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June 1956

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## ABSTRACT

Burnout heat flux data were obtained under conditions of zero exit quality and bulk boiling at the exit of electrically heated test specimens. These specimens were long, narrow channels with various slot thicknesses, surfaces, materials, and length-to-diameter ratios. Tests were run at 2000 psia and mass velocities from approximately $0.2 \times 10^6$ to $3 \times 10^6$ lb/hr-ft$^2$. The effect of inclining the channel at 45° was also investigated.

The rectangular channel burnout results are in reasonable agreement with data previously obtained for round tubes.

A design equation is suggested which yields a conservative estimate of the burnout heat flux in the low subcooling and quality regions for the range of variables investigated herein.

A burnout loop and method of operation are described.

# NOMENCLATURE

The following nomenclature is used in this paper:

D = equivalent diameter of test section - ft
G = mass velocity - $lb/hr\text{-}ft^2$
H = enthalpy of mixture - Btu/lb
L = test section heated length - ft
$\phi$ = heat flux density - $Btu/hr\text{-}ft^2$
rms = root mean square - microinch
x = bulk quality of liquid - vapor mixture, mass fraction of vapor
T = temperature of bulk liquid - °F
$\Delta T$ = saturated temperature minus test water bulk temperature - F°

## Subscripts

B.O. = burnout
in = inlet to test section

## Terminology

Local or Subcooled Boiling - occurs with the surrounding liquid mostly at a temperature below saturation. The bubbles usually condense in the subcooled liquid and as a result, there is no net retention of vapor.

Saturated or Bulk Boiling - occurs in a liquid where temperature is equal to or slightly higher than saturation; it implies a net generation of vapor.

Nucleate Boiling - vapor is formed as discrete bubbles; a condition which is characteristic of wetted heating surfaces.

Film Boiling - condition developed wherein vapor exists as a continuous film on the heating surface.

## INTRODUCTION

A knowledge of the heat flux under which physical burnout of a heat transfer surface occurs is of prime importance for boiling systems with forced circulation of the coolant. Water-cooled and/or moderated nuclear reactors must be designed to avoid physical burnout under the various abnormal conditions that might occur during operation. Information on maximum heat flux or burnout flux is, therefore, essential to this type of reactor core design.

A program of burnout testing has been conducted to investigate the effects of geometry, surface material and finish, length-to-diameter ratio, and test section orientation on burnout heat flux in both the local and bulk boiling regions. The purpose of this investigation is to provide the necessary data for reactor core designs where boiling and high heat flux conditions might exist during operation of the reactor.

## APPARATUS AND TEST PROCEDURE

The burnout loop was designed with two test legs to accommodate both burnout and pressure drop experimentation at pressures up to 2000 psia. Both test sections are heated by a 480 kw d-c power supply. The maximum flow to either section is 30 gpm. A schematic diagram of the facilities is shown in Fig. 1. The major loop components and instrumentation are described in Appendix I.

### Test Specimens

An exploded view of a typical test specimen assembly is shown in Fig. 2. To obtain closer simulation of an actual reactor channel, the test specimens were designed to burn out on the flat plate rather than at the corners. This was accomplished by reducing the thickness of the cross section in each corner.

In order to determine the effect of different channel lengths and equivalent diameters, materials, specimen construction, and specimen surfaces on the burnout flux, the following variables were built into the specimens:

Channel material: commercial grade "A" nickel and Zircaloy-2
Channel flow spacing: 0.050 in., 0.055 in., and 0.097 in.
Channel width: 1 in.
Channel length: 12-1/16 in. and 27 in.
Channel manufacturing technique: roll-bonded or welded
Heat transfer surface: machined or hot-rolled and pickled.

### Test Procedure

The loop was filled with cold, demineralized water and degassed for 4 to 8 hours. Flow was then passed through the ion-exchanger until a minimum purity of 2 megohm-cm was obtained. The loop was raised to the desired test pressure and the preheaters set to give required temperature conditions. The flow rate was set to the desired value and power applied to the test section at a rate that permitted all conditions to remain essentially in thermal equilibrium throughout the test. The burnout point was determined when the burnout detector tripped the circuit breaker of the power supply or when the exit wall thermocouple exhibited an excursion or a steadily increasing reading without an accompanying increase in test section power. The temperature excursion was generally greater than 50 F°.

The test conditons were as follows:

1. Approximately Zero Exit Subcooling, (Zero Exit Quality)

   Burnout Tests

   a. 2000 psia, vertical, upflow
   b. Mass velocity range: $0.2 \times 10^6$ to $1.0 \times 10^6$ lb/hr-ft$^2$.

2. Quality Burnout Tests

   a. 2000 psia, vertical and inclined 45°, upflow
   b. Mass velocity range: $0.15 \times 10^6$ to $3.0 \times 10^6$ lb/hr-ft$^2$
   c. Exit steam quality range: 0 to 100 per cent.

## ACCURACY OF RESULTS

The method of Kline and McClintock[1] was used to evaluate the uncertainty interval of the burnout flux results because of uncertainties in each variable involved in the computation.

The reported burnout heat fluxes are average values over the heated specimen and are based on power and heat transfer area measurements with an error of less than ±1 per cent for 20:1 odds (95 per cent confidence in the specified error of the individual measurements). Considering a possible maximum discrepancy in a heat balance of 5% as discussed below, the uncertainty in the burnout flux would be approximately +1% and -6%.

A heat balance was made to determine the agreement between the amount of heat picked up in the water and the power dissipated in the test section. In the subcooled region, the heat balance generally checked to within 5 per cent. In the quality region, it was not possible to make a heat balance because of the lack of an independent measurement of the exit steam quality.

In the subcooled region, the interval of uncertainty in the calculation (for 95 per cent confidence limit) of the heat picked up in the water was found to be approximately ±2.5 per cent. This error is based on a water temperature

1 - "Describing Uncertainties in Single-Sample Experiments," by S. J. Kline and F. A. McClintock, Mechanical Engineering, vol. 75, 1953, pp. 3-8.

rise of 200°F or a corresponding enthalpy rise (a mean value for the results reported here) as the water passes through the test section.

The difference between the discrepancy in the heat balance and the estimated error caused by errors in the measurement taken is probably due to heat leakage from the test specimen to its environment and to its terminals. It is believed that the accuracy of the heat balance in the quality region is approximately the same as in the subcooled region.

In the course of the investigations, the test specimens had a tendency to expand against the back-up housing and thus increase the nominal channel spacing. Because of this increase, the inaccuracy of the channel dimensions is rather large, as shown in Table 1. The interval of uncertainty (for 95 per cent confidence limit) in the calculation of G, the mass velocity, is ±11.0 per cent for the 0.055 in. channels and ±4.6 per cent for the 0.097 in. channels. The weight flow, which is independent of the spacing, is accurate to within ±2.1 per cent.

The interval of uncertainty associated with each variable employed in these calculations is estimated for 95 per cent confidence level as shown in Table 1.

## RESULTS AND DISCUSSION

### Zero Exit Quality-Zero Exit Subcooled Burnout

The burnout heat flux is defined as the maximum heat flux that can exist in the nucleate boiling region before vapor blanketing of the heat transfer surface begins.

Tests were run to determine the effect of geometry, length-to-diameter (L/D) ratio, and material on the burnout flux. L/D ratios of approximately 64, 120, and 140 were investigated. The data obtained are tabulated in Table 2 and plotted in Fig. 3 (includes some round tube data for comparison). From Fig. 3 the following observations may be noted:

a. Rectangular channels appear to burn out at about the same heat flux as round tubes.
b. A variation in the length-to-diameter ratio between 64 and 140 appears to have no effect on burnout heat flux.
c. There are no apparent effects on burnout due to the materials and surfaces investigated.

### Quality Burnout

Quality burnout heat flux is characterized by the coexistence of net steam and water at the burnout point as calculated by a heat balance for the system. The quality burnout data reported herein for rectangular channels are in reasonable agreement with similar data for round tubes. Typical graphs of the quality data appear in Figs. 4 and 5.

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## Effect of L/D

The L/D effect is interpreted to mean any variation in the burnout flux due to changing the heated length of the channel while the local fluid conditions at the burnout point are kept constant. This series of tests was run on machined Zircaloy-2 test specimens 12-1/16 in. and 27 in. long (L/D = 64 and 140). Data were taken on a 12-1/16 in. long channel at an inlet subcooling of 11 F° and a mass velocity of 0.2 x $10^6$ to 2.5 x $10^6$ lb/hr-ft$^2$. A comparative set of data was run on a 27 in. channel; however, the inlet temperature was adjusted so that 11 F° subcooling existed 12-1/16 in. from the exit of the channel. In conducting the test this way, the L/D effect attributable to a heat balance is separated from any additional L/D effect that might be present. If any discrepancy existed between the data obtained from the two channels, information on the degree of mixing or validity of calculating the exit quality from the First Law could be derived. Data from these runs are reported in Table 4 and compared in Fig. 6.

