H. L. Price, Director
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Signed by M. M. Mann

JUN 29 1960

Marvin M. Mann, Assistant Director
Division of Inspection

TRANSMITTAL OF "BURNOUT" SURVEY

SYMBOL: INS:PAM

Stimulated by the recent fuel melting event at the Westinghouse Testing Reactor, we have had a survey conducted by Mr. V. A. Walker of the present status of knowledge and experience concerning burnout heat flux correlations in low pressure (under 200 psi), light water systems. A copy of Mr. Walker's survey is attached.

In general, we find that there are large uncertainties involved in the prediction of burnout conditions at low flows and pressures. Accordingly, we suggest conservatism in dealing with existing reactors and a research program to help to eliminate or minimize the uncertainties.

We would be glad to discuss this subject further, e.g., with specific regard to operating limitations desirable for the Westinghouse Testing Reactor, should you wish.

Attachment:
Survey

cc: W.F. Finan, AGMRS, w/attach.
F.K. Pittman (ATTN: S.A. Szawlewicz), DRD, w/attach.
C.K. Beck, DLR, w/attach. (5 cys.)
N.H. Woodruff, H&S, w/attach.
L.D. Low, CO, w/attach.
C.F. Eason, OGC, w/attach.
J. Charnoff, DLR, w/attach.
R.H. Engelken, SAN, w/attach.
R.C. Hageman, CH, w/attach.
J.R. Sears, NY, w/attach.
V.A. Walker, ID, w/attach.

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BURNOUT CORRELATIONS FOR APPLICATION TO WATER COOLED TEST REACTORS
A SURVEY

SUMMARY

A survey of the available burnout data and correlations applicable to test reactors operating at low absolute pressures and cooled by water is presented. In the subcooled region (more than 10° F), it is recommended that the burnout heat flux, as calculated by Bernath's extended method, be reduced by forty per cent. In the 0° F subcooled region or net steam generation region, the correlations of Lowdermilk may be used. The latter situation is largely unexplored.

Confirmation testing in an operating nuclear reactor is suggested.

INTRODUCTION

The problem of meltdown of reactor fuel elements through the process of loss of the heat transfer capability of the coolant by a change of phase, called "burnout", has been under investigation for about fifteen years. Unfortunately, the method of solution has for the most part been one of finding the thermal-hydraulic conditions required for burnout for a more or less specific reactor. Considerable effort has been expended in the high pressure region; e. g., references 1 and 2.

There has been some research done, and it is continuing for reactors operating at low pressures. This paper attempts to summarize the research at low pressures and to indicate the areas in which additional work appears to be needed.

The significant differences in bubble dynamics at low pressure and high pressure makes the use of the high pressure research for test reactors a questionable practice and, therefore, the high pressure research was not included in this brief survey.

SUMMARY OF LOW PRESSURE RESEARCH

A brief summary of each research will be presented, together with any correlations that have been developed from these data.

L. Bernath, A Theory of Local Boiling Burnout and Its Application to Existing Data, presented at the Third National Heat Transfer Conference, August 1959.

This comprehensive paper summarizes much of the data obtained in the study of burnout over all pressure ranges. A theory is developed and the constants of a correlation resulting from this theory are obtained

1. WAPD-188, R. A. de Bortoli, S. J. Green, et al., Forced-Convection Heat Transfer Burnout Studies for Water in Rectangular Channels and Round Tubes at Pressures above 500 psia, October 1958.

2. ANL-4627, Jens, W. H. and Lottes, P. A. Analysis of Heat Transfer, Burnout, Pressure Drop and Density Data for High Pressure Water, May 1951.

by the use of some of these data. Bernath attempts to explain any large variances of the data from the correlation; these explanations appear to be well founded.

