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TESTS OF A SINGLE-TUBE-IN-SHELL WATER BOILER WITH HELICAL-WIRE INSERT, INLET NOZZLE, AND TWO DIFFERENT INLET-REGION PLUGS

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16. Abstract

Experimental data were obtained on the performance of a vertical-upflow, single-tube-in-shell water boiler with full-length helical-wire insert (ratio of wire pitch to the tube diameter, 1.90), 0.0285-in.- (0.72-mm-) throat-diameter inlet nozzle, and two different inlet-region plugs of lengths 1.78 and 10 in. (4.52 and 25.4 cm). The boiler tube had an inner diameter of 0.436 in. (1.11 cm) and an effective heated length of 60.5 in. (1.54 m). Steady-state pressure-drop and heat-transfer data were obtained over a range of boiling-fluid flow rates and pressures, both with and without vaporization in the nozzle. Boiler feed conditions ranged from a liquid subcooling of 180° F (100 K) to a flashing condition of 0.04 vapor quality. The highest exit vapor quality obtained was 0.98, but with measured vapor superheat as great as 105° F (58 K). Steady-state heat-transfer and pressure-drop data were compared with existing plain-tube correlations. There were no significant differences in boiler pressure-drop or heat-transfer performance for the two different plug lengths.

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TESTS OF A SINGLE-TUBE-IN-SHELL WATER BOILER WITH HELICAL-WIRE INSERT, INLET NOZZLE, AND TWO DIFFERENT INLET-REGION PLUGS

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SUMMARY

Experimental data were obtained on the performance of a vertical-upflow, single-tube-in-shell water boiler with a full-length helical-wire insert, an inlet nozzle, and two different inlet-region center plugs. One plug was 1.78 inches (4.52 cm) long and the other 10 inches (25.4 cm). The boiler tube had an inner diameter of 0.436 inch (1.11 cm) and an effective heated length of 60.5 inches (1.54 m). The ratio of helical-wire pitch to tube inner diameter was 1.90. The inlet nozzle had a throat diameter of 0.0285 inch (0.72 mm).

Steady-state pressure-drop and heat-transfer data were obtained over a range of boiling-fluid flow rate from 44 to 123 pounds mass per hour (0.0055 to 0.0155 kg/sec), and from 3 to 83 psia (~20 to 570 kN/m^2) boiler exit pressure, both with and without vaporization occurring in the nozzle. Boiler feed conditions ranged from a liquid subcooling of 180° F (100 K) to a flashing condition of 0.04 vapor quality. These heat-transfer and pressure-drop data were compared with correlations based on data for a boiler of the same dimensions, but with no inserts. Mean boiling-side heat-transfer coefficients agreed with the plain-tube correlation for inlet subcoolings of 47° F (26 K) or greater; coefficients were higher than plain-tube values by as much as a factor of 3 for for lower inlet subcoolings and for flashing at the inlet nozzle. The pressure-drop data agreed with the plain-tube model, but with the frictional pressure drop multiplied by 5.8 to account for the helical-wire insert. There were no significant differences in boiler heat transfer or pressure drop for the two different plug lengths.

The highest exit quality obtained was 0.98, although the measured vapor superheat was as great as 105° F (~58 K) in some cases. No regions of negative slope, or increasing boiler pressure drop with decreasing boiling-fluid flow rate, often associated with flow excursion instabilities, were observed. However, under some conditions flow oscillations did occur. The inlet nozzle pressure drop with vaporization occuring agreed sufficiently for design purposes with an existing correlation.

INTRODUCTION

Once-through, forced-convection boilers are more compact and lightweight than conventional natural-circulation boilers. If the boiler is properly designed, the working-fluid loop is simplified since no separator system is needed. For these reasons, once-through, forced-convection boilers are attractive for mercury and alkali-metal Rankine-cycle space power systems. In studies related to the development of boilers for mercury (refs. 1 to 4) and potassium (refs. 5 to 7), it has generally been found necessary to use inserts within the boiler tube, such as swirlers and flow-area-reducing inlet-region plugs, in order to get high exit vapor quality with steady flow; inlet pressure-drop devices have often been needed. In some cases, however, high exit quality with steady flow has been reported for sodium boiling in a tube with no inserts (ref. 8), indicating that in some cases inserts may be unnecessary.

A series of water boiling studies has been conducted at Lewis, since experiments on the boiling of alkali metals are difficult and expensive to perform. With the exception of liquid thermal conductivity, water has physical properties similar to the alkali metals. Reference 9 presents results of experiments on two boilers with no inserts and with inlet pressure drop from only an upstream throttle valve. One boiler was of the same dimensions as the boiler of reference 10 and of the present report; hence, the results of reference 9 were used as a basis for determining the effect of inserts. Reference 10 reports tests of a boiler with a full-length helical-wire insert and with inlet-region plugs, inlet orifices, and a converging-diverging inlet nozzle. The type of inlet restriction, as well as the magnitude of the pressure drop, had an effect on boiler performance. The boiler operated more stably when entrance-region plugs were used. Orifices generally minimized instabilities; however, the boiling-fluid exit temperature rose well above saturation temperature, while the exit quality was considerably less than with the other inlet devices tested. A converging-diverging nozzle inlet with an inlet-region plug performed well over a limited flow range; but the inlet nozzle was not properly sized for the lower portion of the flow range of interest. Although the role of the inlet in stabilizing the system was not fully understood, it appeared that vapor formation (cavitation) was involved; the boiler operated more stably when the inlet nozzle was cavitating. Further information on vapor formation phenomena in small nozzles was obtained on an adiabatic, transparent, converging-diverging nozzle (ref. 11); with cavitation in the nozzle, the boiler was essentially isolated from the feedline.

The purpose of the present study was to continue the work started in reference 10 on the performance of a single-tube-in-shell water-boiling heat exchanger with a converging-diverging nozzle inlet and inserts. In order to achieve stable operation at lower flow rates than in reference 10, an inlet nozzle with a 0.0285-inch (0.72-mm) throat diameter was used instead of the 0.0305-inch (0.78-mm) throat diameter used therein. The inserts consisted of the same full-length wire helix as used in reference 10 and two different length inlet-region plugs; one plug was 10 inches (25.4 cm) long, as in reference 10, and the second was 1.78 inches (4.52 cm) long, ending at approximately the start of the heated zone, which is considered the minimum length. Boiling pressure-drop and heat-transfer data were obtained. More refined comparisons were made with data on a boiler of the same dimensions, but without inserts (ref. 9), than were attempted in reference 10. The pressure-drop characteristics of the inlet nozzle, with and without vaporization occurring, were observed and correlated.

APPARATUS

A schematic diagram of the test apparatus is shown in figure 1. With the exception of the boiler inlet modifications, this test apparatus is identical to that of reference 10. The various parts of the rig are described in the following sections.

Heat Supply Loop

The heat supply loop was designed for operation at temperatures to 350° F (450 K) and pressures to 200 psia (1.38×10^{6} N/m^{2} abs). A centrifugal pump circulated the heating water in the closed loop. The heating fluid was heated in a tank by immersion heaters.

Test Fluid Loop

A gear pump circulated the test fluid. The flow passed through a coiled stainless-steel preheater and throttle valve into the test section inlet plenum. From the exit plenum, the flow passed through a pipe to a multiple-tube heat-exchanger condenser, which was cooled by an external cooling water system.

Test Section

Figure 2 shows a schematic diagram of the test section and plenum chambers with instrumentation. The boiling-fluid flow was vertically upward and the heating-fluid flow downward. The shell, or outer jacket, of the test section and the boiler tube were stainless steel. The helical copper wire, 1/16 inch (1.6 mm) in diameter, was brazed to the inner surface of the tube. Heat transfer in the end sections was reduced by insulating the ends of the center tube as shown in figure 2. The effective length of the boiler was assumed to be limited to the 60.5-inch (1.54-m) uninsulated length. The outer shell of the test section was wrapped with a fiber glass insulating material.

Inlet Nozzle and Plugs

The inlet nozzle used with both configurations tested is shown in figure 3. Figure 3(a) is a diagram of the nozzle, giving important dimensions. The tapered section of the plug was considered to be part of the inlet nozzle; its presence decreased the effective diffuser angle. The extension of the diffuser and both inlet-region plugs were made of brass. A 1/16-inch- (1.6-mm-) diameter copper wire with the same pitch (0.83 in. or 2.1 cm) as in the boiler tube was bonded to the tapered section of the plug within the diffuser. The upstream end of the wire was tapered down to minimize leading-edge bluntness. A short length of stainless-steel tubing was rolled down to form the 0.0285-inch- (0.72-mm-) diameter throat section; figure 3(b) shows a nearly identical throat section cut in half. The rolling process left a small peripheral groove in the diffuser, as can be seen in figure 3(b).

The inlet region of the test section, with each of the two plugs, is shown in figure 4. The 10-inch (25.4-cm) plug is shown in figure 4(a) and the 1.78-inch (4.52-cm) plug in figure 4(b). The length is taken from the start of the constant-diameter section, since the tapered section is considered to be part of the inlet nozzle.

Instrumentation

The flow rates for both loops were measured by turbine-type flowmeters.

The pressures indicated in figure 2, as well as the throttle valve inlet pressure, were measured with Bourdon-type gages. These gages had scales from 0 to 150 psia (0 to 1.03×10^6 N/m^2 abs), and errors less than 1/4 percent of full scale. The smallest division was 1/2 psi (3.45×10^3 N/m^2), and the gage faces were 8 inches (0.203 m) in diameter. The boiler-inlet and exit pressure taps were drilled through the test section end plates and boiler tube wall. The pressure gages were sufficiently damped to eliminate most high-frequency oscillations.

Copper-constantan thermocouples were installed in the boiling-fluid inlet and exit plenum chambers and in the heating-fluid inlet and exit lines. These temperatures were read from mutlipoint strip-chart recorders having a range of 0° to 400° F (255.5 to 478 K), 2° F (1.1 K) smallest division and an 11-inch (0.279-m) scale (believed accurate to at least $\pm0.5^\circ$ F (0.3 K)). A Chromel-Alumel thermocouple was installed at the boiling-fluid exit, upstream of the baffle plates, to measure the temperature as close as possible to the end of the boiler tube. This temperature was continuously recorded on a strip chart having a 6-inch (0.152-m) scale with a 10-millivolt range and 0.1-millivolt smallest division.

Calibration

Before the test data with the short plug were taken, the instrumentation was checked and calibrated. The turbine flowmeters agreed well with their factory calibration. A no-flow pressure check indicated that the gages were consistent with each other, except the boiler-exit and exit-plenum gages indicated some scatter above 50 psia (345 KN/m^2 abs). Since P_{bp} and P_{be} disagree at high pressure and P_{bp} agrees with temperature measurements, as discussed below, P_{be} is not tabulated for values over 50 psia (345 kN/m^2 abs). At this high pressure level, with the low qualities involved, P_{be} should approximately equal P_{bp}. A series of approximately isothermal runs indicated that the temperature measurements were self-consistent. To check the consistency between the temperature and pressure measurements under flowing conditions, a plot of exit-plenum temperature against exit-plenum pressure for equilibrium two-phase conditions was made, as shown in figure 5. The exit-plenum gage was used only with the short-plug data. The data agree well with the saturation temperature against pressure curve from Keenan and Keyes (ref. 12).

PROCEDURE

The long-plug configuration was tested first, and data were obtained to lower boiling-fluid flow rates than in reference 10. However, it was difficult to determine from the data with the long plug under what conditions cavitation occurred in the inlet nozzle. For this reason, the mode of operation was different with the short plug. Note that the inlet nozzle geometry was not affected by the change in plug length.

For both sets of data, with the long plug and the short plug, the conditions for each test run were established by adjusting the power to the main heater and preheater and setting pump speed, throttle valve position, and expansion tank pressures at selected values. When mean inlet and exit temperatures became constant with time, even if in some cases there were slight oscillations, the data for that run were taken. The dissolved-gas content was maintained at or below 4 parts per million by weight, with the exception of one set of runs. (Method of determining gas content is discussed in ref. 13). The operating procedure for each set of runs is described in the following sections.

Long Plug

For each series of runs, the boiling-fluid flow rate was decreased in steps, while holding essentially constant the following:

(1) Boiling-fluid nozzle-inlet temperature
(2) Boiling-fluid exit-plenum pressure
(3) Heating-fluid flow rate
(4) Heating-fluid inlet temperature

The boiling-fluid flow rate was decreased by reducing the pump speed with the throttle-valve fully opened until fairly large oscillations occurred, at which point the first part of the series was terminated. Next, to get lower boiling-fluid flow rates, the throttle valve was set to a selected position; the decreases in boiling-fluid flow rate were continued until large oscillations occurred, at which point the series was terminated. Three throttle valve positions, including fully opened, were used and were repeated as closely as possible for each series. The degree of restriction can be seen from the data listed in table I; the throttle-valve pressure drop is given by $P_{vi} - P_{ni}$.

Short Plug

Since it was difficult to determine under what conditions cavitation occurred in the inlet nozzle using the procedure previously described, a different procedure was adopted. For each series, the exit-plenum pressure was decreased in steps, holding essentially constant the following:

(1) Boiling-fluid flow rate
(2) Boiling-fluid nozzle-inlet temperature
(3) Heating-fluid flow rate
(4) Heating-fluid exit temperature

Thus, an increase in inlet nozzle pressure drop was taken to be an indication of cavitation. For the nonboiling runs, the heating-fluid inlet temperature was low enough that there was essentially no heat transfer in the test section. In one series, the heating-fluid flow rate was varied and the following held essentially constant:

(1) Boiling-fluid flow rate
(2) Boiling-fluid nozzle-inlet temperature
(3) Boiling-fluid exit-plenum pressure
(4) Heating-fluid inlet temperature

This series was run to extend the range of heat-transfer data.

EXPERIMENTAL DATA

The experimental data for each run are given in tables I to III. The heating rate is calculated from a heat balance (heat losses were found negligible in ref. 10) as follows:

$$Q = W_h c_{Ph} (T_{hi} - T_{he}) \tag{1}$$

The exit vapor quality is then calculated from equation (2). (Note that Q and x_e are approximate for small values of $T_{hi} - T_{he}$.)

$$x_e = \frac{Q}{W_b \lambda} - \frac{c_P (T_{be\text{-}sat} - T_{hi})}{\lambda} \tag{2}$$

The nominal conditions for each series are given in the following tables:

[Boiler-exit pressure, P_{be}, 16.5 psia (114 kN/m^2 abs.)]

Series	Part	Runs	Long plug: Boiling fluid: Flow rate, W_b (lbm/hr)	Boiling fluid: Flow rate, W_b (g/sec)	Boiling fluid: Nozzle-inlet temperature, T_{ni} (°F)	Nozzle-inlet temperature, T_{ni} (K)	Heating fluid[a]: Flow rate, W_h (lbm/hr)	Heating fluid[a]: Flow rate, W_h (kg/sec)	Heating fluid[a]: Inlet temperature, T_{hi} (°F)	Inlet temperature, T_{hi} (K)	Throttle-valve setting
1	A	1 to 11	Variable		80	300	10 000	1.26	242	390	Open
2	A	12 to 18							278	410	Open
2	B	19 to 23							278	410	B
3	A	24 to 29							314	430	Open
3	B	30 to 35							314	430	B
4	A	36 to 39							350	450	Open
4	B	40 to 41			↓	↓					B
5	A	42 to 45			170	350					Open
5	B	46 to 50			170	350			↓	↓	B
6	A	51 to 53	↓		232	384			242	390	Open
6	B	54	70	8.8	232	384			242	390	A
6	C	55 to 56	Variable		232	384			242	390	B
7	A	57 to 58	Variable		256	398			314	430	Open
7	B	59	75	9.5	256	398			314	430	A
8	A	60 to 62	Variable		260	400			350	450	Open
8	B	63 to 64			260	400	↓	↓			A
9	A	65 to 68			80	300	4 900	.62			Open
9	B	69 to 70	↓		80	300	4 900	.62	↓	↓	B

[a]Exit temperature is a dependent variable.

[Throttle-valve setting, open.]

Short plug													
Series	Runs	Boiling fluid						Heating fluid					
		Flow rate, W_b		Nozzle-inlet temperature, T_{ni}		Exit plenum temperature, P_{bp}		Flow rate, W_h		Temperature			
										Inlet, T_{hi}		Exit, T_{he}	
		lbm/hr	kg/sec	^oF	K	psia	kN/m^2 abs	lbm/hr	kg/sec	^oF	K	^oF	K
10	71 to 74	65	8.2	66	292	Variable		No significant heat transfer					
11	75 to 79	60	7.5	219	377	↓		↓					
12	80 to 91	80	10.0	64	291	↓		↓					
13	92 to 98	80	10.0	124	324	↓		↓					
14	99 to 105	80	10.0	230	383	↓		↓					
15	106 to 118	100	12.6	65	292	↓		↓					
16	119 to 131	↓	↓	128	326	↓		↓					
17	132 to 140	↓	↓	190	361	↓		↓					
18	141 to 147	↓	↓	220	378	↓		↓					
[a]19	148 to 160	80	10.0	74	296	↓		↓					
20	161 to 169	↓	↓	230	383	↓		8000	1.0	Variable		232	384
21	170 to 177	↓	↓	230	383	↓		↓	↓	↓		260	400
22	178 to 185	↓	↓	230	383	↓		↓	↓	↓		290	417
23	186 to 194	↓	↓	260	400	↓		↓	↓	↓		260	400
24	195 to 205	↓	↓	260	400	↓		↓	↓	↓		290	417
25	206 to 219	↓	↓	260	400	↓		↓	↓	↓		320	433
26	220 to 224	85	10.7	265	403	3.2	22	Variable		350	450	Variable	

[a]Gas-saturated water.