Figure 6 indicates that the burnout flux for the 27 in. channel (L/D = 140) is approximately equal to the corresponding flux for a 12-1/16 in. channel. This evidence may be interpreted to mean that there is excellent mixing in the channels and that the calculated exit quality may be a significant parameter for predicting burnout.

In the L/D effect tests described, it was necessary to increase the inlet subcooling with the longer channel in order to obtain the same bulk coolant conditions at burnout at the end of the channel. It is thus possible that there are two opposing effects occurring that make the burnout fluxes approximately equal: the effect of L/D and the effect of inlet subcooling. The comparison in Table 5 indicates the possible effect of inlet subcooling on burnout for a given geometry (27 in. long, 97 mil channel); in general, the higher the inlet subcooling, the higher the burnout flux. For this comparison the following conditions are maintained.

a. approximately constant bulk quality,
b. constant mass velocity or larger mass velocity for the condition yielding the lower value of burnout flux.

Another method of comparison is shown in Table 6. In this table a comparison of burnout points for 97 mil channels, 12-1/16 in. and 27 in. long, was made on the following basis:

a. constant inlet subcooling,
b. approximately constant exit bulk quality,
c. mass velocity greater for the condition that yields the lower value of burnout flux.

From Table 6, it is noted that, although the inlet temperature and exit quality are the same for both channels and the mass velocity is higher for the longer channel, burnout in general occurs at a lower heat flux in the longer channel.

## Effect of Inclination

Burnout tests were run on 97 mil smooth, and 50 and 55 mil hot-rolled Zircaloy specimens inclined at an angle of 45°. The data are tabulated in

Tables 3 and 7. All inclined specimens were observed to burn out on the upper side only, an indication that preferential stratification did occur at the burnout point.

Zero exit subcooling and zero exit quality data for a vertical and an inclined 187 mil round tube are compared in Fig. 3. No effect on burnout due to inclination can be seen. In Fig. 7 vertical and inclined 50, 55, and 97 mil data are compared with a suggested design equation. The 50 mil inclined quality data are somewhat lower than expected. This is probably due to instabilities as discussed in the following section.

Quality burnout data were obtained for a 50 mil channel with the thin edge in the vertical position. These data are reported in Table 3. It appears that this orientation of the test section has no significant effect on burnout heat flux.

Effect of Instability on Burnout

From time to time other investigators[2] have reported a sudden instability in a test system at fluxes well below the expected burnout flux. Similar instabilities have been encountered occasionally while obtaining the data reported here. The results of specific tests to investigate these instabilities are reported in Table 7 and may be summarized as follows.

a. Instabilities occurred at heat fluxes as much as 21 per cent below the actual burnout heat flux. Such instabilities may be partially responsible for lower burnout in the case of inclined 50 mil channels.
b. Neither the exact nature nor the cause of the instabilities was determined. Loop effects such as control valve chatter and lack of sufficient pump head were investigated and appeared to have little effect on the instability. The rate of heat flux application did not affect burnout in the ranges investigated.

Particular attention was devoted to ascertaining whether or not an instability in flow or autocatalytic effect as discussed by Jens[3] accompanied burnout. This effect was not detected. The flow meter used in these investigations indicated no appreciable decrease in flow at the burnout point.

Effect of Power Pulse on Burnout

Preliminary power pulse tests are reported in Table 8. Pulsing the power from about 20 per cent below the burnout point to the burnout point apparently had no effect on burnout for the few tests conducted. The rate of heat flux application was approximately 100,000 to 200,000 Btu/hr-ft$^2$ per sec.

2 - W. H. Rohsenow and J. A. Clark, Boiling Burnout Newsletter No. 2, Brookhaven National Laboratory BNL-2141, January 5, 1955.

3 - J. A. Clark and W. M. Rohsenow, "Local Boiling Heat Transfer to Water at Low Reynolds Numbers and High Pressures," T.A.S.M.E., vol. 76, May, 1954, pp. 553-562.

## Effect of Surface and Material

Figure 3 includes a comparison of the machined Zircaloy-2 surface and the hot-rolled, pickled Zircaloy-2 surface. Despite the rather obvious difference in surface roughness (32 microin. rms for the machined surface compared to 140 microin. rms for the hot-rolled surface), no apparent effect on burnout was observed. For the few data available from this investigation there was also no observable difference in results obtained on a nickel specimen and on a Zircaloy-2 specimen.

## CORRELATION OF RESULTS

The burnout data obtained in the series of experiments conducted cannot be applied directly to nuclear reactor design because the reactor heat flux distribution in the direction of flow is not uniform as was that of the cases tested herein. To utilize the burnout data in reactor design, it is desirable that burnout be correlated on the basis of the local fluid conditions. An expression was developed which is believed to give approximations of burnout heat flux within the ranges of variables investigated. No generality is intended in this expression, but it is useful as a design equation provided that (a) no extrapolation of the equation to regions beyond the limits of the variables investigated is made except for preliminary evaluations, and (b) the value calculated by Eqs. 1 and 2 is reduced by 25 per cent.

Burnout heat flux is defined as the minimum value calculated from either of the following two equations:

$$\frac{\phi_{B.O.}}{10^6} = 0.60 \left(\frac{G}{10^6}\right)^{0.7} \left(\frac{H}{10^3}\right)^{-0.8} \qquad [1]$$

$$\frac{\phi_{B.O.}}{10^6} = 0.30 \left(\frac{H}{10^3}\right)^{-3.0} \qquad [2]$$

where

$\phi_{B.O.}$ = burnout flux, Btu/hr-ft$^2$
G = mass velocity, lb/hr-ft$^2$
H = enthalpy of fluid, Btu/lb

Limits on the equation are as follows:

Pressure - 2000 psia
Geometry - Round tubes and rectangular channels similar to those tested
Mass velocity - 0.2 x $10^6$ lb/hr-ft$^2$ to 4 x $10^6$ lb/hr-ft$^2$
L/D - 60 to 140
Local Enthalpy at Burnout Point - 650 to 1135 Btu/lb
Test Section Position - 45° and vertical

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The possible influences of the past history effects (inlet tempeature and L/D) on burnout were considered in establishing Eqs. 1 and 2. These equations were developed so that a conservative estimate of burnout heat flux is given, namely, the case when water at the saturation temperature is supplied at the inlet to the longest test channel investigated. Under these circumstances any inlet subcooling effect tends to increase the burnout heat flux. The L/D limit of 140 is very important because increasing L/D appears to lower the burnout flux.

In Fig. 7, Eqs. 1 and 2 are compared with the Bettis Plant burnout data.

Fig. 8 is a graph of Eqs. 1 and 2. On this graph burnout appears to be a function of both mass velocity and bulk quality or enthalpy in certain regions. However, there are also regions where burnout appears dependent only on the fluid enthalpy or, in other words, the effect of mass velocity is insignificant.

## CONCLUSIONS

The following conclusions can be drawn.

1. Zero exit subcooling (i.e. zero exit quality) burnout flux increases as the mass velocity increases in the range from approximately 200,000 to 1,000,000 lb/hr-ft$^2$. Few data are available at higher mass velocities, but, based on the behavior of low quality burnout data in the range of 1,000,000 to 4,000,000 lb/hr-ft$^2$, it appears that zero exit quality and subcooling burnout flux increases only slightly for mass velocities above G = 1,000,000 lb/hr-ft$^2$.

2. There is no significant effect on burnout flux for conditions of zero exit quality and zero exit subcooling as a result of changing channel slot thickness (from 55 to 97 mil), channel geometry (round tube or narrow rectangular channels of approximately the same equivalent diameter), channel length, heat transfer surface finish, or heat transfer material.

3. Quality burnout results, as compared with a suggested design equation are essentially independent of channel position (vertical or 45°), geometry (round tubes or rectangular channel), heat transfer surface finish, or heat transfer materials.

4. In the bulk boiling region, there are apparent inlet subcooling and length-to-diameter ratio effects on burnout. For approximately constant local fluid conditions, increasing the inlet subcooling tends to increase the burnout heat flux, whereas increasing the L/D ratio tends to decrease the burnout heat flux.

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# APPENDIX I

## LOOP COMPONENTS

### Power Supply

Power is supplied by a 480 kw d-c generator designed to operate at 12,000 amp and 40 v. However, for short periods, as much as 20,000 amp can be drawn from the generator.

### Piping System

The main piping system is constructed of 1-1/2 in., schedule-80, type 347 stainless steel. All main system valves have type 316 cast stainless steel bodies and stellite seats and plugs. The valves are Teflon packed. The throttle valves are globe type; all others are gate valves.

### Pumps

Two Westinghouse oil-cooled, 30-A sealed pumps are used to circulate the water. The pumps may be run individually or connected in series. The control circuits are so interlocked that the pumps must be in operation before the generator can deliver power to the test section.

### Pressurizing Tank

This vessel is used both to pressurize and degas the system. Pressurizing is accomplished by means of eight heaters which provide a total of 30 kw: six are manually controlled and two are operated by an automatic pressure controller. A liquid-level controller operates the system's high pressure make-up pump. If the liquid level becomes too low, the main circulating pumps are automatically shut-off. Shutting off these pumps shuts off the test section power.

