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ANL/CP--75321

DE92 019591

Paper submitted to the Fifth International Topical Meeting on
Nuclear Reactor Thermal Hydraulics, American Nuclear Society,
Salt Lake City, Utah
September 21-24, 1992

*Work supported by the U. S. Department of Energy, Office of Technology Support Programs under Contract W-31-109-Eng-38.

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ABSTRACT

Experiments were conducted in which molten aluminum alloys were injected into a 1.2 m deep pool of water. The parameters varied were i) injectant material (8001 aluminum alloy and 12.3 wt% U-87.7 wt% Al), ii) melt superheat (0 to 50 K), iii) water temperature (313, 343 and 373 K) and iv) size and geometry of the pour stream (5, 10 and 20 mm diameter circular and 57 mm annular). The pour stream fragmentation was dominated by surface tension with large particles (~30 mm) being formed from varicose wave breakup of the 10-mm circular pours and from the annular flow off a 57 mm diameter tube. The fragments produced by the 5 mm circular jet were smaller (~10 mm), and the 20 mm jet which underwent sinuous wave breakup produced ~100 mm fragments. The fragments froze to form solid particles in 313 K water, and when the water was ≥343 K, the melt fragments did not freeze during their transit through 1.2 m of water.

An understanding of the mechanisms of pour stream breakup and quench in a liquid coolant is required in analyses of reactor accident scenarios involving melting of core materials and their downward migration into coolant in the vessel lower head region. If the fragments produced by the pour stream of molten core material are cooled to freezing, then a bed of solid particles are formed and the coolability analysis is dependent on the particle size and bed voidage. If the pour stream has not solidified as it passes through coolant, jet impingement heat transfer and attack by a melt layer must be considered. The purpose of this investigation was to characterize the jet breakup, quench and solidification of molten aluminum alloys in water over a range of conditions of importance to reactors using aluminum core materials. Molten aluminum is a low density material with a high surface tension and has a potential for chemical reaction with water. This makes it unique of the many materials used in jet breakup studies.[1,2]

EXPERIMENTAL

The parameters for these experiments were i) injectant material, ii) melt superheat, iii) water temperature, and iv) size and geometry of the pour stream (see Table 1). The pour stream was either cylindrical or annular (flow off the outer surface of a 57-mm diameter tube). The uranium-aluminum alloy mixture approximated that of the Al-U eutectic (13 wt% U-87 wt% A) with a melting point of 919 K. The water depth remained the same at 1.2 m for all of the experiments.

Interaction vessels of two diameters were used: 0.1124 m (steel) and 0.23 m (steel and acrylic). This variation in diameter was inconsequential in affecting the breakup mechanisms. A complete assembly including the melt furnace/injector with the 0.23-m interaction vessel is shown on Figure 1. Resistance heating was used for melting the aluminum alloys. A pneumatic cylinder mounted on the top cover of the furnace forced a cutter through a felt vitreous aluminosilicate fiber crucible for release of the aluminum-alloy melt. Injector tubes of various diameters and geometries which were interchangeable were located below the furnace. The injector tubes had straight through cylindrical bores with a right angle edge at the end. Motion pictures of the pour streams showed a full cylindrical jet flowing from these injector tubes. The furnace and the interaction vessels had provisions for argon gas purges. Provisions were made for gas sampling and measuring steam generation rates with a steam accumulator.

Chromel-alumel thermocouples were used throughout to measure temperature and for control and monitoring purposes. A Honeywell 1858 visicorder and a Honeywell 101 magnetic tape unit were used to record thermocouple and pressure transducer data. A NAC high speed video (equivalent to 200 fps) and two HYCAMS for motion picture filming at 500 fps were used to observe the experiments with the acrylic vessel.

