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FORCED CONVECTION SUBCOOLED CRITICAL HEAT FLUX
PART I. EFFECT OF COOLANT: D_2O VERSUS H_2O

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ABSTRACT

Forced convection critical heat flux data and correlations are presented for both heavy water (D_2O) and light water (H_2O) coolant. The data were obtained on stainless heaters which formed the inner wall of an annular channel. The critical heat flux for D_2O was determined to be 16% greater than that for H_2O at the same coolant velocity and subcooling.

* Part of the information contained in this article was developed during the course of work under Contract AT(07-2)-1 with the U. S. Atomic Energy Commission.

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INTRODUCTION

A reactor at the Savannah River Plant has operated at the highest neutron flux ever achieved in a nuclear reactor, $\sim 5 \times 10^{15}$ n/cm^2 sec. This neutron flux was attained by operating at heat fluxes in excess of 2.23 million Btu/hr/ft^2 [1].

The Savannah River Laboratory has been engaged in studies to define the critical heat flux for subcooled nucleate boiling. The results of these studies are used in optimization of the fuel assembly design and in developing specifications for components required to achieve the very high power densities. Initial efforts were aimed at relating the heat flux to the usual variables of velocity, temperature, pressure, and geometry. In addition, the effect of many nonidealities which lower the burnout heat flux, e.g., spacer ribs and local

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hot spots, were also studied [1-4].

The Savannah River fuel geometry consists of annuli through which D_2O flows past the bounding fuel surfaces. Coolant conditions range up to velocities of 70 ft/sec, pressures of $\sim$150 psia, and effluent temperatures of about 180°F [1].

Most of the experimental studies were made with stainless steel or copper-nickel heaters because of equipment limitations even though coextruded aluminum-clad, uranium-aluminum alloy fuel tubes are used in the Savannah River Plant reactors. Also, light water (H_2O) was used as a coolant in place of D_2O.

More recent studies have been concerned with the accuracy of critical heat flux data, effect of coolant, and effect of heater material. The initial mathematical correlation based on improved data obtained with stainless steel heaters and H_2O ccolant was presented earlier [5]. This paper presents the data used in the earlier correlation along with recent critical heat flux results obtained with D_2O and a correlation generalized for both D_2O and H_2O. Specific numerical correlations for H_2O and D_2O are also presented. The critical heat flux for aluminum surfaces will be presented in another paper [6].

SUMMARY

The subcooled critical heat flux for D_2O was determined to be 16% higher than that for H_2O at equivalent subcooling and velocity. The following empirical correlation was developed to represent the critical heat fluxes for both H_2O and D_2O

$$\left.\frac{Q}{A}\right|_{Cr} = 9650\left(\frac{We}{Re}\right)^{0.567}\left(\frac{C_p\ T_{sub}}{\lambda}\right)^{0.767} \tag{1}$$

The constants were determined by least square regression of 30 H_2O and 37 D_2O burnout points. The standard deviation was 3.5%. The correlation was applied to an additional 155 H_2O burnout points with a standard deviation of 4.6%. Because of the empirical nature of equation (1), it should not be used for predicting critical heat fluxes outside the range of conditions given in Table I.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental data discussed in this paper were obtained at the Columbia University Heat Transfer facility and the Savannah River Laboratory Heat Transfer Laboratory. The ranges of test conditions are summarized in Table I.

The critical heat flux loop at SRL is shown schematically in Figure 1. The loop consists of a pump, deionizer, surge tank, heat exchanger, and the heated section. The loop was filled with distilled water. The water was deionized and degassed at the beginning of each day of testing. Flow is measured with a Potter turbine flow meter. Maximum flow rate is 60 gpm. Flow enters the top of the test section and flows downward past the heater. Both inlet and outlet temperatures are recorded. Outlet pressure and pressure drop across the test section are also recorded. Heat is generated by resistance heating with DC power. Eight welding generators connected in parallel provide 320 kW at 8000 amperes DC.

Tests are made at constant power and flow by increasing the bulk temperature to the point of burnout (point at which the critical heat flux is exceeded). By interrupting a test when a spot on the heater glowed red (before physical burnout), multiple, reproducible tests could be made on the same heater. As-drawn annealed stainless steel tubing was used to fabricate the heaters. No special precautions were taken to assure uniform surface finish on the test sections except that heaters with circumferential scratches or marks were not used.

