BURNOUT IN FORCED CONVECTION NUCLEATE BOILING OF WATER

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Summary

Data are presented for burnout in forced convection nucleate boiling of water at pressures above 500 psia. A dimensionless correlation is devised for the M.I.T. data which is found to be valid for certain recent data reported by Argonne National Laboratory.

INTRODUCTION

The nucleate boiling process is characterized by an unstable maximum heat flux which, if exceeded, results in a large discontinuous increase in surface temperature. The maximum or "burnout" heat flux is naturally of great importance to the designer of apparatus utilizing a boiling liquid as the coolant. Recent experimental investigations of the phenomenon have yielded sufficiently reproducible data to permit correlation of data from different sources in certain flow regimes and system geometries. Burnout data recently taken at M.I.T. is presented here along with a dimensionless correlation of the forced convection burnout heat flux for water at pressures above 500 psia.

Description of the test apparatus

The test section used in this program consists of a 9-inch length of "A" nickel tubing, .1805 inches in internal diameter and .2105 inches in external diameter. The tube is vertical and the flow upward. Electrical heating of the test section is accomplished by passing current through the tube wall. The source of electrical power is two 3000 amp 12 volt DC generators in series which can be effectively controlled from zero to maximum output.

The system consists of a closed loop with a stainless steel DeLaval Hayward-Tyler circulating pump. Pressure is maintained on the system by a pressure vessel in which water is evaporated by electrical heating. The pressure vessel is also used to degass the water before each run.

Distilled water is used in all runs and an ion exchanger is used to maintain the impurity level below 1 ppm NaCl.

The test section instrumentation consists of inlet and outlet pressure and voltage taps and nine chromel-constantan thermocouples on the tube outer wall. The wall thermocouples are insulated from the tube by .0015 in. mica. The temperature difference across the tube wall is computed by the method of ref 1. Inlet and outlet fluid temperatures are measured 5-1/2 inches upstream and 9 inches downstream of the test section.

The tube is surrounded by four thermal shields, each enclosing the tube for one-quarter of its length. The shields are individually variable resistance heaters wound on aluminum tubing, which are adjusted to the average temperature of the portion of the test section under each.

The requirements of the burnout program necessitate the use of a device to prevent failure of the test section at the burnout point. This device, or burnout detector, must be one which can identify the burnout condition and take action to prevent failure, while allowing the experimentor to actually attain burnout heat flux. In principle, the detector relies on the fact that thermodynamic burnout occurs at the test section exit and is characterized by a large temperature rise. Actually, the detector compares the electrical resistance of the final 1/16" of the test section with that of the remaining tube length. These two resistances constitute two legs of a Wheatstone bridge circuit, the other two legs consisting of fixed and variable resistors of suitable ratings. At burnout the resistance of the final length of the test section increases rapidly in relation to the remainder, causing an unbalance in the bridge circuit.

The net voltage at the reference point in the bridge circuit provides the input signal to a four stage DC amplifier. The output of the amplifier fires a triggering circuit which discharges a 7000 volt .10 μf capacitor through a spark gap in the circuit breaker.

The time required by the burnout detector to "decide" when a bona fide burnout has occurred is relatively long, about 6 millisec. At peak pressure and heat flux, this interval is virtually all the time available before the test section allowable overtemperature of 50° F is reached. Consequently, an instantaneous circuit breaker is required to act on the signal from the amplifier.

Rapid circuit interruption is accomplished by using the .10 μf capacitor discharge to fire an explosive cap* which is contained in a hollow copper tube. The test section current flows continually through the copper tube which is one-half inch in outer diameter, 3-1/32" long, and has an .047" wall. The copper tube is restrained by a mechanical device which insures clean circuit interruption when the cap is fired and low voltage drop through the tube and

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* DuPont X-98-N blasting cap, #6 strength, RDX loaded for 300° F temperature stability.

its connections during the run. Details of the breaker construction as well as a complete discussion of the detector circuitry will be subject of a project report to be issued shortly.

