NACA

RESEARCH MEMORANDUM

SOME MEASUREMENTS OF BOILING BURN-OUT

By Warren H. Lowdermilk and Walter F. Weiland

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
February 23, 1955

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

SOME MEASUREMENTS OF BOILING BURN-OUT

By Warren H. Lowdermilk and Walter F. Weiland

SUMMARY

Measurements of boiling burn-out heat flux for water flowing upward through an electrically heated tube were obtained for ranges of velocity from 0.1 to 19 feet per second; pressure from atmospheric to 2000 pounds per square inch; length-diameter ratios of 25, 37.5, and 50; and inlet subcooling from zero to 400° F.

Unsteady flow was obtained for burn-out conditions with a restriction located downstream of the point of burn-out. A compressible fluid plenum chamber located between the restriction and the exit of the test section resulted in steady-flow burn-out with a tenfold increase in the burn-out heat flux.

INTRODUCTION

An experimental investigation was made at the NACA Lewis laboratory during 1951 and 1952 to determine boiling burn-out conditions for water flowing through an electrically heated tube using an open-cycle flow system.

The investigation was first suggested by the Argonne National Laboratory to provide burn-out data primarily in the low-velocity region (0.1 to 1 ft/sec) for pressures up to 2000 pounds per square inch. The investigation was later extended up to velocities of 19 feet per second using tubes having length-diameter ratios of 25, 37.5, and 50 in an attempt to obtain burn-out without net steam generation.

The results obtained using various arrangements of the apparatus are presented in graphical and tabular form.

APPARATUS

Arrangement A

Schematic diagrams of the various arrangements of the apparatus are shown in figure 1. The original arrangement shown in figure 1(a) includes a supply system consisting of a water storage tank, pump, and two accumulators, each of 2.5-gallon capacity. Nitrogen, supplied through a pressure-regulating valve to the accumulators, was first used to deflate the rubber bladders, after which water was pumped from the storage tank into the bladders. When the bladders were filled, the pump was stopped and water was forced through the apparatus by the regulated nitrogen. The water first passed through an electric preheater, then through the electrically heated test section into the cooler where the water was cooled below 200° F. The water was throttled by a valve to atmospheric pressure and discharged into the weighing system where the flow rate was determined. The temperature of the water was measured in mixing tanks located at the inlet and outlet of the test section, and the pressure was measured at the inlet mixing tank. Electric power was supplied to the test section from a 208-volt, 60-cycle supply line through an autotransformer and a 20:1-ratio power transformer. Double-distilled water was used in all the tests.

Arrangement B

A modification of the apparatus is shown in figure 1(b). A rotameter was installed before the preheater, and the cooler at the exit of the test section was removed and a 2.5-gallon-capacity surge tank was installed in its place. Nitrogen was supplied to the surge tank so that the surge tank could be precharged to any desired pressure. A throttling valve was installed before the rotameter to regulate the water-flow rate. Throttling valves were also installed after the surge tank so that the pressure could be maintained constant during the tests by throttling water with the lower valve or by throttling nitrogen and steam with the upper valve.

Arrangement C

A second modification of the apparatus is shown in figure 1(c). The surge tank at the exit of the test section was removed, and the water was discharged from the exit of the test section to the atmosphere through a short length of tubing.

Test Sections

The test sections were made from stainless-steel tubing. Representative sizes are shown in figure 2. Stainless-steel collars (1/4-in.

O.D. by 7/8 in.) were slipped over the ends of each test section and silver-soldered. The heated length of the test section was considered to be the distance between the inner ends of the collars. The dimensions of the test sections are as follows:

Inside diameter, in.	Wall thickness, in.	Heated length, diam.	Total length, diam.
0.120	0.034	50	65
.067	.030	50	76
.067	.030	37.5	63.5
.067	.030	25	51
.040	.028	50	94
.040	.028	37.5	81.5
.040	.028	25	69

RESULTS AND DISCUSSION

Burn-out Measurements Obtained With Arrangement A

The burn-out results obtained using arrangement A of the apparatus as shown in figure 1(a) for tubes having an inside diameter of 0.12 inch and a heated length of 50 diameters are presented in table I. Measurements of inlet pressure and subcooling, mass-flow rate, maximum heat flux, and either the exit quality or the exit subcooling are tabulated.

These results were obtained by adjusting the pressure and flow rate at the desired values and then gradually increasing the electric power input until the tube started to glow at the exit. At this point, the power input was decreased slightly to prevent the wall temperature from exceeding 1500° F. Usually the tube continued to glow for 30 to 60 seconds, after which the tube would suddenly stop glowing and the wall temperature would decrease to 50° to 150° F above the saturation temperature. After 2 or 3 minutes, the wall temperature at the exit would increase suddenly to 1000° or 1500° F and the cycle would repeat several times. This condition was taken as the burn-out point and the electric heat input, flow rate, pressure, and temperature were recorded.

Typical runs selected from table I are presented in figure 3(a), and indicate that the burn-out flux increases with an increase in velocity, inlet pressure, and inlet subcooling. In general, the exit quality decreased with increasing velocity. For some of the higher-velocity runs, burn-out was obtained with subcooled water at the exit.

A variety of noises were heard during burn-out conditions, which indicated that the cyclic nature of burn-out was caused by violent fluctuations in the water flow in the system. The familiar noise accompanying water hammer caused by a sudden closing of a valve in a liquid flow system was heard nearly every time the tube wall suddenly stopped glowing.

A rotameter was installed in the apparatus upstream of the preheater, and check runs were made at 500 pounds per square inch absolute. For low flow rates, it was noted that, as the exit water temperature approached saturation temperature, the flow rate fluctuated slightly. When the electric power input was increased sufficiently to cause the tube to glow at the exit, the water flow reversed direction and flowed toward the supply accumulators as long as the tube continued to glow. At the instant water hammer was heard, the water surged back through the rotameter toward the test section and at the same time the tube stopped glowing. The flow rate then dropped quickly to the original preset value and remained steady until the tube started to glow again, whereupon the action was repeated. At the higher flow rates, the frequency of the cycle increased rapidly.

A throttling valve was next installed near the entrance of the test section to restrict the back-flow of water. The check runs were repeated with a 300-pound-per-square-inch pressure drop across the entrance throttling valve. When the exit water temperature approached the saturation temperature, the flow rate remained constant, while the pressure in the test section fluctuated rapidly. The magnitude of the fluctuations increased with increased power input until the pressure in the test section reached 800 pounds per square inch absolute, whereupon the tube glowed, the flow rate reversed direction, and the pressure dropped to 200 to 300 pounds per square inch absolute. The flow rate and pressure then returned to the original preset values and the cycle was repeated.

