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REPORT

EXPERIMENTAL BOILING BURNOUT HEAT FLUXES
WITH AN ELECTRICALLY HEATED
19-ROD BUNDLE TEST SECTION

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DECEMBER, 1965

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WITH AN ELECTRICALLY HEATED
19-ROD BUNDLE TEST SECTION

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INTRODUCTION

A nuclear reactor fuel element made of a bundle of rods is attractive because its fabrication is relatively simple, and it provides a large heat transfer area to fuel volume and can, therefore, support relatively large power densities without excessive heat transfer rates. The thermal-hydraulic behavior of such fuel elements is quite complex, however. In general, any change in the design of such a fuel element requires experimentation to define its thermal-hydraulic behavior, and in particular, its boiling burnout characteristics.¹

Heat transfer characteristics of 19-rod bundles have been studied before.^(1,2,3,4,5) This report presents the results of further experiments with a 19-rod bundle fuel element and reports effects of introducing the coolant as a steam-water mixture (fog cooling), using a device to concentrate the water at the center of the bundle, and using roughening rings on the inside of the pressure tube to displace the liquid film.

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¹The term boiling burnout is used in this report as a generic term describing a large degradation of the heat transfer coefficient with small changes in the thermal-hydraulic variables. It is recognized that different mechanisms at different conditions are involved in boiling burnout.

SUMMARY AND CONCLUSIONS

A total of 76 boiling burnout experiments was made with an electrically heated model of a 19-rod bundle fuel element. The test section had a heated length of 6.3 ft and was made up of 0.612 in. OD rods spaced 0.040 in. apart by means of warts. The spacing between the test section and the 3.25 in. ID flow housing tube was 0.060 in.

The tests were made under a variety of conditions including two pressures, both rough and smooth wall flow housing, both subcooled and fog (wet steam) inlet coolant, and two inlet piping configurations. A summary of the combinations of these conditions used is given in Table I. The experiments were made at coolant flow rates from 1,000,000 to 3,000,000 lb/hr-ft², and with coolant inlet conditions ranging from 300°F subcooled to 40% quality steam.

The conclusions to be made from these experiments are:

- In general, the plots of the data for fog inlet cases gave smooth extensions of the plots of data for subcooled inlet cases for the same flow rate. This indicates that there is nothing unique about the use of fog coolant with the physical arrangement used in these tests.
- The use of rougheners on the flow tube wall increased the boiling burnout from 10 to 35%, based on the same outlet enthalpy. When the rougheners were used, the magnitude of the temperature excursions upon the start of boiling burnout tended to be less than those found with the smooth wall tests.

- A preferred placement of the water on the heated surfaces at the inlet of the test section during the fog inlet tests had no effect on boiling burnout. Apparently, the beneficial effects of the preferred placing of the water were dissipated by the time the coolant had traveled the length of the test section.
- The boiling burnout heat fluxes obtained with this test section showed a smaller dependence on enthalpy than was found in previous tests with a similar test section, but with 0.050 in. spacing between rods and 0.100 in. spacing between test section and flow housing wall. The boiling burnout heat fluxes with the present test section were lower at the lower outlet enthalpies and about the same at the higher enthalpies than were those from the previous tests. This was in spite of the fact that the present test section is calculated to have a smaller enthalpy disparity across a cross section of the test section than had the previous test section.
- Decreasing the pressure from 1200 psia to 1000 psia caused an increase in the boiling burnout heat flux on the order of 10%.
- Boiling burnout occurred on the center rod when the outlet enthalpy was low. It occurred on any one, and usually on several, of the inner seven rods when the outlet enthalpy was high.

EXPERIMENTAL EQUIPMENT

Test Section

The test section consisted of nineteen 0.612 in. OD Inconel tubes, 76 in. long, arranged in concentric rings of 6 and 12 rods around a central rod (Figure 1). The wall thickness of the tubes was such that the test section would produce a radial heat flux distribution in which the inner 7 rods had heat fluxes 80.5% of that of the outer 12 rods. The spacing between adjacent rods was maintained by means of ceramic warts at 9 3/4 in. intervals. The warts were attached to the rods with a slotted sleeve silver soldered to the rods. Details of the warts and ferrules are shown in Figures 2A and 2B. The bundle was placed in a flow housing 3.25 in. ID with a radial spacing of 0.060 in. between the outside rods and the flow housing. The flow housing, in turn, was placed within a stainless steel pipe which contained the pressure of the coolant. The flow housing consisted of split ceramic cylinders 3 in. long placed around the test section. Viton O-rings held the half cylinders together and sealed the gap between the OD of the cylinders and the ID of the pressure tube. Split ceramic rings were made that could be inserted between the ceramic cylinders of the flow housing to provide a roughened flow housing wall. When these rings were installed, the flow housing was provided with circumferential ridges 0.050 in. high by 0.075 in. long protruding into the flow stream every 3.25 in. (Figure 3).