The burnout detector has been an effective instrument for the study of the burnout phenomenon and is well suited to the characteristics of the process. During a run, the test section current is increased quite slowly. Therefore, any bridge unbalance due to varying tube temperature can be readily compensated by manual adjustment of the variable resistors. At high heat flux, in the neighborhood of burnout, the test section is normally almost isothermal, so that, while the magnitude of the test section resistance may vary, the resistances of the two portions of the tube remain in a relatively constant ratio to each other. This makes manual adjustment unnecessary near the burnout point.

Almost without exception, the burnout detector has successfully prevented failure of the test section and permitted the actual attainment of the burnout condition in the test section. The fact that the detector is not firing prematurely is periodically checked by allowing a test section to fail while observing the time between the discharge of the capacitor and the appearance of steam or other evidence of failure. These two events occur simultaneously.

TEST RESULTS

Burnout data were taken at 500, 1000, and 1500 psia system pressure and at water inlet velocities of 5 and 10 feet per second. These data are presented in Appendix A.

The apparatus used in this work has been employed for a number of years in studying the nucleate boiling process, and its limitations have been discussed in references 1 and 2. The following errors are inherent in the measurement and computation schemes:

a. Heat flux is estimated to ± 3%
b. Flow rate is estimated to ± 2%
c. Inlet and outlet fluid temperatures and test section wall temperatures are estimated to ± 2° F.

These quantities are interrelated in three measures of heat rejection. Heat rejection may be determined from:

a. The difference in inlet and outlet fluid enthalpy as measured by the corresponding temperatures and flow rate.

b. The product of current and test section voltage drop.

c. Summation of heat release in the nine wall sections based on the current and tube resistivity at each of the nine wall temperatures.

These three computations yield the ± 3% heat flux variation.

Burnout data is recorded on a 16-point Brown recorder since it is impossible to achieve steady state at the burnout point. A complete set of data extends 16 seconds before burnout occurs so that some temperature readings must be estimated to ± 3° F. Current and voltage readings are printed three times during each recorder cycle, so that errors in those readings are not increased.

CORRELATION OF THE DATA

The Correlation

Correlation of the test data is an obviously desirable goal which, once attained, allows comparison of data from different sources. Unfortunately, the forced convection burnout process is not yet sufficiently well understood to allow one to use experimental and dimensional analysis techniques to full advantage.in determining correlation groups. Nevertheless, it is hoped that some progress may be made toward a correlation by the "brute force" technique of fitting existing data with whatever combination of properties and system parameters reduce scatter to an acceptable level. Later, these groups may be investigated in the light of present knowledge and further experiments specifically designed to test the correlation.

In attempting to correlate the forced convection nucleate boiling process, one must be somewhat skeptical regarding the usefulness of the normally defined heat transfer coefficient. Those familiar with the forced convection boiling process will recognize that the heat transfer coefficient has meaning only at a point and, when applied to a finite length of heat transfer surface, becomes strongly dependent on the length under consideration. In addition, a useful film coefficient must not strongly depend on heat flux, as it does in nucleate boiling. A further difficulty lies in the measurement of $T_w - T_b$ at high pressure and high flux. Under these conditions, the temperature change across the test section wall may be 3 or 4 times the wall-to-fluid temperature difference. Such conditions enormously increase the difficulty of obtaining reliable data. For these reasons, the present correlation was undertaken with the surface-to-liquid heat transfer coefficient and temperature difference specifically excluded from the list of possibly relevant parameters. In general, the properties to be used for the correlation are restricted to those which do not involve especially sensitive experimental techniques.

The problem of correlating the data becomes somewhat more manageable if attention is directed to the region of burnout with net exit bulk quality. Under these conditions, large variations in exit fluid properties are obtained providing an ideal area for testing groups based on properties at the burnout point. At the same time, it appears reasonable to expect that estimates of flow conditions based on average properties are more accurate in the quality region where large temperature gradients do not exist and vapor generation at the surface is at least partially accounted for in the net steam generation predicted by average flow quality. For example, in the region of burnout with subcooled exit conditions it is possible for vapor generation at the surface to significantly increase the exit flow velocity over the value average exit fluid properties. Consequently, the primary correlating effort was directed toward burnout with the average exit fluid condition in the two-phase region. The following discussion applies exclusively to the two phase flow regime.

