Critical Heat Flux Experimentation in an Annular Test Section

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IN AN ANNULAR TEST SECTION

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CONTENTS

	<u>Page</u>
KEYWORDS	v
ABSTRACT	1
1. INTRODUCTION	1
2. THEORETICAL MODEL	2
3. EXPERIMENTAL EQUIPMENT AND PROCEDURES	4
3.1 Test Facility	4
3.2 Heater Rod	7
3.3 Experimental Procedures	9
4. RESULTS AND DISCUSSION	9
4.1 Experimental Results	9
4.2 Analytical Results	12
4.3 Discussion of Experimental and Analytical Results	21
4.3.1 Steady-State Tests	21
4.3.2 Transient Tests	25
5. CONCLUSIONS	25
6. RECOMMENDATIONS	26
REFERENCES	26

KEYWORDS

Pressurized-water reactor, blowdown heat transfer, Forced Convection Test Facility, electrical fuel pin simulators, critical heat flux (CHF), departure from nucleate boiling (DNB), annular geometry, dryout, MacBeth-Barnett, stepped cosine power profile, transient critical heat flux, 3.66-m (12-ft) heated length.

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ABSTRACT

Steady-state critical heat flux experiments have been performed in the Forced Convection Test Facility (FCTF), an annular test section containing a single electrically heated rod, for the purpose of testing the applicability of existing critical heat flux correlations. Good accuracy has been obtained using the MacBeth-Barnett critical heat flux correlation for annuli, corrected for the "stepped cosine" power profile of the heater.

The equivalent diameter of the test section, based on the wetted perimeter, is 2.1 cm (0.83 in.); the heated-to-wetted-perimeter ratio is 0.252. The heated length of the heater rod is 366 cm (144 in.).

Nominal pressures for the tests have ranged from 7.2 to 15.5 MN/m² (1044 to 2250 psia); coolant flow rates have been 0.32 dm³/sec (5 gpm), 0.63 dm³/sec (10 gpm), and 1.26 dm³/sec (20 gpm); and heater powers of 72 kW, 122 kW, and 144 kW have been used. Maximum error in prediction of first observed critical heat flux is 21%; rms error is 11.7%.

Attempts have also been made to predict the occurrence of critical heat flux during blowdowns (depressurization transients) of the FCTF. The results of these predictions are inconclusive at this time.

1. INTRODUCTION

Single nuclear fuel pin simulators are tested in the Forced Convection Test Facility (FCTF). These simulators are electrical heaters with heated lengths of 366 cm (144 in.) and diameters of 1.07 cm (0.422 in.) and are similar to some pressurized water reactor fuel pins.

The operation of the FCTF is limited, in steady state, by the temperature at the surface of the heater rod used as a nuclear fuel pin simulator. The most desirable heat transfer regimes are forced convection and nucleate boiling in order to keep the heater surface temperature low. In the realm of nucleate boiling, the potential exists to blanket the rod with vapor by boiling so violently that liquid cannot reach the rod. This is referred to as departure from nucleate boiling (DNB). In regions of large void fractions, evaporation of the film of liquid covering

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the rod is possible, causing the phenomenon known as dryout. The heat flux required to cause these phenomena is called critical heat flux (CHF), and this condition is indicated by a sharp rise in the surface temperature of the rod as the heat transfer coefficient drops by as much as three orders of magnitude.

In order to study the conditions under which CHF occurs in steady state in the FCTF, a series of experiments has been run at various pressures, flow rates, and powers. Several CHF correlations were examined; the MacBeth-Barnett CHF correlation for annuli has been found to predict with good accuracy the occurrence of CHF in steady-state tests in the FCTF when corrected for the nonuniform heat flux profile of the heater in use.

This report outlines the tests that have been conducted and presents a comparison between predicted and observed results.

One other area, only briefly explored, is the application of the steady-state CHF correlation to predict CHF in depressurization transients (blowdowns) of the FCTF. A short discussion of these results is included.

