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APRIL 1971

**DEFICIENT COOLING
7TH QUARTERLY PROGRESS REPORT
JANUARY 1-MARCH 31, 1971**

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

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DEFICIENT COOLING

7TH QUARTERLY PROGRESS REPORT

January 1 – March 31, 1971

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ABSTRACT

The Seventh Quarterly Progress Report of the Deficient Cooling Program describes tests conducted and presents data obtained in the period January 1 to March 31, 1971. During the quarter, additional single- and two-phase subchannel data were taken for the three unique subchannels in a nine-rod (3 X 3) calrod heater bundle. Transient flow tests were run with a one-rod heater in which the flow was quickly reduced to a low value, nearly zero, and then the original high flow reestablished after a prescribed time. This test is a simple, partial simulation of a loss-of-coolant accident. Film boiling data, taken with a ball-supported heater with annular flow, are also reported.

SUMMARY

Additional single- and two-phase subchannel data were taken for the three unique subchannels in a nine-rod (3 X 3) calrod heater bundle. Spacers, which closely simulated typical reactor fuel bundle spacers, were used on 19-1/2-inch centers with the last spacer 4 inches from the exit end of the heated length. Comparison of the data to that without spacers, shows a pronounced redistribution of flow and quality due to the spacers. The overall effect is an increase of flow and reduction of quality in the corner subchannels and a reduction of flow and increase of quality in the side and center subchannels.

Transient flow tests were run with a one-rod heater in which the flow was quickly (~ 0.2 sec) reduced to a low value, nearly at shutoff with $G/10^6 \leq 0.1$ lb/h-ft², and then the original high flow reestablished after a prescribed time. This test is a simple, partial simulation of a loss-of-coolant accident (LOCA), and provides some insight for CHF occurrence during transient and LOCA conditions. The results show that CHF generally does not occur immediately upon reducing the flow as might have been expected. This was typical for low flow periods up to about 10 seconds. The results indicate enough cooling is provided by quasi-pool boiling at the lower flow to delay CHF at the exit end of the test heater.

Film boiling data, taken with a ball supported heater with annular flow, are presented. Film and transition boiling resulted in the vicinity of the ball supports, up to 2 feet from the exit, without CHF first occurring at the exit end of the heater, as is usually the case. The Nusselt number was found to increase very rapidly with decrease of the heater wall temperature as is usually the case.

ERRATA And ADDENDA SHEET

<u>APPLICABLE TO</u>	
PUBLICATION NO.	<u>GEAP-10221-7</u>
TITLE	<u>Deficient Cooling, 7th Quarterly Progress</u> <u>Report -- January 1-March 31, 1971</u>
ISSUE DATE	_____

NO.	<u>1</u>
DATE	<u>July 1, 1970</u>
<i>NOTE Correct all copies of the applicable publication as specified below.</i>	

ITEM	REFERENCES (SECTION, PAGE, PARAGRAPH, LINE)	INSTRUCTIONS (CORRECTIONS AND ADDITIONS)
1	Page 2-19, first paragraph, second line	Change "stainless steel" to "Inconel 600"

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 $1000 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$ 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,
- c. Transient decrease of pressure which causes flashing and potentially deficient cooling conditions due to increased void content.

Furthermore, it is proposed to study, under transient conditions, 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, electrically-heated rods.
- 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

Acquisition of the ATLAS 8500 kW (eventually 17,000 kW) 2400 psi heat transfer facility at the General Electric, San Jose, California site has stimulated interest in obtaining full length multirod heat transfer data in 4 X 4 and 7 X 7 heater arrays. Such data will be more valuable than most existing data due to its closer simulation of actual flow and heat distributions in large reactor bundles.

The new facility, which will be ready for operation in the spring of 1971, will have a power supply with capability of very rapid transients. Also, the facility includes a high speed data acquisition system which is ideally suited for the transit power and flow tests required on this program.

The work scope of this program has been reoriented to include transient power and flow tests in the large ATLAS heat transfer facility with 4 X 4 heater arrays with typical reactor lengths of 12 feet. These will use cosine type axial heat flux variation with direct current powered resistance heaters. In addition, Task 8 has been expanded to include subchannel enthalpy measurements in a nine-rod bundle to better evaluate the local effects of geometry changes. The large amount of work added by inclusion of the 16-rod arrays and subchannel measurements necessitated some reorientation within the program subtasks of specific tests considered of lesser priority, or that had been accomplished elsewhere since the inception of this program.

Tasks 3, 4, 5 and 8 in Table 1-1 below designate the revised experimental program. Tasks 4 and 8 show the inclusion of 16-rod transient work and 9-rod subchannel measurements, respectively.

Table 1-1
TASK DESIGNATION AND CONTENT

No.	Title	Content
1	Planning and Analysis	a. Review current technology and plan appropriate tests to integrate with required safety programs b. Analysis as necessary to determine test parameters
2a	Design	a. Design new equipment or modifications of existing equipment to carry out test plans
2b	Manufacture	a. Manufacture or purchase new equipment required
3	One-Rod Exploratory Transient CHF Tests	Exploratory tests involving 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: 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	a. Steady-state CHF with simulated swelling at constant coolant pressure drop
6	Data Reduction and Analysis	a. As required for test Tasks 1, 3, 4, 5, and 8
7	Project Administration, Reporting, and Recommendations	a. Administration of entire program b. Regular and topical reporting c. Future recommendations for continued efforts
8	Multirod Geometry Changes 9-Rod	a. Steady-state CHF data with spacer components and simulated fuel rod bowing and swelling b. Subchannel flow and enthalpy measurements.

2. EXPERIMENTAL WORK

2.1 NINE-ROD SUBCHANNEL SAMPLING MEASUREMENTS WITH SINGLE- AND TWO-PHASE FLOW

2.1.1 Introduction

Single- and two-phase sampling data were taken in a nine-rod assembly. The test geometry and procedure have been described in earlier quarterly reports, notably in the third (GEAP-10196), fifth (GEAP-10221-5) and sixth (GEAP-10221-6). The figures showing the test geometry and sampling system have been reproduced here as a convenient reference. Figure 2-1 shows the bundle cross sections with the relevant dimensions. Subchannels 1, 2, and 3 (also referred to as the corner, side, and center subchannels, respectively) are also indicated.

The sampling was performed 4 inches downstream of the center line of the last of five grid spacers positioned as shown in Figure 2-1.

The heated length of the nine uniformly heated rods was 72 inches. Details of the grid spacers used are shown in Figure 2-2. This type spacer is typical of those presently used in light water cooled nuclear reactors.

The three representative subchannels were sampled simultaneously using the sampling system shown in Figure 2-3. Isokinetic calibration runs obtained as described in the sixth quarterly report (GEAP-10221-6) were used to set the sample flow rates.

2.1.2 Results

Table 2-1 shows a summary of the results. Single-phase runs (100° F, 100 psia) were made at four flow rates and two-phase runs for thirteen test conditions. These test conditions listed in Table 2-2 are nominally the same as for the "clean" (no grid spacers) runs which were made earlier under PA-44 funding (GEAP-13049), except for some runs at low subcooling (indicated by primes) which could not be reproduced. Table 2-1 shows the nondimensionalized mass fluxes in the subchannels and the mass and energy defects as defined in the table. As can be seen from the last two columns, the mass and quality defects are consistently small, the RMS values being 2.47% and 0.68%, respectively. These compare favorably with estimated errors (see Error Analysis, Appendix A) of 4% in subchannel flow and 0.30% to 0.60% in subchannel quality.

