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EXPERIMENTAL STUDIES OF
THE EFFECT OF FLOW RESTRICTIONS IN
A SMALL ROD BUNDLE UNDER EMERGENCY
CORE COOLANT INJECTION CONDITIONS

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During a major loss-of-coolant accident in a pressurized water reactor, cladding overheating in portions of the core is likely to occur and to result in the strength of the fuel cladding being reduced such that gross distortion follows. Since the distortion of the cladding is outward because the internal rod pressure exceeds the external pressure, it tends to block the subchannel flow area. Reduction in subchannel flow area subsequently results in resistance to flow of the emergency core coolant which is employed to prevent further core overheating. A major concern, then, is whether the subchannel flow area reduction will prevent the emergency core coolant from reaching upper core regions in quantities sufficient to prevent continuing heatup and fuel melting.

One of the objectives of the Pressurized Water Reactor -- Full Length Emergency Core Heat Transfer (PWR-FLECHT) program is to investigate the effect of partial and total subchannel flow blockage on the capability of emergency core coolant to remove heat from those portions of the fuel above the blocked area⁽¹⁾. Several experiments have been conducted, and have demonstrated that no loss of emergency core coolant effectiveness results from large subchannel flow area reductions.

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In fact, under certain conditions, the effectiveness of the emergency coolant was shown to be enhanced in certain areas when flow blockage was introduced into the simulated fuel pin array⁽²⁾. The experimental program described herein was undertaken in support of the PWR-FLECHT program. The specific objectives were to:

- (1) Determine by more extensive investigations whether the preliminary results of the PWR-FLECHT flow blockage tests are valid;
- (2) Determine whether a more nearly typical cladding ballooning geometry than that used in the PWR-FLECHT tests would produce different test results;
- (3) Obtain photographic information relating to the flow regimes occurring at and near a blocked region;
- (4) Determine whether bypass flow (emergency coolant flow which is diverted around the blocked area) is a significant factor in cooling the upper core regions.

The experimental equipment utilized in the program consisted of nine electrically heated rods assembled into a three-by-three array and enclosed in a transparent tube. The rods had a 30-in. heated length and consisted of a Nichrome heating element, boron nitride insulation, and stainless steel cladding. These heaters were identical in construction to those used in the PWR-FLECHT tests.

Thirty-six tests were conducted over wide ranges of conditions.

I. APPARATUS AND PROCEDURE

Figure 1 illustrates the basic components of the equipment used in the experiment. Demineralized emergency cooling water is pumped through a flowmeter into the test array of heated rods which are enclosed in a transparent tube. A sight glass is attached to the inlet plenum of the array and extends upward along the array as

shown in the figure. The sight glass provides a means of calculating the pressure buildup in the plenum below the nine-pin array during emergency coolant injection.

The six configurations tested during the program are shown in Figure 2. The outside diameter of the rods and the rod spacing are identical to those currently employed in large pressurized water reactors. Configuration (a) illustrates the unblocked case. Configuration (b) shows the arrangement used to test the effect of no bypass flow at the mid-elevation of the test section. For this configuration a thin steel plate with a square portion removed from the center was placed around the array at the 14.5-in elevation (indicated by the crosshatched area of Figure 2). Configuration (c) shows the array with sleeves attached to the rods to simulate cladding ballooning. Configuration (d) combines the arrangements of Configurations (b) and (c) such that flow through the array is partially blocked and bypass flow is eliminated. Configuration (e) illustrates the array blockage tested with a thin steel plate at the 14.5-in. elevation, and Configuration (f) is the same arrangement with the plate extended out to the wall of the transparent tube to eliminate bypass flow around the blocked region.

Figure 3 illustrates the sleeves used for Configurations (c) and (d) of Figure 2. These sleeves were patterned after actual ballooned areas which occurred on Zircaloy tubing tested under simulated reactor core heatup conditions⁽³⁾. Thirteen thermocouples were used to monitor the temperature of the heaters. Twelve of the thermocouples were mounted on the outside surface of the heaters, and one was attached to the inside surface of the central heater. The locations of the thermocouples are indicated in Figure 4. The thermocouples are identified by denoting the rod first and the elevation second. For example, TC-5-20 is the thermocouple located 20 inches from the bottom of the heated length of Rod 5. The external and internal thermocouples at location 5-15 are designed TC-E5-15

and TC-I5-15, respectively. All thermocouple readings were recorded on magnetic tape. In addition, TC-I5-15 and TC-E5-15 were attached to a strip chart recorder and visually monitored during the tests.

