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MASTER

**RESPONSE OF A SIMULATED
BWR FUEL BUNDLE
COOLED BY FLOODING
UNDER LOSS-OF-COOLANT
CONDITIONS**

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PREPARED FOR IDAHO NUCLEAR CORPORATION
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COOLED BY FLOODING
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ABSTRACT

The cooling effectiveness of bottom-flooding a BWR fuel assembly during loss-of-normal coolant has been investigated. Simulated loss-of-coolant transient tests were conducted with a full-scale electrically heated bundle at atmospheric pressure. The temperature response of the bundle was obtained as a

function of power level, initial temperature, and coolant flow rate. The results are consistent with those obtained by other investigators, and they demonstrate that this cooling method is effective as a standby cooling system to protect a reactor core in the unlikely event of a loss-of-coolant accident.

1. SUMMARY

An investigation of bottom-flooding heat transfer effectiveness was conducted by the Core Development Subsection of the Atomic Power Equipment Department (APED) of the General Electric Company at San Jose. The testing was funded by the Atomic Energy Commission. Technical program management was provided by the Idaho Nuclear Corporation. Simulated loss-of-coolant transient tests were conducted with a full-scale, 12-foot long, 49-rod mockup

of a boiling water reactor fuel bundle.

The results demonstrate that bottom-flooding provides very effective heat transfer. This cooling method is suitable as a standby cooling system to protect a reactor core in the unlikely event of a loss-of-coolant accident.

Parametric studies were conducted on the effect of bundle power, flooding rate and initial temperature.* Power

* These three parameters are defined as follows:

1. Bundle power. Full power - the power at which the corresponding reactor fuel bundle was operating at the time of a loss-of-coolant initiated, reactor scram. Peak power - The maximum power applied to the test bundle, equal to 6% of full power (corresponding to the power level at 3 seconds after the scram).
2. Flooding rate - the rate at which the bundle and outer channel area would fill if the bundle were unheated.
3. Initial temperature - the maximum temperature of the cladding at initiation of flooding.

was programmed to simulate the decay power transients following loss-of-coolant initiated scrams from full power levels of 4 MWt to 6.5 MWt. Tests were conducted with initial temperatures from the 1300 to 2150°F, and flooding rates from 0.63 to 6.05 inches per second. The peak bundle tempera-

ture was found to increase with power level and initial maximum temperature of the bundle, and to decrease with flooding rate. The highest temperature reached, in any case, was approximately 2150°F for a 5 MWt power level, with a 3.7 inch-per-second flooding rate and initial temperature of approximately 2150°F.

2. INTRODUCTION

This report covers the results of transient and steady-state flooding tests conducted on the Full Length Emergency Cooling Heat Transfer (FLECHT) test program [USAEC contract AT(10-1)-1230, subcontract S-7055] stainless-steel clad bundle number one. The testing was done in July 1968. The function of the standby (emergency) core-cooling system in a nuclear reactor is to remove decay heat from the core in order to prevent or minimize fuel damage in the event of a loss-of-coolant accident. Protection against core damage for the entire spectrum of conceivable break sizes (up to and including a double-ended break of the largest line connected to the reactor vessel) requires an engineered safeguard system consisting of two, independent, standby core-cooling subsystems. Core flooding (filling from the bottom) is one such sub-

system of the current General Electric boiling water reactor safeguard system.

Emergency cooling has been investigated earlier using a 36-rod test bundle⁽¹⁾ and 49-rod test bundles.⁽²⁾ The current series of tests was conducted with a 49-rod, 12-foot long, electrically simulated bundle that remained serviceable after conclusion of the testing reported above.⁽²⁾ The bundle had been used for approximately 45 tests, during which the maximum temperature did not exceed 2000°F (see table C-4 of Reference 2). Sixty-seven of the originally installed 79 rod thermocouples were operable at the beginning of FLECHT testing.

The objective of the test series was to extend the range of initial temperatures to 2100°F (previous testing had been limited to a maximum initial

temperature of 1650°F) and evaluate further the ability of the bottom-flooding method of emergency cooling to limit

the cladding temperatures and prevent cladding damage following a loss-of-coolant accident.