The heat flux at burnout is obtained from the following relationships:

$$Q/A)_{BO} = h_{BO} (t_{w,BO} - t_b)$$

$$h_{BO} = 10,890 \left\{\frac{De}{De + Di}\right\} + KV$$

$$t_{w,BO} = 57 \ln P - 54 \left(\frac{P}{P + 15}\right) - \frac{V}{4}$$

where $Q/A)_{BO}$ = burnout heat flux, PCU/hr, ft^2;

h_{BO} = heat transfer coefficient at burnout, PCU/hr, ft^2 $^\circ$ C;

$t_{w,BO}$ = wall temperature at burnout, $^\circ$ C;

t_b = mixed mean bulk water temperature at location of burnout, $^\circ$ C;

De = hydraulic diameter, ft;

Di = heated perimeter divided by π, ft;

V = nominal liquid velocity, ft/sec;

K = $48/De^{0.6}$ for De $\leq$ 0.1 ft. or 90 + 10/De for De $\geq$ 0.1 ft

and P = absolute pressure, psia.

The correlation predicts the measured heat flux on the average within about $\pm$ 15 per cent, but much of the data were selected. The reasons given for careful review of the data were cited by Bernath as:

(1) "Premature" burnouts due to the

(a) use of a burnout detector -- generally unreliable,

(b) use of very thin-walled heaters to permit attainment of heat fluxes with low current input,

(c) use of AC heating with thin-walled heaters,

(d) too rapid an increase of power applied to the heater, and

(e) attainment of flow instability in the apparatus (if not in the test section) without proper recognition of the phenomenon.

SUMMARY OF LOW PRESSURE RESEARCH (Continued)

(2) High experimental burnout heat fluxes due to the

(a) vibration of the heater (causes shedding of vapor patches from the heater surface)

(b) attainment of bulk boiling with sufficient net steam to cause acceleration of the coolant stream, and

(c) experimental arrangement in which the combination of massive power leads and short test sections introduces large conduction errors.

(3) In the case of flat-strip heaters

(a) the edges of thin strips are more effective in dissipating heat than the faces, and

(b) heaters with clamped edges can leak coolant to the back (insulated) face resulting in "high" heat fluxes, or the insulator (mastic or adhesive) can ooze over the edges of the heater strip causing hot spots and "premature" or low burnout heat fluxes.

Quoted from Page 4 of Bernath's paper.

Bernath applied the correlation to bulk boiling at high pressure and concluded that at velocities greater than 10 ft/sec and an effluent vapor void fraction of less than 0.10, the correlation adequately predicts the burnout heat flux.

All of the data used in this study were obtained under constant flow conditions rather than constant pressure drop and the effect of having a channel operating in parallel at less severe conditions was not included. Because of this and other uncertainties, we suggest that values of the burnout heat flux predicted by the Bernath correlation should be reduced by 40%.

The burnout heat flux was measured for the following range of conditions:

(1) Velocity 5 to 45 ft/sec

(2) Subcooling 5 to 75° C

(3) Pressure 25 to 85 psia

(4) Coolant passage equivalent diameter 0.21 to 0.46 inches

(5) Geometry Flat strip 2 inches wide, 19-1/4 inches long and 0.038 inches thick. Annuli 0.5 to 0.8 inches in equivalent diameter

(6) Flow direction - down

(7) Heater materials Type 304 stainless steel and 70-30 Cu-Ni alloy

(8) Heat flux 0.5×10^6 to 1.8×10^6 PCU/hr ft^2

(9) Uniform direct current, electrical heat supply.

SUMMARY OF LOW PRESSURE RESEARCH (Continued)

The following empirical correlation was written from the results of 65 experiments:

$$Q/A)_{BO} = 266{,}000\ (1 + .0365\ V)\ (1 + .0091\ TS)\ (1 + .0131\ P)$$

where $Q/A)_{BO}$ = burnout heat flux PCU/hr, ft^2;

V = fluid velocity, ft/sec;

Ts = subcooling, $(T_{sat} - T_b)$, ° C;

P = absolute pressure, psia.

The maximum deviation of the data from the correlation is reported to be 16 per cent.

These data were obtained under constant flow conditions and did not examine the effect of bulk boiling -- the minimum subcooling, with only two data points taken, was slightly greater than 5° C. Bulk boiling with water flowing downward probably would decrease significantly the burnout heat flux.

Lowdermilk, et al., Investigation of Boiling Burnout and Flow Stability for Water Flowing in Tubes, NACA-TN-4382, September 1958.