A thermocouple was installed at the outlet end of each rod (Figure 4). The thermocouple was imbedded in a 3/8 in. long copper cylinder whose OD was coated with a ceramic and which fit snugly within

the heater tubes. In case of a local hot spot on the tube surface, the cylinder was grooved both circumferentially and axially to direct the heat flow within the copper to the thermocouple. With this installation, the thermocouples read an average of the rod wall temperature over the last $3/8$ in. of its length.

The electrical connection at the inlet of the test section was constructed so that the electrical path was through the side of the pressure tube. This was accomplished by extending each heater rod inlet end with a solid copper rod $16\ 3/4$ in. long and with the same OD as had the heater rods. The first $6\ 3/4$ in. of the copper pieces were interconnected with brazed $1/8$ in. copper webs. The outer 12 rods were connected with identical copper webs to a nickel sleeve whose ID was 3.25 in., the same as that of the flow housing. The electrical power leads were connected to the nickel sleeve. In this manner, the coolant flow disturbances caused by the presence of the electrical connectors were minimized, and the inlet end of the test section was reasonably prototypical of a nuclear reactor fuel element in a pressure tube.

Inlet Device

The test section was provided with a special inlet device designed and constructed by the AECL. It was used for both the subcooled and fog-cooled runs, but served as a coolant flow conditioner only during the fog-cooled runs. During the fog-cooled runs, two coolant streams were delivered to the test section: one a slightly subcooled stream and the other a stream of nearly saturated steam. The inlet device combined the two streams and delivered them to the inlet end of the test section.

The inlet device was provided with two sets of internal components. One set mixed the water and steam thoroughly and delivered a homogeneous steam-water mixture to the test section inlet. The other set was designed to keep the water and steam streams separated, and it delivered a high water content stream into the bundle and a low water content stream into the space between the bundle and pressure tube wall. Hence, most of the water was placed on the heated surfaces of the bundle, and little was wasted on the cold walls of the pressure tube. In this mode of operation, the inlet device is called a concentrator.

Preheater and Steam Generator

The experimental equipment included an electrical preheater. One of the two power sources of the PNL heat transfer laboratories was connected to this preheater while the other was connected to the test section. During the subcooled runs, all of the coolant passed through the preheater, which was used to adjust the temperature of the coolant to the test section. A simplified schematic of the preheater and test section set up for the fog-cooled runs is shown in Figure 5.

During the fog-cooled runs, however, the coolant stream was split in two (Figure 6). Part of the coolant at about 40°F subcooling was delivered to the water port of the inlet device. The rest of the coolant was directed through the preheater, where it was heated to nearly saturated steam conditions; through a valve, across which a 100 psi differential was maintained; and then to the steam port of the inlet device.

General

The test section was operated in the heat transfer laboratory of PNL. (6)

EXPERIMENTAL PROCEDURE

The experiments were performed by establishing a flow rate and inlet enthalpy with a heat flux on the test section below the boiling burnout heat flux. The power to the test section was then increased in a series of steps until boiling burnout was reached. Data were taken at each power step. The size of the steps varied, but at conditions near boiling burnout, the steps were such to give increases in the heat flux of 5,000 to 20,000 Btu/hr-ft².

EXPERIMENTAL RESULTS

The tests included investigating boiling burnout heat fluxes for both fog-cooled and subcooled inlet conditions, with smooth and rough pressure tube walls, with the inlet device functioning both as a homogenizer and concentrator, and at pressures of both 1000 and 1200 psia. The combinations of these various conditions that were investigated are summarized in Table I.

