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DEFICIENT COOLING
TENTH QUARTERLY PROGRESS REPORT
OCTOBER 1-DECEMBER 31, 1971

MASTER

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 55

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DEFICIENT COOLING

TENTH QUARTERLY PROGRESS REPORT
October 1—December 31, 1971

Contributors

Engineers	R. T. Lahey
	Y. H. Kong
	D. W. Radcliffe
Engineering Assistant	Sheila A. Kiernan

Approved:

E. E. Polomik
E. E. Polomik
Project Engineer

Approved:

F. A. Schraub
F. A. Schraub, Manager
Core Development

Prepared for the
U.S. Atomic Energy Commission
Contract AT(04-3)-189
Project Agreement 55

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ATOMIC POWER EQUIPMENT DEPARTMENT • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95114

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ABSTRACT

Steady-state CHF data, at 1000 and 800 psi and three mass fluxes, were taken for several geometric clearance configurations in a nine-rod bundle with 0.563-inch o.d., 6-foot-long, electrically heated calrods. Data, with reduced clearances of 0.060 and 0.030 inches in one of the corners, are lower than that with uniform clearance by about 10 and 20%, respectively, at 1000 psi. CHF data with a corner rod bowed, to within 0.075 and 0.030 inch from the wall, were up to 20% lower than the radially uniform geometry.

Transient flow and depressurization tests are also reported for the nine-rod test bundle. The transient flow results indicate that a multirod bundle can withstand a severe loss in flow, at reduced heat fluxes, without serious temperature excursions. Initial conditions were normally restored when flow was re-established.

Depressurization results showed that the nine-rod bundle could withstand pressure transients at 1000 and 800 psi (at up to 100 psi/sec) from representative initial conditions without the occurrence of CHF. CHF induced by higher initial heat fluxes and qualities, occurred several seconds after the minimum pressure was reached (i.e., after the blowdown terminated).

SUMMARY

Steady-state test data are presented which show the effects on CHF of reduced corner clearance (in one corner) and rod bow in a nine-rod bundle with 0.563-inch-o.d., 6-foot-long, electrically heated calrods. Intra-bundle clearances, except for the reduced clearances and bow, were used which are typical of those in BWR bundles.

Rod spacers, representative of those in reactor fuel, were located on 19-1/2-inch centers, with the last spacer 19-1/2 inches from the end of the heated length. Data were taken at pressures of 1000 and 800 psi with mass fluxes of 0.25, 0.50, and 1.00×10^6 lb/h-ft².

The steady-state data with symmetrical radial clearance (without reduced corner clearance or bow) agreed well with previous data taken, in almost identical assemblies, on a previous AEC research program (Project Agreement 44).

CHF with reduced corner clearances of 0.060 and 0.030 inch, compared with 0.138-inch normal clearances, is lower by about 10 and 20%, respectively, at 1000 psi. A pressure effect was observed below 20% quality, indicating somewhat lower CHF values for 1000 psi compared with 800 psi. Figure 2-9 (in Section 2) is a composite plot, comparing all data at 1000 psi.

Rod bow tests were made with a corner rod bowed to within 0.075 inch of the wall, from a normal 0.138 inch clearance, and with a rod bowed to within 0.030 inch of the wall from a reduced corner clearance of 0.060 inch. CHF data from the two configurations were essentially the same above a quality of 30%. Below 30% quality, the 0.060/0.030 inch bow shows an increasing decrement in CHF, and is about 20% lower than the uniform clearance data at 1000 psi and 15% quality.

Transient CHF data at 1000 psi were obtained, in the nine-rod test bundle described above, by sudden reduction of inlet flow to very low values near shutoff, and by depressurization of the system from 1000 to 800 psi at nominal rates of 50 and 100 psi/sec.

The transient flow results obtained indicate that a multirod bundle, operating at representative heat fluxes can withstand a loss-of-coolant incident for relatively long periods of time (on the order of 25 to 100 seconds) without serious temperature excursions. When flow was re-established, the heater surfaces were readily cooled (from temperatures of 1000 to 1100°F) to their lower initial temperatures of about 600°F.

The depressurization (blowdown) transient results showed that for the initial conditions tested, which were representative of reactor values, multirod bundles can withstand depressurizations from 1000 to 800 psi (at up to 100 psi/sec), and restabilize without CHF occurrence. CHF was induced by depressurizations from much higher initial conditions of heat flux and quality than would occur in an operating reactor bundle. When CHF was induced, the data indicate it was not induced during the depressurization but several seconds after the blowdown was terminated.

1. INTRODUCTION

1.1 GENERAL

The work on the Deficient Cooling Program is directed toward extension of out-of-pile heat transfer data in support of current nuclear-powered, water-cooled plants. A brief review of current technology reveals that the large bulk of data is of the steady- or quasi-steady-state class. Thus, a need exists for data taken under transient conditions of power, flow, and pressure in combination with different geometries. Analysis and study of such data are expected to contribute to the following overall objectives:

- a. A firmer understanding and establishment of heat transfer safety limitations, and
- b. Extension of safe operating limits to higher power densities.

Deficient cooling conditions are considered to be those which result in inadequate cooling of the fuel. They may result in potentially excessive cladding temperature which, in combination with the internal gas pressure of the fuel, may cause some type of fuel damage. Resultant temperatures depend on the mode or modes of heat transfer that arise during deficient cooling conditions. A brief description of these modes of heat transfer follows.

Three different modes of heat transfer can generally occur when heat is removed, during high quality conditions, from a surface such as a fuel rod: nucleate boiling, with a liquid film on the heated surface; transition boiling; and the liquid deficient region. Nucleate boiling occurs at very high surface heat transfer coefficients, usually in excess of $10,000 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$, with steady surface temperatures. Increase of heat flux eventually results in "film dryout" and a change of mode to transition boiling, which is usually characterized by temperature oscillations of varying amplitude on the heated surface. The transition mode of heat transfer exhibits relatively low heat transfer coefficients, on the order of $500 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$ or less. Continued increase of heat flux eventually results in the liquid deficient regions, with some liquid droplets impinging on the heated surface which is mostly steam cooled.

The heat flux at which transition is made from the nucleate to transition mode of boiling, as evidenced by onset of surface temperature oscillations, is usually termed the critical heat flux (CHF). For low qualities, it is also known as the departure from nucleate boiling (DNB), or burnout point. Considerable effort has been made on parametric definition of the CHF with pressure, coolant flow, vapor quality, and the geometry of the system. These parametric studies serve as design data and indicate the operating conditions beyond which fuel surface temperatures increase substantially, with greater risk to fuel cladding integrity.

Most of the work defining limits of CHF has been done with small incremental heat flux increases which would allow it to be classified as quasi-steady-state data. However, the actual modes of heat transfer become more complex in some cases involving transients, when the dynamic characteristics of the fuel-coolant system come into play. Therefore, practical cases of transient conditions which are considered worthwhile for study and test under this Deficient Cooling Program are those involving:

- a. Transient reduction of flow,
- b. Transient increase of power, and
- c. Transient decrease of pressure which causes flashing and potentially deficient cooling conditions due to increased void content.

Furthermore, it is proposed to study typical geometry changes such as those due to fuel spacer components and those caused by rod bowing and swelling. Such studies are expected to define more clearly heat transfer safety limitations, and will eventually result in extension of safe operation to higher limits.

1.2 PROGRAM OBJECTIVES

The objectives expected to be accomplished under this program are as follows:

- a. Determine experimentally the CHF and temperature regimes which may occur in water reactor fuel assemblies due to nonstandard cooling conditions that result from power, flow, or pressure transients, and determine these values relative to steady-state data.

- b. Evaluate temperature regimes likely to be experienced by water reactor fuel assemblies in loss-of-coolant accidents, and determine areas of similarity or relationship between these regimes and those found in transient critical conditions.
- c. Evaluate consequences of fuel rod geometry changes on heat transfer performance from simulated tests on single and nine-rod electrically-heated bundles.
- d. Provide a plan for further in- and out-of-pile work necessary for more complete performance and definition of the performance of water reactor fuel under deficient cooling conditions.

1.3 ORGANIZATION OF PROGRAM

The work in this program was organized into tasks, an outline of which, together with the tasks' work content, is shown in Table 1-1. These task designations have been preserved throughout the program to provide systematic documentation and execution of the program.

Table 1-1
TASK DESIGNATION AND CONTENT

Number	Title	Content
1	Planning and Analysis	<ul style="list-style-type: none"> a. Review current technology and plan appropriate tests to integrate with required safety programs b. Analysis as necessary to determine test parameters
2a	Design	<ul style="list-style-type: none"> a. Design new equipment or modifications of existing equipment to carry out test plans
2b	Manufacture	<ul style="list-style-type: none"> a. Manufacture or purchase new equipment required
3	One-Rod Exploratory Transient CHF Tests	Exploratory tests involving <ul style="list-style-type: none"> a. Steady-state and transient flow, power, and pressure b. Modifications of heaters for nonuniform axial heat flux
4	Multirod Transient Tests 9- and 16-Rod	Tests involving: <ul style="list-style-type: none"> a. Steady state and transient CHF conditions. Power transients with 16-rod tests only b. Combinations of intra-bundle clearance, power distribution, and spacer components.
5	One-Rod Tests with Geometry Changes	<ul style="list-style-type: none"> a. Steady-state CHF with simulated swelling at constant coolant pressure drop
6	Data Reduction and Analysis	<ul style="list-style-type: none"> a. As required for test Tasks 1, 3, 4, 5, and 8
7	Project Administration, Reporting, and Recommendations	<ul style="list-style-type: none"> a. Administration of entire program b. Regular and topical reporting c. Future recommendations for continued efforts
8	Multirod Geometry Changes 9-Rod	<ul style="list-style-type: none"> a. Steady state CHF data with spacer components and simulated fuel rod bowing and swelling b. Subchannel flow and enthalpy measurements.