RESULTS

Pertinent results from each experiment are summarized in Table 1. The first six experiments were conducted with the 0.124-m diameter steel interaction vessel, the seventh experiment with the 0.23-m steel vessel and the remaining four with the acrylic vessel. The fragmentation of the aluminum alloy melts was

Table 1. Aluminum Alloy Fuel Fragmentation Experiments

Experiment Number	Melt Composition	Jet Configuration	Melt Temp. (K)	Melt Mass kg	Melt Delivery Rate (kg/s)	Water Temp. (K)	Comments
1	8001	10 mm circular	929	0.5	0.15	373	Fragments did not freeze Ingot formed
2	8001	10 mm circular	929	0.5	0.15	313	~30 mm fragments
3	8001	57 m annular	958	0.5	0.30	313	~30 mm fragments 80% bed voidage
4	8001	10 mm circular	973	0.5	0.15	373	Fragments did not freeze Ingots formed
5	12.3 wt.-% U-87.7 wt.-%Al	10 mm circular	973	0.5	0.15	373	Fragments did not freeze
6	12.3 wt.-% U-87.7 wt.-% Al	10 mm circular	973	0.5	0.15	313	~30 mm fragments
7	12.3 wt.-% U-87.7 wt.-% Al	5 mm circular	973	0.5	0.04	313	~10 mm fragments
8	8001	10 mm circular	973	0.5	0.15	313	Varicose wave breakup
9	8001	10 mm circular	973	0.5	0.15	343	Fragments did not completely freeze
10	8001	20 mm circular	973	1.0	0.45	313	Sinuous wave breakup
11	8001	20 mm circular	973	1.0	1.2	343	Sinuous wave breakup

