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OBSERVATIONS ON
TRANSITION BOILING HEAT TRANSFER PHENOMENA

by

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NOMENCLATURE

A	Area	ft. ²
D	Diameter	ft.
DNB	Departure from Nucleate Boiling	
G	Mass Flow Rate	lb _{mass} /sec in. ²
N _R	Reynold's Number $\left(\frac{DG}{\mu_f}\right)$	
Q	Heat	Btu
T	Temperature	°F
ΔT	(T _{wall} - T _{sat})	°F
ΔT _i	(T _{HPH₂O} - T _{wall})	°F
c _p	Specific Heat at Constant Pressure	Btu/lb _{mass} °F
K	Thermal Conductivity	Btu/hr ft °F
j _f	Colburn Factor $\left[\left(\frac{h}{C_p G}\right) \frac{C_p N}{K}\right]_f^{\frac{2}{3}}$	
h	Heat Transfer Coefficient	Btu/hr ft ² °F
μ	Viscosity	lb _{force} sec/ft ²
<u>Subscripts</u>		
HPA	High Pressure Water Average	
HP _{H₂O} , HPW	High Pressure Water	
TS	Test Section Pool	
f	Film	
i	Inside	
max	Maximum	
min	Minimum	
o	Outside	
Sat	Saturated Boiling Liquid	
w, wall	Wall of Tube	

ABSTRACT

A study was made of boiling heat transfer from a horizontal tube to a saturated liquid at atmospheric pressure in the nucleate, transition, and film boiling regions. Particular attention was devoted to the beginning and end of the transition boiling region. Two liquids were used, Refrigerant 11 (Freon 11) and demineralized water. An attempt was made to determine what changes in the boiling curve can be produced by wide variations in the surface. Both metallic and non-metallic surfaces were studied. An extensive photographic study was made using both "still" and motion pictures which did much to shed light on the complicated phenomena of boiling. Results indicate (1) that $(Q/A)_{\max}$ for these conditions is almost a constant and is unaffected by a shift of $(\Delta T)_{\max}$ of as much as 40° (2) $(\Delta T)_{\max}$ is strongly dependent on surface conditions (3) that data in the transition region is highly unstable, depending on surface conditions and on wetting properties of the liquid (4) that the inception of transition boiling is marked by violent motions of a two phase mixture which alternately approaches and is driven from the heated surface. Thus a vapor film is gradually produced as the surface temperature rises, and stable film boiling is established only when the surface temperature becomes relatively constant (5) that the liquid does touch the surface during transition boiling (6) that there is no unique minimum point (7) that the minimum point does not necessarily mark the dividing line between transition and film boiling (8) that the criterion for stable film boiling should be the absence of fluctuations in the surface temperature. (9) Heat transfer data for water and Ref. 11 in all the boiling regimes is presented.

Chapter I

GENERAL REMARKS

Boiling heat transfer studies have been conducted during recent months which were directed toward obtaining further information about this complicated phenomena. Attention was directed especially toward the transition region of the boiling curve, the area of the curve between nucleate boiling and complete or stable film boiling. The departure from nucleate boiling (DNB) or "burnout point" received most attention. Photographic and other evidence was found which serves to elucidate this much studied phenomena.

The program was planned during the months of July and August, 1958. Construction of the basic apparatus occupied the period between August 1958 to July 1959. The following report is based on data taken during some twelve weeks throughout the succeeding months.

As an electrically heated test section is not suitable for operation in the transition boiling region because of the danger of "burnout," high pressure water was chosen as the source of heat in the test apparatus. This choice was also indicated by circumstances that high pressure boiling studies were being conducted on three loops in the Heat Transfer Division at Argonne. As a consequence much of the material for the new facility was on hand, and in addition "know how" and experience were available in the planning and construction of the new loop.

The apparatus was designed so that organic fluids with a low boiling point could be studied. Such a choice was indicated because the maximum temperature available from the pressurized water was 575°F, so that high temperature differences would be available only if low boiling point liquids were used. It was found that the transition region could be studied while boiling water also, but only at atmospheric pressure.

The first fluid studied was Ref. 11 (Freon 11). This was chosen for the following reasons:

1. It is easily available and not excessively expensive.
2. It is non-toxic, non-inflammable and odorless.
3. Many thermodynamic properties are tabulated, as it is a recognized heat transfer medium in commercial use.
4. Refrigerant 11 boils at a temperature slightly above ordinary room temperature at atmospheric pressure. This makes it relatively easy to handle. It can be condensed at atmospheric pressure using only ordinary tap water as cooling medium.

5. It has small latent heat of evaporation, requiring only modest heat input for full range boiling studies. The requirements are less than $\frac{1}{10}$ of those for water.
6. It is water white in color, facilitating photographic studies.

The part of the loop handling refrigerant was constructed of stainless steel and had a designed operating pressure of 150 psi. Thus many other fluids could be studied in this facility. The present report is concerned with pool boiling studies on a horizontal tube. A second test section was provided on the facility for the study of boiling with forced convection in an annulus, and most of the components of the basic loop were chosen to meet the needs of this second study.

Since Ref. 11 is not ordinarily boiled at elevated temperatures, no information as to its behavior in the various boiling regimes is available in the literature. Much of the past studies were made to determine its behavior as a refrigerant, and a standard refrigeration compressor was used in the system. Thus the refrigerant usually contained some oil usually of a quantity unknown. No oil could come into contact with the refrigerant in the present system. Thus, conditions were known, and reproducible results could be obtained.

This initial study was therefore designed to supply data for Ref. 11 boiling at higher temperatures throughout all the boiling regimes. The pressure used was nearly atmospheric throughout, and the effect of surface conditions was the primary object of study. Both metallic and non-metallic surfaces were studied.

At the same time an extensive program to study the regimes using both "still" photography and high-speed motion pictures was carried out. It was primarily directed toward finding out what actually happens at the beginning and end of the transition boiling regime. The two phases of the program fitted well together, for the data on boiling was needed to render the photographs meaningful.

The results of these studies are presented in this report. A second report is planned which will give a historical report on studies of this type, and summarization of other data. This second report will also include correlations for the data presented here.

It would seem that a considerable contribution to boiling heat transfer studies can be made through an intensive study of some one fluid, which might become a kind of "standard" heat transfer fluid. Such a "standard" fluid would be of use in two-phase, one-component studies of boiler models which are now being conducted in the field of nuclear power engineering. The existence of a considerable amount of data on some one fluid would be of great assistance in making such studies, and would enable a new worker in the field to compare his results with that of past work.

Refrigerant 11 has the advantages listed above, and would seem to be a logical choice for such studies. The main advantage is the fact that only modest power input is required for full range studies. Water has been extensively studied, but very large amounts of power are required for heating even small tubes and wires. This fact has hampered boiling studies.

Since Ref. 11 has a density about $1\frac{1}{2}$ times that of water (91.88 lb/ft at 80°F) it would seem that void measurements in two phase flow studies using the gamma-ray attenuation method would be facilitated by the use of the denser fluid. Studies are now being planned to check this supposition.

Chapter II

BASIC APPARATUS

This chapter will describe the basic system exclusive of the test section. The system schematic is shown in Fig. 2-1. It is divided into two main parts, one for high pressure water having an operating pressure of 1500 psig, and the other for Ref. 11 or other liquids which has a designed operating pressure of 150 psig. Both parts are constructed throughout of stainless steel. Figure 2-2 and Fig. 2-3 show the system before the instrumentation was installed. Figure 2-5 shows the system after it was completed.

I. High Pressure Water System

This system was designed to heat and circulate high pressure water through the test section. Provision is made for pressurizing the system, circulating the water and heating it to the desired temperature, and controlling and measuring the temperature and flow rate of the water.

The main components are as follows:

(1) Water Circulating Pump

This is a Westinghouse Model 30A centrifugal pump with wetted parts of S.S. construction. Its rated capacity is 55 gpm at zero head at 68°F. It is designed to operate at an inlet pressure of 2000 psia and water temperature of 600°F.

It is cooled by circulating transformer oil through the electrical windings. A supplementary circuit was included to pump and cool the transformer oil.

(2) Electrical Heaters

The water was heated by two sets of calrod type heaters. The first set consisted of three $7\frac{1}{2}$ kw heaters which were wye connected to 440 V, 3 phase lines through a Powerstat variable transformer. Power to large heaters was read on a Weston precision 3 phase wattmeter Model 926.

The second set of heaters consisted of three 2 kw calrod type heaters which were individually switched; one heater was connected through a variable autotransformer for fine heat control. Power input was read by individual ammeters and wattmeters.

(3) Pressurizing Apparatus

The water system was pressurized by using nitrogen gas in a hydraulic accumulator. The accumulator has a rubber diaphragm which separates the water from the pressurizing gas.

The pressurizing procedure was this: the system was filled with demineralized water at atmospheric pressure, then nitrogen at the desired operating pressure was admitted to the accumulator, causing the rubber diaphragm to expand, allowing nitrogen to completely fill the accumulator volume. Then water was pumped into the system by a Hills-McCanna Proportioning pump until water began to enter the accumulator. The pressure on the two sides of the diaphragm then were equal. Gages were installed to facilitate this procedure. The accumulator also absorbed the volumetric expansion of the water as the temperature was raised. A supplementary gas volume was supplied so that this expansion would not produce any large change of pressure.

The accumulator used was a Greer Model 30A - $2\frac{1}{2}$ W.S. Pressure rating was 3000 psi.

(4) Flow Metering

The flow was measured by a sharp-edge orifice mounted between standard orifice flanges. Size of the orifice for these runs was 0.445 in. It was mounted in 1 in. Schedule 80 pipe. Pressure differential was read on a 60 in. mercury manometer for high flows, and by a 60 in. manometer with a fluid of S.G. 2.95 for lower flows. The orifice was calibrated in place by the weight tank method.