Tasks 3, 4, 5, and 8 involve the experimental work. Tasks 3, 5, and 8 have been concluded and the results of Task 8, on nine-rod geometry changes, are included in this report.

The nine-rod transient flow and depressurization tests of Task 4 are complete, and the balance of results are contained in this report. The 16-rod transient tests in Task 8 will be accomplished in the new ATLAS (8600 kW) test facility during the next two quarters.

2. EXPERIMENTAL WORK

2.1 NINE-ROD STEADY-STATE CHF DATA WITH VARIOUS BOWS AND CLEARANCES AT 800 AND 1000 psi (E. E. Polomik, Y. H. Kong)

Nine-rod, steady-state data were obtained in the 2000-kW facility, with various bows and clearances of the corner rod, at pressures of 800 and 1000 psi. Data were also taken with a symmetrical assembly which had typical BWR rod-wall and rod-rod clearances. Mass fluxes of 0.25, 0.50, and 1.0×10^6 lb/h-ft² were used in all the different geometries. The data were taken in a nine-rod bundle having uniform axial and radial heat flux and a 6-foot heated length.

The general arrangement of the test loop is shown in Figure 2-4 of the previous quarterly report, GEAP-10221-9. Figure 2-1 of this report shows the arrangement of rod spacing for a symmetrical assembly, CHF sensing thermocouples, and axial location of the grid spacers.

The nine thermocouple sensing locations, shown in Figure 2-1(a) were used in all three types of rod geometries—symmetrical, bowing, and reduced rod-wall clearance. Twenty-mil, Inconel-sheathed, chromel-alumel thermocouples were placed in 0.025-inch-deep grooves milled in the sheaths of the calrod heaters, with the sensing ends of the thermocouples located 3/8 inch before the end of the heated length. Nickel wires of very small diameter were placed along and in the end of the groove with each thermocouple so the final mass, when brazed, was as nearly like the undisturbed metal as possible. Calculations for circumferential heat flux variation in the vicinity of the thermocouple indicated an increase of 2 to 3% over the mean circumferential value. This should result in some small amount of conservatism in the experimental critical heat flux values.

Further details involved in the geometry of the different test arrangements are included in the appropriate subsections that follow.

2.1.1 Steady-State Data in a Radially Symmetric Assembly

Steady-state CHF data at 800 and 1000 psi were reported in the last quarterly report, GEAP-10221-9, Table 2-1, and are included in this report, for quick reference, as Table 2-1.

A plot of the data in the q_c'' versus X plane, showed appreciable scatter and insufficient data at 800 psi to draw a reasonably good correlation curve at each mass flux. Since these curves are to be used subsequently for prediction of CHF during system flow and depressurization transients, it is important that accurate CHF correlations are available. Thus, additional data were taken at both 800 and 1000 psi. These data were taken early in the following quarter, but are included here to report the entire steady-state data as early as possible. The later data are shown in Table 2-2, and with Table 2-1, comprise the entire steady-state data taken in the radially symmetric assembly.

Plots of the entire data are shown in Figures 2-2 and 2-3. Mean lines, drawn visually, show the usual trend of the decrease in CHF with increase in steam quality, and a decrease of CHF with increase of mass flux at constant quality. A pronounced pressure effect can be noted at a mass flux of 1×10^6 lb/h-ft² where the 800-psi data are about 15% higher than that at 1000 psi.

In general, the 1000-psi data agree well with those reported by Janssen*, in an essentially identical assembly, except that the data presented here at a mass flux of 0.5×10^6 lb/h-ft² are about 10 to 15% lower, as may be noted in Figure 2-3 of GEAP-10221-9, the Ninth Quarterly Report. Two high heat flux points are shown in Figure 2-3 of this report in assembly 14. However, the data from assemblies 15 and 21 agree well, and the mean data from those two assemblies are considered the most reliable.

*Janssen, E., "Two-Phase Flow and Heat Transfer in Multirod Geometries," 19th Quarterly Progress Report, April 1–June 30, 1970, USAEC Contract AT(04-3)-189 P.A. 44.

Table 2-1
NINE-ROD STEADY-STATE CHF DATA IN A SYMMETRICAL ASSEMBLY

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality χ (wt %)	Boiling Length ($l_{in.}$)	Thermocouple Locations at CHF
800 psi							
379	21	0.2517	437.6	328.2	49.6	36.7	A1,C,G,I
383	21	0.2421	296.0	30.5	64.0	67.3	A1,A2,G,I
143	14	0.2538	345.2	108.1	60.6	57.2	I1
148	14	0.2636	447.5	290.3	52.8	40.1	I1
245	15	0.5218	662.2	267.4	32.1	32.6	C1
142	14	0.5108	518.1	65.7	47.4	60.0	I1
146	14	0.5122	657.1	237.3 ⁽¹⁾	37.4	37.45	I1
382	21	0.4872	482.4	124.9	37.4	48.4	G,I
381	21	0.5046	517.3	159.8	34.2	42.9	G,I
243	15	1.0076	698.0	91.0	25.7	47.5	A2,C1
244	15	0.9933	685.6	66.3	29.2	54.1	A2,C1
384	21	0.9833	708.8	117.9	23.2	41.4	
385	21	0.9929	599.0	29.1	29.7	63.0	A1,A2,C,G
1000 psi							
375	21	0.2490	295.8	27.3	66.4	67.7	A1,A2,C,G,I
378	21	0.2696	443.5	345.2	44.7	32.8	G,I
233	15	0.2525	296.6	64.0	60.0	61.8	I1
236	15	0.2471	328.9	99.59	64.0	58.0	I1,G1
238	15	0.2515	368.5	170.5	60.9	50.3	A2,C1,I1
147	14	0.2535	434.0	322.8	51.8	36.8	I1
155	14	0.2570	355.8	137.5	61.0	53.5	A1,A2,I1
227	15	0.4990	495.2	123.1	40.0	48.8	I1,G1
216	15	0.5653	539.9	144.6	34.5	43.7	I1
218	15	0.5086	501.4	147.7	36.0	44.0	I1
229	15	0.5063	460.0	46.3	47.1	62.5	I1,G1
231	15	0.5076	558.4	213.3	32.6	35.8	I1
144	14	0.5040	523.7	99.3	46.5	54.2	I1
145	14	0.5215	620.0	226.1	35.6	36.5	I1
374	21	0.4977	395.2	14.1	44.9	68.7	A1,G
376	21	0.5176	452.0	98.2	36.6	51.0	G,I
377	21	0.5186	546.3	212.5	30.0	34.4	G,I
220	15	0.9956	620.4	81.23	24.6	47.6	I1
140	13	0.9787	534.8	7.99	31.2	69.3	A1,A2,G1
141	13	0.9921	764.8	155.8	21.7	34.3	G1
240	15	1.0039	670.7	39.0	21.6	39.0	I1

Table 2-1 (Continued)

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality χ (wt %)	Boiling Length ℓ (in.)	Thermocouple Locations at CHF
223	15	1.0087	589.8	65.6	24.7	51.0	NR
225	15	0.9964	674.3	129.0	20.4	36.4	E2,G1
373	21	0.9937	515.2	6.91	29.7	69.5	A1,A2,C,G
380	21	1.0019	623.7	94.5	22.4	43.6	G

Note: This table is the same as Table 2-1 from GEAP-10221-9, and is reprinted here for convenience. With Table 2-2, it comprises the full set of nine-rod steady-state CHF data at 800 psi and 1000 psi.