These check runs indicate that, for burn-out conditions in constant-pressure flow systems with a restriction downstream of the heated section, the flow rate varies greatly in the test section as a result of the large changes in specific volume near the tube exit, and that the time-average flow rate measured after the restriction may be of little value in defining burn-out conditions even though the apparent flow rate is constant. For constant-volume flow systems, the pressure in the heated section varies greatly. Hence, the results presented in table I may not be applicable in predicting burn-out even in similar systems.

As an attempt to reduce the fluctuations in flow rate for burn-out conditions, a 1-quart accumulator was installed in the apparatus between the cooler and the exit throttling valve. This arrangement did not produce any significant reduction of the flow fluctuations.

Tests were next conducted with the exit throttling valve removed from the apparatus, and the flow was regulated by the throttling valve located upstream of the rotameter. A very significant improvement was obtained; the rotameter indicated no variation in the flow rate when the electric heat input was increased sufficiently to result in burn-out. These results are presented as runs 50 to 53 in table II. For a mass-flow rate of 0.264×10^6 pounds per hour per square foot, the burn-out heat flux was 0.775×10^6 Btu per hour per square foot, which is approximately 10 times as high as the value obtained when the flow rate was regulated by the exit throttling value.

Burn-out Measurements Obtained with Arrangement B

In order to duplicate this procedure at pressures greater than atmospheric, the cooler was removed from the apparatus, a $2\frac{1}{2}$-gallon accumulator was installed after the tube exit, and the exit throttling valve was reinstalled downstream of the accumulator. For these runs, the accumulator was precharged to the desired pressure and the flow rate was regulated by the exit throttling valve. As the exit water temperature approached saturation, the flow rate became unsteady, although the magnitude of the fluctuations was not as great as that obtained with the original arrangement of the apparatus. The results for runs 54 to 61 for pressures of 250 and 500 pounds per square inch absolute are included in table II. The data are also shown in figure 3(b). The burn-out heat fluxes for 250 and 500 pounds per square inch absolute are less by 50 percent than those obtained at atmospheric pressure with the exit throttling valve removed.

These low values of burn-out flux at the higher pressure indicate that some of the bubbles did not separate from the water in the accumulator, but instead passed through the throttling valve, which resulted in the unsteady behavior of the flow rate for burn-out conditions.

To eliminate this possibility, the bladder was removed from the accumulator and an additional throttling valve was installed in the top of the accumulator, as shown in figure 1(b). With the lower throttling valve closed, the water and steam flowed from the exit of the test section through the bottom of the accumulator, and nitrogen and steam were discharged through the top by means of the throttling valve.

For these runs, the accumulator was precharged with nitrogen to the desired pressure, the flow rate was regulated by the valve upstream of the rotameter, and the pressure in the accumulator was maintained constant by bleeding nitrogen and steam through the top throttling valve. When heat was added to the test section, the flow rate remained very steady and the heat flux necessary to result in burn-out at the higher pressures was increased by more than 50 percent. These results for runs 62 to 74 are presented in table II for a nearly constant inlet temperature of 75° F. The data indicate that the burn-out flux increases with increasing pressure or inlet subcooling. Net steam was generated for all the runs, and the exit quality varied between 0.53 and 0.87. In general, the exit quality decreased with an increase in flow rate and increased slightly with an increase in pressure.

Measurements of burn-out heat flux for various amounts of inlet subcooling were obtained with the same apparatus arrangement (fig. 1(b)). The results are also given in table II (runs 75 to 103) for pressures of 15 and 500 pounds per square inch absolute and flow rates corresponding to inlet velocities of approximately 0.2, 0.5, and 0.9 foot per second. The data indicate that the burn-out flux decreases with a decrease in inlet subcooling.

Comparison of runs 100 and 101 indicates a larger decrease in burn-out heat flux than average when the subcooling was reduced from 195° to 129° F. A section of glass tubing was installed between the exit of the test section and the accumulator. When the runs were repeated for the same pressure and flow rate but with no heat added to the test section, the flow rate through the glass tube started to fluctuate when the inlet subcooling was reduced below 190° F. When the subcooling was reduced to 130° F, a group of small bubbles or a single large bubble was observed at irregular intervals. The number of bubbles increased with a further reduction in inlet subcooling.

Burn-out Measurements Obtained with Arrangement C

In order to extend the burn-out measurements to velocities greater than 1.2 feet per second, the apparatus was modified as shown in figure 1(c). The accumulator and throttling valves at the exit were removed, and a short length of tubing was installed at the exit of the test section to deflect the water from the apparatus. Tubes with inside diameters of 0.12, 0.067, and 0.040 inch were used with effective heated lengths of 25, 37.5, and 50 diameters. The test sections were not provided with thermocouples, and burn-out was determined by increasing the electric power input by small amounts and recording the increase until the tube started to glow at the exit end. For mass-flow rates greater than 0.5 to 0.6×10^6 pound per hour per square foot, the test section usually failed before the power input could be reduced below the burn-out level.

These results are listed in table III and shown graphically in figure 4. The slope of the curve representing the data for the tubes having diameters of 0.12 and 0.040 inch and lengths of 50 diameters has a maximum value near unity in the low- and high-velocity regions, and a minimum value of 0.4 in the intermediate region. The results indicate that the burn-out heat flux increases with a decrease in length-diameter ratio. The maximum value of burn-out heat flux obtained was 6.11×10^6 Btu per hour per square foot for a mass velocity of 4.24×10^6 pounds per hour per square foot (19 ft/sec) with the tube having an inside diameter of 0.040 inch and a length of 25 diameters. The data for 0.067-inch-diameter tubes are consistently higher than that for the 0.040-inch-diameter tubes; however, no conclusions can be drawn as to the effect of tube diameter on burn-out heat flux.

The same data are presented in figure 5, where the burn-out heat flux is plotted against the exit quality. For low and high values of burn-out heat flux corresponding to low and high mass flows, the exit quality is nearly independent of changes in heat flux but varies considerably in the intermediate region. The exit quality approaches constant values depending on length-diameter ratio for high burn-out heat fluxes, and indicates the possibility that some net steam would be generated at much higher velocities at least for these tube diameters.