(5) Safety Devices

(a) Two rupture discs provided emergency over-pressure protection,

(b) Electrical interlocks provided ordinary safety protection. One was provided to cut off high pressure make-up pump if a pressure of 1500 psig were exceeded. This interlock also cut off heaters if they were on when overpressure occurred.

Interlocks were also provided to protect the Westinghouse 30A pump. Since the pump bearings were water lubricated, a positive pressure of at least 10 psig was needed for safe operation. Interlocks were provided so that the pump could not be started without pressure on the system. The same provision was made to ensure coolant oil flow to the pump.

Interlocks were provided also so that the heaters could not be turned on unless the circulating pump was in operation.

The components were given a hydrostatic pressure test at 3750 psia after welds were completed. The ordinary operating pressure was 900 psig.

The entire system was insulated with 1 in. of magnesite high temperature insulation.

II. Refrigerant Circuit

The refrigerant loop was designed to condense and store the liquid being boiled, and was provided with a pump to deliver fluid to the test section. A filter and dryer were included in the circuit, together with necessary valves and flow metering devices.

The main components were as follows:

(1) The condenser was of the shell and tube type 72 in. long and 6 in. in diameter. Condensation took place in shell. Cooling was by tap water. The cooling water flow and temperature were metered.

(2) The receiver was constructed of a piece of 8 in. 347 S.S. pipe 62 in. long with a flange on one end. Valves were provided so that the refrigerant could be sealed in the receiver if it was necessary to open other parts of the system. The receiver could hold about 175# of Ref. 11. A sight glass was provided to check level of Ref. 11.

(3) Circulating Pump

The refrigerant circulating pump was an Aurora Type IZ4 S.S. process pump coupled to a $7\frac{1}{2}$ H.P. variable speed A.C. motor. The pump had a rated head of 370 psig at 3500 rpm, and a flow of 56 gpm at zero head. The shaft seal was a Rott S.S. Duraseal, which uses Teflon as sealing material. This eliminated the possibility of any contamination of the material being pumped. A cooling coil of $\frac{1}{4}$ in. copper tube was placed on the inlet pipe, to help eliminate flashing in the pump. This was needed because the Ref. 11 being pumped was near the boiling point temperature.

(4) Flow Metering Devices

The flow was metered by a venturi with a $\frac{1}{8}$ in. diameter throat mounted in a 1 in. schedule 80 pipe. Differential pressure was measured by a 60 in. mercury manometer. This was intended mainly for the forced convection study.

All connections in the basic Ref. 11 system were welded or flanged. Flanges were standard 150# type. "Durabla" gaskets were used with the flanges. After assembly the circuit was carefully checked for leaks by using high pressure air. The system was also checked by filling it with Ref. 12 gas and using a halide torch to detect leaks. No significant loss of Ref. 11 was reported.

The entire system was insulated with 1 in. of glass wool insulation.

Filling Procedure:

All parts of the system were carefully flushed with trichlorethane before being installed. A further cleansing operation took place during a period of preliminary testing when Ref. 11 was circulated through the whole system. The Ref. 11 was then withdrawn.

The ordinary filling procedure was designed to eliminate as much contamination as possible. The system was evacuated by a vacuum pump to a pressure of $\frac{1}{2}$ in. mercury. The system was then allowed to fill with Ref. 11 gas, and a vacuum was again pumped. The condenser cooling water was then turned on, and the Ref. 11 was allowed to distill into the system from the top of the shipping drum. This was done to eliminate any oil which might be in the Ref. 11 on arrival. The filling operation usually took about 8 hours.

This process was repeated before each series of runs to assure purity of the Ref. 11. This was necessary, since any impurities present in the system would concentrate in the test section; since in effect the pool boiling experiments are a constant distillation process, with the residue remaining in the test section.

An over-pressure relief valve was provided on the Ref. 11 receiver. Over-pressure electrical interlocks were provided to cut off Ref. 11 circulating pump in case of a malfunction. Also the circulating pump could not be started if condenser coolant water was not flowing.

FIGURE 2-1
SCHEMATIC OF BOILING APPARATUS

Fig. 2-2. Center Portion of Apparatus Showing Ref. 11 Condenser, Receiver and Pump

Fig. 2-3. Left Part of Apparatus Showing Test Section, H. P. Water Circulating Pump and Heaters

Fig. 2-4. Electrical Control Panel for Apparatus

Fig. 2-5. Left Part after Completion of Apparatus

Chapter III

TEST SECTION AND INSTRUMENTATION

The apparatus used in these pool boiling experiments has two main parts; the test section proper and the refrigerant make-up tank. A small distillation tank was included in this part of apparatus into which the contents of the test section could be dumped at the end of a series of runs. This device greatly aided in keeping the Refrigerant 11 at high purity.

The make-up tank was constructed of a piece of 6 in. 304 S.S. pipe flanged on both ends. The length was 42 in. It was provided with full length sight glass which was equipped with a steel measuring tape to determine the height of liquid in the tank.

It was mounted in a vertical position and was above the test section so that liquid could flow into test section by gravity. Liquid was pumped into the tank by the circulating pump previously mentioned, and flowed into the test section from the bottom. The flow was monitored by a rotameter and controlled by suitable valves. The rotameter was not used to determine amount boiled during test period. This was determined by change in level in make-up tank.

The test section proper was constructed from a 6 in. sight flow indicator manufactured by Ernst W. C. & Gage Co. The inside volume 6 in. I. D. and 9 in. long. The section was made of 312 S.S. It was machined and polished inside after delivery to aid in cleansing operations. A front view is shown in Fig. 3-1, and an end view in Fig. 3-2.

The end plates were fabricated from standard 6 in. 150# blank flange covers. They were 1 in. thick, made of 347 S.S. A Teflon sleeve with $\frac{1}{8}$ in. wall thickness provided thermal insulation for the heated tube to eliminate end effects. The thermal conductivity of Teflon is 1.7 BTU/hr ft² °F in., hence it provides excellent thermal insulation. The Teflon sleeve also served as a seal around the tube to prevent loss of refrigerant. A view of end plate components is shown in Fig. 3-4.

All of test sections tubes had an I. D. of $\frac{1}{2}$ in. The first series of tests were conducted on tubes with an O. D. of $\frac{5}{8}$ in. The second series of tests were conducted on tubes with an O. D. of $\frac{3}{4}$ in. Only the part inside the test section was of the larger diameter, the other parts of the tube were machined to an O. D. of $\frac{5}{8}$ in. so that the end plates would not have to be modified. The overall length of the heating tube was 23 in. The portion of the tube from which boiling took place was 9 in. long. It was connected to the high pressure water system with "Swagelock" fittings.

Instrumentation

Thermocouples were installed in four groups to read temperatures as follows: at inlet and outlet of high pressure water to test section, at three places at middle of the tube wall, and in the pool to obtain the bulk temperature. These installations are described in greater detail below. I-C thermocouples were used throughout.

Temperatures at inlet and outlet were measured by thermocouples at each spot, which were installed in a 1 in. standard tee which served as a mixing chamber. Inlet to chamber was through a $\frac{1}{2}$ in. pipe, outlet was through a $\frac{1}{2}$ I. D. tube. The thermocouple junctions were installed in copper plugs which were mounted on $\frac{1}{8}$ O. D. S.S. tubes which projected into the mixing chamber volume. Two of the couples on each end of test section were connected in parallel and read by a precision portable potentiometer, the other was connected to a Honeywell 6 point recorder. See Fig. 3-4.

The wall temperatures were read by three couples which were mounted in the middle of the wall 1 in. from the inlet side of the test section. They were spaced axially $\frac{1}{2}$ in. apart, one on top, one on side, and one on the bottom. They were averaged to obtain the wall temperature for each run. They were spaced in this fashion in order to read approximate point conditions, without any severe disturbance of the flow over the surface or of the temperature gradient in the wall of the tube.

The thermocouple wires were of 30 ga. I. C. type encased in a $\frac{1}{16}$ O. D. inconel tube, with ceramic powder insulation. The junction was prepared by removing tube and insulation from about $\frac{1}{4}$ in. of the thermocouple wires. The wires were then carefully cleaned and twisted against the ceramic insulation. Then the end of the tubular sheath was covered with a thin layer of silver solder, which also covered the junction. The wires were then cut off $\frac{1}{64}$ in. from the ceramic insulation.

The assembly was then inserted in $\frac{1}{16}$ diameter holes which had been drilled tangentially into the $\frac{1}{8}$ in. thick wall of the tube. The holes were fluxed, heated, and filled with silver solder prior to insertion of junction assembly. See Fig. 3-5.

Thus, the thermocouple junction was located with considerable accuracy at the middle of the wall. The surface under which the temperature measurement was made was not disturbed, and flow over the surface was not impeded. There would be some fin effect where the inconel sheath emerged from the wall, but the temperature was not read at that point.

This arrangement was used only with nickel and copper tubes, and, as both materials have good thermal conductivity, the temperature gradient through the wall of the tube at the location of the tube would not be

noticeably disturbed. The ceramic insulation occupies over $\frac{1}{2}$ the cross sectional area of the thermocouple sheath, which also helped minimize heat losses along the thermocouple assembly. The thermocouples are shown in Fig. 3-6. These couples gave quite satisfactory results. They were read by precision potentiometer and also recorded on the Honeywell recorder.

The bulk temperature of the pool was measured by 2 couples placed in a $\frac{1}{4}$ in. S.S. tube which was mounted in the test section $1\frac{1}{2}$ in. directly below the heating tube. This reading could be checked by measuring the pressure in the test section, and finding the corresponding temperature. One of the couples was read through a thermocouple switch by a precision portable potentiometer, the other was attached to the Honeywell recorder.

