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**TWO-PHASE FLOW
AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
-FINAL REPORT**

E. JANSSEN

U.S. ATOMIC ENERGY COMMISSION
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PROJECT AGREEMENT 44

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TWO-PHASE FLOW AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
FINAL REPORT

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SUMMARY

The program known as PA-44, for which this is the Final Report, is an investigation of two-phase flow in multirod coolant channels characteristic of a large class of modern water-cooled nuclear reactors. Its purpose is the more accurate determination of the mechanisms associated with boiling heat transfer which ultimately limit the rate of heat transfer from the rods to the coolant.

Phase I of the program started October 26, 1964. Under Task A, detailed measurements were made of pressure drop/wall shear stress, liquid film thickness, liquid film flow rate, local mass velocity, and local quality for fully developed adiabatic flow in both simple and multirod channels. A model of fully developed annular-dispersed flow was developed based on these and other results which shows, for example, the relationship between entrainment fraction and pressure gradient, correlates much of the world data pertaining to entrainment fraction in simple channels, and shows the presence of anomalies in some of the remainder of the world data. Under Task B, measurements were made of critical heat flux in a "clean" nine-rod channel, trends in the data with certain parameters were pointed out, and various schemes for correlating multirod critical heat flux (CHF) data were assessed. It was concluded that the schemes using average channel conditions had serious limitations, but that a scheme considering individual subchannel conditions would provide the means for a more general correlation of multirod CHF data.

Phase II started January 1, 1968. Under Task C, measurements have been made of pressure drop, liquid film thickness, and liquid film flow rate for developing diabatic flow in simple channels, and subchannel and pressure drop measurements have been made for both adiabatic and diabatic developing flow in a nine-rod channel. These latter measurements provide essential, and previously lacking, inputs to subchannel schemes for predicting multirod CHF. Finally, under Task D, measurements have been made of CHF in a nine-rod channel fitted with grid-type spacers characteristic of modern water-cooled reactors. The tests were run with various axial arrangements of the spacers with respect to the heated length, to better understand their effect on CHF. The results showed, for example, that CHF prefers to occur directly ahead of a spacer. An analysis and some simple experiments in a shallow water channel identified mechanisms which would cause "dryout" directly ahead of an obstruction, and so help to explain some of the Task D findings.

There are a total of 12 topical reports (including this final report) which have been generated on PA-44. A total of possibly six papers have been or will be submitted for presentation at technical society meetings and/or publication in their journals. We believe that these will prove to be a contribution to water-cooled reactor technology in the years ahead.

INTRODUCTION

Many important systems involve two-phase flow and boiling heat transfer. Notable among these are water-cooled nuclear power reactors. The nuclear fuel is in the form of metal-clad rods, arranged in evenly spaced arrays or bundles. Each bundle in turn is installed in a channel. The coolant enters at one end of the channel as a liquid, and flows parallel to the rods in the spaces (subchannels) between them. In the process of cooling the rods, boiling of the coolant takes place. The flowing coolant becomes a mixture of liquid and vapor, i.e., it becomes two-phase flow.

The program for which this is the final report is, as its name implies, an investigation of two-phase flow in multirod coolant channels. Its purpose is to determine more accurately the nature of the mechanisms associated with boiling heat transfer which ultimately break down when the heat flux exceeds a certain critical value, and which thereby limit the rate of heat transfer from the rods to the coolant. Hopefully, armed with such knowledge it will then be possible to develop more accurate prediction schemes for the critical heat flux under flow boiling conditions.

Phase I of the program started October 26, 1964. The objectives for Phase I were:

Task A

1. Obtain detailed measurements of flow structure (pressure drop, liquid film thickness, wall shear stress, local mass flux, local impact pressure) for air-water and steam-water mixtures.
2. Carry on an analytical effort in parallel with the air-water tests.

Task B

1. Measure the critical heat flux for a vertical nine-rod geometry, under forced convection conditions, with water at high pressure (600 to 1400 psia) and flow upward. Tests should be performed with a "clean" multirod geometry (as little disturbance as possible to the flow by the provisions for maintaining the rods in correct relative alignment).
2. Investigate the effect of certain parameters; specifically, quality, flow rate, heated length, pressure, and rod-wall spacing.
3. Use the results to evaluate one or more computer models as a basis for CHF prediction.

Phase II of the program started January 1, 1968. The objectives for Phase II were:

Task C

1. Make measurements of both fully developed and developing two-phase flow (steam-water at 600 to 1400 psia, adiabatic and with heat addition, flow vertical upward) from which can be determined rates of mass and energy transfer in the transverse direction, such measurements to be made in a circular tube, eccentric annulus, and nine-rod channel. The nine-rod channel measurements should include representative measurements of subchannel flow and enthalpy from which can be deduced information concerning cross flow and mixing.
2. Determine the relationships between rate and driving potential, or potential gradient, and the effect of certain parameters (e.g., total flow, pressure, local void) on these relationships. In particular, determine the effect of grid-type spacers in the nine-rod channel.
3. Analyze the results to evaluate existing models of two-phase flow. Endeavor to develop an improved model in light of the results. Such a model should be useful in the prediction of flow structure, pressure drop, and critical heat flux in developing two-phase flow in multirod geometries, both "clean" and with grid-type spacers.

Task D

1. Measure critical heat flux in a nine-rod channel fitted with grid-type spacers characteristic of modern water-cooled reactors.
2. Determine, if possible, whether, and to what degree, the effect of spacers on the CHF is caused by a redistribution of the flow among the various subchannels, or by a highly localized disturbance which might, for example, disrupt the liquid film.
3. Modify the prediction methods developed in Task C as appropriate, and check them against the data obtained under Item 1.

Phase I was primarily concerned with fully developed two-phase flow. In Phase II, the emphasis was on developing two-phase flow. The work performed under this program to meet the objectives for both Phase I and Phase II is reviewed in the following section. A list of all reports and papers generated under this program is appended.

REVIEW OF ACCOMPLISHMENTS

PHASE I

The first phase accomplishments are described only briefly here, because reports were issued earlier (GEAP-5480, GEAP-5616, GEAP-5739)* which have already summarized this work.

TASK A

Measurement techniques were developed under Task A. The use of the Preston tube for shear measurement is discussed and some results given for air-water in GEAP-5739, and for steam-water in GEAP-5480. The isokinetic probe and related isokinetic techniques have been used extensively in the program. The application of the probe to two-component systems is described in detail in GEAP-5287, and is discussed for one-component systems in GEAP-5480.

The experimental objectives for Task A are met by the air-water results described in GEAP-5739 and by the steam-water results described in GEAP-5480.

The analytical objectives for Task A are met by the work described in GEAP-4976, GEAP-5157, and GEAP-10094. The analytical work under Task A culminates in the model for fully developed two-phase flow described in GEAP-10094.

TASK B

The objectives for Task B are met by the CHF results given in GEAP-4929 and GEAP-5616, and by the evaluation of subchannel models for prediction of two-phase flow distribution in multirod channels, given in GEAP-5616.

PHASE II

The second phase Task C circular tube and annulus accomplishments are mentioned only briefly here, because the report giving the full account of the work (GEAP-10341) is being issued at approximately the same time as this final report. The Task C, nine-rod accomplishments are given in somewhat more detail, but reference should be made to GEAP-13049 for a complete report of the nine-rod work.

TASK C, CIRCULAR TUBE AND ANNULUS

The experimental objectives for a circular tube test section are met by the circular tube test results described in GEAP-10341. No tests were run in an eccentric annulus because of failure of the test section which had been intended for that purpose. Instead, more emphasis has been given to the analysis of developing flow in an annulus. This analytical work is also described in GEAP-10341.

TASK C, NINE-ROD

The experimental objectives for a nine-rod test section are met by the results described in GEAP-13049. Test conditions typical of operating BWR conditions have been investigated, and results for both uniformly heated and radially peaked nine-rod arrays determined. Detailed pressure-drop measurements have also been taken, under both single-phase and two-phase exit conditions, since this information is of great value both for the designer and in the analysis and prediction of the detailed flow distribution.

At the time these tests were planned, no data of this nature had been reported. Since then, some results of subchannel sampling in slightly different geometries have appeared in the literature. Comparisons have been made with these data as well as theoretical predictions. It is significant that this report gives the only data yet published for true multirod geometries in which all the representative subchannels have been sampled. Hence it is the only multirod data that can be checked for validity from the point of view of conservation of mass and energy.

Test Section

The nine-rod test section used for these tests was built specially for subchannel and flow-structure measurements. The salient geometrical features are:

* See Appendix for listing of GEAP reports.

Number of Rods	9
Rod Diameter	0.570 inch
Radius of Channel Corner	0.400 inch
Rod-Rod Clearance	0.168 inch
Rod-Wall Clearance	0.135 inch
Hydraulic Diameter	0.474 inch
Heated Length	72 inches

The rods are of a new type developed by General Electric. Each rod is clad with a nickel tube, insulated from the electrical heater element so that the exterior of the rod is at ground potential thereby eliminating any shorting problems. The rods pass out the bottom end of the test section through watercooled O-ring glands, permitting differential expansion and access to electrical power leads. The power supplied is three-phase a-c power.

Tests were run with all nine rods heated. The local (radial) peaking was either uniform or a peaking pattern typical of BWR conditions. The peaking of the rods was accomplished with peaking transformers rather than using rods with different resistances.

A sectional view of the test section is shown in Figure 1. Subcooled water enters the channel at the bottom. A mixture of steam and water, generally at a bulk flow quality greater than zero, leaves the channel at the top. Rod-rod and rod-wall clearances are maintained by means of 1/8-inch diameter stainless steel pins. A set of pins is installed at each of several positions along the channel. These are located on 12-inch centers so that the last set is 10 inches before the top end of the test length.

To measure the flow in any given subchannel, that subchannel must be isolated at some point from the rest of the channel. The subchannel flow, also referred to as sample flow, can then be taken through special ducting to another point outside the test section, where both the flow rate and enthalpy (energy content) can be measured. Figure 1 shows typical provisions for sampling Subchannel 1. Thin (0.010 inch) pieces of metal sheet (flow splitters) are installed just past the end of the heated length, to separate Subchannel 1 from its neighbors. Similar splitters are used when Subchannels 2 and 3 are sampled, but the flow is measured for only one subchannel at a time. The splitters, plus continuous segments of rod and channel wall, form a box into which the subchannel flow enters and from which it leaves at the top end via a sample tube. The tube passes out through the top-closure flange, and from there it passes to a heat exchanger (calorimeter). The sample flow is monitored by a turbine flowmeter; two turbine meters of different capacity are used in conjunction with the different subchannels being sampled.

A flow control valve is used to set the sample flow to the desired amount.

