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**NINE-ROD CRITICAL HEAT FLUX
INVESTIGATION, STEAM-WATER AT
600 TO 1400 psia
FINAL SUMMARY REPORT**

E. JANSSEN

U.S. ATOMIC ENERGY COMMISSION
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ATOMIC POWER EQUIPMENT DEPARTMENT

GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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NINE-ROD CRITICAL HEAT FLUX
INVESTIGATION, STEAM-WATER AT 600 TO 1400 psia,
FINAL SUMMARY REPORT

by
E. Janssen

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SECTION I

SUMMARY

Critical heat flux (CHF) data were obtained in two "clean"* nine-rod test channels. The rods were arranged in a square array. The rod-to-wall clearance was 0.135 inch, except for a few runs at 0.060 inch; the rod-to-rod clearance was 0.187 inch or 0.183 inch. The heated length varied from 30 inches to 72 inches. The heat flux was uniform in the axial direction. Data were obtained both with all rods uniformly heated and with one of the corner rods slightly (on the order of 10%) higher than the average. The flow was varied from 0.3×10^6 to 1.25×10^6 lb/h-ft², and the pressure was varied from 600 to 1400 psia. On the basis of the test results it is concluded that:

1. For rods in a normally-spaced square array, the CHF occurs on one of the corner rods.
2. The CHF decreases as the average quality increases, other things being the same. The average quality is the dominant parameter in determining CHF.
3. There is no strong or consistent effect of length on CHF.
4. There is no flow effect on CHF for flows greater than 0.75×10^6 lb/h-ft². For flows less than this, the CHF tends to vary in an inverse manner with the flow, but the effect is not strong.

* "Clean" refers to the fact that the means for maintaining the rods in correct relative alignment were designed to produce as little disturbance as possible to the flow.

5. In the range of pressures from 600 to 1400 psia, the CHF varies in an inverse manner with the pressure, other things being the same.
6. A reduction in rod-to-wall clearance from 0.135 inch to 0.060 inch causes a 15% reduction on CHF.

A comparison of the nine-rod (square array) CHF data reported here with 19-rod, 37-rod, and seven-rod (circular array) CHF data reported elsewhere, shows poor agreement when the comparison is on the basis of the same average exit quality and mass velocity. A comparison, on the same basis, of the nine-rod CHF data with multirod correlations of Becker and Barnett shows similar poor agreement. These two correlations are based largely on results obtained with circular arrays. It is evident that the use of average channel conditions for correlating purposes has significant limitations, in particular for correlating circular-array results with square-array results.

Multisubchannel computer codes consider channel conditions in more detail, thus providing the means for a possible improvement in the correlation of multirod CHF data. Two such codes were investigated, the COBRA (Batelle Northwest) and the HAMBO (U.K. Atomic Energy Establishment, Winfrith). Each of these, in combination with a simple channel (internally-heated annulus) CHF correlation, was used to predict CHF in the nine-rod channel. Fair to good agreement was obtained between predicted and measured CHF. The use of such codes appears to be a promising procedure for predicting CHF in a multirod array.

SECTION II

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. The coolant enters at one end of the bundle as a liquid, and flows parallel to the rods in the spaces between them. When the reactor is operating near rated conditions, very high rates of heat transfer take place. It is important to be able to predict, under conditions where boiling occurs, what the limit of heat transfer is in such a complex channel. We here refer to the limit commonly known as the critical heat flux, but also known as the boiling crisis, departure from nucleate boiling, burnout, or dryout.

A thorough study of this problem (the prediction of CHF in multirod channels) can follow two paths. The first is to make a detailed investigation of how the liquid and vapor phases distribute themselves, i.e., the flow structure, and then to combine this with knowledge of CHF generated in investigations with simpler channels, to predict the CHF in multirod channels. The second is to measure directly the CHF in a variety of multirod channels. In fact, both approaches to the problem are necessary.

The Atomic Power Equipment Department of the General Electric Company entered into a contract with the U.S. Atomic Energy Commission in October 1964, to investigate two-phase flow and heat transfer in multirod

geometries using the two approaches mentioned in the preceding paragraph. Task A of this program was concerned with flow structure investigations and Task B with direct measurement of multirod CHF. The scope for Task B also included the evaluation of one or two multisubchannel hydraulic model computer codes now in existence which predict the two-phase flow distribution in a complex channel. This, in combination with a simple channel CHF correlation, can be used to predict multirod CHF.

This report is the final report on the work carried out under Task B.

The objectives for the work of Task B were as follows:

- a. Measure the critical heat flux for a "clean" vertical nine-rod (3 by 3 square array) geometry with uniform heat flux, under forced convection conditions, with water at a high pressure (600 to 1400 psia), and flow upward.
- b. Investigate the effect of certain parameters, specifically quality, flow rate, heated length, pressure, and rod-to-wall spacing.
- c. Use the results to evaluate one or more computer models as a basis for CHF prediction.

The report of the work follows.

SECTION III

DESCRIPTION OF EQUIPMENT AND TEST PROCEDURE

Two nine-rod test channels were used for the work reported here.

3.1 First Channel

The first nine-rod test channel (hereinafter referred to as the first channel) has been described in detail elsewhere.⁽¹⁾ The salient geometrical features are:

Number of rods	Nine (3 by 3 square array)
Rod Diameter	0.4375 inch
Radius of Channel Corner	0.354 inch
Rod-to-Rod Clearance	0.187 inch
Rod-to-Wall Clearance	0.135 inch
Hydraulic Diameter	0.485 inch
Heated Length	30 and 60 inches
Entrance Calming Length	10 inches

Each of the nine rods has uniform axial heat flux. Most of the data were obtained with the heat flux on one of the corner rods about 10%* higher than the average for the remaining eight rods. The heat flux for these remaining eight was within 5% of uniform.

A sectional view of the first nine-rod channel installed in its pressure vessel is shown in Figure 1. The rods are constructed of Inconel-X tubes. Electrical heating of the tubes simulates internal heat generation in reactor fuel rods. Subcooled water enters the channel at the bottom. The flow leaves the top of the channel as a saturated steam-water mixture. Rod-to-rod and rod-to-wall spacing is maintained by means of 1/8-inch-diameter pins plus slender spool-type pins.

* Actually the heat flux varied from 3% to 14% above the average, depending upon the particular set of rods.

The last set of 1/8-inch pins is located 14.5 inches before the exit end of the heated length. A set of spool-type pins (rod-wall only) is located 6 inches before the end of the heated length.

The first channel was installed in the Heat Transfer Facility loop as it existed prior to July 1967. That loop (together with associated instrumentation) is described in detail in Reference (2).

The CHF was detected by means of thermocouples located near the exit end of the "hot" corner rod mentioned above. The CHF point was approached by holding pressure, flow, and subcooling constant, and gradually increasing the power (in steps of 1 to 2%), until one or more thermocouples indicated a CHF condition.

3.2 New Channel

The second nine-rod test channel (hereinafter referred to as the new channel) was designed around a new type of electrically-heated rod developed by G. E. for this particular application. The rod is clad with a nickel tube insulated from the electrical heater element so that the exterior of the rod may be at ground potential, thereby eliminating any shorting problems. The ends of five individual chromel wires are fusion welded to the inside of the nickel tube close to the exit end of the heated length to form chromel-nickel thermocouple junctions. These are utilized in CHF detection.

The salient geometrical features of the new channel are:

Number of Rods	Nine (3 by 3 square array)
Rod Diameter	0.570 inch

Radius of Channel Corner	0.375 inch
Rod-to-Rod Clearance	0.183 inch
Rod-to-Wall Clearance	0.135 inch
Hydraulic Diameter	0.497 inch
Heated Length	72 inches
Calming Length	5-inch converging area plus 3.5-inch constant area

The cross-sectional dimensions of the channel can be altered by inserting a 0.070-inch liner, which effectively reduces the channel inside dimension by 0.150 inch, thus reducing the channel corner radius to 0.364 inch, the rod-to-wall clearance to 0.060 inch, and the hydraulic diameter to 0.397 inch. Other dimensions remain as listed above.

Each of the nine rods has uniform axial heat flux. Moreover, the heat flux is uniform in the transverse direction, within 2%, based on resistance measurements at room temperature.

A sectional view of the new nine-rod channel is shown in Figure 2. The provision for maintaining rod spacing is similar to that for the first channel, except that no spool-type pins are used. Note also that the first support past the end of the heated length is a tie plate located 19-5/8 inches above the last set of pins.

The new channel was installed in the Heat Transfer Facility loop as modified after September 1967, shown schematically in Figure 3. This facility now consists of a single main loop of 3-inch Schedule-80 stainless steel pipe; two steam drums connected in parallel; steam condenser (in secondary loop off of steam drum); downcomer; turbine-type flowmeter; subcooler, subcooler pump, and remote-operated valve (in secondary loop just ahead of pumps); two canned-rotor pumps in series; flow control valve with remote-operated trimmer valve in parallel with it; orifice-type flowmeter at end of straight horizontal run; and test section and riser. Pressure is controlled by regulating the rate at which cooling air blows over the steam con-

denser. This is accomplished automatically by louvers controlled by a pressure-responsive servo.