All of the couples were calibrated at room temperature and at the boiling point of water. Accuracy is estimated of $\pm \frac{1}{2}^{\circ}\text{F}$ for basic reading of thermocouple, but larger errors in temperature reading resulted from lack of proper mixing of liquid, uncertainty of thermal conductivity of metal, etc. During all the runs, the Honeywell recorder gave a continuous record of temperatures of inlet to heating tube, at three points at middle of the tube wall, and that of the pool itself. This record was of considerable aid in the study of the complex phenomena of the transition boiling region. During the actual taking of data, however, all temperatures were read by a Leeds & Northrup portable precision potentiometer.

Fig. 3-1. Front View of Test Section

Fig. 3-2. End View of Test Section

Fig. 3-3. End Plate Components

Fig. 3-4. Connections to High Pressure Water

Fig. 3-5. End View Showing Heating Tube

Fig. 3-6. View of Wall Thermocouples

Chapter IV

OPERATIONAL PROCEDURES AND COMPUTATIONS

The test section was prepared for each run by carefully wiping all surfaces with acetone, and by polishing the tube surface with four zero polishing paper. End plates were then installed, and connections made to the high pressure water system. A test of the new connections was made at 1500 psig. Then operating pressure of 800 psig was established, and circulating pump was started.

Refrigerant 11 was then pumped into the make-up tank and pre-heated to desired temperature. Pressure in the make-up tank was about 5 psi above that in test section. This was necessary because Ref. 11 in the sight glass boiled as level fell unless temperature in make-up tank was raised slightly above room temperature. Corrections were made for this in the final computations.

Refrigerant 11 was then admitted to the test section. A constant level was maintained in the test section by continuous flow from the make-up tank. When the temperature of the high pressure water had stabilized at the desired point, a data period was begun. The test periods were usually 15 minutes long. At the beginning and end of these periods, the following were recorded:

- (a) Inlet & outlet thermocouples
- (b) Pool thermocouple
- (c) H.P. water pressure
- (d) Wall thermocouples
- (e) H.P. water flow from manometers
- (f) Level of Ref. 11 in make-up tank
- (g) Electrical power input to heaters
- (h) Temperature of Ref. 11 at inlet

Computations

Heat transfer was computed from the amount of Ref. 11 boiled away during the test period. Since H.P. water inlet and outlet temperatures and flow was known, heat balances could be made. The heat input computed from the H.P. water temperatures and flow were always lower than those obtained by measuring the Ref. 11 boiled away by about 15%. This was caused by insufficient mixing at outlet where temperatures were taken. Steps will be taken to correct this if new data is taken.

A check on the method used to measure make-up liquid was made. During some runs with water, condensate was collected after it left the

test section. Make-up liquid was also measured. Agreement between two methods was good, usually within 3%. Accuracy of heat transferred is estimated at $\pm 8\%$.

In computing the temperature difference, the water temperature was taken as the average of inlet and outlet temperatures.

For the first series of runs on the $\frac{5}{8}$ in. O. D. tubes $\frac{Q}{A}$ (BTU/hr ft²) and overall ΔT ($T_{HPH_2O} - T_{sat}$) were computed. The temperature drop through the wall could be computed by using published values of thermal conductivity since $\frac{Q}{A}$ was known. When an attempt was made to separate the inside cooling coefficients from the outside boiling coefficients using the Dittus-Boelter equation, it soon became apparent that results were not satisfactory, as some negative temperature differences resulted from the computations.

A review of literature on the subject revealed that data for water being heated and cooled in a tube which was correlated by the Dittus-Boelter equation gave considerable scatter.⁽¹⁾⁽²⁾ The attempt to separate the inside and outside coefficients was abandoned and only overall ΔT are reported for these runs.

The wall thermocouples as described above were installed and used during the other runs. Thus, average temperatures at the middle of the wall is known. Knowing Q/A , and thermal conductivity of materials used (nickel and copper) inside and outside surface temperatures could be computed. Knowing this, the inside and outside coefficients could be obtained.

The inside coefficients were correlated using the Colburn equation. The results show that the Colburn equation gave a good average value, though the scatter of the data was considerable. This seems to be typical of data for water. The results are reproduced in a later part of the study.

Chapter V

NUMERICAL DATA

This chapter will be composed of two parts; one devoted to the first series of runs, the second part to the remaining runs. Outside boiling coefficients were obtained during the latter runs.

The first series of runs was planned to gain operating experience with the apparatus and to gain some familiarity with the appearance of the various boiling regimes. Certain general observations on the experiment will be included in a description of the first series of runs.

During this series, 150 data points were taken to check the effect of surface variables on the boiling curve. All tubes had an O.D. of 5/8 in. and an I.D. of 1/2 in. Materials used and data points were as follows:

<u>Liq. Boiled</u>	<u>Tube Material</u>	<u>Data Points</u>
Ref. 11	304 SS	53
Ref. 11	ETP Copper	42
Ref. 11	Teflon Coated 304 SS	26
Ref. 11	Ceramic Coated 304 SS	22
Water	ETP Copper	18

The water runs were made to determine whether the apparatus had the capability of exceeding peak heat flux while boiling water. It was found that by use of all the power available (30KW), peak heat flux for water boiling at atmospheric pressure could be exceeded. The available temperature difference ($T_{HP\ H_2O} - T_{sat}$) was 348°F. This was not sufficient to reach the minimum point or second crisis, though points were obtained in the transition region. These first runs with water are not reproduced here.

The first runs were designed to find, in a general way, how much variation in the boiling curve could be produced by surface variables, non-metallic as well as metallic. This had been studied before by Jacob⁽³⁾ and Corty & Foust⁽⁴⁾, but only at low heat fluxes in nucleate boilings, and only with metallic surfaces. No data was available for Ref. 11. These runs were to cover the entire boiling curve.

Data points were taken in sequence as the temperature of the HP water was increased during runs for a day. It was found that data points taken during one day followed a regular curve, and scatter was not of any great consequence. The runs for a subsequent day, however, showed that the whole curve might be shifted to the right or left. This was most noticeable in the data for Ref. 11 boiling on a copper tube. Runs for 4 different days are shown in Fig. 5-1.

It will be noticed that the curves vary most in the transition region. Since there are two film temperature drops included in the temperature difference ($T_{HP\ H_2O} - T_{sat}$) viz, the outside boiling film temperature drop ($T_{wall} - T_{sat}$) and the inside cooling temperature ($T_{HP\ H_2O} - T_{wall}$), it was not evident from the available data what the effect each film coefficient was on the curves. Attempts to compute the inside coefficient using the Dittus-Boelter equation caused the outside boiling coefficients to scatter badly. In the second series of runs, wall couples were installed to allow determination of the inside and outside coefficients independently.

Data taken on 304 S.S. tubes do not show such pronounced scatter. Fig. 5-2 is shown for comparison. During the second set of runs, a chrome-plated copper tube was used because of its more stable surface.

The glass port in the test section made observations possible at all times. Some of the boiling regimes were easily recognized, viz, low nucleate boiling and stable film boiling. It was not easy to detect by visual observation when peak heat flux had been attained. The boiling action is very vigorous at peak heat flux, and the vapor film on the outside of the tube is in violent motion. To an inexperienced observer, the situation is quite confusing. After many hours of observation, however, certain patterns were recognized, which made the identification of the different regimes fairly easy.

In an attempt to find some simple phenomena, which would indicate the DNB point, three thermocouples were spot welded to the outside of the 304 S.S. tube. These were not intended to give a true surface temperature, but it was thought they would give an indication of the variations in the surface temperature. These couples were recorded on the Honeywell 6 point recorder.

These couples provided some significant information about DNB. The recorder was of the constant balance type, and had a printing cycle of about 20 sec. Any variation in the output of the thermocouples would be picked up by the recorder while the balancing process was going on prior to printing.

It was soon observed that surface temperatures fluctuated markedly during transition boiling, and were stable during nucleate and stable film boiling. It was possible to determine the DNB point by observing the appearance of the fluctuation in the movement of the recorder indicator.

These fluctuations were later recorded on a Sanborn continuous strip recorder so that they could be measured and studied in detail. This data will be discussed in a Chapter 6.

The most interesting phenomena observed during these first runs was the very marked shift to the left produced by the ceramic coating on the S.S. tube. Data for three tubes are shown in Fig. 5-3 and 5-4. Fig. 5-3 shows Q/A vs. $(T_{HP\ H_2O} - T_{sat})$ while 5-4 shows data after computed temperature drop through the wall has been subtracted from overall ΔT .

The basic tubes were the same for all three-5/8 O.D. 304 S.S. tube. No. 1 had been polished with 4 zero polishing paper, No. 2 had a sprayed-on coating of aluminum oxide which had an average thickness of 0.0015 in., and tube No. 3 had a smooth coating of Teflon 0.001 in. thick. Both surfaces were durable and could withstand the planned operating temperatures. Teflon was included because of its non-wetting, inert surface which has high anti-friction properties.

It is noticeable that Q/A_{max} is here shown to be almost a constant, despite the wide variation in (ΔT_{max}) . During the second set of runs, outside boiling coefficients were obtained for a ceramic coated tube with the aid of the wall thermocouples.

Second Series

The subsequent runs were made on a tube with an O.D. of 3/4 in. and an I.D. of 1/2 in. They are summarized as follows:

<u>Fluid</u>	<u>Tube</u>	<u>Data Points</u>
Ref.11	SB161 Nickel	39
Ref.11	Chrome-Plated ETP Copper	30
Ref.11	Ceramic Coated SB161 Nickel	24
Water	Chrome-Plated ETP Copper	24
Water	Ceramic Coated ETP Copper	10

For all of these runs, the outside boiling coefficients and the inside cooling coefficients are computed. Boiling data is shown here, the cooling coefficients were correlated using the Colburn equations and data is shown in appendix.