The sample flow rate is set so as to obtain a particular value of static pressure difference between pressure taps located inside and outside the subchannel at the same axial location. Four pressure taps, referred to as C1, C2, W1 and W2, are available for this purpose and their peripheral locations are shown in Figure 2. Axially, they are located at the leading edge of the flow splitters. When sampling the corner subchannel, C1 and either C2 or W2 can be used. Similarly, W1 and W2 can be used for the side subchannel.

A special arrangement was required for the center subchannel. Three different schemes were tried, and the one shown in Figure 2 with a horizontal pressure tap line through a side rod was adopted. CC1, a pressure tap in the wall at the same axial location, was used as the reference tap. The decision to use this arrangement was based on the single-phase data, which can be predicted from analysis and continuity considerations. One method used a pressure tap in one of the splitters, but was found to cause appreciable obstruction in the adjoining side subchannel. Another scheme used two vertical pressure tap lines in two rods as shown in Figure 2, but was found to give erratic results under diabatic conditions.

When the pressure difference is set to the value that exists when the splitters and sample tube are removed and the subchannel flow is not drawn off, the sampling is termed "isokinetic." This pressure difference was generally near zero, but increased with dynamic head. "Nonisokinetic" data were also taken since they yield additional information, such as estimates of the enthalpy of crossflow between subchannels. The static pressure differences were measured by a 0.2-psi-capacity, Pace Δp cell.

Results

Table 1 presents the overall results for the three subchannels. Assuming four identical corner subchannels (total flow area = 0.3128 in.²), eight identical side subchannels (total flow area = 1.4592 in.²), and four identical center subchannels (total flow area = 1.1576 in.²), the total mass flux and enthalpy flux at the channel exit were calculated and compared with the average channel flow rate and average exit quality (as calculated on the basis of a heat balance).

Figure 1. Nine-Rod Test Section for Subchannel and Flow Structure Measurements

Figure 2. Positions of Pressure Taps for Setting Isokinetic Conditions

Table 1 shows that the results check within $\pm 5\%$, with only three runs deviating more than 3%. This increases confidence in the isokinetic sampling procedure, since the energy and continuity equation must balance for valid data.

Figure 3 illustrates the trends in the subchannel qualities with respect to the bundle average quality. The subchannel qualities increase monotonically with the average quality, the center subchannel (3) being the "hottest" and the corner subchannel (1) the "coolest." The center subchannel quality is seen to be consistently higher than the average, and the corner subchannel quality is lower than the average. The quality of the side subchannel (2) is near the average, sometimes higher and sometimes lower. Within the accuracy of the data there appears to be a trend for the subchannel qualities to converge to the average at approximately 5-10% bundle average quality. This has been attributed to enhanced mixing in the slug-annular flow-transition regime. Since this transition may occur in different subchannels at different values of the average quality, the "pinching" effect may not occur simultaneously in all subchannels.

Figure 4 compares the mass fluxes in the three subchannels with the bundle average quality. The flows have been nondimensionalized with respect to the average mass flux. These figures show that the mass flux is highest in the center subchannel and lowest in the corner subchannel. Here also the subchannel mass fluxes approach each other in the neighborhood of 10% average quality. It appears that this trend with flow regime is weaker in actual rod arrays than in two-subchannel test sections.¹ In fact, within the scatter of the data, the trend is often not observed.

By taking nonisokinetic data (i.e., with a set pressure differential between the subchannel being sampled and the diametrically opposite subchannel), some deductions can be made about the flow diversion between subchannels and the enthalpy associated with this cross flow.

The results for some of the nonisokinetic test conditions for the corner subchannel have been plotted against the subchannel quality in Figure 5. The plot shows that the crossflow enthalpy is generally higher than the average enthalpy of the corner (i.e., donor) subchannel. If the data are grouped by flow regime as determined by the Steen-Wallis² criterion $j_g^* = 0.4 + 0.6 j_f^*$, it is found that the data tend to be in two groups, each corresponding to a different flow regime, with a drop in the crossflow enthalpy near the slug-annular transition, probably due to the liquid slugs in this regime. Above this region the crossflow enthalpy increases monotonically, and remains well above the average subchannel enthalpy.

Table 1
OVERALL RESULTS FOR ISOKINETIC SAMPLING

Test Point	Bundle Average Mass Flux, $\bar{G} \times 10^{-6}$	Bundle Average Exit Quality $\bar{x}$	Mass Flux: Corner Subchannel $G_1 \times 10^{-6}$	Quality: Corner Sub-channel x_1	Mass Flux: Side Sub-channel $G_2 \times 10^{-6}$	Quality: Side Sub-channel x_2	Mass Flux: Center Subchannel $G_3 \times 10^{-6}$	Quality: Center Sub-channel x_3	Bundle Average Mass Flux Error $\frac{\hat{G} - \bar{G}}{\bar{G}}$ (%)	Bundle Average Quality Error $\frac{\hat{x} - \bar{x}}{\bar{x}}$
1B	0.480	—	0.311	—	0.462	—	0.526	—	-1.6	—
1C	0.990	—	0.701	—	0.939	—	1.150	—	+0.70	—
1D	1.510	—	1.095	—	1.441	—	1.690	—	+0.46	—
1E	1.97	—	1.62	—	1.91	—	2.190	—	+1.06	—
2B2	0.530	0.029	0.372	0.003	0.521	0.014	0.540	0.030	-1.51	-0.010
2B3	0.535	0.090	0.550	0.072	0.530	0.076	0.521	0.104	-1.12	-0.004
2B4	0.535	0.176	0.524	0.133	0.517	0.180	0.560	0.220	-0.0	+0.015
2C1	1.060	0.042	0.965	0.029	1.066	0.018	1.077	0.059	-0.05	-0.006
2C2	1.068	0.075	0.968	0.063	1.028	0.075	1.144	0.100	0.05	+0.009
2D1	0.540	0.110	0.425	0.083	0.560	0.105	0.556	0.117	0.74	-0.002
2D3	0.540	0.318	0.490	0.260	0.532	0.330	0.563	0.364	0.03	+0.019
2E1	1.080	0.035	0.950	0.004	1.102	0.026	1.162	0.051	2.77	0.000
2E2	1.080	0.106	1.046	0.049	1.078	0.097	1.180	0.105	3.24	-0.007
2E3	1.060	0.215	0.965	0.160	1.081	0.185	1.126	0.249	2.55	-0.007
2G1	1.070	0.038	0.882	0.032	0.968	0.044	1.142	0.043	-4.86	0.003
2G2	1.080	0.090	0.100	0.020	1.111	0.068	1.130	0.110	2.50	-0.008
2G3	1.070	0.160	0.865	0.074	1.132	0.127	1.160	0.176	4.11	-0.009

$$\hat{G} = \frac{\sum G_i A_i}{\sum A_i}, \quad \hat{H} = \frac{\sum G_i H_i A_i}{\sum G_i A_i}, \quad \hat{x} = \frac{\hat{H} - H_f}{H_{fg}}$$

In a similar manner, the crossflow enthalpy from the center subchannel has been plotted versus the subchannel quality in Figure 6. Again the data fall into two groups, representative of different flow regimes. The crossflow enthalpy is generally greater than the subchannel enthalpy, though near the slug-annular transition it is below the average value.

Unfortunately not enough nonisokinetic data were taken on the side subchannel to prepare plots of crossflow enthalpy. However, it would be expected to agree with the trends of the other subchannels. In summary, it appears that the crossflow enthalpy is strongly dependent upon flow regime and is, in general, higher than the average enthalpy of the donor subchannel.

Comparison With Analytical Predictions

There are several subchannel computer programs in the open literature that predict the enthalpy and flow distributions in multirod bundles. Examples are HAMBO,³ SASS,⁴ and COBRA.⁵ The programs are all similar in principle; the rod bundle is divided into subchannels. Each subchannel is then divided into axial nodes. Finite-difference forms of the conservation equations are then solved for this system numerically using a high speed digital computer. For purposes of comparison with data, the COBRA program has been chosen.

Figure 3. Variation of Subchannel Qualities with Average Quality: 2E Test Series

Figure 4. Comparison of Flows for Three Subchannels: 2E Test Series

Figure 5. Crossflow Enthalpy from a Corner Subchannel

Figure 6. Crossflow Enthalpy from the Center Subchannel

One of the variables that has to be specified in the computer solution is the amount of "mixing" between adjoining subchannels. For this purpose, COBRA uses a parameter β defined by:

$$w' = \beta s \tilde{G}$$

where

- w' = fluctuating mass flow rate per unit length in the axial direction
- β = Dimensionless mixing parameter (Mixing Stanton Number)
- s = gap spacing (rod-rod or wall-rod spacing)
- $\tilde{G}$ = average mass flux of adjacent subchannels

The latest indications^{1,6,7,8} are that two-phase mixing is a function of the subchannel geometry, quality, and flow regime. Values of β between 0.01 and 0.04 are probably appropriate for the present range of test conditions. Actually, the mixing should depend on local conditions and should thus vary in the axial direction. Nevertheless a constant value of β was used, as described above, since the exact dependence of β on flow regime and local conditions was not known. In any event this is compatible with previous practice and thus produces a consistent comparison. Table 2 shows a comparison between some of the data and the predictions with COBRA for β equal to 0.01 and 0.04.

Table 2
TWO-PHASE: MEASURED AND PREDICTED FLOW AND
ENTHALPY DISTRIBUTION

Test Point	$\bar{G} \times 10^{-6}$ (lb/ft ² -h)	$\bar{x}_e$		$G_1 \times 10^{-6}$ (lb/ft ² -h)	x_1	$G_2 \times 10^{-6}$ (lb/ft ² -h)	x_2	$G_3 \times 10^{-6}$ (lb/ft ² -h)	x_3
2B2	0.530	0.029	Data	0.372	0.003	0.521	0.014	0.540	0.030
			COBRA $\beta = 0.04$	0.482	0.030	0.523	0.026	0.552	0.031
			COBRA $\beta = 0.01$	0.491	0.046	0.516	0.025	0.558	0.029
2B3	0.535	0.090	Data	0.550	0.072	0.530	0.076	0.521	0.104
			COBRA $\beta = 0.04$	0.478	0.090	0.528	0.086	0.560	0.092
			COBRA $\beta = 0.01$	0.454	0.104	0.524	0.084	0.571	0.092
2B4	0.535	0.176	Data	0.524	0.133	0.517	0.180	0.560	0.220
			COBRA $\beta = 0.04$	0.489	0.177	0.526	0.172	0.565	0.178
			COBRA $\beta = 0.01$	0.417	0.194	0.524	0.169	0.581	0.179
2E1	1.080	0.035	Data	0.950	0.004	1.102	0.026	1.162	0.051
			COBRA $\beta = 0.04$	0.990	0.035	1.082	0.031	1.102	0.038
			COBRA $\beta = 0.01$	0.874	0.057	1.068	0.030	1.151	0.034
2E2	1.080	0.106	Data	1.048	0.049	1.078	0.097	1.180	0.105
			COBRA $\beta = 0.04$	0.979	0.106	1.073	0.102	1.117	0.109
			COBRA $\beta = 0.01$	0.878	0.125	1.073	0.099	1.143	0.109
2E3	1.060	0.215	Data	0.965	0.160	1.081	0.185	1.126	0.249
			COBRA $\beta = 0.04$	0.938	0.215	1.044	0.211	1.113	0.217
			COBRA $\beta = 0.01$	0.826	0.234	1.046	0.206	1.140	0.220

Somewhat better agreement is obtained with data for $\beta = 0.04$. However, the trends in subchannel qualities are not predicted by the computer code. Even with the high mixing, COBRA cannot predict the substantially lower-than-average qualities in the corner subchannel, and higher-than-average qualities in the center subchannel. In fact, if mixing were made infinitely large the three subchannels would all be at average conditions and thus the data cannot be explained in terms of mixing.