Some of the steps in the processing of the data are worth mentioning. Heat losses from the subchannel piping between the test section exit and the heat exchanger, and the heat exchanger itself were calibrated with single-phase runs at 400 – 500° F. These corrections were used in determining the subchannel enthalpies at the test section exit. Most of the runs were repeated to check the repeatability of the data which were found to be very good. The data in the table represent the averaged values of these runs.

During some of the high quality tests (e.g., 2B4', 2D3, and 2G3') a small oscillating instability occurred in the side subchannel sampling system (see Figure 2-3).

It was found that this could be eliminated by valving the side subchannel sample through the two-heat-exchanger system normally used for the corner subchannel. Thus for these tests, two sets of data were taken; one, with normal valving (V2, V4, V5 open) to obtain accurate measurement of the corner subchannel, and then with the valving for the corner and side subchannels reversed (i.e., valves V1, V4, V6 open) for accurate sampling of the side subchannel.

At the end of the tests accurate measurements were made of the dimensions of the corner and side subchannels formed by the channel wall, rods, and splitters. This was done by making plaster of paris casts as well as micrometer measurements. The areas were calculated to be 0.0843 in.² and 0.1781 in.², respectively, instead of the nominal values of 0.0796 in.² and 0.1851 in.². The measured areas were used in calculating the mass fluxes in the two subchannels. The dimensions of the center subchannel were also measured and found to be very close to nominal.

Table 2-3 shows a comparison between the present single-phase "cold" data and that taken earlier (reported in the sixth Quarterly Report). Leakage was suspected from the side subchannel at that time and the channel top was reassembled with new gaskets. The agreement between the two sets of data is good for the corner and center subchannels. The side subchannel flow is higher as expected.

Figure 2-4 shows a plot of the subchannel mass fluxes vs the average mass flux. The corner subchannel is seen to have the highest mass flux and the center subchannel the lowest. An examination of the spacer (Figure 2-2) indicates that this is not surprising since the relatively open corner offers much lower resistance to the flow than the "lantern spring" in the center subchannel. The flow split downstream of the spacer remains fairly constant as the bundle average flow is increased.

Figures 2-5 and 2-6 show the subchannel mass fluxes nondimensionalized with respect to the bundle average mass flux) plotted against bundle average quality. Each figure is for a particular series of runs in which the average flow and heat flux were maintained constant. Assuming that the inlet subcooling does not affect the flow distribution to an appreciable extent, these plots can also be interpreted as a reflection of the variation of subchannel flow along the length of the channel. Both figures show that the corner subchannel retains the highest mass flux downstream of the spacer, while the center subchannel has the lowest. The side subchannel has a mass flux close to the average mass flux.

Figures 2-7 and 2-8 show the subchannel quality variations as a function of the average quality. The corner subchannel was found to be the "coldest", being well below bundle average quality. The center and side subchannels have similar qualities and are slightly above the bundle average. The low quality in the corner subchannel is presumably due to the liquid film on the cold canister wall, and the high local flow rates downstream of the spacer.

Figures 2-9, 2-10, and 2-11 show composite plots for the subchannel qualities vs average quality for the individual subchannels. It can be seen that the data for the various series can be superposed showing the subchannel qualities are functions mainly of the bundle average quality and not of the heat flux or flow rate. Examination of the subchannel flow rates shows that these are affected strongly by the heat flux but not by the average flow rate.

2.1.3 Comparison of Data with Spacers to "Clean" Data*

Table 2-4 compares the present data with spacers to corresponding "clean" data* (GEAP-13049, "Subchannel and Pressure Drop Measurements in a Nine-Rod Bundle for Diabatic and Adiabatic Conditions," R. T. Lahey, et al., March 1970, Two-Phase Flow and Heat Transfer in Multirod Geometries, AEC Contract AT (04-3)-189, PA44). The enormous redistribution of flow due to the spacers can be readily observed. This indicates that satisfactory prediction of subchannel thermal-hydraulic parameters requires adequate modeling of the spacer. The spacer used has the highest resistance in the center subchannel and the lowest in the corner subchannel. This is reflected in the data, i.e., a large increase in flow occurs in the corner subchannel while there is a corresponding decrease in flow in the center subchannel. The spacer also has the effect of further reducing the quality in the corner subchannel, and increasing it in the side subchannel.

2.1.4 Conclusion

Two-phase subchannel measurements indicate considerable redistribution of flow and enthalpy downstream of a grid spacer. Prediction of multirod subchannel thermal-hydraulic parameters requires adequate modeling of effects due to rod spacers.

* 1/8 inch pin spacers only.

Figure 2-1 Nine-Rod Test Section Showing Sample Subchannels and Grid Spacer Locations

Figure 2-2 Grid-Type Spacer Details

Figure 2-3 Flow Diagram for Three-Subchannel Sampling System (Nine-Rod Test Section)

Figure 2-4 Subchannel Data for Single-Phase Flow

Figure 2-5 Two-Phase Subchannel Mass Flux Comparisons — 2B Series Runs

Figure 2-6 Two-Phase Subchannel Mass Flux Comparisons – 2E Series Runs

Figure 2-7 Two-Phase Subchannel Quality Comparisons – 2B Series Runs

Figure 2-8 Two-Phase Subchannel Quality Comparisons – 2E Series Runs

Figure 2-9 Two-Phase Subchannel Steam Quality — Subchannel 1 (Corner)

Figure 2-10 Two-Phase Subchannel Steam Quality — Subchannel 2 (Side)

Figure 2-11 Two-Phase Subchannel Steam Quality — Subchannel 3 (Center)

Table 2-1
SUMMARY OF NINE-ROD SUBCHANNEL DATA
(GRID SPACER FOUR INCHES UPSTREAM OF SAMPLING POSITION)

Test Point	$\bar{G}/10^6$ lb/h-ft ²	Steam Weight Fraction $\bar{x}$	Corner		Side		Center		$G_1/\bar{G}$	$G_2/\bar{G}$	$G_3/\bar{G}$	* M. D. % (mass defect)	** E. D. % (energy defect)	$\bar{x} - \hat{x}$
			$G_1/10^6$	x_1	$G_2/10^6$	x_2	$G_3/10^6$	x_3						
1B	0.506		0.568		0.534		0.491		1.123	1.057	0.970	-2.86		
1C	0.988		1.109		1.034		0.963		1.123	1.046	0.975	-2.60		
1D	1.520		1.706		1.622		1.489		1.123	1.070	0.978	-3.81		
1E	2.000		2.303		2.201		1.960		1.151	1.098	0.952	-5.80		
2B2	0.538	0.024	0.593	0.013	0.576	0.020	0.530	0.041	1.101	1.070	0.985	-3.99	-1.38	-0.0033
2B3	0.537	0.089	0.643	0.041	0.511	0.090	0.512	0.100	1.197	1.013	0.953	-0.89	-1.02	-0.0025
2B4	0.547	0.118	0.664	0.063	0.523	0.121	0.522	0.123	1.215	0.971	0.954	1.72	1.57	0.0039
2C1	1.075	0.010	1.228	0.0008	1.106	0.011	1.007	0.018	1.142	1.030	0.936	-0.43	-2.04	-0.0025
2C2	1.086	0.016	1.283	0.006	1.115	0.016	1.079	0.010	1.181	1.026	0.993	-2.99	2.71	0.0033
2D1	0.548	0.109	0.792	0.015	0.542	0.134	0.508	0.137	1.445	0.989	0.927	-1.30	-1.62	-0.0079
2D3	0.542	0.315	0.763	0.146	0.521	0.325	0.411	0.326	1.407	0.961	0.869	2.78	3.43	0.0173
2E1	1.081	0.032	1.440	0.003	1.054	0.034	1.028	0.040	1.332	0.976	0.951	-0.35	-0.101	-0.0002
2E2	1.064	0.118	1.462	0.046	1.034	0.122	0.982	0.128	1.374	0.972	0.923	0.475	1.98	0.0050
2E3	1.095	0.134	1.503	0.071	1.050	0.130	0.968	0.144	1.372	0.959	0.884	2.67	3.17	0.0078
2G1	1.122	0.024	1.614	-0.009	1.018	0.043	1.119	0.033	1.438	0.907	0.955	0.048	-1.90	-0.0069
2G2	1.082	0.096	1.663	0.015	0.886	0.125	1.014	0.100	1.541	0.819	0.937	5.72	-0.0006	-0.0000
2G3	1.030	0.195	1.554	0.080	0.990	0.213	0.913	0.201	1.509	0.961	0.886	1.01	1.98	0.0079