SUMMARY OF RESULTS

The results of the investigation of boiling burn-out for water flowing vertically upward through electrically heated tubes with various arrangements of apparatus at constant pressure and open-cycle flow system may be summarized as follows:

1. When the system was operated with a restriction or a throttling valve downstream of the test section and without a compressible fluid plenum chamber between the test section and the restriction, the water-flow rate varied so greatly at burn-out conditions that the process of burn-out cannot be classified as a steady-flow process.

2. A restriction located upstream of the test section delayed the occurrence of flow variations until the pressure in the test section increased sufficiently to overcome the pressure drop across the restriction, after which the flow rate again varied greatly.

3. Fluctuations of flow rate and pressure were eliminated entirely when a compressible-volume chamber was located at the exit of the test section. The burn-out heat flux was increased by as much as a factor of 10.

4. For steady-flow conditions, net steam was generated for all conditions. The bulk exit quality varied with velocity, inlet subcooling, pressure, and length-diameter ratio.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 23, 1954

TABLE I. - LOW-VELOCITY BURN-OUT

[Arrangement A; tube diameter, 0.12 in.; length, 6 in.]

Run	Inlet pressure, lb/sq in. abs	Inlet subcooling, °F	Mass velocity, lb/(hr)(sq ft)	Burn-out heat flux, Btu/(hr)(sq ft)	Exit quality	Exit subcooling, °F
24	20	28	0.037×10^6	0.028×10^6	0.13	
25		18	.113	.045	.06	
26		68	.213	.069		3
27	250	166	.040	.058	.13	
28		151	.127	.128	.05	
29		171	.251	.277	.05	
37	500	206	.028	.063	.42	
35		189		.055	.24	
36		104		.045	.24	
39		101		.045	.26	
38		14		.079	.70	
18		232		.063	.10	
41		187		.069	.08	
40		77		.053	.14	
42		57		.048	.16	
17		237	.067	.109	.10	
1	515	228	.065	.098	.07	
43	500	202	.104	.137	.06	
44		127		.110	.08	
45		52		.061	.07	
2		267	.134	.199	.02	
48		207	.227	.294	.05	
46		107		.161	.03	
47		57		.109	.04	
19		247	.237	.335	.03	
20	1000	410	.020	.089	.68	
23		360	.037	.108	.31	
3	1015	376	.040	.128	.36	
30	1000	147	.040	.067	.23	
21		310	.087	.170	.08	
15		330	.120	.261	.12	
16		325	.120	.224	.03	
31		152	.130	.127	.03	
22		325	.183	.313		15
32		167	.224	.213		4
14		335	.237	.390		30
8	1480	443	.028	.115	.58	
34	1500	351	.055	.117	.07	
5	1515	418	.075	.221	.24	
13	1500	366	.082	.208	.19	
6		385	.120	.260	.02	
7		386	.231	.464		28
4	1850	476	.058	.181	.21	
12	2000	474	.023	.110	.90	
9		441	.052	.163	.31	
33		364	.070	.184	.24	
10		406	.120	.263		52
11		446	.207	.457		55

TABLE II. - LOW-VELOCITY BURN-OUT

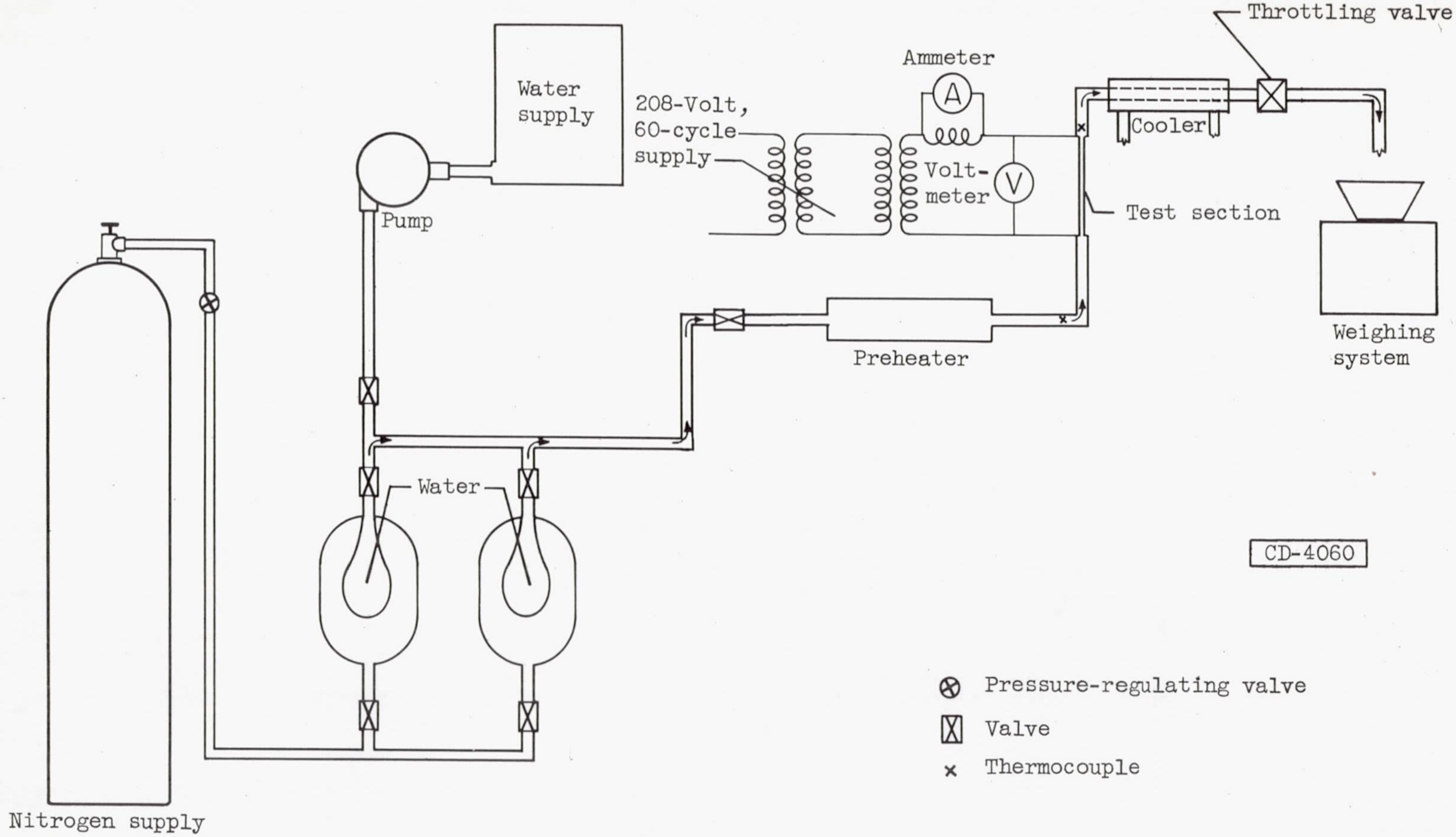
[Arrangement B; tube diameter, 0.12 in.; length, 6 in.]