If one computes the various exit flow parameters, it becomes apparent that the average exit velocity, assuming no slip between the phases, exhibits strong potentialities as a correlating factor. Quite simple relations between burnout heat flux and exit velocity can be devised to correlate data over a reasonably wide range of conditions. For example, a plot of v_{exit} vs. q''/H_{fg} correlates the M.I.T. data reported in Appendix A as well as the more complicated final result presented here. It is not possible, however, to extend such a simple correlation outside the range covered by this particular set of data.

A second correlating factor may be found by reasoning that, in the absence of large changes in slip ratio, the quantity of liquid adhering to the wall at the exit section must become small at high quality. Since the boiling process depends on a liquid covered surface, it is reasonable to expect that the average depth of the liquid film on the surface is an important variable when this depth is small. Under these conditions, the maximum bubble diameter would be limited by the liquid film thickness. Computation of the film thickness based on all the liquid in the stream at average exit quality yields encouraging results. This term, δ, proves to be a strong correlating factor.*

Having V_0 and δ available as correlating factors, dimensional reasoning leads one to a relation of the following type:

$$\frac{\delta}{R} = f\left[\left(\frac{q''D}{\sigma V_0}\right), \left(\frac{\gamma_0}{\gamma_f}\right), \left(\frac{GD}{\mu}\right), \left(\frac{h_{fg} g_0}{gD}\right)\right] \qquad (1)$$

Correlation of the data with these groups results in the following specific relation,

$$\left(\frac{\delta}{R}\right)^{1.94} = 1.49 \times 10^{-23} \left(\frac{q''D}{\sigma V_0}\right)\left(\frac{\gamma_0}{\gamma_f}\right)\left(\frac{GD}{\mu_\ell}\right)^{1.5}\left(\frac{h_{fg} g_0}{gD}\right) \qquad (2)$$

Discussion of the Correlation

The results of applying the correlation to the M.I.T. and ANL data are shown in Figures 1 and 2. The range of operating points covered by the data correlated is:

a) Heat flux from 0.6×10^6 to 2.8×10^6 Btu/hr ft^2
b) Flow rate from 0.66×10^6 to 3.6×10^6 lb/hr ft^2
c) Pressure from 500 to 2000 psia
d) Average exit quality from 0.01 to 0.60
e) Test section L/D 50 and 76 (D of .18" and .306")

The correlation may be conveniently broken down to show the predicted dependence of q" on the various flow parameters and water properties.

$$1.49 \times 10^{-23} \frac{g_0}{g} q'' G^{0.5} D^{1.5} = f(x, p) \qquad (3)$$

where $$f(x, p) = \left(\frac{\delta}{R}\right)^{1.94} \frac{\sigma \mu_\ell^{1.5} \gamma_f}{\gamma_0^{2} h_{fg}} \qquad (4)$$

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* $\frac{\delta}{R} = 1 - \sqrt{y}$ where $y = x v_g / (v_f + x v_{fg})$

From Fig. 3, one can see that the variation of $f(x,p)$ is such that the correlation predicts a continuously decreasing peak flux with increasing pressure (except very near the critical pressure). It is improbable that such a relationship is valid at low pressures. The limit of validity of this particular group of properties has not been fully established; it appears to fit the experimental facts for pressures as low as 500 psia at flow rates as low as 1×10^6 lb/hr ft^2.

The correlation given by equation (3) indicates an inverse relationship between burnout heat flux and flow rate at constant exit fluid properties. This is contrary to the relationship reported in other operating regimes (ref. 3), specifically, with subcooled exit conditions. Both the direct and inverse variation of q" with G appear well established in specific operating ranges, but the dividing line between the two variations has not yet been clearly defined. The present correlation indicates that the inverse relationship is valid over at least the following very roughly defined region in water systems.

a) Average exit bulk quality below 50%
b) Pressure above 500 psia
c) In the region of inlet subcooling below 250° F on the M.I.T. test section

The effect of approaching these limits may be seen in Fig. 2 in which a systematic deviation from the correlation line is observed at qualities greater than 60% or $\frac{\delta}{R} < .06$.