RESULTS AND DISCUSSION

Inlet Nozzle Pressure Drop

Several series of runs (series 10 to 19) were made with no significant heat transfer in the test section. These results are presented in table II. With boiling-fluid flow rate and nozzle inlet temperature held constant, the exit-plenum pressure was decreased in steps. An increase in inlet-nozzle pressure drop was taken to indicate cavitation. The exit-plenum pressure was lowered as much as possible, in some cases, into the regime of net vaporization (flashing) in the inlet nozzle. Including the boiling runs (series 20 to 26), boiler-inlet (nozzle-exit) vapor qualities as high as about 0.04 were obtained.

One series of runs (series 19) was made with water saturated with dissolved gas. The only apparent effect was that cavitation occurred at a slightly higher pressure than for a dissolved-gas content of ~4 parts per million (by weight).

It is desirable to normalize the flow-pressure-drop data in terms of flow coefficients, in order to size similar inlet nozzles for different applications. The faired curve for flow coefficients as functions of Reynolds number was based on the short-plug data; then, the data for the long plug, where it was difficult to determine whether or not cavitation occurred, were added to the figures arbitrarily, for completeness. In this manner, all the data taken under steady conditions are compared with the normalizations.

All liquid. - In order to normalize the all-liquid pressure drop of the inlet nozzle as a function of flow rate and temperature, an overall flow coefficient (eq. (3)) is plotted against throat liquid Reynolds number in figure 6(a).

$$C = \frac{W_b}{A_{min}\sqrt{\frac{2\rho_l g_c (P_{ni} - P_{bi})}{K}}} \tag{3}$$

The faired curve agrees with the data to within less than ±10 percent.

Cavitation and flashing. - In order to show the effect of cavitation and flashing on inlet nozzle pressure drop, C values (eq. (3)) for cavitation and flashing tests are plotted against throat liquid Reynolds number in figure 6(b) and compared with the faired curve for all-liquid pressure drop from figure 6(a). It is apparent that additional factors must be considered in order to normalize cavitating and flashing data.

To normalize the performance of the inlet nozzle with two-phase flow occurring, a flow coefficient based on the inlet to throat (minimum) pressure difference (eq. (4)) is used

$$C_t = \frac{W_b}{A_{min}\sqrt{\frac{2\rho_l g_c (P_{ni} - P_{min})}{K}}} \tag{4}$$

But since the minimum pressure at the nozzle throat was not measured, it must be estimated. Burnell (ref. 14) suggests the following empirical relation:

$$P_{min} = \left(1 - 0.264\frac{\sigma}{\sigma_{ref}}\right)P_{sat} \tag{5}$$

where σ_{ref} = 0.00288 pound force per foot (0.042 N/m). Using P_{min} from equation (5), C_t is plotted against throat liquid Reynolds number in figure 7. Values of C_t range only from 0.924 to 1.078 with no significant Re effect. Thus, although there are other valid interpretations of the data, with lower P_{min} and C_t less than 1.0, it appears that Burnell's correlation (ref. 14) provides an equation adequate for nozzle design.

General Performance - Short Plug

Nearly all of the boiling data for the shorter plug were taken with a boiling-fluid flow rate of approximately 80 pounds per hour (~0.01 kg/sec) and a heating-fluid flow rate of approximately 8000 pounds per hour (~1.0 kg/sec). These data are shown in figures 8 and 9; exit-plenum temperature, nozzle-inlet pressure, boiler-inlet pressure, boiler-exit pressure, and exit vapor quality are plotted against exit-plenum pressure for constant nozzle-inlet and heating-fluid exit temperatures as well as constant flow rates. Figure 8 shows data for a nozzle-inlet temperature of approximately 230° F (~383 K) (series 20 to 22). Figure 9 shows data for a nozzle-inlet temperature of approximately 260° F (~400 K) (series 23 to 25).

The results of series 26, variable heating-fluid flow rate, are shown in figure 10. Exit vapor quality, exit-plenum temperature, and nozzle-inlet, boiler-inlet, boiler exit, and exit-plenum pressures are plotted against heating-fluid flow rate.

Some observations which can be made from figures 8 to 10 are the following:

(1) The nozzle-inlet pressure P_{ni} decreases linearly, goes through a transition region, and then becomes essentially constant as exit-plenum pressure decreases (figs. 8 and 9, also nonboiling runs of table II). This allowed the simple correlation of cavitating and flashing nozzle performance discussed in the preceding section. This insensitivity of the nozzle inlet to boiler-inlet (nozzle-exit) pressure variations tends to isolate the boiler from the feed system, when cavitating or flashing at the inlet nozzle.

(2) The boiler-inlet pressure P_{bi} generally decreases with decreasing exit-plenum pressure. But at very low exit pressures, the boiler-inlet pressure becomes essentially constant over a range of exit pressures. This might tend to dynamically isolate the boiler inlet from pressure changes occurring near the exit.

(3) The boiler-exit pressure P_{be} decreases with decreasing exit-plenum pressure, until the exit-plenum pressure reaches values below approximately 3.5 psia (~24 kN/m^2 abs). At these low pressures, there is a fairly large pressure drop between the boiler exit and the exit plenum; this effect is most pronounced at high exit qualities (see figs. 8(c), 9(b) and (c), and 10). The differences are too great to be due entirely to instrument error. This pressure drop could well be due to two-phase choking at the tube exit; with no exit vapor superheat, the data are in the range predicted from Fauske's slip-equilibrium model for two-phase critical flow (ref. 15).

(4) Vapor superheat at the exit plenum is observed for exit vapor qualities less than 1.0; this can be seen in figures 9(c) and 10. Figure 10 shows superheat as great as 105° F (~58 K). Similar results have been reported for water (refs. 10 and 16) and mercury (refs. 1 to 4).

General Performance - Long Plug

The experimental data for this configuration are shown in figures 11 to 14. Exit quality, boiler-tube pressure drop, and inlet-nozzle pressure drop are plotted against boiling-fluid flow rate. Figures 11, 12, and 13 show data for nominal nozzle inlet temperatures of 80° F (300 K) (series 1 to 4), 170° F (350 K) (series 5), and 231° to 270° F (384 to 405 K) (series 6 to 8), respectively; the latter set of data (fig. 13) exhibits flashing at the inlet nozzle (i.e., net two-phase flow into the boiler). For figures 11 to 13 the heating-fluid flow rate is approximately 10 000 pounds per hour (~1.26 kg/sec). Figure 14 shows the data for series 9 ($T_{ni} \approx 80^\circ$ F (~300 K) and $W_h \approx 4900$ lb/hr (~0.62 kg/sec)).

The following observations can be made from figures 11 to 14:

(1) Exit quality increases as boiling-fluid flow rate decreases until exit vapor superheat is observed (then decreases in some cases). As with the short plug, vapor superheating occurs at exit qualities less than 1.0. No consistent trends of quality against boiling-fluid flow rate are seen in the superheat region.

(2) No regions of negative slope, or increasing boiler-tube pressure drop with decreasing boiling-fluid flow rate were observed over the range of this investigation. The existence of such a negative slope region could allow flow excursion instabilities. However some flow oscillations were observed, as discussed in Procedure.

Boiling Pressure Drop

The effect of the wire helix and inlet plugs on boiler-tube pressure drop is examined in this section. The experimental data are compared with a correlation of boiler-tube pressure drop with no inserts previously obtained in reference 9.

This correlation was based primarily on data for water at near atmospheric pressure with a boiler of the same dimensions as the one used in this study, but with no inserts. The correlation is based on a modification of the method of Thom (ref. 17). From this correlation the boiler-tube pressure drop is given by the sum of the inertial, gravitational, and frictional pressure drops (ΔP_I, ΔP_G, and ΔP_F). These are given in reference 9 as follows:

$$\Delta P_I = \frac{G^2}{K\rho_l g_c}\left\{\left[1 + x_e\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right]^2 - 1\right\} \qquad (6)$$

$$\Delta P_G = \frac{\rho_l L_H g}{K g_c}\left\{\frac{\left(\sqrt{\frac{\rho_l}{\rho_g}} - \sqrt{\frac{\rho_g}{\rho_l}}\right)\ln\left[1 + x_e\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right]}{x_e\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)^2} + \frac{\sqrt{\frac{\rho_g}{\rho_l}} - 1}{\sqrt{\frac{\rho_l}{\rho_g}} - 1}\right\} \tag{7}$$

$$\Delta P_F = \frac{f_{TP} G^2 L_H}{K \rho_l g_c D_1}\left\{\left[1 + x_e\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right]^2 + 1\right\} \tag{8}$$

The inertial pressure drop ΔP_I is a function of inlet and exit conditions only, and is independent of the local heat-flux distribution within the boiler. Pressure losses in the unheated end sections were neglected. (These lengths are small compared with L_H.) Uniform heat flux and constant densities were assumed in order to obtain the gravitational and frictional pressure-drop equations. Since the heat flux was not necessarily uniform and the two-phase friction factor f_{TP} not necessarily constant (as assumed in obtaining eq. (8)), the experimental values of f_{TP} were effective-mean values. The two-phase friction factor was correlated for no inserts (ref. 9) as follows:

$$f_{TP} = 0.020\left[\frac{D_1 G}{\mu_g}\left(\frac{x_e}{2}\right)\right]^{-0.2}\left\{1 + 0.027\left[\frac{D_1 G}{\mu_l}\left(1 - \frac{x_e}{2}\right)\right]^{0.5}\right\} \tag{9}$$

To determine the actual frictional pressure drop from the experimental data, it was assumed that the insert affected only the frictional pressure drop. Any rotational effects, as well as any changes in ΔP_I and ΔP_G, are lumped with the actual frictional pressure drop. Inertial and gravitational pressure drops calculated from equations (6) and (7) were subtracted from experimental boiler-tube pressure drops. The resulting frictional pressure drop calculated from experimental data is plotted against a plain-tube frictional pressure drop calculated from equations (8) and (9) in figure 15(a), for data taken with no flashing at the boiler inlet. The data of reference 10, for the same boiler with a 10-inch (25.4-cm) plug, but for a larger inlet nozzle, are also shown. (The correlation of ref. 9

does not provide any direct means of accounting for inlet flashing.) The data of this report and reference 10 yield ΔP_F values about 5.8 times the plain-tube values. There were no significant differences in boiler-tube pressure drop for the two different plug lengths. Experimental data with flashing at the inlet nozzle are shown in figure 15(b). The following corrected equations account roughly for the two-phase starting condition.

$$\Delta P_I = \frac{G^2}{K\rho_l g_c}\left\{\left[1 + x_e\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right]^2 - F\left[1 + x_{bi}\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)\right]^2\right\} \qquad (10a)$$

where the factor F is the inverse square of the ratio of the axial-flow area in the plug region to that in the rest of the boiler

$$\Delta P_G = \frac{\rho_l L_H g}{K g_c}\left\{\left(R_2\right)_{be} - \left[\left(R_2\right)_{bi} - \left(R_2\right)_{be}\right]\frac{x_{bi}}{x_e - x_{bi}}\right\} \qquad (10b)$$

where R_2 is the parameter multiplying $\rho_l L_H g/K g_c$ in equation (7). These corrections amounted to a total of at most 0.12-psi (0.83-kN/m^2) difference from the result obtained using equations (6) and (7). Data for $P_{bi}/P_{be} > 2$ are not shown; these data show considerable deviation, probably due to compressibility effects, which are not accounted for in the equations. For the data without flashing at the inlet, no data were obtained for P_{bi}/P_{be} much greater than 2. The data with inlet flashing agree well with the data for no flashing.

Boiling Heat Transfer

The effect of the wire helix on boiler heat transfer is examined in this section. The experimental data are compared with a correlation of boiling heat transfer developed for a tube of the same dimensions, but with no inserts (ref. 9).

It is necessary to know the combined thermal resistances of the wall and the heating fluid in order to determine the boiling-side heat-transfer coefficient from experimental overall heat-transfer data. The combined wall and heating-fluid thermal resistance for this same boiler was determined in reference 10 to be

$$R_o = 0.00030 + 40\left(\frac{D_2}{12k_h}\right)\left[\frac{\pi(D_2 + D_3)\mu_h}{4 \times 12W_h}\right]^{0.8} Pr_h^{-0.5}, \quad \frac{(hr)(ft^2)(^oF)}{Btu} \tag{11}$$

or

$$R_o = 0.0053 + 40\left(\frac{D_2}{k_h}\right)\left[\frac{\pi(D_2 + D_3)\mu_h}{4W_h}\right]^{0.8} Pr_h^{-0.5}, \quad \frac{(m^2)(K)}{W} \tag{11a}$$

The correlation of mean boiling-side heat-transfer coefficients for plain tubes, previously obtained in reference 9, was based on data for water at near atmospheric pressure, primarily with a boiler of the same dimensions as the one used in this study but with no inserts. This correlation was based on an enthalpy-weighted mean temperature difference between heating and boiling fluids

$$\Delta T_m = \overline{\Delta T_{sc}}\left[\frac{W_b c_P}{Q}(T_{be,sat} - T_{bi})\right] + \overline{\Delta T_B}\left(\frac{x_e W_b \lambda}{Q}\right) \tag{12}$$

The arithmetic mean temperature difference in the subcooled region $\overline{\Delta T_{sc}}$ was averaged with the arithmetic mean temperature difference over the remainder of the boiler $\overline{\Delta T_B}$, with the heat loads in each region as weighting factors; pressure drop was neglected. Note that for constant heat flux ΔT_m is the arithmetic mean temperature difference. The correlation of boiling-side heat-transfer coefficients was given as follows:

$$\frac{h_b}{h_l} = 1 + 200\, x_e \sqrt{\frac{P_e}{P_c}} \tag{13}$$

in which P_c is the critical pressure and h_l is the heat-transfer coefficient for all-liquid flow at the same flow rate and temperature, where

$$h_l = 0.023\left(\frac{12k_l}{D_1}\right)\left(\frac{D_1 G}{12\mu_l}\right)^{0.8} Pr_l^{0.5}, \quad \frac{Btu}{(hr)(ft^2)(^oF)} \tag{14}$$

or

$$h_l = 0.023\left(\frac{k_l}{D_1}\right)\left(\frac{D_1 G}{\mu_l}\right)^{0.8} Pr_l^{0.5}, \ \frac{W}{(m^2)(K)} \tag{14a}$$

In applying this correlation to boilers with inserts, because of the larger pressure drops with the inserts, pressure drop must be accounted for in ΔT_m; therefore,

$$\Delta T_m = \overline{\Delta T_{sc}}\left[\frac{W_b c_P(T_{bi,sat} - T_{ni})}{Q}\right] + \overline{\Delta T_B}\left[1 - \frac{W_b c_P(T_{bi,sat} - T_{ni})}{Q}\right] \tag{15}$$

for flashing at the inlet nozzle, $\Delta T_m = \overline{\Delta T_B}$. Experimental values of the coefficient ratio $h_b/h_{l,pt}$, for runs showing no indications of vapor superheat or flow oscillations as great at ±5 percent, are plotted against the parameter $x_e\sqrt{P_e/P_c}$ in figure 16(a). The data of reference 10 for the same boiler and plug, but for a larger inlet nozzle, are also shown. For inlet subcoolings of 47° F (26 K) or greater, the experimental data agree with the plain-tube correlation. But for inlet subcoolings of 31° F (17 K) or less and for flashing at the inlet nozzle, coefficient ratios range from plain-tube values to about 4 times as great. No appreciable effect could be noted on the heat-transfer results between the short plug, which only reached to the beginning of the heated zone, and the long plug which extended more than 8 inches (~20 cm) into the heated zone. Experimental data with exit vapor superheat are shown in figure 16(b). As might be expected, the coefficient ratios are generally less than with no indication of superheat, and no general trend can be cited.

SUMMARY OF RESULTS

1. With vaporization (net or local) in the inlet nozzle, the nozzle-inlet pressure became relatively insensitive to changes in nozzle-exit pressure, for constant flow rate and nozzle-inlet temperature. The relation between flow rate and nozzle-inlet pressure and temperature agreed well with Burnell's correlation.

2. So long as the boiler-inlet pressure was no more than about twice the boiler-exit pressure, the boiler-tube pressure drop agreed well with a modified plain-tube boiling pressure-drop correlation; the correlation was that of reference 9, with the frictional pressure drop multiplied by 5.8 to account for the helical wire insert.

3. No regions of negative slope, or increasing boiler-tube pressure drop with decreasing boiling-fluid flow rate, often associated with flow excursions, were observed. However, under some conditions flow oscillations did occur.

4. Mean boiling-side heat-transfer coefficients for the boiler with helical-wire insert were compared with the plain-tube correlation of reference 9. For inlet subcoolings of 47^{o} F (26 K) or greater, the experimental data agree with the plain-tube correlation. But for inlet subcoolings of 31^{o} F (17 K) or less and for flashing at the inlet nozzle, coefficients range from plain-tube values to about four times as great.

5. The maximum boiler-exit vapor quality obtained with this 0.0285-inch (0.72-mm) throat-diameter inlet nozzle was <1.0, although exit vapor superheat as great as 105^{o} F (58 K) was indicated. But with the 0.0305-inch (0.78-mm) throat-diameter inlet nozzle of reference 10, boiler-exit vapor qualities in excess of 1.0 were reported.

6. There were no significant differences in boiler-tube pressure-drop or heat-transfer performance for the two different plug lengths.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 25, 1969,
120-27.