### Deionizer

A deionizer is in the system to maintain the water purity at a high value (resistivity approximately 2 megohm-cm). The deionizer loop draws about 1/2 gpm. It contains a bed of Amberlite MB-1 resin, 3-1/2 in. diameter by 36 in. long, and two filters, a Neva Clog filter at the ion-bed inlet and a Micrometallic Filter at its outlet. Automatic controls prevent the ion-exchanger from overheating during operation.

### Preheater

In order to vary the inlet temperature to the test section, the loop has an immersion type preheater with a capacity of 20 kw. Half of the power is controlled by switches and half by a hand-operated variac. The preheater cannot be turned on unless there is flow in the test section. The loop overall temperature is controlled by 70 kw of "cast-in-bronze" line heaters. These heaters operate through the same type of safety circuit as the immersion preheater.

## Heat Exchanger

There is a water-to-water heat exchanger in the system to remove heat from the primary flow.

# INSTRUMENTATION

## Burnout Detection

Incipient burnout of the test specimen is prevented from proceeding to actual failure by the use of a burnout detector or by observation of a wall temperature excursion with a thermocouple. The burnout detector consists of the following:

a. a bridge-type circuit of which the test specimen forms two legs,
b. an amplifier that magnifies the bridge unbalance caused by a portion of the tube overheating,
c. a thyratron that receives the amplified unbalance signal and strikes when the signal reaches a predetermined magnitude, permitting a condenser to discharge,
d. a high speed breaker whose trip coil is actuated by the condenser discharge.

Such a detection system is based on using a test specimen material that has a large and continuous temperature coefficient of resistivity. When the test material meets these specifications, the detector will interrupt the power very close to the physical burnout point. When the specimen is constructed of a material whose resistivity does not increase with increasing temperature at high temperature levels (for example, Zircaloy-2), the detector does not function properly, and burnout must be detected either through a sudden, continuous rise in the wall temperature or through physical rupture of the specimen.

Burnouts have been checked with and without a detector. In all cases, the detector fired at heat flux values greater than 90 per cent of the physical burnout flux.

## Flow Meter

Flow is measured by a Potter turbine-type flow meter. The instrument is calibrated to be accurate to within 1/2 per cent of the instantaneous flow reading.

## Temperature Measurement

Temperatures are measured by either a Leeds and Northrup 24-point precision indicator or a 16-point recorder. Both instruments have 10 suppressed ranges and are accurate to approximately 0.03 Mv or slightly greater than 1 F° at 635°F. All thermocouples are chromel-alumel.

Current Measurement Shunts

Current is measured by the voltage drop across two calibrated 6000 amp Westinghouse type-G shunts. The readings are taken on a 5-range Brown recorder.

Voltage Measurement

The voltage drop across the test section is recorded on a 2-range Brown recorder.

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Table 1. Uncertainty of Variables

| | | |
|---|---|---|
| Voltage | $v:w_v$ | ±0.005 v |
| Current | $I:w_I$ | ±0.0016 I |
| Flow Rate, gpm | $W:w_W$ | ±0.005 W |
| Test Section Length | $L:w_L$ | ±1/64 in. |
| Channel Spacing | $D:w_D$ | ±0.006 in. for 0.055-in. channels<br>±0.004 in. for 0.097-in. channels |
| Inlet Temperature* | $T_i:w_{T_i}$ | ±2F° |
| Outlet Temperature* | $T_o:w_{T_o}$ | ±2F° |
| Fluid Density | $\rho:w_\rho$ | ±0.02$\rho$ |
| Channel Width | $b:w_b$ | ±0.001 in. |

* The inlet and exit temperatures are used to calculate the enthalpies of the fluid.

Table 2. Zero Exit Quality and Subcooled Burnout Data, Exit Pressure 2000 psia

| Test Channel | Exit Subcooling F° | Mass Velocity $10^6$ lb/hr-ft$^2$ | Burnout Flux* $10^6$ Btu/hr-ft$^2$ |
|---|---|---|---|
| Vertical nickel (machined) | 3 | 1.35 | 1.120 |
| Flow dimension: 1 in. x 0.055 in. | 5 | 1.32 | 0.920 |
| Length: 12-1/16 in. | 2 | 0.926 | 0.938 |
| | 4 | 0.667 | 0.949 |
| | 6 | 0.578 | 0.786 |
| | 3 | 0.269 | 0.360 |
| Vertical Zircaloy-2 (hot-rolled) | 3 | 1.47 | 1.42 |
| Flow dimension: 1 in. x 0.055 in. | 12 | 0.919 | 0.765 |
| Length: 12-1/16 in. | 11 | 0.858 | 0.786 |
| | 4 | 0.571 | 0.695 |
| | 0 | 0.195 | 0.300** |
| Vertical Zircaloy-2 (machined) | 11 | 1.24 | 0.979 |
| Flow dimension: 1 in. x 0.097 in. | 14 | 0.888 | 0.921 |
| Length: 12-1/16 in. | 3 | 0.529 | 0.851 |
| | 4 | 0.208 | 0.333 |
| Vertical Zircaloy-2 (machined) | 3 | 1.21 | 1.11 |
| Flow dimension: 1 in. x 0.097 in. | 4 | 0.906 | 0.847 |
| Length: 27 in. | 4 | 0.906 | 0.841 |
| | 4 | 0.604 | 0.747 |

* Burnout Flux is evaluated from 94% of the total power as generated in the thick portion of the rectangular channel (6% of the power is generated in the thin edges). The surface area of the thick portion of the channel is 0.88 in. x length x 2.

** This value is estimated as the maximum heat flux in the nucleate boiling region. Physical burnout occurred in the film boiling region at a heat flux of approximately 0.560 x $10^6$ Btu/hr-ft$^2$.

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Table 3. Quality Burnout Data, Exit Pressure 2000 psia

| Test Channel | Inlet Subcooling F° | Mass Velocity $10^6$ lb/hr-ft$^2$ | Burnout Flux $10^6$ Btu/hr-ft$^2$ | Quality % |
|---|---|---|---|---|
| Vertical Zircaloy-2 (machined) | 8 | 2.67 | 0.808 | 12.3 |
| Flow dimension: 1 in. x 0.097 in. | 11 | 2.57 | 0.860 | 13.0 |
| Length: 12-1/16 in. | 8 | 1.94 | 0.771 | 17.0 |
| | 9 | 1.38 | 0.718 | 22.6 |
| | 8 | 1.19 | 0.773 | 29.2 |
| | 9 | 0.864 | 0.704 | 37.1 |
| | 10 | 0.479 | 0.558 | 54.3 |
| | 10 | 0.187 | 0.376 | 97.0 |
| | 36 | 2.74 | 1.08 | 7.7 |
| | 36 | 2.74 | 1.10 | 3.1 |
| | 34 | 2.72 | 1.08 | 8.4 |
| | 37 | 2.10 | 0.970 | 11.0 |
| | 36 | 1.28 | 0.839 | 20.5 |
| | 63 | 2.92 | 1.24 | 0.9 |
| | 60 | 2.17 | 1.08 | 5.7 |
| | 62 | 1.41 | 0.969 | 14.0 |
| | 60 | 1.32 | 0.959 | 16.9 |
| | 60 | 0.924 | 0.760 | 21.6 |
| | 60 | 0.466 | 0.618 | 46.7 |
| | 62 | 0.179 | 0.402 | 92.5 |
| Inclined (45°) Zircaloy-2 (machined) | 11 | 1.22 | 0.731 | 25.8 |
| Flow dimension: 1 in. x 0.097 in. | 12 | 0.843 | 0.625 | 32.4 |
| Length: 12-1/16 in. | 11 | 0.443 | 0.502 | 52.6 |
| | 10 | 0.171 | 0.330 | 93.3 |
| | 58 | 1.31 | 0.974 | 17.5 |
| | 59 | 0.915 | 0.823 | 25.2 |
| | 60 | 0.469 | 0.622 | 46.3 |
| | 60 | 0.176 | 0.375 | 87.2 |
| Vertical Zircaloy-2 (machined) | 10 | 2.71 | 0.557 | 19.2 |
| Flow dimension: 1 in. x 0.097 in. | 10 | 2.03 | 0.504 | 24.1 |
| Length: 27 in. | 10 | 1.35 | 0.448 | 33.0 |
| | 9 | 1.13 | 0.436 | 39.6 |
| | 10 | 0.840 | 0.397 | 48.7 |
| | 10 | 0.438 | 0.320 | 76.9 |
| | 9 | 0.157 | 0.170 | 100.0* |
| | 63 | 3.29 | 0.902 | 10.7 |
| | 62 | 2.88 | 0.848 | 12.2 |
| | 61 | 2.24 | 0.732 | 15.7 |
| | 66 | 1.49 | 0.594 | 24.6 |
| | 62 | 1.32 | 0.565 | 27.4 |
| | 62 | 0.937 | 0.487 | 37.4 |
| | 62 | 0.467 | 0.392 | 72.6 |
| | 62 | 0.187 | 0.207 | 100.0* |
| Inclined (45°) Zircaloy-2 (hot-rolled) | 11 | 1.33 | 0.596 | 35.4 |
| Flow dimension: 1 in. x 0.055 in. | 9 | 0.894 | 0.496 | 45.6 |
| Length: 12-1/16 in. | 9 | 0.473 | 0.403 | 72.0 |
| | 10 | 0.175 | 0.242 | 100.0* |
| | 60 | 1.42 | 0.755 | 23.5 |
| | 59 | 0.955 | 0.613 | 37.6 |
| | 60 | 0.499 | 0.472 | 64.0 |
| | 60 | 0.173 | 0.253 | 100.0* |
| Inclined (45°) Zircaloy-2 (hot-rolled) | 35 | 1.47 | 0.700 | 34.0 |
| Thin edge up | 34 | 1.46 | 0.697 | 34.7 |
| Flow dimension: 1 in. x 0.050 in. | 36 | 1.10 | 0.558 | 36.1 |
| Length: 12-1/16 in. | 34 | 1.03 | 0.598 | 44.9 |
| | 37 | 1.02 | 0.602 | 44.2 |
| | 38 | 0.494 | 0.446 | 74.6 |
| | 37 | 0.490 | 0.446 | 75.6 |
| Vertical Zircaloy-2 (hot-rolled) | 335 | 1.05 | 1.142 | 18.55 |
| Flow dimension: 1 in. x 0.050 in. | 335 | 0.626 | 0.842 | 43.2 |
| Length: 12-1/16 in. | 335 | 0.333 | 0.573 | 79.5 |
| | 136 | 1.91 | 0.855 | 5.6 |
| | 137 | 0.891 | 0.713 | 36.7 |
| | 135 | 0.595 | 0.595 | 56.6 |
| | 11 | 1.58 | 0.586 | 30.6 |
| | 11 | 0.842 | 0.526 | 55.9 |
| | 11 | 0.578 | 0.509 | 81.6 |