The most probable explanations for this behavior are the tendency for the steam to move preferentially to the center of the rod bundle and/or the presence of a thick liquid film on the unheated channel wall. This latter hypothesis is consistent with the trends in the void fraction and flow regime measurements of the air-water tests described in GEAP-5739 and further discussed in Reference 6. Although the reasons for the failure of the subchannel approach for a typical present generation computer code (COBRA) are not completely clear, it is evident that without modification of the thermal-hydraulic physics in these codes, agreement with actual multirod data cannot be achieved.

Results With Radial Peaking

Subchannel sampling tests were run with different power on the nine rods in order to obtain a radial peaking distribution. Axially, the heat flux was uniform.

The radial peaking pattern was achieved by using three peaking transformers, one for each phase as shown in Figure 7. Each phase supplies power for three rods. In this way, a peaking pattern approximately symmetrical (but not exactly symmetrical due to variations in the individual transformers) about the diagonal was achieved as shown in Figure 8. For this configuration, there are approximately ten different types of subchannels. Due to the shortage of test loop time, only subchannels 1 through 5 were sampled. Subchannels 1, 3, and 5 were sampled with the peaking pattern in Figure 8 in the usual manner. In order to sample subchannels 2 and 4 without changing the splitter locations the peaking pattern was reversed as in Figure 9, and the same side and corner subchannels were sampled. These peaking factors are defined with respect to the average heat flux and were determined from actual measurements. In addition to the total power, the power to each rod was measured separately. The test conditions are shown in Table 3. These test conditions are nominally the same as 2B2, 2D1, 2E1, and 2E2. A slightly lower total power was used for Test 3E2 because of the possibility of critical heat flux (CHF) in the presence of 1.3 peaking on the corner rod.

Table 4 shows results obtained for the peaking runs. These cover the hot (No. 1) and cold (No. 2) corner subchannels, hot (No. 3) and cold (No. 4) side subchannels, and the hot (No. 5) center subchannel. The hot center subchannel ran at the highest quality in all cases. Unfortunately not much data are available for the hot side subchannel. It was found that the cold side subchannel was the lowest in quality and generally had the highest mass flux. In fact, in three of the four runs the cold subchannel was substantially subcooled at the exit, so that the exit enthalpy could be accurately determined by measurement of the temperature of the sample at the inlet to the heat exchanger. The hot corner subchannel ran at higher than average quality and was the lowest in mass flux for all the runs considered.

Table 3
TEST CONDITIONS FOR PEAKING RUNS

Test Point	Average Mass Flux (lb/ft ² -h) $\bar{G} \times 10^{-6}$	Power (kW)	Average Heat Flux (Btu/ft ² -h) q''	Subcooling (Btu/lb)	Average Exit Quality $\bar{x}_e$
3B2	0.535	532	225,000	146.1	0.032
3D1	0.545	1064	450,000	273.0	0.084
3E1	1.080	1064	450,000	142.9	0.035
3E2	1.060	994	420,000	92.4	0.100

Figure 7. Typical Power Hook-Up for Radial Peaking Runs

Figure 8. Subchannels and Peaking Pattern

Figure 9. Peaking Pattern Used for Subchannels 2 and 4

Table 4
MASS FLUX AND ENTHALPY DATA
FOR RADIAL PEAKING PATTERNS

Test Point	Average Mass Flux (lb/ft ² ·h) $\bar{G} \times 10^{-6}$	Average Exit Quality $\bar{x}$	Average Heat Flux (Btu/ft ² ·h) $\bar{q}$	$G_1 \times 10^{-6}$	x_1	$G_2 \times 10^{-6}$	x_2	$G_3 \times 10^{-6}$	x_3	$G_4 \times 10^{-6}$	x_4	$G_5 \times 10^{-6}$	x_5
3B2	0.535	0.032	225,000	0.400	0.080	0.320	0.009	0.507	0.042	0.505	-0.043	0.555	0.108
3D1	0.545	0.064	450,000	0.322	0.123	0.335	0.024	—	—	0.628	-0.037	—	—
3E1	1.080	0.035	450,000	0.794	0.105	0.925	0.002	—	—	1.430	-0.036	0.852	0.163
3E2	1.060	0.100	420,000	0.800	0.160	0.940	0.075	0.755	0.167	1.475	0.034	0.890	0.227

Since not all ten subchannels were sampled, errors in the continuity and energy balance could not be evaluated. Comparisons with uniform data are made for a representative run in Figures 10 to 15. Figure 10 shows that the quality of the hot corner subchannel runs much higher than that of the corner subchannel for uniform local peaking conditions and that it also runs higher than the average bundle quality. The quality of the cold corner subchannel is not affected as much, and runs close to the corner subchannel under conditions of uniform heat flux. Sometimes, as shown here, the cold corner subchannel quality appears to be a little higher than that in the uniform case. This trend is closely related to the subchannel mass flux as may be seen in Figure 13. The probable error in these quality measurements is of the order of $\pm 2\%$. Since this is true, the uniform and cold subchannel qualities can be considered the same in most cases. Figure 11 shows the qualities in the hot and cold side subchannels, and the side subchannel for uniform heat flux (referred to hereafter as "uniform" side subchannel). Here the cold subchannel is seen to be at a much lower quality and subcooled for three out of the four test runs. The quality of the hot side subchannel is higher than in the uniform side subchannel and higher than the bundle average quality. Figure 12 shows the quality in the hot center subchannel together with previously obtained results for the center subchannel in the absence of local peaking. The hot subchannel is seen to run at a substantially higher quality. This is the hottest subchannel in the bundle.

Figures 13 to 15 show the trends in the normalized mass flux. These trends are not as clearly defined as the trends in quality. The hot corner subchannel has the least flow when compared to the uniform and cold corner subchannel flows (except at low flow and quality). The cold corner subchannel flow appears generally to be below the uniform corner subchannel flow, but greater than the hot subchannel flow. In every case, the uniform corner subchannel has higher flow than the corresponding cold subchannel. Since not all subchannels were sampled, it is not possible to check the validity of this trend. It may be possible that the subchannel size was different in this particular assembly due to the tolerances on the rod/wall spacing or that the relatively unrestricted cold center subchannel (subchannel 10 in Figure 8) had very high flow rates for these peaking runs and thus the cold corner subchannel (subchannel 2) was "flow starved."

Figure 14 indicates that the cold side subchannel (see Figure 8) had a greater mass flux than the uniform side subchannel (except at low flow and quality). The hot side subchannel flow is lower than the uniform side subchannel flow in every case tabulated. As indicated in Figure 15, the trends are reversed for the hot center subchannel, which has lower flow rate than the uniform case (except at low values of average flow rate and quality).

Conclusions

The present study of subchannel and pressure drop measurements was conducted in an electrically heated nine-rod assembly that was constructed specifically for this test series. At the start of the program, exploratory calibration runs indicated that great care was needed in data acquisition and reduction. A technique was developed in which daily calibration runs were made to establish the isokinetic setting and to determine the "heat loss" to be used in data reduction. In order to simplify the test rig and operations, only a single subchannel was sampled at a time. This proved to be a reliable method of data acquisition but had the undesirable feature that the same test conditions had to be established each time a new subchannel was sampled. Nevertheless, subsequent checks of the conservation of mass and energy have indicated that the data taken in this manner are valid.

Subchannel test data were taken for both isokinetic (natural flow split) and nonisokinetic conditions. The isokinetic data gave the normal local conditions that occurred in the test bundle. The nonisokinetic data were used to determine the flow diversion enthalpy and the sensitivity of the isokinetic setting. At the same time subchannel measurements were being made, detailed pressure drop data were taken for both adiabatic and diabatic conditions. It was found that these pressure drop readings were quite insensitive to the sample flow, indicating that the axial length for flow diversion was small.

The main conclusions that can be drawn for the data have been tabulated below:

A. Conclusions from Isokinetic Data (Uniform Radial)

1. The corner subchannel runs at a mass flux below the bundle average mass flux and at a quality below the bundle average quality.
2. The side subchannel has mass flux and quality approximately equal to or slightly below the bundle average.
3. The center subchannel has both mass flux and quality above the bundle average values.
4. There is an observable, though somewhat inconsistent, tendency for the subchannels to approach bundle average conditions in the regions of slug-annular flow-regime transition. This effect is less pronounced than that observed in two-subchannel tests.^{1,8}

Figure 10. Comparison of Non-Uniform and Uniform Data: Corner Subchannel Qualities 3E2

Figure 11. Comparison of Non-Uniform and Uniform Data: Side Subchannel Qualities 3E2

Figure 12. Comparison of Non-Uniform and Uniform Data: Center Subchannel Qualities 3E2

Figure 13. Comparison of Non-Uniform and Uniform Data: Corner Subchannel Mass Fluxes 3E2

Figure 14. Comparison of Non-Uniform and Uniform Data: Side Subchannel Mass Fluxes 3E2

Figure 15. Comparison of Non-Uniform and Uniform Data; Center Subchannel Mass Flow.3E2

5. The effect of bundle average mass flux on the normalized enthalpy distribution is small.
6. The effect of heat flux on subchannel enthalpy distribution was small for low flow cases but showed a strong effect at the higher flows. There appeared to be a reversal of the trend at a bundle average quality of $\sim 6\%$.
7. The effect of the bundle average mass flux on subchannel mass flux distribution was to increase the mass flux in the corner and center subchannels, and decrease the mass flux in the side subchannel as the bundle average mass flux was increased.
8. The effect of heat flux on subchannel mass-flux distribution was to decrease the mass flux in the corner subchannel but leave the mass fluxes in the other subchannels relatively unchanged (i.e., the total flow change was small since the corner subchannel has a small flow area, thus its flow perturbation is not strongly felt by the other subchannels).