In addition to a wide range of velocity, tube diameters and length-to-diameter ratios, the effect of restricting the flow just upstream of the test section and also of placing a compressible volume just upstream of the test section upon the burnout heat flux were examined.

The range of conditions at which burnout heat flux in the stable-flow region was measured were:

Velocity	0.1 to 98 ft/sec
Geometry	Round tubes
Tube diameter	0.051 to 0.188 inches
Uniform electrical AC current heat supply	
Length to diameter ratio	25 to 250
Exit pressure	Atmospheric
Subcooling	0 to wet stream (quality of about 60 per cent)
Flow direction	Upward

The minimum pressure drop across the upstream restriction required to stabilize the flow and obtain a burnout heat flux independent of this pressure drop varied with the flow. The required pressure drop increased as the flow rate was raised. A circulating pump was not used and, therefore, any changes in system pressure were known and deliberately applied.

Two correlations were written: One for low velocity and high-exit quality (1) and another for high velocity and low-exit quality (2). They are:

SUMMARY OF LOW PRESSURE RESEARCH (Continued)

(1) $$(Q/A)_{BO} = 270\ G^{0.85}\ D^{-0.2} \left(\frac{L}{D}\right)^{-0.85}$$

for $G/(L/D)^2 < 150$

(2) $$(Q/A)_{BO} = 1400\ G^{0.5}\ D^{-0.2} \left(\frac{L}{D}\right)^{-0.15}$$

for $G/(L/D)^2 > 150$

where $(Q/A)_{BO}$ = burnout heat flux, Btu/hr, ft^2;

G = mass velocity lb/hr, ft^2;

D = tube diameter ft^2;

and L = tube length, ft.

The use of a compressible volume (a tank partially filled with water and an inert gas above the water) approximates the parallel channel situation found in reactors. The use of this volume decreased the burnout heat flux from about 1.3×10^6 Btu/hr, ft^2 with no gas above the liquid to about 0.3×10^6 Btu/hr, ft^2 with about 100 cc of gas above the liquid; both results were obtained with a constant mass velocity of about 0.75×10^6 lbs/hr, ft^2. Apparently, a flow instability was established when the gas occupied part of the tank volume.

There are two reasons that these data may not be directly applied to test reactors. The test section was heated with AC power and Ellion 3/ in a photographic study, showed that bubble dynamics were affected by the alternating current. The flow through the test section was upward and the buoyancy of the steam probably enhanced the heat transfer process; at low velocities in downward flow the steam buoyancy may have a significant effect, particularly in the bulk boiling region.

The results of this study indicate that the flow system characteristics have a signficant effect upon the heat flux at burnout when in bulk boiling. Apparently, flow instability and burnout are closely related and are difficult to separate unless particular care in the loop design is exercised. A logical conclusion is that the low pressure research done to date needs to be used very cautiously. This is not necessarily true at high pressure since flow instabilities are more difficult to obtain with higher pressure. 4/

Several experimental data points were obtained at 0° F inlet subcooling. The burnout heat flux was a weak function of inlet subcooling since it only decreased about 20 per cent when the inlet water temperature was raised from 70° F to 212° F. These data lend credence to the idea that burnout is a localized phenomenon.

3/ JPL-Memo No. 20-88, Ellion, M. E., A Study of the Mechanism of Boiling Heat Transfer, March 1954.

4/ Anderson, R. P. and Lottes, P. A. Boiling Stability, to be published, January 1960.

SUMMARY OF LOW PRESSURE RESEARCH (Continued)

Increasing the outlet pressure from atmospheric to 100 psia raised the burnout heat flux by about 15 per cent. These results are not in agreement with Mirshak's correlation; pressure is a relatively strong function in the latter correlation. However, Lowdermilk's data were obtained with bulk boiling at the burnout point whereas Mirshak's data were for subcooled water.

OTHER DATA

Several other studies have been made in the low pressure range. The data were limited and examined special cases briefly.

In 1948, McAdams[5/] and co-workers obtained nine burnout data points. From these limited data a correlation was written. This work can only be called exploratory.