* Exit fluid is actually a few degrees superheated.

Table 4. Comparison of Burnout Flux (Subcooled and Bulk Boiling) in Zircaloy-2 Channels (Machined)
Exit Pressure 2000 psia

| Mass Velocity $10^6$ lb/hr-ft$^2$ | | Burnout Flux $10^6$ Btu/hr-ft$^2$ | | Quality % | |
|---|---|---|---|---|---|
| 12-1/16 in. | 27 in. | 12-1/16 in. | 27 in. | 12-1/16 in. | 27 in. |
| 2.67 | 2.74 | 0.808 | 0.892 | 12.3 | 11.8 |
| 2.57 | 2.47 | 0.860 | 0.806 | 13.0 | 13.0 |
| 1.94 | 2.03 | 0.771 | 0.793 | 17.0 | 14.3 |
| | 2.08 | | 0.806 | | 13.4 |
| 1.38 | 1.38 | 0.718 | 0.712 | 22.6 | 21.9 |
| 1.19 | 1.21 | 0.773 | 0.699 | 29.2 | 24.6 |
| 0.864 | 0.897 | 0.704 | 0.649 | 37.1 | 29.5 |
| 0.479 | 0.481 | 0.588 | 0.522 | 54.3 | 49.0 |
| 0.187 | 0.188 | 0.376 | 0.367 | 97.0 | 88.3 |
| | | | | Exit Subcooling, F° | |
| 1.24 | 1.21 | 0.979 | 1.11 | 11 | 3 |
| 0.888 | 0.906 | 0.921 | 0.847 | 14 | 4 |
| | 0.906 | | 0.841 | | 4 |
| 0.529 | 0.605 | 0.851 | 0.747 | 3 | 4 |

Table 5. Possible Effect of Inlet Subcooling on Burnout

| Comparison Set | Quality % | Mass Velocity $10^6$ lb/hr-ft$^2$ | $\Delta T_{IN}$ F° | Burnout Flux $10^6$ Btu/hr-ft$^2$ |
|---|---|---|---|---|
| I | 88.3 | 0.188 | 513 | 0.367* |
| I | 100.0 | 0.187 | 62 | 0.207 |
| II | 49.0 | 0.481 | 263 | 0.522 |
| II | 48.5 | 0.840 | 10 | 0.397 |
| III | 29.5 | 0.897 | 177 | 0.649 |
| III | 27.4 | 1.32 | 62 | 0.565** |
| IV | 24.6 | 1.21 | 133 | 0.699 |
| IV | 24.6 | 1.49 | 66 | 0.594 |
| IV | 24.1 | 2.03 | 10 | 0.504 |
| V | 13.0 | 2.47 | 73 | 0.806 |
| V | 14.3 | 2.03 | 94 | 0.793 |
| V | 15.7 | 2.24 | 61 | 0.732 |

* For comparison purposes, if quality = 100%, burnout flux may be estimated as approximately 0.325 x $10^6$.

** For comparison purposes, if quality = 29.5%, burnout flux may be estimated as approximately 0.550 x $10^6$.

Table 6. Possible Effect of L/D on Burnout

| Comparison Set | $\Delta T_{IN}$ F° | Quality % | Mass Velocity $10^6$ lb/hr-ft$^2$ | Length in. | Burnout Flux $10^6$ Btu/hr-ft$^2$ |
|---|---|---|---|---|---|
| I | 62 | 14.0 | 1.41 | 12-1/16 | 0.969 |
| I | 62 | 12.2 | 2.88 | 27 | 0.848 |
| II | 60 | 16.9 | 1.32 | 12-1/16 | 0.959 |
| II | 61 | 15.7 | 2.24 | 27 | 0.732 |
| III | 60 | 21.6 | 0.924 | 12-1/16 | 0.760 |
| III | 66 | 24.6 | 1.49 | 27 | 0.594 |
| IV | 60 | 46.7 | 0.466 | 12-1/16 | 0.618 |
| IV | 62 | 37.4 | 0.937 | 27 | 0.487* |
| V | 62 | 92.5 | 0.179 | 12-1/16 | 0.402 |
| V | 62 | 72.6 | 0.467 | 27 | 0.392** |
| VI | 8 | 29.2 | 1.19 | 12-1/16 | 0.773 |
| VI | 10 | 24.1 | 2.03 | 27 | 0.504 |
| VII | 9 | 37.1 | 0.864 | 12-1/16 | 0.704 |
| VII | 10 | 33.0 | 1.35 | 27 | 0.448 |
| VIII | 10 | 97.0 | 0.187 | 12-1/16 | 0.376*** |
| VIII | 9 | 100.0 | 0.157 | 27 | 0.170 |

* For comparison purposes, if quality = 46.7%, burnout flux may be estimated as approximately $0.450 \times 10^6$.

** For comparison purposes, if quality = 92.5%, burnout flux may be estimated as approximately $0.300 \times 10^6$.

*** For comparison purposes, if mass velocity = $0.157 \times 10^6$, burnout flux may be estimated as approximately $0.300 \times 10^6$.

Table 7. Subcooled and Bulk Boiling Burnout Flux in Zircaloy-2 Hot-Rolled Channels Inclined 45°, Exit Pressure 2000 psia
(Channel flow dimensions: 0.050 in. by 1 in. Length: 12-1/16 in.)