With the exception of the provisions for redundant flow measurement and remote control of subcooling and primary flow, these are features which the loop had before modification. However, there are certain features which the loop did not have before modification, namely: a.) internal provision for flow calibration against a volumetric standard; thus permitting calibration with high temperature water; b.) improved provision for venting the loop of air during warmup; and c.) larger blowdown line, elimination of dead ends, and generally better provision for cleaning the loop and keeping it clean, thus enhancing the water purity.

In addition to the modification made directly to the loop, the instrumentation for measurement and control of loop conditions was modified, to increase the rate and accuracy of data acquisition. The addition of a turbine-type flowmeter has already been mentioned. A Hewlett-Packard DYMEC data acquisition system now prints out the millivolts corresponding to all the significant parameters, i.e., the flow (turbine flowmeter), the inlet subcooling (differential thermocouples between inlet and test section exit), the pressure, the power (new SCI wattmeter), and also the temperature at the turbine meter (chromel-alumel thermocouples with 150°F cold junction temperature). A considerable saving in time is realized in both reduced time to set conditions and reduced time to record data. The estimated accuracies of the various quantities, when properly zeroed and calibrated, are:

Quantity	Instrument	Estimated Accuracy
Pressure	Statham Strain Gage Transducer	3 psi
Flow	Potter Turbine Meter	1.5%
Inlet Subcooling	Conax-Sheathed Chromel-Alumel Thermocouples	4 Btu/lb
Power	SCI Wattmeter	1%

FIGURE 1. SECTIONAL VIEW OF FIRST NINE-ROD ASSEMBLY WITH PRESSURE VESSEL

FIGURE 2. SECTIONAL VIEW OF NEW NINE-ROD ASSEMBLY WITH PRESSURE VESSEL

FIGURE 3. SCHEMATIC OF HEAT TRANSFER FACILITY LOOP AFTER SEPTEMBER 1967

The CHF continues to be detected by thermocouples located near the exit end of the rods most likely to experience it. There are 16 Sanborn channels for thermocouple signal traces—enough to monitor all nine rods if necessary.

The procedure in approaching a CHF point is essentially the same as be-

fore. Immediately following the occurrence of a CHF, the power is dropped to zero, then brought back on at a lower level, so that normal boiling heat transfer is re-established. The subcooling is then changed and the process is repeated to get a CHF point at a slightly different condition.

SECTION IV

RESULTS AND DISCUSSION

The measured values of CHF for various pressures, flows, and qualities are listed in Tables 1A and 1B (first test channel and new test channel, respectively). The listed values for both the mass velocity and the exit quality are average values for the channel as a whole. The listed value for the heat flux is the average for all nine rods when they are intended to be uniform, but is the value for the "hot" corner rod where this one rod is intentionally about 10% higher in heat flux than the others. The results are presented graphically in Figures 4 through 12.

Twelve of the runs with the first test channel were made using uniform rods; i.e., the heat flux was uniform across the rods as well as axially. The remainder of the runs with the first test channel were made using one corner rod which had a slightly (~10%) higher heat flux than the other rods. The CHF invariably occurred on one of the corner rods, on the side of the rod facing the channel corner, whether all the rods were uniform or one corner rod was 10% higher in heat flux. (It always occurred on the "hot" rod when one was used.) When the CHF on the "hot" corner rod is plotted versus average exit quality, it cannot be distinguished from the CHF of the uniform rods versus average exit quality [see Reference (1)]. In the ensuing discussion of test results, no differentiation will be made between "uniform rods" and "hot rod" data.

All the runs with the new test channel were made using uniform rods.

4.1 Effect of Quality

The CHF invariably occurred at the exit end, which is to be expected with uniform axial heat flux. Thus the average quality for the channel at the position of CHF is identically the average exit quality. It is shown by the data (see Figures 4 through 12) that the CHF decreases as the average quality increases, other things being the same. Even though other parameters do have an effect on CHF, as will be noted below, the average quality is the dominant parameter. Thus, at a flow of 0.5×10^6 lb/h-ft² and a pressure of 1000 psia, an increase in quality from 20% to 50% brings about a 50% reduction in CHF.

4.2 Effect of Heated Length

A comparison (refer to Figures 4 through 7) between data taken with a 30-inch heated length and data taken with a 60-inch heated length suggests that: a.) the CHF is higher with the shorter heated length, and b.) the improvement in CHF of the shorter over the longer length is greatest at the highest flow (1.25×10^6 lb/h-ft²), but is so small as to be practically nonexistent at the lowest flow (0.5×10^6 lb/h-ft²).

TABLE 1A
CRITICAL HEAT FLUX CONDITIONS
FIRST NINE-ROD TEST CHANNEL 0.4375-INCH-DIAMETER RODS

Run No.	Heated Length (inches)	Pressure (psia)	Flow ₂ (lb/h-ft ²) × 10 ⁻⁶	Inlet Subcooling (Btu/lb)	Heat Flux (Btu/h-ft ²) × 10 ⁻⁶	Exit Quality	Remarks
	30	1000					
77			0.491	36.0	0.680	0.256	Hot Corner Rod
85			0.492	167.0	0.906	0.158	
101			0.498	27.0	0.687	0.282	Uniform Bundle
102			0.496	64.0	0.718	0.242	
103			0.504	109.0	0.805	0.207	
104			0.493	146.0	0.899	0.203	
105			0.496	145.0	0.906	0.205	
106			1.024	46.0	0.925	0.141	
107			0.764	16.0	0.881	0.172	
108			0.769	55.0	0.957	0.128	
109			0.769	94.0	0.897	0.130	
110			0.769	129.0	0.957	0.094	
111			0.764	17.0	0.761	0.208	
112			1.021	17.0	0.859	0.172	
113			1.023	17.0	0.900	0.165	Hot Corner Rod
114			1.028	40.0	0.922	0.133	
115			1.027	51.0	0.946	0.121	
116			1.026	63.0	0.993	0.112	
117			1.279	20.0	0.953	0.130	
118			1.274	22.0	0.983	0.133	
119			1.278	34.0	1.005	0.117	
120			1.276	44.0	1.040	0.108	
121			1.276	55.0	1.064	0.096	
122			1.275	63.0	1.087	0.087	
123			1.274	69.0	1.108	0.082	
124			1.024	88.0	1.076	0.091	
125			1.025	100.0	1.064	0.071	
126			1.025	102.0	1.084	0.071	
127			1.022	76.0	1.028	0.101	
128			1.026	21.0	0.851	0.148	
129			1.022	18.0	0.842	0.154	
130			1.028	65.0	0.957	0.101	
131			1.021	100.0	1.040	0.066	
132			1.022	113.0	1.076	0.053	
133			0.304	25.0	0.606	0.392	
134			0.302	185.0	0.810	0.294	
135			0.302	223.0	0.886	0.201	
136			0.300	247.0	0.952	0.304	
137			0.300	273.0	0.993	0.293	
	60						
184			0.764	13.0	0.543	0.301	
185			0.769	42.0	0.588	0.281	
186			0.768	54.0	0.599	0.270	
187			0.770	80.0	0.630	0.247	
188			0.768	98.0	0.653	0.233	
189			0.766	118.0	0.668	0.212	
190			0.770	140.0	0.702	0.197	
191			0.770	160.0	0.717	0.175	
192			1.021	13.0	0.616	0.253	
193			1.025	41.0	0.668	0.231	
194			1.024	61.0	0.695	0.213	
195			1.021	78.0	0.723	0.200	
196			1.024	98.0	0.746	0.179	
197			1.022	117.0	0.770	0.161	
198			1.271	55.0	0.736	0.178	
199			1.267	68.0	0.763	0.168	
200			1.269	85.0	0.791	0.151	
201			1.275	99.0	0.820	0.139	

TABLE 1A (Continued)