Run	Inlet pressure, lb/sq in. abs	Inlet subcooling, $^{\circ}F$	Mass velocity, $\frac{lb}{(hr)(sq\ ft)}$	Burn-out heat flux, $\frac{Btu}{(hr)(sq\ ft)}$	Exit quality	Exit subcooling, $^{\circ}F$
50	15	139	0.036×10^6	0.150×10^6	0.71	
51		138	.109	.398	.61	
52			.185	.528	.45	
53			.264	.775	.46	
54	255	328	.042	.074	.02	
55	250	326	.109	.158		41
56			.190	.251		63
57			.264	.345		66
58	500	390	.044	.079		37
59			.111	.186		62
60			.189	.300		72
61			.265	.418		81
62	15	138	0.044×10^6	0.186×10^6	0.74	
63		137	.109	.447	.70	
64		136	.190	.613	.53	
65		135	.265	.873	.55	
66	250	324	.044	.214	.79	
67		324	.109	.504	.72	
68		323	.190	.843	.68	
69			.224	.936	.61	
70			.224	1.01	.69	
71	500	389	.044	.231	.87	
72			.109	.527	.75	
73			.190	.910	.74	
74			.224	1.05	.71	
75	15	136	0.042×10^6	0.189×10^6	0.80	
76		95		.173	.76	
77		58		.166	.77	
78		28		.160	.77	
79		0		.151	.75	
80		135	.108	.388	.60	
81		92		.382	.63	
82		55		.417	.74	
83		30		.391	.71	
84		9		.380	.71	
85		2		.374	.71	
86		137	.185	.653	.59	
87		91		.653	.64	
88		53		.649	.67	
89		14		.624	.68	
90	500	299	.044	.197	.78	
91		197		.179	.80	
92		138		.165	.80	
93		46		.149	.84	
94		299	.109	.527	.86	
95		197		.497	.93	
96		133		.427	.84	
97		39		.389	.89	
104		388		.535	.77	
105		195		.500	.94	
106		126		.443	.89	
98		392	.190	.910	.75	
99		304		.892	.82	
100		195		.824	.87	
101		129		.666	.74	
102		51		.612	.78	
103		188		.707	.72	

TABLE III. - HIGH-VELOCITY BURN-OUT

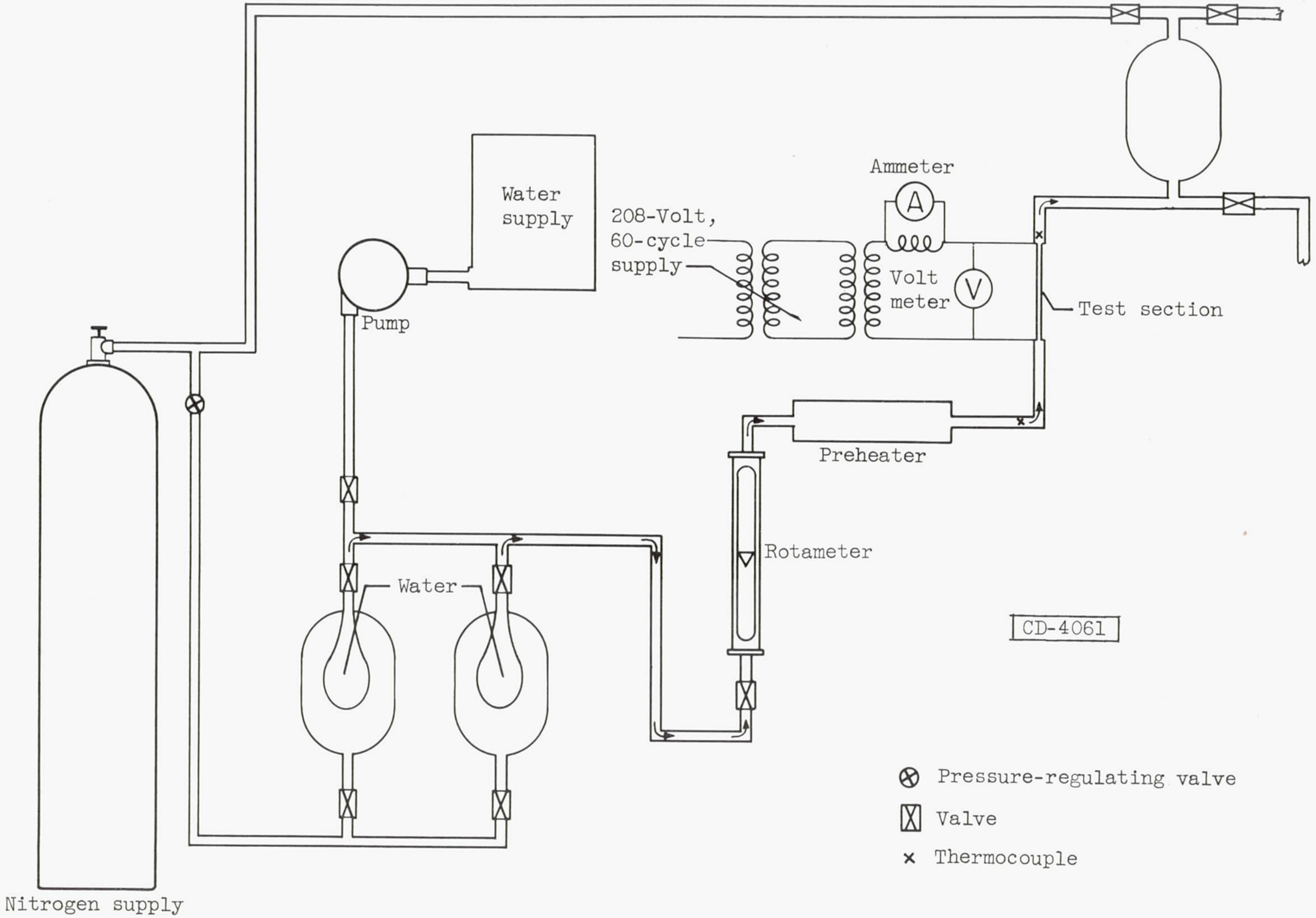
[Arrangement C; inlet subcooling, 137° F; exit pressure, 14.7 lb/sq in. abs.]