An initial check test was run on each heater. This check test was repeated after approximately every five tests. If the check test varied by more than 5% from the original check test, the heater was discarded. A change in critical heat flux for the same experimental conditions was usually caused by bowing of the heater. Alignment of the heater and housing was one of the most important factors in obtaining reproducible data. The heaters have four alignment pins, 2.5 inches from the end of the heated length of either end.

The critical heat flux test loop at the Chemical Engineering Research Laboratory at Columbia University is similar to the SRL loop. The maximum flow rate (250 gpm) and electrical power input (3.5 mW at 22,000 amperes DC) exceed present SRL capacities; this permits the use of aluminum test sections and larger test sections. The outlet pressure of the test section can be closely controlled. Tests are, therefore, made at constant subcooling and flow by increasing the power and simultaneously decreasing the inlet temperature to the point of burnout. Multiple tests could be made on stainless steel heaters with a resistance bridge burnout detector. The coolant in the loop was deionized regularly.

RESULTS

H_2O Coolant

The SRL H_2O results are correlated by the following empirical correlation and are shown in Figure 2

$$\left.\frac{Q}{A}\right|_{Cr} = 153{,}600(1 + 0.0515\ V)(1 + 0.069\ T_{sub}) \qquad (2)$$

The correlation is based on 132 experimental burnout points* obtained with 10 different heaters. The standard deviation was 3.5%. The correlation has been verified by an additional 106 points obtained on 10 additional heaters. The correlation of the additional 106 points had a standard deviation of 4.4%. The magnitude of the standard deviation and the maximum deviation (10%) indicate that the scatter in the data can be attributed to experimental errors. Data for subcooling below 45°F were not used; hence, the correlation is not applicable below 45°F subcooling. Data obtained on bowed heaters, on heaters with fabrication defects, or in tests with poor heat balances were excluded from the analysis. Equation (2) was based on SRL data for one geometry, i.e., annular downward flow with 1/2-inch-OD x 24-inch-long heaters and a 0.875-inch-ID housing.

However, the Columbia University data (Figure 3) on both 3/4-inch and 2.1-inch-OD heaters agree well with the correlation by equation (2); although the scatter of these results is more than with the SRL results. A total of more than 100 tests were conducted. Of these, 73 points were discarded because

* All the critical heat flux data discussed in this paper and physical properties of D_2O used in the analysis are available from the Technical Information Service, Savannah River Laboratory, Aiken, S. C. 29801

of heater defects, poor alignment, or poor heat balances. The remaining 27 points are shown in Figure 3.

Critical heat flux data were obtained by Thorgerson [7] at SRL with a 2-inch-wide rectangular channel heated from one side. These data (68 points), shown in Figure 4, agree very well with equation (2). Thorgerson's data for gap thicknesses of 0.2 to 0.24 inches had a standard deviation of 5.9% and a maximum deviation of 14% from equation (2).

The improved correlations of data can be attributed to better data acquisition. Furthermore, by limiting the correlations to subcoolings greater than 45°F, the correlations are even more improved. As shown in Figure 5, there is a distinct break at about 45°F in the critical heat flux curve when plotted versus subcooling at constant mass velocity or linear velocity based on inlet volumetric flow rate. The break in the curve can be accounted for by increased vapor volume, which causes an increase in the local velocities; hence, the increased critical heat fluxes. The results presented in Figure 2 were obtained at pressures of 30, 55, and 95 psia. No pressure effect was apparent for subcoolings greater than 45°F. However, at lower subcoolings (<45°F) there was a pressure effect, but additional data are required to verify the extent of the effect.

Equation (1) has been compared with a number of other critical heat flux correlations by Gambill [5]. He compared his correlation with equation (2), Towell [4], Provarnin and Semonov [8], and Griffel [9]. The critical heat fluxes agreed reasonably well. However, both Towell and Griffel developed correlations applicable to subcoolings below and above 45°F, which accounts

H_2O and D_2O Coolant

The most striking differences in physical properties between D_2O and H_2O at 176°F are in the density, viscosity, and heat of vaporization as indicated below:

	D_2O	H_2O
Density, lb_m/ft^3	67.4	60.7
Viscosity, lb_m/ft hr	1.0	0.863
Heat capacity, Btu/lb_m °F	0.995	1.002
Heat of vaporization, Btu/lb_m	914.3	992.6
Surface tension, lb_f/ft	0.0042	0.0042

Although the density affects the volumetric heat capacity, and the viscosity represents a measure of the shear stress in the laminar sub-layer, factors containing only the density and viscosity have not been applied quantitatively with success to correlate the critical heat flux.