APPENDIX - SYMBOLS

A cross-sectional flow area, ft^2; m^2

C overall flow coefficient, dimensionless

C_t inlet-to-throat flow coefficient, dimensionless

c_p liquid specific heat, Btu/(lbm)(^oF); J/(kg)(K)

D diameter, in.; m

F inlet-region area factor, dimensionless

f_{TP} two-phase friction factor, dimensionless

G boiling-fluid superficial mass velocity, $4W_b/K\pi D_1^2$, lbm/(hr)(ft^2); kg/(sec)(m^2)

g acceleration due to gravity, 4.17×10^8 ft/hr^2; 9.81 m/sec^2

g_c conversion factor, 4.17×10^8 (lbm)(ft)/(lbf)(hr^2); 1.00 (kg)(m)/(N)(sec^2)

h heat-transfer coefficient, Btu/(hr)(ft^2)(^oF); W/(m^2)(K)

K conversion factor, (1/144) ft^2/in.^{2}; 1.00 m^2/m^2

k liquid thermal conductivity, Btu/(hr)(ft)(^oF); W/(m)(K)

L_H heated length of test section, 60.5 in.; 1.54 m

P pressure, psia; N/m^2 abs

P_c thermodynamic critical pressure, psia; N/m^2 abs

ΔP_B boiler-tube pressure drop, $P_{bi} - P_{be}$, psi; N/m^2

ΔP_F frictional pressure drop, psi; N/m^2

ΔP_G gravitational pressure drop, psi; N/m^2

ΔP_I inertial pressure drop, psi; N/m^2

ΔP_n inlet-nozzle pressure drop, $P_{ni} - P_{bi}$, psi; N/m^2

ΔP_V throttle-valve pressure drop, $P_{vi} - P_{ni}$, psi; N/m^2

Pr liquid Prandtl number, $c_p\mu/k$, dimensionless

Q heating rate, Btu/hr; W

R_o combined thermal resistance of wall and heating fluid, (hr)(ft^2)(^oF)/Btu; (m^2)(K)/W

R_2 gravitational pressure-drop parameter, dimensionless

T temperature, ^oF; K

$\overline{\Delta T_B}$ mean temperature difference in net boiling region, ^oF; K

ΔT_m mean temperature difference in boiler, ^oF; K

$\overline{\Delta T_{sc}}$ mean temperature difference in subcooled region, ^oF; K

U average overall heat-transfer coefficient, Btu/(hr)(ft^2)(^oF); W/(m^2)(K)

W mass flow rate, lbm/hr; kg/sec

x vapor quality, dimensionless

λ	enthalpy of vaporization, Btu/lbm; J/kg
μ	viscosity, lbm/(ft)(hr); kg/(m)(sec)
ρ	density, lbm/ft^3; kg/m^3
σ	surface tension, lbf/ft; N/m

Subscripts:

b	boiling fluid or boiler
calc	calculated value
e	exit
g	gas property
h	heating fluid
i	inlet
l	liquid property
min	at minimum area
n	nozzle
p	exit planum
pt	plain tube
ref	reference value
sat	boiling-fluid saturation
1	inner wall of boiler tube
2	outer wall of boiler tube
3	inner wall of shell tube

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TABLE I. - EXPERIMENTAL BOILING DATA WITH 10-INCH (25.4-CM) PLUG

(a) U.S. customary units

Series	Part	Run	Boiling fluid									Heating rate, Q, Btu/hr	Heating fluid		
			Flow rate, W_b, lbm/hr	Temperature, °F			Pressure, psia				Exit quality, x_e		Flow rate, W_h, lbm/hr	Temperature, °F	
				Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Valve inlet, P_{vi}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}				Inlet, T_{hi}	Exit, T_{he}
1	A	1	123.2	76.0	222.5	218	104	105	18.7	16.8	0.02	20×10³	10 130	242.0	240.0
		2	108.3	75.0	221.5		83	83		16.8	.07	23		243.0	240.8
		3	100.0	74.5	222.0		70.9	71.5		16.8	.06	20		242.7	240.7
		4	86.9	75.0	221.5		58.1	58.9		16.9	.05	16		242.0	240.4
		5	75.5		221.5		48.8	49.5	18.6		.09	17		242.5	240.8
		6	69.5		220.0		44.7	45.3	18.4		.11	17		243.2	241.5
		7	63.9		220.3		40.6	41.2	18.4		.12	16		242.3	240.7
		8	57.9		220.3		36.8	37.0	18.4		.11	14		241.8	240.4
		9	53.0		221.5		33.3	34.8	18.2		.14	14		242.2	240.8
		10	48.5		220.7		32.4	31.6	18.1		.16	14		242.4	241.0
		11	44.7	75.5	220.7		30.1	29.5	18.0		.13	12		242.6	241.4
2	A	12	123.2	77.0	224.0	217.8	109	109	21.0	16.6	0.23	46×10³	10 070	278.0	273.5
		13	108.8	76.0	222.5	217.0	85.5	87	20.9		.30	47		278.6	274.0
		14	100.0	77.0	221.5	217.3	74.5	75	20.7		.33	46		278.2	273.7
		15	88.2	77.0	220.3	217.3	60.0	59.2	20.7		.38	45		278.2	273.8
		16	76.9	80.0	218.0	217.0	47.8	46.8	20.4		.44	43		278.2	274.0
		17	69.6	79.0	220.7	217.0	40.8	41.5	20.1		.50	43		278.0	273.8
		18	[a]64.0	78.0	220.7	217.0	38.3	38.9	20.1		.52	41		277.8	273.8
	B	19	77.2	77.0	220.7	217.0	[b]85.5	50.6	20.4		.43	43		278.0	273.8
		20	69.0	79.0	219.5		[b]74.5	45.2	20.3		.50	43		277.7	273.5
		21	64.0	78.0	220.0		[b]66.7	42.4	20.2		.57	44		278.7	274.4
		22	57.5	79.0	220.0		[b]53.4	35.4	20.0		.63	43		277.7	273.5
		23	[a]56.5	77.0	219.5	217.3	[b]42.9	30.8	19.7	16.5	.61	41		278.7	274.7
3	A	24	117.0	76.0	221.5	217.0	100	100	26.4	16.6	0.48	71×10³	10 120	313.8	307.0
		25	108.8	76.0	222.0		86.5	87.5	26.2	16.6	.53			313.8	307.0
		26	99.8	77.0	220.7		76.5	76.5	26.0	16.5	.59			314.0	307.2
		27	86.7	78.0	220.0		64.0	64.2	25.6	16.4	.71			314.0	307.2
		28	79.8	78.0	219.5	217.3	56.3	57.3	24.8	16.3	.79			313.6	306.8
		29	[a]72.6	79.0	220.3	216.8	49.6	50.5	24.1		.86	70		314.0	307.3
	B	30	82.5	82.5	219.0	217.3	[b]93.5	59.5	25.1		.74	70		314.0	307.3
		31	72.1	83.5	219.5	217.5	[b]80.2	52.0	24.3		.87	70		314.5	307.8
		32	68.6	85.0	228	217.8	[b]74.0	49.8	23.8		.89	68	10 110	314.3	307.8
		33	63.3	85.0	243.5	230.0	[b]63.1	43.1	23.2		.91	65	10 110	314.2	308.0
		34	[a]59.3	84.0	259.7	257.5	[b]57.0	39.8	22.6		.90	59	10 100	314.5	308.8
		35	[a]55.3	83.5	276.5	270.5	[b]47.9	36	21.7	16.4	.80	50	10 100	313.8	309.0
4	A	36	116.0	76.0	222.5	217.5	102.4	103	32.8	16.5	0.81	106×10³	10 100	350.7	340.7
		37	107.0	78.0	222.0	217.5	90.0	90.0	32.1	16.3	.85	103		349.7	340.0
		38	100.2	80.0	221.0	216.2	82.6	82.4	31.5	16.0	.89	100		350.0	340.5
		39	[a]90.6	81.0	246.5	247.5	71.5	71.9	29.6	16.0	.97	97		349.7	340.5
	B	40	[a]83.8	85.0	268	267.5	[b]98	63.5	27.7	16.0	.96	90	10 090	350.0	341.5
	B	41	[a]78.4	86.0	287	283.0	[b]87	60.5	27.8	16.1	.90	79	10 080	350.0	342.5

[a]Boiling-fluid flow rate oscillation of greater than ±5 percent.
[b]Valve setting B.

TABLE I. - Continued. EXPERIMENTAL BOILING DATA WITH 10-INCH (25.4-CM) PLUG

(a) Concluded. U.S. customary units

Series	Part	Run	Boiling fluid										Heating rate, Q, Btu/hr	Heating fluid		
			Flow rate, W_b, lbm/hr	Temperature, °F			Pressure, psia				Exit quality, x_e		Flow rate, W_h, lbm/hr	Temperature, °F	
				Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Valve inlet, P_{vi}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}				Inlet, T_{hi}	Exit, T_{he}
5	A	42	121.4	170.5	222.0	217.2	100.5	101	34.7	16.5	0.74	93×10^3	10 100	350.0	341.2
	↓	43	122.7	172.0	223.5	218.0	102	101	34.6	16.4	.73	95	10 060	350.2	341.2
	↓	44	112.0	170.0	224.0	218.7	88.7	89.7	33.7	16.3	.85	97	10 100	350.2	341.0
	↓	45	[a]99.5	170.0	235	230	74.0	75.0	32.1	16.0	.94	95	10 100	350.0	341.0
	B	46	[a]84.5	170.5	279	277.0	[b]96.5	55	29.2	16.2	.96	83	10 080	350.2	342.3
	↓	47	73.8	170.0	302.0	296.5	[b]73.0	48.5	27.5	16.3	.90	68	10 130	350.0	343.6
	↓	48	61.5	169.5	313.0	306.5	[b]57.8	40.6	25.2	16.2	.94	59	10 180	349.8	344.3
	↓	49	55.0	170.5	321.0	312.0	[b]50.2	36.1	24.2	16.3	.95	53	10 180	350.5	345.5
	↓	50	44.4	171.5	333.5	320.5	[b]38.0	30.1	22.1	16.4	.95	43	10 170	350.7	346.7
6	A	51	108.3	[c]231.0	221.5	217.0	92	91	19.1	16.7	0.14	13×10^3	10 070	243.0	241.7
	A	52	90.6	[c]231.5	220.2	217.5	68.3	68.7	19.0	16.8	.16	13	10 120	242.3	241.0
	A	53	80.6	[c]232.0	219.5	217.5	56.5	57.2	18.8	16.7	.14	10	10 120	242.8	241.8
	B	54	70.1	[c]233.0	217.5	217.0	[d]56.3	47.7	18.5	16.7	.18	11	10 120	242.3	241.2
	C	55	62.6	[c]231.0	218.0	217.0	[b]63.2	39.4	18.3	16.8	.22	12	10 120	242.0	240.8
	C	56	58.2	[c]231.0	217.7	216.8	[b]56.2	36.0	18.2	16.7	.23	12	10 120	242.2	241.0
7	A	57	96.2	[c]258.0	223.7	216.0	84.5	84	29.1	16.5	0.78	68×10^3	10 150	314.3	307.8
	A	58	[a]84.0	[c]256.0	224.5	216.3	68.7	69.7	27.7	16.4	.85	66	10 150	314.0	307.7
	B	59	75.5	[c]256.0	246.0	241.0	[d]95.5	58.1	26.4	16.4	.90	63	10 150	314.5	308.5
8	A	60	99.5	[c]270.0	262.5	260.0	98.0	99.0	34.2	16.1	0.95	86×10^3	10 280	350.0	342.0
	A	61	88.4	[c]261.0	284.7	282.0	80.0	80.5	32.0	16.1	.97	79	10 280	350.5	343.2
	A	62	[a]79.7	[c]258.0	301	296.0	65	66	29.8	16.1	.92	68	10 260	351.0	344.7
	B	63	76.3	[c]258.0	300.0	298.0	[d]80.5	63.7	29.6	16.3	.95	67	10 260	350.2	344.0
	B	64	[a]70.4	[c]255.0	307.7	304.0	[d]69.7	57.8	28.1	16.3	.98	64	10 270	350.7	344.8
9	A	65	118.0	77.0	221.5	216.8	98.0	97.5	29.3	16.5	0.63	81.3×10^3	4 920	350.0	334.2
	↓	66	105.0	77.0	220.3	216.3	81.4	82.0	28.5	16.5	.66	81.3	↓	349.5	333.7
	↓	67	94.5	79.0	220.3	216.8	72.7	72.7	28.0	16.3	.75	81.3	↓	349.8	334.0
	↓	68	[a]87.5	80.0	220.7	217.0	65.3	66.3	27.4	16.3	.80	79.8	↓	349.5	334.0
	B	69	82.3	85.0	226	216.5	[b]98	60	26.6	16.1	.85	78.2	4 920	350.0	334.8
	B	70	[a]78.2	84.0	248	245.0	[b]89	52	25.8	16.2	.87	76.2	4 920	350.8	336.0

[a]Boiling-fluid flow rate oscillation of greater than ±5 percent.
[b]Valve setting B.
[c]Flashing at boiler inlet.
[d]Valve setting A.

TABLE I. - Continued. EXPERIMENTAL BOILING DATA WITH 10-INCH (25.4-CM) PLUG

(b) SI units

Series	Part	Run	Boiling fluid									Heating rate, Q, kW	Heating fluid		
			Flow rate, W_b, kg/sec	Temperature, K			Pressure, kN/m^2 abs				Exit quality, x_e		Flow rate, W_h, kg/sec	Temperature, K	
				Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Valve inlet, P_{vi}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}				Inlet, T_{hi}	Exit, T_{he}
1	A	1	15.52×10^{-3}	297.6	379.0	376.5	717	724	129	116	0.02	5.9	1.276	389.8	388.7
		2	13.65	297.1	378.4		572	572		116	.07	6.7		390.4	389.2
		3	12.60	296.8	378.7		489	493		116	.06	5.9		390.2	389.1
		4	10.95	297.1	378.4		401	406		117	.05	4.7		389.8	388.9
		5	9.51		378.4		336	341	128		.09	5.0		390.1	389.2
		6	8.76		377.6		308	312	127		.11	5.0		390.5	389.6
		7	8.05		377.8		280	284	127		.12	4.7		390.0	389.1
		8	7.30		377.8		254	255	127		.11	4.1		389.7	388.9
		9	6.68		378.4		230	240	125		.14	4.1		389.9	389.2
		10	6.11		378.0		223	218	125		.16	4.1		390.0	389.3
		11	5.63	297.3	378.0		208	203	124		.13	3.5		390.2	389.5
2	A	12	15.52×10^{-3}	298.2	379.8	376.4	752	752	145	114	0.23	13.5	1.269	409.8	407.3
		13	13.71	297.6	379.0	375.9	590	600	144		.30	13.8		410.2	407.6
		14	12.60	298.2	378.4	376.1	514	517	143		.33	13.5		409.9	407.4
		15	11.11	298.2	377.8	376.1	414	408	143		.38	13.2		409.9	407.5
		16	9.69	299.8	376.5	375.9	330	323	141		.44	12.6		409.9	407.6
		17	8.77	299.3	378.0		281	286	139		.50	12.6		409.8	407.5
		18	[a]8.06	298.7	378.0		264	268	139		.52	12.0		409.7	407.5
	B	19	9.73	298.2	378.0		[b]590	349	141		.43	12.6		409.8	407.5
		20	8.69	299.3	377.3		[b]514	312	140		.50	12.6		409.6	407.3
		21	8.06	298.7	377.6		[b]460	292	139		.57	12.9		410.2	407.8
		22	7.25	299.3	377.6		[b]368	244	138		.63	12.6		409.6	407.3
		23	[a]7.12	298.2	377.3	376.1	[b]296	212	136		.61	12.0		410.2	408.0
3	A	24	14.74×10^{-3}	297.6	378.4	375.9	690	690	182	114	0.48	20.8	1.275	429.7	425.9
		25	13.71	297.6	378.7		596	603	181	114	.53			429.7	425.9
		26	12.57	298.2	378.0		527	527	179	114	.59			429.8	426.0
		27	10.92	298.7	377.6		441	443	177	113	.71			429.8	426.0
		28	10.05	298.7	377.3	376.1	388	395	171	112	.79			429.6	425.8
		29	[a]9.15	299.3	377.8	375.8	342	348	166		.86	20.5		429.8	426.1
	B	30	10.40	301.2	377.0	376.1	[b]645	410	173		.74	20.5		429.8	426.1
		31	9.08	301.8	377.3	376.2	[b]553	359	168		.87	20.5		430.1	426.4
		32	8.64	302.6	382.0	376.4	[b]510	343	164		.89	19.9	1.274	430.0	426.4
		33	7.98	302.6	390.7	383.2	[b]435	297	160		.91	19.0	1.274	429.9	426.5
		34	[a]7.47	302.0	399.7	398.4	[b]393	274	156		.90	17.3	1.273	430.1	426.9
		35	[a]6.97	301.8	409.0	405.4	[b]330	248	150	113	.80	14.6	1.273	429.7	427.0
4	A	36	14.62×10^{-3}	297.6	379.0	376.2	706	710	226	114	0.81	31.1	1.273	450.2	444.6
		37	13.48	298.7	378.7	376.2	621	621	221	112	.85	30.2		449.6	444.3
		38	12.63	299.8	378.2	375.5	570	568	217	110	.89	29.3		449.8	444.5
		39	[a]11.4	300.4	392.3	392.9	493	496	204	110	.97	28.4		449.6	444.5
	B	40	[a]10.6	302.6	404.3	404.0	[b]676	438	191	110	.96	26.4	1.271	449.8	445.1
	B	41	[a]9.88	303.2	414.8	412.6	[b]600	417	192	111	.90	23.1	1.270	449.8	445.6

[a]Boiling-fluid flow rate oscillation of greater than ±5 percent.
[b]Valve setting B.