RMS MASS AND ENERGY DEFECTS

A. Two-Phase Data

RMS Mass Defect = 2.47%
RMS Mass Defect Excluding 2G2 (Questionable Side Subchannel Measurements) = 1.97%
RMS Energy Defect = 2.01%
RMS Quality Defect = 0.0068

B. Cold Data

RMS Mass Defect = 3.97%

* M.D. % $\Delta = \left\{ \frac{\bar{G} \sum A_i - \sum G_i A_i}{\bar{G} \sum A_i} \right\} \times 100$, $\hat{x} \Delta = \frac{\sum G_i A_i x_i}{\sum G_i A_i}$

** E.D. % $\Delta = \left\{ \frac{H \sum G_i A_i - \sum H_i G_i A_i}{kW \times 3413} \right\} \times 100$

Table 2-2
TEST CONDITIONS

Test Point	Pressure (psia)	Bundle Average Mass Flux, $\bar{G}/10^6$ (lb/ft ² /h)	Power (kW)	Heat Flux (Btu/ft ² /h)	Subcooling (Btu/lb)	Exit Quality $\bar{x}$
1B	100.	0.506	0.0	0.0	250.0	
1C	100.	0.988	0.0	0.0	250.0	
1D	100.	1.520	0.0	0.0	250.0	
1E	100.	2.000	0.0	0.0	250.0	
2B2	1000.	0.538	525.	225,000.	145.7	0.024
2B3	1000.	0.537	525.	225,000.	103.7	0.089
2B4'	1000.	0.547	525.	225,000.	82.0	0.118
2C1'	1000.	1.075	525.	225,000.	74.2	0.010
2C2'	1000.	1.086	525.	225,000.	69.5	0.016
2D1	1000.	0.548	1050.	450,000.	245.8	0.109
2D3	1000.	0.542	1050.	450,000.	115.5	0.315
2E1	1000.	1.081	1050.	450,000.	139.7	0.032
2E2	1000.	1.064	1050.	450,000.	86.7	0.118
2E3'	1000.	1.095	1050.	450,000.	71.4	0.134
2G1	1000.	1.122	1575.	675,000.	216.4	0.024
2G2	1000.	1.082	1575.	675,000.	178.2	0.096
2G3'	1000.	1.030	1575.	675,000.	126.0	0.195

Table 2-3
SINGLE-PHASE "COLD" DATA (100 psi, 80° F)

$\bar{G}/10^6$	6th Quarterly			Present Data		
	$G_1/\bar{G}$	$G_2/\bar{G}$	$G_3/\bar{G}$	$G_1/\bar{G}$	$G_2/\bar{G}$	$G_3/\bar{G}$
0.50	1.082	0.945	0.896	1.123	1.057	0.970
1.00	1.136	0.969	0.959	1.123	1.046	0.975
1.50	1.138	0.973	0.980	1.123	1.070	0.978
2.00	1.139	0.960	0.981	1.151	1.098	0.952

Table 2-4

COMPARISON OF DATA WITH SPACERS TO "CLEAN" DATA

Test Point	Average Conditions (Spacer Data)		Four Inches Downstream of Spacer						"Clean" Data*					
			Corner		Side		Center		Corner		Side		Center	
	$\bar{G}/10^6$	$\bar{x}$	$G_1/\bar{G}$	$x_1 - \bar{x}$	$G_2/\bar{G}$	$x_2 - \bar{x}$	$G_3/\bar{G}$	$x_3 - \bar{x}$	$G_1/\bar{G}$	$x_1 - \bar{x}$	$G_2/\bar{G}$	$x_2 - \bar{x}$	$G_3/\bar{G}$	$x_3 - \bar{x}$
1B	0.506		1.123		1.057		0.970		0.648		0.962		1.096	
1C	0.988		1.123		1.046		0.975		0.708		0.908		1.162	
1D	1.520		1.123		1.070		0.978		0.725		0.954		1.120	
1E	2.00		1.151		1.098		0.952		0.820		0.969		1.110	
2B2	0.538	0.024	1.101	-0.011	1.070	-0.004	0.985	0.017	0.702	-0.026	0.983	-0.015	1.019	0.001
2B3	0.537	0.089	1.197	-0.048	1.013	0.009	0.953	0.011	1.028	-0.018	0.991	-0.014	0.974	0.014
2C1	1.075	0.010	1.142	-0.009	1.030	0.001	0.936	0.008	0.910	-0.013	1.005	-0.024	1.016	0.017
2D1	0.548	0.109	1.445	-0.094	0.989	0.025	0.927	0.028	0.787	-0.027	1.037	-0.005	1.030	0.007
2D3	0.542	0.315	1.407	-0.169	0.961	0.010	0.869	0.011	0.907	-0.058	0.985	0.012	1.043	0.046
2E1	1.081	0.032	1.332	-0.029	0.976	0.003	0.951	0.008	0.879	-0.031	1.020	-0.009	1.076	0.016
2E2	1.064	0.118	1.374	-0.072	0.972	0.004	0.923	0.010	0.968	-0.057	0.998	-0.009	1.092	-0.001
2G1	1.122	0.024	1.438	-0.033	0.907	0.019	0.955	0.009	0.824	-0.006	0.905	+0.006	1.067	0.005
2G2	1.082	0.096	1.541	-0.081	0.819	0.029	0.937	0.004	0.926	-0.070	1.028	-0.022	1.046	0.020

* 'Clean' Data refers to data taken with 1/8-inch pin type spacers during 1969-70 under PA-44 funding (GEAP-13049).

2.2 ONE-ROD TRANSIENT CRITICAL HEAT FLUX DATA

Critical heat flux data have been taken for transient conditions of system pressure and flow rate in a single-rod annulus. An electrically heated stainless steel heater tube was used which had a 0.540-inch outside diameter, 9-foot heated length and a 0.355-inch annular gap. A schematic of the test arrangement is shown in Figure 2-12. Control of the flow transient is shown schematically in Figure 2-13, and the thermocouples for CHF detection on Figure 2-14. The schedule for visual display of the parameters on two Sanborn recorders is illustrated on Figure 2-15.

The flow transients which were performed were representative of that portion of the BWR design basis loss-of-coolant accident (LOCA) which involves a flow stoppage for a given number of seconds followed by reestablishment of the flow due to lower plenum flashing. This type of flow transient is shown schematically in Figure 2-15. Forty-one runs were made, at initial mass fluxes ranging from 1.0×10^6 to 0.2×10^6 , in which the system pressure was held approximately constant*, and in all except the last few runs, the power was held constant. In the last seven runs, the power was decayed at about 7%/sec to try and obtain CHF at power levels which were more representative of those expected during the LOCA.

In many of the simulated LOCA flow transient runs it was found that the flow could be nearly off for an appreciable period of time (up to ~ 10 seconds) before any indication was seen on the thermocouples, located as shown schematically in Figure 2-14. In fact, it was observed that unless the flow "off" time was sufficiently long, no indication would be seen on the thermocouples during the off time or that period subsequent to reestablishment of the flow.