The correlation of both D_2O and H_2O data by equation (1) is based on least squares regression analysis. The resulting empirical equation fits the data with a standard deviation of 3.5%. The ratio of the Weber and Reynolds numbers can be interpreted as the ratio of viscous forces to surface tension forces acting on a bubble at the surface. The viscous forces are attempting to remove the bubble (delaying burnout), and the surface tension forces are attempting to retain the bubble on the surface.

As shown in Table II, the ratio of the Weber and Reynolds number accounts for the difference in critical heat fluxes for D_2O and H_2O. The empirical fit by equation (1) provides the final tune up. The second term in equation (1)

(C_p T_{sub}/λ) relates the amount of heat removed by convection to that removed by vaporization. However, because the heat capacities of H_2O and D_2O are approximately the same, the heat of vaporization may be a qualitative measure of the number of bubbles or bubble volume (D_2O would have more bubbles than H_2O/unit of heat transfer). The greater number of bubbles would cause more turbulence and a higher critical heat flux. Because equation (1) is based on only two coolants, data on a third coolant is needed to verify the general applicability of the equation. Equation (1) should not be extrapolated to conditions outside those used in the correlation (Table I).

REFERENCES

1. Crandall, J. L., Smith, J. A., and Towler, O. A., "A description of the Savannah River High Flux Charge," USAEC Report DP-999, Savannah River Laboratory (1965).

2. Mirshak, S., Durant, W. S., and Towell, R. H., "Heat Flux at Burnout," USAEC Report DP-355, Savannah River Laboratory (1959).

3. Menegus, R. L., "Burnout of Heating Surfaces in Water," USAEC Report DP-363, Savannah River Laboratory (1959).

4. Mirshak, S., and Towell, R. H., "Heat Transfer Burnout of a Surface Contacted by a Spacer Rib," USAEC Report DP-562, Savannah River Laboratory (1961).

5. Gambill, W. R., "Burnout in Boiling Heat Transfer — Part II: Subcooled Forced Convection Systems," *Nuclear Safety 9*, 467 (1968).

6. Knoebel, D. H., Harris, S. D., Crain, Jr., B., and Biderman, R. M., "Forced Convection Subcooled Critical Heat Flux — Part II. Heater Material Effect: Aluminum versus Stainless Steel," submitted for publication in *ASME Journal of Heat Transfer Series C* (1971).

7. Thorgerson, E. J., "Hydrodynamic Aspects of the Critical Heat Flux in Subcooled Convection Boiling," Ph.D. Thesis, University of South Carolina, Columbia, South Carolina (1969).

8. Povarnin, P. I. and Semenov, S. T., "Investigation of the Abrupt Change in Boiling of Water Heated Under the Saturation Temperature at High Flow Rates Through Pipes," *Teploenergetika 4*, 72 (1959).

9. Griffel, J., "Forced Convection Boiling Burnout for Water in Uniformly Heated Tubular Test Sections," USAEC Report NYO-187-7, New York Operations Office (1965).

PW:sce

NOMENCLATURE

$\left.\frac{Q}{A}\right|_{Cr}$ = critical heat flux, Btu/hr ft^2

$\frac{We}{Re}$ = ratio of the Weber and Reynolds number, $\mu V/\sigma g_c$

We = Weber number at film temperature, $\frac{\rho V^2 D}{\sigma g_c}$ dimensionless

Re = Reynolds number at film temperature, $\frac{DV\rho}{\mu}$ dimensionless

T_{film} = film temperature, °F; $\frac{T_{sat} + T_{bulk}}{2}$

T_{sub} = subcooling, °F; $T_{sat} - T_{bulk}$

T_{sat} = saturation temperature, °F

T_{bulk} = bulk coolant temperature, °F

D = bubble diameter on surface, ft

g_c = gravitational constant, lb_m ft/lb_f sec^2

C_p = specific heat capacity, Btu/lb_m °F

V = velocity, ft/sec

μ = viscosity at film temperature, lb_m/ft sec

σ = surface tension, lb_f/ft

λ = heat of vaporization at saturation temperature, Btu/lb_m

ρ = coolant density, lb_m/ft^3

TABLE I

Summary of Test Conditions[a]