TABLE I. - Concluded. EXPERIMENTAL BOILING DATA WITH 10-INCH (25.4-CM) PLUG

(b) Concluded. SI units

Series	Part	Run	Boiling fluid									Heating rate, Q, kW	Heating fluid		
			Flow rate, W_b, kg/sec	Temperature, K			Pressure, kN/m^2 abs				Exit quality, x_e		Flow rate, W_h, kg/sec	Temperature, K	
				Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Valve inlet, P_{vi}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}				Inlet, T_{hi}	Exit, T_{he}
5	A	42	15.30×10^{-3}	350.1	378.7	376.0	693	696	239	114	0.74	27.2	1.273	449.8	449.9
	↓	43	15.46	350.9	379.5	376.5	703	696	239	113	.73	27.8	1.268	449.9	444.9
	↓	44	14.11	349.8	379.8	376.9	612	618	232	112	.85	28.4	1.273	449.9	444.8
	↓	45	[a]12.5	349.8	385.9	383.2	510	512	221	110	.94	27.8	1.273	449.8	444.8
	B	46	[a]10.6	350.1	410.4	409.3	[b]665	379	201	112	.96	24.3	1.270	449.9	445.5
	↓	47	9.30	349.8	423.2	420.1	[b]503	334	190	↓	.90	19.9	1.276	449.8	446.3
	↓	48	7.75	349.5	429.3	425.6	[b]399	280	174	↓	.94	17.3	1.283	449.7	446.7
	↓	49	6.93	350.1	433.7	428.7	[b]346	249	167	↓	.95	15.5	1.283	450.1	447.3
	↓	50	5.59	350.7	440.7	433.4	[b]262	208	152	113	.95	12.6	1.281	450.2	448.0
6	A	51	13.65×10^{-3}	[c]383.7	378.4	375.9	634	627	132	115	0.14	3.8	1.269	390.4	389.7
	A	52	11.42	[c]384.0	377.7	376.2	471	474	131	116	.16	3.8	1.275	390.0	389.3
	A	53	10.16	[c]384.3	377.3	376.2	390	394	130	115	.14	2.9	↓	390.3	389.7
	B	54	8.83	[c]384.8	376.2	375.9	[d]388	329	128	115	.18	3.2	↓	390.0	389.4
	C	55	7.89	[c]383.7	376.5	375.9	[b]436	272	126	116	.22	3.5	↓	389.8	389.2
	C	56	7.33	[c]383.7	376.3	375.8	[b]387	248	125	115	.23	3.5	↓	389.9	389.3
7	A	57	12.12×10^{-3}	[c]398.7	379.6	375.4	583	579	201	114	0.78	19.9	1.279	430.0	426.4
	A	58	[a]10.6	[c]397.6	380.1	375.5	474	481	191	113	.85	19.3	1.279	429.8	426.3
	B	59	9.51	[c]397.6	392.0	389.3	[d]658	401	182	113	.90	18.5	1.279	430.1	426.8
8	A	60	12.54×10^{-3}	[c]405.4	401.2	399.8	676	683	236	111	0.95	25.2	1.295	449.8	445.4
	A	61	11.14	[c]400.4	413.6	412.1	552	555	221	111	.97	23.1	1.295	450.1	446.1
	A	62	[a]10.0	[c]398.7	422.6	419.8	448	455	205	111	.92	19.9	1.293	450.4	446.9
	B	63	9.61	[c]398.7	422.1	420.9	[d]555	439	204	112	.95	19.6	1.293	449.9	446.5
	B	64	[a]8.87	[c]397.0	426.3	424.3	[d]481	399	194	112	.98	18.8	1.294	450.2	446.9
9	A	65	14.87×10^{-3}	298.2	378.4	375.8	676	672	202	114	0.63	23.8	0.620	449.8	441.0
	↓	66	13.23	298.2	377.8	375.6	561	565	197	114	.66	23.8	↓	449.5	440.8
	↓	67	11.91	299.3	377.8	375.8	501	501	193	112	.75	23.8	↓	449.7	440.9
	↓	68	[a]11.0	299.8	378.0	375.9	450	457	189	112	.80	23.4	↓	449.5	440.9
	B	69	10.37	302.6	380.9	375.7	[b]676	414	183	111	.85	22.9	↓	449.8	441.4
	B	70	[a]9.85	302.1	393.2	391.5	[b]614	385	178	112	.87	22.3	↓	450.3	442.0

[a]Boiling-fluid flow rate oscillation of greater than ±5 percent.
[b]Valve setting B.
[c]Flashing at boiler inlet.
[d]Valve setting A.

TABLE II. - EXPERIMENTAL DATA FOR INLET NOZZLE, NONBOILING RUNS WITH 1.78-INCH (4.52-CM) PLUG

Series	Run	Flow rate, W_b		Inlet temperature, T_{ni}		Inlet pressure, P_{ni}		Exit pressure, P_{bi}	
		lbm/hr	kg/sec	°F	K	psia	kN/m² abs	psia	kN/m² abs
10	71	64.3	8.10×10^{-3}	67.8	293.1	45.9	316	18.6	128
	72	64.9	8.16	66.0	292.0	41.3	285	14.2	98
	73	64.9	8.16	65.5	291.8	37.2	256	10.1	70
	74	64.6	8.13	64.5	291.2	31.9	220	4.9	34
11	75	60.3	7.59×10^{-3}	218.5	376.8	54.6	376	37.6	259
	76	59.7	7.51	219.5	377.3	43.2	298	26.2	181
	77	59.7	7.51	219.5	377.3	37.3	257	17.4	120
	78	59.7	7.51	217.5	376.2	33.6	232	12.0	83
	79	[a]59.1	[a]7.43	220.0	377.6	32.8	226	7.9	54
12	80	79.6	10.01×10^{-3}	65.0	291.5	106.6	734	74.4	512
	81	79.9	10.05	64.0	290.9	90.5	623	57.7	398
	82	79.9	10.05	63.7	290.7	78.2	539	45.6	314
	83	80.2	10.09	63.5	290.6	67.7	467	35.0	241
	84	80.2	10.09	↓	↓	61.0	420	28.0	193
	85	79.6	10.01	↓	↓	56.7	391	21.8	150
	86	80.2	10.09	↓	↓	53.0	365	18.6	128
	87	79.9	10.05	↓	↓	48.1	332	13.7	94
	88	79.9	10.05	↓	↓	44.2	304	9.8	68
	89	79.9	10.05	↓	↓	45.3	312	5.0	34
	90	80.2	10.09	63.7	290.7	47.1	325	10.1	70
	91	80.2	10.09	64.3	291.1	48.9	337	14.2	98
13	92	80.5	10.13×10^{-3}	123.5	324.0	70.3	484	42.0	289
	93	79.9	10.05	123.0	323.7	58.7	404	31.1	214
	94	↓	↓	123.5	324.0	52.6	362	24.9	172
	95	↓	↓	123.5	324.0	46.6	321	18.8	130
	96	↓	↓	124.0	324.3	40.8	281	12.9	89
	97	80.2	10.09	123.5	324.0	37.4	258	9.6	66
	98	80.5	10.13	123.5	324.0	44.0	303	5.5	38
14	99	80.2	10.09×10^{-3}	227.0	381.5	101.7	701	72.3	498
	100	79.9	10.05	230.0	383.2	86.6	597	56.9	392
	101	79.6	10.01	231.0	383.7	67.8	467	37.6	259
	102	79.3	9.97	230.0	383.2	61.5	424	26.7	183
	103	80.2	10.09	229.5	382.9	59.0	407	17.6	121
	104	79.6	10.01	234.3	385.5	58.3	402	12.0	83
	105	80.2	10.09	225.5	380.6	57.2	394	8.2	57
15	106	99.3	12.50×10^{-3}	68.3	293.3	85.5	589	38.3	264
	107	99.3	12.50	67.0	292.6	76.7	529	27.3	188
	108	100.8	12.67	66.0	292.0	108.0	744	56.7	388
	109	100.2	12.60	65.5	291.8	97.5	672	47.4	336
	110	99.6	12.53	65.5	291.8	90.5	623	39.3	271
	111	100.2	12.60	65.0	291.5	82.3	567	32.8	226
	112	100.2	12.60	64.5	291.2	77.6	535	26.0	179
	113	97.7	12.29	↓	↓	71.0	489	18.7	129
	114	100.2	12.60	↓	↓	74.5	524	18.7	129
	115	100.2	12.60	↓	↓	73.2	505	15.0	103
	116	100.2	12.60	↓	↓	72.0	496	11.3	78
	117	100.5	12.63	↓	↓	71.8	495	8.3	57
	118	100.2	12.60	64.3	291.1	70.7	487	5.1	35
16	119	99.9	12.56×10^{-3}	126.3	325.5	106.2	732	61.1	421
	120	100.2	12.60	126.7	325.7	95.2	656	50.0	345
	121	100.2	12.60	127.0	325.9	87.1	600	41.0	283
	122	99.9	12.56	126.5	325.6	78.2	539	32.7	225
	123	99.6	12.53	127.5	326.2	71.2	491	24.9	172
	124	99.6	12.53	127.0	325.9	64.8	446	18.7	129
	125	99.6	12.53	127.5	326.2	79.7	550	35.7	246
	126	100.5	12.63	128.0	326.5	63.6	438	18.8	130
	127	100.2	12.60	129.5	327.3	61.8	626	14.7	101
	128	100.2	12.60	128.0	326.5	65.5	451	10.0	69
	129	100.2	12.60	128.5	326.8	69.4	478	5.0	34
	130	99.3	12.50	133.0	329.3	63.8	440	11.0	76
	131	99.6	12.53	130.0	327.6	62.1	428	18.3	126
17	132	100.2	12.60×10^{-3}	189.0	360.4	85.2	587	42.2	291
	133	100.2	12.60	190.0	360.9	74.3	512	32.0	220
	134	100.5	12.63	188.5	360.1	74.0	510	29.0	200
	135	99.6	12.53	187.5	359.6	68.3	470	24.0	165
	136	99.9	12.56	187.5	359.6	72.2	498	18.6	128
	137	99.6	12.53	188.3	360.0	71.8	495	15.0	103
	138	99.9	12.56	188.0	359.8	75.8	522	11.1	76
	139	99.6	12.53	189.0	360.4	74.0	510	8.0	55
	140	100.8	12.67	192.5	362.3	75.0	517	7.6	52
18	141	99.9	12.56×10^{-3}	223.5	379.5	98.2	677	55.1	380
	142	99.9	12.56	223.0	379.3	87.8	605	43.3	298
	143	98.9	12.43	223.5	379.6	82.3	567	34.1	235
	144	99.3	12.50	225.0	380.4	85.3	588	25.4	175
	145	[a]100	[a]12.6	223.5	379.6	85.8	591	18.1	125
	146	100.5	12.63	220.0	377.6	83.8	577	11.2	77
	147	99.6	12.53	217.0	375.9	81.2	560	6.9	48
[b]19	148	80.2	10.09×10^{-3}	76.0	297.6	136.5	941	104.2	719
	149	79.6	10.01	73.5	296.2	122.0	841	88.7	611
	150	80.2	10.09	↓	↓	114.3	789	78.3	540
	151	80.2	10.09	↓	↓	102.5	706	66.8	460
	152	80.2	10.09	↓	↓	89.7	618	56.3	388
	153	79.6	10.01	↓	↓	82.4	568	46.8	322
	154	79.3	9.97	↓	↓	75.0	517	39.3	271
	155	80.5	10.13	74.0	296.5	69.0	475	33.8	226
	156	79.6	10.01	74.0	296.5	63.0	434	26.8	185
	157	79.6	10.01	74.0	296.5	54.8	378	18.7	129
	158	79.3	9.97	74.5	296.8	49.5	341	14.0	96
	159	79.3	9.97	74.5	296.8	47.8	329	9.3	64
	160	79.6	10.01	74.5	296.8	46.7	322	4.9	34

[a]Oscillation of ±6 percent.
[b]Water not degassed.

TABLE III. - EXPERIMENTAL BOILING DATA WITH 1.78-INCH (4.52-CM) PLUG

(a) U.S. customary units

Series	Run	Boiling fluid									Heating rate, Q, Btu/hr	Heating fluid		
		Flow rate, W_b, lbm/hr	Temperature, °F			Pressure, psia				Exit quality, x_e		Flow rate, W_h, lbm/hr	Temperature, °F	
			Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}	Exit plenum, P_{bp}				Inlet, T_{hi}	Exit, T_{he}
20	161	79.9	233.0	227.3	232.0	75.3	46.6	44.2	45	Liquid	---------	8140	231.9	232.0
	162	79.6	232.0	228.5	233.0	60.3	29.1	27.0	27.8	Liquid	0.08×10^3	8120	233.3	233.2
	163	80.5	232.2	226.7	230.8	63.6	22.1	20.9	21.2	0.01	.8	8140	233.7	233.6
	164	80.2	230.0	214.5	221.5	62.3	18.6	17.4	17.6	.08	6	8140	231.4	230.7
	165	80.8	227.5	195.7	204.0	60.1	15.0	12.4	12.7	.21	15	8140	233.2	231.5
	166	79.6	227.5	183.5	193.0	58.5	14.1	9.6	10.0	.32	21	8160	233.3	230.7
	167	80.2	226.0	168.5	176.5	59.3	13.2	6.8	6.9	.33	22	8160	235.3	232.6
	168	80.2	225.0	160.3	167.8	58.2	13.1	5.6	5.8	.39	26	8160	234.6	231.5
	169	80.2	224.0	141.5	144.0	58.5	12.8	3.3	2.9	.44	29	8150	233.5	230.0
21	170	79.9	230.5	255.3	260.5	80.3	52.7	49.8	51	Liquid	2.4×10^3	8040	260.2	260.0
	171	79.9	229.0	255.0	260.8	72.7	43.4	41.8	42.7	Liquid	2.6	8040	260.7	260.3
	172	80.5	223.5	242.0	249.5	61.4	30.2	28.7	29.5	0.04	5	8050	260.0	259.4
	173	80.2	229.0	213.3	221.5	62.7	20.2	17.1	17.5	.19	14	8040	262.3	259.7
	174	80.5	230.0	193.0	204.0	61.0	17.3	12.3	12.3	.40	30	8020	265.0	261.3
	175	80.2	228.0	182.0	191.0	59.9	17.4	9.2	9.5	.49	35	↓	264.3	260.0
	176	80.5	229.3	167.5	174.5	61.2	17.2	6.4	6.4	.51	36	↓	265.0	260.5
	177	80.5	227.6	147.7	146.5	61.2	17.1	4.1	3.2	.54	38	↓	266.0	261.4
22	178	79.3	234.0	289.0	291.2	92.0	67.0	----	65	Liquid	4.6×10^3	7980	291.6	291.0
	179	79.6	235.5	285.5	286.2	80.9	55.2	----	53.5	0.02	5.6	7960	290.7	290.0
	180	79.9	236.0	264.0	267.0	67.3	39.8	38.6	39.6	.10	18	7980	292.3	290.2
	181	[a]80	234	234.5	240	66.0	27.6	23.9	24.5	.45	34	8000	294.8	290.6
	182	79.6	230.0	216.0	222.0	63.0	23.7	17.0	17.5	.60	46	8020	294.4	288.8
	183	80.5	230.0	187.5	190.5	63.3	21.5	8.8	9.2	.75	56	8020	295.4	288.6
	184	80.2	231.5	171.0	168.8	62.0	21.3	5.7	5.7	.79	58	8000	297.3	290.2
	185	79.3	242.0	159.0	150.0	62.2	21.7	4.7	3.3	.83	59	8020	298.2	290.8
23	186	80.2	265.5	262.0	265.3	89.8	64.8	----	63.7	Liquid	---------	8020	265.3	265.1
	187	79.6	266.5	262.0	265.8	77.6	52.3	49.6	50.3	Liquid	---------	8040	265.8	265.8
	188	80.2	262.3	262.5	267.3	78.7	42.1	40.3	41.6	0	0.8×10^3	8040	267.4	267.3
	189	79.9	258.7	255.3	260.5	73.2	35.8	34.2	35.2	0.03	2	8020	264.0	263.7
	190	79.9	253.5	228	236.3	67.4	24.2	22.4	23.0	.22	15	8040	261.0	259.2
	191	79.9	254.0	223.3	221.8	66.0	20.4	17.2	17.5	.34	23	8040	262.0	259.2
	192	80.8	255.0	192.3	198.0	66.2	18.1	10.7	11.0	.49	34	8030	265.0	260.8
	193	79.9	252.5	173.0	177.3	66.0	17.5	6.7	6.7	.54	37	8030	265.0	260.5
	194	79.0	253.5	151.5	148.5	64.0	17.0	3.8	3.2	.61	40	8020	263.5	258.6

[a]Drifting, ±8 percent.

