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ROD BUNDLE CRITICAL HEAT FLUX AT LOW PRESSURE

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I. INTRODUCTION

A study of critical heat flux (CHF) in a close-packed bundle of electrically heated rods which simulated the closely spaced nuclear fuel rods of the Power Burst Facility (PBF) was performed. The study examined the effects that close rod spacing and rod bowing would have on CHF at low, near-atmospheric, pressure conditions similar to PBF conditions.

The PBF nuclear reactor, which is used in the Nuclear Regulatory Thermal Fuels Behavior Program, has an open vessel and a driver core with forced upward flow through the close-packed rods. The core design power is 40 MW. An effort was undertaken to design a reload core with a steady state power level of 50 MW.

The core power is potentially limited by the CHF as shown by a preliminary design study. Extensive studies of the CHF phenomenon at high pressures[1,2] have resulted in a number of empirical correlations. However, little data have been taken at low pressures, and only one study performed by Lund[3] has provided data taken at low pressure with closely spaced rod bundles. In these circumstances a general correlation for CHF, such as Bernath's[4,5], is commonly used. For the PBF reload core, however, the need to maintain the smallest safe margin and the low-pressure, closely spaced core design indicated the need for more accurate correlations with a good data base. Although high-pressure CHF tests[6-9] have indicated that rod spacing has little or no effect on CHF, a recent experiment by Lund[3] at low pressure, similar to the PBF conditions, did show a spacing effect. However, Lund's experiment had a limited data base which did not allow development of a sufficiently accurate CHF correlation for the PBF purposes. An experimental program was therefore undertaken to obtain sufficient data for accurate correlation of CHF in the range of the PBF operating conditions. Because rod bowing can substantially reduce the gaps between rods in a close-packed rod bundle, bowed rod tests were also performed. The results of this study apply to similar rod bundles at low pressures in water. The qualitative effects are also expected with close-packed rod bundles and coolants with large vapor-to-liquid-volume ratios.

The test program investigated a low-pressure, water cooled, electrically heated rod bundle with close-packed rods that simulated a portion of the PBF nuclear core. The tests were conducted at the Heat Transfer Research Facility of Columbia University. The variables in the tests were: absolute pressures of 117 to 255 kPa, outlet subcoolings in subchannels of 0 to 53°C, and mass flow rates of 1992 to 4830 kg/s·m^2.

Data were obtained with rod spacings of 0.0508 to 1.016 mm. Rod spacing was varied to determine any reduction in CHF because of close-spacing.

Two series of tests of unbowed rods, Test Series 1 and Test Series 2, and a series of bowed-rod tests were performed. Early in Test Series 1, one rod burned out. The power from this rod was conducted to adjacent rods, thus requiring adjustments in data evaluation between the two test series because of a variation in power to the other rods in the test bundle. Test Series 2 differed slightly from Test Series 1, in that it utilized modified spacer grids and different locations for CHF-detecting thermocouples in some rods. The initial Bowed-Rod Test Series was conducted with the same bundle as Test Series 1. The second series of bowed-rod data points were taken with a modified rod bundle prior to the Test Series 2.

II. EXPERIMENTAL AND TEST FACILITY DESCRIPTION

The test section consisted of a flow housing with a viewing port so that CHF could be observed visually and four-by-four rod test bundle instrumented with standard CHF detection thermocouples and instrumentation to measure coolant conditions.

The flow housing consisted of four major components: the grid plates, the outlet tee and top flange, the shroud box, and the inlet tee and bottom flange.

The grid plates were each machined from copper plate and maintained the rod spacing. The top grid plate served as the top electrical connection, from the rods through insulated cables to the copper busses.

The inlet and outlet tees provided a transition from the geometry of the shroud box to a circular geometry for connecting the flow piping. The tees also provided flanges for test penetrations. The top flange had a loop vent and penetrations for the subchannel thermocouples. The bottom flange had penetrations for the heated rods; these penetrations in the bottom flange had O-ring seals that permitted axial movement of each rod.

The aluminum shroud box held a ceramic liner which formed the flow channel. The ceramic shroud liner was fabricated from 98% dense Al_2O_3 in sections and ground to the desired dimension within a tolerance of ±0.0508 mm. The inner dimension of the installed shroud liner was 80.47 mm. The front of the shroud box held a rectangular window approximately 80.47 by 304.8 mm to allow high-speed photography and visual observation of the front four rods. A high temperature glass was bonded to the aluminum and replaced the ceramic liner in the window region.