The inside and outside wall temperatures are computed using the temperatures at the middle of the wall provided by the three wall thermocouples as explained in Chapter IV.

The average of the readings for the three couples was taken as the temperature at the middle of the wall. During nucleate boiling, the variation from the average was $\pm 2^\circ\text{F}$. During film boiling, the variation was $\pm 1^\circ\text{F}$. During transition boiling, the variation between top and bottom couples was often as large as 8°F , for it was quite possible to have low transition boiling on bottom and high transition boiling on the top of the tube.

In this regime, boiling often was "patchwise," as some of the pictures in a later chapter show. Thus, both Q/A and $(T_{\text{wall}} - T_{\text{sat}})$ are averages in the transition region. In the nucleate and stable film boiling regimes, conditions on the tube were uniform over the whole length.

The data is summarized in the accompanying graphs.

Discussion of Data

Certain characteristics of the data should be pointed out. The apparatus was designed to study the boiling curve in the transition region, and in particular the DNB point. Accuracy in measuring Q/A was greatest when it was large, consequently the points near DNB are the most accurate.

The lowest points in the nucleate boiling region were obtained during fairly vigorous boiling. Since Ref. 11 boils at 75° at atmospheric pressure, a moderate rise in the temperature of the HP water above ambient produced vigorous boiling. The heating produced by the work of the circulating pump was enough to initiate boiling. This fact usually determined the lowest point in the nucleate boiling region. Points in the non-boiling region were not obtained.

It is noted that $(Q/A)_{\text{max.}}$ is almost the same for all materials used. The two metallic surfaces have the same slope in the nucleate region, and very nearly the same $(\Delta T)_{\text{max.}}$ Ceramic produces a pronounced shift to the left as shown. The curves for the three surfaces converge after stable film boiling has been established. See Fig. 5-9.

It should be noted that in all the cases that ΔT for peak heat transfer coefficient is not the same as ΔT for peak Q/A .

It will be noted in Fig. 5-10 that no points were obtained for water in most of the transition boiling region. The following remarks can explain this situation. It is evident from the graph that in the nucleate boiling region Q/A is almost independent of surface temperature. Therefore, when the peak heat flux condition is reached, the average HP water temperature is already quite high. Two adjacent points in the runs for (1-26) will illustrate the situation.

<u>Data Points</u>	<u>(1-26-5)</u>	<u>(1-26-6)</u>
HP water temp.	440°F.	463°F.
Pool Temp.	212	212°
$(T_w - T_{\text{sat}})$	53.0	235°
$(\Delta T)_{\text{wall}}$	29.2	2.0°
Q/A	527,800	33,890

Thus it can be seen that when the DNB point is reached, a film with a high thermal resistance is formed on the outside of the tube quite rapidly, and the wall temperature almost immediately assumes a value close to that of the water flowing in the tube. Only a few points were obtained in the film boiling region because the apparatus was then operating at the limit of its capabilities.

No data is available for comparison with the Ref. 11 curves. There is, however, data available to compare with that here obtained for water. That was one of the reasons data for water was obtained.

The data obtained for water in the nucleate boiling region is very close to that given by Addoms⁽⁵⁾ for water boiling at atmospheric pressure off a 0.024 in. platinum wire. The points in the low transition boiling region are very close to those obtained by Farber & Scorah⁽²¹⁾ for water at atmospheric pressure boiling off a 0.040 in. diameter nickel wire. This agreement does not exist in the nucleate region.

Since Farber & Scorah determined surface temperatures by means of a thermocouple attached to their heating wire, their wall temperatures were probably accurate in the film boiling region only. In that region the couple junction would be effectively shielded from the cooling effects of the boiling pool by the film of vapor which forms. This behavior was noticed on some junctions, which were welded outside of the tube during the course of these experiments.

Addoms used the heating wire as a resistance thermometer to obtain his wall temperature. This is undoubtedly the more accurate method.

The three sets of data are compared in Fig. 5-11.

FIGURE 5-1
REF. II ON COPPER TUBE

FIGURE 5-2
REF. II ON 304 STAINLESS STEEL TUBE

FIGURE 5-3
REF. II ON THREE SURFACES

FIGURE 5-4
REF. II ON THREE SURFACES

FIGURE 5-9
WATER ON CHROME P. COPPER

FIGURE 5-10
WATER AT ATMOSPHERIC P.

Chapter VI

DEPARTURE FROM NUCLEATE BOILING

Data presented here will shed some light on the complex phenomena of transition boiling. It is taken from 3 couples welded to the heating tube and gives a rather complete description of the surface temperature variations. This will be combined with the data from the photographic study to be presented in the next chapter to give an explanation of departure from nucleate boiling (DNB).

The data was obtained from three chromel-alumel thermocouples which were spot welded to a $\frac{5}{8}$ in. O.D. 304 S.S. horizontal tube. One was on the top, one on the side, and one on the bottom. They were 30 ga. (0.010 in. dia.), and were placed 2 in. from the end of the test section tube. They were all in the same plane perpendicular to the axis of the tube. Each wire of the junction was individually welded to the tube, with about 0.010 in. between the wires. Thus the actual junction was made through the S. S. wall of the tube. An ice bath was used as the cold junction.

The EMF of the couple was recorded on a Honeywell "Brown" six point recorder and also on a Sanborn continuous strip recorder which utilized a hot wire stylus. Arrangements were made so that the readings could be checked on a portable precision potentiometer. The basic sensitivity of the Sanborn recorder was 100 microvolts per cm. Provisions were made on the recorder for other sensitivities, 2X, 5X, etc. the basic sensitivity. Provisions were also incorporated for a **zero suppression** voltage so that perturbations in a high level signal could be recorded.

The data here presented was all taken during one day, and covers the whole boiling curve. Refrigerant 11 was the boiling fluid. Figure 6-1 shows the Q/A vs. overall ΔT curve for the 14 data points obtained during the runs for the day. Runs were taken consecutively as numbered.

The traces given in Figs. 6-2 to 6-7 give a good picture of the phenomena of transition boiling, and present evidence to show what happens at the DNB point. In most cases traces are shown for top, side, and bottom couples for each run in the transition and film boiling regions. These traces were not taken simultaneously but consecutively since only one low-level preamplifier was available for our recorder. A standard L & N thermocouple switch was used to connect each of the couples in turn to the Sanborn recorder. The time base is shown below the trace. The marks represent an interval of 1 sec. Grid marking is at 1 cm spacing.

The surface temperature is essentially constant in the nucleate boiling region. Traces were obtained for Runs 1 to 5, but they are not reproduced here because they do not contain any significant information.

In Fig. 6-3, the traces illustrate the situation existing during Run 6, which represents $(Q/A)_{\max}$. Trace a has a "slow motion" time base to the left. It is clear that fluctuations have begun to appear at the top of the tube. Sensitivity is here $100 \mu\text{v}/\text{cm}$ indicated by the symbol X1. The fluctuation represented by the "pip" in the middle, therefore, represents a variation of about 17°F . The fluctuations do not persist, however. Note that the trace for the side and bottom (b & c) couples are essentially constant, indicating that these areas are in nucleate boiling.

The traces in Fig. 6-3 were taken as the temperature was raised between Runs 6 and 7. All are from the top couple. In trace a, the part to the left is from the steady condition during Run 6. As H.P. water temperature is raised, the temperature fluctuations increase and become fairly constant in amplitude. Trace b (X1) show the variations as the tube was allowed to cool to return to Run 6. Trace 6-3C (X2) shows how the temperature can vary between wide limits near the DNB point. The maximum variation shown to the left is approximately 50°F . The expanded portion to the right shows the general nature of the variations.

The traces for Run 7 are shown in Fig. 6-4. Q/A has fallen off from $59,100 \text{ Btu/hr ft}^2$ to $49,800 \text{ Btu/hr ft}^2$. In other words, we are just "over the peak." It will be noted that bottom and side couples show a temperature still practically constant. Figure 6-4 b & c show a long trace of the top thermocouple.

During Run 8, Q/A has dropped to $8,080 \text{ Btu/hr ft}^2$. Figure 6-5a shows what has happened to the surface temperatures. All the couples show disturbances, as three traces to right show. Side couple now show well established fluctuations.

The situation for Run 10 shows that conditions are about the same as Run 9, except that the bottom couple is evidently becoming more unstable. In data for Run 11, the fluctuations for the three couples have become quite similar with nearly equal amplitudes.

It will be noticed that during Run 11, the fluctuations are roughly equal, though that on the top has decreased while that on the bottom has increased.

During Run 12, Q/A again falls off from $11,400$ to $9,900$. This is due to the great activity revealed by the bottom couple. A long trace is shown for those who might desire to analyze the trace for a fundamental frequency.

During Run 13, Q/A has risen to $11,600$, and there is less activity at the bottom couple. At Run 14, Q/A rises slightly again, and now the perturbances are of equal amplitude at all couples, and they show a decrease from the previous point. This is an indication that stable film boiling has been established.

The data for these 14 runs is summarized in Fig. 6-8. The surface temperatures are taken from the traces given in Fig. 6-2 to Fig. 6-7. The variations are estimates of "peak to peak" fluctuations. Note that the peak fluctuations for the bottom occur at a surface temperature of 280°F while the peak for the top couple is at a surface temperature of 176°F. This effect is probably produced by the natural convection current in the boiling pool. Note that the surface temperature and temperature-fluctuations become equalized as stable film boiling is established as shown by Runs 13 and 14.