Run No.	Heated Length (inches)	Pressure (psia)	Flow ² (lb/h-ft ²) × 10 ⁻⁶	Inlet Subcooling (Btu/lb)	Heat Flux (Btu/h-ft ²) × 10 ⁻⁶	Exit Quality	Remarks
202	60	1000	0.491	16.0	0.475	0.412	Hot Corner Rod
203			0.491	24.0	0.478	0.404	
204			0.488	33.0	0.488	0.400	
205			0.491	46.0	0.497	0.387	
206			0.492	53.0	0.512	0.388	
207			0.492	62.0	0.520	0.382	
208			0.491	79.0	0.526	0.362	
209			0.497	18.0	0.490	0.418	
210			0.495	102.0	0.553	0.348	
211			0.491	108.0	0.555	0.345	
212			0.492	118.0	0.565	0.337	
213			0.496	130.0	0.569	0.318	
214			0.491	140.0	0.580	0.319	
215			0.491	149.0	0.588	0.312	
216			0.491	159.0	0.613	0.320	
217	0.492	167.0	0.622	0.314			
218	0.492	178.0	0.639	0.313			
219	0.491	190.0	0.637	0.293			
220	0.492	201.0	0.640	0.278			
221	0.492	210.0	0.645	0.269			
269	30	600	1.019	135.0	1.148	0.056	
419	60		1.023	17.0	0.663	0.248	
422			1.023	149.0	0.940	0.159	
434			0.490	17.0	0.538	0.389	
435			0.493	63.0	0.591	0.364	
436			0.491	100.0	0.629	0.344	
437			0.491	152.0	0.687	0.318	
438			0.489	203.0	0.747	0.297	
439			0.490	131.0	0.652	0.322	
440			0.490	78.0	0.609	0.360	
441			1.021	8.0	0.747	0.264	
442			1.019	51.0	0.820	0.233	
443			1.024	99.0	0.948	0.213	
444			1.023	156.0	1.051	0.173	
445			1.023	132.0	0.998	0.186	
446	60	1400	0.486	21.0	0.415	0.371	
447			0.487	53.0	0.459	0.358	
448			0.489	103.0	0.505	0.314	
449			0.489	154.0	0.556	0.275	
450			0.489	197.0	0.592	0.235	
451			0.490	126.0	0.526	0.294	
452			0.488	77.0	0.471	0.327	
476	30		1.026	13.0	0.777	0.159	
477			1.027	53.0	0.927	0.125	

TABLE 1B
CRITICAL HEAT FLUX CONDITIONS NEW
NINE-ROD TEST CHANNEL 0.570-INCH-DIAMETER RODS

Run No.	Heated Length (inches)	Pressure (psia)	Flow (lb/h-ft ²) × 10 ⁻⁶	Inlet Subcooling (Btu/lb)	Heat Flux (Btu/h-ft ²) × 10 ⁶	Exit Quality	Remarks
N001	72	1000	0.521	20.0	0.440	0.457	Runs N001 through N034 are with a rod-to-wall clearance of 0.135 inch.
N002			0.510	21.0	0.427	0.453	
N003			0.504	85.0	0.500	0.443	
N004			0.511	133.0	0.514	0.378	
N005			0.500	158.0	0.562	0.408	
N006			0.502	170.0	0.576	0.402	
N007			0.486	227.0	0.623	0.391	
N008			0.484	273.0	0.614	0.310	
N009			0.488	24.0	0.448	0.494	
N010			0.956	14.0	0.550	0.310	
N011			1.002	45.0	0.589	0.294	
N012			0.936	74.0	0.630	0.275	
N013			0.943	87.0	0.646	0.262	
N014			0.704	18.0	0.511	0.392	
N015			0.712	58.0	0.535	0.346	
N016			0.715	49.0	0.542	0.363	
N017			0.720	76.0	0.578	0.347	
N018			0.721	101.0	0.608	0.332	
N019			0.721	142.0	0.614	0.274	
N020			1.208	12.0	0.602	0.270	
N021			1.202	29.0	0.609	0.248	
N022			1.214	30.0	0.636	0.257	
N023			0.974	12.0	0.576	0.324	
N024			0.975	36.0	0.575	0.287	
N025			0.982	35.0	0.583	0.290	
N026			0.988	59.0	0.616	0.270	
N027			0.736	13.0	0.507	0.378	
N028			0.740	49.0	0.553	0.357	
N029			0.730	74.0	0.581	0.347	
N030			0.732	98.0	0.596	0.320	
N031			0.494	21.0	0.431	0.473	
N032			0.496	103.0	0.506	0.431	
N033			0.500	144.0	0.561	0.428	
N034			0.494	232.0	0.622	0.372	
N035			0.498	28.0	0.363	0.496	Runs N035 through N049 are with a rod-to-wall clearance of 0.060 inch.
N036			0.506	84.0	0.411	0.473	
N037			0.509	124.0	0.426	0.430	
N038			0.524	154.0	0.455	0.407	
N039			0.530	208.0	0.476	0.347	
N040			0.533	243.0	0.500	0.319	
N041			0.761	22.0	0.428	0.382	
N042			0.732	64.0	0.455	0.361	
N043			0.731	63.0	0.465	0.374	
N044			0.725	111.0	0.503	0.343	
N045			0.704	195.0	0.545	0.274	
N046			0.699	196.0	0.539	0.269	
N047			0.763	25.0	0.434	0.382	
N048			0.498	31.0	0.376	0.510	
N049			0.452	254.0	0.475	0.386

FIGURE 4. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia,
 $0.5 \times 10^6 \text{ lb/h-ft}^2$, VARIOUS HEATED LENGTHS

FIGURE 5. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 0.75×10^6 lb/h-ft², VARIOUS HEATED LENGTHS

FIGURE 6. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 1.0×10^6 lb/h-ft², VARIOUS HEATED LENGTHS

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FIGURE 7. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 1.25×10^6 lb/h-ft², VARIOUS HEATED LENGTHS

FIGURE 8. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY, VARIOUS FLOWS

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FIGURE 9. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT $0.5 \times 10^6 \text{ lb/h-ft}^2$, VARIOUS PRESSURES

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FIGURE 10. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT $1.0 \times 10^6 \text{ lb/h-ft}^2$, VARIOUS PRESSURES

FIGURE 11. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 0.5×10^6 lb/h-ft², TWO ROD-TO-WALL CLEARANCES

FIGURE 12. NINE-ROD CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 0.75×10^6 lb/h-ft², TWO ROD-TO-WALL CLEARANCES

A comparison of the 60-inch heated length data with the 72-inch heated length data shows a reversal of the length effect described above; i.e., the CHF is lower with the shorter heated length. The 60-inch heated length rods, in addition to being slightly shorter, were also slightly smaller in diameter than the 72-inch rods (0.4375 inch instead of 0.570 inch). However, data taken with single rods⁽³⁾ show no diameter effect.

On the evidence of the data plotted in Figures 4 through 7, it may be concluded that there is no strong or consistent length effect.

4.3 Effect of Flow Rate

Referring to Figure 8, the data show that for average channel flows of 0.75×10^6 lb/h-ft² and higher, the CHF does not vary with flow, whereas for flows less than 0.75×10^6 lb/h-ft², the CHF tends to vary in an inverse manner with the flow. For example, in the range of qualities from 20 to 30%, the CHF at 0.5×10^6 lb/h-ft² is the order of 10% higher than at 0.75×10^6 lb/h-ft². It appears, however, that the flow effect is not very strong, and it is shown in Figure 8 to be of the same order as the heated length effect.

4.4 Effect of Pressure

Referring to Figures 9 and 10, where the flow is 0.5×10^6 lb/h-ft², an increase in pressure from 1000 psia to 1400 psia causes about a 10% decrease in CHF, whereas a decrease in pressure from 1000 psia to 600 psia causes about a 10% increase in CHF. There are fewer "pressure effect" data at a flow of 1×10^6 lb/h-ft² than at a flow of 0.5×10^6 lb/h-ft², particularly at 1400 psia, and the length effect tends to mask the pressure effect. However, the general effect of pressure at

the higher flow appears to be the same as at the lower flow. In the range of pressures from 600 to 1400 psia, the CHF varies in an inverse manner with pressure, other things being the same.

4.5 Effect of Rod-to-Wall Spacing

Referring to Figures 11 and 12, for flows in the range 0.5×10^6 to 0.75×10^6 lb/h-ft² and qualities from 30 to 50%, a reduction in rod-to-wall clearance from 0.135 inch to 0.060 inch by installing a 0.070-inch liner in the new test channel (refer to Section III) causes a reduction in CHF of 15%.

It should be pointed out that the rod-to-wall clearances mentioned above, at the location of CHF and the time of CHF, could have been several thousandths of an inch in error. It will be noted from the description of the new test channel that the distance between supports at the top end of the rods (the last set of pins and the top tie plate) is 19-5/8 inches. It was apparent from the dark appearance of some of the rods at the termination of the tests with the 0.135-inch rod-to-wall clearance, that a few of them had experienced high temperature gradients, and thermal bowing must have occurred. Rod G had even taken on a permanent inward bow at room temperature of an estimated 0.02 inch. Rod C, however, was installed new just before the 0.070-inch liner tests. The rod C thermocouples were the ones which indicated CHF for all the subsequent 0.070-inch liner runs. At the end of these runs, rod C showed little evidence of over-heating, and was not bowed. It is believed that any bowing of rod C during the runs was negligible and that the results correctly show the effect of reduced rod-to-wall clearance on CHF.

SECTION V

COMPARISON WITH OTHER MULTIROD RESULTS

The direct measurement of CHF for multirod geometries has now been done at a number of laboratories. Some of the best of these data are listed in References (4) and (5). Salient features of the test channels for certain data selected from these two references (19-rod, 37-rod, and seven-rod bundles in a circular array with rod-to-rod and rod-to-wall spacings comparable to the spacings for our nine-rod square array bundles) are summarized in Table 2. The data are plotted in Figures 13 through 16. Superposed are shaded areas to indicate the location of the nine-rod data reported here.