3. EQUIPMENT AND INSTRUMENTATION

The 49-rod test assembly has the same dimensions and geometry as a General Electric BWR fuel bundle for the 1967 product line reactors (e.g., Peach Bottom and Brown's Ferry). The test configuration consisted of a full-scale mockup of one bundle only, with provision for simulating the flow of the cooling water along the outside of this bundle. A schematic of the overall test setup is shown in Figure 1.

The basic element represented by the test configuration, as compared with the true reactor geometry, is shown in Figure 2. As pictured, the dual-channel arrangement creates a flow path that simulates the path occurring between a fuel bundle and the approximately adiabatic surface resulting from adjacent bundles in a reactor. The channels were fabricated from 0.10-inch wall-thickness stainless steel tube and were 14.5 feet long. The inner channel was 5.278 by 5.278 inches, which corresponds with the dimensions for 1967 product line channels. The outer channel was 5.84 by 5.84 inches. During test

operations the outer channel was covered with insulation.

A 24-1/4-inch diameter x 27-inch high plenum chamber enclosed the top of the channels. The plenum was set eccentrically over the test, with the center of the inner channel being approximately 8 inches off the center of the plenum. A 12-foot long, 6-inch pipe, rising from the top of the plenum, vented steam to the atmosphere. The plenum was also equipped with two Plexiglas windows and an underwater light to allow visual observation. Flooding water was supplied to the inner channel (bundle) and to the outer channel region through a common, metered line, connected at the bottom of the test section. Any water thrown out the top of the bundle fell in the plenum and returned to the reservoir through another metered line. In BWR's, water thrown out the top is allowed to fall back into the bundle and provide further cooling. The 49 heater rods were held in a 7 x 7 square array inside the inner channel by means of eight, typical, product-line BWR spacers.

FIGURE 1. Forty-Nine Rod Emergency Cooling Flooding Test Section Schematic

LOCAL PEAKING

5 RODS PEAKED AT 1.21 TIMES AVERAGE LOCAL POWER (3, 12, 15, 17, 30)

8 RODS PEAKED AT 1.12 TIMES AVERAGE LOCAL POWER (1, 4, 9, 13, 18, 22, 24, 37)

36 REMAINING RODS PEAKED AT 0.94 TIMES AVERAGE LOCAL POWER

FIGURE 2. Comparison of Test Section and Reactor Geometry. Rod Numbering System and Local Power Distribution are also indicated.

A simulated product-line, upper tie plate held the rods at the top and served as a common electrical conductor to all 49 rods. The lower ends of the rods were retained by a 49-gland structure which maintained spacing but permitted a certain amount of individual expansion or contraction due to changes in temperature. This arrangement is somewhat different from that found in the reactor, in which only a limited amount of differential expansion is allowed.

The water supply and control system is shown schematically in Figure 1. Demineralized water was supplied to the inner and outer channel areas with a Westco pump (20 gpm at 400 foot head) through a heat exchanger which controlled the supply-water temperature.

Heat was generated in the test section by 49 electrically heated rods. The rods used were 166 inches long, had an outside diameter of 0.570 inches and had a 144-inch heated length. These were "Calrod" type heaters, with wire-wound internal coils as heater elements. The pitch of the coil varied along the length in such a way as to provide the desired axial power distribution. Magnesium oxide powder was used to insulate the heater elements from the cladding. A rod schematic and the axial power shape are shown in

in Figures 3 and 4.

The heaters were made with Nichrome V coils. Nichrome melts at 2550°F, so heaters of this type cannot operate long with surface temperatures much above 2000°F. However, the electrical resistivity of Nichrome is almost independent of temperature, so these heaters are best suited for flooding test where strong axial-temperature gradients will exist.

A 360 kW, three-phase diesel generator was used as the power supply for the heater bundle. A set of transformers was used to increase the voltage supplied to particular rods in order to simulate the local power peaking used in previous testing.⁽²⁾ The local peaking arrangement is shown in Figure 2.