The data used for this graph are shown below:

DATA FOR FIGS. 6-1 AND 6-8

Ref. 11 on 304 S.S. Tube; O.D. = $\frac{5}{8}$ "; I.D. = $\frac{1}{2}$ "; Length = 9"

Run	HP H ₂ O Temp. °F	Q/A Btu/hr ft ²	(T _{HPH₂O} - T _{sat}) °F	Top Couple		Side Couple		Bottom Couple	
				S. Temp.	Temp. Var.	S. Temp.	Temp. Var.	S. Temp.	Temp. Var.
1	113	9,800	38	98	0	96	0	97	0
2	135	25,900	59	100	0	98	0	102	0
3	155	38,200	78	102	0	104	0	108	0
4	162	46,100	85	105	0	105	0	110	0
5	177	54,600	100	107	0	108	0	113	0
6	187	59,100	111	107	2	108	0	114	0
7	195	49,800	117	159	11	110	0	117	0
8	210	8,100	132	171	13	145	9	149	2
9	233	10,100	156	177	15	163	10	158	4
10	279	11,400	200	225	13	221	11	201	9
11	311	11,400	234	258	11	254	11	234	14
12	350	9,960	271	291	11	296	10	280	20
13	396	11,600	317	341	7	348	6	339	5
14	429	12,100	349	379	5	382	4	375	5

FIGURE 6-1
REF. II ON S.S. DATA FOR 9-26-59

Run 8

FIG. 6-5a Run 8
xl S.V. 2.80 mv. FIG. 6-5b Run 9
xl S.V. 3.30 mv. FIG. 6-5c Run 10
xl S.V. (as Given)

FIGURE 6-8
SURFACE TEMPERATURE AND SURFACE TEMPERATURE VARIATION DATA FOR 9-26

Chapter VII

PHOTOGRAPHIC STUDIES

In this chapter will be reproduced a few of the many photographs that were made during the course of this investigation. All of the photographs were taken with a 35 mm "still" camera, with the exception of those noted. The speed of all pictures was 0.001 sec. A 135 mm focal length telescopic lens was used in conjunction with an extension bellows. Two standard photofloods were used for front lighting, and another was used to give a light background by illuminating a white porcelain surface which was placed behind the rear port of the test section. A Leica M3 with a reflex housing was used for Figs. 7-2 to 7-5 and 7-10 to 7-21. A Practina FX reflex camera was used for the remainder. Figures 7-2 to 7-17 show the boiling of Ref. 11, the remainder are devoted to the boiling of water.

Figure 7-2 shows low nucleate boiling. The very regular spacing of the bubbles after the departure from the surface, and the uniformity of size of the bubbles is clearly demonstrated. Such phenomena has been frequently used as the basis for mathematical analyses of nucleate boiling. However, it was observed that this regularly seems to disappear at higher heat fluxes.

Figure 7-3 is at a slightly higher heat flux. It shows one nucleating site producing a continuous stream of agglomerated bubbles. This type of bubble genesis is characteristic of higher heat fluxes.

Figure 7-4 shows agglomerated bubbles rising from the bottom of the tube.

Figure 7-5 shows surface conditions near peak heat flux. The natural convection produced by the rising vapors has momentarily cleared vapor from one side of the tube. New bubbles can be seen forming on the surface.

Figure 7-6 shows one of the forms that transition boiling can assume. The irregular liquid-vapor boundary is typical of this type of boiling.

Figure 7-7 shows transition boiling near the minimum point. Note that there are two rows of bubbles on the top of the tube.

Figure 7-8 is included to show how film boiling changes to nucleate boiling when the flow of heating water inside the tube is interrupted. Nucleate boiling begins at one end of the tube and slowly progresses along it as shown.

Figure 7-9 shows how film boiling well beyond the minimum point may appear. The liquid-vapor interface on the top of the tube is in violent agitation, and the vapor does not depart as bubbles with a uniform size. Film boiling from a horizontal surface would probably have a similar appearance.

Figure 7-10 shows how nucleate boiling is initiated on a ceramic coated tube. Note that portion of the tube to the left shows no boiling. Boiling starts at the wall of the test section and advances rather slowly as shown. The ceramic coating provides many good nucleation points for Ref. 11. There are no widely separated points scattered at random as on a metallic surface.

Figures 7-11 and 7-12 should be compared. The first photograph was taken at the start of a run, whereas the second was taken after the tube had been allowed to cool rapidly from a high temperature. This active nucleation pattern no doubt accounts for the marked shift of the nucleate part of the boiling curve to the left.

Figure 7-13 shows nucleate boiling about half of peak heat flux.

Figure 7-14 shows boiling near peak heat flux. Note the bubble pattern near the bottom of the tube.

Figure 7-15 shows low transition boiling. Two pictures of stable film boiling at different heat fluxes are shown for comparison in Fig. 7-16 and 7-17.

Figure 7-18 shows subcooled low nucleate boiling. The nucleus bubbles remaining after most of the vapor has condensed can be seen rising above the tube.

Figure 7-19 shows saturated low nucleate boiling for comparison.

Figure 7-20 shows how new nucleation centers form on a surface after the vapor has been swept from the surface during vigorous boiling.

Figure 7-21 shows high transition boiling. The opening through the turbulent vapor film shows that the liquid is apparently in contact with the surface during transition boiling. This is in contrast with the commonly accepted view.

Figure 7-22 and 7-23 show continuous vapor streams being produced from separate sites. Some of the sites show very vigorous vapor generation, so that vapor seems to "spray" from the surface. After many hours of observation of boiling, it is the opinion of the present author that this is the typical vapor production pattern for vigorous nucleate boiling.

These photographs were taken after the tube had been rapidly cooled from a high temperature by stopping the HP water circulating pump. It would seem that some of the nucleating sites had retained vigorous vapor generation pattern that they had acquired at the higher temperature.

Figures 7-24 and 7-25 show how new nucleation points are formed at two different heat fluxes. Each was taken as the side of the tube was swept free of vapor. Note that the lower photograph shows a greater portion of the tube covered with vapor. Note that the vapor patches are rather flat. Figure 7-25 shows conditions near the peak heat flux.

Figures 7-26 and 7-27 show conditions which are characteristic of the peak heat flux. The "explosions" from the surface which produce the DNB is clearly evident. The peak heat flux for the ceramic coated tube was lower than that for the chrome plated tube.

Figures 7-28, 7-29, and 7-31 show conditions at point F on the boiling curve. The condition could be best described as low transition boiling. The liquid-vapor interface is not so smooth as it would be in stable film boiling. Typical bubble formations are shown.

Figure 7-30 shows subcooled film boiling. Note that the bubble generation has practically ceased and that the bubbles that do rise are of a spherical shape. Previous observers had noted a regularity in bubble formation during film boiling. The only regularity of this type observed in this study occurred during subcooling film boiling, when most of the heat transfer takes place at the liquid-vapor interface. There is little bubble formation, but some of the pictures do show that bubbles do rise from the vapor "rod" in a kind of diamond array. For saturated film boiling, no such regularity was observed. The high speed movies described later gave a good opportunity to study bubble formation during film boiling.

The second part of the photographic study consisted in high speed motion pictures taken with a "Fastax" camera. They were taken by the Graphic Arts Dept. of ANL, and have been edited for general use*. These movies were intended to demonstrate the development of each type of boiling. The apparatus was such that this could easily be done.

The general procedure was the following. If it was desired to discover what happened at the DNB point, for example, conditions as at Point E on the boiling curve would be established by raising the HP water temperature to the proper point. Then the HP water circulating pump would be shut off, and the tube on which boiling took place cooled until conditions at Point A were established. The "Fastax" camera and the HP water circulating pump were turned on simultaneously, and the heating curve would be rapidly retraced from Point A to Point E. With Ref. 11 it was possible to show the phenomena of the entire boiling curve from Point A' to Point E' in one run of film.

* ANL-MP-111-9020

The film runs were 100 ft in length, and most of the runs were taken at 4000 frames per sec. The normal length of each run was thus about 1.25 sec. Motion pictures were taken of both water and Ref. 11.

The movies showed in a graphic way what actually produced the first crisis or DNB. It could be observed that nucleate boiling characterized by a vapor motion which has a uniform velocity. The DNB point is indicated by the appearance of perturbances which can be observed in the vapor film, which causes a disruption in the even flow of vapor upward. The development of one such disturbance is shown in Figure 7-32. These photographs may be compared with Fig. 7-26 and 7-27. The evidence is rather conclusive that the appearance of such "explosions" characterized the DNB point. The topic will be discussed further in the next chapter.

Figure 7-33 shows the formation of bubbles during low nucleate boiling. This series illustrates the various types of bubble formation that may take place. Note that many of the bubbles are not spherical in shape even at the instant of departure from the heated surface. Agglomerated bubble sequences are also evident. The motion pictures could be studied with profit by those interested in bubble formation in boiling.

FIGURE 7-1
CHARACTERISTIC BOILING CURVE

Fig. 7-2. Ref. 11 on S.S. Tube. Low nucleate boiling

Fig. 7-3. Ref. 11 on S.S. Tube. Low nucleate boiling.
Point A' on boiling curve.

Fig. 7-4. Ref. 11 on S.S. Tube. O.A. $\Delta T = 55^\circ \text{F}$;
 $Q/A = 24,000 \text{ Btu/hr ft}^2$

Fig. 7-5. Ref. 11 on S.S. Tube. Peak heat flux.
O.A. $\Delta T = 102^\circ \text{F}$; $Q/A = 60,000 \text{ Btu/hr ft}^2$

Fig. 7-6. Ref. 11 on Chrome-plated Tube.
 $T_w - T_{sat} = 111^\circ\text{F}$; $Q/A = 28,800 \text{ Btu/hr ft}^2$

Fig. 7-7. Ref. 11 on Chrome-plated Tube.
 $T_w - T_{sat} = 171^\circ\text{F}$; $Q/A = 5,800 \text{ Btu/hr ft}^2$

Fig. 7-8. Ref. 11 on Chrome-plated Tube.
 Showing nucleate and film boiling.