Agreement between the multirod data of Figures 13 through 16 with our nine-rod data is poor, on the basis of average exit quality and mass velocity. Only four of the multirod data points, from a total of 125, lie within the shaded areas. It is evident that for correlation purposes, where the data have been obtained with other than square arrays of rods, this way of presenting multirod CHF results (i.e., versus average exit quality and mass velocity) has limitations as will be discussed later.

Matzner and Casterline⁽⁸⁾ tested a series of 19-rod (circular array) bundles at various pressures from 500 psia to 1200 psia and flows from 0.1×10^6 to 3.0×10^6 lb/h-ft². The heat flux on the inner rods and center rod was in all cases approximately 71% of the flux on the outer circle of rods. The rod-to-rod clearance was 0.040 inch, and the rod-to-wall clearance was 0.060 inch, which is a much more compact array than our nine-rod bundle or the bundles listed in Table 2. The results are summarized in their conclusions:

"At the very low mass velocities of 0.1 and 0.2×10^6 lb/h-ft², the critical heat flux was practically independent of mass velocity, pressure, and length, and linearly dependent on only exit quality from 45 to 95%.

"At mass velocities of 0.5×10^6 lb/h-ft² and greater, the following trends were apparent:

1. At constant exit quality, mass velocity, and length, the critical heat flux increased with decreasing pressure from 1200 to 500 psia.
2. At constant exit quality, mass velocity, and pressure, the critical heat flux decreased with increasing length from 19 inches to 9 feet.
3. At constant exit quality, pressure, and length, the critical heat flux increased with increasing mass velocity from 0.5 to 3.0×10^6 lb/h-ft².
4. The slopes of the critical heat flux versus exit quality curves for all the test sections were smaller than usual.
5. As the bundle length was increased from 18 inches to 9 feet, the critical heat flux location shifted from the outer rods to the center rod despite a 30% heat flux depression on the center and inner rods.

"It has been postulated that the performance of these bundles was strongly dependent on the rods in the bundle closely spaced (large D/s ratio), thus minimizing subchannel mixing. Lack of mixing then allowed substantial enthalpy imbalance to develop in the subchannels of the bundle which resulted in a lower critical heat flux performance than had been observed for low D/s ratio bundles."

TABLE 2
SELECTED ROD BUNDLES FOR
WHICH CHF DATA AT 1000 PSIA ARE AVAILABLE

Bundle No. *	Source (Reference)	No. of Rods	Method of Positioning Rods	Heated Length (inches)	Rod Diameter (inches)	Minimum Rod Spacing (inches)		Heat Flux Distribution**
						Rod-to-Rod	Rod-to-Wall	
13	(6)	19	Grids	48	0.625	0.112	0.067	1/0.714/0
15	(6)	19	Grids	48	0.625	0.112	0.067	1/0.697/0
17	(6)	19	Grids	48	0.625	0.085	0.085	1/0.716/0
21	(7)	37	Grids	144	0.625	0.104	0.119	1/0.629/0.565/0
26	(7)	37	Grids	144	0.625	0.117	0.102	1/0.652/0.568/0
27	(5)	7		118	0.394	0.158	0.158	1/1

* The bundle numbering scheme is the same as used in Reference (4). Bundle No. 27 has been added to the original listing.

** Rods are arranged in circles. The heat flux distribution is in the radial direction, from outer circle to center.

FIGURE 13. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 0.5×10^6 lb/h-ft², VARIOUS ROD BUNDLES

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FIGURE 14. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 0.75 x 10⁶ lb/h-ft², VARIOUS ROD BUNDLES

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FIGURE 15. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 1.0×10^6 lb/h-ft², VARIOUS ROD BUNDLES

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FIGURE 15. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 1.25×10^6 lb/h-ft², VARIOUS ROD BUNDLES

Concerning Item 5 of the above quoted conclusions, it was apparent from the Columbia data that the CHF location also tended to shift from the outer rod toward the center rod with a decrease in flow and, to a slight extent, with increase in quality.

Our nine-rod results show: a.) the same CHF effect with pressure as noted in Item 1, b.) no definite length effect, except that the decrease in CHF with increase in length from 30 inches to 60 inches at the higher flows agrees with Item 2, c.) no strong flow effect, except that the decrease in CHF with increase in flow from 0.5×10^6 to 0.75×10^6 is the reverse of the trend noted in Item 3, and d.) no tendency for the CHF location to shift toward the center with any change in length, flow, or quality. It is presumed that the difference between our nine-rod results and the Columbia 19-rod results is due primarily to the much closer spacing of the latter, which is in line with the conclusion drawn by Matzner and Casterline relative to the generally lower level of the CHF which they observed.

Becker⁽⁹⁾ has correlated a considerable amount of multirod CHF data, most of which was obtained with bundles in circular array, by means of a correlation of round tube data. Becker's round tube correlation is of the form

$$X_c \text{ (round)} = a_0 \left[\frac{10^9}{G^{1/2} \phi_c} - a_1 \right], \quad (1)$$

where a_0 and a_1 are functions of pressure. For a multirod bundle,

$$X_c = X_c \text{ (round)} \eta_1 \eta_2, \quad (2)$$

where

$$\eta = \frac{\text{Heated perimeter}}{\text{Total wetted perimeter}},$$

$$\eta_1 = \eta_1(\phi_c) \text{ [See Figure 14 of Reference (9)] ,}$$

and

$$\eta_2 = 0.68 \text{ for multirod bundles.}$$

The heat balance equation is

$$\phi_c = \frac{\eta G D_{HY} h_{fg}}{4L} \left[\frac{\Delta h_s}{h_{fg}} + X_c \right]. \quad (3)$$

Equations (1), (2), and (3) are solved together for ϕ_c and X_c . Becker suggests that this correlation may be used for nonuniform axial flux as well as uniform. For nonuniform radial flux, η is redefined

$$\eta = \frac{\frac{1}{n} \sum_{i=1}^n \xi \times \text{Heated perimeter}}{\text{Total wetted perimeter}}, \quad (4)$$

where

n = Number of rods, and

ξ = Ratio, heat flux on i^{th} rod to maximum heat flux.

Barnett⁽⁴⁾ has also correlated multirod CHF data, but by means of a correlation of internally-heated annulus data, in contrast to the round tube correlation used by Becker. The method involves choosing, for the particular multirod bundle, an equivalent inner diameter D_I^* and equivalent outer diameter D_O^* , and then treating the bundle as an annulus. According to Method II of Reference (4),

$$D_I^* = D_R, \text{ and} \quad (5)$$

$$D_O^* = \{D_R (D_{HE} + D_R)\}^{1/2} \quad (6)$$

where

$$D_{HE} = \frac{4 \times \text{Flow area}}{\pi D_R \sum_{i=1}^n \xi}, \quad (7)$$

and n and ξ are as defined above.

The hydraulic diameter D_{HY} has the usual definition

$$D_{HY} = \frac{4 \times \text{Flow area}}{\text{Total wetted perimeter}}. \quad (8)$$

Note, per Equations (4), (7), and (8), that

$$\frac{D_{HY}}{D_{HE}} = \eta. \quad (9)$$

The schemes for accounting for radial flux variation employed by Becker and by Barnett are essentially the same.

The internally-heated annulus correlation used by Barnett has the form

$$\frac{\phi_c}{10^6} = \frac{A + B \Delta h_s}{C + L}, \quad (10)$$

where A, B, and C are functions of D_{HE} , G, and D_{HY} . They are presumably also functions of pressure, but only the single pressure, 1000 psia, was considered in Reference (4).

One difference between the Becker and Barnett correlation methods which is immediately apparent is that the Becker model is independent of heated length, whereas the Barnett model has a length dependence. Other differences become apparent in the application of the two correlations.

CHF predictions based on these two correlations, for the same conditions as the nine-rod tests, are plotted in Figures 17 through 20. Shaded areas corresponding to the nine-rod data are superposed. The correlations for the two lower flows (Figures 17 and 18) for a heated length of 30 inches were calculated using a uniform radial heat flux, consistent with most of the 30-inch data at the same two flows. The correlations for the remainder of the 30-inch, and all of the 60-inch cases were calculated using one hot rod (approximately 10% higher in heat flux than the other rods), again consistent with the data.

Both the Becker and Barnett correlations lie generally below the data. In the low-quality region, where the data were (necessarily) obtained with the short (30-inch) heated length, the Becker correlation does a fair job; the Barnett correlation is low. In the middle

quality region, where the data were obtained with the 60-inch heated length, both correlations are low with respect to the data, but are in good agreement with each other.

It will be noted that there is a discontinuity between the Barnett correlations for the 30-inch and 60-inch heated lengths. This is due both to the difference in length and, at the lower flows, the difference in radial flux distribution. The discontinuity has nearly disappeared at the two higher flows (Figures 19 and 20). The corresponding discontinuity for the Becker correlations is much less pronounced, is due only to difference in radial flux distribution, and hence exists only at the two lower flows.