TABLE III. - Continued. EXPERIMENTAL BOILING DATA WITH 1.78-INCH (4.52-CM) PLUG

(a) Concluded. U.S. customary units

Series	Run	Boiling fluid									Heating rate, Q, Btu/hr	Heating fluid		
		Flow rate, W_b, lbm/hr	Temperature, °F			Pressure, psia				Exit quality, x_e		Flow rate, W_h, lbm/hr	Temperature, °F	
			Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}	Exit plenum, P_{bp}				Inlet, T_{hi}	Exit, T_{he}
24	195	79.6	265.0	286.0	288.2	116.0	91.3	----	89.6	Liquid	1.9×10^3	7990	289.3	289.0
	196	79.9	268.0	285.5	289.2	101.2	76.0	----	74.6	Liquid	1.8	8010	290.3	290.0
	197	[b]79.6	269.5	285.0	289.7	91.5	66.2	----	64.8	Liquid	1.7	8010	290.6	290.3
	198	[c]79	268.5	279.3	286.2	81.5	55.2	----	53.8	0.04	4	8010	290.5	290.0
	199	79.3	263.5	266.0	271.3	76.7	44.0	42.8	43.7	.12	9.6	8030	290.6	289.4
	200	[b]80.5	260.0	249	259.8	76.0	35.6	34.0	34.6	.30	22	7990	293.2	290.5
	201	[b]80.2	253.5	229	240.0	69.4	28.4	24.2	25.0	.46	34	↓	294.8	290.6
	202	81.1	252.0	210	221.0	67.3	24.2	17.1	17.5	.66	49	↓	295.4	289.5
	203	80.2	249.5	187.5	195.0	64.0	22.2	9.7	10.1	.79	57	↓	296.5	289.5
	204	80.2	250.0	171	176.5	64.1	22.0	6.6	6.6	.83	60	7970	297.8	290.5
	205	79.3	250.0	154	148.7	64.1	21.9	4.8	3.3	.85	61	7990	298.2	290.8
25	206	80.2	262.0	317.5	318.0	124.5	97.9	----	96.2	Liquid	4.8×10^3	7960	321.4	320.7
	207	79.6	265.5	313.5	315.0	109.5	83.8	----	82.6	0.07	9	7950	322.5	321.5
	208	79.9	261.0	307	308.4	101.5	75.3	----	74.7	.06	8	7970	320.8	319.8
	209	79.6	270.0	293	295.0	90.8	64.3	----	63.6	.20	17	7980	322.6	320.6
	210	[d]80.2	258.5	275	282.0	77.0	50.0	48.2	49.3	.35	29	7930	324.8	321.4
	211	[d]79.6	256.5	252.5	261.5	75.7	38.8	34.8	35.5	.64	48	7930	326.2	320.4
	212	[e]79.9	252.5	232	239.7	71.2	31.5	24.0	24.8	.83	62	7920	326.5	319.0
	213	79.6	254.0	213	221.0	67.1	27.7	16.7	17.3	.92	68	7960	326.7	318.5
	214	79.6	254.7	231	245.0	66.8	26.7	14.3	14.7	.92	68	7960	328.2	320.0
	215	80.2	250.7	230	246.5	66.8	25.9	11.1	12.0	.90	67	7930	327.5	319.5
	216	80.2	250.0	228	244.5	66.7	25.4	8.1	9.3	.92	68	7930	327.8	319.5
	217	79.9	250.0	232	246.5	66.3	25.2	5.7	6.7	.92	66	7930	328.7	320.7
	218	79.9	247.5	206 to 219	239.0	67.2	25.3	4.5	4.9	.94	68	7950	328.5	320.2
	219	79.9	249.5	210 to 224	237.3	69.1	25.1	4.2	3.4	.96	70	7950	328.5	320.0
26	220	87.1	260.5	157.7	147.0	75.8	21.2	4.7	3.2	0.73	50×10^3	1460	352.0	319.4
	221	86.2	262.0	159	148.0	77.2	24.2	4.9	↓	.85	65	2720	349.5	326.7
	222	86.4	265.0	~173	221.0	77.3	25.8	4.3	↓	.93	71	3860	350.0	332.3
	223	84.9	267.5	240.3	248	77.2	26.3	4.4	↓	.92	69	4950	350.2	336.6
	224	[d]84.6	266.0	255.7	265	77.2	27.2	4.7	3.1	.95	72	6840	349.2	339.2

[b]Oscillations of ±5 to ±6 percent.
[c]Drifting, ±8 percent.
[d]Oscillations of ±7 to ±9 percent.
[e]Oscillations of ±5 percent.

TABLE III. - Continued. EXPERIMENTAL BOILING DATA WITH 1.78-INCH (4.52-CM) PLUG

(b) SI units

Series	Run	Boiling fluid: Flow rate, W_b, kg/sec	Boiling fluid: Temperature, K: Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Boiling fluid: Pressure, kN/m^2 abs: Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}	Exit plenum, P_{bp}	Exit quality, x_e	Heating rate, Q, kW	Heating fluid: Flow rate, W_h, kg/sec	Heating fluid: Temperature, K: Inlet, T_{hi}	Exit, T_{he}
20	161	10.07×10^{-3}	384.8	381.7	384.3	519	321	305	310	Liquid	-----	1.026	384.2	384.3
	162	10.03	384.3	382.3	384.8	416	201	186	192	Liquid	0.02	1.023	385.0	384.9
	163	10.14	384.4	381.3	383.6	438	152	144	146	0.01	.2	1.026	385.2	385.2
	164	10.11	383.2	374.6	378.4	430	128	120	121	.08	1.7	1.026	383.9	383.6
	165	10.18	381.8	364.1	368.7	414	103	86	88	.21	4.4	1.026	384.9	384.0
	166	10.03	381.8	357.3	362.6	403	97	66	69	.32	6.2	1.028	385.0	383.6
	167	10.11	380.9	349.0	353.4	409	91	47	48	.33	6.4	1.028	386.1	384.6
	168	10.11	380.4	344.4	348.6	401	90	39	40	.39	7.6	1.028	385.7	384.0
	169	10.11	379.8	334.0	335.4	403	88	23	20	.44	8.5	1.027	385.1	383.2
21	170	10.07×10^{-3}	383.4	397.2	400.1	554	363	343	352	Liquid	0.70	1.013	399.9	399.8
	171	10.07	382.6	397.1	400.3	501	299	288	294	Liquid	.76	1.013	400.2	400.0
	172	10.14	379.6	389.8	394.1	423	208	198	203	0.04	1.5	1.014	399.8	399.5
	173	10.11	382.6	373.9	378.4	432	139	118	121	.19	4.1	1.013	401.1	399.7
	174	10.14	383.2	362.6	368.7	421	119	85	85	.40	8.8	1.011	402.6	400.6
	175	10.11	382.1	356.5	361.5	413	120	63	66	.49	10.3	↓	402.2	399.8
	176	10.14	382.8	348.4	352.3	422	119	44	44	.51	10.5		402.6	400.1
	177	10.14	381.8	337.4	336.8	422	118	28	22	.54	11.1		403.2	400.6
22	178	9.99×10^{-3}	385.4	415.9	417.2	634	462	---	448	Liquid	1.3	1.005	417.4	417.1
	179	10.03	386.2	414.0	414.4	558	381	---	369	0.02	1.6	1.003	416.9	416.5
	180	10.07	386.5	402.1	403.7	464	274	266	273	.10	5.3	1.005	417.8	416.6
	181	[a]10.1	385.4	385.7	388.7	455	190	165	169	.45	10.0	1.008	419.2	416.8
	182	10.03	383.2	375.4	378.7	434	163	117	121	.60	13.5	1.011	418.9	415.8
	183	10.14	383.2	359.6	361.2	436	148	61	63	.75	16.4	1.011	419.5	415.7
	184	10.11	384.0	350.4	349.2	428	147	39	39	.79	17.0	1.008	420.6	416.6
	185	9.99	389.8	343.7	338.7	429	150	32	23	.83	17.3	1.011	421.1	416.9
23	186	10.11×10^{-3}	402.9	400.9	402.8	619	447	---	439	Liquid	-----	1.011	402.8	402.7
	187	10.03	403.4	400.9	403.1	535	361	342	347	Liquid	-----	1.013	403.1	403.1
	188	10.11	401.1	401.2	403.9	543	290	278	287	0	0.2	1.013	403.9	403.9
	189	10.07	399.1	397.2	400.1	505	247	236	243	.03	.6	1.011	402.1	401.9
	190	10.07	396.2	382.1	386.7	465	167	154	159	.22	4.4	1.013	400.4	399.4
	191	10.07	396.5	379.4	378.6	455	141	119	121	.34	6.7	1.013	400.9	399.4
	192	10.18	397.1	362.2	365.4	456	125	74	76	.49	10	1.012	402.6	400.3
	193	10.07	395.6	351.5	353.9	455	121	46	46	.54	11	1.012	402.6	400.1
	194	9.95	396.2	339.6	337.9	441	117	26	22	.61	12	1.011	401.8	399.1

[a]Drifting, ±8 percent.

TABLE III. - Concluded. EXPERIMENTAL BOILING DATA WITH 1.78-INCH (3.52-CM) PLUG

(b) Concluded. SI units

Series	Run	Boiling fluid									Heating rate, Q, kW	Heating fluid		
		Flow rate, W_b, kg/sec	Temperature, K			Pressure, kN/m^2 abs				Exit quality, x_e		Flow rate, W_h, kg/sec	Temperature, K	
			Nozzle inlet, T_{ni}	Boiler exit, T_{be}	Exit plenum, T_{bp}	Nozzle inlet, P_{ni}	Boiler inlet, P_{bi}	Boiler exit, P_{be}	Exit plenum, P_{bp}				Inlet, T_{hi}	Exit, T_{he}
24	195	10.03×10^{-3}	402.6	414.3	415.5	800	630	---	618	Liquid	0.6	1.007	416.1	415.9
	196	10.07	404.3	414.0	416.1	698	524	---	514	Liquid	.5	1.009	416.7	416.5
	197	[b]10.0	405.1	413.7	416.3	631	456	---	447	Liquid	.5	1.009	416.8	416.7
	198	[c]10.0	404.6	410.6	414.4	562	381	---	371	0.04	1.2	1.009	416.8	416.5
	199	9.99	401.8	403.2	406.1	529	303	295	301	.12	2.8	1.012	416.8	416.2
	200	[b]10.1	399.8	393.7	399.7	524	245	234	239	.30	6.4	1.007	418.3	416.8
	201	[b]10.1	396.2	382.6	388.7	479	196	167	172	.46	10	↓	419.2	416.9
	202	10.22	395.4	372.1	378.2	464	167	118	121	.66	14	↓	419.5	416.2
	203	10.11	394.0	359.6	363.7	441	153	67	70	.79	17	↓	420.1	416.2
	204	10.11	394.3	350.4	353.4	442	152	46	46	.83	18	1.004	420.8	416.8
	205	9.99	394.3	340.9	338	442	151	33	23	.85	18	1.007	421.1	416.9
25	206	10.11×10^{-3}	400.9	431.8	432.1	858	675	---	663	Liquid	1.4	1.003	433.9	433.6
	207	10.03	402.9	429.6	430.4	755	578	---	570	0.07	2.6	1.002	434.6	434.0
	208	10.07	400.4	425.9	426.7	700	519	---	515	.06	2.3	1.004	433.6	433.1
	209	10.03	405.4	418.2	419.3	626	443	---	439	.20	5.0	1.005	434.6	433.5
	210	[d]10.1	399.0	408.2	412.1	531	345	332	340	.35	8.5	.999	435.8	433.9
	211	[d]10.0	397.9	395.7	400.7	522	268	240	245	.64	14	.999	436.6	433.4
	212	[e]10.1	395.7	384.3	388.6	491	217	165	171	.83	18	.998	436.8	432.6
	213	10.03	396.5	373.7	378.2	463	191	115	119	.92	20	1.003	436.9	432.3
	214	10.03	396.9	383.7	391.5	461	184	99	101	.92	20	1.003	437.7	433.2
	215	10.11	394.7	383.2	392.3	461	179	77	83	.90	20	.999	437.3	432.9
	216	10.11	394.3	382.1	391.2	460	175	56	64	.92	20	.999	437.5	432.9
	217	10.07	394.3	384.3	392.3	457	174	39	46	.92	19	.999	438.0	433.6
	218	10.07	392.9	369.8 to 377.1	388.2	463	174	31	34	.94	20	1.002	437.9	433.3
	219	10.07	394.0	372.1 to 379.8	387.2	476	173	29	23	.96	21	1.002	437.9	433.2
26	220	10.97×10^{-3}	400.1	343.0	337.1	523	146	32	22	0.73	15	0.184	450.9	432.8
	221	10.86	400.9	343.7	337.6	532	167	34	22	.85	19	.343	449.6	436.9
	222	10.89	402.6	351.5	378.2	533	178	30	22	.93	21	.486	449.8	440.0
	223	10.70	404.0	388.9	393.2	532	181	30	22	.92	20	.624	449.9	442.4
	224	[d]10.7	403.2	397.4	402.6	532	188	32	21	.95	21	.862	449.4	443.8

[b]Oscillations of ±5 to ±6 percent.
[c]Drifting, ±8 percent.
[d]Oscillations of ±7 to ±9 percent.
[e]Oscillations of ±5 percent.

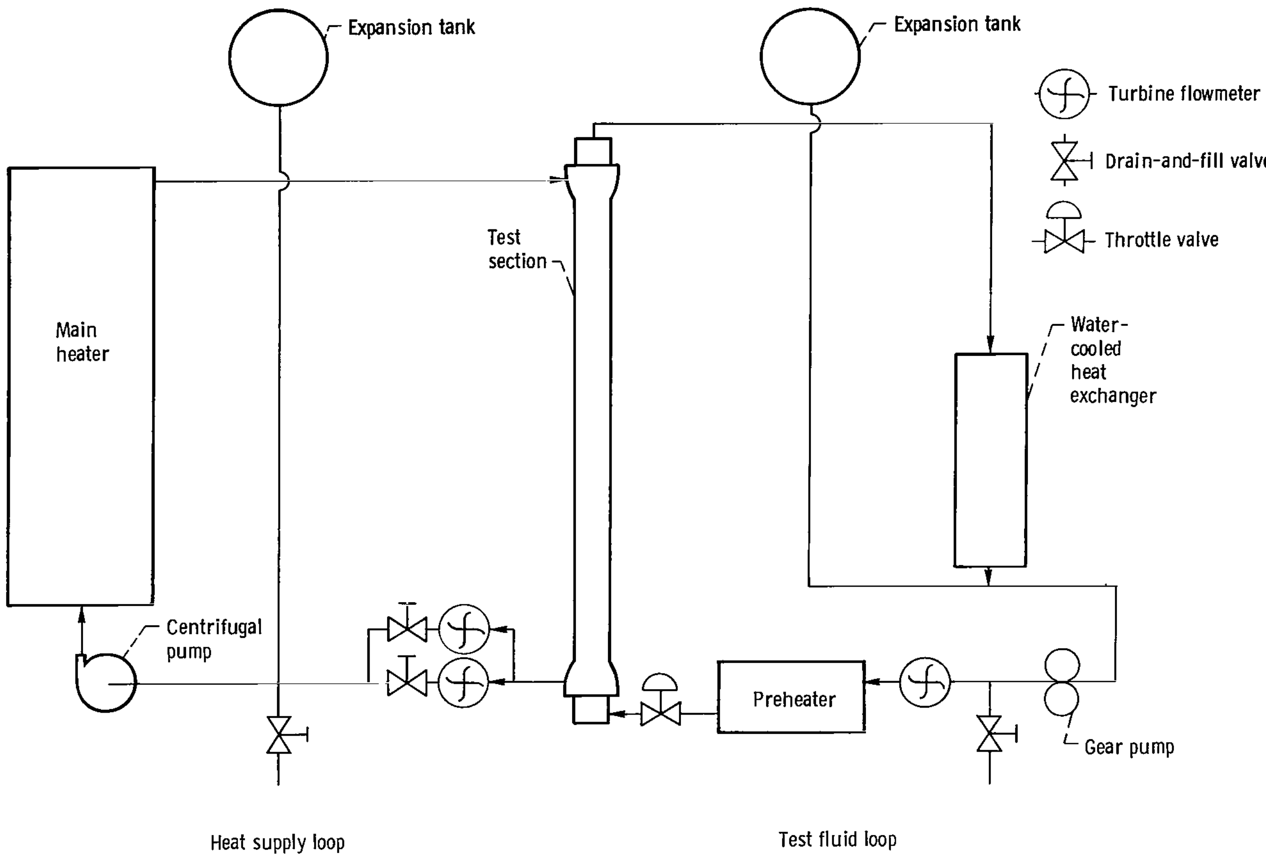


Figure 1. - Schematic diagram of test apparatus.