Run	Diameter, in.	Length-diameter ratio	Mass velocity, lb/(hr)(sq ft)	Burn-out heat flux, Btu/(hr)(sq ft)	Exit quality
107	0.120	50	0.044×10^6	0.180×10^6	0.71
108			.109	.440	.69
109			.185	.654	.59
110			.265	.869	.54
111			.441	1.11	.38
112	.067	50	.114	.522	.80
113			.184	.764	.72
114			.229	.881	.65
115			.339	1.12	.54
116			.457	1.34	.46
117			.690	1.81	.40
118		37.5	.118	.644	.70
123			.176	.865	.62
119			.233	1.03	.54
124			.363	1.30	.41
120			.445	1.43	.36
125			.722	1.74	.23
121			.951	2.15	.21
122			1.45	2.62	.14
126		25	.118	.906	.65
127			.224	1.26	.44
131			.343	1.65	.35
130			.453	1.78	.26
128			.482	1.83	.25
129			.959	2.20	.10
132			1.48	2.93	.06
133	.040	50	.294	.945	.52
134			.504	1.20	.35
135			.653	1.31	.28
136			.985	1.54	.18
137			1.32	1.76	.14
138			2.08	2.26	.08
139			2.74	2.66	.06
140			4.12	3.82	.05
141		37.5	.355	1.28	.42
142			.515	1.42	.29
143			.664	1.53	.22
144			1.01	1.73	.12
145			1.31	1.87	.08
146			2.05	2.38	.04
147			2.77	3.08	.03
148			4.16	4.66	.03
149		25	.338	1.37	.28
150			.521	1.56	.17
151			.687	1.67	.11
152			.997	1.86	.05
153			1.39	2.24	.03
154			2.06	3.07	.01
155			2.75	3.99	.01
156			4.24	6.11	.01



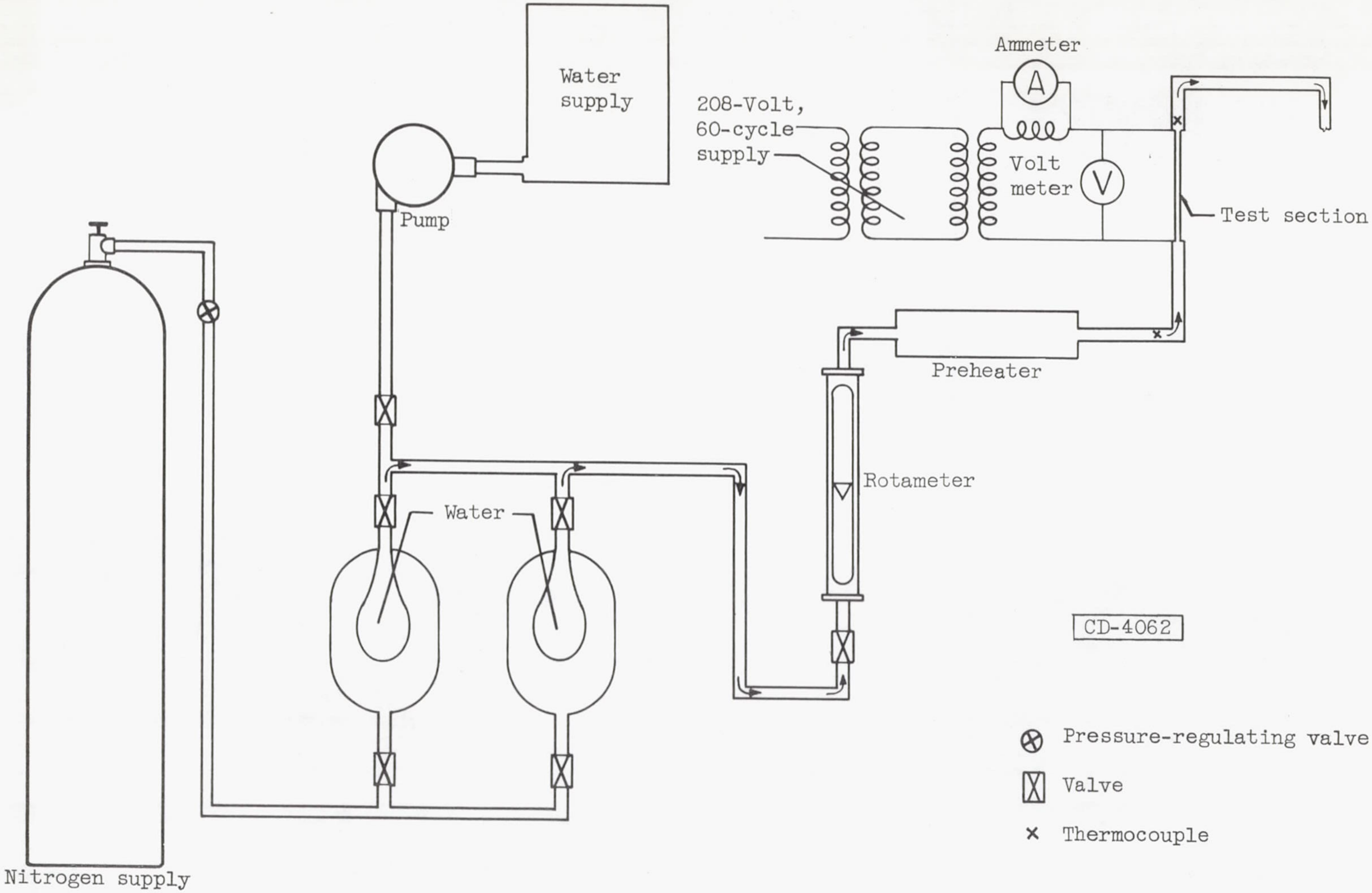
(a) Arrangement A.

Figure 1. - Schematic diagrams of system.



(b) Arrangement B.

Figure 1. - Continued. Schematic diagrams of system.



(c) Arrangement C.

Figure 1. - Concluded. Schematic diagrams of system.