A setscrew was installed in the side of the shroud box and against one of the rods so that the rod could be adjusted to bow toward an adjacent rod.

The electrically heated test section was a 16-rod bundle in a four-by-four square array with a 0.9144-m heated length. The bundle simulated a portion of the proposed PBF reload core. The physical characteristics of the rod bundle are shown in Figures 1 and 2.

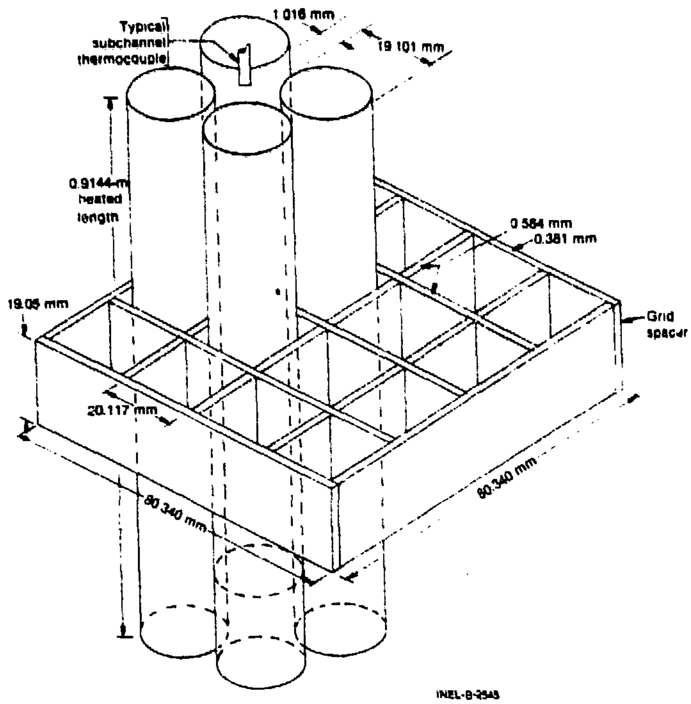


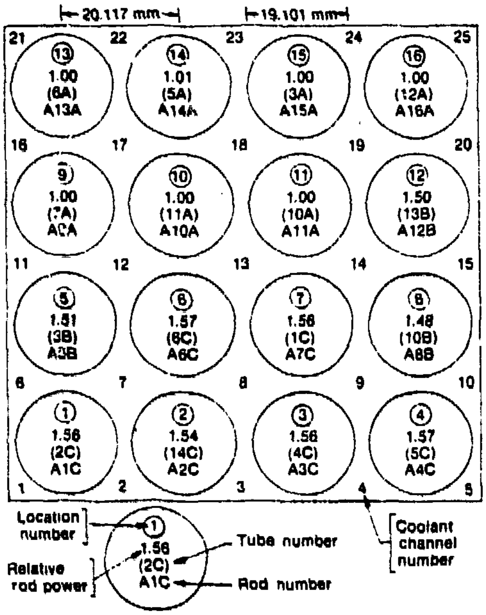
Fig. 1 Rod array in grid spacer arrangement.

The test section was instrumented to obtain flow and pressure conditions; to obtain local subchannel coolant inlet and exit temperatures so that local coolant conditions could be calculated accurately; and to obtain indications of CHF by means of thermocouples internal to the heater rods. Coolant instrumentation was standard. CHF detection thermocouple installations were those developed at Columbia University and used in many similar CHF studies.

Critical heat flux data points were obtained at stable test section centerline pressure, inlet temperature, and mass flow rate by increasing test section power until CHF was detected visually (in bowed rod tests) or from CHF detection thermocouple indications. CHF was determined to occur when a continued rise in the temperature indicated by at least one of the thermocouples occurred with no further increase in test section power. The test section power was then reduced approximately 50% manually. During the approach to CHF all measurements were scanned. The measurements at the highest test section power were used as the CHF conditions.