It was also noted that the temperature excursions experienced by the thermocouples were quite sensitive to the flow off time. A typical example might be that if the flow "off" time was 5.1 seconds, no temperature excursion into and through CHF would be experienced; for 5.25 seconds a temperature excursion would be experienced, but "rewetting" would occur without having to trip the power; for 5.35 seconds a stronger temperature excursion would be experienced which would necessitate a power trip to save the rod. Although this is a hypothetical case, it does illustrate the sensitivity observed to the flow "off" time. It appears that there is enough residual liquid in the test section to maintain cooling by pool boiling, for appreciable periods of time, during the flow "off" condition. Moreover, it appears that in many cases the rod can be "rewet" (i.e., reduce the rod temperature to nucleate boiling levels) with no apparent difficulties once the flow is reestablished. This is illustrated on Figures 2-16 to 2-19.

The single-rod flow transients are tabulated in Table 2-5. The salient parameters of interest, such as flow off time, time to rewet, etc., have been tabulated in self-explanatory fashion to provide an easy reference to the overall trends noted. Typical time tracks of these transients can be seen in Figures 2-16 through 2-19 which are reproductions of the Sanborn recordings of runs 1-139 and 1-165. It can be seen that for run 1-139 the temperature excursions did not occur until the flow had been reestablished. Since at $G = 0.5 \times 10^6$, for run 1-139 on Figures 2-16 and 2-17, the throughput time is about 2.7 seconds, it is apparent that the thermocouples remain uncooled for several seconds after the flow sensor indicates that flow has been reestablished. Once the active coolant reaches the upper thermocouples, they rewet and return to their normal level without a power trip being required.

Run 139, Figures 2-16 and 2-17, was made with a power which corresponded to a uniform heat flux of 215,000 Btu/h-ft². The smooth increase and decrease of the temperature-time gradient may be noted. Run 165, Figures 2-18 and 2-19 was one of the few runs in which CHF occurred before reestablishment of the flow. CHF was expected due to the extremely long time period set for the low flow condition. CHF occurred at 3.5 and 1.9 seconds, on the maximum and minimum temperature thermocouples, respectively, before the end of the 12.7-second low flow period ($G/10^6$ was changed from 0.342 $\rightarrow$ 0.102 $\rightarrow$ 0.342). That is, CHF had not occurred for the first 9.2 to 10.8 seconds, at low flow.

* Even though this is not representative of the level swell causing depressurization in the LOCA, it allows one to separate effects.

Figure 2-12 Test Arrangement

Figure 2-13 Control Schematic for Timing of High-Low-High Flow Transient

RUN NO.	ASSEMBLY NO.	CHANNELS - SANBORN NO. 1				CHANNELS - SANBORN NO. 2*			
		5	6	7	8	1	2	3	4
		CHF - THERMOCOUPLE NO.				CHF THERMOCOUPLE NO.			
116-117	1-14	1	2	4	7	3	5	6	4
118T	↓	↓	↓	↓	↓	↓	↓	↓	↓
122-123	↓	↓	↓	↓	↓	↓	↓	↓	↓
124-138	1-15	5	6	7	8	1	2	4	9
139-153	↓	↓	↓	↓	↓	↓	↓	↓	↓
161-166	↓	↓	↓	↓	↓	↓	↓	↓	↓
178-179	↓	3	5	6	4	1	2	7	9

*THERMOCOUPLES ON SANBORN NO. 2 WERE ALSO RECORDED ON MAGNETIC TAPE THROUGHOUT THE RUNS, FOR RUNS AFTER AND INCLUDING NO. 124.

Figure 2-14 Thermocouple Arrangement for CHF Detection

Figure 2-15 Sanborn Chart Recorders' Schedule with Typical Traces and Nomenclature

Figure 2-16 Sanborn No. 1 Traces — Run No. 1-139

Figure 2-17 Sanborn No. 2 Traces - Run No. 1-139

Figure 2-18 Sanborn No. 1 Traces — Run No. 1-165

Figure 2-19 Sanborn No. 2 Traces — Run No. 1-165

Run 165 was also one of the runs in which a power decay was initiated at the start of the flow transient. The power decay may be noted on Figure 2-19. The power supply has a relatively slow induction regulator which, at its maximum decay rate used on this run, resulted in a change in heat flux on the heater of 231,000 to 139,500 Btu/h-ft² in about 8 seconds. The strong decrease in the rate of temperature rise, due to reduced heat flux and reestablishment of flow, may be noted on Figure 2-18, at 1.5 to 2.0 seconds after flow was increased. Thermocouple 4, Figure 2-18, automatically tripped the power at the preset value of 1500° F. The thermocouples were almost at their maximum temperature just prior to the power trip. The temperature traces indicate the heater would have recovered initial conditions, without the power trip, at a maximum temperature of about 1600° F.

The single-rod flow transient data have been reduced using the code TAPER which has been previously described in the Fourth Quarterly Report (GEAP-10221). This data is quite bulky and will be presented in a separate topical report along with analysis using MAYU (GEAP-10221, 10221-5, the fourth and fifth quarterly reports, respectively).

Ten single-rod depressurization runs have been made. These runs were performed at depressurization rates around 200 psi/sec. This simulates the most rapid depressurization which would be expected during a BWR accident condition. The purpose of this test was to determine if a rapid depressurization might cause a premature CHF condition due to "flash off" of the liquid film on the heater rod. Although the data reduction is not complete, preliminary indications are that depressurization is not detrimental to the thermal performance of the heater rod. This depressurization data will be reported in the next quarterly report along with the appropriate analysis using MAYU.

2.3 SINGLE-ROD FILM AND TRANSITION BOILING DATA

Transition and film boiling data were obtained, as noted in GEAP-10221, the fourth quarterly report, with a 0.540 in. o. d. one-rod direct (resistance) heater with a 9 foot heated length, supported by 1/4-inch diameter sapphire balls with flow in a 0.132-inch annulus. Details of the test heater are shown in Figure 2-20. It was noted, at the time the data were taken, that "hot spots" and film boiling resulted in the vicinity of the balls. This effect was attributed to stagnation areas, with attendant poor circulation and cooling, caused by flow around the closely spaced balls. A typical heat pattern is shown in the Fourth Quarterly Report, GEAP-10221, Figure 4-3. The effect of the closely spaced balls in the small annulus, 0.132 inch, was that transition and film boiling resulted in the vicinity of the balls, located in the last 25 inches of the boiling area, before CHF was experienced at the exit end of the heater. The result emphasizes the need, in reactor fuel rod spacer designs, of good coolant circulation around the areas of contact between the spacer and rod, and avoidance of excessively tight clearances. The latter may not only cause hot spots, but also result in adverse flow and enthalpy distributions.