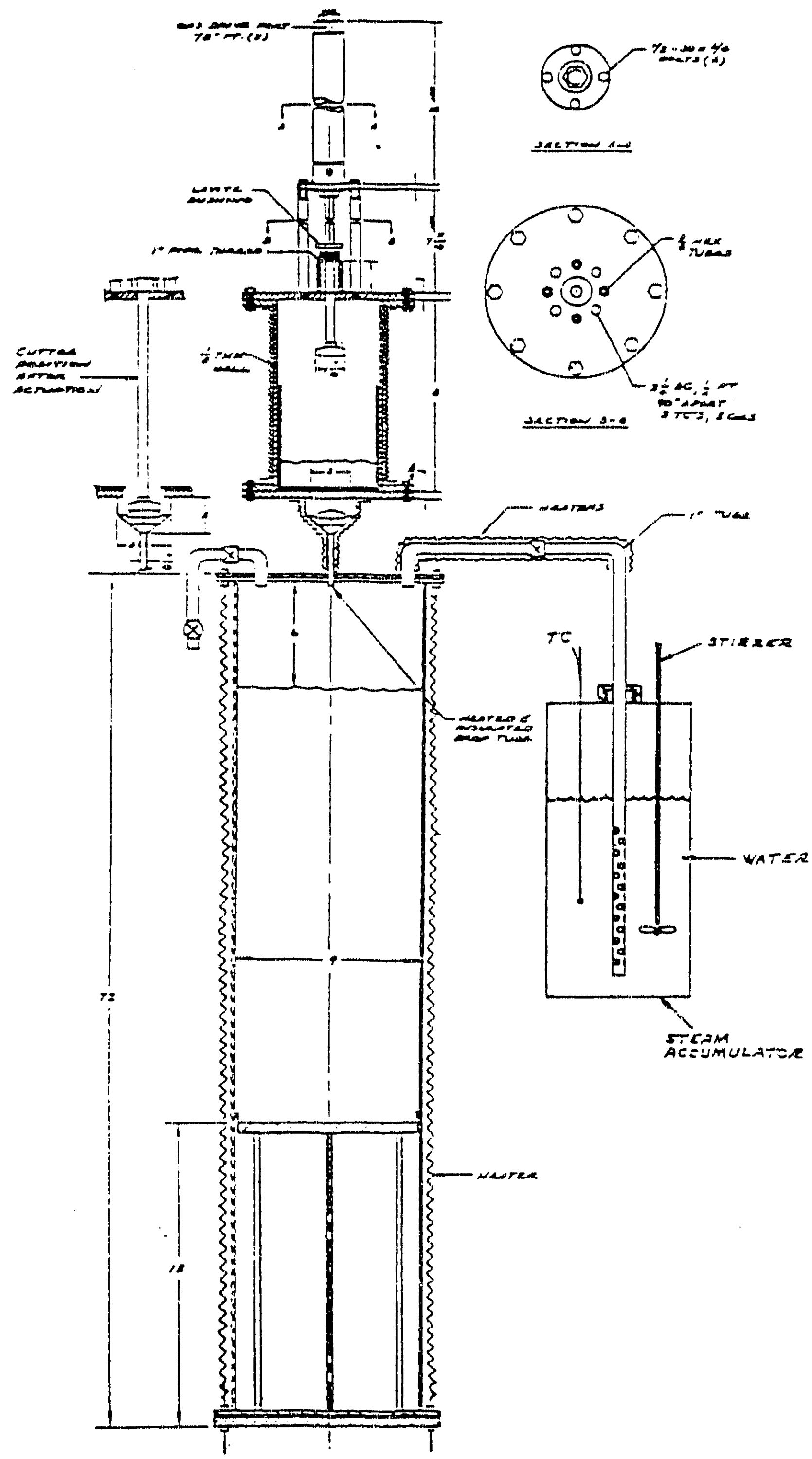

Figure 1. Assembly for Fragmentation Experiments

dominated by capillarity. The fragments were all quite large (>10 mm), and there was no fine particle formation by surface erosion from any of the jets. The 10 mm circular jets were observed to undergo varicose wave growth which led to breakup and formation of ~30 mm fragments in 313 K water. In Experiment 8, where the water surface was 180 mm below the end of the drop tube, the 10 mm jet had practically broken up from capillarity before entering the water. In the subsequent experiments (9 to 11) the drop distance to the water surface was reduced to 75 mm to assure breakup by interaction with the water.

The ratio of the length of the jet, L, at breakup in the water to the diameter of the jet, D, for the four experiments in the acrylic vessel are given on Table 2. The L/D ratio of 4 for Experiment 8 is quite low since the jet had practically broken up during its 180 mm fall in the atmosphere above the water. However, with reduction of this drop distance to 75 mm the L/D ratio increased to 9. Increasing the jet diameter to 20 mm from 10 mm in Experiment 10 had essentially no effect on L/D (10). Increasing the velocity in Experiment 11 by pressurizing the furnace/injector with argon to 5 m/s increased the L/D ratio to 14.

The distance at which the jet was observed to be beginning varicose breakup in the argon atmosphere above the water in Experiment 8 was shorter than that predicted by previous correlations. The ambient Weber number, We_a, for this case was 0.12. The jet flow should therefore be in the Rayleigh Regime.[1] The Grant and Middleman[3] correlation based on organic solutions in water is:

$$L/D = 19.5 \left\{ We_j^{0.5} + 3 \frac{We_j}{Re_j} \right\}^{0.85} . \qquad (1)$$

This correlation predicts an L/D ratio of 180 or a breakup distance of 1.8 m. Levich[4] related the length of jet breakup, L, to initial jet velocity, V_o, by:

$$L \approx V_o t = 8.46 \, V_o \sqrt{\frac{\rho \, D^3}{8 \, \sigma}} . \qquad (2)$$

Table 2. Observed Breakup Lengths in Water

Experiment Number	Jet Diameter, mm	Observed L/D	Jet Velocity	We_j $\frac{\rho_j V_j^2 D}{\sigma}$
8	10	4	2.8	186
9	10	9	2.5	165
10	20	10	2.5	330
11	20	14	5.0	1319

This correlation predicts a breakup length of 0.38 m which is closer to an observed distance of slightly greater than 0.18 m.

Because of the high temperature of the aluminum alloy melt, the breakup length in the water is affected not only by the water but by the steam generated. The steam layer surrounding the jet and its fragments appeared to be thin with relatively small bubble formation. Epstein and Fauske[5] obtained the following equation for a jet blanketed by the vapor of the liquid in which it was injected:

$$L/D = \frac{\sqrt{3}}{2} \left(1 + \frac{\rho_v}{\rho_j}\right) \left(\frac{\rho_j}{\rho_v}\right)^{1/2} . \tag{3}$$

Equation 3 is for an essentially infinitely thick vapor blanket. For a very thin vapor blanket

$$L/D = \frac{\sqrt{3}}{2} \left(1 + \frac{\rho_1}{\rho_j}\right) \left(\frac{\rho_j}{\rho_1}\right)^{1/2} . \tag{4}$$

Epstein and Fauske model predicts an L/D of 2 for a very thin vapor blanket and an L/D of 55 for a thick vapor blanket. The observed L/D/s (Table 2) are within this range.