The Barnett correlation has been superposed on the graphs of Figures 11 and 12, which show the effect of reducing the rod-to-wall clearance from 0.135 inch to 0.060 inch. The correlation is only affected by the reduction in channel flow area. It predicts a 10 to 15% improvement in CHF, whereas the test results show the opposite effect, i.e., a 15% reduction in CHF.

Both correlations are based largely on data for bundles in a circular array, and both consider only average quality and mass velocity. It has already been pointed out that agreement between other multirod (circular array) data and our nine-rod data is poor when compared on the basis of average quality and mass velocity. Agreement between the Becker and Barnett correlations and our nine-rod data is also poor, on the same basis. It is evident that for a general correlation scheme the average channel conditions are not enough. A more detailed consideration of conditions is needed for CHF prediction in multirod geometries. Fortunately, such a detailed consideration, in which the channel is divided into a number of subchannels, is now receiving attention at a number of R and D centers. The conditions in each of the subchannels are considered rather than treating the channel as a whole. The pertinence of this work to our nine-rod results will be discussed in Section VI.

FIGURE 17. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, $0.5 \times 10^6 \text{ lb/h-ft}^2$, TWO CORRELATIONS

FIGURE 18. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, $0.75 \times 10^6 \text{ lb/h-ft}^2$, TWO CORRELATIONS

FIGURE 19. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, $1.0 \times 10^6 \text{ lb/h-ft}^2$, TWO CORRELATIONS

FIGURE 20. CRITICAL HEAT FLUX VERSUS QUALITY AT 1000 psia, 1.25×10^6 lb/h-ft², TWO CORRELATIONS

SECTION VI

EVALUATION OF MULTISUBCHANNEL COMPUTER CODES

A multirod channel can be divided into two or more subchannels. The location of the imaginary surfaces which separate each subchannel from its neighbors can be selected quite arbitrarily. It is customary, however, to locate each such surface at the narrowest position along the passage connecting the two subchannels. Thus, a nine-rod channel may be divided into as many as 16 subchannels as shown in Figure 21. It is also possible to take advantage of symmetry and consider as few as three* subchannels, provided all the rods are uniformly heated.

Referring to Figure 21, we have a special interest in Subchannel No. 1, the subchannel bounded by the corner rod and the channel corner. Our interest in this particular subchannel stems from the fact that the CHF condition always occurs on the side of the rod facing this subchannel, as noted earlier. Subchannel No. 1 may be likened to a 90-degree sector of an internally-heated annulus. If the average conditions in Subchannel No. 1 could be calculated from a knowledge of channel geometry, inlet conditions, and heat flux, then the CHF could be predicted using a CHF correlation for internally-heated annuli.

A number of codes suitable for predicting subchannel conditions in multirod arrays now exist: the Westinghouse THINC II** and the Battelle Northwest COBRA⁽¹⁰⁾ in this country; the SASS code,⁽¹¹⁾ Chalk River, Canada; and the HAMBO code⁽¹²⁾ of the U.K. Atomic Energy Establishment, Winfrith, England. Other

codes of this same general type are under development at various laboratories.

We will consider in some detail two of these codes, the COBRA* and the HAMBO.* Each code solves the steady-state version of the continuity, energy, and momentum equations for each of the subchannels considered in the analysis. The analytical model for each is based on the following assumptions.

- a. Steady one-dimensional, two-phase slip flow exists in each subchannel during boiling.
- b. A static pressure difference can exist between adjacent subchannels. This is the driving potential for crossflow.
- c. Crossflow consists of the same average mixture of liquid and vapor that exists in the subchannel from which the crossflow originates.
- d. Turbulent mixing takes place between adjacent subchannels. There can be a direct transfer of enthalpy but not of mass as a result of this mixing.

The HAMBO code accounts for subcooled voids; the COBRA code assumes subcooled boiling effects are negligible. The COBRA code takes into account changes in saturated liquid and vapor properties with pressure drop along the channel; the HAMBO assumes the effect of pressure drop on properties can be neglected.

* If two of the subchannels are treated as a single subchannel, then the total number of subchannels considered in the analysis is reduced to two.

** This code is proprietary at the present time. Very little information is available in the open literature.

* These codes are continually being improved by their developers. This discussion applies to the codes as they existed at the beginning of 1967. Some of the remarks may not apply to the current versions.

FIGURE 21. DIVISION OF NINE-ROD CHANNEL INTO SUBCHANNELS, AND SUBCHANNEL NUMBERING SCHEME

The following equations apply to sub-channel i , with j being the index for any particular one of the subchannels adjacent to i and in communication with it. In summing the contributions of the adjacent subchannels, it does not matter whether the summation is taken over all of the subchannels or just the adjacent ones. The contribution of the nonadjacent subchannels is zero.

CONTINUITY*

COBRA:

$$\frac{dm_i}{dz} = - \sum_{j=1}^N w_{ij}, \quad N = \text{Total number of subchannels.} \quad (11)$$

* The notation and general format of this and the following equations are the same as used in Reference (10), except that z is used in place of x as the axial coordinate, and only vertical channels are considered.

HAMBO:

(Same)

ENERGY

COBRA:

$$\frac{d(m_i h_i)}{dz} = q_i' + \sum_{j=1}^N w_{ij}' (h_j - h_i)$$

$$- \sum_{j=1}^N \begin{bmatrix} w_{ij} h_i; w_{ij} \geq 0 \\ w_{ij} h_j; w_{ij} < 0 \end{bmatrix} \quad (12)$$

HAMBO:

(Same)

AXIAL MOMENTUM

COBRA:

$$\begin{aligned}
-\frac{dp_i}{dz} = & \rho_i + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left(\frac{f_i \phi_i}{2 \rho_i D_i} \right) \\
& + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left(\frac{\partial v_i'}{\partial h} \frac{dh_i}{dz} + \frac{\partial v_i'}{\partial p} \frac{dp_i}{dz} \right) \\
& + \frac{1}{g_c A_i} \sum_{j=1}^N f_T w_{ij}' (u_i - u_j) \\
& + \frac{1}{g_c A_i} \sum_{j=1}^N \left[w_{ij} (f_D u_i - 2u_i); w_{ij} \geq 0 \right] \\
& \left[w_{ij} (f_D u_j - 2u_j); w_{ij} < 0 \right], \quad (13)
\end{aligned}$$

where:

$$u_i = \frac{m_i v_i'}{A_i}, \quad \text{and} \quad (14)$$

$$v_i' = \frac{X_i^2}{\alpha_i} v_g + \frac{(1 - X_i)^2}{1 - \alpha_i} v_f. \quad (15)$$

The two-phase multiplier ϕ_i and the void fraction α_i are due to Armand. (13)

HAMBO:

(Same except $\frac{\partial v_i'}{\partial p} = 0$ and $f_D = 1$. The third term in the right of equation 13, i.e., the acceleration term, is replaced by its equivalent in terms of slip and quality, viz.,

$$\begin{aligned}
-\frac{dp_a}{dz} = & \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{d}{dz} \left[\frac{1}{\rho_i} \left\{ 1 - \frac{(S_i - 1)}{S_i} x_i \right\} \right. \\
& \left. \left\{ 1 + (S_i - 1) x_i \right\} \right] \quad (16)*
\end{aligned}$$

where

$$\frac{1}{\rho_i} = v_i = \frac{v_f}{\alpha_i \frac{v_f}{v_g} + (1 - \alpha_i)}$$

The two-phase multiplier is given by

$$\phi_i = 1 + 34 x_i, \quad (17)*$$

derived by the people at Winfrith from analysis of some cluster experimental data. It is close to, but slightly below, the Martinelli-Nelson two-phase multiplier⁽¹⁴⁾ over most of the quality range of interest.

The calculation of the void fraction α_i is based on a constant value for the slip ratio $S_i = 1.6$.)

TRANSVERSE MOMENTUM

COBRA:

$$p_i - p_j = c_{ij} w_{ij} |w_{ij}|. \quad (18)$$

HAMBO:

(Same except that a two-phase multiplier is included.)

TURBULENT CROSSFLOW

COBRA:

$$w_{ij}' = \frac{1}{2} \beta S_{ij} \left(\frac{m_i}{A_i} + \frac{m_j}{A_j} \right). \quad (19-C)$$

HAMBO:

$$w_{ij}' = \begin{cases} 0; & w_{ij} > 4 w_{ij}'' \\ w_{ij}'' \left\{ 1 - \frac{w_{ij}}{2 w_{ij}''} + \left(\frac{w_{ij}}{4 w_{ij}''} \right)^2 \right\}; & w_{ij} \leq 4 w_{ij}'' \end{cases}, \quad (19-H)$$

* We are indebted to Mr. Bob Bowring of Winfrith for information concerning these two relationships in private communication April 25, 1968. We understand more information will be given in the forthcoming Winfrith report AEEW-R582.

where:

$$w_{ij}'' = F_m \frac{N_{ij} \gamma_{ij}}{(S_m)_{ij} d_{ij}} \frac{\sqrt{f_i + f_j}}{80} \left(D_i \frac{m_i}{A_i} + D_j \frac{m_j}{A_j} \right), \quad (20)$$

and

- N_{ij} = Number of rod gaps between i and j,
- γ_{ij} = Minimum rod gap between i and j (feet),
- d_{ij} = Diameter of rods forming gap (feet),
- $(S_m)_{ij}$ = Shape factor for gap geometry,
- f_i = Single phase friction factor in subchannel i, and
- D_i = Equivalent wetted diameter in subchannel i (feet).