The data obtained have been reduced recently and are summarized in Table 2-6. Standard correlating groups and equations used to examine trends in the data are the Colburn equation

$$\left(\frac{hD}{k}\right)_f = 0.023 \left(\frac{DG}{\mu}\right)_f^{0.8} \left(\frac{c_p \mu}{k}\right)_f^{0.4} \quad (2-1)$$

using the Nusselt, Reynolds, and Prandtl groups, and the Martinelli Chi parameter

$$\frac{1}{X_{tt}} = \left(\frac{x_L}{1-x_L}\right)^{0.9} \left(\frac{\rho_L}{\rho_{gf}}\right)^{0.5} \left(\frac{\mu_L}{\mu_{gf}}\right)^{0.1} \quad (2-2)$$

where

- x_L = local steam weight quality
- ρ_L, ρ_g = density of liquid and gas phases
- μ_L, μ_g = viscosity of liquid and gas phases

Table 2-5

SUMMARY OF SALIENT VARIABLES DURING ONE-ROD TRANSIENT FLOW TESTS (HIGH-TO-LOW-TO-HIGH FLOW)

P = 1000 psia
All times in seconds
All temperatures in °F

Date	Run Number	T _i Inlet Temperature (°F)	Δh _s Sub-cooling (Btu/lb)	kW Power	φ/10 ³ (Btu/h-ft ²)	w _H Filter Orifice (lb/sec)	w _L (lb/sec)	G _H /10 ⁶ (lb/h-ft ²)	G _L /10 ⁶ (lb/h-ft ²)	x _e %	T _O (1)	ΔT _c		T _m (4)		T _m - T _O		T _{w1}		T _{w2}		ΔT _w		T _m		TC9 (-) is no CHF	T _{PT}	ΔT _{PT}	Manual or Auto Power Trip or Power Decay (Blank - if no trip)		Comments
												T _c (2)	(T _c - T _O)	T _{max}	T _{min}	max/min	max/min	T _{max} /T _{min}	T _{max} /T _{min}	T _{max} /T _{min}	T _{max} /T _{min}	max/min	max/min	Max TC No./°F	Min TC No./°F						
1/20	116	484	69.5	212	568			0.509	0.414	17.8	4.0																				No CHF, No Orifice Flow Reading
	117	484	69.5	212	568			0.509	0.342	17.8	4.0	1.8/1.8	-2.2/-2.2	4.0	+3.6	0/-0.40		6.4/5.8	N.D.	N.D.	-/600	1313/913	850/475	3/1510	5/1030		3.0	-1.0	1313/888	Auto	
1/21	118T	456	106	147	394	0.91	0.467	0.473	0.243	27.5	1.4	2.0/2.0	0.60/0.60	5.0	3.12	3.6/1.72		5.0/3.12	7.55/4.02	2.55/1.9	537/512	1394/895	825/400	2/1394	7/895						
1/22	122	522	28	160.5	430	1.94	0.640	1.008	0.333	8.0	1.16	-1/92	-0/76		5.28	-4.12		-10.6	N.D.	N.D.	625	-/1000	N.D.		3/1425		4.84	3.68	-/1375	Auto	Max Exceeds Chart: Max on TC 7, Magnetic Tape Data Not Taken
	122R	522	28	160.5	430	1.94	0.620	1.008	0.322	8.0	1.12	-1/72	-0/60		4.96	-3.84		-12.76	-/14.88	-/2.12	625	-/838	-/275		3/1438		4.56	3.44	-/1388	Auto	T _{ss} is for thermocouple 3 (T _{min}), T _{max} exceeds chart.
	123	522	28	161.5	433	1.94	0.615	1.008	0.320	8.1	1.04	1.88	0.84			-/-		N.D.	N.D.		575	N.D.	N.D.								Rod burned out.
1/26	124										3.04	3.14/3.96	0.10/0.92	4.64	4.44	1.6/1.4		N.D.	N.D.	N.D.	650/600	N.D.		8/750	6/650						No Sanborn 2, No power trip.
	125	524	25.0	104.1	279	1.823	0.218	0.947	0.113	4.5	3.08	-3/64	-0/56	10.375	10.44	7.295/7.36		-18.64	-/21.84	-/3.2	-/575	-/813	-/238	4/1677	5/1369		8.0			Auto	T _m max and T _m max from digital output.
	126	520	32.0	78.0	209	1.588	0.159	0.825	0.083	2.2	4.92	5.52/5.32	0.6/0.4	10.16	10.16	5.24/5.24		14.44/14.84	16.44/16.36	2.0/152	600/575	1005/800	475/225	4/1463	5/1075		9.88	4.96	1660/1200	Auto	
	126R	521	29.6	78.8	211	1.625	0.180	0.844	0.094	2.5	4.86	4.76/4.66	-0.10/-0.20	9.90	8.86	5.04/4.0		9.9/8.86	12.9/10.86	3.0/2.0	588/638	1433/1125	825/475	4/1433	8/1125						
	128	521	30.2	101.2	271	1.624	0.189	0.844	0.098	4.4	3.0	3.6/4.1	0.60/1.1	4.75	4.75	1.75/1.75		N.D.	N.D.	N.D.	650/612	N.D.	N.D.	8/775	6/725						Sanborn 2 missing.
	129	520	32.0	100.9	270	1.610	0.178	0.837	0.092	4.2	3.18	3.78/3.68	0.60/0.50	8.54	8.74	5.36/5.08		15.94/15.02	17.9/17.02	1.96/2.0	588/575	825/738	238/175	0/1480	9/1200						Sanborn 2 missing.
	130	504	50.4	79.2	212	0.995	0.122	0.501	0.063	4.4	5.24	6.04/5.44	0.80/0.20	11.04	11.44	5.8/5.2		15.56/15.92	N.D.	N.D.	588/563	955/770	N.D.	4/1425	5/1075						
	131	506	47.8	79.5	213	0.982	0.113	0.500	0.059	4.7	5.32	6.08/6.32	0.75/1.0	6.92	6.82	1.5/1.5		N.D.	N.D.	N.D.	588/575	900/763	325/200	4/900	1/763						
	132	506	47.2	79.2	212	0.970	0.103	0.504	0.054	4.6	5.48	6.56/6.56	1.08/1.08	8.16	8.40	2.68/2.92		8.16/8.4	10.66/10.7	2.5/2.3	588/575	960/775	425/213	4/1813	5/1350						
	133	506	46.7	79.3	213	0.960	0.102	0.499	0.053	4.9	5.68	6.12/6.12	0.44/0.44	14.12	15.32	8.44/9.64		21.72/22.8	N.D.	N.D.	588/562	960/775	425/213	4/1813	5/1350						
	134	504	51.3	83.9	225	0.956	0.101	0.497	0.052	4.8	5.64	6.04/6.64	0.40/1.0	14.64	15.64	9.0/10.0		22.64/22.89	N.D.	N.D.	613/563	1000/788	N.D.	4/1620	5/1383						
	135	500	56.4	83.2	223	0.960	0.099	0.499	0.051	4.0	5.60	6.12/6.7	0.52/1.1	16.125	16.44	10.525/10.84		N.D.	N.D.	N.D.	600/563	N.D.	N.D.	4/1680	5/1383						
	136	503	53.7	100.9	270	0.958	0.125	0.498	0.065	7.2	3.44	4.12/4.14	0.68/0.7	8.3	8.32	4.86/4.88		10.9/11.4	15.7/15.7	4.8/4.3	625/575	1200/913	663/413	4/1463	5/1125						T _{max} and T _{max} from digital.
	137	504	53.1	101.3	271	0.949	0.132	0.493	0.069	7.2	3.36	4.86/4.36	1.5/1.0	6.00	5.40	2.64/2.04		6.0/-	7.8/-	1.8/-	638/575	838/-	213/-	8/838	5/600						
	138	503	52.6	101.4	272	0.949	0.111	0.493	0.058	7.3	3.44	4.68/4.84	1.24/1.4	13.64	13.44	10.2/10.0		N.D.	N.D.	-/10.0	638/588	-/1225	N.D./700	8/1750	1/1500						Wetting data after second power trip.
1/27	139	506	48.1	80.3	215	0.956	0.170	0.497	0.088	4.6	5.56	6.26/7.06	0.70/1.5	11.48	15.28	5.92/9.72		N.D.	N.D.	N.D.	600/563	N.D.	N.D.	4/1500	8/913						
	140	502	52.9	100.5	269	0.961	0.172	0.499	0.089	6.4	3.4	4.6/4.9	1.2/1.5	5.24	5.4	1.84/2.0		N.D.	N.D.	N.D.	600/575	N.D.	N.D.	4/650	1/588						
	141	505	50.3	98.7	265	0.950	0.206	0.494	0.107	6.5	3.32	4.4/5.67	1.08/2.35	10.6	13.4	7.28/10.08		14.4/-	18.6/-	4.2/-	600/575	1375/975	850/-	4/1613	8/1125						
	142	504	51.1	97.6	262	0.962	0.193	0.500	0.100	6.1	3.32	4.0/5.22	0.68/1.9	11.80	14.0	8.48/10.68		N.D.	N.D.	-/-	600/575	1400/1225	N.D.	4/1605	8/1233						
	143	502	53.6	98.8	265	0.966	0.207	0.502	0.108	6.0	3.28	4.58/5.58	1.3/2.3	10.52	13.84	7.24/10.56		17.32/-	N.D./N.D.	N.D.	588/575	975/1050	N.D./N.D.	4/1608	8/1138						
	144	507	48.7	99.6	267	0.958	0.206	0.498	0.107	6.8	3.20	4.32/5.3	1.12/2.1	11.0	13.52	7.8/10.32		N.D.	N.D.	N.D.	613/588	1200/1225	N.D./N.D.	4/1673	8/1250						
	145	505	50.1	99.5	267	0.953	0.210	0.495	0.109	6.7	3.08	4.08/4.18	1.0/1.1	5.52	5.48	2.44/2.40		N.D.	N.D.	N.D.	600/588	N.D.	N.D./N.D.	4/855	5/700						Digital used for T _{max} .
	146	506	48.7	100.5	269	0.965	0.200	0.501	0.104	6.6	3.16/3.16	N.D.	-	N.D.	N.D.	-		N.D.	N.D.	N.D.	588/600	1375/-	N.D.	4/1677	8/1470						
	147	505	48.9	98.5	264	0.951	0.175	0.494	0.091	6.3	3.2	4.25/5.5	1.05/2.3	11.825	14.88	8.625/11.68		N.D.	N.D.	N.D.	575/575	1350/-	700/-	4/1508	8/925						CHF indicated for thermocouple 2 for 0.4 sec. at τ = 4.66
	148	502	51.0	83.3	223	1.00	-	-	-	4.4	15.72	5.92/8.52	-9.8/7.2	12.12	15.32	-3.6/-0.40		14.92/-	16.92/-	-2.0/-	N.D.	N.D.	N.D.	4/1677	8/1470						
	150	482	75.8	78.7	211	0.671	0.225	0.349	0.117	7.4	5.4	6.6/6.6	1.2/1.2	7.6	7.15	2.2/-		N.D.	N.D.	-	600/600	N.D.	N.D.	2/625	-						Flow did not come back to original value until τ = 8.52
	151	485	73.4	78.5	210	0.578	0.221	0.300	0.115	5.5	7.65	7.25/6.95	-0.40/-0.70	8.7	7.15	1.05/-0.50		8.7/-	10.5/-	1.8/-	600/575	837.5/-	250/-	4/837.5	7/600						Valve stuck, partially opened from τ = 6 to τ = 7.65
	152	483	76.6	78.6	211	0.596	0.211	0.310	0.110	7.4	6.4	6.9/6.9	0.50/0.50	8.3	8.10	1.9/1.7		N.D.	N.D.	N.D.	625/575	N.D.	N.D.	4/838	5/613						
	153	488	69.8	79.9	214	0.656	0.228	0.341	0.118	8.4	7.70	6.7/8.3	-1.0/0.60	13.5	17.70	5.8/10.0		22.05/-	26.25/-	4.2/-	650/588	1000/-	450/-	4/1670	8/1175						
1/28	163	482	95.9	85.4	229	0.592	0.191	0.308	0.099	7.4	6.3					-/-		N.D.	N.D.	N.D.	-/588	N.D.	N.D.	4/825	1/600						Power - decay
	164	482	95.0	84.9	228	0.618	0.202	0.321	0.105	5.43	10.60	10.6/10.6	0.0/0.0	11.50	11.60	0.9/1.0		N.D.	N.D.	N.D.	-/563	1063/-	375/-	8/1500	8/1135						Power - decay
	165	488	89.1	86.8	233	0.659	0.197	0.342	0.102	7.3	12.70	9.2/10.8	-3.5/-1.9	23.2	24.80	10.5/12.1		28.1/-	44.7/-	16.6/-	-/563	1063/-	375/-	8/1500	8/1135						Power - decay
	166	(not recorded)									11.6	10.5/12.3	-1.1/+0.70	16.8	18.3	5.2/6.7		16.8/-	25.0/-	8.2/-	-/575	1215/-	500/-	4/1215	8/713						Power - decay
2/2	178	473	78.0	80.0	214	0.385	0.245	0.200	0.127	11.0	6.0	-/-	-/-			-/-				5.0/7.2	600/563	913/825	400/325	6/1300	5/1187						Recorder off - Sanborn drive stopped. T _c not available.
	179	466	87.0	80.0	214	0.385	0.278	0.200	0.144	10.4	5.56	-/-	-/-			-/-															Recorder off - Power decay to minimum in 10 sec. No CHF.