The particles were irregular in shape with a generally smooth surface and a hollow interior. Figure 2 shows some typical fragments in the 15 to 25 mm size range, and Figure 3 is a photograph of fragments in the 35 to 60 mm size range from Experiment 3. The mechanism of formation of hollow interiors in the fragments has not been definitively determined. It could be simply drainage of the molten core through an opening in the solidified crust of the fragment. Liquid water and/or steam then entered the internal void of the fragment. In some cases the fragments burst apart from the internal steam pressure.

The size of the fragments were related to the pour stream diameter. The fragments averaged about 10 mm in size from the 5 mm pour stream (Figure 4), about 30 mm from the 10 mm circular pour stream and from the pour streams produced by annular flow off a 57 mm tube, and about 100 mm from the 20 mm circular pour stream (Figure 5). The voidage both internal and interstitial for the particle beds was 0.8. The density of individual particles varied from 1400 to 2300 kg/m^3. An estimate of the internal voidage can be obtained by comparing this to an aluminum density at room temperature of 2700 kg/m^3.

The large size of the fragments resulted in low quench rates. In the cases where the water temperature was 313 K the fragments had solidified before they reached the bottom of the 1.2 m deep pool. When the water was 343 K or greater the fragments were not frozen and agglomerated at the bottom of the pool. In the experiments where the water was at 373 K a molten pool was formed which froze into a dense ingot (Figure 6). The molten pool did not fuse with the aluminum base plate. The solidified ingot was easily removed after the experiment. In fact, the maximum temperature recorded on the surface of the base plate was only 423 K. Either the base thermocouples were located under a pocket of vapor under the molten aluminum pool or a layer steam insulated the entire melt layer from the base plate. Figure 7 is a photograph of the bottom of the ingot formed in Experiment 4.

Steam was generated off the top surface of the molten aluminum layer on the base of the interaction vessel at the rate of 4 g/sec (Experiment 5 with saturated water). This is equivalent to a heat flux of 7.5×10^5 W/m^2. The