The heater rods were instrumented with up to seven 0.040-inch diameter, Inconel-sheathed chromel-alumel thermocouples, placed in grooves in the inner cladding (see Figure 3). A 0.036-inch wall stainless-steel tube was swaged over the inner cladding to hold the thermocouples in place and to bring the final outside diameter to 0.570 inches with a smooth finish. A total of 79 thermocouples was placed in the test assembly. The thermocouples (TC's) were placed on 16 rods at 6 elevations (67 TC's), at 4 elevations on the inner channel (8 TC's),

FIGURE 3. Schematic of Heater Rod Showing Manner of Instrumentation

FIGURE 4. Heater Axial Power Profile

and 3 on the outer channel (4 TC's). The thermocouple arrangement is given in Figure 5. Temperatures were also recorded at crucial points in the water circulation system.

All the thermocouples from the rods and channels were connected to a Hewlett Packard Dymec Data Acquisition System (Model 2017-D). Data were

recorded on punched paper tape and then reduced on a GE-635 digital computer. The data acquisition system and the data reduction program are described in more detail in Reference 2. Accuracy of temperatures from the rod thermocouples and the data acquisition system is estimated to be approximately $\pm 50^{\circ}\text{F}$.

4. EXPERIMENTAL PROCEDURE

Two types of tests of effectiveness of emergency cooling heat transfer were conducted in the present series: steady-state flooding and transient flooding. The test procedures for these experiments are outlined in this section.

4.1 STEADY-STATE FLOODING TEST PROCEDURE

For the steady-state tests, a constant head of water was maintained in the bundle. The power was brought on at a low level until the water in the bundle reached the saturation temperature. The power was then increased to a predetermined level and held constant, and the head of water in the bundle was maintained by providing a continuous supply of makeup water. After steady-

state (temperature gradients less than 5 degrees/minute) has been attained, power was decreased, and another test was conducted. This type of test was conducted to investigate the minimum head of water required to cool the bundle for a given power level.

4.2 TRANSIENT FLOODING TEST PROCEDURE

In the transient tests the power was brought on first, and the rod and inner channel wall temperatures allowed to rise to predetermined levels;* the flooding was then started at a constant rate while, simultaneously, the power was started on a programmed function of time to simulate the decay heat transient. When the head of water in the

* Channel temperatures were limited to approximately 600° F to protect the channel from damage.

FIGURE 5. Thermocouple Arrangement of FLECHT Test Bundle, Stainless Steel Number 1

bundle reached the 2/3 level, it was held at that position by regulating the makeup flow. The test was terminated when all the thermocouples reached saturation temperature.

The sequence of events in a transient flooding test is shown graphically in Figure 6.

This type of test was designed to approximate, as closely as possible, the actual loss-of-coolant accident in a reactor. The thermal behavior of the bundle as a function of flooding rate, initial temperatures, and power level are to be determined.

FIGURE 6. Sequence of Events in Transient Flooding Tests Conducted on FLECHT Stainless Steel Clad Bundle Number 1

5. TEST RESULTS

5.1 STEADY-STATE FLOODING RESULTS

Steady-state flooding tests were conducted to determine the minimum "coolant head" in the bundle, required to cool the heater bundle at power levels between 25 and 325 kW. Two coolant heads were determined for each power level considered: the head at which the bundle remained at saturation temperature, and a second head, below the other, at which the bundle and channel temperatures increased until the channel temperatures exceeded 600°F, at which time the maximum bundle temperatures were 1400-1500°F for the high power cases, and at which time the test was terminated to protect the channel from damage.

The results of the steady-state testing and earlier results of similar testing⁽²⁾ are shown in Figure 7. The FLECHT data confirm that data obtained earlier. As the bundle power level decreases, an increasing head of water is required to maintain the bundle at saturation temperature.

Closely related to the cooling of the bundle was the expulsion of water from the top of the inner channel.

In each case where a steady-state condition at saturation temperature was attained, water was observed to be spouting from the top of the inner channel. When this expulsion of water did not occur, the bundle showed a continuous rise in temperature near the top of the bundle until the channel limit was reached and the test was terminated. This "volcanic" action of coolant carried upward by the voids created in the lower parts of the bundle is essential to the cooling of the upper part of the bundle. This explains why less head of water is required to cool the bundle as the power is increased (Figure 7). That is, the higher power level produces more voids, more violent "volcanic" action, and better cooling of the upper portions of the bundle.