Flow was monitored for Tests 14 through 36 by a turbine flow meter and recorded through use of a strip chart recorder. The water level in the plenum below the test section was monitored by high-speed motion pictures taken through the sight glass. Pressure versus test time was then computed from the information obtained from the motion pictures.

To start a test, low power was applied to the heaters to establish gradual heatup. TC-E5-15 was continuously monitored and used as the controlling temperature during the test sequence. When a temperature of about 1000°F was reached at TC-E5-15, the power was increased to 1 kW/ft per heater (22.5 kW total) which corresponds to the initial decay-heat power level occurring at the time of reactor shutdown following a loss-of-coolant accident. Flooding was initiated by starting the pump when TC-E5-15 indicated a temperature of either 1600 or 1800°F; both temperatures were used for each configuration. The flooding rate was maintained constant throughout each test, and corresponded to a filling rate of 2 in./sec in the tube when the nine-pin bundle was unheated. Full power (1 kW/ft) was maintained until quenching (return to saturation temperature) was attained at TC-E5-15. In some cases, the test continued until quenching occurred at the 25-in. elevation as determined by a visual indication of the termination of boiling at the heater surface. A typical temperature history is illustrated in Figure 5.

Table 1 lists the test sequence with appropriate information identifying the features of each test.

II. TEST RESULTS

Figure 6 shows the temperature-time relationships for Configurations (b), (d), and (f) (no bypass flow) at TC-5-25. Except for the changes in configuration,

TABLE 1 - Run Sequence

<u>Test (a)</u>	<u>Initial Temperature (°F)</u>	<u>Motion Pictures</u>	<u>Configuration (b)</u>
2	1600	X	a
3	1800	X	a
6	1600	X	c
7	1800	X	c
8	1600		c
9	1800		c
10	1600		c
11	1800	X	c
12	1600	X	c
13	1800		c
14	1600		f
15	1800		f
16	1600		f
17	1800		f
18	1600	X	f
19	1800	X	f
23	1600		f
24	1800		f
25	1600		f
26	1800		f
27	1600	X	b
28	1800	X	b
29	1600		b
30	1800		b
32	1600		d
33	1800	X	d
34	1600		d
35	1800	X	d

(a) Missing numbers indicate aborted tests.

(b) Configurations are identified in Figure 2.

all test conditions are identical. Figure 7 shows the temperature behavior immediately after flooding at the TC-5-25 location for Configurations (a), (c), and (e) (bypass flow). Figure 8 illustrated the temperature profiles of the central heater (Rod 5) during Test 28 (Configuration (b), no bypass flow) for various times with respect to distance from the bottom of the rod. The turnaround time (the time at which the temperature rise ceases) occurs at about one second intervals for each 5 inches of heated length. The quenching front, as indicated by Figure 8, moves 5 inches in 14 to 23 seconds, moving slower as it nears the top of the rod. Figure 9 is a photograph taken at the instant that temperature turnover was recorded at the TC-5-14 location in Test 19 (Configuration (f), no bypass flow). Temperature turnover at TC-5-15 has not occurred.

One technique for determining the effectiveness of emergency coolant for various configurations is to compare the temperature rise which occurs after initiation of flooding. Figures 10 through 13 illustrate the temperature rise as a function of rod elevation for the various configurations for 1600 and 1800°F temperatures at the initiation of flooding. At each location the temperature rise was the average which occurred for the tests conducted at a given set of conditions. For identical tests, a difference of as much as 20°F in temperature rise was noted.