B. Conclusions from Nonisokinetic Data (Uniform Radial)

1. The agreement between theoretical results and data indicates that the assumptions made in the analytical model are valid: the length for flow diversion is small, and the separated flow model is appropriate for two-phase conditions.
2. The crossflow enthalpy which is transported from one subchannel to the other during flow diversion is generally higher than the subchannel enthalpy of the donor subchannel and appears to be a strong function of flow regime.

C. Comparison of Data and Subchannel Code (COBRA) Predictions

Single-phase predictions of COBRA agree quite well with the data. The two-phase predictions do not agree with the trends in data since classical subchannel analysis predicts that the corner subchannel runs at a lower mass flux and a higher quality and that the center subchannel runs at a lower quality than actually exists in the subchannels.

D. Conclusion from Isokinetic Data with Radial Peaking Pattern

Although insufficient funds and loop time prevented the acquisition of complete subchannel data the trends in the data taken for the peaking runs agreed with the uniform data (i.e., the "hottest" regions were found to be in the interior of the bundle).

E. Conclusions from Pressure Drop Data

1. The adiabatic single-phase friction factor for the clean nine-rod bundle under consideration was slightly higher than the smooth-tube friction factor, at all Reynolds numbers.
2. The two-phase friction pressure-drop multiplier ϕ_{LO}^2 showed only a very minor flow effect, and the data were well correlated by the classical Martinelli-Nelson curve.

Although it was not possible to take all the data of interest, the overall scope of the subchannel test program was completed. It is felt that the overall program was quite successful because it identified various trends which occur in true multirod geometries, which were not known previously.

It is recommended that future work in this area include more extensive data with radial peaking and also data with axial heat flux profiles. In addition, subchannel data taken for off design conditions of rod swell and rod bowing would be of great interest. Finally, data taken with grid type spacers could be used to establish quantitatively the effect of local disturbances on the flow and enthalpy distribution in a rod bundle.

TASK D, NINE-ROD

The experimental objectives for Task D are met by the results described in the Nineteenth Quarterly Report (GEAP-10253). These results are reproduced below.

In addition, certain special tests were run in a low pressure air-water channel to examine the behavior of the liquid film in the presence of obstacles. The obstacles simulated spacer elements in contact with fuel rod surfaces. Disruption of the liquid film on a heated surface due to local spacer contacts could conceivably produce dry patches, and hence premature CHF. The results of these special tests, including a simplified analysis, are described in GEAP-10248. The highlights of these results are also reproduced below.

Test Section

The test section is the same as used for the subchannel tests in Task C, described above. The only changes needed for CHF work were:

1. Omission of the flow splitters and sampling circuit and associated instrumentation.
2. Addition of thermocouples to the rods for CHF detection.

Each rod is lettered for identification purposes according to its position in the array. The lettering scheme, as viewed from above, is shown in Figure 16.

Tests can be run with all nine rods heated, or alternately with only six or only three of the nine rods heated. All the rods used for the tests reported here were heated. The heat flux was uniform, both axially and in the transverse direction. Two different sets of rods were used. The 6-foot heated length for the first set (used with test channel Nos. 1, 2, 2A, and 3), was located 3-1/2 feet before the end of the 10-foot test length. The 6-foot heated length for the second set (used with test channel No. 4) was located right at the end of the 10-foot test length.

For CHF detection, four 0.020-inch-o.d. sheathed chromel-alumel thermocouples with ungrounded junctions were placed on the outside of each of the rods by milling 0.025-inch-deep grooves in the nickel cladding, and then inserting the thermocouples and silver soldering in place (see Figure 3). Two of the thermocouple junctions were located 0.5 inch before the end of the heated length, and two were located 3.2 inches before the end of the heated length. All four thermocouples were located within a 65-degree sector, as shown in Figure 17. The thermocouples on the outside rods faced outward, and on the center rod faced one of the interior subchannels.

A set of critical heat flux runs was made for each of five test channels. All five of the channels used the same grid-type spacers (needed to maintain rod-rod and rod-wall clearances, and typical of modern water-cooled and moderated power reactors), and essentially the same rods. The principal features that differed between the various channels were: (1) the axial position of the 6-foot heated segment of the rods, and (2) the axial positions of the spacers, particularly with respect to the end of the heated length. The spacer and heated length positions, and certain other features of the five channels, are shown schematically in Figure 18. A close-up view of one of the spacers is shown in Figure 19.

The end of the heated length for test channel No. 4 is located 2 inches before the channel exit. This arrangement is typical for most out-of-core CHF test assemblies with which the results reported here can be compared. Test channel No. 4 is therefore the "reference" channel in the discussion of results which follows.

Figure 16. Lettering Scheme for Rod Identification

Figure 17. Location of Thermocouples

TEST CHAN. 1

TEST CHAN. 2

TEST CHAN. 2A

TEST CHAN. 3

TEST CHAN. 4

Figure 18. Schematic View of Test Channels, Showing Axial Positions of Heated Length and Grid-Type Spacers

Figure 19. Grid-Type Spacer Details

It has been observed that when the spacer at the end of the heated length is located with its leading (i.e. stream) side 1/2 inch past the end of the heated length, the CHF is less than when this same spacer is located a few inches before the end of the heated length.⁹ To investigate further the effect of axial position of this particular spacer, it has been placed so that its leading side is (1) 3 inches ahead of the end of the heated length (test channel No. 1), (2) 1/2 inch past the end (test channels Nos. 2, 2A and 4), and (3) removed all together (test channel No. 3).

Because of the conjecture that the difference between the test channel No. 2 and the test channel No. 4 results might be due to flow diversion toward the outside of the bundle in the case of No. 4, a "diversion plate" was added to No. 2 in an effort to bring about a similar diversion. The plate is shown in Figure 18, test channel No. 2A. A detail of the plate appears in Figure 20.

Test Procedure

CHF was determined by means of the thermocouples already described, which were located near the end of the heated length. The CHF point was approached by holding pressure, flow, and subcooling constant, and gradually increasing power (in steps of 1% to 2%) until one or more thermocouples indicated a CHF condition.

The following quantities were measured and recorded at the onset of CHF:

- System pressure (at exit end of test section).
- Flow rate (just ahead of test section inlet).
- Inlet temperature
- Power to test section

The particular thermocouples indicating CHF were also noted and recorded.

The data were reduced, using the relationships given in Reference 10 for flow and quality, and dividing the power to test section by the total heat transfer area for heat flux.

Results

The results are listed in Tables 5, 6, 7, 8, and 9 for test channels Nos. 1, 2, 2A, 3, and 4, respectively. Each table gives the location of CHF in terms of distance ahead of the end of the heated length at which the thermocouple that detected it was located. It will be noted that for test channel No. 1, CHF always occurred just before the last spacer on the heated length. For all the other test channels, CHF always occurred at the end of the heated length. In all plots of critical heat flux versus quality given in this report, the quality is always the average channel value at the CHF location.

Figure 20. Diversion Plate

Table 5
CHF RESULTS
TEST CHANNEL NUMBER 1

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
1	1005.0	1.008	9.2	0.539	0.2966	H	3.2
2	775.0	0.998	20.1	0.635	0.3172	H	3.2
3	825.0	1.016	13.3	0.609	0.3115	H	3.2
4	1005.0	1.012	11.7	0.535	0.2897	H	3.2
5	1095.0	1.010	9.4	0.500	0.2804	H	3.2
6	1195.0	1.018	12.2	0.465	0.2609	H	3.2
7	1395.0	1.010	11.4	0.406	0.2430	H	3.2
8	1419.0	0.991	83.7	0.512	0.1943	H	3.2
10	811.0	1.013	58.4	0.672	0.2799	H	3.2
11	1005.0	1.007	59.0	0.603	0.2576	H	3.2
12	1105.0	1.012	61.5	0.576	0.2437	H	3.2
13	1197.0	1.016	64.6	0.540	0.2218	H	3.2
14	1411.0	1.011	74.7	0.497	0.1931	H	3.2
15	1005.0	1.009	93.6	0.648	0.2293	H	3.2
16	637.0	1.007	86.5	0.749	0.2697	H	3.2
17	801.0	1.008	83.2	0.721	0.2717	H	3.2
18	1095.0	1.011	91.7	0.621	0.2218	H	3.2
19	1185.0	1.012	97.1	0.589	0.1999	H	3.2
20	1403.0	1.014	106.8	0.544	0.1667	H	3.2
21	990.0	0.999	143.5	0.726	0.2008	H	3.2
22	810.0	1.005	123.3	0.816	0.2523	H	3.2
23	805.0	1.010	124.0	0.775	0.2415	H	3.2
24	1095.0	1.012	144.4	0.705	0.1880	H	3.2
25	1207.0	1.011	152.0	0.685	0.1699	H	3.2
26	1395.0	1.013	169.5	0.657	0.1306	H	3.2
27	1005.0	1.013	185.5	0.819	0.1853	H	3.2
28	797.0	1.007	170.1	0.861	0.2224	H	3.2
29	1105.0	1.012	193.3	0.794	0.1636	H	3.2
30	1195.0	1.013	197.6	0.764	0.1428	H,I	3.2
31	1407.0	1.012	208.2	0.714	0.1017	H,I	3.2
32	1207.0	1.006	213.6	0.770	0.1240	H	3.2
**33	1415.0	1.012	220.5	0.749	0.1036	H	3.2
34	995.0	1.007	8.9	0.517	0.2838	G	3.2
35	1000.0	0.499	17.8	0.441	0.4847	G,D	3.2
36	599.0	0.500	13.4	0.434	0.4296	G	3.2
37	805.0	0.500	18.2	0.435	0.4495	G	3.2
38	995.0	0.501	19.5	0.432	0.4693	G,D,A	3.2
39	1093.0	0.497	16.1	0.404	0.4586	G	3.2

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

** Rod "G" lost at the end of this run.

Table 5 (Continued)