The eight-foot elevation is particularly significant for BWR's with jet pumps. Should a break in the recirculation line be the cause of the postulated loss-of-coolant accident, water will drain from the jet pump nozzles of these plants, limiting the coolant head to eight feet. On the other hand, in the case of a steam line break, bottom flooding rapidly submerges the core. The test results show that the bundle will be cooled to

FIGURE 7. Minimum Water Head Needed to Cool Bundle in Steady-State Flooding of FLECHT Stainless Steel Clad Bundle Number 1

saturation at an eight-foot coolant head at power levels above 25 kW. Minimum heads to cool the bundle at lower power levels were not determined because of the difficulty in accurately measuring these powers and because of the much longer time required to attain a steady state. Future tests are recommended to provide experimental confirmation of this "long term cooling" capability at these power levels.

5.2 TRANSIENT FLOODING RESULTS

Transient flooding tests were conducted to confirm the ability of the core-flooding system to protect the core from damage following a loss-of-coolant accident. Specifically, the following effects were investigated:

1. The effect of flooding rate on temperature response of the bundle at peak powers of 240 and 390 kW.
2. The effect of initial temperature on temperature response of the bundle at peak powers of 240, 300 and 390 kW.

A summary of the test conditions and the more significant test results is given in Table 1. One run from the Westinghouse FLECHT program is included for comparison.

5.2.1 Effect of Flooding Rate

The effect of flooding rate with a peak bundle power of 240 kW and initial

temperatures between 1300 and 1420°F is shown in Figure 8. As previously determined, ⁽²⁾ increasing the flooding rate lowers the increase in bundle temperature (initial to maximum) and cools the bundle to saturation more quickly. The case of lowest flow tested (0.63 inch-per-second flooding rate) resulted in a bundle temperature increase of 150°F with the entire bundle cooling to saturation 7.5 minutes after flooding initiation. Typical flooding rates for General Electric BWR's are 2 to 5 inches per second for low power density and 6 to 10 inches per second for high power density plants. Figure 9 shows similar results for three flooding rates with the initial temperature at approximately 1400°F and a peak power of 390 kW.

5.2.2 Effect of Initial Temperature

The effect of initial maximum temperature of the bundle at a flooding rate of 3.7 inch per second and bundle peak powers of 240, 300 and 390 kW is shown in Figures 10, 11, and 12. The current data show the same trends experienced in earlier testing. ⁽²⁾ As the initial temperature is increased at a given power level and flooding rate, the temperature rise experienced by the bundle during the flooding transient is decreased. The plots in Figure 13 further increase this trend, and

TABLE 1. FLECHT STAINLESS STEEL BUNDLE NO. 1
TRANSIENT FLOODING RESULTS

RUN	DATE	PEAK POWER (kW)	FLOOD RATE (in./sec)	* T_i (°F)	* T_{max} (°F)	* ΔT (°F)	** θT_{max} (min)	** $\theta 2/3$ (min)	** θSat (min)	*** $h(T_{max})$
6	7/8/68	240	0.63	1400	1550	150	2.5	7.0	7.5	4.86
7	7/8	240	1.32	1300	1370	70	1.0	3.5	4.5	8.30
8	7/9	240	3.70	1340	1360	20	0.5	2.0	2.7	8.31
9	7/9	240	4.87	1430	1430	~0	~0.5	1.4	2.3	10.27
10	7/9	240	6.05	1350	1350	~0	~0.3	1.0	1.8	11.07
11	7/9	390	1.32	1430	1540	90	1.3	4.0	4.5	11.60
12	7/9	390	3.70	1400	1450	50	0.8	2.0	2.7	15.20
13	7/9	390	6.05	1380	1420	40	~0.4	2.0	2.0	13.90
PWR1†			6.00	1328	1400	72	0.2		1.9	
8	7/9	240	3.70	1340	1360	20	~0.5	2.0	2.7	8.31
14	7/10	240	3.70	1560	1570	10	~0.2	2.0	2.0	6.90
15	7/10	240	3.70	2000	2000	~0	~0.0	2.0	2.8	††
16	7/10	300	3.70	1330	1360	30	0.5	2.0	2.8	11.09
17	7/10	300	3.70	1720	1735	15	0.4	2.0	4.5	7.15
20	7/10	300	3.70	2150	2150	~0	~0.0	3.5	3.0	6.40
12	7/9	390	3.70	1400	1450	50	0.8	2.0	2.7	15.20
18	7/11	390	3.70	1605	1620	15	~0.2	2.5	4.2	11.52
19	7/11	390	3.70	1820	1820	~0	~0.1	2.5	4.4	10.85
21	7/11	390	3.70	2010	2010	~0	~0.0	2.5	4.4	8.50