The experimental results are summarized in:

- Table II, giving the results for Conditions 1 and 7 of Table I
- Table III, giving the results for Conditions 3 and 4 of Table I
- Table IV, giving the results for Condition 2 of Table I
- Table V, giving the results for Conditions 5 and 6 of Table I

DISCUSSION

Definition of Boiling Burnout

The start of boiling burnout was determined from the wall temperatures of the 19 rods. Under nonburnout conditions, the temperature increases were on the order of 1-3°F following each power increase. In most cases, the onset of boiling burnout was indicated by a temperature excursion of 20 to 80°F on one or more rods during the power increase. In general, the temperatures would level out to a reasonably steady value, and operation in a condition of boiling burnout continued until all of the data were recorded. In many cases, however, the start of film boiling was typified by much smaller rod temperature increases, perhaps as small as 5°F. In these cases, several power increase steps were made beyond that at which the start of boiling burnout was first suspected. It must be remembered that the thermocouple installation used in these tests was such that they read an average circumferential temperature. For example, a 5°F rise could result from a 20°F rise over a quarter of the circumference, with no rise over the remainder.

To provide a consistent method of defining boiling burnout, plots of rod wall temperatures vs. heat fluxes were made. Such plots yielded straight lines for the nonburnout heat fluxes. Boiling burnout is indicated by a single point away from the straight line when the temperature excursions were large. Plots of this type are shown in Figures 7 and 8. Boiling burnout, however, was indicated by a gradual curving away of the data points from an extension of the straight-line portion of the plots when the temperature excursions were small. In these cases, a second

straight line was drawn on these plots offset to 2% lower heat fluxes from the straight-line portion of the data curve. The start of film boiling was defined as the first data point at a higher heat flux than that at the intersection of the offset line and the curve through the data. Plots of this type are shown in Figures 9 and 10.

Smooth Tube Data

All of the data obtained with the smooth-wall flow tube and homogenizer inlet are shown in Figure 11, which is a plot of the average boiling burnout heat flux vs. outlet enthalpy for all flows investigated. It may be emphasized that the plotted heat flux is the average. In general, boiling burnout occurred on the inner 7 rods whose heat flux was 86.8% of the average.

Included on the plot are two nonburnout data points. These represent the maximum conditions of inlet enthalpy and heat flux that could be obtained at the flow rates of 2,000,000 and 3,000,000 lb/hr-ft². Boiling burnout was not obtained at these conditions.

The data points for the fog inlet cases give smooth extensions of the points for subcooled inlet cases for the same flow rate. This indicates that there is nothing unique nor peculiar about the use of wet steam coolant, at least with the physical arrangement used in these tests. It may be pointed out that the 100 psid pressure drop across the valve in the steam line provided a stiff hydraulic supply system. This was done deliberately to reduce or eliminate the discrepancies between subcooled and fog-cooled data found in earlier tests which did not have the stiff supply characteristics. (1)

The curves of Figure 11 are not particularly steep, indicating a rather weak dependency of boiling burnout on enthalpy of the bulk coolant. Furthermore, there is but a small separation between the curves for the four flow rates, indicating a somewhat unexpected weak dependence of boiling burnout on flow rate.

Rough Tube Data

All of the data obtained with the rough wall flow tube and homogenizer inlet are shown in Figure 12, which is a plot of the average boiling burnout heat flux vs. outlet enthalpy. The data follow the same pattern as did those for the smooth wall tube.

Not shown in Figure 12 is that, in general, the temperature excursions following the start of boiling burnout when the rough tube wall was used were neither so abrupt nor as large as were those obtained when the smooth tube wall was used. A greater proportion of the rough wall boiling burnout points were defined by using the 2% offset method.

Also on Figure 12, the single fog inlet data point for each of the flow rates of 2,000,000 and 3,000,000 lb/hr-ft² fell well above the extension of the lines through the subcooled inlet data points. The reason for this is not known, but is believed to be partly due to difficulty in defining boiling burnout. These two fog-inlet points and the highest enthalpy subcooled inlet data points for these flow rates had the least pronounced departure from the nonboiling burnout temperatures. Figure 9 is the temperature-heat flux plot for the condition of 3,000,000 lb/hr-ft² and 1.8% inlet quality, and illustrates the type of

behavior of these runs. The two high heat flux points plotted on Figure 12 may be due to the inability to closely define the start of boiling burnout in these cases.

Effect of Concentrator

Figures 13 and 14 show the effect of the concentrator for the cases of the smooth wall and rough wall tubes, respectively.