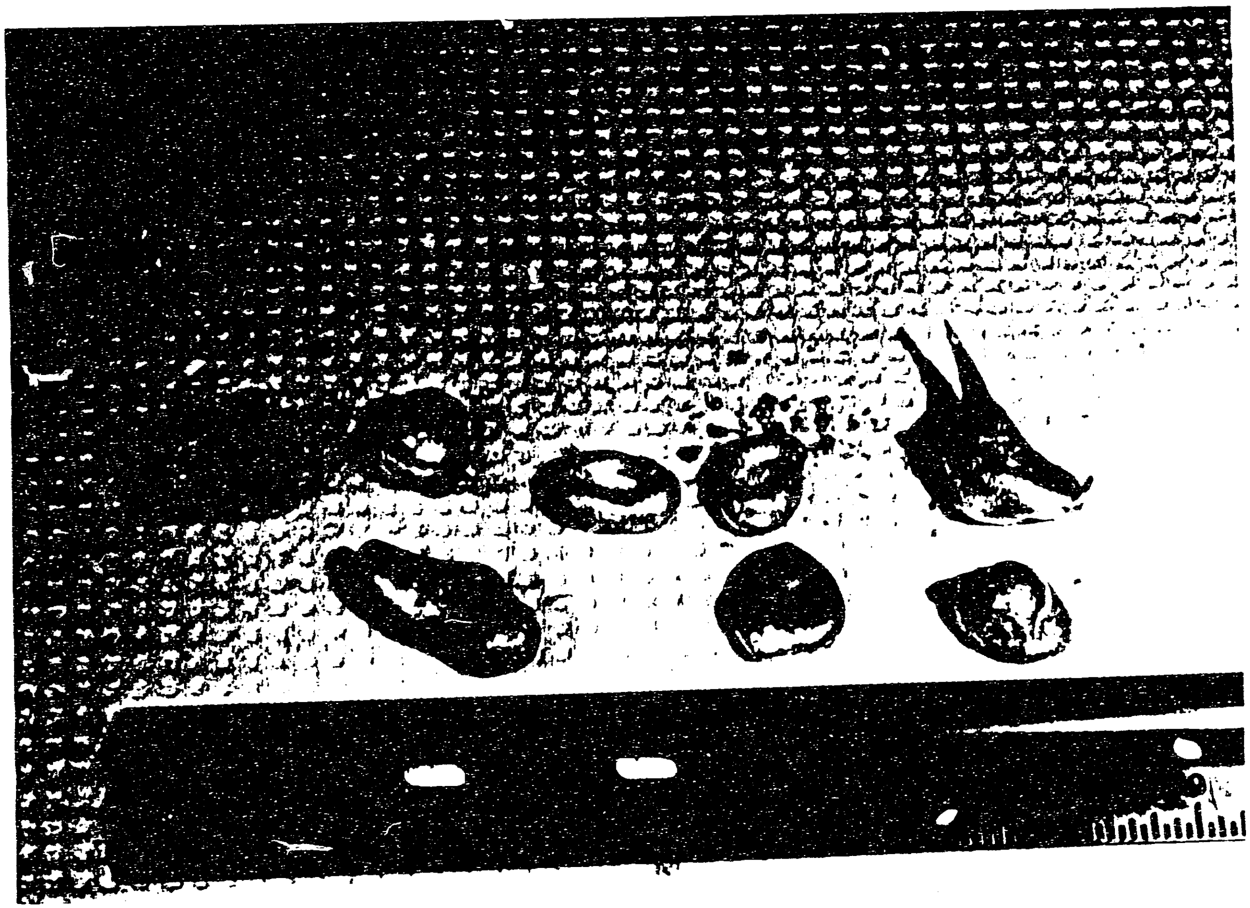

Figure 2. Typical Fragments in 15 to 25 mm Size Range

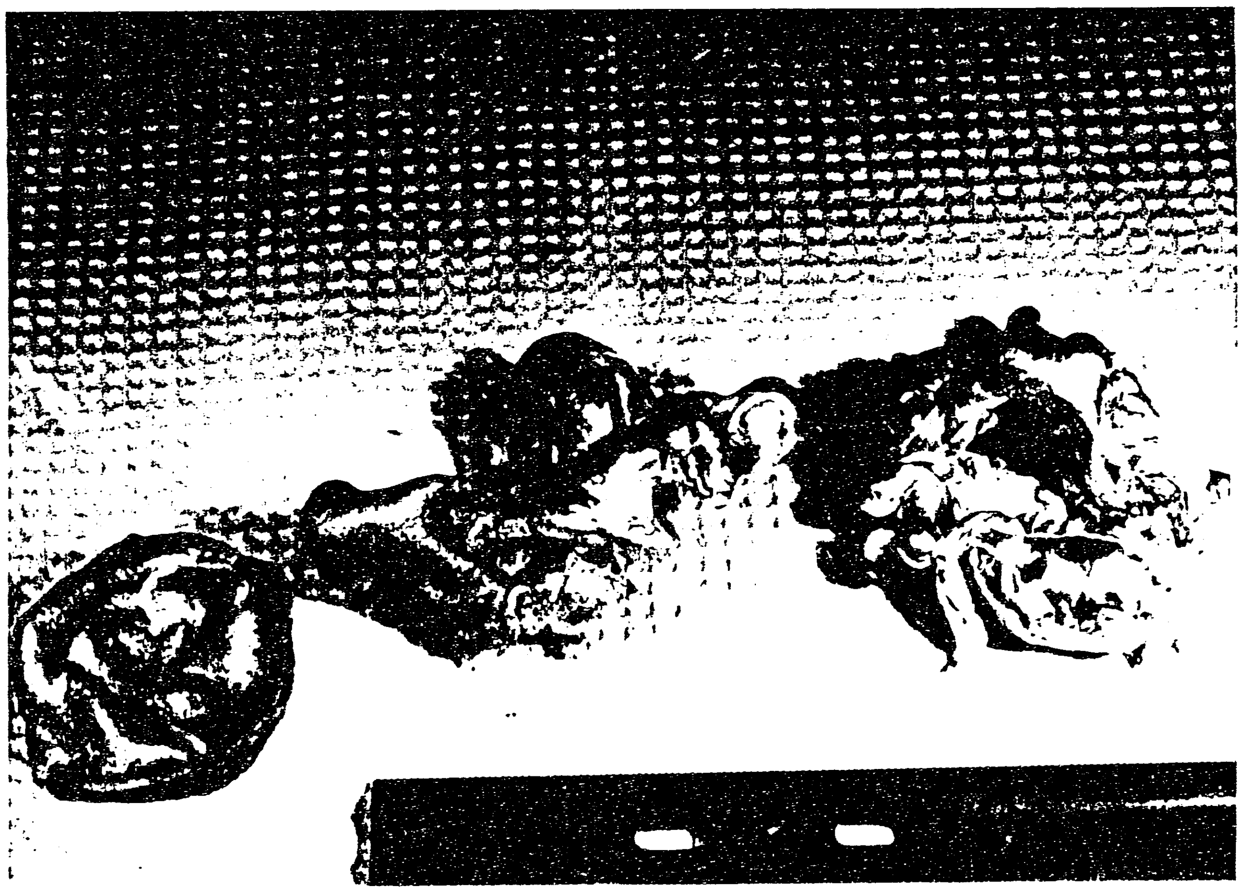