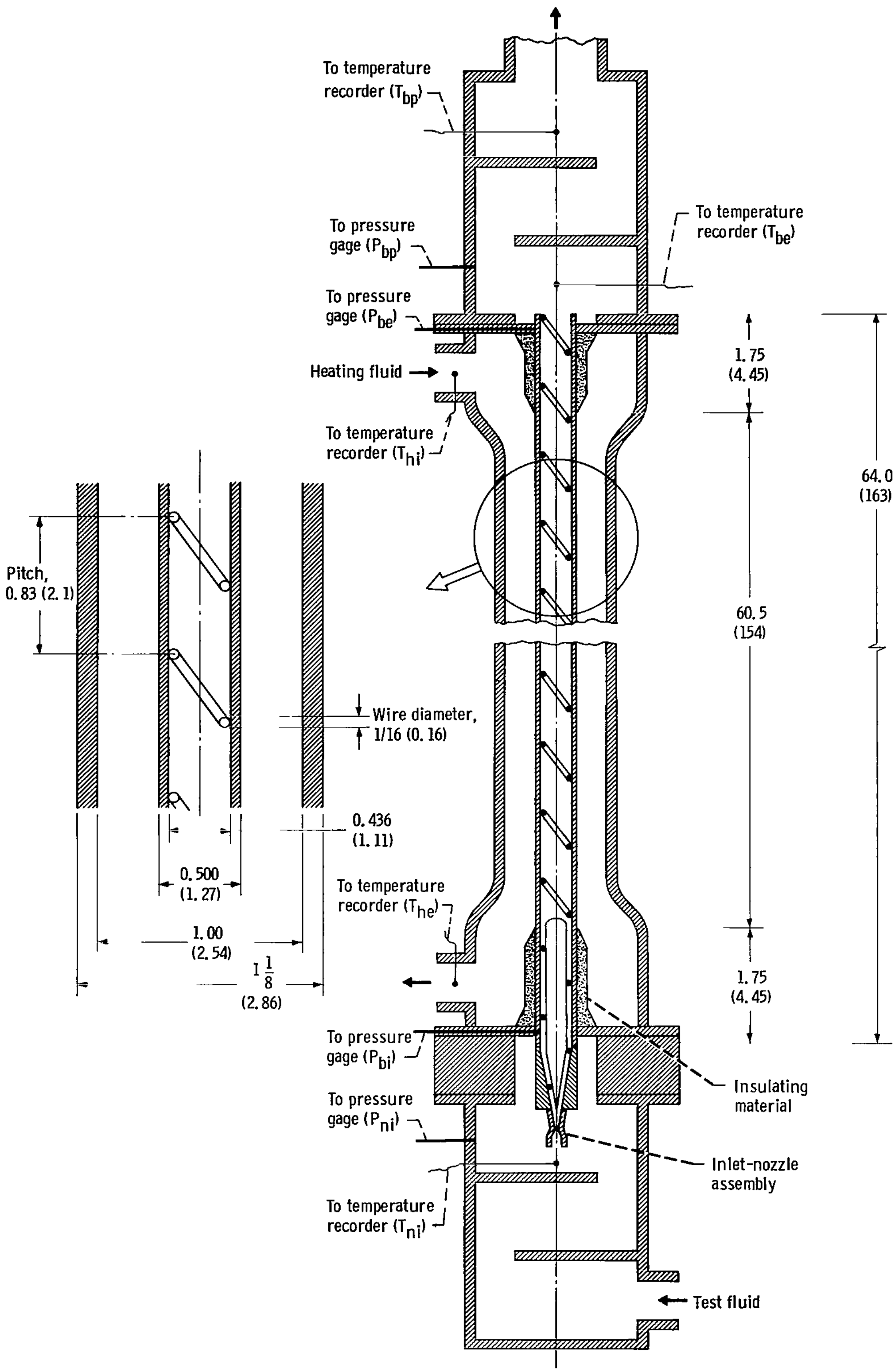
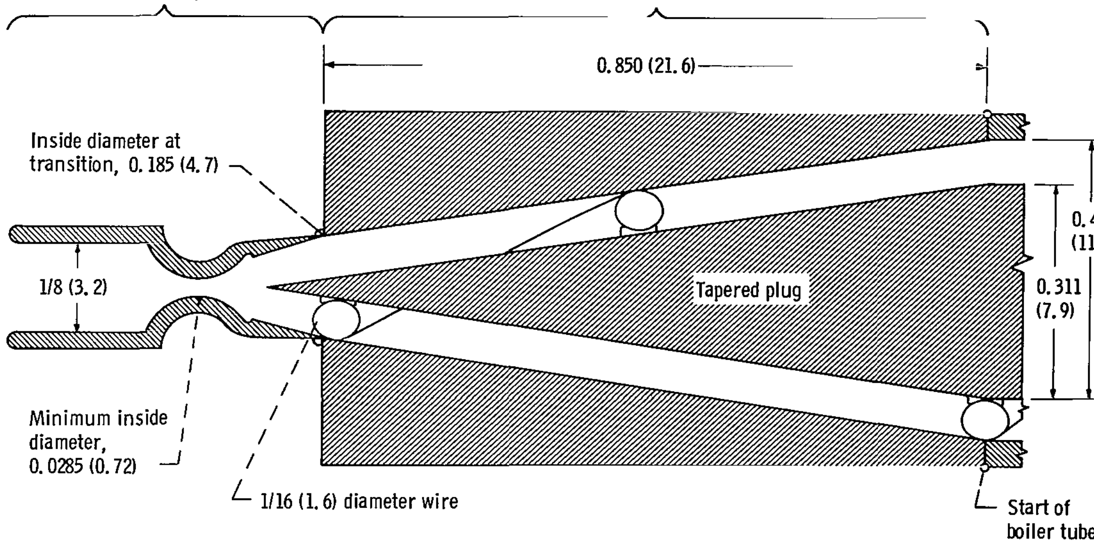
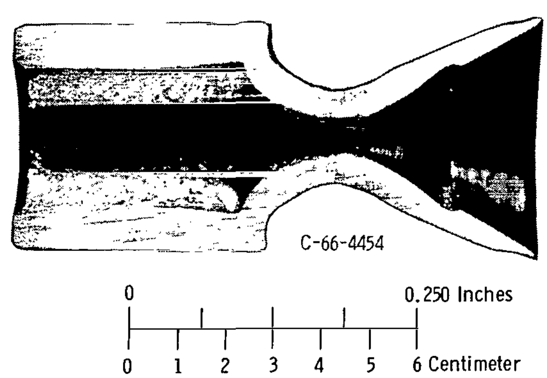


Figure 2. - Diagram of test section and plenum chambers, showing instrumentation. (Dimensions are in inches (cm).)

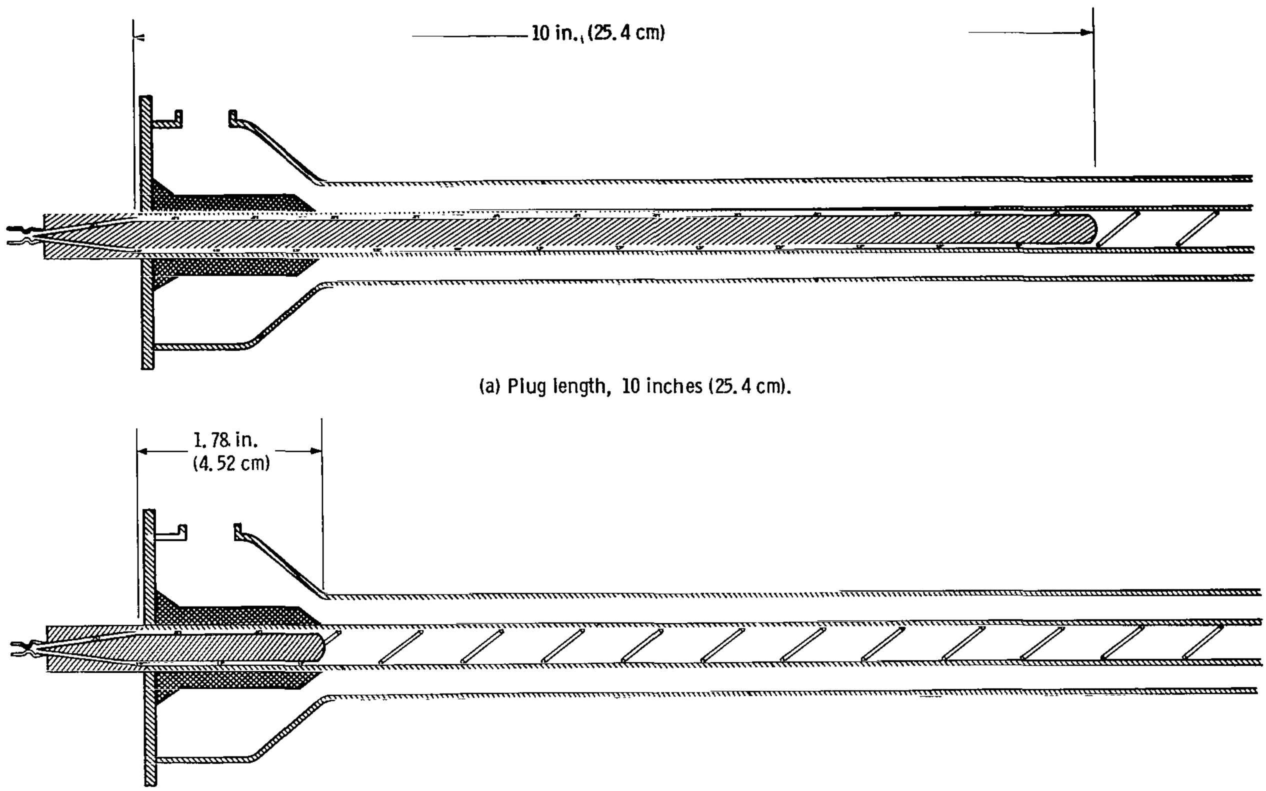


(a) Diagram of nozzle assembly, showing dimensions in inches (mm).



(b) Throat section.

Figure 3. - Inlet nozzle.



(a) Plug length, 10 inches (25.4 cm).

(b) Plug length, 1.78 inches (4.52 cm).

Figure 4. - Inlet end of test section, showing inlet nozzle and two different-length inlet-region plugs.

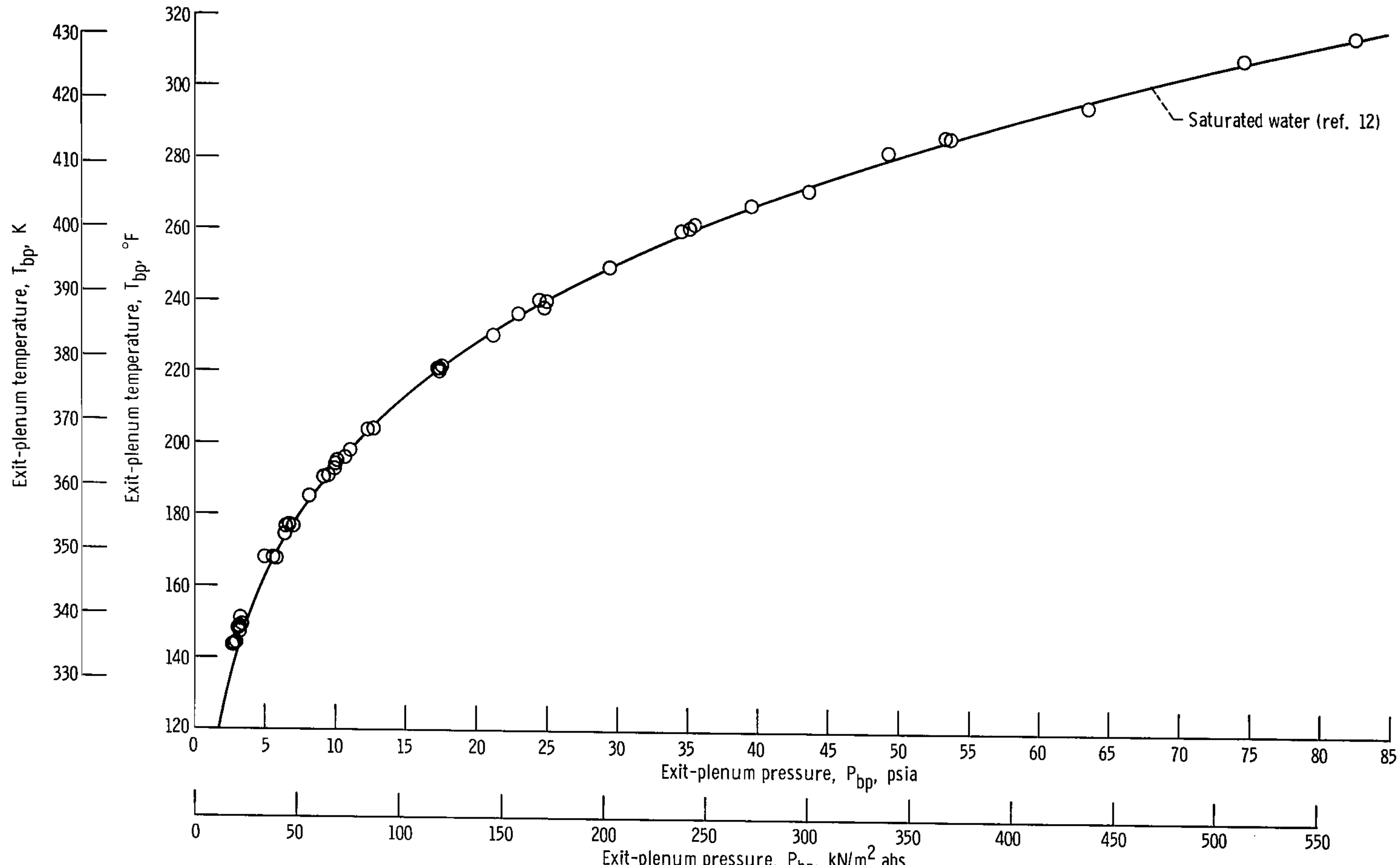
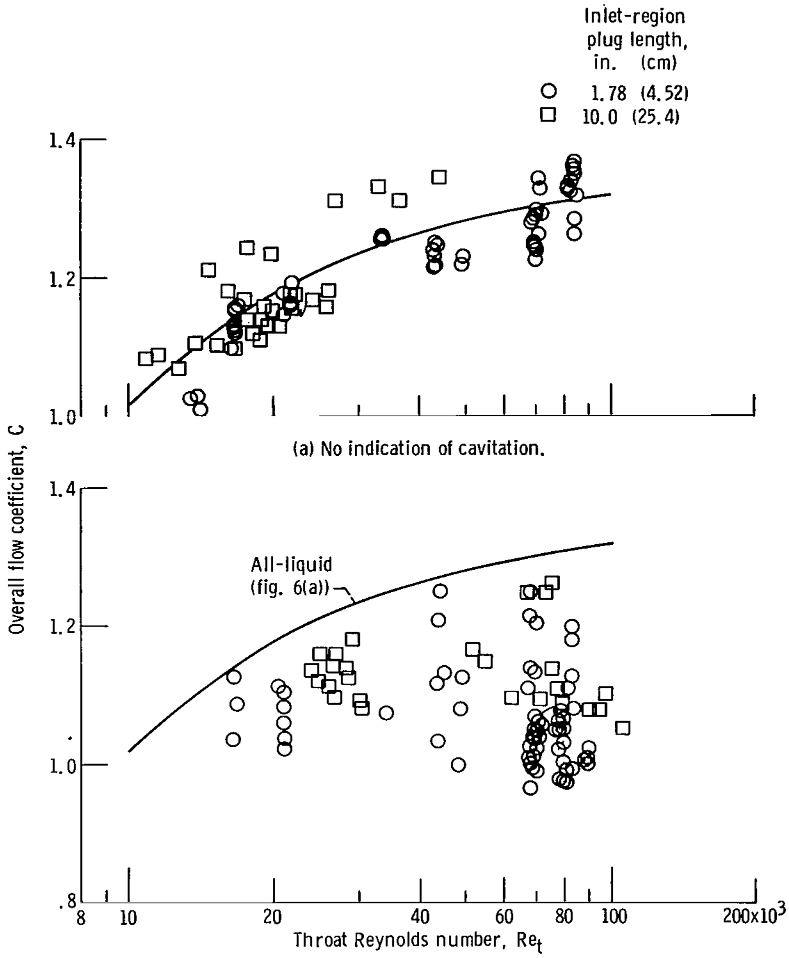


Figure 5. - Comparison of exit-plenum temperature and pressure measurements for equilibrium two-phase conditions.



(b) With cavitation or flashing.

Figure 6. - Overall flow coefficient of inlet nozzle as function of throat Reynolds number.

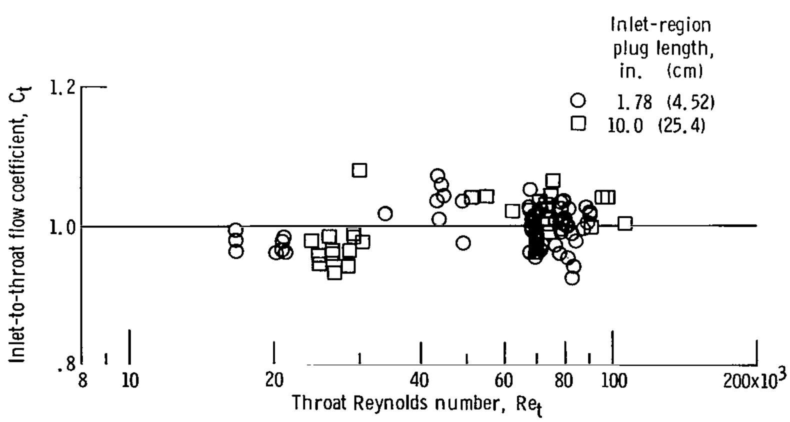
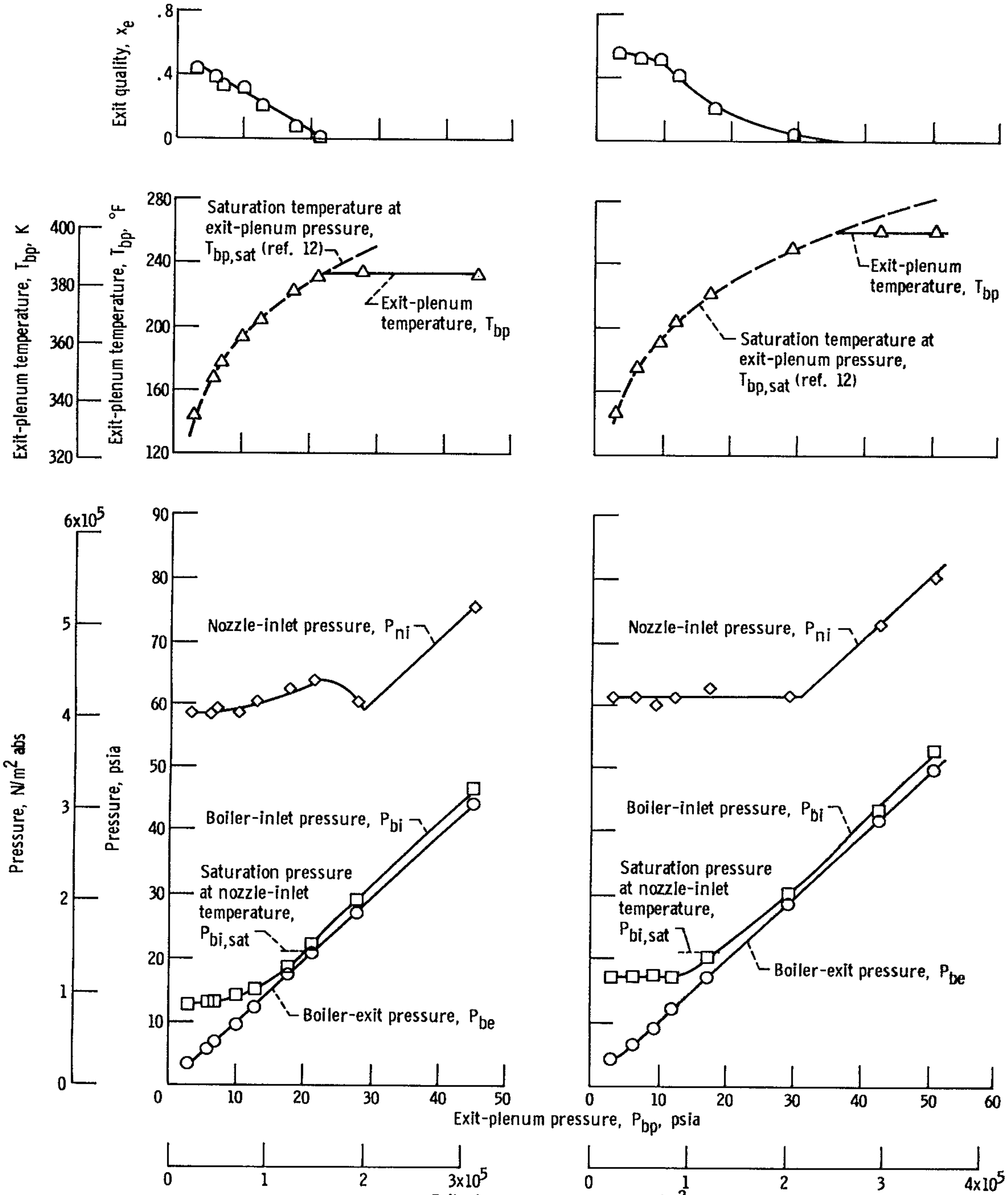