III. DATA ANALYSIS

A standard method of analysis for developing a CHF correlation is to reduce the rod bundle exit conditions to local conditions where CHF occurs. The local coolant conditions were obtained with a modified version of the COBRA IV-I computer code[10]. The standard COBRA IV-I code was modified to allow use of up to nine friction factor relationships for matching measured subchannel coolant temperatures. The basic COBRA IV-I code which determines the enthalpy and flow distributions in rod bundles for both steady state and transients was not changed for low pressure. In some cases, CHF can be treated as a local phenomenon[11]. As observed in the high-speed motion pictures, the CHF was achieved in the narrow "gap" between rods. Thus, local conditions were judged to be appropriate for analyzing these data. The conventional 25 subchannel model was used to develop the final empirical CHF correlation. A detailed COBRA IV-I model was used, as shown in Figure 3, to predict local fluid velocities in the rod gaps where CHF occurred most frequently. For this model, six additional subchannels were added to the conventional 25 subchannel model.



Channels	Wetted Perimeter	Heated Perimeter	Area
1,5,21,25	35.128 mm	15.011 mm	29.548 mm²
2,3,4,6,10,11,15,16,20,22,23,24	50.038 mm	29.997 mm	59.097 mm²
7,8,9,12,13,14,17,18,19	59.842 mm	59.842 mm	119.935 mm²

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Fig. 2 Top view of four-by-four rod array simulating portion of PBF reactor core.

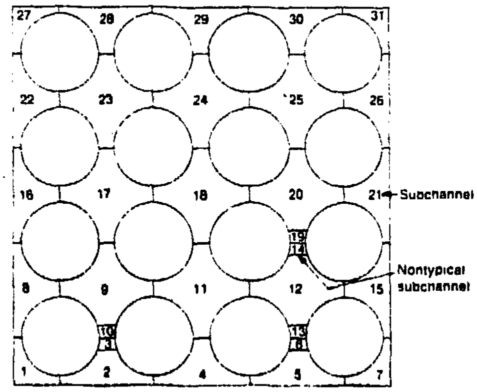

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Fig. 3 COBRA IV-I, 31-subchannel model of four-by-four rod bundle.

IV. EVALUATION OF EXISTING CHF CORRELATIONS

The Bernath correlation[4,5] because of its generality, has been used extensively for CHF analyses; however, using Bernath's correlation resulted in large errors for this application. The values in Table I show measured CHF data compared with those predicted by Bernath's correlation. The comparison indicates Bernath's correlation is unacceptable for a tightly packed, low-pressure, rod bundle prediction.

TABLE I

COMPARISON OF MEASURED CHF VALUES WITH
CALCULATED CHF VALUES USING BERNATH CORRELATION

	CHF Value (MW/m^2)	
Run	Measured	Bernath
9	0.949	1.58
10	0.968	1.85
11	0.851	1.17
12	0.681	2.23
14	1.05	2.72
15	1.08	4.11
16	0.854	4.74
17	1.06	4.05
18	1.10	3.96
19	1.00	3.95
20	0.949	4.76
21	0.921	3.85
22	0.965	3.55
23	0.949	3.65
24	0.921	3.49
25	0.930	3.29
26	0.933	3.29
27	0.933	3.23
28	0.804	2.30
29	0.845	2.66

The Lund correlation[3] was developed specifically for low-pressure rod bundle CHF calculations. This correlation correctly recognizes that flow conditions in the gaps between rods are not well predicted by the conventional use of subchannel flow conditions. Lund's correlation, therefore, includes an equation for the velocity in the gap. It then uses average flows for a rod bundle without recourse to a subchannel analysis. Because of its apparent adaptability to the present tests, it is presented in detail.

Lund's CHF correlation, based on the Reynolds analogy, is:

$$q_c = \frac{1}{2} f_c \rho V_g c_p \, (T_c - T_o) \qquad (1)$$

where

$$f_c = 0.55 \, Re_g^{-0.37} \qquad (2)$$

$$Re_g = 2\rho V_g D_r\ (S-1)/\mu_{sat} \quad (3)$$

$$V_g = V\ [1 - 0.98e^{-2.2(S-1)}] \quad (4)$$

$$\frac{T_c}{T_{sat}} = 1 + 6\sqrt{\frac{1}{\theta_c}} \quad (5)$$

$$\theta_c = \frac{q_c\ T_{sat}}{P_{sat}\ H_{fg}} \quad (6)$$

and

q_c	=	critical heat flux (MW/m^2)
f_c	=	critical fanning friction factor
ρ	=	liquid density (kg/m^3)
V_g	=	local gap velocity (m/s)
c_p	=	constant pressure specific heat (J/kg·K)
T_c	=	critical wall temperature (^oC)
T_o	=	outlet temperature (^oC)
Re_g	=	Reynolds number in rod gap
D_r	=	rod diameter (m)
S	=	rod spacing (mm) or pitch-to-diameter ratio
μ_{sat}	=	saturation liquid viscosity (Pa·s)
V	=	average velocity (m/s)
T_{sat}	=	saturation temperature (^oC)
θ_c	=	dimensionless heat flux
P_{sat}	=	saturation pressure (kPa/kg)
H_{fg}	=	heat of vaporization (kJ/kg).