Fig. 7-9. Ref. 11 on Chrome-plated Tube.
 $T_w - T_{sat} = 346^\circ\text{F}$; $Q/A = 11,900 \text{ Btu/hr ft}^2$

SCALE
 $\frac{1}{2}''$

Fig. 7-10. Ref. 11 on Ceramic-coated Tube.
Shows initiation of nucleate boiling.

Fig. 7-11. Ref. 11 on Ceramic-coated Tube.
Low nucleate boiling.

Fig. 7-12. Ref. 11 on Ceramic-coated Tube.
Low nucleate boiling after tube had suddenly
cooled from high temperature.

Fig. 7-13. Ref. 11 on Ceramic-coated Tube.
O.A. $\Delta T = 52^\circ \text{F}$; $Q/A = 30,900 \text{ Btu/hr ft}^2$

Fig. 7-14. Ref. 11 on Ceramic-coated Tube.
O.A. $\Delta T = 76^\circ\text{F}$; $Q/A = 60,000 \text{ Btu/hr ft}^2$
Point B' on boiling curve.

Fig. 7-15. Ref. 11 on Ceramic-coated Tube.
O.A. $\Delta T = 115^\circ\text{F}$; $Q/A = 15,000 \text{ Btu/hr ft}^2$
Point C' on boiling curve.

Fig. 7-16. Ref. 11 on Ceramic-coated Tube.
O.A. $\Delta T = 274^\circ\text{F}$; $Q/A = 9,500 \text{ Btu/hr ft}^2$
Point D' on boiling curve.

Fig. 7-17. Ref. 11 on Ceramic-coated Tube.
O.A. $\Delta T = 372^\circ\text{F}$; $Q/A = 11,100 \text{ Btu/hr ft}^2$
Point E' on boiling curve

Fig. 7-18. Water on Copper Tube.
Subcooled nucleate boiling.

Fig. 7-19. Water on Copper Tube.
O.A. $\Delta T = 72^{\circ}\text{F}$; $Q/A = 38,700 \text{ Btu/hr ft}^2$
Point B on boiling curve.

Fig. 7-20. Water on Copper Tube.
O.A. $\Delta T = 84^{\circ}\text{F}$; $Q/A = 96,000 \text{ Btu/hr ft}^2$
Point C on boiling curve.

Fig. 7-21. Water on Copper Tube.
O.A. $\Delta T = 316^{\circ}\text{F}$; $Q/A = 283,000 \text{ Btu/hr ft}^2$
Point E on boiling curve.

Fig. 7-22. Water on Chrome-plated Copper Tube. Point A on boiling curve.
Tube has been suddenly cooled from high temperature.

Fig. 7-23. Water on Chrome-plated Copper Tube. Point A on boiling curve.
Shows sites producing a continuous stream of vapor.

Fig. 7-24. Water on Chrome-plated Copper Tube.
 $T_w - T_{sat} = 29^\circ\text{F}$; $Q/A = 196,000 \text{ Btu/hr ft}^2$

Fig. 7-25. Water on Chrome-plated Copper Tube
 $T_w - T_{sat} = 37^\circ\text{F}$; $Q/A = 443,000 \text{ Btu/hr ft}^2$

Fig. 7-26. Water on Ceramic-coated Copper Tube
 $T_w - T_{\text{sat}} = 39^\circ \text{F}$; $Q/A = 445,000 \text{ Btu/hr ft}^2$

Fig. 7-27. Water on Chrome-plated Copper Tube
 $T_w - T_{\text{sat}} = 38^\circ \text{F}$; $Q/A = 584,000 \text{ Btu/hr ft}^2$

Fig. 7-28. Water on Chrome-plated Copper Tube
 $T_w - T_{sat} = 288^\circ\text{F}$; $Q/A = 18,000 \text{ Btu/hr}$

Fig. 7-29. Water on Chrome-plated Copper Tube
 $T_w - T_{sat} = 288^\circ\text{F}$; $Q/A = 18,000 \text{ Btu/hr ft}^2$

Fig. 7-30 Water on Chrome-plated Copper Tube
 Subcooled film boiling

Fig. 7-31. Water on Chrome-plated Copper Tube
 $T_w - T_{sat} = 288^\circ\text{F}$; $Q/A = 18,000 \text{ Btu/hr ft}^2$

0

2.22

4.44

6.66 milliseconds

Fig. 7-32 Ref. 11 on Chrome Plated Copper

A typical explosion characterizing departure from nucleate boiling

SCALE

Fig. 7-33. Water on Chrome Plated Copper Tube.
The Genesis of Bubbles.

Chapter 8

CONCLUSIONS

The remarks in this chapter will be of a general nature, based on the results of this investigation and on the published work of other experimenters. It will be concerned mainly with basic assumptions which have formed the grounds for various heat transfer theories. These assumptions will be examined in the light of the findings of this study, and of other recent data. The chapter will examine the situation in each of three boiling regimes in order.

As this report was being prepared a study by Berenson⁽⁶⁾ came to hand. This work was concerned with data obtained from n-pentane boiled from a horizontal copper surface at atmospheric pressure. It corroborated some of the results presented here. Most notable was the conclusion that the liquid does wet the surface during transition boiling.

(1) Nucleate Boiling

The data as presented here show that marked shifts in the nucleate portion of the boiling curve can be produced by even minor changes in the surface characteristics. This study showed that relatively stable surfaces such as 304 S.S., chrome and nickel when Ref. 11 is boiled produced a stable nucleate portion of the boiling curve. However, the results for a copper surface showed wide variations. The most marked change was produced by the addition of the aluminum oxide surface to the nickel tube. The $(\Delta T)_{\max}$ for the nickel tube was 55°F, while that for the ceramic coated tube was about 18°F. This was a shift of about 37°F. Despite this radical shift, $(Q/A)_{\max}$ was almost unchanged at 64,000 BTU/hr ft². In computing the surface temperature of the ceramic coated surface no allowance was made for the temperature drop through the coating. Thus the surface temperature may have been even lower than what is recorded in the data. Berenson reports a similar shift, which in that case was produced by a change in the treatment of the copper surface. For a mirror finish he obtained a $(\Delta T)_{\max}$ of about 80°F, while that for a lapped surface was about 25°F. This was a shift of about 55°F caused by a minor variation in the surface condition. Here also this marked shift had no notable effect on $(Q/A)_{\max}$, which was about 85,000 BTU/hr ft². It is important to note that the lapped surface was actually quite smooth, that is, the average heights of the roughness peaks was not great. However, the surface has excellent nucleating properties, apparently produced by the grains which roll on the surface during the lapping process. A similar effect was noted during these studies while using a nickel surface treated by "Vapor Blast," which is equivalent to a very fine sandblasting. However, no data was presented for the surface in this report.

The fact that even very wide variations in the $(\Delta T)_{\max}$ does not cause any important shift in the value of $(Q/A)_{\max}$ seems to indicate that the analysis by Kutateladze⁽⁷⁾ and Zuber⁽⁸⁾ of the $(Q/A)_{\max}$ as purely hydrodynamic phenomena is correct. The key notion in this analysis is that there are two motions in the two-phase boundary layer on the heated surface; that of the vapor from the surface, and that of the liquid to the surface. Maximum heat transfer occurs when the vapor generation becomes so great that the liquid can no longer reach the surface. Thus maximum heat flux is a function directly of Q/A alone, and only indirectly depends on ΔT , which as we have seen, is a function of the surface conditions.

There is, however, a shift which takes place in the transition region of the boiling curve which does produce a significant shift value of $(Q/A)_{\max}$. This will be discussed in greater detail in a later part of this chapter.

Most of the analyses of nucleate boiling are based on data taken from bubbles at low heat flux. The most commonly accepted are those by Rohsenow⁽⁹⁾ and Foster and Zuber⁽¹⁰⁾ and Levy.⁽¹¹⁾ The data taken at low heat flux are then extended over the whole range of the nucleate regime. The photographs (Fig. 7-26 and 7-27) show that even at low heat flux, vapor generation at a preferred site can be in the form of a continuous stream. Since vapor trapped in a crevice in the surface has been shown to be a cause of nucleation at a preferred site, the presence of the vapor stream would in itself be sufficient to cause vapor generation in any superheated liquid which would be drawn to the base of the vapor stream by the natural convection currents produced by that stream. Thus, it would seem that there would be no strong reason why the vapor generation should be intermittent in the form of bubbles at high heat fluxes. Vapor streams in boiling water are reported by Yamagata and Nishikawa.⁽¹²⁾

This fact lent some evidence to support the hypotheses which Kutateladze used in his analysis of the critical heat flux. "In this way we arrive at the hypothesis that the initiation of film boiling is due to the destruction of the stability of the structure of a boundary, two-phase layer which itself has displaced the nucleate type of boiling."⁽¹³⁾ The emphasis here is on the high nucleate boiling. It is a different type of boiling and has displaced the ordinary nucleate boiling which can be studied, as far as bubble details are concerned, only at low heat flux. The application of bubble data by extension to high heat fluxes would seem to be a rather questionable procedure.

The 40°F to 50°F shift in the nucleate part of the boiling curve is probably accounted for in part by the fact that some surfaces have a kind of catalytic effect on the boiling process. Larson⁽¹⁴⁾ has reported that such surfaces as aluminum, zinc, magnesium, etc., can cause water to boil at temperatures less than 212° at atmospheric pressure. During the

present investigation it was found that Ref. 11 would boil off the wood in an ordinary lead pencil at a temperature about 6°F below its ordinary boiling point. A photograph of this is shown in Fig. 8-1. An unglazed ceramic tube showed the same effect.