Limitations of the correlation

The correlation presented in this paper is inherently restricted to the prediction of burnout in water systems with vertical test sections and upflow. In addition, it is specifically directed toward burnouts with net exit bulk qualities. The correlation is presently untried for test section hydraulic diameters outside the range .18" to .306", the L/D range from 50 to 76, and pressures below 500 psia. In addition, the data correlated were taken with DC electrical heating and burnout was induced by increasing heat flux at constant pressure, flow rate, and inlet temperature. To date, no data have been taken to specifically test the correlation so that, in its present state, it must be recognized as tentative.

In addition to the above limitations of the data correlated, the form of the parameters involved have the characteristic of greatly amplifying experimental errors in certain ranges. These parameters are, to a certain extent, self compensating. For example, a positive error in exit quality produces a negative error in the ordinate and a negative error in the abscissa tending to bring the point back on the curve. In general, increasing over-compensation exists at high quality (> 60%) and low pressure. Experimental errors in the determination of exit quality are reflected in the correlating parameters according to the following relations

$$-\frac{d(\delta/R)}{\delta/R} = \frac{\sqrt{y}}{2(1-\sqrt{y})}\left(1-\frac{x\,v_{fg}}{V_0}\right)\frac{dx}{x} \qquad (5)$$

$$-\frac{d\gamma_0}{\gamma_0} = \frac{x\,v_{fg}}{V_0}\,\frac{dx}{x} \qquad (6)$$

Errors in the direct measurements of heat flux and flow rate are reflected in quality as a function of inlet subcooling.

$$\frac{dx}{x} = \frac{\Delta H}{\Delta H - \Delta h_i}\left(\frac{dq''}{q''} - \frac{dG}{G}\right) \qquad (7)$$

Where $\Delta H = 4\frac{L}{D}\frac{q''}{G}$ is the enthalpy rise in the test section and Δh_i is the difference between saturated liquid enthalpy (h_f) and fluid inlet enthalpy.

Prediction of peak heat flux from the correlation

Unfortunately, heat flux is implicit in δ and γ_0 so that it cannot be read directly from the curve for a given pressure and flow rate. A trial and error computation is required. However, experience with the correlation indicates that three trials are sufficient for an accurate graphical solution. Convergence on the predicted value is rapid and the value itself clearly defined.

References

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2. Clark, J. A., and Rohsenow, W. M., "Local Boiling Heat Transfer to Water at Low Reynolds Numbers and High Pressures", Transactions of the ASME? Vol. 76, No. 4, May 1954.
3. Jens, W. H., and Lottes, P. A., "Analysis of Heat Transfer, Burnout, Pressure Drop and Density Data for High-Pressure Water", Argonne National Laboratory, ANL-4627, May 1, 1951.
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Nomenclature

q''	heat flux, ft-lbf/ft^2-hr
G	specific flow rate, lbm/hr-ft^2
D	inner diameter of test section, ft
R	$D/2$
V_o	test section exit velocity based on average exit fluid condition, ft/hr
L	test section heated length, ft
ΔH	change in enthalpy of a unit mass flowing through the test section, ft-lbf/lbm
Δh_i	saturated liquid enthalpy minus test section inlet enthalpy, ft-lbf/lbm
h_{fg}	heat of vaporization ft-lbf/lbm
g_o	conversion factor, ft-lbm/lbf-sec^2
g	gravitational acceleration, ft/hr^2
γ_o	average outlet density, lbm/ft^3
γ_f	saturated liquid density, lbm/ft^3
σ	surface tension at saturation temperature, lbf/ft
μ_l	saturated liquid viscosity, lbm/ft-hr
x	mass quality, dimensionless
y	volume quality = $xv_g/(v_f + xv_{fg})$, dimensionless
v_g	saturated vapor specific volume, ft^3/lbm
v_f	saturated liquid specific volume, ft^3/lbm
v_{fg}	$v_g - v_f$
δ	height of liquid film on heating surface at average exit fluid condition with no slip between phases, ft