(1) Subcooling on Run 146 was corrected from 37.5 to 237.3

Table 2-2

NINE-ROD STEADY-STATE CHF DATA IN A RADIALLY SYMMETRIC ASSEMBLY

Assembly Number 9R-21: 0.563-in. o. d. x 6 ft Heaters, Uniform Axial Flux, 0.474-in. Hydraulic diameter

Run Number	Pressure (psia)	Mass ⁽¹⁾ Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality χ (wt %)	Boiling Length ℓ (in.)	Thermocouple Locations at CHF
399	789	0.2465	303.8	33.8	0.638	66.9	A1,A2
400	803	0.2486	334.3	91.5	0.620	59.3	A1,A2,I
401	806	0.2472	363.1	163.8	0.585	51.2	A1,A2,I
402	799	0.2523	437.9	305.2	0.527	39.1	I only
403	807	0.2463	399.1	245.2	0.551	43.7	I only
392	805	0.4937	434.0	20.8	0.462	67.6	A1,A2
393	798	0.4904	455.1	49.8	0.446	62.0	A1,A2,I
394	801	0.5044	489.5	94.6	0.405	53.8	A2 only
395	800	0.4960	533.0	163.1	0.364	43.6	A2,I
396	799	0.4987	572.3	213.6	0.332	37.2	I only
397	806	0.4997	580.5	232.7	0.312	34.6	I only
398	820	0.4974	639.1	286.6	0.304	30.3	A2,I
386	820	0.9007	560.7	6.63	0.340	70.0	A2 only
387	810	0.9884	595.3	8.82	0.325	69.3	A1,A2,C,I
388	801	1.011	643.7	53.8	0.278	56.2	A1,A2
389	803	0.9918	693.8	97.8	0.249	45.9	A2 only
390	803	0.9937	745.5	137.9	0.220	37.7	A2 only
391	812	0.9856	818.7	186.9	0.194	30.0	A1,A2
404	1007	0.4987	416.6	20.95	0.464	67.3	A1,A2,I
405	997	0.4964	456.1	76.4	0.427	56.5	A2,C,I
406	1007	0.4995	492.9	137.0	0.375	46.1	I only
407	1000	0.9914	601.1	73.5	0.246	49.3	A1,A2,C
408	1004	0.9865	677.4	127.9	0.211	37.2	A1,A2,C
409	1004	0.9949	566.9	43.0	0.272	57.9	A1,A2,C
410	1004	0.9851	633.5	94.5	0.236	44.6	A2,C,I

(1) Flow, Mass Flux, Boiling Length and Steam Quality are based on flow measured by Orifice.

(a) CLEARANCES AND CHF THERMOCOUPLE LOCATIONS IN A SYMMETRICALLY ARRANGED BUNDLE

(b) AXIAL LOCATION OF SPACERS

Figure 2-1. Symmetrical Nine-Rod Test Section Showing Grid Spacer, Thermocouple, and Rod Locations

Figure 2-2. Nine-Rod Steady-State CHF at 800 psi in a Radially Symmetrical Assembly

Figure 2-3. Nine-Rod Steady-State CHF at 1000 psi in a Radially Symmetrical Assembly

Some scatter in CHF can be attributed to small changes in bow and clearance that may occur during heatup and at test conditions. These remain undetected as the test sections usually return to nominal dimensions on cooling. If a rod becomes badly bowed during testing, it can usually be detected by data which are comparatively very low, with CHF occurring consistently at or near the vicinity of the distortion.

The effect of pressure is negligible at mass fluxes of 0.25 and 0.5×10^6 lb/h-ft² in the ranges of 50 to 65% and 30 to 50% quality, respectively. However, at a mass flux of 1.0×10^6 , in the 15 to 30% quality range, an increase of 15 to 20% in CHF is obtained at the lower pressure.

Clearance measurements taken on the different assemblies used are shown in Table 2-3. Corner and side clearance measurements for assembly 13 are very close to the nominal dimensions shown in Figure 2-1(a). Assembly 14 also has clearances close to nominal except that corner rod-wall clearances are up to 0.018 inch high on the A, C, and G rods. Assembly 15 had clearances which agreed well with nominal before testing, but dimensions after testing showed appreciable bowing and distortion of the I rod. The I rod bowed toward the C rod, which resulted in a high corner rod-wall dimension and a lower F-I dimension (130 mils compared with a nominal of 174). Examination of CHF thermocouple locations in Table 2-1 shows frequency of CHF on the I rod to be quite high. These results are probably due to the I rod's being within 132 mils of the F rod, which was also heated, and simultaneously at 130 mils from the unheated side-wall. Despite the observed distortion of the I rod in assembly 15, it was not severe enough to prevent favorable comparison with data from assembly 21. The latter had nominal dimensions, and CHF was observed (Table 2-2) at the A, C, and I corner locations.

2.1.2 Corner Rod at Nominal 0.060 and 0.030 Inch from the Wall in the Last 18 Inches

2.1.2.1 Test Equipment

The nominal symmetrical corner clearance of 0.138 inch in the test section was obtained by using stainless steel corner inserts, shown in Figure 2-4(a). Each insert was about 20 inches long, and several were placed end-to-end axially to form the smooth radius in the corner of the test channel. The inserts were manufactured to very close tolerances, as were the channel walls, so the final assembly had a very smooth contour in the corner radius.

Reduced corner clearances were obtained on the corner rod (A-rod) by making special inserts for the last 19 inches of the heated length. These were like the normal inserts, except that they had additional material which reduced the annular corner clearance to the desired value. Details for the 0.060-inch clearance between the rod and the corner insert are shown in Figure 2-4(c).

Two sizes of inserts were made: one to produce a 0.060-inch rod-corner clearance, and the other for 0.030-inch clearance. There is virtually zero probability that two spacers could simultaneously deform to produce such low clearances in an actual BWR fuel bundle. However, it was decided to reduce the corner clearance parametrically to appraise the effect of reduced corner-rod clearances on CHF.

The inserts were designed so the reduced clearance was obtained over the corner quadrant, and additional material was provided to form a smooth transition to the channel walls, as shown in Figure 2-4(a). An axial profile of the assembly is shown in Figure 2-4(b). For the 0.030 clearance case, two small buttons, 0.030 inch high, were brazed to the outside of the calrod sheath to maintain as constant a clearance as possible in the corner annulus in the 18-inch approach length to the end of the heated length, where CHF occurred. For the 0.060-inch clearance case, only one button was used. The 0.030-inch clearance assembly had 1/8-inch-o.d. pins brazed onto the A, C, and G rods at 9-3/4 inches below the end of the heated length to provide radial support for the A rod. The latter and the corner pins were installed to prevent undue distortion in the 18-inch-long reduced clearance corner channel. The unobstructed length-to-diameter ratios in the annulus were 79 to 133 for the 0.060- and 0.030-inch clearances, respectively, which provided sufficient length for development of flow before detection of CHF.

Clearance measurements made on the assemblies before and after testing are shown in the tabulations below. Assembly 9-17, with 0.060-inch corner clearance, retained its dimensions reasonably well. Some bow resulted 4 to 7 inches below the end of the heated length; however, the average gap was within 10% of the *before* test condition.

Table 2-3
CLEARANCE MEASUREMENTS ON NINE-ROD RADIALY SYMMETRIC ASSEMBLIES

Dimensions in the table are 1/1000 inch and are taken at the end of the heated length where CHF occurred.

	<u>13⁽¹⁾</u>	<u>14⁽¹⁾</u>	<u>15⁽²⁾</u>	
Corner Rod-Wall			Before Test	After Test
Rod A	139-140	145-151	142-147	145
Rod C	135-147	138-149	141-142	131
Rod G	131-140	140-156	123-128	125
Rod I	131	138	145	144-241
Side Rod-Wall				
Rod A	133-137			
Rod C	133-153			127
Rod G	134-154	135		
Rod I	118-137			130
Rod F		136		130
Rod H		134		
Rod-Rod				
Outer Rods	169-177	165-179	164-193 (180 Avg.)	
F-I				132
C-F				152

(1) No serious deformation was noted after testing in these assemblies.

(2) Assembly 15 - The I rod failed and had a 1/16 diameter hole at the end of the heated length. The I rod had bowed and was distorted, and the dimensions show the F and I rods had moved toward the C corner.

Figure 2-4. Schematic and Detail of Corner Rod Clearances

Assembly 9-18 had a 0.030-inch corner clearance, with excellent uniformity over the 18 inches. *After* test measurements show a severe bow in the midspan at 9 inches below the end of the heated length. The rod failed during the last run, No. 325, and this failure was probably caused by severe rod bowing, which wasn't present in the previous runs. The reason this explanation is most likely is the good agreement obtained between runs taken early and late in the series of runs at this clearance. For example, runs 302 and 322 at 1000 psi agree well, as may be noted in Figure 2-6. Also, both of the latter show a smooth trend, with run 291 at 30% quality, the second run made after testing was initiated.

"A" Rod Clearance Measurements (Measurements in Mils)

Assembly 9-17 (0.060-inch Corner Clearance)

Corner Clearance	Before Test (mils)	After Test (mils)	
End Heated Length	60	64	} Slight bow in this region.
4 inches Below Heated Length	—	75	
5 to 7 inches Below Heated Length	—	69	
9 inches Below Heated Length	57–58	—	
7 to 18 inches Below Heated Length	—	62–64	
18 inches Average	58	66	

Assembly 9-18 (0.030-inch Corner Clearance)

Corner Clearance

End Heated Length	28–30	40	} Severe bow at 9 inches below the end of the heated length
9 inches Below Heated Length	—	96/156	
9 inches, Rod-Rod A-B	—	20	
9 inches, Rod-Rod A-D	—	104	

2.1.2.2 Data

CHF data were taken at pressures of 800 and 1000 psi with each insert. Mass fluxes of 0.25, 0.50, and 1.0×10^6 lb/h-ft² were used at each pressure. The reduced data are listed in Tables 2-4 through 2-7 for the various test parameters.