Laboratory	S/S Heater: Diameter or Width, in.	S/S Heater: Length, in.	Coolant: Material	Coolant: Equivalent Diameter, in.	Coolant: Geometry
SRL	0.5	24	H_2O	0.375	annular
SRL	0.5	24	D_2O	0.375	annular
SRL	2.0	20	H_2O	0.4-0.5	rectangular
CU	2.125	24	H_2O	0.4	annular
CU	0.75	24	H_2O	0.4	annular
CU	0.75	24	D_2O	0.4	annular

a. Range of Test conditions:
Coolant velocity 15-60 ft/sec
Coolant subcooling 7-160°F
Critical heat flux $1\text{-}6.5 \times 10^6$ Btu/hr ft^2

Burnout detection:
SRL - visual observation of incandescent spot
CU - bridge-type detector or physical failure

TABLE II

Comparison of the Ratio $(We/Re)_{D_2O}/(We/Re)_{H_2O}$

Temperature, °F	$\frac{(We/Re)_{D_2O}}{(We/Re)_{H_2O}} = \frac{(\mu/\sigma)_{D_2O}}{(\mu/\sigma)_{H_2O}}$
140	1.208
180	1.169
220	1.144
260	1.140

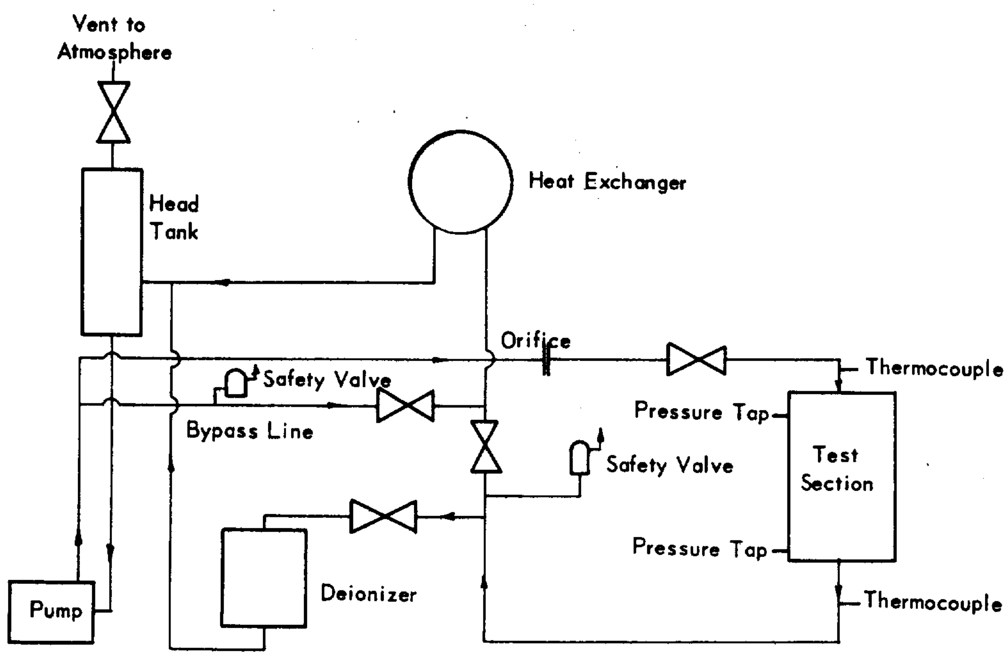