Figure 3. Fragments in the 35 to 60 mm Size Range

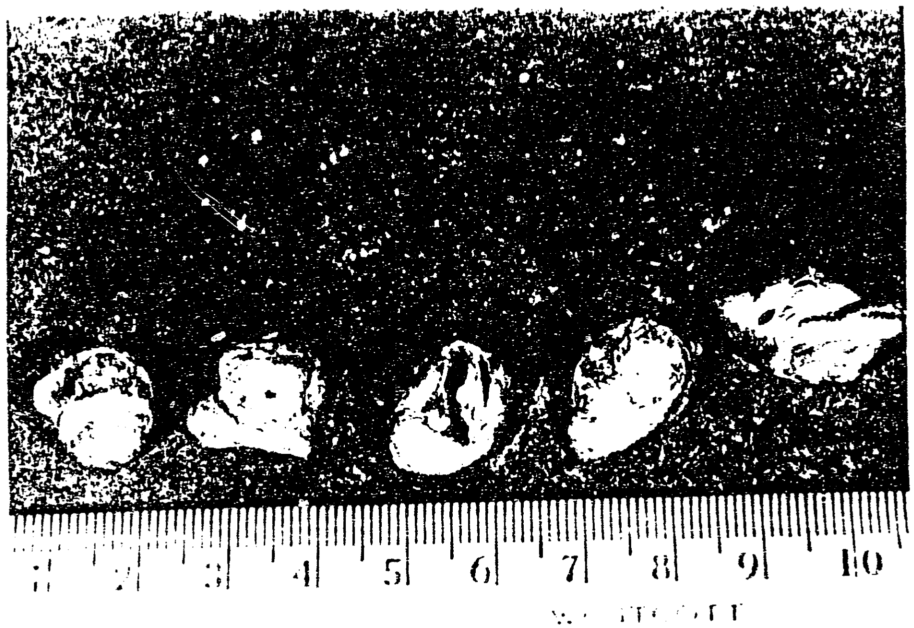

Figure 4. Representative Particles Produced by 5-mm Pour Stream (Experiment 7)