Plots of the data for the 0.030-inch corner clearance are shown in Figures 2-5 and 2-6. The effect of the very low corner clearance at 800 psi is negligible at the lowest mass flux tested, while at 1000 psi, a reduction of about 10% in CHF was obtained. At both pressures, reduction of CHF, compared with a symmetrical 0.138-inch corner spacing, increases monotonically with increasing mass flux and decreasing quality. At the mass flux of 1.0×10^6 and 20% quality, reduction of CHF, compared with a symmetrical 0.138-inch clearance, is greater at the lower pressure, with reductions of about 23 and 18% at 800 and 1000 psi, respectively. This may be mainly attributed to higher sensitivity of the reduced area to the higher steam void fraction at the lower pressure and high mass flux.

The pressure effect in the 0.030-inch corner clearance shows a consistent average decrease of about 30,000 Btu/h-ft² at 1000 psi when compared with that at 800 psi. This is a decrease of 4 to 10% in critical heat flux over the test range.

CHF data for the 0.060-inch corner clearance are shown in Figures 2-7 and 2-8. As for the 0.030-inch clearance, the CHF reduction, compared with the symmetrical 0.138-inch assembly, is about 5 to 10% at the lowest mass flux and increases to 20% at a mass flux of 1.0×10^6 for 20% quality and 800 psi. The CHF reduction for 1000 psi is about 10% throughout the mass flux and quality ranges tested.

Table 2-4
NINE-ROD CHF DATA WITH 0.030-INCH CORNER CLEARANCE—800 psi

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality χ (Wt %)	Boiling length (in.)	Thermocouple locations at CHF
304	18	0.2539	332.0	77.8	62.0	60.9	E,A2
306	18	0.2615	354.9	129.9	57.2	54.1	E,A2
317	18	0.2574	383.7	194.5	55.1	47.6	E,A1,A2
319	18	0.2632	436.9	288.9	50.9	39.5	A2,A1
324	18	0.2657	457.2	352.2	45.2	33.8	A1,A2,E
307	18	0.5081	450.1	98.1	35.4	51.3	A2
308	18	0.5046	475.5	145.8	31.6	43.1	A2
309	18	0.5170	498.9	201.6	24.8	33.0	A2
310	18	0.5133	560.7	283.7	19.9	23.5	A1,A2
311	18	0.5003	433.5	54.9	40.4	60.2	A2
313	18	0.4888	388.2	14.7	42.3	68.6	A2
312	18	0.9950	594.7	29.0	29.3	62.9	A1,A2
314	18	0.9800	548.4	7.93	30.3	69.4	A2
316	18	0.9976	589.8	55.4	25.1	54.5	A2,A1,C
318	18	1.0067	623.2	111.7	18.4	38.3	A2
320	18	1.0078	649.9	151.3	14.2	28.2	A2,A1
321	18	0.9988	675.3	184.7	11.1	21.0	A2,A1

Table 2-5
NINE-ROD CHF DATA WITH 0.030-INCH CORNER CLEARANCE—1000 psi

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Sub-Cooling Δh (Btu/lb)	Steam Quality χ (Wt %)	Boiling length (in.)	Thermocouple locations at CHF
290	18	0.2544	290.4	26.4	63.5	67.7	A1,A2
290 HP(a)	18	0.2562	293.5	28.2	63.6	67.4	A1,A2
294	18	0.2578	316.9	95.55	58.1	57.5	E1,A1
295	18	0.2663	353.6	158.5	54.3	49.7	E1,A1
303	18	0.2509	383.8	259.9	50.6	38.9	A2
305	18	0.2526	338.6	139.0	58.1	52.5	E1,A2
323	18	0.2587	435.8	324.5	49.8	36.0	A1,A2
289 HP	18	0.5003	389.8	20.0	43.1	67.2	A1,A2
289	18	0.4973	381.2	16.9	42.7	67.9	A1,A2
293	18	0.5053	398.1	57.7	37.9	58.3	A1,A2
293 HP	18	0.5084	404.7	57.2	38.4	58.6	A1,A2
297	18	0.5253	445.7	153.4	26.8	38.2	A1,A2
298	18	0.5057	424.5	110.1	32.8	47.5	A1,A2
299	18	0.5109	527.7	261.2	21.1	35.8	A1,A2
325	18	0.5288	586.9	319.7	16.6	18.2	A1,A2

Table 2-5 (Continued)

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Sub-Cooling Δh (Btu/lb)	Steam Quality χ (Wt %)	Boiling length (in.)	Thermocouple locations at CHF
291	18	0.9485	502.9	8.14	30.2	69.1	A1,A2
292	18	0.9927	524.2	41.2	25.0	57.4	A1,A2
300	18	1.0083	540.6	57.2	23.0	52.1	A1,A2
301	18	0.9994	586.9	115.6	17.0	35.2	A1
302	18	0.9914	631.7	176.2	10.7	20.3	A1,A2
322	18	0.9980	615.0	147.0	13.9	27.4	A2,A1

(a) H.P. signifies that 1 to 2% higher power was added to that at the first CHF indication, to verify that the first faint CHF indication was a true sustained CHF and not a transitory effect due to the first slight power increase.

Table 2-6
NINE-ROD CHF DATA WITH 0.060-INCH CORNER CLEARANCE—800 psi

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Sub-Cooling Δh (Btu/lb)	Steam quality χ (Wt %)	Boiling length (in.)	Thermocouple locations at CHF
272	17	0.2561	319.6	53.5	62.1	64.0	A2,A1
273	17	0.2581	356.8	118.9	60.5	55.9	A2,E,A1
274	17	0.2554	397.3	258.2	49.6	41.0	A2
275	17	0.2426	436.0	356.5	48.9	34.9	A2,A1
276	17	0.5326	607.5	275.8	23.6	26.8	E,A2
277	17	0.5167	550.7	219.8	27.8	33.5	E,A2
278	17	0.5001	486.2	152.2	32.3	42.8	E,A2
279	17	0.4954	452.5	92.8	37.6	53.0	A1,A2
280	17	0.5013	403.7	23.2	41.7	66.6	A1,A2
281	17	0.9699	554.2	9.3	30.8	69.0	A1,A2
282	17	1.0190	576.9	45.6	25.0	57.0	A1,A2
283	17	1.0228	623.2	88.5	21.2	44.9	A1,A2
284	17	1.0159	687.7	129.1	19.1	36.4	A1,A2
285	17	1.0244	759.9	189.0	14.0	24.4	E

Table 2-7
NINE-ROD CHF DATA WITH 0.060-INCH CORNER CLEARANCE—1000 psi

Run Number	Assembly Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Sub-Cooling Δh (Btu/lb)	Steam Quality χ (Wt %)	Boiling length (in)	Thermocouple locations at CHF
252	16	0.2539	287.0	25.8	63.0	67.7	I,G,A1,A2,C
254	17	0.2819	332.4	90.6	56.3	57.6	E
255	17	0.2667	362.1	180.4	53.0	47.2	E,A2
257	17	0.2497	409.8	276.2	54.9	40.6	A2,A1,E
258	17	0.2548	429.2	350.9	46.1	33.1	A2,A1,E
259	17	0.5071	548.7	217.2	30.9	34.5	E
260	17	0.5046	488.1	158.0	33.0	41.5	E,A2
261	17	0.5016	387.4	13.1	43.8	68.8	A1,A2
262	17	0.5137	428.8	62.3	39.9	58.1	A1,A2
263	17	0.5053	455.6	117.4	35.4	47.7	E
271	17	0.4960	440.2	96.9	37.8	51.6	A1,A2,E
287	17	0.5102	590.8	274.2	26.4	27.8	
249	16	1.0011	534.3	7.9	30.5	69.3	
264	17	0.9902	564.3	56.6	25.2	53.5	A1,A2
265	17	1.0012	533.2	8.8	30.3	68.9	A1,A2
266	17	0.9608	531.4	29.8	28.3	61.9	A1,A2
266HP	17	0.9600	540.7	29.6	28.9	62.2	A1,A2,E
267	17	0.9992	592.3	80.3	22.9	46.7	A1,A2,E
268	17	1.011	628.6	101.1	21.3	41.6	E,A1,A2
269	17	1.0067	659.7	140.3	17.24	32.0	E
270	17	1.0076	687.7	175.9	13.4	23.9	E
286	17	1.0080	677.9	164.2	14.6	26.4	E

The CHF for 1000 and 800 psi is essentially the same, with the 0.060-inch clearance, above 20% quality, for all mass fluxes. Below 20% quality, the 1000-psi data at 1.0×10^6 mass flux show lower values than the 800-psi data.

A composite plot of the 1000 psi data for all corner-clearance conditions and test conditions is shown in Figure 2-9. The figure clearly indicates the monotonic decrease in CHF for the smaller corner clearances, compared with the symmetrical assembly, as quality decreases and mass flux increases. A similar trend occurs at 800 psi, except the CHF penalty (compared with nominal clearance) is somewhat greater.

2.1.3 Corner Rod Bowed in Last 19 Inches to Within 0.075 and 0.030 Inches of the Wall

2.1.3.1 Test Equipment

The corner rod (A-rod) was bowed toward the corner of the channel by means of diagonal pins, as illustrated in Figure 2-10(a). The pins were brazed onto the E and I rods at the 9-3/4-inch level, below the end of the heated length, to result in a bow with minimum clearance at the midpoint between the last spacer and the end of the heated length, as shown in Figure 2-4(b). A streamlined pin was brazed onto the A rod, facing the corner, to prevent the rod from further bowing. Additional streamlined, 1/8-inch-o.d. pins were brazed onto the A, C, and G rods to give the A rod lateral support and prevent it from slipping off of the diagonal pin.