FIG. 1 SCHEMATIC OF CRITICAL HEAT FLUX LOOP AT SRL

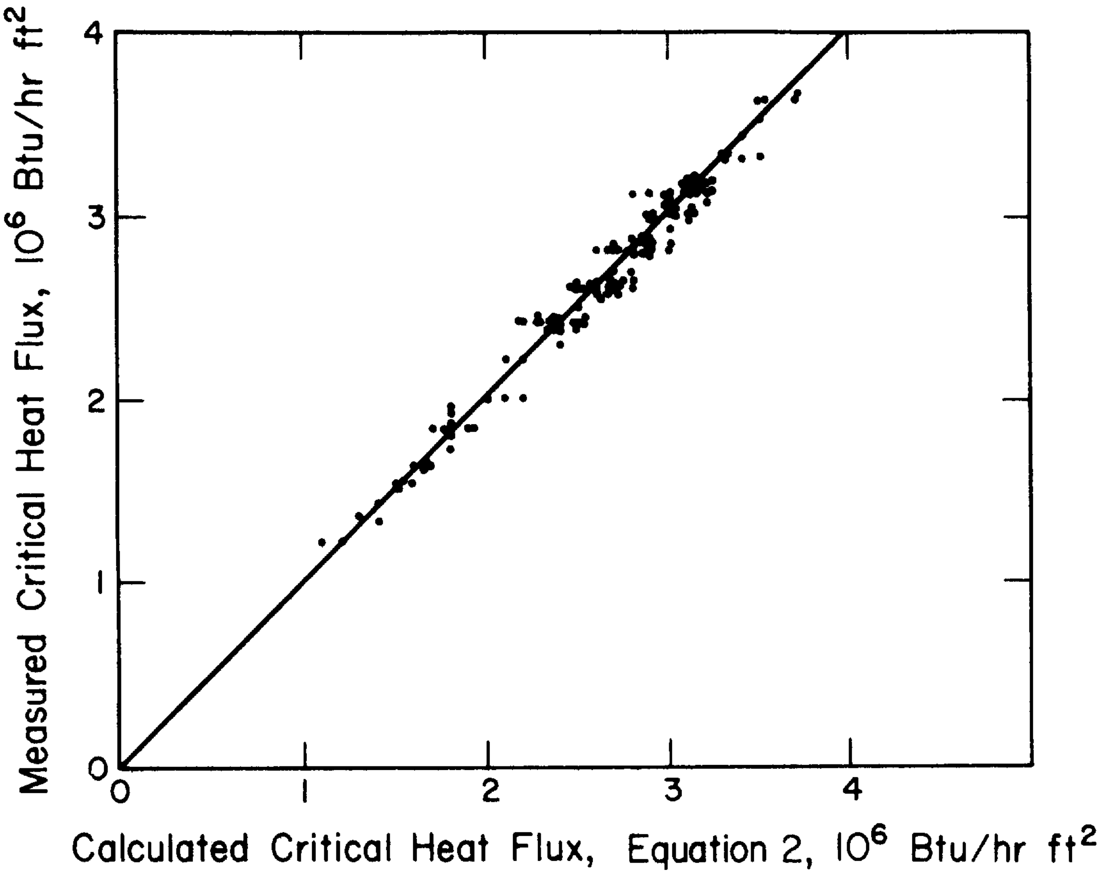

FIG. 2 SRL CRITICAL HEAT FLUX RESULTS WITH H_2O

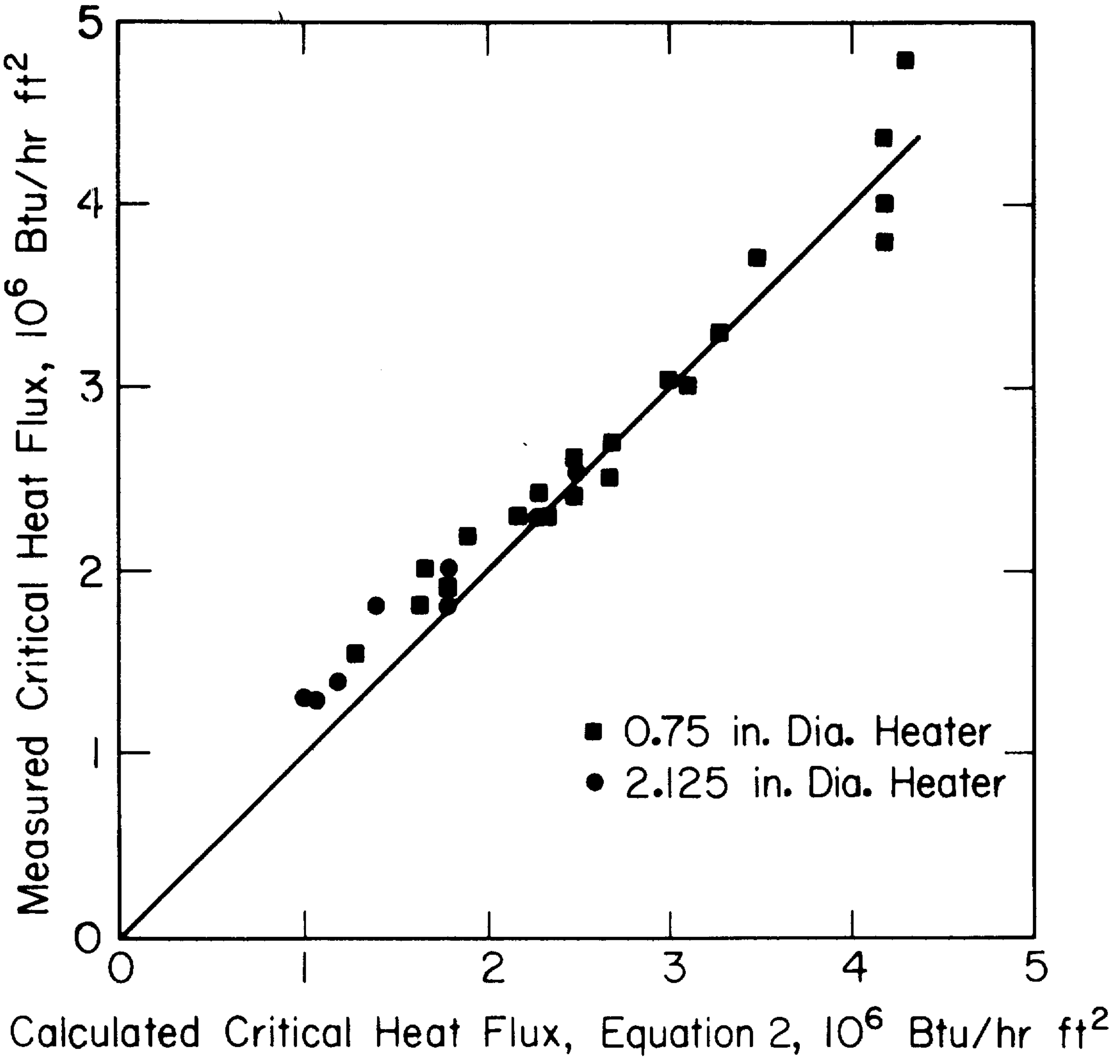

FIG. 3 COLUMBIA UNIVERSITY CRITICAL HEAT FLUX RESULTS WITH H_2O