APPENDIX A

MIT Burnout Data

Inlet Temp (°F)	Pressure (Psia)	Flow Rate (lbm/hr-ft^2) 10^{-6}	Heat Flux (Btu/hr-ft^2) 10^{-6}	Exit Quality
264	540	2.10	2.86	.036
249	545	2.12	2.80	.029
298	555	2.13	2.59	.057
308	545	2.04	2.54	.089
372	516	1.97	2.22	.153
400	565	2.01	2.14	.157
414	575	1.93	2.12	.180
395	555	2.00	2.11	.173
380	585	1.94	2.07	.139
461	585	1.86	1.90	.237
462	555	1.86	1.87	.230
249	535	1.04	2.30	.260
291	535	1.02	2.19	.297
314	545	1.02	2.09	.312
356	565	1.10	2.05	.325
387	530	0.962	2.01	.393
427	575	0.971	2.00	.454
394	545	0.990	1.98	.418
410	535	0.936	1.92	.422
465	539	0.936	1.82	.470
462	527	0.939	1.82	.466
232	1035	2.13	2.81	Sub.
253	1010	2.13	2.56	"
279	981	2.08	2.55	"
312	1020	2.05	2.39	"
347	1025	2.02	2.18	"
409	1065	1.88	1.97	.072
421	1053	1.91	1.82	.053
424	1015	1.91	1.80	.062
542	1020	1.70	1.67	.196
509	1020	1.80	1.62	.208
463	1025	1.85	1.60	.123
476	1005	1.77	1.53	.145
474	1005	1.64	1.53	.155
485	1035	1.84	1.47	.138
259	999	1.04	2.08	.142
357	1015	1.00	1.84	.238
318	1065	1.02	1.83	.160
343	985	0.965	1.82	.196
323	1015	1.02	1.81	.183
336	1040	1.01	1.79	.190
436	993	0.961	1.62	.291
499	1010	0.886	1.52	.440
497	1010	0.889	1.51	.428
420	1055	0.964	1.51	.254
461	1015	0.950	1.49	.354

Appendix A (continued)

Inlet Temp (°F)	Pressure (Psia)	Flow Rate (lbm/hr-ft^2) 10^{-6}	Heat Flux (Btu/hr-ft^2) 10^{-6}	Exit Quality
502	1009	0.886	1.43	.406
538	985	0.866	1.41	.464
396	975	0.895	1.39	.381
509	1015	0.890	1.32	.409
544	1045	0.859	1.29	.443
388	1525	1.94	1.97	Subc.
438	1525	1.89	1.89	"
464	1525	1.88	1.60	.006
434	1533	1.89	1.59	Subc.
495	1525	1.79	1.45	.056
509	1515	1.76	1.37	.076
530	1520	1.76	1.25	.112
320	1510	1.02	1.67	.019
375	1505	0.990	1.61	.122
352	1485	0.986	1.52	.059
382	1505	0.964	1.47	.097
400	1510	0.954	1.45	.127
454	1515	0.938	1.33	.196
495	1510	0.881	1.21	.270
506	1550	0.882	1.15	.241
516	1511	0.860	1.14	.292

APPENDIX B

ARGONNE NATIONAL LABORATORY
Burnout Data, .18" Tube
2000 psia, L/D = 64.5
(Ref. 4)

Inlet Temp (°F)	Flow Rate (lb/hr-ft^2) 10^{-6}	Heat Flux (Btu/hr-ft^2) 10^{-6}	Exit Quality
625	3.50	0.850	.094
613	3.56	1.00	.074
636	3.44	0.745	.121
595	2.57	0.995	.077
633	2.94	0.682	.118
586	3.30	1.15	.028
590	3.68	1.15	.016
627	3.50	0.820	.095
614	3.58	1.00	.077
635	3.47	0.742	.115
608	2.54	0.863	.091
613	2.51	0.845	.104
619	3.00	0.820	.090
587	3.58	1.14	.014
622	2.71	0.746	.101
623	2.68	0.735	.104
616	2.74	0.805	.091
613	2.88	0.799	.071
611	2.94	0.850	.072
612	2.90	0.840	.075
597	3.05	0.990	.048
598	3.10	1.00	.049
581	3.22	1.15	.019
624	2.04	0.658	.136
610	1.89	0.660	.102
624	1.86	0.660	.151

Appendix B (continued)

ARGONNE NATIONAL LABORATORY

Burnout Data .306" Tube
2000 psia, L/D = 76

(Ref. 4)