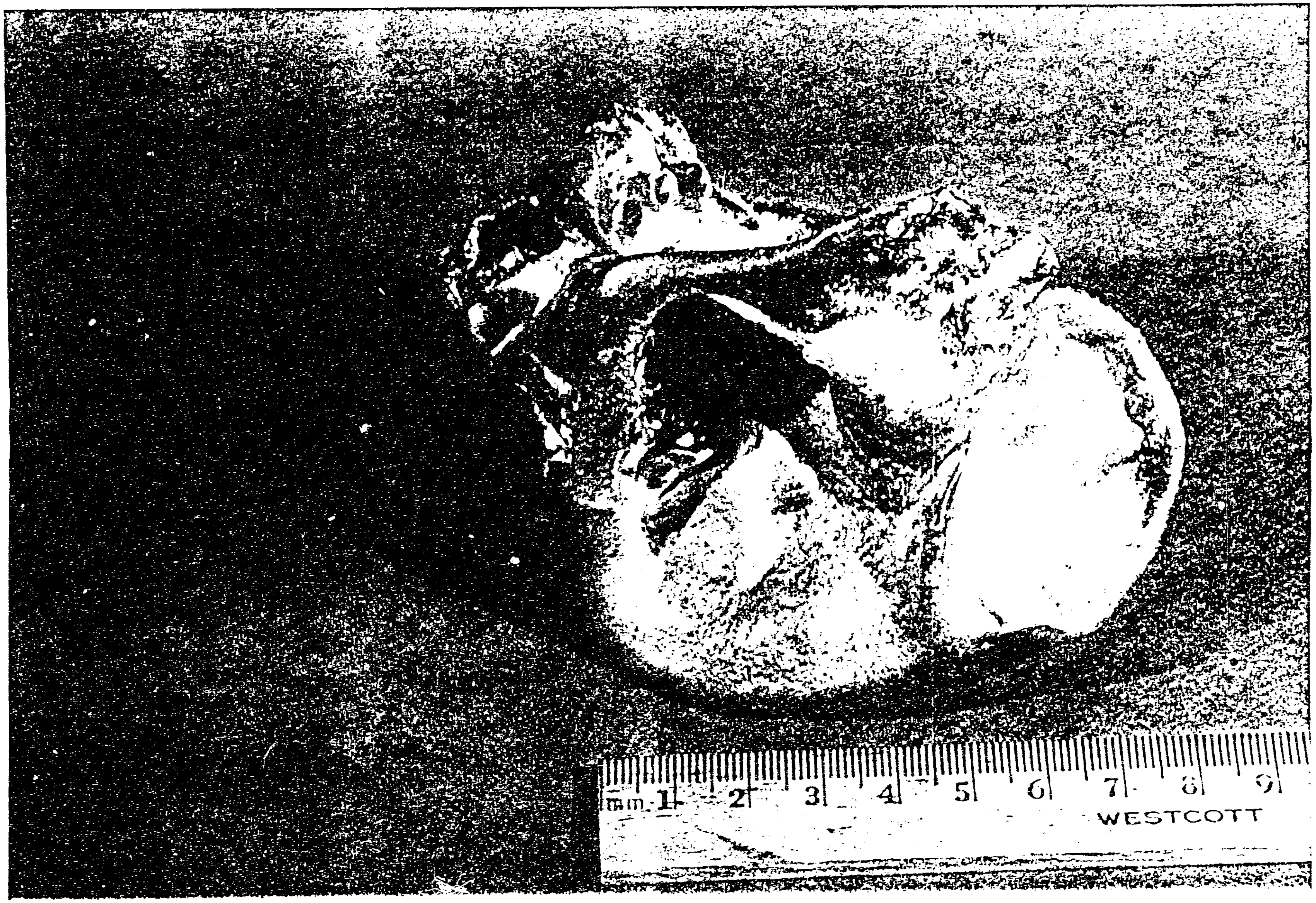

Figure 5. Particle Produced by 20 mm Pour Stream (Experiment 10)