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Location of CHF,	
						Rod*	Distance Before End of Heated Length (Inches)
40	1197.0	0.504	24.8	0.404	0.4519	G	3.2
41	1400.0	0.502	23.7	0.353	0.4194	G	3.2
42	1403.0	0.503	21.4	0.361	0.4330	G,I	3.2
43	1009.0	0.500	41.2	0.465	0.4772	G	3.2
44	601.0	0.497	69.6	0.490	0.4136	G	3.2
45	803.0	0.501	77.9	0.503	0.4375	G	3.2
46	997.0	0.496	70.6	0.481	0.4535	G,I,D	3.2
47	1107.0	0.501	73.7	0.466	0.4397	G	3.2
48	1195.0	0.501	72.1	0.441	0.4228	G	3.2
49	1405.0	0.505	89.1	0.402	0.3674	G	3.2
50	995.0	1.013	12.0	0.537	0.2886	G,I	3.2
51	990.0	0.499	118.8	0.498	0.3944	G	3.2
52	605.0	0.495	99.8	0.498	0.3831	G,I	3.2
53	797.0	0.492	110.1	0.516	0.4139	A,D,G,I	3.2
54	1005.0	0.497	119.4	0.494	0.3936	I,G,D	3.2
55	1095.0	0.499	123.9	0.466	0.3615	I,G,D	3.2
56	1195.0	0.493	128.7	0.460	0.3632	G,D	3.2
57	1410.0	0.499	145.2	0.438	0.3226	G	3.2
58	1005.0	0.501	172.7	0.531	0.3499	G,I	3.2
59	593.0	0.498	143.2	0.533	0.3559	I,G,A	3.2
60	800.0	0.495	161.1	0.539	0.3628	G,I	3.2
61	1005.0	0.492	177.5	0.530	0.3526	G	3.2
62	1105.0	0.495	193.3	0.524	0.3269	G	3.2
63	1209.0	0.496	201.1	0.521	0.3201	G	3.2
64	1405.0	0.497	239.4	0.517	0.2671	G	3.2
65	601.0	0.496	182.3	0.558	0.3312	G	3.2
66	797.0	0.498	193.2	0.575	0.3511	G,I	3.2
67	1007.0	0.528	211.6	0.571	0.3030	G	3.2
68	1095.0	0.501	218.9	0.576	0.3407	G	3.2
69	1203.0	0.499	227.8	0.552	0.3097	G	3.2
70	1395.0	0.500	258.2	0.539	0.2581	G	3.2
71	998.0	0.499	256.0	0.609	0.3138	G	3.2
72	605.0	0.497	219.1	0.589	0.3120	G	3.2
73	805.0	0.499	241.6	0.619	0.3303	G	3.2
74	1095.0	0.499	264.6	0.609	0.3099	G	3.2
75	1199.0	0.500	288.1	0.610	0.2810	G	3.2
76	1397.0	0.500	313.4	0.584	0.2209	G	3.2
77	1008.0	0.500	19.6	0.444	0.4858	G	3.2
78	1000.0	0.744	11.5	0.500	0.3725	G	3.2
79	623.0	0.746	14.7	0.567	0.3753	G	3.2
80	803.0	0.739	9.5	0.546	0.3908	G	3.2

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 5 (Continued)

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
81	1109.0	0.750	12.8	0.486	0.3682	G	3.2
82	1195.0	0.751	18.1	0.443	0.3337	G	3.2
83	1395.0	0.746	16.3	0.384	0.3083	G	3.2
84	1005.0	0.753	68.4	0.552	0.3211	G	3.2
85	1000.0	0.748	62.4	0.565	0.3422	I,G	3.2
86	610.0	0.756	57.0	0.603	0.3358	A,G	3.2
87	805.0	0.750	61.3	0.591	0.3128	G,A	3.2
88	1000.0	0.747	67.6	0.556	0.3282	I,G	3.2
89	1100.0	0.747	70.9	0.532	0.3138	G,I,A	3.2
90	1200.0	0.748	79.3	0.509	0.2897	G,I	3.2
91	1395.0	0.747	93.8	0.464	0.2437	G	3.2
92	995.0	0.750	117.9	0.618	0.2969	I,G,A	3.2
93	610.0	0.745	101.9	0.638	0.3045	I,A,G	3.2
94	805.0	0.750	109.3	0.629	0.3013	G	3.2
95	1005.0	0.743	113.3	0.596	0.2921	I,G,A	3.2
96	1105.0	0.746	117.5	0.591	0.2879	G,I,A	3.2
97	1195.0	0.750	119.1	0.571	0.2740	I,G	3.2
98	1415.0	0.747	136.2	0.529	0.2290	G	3.2
99	1000.0	0.751	176.2	0.669	0.2464	D,G	3.2
100	605.0	0.744	143.5	0.679	0.2759	G,A,I	3.2
101	795.0	0.744	159.7	0.674	0.2647	G,I,E	3.2
102	1000.0	0.736	170.9	0.675	0.2695	I,G,A	3.2
103	1095.0	0.747	176.9	0.665	0.2516	G,I,A,D	3.2
104	1195.0	0.743	184.7	0.632	0.2223	G	3.2
105	1405.0	0.740	193.9	0.585	0.1814	G	3.2
106	1000.0	0.747	247.9	0.751	0.2036	G	3.2
107	597.0	0.747	198.1	0.745	0.2445	G	3.2
108	798.0	0.746	219.8	0.751	0.2333	G	3.2
109	1099.0	0.743	239.8	0.744	0.2197	G	3.2
110	1207.0	0.749	251.4	0.720	0.1828	G	3.2
111	1401.0	0.753	259.5	0.694	0.1540	G	3.2
112	1005.0	0.763	261.7	0.778	0.1910	G	3.2
113	999.0	0.749	14.5	0.500	0.3655	G	3.2
114	997.0	0.246	32.1	0.294	0.6413	A,G,I	3.2
115	970.0	0.249	67.0	0.320	0.6340	G	3.2
116	1001.0	0.249	111.6	0.331	0.5974	G	3.2
118	997.0	0.249	208.5	0.385	0.5724	G	3.2
119	1003.0	0.250	254.7	0.408	0.5547	G	3.2
120	1007.0	0.249	300.2	0.428	0.5371	G	3.2
121	995.0	0.249	372.9	0.459	0.4935	I,G	3.2
122	999.0	0.247	436.3	0.488	0.4726	I,G	3.2

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 5 (Continued)

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Location of CHF, Distance Before End of Heated Length (Inches)	
						Rod*	
123	1000.0	0.250	162.3	0.353	0.5681	G	3.2
124	1000.0	0.249	45.2	0.299	0.6247	I,G	3.2
125	1005.0	1.248	7.9	0.544	0.2412	G,I	3.2
126	1005.0	1.245	55.5	0.618	0.2036	I,G	3.2
127	997.0	1.243	14.2	0.555	0.2374	I,G	3.2
128	1000.0	1.249	29.5	0.578	0.2234	G,I	3.2
129	993.0	1.247	72.9	0.650	0.1903	G	3.2
130	1005.0	1.248	104.4	0.697	0.1645	G	3.2
131	1000.0	1.248	170.3	0.821	0.1205	G	3.2
132	993.0	1.249	142.8	0.765	0.1363	G	3.2
133	1000.0	1.441	8.4	0.552	0.2097	A,I,G	3.2
134	1000.0	1.443	42.8	0.612	0.1806	G	3.2
135	995.0	1.430	79.0	0.680	0.1548	G	3.2
136	1000.0	1.506	102.5	0.723	0.1216	G	3.2
137	1000.0	1.518	143.9	0.842	0.1012	G	3.2
138	995.0	1.504	128.9	0.789	0.1066	G	3.2
139	997.0	1.472	56.0	0.639	0.1660	G	3.2
140	1005.0	1.473	26.6	0.586	0.1906	A,G,I	3.2
141	1005.0	1.019	44.2	0.573	0.2591	A,I,G	3.2
142	1000.0	1.010	78.0	0.638	0.2471	I,G,A	3.2
143	1003.0	1.009	110.8	0.665	0.2130	A,G,I	3.2
144	1002.0	1.011	8.7	0.525	0.2886	I,G	3.2

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 6
CHF RESULTS
TEST CHANNEL NUMBER 2

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
145	1003.0	0.742	17.6	0.505	0.3857	G	0.50
146	998.0	0.748	49.7	0.544	0.3639	G	0.50
147	1000.0	0.746	80.3	0.586	0.3530	A,D,G	0.50
148	1001.0	0.748	110.5	0.631	0.3418	A,D,G	0.50
149	1003.0	0.751	142.7	0.641	0.2985	D,G	0.50
150	1003.0	0.750	174.0	0.648	0.2566	G	0.50
151	1001.0	0.742	202.9	0.651	0.2194	G,D	0.50
152	1005.0	0.747	234.8	0.671	0.1838	A,G,D,I	0.50
153	1000.0	0.753	15.3	0.518	0.3936	D,G	0.50
154	1001.0	0.750	48.3	0.554	0.3733	G	0.50
155	995.0	0.749	86.4	0.584	0.3393	D,G	0.50
156	1001.0	0.742	121.0	0.610	0.3124	D,G	0.50
157	1005.0	0.747	145.2	0.613	0.2749	D,G	0.50
158	1000.0	0.747	178.3	0.623	0.2314	D,G	0.50
159	995.0	0.737	229.1	0.661	0.1909	D,G	0.50
160	1000.0	0.748	255.8	0.698	0.1719	D,G	0.50
161	1000.0	0.749	133.0	0.631	0.3063	A,H,G	0.50
162	995.0	0.748	181.8	0.660	0.2549	G,H	0.50
163	1005.0	0.743	235.8	0.712	0.2192	G,H	0.50
164	993.0	1.247	12.3	0.562	0.2535	I,A	0.50
165	1000.0	1.248	46.4	0.612	0.2260	I,A	0.50
166	1005.0	1.242	75.9	0.672	0.2116	I,G	0.50
167	1000.0	1.242	97.4	0.710	0.1970	I,G,A	0.50
168	1003.0	1.248	135.6	0.760	0.1607	G,I	0.50
169	1003.0	1.246	159.5	0.788	0.1387	G,I	0.50
170	1000.0	1.250	188.4	0.819	0.1077	G	0.50
171	1001.0	1.245	194.4	0.822	0.1017	G	0.50
172	1000.0	1.249	136.8	0.748	0.1526	G,I	0.50
173	1000.0	1.246	117.0	0.719	0.1699	G,I	0.50
174	985.0	1.247	92.3	0.699	0.1970	A,G,I	0.50
175	1005.0	1.247	80.5	0.670	0.2019	I	0.50
176	1003.0	1.237	10.7	0.548	0.2522	I,A	0.50
177	1000.0	0.252	41.6	0.283	0.6115	A,G,I	0.50
178	1000.0	0.247	66.4	0.292	0.6113	A,G,I	0.50
179	1001.0	0.250	124.3	0.323	0.5880	A,G	0.50
180	1000.0	0.250	200.6	0.346	0.5282	G,I	0.50
181	1000.0	0.249	242.9	0.371	0.5258	G	0.50
182	992.0	0.248	288.3	0.392	0.5091	G,I	0.50

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 6 (Continued)

