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EXPERIMENTAL DETERMINATION OF THE DEPARTURE FROM NUCLEATE BOILING

IN LARGE ROD BUNDLES AT HIGH PRESSURE

EXPERIMENTAL EQUIPMENT AND EXPERIMENTAL OPERATION

FILES ROUTE DATE	LOCATION	P.N.O.	ROUTE TO

D. E. Fitzsimmons
W. L. Thorne
J. M. Batch

Reactor Engineering Section
Engineering Development Department

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PACIFIC NORTHWEST LABORATORY
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EXPERIMENTAL DETERMINATION OF DEPARTURE FROM NUCLEATE

BOILING IN LARGE ROD BUNDLES AT HIGH PRESSURE

II. EXPERIMENTAL EQUIPMENT

A. Flow Facility

The experimental studies were performed in the heat transfer and fluid flow facilities of the Pacific Northwest Laboratory operated by Battelle Memorial Institute. The test section was installed in the high pressure heat transfer apparatus, a stainless steel loop which has a design rating of 2500 psig at 650°F. Recirculating flow was provided by a 250 gpm, 1450 ft head centrifugal pump, and the flow rate through the test section was adjusted by air-operated control and bypass valves. The loop was pressurized and controlled at the desired operating pressure by a feed-and-bleed arrangement using a positive displacement 3-piston injection pump and an automatically controlled air-operated bleed valve. All feed water passed through a deaerator, a deionizer, and a filter before entering the injection pump. Injection pump pulsations were dampened with a 10-gal accumulator. During operation of the third test section, all recirculating water passed through a porous metal filter unit having a 10 micron removal rating. A three-way valve downstream of the test section was used to adjust the loop flow split through and around a water-cooled heat exchanger. The valve was automatically controlled to maintain the desired water temperature entering the test section.

Measurement of the flow rate to the test section was made by a venturi in conjunction with a high pressure mercury manometer; two venturis were used to cover the range of flow rates. Test section

power was supplied by a 120 V, 32,000 amp silicon rectifier system having stepless voltage control. Current was measured by a current transformer read on an indicating potentiometer while the test section voltage drop was read on a null-type voltmeter. Differential pressures along the test section were determined using strain gage transducers recorded by the DAS (Data Acquisition System) equipment of the laboratory which provided both typewriter and tape punch records. Bulk fluid inlet and outlet temperatures, as measured by platinum resistance thermometers, were read on a precision recording bridge while thermocouples sensed the subchannel water temperatures as well as the individual test section heater rod temperatures. The DAS equipment recorded the water and rod thermocouple signals. In addition, strip chart recorders were used to continuously monitor the heater rod thermocouples either individually or grouped to form thermopiles. Additional information on the heat transfer facilities is available in Reference (1).

(1) J. M. Batch, K. G. Toyoda, and H. E. Hanthorn. The Thermal Hydraulics Laboratory at Hanford, HW-65722 REV, November, 1961.

B. Test Section Description

The basic test section geometry consisted of a 25-rod bundle in a 5 x 5 square array, as shown in Figure 1. The rods were of 0.422 in. OD placed on 0.555 in. centers and had an 84 in. electrically heated length. A flow housing provided a square enclosure for the bundle and was in turn enclosed in a pressure housing.

Three test section configurations were built in which the primary difference was the cross-sectional heat flux distribution of the bundle. The first section had a uniform flux and the second had the inner 9 rods at a heat flux 20% higher than the outer 16 rods. The third bundle had a nonheated center rod of 0.535 in. OD and the inner 8 heated rods had a flux 15% higher than the outer rods. The axial heat flux was uniform in all cases. Table I gives the pertinent characteristics of the three test sections.

Each of the 25 heater rod assemblies consisted of a 0.422 in. OD Inconel heater tube silver brazed at each end to connection rods of the same diameter as the tube. Wall thickness of the Inconel tubes were 0.030 in. for the uniform flux rods and 0.035 in. for the inner rods of the peaked flux sections. Both support and temperature sensing components were inserted in each tube prior to brazing on the outlet connector end. The support components consisted of snug fitting aluminum oxide coated 321 SS rod and tube which prevented collapse of the heater tube by external pressure.

Heater rod temperature sensing and DNB detection were accomplished using thermocouples in conjunction with "temperature sensing cylinders." The sheathed MgO insulated thermocouple was imbedded on the axis of a

TABLE I.

<u>Test Section</u>	<u>I</u>	<u>II</u>	<u>III</u>
Heater rod diameter (in.)	0.422	0.422	0.422
Unheated rod diameter (in.)	---	---	0.535
Number of heated rods	25	25	24
Center-to-center spacing (in.)	0.555	0.555	0.555
Heated length of rods (in.)	84.0	84.0	84.0
Flow housing inside dimensions (in.)	2.915	2.959	2.962
	x	x	x
	2.913	2.936	2.957
Heat flux distribution, inner rod:outer rod	1:1	1.204:1	1.154:1

copper cylinder whose OD was coated with a 0.005 in. ceramic glaze and which fit snugly within the heater tube. These cylinders had four equally spaced radial grooves and a circumferential groove. In the case of a local hot spot anywhere around the tube circumference at one of these cylinder locations, the grooves directed the heat flow to the thermocouple. With this installation, the thermocouple read the average of the tube wall temperature over the length of the cylinder. For example, a 40°F rise over a quarter of the circumference would show up as a 10°F rise at the thermocouple.