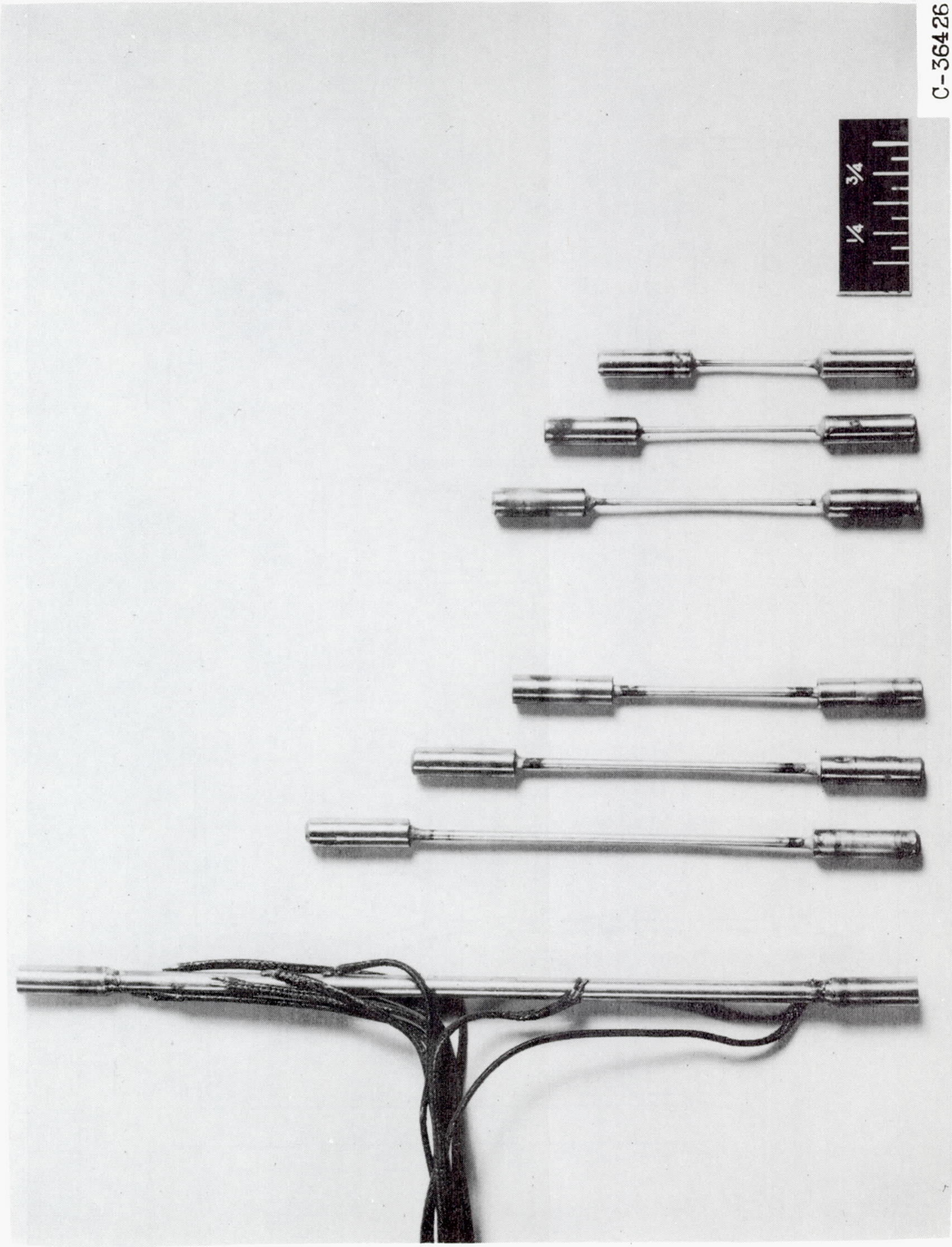
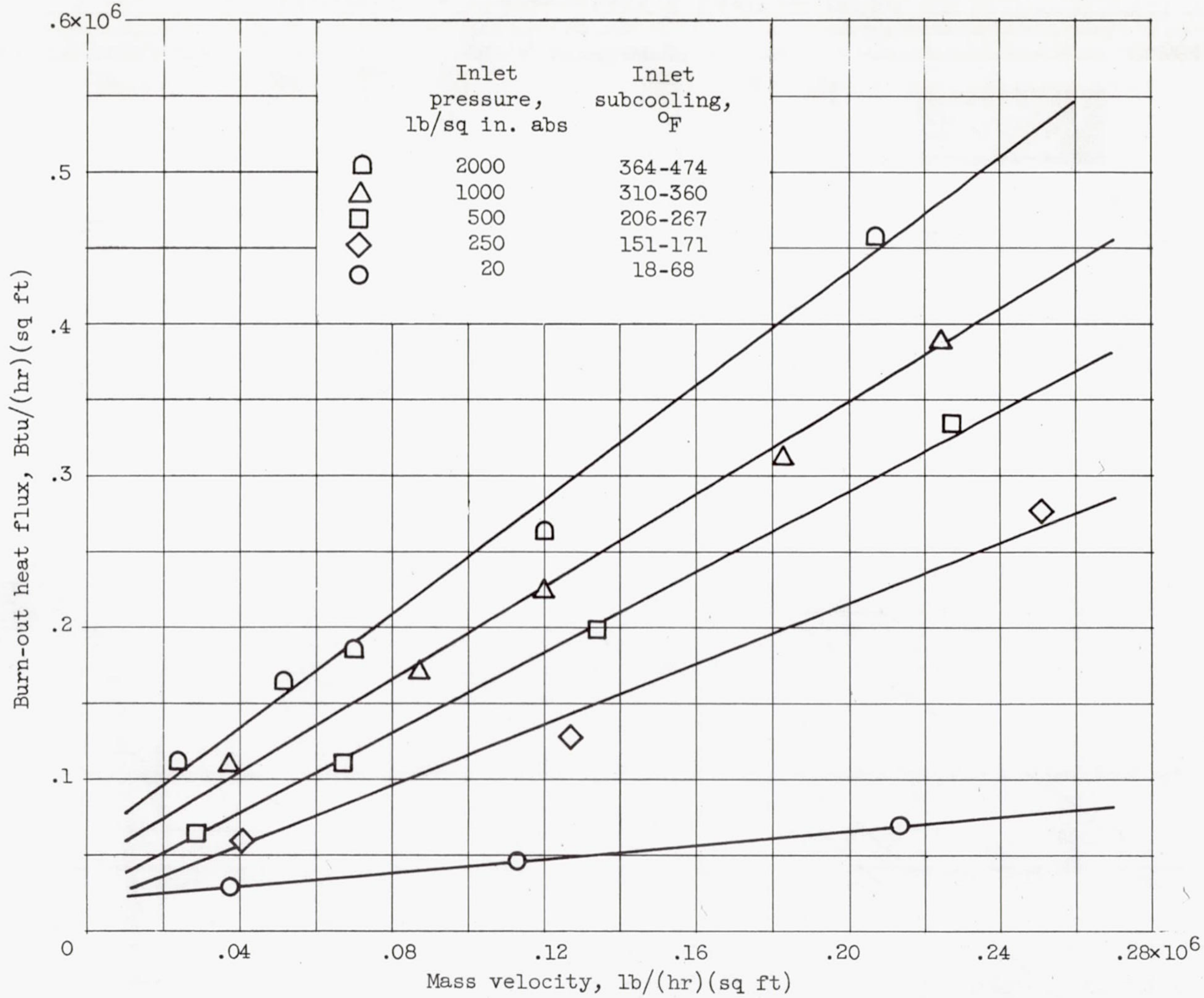