Gunther[6/] conducted a photographic study and contributed substantially to the understanding of bubble dynamics. His burnout data are not considered accurate since the test section consisted of a thin, heated strip cooled on both sides by flowing water; vibrations were probably induced in the strip and resulted in abnormally high burnout heat fluxes.

Levy and co-workers[7/] examined the special case of horizontal, rectangular channel (2.625 inches by 0.100 inches by 18 inches) heated uniformly and completely around the periphery. Burnout occurred in the corners of the channel at heat fluxes approximately a factor of five below that predicted from other correlations.

There have been several correlations[8/] [9/] written using statistics to improve the "fit" to the data. None of these correlations should be applied at conditions different than those used in the experimental study from which the correlations are derived.

HAPO has a heat transfer loop which has been used in solving their particular problems. The data are classified.

5/ McAdams, W. H., et al., Heat Transfer at High Rates to Water with Surface Boiling, Ind. Eng. Chem., 41, 1945 (1949).

6/ Gunther, F. C. Photographic Study of Surface Boiling Heat Transfer to Water with Forced Convection, Trans. A.S.M.E. 73, 115 (1951).

7/ GEAP-3011, Levy, S., et al., Heat Transfer to Water in Thin Rectangular Channels, May 1958.

8/ DP-363, Menegus, R. L. Burnout of Heating Surfaces in Water, May 1959.

9/ IDO-16460, Merrill, J. A. and Nertney, R. J. The Application of Statistical Methods of Analysis and Experimental Design in Predicting Burnout Heat Flux, June 1958.

RESEARCH IN PROGRESS

Several organizations are presently determining burnout heat flux for various conditions which have fairly direct application to their particular reactors. In all cases, the test sections are electrically heated. The Engineering Research Laboratory at Columbia University and Savannah River Laboratory are both active. Stein at Columbia is determining various aspects of burnout in conjunction with the Components Basic Research program. Mirshak is examining the effects of roughened surfaces, different test section materials, the length of the test section and localized hot spots.

The University of Minnesota, with R. P. Hartnett as the principal research man, is setting up a heat transfer loop. He expects to do basic research upon burnout at low pressure.

Phillips Petroleum Company has a heat transfer loop under construction. They expect to direct their efforts toward solution of the burnout and flow stability problems associated with operation of the MTR and ETR.

COMMENT

To calculate the burnout heat flux in test reactors operating from atmospheric to 200 psia, with narrow coolant channels in the core (not less than 0.075 inches thick) in well developed turbulent flow and with temperature subcooling of more than 10° F, it is recommended at the present time that Bernath's extended method be applied with a forty per cent reduction in calculated burnout heat flux. If the subcooling is less than 10° F or the bulk water temperature at the hot spot reaches the saturation temperature, it is suggested that Lowdermilk's correlations be applied in conjunction with J. B. Reynolds[10/] data for local boiling pressure drop and the Martinelli-Nelson method[11/] for two phase pressure drop.

The information gathered by Lowdermilk and co-workers is an adequate beginning in the matter of burnout with 0° F subcooling or wet steam generation. There is a great deal of work yet to be done before complete knowledge is available, however; for example, did the burnout experienced by Lowdermilk occur in the wet steam area of the tube, in the subcooled region, or at the transition point? The problem of flow stability in the heat transfer loop may be a severe one and needs further investigation particularly in closed loop pressurized water reactors (e.g., the ETR). The inclination of the test section may also be important but no one has examined the down-flow situation.

Actual burnout data within an operating reactor appears to be needed to allow the verification of present analytical methods or the development of improved methods. This work could be performed in SPERT-III.

10/ ANL-5178, Reynolds, J. B. Local Boiling Pressure Drop, March 1954. It is to be noted that Reynolds only studied local boiling pressure drop up to 3.0×10^5 Btu/hr, ft^2. These data should be extended to a heat flux of at least 7.5×10^5 Btu/hr, ft^2.

11/ Martinelli, R. C. and Nelson, D. B. Prediction of Pressure Drop During Forced Convection Boiling of Water, Trans. A.S.M.E. 70, (1948).