In practice the foregoing equations are solved numerically by taking discrete steps in the independent variable z . The equations are solved for all the subchannels at the end of each step by an iterative procedure, thus determining the initial conditions for the next step, etc.

Arrangements were made with Mr. D.S. Rowe of Batelle Northwest to calculate, using the COBRA code, the conditions in Subchannel No. 1 corresponding to six different CHF data points obtained with the first nine-rod channel. Subsequently arrangements were also made with Mr. R.W. Bowring of the U.K. Atomic Energy Establishment, Winfrith, to perform calculations using the HAMBO code corresponding to the same six CHF data points.

Table 3 is a list of the six CHF conditions, all for steam-water at 1000 psia, flow upward. The pertinent channel dimensions are given in Figure 22. It should be noted that one corner rod is 10% higher in heat flux

than the average. Both the average heat flux $\bar{\phi}$ and the hot corner rod heat flux ϕ_1 are listed in Table 3. The data have been "adjusted" to correspond to a hot rod which is always 10% above the average. Actually, the heat flux varied from 3% to 15% above the average, depending on the particular set of rods. Even when the hot rod is exactly 10% above the average, the other rods may be from zero to 5% below the average, depending on which electrical phase they are in. It is felt that more detailed consideration of these variations in heat flux is not justified at this time. Therefore, one rod has been treated as having 1.1000 times the average power and the remaining eight rods have been treated as though each has 0.9875 times the average power.

Table 4 is a list of the channel exit conditions calculated with the COBRA code, for Subchannels Nos. 1 through 6, all six CHF conditions, and for the three values for the COBRA turbulent mixing parameter $\beta = 0$, $\beta = 0.02$, and $\beta = 0.05$. The subchannel numbering scheme used for the calculations is shown in Figure 21. A six subchannel approximation was used for the COBRA calculations by assuming the diagonal plane of symmetry as indicated in Figure 21, it having been established that the effect on the results would be negligible.⁽¹⁵⁾ Table 5 is a list of the exit conditions for the same subchannels but calculated with the HAMBO code for three values of the HAMBO mixing parameter: $F_m = 0$, $F_m = 5$, and $F_m = 10$. All ten subchannels were involved in this calculation, but only the results for subchannel 1 through 6 are listed.

It is shown by a comparison of Tables 4 and 5 that for Subchannel No. 1, the HAMBO code gives generally lower values for subchannel flow and higher values for exit enthalpy (exit quality). The results of the calculations for Subchannel No. 1 are shown graphically in Figures 23 and 24 (COBRA) and Figures 25 and 26 (HAMBO).

The two graphs for each code correspond to the two values of mass velocity used in the tests. Each graph is a plot of the heat flux for the hot rod versus the Subchannel No. 1 exit quality. It will be noted that there are three points at each value of heat flux corresponding to the three values for the mixing parameter.

Two internally-heated annulus correlations were used, the modified Collier-Hewitt, ⁽¹⁶⁾ and one from GEAP-3899. ⁽³⁾ Each correlation is flow dependent. Each code gives a different value of flow for Subchannel No. 1 for each of the three assigned values of its mixing parameter. Hence, for each correlation there are three correlating lines at each CHF condition. The correlating lines are superposed on the graphs of Figures 23 through 26.

Referring to Figures 23 and 24 (COBRA results), there is a consistently wide disparity between the point for $\beta = 0$ and both of the correlations based on the corresponding Subchannel No. 1 exit conditions. Referring to Figures 25 and 26 (HAMBO results), there is similarly a wide disparity between the point for $F_m = 0$ and both correlations. Although the two models give somewhat different values for the Subchannel No. 1 exit conditions, the difference is small compared with the disparity noted above. It is evident that a model based on zero turbulent mixing is not satisfactory.

Referring again to Figures 23 through 26, the points for $\beta = 0.02$ and $\beta = 0.05$ (COBRA medium and high mixing, respectively) are in surprisingly good agreement with each other. Similarly, the points for $F_m = 5$ and $F_m = 10$ (HAMBO medium and high mixing) are in good agreement with each other. Results for medium and high values of the mixing parameter indicate that,

at least for a relatively open square lattice such as the nine-rod array used for the Task B tests, the conditions in Subchannel No. 1 are not very sensitive to the amount of mixing as long as it is above some minimum. This may not apply to lattices with different rod-to-rod clearances, i.e., results may be more sensitive to the mixing parameter than indicated here.

The modified Collier-Hewitt correlation is in relatively good agreement with both the $\beta = 0.02$ and $\beta = 0.05$ points in Figures 23 and 24, and the $F_m = 5$ and the $F_m = 10$ points on Figures 25 and 26, but tends to give slightly lower values for the CHF than were measured in the nine-rod tests. The GEAP-3899 correlation is in poor agreement with the points at the lower flow condition ($\bar{G} = 0.5 \times 10^6$ lb/h-ft², Figures 23 and 25), but is in good agreement at the higher flow ($\bar{G} = 1.0 \times 10^6$ lb/h-ft², Figures 24 and 26). The probable reason for the poor showing of the GEAP-3899 correlation at the lower flow is that very few of the data upon which it is based were obtained at flows as low as the calculated flow for Subchannel No. 1.

Although the last few paragraphs above point out strong similarities between the COBRA and HAMBO results, there is no disputing the fact that the COBRA and HAMBO codes give different values for the Subchannel No. 1 exit conditions, as was noted earlier. The models used for turbulent crossflow are different for the two codes, but even when the turbulent crossflow is set to zero, the two codes give different values. Both References (10) and (12) report that relatively large variations in the resistance to crossflow (represented by the coefficient c_{ij} in the transverse momentum equation) cause very little change in exit conditions. It is pointed out in Reference (10) that the COBRA results are not sensitive to the crossflow momentum parameter f_D , for $0 \leq f_D \leq 1.0$.

From the process of elimination of the preceding paragraph it is concluded that the difference between the COBRA and HAMBO results must be due to: a.) subcooled voids, accounted for in HAMBO but not in COBRA, or b.) the use of the Equation (17) two-phase multiplier in HAMBO versus the Armand multiplier in COBRA (the latter being the smaller of the two).

To ascertain more definitely the reason for the difference between the COBRA and the HAMBO results, the COBRA calculations were repeated using the same expression for ϕ_1 as used in the HAMBO calculations, i.e., the two-phase multiplier given by Equation (17). The results are listed in Table 6. The agreement with the HAMBO results is greatly improved. Presumably if the Armand multiplier had been used in both codes rather than Equation (17), the agreement would have been equally good. The results for the two codes correspond to conditions which are generally well into the quality region. If the conditions were near zero quality a big difference in the

results would be expected* due to the relatively greater influence of subcooled voids, accounted for in HAMBO but not in COBRA. It is concluded that the difference between the first COBRA results and the HAMBO results is due primarily to the difference in two-phase multiplier. At near zero quality conditions a difference may also be expected due to the presence of subcooled voids model in HAMBO but not in COBRA.

Though there are differences between the COBRA and HAMBO results, the differences are not large, and can, for the most part, be accounted for. Moreover, either code, in combination with the modified Collier-Hewitt correlation for example, will do a pretty fair job of predicting the occurrence of CHF. Bowring⁽¹⁷⁾ has applied Barnett's annulus correlation⁽⁴⁾ to the HAMBO results with some success. The use of a multisubchannel computer code in combination with a good annulus correlation appears to be a promising procedure for predicting CHF in a multirod channel with rods in a square array.

* This was pointed out by Bowring in private communications April 25, 1968. He ran a test case from Reference 10, using the HAMBO code both with and without the subcooled void model.

TABLE 3
SIX NINE-ROD CRITICAL HEAT FLUX CONDITIONS

Run No.	Heated Length (inches)	$\dot{W}$ (lb/sec)	Δh_s (Btu/lb)	Power (kW)	$\bar{G}/10^6$ (lb/h-ft ²)	$\bar{\phi}/10^6$ (Btu/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	X_e
77	30	2.25	30.5	400	0.491	0.618	0.680	0.256
85	30	2.25	160.0	622	0.491	0.824	0.906	0.158
211	60	2.25	97.5	763	0.491	0.505	0.555	0.345
269	30	4.66	124.0	788	1.018	1.042	1.148	0.056
419	60	4.69	23.5	911	1.023	0.603	0.663	0.248
422	60	4.69	158.5	1293	1.023	0.855	0.940	0.159

NOTE: ALL DIMENSIONS ARE IN INCHES.