To recapitulate briefly, the inlet device to the test section operated either as a homogenizer or as a concentrator during fog inlet runs. When it functioned as a homogenizer, it provided a homogeneous two-phase stream to the inlet. When it functioned as a concentrator, it concentrated the liquid phase of the two-phase mixture at the center of the flow tube and, therefore, placed most of the water on the heat transfer surfaces of the bundle. It was postulated that this preferential placement of the water would increase the boiling burnout heat fluxes.

Such was not the case, however. Figures 13 and 14 show no difference in the boiling burnout heat fluxes for the cases of homogeneous and concentrated fog inlets. Apparently, the beneficial effects of the preferred placing of the water were dissipated by the time the coolant had traveled the 23 1/2 in. unheated length and 6.3 ft heated length of the test section.

Effect of Rough Wall

Figures 15 through 18 show the effect of the rough tube wall on boiling burnout for each of the four flow rates investigated. Each figure shows plots of the boiling burnout heat flux vs. outlet enthalpy for both the smooth wall and the rough wall cases for a given flow rate.

The rough wall did cause a significant increase in the boiling burn-out heat flux. The increase varied from 10 to 35% for a given outlet enthalpy. The increase tended to be larger at the lowest and highest outlet enthalpies, and somewhat less at the intermediate outlet enthalpies. The increase also tended to be greater at the higher flow rates.

There are two mechanisms by which the rougheners are expected to increase boiling burnout heat fluxes. One applies only in the higher steam quality regions where annular flow is believed to exist. That is, the coolant flow consists of a film of liquid on the channel walls and a two-phase mixture of liquid droplets in a continuous vapor phase occupying the rest of the channel cross section. Boiling burnout occurs when the liquid film is removed from the heated surface. In these cases, the liquid film on the unheated walls of the channel is lost from effective cooling. Rougheners, such as were used in these tests, strip the liquid film from the unheated walls and place it into the bundle, where it is available to replenish the liquid film on the heated walls.

The other mechanism arises from the fact that there can be severe enthalpy imbalances in a bundle fuel element.⁽²⁾ For this bundle, for example, if no cross-channel mixing is assumed, the enthalpy increase of the coolant in the small triangular flow passages next to the central rod will be approximately 2.6 times the average. Boiling burnout would be expected to take place in these high enthalpy regions. Any cross-channel mixing decreases the magnitude of the enthalpy imbalances and

would be expected to increase the boiling burnout heat flux. The rougheners on the tube wall of these tests are believed to increase the cross-channel mixing.

Which of these two mechanisms is the more important is not known. Obviously, for the cases of high inlet subcooling where the boiling length is short and outlet qualities are low, the mixing mechanism is predominant. For the higher inlet enthalpy cases, either or both mechanisms may be effective.

It may be pointed out that rather severe roughening was used in these tests. The rougheners protruded 0.050 in. into the 0.060 in. space between the bundle and the flow housing wall.

Effect of Pressure

The effect of pressure is shown in Figures 19 through 21 for the case of smooth pressure tube wall, homogenizer inlet and subcooled inlet coolant. Two pressures were investigated, 1000 psia and 1200 psia. The data show that the 1000 psia boiling burnout heat fluxes were of the order of 10% higher than were those of the 1200 psia case.

Effect of Rod Spacing

Figures 19 through 21 also show the effect of rod spacing. The data from these tests are compared with data from 6.3 ft long, 19-rod, electrically heated bundle that had 0.587 in. OD rods, 0.050 in. spacing between rods, 0.100 in. radial spacing between rods and tube wall, and which used wire wraps to maintain rod spacing. (3)

The overlap of the 0.050 in. spaced data and the 0.040 in. spaced data is not large. However, the plots on Figures 19 through 21 do show that the 0.050 in. spaced boiling burnout heat fluxes curves are much

steeper than those of the 0.040 in. spaced; i.e., the boiling burnout heat fluxes for the 0.050 in. spacing tend to be about the same as those for the 0.040 in. spacing at the higher enthalpies, but greater than those of the 0.040 in. spacing at the intermediate enthalpies.

The effect of rod spacing on boiling burnout is a complex matter about which little is known. This is particularly true of the bundles where the rods are arranged in a circular pattern as they are for this test section. In these cases, the flow distribution and heat generation distribution are such that very high local enthalpies can occur. The high local enthalpies are a function of not only the flow and heat generation distribution, but also the cross-channel mixing and the effect of local steam generation, if it occurs.

