a location at which the film is very thin.

At slightly higher levels of agitation, and with a nitrogen void fraction of less than 5% a portion of the film may be entrained into the pool. It is clear that the effect of pool agitation must be included in the description of the stability of the film to obtain reasonable results. Two important results obtained are: the stability of the water film is very

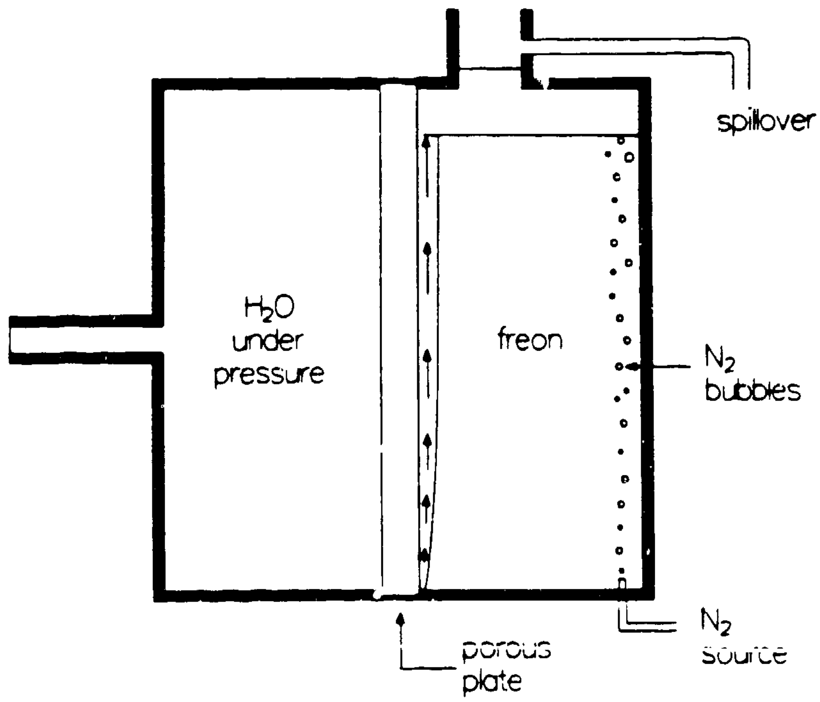


Fig. 3.
Melting wall experiment apparatus.

sensitive to the level of agitation, and for locally high levels of agitation in the pool, but with the nitrogen void fraction still less than 5%, complete entrainment of the water into the pool occurs with no film visible on the wall.

The stability of a boiled-up pool experiencing decay power conditions depends on stable steel vapor production. Because of the large amount of entrainment at relatively low void fractions observed in the experiments, we believe that it is unlikely that a pool could remain in a stable boiled-up configuration at decay power conditions. Rather, it appears more likely that the wall steel entrained will cause an initial decrease in the steel vapor production, and hence pool collapse. Previous SIMMER-II calculations have shown that decay power levels are insufficient to maintain pool boiling.(8) These two pieces of evidence argue against a stable boiling subassembly pool.

CONCLUSIONS

We have found the Los Alamos transition-phase experiments to be instrumental in providing a better understanding of the transition phase and pool behavior in the subassembly-pool subphase. We conclude from the transient boilup experiments that in the subassembly-pool subphase, elevated fuel should not fall back as a coherent slug, that the severity of a recriticality may be influenced by the severity of the previous one, and that steel vapor condensation should not significantly affect the transient behavior of the pool. From the melting wall experiments we conclude that because of rapid entrainment, a boiling pool would probably collapse, adding reactivity and promoting a neutronically active CDA behavior. The valuable data from the Los Alamos transition-phase experiments have provided us with significant insights and a better understanding of the transient behavior of boiling pools of molten fuel, molten steel and steel vapor in the transition phase of a core-disruptive accident in an LMFBR.

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