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
183	1005.0	0.249	341.7	0.421	0.4963	A,G,H	0.50
184	1003.0	0.250	402.7	0.449	0.4669	G,I	0.50
185	1000.0	0.251	428.2	0.472	0.4783	G,I	0.50
186	1001.0	0.248	166.7	0.334	0.5547	A,G	0.50
187	995.0	0.250	143.1	0.329	0.5732	A,G	0.50
188	1007.0	0.247	48.1	0.282	0.6148	A,G	0.50
189	1000.0	1.011	7.1	0.535	0.3095	I	0.50
190	671.0	1.000	19.9	0.645	0.3273	A,G	0.50
191	809.0	1.011	12.3	0.599	0.3220	A,G	0.50
192	1099.0	1.012	10.0	0.496	0.2901	I	0.50
193	1195.0	1.015	11.6	0.463	0.2739	A,I	0.50
194	1397.0	1.015	15.1	0.392	0.2374	A,G,I	0.50
195	1000.0	1.012	49.4	0.598	0.2825	A,G,I	0.50
196	675.0	1.010	42.5	0.683	0.3136	A,G,I	0.50
197	800.0	1.005	35.1	0.635	0.3105	A,G,I	0.50
198	1101.0	1.014	40.4	0.544	0.2708	A,I	0.50
199	1203.0	1.013	45.2	0.514	0.2527	A,I	0.50
200	1397.0	1.014	47.7	0.449	0.2193	I	0.50
201	1003.0	1.019	97.9	0.643	0.2323	G,I	0.50
202	671.0	1.008	84.8	0.722	0.2763	G,I	0.50
203	803.0	1.010	81.3	0.685	0.2705	G,I	0.50
204	1099.0	1.012	94.5	0.608	0.2251	G,I	0.50
205	1199.0	1.013	96.2	0.579	0.2106	I	0.50
206	1403.0	1.013	105.6	0.549	0.1877	A,G,I	0.50
207	997.0	1.015	145.6	0.689	0.1876	G	0.50
208	675.0	1.006	125.0	0.733	0.2268	G,H,I	0.50
209	803.0	1.005	129.6	0.713	0.2183	G,H,I	0.50
210	1101.0	1.008	149.6	0.661	0.1726	G	0.50
211	1203.0	1.011	151.5	0.649	0.1658	G	0.50
212	1399.0	1.012	160.6	0.603	0.1291	G	0.50
213	997.0	1.008	178.4	0.711	0.1536	G	0.50
214	677.0	1.009	158.8	0.749	0.1878	G,H	0.50
215	801.0	1.005	167.6	0.730	0.1723	G,H	0.50
216	1100.0	1.006	188.9	0.701	0.1359	G	0.50
217	1203.0	1.012	194.9	0.684	0.1172	G	0.50
218	1399.0	1.010	203.4	0.660	0.0938	G	0.50
219	1001.0	1.012	231.1	0.759	0.0997	G	0.50
220	673.0	1.007	206.4	0.770	0.1330	G,H	0.50
**221	795.0	1.008	217.8	0.760	0.1151	G	0.50
222	1000.0	0.742	11.5	0.525	0.4110	C,G	0.50

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

** Rod "F" lost at end of this run.

Table 6 (Continued)

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
223	1001.0	0.749	183.8	0.672	0.2617	G	0.50
224	1000.0	0.741	209.5	0.706	0.2561	G	0.50
225	1030.0	0.743	257.2	0.731	0.2025	G	0.50
226	1000.0	0.751	226.2	0.628	0.1585	G	0.50
227	995.0	0.748	224.4	0.637	0.1703	G	0.50
228	1001.0	1.013	234.2	0.750	0.0889	G	0.50
229	1100.0	1.000	245.2	0.758	0.0839	G	0.50
230	1200.0	1.014	249.4	0.744	0.0654	G	0.50
231	1401.0	1.011	264.7	0.733	0.0364	G	0.50
232	998.0	0.498	21.2	0.437	0.4980	C	0.50
233	601.0	0.499	14.4	0.462	0.4785	C	0.50
234	799.0	0.498	19.0	0.456	0.4947	C	0.50
235	1105.0	0.497	20.5	0.424	0.5003	C	0.50
236	1200.0	0.500	22.7	0.407	0.4852	C	0.50
237	1398.0	0.497	22.8	0.360	0.4538	C	0.50
238	985.0	0.503	53.6	0.469	0.4798	C	0.50
239	598.0	0.492	13.8	0.449	0.4714	C,A,G	0.50
240	805.0	0.499	67.0	0.486	0.4593	C,G	0.50
241	605.0	0.499	50.4	0.477	0.4468	C	0.50
242	995.0	0.503	62.2	0.447	0.4416	C	0.50
243	1000.0	0.504	64.1	0.459	0.4523	C	0.50
244	1100.0	0.505	60.2	0.449	0.4595	C	0.50
245	1200.0	0.496	71.0	0.431	0.4429	C	0.50
246	1403.0	0.500	83.4	0.398	0.3996	C	0.50
247	1000.0	0.500	114.2	0.475	0.3997	C	0.50
248	801.0	0.492	95.2	0.421	0.3294	C,G,I	0.50
249	797.0	0.497	97.5	0.439	0.3624	C,G,I	0.50
250	1000.0	0.500	107.5	0.444	0.3717	C,G,I	0.50
251	1103.0	0.499	108.2	0.442	0.3800	C,G,I	0.50
252	1201.0	0.498	110.8	0.444	0.3914	C,G,I	0.50
253	1401.0	0.500	129.2	0.421	0.3499	C,G,I	0.50
254	1005.0	0.499	170.6	0.481	0.3207	C,G,F	0.50
255	601.0	0.498	138.5	0.442	0.2882	G,C	0.50
256	803.0	0.498	147.3	0.463	0.3175	C,G	0.50
257	1003.0	1.012	81.9	0.616	0.2436	C,G,F	0.50
258	1005.0	1.014	132.6	0.640	0.1789	C,G	0.50
259	1015.0	1.013	197.6	0.689	0.1089	C,G,I	0.50

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 7
CHF RESULTS
TEST CHANNEL NUMBER 2A

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
260	1002.0	1.010	16.8	0.541	0.2987	E	0.50
261	1003.0	1.015	62.9	0.602	0.2631	E	0.50
262	1007.0	1.015	107.0	0.655	0.2270	E,I,G	0.50
263	1005.0	1.013	150.1	0.676	0.1738	G,E,I	0.50
264	1005.0	1.002	172.2	0.677	0.1453	G,I,E	0.50
265	1005.0	1.000	205.1	0.710	0.1153	C,F,E,I	0.50

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

Table 8
CHF RESULTS
TEST CHANNEL NUMBER 3

Run Number	Pressure (psia)	Mass Velocity (Millions lb/h-ft ²)	Inlet Subcooling (Btu/lb)	Local Heat Flux at CHF (Millions Btu/h-ft ²)	Local Quality at CHF	Rod*	Location of CHF, Distance Before End of Heated Length (Inches)
266	1005.0	1.008	7.1	0.510	0.2957	I	0.50
267	1005.0	1.001	53.1	0.561	0.2582	I	0.50
268	1015.0	1.004	96.5	0.633	0.2349	I	0.50
**269	1005.0	1.005	149.0	0.726	0.2091	G,I	0.50
270	1000.0	1.000	101.8	0.785	0.1815	G,I,E	0.50
271	1010.0	0.755	11.9	0.489	0.3749	I	0.50
272	995.0	0.755	48.7	0.533	0.3518	I	0.50
273	1000.0	0.752	80.2	0.566	0.3328	I	0.50
274	997.0	0.769	106.7	0.608	0.3142	I	0.50
275	1003.0	0.757	146.5	0.646	0.2927	I	0.50
276	997.0	0.759	170.4	0.680	0.2807	I	0.50
277	995.0	0.757	223.3	0.740	0.2490	I	0.50
278	1000.0	0.502	27.5	0.440	0.4885	C,G,I	0.50
279	1000.0	0.500	70.7	0.474	0.4640	C,G	0.50
280	995.0	0.500	133.8	0.521	0.4242	G	0.50
281	1000.0	0.497	175.4	0.552	0.4023	C,I	0.50
282	995.0	0.498	213.0	0.582	0.3799	C	0.50
283	995.0	0.497	245.3	0.599	0.3520	C	0.50
284	995.0	0.500	274.3	0.635	0.3473	C,I	0.50
285	995.0	0.494	326.1	0.661	0.3098	C,I	0.50
286	997.0	0.249	42.0	0.289	0.6334	C,G,I	0.50
287	999.0	0.249	74.4	0.299	0.6092	C,G,I	0.50
288	995.0	0.250	106.7	0.316	0.5978	C,G,I	0.50
289	1000.0	0.250	136.8	0.327	0.5786	C,G,I	0.50
290	1003.0	0.249	164.5	0.333	0.5540	C,G,I	0.50
291	1005.0	0.248	200.0	0.360	0.5697	C,G,I	0.50
292	1000.0	0.250	247.3	0.383	0.5457	C,G,I	0.50
293	997.0	0.251	301.8	0.408	0.5195	C,G,I	0.50
294	1001.0	0.246	344.5	0.427	0.5191	C,G,I	0.50
295	1000.0	0.248	419.3	0.465	0.4879	C,G,I	0.50
296	1000.0	1.248	12.8	0.522	0.2338	I	0.50
297	999.0	1.246	58.8	0.605	0.2038	I	0.50
298	997.0	1.247	110.4	0.716	0.1783	I	0.50
299	1000.0	1.244	149.9	0.782	0.1510	I	0.50
300	1000.0	1.243	186.6	0.850	0.1277	I,E	0.50

* When more than one rod is shown for the same run, the strongest indication occurred on the first rod.

** Rod lost at end of this run.

Table 9
CHF RESULTS
TEST CHANNEL NUMBER 4

Run Number	System Pressure (psia)	Mass Flux (lb/h-ft ² X 10 ⁶)	Subcooling (Btu/lb)	Heat Flux (Btu/h-ft ² X 10 ⁶)	Exit Quality (%)
301	1019	1.051	29.4	0.518	25.54
302	1007	1.075	54.6	0.560	23.26
303	1018	1.134	110.2	0.665	18.77
304	1020	0.977	34.9	0.513	26.65
305	1038	0.936	13.1	0.460	28.16
306	1026	0.985	57.0	0.520	23.44
307	1001	1.033	97.1	0.602	20.49
308	1020	0.521	25.1	0.440	47.70
309	1022	0.538	57.0	0.478	45.50
310	1025	0.576	102.3	0.537	41.26
311	1020	0.598	155.6	0.587	35.97
312	1021	0.602	197.8	0.639	34.30
313	1025	0.508	66.7	0.459	44.89
314	1022	0.508	25.5	0.428	47.46
315	1045	0.495	104.8	0.484	43.92
316	1013	0.266	40.3	0.299	62.02
317	985	0.292	94.7	0.347	57.05
318	1011	0.286	76.0	0.327	57.80
319	900	0.298	148.8	0.376	54.10
320	1027	0.306	197.4	0.410	51.36
321	1011	0.269	211.7	0.386	54.62
322	1044	0.267	179.1	0.367	56.49
323	1038	0.251	107.3	0.323	62.17
324	1024	0.246	48.9	0.283	62.48
325	1031	0.244	38.2	0.271	61.84
326	781	0.934	221.7	0.820	18.11
327	783	0.490	12.3	0.456	51.23
328	798	0.508	66.2	0.495	46.19
329	775	0.495	164.3	0.533	37.76
330	773	0.500	254.0	0.601	31.86
331	786	0.266	26.0	0.315	63.75
332	765	0.288	86.3	0.367	59.99
333	792	0.250	180.4	0.379	60.75
334	755	0.252	235.6	0.408	57.76

For most runs, CHF occurred primarily on the corner rods. There is a notable exception in the case of test channel No. 2A, and this will be discussed in the text.