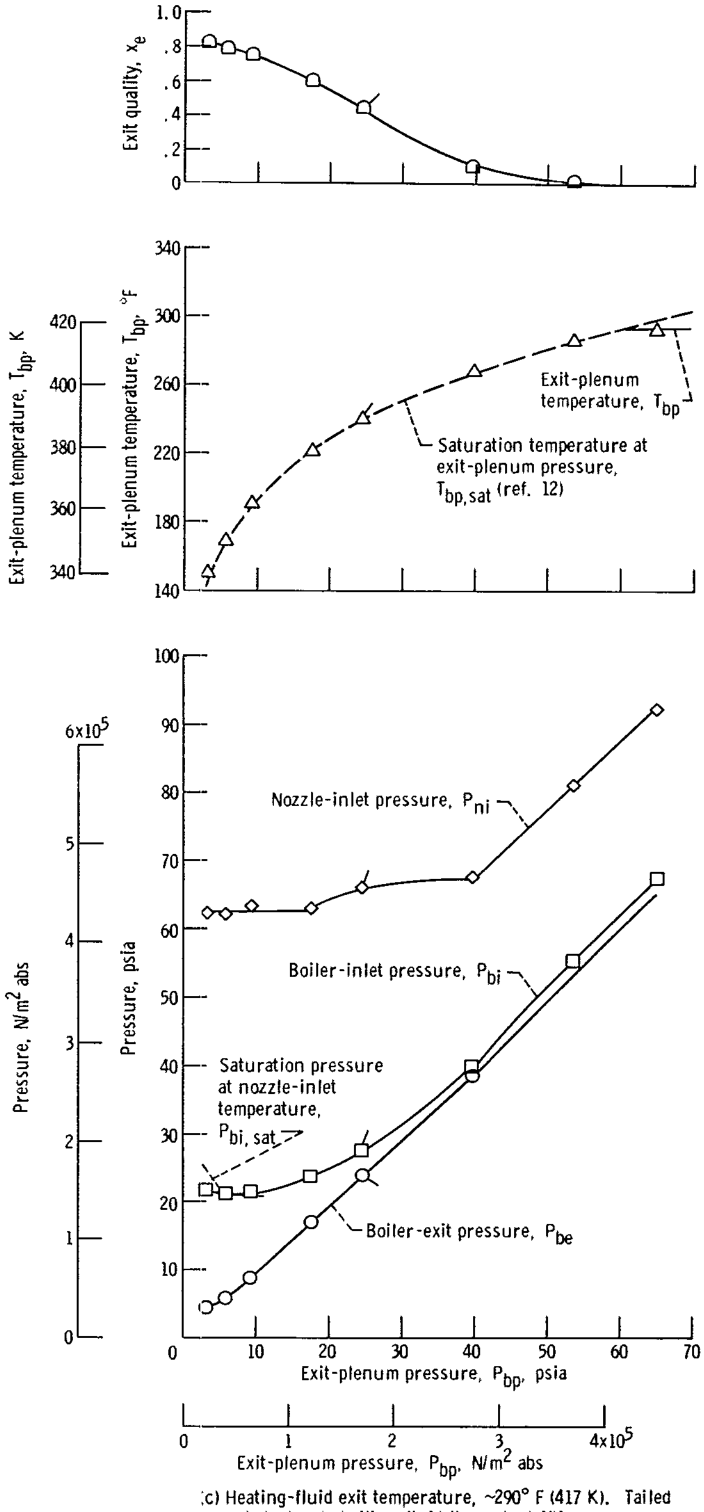
Figure 7. - Nozzle inlet-to-throat flow coefficient with vaporiation (eqs. (4) and (5)) as function of throat Reynolds number.



(a) Heating-fluid exit temperature, ~232° F (385 K).

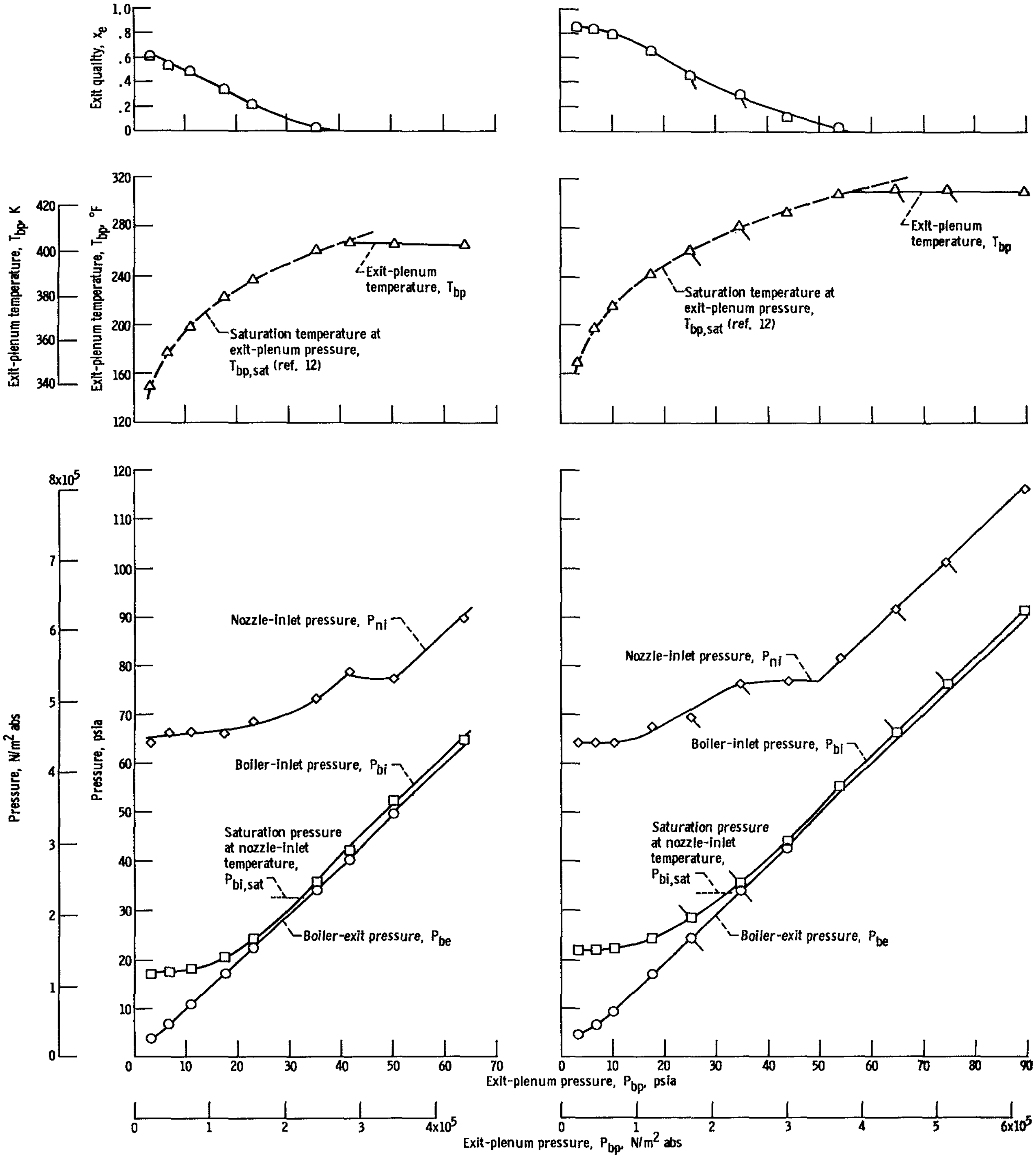
(b) Heating-fluid exit temperature, ~260° F (400 K).

Figure 8. - General performance of boiler with short plug (1.78 in. or 4.52 cm) at nozzle-inlet temperature of ~230° F (384 K). Boiling-fluid flow rate, ~80 pounds mass per hour (0.010 kg/sec); heating-fluid flow rate, ~8000 pounds mass per hour (1.0 kg/sec).



(c) Heating-fluid exit temperature, ~290° F (417 K). Tailed symbols denote boiling-fluid flow rate drifting.

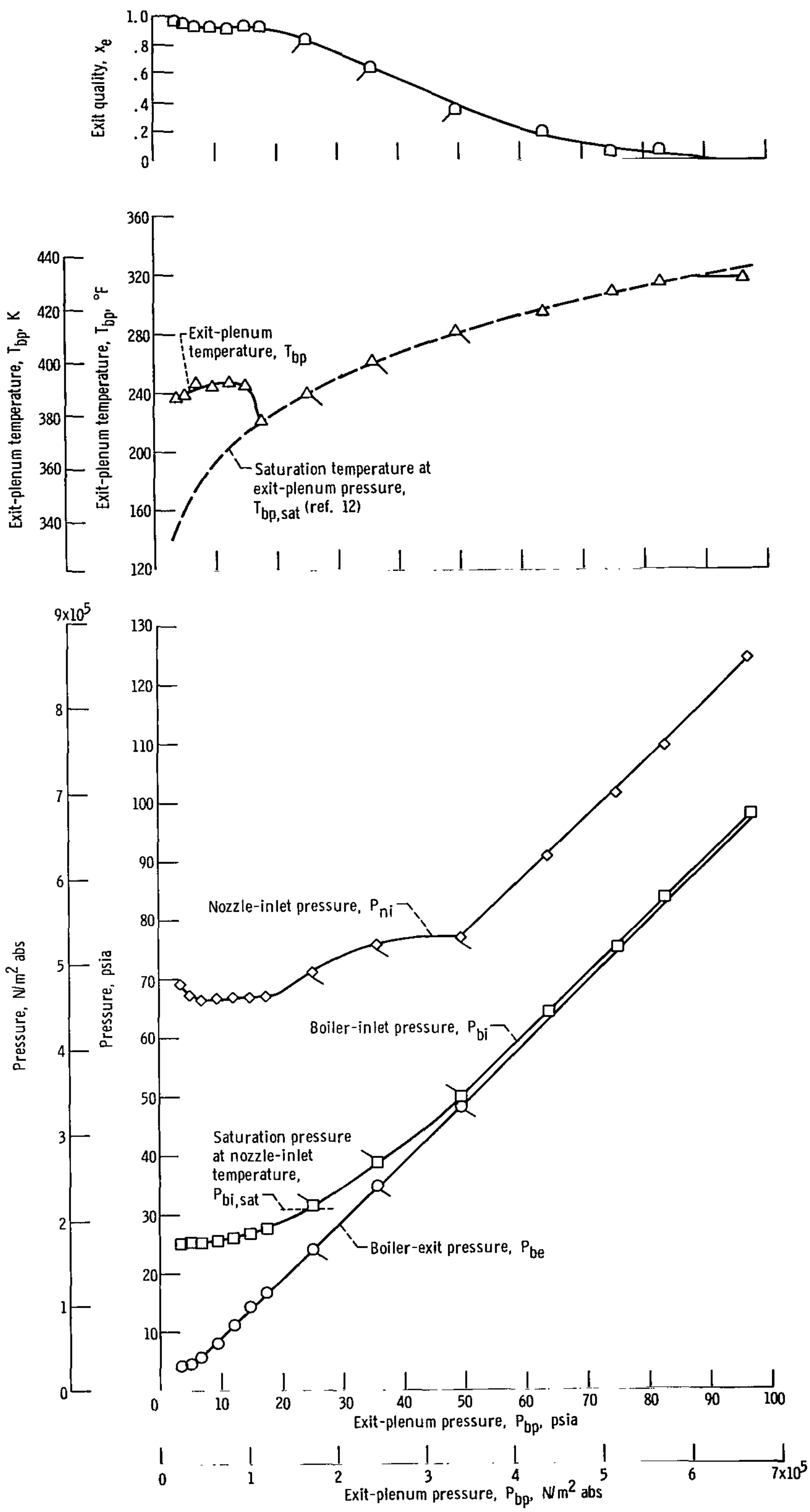
Figure 8. - Concluded.



(a) Heating-fluid exit temperature, ~260° F (400 K).

(b) Heating-fluid exit temperature, ~290° F (417 K). Tailed symbols denote boiling-fluid flow rate oscillations of ±5 percent or greater.

Figure 9. - General performance of boiler with short plug (1.78 in. or 4.52 cm) at nozzle-inlet temperature of ~260° F (400 K). Boiling-fluid flow rate, ~80 pounds mass per hour (0.010 kg/sec); heating-fluid flow rate, ~8000 pounds mass per hour (1.0 kg/sec).



(c) Heating-fluid exit temperature, ~320° F (433 K). Tailed symbols denote boiling-fluid flow rate oscillations of ±5 percent or greater.

Figure 9. - Concluded.

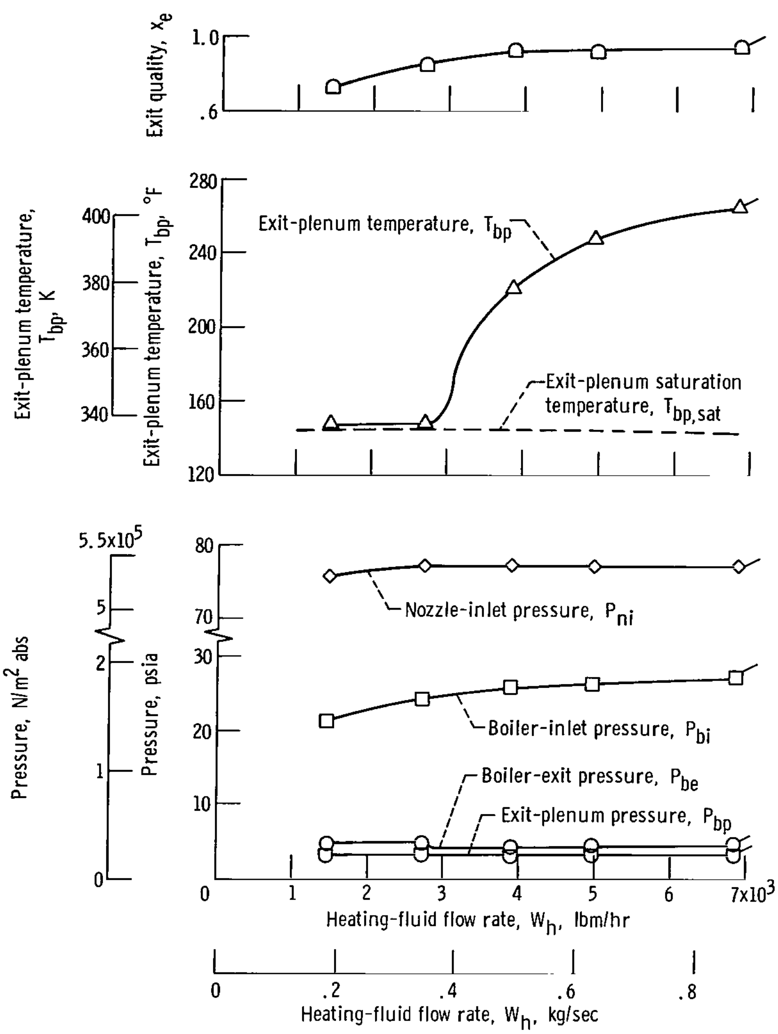


Figure 10. - General performance of boiler with short plug (1.78 in. or 4.52 cm) for variable heating-fluid flow rate. Boiling-fluid flow rate, ~85 pounds mass per hour (0.011 kg/sec); nozzle-inlet temperature, ~265° F (403 K); heating-fluid inlet temperature, ~350° F (450 K). Tailed symbols denote boiling-fluid flow rate oscillations of ±5 percent or greater.