Thus it is easy to see why it is very difficult to obtain a satisfactory correlation for nucleate boiling. It is possible to get reproducible results if proper care is taken in the experimental procedures, but a small change in the preparation of the surface can cause a pronounced shift in the boiling curve, which can also be reproduced, if care is taken.

(2) Transition Boiling

There is a marked shift in the transition region boiling curve which can be observed in Fig. 5-1. Ordinarily the points in the transition boiling regime are located on a straight line joining the maximum and minimum points. Under certain conditions, however, the curve in the transition region can be an arc which is substantially above the straight line joining the maximum and minimum points. This shift is reported by Berenson⁽⁶⁾ and by Lowery and Westwater⁽¹⁵⁾ and Gaertner and Westwater.⁽¹⁶⁾ The usual result on the general shape of the boiling curve is to broaden and flatten the curve at the peak, and usually to increase the value of $(Q/A)_{\max}$, and to shift the $(\Delta T)_{\max}$ to the right. There is no easy explanation for the shift, but important conclusions can be drawn from its existence.

During this study and also during that of Berenson the shift from one curve to the other would seem to be the result of the oxidation of the copper surface. Berenson afterward found that Q/A could be caused to shift from the lower to the higher curve if a few drops of oleic acid were added to the boiling pentane. The shift was noted in reference (15) while the effects of additives were being investigated while methanol was being boiled on a copper tube. In reference (16) the phenomena was noted while boiling an aqueous plating solution on a copper disc.

It seems correct to deduce from this, as Berenson did, that the liquid does touch the surface during transition boiling, contrary to the commonly accepted opinion. The condition of the surface can produce such marked effects only if there is some contact with it. The photographic evidence presented here points to the same conclusion.

This fact, coupled with the evidence from the couples attached to the surface as reported in Chapter 6, provides the basis for a mechanism of transition boiling. When heat flux is at the maximum, there is necessarily a steep temperature gradient in the wall through which heat is transmitted. For example, the temperature distribution was follows in a 3/4" O.D., 1/2" I.D. copper tube heated by flowing pressurized water while boiling water at atmospheric pressure.

Bulk temperature inside the tube	447°F
Inside wall temperature	294°F
Outside wall temperature	265°F
Pool temperature	212°F
Q/A	528,000 BTU/hr ft ²

It is not difficult to see what happens during transition boiling. At peak heat flux the vapor generation is so great that liquid is prevented from reaching heating surface. As the liquid is lifted from the heating surface, the surface temperature rises suddenly, heating the thin vapor layer very rapidly, causing it to expand and drive the two phase boundary layer away from the surface with explosive force. This produces the "explosion" from the surface which can be seen in Figs. 7-26 and 7-27. These surface eruptions can be seen very clearly in the high speed movies which were taken.

After the initial "explosion" however, the process cannot continue, for no more vapor can be generated if the liquid is not in contact with the surface. So after the initial "explosion" the liquid rushes back in and wets, and, as a consequence, cools the surface. Chapter 6 is the history of the development of transition boiling. The maximum temperature variation recorded is about 20°F, but the actual surface variations are probably much greater than that because the instrument used in recording these temperature variations had a relatively low frequency response. The traces of the thermocouple EMF's show that the frequency of this alternate cooling and heating process is quite high, on the order of 30 to 60 cycles per second.

The thermocouples show point conditions on the surface, and also indicate quite clearly that the boiling is "patchwise" in the transition region.

In this description of transition boiling a vapor film forms gradually on the surface as ΔT increases. The "explosions" from the surface become less and less violent as the temperature of the surface rises, as the liquid has a decreasing ability to contact and cool the surface. During stable film boiling the liquid is no longer able to come into direct contact with the surface, and the surface temperature becomes relatively stable.

This gradual development of a stable vapor film seems to be in better accord with our intuition as to how physical processes actually develop. The assumption that liquid does not touch the surface during transition boiling involves the proposition that a vapor film suddenly forms on the heated surface at the inception of transition boiling. That notion seems to represent a mathematical type of thinking, for in the physical world few phenomena occur instantaneously.

A study of the graph (Figs. 5-1 and 5-9) shows that there does not appear to be a well defined minimum point. A study of Figs. 6-1 and 6-8 shows that the lowest point on the boiling curve corresponds to a point of maximum variation in surface temperature, which would seem to indicate that that point was still in the transition region.

If we compare the data for the nickel tube to that obtained for the ceramic coated nickel tube we note the following:

	$(Q/A)_{\max}$	$(\Delta T_o)_{\max}$	$(Q/A)_{\min}$	$(\Delta T_o)_{\min}$
Nickel Tube	64,000	55°	6,000	180°
Ceramic Coated Ni Tube	62,000	18°	8,500	250°

Thus we can see that at a ΔT of 180° surface conditions are still an important factor in determining the heat flux. Figure 5-1 shows what great variations can occur in this region during the runs for successive days.

Berenson found a minimum-minimum point at about $\Delta T=100^\circ\text{F}$. When the curve in the transition region describes a wide arc above the straight line connecting maximum and minimum points he found that the minimum point occurred at a ΔT of about 200°F . He shows a rather limited amount of data in this region, and concludes that the "minimum minimum" point has possibilities from the standpoint of mathematical analysis. However, on the basis of this study and others, such as (15) it would seem safer to say that the "minimum minimum" point is in the transition region, and does not mark the inception of stable film boiling. The curves in the transition region do not fall on one line until ΔT reaches at least 200°F in Berenson report using n-pentane, and until ΔT reaches about 300° in this study using Ref. 11.

(3) Film Boiling

This raises a question as to the criterion for film boiling. It is usually assumed that the minimum point on the boiling curve corresponds to the beginning of the film boiling region. Berenson found that his lowest point occurred at a ΔT of 100°F , and the low point of this study occurred at a ΔT of about 180° . This is a region of considerable instability, however. Bromley gives as the minimum values for stable film boiling from a horizontal tube at one atmosphere the following [as quoted in (17)] nitrogen 330°F , pentane 310°F , ethanol 350°F , benzene 415°F , carbon tetrachloride 600°F , and water 700°F . It is interesting to note that Berenson found a minimum-minimum for carbon tetrachloride at a ΔT of about 160°F based on two runs. The large difference may in part be due to the fact that Berenson used a horizontal surface, whereas Bromley used a tube.

It would seem safe to say that caution should be exercised in using what purports to be film boiling data in the range of ΔT from 100°F to 300°F, when liquids are boiled at atmospheric pressure. It would seem that it would be more proper to consider this range as part of the transition region, even though this may include part of the curve beyond the minimum-minimum point.

This suggests a criterion for determining when stable film boiling actually begins. It would seem that stable film boiling can occur only when the surface temperature is relatively constant. This would indicate that a stable vapor film has formed, and that the liquid no longer alternately comes into contact with, and is expelled from, the surface. As a consequence the minimum point would no longer mark the dividing line between transition and film boiling.

Most analyses of film boiling assume the existence of an isothermal surface, such as that by McFadden and Grosh,⁽¹⁸⁾ Bromley,⁽¹⁹⁾ Ellion,⁽²⁰⁾ etc. In selecting data for comparison with these theoretical equations it would be well to check to see if isothermal surface conditions were approximated. It has been shown here that surface temperatures near the minimum point are subject to wide variations.

One of the notable things about film boiling is that the "rod" or "ridge" of vapor on the top of the tube which has been commented on by other investigators assumes a different appearance at heat fluxes well beyond the minimum, as Fig. 7-9 shows. It was observed that when the heat flux in film boiling is high the bubbles depart from a vapor-liquid interface which is approximately the same as the projected area of the tube. There is no longer a single row of bubbles. The situation is, as the photograph shows, one of considerable disorder.

Fig. 8-1. Ref. 11 boiling off wood at 4° below its ordinary boiling point.

APPENDIX A
DATA

Table 1

Ref. 11 on $\frac{3}{4}$ " O.D., $\frac{1}{2}$ " I.D. Nickel Tube Length = 9 in.								
Run	T_{TS}	ΔT_0	$(Q/A)_0$	T_{HPA}	ΔT_i	$G \times 10^{-6}$	$j_f \times 10^3$	$N_R \times 10^{-4}$
11-30-	1	81	22	8,260	109.0	3.5	1.91	4.80
	2	69	38	23,800	134.3	19.2	1.90	2.21
	3	71	54	58,600	168.7	24.5	1.88	3.68
	4	69	110	5,900	186.4	4.4	1.88	1.74
	5	71	89	17,200	172.2	6.6	1.91	3.57
	6	72	124	10,230	203.4	4.2	1.91	1.44
	7	73	183	5,730	266.2	4.9	1.82	1.17
	8	75	252	7,780	334.3	5.5	1.80	1.19
11- 2-	1	73	23	7,000	101.3	3.2	1.71	4.57
	2	74	33	26,500	126.4	11.3	1.73	4.76
	3	77	38	35,000	142.8	16.5	1.73	4.11
	4	78	47	55,100	168.6	25.1	1.72	3.76
	5	78	47	62,400	173.8	27.2	1.71	3.68
	6	77	92	26,120	184.8	18.1	1.72	2.07
	7	78	110	17,860	201.1	7.0	1.69	3.47
	8	77	133	8,210	218.5	5.7	1.69	1.84
	9	75	185	6,500	266.7	4.1	1.69	1.70
	10	77	266	8,100	351.8	6.3	1.64	1.10
11- 3-	1	74	45	52,000	162.6	27.0	1.73	1.95
	2	76	41	44,500	168.2	35.1	1.22	3.06
	3	74	49	56,900	161.9	19.9	2.43	3.32
	4	74	55	60,720	167.4	18.3	3.00	3.08
11- 4-	1	74	33	16,500	117.7	4.9	3.04	4.07
	2	76	44	50,400	151.4	14.4	3.07	3.48
	3	74	172	5,850	252.1	4.4	2.94	0.861
	4	74	221	7,930	302.0	4.5	2.93	0.985
	5	75	268	8,280	351.9	5.6	2.82	0.772
	6	75	347	11,200	430.5	4.6	2.65	1.15
	7	75	413	13,700	499.9	5.3	2.49	1.27