Test Channel No. 4

Consider first test channel No. 4, the "Reference" channel. The critical heat flux at 1000 psia is plotted versus the quality $\bar{X}$ for mass velocities $\bar{G} = 0.25 \times 10^6$, 0.5×10^6 , and 1.0×10^6 lb/h-ft², in Figures 21, 22, and 23, respectively. Superposed on Figures 22 and 23 are data from Reference 11 for the same channel cross section, but no grid-type spacers. (Pin spacers were used to minimize disturbance to the flow. This arrangement was called a "clean" channel in Reference 11, and will be so called here.)

The critical heat flux always occurred at the end of the heated length for test channel No. 4 (the same as for the clean channel) and hence just before the last spacer. Figures 21, 22, and 23 show the usual trend of critical heat flux with $\bar{X}$. The test channel No. 4 data can be fitted by straight lines, with scatter less than $\pm 10\%$.

Referring to Figure 22, the test channel No. 4 points are in good agreement with the clean channel data at $\bar{G} = 0.5 \times 10^6$ lb/h-ft². In contrast to this, Figure 23 shows the test channel No. 4 points to be about 25% below the clean channel data at $\bar{G} = 1.0 \times 10^6$ lb/h-ft². The arrangement of spacers for test channel No. 4 had an adverse effect on the critical heat flux (relative to the clean channel) at high flows, but not at low flows.

Test Channel No. 1

The critical heat flux for test channel No. 1 at 1000 psia is plotted versus $\bar{X}$ for mass velocities 0.5×10^6 and 1.0×10^6 lb/h-ft² in Figure 24. Superposed are best-fit lines through the test channel No. 4 data of Figures 22 and 23.

The critical heat flux always occurred just before the last spacer on the heated length for test channel No. 1 rather than at the end of the heated length as in the case of test channel No. 4. The $\bar{X}$ plotted in Figures 24, 25, and 26 is the average channel quality just before the last spacer. The test channel No. 1 data can be fitted by straight lines, with scatter less than $\pm 5\%$.

Referring to Figure 24, the test channel No. 1 points tend to lie below the test channel No. 4 data at $\bar{G} = 0.5 \times 10^6$ lb/h-ft² and qualities less than about 0.45 but lie consistently above (by 12% to 28%) the test channel No. 4 data at $\bar{G} = 1.0 \times 10^6$ lb/h-ft². The arrangement of spacers and position of heated length for test channel No. 1 has an adverse effect on CHF at low flows and a beneficial effect at high flows, relative to test channel No. 4.

The critical heat flux for test channel No. 1 at various pressures is plotted versus $\bar{X}$ for mass velocities 0.5×10^6 and 1.0×10^6 lb/h-ft² in Figures 25 and 26, respectively. Referring to both figures, for any given quality, as the pressure is *increased* in the range $1000 \leq P \leq 1400$ psia, the critical heat flux *decreases*. Conversely, as the pressure is *decreased* in the range $1000 \geq P \geq 800$ psia the critical heat flux *increases*. This is the well-known inverse pressure effect. Considering just Figure 25 ($\bar{G} = 0.5 \times 10^6$ lb/h-ft²), however, a decrease in the pressure below 800 psia brings about a significant decrease in critical heat flux; i.e., the relationship between critical heat flux and pressure changes from inverse to direct. At 600 psia, the critical heat flux has decreased enough that it is equal to the critical heat flux at 1000 psia, within the scatter of the data.

Considering just Figure 26 ($\bar{G} = 1.0 \times 10^6$ lb/h-ft²), on the other hand, a decrease in the pressure from 800 psia to 600 psia brings about no change in the critical heat flux, within the scatter of the data. Comparing Figure 26 with Figure 25 at $\bar{X} = 0.3$, an increase in pressure from 1000 psia to 1200 psia brings about a decrease in CHF of 0.04×10^6 Btu/h-ft² at $\bar{G} = 0.5 \times 10^6$ lb/h-ft², but a decrease in CHF of 0.15×10^6 Btu/h-ft² at $\bar{G} = 1.0 \times 10^6$ lb/h-ft² — nearly a fourfold difference. The inverse pressure effect is much stronger at higher flows.

Test Channel No. 2

The critical heat flux for test channel No. 2 at 1000 psia is plotted versus $\bar{X}$ for $\bar{G} = 0.5 \times 10^6$ and 1.0×10^6 lb/h-ft² in Figure 27. Best-fit lines through test channel No. 4 data are superposed.

There is a spacer just past the end of the heated length for test channel No. 2, the same as for test channel No. 4. The critical heat flux always occurred at the end of the heated length, the same as for test channel No. 4 (and hence just before the spacer). The quality against which the critical heat flux is plotted in Figures 27, 28, and 29 is therefore the exit quality. The test channel No. 2 data can be fitted by straight lines with scatter less than $\pm 5\%$.

Referring to Figure 27, the slope of the test channel No. 2 points, both flows, is much less than for test channel No. 4. Thus, at $\bar{G} = 0.5 \times 10^6$ lb/h-ft², $\bar{X} < 0.45$, the points are below test channel No. 4, whereas at the same flow and $\bar{X} > 0.45$, the points are above test channel No. 4. Similarly, at $\bar{G} = 1.0 \times 10^6$ lb/h-ft², $\bar{X} < 0.2$, the points are below test channel No. 4, but at $\bar{X} > 0.2$ the points are above. Comparing Figure 27 with Figure 24, at $\bar{G} = 1.0 \times 10^6$ lb/h-ft², $\bar{X} > 0.27$, the test channel No. 2 points are even above test channel No. 1.

Figure 21. Critical Heat Flux Versus Quality, Test Channel No. 4.
 $P = 1000 \text{ psia}, \bar{G} = 0.25 \times 10^6 \text{ lb/h-ft}^2$

Figure 22. Critical Heat Flux Versus Quality, Test Channel No. 4.
 $P = 1000 \text{ psia}$, $\bar{G} = 0.5 \times 10^6 \text{ lb/h-ft}^2$, Clean Channel Data Superposed

Figure 23. Critical Heat Flux Versus Quality, Test Channel No. 4.
 $P = 1000 \text{ psia}$, $\bar{G} = 1.0 \times 10^6 \text{ lb/h-ft}^2$, Clean Channel Data Superposed

Figure 24. Critical Heat Flux Versus Quality, Test Channel No. 1.
 $P = 1000 \text{ psia}$, $\bar{G} = 0.5 \times 10^6$ and $1.0 \times 10^6 \text{ lb/h-ft}^2$

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Figure 25. Critical Heat Flux Versus Quality, Test Channel No. 1.
 $\bar{G} = 0.5 \times 10^6 \text{ lb/h-ft}^2$, Various Pressures

Figure 26. Critical Heat Flux Versus Quality, Test Channel No. 1.
 $\bar{G} = 1.0 \times 10^6 \text{ lb/h-ft}^2$, Various Pressures

Figure 27. Critical Heat Flux Versus Quality, Test Channel No. 2.
 $P = 1000 \text{ psia}$, $\bar{G} = 0.5 \times 10^6$ and $1.0 \times 10^6 \text{ lb/h-ft}^2$

Figure 28. Critical Heat Flux Versus Quality, Test Channel No. 2.
 $\bar{G} = 0.5 \times 10^6 \text{ lb/h-ft}^2$, Various Pressures

Figure 29. Critical Heat Flux Versus Quality, Test Channel No. 2.
 $\bar{G} = 1.0 \times 10^6 \text{ lb/h-ft}^2$, Various Pressures

The critical heat flux for test channel No. 2 at various pressures is plotted versus $\bar{X}$ for mass velocities 0.5×10^6 and 1.0×10^6 lb/h-ft² in Figures 28 and 29, respectively. These two figures reveal essentially the same effect of pressure on CHF for test channel No. 2, which was shown in Figures 25 and 26 for test channel No. 1. It is an inverse effect for pressures in the range $1000 \leq P \leq 1400$, and is much stronger at the $\bar{G} = 1.0 \times 10^6$ lb/h-ft² condition (Figure 29) than at $\bar{G} = 0.5 \times 10^6$ lb/h-ft² (Figure 28). This reinforces the conclusion already made, that the inverse pressure effect is much stronger at higher flows.

Considering Figure 28, the change in CHF with pressure for pressures less than 1000 psia is less than the scatter in the data. The data for both Figures 28 and 29 are characterized by the fact that the slope is quite flat, particularly at the lower pressures.

Test Channel No. 2A

The critical heat flux for test channel No. 2A at 1000 psia is plotted versus $\bar{X}$ for $\bar{G} = 1.0 \times 10^6$ lb/h-ft² in Figure 30. Test channel No. 2 data and the channel No. 4 best-fit line are superposed.

CHF always occurred at the end of the heated length, the same as for test channels Nos. 4 and 2, and hence occurred just before the spacer which was located immediately past the end of the heated length (see Figure 18). For qualities less than 20%, CHF occurred primarily on the corner rods, but there was some indication of CHF on the center rod. For qualities greater than 20%, CHF occurred primarily on the center rod. At the 30% quality point, CHF occurred *only* on the center rod. This is in contrast to the other test channels; for them there was no indication of CHF on the center rod at any time. The diversion plate, even though located 6 inches past the end of the heated length, brought about early dryout of the film on the center rod.

Referring to Figure 30, the test channel No. 2A points are seen to agree well with the test channel No. 2 data. There was at least indication of CHF on the corner rods for all the points except the one at 30% quality. The diversion plate evidently brought about no change in CHF on the corner rods, except possibly at the 30% quality point.

Test Channel No. 3

The critical heat flux for test channel No. 3 at 1000 psia is plotted versus $\bar{X}$ for mass velocities 0.5×10^6 and 1.0×10^6 lb/h-ft² in Figure 31. Test channel No. 4 best-fit lines are superposed.

CHF always occurred at the end of the heated length, and always on the corner rods. The test channel No. 3 data can be fitted by straight lines with scatter less than $\pm 5\%$.