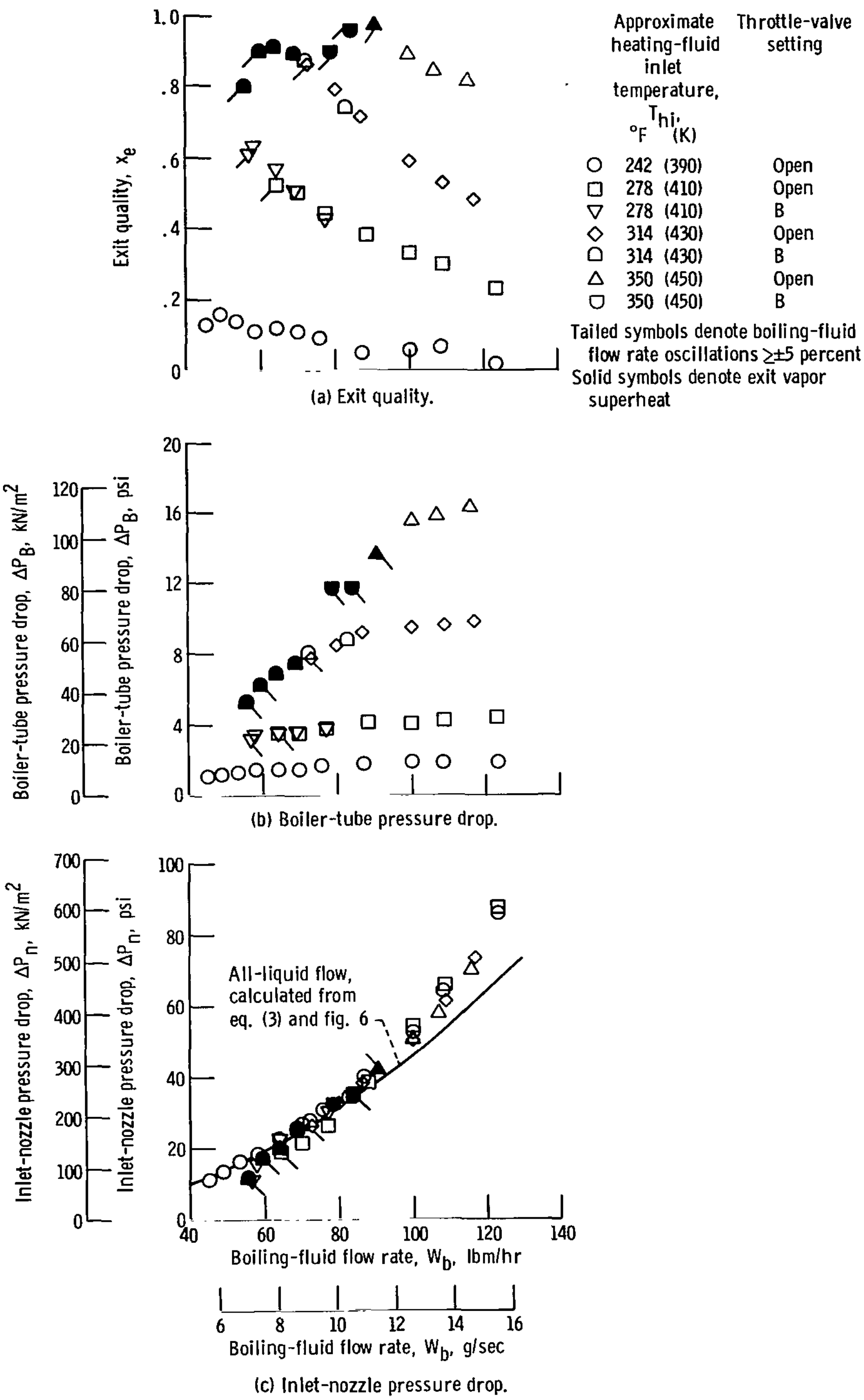


Figure 11. - Boiler performance as function of boiling-fluid flow rate at boiling-fluid inlet temperature of ~80° F (300 K). Heating-fluid flow rate, ~10 000 pounds mass per hour (1.26 kg/sec); boiler-exit pressure, ~16.5 psia (114 kN/m^2); 10-inch (25.4-cm) plug.

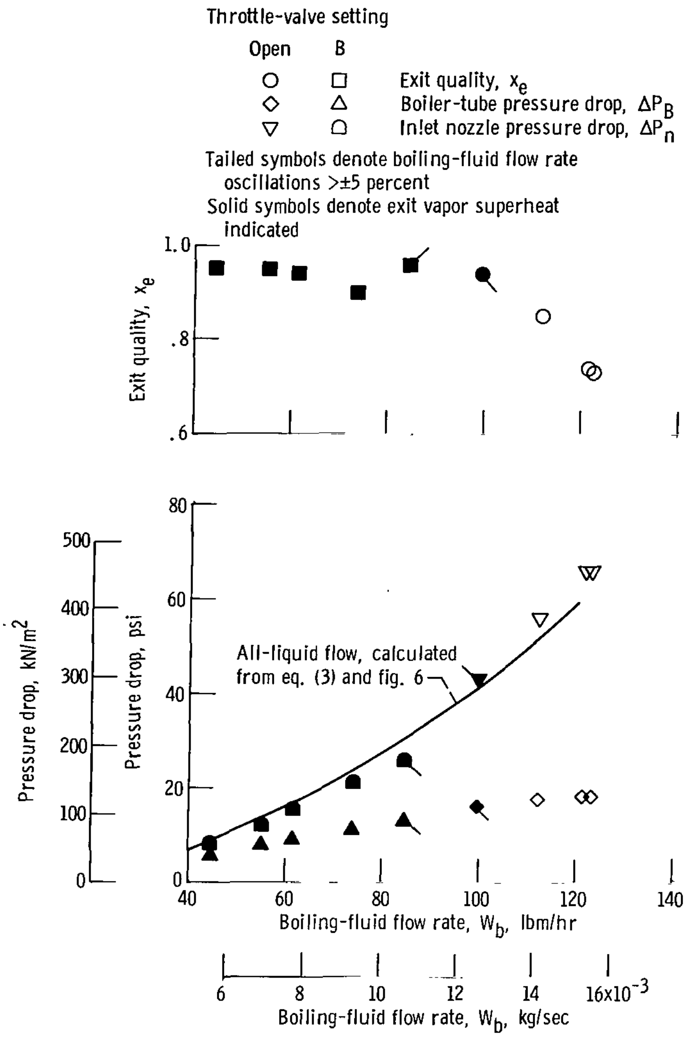


Figure 12. - Boiler performance as function of boiling-fluid flow rate at boiling-fluid inlet temperature of ~170° F (350 K). Heating-fluid flow rate, ~10 000 pounds mass per hour (1.26 kg/sec); heating-fluid inlet temperature, ~350° F (450 K); 10-inch (25.4-cm) plug.

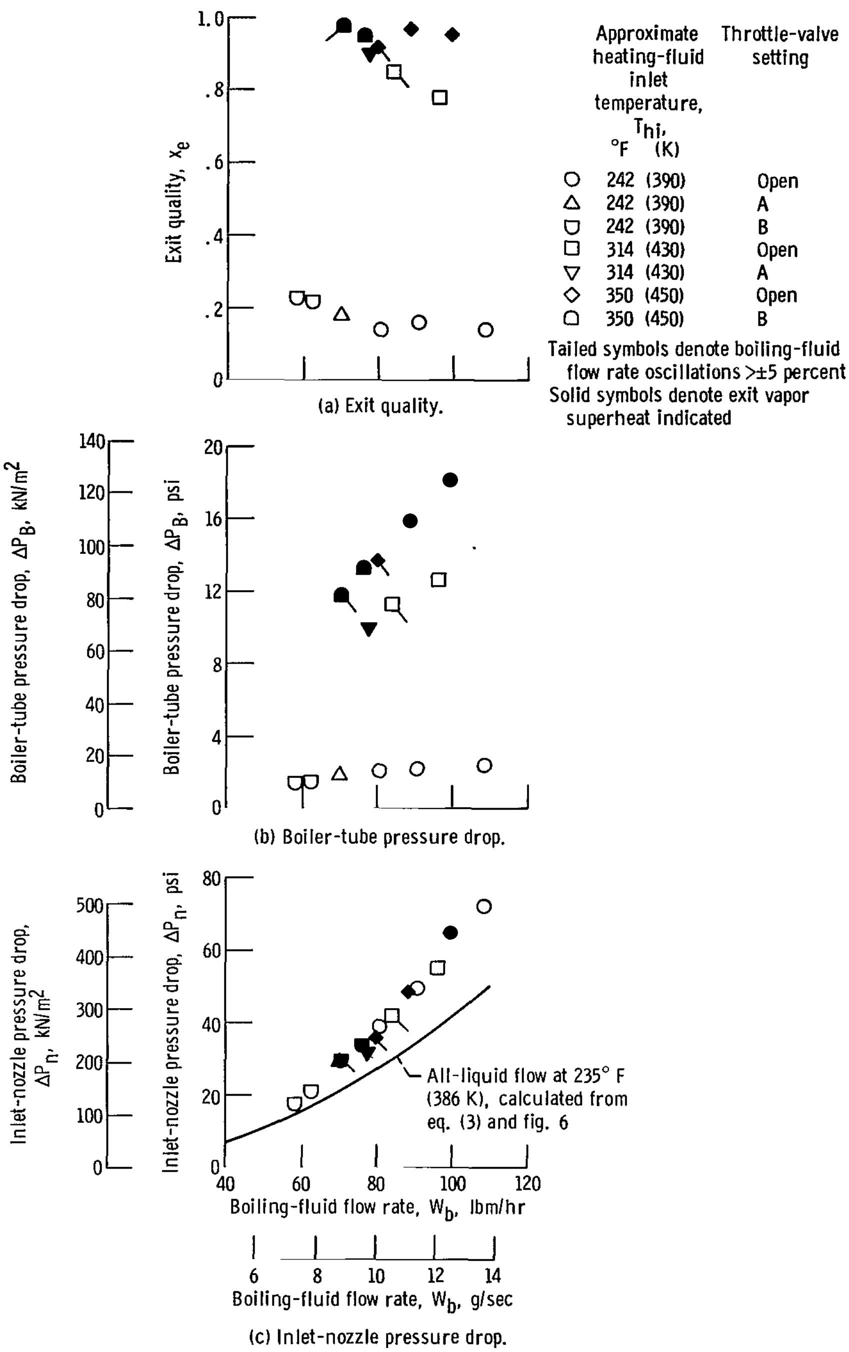


Figure 13. - Boiler performance as function of boiling-fluid flow rate for flashing in inlet nozzle. Nozzle-inlet temperature, 231° to 270° F (384 to 405 K); boiler-exit pressure, ~16.5 psia (114 kN/m^2); heating-fluid flow rate, ~10 000 pounds mass per hour (1.26 kg/sec); 10-inch (25.4-cm) plug.

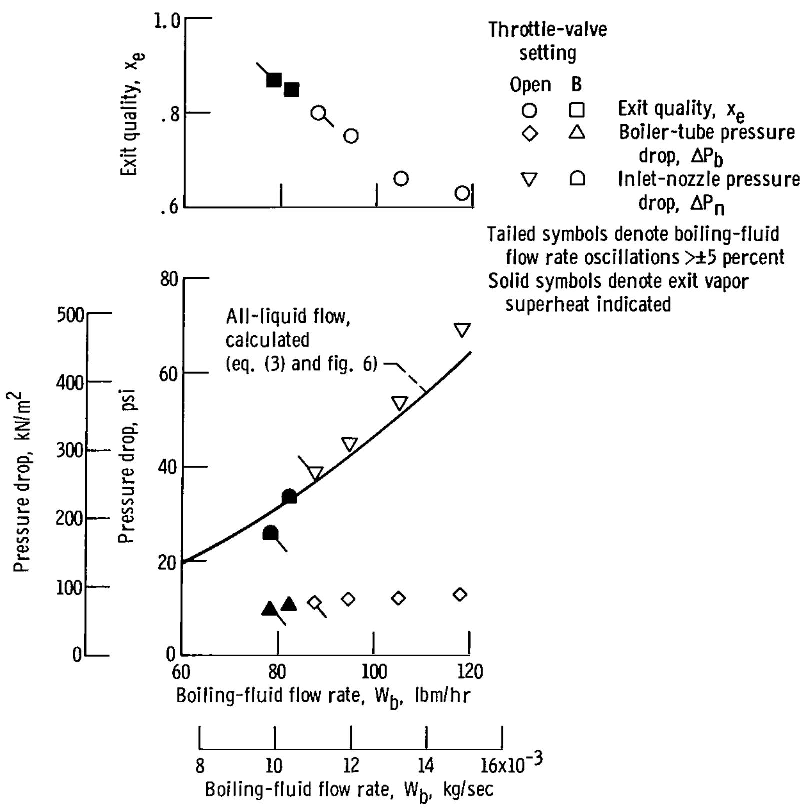


Figure 14. - Boiler performance as function of boiling-fluid flow rate for boiling-fluid inlet temperature of ~80° F (300 K). Heating-fluid flow rate, ~4900 pounds mass per hour (0.62 kg/sec); heating-fluid inlet temperature, ~350° F (450 K); 10-inch (25.4-cm) plug.

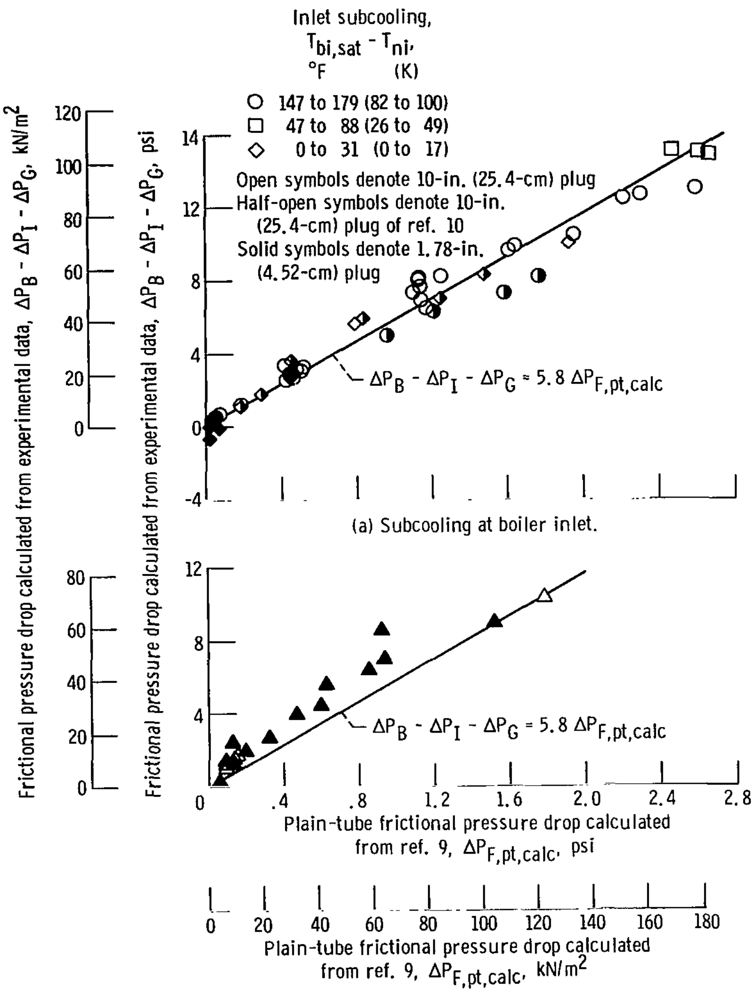


Figure 15. - Comparison of frictional pressure drop calculated from experimental data with calculated values for a boiler of the same dimensions but with no inserts (ref. 9).

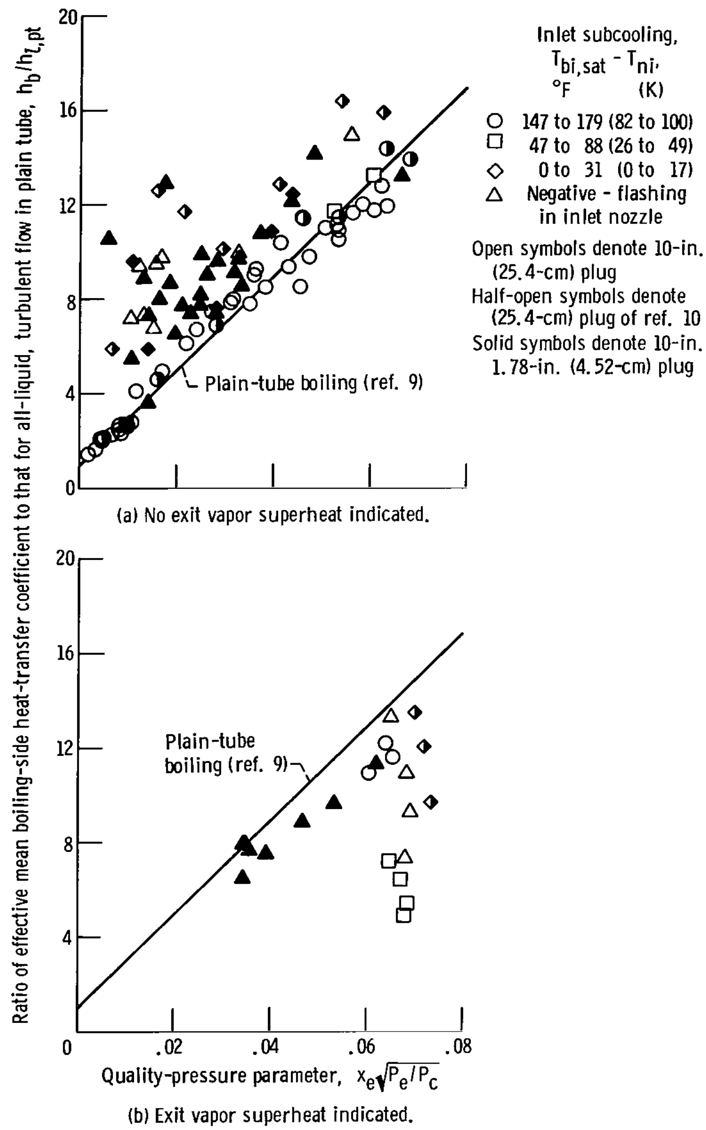


Figure 16. - Ratio of effective mean boiling-side heat-transfer coefficient to that for all-liquid turbulent flow in plain tube as function of quality-pressure parameter; comparison with plain-tube boiling (ref. 9).

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