| Inlet Temp °F | Inlet Vel fps | Mass Velocity G $10^6$ lb/hr-ft² | Exit Subcooling or Quality F° or % | Burnout Flux $\phi_{B.O.}$ $10^6$ Btu/hr-ft² | Remarks |
|---|---|---|---|---|---|
| 301 | 2.08 | 0.431 | 49.6% | 0.611 | Burnout indicated by excessive wall temp |
| 300 | 2.06 | 0.428 | 53.3% | 0.642 | Previous run reproduced |
| 300 | 2.06 | 0.428 | 52.8% | 0.622 | Heat flux applied in increments of 10,000 Btu/hr-ft² every 2 min, commencing well below $\phi_{B.O.}$ and increasing until burnout occurred |
| 301 | 2.00 | 0.417 | 54.3% | 0.611 | Heat flux applied in increments of 10,000 Btu/hr-ft² every min, commencing well below $\phi_{B.O.}$ and increasing until burnout occurred |
| 301 | 2.08 | 0.431 | 55.6% | 0.638 | Same as above |
| 302 | 5.03 | 1.04 | 1F° | 0.909 | Burnout indicated by wall temp excursion |
| 300 | 5.09 | 1.05 | 1F° | 0.924 | Instability occurred indicating incipient burnout |
| 300 | 5.08 | 1.05 | 1F° | 0.924 | Previous instability reproduced |
| 300 | 5.06 | 1.05 | 11.4% | 1.05 | Heat flux applied in increments of 5,000 Btu/hr-ft² every 2 min, commencing at $\phi$ = 0.820 x $10^6$, until instability was noted at $\phi$ = 0.911 x $10^6$. Flux was increased until wall temp excursion occurred at $\phi_{B.O.}$ = 1.05 x $10^6$ |
| 301 | 5.16 | 1.07 | 2F° | 0.939 | Previous run reproduced with different test section and operating crew |
| 295 | 9.00 | 1.85 | 31F° | 1.44 | Burnout indicated by excessive wall temp |
| 500 | 5.8 | 1.03 | 15.26% | 0.581 | Instability first noted at $\phi$ = 0.528 x $10^6$ Btu/hr-ft² at G = 1.03 x $10^6$ and quality = 11.6%. Heat flux was increased until burnout occurred at $\phi_{B.O.}$ = 0.581 Btu/hr-ft². |
| 501 | 5.4 | 0.951 | 19.7% | 0.562 | Heat flux applied in increments of 20,000 Btu/hr-ft² every min. commencing at $\phi$ = 0.350 x $10^6$ Btu/hr-ft². Instability observed at $\phi$ = 0.436 x $10^6$ Btu/hr-ft², G = 0.957 and quality = 7%. Heat flux was increased until burnout occurred. |
| 500 | 6.1 | 1.09 | 31.7% | 0.798 | Burnout indicated by excessive wall temp |
| 501 | 6.2 | 1.10 | 32.7% | 0.810 | Previous runs reproduced |
| 500 | 9.8 | 1.74 | 2.95% | 0.722 | Instability occurred indicating incipient burnout |
| 500 | 9.5 | 1.69 | 7.4% | 0.770 | Heat flux applied in increments of 20,000 Btu/hr-ft² every min, commencing at a flux well below burnout. Instability noted at $\phi$ = 0.708 x $10^6$ Btu/hr-ft², G = 1.69 and quality = 3.7%. Heat flux was increased until burnout occurred. |
| 599 | 5.4 | 0.828 | 45.15% | 0.495 | Incipient burnout |
| 600 | 5.2 | 0.799 | 46.9% | 0.492 | Heat flux applied in increments of 10,000 Btu/hr-ft² every min, commencing at $\phi$ = 0.802 x $10^6$ Btu/hr-ft². Incipient burnout was indicated at $\phi_{B.O.}$ = 0.482 x $10^6$ by instability in wall temp. |
| 600 | 5.0 | 0.800 | 45.99% | 0.477 | Heat flux applied in increments of 20,000 Btu/hr-ft² every min, commencing at $\phi$ = 0.315 x $10^6$. Incipient burnout was indicated by severe instability in wall temp. |
| 599 | 9.7 | 1.5 | 29.7% | 0.660 | Burnout indicated by excessive wall temp |

Table 8. Effect of Power Pulse on Burnout in Zircaloy-2 Hot-Rolled Channels Inclined 45°, Exit Pressure 2000 psia*
(Channel flow dimensions: 0.050 in. by 1 in. Length: 12-1/16 in.)

| Inlet Temp °F | Inlet Vel fps | Mass Velocity $10^6$ lb/hr-ft$^2$ | Heat Flux $10^6$ Btu/hr-ft$^2$ Initiation of Pulse | Heat Flux $10^6$ Btu/hr-ft$^2$ Termination of Pulse** | Duration of Transient sec | Expected Steady-State Burnout Flux $10^6$ Btu/hr-ft$^2$ |
|---|---|---|---|---|---|---|
| 301 | 5.0 | 1.04 | 0.692 | 0.853 | 1.5 | 0.900 |
| 300 | 5.0 | 1.04 | 0.692 | 0.858 | 1.5 | 0.900 |
| 300 | 5.0 | 1.04 | 0.692 | 1.31 | 2.5-3 | 0.900 |

* Exit subcooling not known because, due to the nonequilibrium condition of the loop, the exit water conditions were difficult to estimate.