In general, the results indicate that blockage, whether bypass flow was allowed or not, did not significantly change the thermal response of the bundle. In addition, different types of blockage (sleeves or plate) did not result in any marked difference in thermal response. However, the following trends were noted:

- (1) For the configurations in which bypass flow was allowed, Configurations (a), (c), and (e), the blockage tended to cause a larger temperature rise as indicated in Figures 10 and 11. This rise was more pronounced in the 1600°F tests (Figure 10), in which a difference of 45°F was recorded at the 20-in. elevation for Configurations (a) and (c).

- (2) For the configurations in which bypass flow was prevented [Configurations (b), (d), and (f)] the blocked arrays tended to produce smaller temperature rises.
- (3) For the configurations in which bypass flow was prevented, the higher (1800°F) initial temperature tests tended to produce smaller temperature rises.

Figure 14 illustrates the pressure buildup as computed from the movies obtained through the sight glass attached to the entrance of the bundle. The region of temperature turnaround is indicated. The boundaries of this region are defined by the shortest turnaround time (3.5 seconds at the TC-5-5 location) and the longest turnaround time (6.5 seconds at the TC-5-25 location). All tests in which bypass flow was eliminated and which had 75% blockage [Configurations (d) and (f)] exhibited a pressure buildup generally similar to that of Test 33 (dashed line of Figure 14). All other configurations demonstrated a pressure buildup similar to that of Test 3. The buildup in the cold system is also shown on Figure 14. This pressure buildup, which would occur if flooding occurred while the pins were unheated, corresponds to the flooding rate of 2 in./sec used for all of the tests.

III. CONCLUSIONS

The experimental results lead to the following conclusions:

- (1) Severe blockage in small pin arrays does not have serious effect on the capability of emergency coolant to cool the rods under simulated postblowdown loss-of-coolant accident conditions.

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- (2) The geometry of the blocked region (plate versus sleeves) is not a significant factor in the cooling process.
- (3) The cooling process appears to be characterized by a front consisting of many various-sized water droplets (Figure 9) which move up the bundle at a velocity of about 5 in./sec. This front is produced after about the first three inches of the heated section are immersed. The front represents an effective heat removal process.
- (4) Bypass flow has an effect on the cooling process. The dispersed water flow of the front apparently had a tendency to migrate outward to the cooler walls of the transparent tube, since elimination of bypass flow without subchannel blockage did result in an increase in the temperature rise (Figure 11) and 13, Configuration b) above the bypass flow blockage.
- (5) The pressure buildup in the region below the bundle was always less than the equivalent head produced from cold flooding for all configurations except Configurations (d) and (f). As blockage becomes more severe, greater pressure buildup can be expected as indicated by the results of Test 33 shown in Figure 14.

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Experimental Equipment

FIGURE 1.

TEST CONFIGURATIONS

(a) BYPASS FLOW- NO BLOCKAGE

(b) NO BYPASS FLOW-NO BLOCKAGE

(c) BYPASS FLOW-SLEEVE BLOCKAGE (75%)

(d) NO BYPASS FLOW-SLEEVE BLOCKAGE (75%)

(e) BYPASS FLOW-PLATE BLOCKAGE (75%)

(f) NO BYPASS FLOW-PLATE BLOCKAGE (75%)

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FIGURE 2.

Sleeves Used to Simulate Cladding Ballooning

FIGURE 3.

Instrumented Heaters with the Location of Both Sleeve and Plate Blockage Indicated

FIGURE 4.

FIGURE 5.

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FIGURE 6.

Temperature Behavior at TC5-25 (enlarged view)

FIGURE 7.

Temperature Profile for Selected Times (Pin 5, Test 28)

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FIGURE 8.

Water Droplet Front Reaching The Plate Blockage (Configuration ' 2 ')

FIGURE 9

Turnaround Temperature vs Distance from Configurations a,c and e
(bypass flow) at 1600 °F

FIGURE 10.

Turnaround Temperature vs Distance from Configurations a,c and e
(bypass flow) at 1800 °F

FIGURE 12.

Turnaround Temperature vs Distance from Configurations b,d and f
(no bypass flow) at 1600 °F

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FIGURE 12.

Turnaround Temperature vs Distance from Configurations b,d and f
(no bypass flow) at 1800 °F

FIGURE 13.

FIGURE 14.

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