FIGURE 22. PERTINENT CHANNEL DIMENSIONS FOR MULTISUBCHANNEL COMPUTER CODE

TABLE 4

SUBCHANNEL EXIT CONDITIONS CALCULATED WITH COBRA CODE
USING ARMAND TWO-PHASE MULTIPLIER

Run No.	β	Subchannel Number											
		1		2		3		4		5		6	
		h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶
77	0.05	720.7	0.391	711.9	0.478	708.1	0.480	713.8	0.396	712.9	0.529	710.2	0.531
	0.02	734.5	0.381	712.9	0.477	705.1	0.484	719.6	0.396	714.0	0.528	707.9	0.533
	0	827.0	0.311	707.7	0.484	695.5	0.498	785.0	0.338	710.7	0.530	704.8	0.537
85	0.05	657.6	0.439	648.6	0.493	645.2	0.491	650.9	0.441	649.4	0.505	647.6	0.500
	0.02	677.5	0.430	652.7	0.491	646.5	0.488	663.2	0.438	643.1	0.512	640.6	0.503
	0	791.9	0.335	649.5	0.498	634.4	0.507	737.9	0.374	637.4	0.518	633.8	0.506
211	0.05	730.3	0.372	772.0	0.471	769.0	0.473	774.7	0.375	770.8	0.544	768.9	0.545
	0.02	734.5	0.364	773.5	0.471	766.4	0.476	780.7	0.367	770.8	0.542	766.7	0.545
	0	931.5	0.275	767.6	0.476	746.9	0.497	902.9	0.301	766.7	0.544	759.3	0.551
269	0.05	533.7	0.859	585.4	0.959	581.3	0.988	586.9	0.878	577.5	1.077	573.9	1.142
	0.02	610.8	0.822	588.9	0.952	582.3	0.977	598.3	0.850	572.3	1.136	569.3	1.122
	0	741.5	0.542	588.3	0.919	578.0	0.951	680.5	0.629	565.7	1.188	560.0	1.268
419	0.05	711.7	0.761	706.7	0.976	705.0	0.980	708.5	0.768	705.2	1.142	704.1	1.144
	0.02	721.1	0.744	708.3	0.972	703.8	0.983	712.6	0.761	704.8	1.143	702.0	1.150
	0	834.4	0.541	704.7	0.982	690.6	1.024	810.1	0.599	701.4	1.151	694.7	1.173
422	0.05	655.7	0.834	649.8	0.999	646.9	1.005	650.6	0.845	649.3	1.090	647.1	1.099
	0.02	670.9	0.805	654.5	0.993	647.8	1.008	658.5	0.835	645.4	1.096	640.5	1.109
	0	948.8	0.447	658.4	0.986	638.5	1.041	829.9	0.542	629.0	1.156	619.2	1.180

h = Enthalpy, Btu/lb.

G = Mass velocity, lb/h-ft². β = Turbulent intensity, dimensionless.

TABLE 5

SUBCHANNEL EXIT CONDITIONS CALCULATED WITH HAMBO CODE
 USING TWO-PHASE MULTIPLIER $\phi = 1 + 34 \times$

Run No.	F_m	Subchannel No.											
		1		2		3		4		5		6	
		h	$G/10^6$	h	$G/10^6$	h	$G/10^6$	h	$G/10^6$	h	$G/10^6$	h	$G/10^6$
77	10	731.8	0.384	712.1	0.476	706.1	0.484	717.7	0.400	712.0	0.520	708.5	0.525
	5	754.7	0.353	712.5	0.474	703.5	0.485	732.0	0.372	712.2	0.527	707.3	0.534
	0	876.7	0.279	712.6	0.466	697.8	0.482	822.8	0.303	704.7	0.550	697.7	0.558
85	10	674.7	0.376	648.9	0.478	641.7	0.484	657.1	0.398	648.9	0.523	644.7	0.526
	5	704.8	0.336	649.4	0.476	638.7	0.484	675.6	0.364	648.8	0.533	643.1	0.537
	0	850.5	0.253	651.8	0.471	633.1	0.482	781.6	0.284	640.4	0.552	631.9	0.562
211	10	788.7	0.382	771.3	0.473	765.7	0.480	775.7	0.394	769.7	0.526	766.2	0.531
	5	814.3	0.348	774.2	0.467	764.2	0.478	790.0	0.365	769.6	0.536	763.9	0.543
	0	1082.4	0.235	772.6	0.461	746.8	0.485	980.6	0.262	762.9	0.557	751.7	0.568
269	10	595.4	0.809	582.3	0.984	576.8	1.004	586.4	0.846	582.0	1.072	578.7	1.085
	5	623.0	0.712	583.7	0.971	575.3	0.999	601.3	0.773	580.9	1.098	576.3	1.115
	0	773.3	0.443	594.0	0.910	578.1	0.953	717.0	0.505	565.8	1.223	559.8	1.250
419	10	716.8	0.804	706.3	0.985	702.8	0.998	708.8	0.827	705.3	1.097	703.1	1.106
	5	732.8	0.730	708.3	0.972	701.9	0.992	717.6	0.765	705.3	1.119	701.6	1.132
	0	919.6	0.482	711.0	0.942	694.8	0.986	853.3	0.534	696.0	1.189	688.8	1.214
422	10	665.8	0.791	650.3	0.982	644.7	1.008	652.5	0.838	649.2	1.076	645.6	1.093
	5	692.3	0.691	653.9	0.964	643.4	1.007	666.3	0.760	649.2	1.095	643.0	1.123
	0	1085.8	0.343	672.6	0.881	644.0	0.972	938.0	0.408	625.4	1.228	614.0	1.287

h = Enthalpy, Btu/lb.
 G = Mass velocity, lb/h-ft².
 F_m = Turbulent mixing factor, dimensionless.

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FIGURE 23. CRITICAL HEAT FLUX VERSUS QUALITY CALCULATED BY COBRA FOR SUBCHANNEL NO. 1, AT 1000 psia, 0.5×10^6 lb/h-ft²

FIGURE 24. CRITICAL HEAT FLUX VERSUS QUALITY CALCULATED BY COBRA FOR SUBCHANNEL NO. 1, AT 1000 psia, 1.0×10^6 lb/h-ft²

FIGURE 25. CRITICAL HEAT FLUX VERSUS QUALITY CALCULATED BY HAMBO FOR SUBCHANNEL NO. 1, AT 1000 psia, 0.5×10^6 lb/h-ft²

FIGURE 26. CRITICAL HEAT FLUX VERSUS QUALITY CALCULATED BY HAMBO FOR SUBCHANNEL NO. 1, AT 1000 psia, 1.0×10^6 lb/h-ft²

TABLE 6

SUBCHANNEL EXIT CONDITIONS CALCULATED WITH COBRA CODE
USING TWO-PHASE MULTIPLIER $\phi = 1 + 34 \times$

Run No.	β	Subchannel No.											
		1		2		3		4		5		6	
		h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶	h	G/10 ⁶
77	0.05	723.9	0.367	713.5	0.468	709.5	0.471	716.5	0.372	710.9	0.547	708.3	0.549
	0.02	742.2	0.353	715.8	0.465	707.2	0.474	725.5	0.365	710.4	0.547	704.4	0.553
	0	865.7	0.276	710.8	0.471	696.4	0.489	813.6	0.302	706.2	0.550	699.3	0.560
85	0.05	663.1	0.396	651.2	0.481	646.8	0.485	654.8	0.404	647.7	0.524	645.3	0.524
	0.02	689.8	0.374	656.6	0.474	648.6	0.482	671.7	0.390	640.7	0.534	636.9	0.534
	0	862.8	0.263	653.3	0.480	635.4	0.503	788.2	0.299	634.0	0.542	628.0	0.544
211	0.05	783.0	0.353	773.6	0.461	770.6	0.463	777.1	0.356	769.0	0.560	767.1	0.561
	0.02	801.4	0.342	777.3	0.458	769.5	0.464	786.4	0.351	766.9	0.562	762.3	0.566
	0	1087.0	0.230	777.9	0.457	749.4	0.484	978.2	0.260	760.2	0.567	741.0	0.589
269	0.05	595.4	0.788	588.2	0.819	581.7	0.977	588.2	0.819	576.9	1.112	573.7	1.172
	0.02	616.3	0.713	580.3	0.923	583.0	0.964	601.7	0.764	571.8	1.177	568.6	1.182
	0	769.8	0.429	580.0	0.908	577.9	0.971	709.5	0.496	565.3	1.251	560.7	1.257
419	0.05	713.3	0.724	707.6	0.957	705.8	0.961	709.9	0.730	704.3	1.174	703.1	1.177
	0.02	725.6	0.701	710.7	0.949	705.9	0.961	716.4	0.718	702.2	1.181	699.3	1.190
	0	912.2	0.483	710.1	0.945	693.8	0.994	846.0	0.538	694.9	1.203	687.6	1.232
422	0.05	657.9	0.768	650.7	0.978	648.1	0.986	653.0	0.780	647.6	1.133	645.9	1.138
	0.02	679.7	0.718	658.4	0.955	649.5	0.984	663.5	0.755	643.2	1.145	636.5	1.176
	0	1061.7	0.358	664.5	0.921	640.9	1.005	918.3	0.427	625.8	1.214	612.5	1.296

h = Enthalpy, Btu/lb.
G = Mass velocity, lb/h-ft².
 β = Turbulent intensity, dimensionless.