Figure 2-5. Nine-Rod CHF Data, 0.030-inch Corner Clearance, 800 psi

Figure 2-6. Nine-Rod CHF Data, 0.030-inch Corner Clearance, 1000 psi

Figure 2-7. Nine-Rod CHF Data, 0.060-inch Corner Clearance, 800 psi

Figure 2-8. Nine-Rod CHF Data, 0.060-inch Corner Clearance, 1000 psi

Figure 2-9. Comparison of Nine-Rod Low Corner Clearance CHF Data with Symmetric Assembly, 1000 psi

(a) VIEW OF PIN LOCATIONS TO MAINTAIN BOW OF ROD A

Figure 2-10. Detail of Pins for Bowed Corner Rods

Two magnitudes of bow were assembled and tested. The first, assembly 9-19, was assembled with normal symmetrical inserts [nominal 0.138-inch corner clearance as in Figure 2-4(a)] and the A-rod bowed to within 0.075 inches of the wall as in Figure 2-10(b). Details of measurements on this assembly are listed in Table 2-8. The *before* and *after* test dimensions A, B, C on rod A show that no undue distortion of the rod occurred during test. The A-D dimensions showed the A-rod did shift about 32 mils; however, the average minimum clearance of the bow, to 75 to 90 mils, remained essentially the same.

Table 2-8
CLEARANCE DIMENSIONS FOR NOMINAL 0.138-/0.075-INCH BOW IN CORNER ROD ASSEMBLY 9-19

	Before Test (Mils)	After Test (Mils)
<u>At End Heated Length</u>		
Rod G, Mean d	134	—
A-D	236	195
D-G	175	172
<u>9¼-in. Below End Heated Length (Maximum Bow)</u>		
Rod A - Mean a	75	—
Rod A - Mean b	78	77
Rod A - Mean c	89	90
Rod G - Mean d	130	—
A-D	198	232
D-G	174	175

The second magnitude of bow tested was accomplished with a 0.060-inch insert in the A-rod corner [Figure 2-4(b)] with pins designed for a minimum rod-corner dimension of 0.030 inch. An elevation of the assembly, No. 9-20, is schematically shown in Figure 2-10(c). The main dimensions describing the bow, *before* and *after* test are listed in Table 2-9. The minimum bow dimension is noted to have increased slightly from about 33 to an average of about 38 mils. Very little net movement of the rod occurred during test operations.

2.1.3.2 Data

CHF data were taken with both bowed assemblies at 800 and 1000 psi with mass fluxes of 0.25, 0.50, and 1.0×10^6 lb/h-ft². Results are listed in Tables 2-10 and 2-11.

Results at 800 and 1000 psi for the 0.138/0.075-inch bow are shown in Figures 2-11 and 2-12, respectively. The 800-psi data are 20,000 to 30,000 Btu/h-ft² higher (about 4 to 8%) than those at 1000 psi over the quality and mass flux range.

Data for the 0.060/0.030-inch bow are displayed in Figures 2-13 and 2-14. There is essentially no change in CHF due to the 200-psi change in system pressure at the 0.25×10^6 mass flux and high quality. At the higher mass fluxes and qualities below 40%, the 1000-psi data are about 10% lower.

Comparisons of the CHF data with the bowed configurations, to those with a symmetrical 0.138-inch corner clearance or 0.060-inch corner clearance, are made in Figures 2-15 and 2-16, for 800 and 1000 psi, respectively. There is very little difference between the 0.075- or 0.030-inch bow beyond a quality of 30%. Below 30% quality, the 0.030-inch bow shows an increasing decrement in CHF, and is about 20% lower than the 0.075-inch bow at 1000 psi and 15% quality.

Table 2-9

CLEARANCE DIMENSIONS FOR NOMINAL 0.060-/0.030-INCH BOW IN CORNER ROD ASSEMBLY 9-20

	Before Test (Mils)	After Test (Mils)
End of Heated Length		
Rod A - Mean b	---	59
Rod A - Mean c	---	45
A-D	195	181
D-G	171	169
9½-in. Below End Heated Length (Maximum Bow)		
Rod A - Mean b	34	35
Rod A - Mean c	32	38-40
A-D	191	183
D-G	197	174
19-in. Below End Heated Length (At Top Spacer)		
Rod A - Mean b	---	26
Rod A - Mean c	---	42
A-D	175	200
D-G	170	144

An interesting result is that at both 800 and 1000 psi the decrease in CHF, from a symmetrical 0.138-inch corner clearance, is essentially the same for a corner clearance of 0.060 inch in the last 18 inches as it is for the rod bowed to within 0.075 inch of the wall at midspan of the 18-inch length. The 0.030-inch clearance and 0.060/0.030-inch bow exhibit a similar result at high quality, except the 18-inch-long, 0.030-inch clearance results in lower CHF than the bow for a mass flux of 0.5×10^6 lb/h-ft².

One would probably expect the 0.060-inch uniform clearance to be a more severe geometric condition for CHF conditions than a 0.075-inch bow over the same length. A contributing reason for the same CHF performance in both geometries, is that the bowed rod can divert flow away from the corner subchannel, as the flow moves up the rod from the last spacer to the end of the heated length. Then, if the reduction in corner subchannel flow were severe enough, CHF conditions could result that were approximately equivalent to those with the reduced clearance. Additional results to verify these data trends should be obtained in representative geometries. Future experiments to be performed under P.A. 55 with 16-rod bundles having a 12-foot cosine axial heat flux distribution, should aid in clarification of the effect of rod bow and corner clearance on CHF.

Table 2-10
NINE-ROD CHF DATA WITH 0.138-/0.075-INCH CORNER ROD BOW (ASSEMBLY 9-19)

Run Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality X (Wt %)	Boiling length ($\ell_{in.}$)
1000 psi					
327	0.2550	279.6	29.4	60.4	67.0
327HP ^(a)	0.2493	284.3	27.6	63.1	67.5
331	0.2544	364.9	208.9	52.8	44.8
335	0.2507	338.7	133.9	59.5	53.5
336	0.2587	433.5	331.4	48.5	35.1
326	0.5026	423.8	15.3	47.8	68.6
330	0.5008	451.8	115.0	35.7	48.2
332	0.5076	517.3	190.6	31.1	37.1
334	0.5159	630.4	315.6	23.9	23.7
349	0.5129	421.1	73.3	37.6	55.3
328	0.9767	534.0	8.9	31.1	69.0
328HP	0.9786	540.4	8.5	31.5	69.1
329	1.0190	623.2	82.2	23.6	46.9
333	0.9910	643.7	118.9	20.2	37.8
348	1.0118	720.1	185.8	13.6	23.2
800 psi					
337	0.2590	448.4	325.6	49.9	36.9
337HP	0.2581	454.6	322.6	51.9	322.6
344	0.2461	298.6	25.8	63.9	68.0
344HP	0.2467	304.8	27.5	65.1	67.8
346	0.2514	365.4	163.5	57.5	51.0
338	0.5072	516.8	174.6	31.6	40.0
341	0.5118	470.0	115.5	34.7	48.5
342	0.5014	410.4	18.6	43.1	67.7
345	0.5032	610.1	285.4	26.4	28.0
339	0.9399	648.6	99.3	24.2	45.13
340	0.9947	634.7	70.0	25.6	51.5
343	0.9797	565.6	8.93	31.1	69.1
347	1.0186	728.3	182.0	13.59	24.4

(a) H.P. signifies that 1 to 2% higher power was added to that at the first CHF indication, to verify that the first faint CHF indication was a true sustained CHF and not a transitory effect due to the first slight power increase.

Table 2-11
NINE-ROD CHF DATA WITH 0.060-/0.030-INCH CORNER ROD BOW (ASSEMBLY 9-20)

Run Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Subcooling Δh (Btu/lb)	Steam Quality X (Wt %)	Boiling length (l_{in})
1000 psi					
352	0.2441	286.7	26.6	65.4	67.8
356	0.2624	344.6	145.3	55.2	51.3
358	0.2621	377.8	230.0	50.1	42.2
362	0.2598	448.2	348.0	48.6	34.3
351	0.4858	396.0	17.2	45.8	68.1
354	0.4977	512.2	207.0	29.1	34.4
357	0.5026	454.6	112.7	36.3	48.7
359	0.5063	532.2	314.9	13.9	16.0
360	0.5042	547.4	310.2	16.6	18.6
361	0.4954	549.4	249.0	27.4	20.1
363	0.5065	559.4	276.1	23.1	25.3
350	0.9694	506.3	7.92	29.8	69.2
353	0.9905	550.7	66.3	22.8	49.7
355	0.9905	557.9	121.4	14.72	31.7
800 psi					
366	0.2514	304.3	23.6	64.2	60.4
369	0.2445	350.8	148.4	58.7	52.7
371	0.2596	433.8	323.6	46.6	35.8
365	0.4960	411.4	16.3	44.2	68.3
368	0.4957	508.3	146.6	36.0	45.3
370	0.5041	614.7	298.3	25.0	26.3
364	1.0096	568.7	8.52	30.25	69.2
367	1.0073	592.9	97.4	18.78	41.1
372	1.0051	663.0	172.9	11.82	23.0

Figure 2-11. Nine-Rod CHF Data, 0.138/0.075-Inch Bow, 800 psi

Figure 2-12. Nine-Rod CHF Data, 0.138/0.075-Inch Bow, 1000 psi

Figure 2-13. Nine-Rod CHF Data, 0.060/0.030-Inch Bow, 800 psi

Figure 2-14. Nine-Rod CHF Data, 0.060/0.030-Inch Bow, 1000 psi

Figure 2-15. Comparison of CHF with Bow to Uniform Clearances, 800 psi

Figure 2-16. Comparison of CHF with Bow to Uniform Clearances, 1000 psi

NINE-ROD TRANSIENT DATA (Y. H. Kong, R. T. Lahey, E. E. Polomik, D. W. Radcliffe)

The equipment, test arrangements, and test procedures used for transient flow and depressurization are described in the Ninth Quarterly Report, GEAP-10221-9, Subsection 2.2. Only a few transient flow runs were presented in the latter report as data reduction had not been completed. This report was delayed in order to complete the analysis of all the nine-rod transient flow and depressurization runs and presents a complete tabulation of all these data, together with some of the typical results as shown in computer plots.