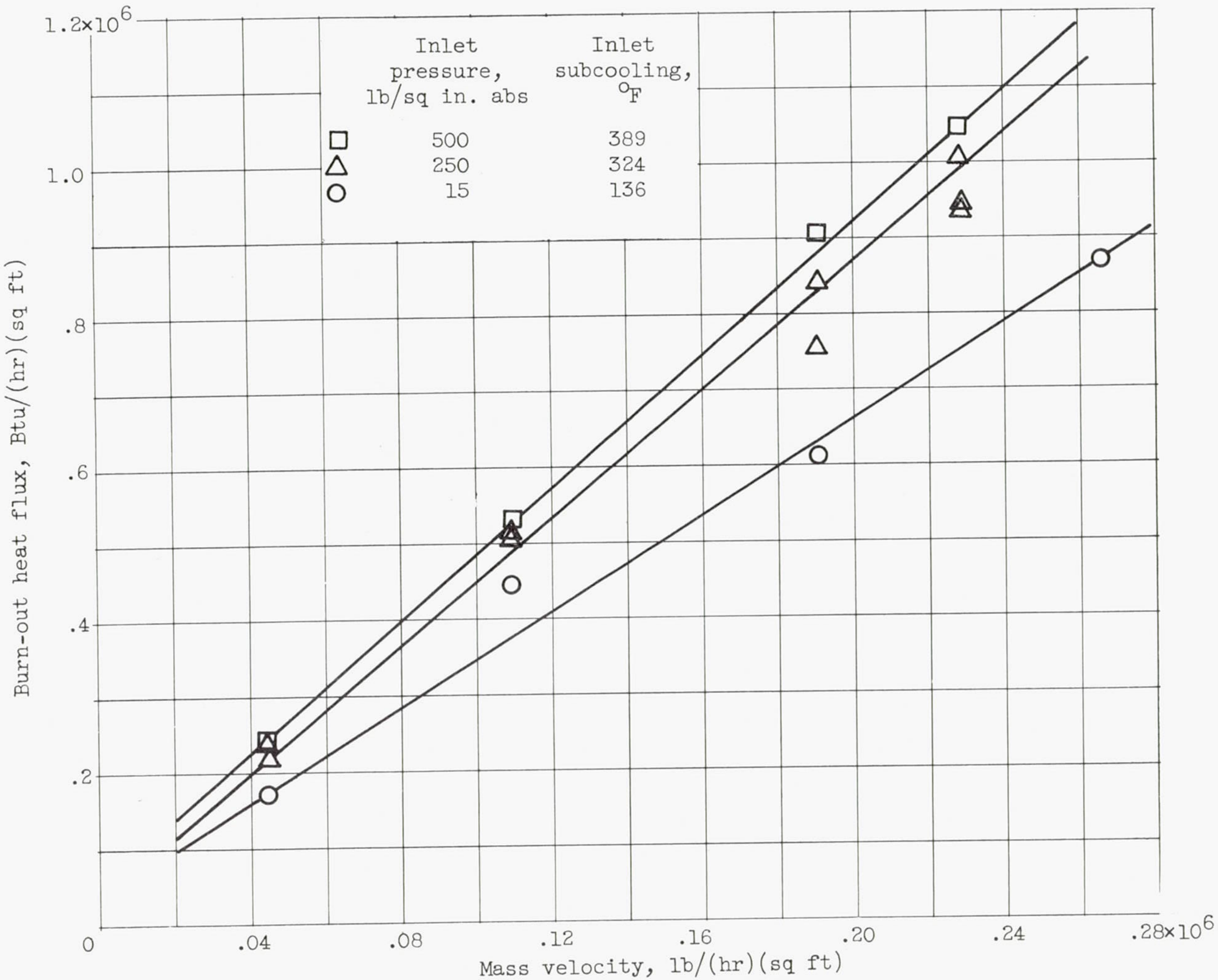