600	0.186	0.176	.495
631	0.188	0.169	.574
609	0.167	0.198	.676
628	0.210	0.196	.580
633	0.241	0.215	.580
615	0.183	0.258	.840
632	0.304	0.245	.515
584	0.314	0.275	.407
629	0.353	0.278	.491
525	0.230	0.328	.619
525	0.246	0.327	.560
633	0.435	0.318	.470
510	0.268	0.360	.525
504	0.226	0.357	.670
513	0.241	0.356	.620
599	0.398	0.356	.459
618	0.505	0.346	.384
507	0.618	0.587	.262
523	0.725	0.600	.218
580	0.441	0.393	.403
465	0.534	0.595	.380
627	0.550	0.346	

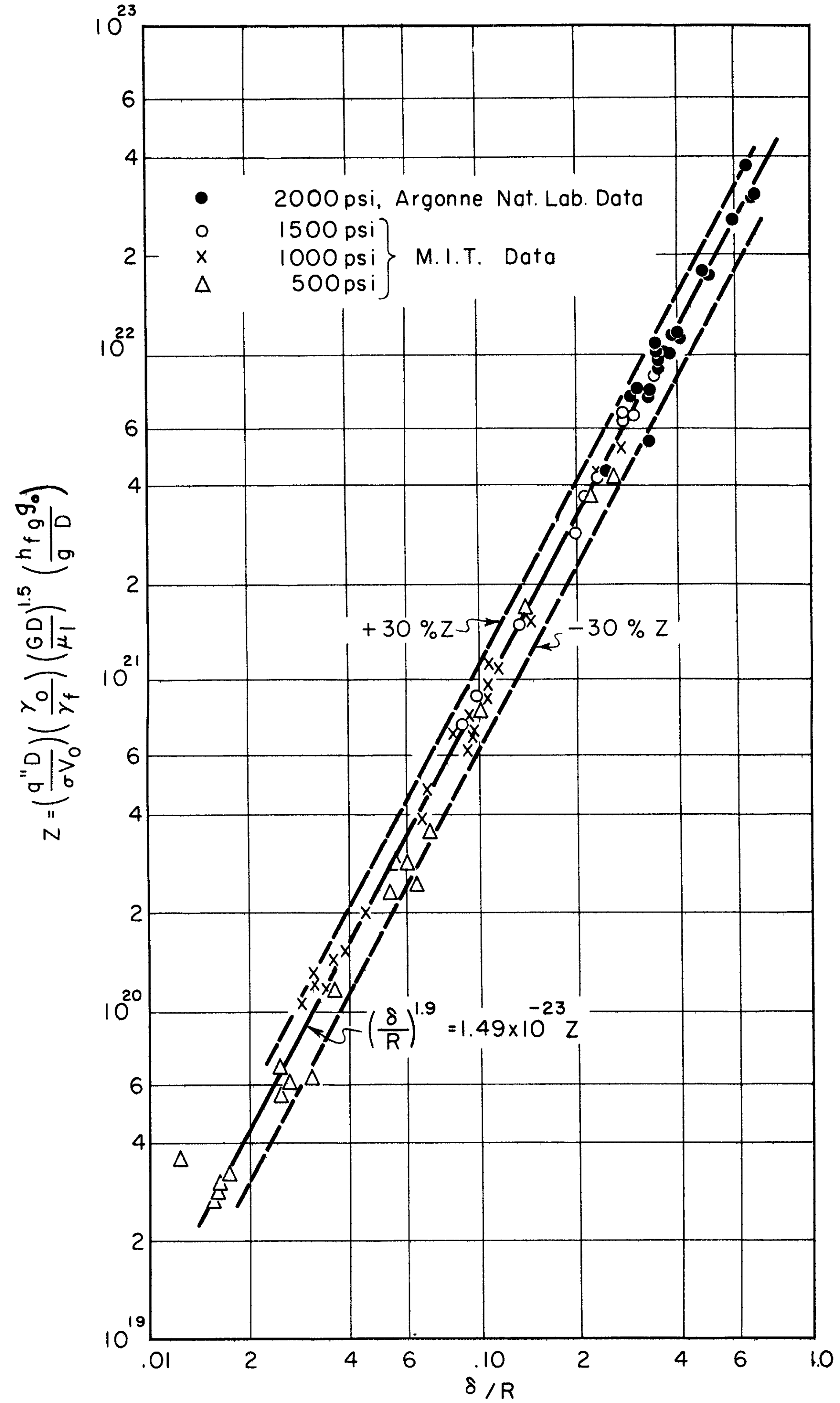

FIG. I— CORRELATION OF BURNOUT HEAT FLUX FOR WATER IN .18" I. D. TUBES.