Referring to Figure 31, the test channel No. 3 points agree with the test channel No. 4 data at $\bar{G} = 0.5 \times 10^6$ lb/h-ft², but lie consistently above (by 12% to 22%) at $\bar{G} = 1.0 \times 10^6$ lb/h-ft². Comparing Figure 31 with Figure 24, the test channel No. 3 points agree well with the test channel No. 1 points at $\bar{G} = 1.0 \times 10^6$ lb/h-ft².

Comparison with Sixteen-Rod Results

The sixteen-rod test channel No. 3 configuration of Reference 2 corresponds to the nine-rod test channel No. 4 configuration reported here, in that:

1. The end of the heated length is close to the end of the channel. (The heated length is actually 5 inches before the end of the channel, and the underside of the grid plate is 3 inches past the end of the channel. These may be compared with the nine-rod dimensions given in Figure 18.)
2. The heat flux is uniform in both the axial and transverse directions.
3. The spacer at the end of the heated length is just 1/2 inch past the end of the heated length. The remainder of the spacers are located on 19-1/2-inch centers along the channel. (This latter dimension may be compared with the 18-inch centers for the nine-rod case.)

The 1000-psia, sixteen-rod and the 1000-psia, nine-rod data are compared at the two mass velocities, 0.5×10^6 and 1.0×10^6 lb/h-ft², in Figure 32.

CHF for the sixteen-rod channel always occurred at the end of the heated length and always on a corner rod, the same as for the nine-rod channel. Referring to Figure 32, the sixteen-rod points are seen to agree well with the nine-rod data at 0.5×10^6 lb/h-ft², but to lie above the nine-rod data at 1.0×10^6 lb/h-ft² by about 16% (except for two high points at the low end of the quality range which lie 27% and 35% above, respectively). At the higher flow, for the particular spacers tested, the nine-rod test channel No. 4 (i.e., the "Reference" channel) gives results which are low, compared with sixteen-rod results.

Figure 30. Critical Heat Flux Versus Quality, Test Channel No. 2A.
 $P = 1000$ psia, $\bar{G} = 1.0 \times 10^6$ lb/h-ft², Test Channel No. 2 Data Superposed

Figure 31. Critical Heat Flux Versus Quality, Test Channel No. 3.
 $P = 1000 \text{ psia}$, $\bar{G} = 0.5 \times 10^6$ and $1.0 \times 10^6 \text{ lb/h-ft}^2$

Figure 32. Critical Heat Flux Versus Quality, Test Channel No. 4.
 $P = 1000 \text{ pisa}$, $\bar{G} = 0.5 \times 10^6 \text{ and } 1.0 \times 10^6 \text{ lb/h-ft}^2$, 16-rod Data Superposed

Conclusion

Multirod critical heat flux data were obtained, using an array of nine uniformly heated rods held in their correct positions in a square channel by means of five grid-type spacers typical of modern water-cooled and moderated power reactors. Five combinations of axial position of heated length in relation to end of channel, and axial position of spacers with respect to end of heated length, were tested at various mass velocities and pressures. The effect on CHF of moving the end of the heated length from a position 2 inches before the end of the channel (test channel No. 4) to a position 3-1/2 feet before the end of the channel (test channel No. 2) was to reduce the CHF at low qualities. The effect on CHF of moving the last spacer from a position just past the end of the heated length (test channel No. 2) to a position just before the end of the heated length (test channel No. 1) was generally to raise the CHF, particularly at low qualities and high flows. The effect on the magnitude of CHF of adding a diversion plate 6 inches past the end of the heated length (test channel No. 2A) was insignificant, but the location of CHF moved from the corner rods to the center rod. The effect on CHF (relative to test channel No. 2) of removing the last spacer (test channel No. 3) was to raise the CHF at low qualities and lower the CHF at high qualities. The presence of the spacer just past the end of the heated length helped CHF at high qualities. At pressures greater than 1000 psia, the CHF decreases as the pressure is increased. This inverse pressure effect is stronger at higher flows. Sixteen-rod results were compared with nine-rod results (test channel No. 4) where, for both the sixteen-rod and the nine-rod channels, the rods were uniform, the ends of the heated lengths were close to the ends of the channels, and the axial positions of the spacers were the same. The sixteen-rod points agree well with the nine-rod data at $\bar{G} = 0.5 \times 10^6$ lb/h-ft², but lie above the nine-rod data at $\bar{G} = 1.0 \times 10^6$ lb/h-ft².

The distribution of the flow at the end of the heated length, among the various subchannels must change when the end of the heated length is moved from 2 inches before the end of the channel (where expansion into a larger cross section is possible) to 3-1/2 feet before the end of the channel. Moreover, the distribution must change when a diversion plate is added shortly past the end of the heated length, or when the spacer just past the end of the heated length is removed. These changes in geometry are accompanied by changes in the magnitude or location of CHF. It is evident that CHF is affected by the flow redistribution caused by the presence of spacers.

On the other hand, no CHF occurred directly under or past the last spacer on the heated length of Test Channel No. 1. Local disruption of the liquid film by the spacer is evidently not a contributor to CHF.

It may be concluded from the foregoing that at least part of the effect of spacers on CHF is due to a redistribution of the flow among the various subchannels. For the particular spacer tested it is a definite effect, although not a strong one.

A contributing cause to the effect of spacers on CHF may or may not be a highly localized disturbance such as might disrupt the liquid films. For the particular spacer tested there was no deleterious effect on CHF caused in this way, and a beneficial effect may have been occurring.

The question of localized disturbances to the liquid film has been examined further in the special study which is described next.

TASK D, LOW PRESSURE CHANNEL

There is no certainty that a spacer of arbitrary design might not affect CHF by disruption of the liquid film. A study was therefore made of the mechanisms of disruption of a liquid film in the presence of various shaped obstacles. Such a study might give some clues about the potentially most disruptive elements in a spacer design.

The experimental part of the study was of a water film in a 6-inch wide by 1-inch high rectangular channel in air-water flow at atmospheric pressure. Two-phase parameters such as the film thickness and wall shear stress were measured. A photographic and quantitative study was conducted on the phenomenon of film disruption due to various shapes of obstacles to simulate grid spacer contacts in multirod geometries. A simplified analysis of this phenomenon was made in terms of the momenta of the air and water streams.

The film thickness was measured by two different techniques, a film conductivity cell and a traversing electrical contact probe. The wall shear was measured with a flush shear probe made by DISA Electronics (Model No. 55-A-93). The obstacles used in the study are shown in Figure 33. The two characteristic types of film disruption are shown schematically in Figure 34, and photographically in Figures 35 and 36.

Conclusions

1. Liquid film thickness and flow rate measurements indicate that the normal manner of correlating these variables in terms of G_{f} and δ_{f} is useful, but does not take into account some velocity dependence in the data.

Figure 33. Obstacles for Film Disruption Study

(a)
TYPE I

(b)
TYPE II

Figure 34. Location of Dry Patch

Figure 35. Long Cylinder— $V_a = 47$ ft/sec, $\Gamma = 100$ lb/ft-h

Figure 36. Short Cylinder— $V_a = 47$ ft/sec, $\Gamma = 80$ lb/ft-h

2. The flush shear probe proved to be a useful and direct means of measuring the shear stress. Perhaps this method can be used more extensively in two-phase flow studies, where there is a liquid film on the wall.
3. In the presence of obstacles, two main types of dry patch formation were obtained. The first type, involving upstream dryout, can be satisfactorily explained in terms of stagnation of the liquid film. The kinetic energy of the waves in the liquid and the pressure rise in the air stream are the dominating factors in the phenomenon. The ratio of the momenta of the air and liquid appears to be a promising parameter for correlating the incipience of dry patches.
4. Dry patches of the second type, which occur due to stagnation of the wake flow behind obstacles, are dependent on the strength of the air vortex (a function of the air velocity) and the liquid momentum in that region.
5. The general trends in the behavior of the obstacles are expected to be similar in diabatic flow. The experimental channel is a useful tool in obtaining qualitative information about their performance.

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APPENDIX A **REPORTS GENERATED ON PA-44**

TECHNICAL REPORTS, PHASE I

QUARTERLY REPORTS

Quarter	Period	GEAP No.
1	October 26, 1964 – January 25, 1965	4798
2	January 26, 1965 – April 25, 1965	4863
3	April 26, 1965 – July 25, 1965	4933
4,5	July 26, 1965 – January 25, 1966	5056
6	January 26, 1966 – April 25, 1966	5161
7	April 26, 1966 – July 25, 1966	5207
8	July 26, 1966 – October 25, 1966	5300
9	October 26, 1966 – January 25, 1967	5441

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Levy, S., *Turbulent Flow in an Annulus*, October 1965, (GEAP-4976).

Hench, J. E., and Boehm, R. F., *Nine-Rod Critical Heat Flux Investigation at 1000 psia*, January 1966, (GEAP-4929).

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Schraub, F. A., *Isokinetic Sampling Probe Technique—Applied to Two-Component, Two-Phase Flow*, November 1966, (GEAP-5287).

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TECHNICAL REPORTS, PHASE II

QUARTERLY REPORTS

Quarter	Period	GEAP No.
10	January 1, 1968 – March 31, 1968	5497
11	April 1, 1968 – June 30, 1968	5679
12	July 1, 1968 – September 30, 1968	5709
13	October 1, 1968 – December 31, 1968	10009
14	January 1, 1969 – March 31, 1969	10055
15	April 1, 1969 – June 30, 1969	10067
16	July 1, 1969 – September 30, 1969	10114
17	October 1, 1969 – December 31, 1969	10151
18	January 1, 1970 – March 31, 1970	10214
19	April 1, 1970 – June 30, 1970	10253

Note: The issuing of quarterly reports was discontinued after June 30, 1970, in favor of concentrating on topical reports. The experimental and analytical work performed in the 20th and 21st quarters is described in Topical Report GEAP-10341 (see below).

TOPICAL REPORTS

Lahey, R. T., Jr., Shiralkar, B. S., and Radcliffe, D. W., *Subchannel and Pressure Drop Measurements in a Nine-Rod Bundle for Diabatic and Adiabatic Conditions*, March 1970, (GEAP-13049).

Shiralkar, B. S., *A Study of the Liquid Film in Adiabatic Air-Water Flow With and Without Obstacles*, October 1970, (GEAP-10248).

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Janssen, E., *Two-Phase Flow and Heat Transfer in Multirod Geometries, Final Report*, March 1971, (GEAP-10347).

TECHNICAL PAPERS SUBMITTED FOR PRESENTATION AND/OR PUBLICATION

Schraub, F. A., *Isokinetic Sampling Probe Technique—Applied to Two-Component, Two-Phase Flow*, ASME Paper 67-WA/FE-28.

Levy, S., "Turbulent Flow in an Annulus," *Journal of Heat Transfer*, Trans. ASME, Series C, Vol. 89, 1967, pp. 25-31.

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