A comparison of Equation (1) with data collected in this study is shown in Figures 4 and 5 for Test Series 1 and 2, respectively. Two standard deviations for Equation (1) using bundle average outlet temperatures, pressures, and mass velocities are 71% and 56% for Test Series 1 and Test Series 2 data, respectively. The poor fit is apparently due to the velocities in the gap between rods, as calculated by Equation (4), being too low. Table II shows three velocities in the gap: (a) as predicted by the 31 subchannel COBRA model of Figure 3, (b) as determined from high-speed motion pictures, (c) and as calculated using Equation (4). The results of Equation (4) are approximately a factor of five lower than those obtained by other methods. The constants in Equation (4) were determined by Lund to produce a fit to his CHF data rather than by comparison with velocity data. They appear to be subject to considerable error.

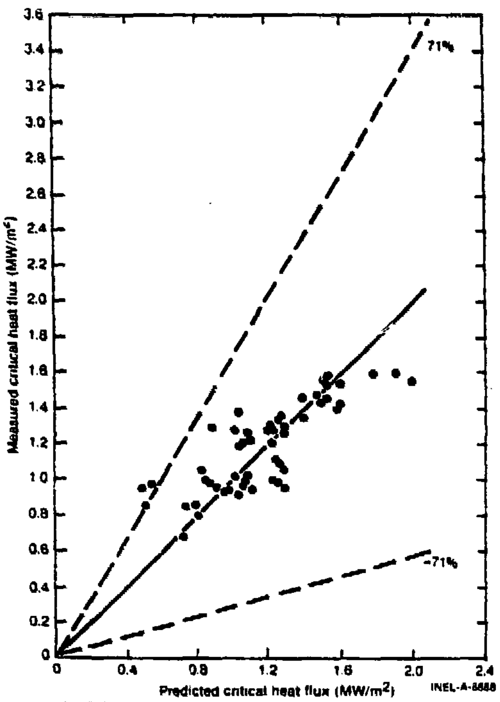

Fig. 4 Comparison of CHF data from Test Series 1 with Lund's correlation of Equation (1).

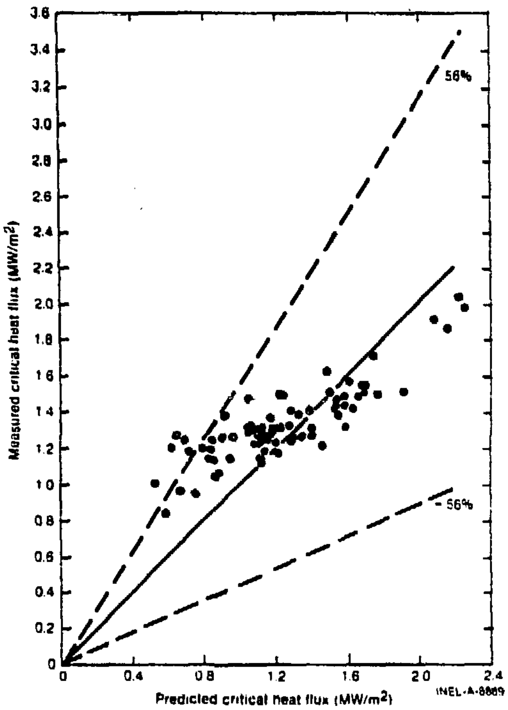

Fig. 5 Comparison of CHF data from Test Series 2 with Lund's correlation of Equation (1).