A 10-1/2 in. long thermocouple train made up of three temperature sensing cylinders and spaced with support tubes was inserted into the outlet end of the heater tube. One 3/8 in. long cylinder was located at the end of the heater tube; two 1-1/4 in. long cylinders were upstream on either side of the location of a prototype mixing grid whose flow disturbances might cause DNB. The uncertainty of any DNB axial location necessitated monitoring the grid vicinity with long cylinders. A tapered hole was drilled 1/2 in. deep from each end of the 1-1/4 in. long cylinder to reduce its mass and improve its temperature response.

Electrical connections to the heater rod assembly were made by tapered mechanical joints at the ends of the connector rods. The 25 rod assemblies were connected by the taper joints to a common terminal plate at the inlet end of the test section while at the outlet end the tapered connectors were joined to individual terminal blocks. These blocks, in turn, were connected to a common outlet terminal plate through separate flexible cables thereby permitting

individual thermal expansion of the rods. Both the inlet and the outlet terminal plates were drilled to permit axial flow for the entire length of the bundle.

The rod spacing of the bundle was maintained using 10 egg-crate type sheet metal spacer grids located about 8 in. apart along the heated length of the bundle. Projections in each cell of the grid centered each rod in its cell. Four of these spacers were prototype flow mixing grids which had 1/2 in. long vanes projecting upstream and downstream from the grid. These vanes, scalloped to fit close to the rods, were bent so as to mix the flow among the bundle subchannels. Beyond the downstream end of the heated section were a set of three grids which also served to position 15 thermocouples for measuring the water temperature in selected subchannels of the bundle. These locations are noted by the letter designations in Figure 1.

The square cross section flow housing was made of four side plates joined together with tongue-and-groove type joints and flanged at its inlet end to fasten to the inlet terminal plate. The surface of these plates which faced the bundle had a zirconium oxide coating to prevent electrical shorts in case the rods bowed. The coating came loose during operation of Test Section I. Since no evidence of rod bowing was observed during disassembly of Test Section I, the coating was removed for the subsequent test sections. The inside dimensions of the flow housing were increased for Test Section III to provide additional flow between the housing and the outer rods of the bundle.

Westinghouse
Drawing ED/SK 313359C

Figure 1.

Four pressure taps were located along one side of the flow housing. The extreme taps provided the pressure drop over the heated length of the bundle while the intermediate taps were located to permit measurement of the drop across the downstream mixing grid and the downstream support grid.

III. EXPERIMENTAL OPERATION

A. Procedure Used for Obtaining Data

Prior to making any power runs on a test section, a series of zero-power runs was made to provide data on heat losses, pressure drops and relative calibration of the various temperature sensors. These runs were made at 4 or 5 coolant temperatures from ambient to 610°F and at mass flow rates corresponding to those used during the power runs. An electrically heated preheater was used to heat the loop water during these runs.

The power runs were performed by setting the pressure, flow rate, and coolant inlet temperature and increasing the power to the test section in a series of steps. The size of the power steps varied, but at conditions near DNB, the steps gave increases in the heat flux of 10,000 to 20,000 Btu/hr-ft². After each power increase, the process variables were allowed to stabilize and the data for the run were recorded.

The start of DNB was determined from the wall temperatures of the heater rods. Prior to DNB, the temperature increases were 5 to 15°F following a power increase. Generally, the onset of DNB was indicated by a temperature rise of 20 to 100°F (or larger) on one or more rods, during the power rise. Usually, the temperature would level out and the power was maintained until the data were recorded. In other cases, however, DNB was typified by temperature increases of 10 to 20°F. In these instances, it was necessary to take a few extra power increase steps so that the DNB run could be determined. This determination was done by plotting the suspected rod temperatures versus power. The points prior to DNB would fall on a straight line

while a second straight line of a different slope could be drawn through the remaining points. The run immediately following the slope change was defined to be the DNB run.

B. Observations Made During Operation and
Subsequent Examination of the Test Sections

Operation of the test section was accomplished in extended operating periods so as to limit the number of thermal cycles that the test section was exposed to. Data were collected during 12-hour periods of each operating day. Following collection of the zero-power data, shutdowns were limited to weekends and those necessary for equipment maintenance. Upon completion of the experiments, the test section was removed from the facility for disassembly and examination.

Test Section I

DNB operation for this test section was divided into two operating periods. During the second period, it was noted that higher DNB fluxes and pressure drops were being encountered than were produced earlier in the program.