(1) T_O, from filtered orifice readings on Sanborn Chart SB1.(2) T_c,

Table 2-6

SINGLE-ROD FILM BOILING RESULTS, PRESSURE = 1000 psia

Run Number	$G/10^6$ (lb/h-ft ²)	$\phi/10^3$ (Btu/h-ft ²)	TC Number Location From Start of Heated Length (in.)	ΔT Film (°F)	h_f (Btu/h-ft ² °F)	NRE At Mean Film Temperature	$\left(\frac{hD}{k}\right)_f$ At Mean Film Temperature	x_L Local Steam Quality	x_e Exit	h_o (Btu/h-ft ² °F) At Saturation	h_f/h_o	$1/X_{tt}$
87	0.489	354.7	6/95.63	230	1543	200,390	1000	0.494	0.494	1770	0.872	5.847
88	0.489	365.3	6/95.625	390	963	183,850	580	0.425	0.511	1770	0.544	4.781
90	0.967	510.8	6/95.625	302	1688	381,030	1070	0.309	0.369	3054	0.553	2.965
91	0.967	523.7	6/95.625	354	1478	370,388	920	0.329	0.391	3054	0.484	3.271
91	0.967	523.7	9/82.625	106	4932	427,550	3190	0.264	0.391	3054	1.615	2.257
91	0.967	523.7	8/87.625	204	2569	402,740	1670	0.289	0.391	3054	0.841	2.632
101	0.479	306.4	6/95.625	287	1067	190,140	680	0.426	0.499	1741	0.613	4.656
101	0.479	306.4	5/99.25	110	2793	211,180	1810	0.447	0.499	1741	1.604	4.695
101	0.479	306.4	9/82.625	802	382	149,370	290	0.349	0.499	1741	0.219	3.916
95	0.481	291.0	6/95.625	52	5596	220,520	3540	0.411	0.480	1747	3.204	3.990
95	0.481	291.0	9/82.625	129	2255	209,830	1470	0.338	0.480	1747	1.291	3.134
96	0.947	448.4	9/82.625	150	2991	407,660	1950	0.263	0.374	3003	0.996	2.292
97	0.946	451.8	9/82.625	400	1128	353,840	690	0.267	0.379	3000	0.376	2.536
102	0.955	458.1	8/87.625	179	2556	403,550	1670	0.299	0.389	3023	0.845	2.723
102	0.955	458.1	7/91.625	181	2524	403,000	1650	0.317	0.389	3023	0.835	2.940
103	0.505	405.7	6/95.625	404	1003	189,130	620	0.400	0.491	1816	0.552	4.373
103	0.505	405.7	5/99.25	340	1194	195,610	750	0.427	0.491	1816	0.657	4.749
104	0.993	601.5	6/95.625	468	1285	358,770	770	0.288	0.358	3119	0.412	2.835
104	0.993	601.5	8/87.625	259	2320	400,270	1490	0.243	0.358	3119	0.744	2.170
104	0.993	601.5	7/91.625	220	2740	409,470	1780	0.265	0.358	3119	0.878	2.376
104	0.993	601.5	9/82.625	154	3899	425,720	2550	0.215	0.358	3119	1.250	1.809
106	0.267	234.5	1,2,3/107.625	360	651	101,840	5.0	0.644	0.647	1091	0.597	10.61
75	0.602	356.7	6/95.625	307	1162	236,820	740	0.393	0.461	2090	0.556	4.143
100	0.976	559.9	6/95.625	344	1629	377,110	1020	0.312	0.377	3076	0.530	3.041
100	0.976	559.9	7/91.625	194	2885	410,270	1880	0.291	0.377	3076	0.938	2.645
100	0.976	559.9	8/87.625	168	3337	416,820	2180	0.270	0.377	3076	1.085	2.384
100	0.976	559.9	9/82.625	75	7490	442,070	4780	0.243	0.377	3076	2.435	2.010
105	1.584	741.3	9/82.625	156	4742	677,640	3100	0.151	0.261	4532	1.046	1.228
98	1.931	574.7	8/87.625	140	4102	835,340	2680	0.169	0.226	5310	0.772	1.375
98	1.931	574.7	9/82.625	154	3743	828,470	2450	0.156	0.226	5310	0.705	1.260
99	1.57	678.1	8/87.625	195	3478	657,490	2270	0.189	0.27	4500	0.773	1.590
99	1.57	678.1	9/82.625	152	4472	674,890	2920	0.169	0.27	4500	0.994	1.382
93	1.48	605.5	9/82.625	434	1396	543,620	850	0.195	0.291	4292	0.325	1.772
94	1.468	596.5	9/82.625	327	1826	570,910	1150	0.201	0.296	4264	0.428	1.780