A further difficulty with Lund's approach seems to be the use of Reynolds analogy for subcooled CHF in this instance. The critical friction factor, f_c, must be smaller than given by Equation (2) to be consistent with the observed velocity in the gap. Tong's[12] recommendation of $Re^{-0.60}$ could bring Equation (2) into better agreement with the data and make Equation (4) more nearly correct. In addition to the velocity and friction factor problems, the density in the gaps is much smaller than the bundle average density. COBRA generally shows a small positive quality, χ, in the gap which, at low pressure, results in high void fraction, α, and a density which is approximately a factor of five less than the bundle average density. A further major effect on the density in the gap is the mixing Stanton number (β in COBRA terminology), as the 31-subchannel COBRA model shows. If the

TABLE II

COMPARISON OF GAP VELOCITIES

	Gap Velocity (m/s)		
Run	31-Subchannel COBRA Model	Photographs	Equation (4)[a]
12	2.18	1.75	0.38
15	1.60	1.43	0.29
18	1.58	1.42	0.29
21	2.62	2.35	0.48
40	3.15	2.54	0.51
46	2.23	2.37	0.38
65	2.90	2.24	0.47
67	3.09	2.48	0.51

[a] Equation (4) in text. Value based on bundle average activity.

mixing Stanton number is large, the flow through the gap can result in a high void fraction at one axial location which does not flow downstream in the gap. This behavior of the voids was shown in the high-speed motion pictures. During CHF, a bubble formed in the gap and moved to the adjacent subchannel rather than propagating along the gap. Thus, the fundamental concept of the Reynolds analogy, substitution of the sensible heat for the momentum of the fluid, is incorrect for closely spaced rods because of the effect of turbulent cross flow on void behavior.

The preceding evaluation shows that Lund's correlation, although it properly emphasizes the effect of local conditions in the gap, is not sufficiently well founded to be used with average flow conditions. Lund's concept with an unconventional subchannel model, such as the 31-subchannel COBRA model, is being considered for use and could result in accurate predictions.

V. DEVELOPMENT OF A CHF CORRELATION FROM COLUMBIA TEST DATA

The approach to a correlation for the Columbia test data was to use local conditions, as determined from the 25-subchannel COBRA model, to correlate with commonly used correlation parameters. Linear and nonlinear regression analysis models were used to develop empirical correlations from the test data. The statistical analyses provided an additive and multiplicative CHF correlation for various sets of data.

The additive correlation included pressure and mass flux as the independent variables, whereas the multiplicative correlation also included subcooling (ΔT_{sub}). The general forms of the two correlations are as follows:

(1) Additive correlation –

$$q_{pred} = A + BP + CG$$

(2) Multiplicative correlation –

$$q_{pred} = D \times P^E \times G^F \times (H \times \Delta T_{sub} + J)^K$$

where

q_{pred} = predicted critical heat flux (MW/m^2)

P = absolute pressure (Pa)

G = mass velocity ($kg/s{\cdot}m^2$)

ΔT_{sub} = coolant subcooling (^oC).

A regression analysis was performed on the data from Test Series 1, Test Series 2, and the combined data for both tests. Equations were developed for each set of test series data separately and for combined data sets for the additive and multiplicative relationships, respectively.

Some of the subchannel data included ΔT_{sub} values which were equal to zero. These data were observed to fall consistently outside the 20% error band. Consequently, these data were omitted from the combined data base, and a statistical analysis on the remaining data (qualified data) was performed. The resultant CHF correlation is given in Equation (7).

$$q_{pred} = \frac{1.59 \times 10^{-3} \, P^{0.131} \, G^{0.649}}{\Delta T_{sub}^{\;0.032}} \, . \tag{7}$$

The measured CHF versus the predicted CHF given by Equation (7) is shown in Figure 6. Figure 7 is a histogram showing the error distribution for all measured-to-predicted CHF ratios for all test data. A Kolmogorov-Smirnov normality test was conducted which indicates that the data are normally distributed at a 20% level of significance.

VI. EVALUATION OF BOWED ROD TESTS

Testing was performed to determine whether CHF would occur at lower heat fluxes than those observed with nominal rod spacing and also to determine whether CHF would propagate azimuthally on the rod surface. The CHF data for bowed rods showed a wider