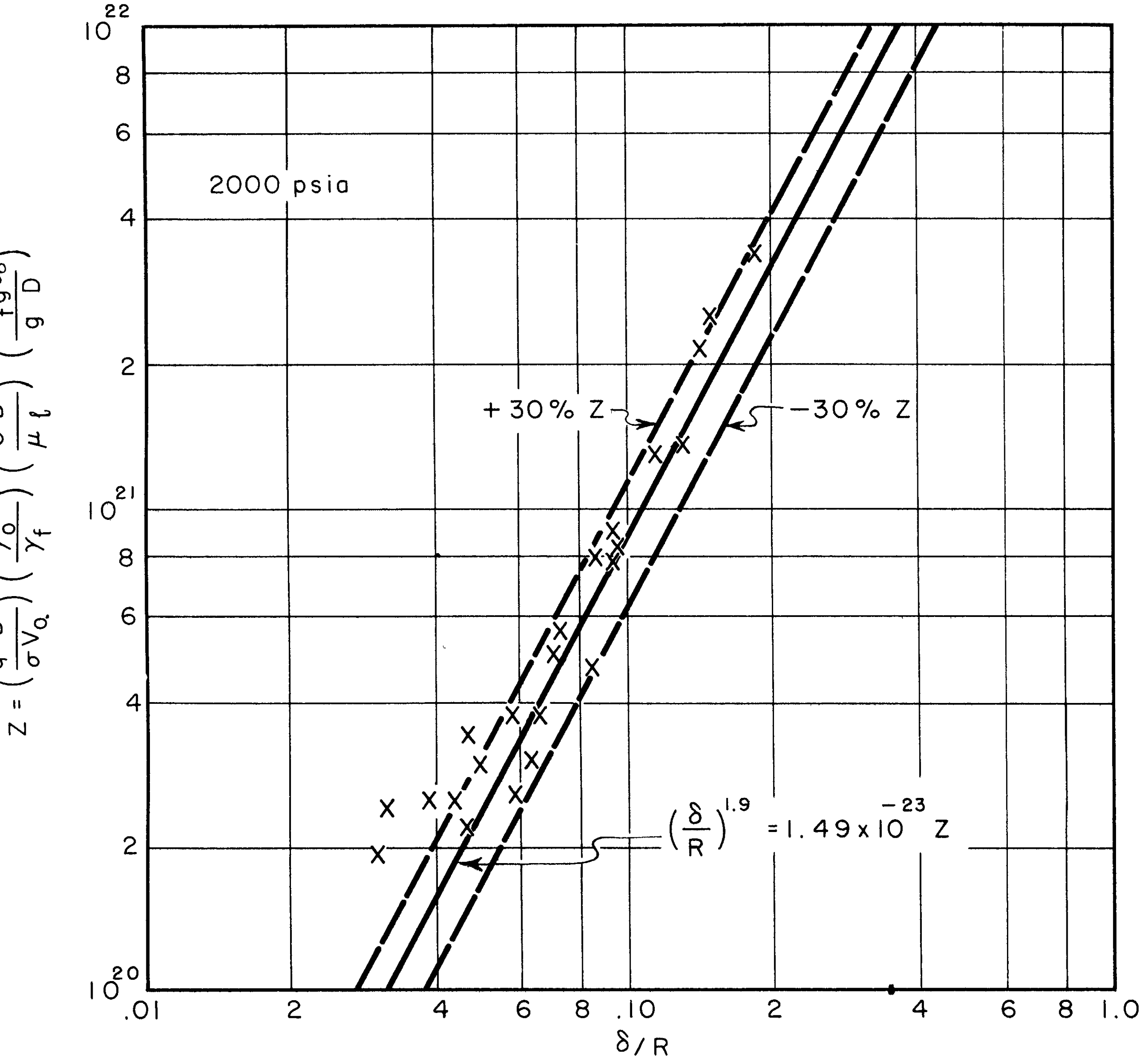

FIG. 2 — CORRELATION OF BURNOUT HEAT FLUX WATER IN .306" I.D. TUBE. ARGONNE NATIONAL LABORATORY DATA