Figure 2. - Representative test sections.



(a) Arrangement A.

Figure 3. - Effect of arrangement of apparatus on burn-out for low velocity.



(b) Arrangement B.

Figure 3. - Concluded. Effect of arrangement of apparatus on burn-out for low velocity.

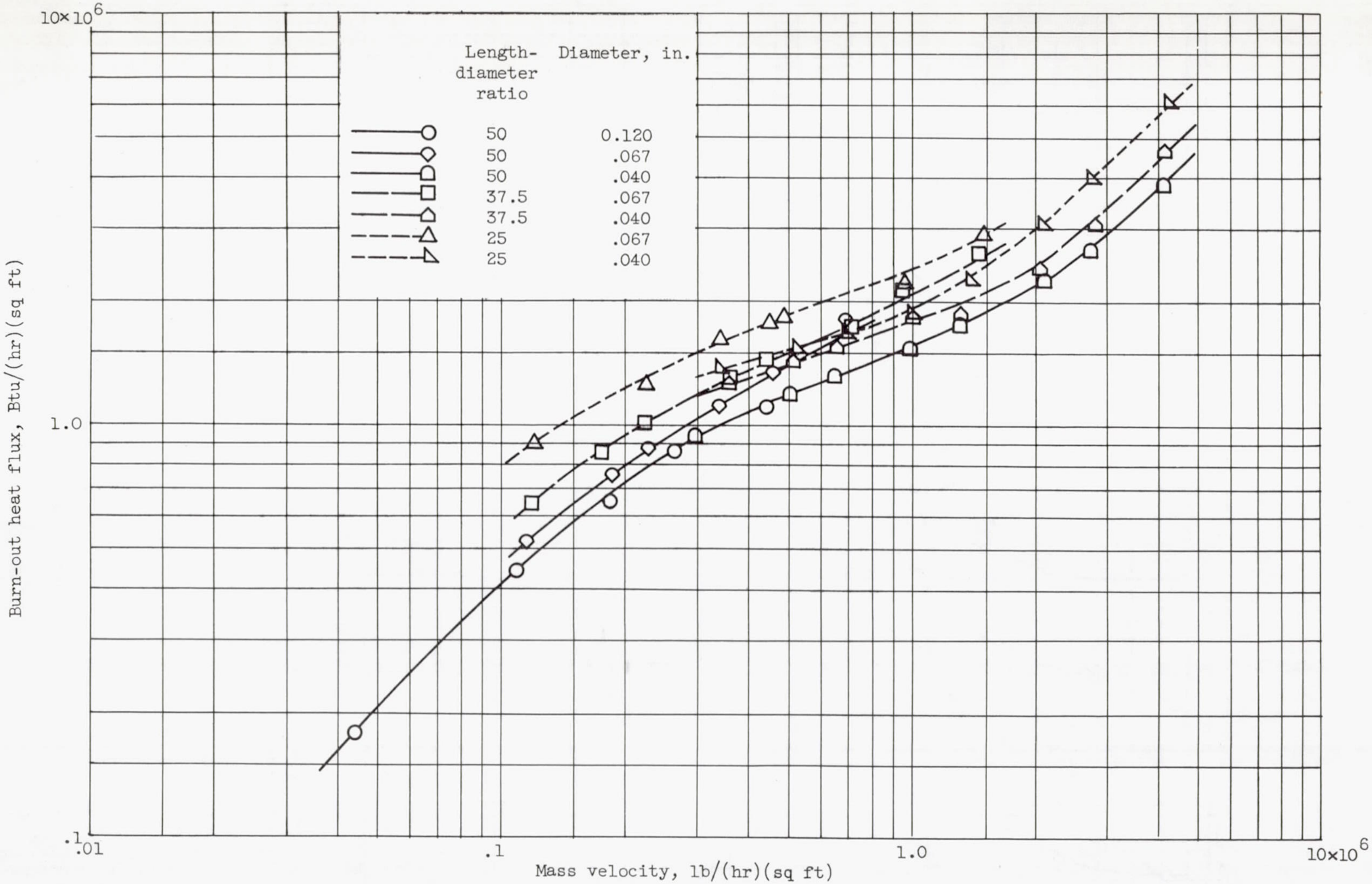


Figure 4. - Variation of burn-out heat flux at high velocity for various length-diameter ratios using arrangement C. Exit pressure, 14.7, pounds per square inch absolute; inlet subcooling, 137° F.

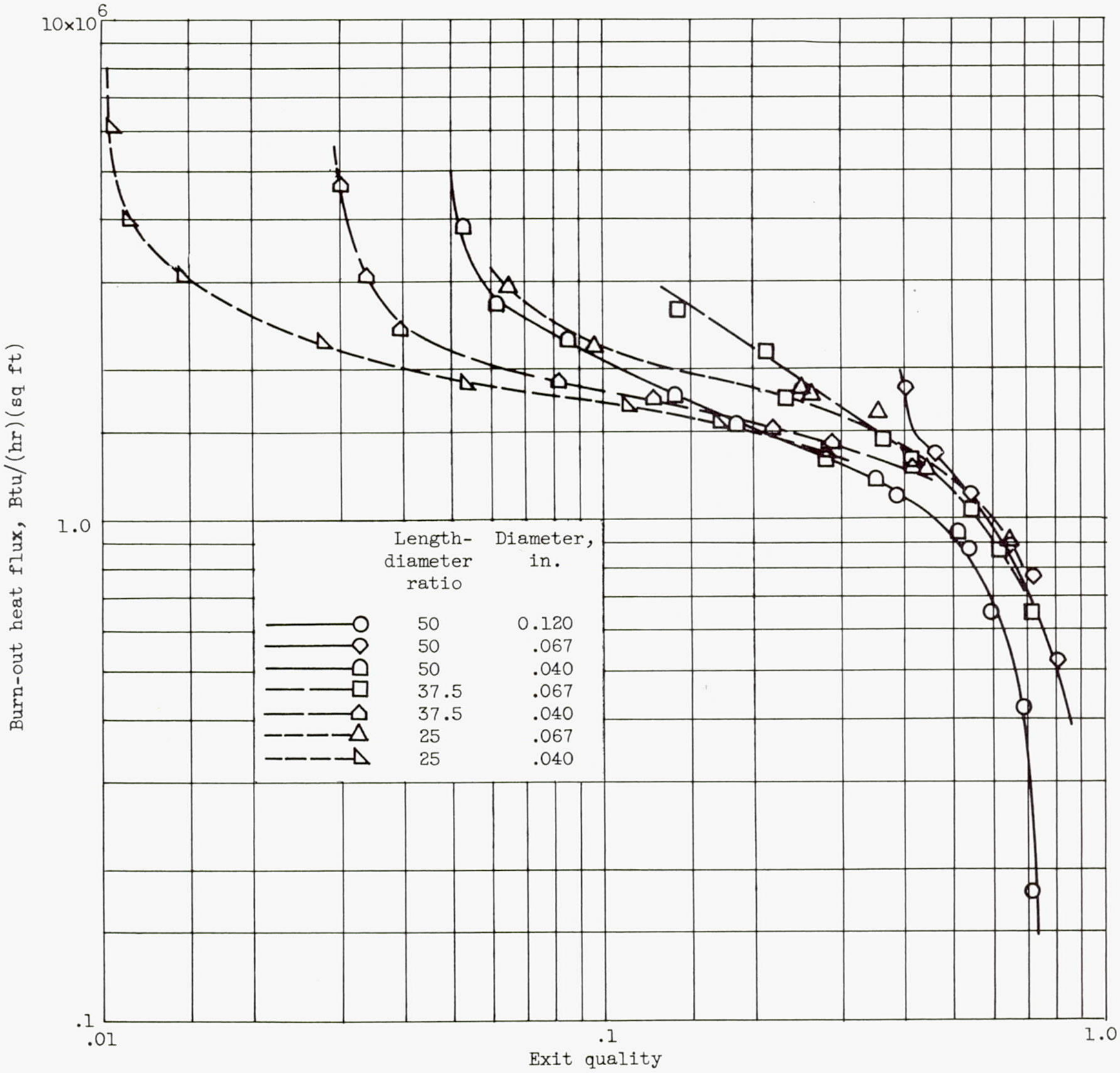


Figure 5. - Variation of exit quality at high velocity for various length-diameter ratios using arrangement C. Exit pressure, 14.7 pounds per square inch absolute; inlet subcooling, 137° F.