SECTION VII

CONCLUSIONS

On the basis of the test results it is concluded that:

1. For rods in a normally-spaced square array the CHF occurs on one of the corner rods.
2. The CHF decreases as the average quality increases, other things being the same. The average quality is the dominant parameter in determining CHF.
3. There is no strong or consistent effect of length on CHF.
4. There is no flow effect on CHF for flows greater than 0.75×10^6 lb/h-ft². For flows less than this the CHF tends to vary in an inverse manner with the flow, but the effect is not strong.
5. In the range of pressures from 600 to 1400 psia, the CHF varies in an inverse manner with the pressure, other things being the same.

6. A reduction in rod-to-wall clearance from 0.135 inch to 0.060 inch causes a 15% reduction in CHF.

Comparisons of the nine-rod (square array) CHF data reported here with 19-rod, 37-rod, and seven-rod (circular array) CHF data reported elsewhere, and with multirod correlations due to Becker and to Barnett (obtained largely with bundles in a circular array) show generally poor agreement, when the comparison is on the basis of the same average exit quality and mass velocity. It is evident that the use of average channel conditions for correlating purposes has significant limitations, in particular for correlating circular array results with square array results.

Multisubchannel computer codes consider channel conditions in more detail, thus providing the means for a possible improvement in the correlation of multirod data. Two such codes, the COBRA and the HAMBO, when used in combination with a simple channel (internally-heated annulus) CHF in the nine-rod channel, give fair to good agreement with measured CHF. The use of such codes appears to be a promising procedure for predicting CHF in a multirod array.

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Direction of Test Work	R. F. Boehm J. E. Hench E. E. Polomik
Test Setup	B. B. Duncan V. M. Horn

Special Heater Rod Development

J. A. Kervinen

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NOMENCLATURE

a_0, a_1	= Terms in Becker's CHF correlation for round tubes.	G	= Mass velocity, lb/h-ft ² .
A, B, C	= Terms in Barnett's CHF correlation for internally-heated annuli.	h	= Enthalpy, Btu/lb.
A	= Area, ft. ²	h_{fg}	= Latent heat of vaporization, Btu/lb.
c_{ij}	= Coefficient in transverse momentum equation.	Δh_s	= Subcooling, Btu/lb.
d_{ij}	= Diameter of rods forming gap between subchannels i and j , ft.	L	= Heated length, in.
D	= Equivalent wetted diameter, ft.	m	= Mass flow ratio, lb/sec.
D_{HY}	= Hydraulic diameter, in.	n	= Number of rods.
D_{HE}	= Heated equivalent diameter, in.	N	= Number of subchannels.
D_R	= Rod diameter, in.	N_{ij}	= Number of rod gaps between subchannels i and j .
D_I^*	= Equivalent inner diameter (annulus), in.	p	= Pressure, lb/ft ² or psi.
D_O^*	= Equivalent outer diameter (annulus), in.	q'	= Heat transfer to subchannel per unit length, Btu/sec-ft.
f	= Single-phase friction factor.	s_{ij}	= Rod spacing between subchannels i and j , ft or in.
f_D, f_T	= Correction terms for diversion and turbulent momentum, respectively.	S	= Slip ratio = u_g/u_f .
F_m	= Turbulent mixing parameter (HAMBO).	$(S_m)_{ij}$	= Shape factor for rod geometry.
g_c	= Gravitational constant.	u	= Velocity, ft/sec.
		v_f	= Specific volume of liquid phase, ft ³ /lb.

NOMENCLATURE (Continued)

v_g	= Specific volume of vapor phase, ft ³ /lb.	η	= Heated perimeter ÷ total wetted perimeter.
v	= Specific volume of two-phase mixture, ft ³ /lb.	η_1, η_2	= Factors in Becker's CHF correlation for multirod bundles, defined in text.
v'	= Effective specific volume for momentum considerations.	ξ_i	= Ratio, heat flux on i th rod to maximum heat flux.
w_{ij}	= Crossflow from subchannel i to subchannel j , lb/sec-ft.	ρ_f	= Density of liquid phase, lb/ft ³ .
w_{ij}'	= Turbulent interchange between subchannels i and j (always positive), lb/sec-ft.	ρ	= Density of two-phase mixture, lb/ft ³ .
w_{ij}''	= Turbulent interchange between subchannels i and j , uncorrected for cross flow.	ϕ	= Two-phase friction multiplier.
X	= Quality = mass rate of steam ÷ total mass rate.	$\bar{\phi}$	= Average heat flux, Btu/h-ft ² .
X_c	= Quality at CHF.	ϕ_c	= Critical heat flux, Btu/h-ft ² .
z	= Axial coordinate, positive in direction of flow (Note: flow is vertical and upward), ft or in.	ϕ_1	= Hot corner rod heat flux, Btu/h-ft ² .
α	= Void fraction.	<u>Subscripts</u>	
β	= Turbulent mixing parameter (COBRA).	i	= Refers to subchannel i .
γ_{ij}	= Minimum rod gap between subchannels i and j , ft.	j	= Refers to subchannel j , which is adjacent to and in communication with subchannel i .

REFERENCES

1. Hench, J. E., and Boehm, R. F., "Nine-Rod Critical Heat Flux Investigation at 1000 psia," GEAP-4929, January 1966.
2. Janssen, E., and Kervinen, J. A., "Two-Phase Pressure Drop in Straight Pipes and Channels; Water-Steam Mixtures at 600 to 1400 psia," GEAP-4616, May 1964.
3. Janssen, E., and Kervinen, J. A., "Burnout Conditions for Single Rod in Annular Geometry; Water at 600 to 1400 psia," GEAP-3899, February 1963.
4. Barnett, P. G., "A Correlation of Burnout Data for Uniformly Heated Annuli and its Use for Predicting Burnout in Uniformly Heated Rod Bundles," AEEW-R463, Winfrith, England, September 1966.
5. Becker, K. M., "Measurements and Predictions of Burnout Conditions in Rod Bundles," Studsvik, Sweden, S-366, May 1967.
6. Matzner, B., "Comparison of Burnout Heat Fluxes in Wire Wrapped and Grid Spaced 19-Rod Bundles for the United Kingdom Steam Generating Heavy Water Reactor," Columbia U. Engineering Research Laboratories Report NP-14831, December 1964.

REFERENCES (Continued)

7. Edwards, P. A., and Obertelli, J. D.,
"Burnout and Pressure Drop Data on
37-Rod Clusters in High Pressure
Water," AEEW-R488, 1966.	Analysis of the Hydraulic and Burnout
Characteristics of Rod Clusters,
Part I: General Description," AEEW-
R524, Winfrith, England, May 1967.
8. Matzner, B., and Casterline, J. E.,
"The Effect of Length and Pressure on
the Critical Heat Flux for a Closely
Spaced 19-Rod Bundle in Forced Con-
vection Boiling," Columbia U. Engi-
neering Research Laboratories Topical
Report No. 7, Task XVI of Contract
AT (30-3)-187, December 1965.	13. Armand, A. A., "The Resistance
During the Movement of a Two-
Phase System in Horizontal Pipes,"
Translated by V. Beak, AERE
Trans. 828. Izvestiya Vsesojuznogo
Teplotekhnicheskogo Instituta (1),
pp. 16-23, 1946.
9. Becker, K. M., "A Burnout Correla-
tion for Flow of Boiling Water in Verti-
cal Rod Bundles," AE-276, Studsvik,
Sweden, 1967.	14. Martinelli, R. C., and Nelson, D. B.,
"Prediction of Pressure Drop During
Forced Circulation Boiling of Water,"
Trans. ASME, V. 70, pp 695 - 702,
August 1948.
10. Rowe, D. S., "Cross Flow Mixing
between Parallel Channels During
Boiling, Part I: COBRA - Computer
Program for Coolant Boiling in Rod
Arrays," BNWL-371 PT 1, Battelle
Northwest, March 1967.	15. Rowe, D. S., Private Communication,
January 1967.
11. St. Pierre, C. C., "SASS Code I, Sub-
channel Analysis for the Steady State,"
APPE-41, Chalk River, Canada,
September 1966.	16. Moeck, E. O., Matzner, E.,
Casterline, J. E., and Yuill, G. K.,
"Critical Heat Fluxes in Internally-
Heated Annuli of Large Diameter
Cooled by Boiling Water at 1000 psia,"
International Heat Transfer Conference
Paper 90, Chicago, August 1966.
12. Bowring, R. W., "HAMBO, A Com-
puter Programme for the Subchannel.	17. Bowring, R. W., Private Communica-
tion, April 1967.

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