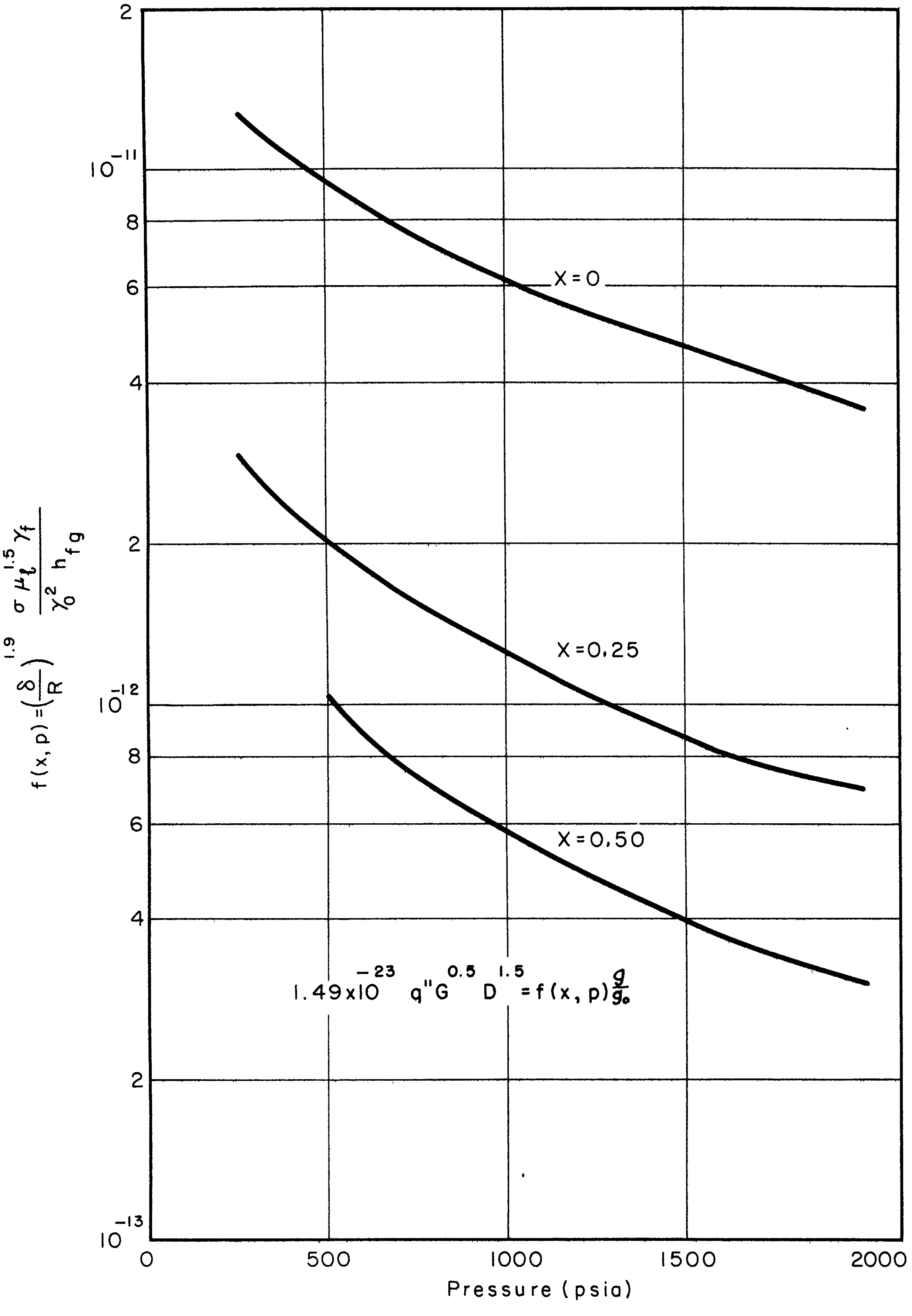

FIG. 3— DEPENDENCE OF CORRELATION ON WATER PROPERTIES f(x,p) vs. PRESSURE