COO-2554-7
September 12, 1976

CRUST FORMATION AND MIXING IN A GASSY TWO-LIQUID POOL

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This work was performed for the U.S. Energy Research and Development Administration under Contract AT(11-1)2554

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Crust Formation And Mixing In A Gassy Two-Liquid Pool

Introduction

Molten fuel pools with an overlying layer of steel can be expected to form in various stages of the post-accident heat removal sequence, either on in-vessel or ex-vessel core catchers, or on a concrete or refractory floor beneath the reactor vessel. Since the boiling point of steel is approximately the same as the freezing point of UO_2, one can expect that a crust of frozen UO_2 may form at the interface. However, there may be significant bubbling through the interface, either by boiling within the fuel pool or by gas released from the concrete or sacrificial material. The objective of this work was to study the conditions for crust formation in a two-liquid layer pool with gas evolution. A unique physical phenomenon was observed, however, in the course of operation, consisting of the formation of 'ping-pong' balls of ice formed by water transported by the bubbles entering the cold hexane. These formed a raft of hollow spheres at the top of the hexane layer. By analogy, one might expect considerable mixing of UO_2 in the form of hollow spheres into the molten steel, with important consequences for the pool geometry and heat transfer.

Equipment

The apparatus consisted of 3" i.d. tubes joined together, a 12-in. section of 3-in. glass pipe, containing water, joined to an upper 24-in. section of 3-in. lucite tubing containing hexane. A vacuum jacket was fitted around the glass tube to prevent frost buildup as the hexane cooled. The hexane temperature could be reduced to $-30^{\circ}C$ by a refrigerant coil, and the water could be warmed by a electrical heater. The air could be bubbled in from a porous plate at the bottom or from a single tube. Five thermocouples were used to monitor temperatures in the two layers and above the pool. The porous plate produced bubbles of ½ to 5 mm diameter, depending on the air flow, while the tube produced bubbles of 5 to 10 mm diameter. The upper hexane was cooled by a refrigerant coil.

Two methods of cooling the hexane were used. At very low air flow rates, the hexane was cooled after pouring into the tube. However, as the air flow was increased, a significant amount of water would freeze on the refrigerant coil. Above 20 cc/min air flow, therefore, the hexane was cooled to -20°C before starting the air flow. The cooling coil was then taken out when the air flow was started and as the hexane warmed up measurements were made of the interface level and temperatures as a function of time.