Previous tests have shown that reducing the rod spacing significantly reduces the boiling burnout heat flux. However, a study of these data concludes that the reduction is due to high local enthalpies, and that the boiling burnout heat flux actually increases with decreasing rod spacing, based on local enthalpy.⁽²⁾

The 0.040 in. spaced test section had a much smaller radial spacing between the test section and flow tube wall, 0.060 in., rather than 0.100 in. The reduction in the space between the test section and flow housing wall forced a larger fraction of the coolant flow into the interior of the bundle and thus should have reduced the extent of the high local enthalpies.

If it is assumed that no cross-channel mixing occurs, the small triangular channels next to the center rod have calculated enthalpy increases 2.6 times the bulk average. This may be compared with a similar value of

2.9 for the 0.050 in. spaced bundle. Since the rod spacing and rod diameters for the 0.050 in. and 0.040 in. spaced test sections are not greatly different, the cross-channel mixing was expected to have been about the same for the two test sections. Therefore, the magnitude of the local high enthalpies for the 0.040 in. spaced test sections was expected to have been less than that of the 0.050 in. spaced test section, and the burnout heat fluxes were expected to have been about the same or higher for the same conditions.

It is not known why the boiling burnout heat fluxes for the 0.040 in. spaced test section were lower. The fact that they were points out that further experimentation concerning the effect of rod spacing on boiling burnout and concerning the extent of cross-channel mixing, both two-phase and single-phase, is required to permit optimum use of rod bundle fuel elements.

Location of Boiling Burnout

Boiling burnout always occurred on the inner 7 rods. For cases of low enthalpy, boiling burnout occurred on the center rod. For cases of the higher outlet enthalpies, boiling burnout occurred on one and usually several of the rods of the 6-rod ring.

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TABLE ISummary of Test Conditions

<u>Condition</u>	<u>Inlet Configuration</u>	<u>Pressure Tube Wall</u>	<u>Inlet Coolant Condition</u>	<u>Pressure psia</u>
1	Homogenizer	Smooth	Subcooled	1000
2	Homogenizer	Smooth	Subcooled	1200
3	Homogenizer	Rough	Subcooled	1000
4	Homogenizer	Rough	Fog	1000
5	Concentrator	Rough	Fog	1000
6	Concentrator	Smooth	Fog	1000
7	Homogenizer	Smooth	Fog	1000

TABLE II.

Experimental Results for the Conditions of Homogeneous Inlet, Smooth
Pressure Tube Wall and 1000 psia Pressure
(Conditions 1 and 7 of Table I)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Temperature °F	Inlet Quality or Subcooling % or °F	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality or Subcooling % or °F
1	1.04	530	14°F	525	1650	289	0.292	814	41.8%
5	1.05	502	42°F	490	1650	287	0.293	776	36.0%
12	1.05	462	82°F	444	1800	307	0.319	751	32.1%
13	1.06	423	121°F	400	1910	325	0.339	725	28.1%
20	1.07	345	200°F	316	1970	336	0.348	652	16.9%
21	1.06	248	295°F	216	2200	375	0.390	591	7.3%
69	1.07	-	17.6%	657	1170	211	0.207	868	50.1%
70	1.01	-	10.4%	610	1310	237	0.233	847	46.9%
71	1.01	-	5.5%	497	1390	232	0.246	829	44.2%
74	1.01	-	39.3%	797	820	147	0.145	944	61.9%
2	1.55	533	12°F	528	1740	204	0.308	732	29.1%
6	1.52	499	45°F	487	1910	229	0.338	716	26.7%
11	1.53	463	82°F	444	2100	249	0.372	693	23.2%
14	1.55	424	120°F	401	2240	261	0.396	662	18.5%
19	1.54	344	199°F	316	2370	279	0.420	596	8.2%
22	1.55	220	293°F	220	2780	326	0.492	546	0.5%
3	2.00	536	8°F	531	1910	173	0.339	704	24.9%
7	1.98	501	44°F	488	2100	192	0.371	680	21.2%
10	2.02	462	82°F	444	2320	208	0.411	652	16.9%
15	1.99	425	119°F	402	2510	229	0.445	631	13.7%