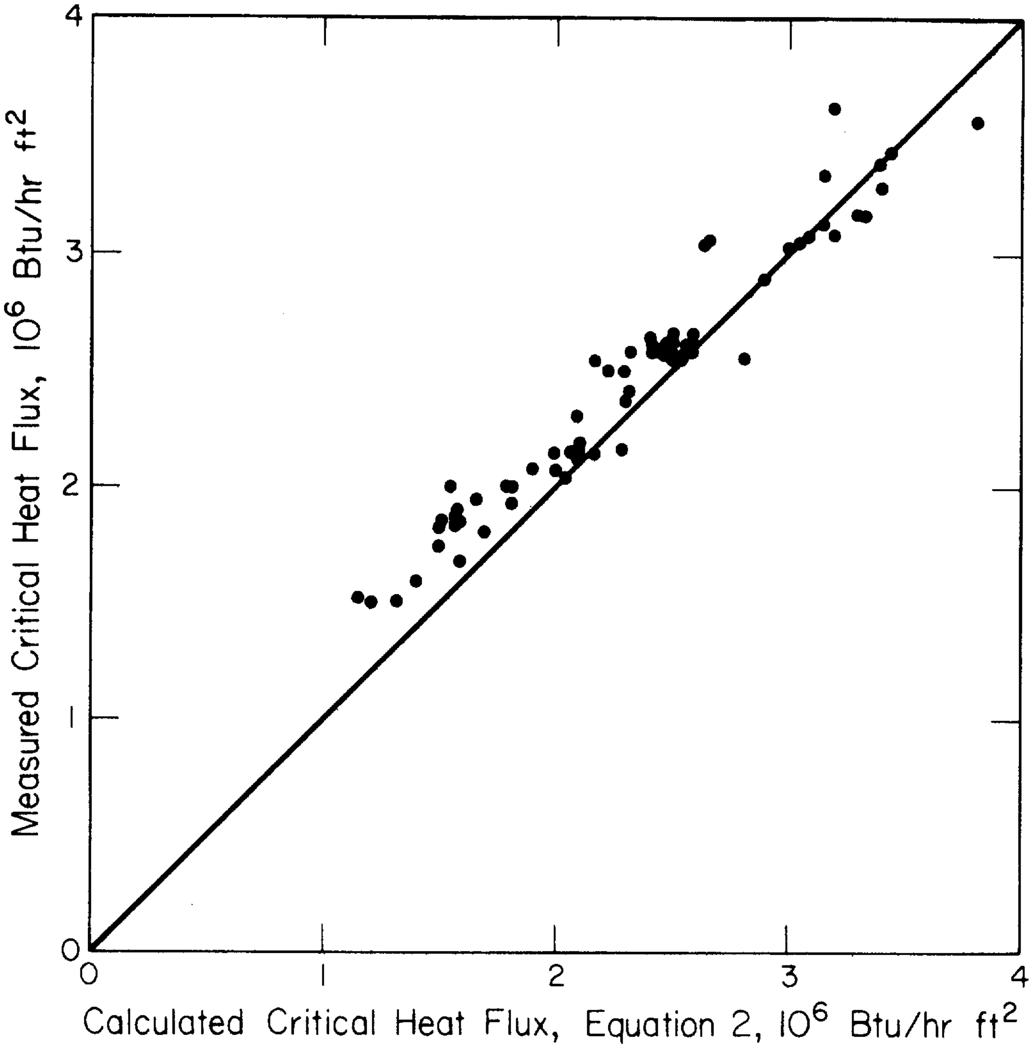

FIG. 4 SRL CRITICAL HEAT FLUX WITH 2-in-WIDE RECTANGULAR CHANNEL

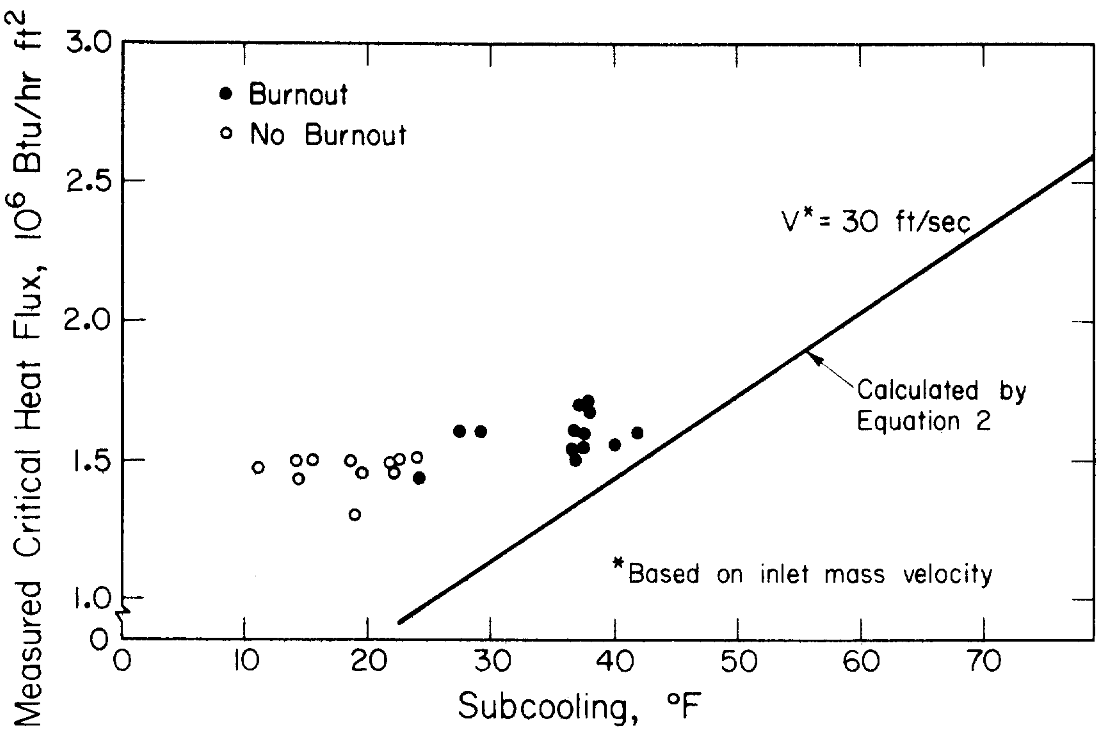

FIG. 5 CRITICAL HEAT FLUX AT LOW SUBCOOLING WITH H_2O

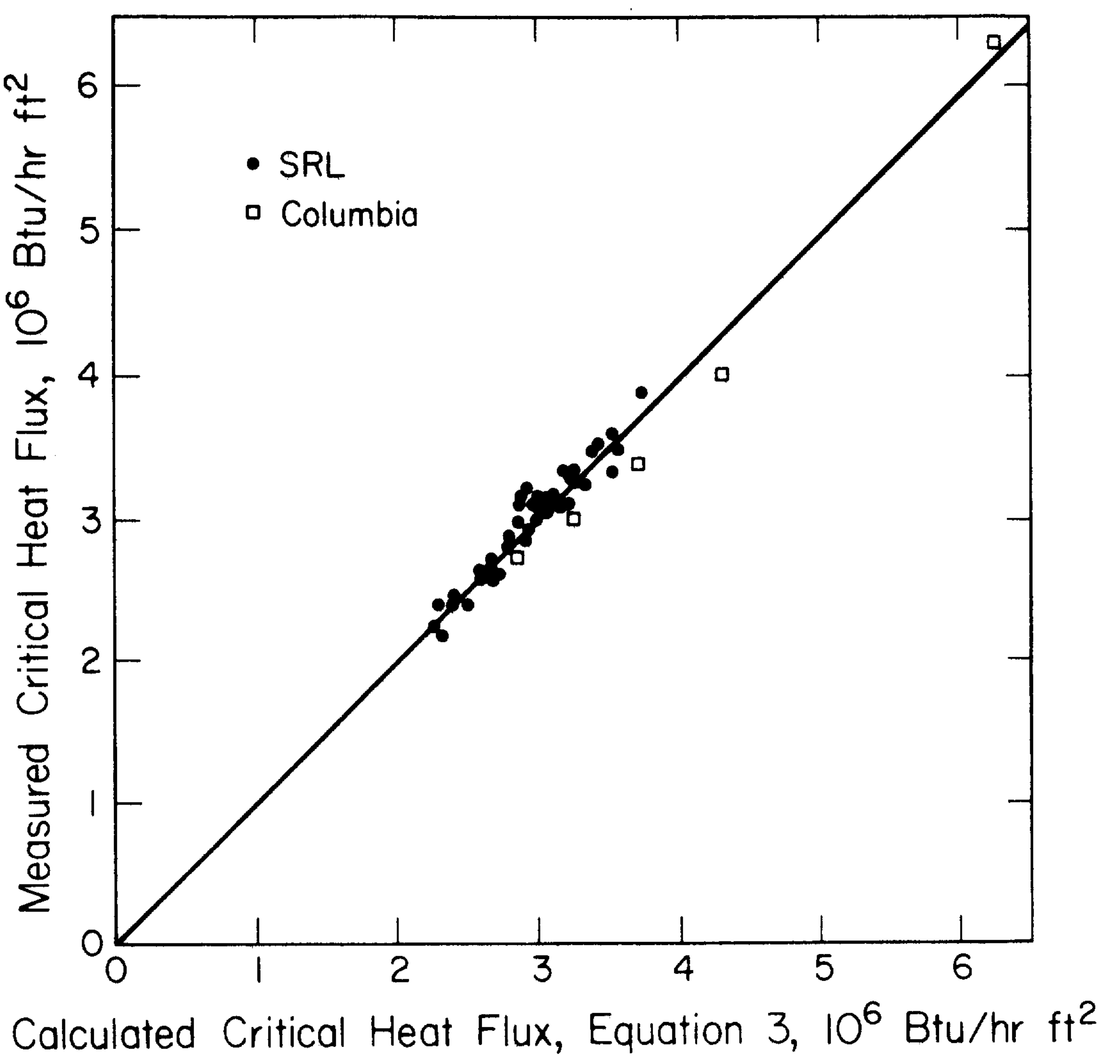

FIG. 6 CRITICAL HEAT FLUX RESULTS WITH D_2O