2. THEORETICAL MODEL

There does not exist, at present, any completely theoretical model to describe CHF. Most correlations, therefore, are wholly or partially empirical in nature. The MacBeth-Barnett correlation for annuli is completely empirical and is presented for steady-state uniform heat flux operation. This correlation was chosen due to its specific applicability to FCTF annular geometry. Since the heater rods used in the FCTF have a stepped power profile approximating a chopped cosine (with an integrated power profile similar to that found in nuclear reactors), the effect of this nonuniform heat flux distribution must be considered. This has been done using a "local conditions" hypothesis, namely, that CHF occurs at a point of constant thermodynamic equilibrium enthalpy, irrespective of the rod power profile.

The MacBeth-Barnett correlation is presented in Collier¹ as

$$\frac{q''_{cr}(z)}{10^6} = \frac{A(h_{fg}/649) + B(\Delta h_{sub})_i}{C + z}, \quad (1)$$

where

$$\begin{aligned} h_{fg} &= \text{latent heat of vaporization (Btu/lb}_m\text{)}, \\ (\Delta h_{sub})_i &= \text{inlet subcooling of the coolant (Btu/lb}_m\text{)}, \\ z &= \text{axial position on the heater (in.)}, \end{aligned}$$

and

$$A = 67.45 D_h^{0.68} (G \times 10^{-6})^{0.192} \times [1 - 0.744 \exp(-6.512 D_e) (G \times 10^{-6})], \quad (2)$$

$$B = 0.25787 D_h^{1.261} (G \times 10^{-6})^{0.817}, \quad (3)$$

$$C = 185.0 D_e^{1.415} (G \times 10^{-6})^{0.212}, \quad (4)$$

where, for an annulus of inner diameter D_i and outer diameter D_o ,

$$D_e = D_o - D_i \text{ (in.)}, \quad (5)$$

$$D_h = (D_o^2 - D_i^2)/D_i \text{ (in.)}, \quad (6)$$

and G = mass velocity ($\text{lb}_m/\text{hr ft}^2$).

Since the nonuniform heat flux correction involves thermodynamic equilibrium enthalpy, the enthalpy at any point in the fluid along the rod must be calculated.² Thus

$$h(z) - h_{f,sat} = \frac{4q''_{max}}{GD} \int_0^z f(z) dz - (\Delta h_{sub})_i, \quad (7)$$

where

$$f(z) = q''(z)/q''_{max}. \quad (8)$$

If the MacBeth-Barnett correlation is put into the form

$$q''_{cr}(z) = X - YDG[h(z) - h_{f,sat}]/4 \quad (9)$$

then, by substituting (7) into (9) and transforming back to the original form (1),

$$\frac{q''_{max,cr}(z)}{10^6} = \frac{A(h_{fg}/649) + B(\Delta h_{sub})_i}{C f(z) + \int_0^z f(z) dz} \quad (10)$$

This can be further simplified to

$$q''_{max,cr}(z) = q''_{cr,u} \frac{C + z}{C f(z) + \int_0^z f(z) dz}$$

where $q''_{cr,u}$ is the uniform heat flux CHF predicted by (1).

The term $q''_{max,cr}(z)$ is the value of the peak heat flux required for CHF to occur at point z on a rod with the specified heat flux profile $f(z)$. Dividing $q''_{max,cr}(z)$ by the actual rod maximum heat flux at a certain power gives the ratio of the critical heat flux to the actual heat flux. This number is called the departure from nucleate boiling ratio (DNBR) and can be multiplied by the heat flux at a point z to find the predicted critical heat flux at that point.³ A DNBR of unity predicts that a CHF condition will occur. This method of prediction was used during this series of tests. The results of the predictions are discussed in Part 4.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1 Test Facility

All steady-state CHF tests were carried out in the FCTF, a schematic of which is shown in Fig. 1. The annular test section has a hydraulic equivalent diameter of 2.10 cm (0.828 in.), and the heated-to-wetted-perimeter ratio is 0.252. Coolant flows down a downcomer and up through

Fig. 1. Forced Convection Test Facility.

the test section, exiting through a spool piece containing flow instrumentation. The test section, a cross-sectional view of which is shown in Fig. 2, consists of a pressure vessel (containment), core barrel, and heater rod. The space between the containment and the core barrel forms the downcomer. Only the heater rod is heated by power in this apparatus; the core barrel and containment are heated only by the fluid passing over them. There is, however, a guard heater outside the containment to hinder heat losses from the fluid in the downcomer.