TABLE II. (Continued)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Temper- ature °F	Inlet Quality or Subcooling % or °F	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality or Subcooling % or °F
18	2.04	346	198°F	249	2790	317	0.494	566	3.6%
23	2.02	248	296°F	217	3310	297	0.585	513	23.2°F
72	2.00	-	5.3%	577	1800	164	0.319	741	30.6%
75* ^c	2.01	-	30.0%	737	830	75	0.147	812	41.6%
4	3.00	534	10°F	530	2320	140	0.410	670	19.6%
8	3.00	494	50°F	481	2540	154	0.450	635	14.3%
9	3.00	460	85°F	441	2830	171	0.500	612	10.8%
16	2.98	421	123°F	398	3010	184	0.533	582	6.0%
17	2.99	346	198°F	318	3610	219	0.639	537	4.0°F
73	3.00	-	2.3%	558	2220	134	0.393	692	23.0%
76* ^c	3.00	-	20.8%	677	820	50	0.145	727	28.4%

^aThe burnout points were numbered consecutively as the experiments were performed. The numbers, therefore, give the order of performance.

^bThe heat flux reported in these Tables is the average heat flux of the 19 rods. The inner 7 rods had a heat flux of 0.867 times the average heat flux.

^cThose runs marked with an asterisk did not reach boiling burnout. They are at the maximum conditions that could be reached with the equipment.

TABLE III.

Experimental Results for the Conditions of Homogeneous Inlet, Rough
Pressure Tube Wall and 1000 psia Pressure
(Conditions 3 and 4 of Table I)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Temper- ature °F	Inlet Quality or Subcooling % or °F	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality or Subcooling % or °F
33	1.05	539	5°F	535	1670	289	0.296	824	43.4%
40	1.06	500	44°F	488	1830	315	0.324	803	40.1%
41	1.08	462	82°F	443	1960	330	0.347	773	35.6%
47	1.04	421	123°F	398	1980	346	0.351	744	31.0%
49	1.04	342	202°F	313	2270	395	0.402	708	25.5%
53	1.09	246	298°F	214	2680	446	0.474	661	18.2%
54	1.04	-	19%	666	1380	241	0.245	906	56.0%
55	1.04	-	8.2%	591	1540	268	0.273	858	48.6%
56	1.04	-	2.6%	559	1620	282	0.288	841	46.0%
34	1.54	537	7°F	533	1980	234	0.351	767	34.6%
39	1.54	500	44°F	488	2170	256	0.384	744	31.0%
42	1.56	463	81°F	445	2260	264	0.401	709	25.7%
48	1.50	422	122°F	399	2380	288	0.421	687	22.2%
50	1.50	344	200°F	315	2740	332	0.484	647	16.1%
52	1.54	245	299°F	213	3360	395	0.594	608	10.1%
35	1.99	539	5°F	536	2270	206	0.402	742	30.7%
38	2.00	499	46°F	486	2470	224	0.437	710	25.9%
43	2.00	459	85°F	441	2570	233	0.454	674	20.2%

TABLE III. (Continued)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Temper- ature °F	Inlet Quality or Subcooling % or °F	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality or Subcooling % or °F
46	2.00	422	123°F	398	2810	255	0.497	654	17.1%
51	2.03	345	199°F	317	3300	295	0.584	612	10.6%
57	2.02	-	4.7%	573	2410	217	0.427	790	38.1%
36	3.02	538	6°F	535	2880	173	0.510	708	25.5%
37	3.03	500	44°F	488	3110	186	0.551	674	20.3%
44	2.93	464	80°F	446	3230	200	0.571	646	16.0%
45	2.97	427	117°F	404	3560	218	0.630	622	12.2%
58	3.02	-	1.8%	554	3000	180	0.530	734	29.4%

^aThe burnout points were numbered consecutively as the experiments were performed. The numbers, therefore, give the order of performance.

^bThe heat flux reported in these Tables is the average heat flux of the 19 rods. The inner 7 rods had a heat flux of 0.867 times the average heat flux.

TABLE IV.

Experimental Results for the Conditions of Homogeneous Inlet, Smooth
Pressure Tube Wall and 1200 psia Pressure
(Condition 2 of Table I)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Temper- ature °F	Inlet Quality or Subcooling % or °F	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality or Subcooling % or °F
30	1.05	538	33°F	534	1420	246	0.252	780	34.1%
26	1.05	346	221°F	318	1780	307	0.315	625	8.7%
25	1.06	246	322°F	214	2080	357	0.364	571	0.6°F
29	2.04	538	29°F	534	1800	161	0.319	695	29.4%
31	2.04	503	64°F	491	1930	172	0.342	663	14.9%
27	2.03	345	222°F	317	2750	246	0.487	563	6.4°F
24	2.05	247	320°F	216	3020	278	0.554	493	62.8°F
28	3.02	539	28°F	535	2260	136	0.401	671	16.2%
32	3.03	502	66°F	490	2370	142	0.419	632	9.8%

^aThe burnout points were numbered consecutively as the experiments were performed. The numbers, therefore, give the order of performance.