DATA

Table 2

Ref. 11 on $\frac{3}{4}$ " O.D., $\frac{1}{2}$ " I.D. Chrome Plated Copper Tube Length = 9"								
Run	T _{TS}	ΔT_0	(Q/A) ₀	T _{HPA}	ΔT_i	G x 10 ⁻⁶	j _f x 10 ³	N _R x 10 ⁻⁴
11-19-1	73.6	29.9	17,200	111.8	7.3	2.22	4.09	6.02
2	69.6	44.4	43,200	138.1	21.3	2.17	3.14	7.16
3	69.6	57.4	50,400	156.6	25.1	2.19	2.82	8.14
4	68.0	62.2	59,600	158.7	23.2	2.16	3.58	8.24
5	69.5	95.6	30,600	179.7	11.8	2.15	3.06	10.4
6	69.8	114.8	25,000	197.3	10.5	2.15	2.63	11.3
7	70.8	145.7	8,600	223.0	5.7	2.14	1.49	13.3
8	71.3	235.4	7,200	313.7	6.4	2.14	0.831	20.6
11-20-1	70.9	40.0	27,200	121.0	11.7	1.99	4.84	5.81
2	73.0	47.6	43,900	140.9	22.8	1.94	3.33	6.51
3	74.7	50.7	54,200	150.1	27.8	1.93	3.32	6.76
4	74.1	56.0	60,100	172.2	30.2	1.92	3.17	7.15
5	77.7	59.8	68,500	173.7	35.6	1.90	2.87	7.84
6	78.2	141.7	7,910	222.9	4.9	1.88	1.92	11.7
11-23-1	78.1	65.3	71,100	170.1	32.0	1.91	3.36	7.90
2	78.3	268.4	7,970	349.7	6.7	1.75	1.05	19.1
3	78.3	343.4	10,600	430.4	13.0	1.66	0.66	23.5
1-26-1	77.0	38.1	20,500	134.7	12.9	2.07	2.55	7.01
2	80.3	40.6	40,300	151.6	17.5	2.07	3.26	8.29
3	79.8	45.5	55,700	167.2	23.5	2.06	3.08	9.23
1-27-1	72.6	33.2	20,500	121.3	8.8	2.11	3.91	6.55
2	75.1	38.0	39,800	143.4	17.2	2.11	3.62	7.83
3	77.5	41.7	56,400	159.6	22.0	2.10	3.39	9.02
4	78.3	83.9	16,100	173.8	6.2	2.09	3.18	9.91
5	76.5	111.6	7,960	194.1	3.5	1.84	2.91	9.96
6	74.3	163.4	7,070	243.8	3.6	1.68	2.27	11.9
7	76.9	209.2	10,500	293.9	4.1	1.72	2.48	15.3
8	76.1	258.2	9,390	343.3	5.6	1.70	1.45	18.2
9	78.1	303.1	10,100	390.4	5.5	1.65	1.48	22.7
10	79.0	468.1	14,800	562.6	9.8	1.21	1.35	20.1

DATA

Table 3

Ref. 11 on $\frac{3}{4}$ " O.D.; $\frac{1}{2}$ " I.D. Ceramic Coated Nickel Tube Length = 9"									
Run	T _{TS}	ΔT ₀	(Q/A) ₀	T _{HPA}	ΔT _i	G x10 ⁻⁶	j _f	N _R x10 ⁻⁴	
1-29-	1	74.3	17.7	14,600	100.4	4.8	2.43	10.7	5.39
	2	74.9	20.5	40,840	117.0	11.9	2.47	4.94	6.36
	3	79.5	20.4	50,150	126.0	14.3	2.38	4.74	7.04
	4	81.6	20.8	61,100	133.3	15.9	2.41	5.08	7.85
	5	73.6	54.1	30,850	145.7	10.0	2.41	3.88	8.52
	6	74.1	73.4	20,950	160.9	8.1	2.39	4.22	10.84
	7	75.4	91.2	17,590	177.8	6.7	2.39	2.21	14.7
	8	73.7	112.5	14,760	195.5	6.5	2.36	1.46	18.3
	9	75.0	134.7	12,000	219.2	6.3	2.35	1.53	23.9
	10	76.1	168.7	9,110	252.6	5.3	2.20	1.01	30.6
	11	77.4	217.2	8,610	302.4	5.4	2.10	0.94	34.5
	12	76.8	266.6	8,290	352.1	6.3	2.00	1.51	34.7
2-1-	1	73.5	12.7	5,430	88.4	0.9	2.43	10.7	5.39
	2	78.6	18.0	12,400	104.3	4.7	2.47	4.24	6.36
	3	79.3	23.1	39,500	121.0	8.9	2.38	6.50	7.04
	4	81.7	23.7	63,300	137.5	17.3	2.41	6.10	7.85
	5	79.2	39.5	43,700	143.6	14.2	2.41	3.88	8.52
	6	80.0	77.8	23,100	169.6	5.9	2.39	4.22	10.84
	7	79.5	132.4	13,600	220.9	5.4	2.39	2.21	14.7
	8	79.1	183.2	8,920	269.2	4.5	2.36	1.46	18.3
	9	78.3	250.2	9,100	334.9	3.8	2.35	1.53	23.9
	10	80.3	342.1	10,300	431.3	5.8	2.20	1.01	30.6
	11	80.6	385.8	13,100	496.5	7.7	2.10	0.94	34.5
	12	80.2	470.9	14,950	561.5	5.4	2.00	1.51	34.7

DATA

Table 4

Water on $\frac{3}{4}$ " O.D. $\frac{1}{2}$ " I.D. Chrome Plated Copper Tube Length = 9"								
Run	T _{TS}	ΔT_0	(Q/A) ₀	THPA	ΔT_i	G x 10 ⁻⁶	j _f x 10 ³	N _R x 10 ⁻⁴
11-25-1	211.8	25.8	82,800	282.9	40.9	2.13	1.74	16.4
2	211.6	31.3	156,000	314.2	62.9	2.06	2.08	17.5
3	211.5	35.5	320,000	361.0	96.9	2.04	2.51	19.3
4	211.5	36.9	371,000	377.0	108.4	2.02	2.44	20.1
5	211.5	38.7	457,000	396.4	111.6	1.96	2.77	20.8
6	211.5	40.2	519,000	419.0	127.1	1.93	2.70	20.6
7	211.5	44.0	584,000	433.7	147.0	1.91	2.84	20.9
11-30-1	211.3	15.1	47,400	253.4	24.5	2.17	1.74	14.8
2	211.7	28.8	196,100	301.1	50.2	2.02	3.38	16.5
3	212.0	34.5	281,100	358.9	97.5	1.98	2.28	18.8
4	211.6	40.0	443,400	424.0	148.7	1.92	2.17	20.6
5	211.6	40.3	567,900	438.4	156.2	1.88	2.63	20.6
1-22-1	212.4	23.4	95,400	284.2	42.9	1.81	1.89	15.42
2	212.6	33.7	239,800	325.9	65.7	1.70	3.31	16.84
3	211.9	278.6	28,400	513.0	20.8	1.83	0.817	30.50
1-25-1	211.5	28.1	136,300	300.5	63.3	2.05	1.64	18.56
2	211.9	36.4	288,200	347.2	82.2	1.97	2.60	23.62
3	211.5	42.0	549,500	407.1	121.8	1.90	3.12	24.78
4	211.7	43.7	551,000	423.2	135.9	1.90	2.73	29.95
5	211.8	52.9	527,800	440.8	146.9	1.88	2.36	26.95
6	211.3	235.7	33,900	463.3	14.2	1.84	1.56	30.80
7	211.5	264.8	24,860	488.8	11.0	1.77	1.49	28.32
8	211.4	288.8	18,320	523.4	22.1	1.71	0.548	28.41

APPENDIX B

COMMENTS ON COOLING DATA

The accompanying graph (Fig. B-1) shows the correlation for the data on the heat transfer from the H.P. water which was cooled during the boiling process. The heat transfer $(Q/A)_i$ was determined by the amount of liquid boiled away on the outside surface. The ratio of inside to outside surface was 3:2, so after $(Q/A)_o$ was determined, as previously mentioned, it was multiplied by 1.5 to determine inside heat loading.

The data shown in Fig. B-1 includes only that from the chrome plated copper tube. The surface temperatures for this tube could be obtained more accurately since the temperature drop through the tube wall was smaller. The uncertainty in the surface temperature was largely the result of the lack of precise knowledge of the thermal conductivity of the particular metal of which the tube is constructed. The property values published in Eckert's and Drake's "Introduction to Transfer of Heat and Mass" were used in the computations. There is some indication that the values given for thermal conductivity for nickel are too low to represent the specimen of nickel used in these experiments.

It will be noted that the Colburn equation gives a fairly good average value, though the scatter is considerable. An accuracy of $\pm 40\%$ maximum deviation is usually claimed for this equation. Since the data for boiling water are at fairly high flux (850,000 Btu/hr ft² maximum) it was thought that the data would be of some general interest.

FIGURE B-1
CORRELATION FOR COOLING INSIDE TUBE

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