ORNL - DWG 74 - 10784R

Fig. 2. PCTF test section cross-sectional view.

3.2 Heater Rod

The heater used in the FCTF, a cross-sectional view of which is seen in Fig. 3, is an electrically heated nuclear fuel pin simulator produced by the Watlow Electric Manufacturing Company of St. Louis, Missouri. A schematic of the rod, showing heater zone lengths, powers, and thermocouple locations, is shown in Fig. 4. The power profile of the rod is a "stepped cosine," designed to approximate the chopped cosine profile found in some nuclear reactors. The heater is instrumented with thermocouples spot-welded into grooves in the inner sheath of the heater and also with thermocouples placed in the central ceramic core of the heater. The sheath thermocouples are monitored during experiments for indications of CHF conditions.

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HEATER ROD CROSS SECTION (0.422-in. DIAM)

Fig. 3. Heater rod cross section.

Fig. 4. Schematic of FCTF heater showing thermocouple locations and heat zone layouts. Dimensions in meters.

3.3 Experimental Procedures

The MacBeth-Barnett equation contains five independent parameters that depend on either the coolant conditions or the system geometry. These are the only parameters that can be altered in order to change the critical heat flux prediction. These parameters are the mass velocity, latent heat of vaporization (related to system pressure), inlet subcooling (related to system pressure and coolant inlet temperature), and the equivalent diameters based on both heated and wetted perimeter. Since the last two parameters are fixed by the geometry of the test section, the testing procedure involved changing only two parameters — mass velocity and pressure. Once these two properties were fixed for a test, the coolant inlet temperature was slowly increased until CHF was indicated by a sheath thermocouple. The sheath thermocouple can be used to indicate the occurrence of CHF because the immediate degradation of surface heat transfer capability accompanying CHF causes a rapid escalation in the surface and sheath temperatures and a corresponding rapid escalation in the thermocouple output. When the thermocouple output reached a preset level, it activated an overtemperature power trip set to prevent permanent damage to the rod.

During a test, data on flow rate, pressures, and temperatures were recorded on a Beckman ANSCAN data acquisition system and stored on magnetic tape. When processed, this information provides a continuous record of system conditions before, during, and after CHF. The coolant conditions at the point of first CHF provide input to the MacBeth-Barnett CHF correlation so that DNBR can be calculated where CHF occurred.

4. RESULTS AND DISCUSSION

4.1 Experimental Results

In order to adequately test the correlation, experiments were carried out over a wide range of pressures and flow rates. The nominal conditions for each test are listed in Table 1. The actual pressures at which the tests were performed varied somewhat from the nominal. The pressure variance in experiments 76-6-1, 76-7-1, 76-7-2, and 76-7-4 was not more

Table 1. Nominal conditions for steady-state CHF test

Run No.	Flow rate [dm ³ /sec (gpm)]	Power (kW)	Pressure [MN/m ² (psia)]
76-6-1	0.63 (10)	144	15.51 (2250)
76-6-3	0.63 (10)	122	15.51 (2250)
76-6-4	0.32 (5)	144	15.51 (2250)
76-6-5	0.32 (5)	122	15.51 (2250)
76-6-6	0.32 (5)	72	15.51 (2250)
76-7-1	0.63 (10)	144	15.51 (2250)
76-7-2	1.26 (20)	144	15.51 (2250)
76-7-4	0.63 (10)	144	10.34 (1500)
76-8-1	0.63 (10)	144	7.20 (1044)

than 0.34 MN/m² (50 psi) from the nominal value. In the other tests, however, the pressure was considerably higher than nominal. This was due to the effect of bulk boiling in the test section. At flow rates of 0.32 dm³/sec (5 gpm), coolant velocity is about 0.45 m/sec (1.5 fps). Flow boiling at such a low flow rate tended to override the effect of the pressurizer in the system, causing the system pressure to rise. The same behavior was observed at low inlet subcoolings, where boiling occurred through the entire test section. For example, in test 76-6-6, the inlet temperature was taken to saturation before CHF occurred at a thermocouple level protected by an overtemperature power trip. This caused bulk boiling throughout the entire test section, causing the pressure to rise to 17.7 MN/m² (2570 psia).