Figure 2-20 Thermocouple and Support Arrangement for One-Rod Heater

In both of the above equations and Table 2-6, the subscript f, means all steam properties are evaluated at 1000 psia and the mean film temperature,

$$\bar{T} = T_s + \frac{\Delta T}{2}, \text{ where}$$

T_s = saturation temperature

ΔT = temperature difference between heater wall and saturation

The subscript, o, means all properties are evaluated at saturated conditions.

The data are plotted with different combinations of parameters on Figures 2-21 through 2-23. Figure 2-21 shows the characteristic rapid decrease of the Nusselt number as quality increases, due to large decrements of h_f , and increase of k for steam at the heated wall. Error in the Nusselt number will be relatively high due to the use of standard uncalibrated thermocouples. However, the quality range in which transition occurs increases as mass flux is reduced.

The graph of Nusselt number vs Reynolds number, Figure 2-22, shows a smooth, rapidly increasing Nusselt number, from stable film boiling to high values with nucleate boiling. The Nusselt number is not simply correlated by the Reynolds number, in two-phase transition boiling, and separate transition curves are obtained at each mass flux. Reynolds numbers were calculated using k for steam at the mean film temperature

Figure 2-23 shows the Martinelli Chi parameter plotted against the ratio of the actual two-phase heat transfer coefficient, and that for saturated liquid, h_o , using Equation 2-1 evaluated with properties at saturated conditions. This type of plot was suggested by Figure 5-7 of reference¹ below. The Chi parameter and heat transfer coefficient ratio show a trend, at each mass velocity, with considerable scatter. Correlation is poor for the conditions at which the data were taken.

The data were put into the correlating groups used in reference 2 for stable film boiling. The equation from the latter is

$$\left(\frac{hD}{k}\right)_f \left(\frac{1-\alpha}{\alpha}\right) = 0.492 \left(N_{RE} \frac{(1-x_L)}{x_L} \cdot 10^{-3}\right)^{0.853} \cdot Pr^{1.3}, \quad (2-3)$$

where α , the steam area fraction, is given by

$$\alpha = \frac{1}{1 + \frac{S\rho_g}{\rho_L} \left(\frac{1-x}{x}\right)}, \text{ and}$$

S , the slip ratio is given by $S = (\rho_L/\rho_g)^{1/3}$. Comparison of Equation 2-3, with the present data, is shown on Figure 2-24. The figure shows that most of the data is in the transition boiling region. The same conclusion may be reached from Figure 2-22, where unweighted Nusselt and Reynolds numbers were used.

(1) L. S. Tong, Boiling Heat Transfer and Two-Phase Flow, John Wiley and Sons, (1967).

(2) E. E. Polomik, S. Levy, S. G. Sawochka, "Film Boiling of Steam-Water Mixtures in Annular Flow at 800, 11,00, and 1400 psi," ASME Paper 62-WA-136 (1962).

Figure 2-21 Film and Transition Boiling — Nusselt Number vs Steam Quality

Figure 2-22 Film and Transition Boiling — Nusselt vs Reynolds Number

Figure 2-23 Film and Transition Boiling - Martinelli Chi Parameter vs h_f/h_o

Figure 2-24 Film and Transition Data Compared to Correlation of Reference Cited

3. COMPUTER PROGRAMS FOR TRANSIENT DATA REDUCTION

Two types of programs have been written: (1) TAPER, which is designed primarily for use with analog — magnetic tape recording techniques, and (2) FILTER, and TRDATA which are adaptable to the analog or digital data acquisition systems.

The TAPER program for filtering; backing out instrumentation lags; and conversion to engineering units has been completed. The program was checked out on a series of cold flow transients and was applied to the reduction of the latest one-rod transient data. An improved version of TAPER, which separates the numerical filtering and the conversion to engineering units into two separate activities, has also been written.

The new programs, which were primarily written to gain flexibility for data taken in the ATLAS loop, are a numerical filtering and data sorting program called FILTER, and a reduction program called TRDATA. Both programs have been successfully checked out against TAPER for the latest one-rod data. The TRDATA program includes a computer plotting routine which can show four variables. A sample plot is shown in Figure 3-1.

Figure 3-1 Sample Computer Plot

4. HEATER DEVELOPMENT

Calrod type heaters* are required on this program, in nine-rod test sections which use metallic spacers and a three-phase power supply, to avoid stray currents between heaters.

At the initiation of this program it was planned to purchase the bulk of calrod-type heaters from outside vendors, as the personnel and heater manufacturing facilities at San Jose were limited. Thus calrod heaters were ordered, early in the program, from two outside vendors.

The 9/16-inch diameter heaters on this program must withstand rugged operating conditions of up to 1×10^6 Btu/h-ft² surface heat flux and desired surface temperatures up to 1200°F, or more if feasible, and be sealed for operation up to 1500 psi. These special requirements necessitate many design and manufacturing techniques that must be developed by suppliers who are not experienced. Delivery on calrod orders has fallen behind schedule very seriously. It was necessary to reject one order of uniform flux rods due to excessive failures in pretesting prior to assembly. Backup rods were made at the San Jose facility to avoid further delays in test schedules. Delivery on axial cosine flux rods is expected in the next quarter, when they will be pretested to determine adequacy for full-scale operating conditions.

The Development Test Engineering Group at San Jose, under B. Matzner, has manufactured direct uniform flux heaters which will be used in shakedown tests for the new ATLAS, 8.6 MW, Heat Transfer Facility at San Jose in June of the next quarter. In addition, direct heaters with a cosine-type axial heat flux have been designed, and are under construction. It has been planned that the above types of heaters will also be used on this program, although some minor modifications may be incorporated as indicated by the shakedown tests.