A separate topical report on the transient CHF experiments will contain all the data as well as computer plots and analyses of the transients.

Table 2-12 shows a complete list of the nine-rod transient flow and depressurization runs with the nominal flow rates. This tabulation serves as a general index, and more detailed conditions for each run are tabulated in Tables 2-13 and 2-14.

Table 2-12
LIST OF NINE-ROD TRANSIENT FLOW AND DEPRESSURIZATION RUNS

Date	Tape	Run Numbers	Flow Decay And On/Off/On Flow Transients 1000 psi		Depressurization Nominal 1000/800 psi	
			Nominal G/10 ⁶ (lb/h-ft ²)	Number of Runs	Nominal G/10 ⁶ (lb/h-ft ²)	Number of Runs
8/20/71	(1)	9-149 → 9-186				
		149-154	1/0.5	6		
		156-160	"	5		
		161-164	"	4		
		165-168	0.6/0.3	4		
		169-176	"	8		
		177-178	1/0.5	2		
		179-180	1/0.3	2		
		181-183	"	3		
		184	1/0	1		
		185-186	0.6/0	2		
	(2)	9-187 → 9-224				
		187-190	0.6/0	4		
		191-195	1/0	5		
		196-197	0.85/0	2		
		198-202 (Repeats)	0.6/0	5		
		203-205 (Repeats of 198)	"	3		
9/15/71	(2)	206-7, 212,			0.25	3
	(3)	234-5, 237, 239			"	4
	(2)	208, 211, 213, 217, 219			0.50	5
	(3)	226, 228, 230, 232			"	4
	(2)	209-10, 214-5, 221-2, 224			1.00	7
	(3)	241			"	1
Total Runs				56		24

Table 2-13
NINE-ROD TRANSIENT FLOW DECAY DATA, 1000 psi
ASSEMBLY 9R-14

Initial Conditions - Steady-State Values							Transient Values							
Date	Run Number	Mass Flux $G/10^6$ (lb/h-ft ²)	Heat Flux $q''/10^3$ (Btu/h-ft ²)	Power (kW)	Subcooling Δ (Btu/lb)	Exit Quality X_e (wt %)	Time Flow at Low Value (t-sec)	G_{low} average (lb/h-ft ²)	Δh (Btu/lb)	CHF Condition During Transient	$\Delta\tau_{c,min}$ (sec)	Thermocouple Number	$\Delta\tau_{c,max}$ (sec)	Thermocouple Number
8/20/71	9-149	1.024	360.5	842	52.8	12.8	11.05	0.519	52.8	No	—	—	—	—
8/20/71	9-150	1.007	424.9	993	35.9	19.3	8.02	0.506	35.9	No	—	—	—	—
8/20/71	9-151	1.007	467.8	1093	29.8	23.0	10.49	0.496	29.8	Yes	1.14	I1	1.54	A2
8/20/71	9-152	0.983	457.8	1070	34.2	22.8	24.58	0.517	34.2	Yes	1.37	I1	1.64	A2
8/20/71	9-153	1.042	472.7	1104	28.3	22.8	13.53	0.520	28.3	Yes	1.2	I1	1.45	A2
8/20/71	9-154	1.029	515.2	1204	35.7	24.2	13.74	0.520	35.7	Yes	0.6	I1	1.0	A2
8/23/71	9-156	1.002	361.3	844	42.5	14.9	9.57	0.503	42.5	No	—	—	—	—
8/23/71	9-157	1.009	431.6	1008	36.1	19.8	10.81	0.495	36.1	No	—	—	—	—
8/23/71	9-158	1.007	448.0	1047	39.4	20.2	9.75	0.502	39.4	No	—	—	—	—
8/23/71	9-159	1.000	474.3	1108	38.9	22.1	26.76	0.509	38.9	Yes	0.7	A1	1.8	I1
8/23/71	9-160	1.008	484.1	1131	36.5	22.7	22.74	0.495	36.5	Yes	1.0	I1	1.05	A2
8/24/71	9-161	1.002	358.2	837	41.4	14.8	22.70	0.497	41.4	No	—	—	—	—
8/24/71	9-162	0.996	426.1	995	35.8	19.7	15.34	0.510	35.8	Yes	0.5	I1	—	—
8/24/71	9-163	0.995	441.5	1031	37.1	20.6	14.26	0.515	37.1	Yes	1.1	I1	1.6	A2
8/24/71	9-164	1.008	446.0	1042	37.7	20.3	23.40	0.513	37.7	Yes	1.3	I1	2.0	A2
8/26/71	9-165	0.616	248.0	579	41.4	17.5	10.40	0.287	41.4	No	—	—	—	—
8/26/71	9-166	0.614	278.4	650	44.4	20.1	10.89	0.304	44.4	No	—	—	—	—
8/26/71	9-167	0.641	296.0	691	42.2	20.9	12.43	0.308	42.2	No	—	—	—	—
8/26/71	9-168	0.640	318.8	745	43.2	22.9	8.73	0.314	43.2	No	—	—	—	—
8/26/71	9-169	0.634	339.7	794	41.8	25.3	13.56	0.318	41.8	Yes	3.7	I1	—	—
8/26/71	9-170	0.630	357.1	834	41.4	27.2	22.20	0.287	41.4	Yes	1.6	I1	2.2	A2
8/26/71	9-171	0.620	359.0	839	39.6	28.2	35.47	0.311	39.6	Yes	0.8	I1	0.8	A2
8/26/71	9-172	0.610	321.0	750	40.3	23.5	8.31	0.325	40.3	No	—	—	—	—
8/26/71	9-173	0.638	360.8	843	45.4	26.6	29.95	0.316	45.4	Yes	0.7	I1	2.2	A2
8/26/71	9-174	0.609	313.2	732	44.2	23.7	7.17	0.290	44.2	No	—	—	—	—
8/26/71	9-175	0.622	347.6	812	46.0	26.1	18.47	0.295	46.0	Yes	1.6	I1	1.6	A2
8/26/71	9-176	0.617	356.6	833	44.6	27.4	31.90	0.308	44.6	Yes	1.2	I1	1.2	A2
8/27/71	9-177	1.033	464.2	1084	40.2	20.4	23.22	0.515	40.2	Yes	1.65	I1	1.65	A2
8/27/71	9-178	1.013	470.0	1098	41.9	21.1	27.32	0.519	41.9	Yes	1.2	A2	1.5	I1
8/27/71	9-179	1.028	360.0	841	41.6	14.4	32.02	0.306	41.6	Yes	1.9	I1	3.1	A2
8/27/71	9-180	1.013	365.1	853	39.8	15.2	21.45	0.268	39.8	Yes	1.8	I1	2.4	A2
8/27/71	9-181	1.014	366.3	856	42.9	14.8	8.56	0.284	42.9	Yes	1.2	I1	1.6	A2
8/27/71	9-182	1.021	367.4	858	36.9	15.5	27.92	0.302	36.9	Yes	1.6	I1	2.4	A2
8/27/71	9-183	1.017	356.3	832	37.7	14.8	32.01	0.314	37.7	Yes	1.5	I1	3.0	A2
8/27/71	9-184	0.551	264.8	619	41.9	22.0	57.64	0.110	41.9	Yes	1.9	I1	1.9	A2
8/27/71	9-185	0.624	263.7	616	46.1	18.0	36.05	0.115	46.1	Yes	0.4	A2	1.4	I1
8/27/71	9-186	0.630	269.3	629	47.4	18.1	58.34	0.066	47.4	Yes	0.8	A2	2.0	I2