The results of the tests, including predictions of DNBR, are listed in Table 2. Although it is not immediately apparent from the table, these tests showed a high degree of reproducibility. Tests 76-6-1 and 76-7-1 were run at the same flow rate and about the same pressure. The incidence of CHF is seen at about the same inlet temperature, and the same thermocouple exhibits first CHF, with subsequent rewet. More thermocouples showed CHF in test 76-7-1 due to the fact that the overtemperature trip point was set at a higher level, allowing the power to remain on longer.

Although none of the other tests are duplicated in the table, two experiments were actually run at the same conditions for each test. The

Table 2. Results of CHF tests

Run No.	Core barrel inlet temperature at CHF [K (°F)]	Test section inlet pressure at CHF [MN/m ² (psia)]	Thermocouple(s) on which CHF was observed	Predicted DNBR at point of CHF
76-6-1 ^a	600 (621)	15.46 (2243)	DH ^b DI	0.985 1.15
76-6-3	611 (640)	15.94 (2313)	DH DI ^b EJ EK	0.93 1.07 1.036 1.121
76-6-4	575 (575)	16.51 (2395)	DH DI ^b	0.914 1.044
76-6-5	594 (610)	16.28 (2361)	DI ^b EJ EK FL	1.12 1.075 1.164 1.125
76-6-6 ^c	628 (671)	17.72 (2570)	DI ^b	0.967
76-7-1 ^a	598 (617)	15.59 (2262)	DH ^b DI EJ	1.035 1.19 1.15
76-7-2	614 (646)	15.81 (2294)	DH ^b DI EJ EK	0.89 1.033 0.997 1.087
76-7-4	583 (590)	10.50 (1523)	EK ^b FL ^b FM	1.207 1.177 1.45
76-8-1 ^d			None	

^a CHF on DH subsequently rewet before reaching power trip point.

^b First CHF.

^c Run 76-6-6 was done at low flow and low power, and, as a result, the rod was cooled by steam at the upper end with liquid present only as entrained droplets. Because of this, extremely high temperatures were reached, due to the fact that there were no overtemperature trips on the upper four thermocouples. It is somewhat unclear as to whether to consider this as CHF, since the rod operated at steady state at these levels without burning out.

^d This experiment was performed in order to test whether CHF would occur at saturated conditions with an inlet temperature of 561 K (550°F). The MacBeth-Barnett correlation predicts a minimum DNBR of 1.092 for these conditions. Since no CHF was observed, the experiment confirms the predictions.

first was used to show when CHF could be expected, thus indicating when the ANSCAN system should be activated, since a limited amount of data can be processed. In each case, the first and second runs showed close agreement; however, only the run for which the ANSCAN operated is listed in Table 2. Plots of sheath thermocouple temperature vs time are shown in Figs. 5-8. The time scales are arranged so that the first occurrence of CHF falls approximately at zero seconds. The graphs were drawn by a Calcomp plotter from information taken from the ANSCAN system. The plots are developed from data points taken every tenth of a second.

As can be seen in the plots, the onset of CHF is readily apparent due to the rapid rise in the sheath temperatures that immediately follows the departure from nucleate boiling or dryout. The features of these plots will be discussed in more detail in the following section.