Results

Crust Formation

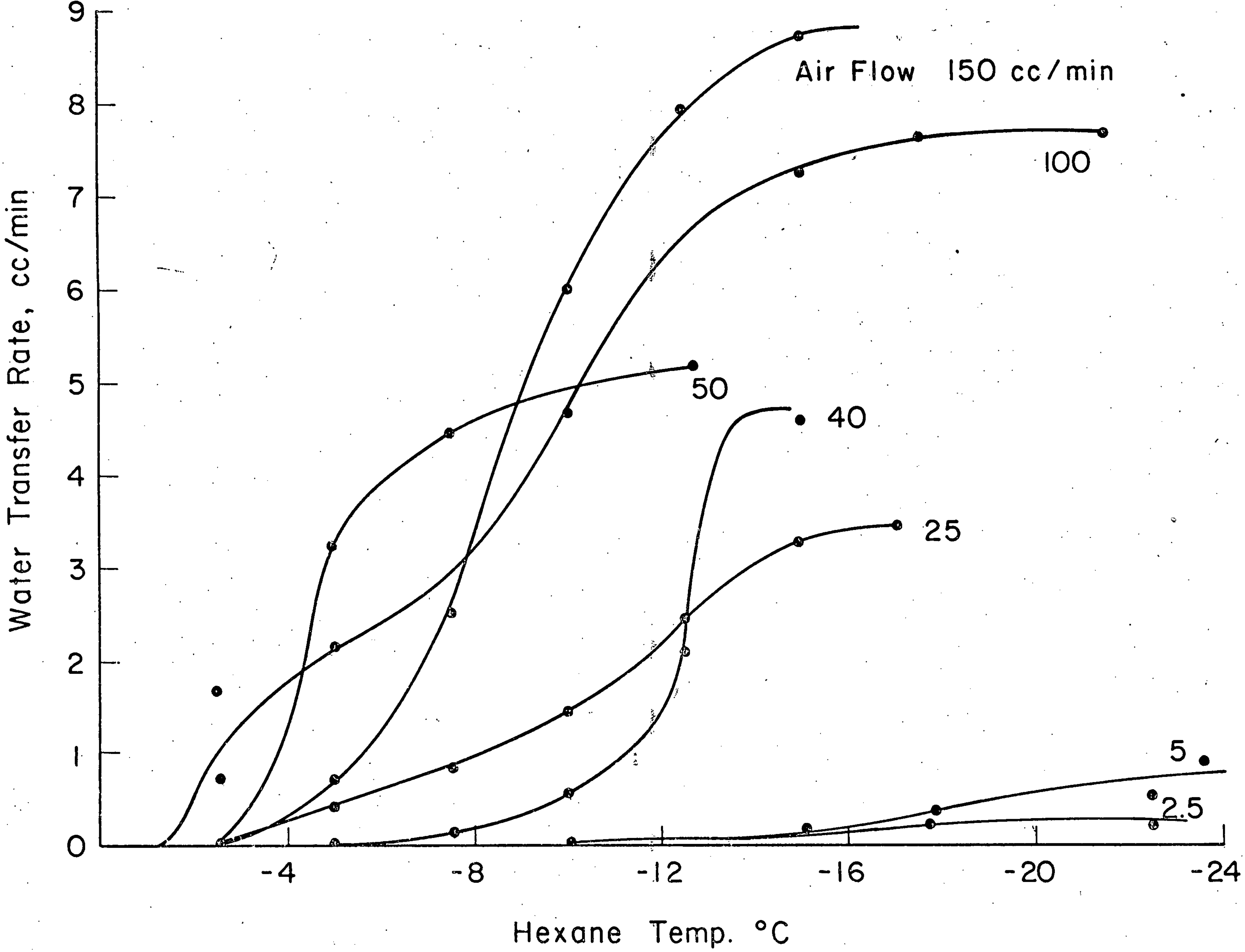
A crust of ice formed with no air flow below a hexane temperature of -5°C. The crust grew in patches as the hexane was cooled until finally it covered the interface completely. When an air flow was started, the crust formation was dominated by growth from the edges of the tube, and even very low air flow rates prevented the patches in the center of the interface from forming. At six bubbles per minute, crust patches in the center of the interface were observed at -25°C, but the crust formation was dominated by ice growth from the edges. The significant result here is that very low flows destabilize the crust strongly.