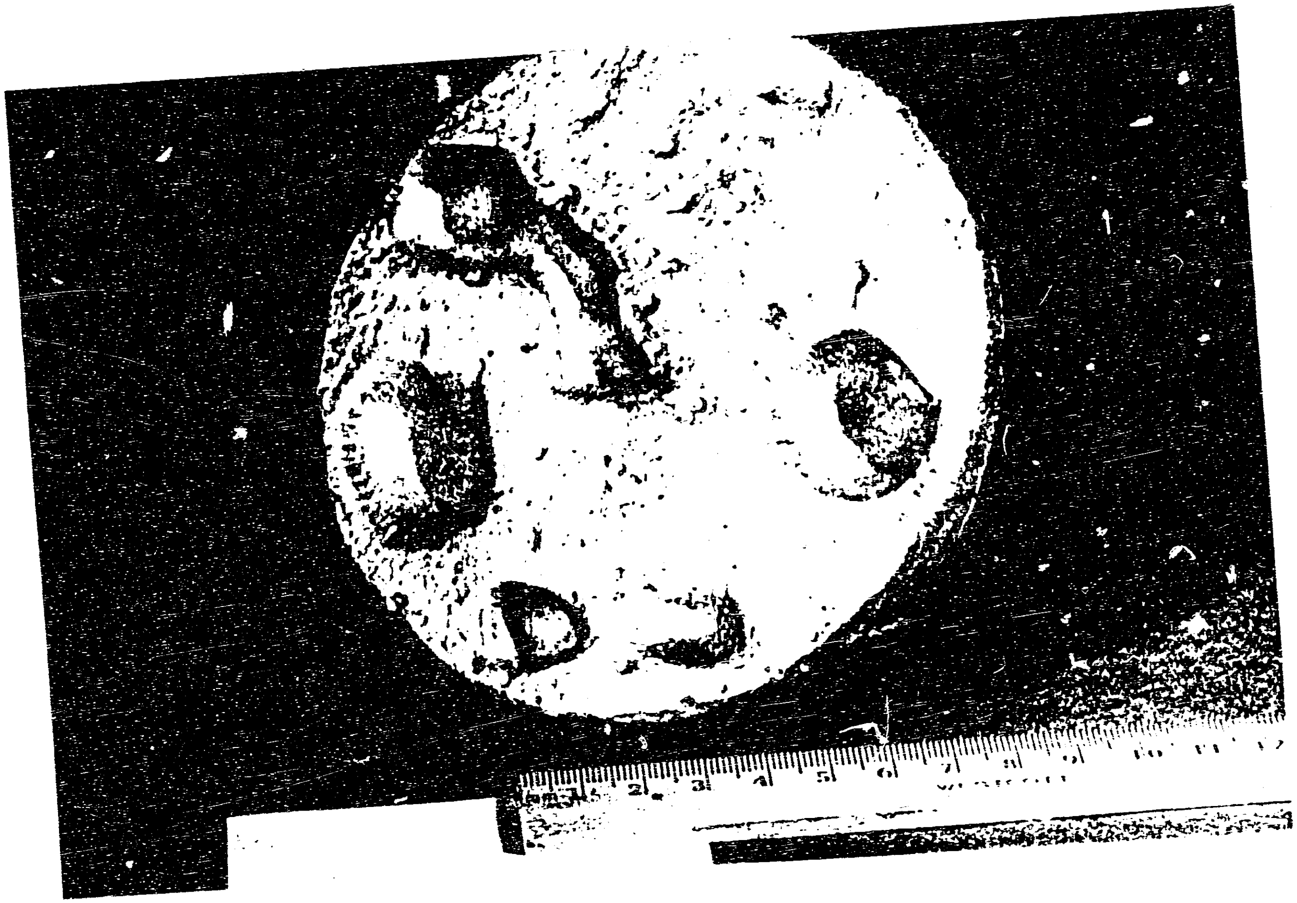

Figure 7. Bottom of Ingot Formed in Experiment 4

steam generation rate was 10 g/sec initially after the pour in Experiment 5 which is equivalent to a heat flux of 4×10^5 W/m^2 assuming heat transfer from settling fragments of 30 mm diameter.

In all of the experiments the melt-water interactions were benign. There were no rises in pressure or pressure spikes indicated by the pressure transducers. Hydrogen concentrations of 0.18 to 1.09 vol % in gas samples from the plenum indicate some hydrogen generation from an aluminum-water reaction. If it is assumed that these concentrations in the plenum above the water are representative of all hydrogen produced, the extent of aluminum reaction with water would be in the range of 0.02 to 0.07%.

SUMMARY

There appeared to be a very thin layer of steam blanketing on the pour stream and fragments. This resulted in low L/D ratios which ranged from 4 to 14 for breakup within the water phase. While these values for L/D would be expected for jet breakup in water, the 10 mm jet appeared on the verge of breakup after falling through 180 mm of argon before entering the water in Experiment 8. The low L/D in argon as well as the large fragment sizes is evidence of the effect of aluminum alloy high surface tension. The fragments produced by a 5 mm pour were about 10 mm in size; a 10 mm pour produced 30 mm fragments; and the 20 mm pour produced 100 mm fragments. The 20 mm pour stream experienced sinuous wave breakup, and the 10 mm pour stream underwent varicose wave breakup.

The fragments were froze when they reached the bottom of the 1.2-m deep pool of 313 K water. The voidage both internal and interstitial was 0.8. However, with the water ≥343 K the fragments remained molten at the bottom of the pool and eventually frozen to form an essentially solid ingot.

Hydrogen concentrations of 0.18 to 1.09 vol % in gas samples from the plenum indicate some hydrogen generation from an aluminum-water reaction. The melt-water interactions were benign. There were no rises in pressure or pressure spikes indicated by the pressure transducers in any of the experiments.

NOMENCLATURE

D	Initial stream diameter
L	Breakup length
V	Melt stream entry velocity
V_o	Initial melt stream velocity
Re	Reynolds number, $\frac{VDP}{\mu}$
We	Weber number, $\frac{\rho V^2 D}{\sigma}$
μ	Viscosity
ρ	density
σ	Surface tension

Subscripts

a	ambient fluid
j	jet
l	ambient liquid
v	ambient vapor

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9 /29/92