4.2 Analytical Results

The results of predictions using posttest results are presented in Table 2 and Fig. 9. Posttest calculations were necessary due to the variance of the system conditions from the nominal. The maximum error at first CHF is 20.7% through 76-7-4, and the rms error for all tests through 76-7-4 is 11.7%. Run 76-8-1 is not included in these calculations because no CHF occurred. The predicted DNBR, as noted, is 1.09 at the 229-cm (90-in.) level. Since CHF did not occur, the error cannot be evaluated but is assumed to be less than 9.2%. The error at first occurrence of CHF is emphasized here, and the reasons will be explained in the following section.

Predictions were also made, assuming nominal conditions, for three flow rates [0.32, 0.63, and 1.26 dm³/sec (5, 10, and 20 gpm)] over a range of pressures from saturation at 561 K (550°F) coolant inlet temperature to 15.51 MN/m² (2250 psia) at the same temperature and over a range of coolant inlet temperatures from 561 K (550°F) to saturation temperature [618 K (652.9°F)] at 15.51 MN/m² (2250 psia). Results of some of these predictions are presented in Figs. 10-12.

Predictions of DNBR at 0.63 dm³/sec (10 gpm), 561 K (550°F), and 15.51 MN/m² (2850 psia) were also made using the W-3, B&W-2, and Janssen-

Fig. 5. Heater sheath thermocouple outputs during experiment 76-6-4.

Fig. 6. Heater sheath thermocouple outputs during experiment 76-7-1.

Fig. 7. Heater sheath thermocouple outputs during experiment 76-7-2.

Fig. 8. Heater sheath thermocouple outputs during experiment 76-7-4.

ORNL-DWG 76-14856

Fig. 9. Steady-state CHF results for the single-rod annular flow geometry compared with the predictions of the MacBeth-Barnett correlation for annuli.

Fig. 10. DNBR calculated by MacBeth-Barnett correlation for FCTF for different flow rates.

Fig. 11. DNBR calculated by MacBeth-Barnett annulus correlation for FCTF for different inlet temperatures.

Fig. 12. DNBR calculated by MacBeth-Barnett annulus correlation for FCTF for different pressures.

Levy CHF correlations. These represent normal steady-state operating conditions for FCTF. One or more system parameters is outside the suggested range of each correlation. The predictions are presented in Table 3, for the sake of comparison, along with the prediction from the MacBeth-Barnett correlation. All predictions are those at the 229-cm (90-in.) level, the point at which minimum DNBR is predicted by the MacBeth-Barnett correlation.

Table 3. Predictions of DNBR
at 229-cm (90-in.) level

Correlation	Predicted DNBR
W-3	0.83
B&W-2	0.93
Janssen-Levy	0.44
MacBeth-Barnett (annulus)	1.60

4.3 Discussion of Experimental and Analytical Results

4.3.1 Steady-state tests

The temperature-time curves presented in Sect. 4.1 give a very good representation of the phenomenon of critical heat flux and suggest some of the causes. In experiment 76-6-4, presented in Fig. 5, only two thermocouples exhibited CHF. The temperature of thermocouple DH, located in the highest power zone, climbs at a rate of 188 K (338°F) per second, clearly illustrating the drastic reduction in surface heat transfer coefficient. Also of some interest is the behavior of thermocouple EJ. The temperature begins to fall, then rises slightly, only to quench about 2.5 sec later. The initial drop in temperature is due to the loss of power, due to thermocouple DI reaching the overtemperature trip level. When rod power is shut off, voids in the coolant immediately collapse. This, in turn, causes a drop in pressure; when saturation pressure is reached, some boiling may occur. There remains some stored energy in

the heater, and it is probably this stored energy combined with the power-trip-related pressure drop that causes the heater to go into CHF at this level. This incident would seem to indicate, too, that conditions causing CHF verge on a metastable fluid state and that any slight stimulus can cause CHF to occur.