* T_i = Initial maximum temperature of the bundle

T_{max} = Maximum bundle temperature

ΔT = $T_{max} - T_i$

** θT_{max} = Time at which maximum temperature occurred

$\theta 2/3$ = Time for bundle to flood to 2/3 (3-foot) level

θSat = Time for entire bundle to cool to saturation temperature

*** $h(T_{max})$ = Film coefficient (Btu/h-ft²°F) at time of maximum temperature

† This data (from the Westinghouse PWR preliminary test results⁽³⁾), taken with a peak power of 1.24 kW/ft and pressure of 60 psia is included for comparison with run 13 (1.10 kW/ft, 15 psia)

†† Insufficient data

FIGURE 8. Effect of Flooding Rate in Transient Flooding at 240 kW Peak Power, FLECHT Stainless Steel Clad Bundle Number 1

FIGURE 9. Effect of Flooding Rate in Transient Flooding at 390 kW Peak Power, FLECHT Stainless Steel Clad Bundle Number 1

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FIGURE 10. Effect of Initial Temperature in Transient Flooding at 240 kW Peak Power and 3.70 Inch-Per-Second Flooding Rate; FLECHT Stainless Steel Clad Bundle Number 1

FIGURE 11. Effect of Initial Temperature in Transient Flooding at 300 kW Peak Power and 3.70 Inch-Per-Second Flooding Rate, FLECHT Stainless Steel Clad Bundle Number 1

FIGURE 12. Effect of Initial Temperature in Transient Flooding at 390 kW Peak Power and 3.70 Inch-Per-Second Flooding Rate, FLECHT Stainless Steel Clad Bundle Number 1

FIGURE 13. Effect of Initial Temperature on Bundle Temperature Increase in Transient Flooding at 3.7 Inch-Per-Second Flooding Rate, FLECHT Stainless Steel Clad Bundle Number 1

indicate that at high temperatures the cooling mechanism becomes more effective.

Note that the combination of high power (390 kW) and high initial temperature (1750°F) results in lower temperature increases in the bundle (Figure 13). This suggests that at lower power levels the void generation rate is smaller low in the bundle, that water is ejected above the swollen water level in a less violent manner, and that therefore less effective cooling occurs in the central region where the maximum temperatures appear.

5.3 CONDITION OF BUNDLE AFTER TESTING

The test bundle was examined and photographed after testing. The cladding developed an oxidized coating about 2 to 5 mils thick but scaling had not occurred. Moderate rod bowing had occurred (approximately one rod diameter at the bundle center) during testing. A photograph of the bundle after its removal from the test facility is shown in Figure 14. The lower three spacers were pulled from the bundle as it was removed from the inner channel which had suffered some distortion (approximately 1/4 inch "ripples" at the channel center) during the test series.

6. DISCUSSION

6.1 AXIAL COOLING OF RODS

The temperature response at six elevations of two rods in run 6 (0.63 ips flooding rate) is shown in Figure 15. The lower elevations, 1.2 and 4.0 feet, cool relatively quickly. The mid elevation, 6.0 feet, with the highest initial temperature and highest local power, 1.37 times the average, cools more slowly and remains the hottest portion of the rod throughout the transient. In several runs the eight foot

elevation of rod 17 was the hottest portion of the rod for one to two minutes. A comparison of the elevations equidistant from the center (1.2 feet, 10.8 feet, and 4 feet, 8 feet) further illustrates the effect of elevation. Thermocouples above the center cool much more slowly than their counterparts below the center with the same local power. The earlier turnover of the 8-foot elevation compared to the 4-foot elevation of rod 25 is an

FIGURE 14. FLECHT Stainless Steel Clad Bundle Number 1, After Testing.