Table 2-14
NINE-ROD TRANSIENT ON/OFF/ON FLOW DATA, 1000 psi
ASSEMBLY 9R-15

Initial Conditions - Steady-State Values							Transient Values								
Date	Run Number	Mass Flux G/10 ⁶ (lb/h-ft ²)	Heat Flux q"/10 ³ (Btu/h-ft ²)	Power (kW)	Subcooling Δh (Btu/lb)	Exit Quality X _e (wt %)	Time Flow at Low value (t-sec)	G _{low} Average (lb/h-ft ²)	Δh (Btu/lb)	X _{exit} Average Steady-State (wt %)	CHF Condition During Transient	Δτ _{c,min} (sec)	Thermocouple Number	Δτ _{c,max} (sec)	Thermocouple Number
9/7/71	9-187	0.613	27.5	64	13.5	0.5	125	0.025	10.7	40.4	Yes	94.44	I1	111.80	A2,G1
9/7/71	9-188	0.613	99.6	232	8.2	8.4	50	0.039	9.7	88.2	Yes	35.08	A1	40.34	I1
9/7/71	9-189	0.610	28.3	66	11.0	1.05	155	0.055	10.4	25.3	Yes	86.22	I1	103.79	A2
9/7/71	9-190	0.610	99.7	233	7.9	8.5	41	0.06	8.9	103.0	Yes	23.00	A1	33.60	G1
9/8/71	9-191	1.006	43.4	101	5.3	1.7	170	0.07	4.1	36.8	Yes	140.69	C1,G1,I1	141.43	A1,A2
9/8/71	9-192	0.986	43.1	101	3.8	2.0	190	0.04	3.5	44.9	Yes	103.30	A1	103.30	G1
9/8/71	9-193	1.013	96.0	224	5.0	4.9	33	0.03	3.6	261.8	No				
9/8/71	9-194	0.988	95.8	224	2.7	5.3	35	0.03	3.3	53.0	Yes	28.54	A1,A2	28.54	A1,A2
9/8/71	9-195	0.994	97.0	226	4.6	5.1	Timer Malfunction	0.05	2.8	39.8	Yes		Timer Malfunction		
9/8/71	9-196	0.845	99.2	232	11.0	5.3	21	0.05	12.4	43.8	No				
9/8/71	9-197	0.854	98.8	231	10.0	5.4	33	0.05	9.1	116.0	Yes	21.27	A2	21.27	A1
9/8/71	9-198	0.617	28.1	66	11.3	1.0	310	0.035	10.1	31.3	Yes	223.20	A1,C1,G1,I1,A2	223.20	A1,C1,G1,I1,A2
9/8/71	9-199	0.601	28.2	66	11.3	1.1	300	0.05	10.5	34.7	Yes	205.50	I1,A2	208.50	C1,G1
9/8/71	9-200	0.611	28.3	66	9.1	1.4	300	0.04	10.0	27.4	Yes	202.30	I1	204.50	A1,C1
9/8/71	9-201	0.615	28.1	66	8.4	1.4	300	0.03	8.9	31.8	Yes	207.10	G1,I1	209.10	A2
9/8/71	9-202	0.622	28.0	65	9.0	1.3	300	0.03	10.4	160.0	Yes	205.10	I1	207.10	A2
9/8/71	9-203	0.609	28.1	66	11.1	1.0	310	0.05	9.7	19.7	Yes	200.10	I1	202.30	A1,C1,G1
9/8/71	9-204	0.615	28.2	66	8.6	1.4	309	0.07	10.1	19.3	Yes	212.30	A2	213.50	A1,C1,G1,I1
9/8/71	9-205	0.604	28.2	66	11.4	1.0	300	0.03	9.8	65.3	Yes	204.60	G1	207.60	C1

2.2.1 Transient Flow

The entire flow transient results are tabulated in detail in Tables 2-13 and 2-14. Typical results of the flow decay data tabulated in Table 2-13 were included as transient computer plots in the last quarterly report, GEAP-10221-9. The ON/OFF/ON flow transient data are tabulated in Table 2-14, and typical computer plots of those transients are shown in the following figures.

Figure 2-17 illustrates the nomenclature used in the tables as it applies to flow, time at low flow, and time of CHF indication.

Figure 2-17. Time Definitions for Transient Flow and CHF

The objective of the test runs 9-187 through 9-205 (Table 2-14) was to determine the heat transfer performance of the test bundle when it experienced a sudden loss-of-coolant flow. Initial mass flux was in the range of 0.6 to 1.0×10^6 lb/h-ft², and the lower transient values are about 0.05×10^6 lb/h-ft² or about 5 to 10% of the initial values. Lower flow values during the low flow period of the transient were not used to avoid mechanical damage to the valve and/or valve seat during the sudden valve closure. Heat fluxes were set in the range of 28,000 to 100,000 Btu/h-ft² which are typical of the heat flux during hypothetical accident conditions in a BWR (i.e., subsequent to a scram). It may be noted that the low-flow condition was sufficient in some cases to raise the average steady-state exit quality to over 100%, which indicates vapor superheating (unlikely) or countercurrent liquid and vapor flow at the exit of the test section.

Figures 2-18 through 2-23 are computer plots of several of the runs in Table 2-14, which show typical results when the flow to the test section is rapidly reduced to a very low value. Figure 2-18 shows that a heat flux of 99,700 Btu/h-ft² can be sustained with an inlet mass flux of about 0.06×10^6 lb/h-ft² for 41 seconds, with no serious overheating. As noted in Table 2-14, after 23.0 and 33.6 seconds from the time of flow reduction, thermocouples A1 and G1 (Figure 2-1), respectively, started to gradually increase in temperature. This temperature rise indicates the lower heat transfer coefficients that resulted, due to the gradual deterioration of quasi-pool boiling conditions, as the system stabilized and approached an average steady-state quality in excess of 100%.* The temperature rise on the thermocouples is approximately linear, indicating a uniform rate of heat transfer from the heater and heat storage in the heater materials. When flow was re-established after 41 seconds, heat transfer from the rod was immediately improved and the heaters were cooled to their initial temperatures in about 40 seconds.

In most of the computer plots here (except Figure 2-21), complete traces of the transient data, starting from the time of flow reduction, are not shown. Data were recorded in this manner since in many tests the flow was at the low value for a significant amount of time before temperature excursions resulted. It was decided not to record such long steady-state periods on the magnetic tape, in order to avoid an excess amount of data reduction which would result in many repetitions of steady-state values. Thus, data recording by magnetic tape was initiated at about the time temperature excursions were expected, or immediately after they started. A separate timer, and the Sanborn temperature traces, provided necessary data to synchronize times within about 0.2 second. Thus, on the figures shown here the first part of the transient, not recorded on magnetic tape, is sketched in with the time during which the flow was at the low value. In future runs of this type, it may be more expeditious to record the entire run on magnetic tape and use event markers to determine sections of the tape which will later be used for complete reduction to engineering units.

Figures 2-19 through 2-21 are plots of other flow ON/OFF/ON runs at various conditions for different times at low flow. In run 9-192, Figure 2-19, the flow was at the low value for 190 seconds, with a temperature excursion at 103 seconds from the time of flow reduction. In all three cases, mild, linear temperature excursions of 300°F or less resulted, and temperatures returned to normal initial values after re-establishment of the flow.

Runs 198-205, in Table 2-14, are runs made at essentially the same conditions, to determine whether the transient characteristics were reproducible. The last two columns of Table 2-14 show that temperature excursions resulted in all these runs, in 200 to 223 seconds from the time of flow reduction. The maximum temperatures reached were about 900°F, in all cases, and returned to initial values after re-establishment of flow. Figures 2-22 and 2-23 are plots of runs early and late in the sequence, and it can be seen that the repeatability is quite good.

The results in Table 2-14 and the typical plots presented in Figures 2-18 through 2-23 indicate that a multirod bundle operating at representative heat fluxes can withstand a loss-of-coolant incident for relatively long periods of time (on the order of 25 to 100 seconds) without serious temperature excursions. When flow was re-established, the heated surfaces were readily cooled to the initial operating temperature. In comparison, the no-flow "window period" of the BWR loss-of-coolant accident (LOCA) is only 2 to 5 seconds in duration, and thus the present design assumption that the heat transfer coefficient is zero seems quite conservative.

The foregoing results are similar to the flow decay runs at typical reactor heat fluxes and qualities presented in the Ninth Quarterly Report, GEAP-10221-9, except that in the latter case the temperature excursions occurred much sooner due to the higher heat fluxes (350,000 to 460,000 Btu/h-ft²) and qualities (14 to 28%). In the latter flow decay runs, temperatures up to about 1050°F were obtained and re-establishment of flow resulted in rewetting of the heater surface and normal heat transfer conditions.

2.2.2 Transient Pressure (Blowdown)

Depressurization runs were made from an initial pressure of 1000 psi to a nominal value of 800 psi. Typical depressurization rates of 50 and 100 psi/sec were used at mass fluxes of 0.25, 0.50, and 1.00×10^6 lb/h-ft².

*Flow fluctuations existed at low flows. Average flows at the low values are tabulated and the transient value of exit quality is based on these averages.

Figure 2-18. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.61$, Run 9-190

Figure 2-19. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.99$, Run 9-192

INITIAL MASS FLUX
 $G/10^6 = 0.988$

Figure 2-20. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.988$, Run 9-194

Figure 2-21. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.854$, Run 9-197

Figure 2-22. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.60$, Run 9-199

Figure 2-23. Nine-Rod ON/OFF/ON Flow Transient, $G/10^6 = 0.62$, Run 9-204

Previous tests, with the one-rod test section showed that depressurization from normal reactor conditions did not result in CHF. Thus, the initial conditions of heat flux and quality in these nine-rod tests were set well above those in a typical reactor bundle (240,000 Btu/h-ft² and 23%). This test strategy ensured that CHF conditions would result during some of the transients, in order to provide data for analysis.