Shell Formation

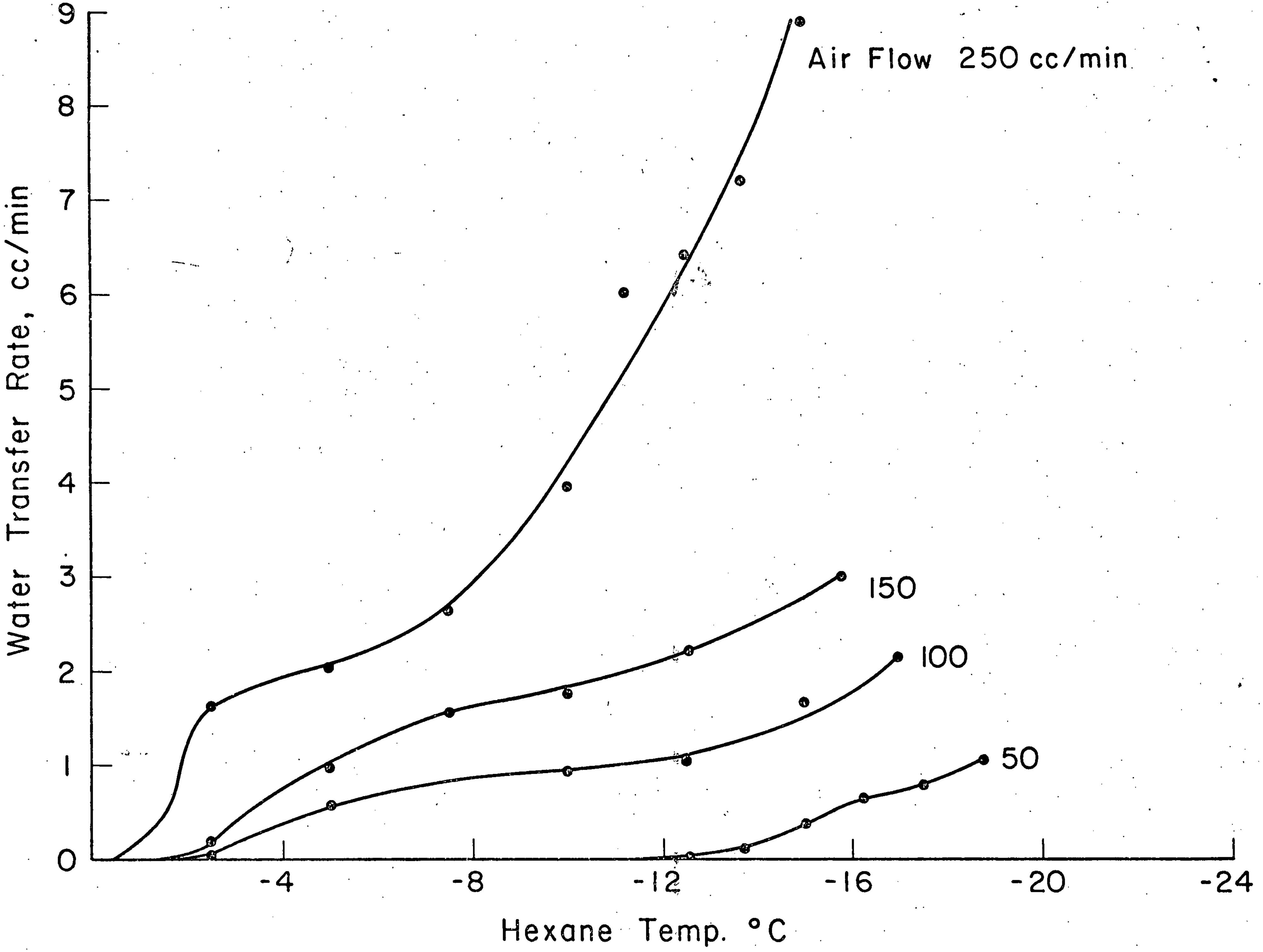
Air flows up to 250 cc/min were used to observe hollow ball or shell formation. Significant transfer of ice to the hexane was observed at these flow rates. Even when the temperature was not low enough to freeze the water as it was pushed through the interface by the bubble, water was carried upward with each air bubble. Under these conditions, when the air bubble reached the top of the hexane, the air broke free and the water dropped back through the hexane to the interface. When large bubbles ($d > 3$-4 mm) reached the interface there was a short time lag before the bubble continued to rise through the hexane. However, smaller bubbles, such as produced with a porous plate, stopped at the interface temporarily until enough coalesced to break free from the water interface. The longer the delay time at the interface, the less was carried upwards by the bubble. This would explain the lower water transfer rates observed for the porous plate, as opposed to the tube, for equal total flow rates. There was essentially no hesitation upon passing through the interface for bubbles greater than 5 mm. At hexane temperatures of 0-5°C, partial ice shells detached from the bubbles and fell down through the hexane. At -5°C to -10°C the ice shell was carried to the top of the hexane, but liquid drained down. At temperatures below -10°C, all bubbles were surrounded with continuous shells and below -15°C, the water transfer rate appears to become about constant, as might be expected. Figure 1 shows that with the porous plate the water transfer rate increases fairly linearly with temperature below -5°C, with the slope increasing with higher air flows. Figure 2 shows data for a single column of air bubbles, with a tendency to level off at a maximum transport rate with temperature is clearly seen.

Consider now a 20 cm. layer of fuel with 30 cm. steel above it, lying on a concrete floor. Supposing the concrete specific gravity to be 5, and its weight fraction of water to be 0.1, a layer of concrete only 1 cm. thick need to be dried out in order to intersperse the fuel-gas balls completely in the steel. If the concrete were intact, this would require less than 10^3 sec., but if spalling and cracking occurs, with a mean heat conduction distance of 0.1 cm., the time is reduced to 10 sec. Hence the stratified fuel-steel pool never exists, and a three (and possibly four) phase homogeneous mixture is formed immediately. This mixture is stable, since the boiling point of steel is about the same as the melting point of fuel. Hence the mixture acts as a natural heat pipe, excess heat being removed by boiling of the steel, which condenses in the colder region above the mixture, and then returns by gravity.

The heat transfer from the fuel is greatly improved by embedding fuel balls in molten steel, and the pool containment problem is similar to that in steel foundries.



Air Flow 150 cc/min
100
50
40
25
5
2.5
Water Transfer Rate, cc/min
0
1
2
3
4
5
6
7
8
9
-4
-8
-12
-16
-20
-24
Hexane Temp. °C


Water Transfer Rate, cc/min
0
1
2
3
4
5
6
7
8
9
-4
-8
-12
-16
-20
-24
Hexane Temp. °C
Air Flow 250 cc/min
150
100
50