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FIGURE 15. Effect of Elevation in Transient Flooding at 0.63 Inches Per Second and 240 kW Peak Power (Run 6), FLECHT Stainless Steel Clad Bundle Number 1

unexplained exception. The 8-foot thermocouple started giving erratic readings a few runs later in the test series, and inaccurate thermocouple readings may be the reason for this inconsistency.

The current results show much more effective cooling of the upper portions of the rods than the previous results. Previous data (for example, see Figure 32 of Reference 2) showed the maximum temperature shifting up the rods throughout the transient. The reason for this different behavior is not known. The test bundle suffered further distortion in the second (FLECHT) test series, which may have contributed to the difference in results*. Later tests are planned to evaluate the effects of bundle distortion on emergency cooling performance.

6.2 RADIAL COOLING OF THE BUNDLE

Radial temperature profiles of the bundle at the midplane are shown in Figure 16 for several points in time during two flooding transients. The radial section shown was selected to provide the maximum number of operable, midplane thermocouples. The relatively

rapid cooling of rod 46 and rod 33 suggests possible channeling of flooding water to the lower power corner of the bundle (see local peaking on Figure 2).

6.3 FILM COEFFICIENTS

6.3.1 Film Coefficients at Maximum Temperature

Film heat-transfer coefficients were calculated, with the following assumptions: (1) zero storage rate, (2) radiation to a sink at a temperature equal to the average temperature recorded on adjacent rods, and (3) convection to a sink at 212°F. Coefficients were calculated at the position (midpoint of rod 17) and time (from 0 to 2.5 minutes after initiation of flooding) of maximum temperature. These coefficients represent estimates of local "overall" coefficients. The calculated surface heat transfer, other than radiation to adjacent rods, is assigned to "convective" heat transfer to a sink temperature at 212°F representing the coolant. Thus true convection and radiation to the coolant is combined in this "convective" term.

The coefficients thus calculated (listed in Table 1) ranged from 5 to 15

* Westinghouse has obtained preliminary data⁽⁴⁾ indicating that flow blockage results in smaller temperature increases.

FIGURE 16. Bundle Radial Temperature Profiles in Flooding Transients, FLECHT Stainless Steel Clad Bundle Number 1

Btu/h-ft²-°F and showed a general increase with flooding rate. This range of film coefficients can be explained almost entirely by radiative heat transfer from the rod surfaces to the water ejected from the lower portions of the bundle. Consider the cylindrical surface of the rod at absolute temperature T_s , and emissivity ϵ_s , surrounded by water at absolute temperature T_w and emissivity ϵ_w . The net radiative heat transfer as given by Hottel⁽⁵⁾ is

$$\frac{q_r}{A} = \sigma (T_s^4 - T_w^4) \frac{1}{\frac{1}{\epsilon_s} + \frac{1}{\epsilon_w} - 1}$$

The "radiation heat-transfer coefficient" h_r , defined by

$$\frac{q_r}{A} = h_r (T_s - T_w)$$

is therefore

$$h_r = \frac{\sigma (T_s^4 - T_w^4)}{T_s - T_w} \frac{1}{\frac{1}{\epsilon_s} + \frac{1}{\epsilon_w} - 1}$$

Analysis of motion pictures taken by the Idaho Nuclear Corporation during bottom flooding tests⁽⁶⁾ indicates that at the time of maximum temperature, the void fraction of the two-phase mixture surrounding the rod surfaces is approximately 0.5. Therefore, assuming a radiation view factor of 0.5

from the rod surface to the water seems reasonable, and the radiation heat-transfer coefficient becomes half of that expressed above. By making the following assumptions: 1) $1350^\circ\text{F} < T_s < 2150^\circ\text{F}$ (The range of maximum temperatures obtained), 2) $T_w = 212^\circ\text{F}$, 3) $\epsilon_s = 0.6$, and 4) $\epsilon_w = 0.96$; the calculated range of the radiation heat transfer coefficient* is $7 < h_r < 13$ Btu/h-ft²-°F.

This range is in excellent agreement with that obtained from the test data (5 to 15 Btu/h-ft²-°F), indicating that the dominant heat transfer mechanism at the time of maximum temperature is radiation to the water ejected from the lower regions of the bundle.