* "Calrod-type" heaters have a heating element enclosed in, and electrically insulated from, the heat transmitting sheath, as opposed to "direct" heaters in which the heat is electrically generated in the heat transmitting sheath.

APPENDIX A

ERROR ANALYSIS FOR SIMULTANEOUS SAMPLING OF THREE SUBCHANNELS
OF A NINE-ROD SQUARE ARRAYED BUNDLE

A-1 ERROR IN SUBCHANNEL FLOW

Due to error in isokinetic setting and turbine flow measurement,

$$\Delta G_{ch}^2 = \left[\frac{\partial G_{ch}}{\partial (\Delta P)} \cdot d(\Delta P) \right]^2 + \left[\frac{\partial G_{ch}}{\partial W_{ch}} \cdot dW_{ch} \right]^2$$

ΔP = Isokinetic pressure differential

W_{ch} = Turbine meter flow rate

Typical values for the corner subchannel for $G_{ch} \sim 1.0 \times 10^6$ lb/ft²-h, $d(\Delta P) = 0.010$ psi (inaccurate setting and reading)

$$\frac{\partial G_{ch}}{\partial (\Delta P)} = 3.25 \times 10^6 \frac{\text{lb/ft}^2 \cdot \text{h}}{\text{psi}} \quad (\text{from nonisokinetic data, GEAP-13049})$$

$$dW_{ch} = 11 \text{ lb/h (i.e., 2\% of } W_{ch})$$

$$\frac{\partial G_{ch}}{\partial W_{ch}} = \frac{1}{A_{ch}} = \frac{1}{0.000552} \text{ ft}^2$$

$$\Delta G_{ch}^2 = (3.25 \times 10^6 \times 0.01)^2 + (11/0.000552)^2$$

$$\therefore \left[\frac{\Delta G_{ch}}{10^6} \right]^2 = (0.0325)^2 + (0.0100)^2$$

$$\Delta G_{ch} \approx 0.038 \times 10^6 \text{ lb/ft}^2 \cdot \text{h}$$

Similar numbers are obtained for the other two subchannels. For $G_{ch} \sim 0.5 \times 10^6$, the percentage error is a little larger due to the higher value of $\frac{\partial G_{ch}}{\partial (\Delta P)}$.

A-2 ERROR IN SUBCHANNEL QUALITY

A-2.1 Heat Balance Runs.

A number of heat balance runs were made (see Table A-1) under single-phase conditions at 400-500°F, which yield the total error due to measurement and heat loss.

Table A-1
HEAT BALANCE RUNS

Run Number	Corner Subchannel Btu/h	Side Subchannel Btu/h	Center Subchannel Btu/h
1	6,431	3,192	-3,210
2	5,540	1,552	7,921
3	5,140	11,981	-4,758
4	5,781	10,902	-3,386
5	5,627	6,700	6,316
6	6,523	9,064	12,473
7	5,119	16,680	13,083
8	5,414	9,744	14,677

The mean values and standard deviations for the "heat balance defects" in Btu/h are:

$$\bar{Q}_1 = 5697, \quad \sigma_{Q_1} = 496$$

$$\bar{Q}_2 = 8727, \quad \sigma_{Q_2} = 4554$$

$$\bar{Q}_3 = 5390, \quad \sigma_{Q_3} = 7556$$

It is assumed that $\bar{Q}$ is the mean heat loss from the heat exchanger and σ_{Q_1} is the mean error in the measurement of temperatures and flows.

A-2.2 Accurate Subchannel.

This is the subchannel sampling scheme (1) with two heat exchangers HE1 and HE1' shown in Figure 2-3 (normally used with the corner subchannel). The error in measured enthalpy from the true isokinetic enthalpy is obtained from

$$H_{ch} = \underbrace{\left[H_2 + H_3 - H_4 + \frac{\bar{Q}_1}{W_{ch}} \right]}_{\text{measurement}} + \underbrace{\Delta H_{iso}}_{\text{nonisokinetic sampling error}} + \underbrace{d \left[\frac{\bar{Q}_1}{W_{ch}} \right]}_{\text{heat balance error}}$$

$$\Delta H_{iso} = \frac{\partial H_{ch}}{\partial (\Delta P)} \cdot d(\Delta P)$$

$$d \left[\frac{\bar{Q}_1}{W_{ch}} \right] = \frac{\sigma_{Q_1}}{W_{ch}} + \frac{\bar{Q}_1}{W_{ch}^2} \cdot dW_{ch}$$

Thus the best estimate of ΔH_{ch} (error in subchannel enthalpy) is given by

$$\Delta H_{ch}^2 = \left[\frac{\partial H_{ch}}{\partial (\Delta P)} \cdot d(\Delta P) \right]^2 + \left[\frac{\sigma_{Q_1}}{W_{ch}} + \frac{\bar{Q}_1}{W_{ch}^2} \cdot dW_{ch} \right]^2$$

For $G \sim 1.0 \times 10^5$ lb/ft²-h

$$\frac{\partial H_{ch}}{\partial (\Delta P)} = 125 \frac{\text{Btu/lb}}{\text{psi}}, \quad (\text{from nonisokinetic data, GEAP-13049}), \quad d(\Delta P) = 0.010 \text{ psi}$$

$$\sigma_{Q_1} = 500 \text{ Btu/h}, \quad W_{ch} = 550 \text{ lb/h}, \quad dW_{ch} = 11 \text{ lb/h},$$

$$\text{and } \Delta H_{ch}^2 = \left[125 \times 0.01 \right]^2 + \left[\frac{500}{550} + \frac{5700}{(550)^2} \times 11 \right]^2$$

$$\Delta H_{ch} = 1.67 \text{ Btu/lb}$$

$$\Delta x_{ch} = 0.0026$$

A-2.3 Side Subchannel.

$$H_{ch} = \underbrace{\left[\frac{F_{cw}}{W_{ch}} \cdot C_p \cdot \Delta T_{cw} + H_{out} + \frac{\bar{Q}_2}{W_{ch}} \right]}_{\text{measurement}} + \underbrace{d \left[\frac{\bar{Q}_2}{W_{ch}} \right]}_{\text{measurement error}} + \underbrace{\Delta H_{iso}}_{\text{nonisokinetic error}}$$

$$F_{cw} = \text{cooling water flow}$$

$$\Delta T_{cw} = \text{cooling water } \Delta T$$

For $G_{ch} \sim 1.0 \times 10^6$ lb/ft²-h, $W_{ch} = 1285$ lb/h, $dW_{ch} = 26$ lb/h

$$\therefore \Delta H_{ch}^2 = \left[\frac{\sigma_{Q_2}}{W_{ch}} + \frac{\bar{Q}_2}{W_{ch}^2} \cdot dW_{ch} \right]^2 + \left[\frac{\partial H_{ch}}{\partial \Delta P} \cdot d\Delta P \right]^2$$

$$= \left[\frac{4550}{1285} + \frac{8730}{(1285)^2} \times 26 \right]^2 + (125 \times 0.01)^2$$

$$\Delta H_{ch} = 3.88 \text{ Btu/lb}$$

$$\Delta x_{ch} = 0.0060$$

A-2.4 Center Subchannel.

Same as the side subchannel above but with $\bar{Q}_3 = 5390 \text{ Btu/h}$, $\sigma_{Q_3} = 7550 \text{ Btu/h}$, $W_{ch} = 2085 \text{ lb/h}$, $dW_{ch} = 42 \text{ lb/h}$.

$$\Delta H_{ch}^2 = \left[\frac{7550}{2085} + \frac{5390}{(2085)^2} \times 42 \right]^2 + (125 \times 0.01)^2$$

$$\Delta H_{ch} = 3.88 \text{ Btu/lb}$$

$$\Delta x_{ch} = 0.0060$$

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