** No burnout occurred in any of the tests.

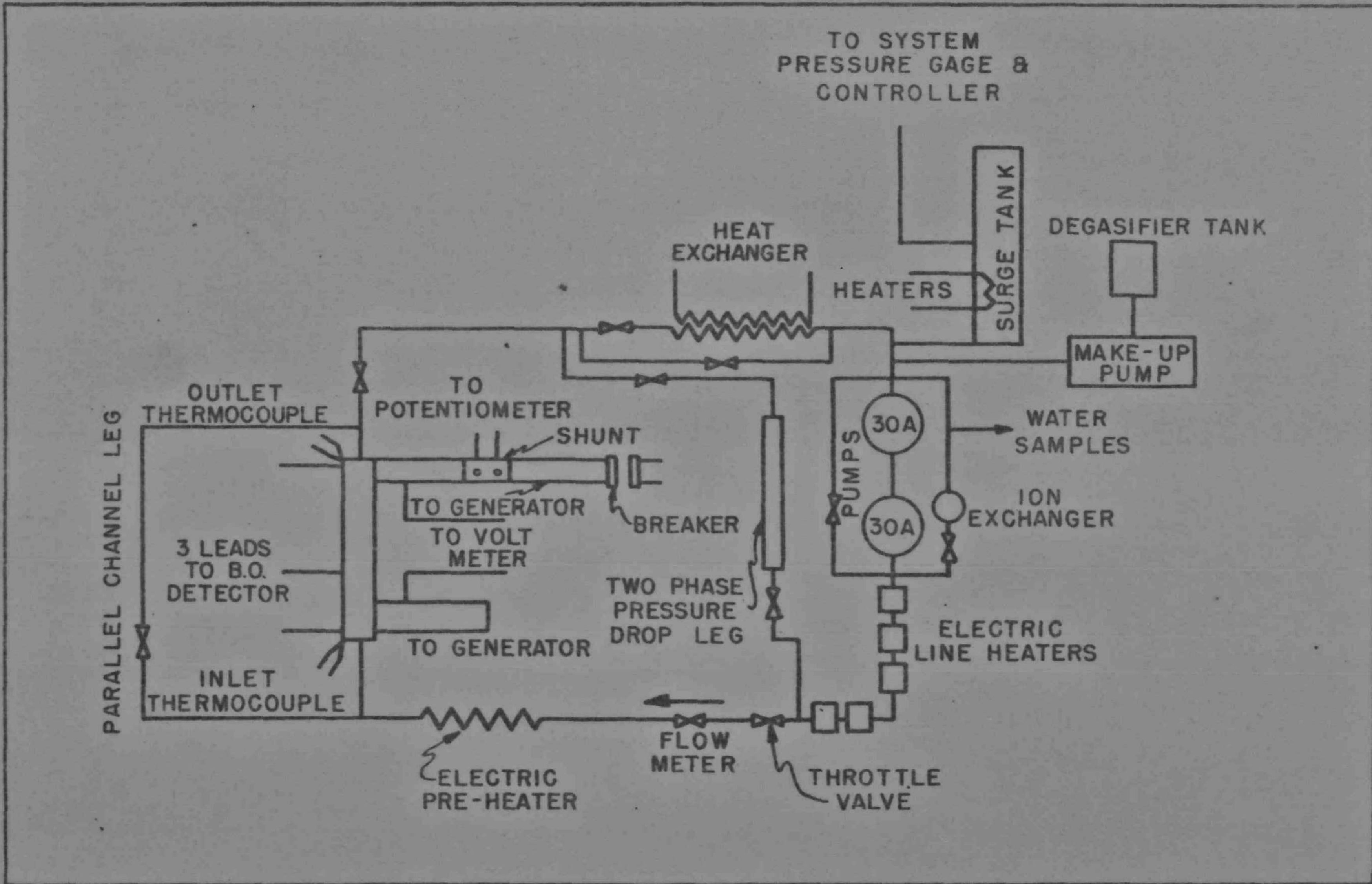


Fig. 1 Schematic Diagram of Burnout Loop

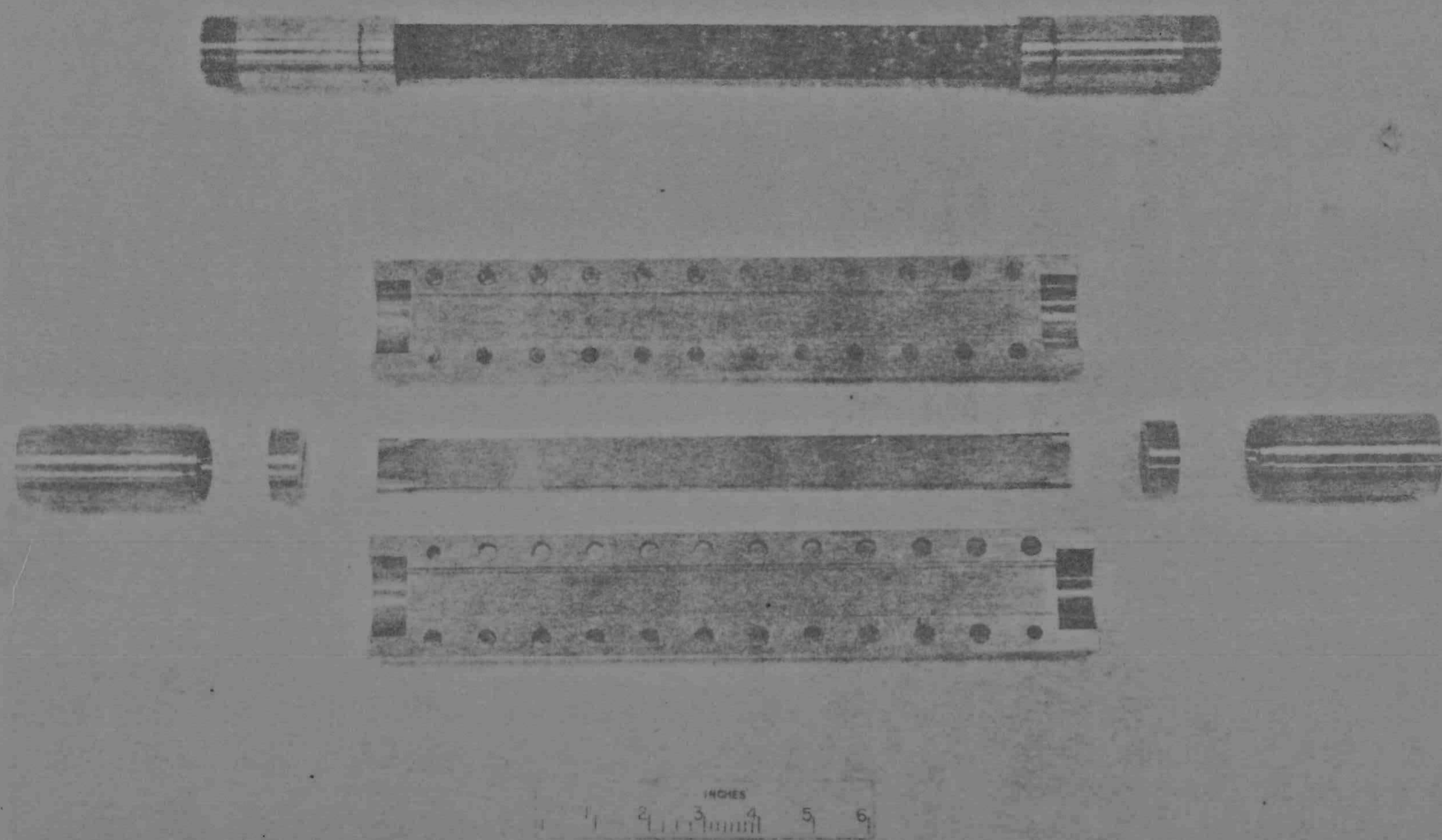


Fig. 2 Typical Test Specimen Assembly

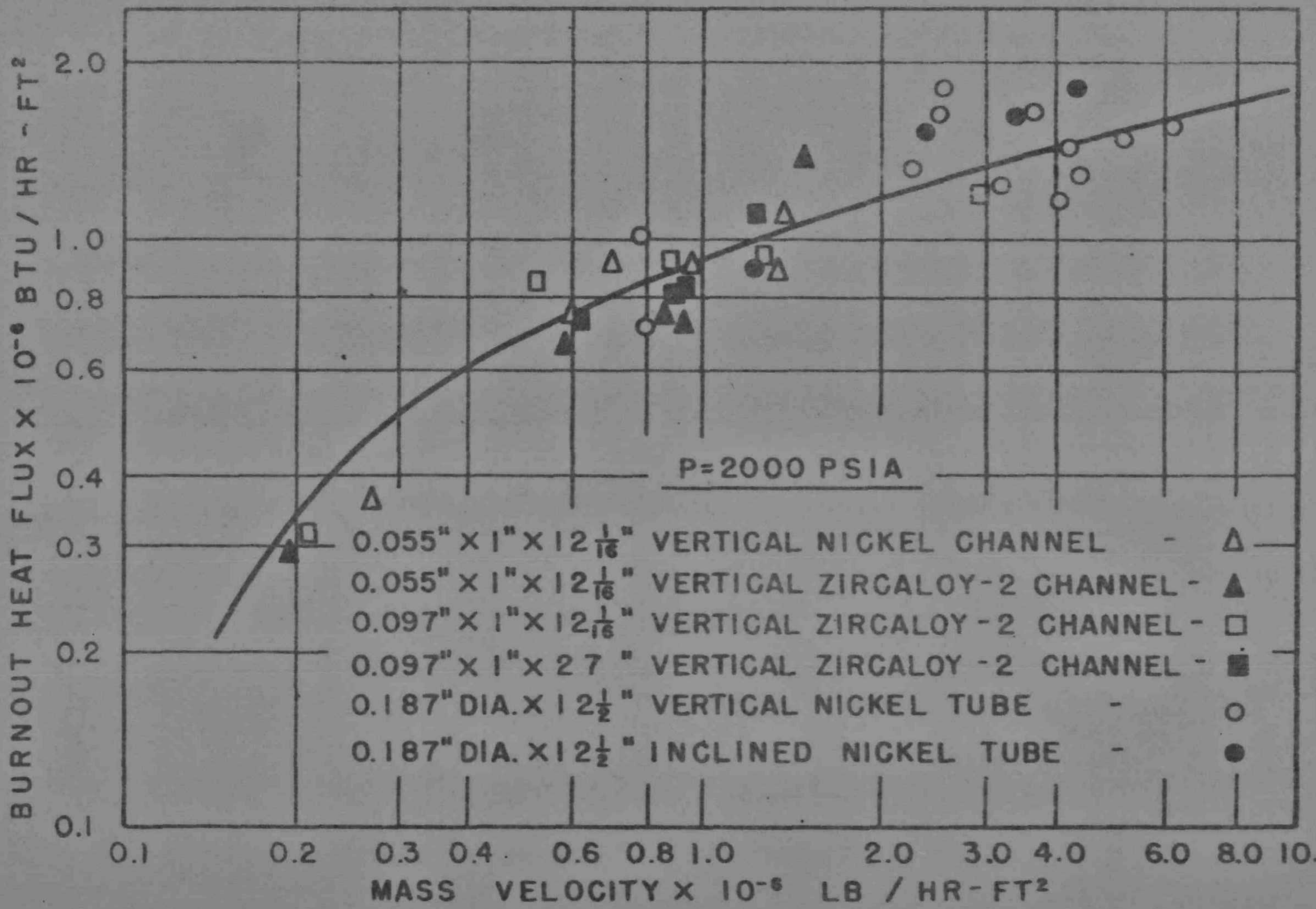


Fig. 3 Burnout Heat Flux vs Mass Velocity for Approximately Zero Exit Quality and Zero Exit Subcooling