Upon careful removal and disassembly of the test section, it was found that the zirconium oxide coating had flaked off the downstream third of the square flow housing. Numerous chips of 1/2 to 3/4 in. on the side, as well as larger and smaller sizes, became trapped within the bundle. The rod spacing grids prevented the chips from flushing out of the bundle. Since the majority of the chips were trapped by the grids just upstream and downstream of the end of the bundle heated section, it was not surprising that the DNB data were affected. Loss of the coating from the wall increased the rod-to-wall spacing about 15%. It is believed that the coating loosened because of an electrolysis action; the thermal cycle then broke it free.

The outer surface of the outer rods of the bundle was covered by two different deposits. The major deposit had a black sooty appearance

which loosely covered the inlet half of the bundle and consisted mainly of oxides of copper, iron, and aluminum. The other deposit was a 3/16 in. wide strip of brown adhering scale along the inlet 20 in. of each of the outer rods. It was largely corrosion product from the Inconel tubes caused by electrolysis.

Test Section II

Operation, following collection of the zero-power data, was divided into two extended operating periods in which 44 hours and 22 hours, respectively, were required for data collection.

During the first period, operation was satisfactory except for the early failure of Rod No. 5, a corner heater rod. The failure was complete as evidenced by a 4% increase in test section resistance; however, the loss did not seem to affect the performance of the test section or the validity of the DNB points.

Temperature excursions resulting from burnout were observed on both the high and the low flux rods. Thermocouples at the exit end of the rods sensed all but one of the indications. On four occasions, the thermocouples upstream of the exit flow mixing grid showed excursions, three times accompanying the end position rise and once without any indication at the end of the active section.

The second operating period was less satisfactory in that some fouling of the heater rods took place during the interim between the two data collection periods. This resulted in rod temperatures ranging from 100 to 300°F higher than before the shutdown. In addition, the pressure drop across the active section increased up to twice what it was during the first operating period. The fouling did not

have a significant effect on the DNB heat flux for three points which were rechecked. In some cases, the high temperatures masked the so-called "slow burnouts." It was necessary to plot temperature versus power for several rods to determine the flux at which a change in slope took place. Some of the higher flow rate, high power runs were cancelled or terminated by high rod temperatures, 1100 to 1200°F, because of concern for the silver braze joint connecting the heater rod to the copper end rod.

Following completion of the DNB experiments, the test section was removed from the vertical loop and disassembled. Large quantities of foreign materials were found in various locations in the test section. About 5 in.³ of a gray and white powder were found in the dead leg zone between the flow housing and the pressure housing. This apparently was carried in with water used to purge this zone and settled out in the low velocity stream. This powder was identified as magnesium oxide and resulted when some sheath type electrical heater elements in the loop ruptured during operation.

The heater rods were severely fouled with a scale. The scale was tightly adhering to the rod surfaces but the buildup varied because the outer layers had broken away quite generally. The color of the scale was grayish tan to brown on the heated surfaces and whitish tan on the downstream end rods. The scale had a thickness of 2 to 4 mils on the heater rods and was identified as a magnesium compound. There was a preferential buildup of additional scale on the outer surface of the outer rods toward the inlets (positive terminal) end. This buildup appeared to be the result of the electrical field between the

rods and the flow housing walls and was promoted by the generally high conductivity water which resulted from the addition of excess hydrazene at the beginning of the zero-power runs. Radial variation of the scale caused nonuniform thermal stresses to bow the outer rods. There was also a severe preferential etching of the inlet end of the 16 outer rods. All of these rods were replaced for Test Section III.

The failure of Rod No. 5 was caused by a breakdown of the aluminum oxide coating on the support rod which permitted an electrical short and local melting until the rod separated. The failure occurred about half way along the length of the heater rod and was not related to DNB.

Test Section III

Following collection of the zero-power data, the test section was raised and held at operating temperatures for 96 hours. All 40 DNB points were obtained in just over four 12-hour data-collection periods.

Operation of the test section was generally good throughout the operating period. No heater rod failures, which would result in a higher test section resistance and a reduced rod temperature, were encountered.

Temperature excursions resulting from DNB were observed on both the high and the low flux rods. In this test section, in addition to the exit rod thermocouples, the inner rods had thermocouples upstream and downstream of the exit flow mixing grid while the outer rods had thermocouples on the same plane as the grid. Thermocouples at the exit end of the rods sensed all of the indications while no excursions were noted on any of the upstream thermocouples.

During the course of operation, a gradual increase in the rod temperatures of 50 to 100°F was noted which indicated some fouling of the heater surfaces. There was no detectable effect on the burnout heat fluxes; however, at DNB, the slope change of the heat flux versus temperature plot was not as large.

Examination of the test section disclosed that the repeated circulation and draining of the loop water had not been fully successful in removing the remaining magnesium oxide contamination. A light coating of a magnesium compound was found over most of the length of the bundle. The coating was ~~thick~~^{est} (4 to 6 mils) on the outer surface of the outer rods at the outlet end of the bundle. The inner rods had a 1 to 3 mil coating at this end. The coating diminished in thickness toward the inlet end.

Deposits like those on the inlet end of Test Section I were found to minor degree on this section. The black oxides were much thinner and covered about a third of the length; the corrosion product was quite negligible.