It should be noted that if a radiation view factor of 0.5 from the rod surface to the water is assumed, the view factor from the rod surface to adjacent rods would not be 1.0 as used in the calculations, but 0.5. At the time of maximum temperature, radiation to adjacent rod surfaces (with a 1.0 view factor) is typically about 25 percent of the total surface-heat transfer. Correction of this term by assuming a 0.5 view factor would result in calculated surface heat-transfer coefficients approximately 15 percent higher than

* Radiation to the weakly absorbing vapor is an order of magnitude lower.

those recorded in Table 1. Later in the transients, when radiation becomes less significant, this difference would be reduced.

6.3.2 Film Coefficient Variation with Time

The variation of film coefficient with time for several flooding transients is shown in Figure 17. The storage term was included in these calculations. A non-dimensional time parameter θ' (equal to time elapsed after flooding starts divided by the time for the bundle to flood to the 2/3 level), was selected so that the coefficients calculated from tests with different flooding rates could be compared easily. The general trend may be described as follows: The film coefficient increased rapidly to $7 \pm 3 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$ immediately after flooding starts, then increases slowly during the first "half (i. e., $\theta' = 0.5$) of the transient." At $\theta' = 0.75$ (which corresponds approximately to the time when the head of the coolant in the bundle is 6.0 feet), the film coefficient increases rapidly with time. After the bundle has been flooded to the 2/3 level ($\theta' = 1.0$), the film coefficients range from 100 to 400 and have begun to level off.

6.4 POSSIBLE FLOODING CORRELATIONS

The convective heat flux and film coefficient are plotted against the difference in wall temperature in Figures 18 and 19. These plots are presented to suggest possible flooding correlations, which may be obtainable from these and later flooding data.

It must be noted that the maximum heat fluxes recorded corresponded to the maximum cooling rates. It was necessary to estimate the slope of these curves by noting the change in temperature ($\sim 800^\circ\text{F}$) occurring between two time sweeps (an interval of 45 seconds) of the data acquisition system. The actual maximum slope would be larger than this average value. Therefore, the maximum heat fluxes shown in Figure 18 represent minimum heat fluxes at these temperature differences. Also, the temperature differences are subject to a large error since the wall temperature at which the maximum cooling rate occurred cannot be accurately determined.

The data indicate a wide variation in heat flux at wall-temperature differences above 1000°F . This variation tends to indicate that the heat-transfer

FIGURE 17. Variation of Film Coefficient with Time, FLECHT
Stainless Steel Clad Bundle Number 1 Flooding
Transients

FIGURE 18. Variation of Convective Heat Transfer with Temperature Difference, FLECHT Stainless Steel Clad Bundle Number 1 Flooding Transients

FIGURE 19. Variation of Heat Transfer Coefficient with Temperature Difference, FLECHT Stainless Steel Clad Bundle Number 1 Flooding Transients

mechanism in effect at these temperatures, which occur shortly after the initiation of flooding, is of a somewhat random nature. The dominant heat-transfer mechanism at this time is believed to be provided by water drops ejected at high velocities from the lower bundle region and steam impinging on the higher rod surfaces. Such a mechanism would be expected to provide a

somewhat random cooling mechanism at the bundle center where the maximum temperatures occur.

The variation in film coefficient with difference in wall temperature (Figure 19) indicates that the data are reasonably well correlated ($\pm 20\%$) as shown by the best fit line up to a temperature difference of 1000°F .

7. CONCLUSIONS

1. Previous testing^{1,2} has demonstrated the ability of spray cooling to protect a BWR core from damage following a loss-of-coolant accident. The current results have extended the range of initial temperatures considered in flooding tests to 2150°F and are in substantial agreement with previously obtained flooding data. The results indicate that the flooding mode of emergency cooling is even more effective than the spray mode even with flooding rates lower than the current General Electric BWR minimums.
2. The major cooling mechanism at the time of maximum cladding temperature appears to be radiation to the two-phase mixture being violently ejected up the bundle after flooding is initiated. The data indicate that flooding correlations may be attainable from this and later test series.
3. The ability of flooding to the 2/3 level to maintain the bundle cladding temperatures below a prescribed limit when the bundle power is less than 25 kW has not been experimentally verified. Future tests are recommended to confirm this "long term cooling capability".

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Test Engineers	J. E. Leonard J. D. Duncan
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