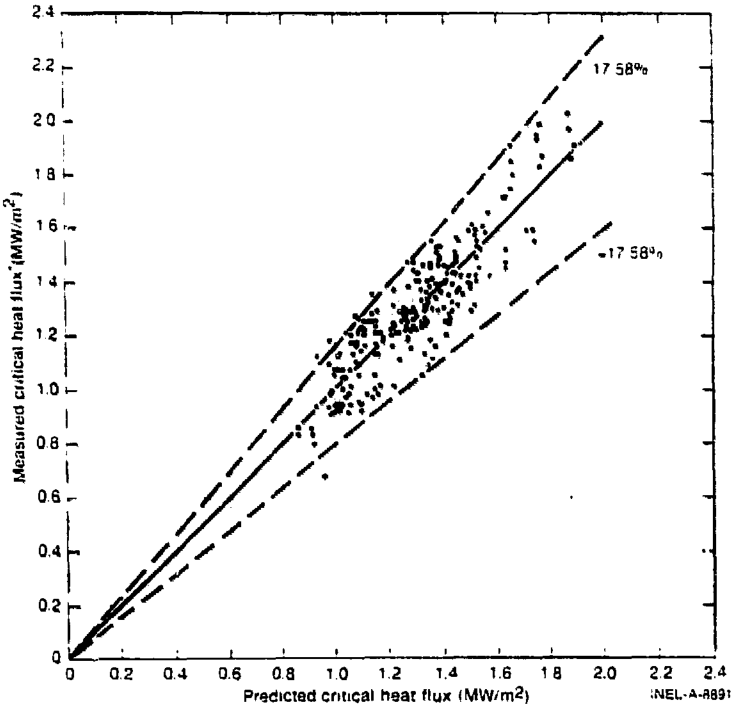

Fig. 6 Comparison of combined CHF data (omitting coolant subcooling data points where $\Delta T_{sub} = 0$) from Test Series 1 and 2 with multiplicative correlation of Equation (7).

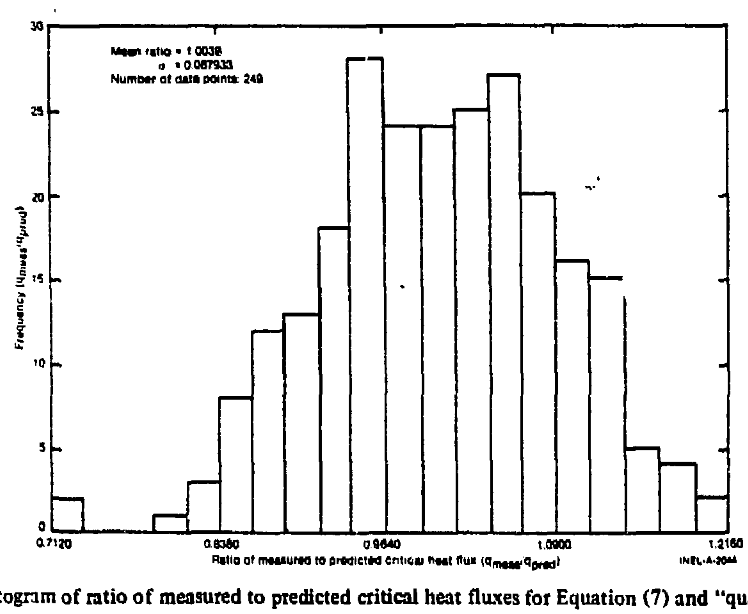

Fig. 7 Histogram of ratio of measured to predicted critical heat fluxes for Equation (7) and "qualified" data.

scatter than for nonbowed rod tests with the average value of q_{meas}/q_{pred} of 0.916 [where q_{pred} is based on Equation (7)]. Comparison of this mean value with that obtained from the nominal gap spacing data indicates that a lower heat flux is required to instigate CHF when the rod spacing is reduced. A detailed discussion of the bowed rod tests is not presented here due to space limitations.

VII. CONCLUSIONS

It was concluded from this study that close-packed rod bundles operating at low pressure have low CHF values; the CHF is not well predicted by either the commonly used general correlation of Bernath or the Lund correlation, which is based on data similar to those reported here.

Conditions in the gap between rods have a dominant effect on CHF, and CHF initiates in these gaps. CHF is confined to the gaps and does not propagate azimuthally around the rod. To evaluate gap conditions, a COBRA model with additional detail in the gaps should be used.

It was also concluded that rod bowing further reduces CHF in the conditions tested.

The experimental data can be correlated by

$$q_c = \frac{1.59 \times 10^{-3}\, P^{0.131}\, G^{0.649}}{(\Delta T)^{0.032}}$$

with a standard deviation of 8.79%. The correlation should be used only within the range of test conditions.

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