^bThe heat flux reported in these Tables is the average heat flux of the 19 rods. The inner 7 rods had a heat flux of 0.867 times the average heat flux.

TABLE V.

Experimental Results for the Conditions of Concentrated Inlet, Rough
and Smooth Pressure Tube Wall and 1000 psia Pressure
(Conditions 5 and 6 of Table I)

Number ^a	Mass Velocity lb/hr-ft ² x 10 ⁻⁶	Inlet Quality %	Inlet Enthalpy Btu/lb	Power kW	Enthalpy Gain Btu/lb	Burnout Heat Flux ^b Btu/hr-ft ² x 10 ⁻⁶	Outlet Enthalpy Btu/lb	Outlet Quality %	Tube Wall
59	1.03	17.2	654	1470	257	0.260	911	56.8	Rough
60	1.03	9.5	604	1540	272	0.273	876	51.4	"
61	1.03	5.4	578	1630	287	0.288	864	49.6	"
62	2.04	5.4	578	2270	202	0.401	779	36.5	"
63	3.03	2.5	559	3100	176	0.550	735	29.6	Rough
64	1.01	17.9	658	1160	208	0.205	866	49.8	Smooth
65	1.01	10.3	609	1370	246	0.243	854	48.1	"
66	1.01	5.3	577	1380	246	0.245	823	43.2	"
67	2.01	5.3	577	1750	158	0.310	735	29.7	"
68	3.02	2.3	558	2260	135	0.400	693	23.2	Smooth

^aThe burnout points were numbered consecutively as the experiments were performed. The numbers, therefore, give the order of performance.

^bThe heat flux reported in these Tables is the average heat flux of the 19 rods. The inner 7 rods had a heat flux of 0.867 times the average heat flux.

Figure 1.

Cross Section Arrangement of 19-Rod Test Section

Figure 2A.

Details of the Warts used to Maintain Spacing Between Rods

Figure 2B.

Details of the Ferrules used to Attach the Wart
Spacers to the Heated Rods

Figure 3. Details of the Flow Housing Tube Liner and Roughening Devices

Figure 4.

Details of the Thermocouple Plug and Thermocouple Installation

Figure 5.

Schematic Diagram of Piping Arrangement for the Subcooled Runs

Figure 7.

Typical Rod Temperature Behavior Where a Large Sudden Excursion Occurred

Figure 8.

Typical Rod Temperature Behavior Where a Large Sudden Excursion Occurred

Figure 9.

Typical Rod Temperature Behavior Where the Excursion was Small and Gradual

Figure 10.

Typical Rod Temperature Behavior Where the Excursion was Small and Gradual

Figure 11. Boiling Burnout Results for Smooth Wall Tube and 1000 psia

Figure 12. Boiling Burnout Results for Rough Wall Tube and 1000 psia

Figure 13. Effect of Concentrator on Boiling Burnout at 1000 psia and with Smooth Flow Tube Wall

Figure 14. Effect of Concentrator on Boiling Burnout at 1000 psia and with Rough Flow Tube Wall

Figure 15. Effect of Rough Flow Housing Wall on Boiling Burnout at 1000 psia and a Flow Rate of 1,000,000 lb/hr-ft²

Figure 16. Effect of Rough Flow Housing Wall on Boiling Burnout at 1000 psia and a Flow Rate of 1,500,000 lb/hr-ft²

Figure 17. Effect of Rough Flow Housing Wall on Boiling Burnout at 1000 psia and a Flow Rate of 2,000,000 lb/hr-ft²

Figure 18. Effect of Rough Flow Housing Wall on Boiling Burnout at 1000 psia and a Flow Rate of 3,000,000 lb/hr-ft²

Figure 19. Effect of Pressure and Spacing on Boiling Burnout at a Flow Rate of 1,000,000 lb/hr-ft²

Figure 20. Effect of Pressure and Spacing on Boiling Burnout at a Flow Rate of 2,000,000 lb/hr-ft²

Figure 21. Effect of Pressure and Spacing on Boiling Burnout at a Flow Rate of 3,000,000 lb/hr-ft²

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