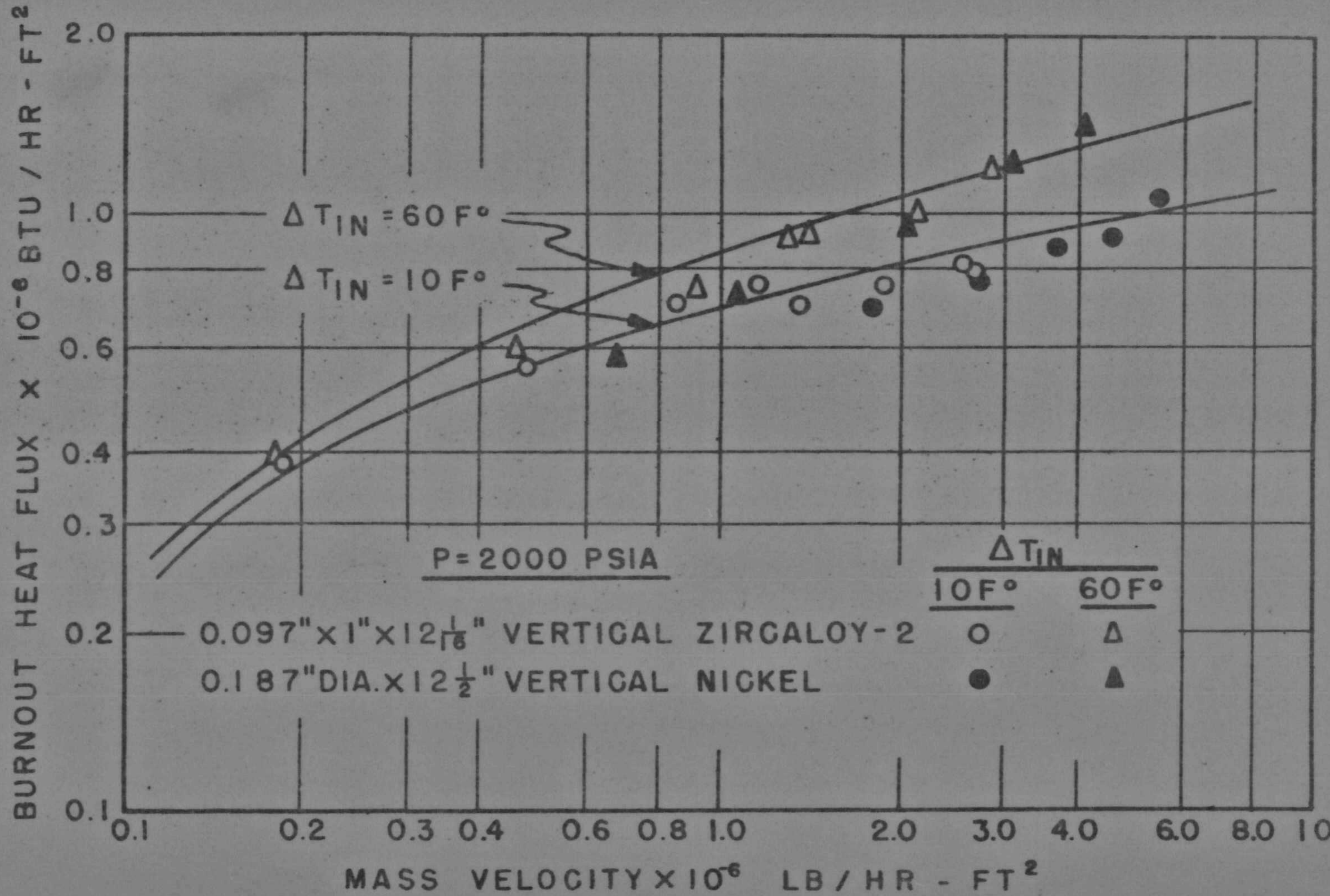


Fig. 4 Bulk Boiling Burnout Heat Flux vs Mass Velocity for 10F° and 60F° Inlet Subcoolings. (Note: The enthalpy at exit of the round tube and rectangular channel is approximately equal for a given heat flux, mass velocity, and inlet subcooling.)

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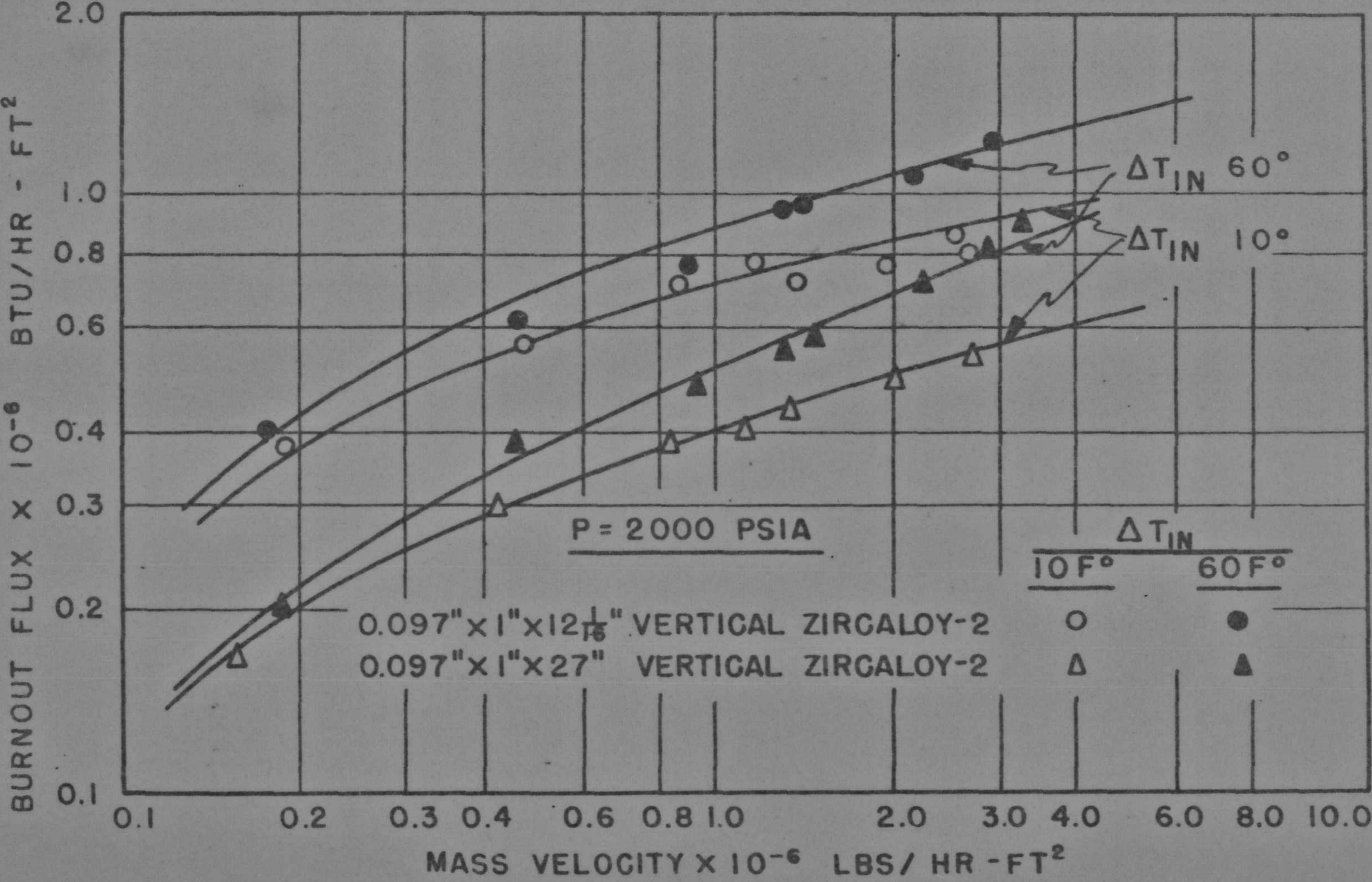


Fig. 5 Bulk Boiling Burnout Data vs Mass Velocity for 10F° and 60F° Inlet Subcoolings. (Note: The enthalpy at the exit of each channel is different for a given heat flux, mass velocity, and inlet subcooling.)

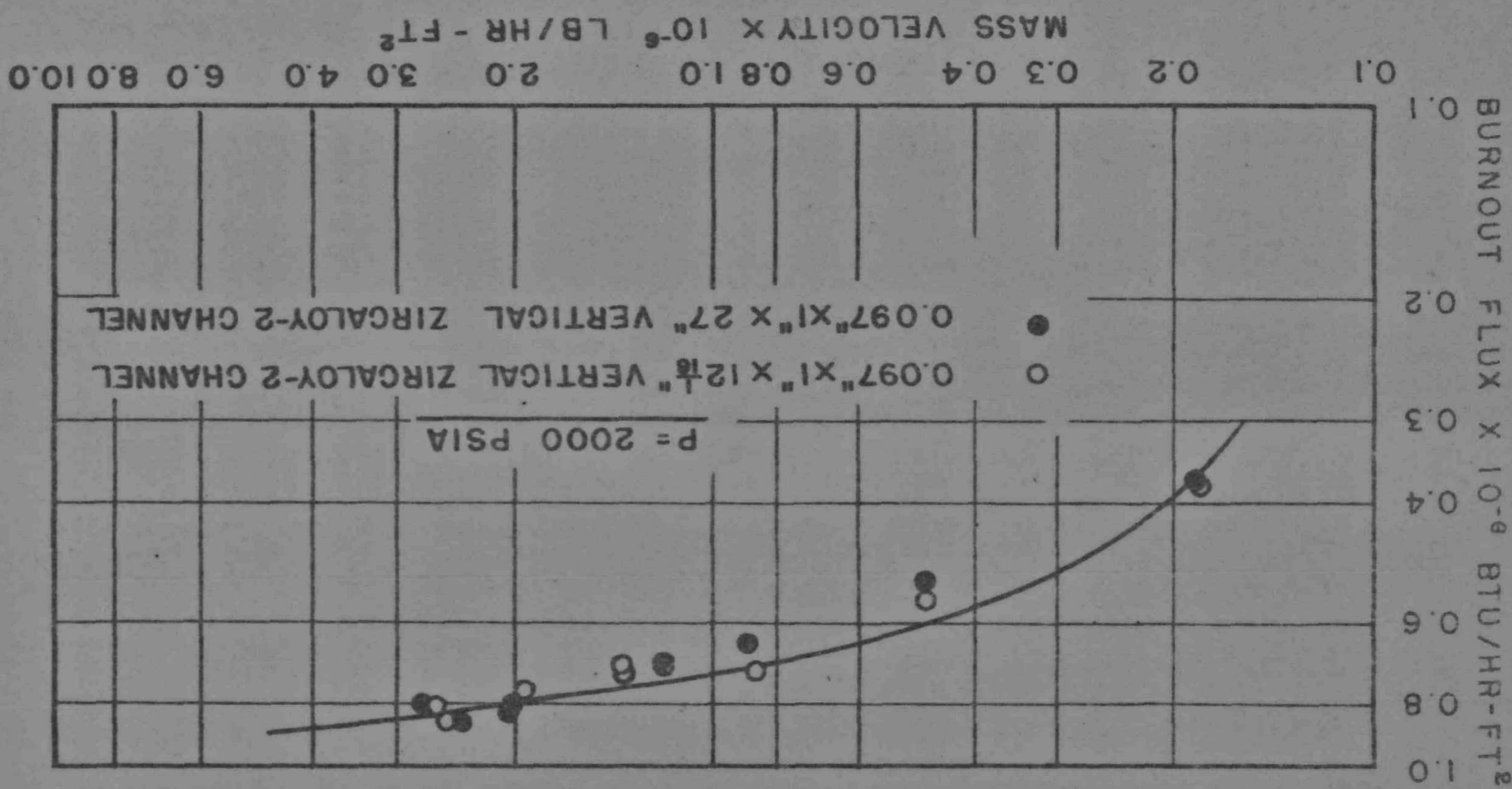


Fig. 6 An Investigation of the Effect of L/D Ratio on Burnout Flux for Vertical Rectangular Channels (Note: The enthalpy of the fluid at the exit was the same in each channel for a given heat flux and mass velocity.)