A complete listing of the nine-rod depressurization data is shown in Table 2-15. Actual times of depressurization, as well as the resultant rate, are shown. Occurrence of CHF is noted in the table, with the thermocouple locations at which it occurred. The thermocouple notation and location are the same as those shown in Figure 2-1. The notation used for depressurization time and time to CHF in Table 2-15 is shown in Figure 2-24.

Graphical representation of the data is clearly illustrated on the computer (Cal Comp) plots shown as Figures 2-25 through 2-32. These are typical of the results obtained and are arranged in an order to show more clearly the effect of test parameters. Figures 2-25, 2-26, and 2-27 are for a nominal mass flux of 0.25×10^6 . No CHF resulted on run 9-212 with a 2.13-second blowdown. Heat flux was increased slightly, to 253,000 Btu/h-ft² with quality at 36.4%, and blowdown time increased to 4.11 seconds, and CHF conditions still did not result. Quality was then increased to 44.9% with a heat flux slightly higher at 257,000. The latter run, 9-237, shown in Figure 2-27, resulted in CHF conditions, with a 4.13 second blowdown. It may be noted that the temperature excursion ended abruptly, about 22 seconds after start of depressurization. This was due to limit switches on the Sanborn recorder which were preset to trip the power at temperatures of about 900 to 1000°F, to protect the assembly from actual burnout. The assembly was designed for temperatures up to about 1200°F. In all three runs, the lowest pressure that resulted was about 750 psi—somewhat lower than the nominal value of 800.

Figure 2-27, the run in which CHF occurred, shows that CHF did not occur until several seconds after the depressurization, when flow and pressure were relatively stable at a much higher quality. This clearly indicates that in a multirod bundle there is no catastrophic "flash off" of the liquid film, during depressurization, causing a premature CHF.

Depressurization data at $G = 0.5 \times 10^6$ lb/h-ft² are shown in Figures 2-28 through 2-30. The first two figures show that depressurizations of about 50 to 100 psi/sec can be withstood without CHF occurrence, at the relatively severe initial conditions of about $q'' = 500,000$ Btu/h-ft² and over 30% quality. A mild transient CHF condition (50°F temperature rise) was induced at 541,000 Btu/h-ft² with a 4.11-second blowdown as shown in Figure 2-30.

Figures 2-31 and 2-32 show depressurization transients for mass fluxes of 1.00×10^6 lb/h-ft². CHF was not obtained in any of these runs, below 666,000 Btu/h-ft² and qualities around 20% at either blowdown rate. In Figure 2-32 it can be seen that a transient CHF, with a temperature excursion of only 100°F, finally occurred at 666,000 heat flux with a 4.11-second blowdown. The temperature excursion occurred for 6 to 8 seconds, during the time when the flow passed through its minimum value. The CHF condition was removed (i.e., rewetting occurred) within 2 seconds as flow restabilized to its initial value. The initial condition of 666,000 Btu/h-ft² and 21% quality is quite severe compared with typical reactor bundle conditions of about 240,000 Btu/h-ft² and 23% quality in a modern BWR.

The results at all normal initial conditions tested indicate that multirod bundles can withstand depressurizations from 1000 to 800 psi at up to 100 psi/sec and restabilize, without CHF occurrence. CHF can be induced by depressurizations from much higher initial conditions of heat flux and quality, than occur in an operating reactor bundle. When CHF was induced, the data indicate it was not induced during the time of depressurization, but several seconds after the depressurization.

Table 2-15
NINE-ROD DEPRESSURIZATION DATA

Initial Conditions, Pressure = 1000 psi							Blowdown Data										CHF (Magnetic Tape)					CHF (Sanborn)		$\Delta\tau_{c, \min}$ (sec)		$\Delta\tau_{c, \max}$ (sec)	
Date	Run Number	Mass Flux G/10 ⁶ (lb/h-ft ²)	Heat Flux q''/10 ³ (Btu/h-ft ²)	Subcooling Δh (btu/lb)	Exit Quality X _e (wt %)	Power (kW)	P _{initial} (psi)	$\tau_{initial}$ (sec)	P _{min} (psi)	τ_{min} (sec)	ΔP (psi)	$\Delta\tau_p$ (sec)	$\Delta P/\Delta\tau_p$ (psi/sec)	CHF After Depressurization	Thermocouple Number					Thermocouple Number		Thermocouple Number		Thermocouple Number			
9/9/71	206	0.272	206	53.4	36.1	480	997	3.36	749	5.53	248	2.17	114.3	Yes	A1	A2	C1	G1	I1	B1	E2	7.05	I1	11.65	A2		
	207	0.281	204	68.9	32.4	477	995	3.27	786	5.50	209	2.23	93.7	No	A1	A2	C1	G1	I1	B1	E2	5.20	I1	9.35	C1		
9/10/71	208	0.503	271	32.8	26.8	632	1004	2.67	770	5.40	234	2.73	85.7	Yes ⁽¹⁾	A1	A2	C1	G1	I1	B1	E2	3.75	I1	7.63	C1		
	209	0.976	386	21.2	20.2	901	1003	3.45	819	5.66	184	2.21	83.3	Yes ⁽¹⁾													
9/13/71	210	1.011	448	52.2	18.2	1047	1001	3.61	796	5.77	205	2.16	94.9	No													
	211	0.516	392	123.1	26.1	915	1001	3.64	779	5.78	222	2.14	103.7	No													
	212	0.267	244	103.6	38.1	511	987	3.59	752	5.72	235	2.13	110.3	No													
	213	0.506	276	51.2	24.5	645	1014	3.52	808	5.67	206	2.15	95.8	No													
	214	0.975	457	49.1	20.2	1068	1003	3.35	791	5.51	212	2.16	98.1	No													
	215	0.997	567	110.0	16.7	1324	992	3.46	772	5.68	220	2.22	99.1	No													
	217	0.574	523	147.0	31.5	1223	1002	3.31	796	5.48	206	2.17	94.9	No													
	219	0.513	493	145.8	34.4	1151	991	3.35	760	5.51	231	2.16	106.9	No													
	221	0.987	607	78.1	24.4	1418	999	3.38	790	5.58	209	2.20	95.0	No													
	222	0.998	605	78.0	23.9	1413	1001	3.49	813	7.62	188	4.13	45.5	No													
	224	0.997	585	61.5	25.3	1366	1005	3.40	828	7.52	177	4.12	43.0	No				G1	I1			8.02	G1	8.46	I1		
	226	0.979	666	125.1	21.2	1557	1014	2.67	783	6.78	231	4.11	56.2	Yes													
228	0.515	483	122.4	36.9	1129	1010	2.74	755	6.88	255	4.14	61.6	No														
9/14/71	230	0.493	460	41.8	49.0	1074	1008	2.82	800	6.85	208	4.03	51.6	No					I1			9.20	I1				
	232	0.503	541	212.0	31.2	1264	1012	2.77	812	6.88	200	4.11	48.7	Yes													
	234	0.246	180	63.2	33.7	421	1007	2.73	766	6.84	241	4.11	58.6	No													
	235	0.252	206	61.9	39.0	481	1001	2.79	794	6.93	207	4.14	50.0	No		A2	C1	G1	I1	B1	E2	10.58	G1, I1	16.15	C1		
	237	0.258	257	93.2	44.9	601	1008	2.83	751	6.96	257	4.13	62.2	Yes													
9/15/71	239	0.242	253	166.6	36.4	590	1001	2.99	736	7.10	265	4.11	64.5	No													
	241	0.973	645	115.9	21.5	1507	1010	2.97	776	5.11	234	2.14	109.3	No													

(1) In runs 208 and 209, flashing at the inlet due to too low a subcooling (high inlet temperature); thus the transient inlet flow rate readings were unreliable.

Figure 2-24. Time Definitions for Blowdown and CHF

Figure 2-25. Nine-Rod Depressurization, Nominal $G/10^6 = 0.25$, Run 9-212

Figure 2-26. Nine-Rod Depressurization, Nominal $G/10^6 = 0.25$, Run 9-239

Figure 2-27. Nine-Rod Depressurization, Nominal $G/10^6 = 0.25$, Run 9-237

Figure 2-28. Nine-Rod Depressurization, Nominal $G/10^6 = 0.50$, Run 9-217

Figure 2-29. Nine-Rod Depressurization, Nominal $G/10^6 = 0.50$, Run 9-228

Figure 2-30. Nine-Rod Depressurization, Nominal $G/10^6 = 0.50$, Run 9-232

Figure 2-31. Nine-Rod Depressurization, Nominal $G/10^6 = 1.00$, Run 9-241

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Figure 2-32. Nine-Rod Depressurization, Nominal $G/10^6 = 1.00$, Run 9-226

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1 U. S. Atomic Energy Commission
Div. of Reactor Standards
Washington, D. C. 20545
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1 William B. Cottrell, Director
Nuclear Safety Program
Oak Ridge National Laboratory
Union Carbide Corporation
Post Office Box Y
Oak Ridge, Tenn. 37830