Test 76-7-1, shown in Fig. 6, exhibited one other characteristic sometimes seen in CHF experiments: that of rewetting of the surface. This occurs when the vapor film that has built up around the heater surface suddenly collapses, allowing liquid to reach the surface, hence the term "rewet." This rewetting of the rod is followed 4.5 sec later by CHF indicated by thermocouple DI. Coolant conditions did not change appreciably in the time span 0 to 5 sec, indicating once again that the coolant is in a metastable condition, needing only the slightest stimulus to cause CHF. The CHF condition spreads from DI to thermocouple EJ about 3 sec later. Thermocouple EK also exhibits what appears to be CHF; however, this happened after the power trip, which occurred at 7.6 sec. This behavior is the same sort that was seen on EJ in run 76-6-4 and is very likely due to the same effect.

Experiment 76-7-2, a plot for which is shown in Fig. 7, shows the same basic behavior that has been seen in previous tests. There is, however, one feature unique to this run, that being the temperature trace of DH. Although the temperature at that level begins to rise at zero seconds, the rate of increase is only about 17 K (31°F) per second, as compared with the 115 K (207°F) per second increase several seconds later. This effect has not been observed on any other run, and the reason for the slow coast-up has not yet been determined. One possible explanation, however, is that CHF occurred at a point very close to DH, possibly on a part of the surface at the same level but at an azimuthal location 1.57 radians (180°) from the thermocouple. A gradual spreading of the departure from nucleate boiling could account for the thermocouple's behavior.

The final experiment shown, 76-7-4, in Fig. 8, also has several unique characteristics. The first is the behavior of thermocouple FL. It should be noted that this test was carried out at about 10.34 MN/m² (1500 psia). If the MacBeth-Barnett correlation is examined, it will be

seen that, for all conditions fixed except pressure, the critical heat flux increases as pressure decreases, since h_{fg} increases with lower pressure. This behavior was exhibited in this test, since the inlet temperature had to be taken almost to saturation before CHF occurred, as compared with runs 76-6-1 and 76-7-1, where the inlet subcooling was substantial at CHF. The mechanism for CHF here is very likely dryout, and it is possible that the erratic behavior of FL from 0 to 4.5 sec is due to the unstable behavior of the thin liquid film present on the rod immediately preceding dryout. Another possible explanation for this behavior is that the flow regime was that of slug flow, and the erratic behavior could be due to alternate slugs of vapor and liquid passing by the rod surface at this level, causing entrance into CHF followed by a rapid rewet. Also of note is the rewetting of the rod at thermocouple EK, followed by a return to CHF. Again, this is due most likely to instabilities in the coolant and could possibly be a result of entrained liquid droplets striking the heater surface at that point. CHF conditions occurred only in the upper regions of the rod and spread gradually upward to the M level, indicating a dryout of the liquid film at the end of the rod.

The geometry of the test section also has an effect on the CHF behavior of the rod. The most important geometric effect is probably that due to the rod centering screws, which are placed at 22.9-cm (9-in.) intervals along the rod (see Fig. 2). The screws can possibly act as turbulence inducers in the lower quality regions, providing better flow mixing than expected. There are centering screws in the close proximity of both the H and K levels of the rod, and their presence may account in part for the rewetting seen on thermocouples DH and EK in runs 76-7-1 and 76-7-4 respectively. In areas of annular flow, these screws can possibly act to disrupt the liquid film at the heater surface and could account for dryout CHF occurring earlier than predicted.

As shown in Table 2, the accuracy with which first CHF is predicted is very good at 15.51 MN/m^2 (2250 psia), but the accuracy decreases somewhat at lower pressure. The prediction at first CHF is stressed, due to the effect that CHF has upon rod surface conditions. When CHF occurs, the heater surface temperature rises rapidly, as has been seen previously. This rise in temperature can spread by conduction to other levels of the

rod, causing increased nucleation and an entry into CHF sooner than the correlation would predict. This "spreading" of the CHF, for example, may be responsible for the occurrence of critical heat flux at thermocouple FM in test 76-7-4, though the predicted DNBR was 1.45.