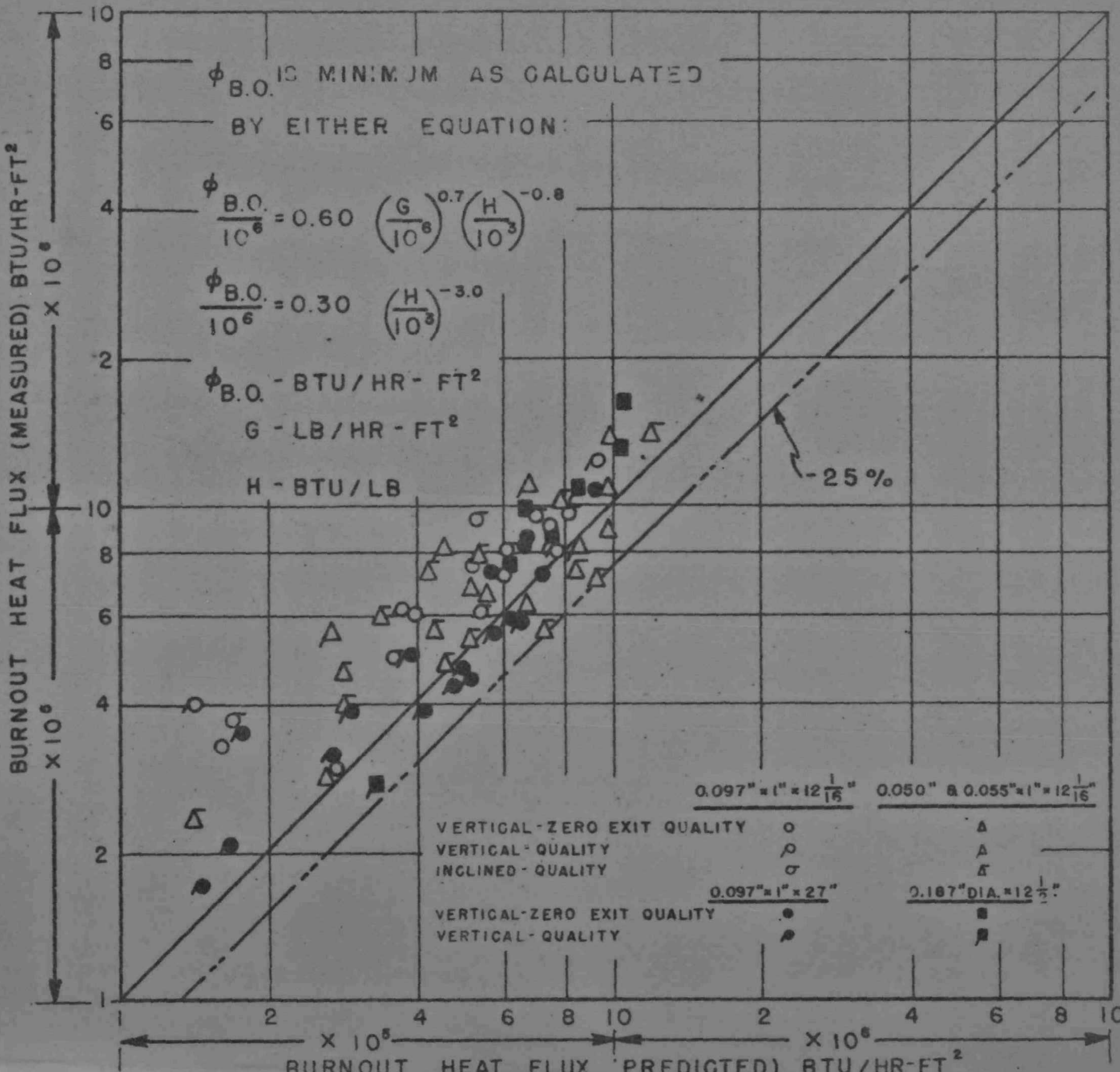


Fig. 7 Comparison of Bettis Data with Burnout Design Equation
(P = 2000 psia)

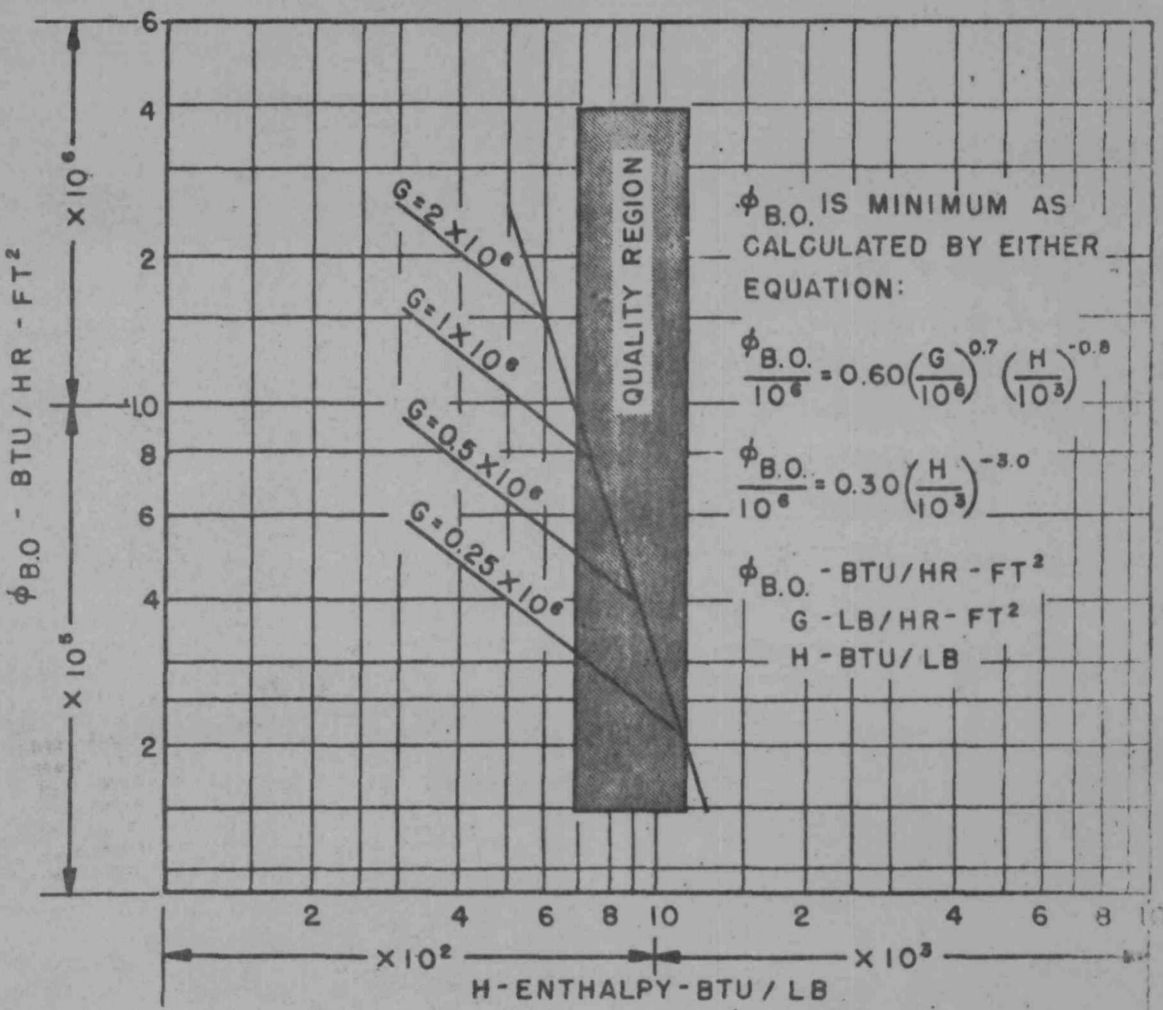


**Fig. 8 Graph of Burnout Design Equation (P = 2000 psia)**

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