One other explanation exists for the discrepancies in predicted vs actual DNBR (assuming that CHF occurs at a DNBR of 1.0), having to do with the "local conditions" assumption made in the nonuniform heat flux correction term. The local conditions hypothesis, as mentioned previously, assumes that CHF occurs at a certain thermodynamic equilibrium enthalpy (or quality), regardless of the heater power profile. Use of this assumption, therefore, does not take into account any "flow memory," that is, the transport of steam along the test section and the resultant alterations of slip ratios, void fractions, and flow regimes. The flow memory effect would not be much of a factor in low-quality flows, and, in fact, the correlation does a better job of prediction at higher inlet subcooling. In the low-quality zone in the test section, the average power is somewhat less than that of the entire rod, whereas the correction factor is close to unity. This would cause too low a DNBR to be predicted. This has been indicated in analytical calculations by the fact that predicted DNBR has been less than unity at the F and G levels of the rod, with no occurrence of CHF. In the high-quality zone, however, the neglecting of any flow memory effects would tend to cause the predicted DNBR to be too high, as has been seen in Table 2.

The inlet temperature used for predictions was not the coolant temperature at the entrance to the downcomer but rather the temperature at the bottom of the downcomer (the "core barrel" inlet). The decision to use this temperature was made because local fluid conditions within the test section were better represented by using the temperature at the beginning of the heater. Although this was not a large factor at the higher flow rates, the temperature rise in the downcomer was significant in the $0.32\text{-dm}^3/\text{sec}$ (5-gpm) tests, especially in run 76-6-4. The heating of the water in the downcomer is partially due to losses by the water in the core, and these losses may also be partly responsible for inaccuracies in the analytical calculations.

4.3.2 Transient tests

The FCTF is designed to test heater rods during blowdowns of the system. During these blowdowns, the time to CHF is measured, and data are taken in much the same way as in steady-state CHF tests. Attempts have been made to predict DNBR at the point of CHF during transients using the steady-state correlation. Such attempts have met with mixed success. Two such predictions have been made. One had an error of less than 10%; the error in the second was more than 80%. This large inaccuracy is due largely to uncertainties in the flow in the test section during blowdown.

When blowdown occurs, flow immediately reverses; thus the test section outlet becomes the "inlet" for the purposes of the correlation. Flow-measuring devices currently exist several feet downstream of the test section outlet, as shown in Fig. 1. The flow-measuring devices in the FCTF (turbine meter and drag disk) do not operate accurately in two-phase flow, which exists in the entire test section during blowdown. Estimation of the flow rates in the test section is, therefore, difficult, and it is these uncertainties that are discussed. Attempts are currently under way to increase the reliability of these instruments in two-phase flow. If the instrumentation can be made more reliable, more accurate input to the correlation will then be available to test the accuracy of a steady-state correlation under transient conditions.

5. CONCLUSIONS

The MacBeth-Barnett critical heat flux correlation for annuli does a good job of predicting steady-state critical heat flux when corrected for the nonuniform heat flux profile of the FCTF heaters. Although Collier lists the range of the correlation as 4.2 to 9.7 MN/m² (600 to 1400 psia) and 61 to 274 cm (20 to 108 in.) heated length,¹ this series of experiments indicates that the range can be extended to at least 15.9 MN/m² (2300 psia) and 366 cm (144 in.). The local conditions assumption for the nonuniform power correction works well in the low-quality region; however, in high-quality flows the effect of flow memory is believed to cause the correction factor to be less accurate. Indications are that

the steady-state CHF correlation may be used to predict the occurrence of critical heat flux in transients; however, more data must be examined before this point is clear.

6. RECOMMENDATIONS

Further work should be conducted in order to more thoroughly test the applicability of the MacBeth-Barnett correlation. A new test section, with a smaller hydraulic diameter and no centering screws, is currently under construction. Steady-state CHF tests and blowdowns should be conducted in the new facility as before, with the analytical predictions continuing.

Further work on correcting the MacBeth-Barnett correlation for non-uniform heat flux should also be done. Such corrections as the Tong "F" factor and the B&W "F" factor should be evaluated.

Finally, more work should be done to improve the accuracy of two-phase flow measurements. Flow-measuring devices should be installed at the test section inlet to obtain better mass flow rate information, especially during blowdowns. These steps are essential to obtaining and testing predictions of transient CHF.

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