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BOILOUT EXPERIMENT

INTRODUCTION

There is a definite need to determine the time required for the water in a process tube to boil out after loss of inlet flow. This information is required to evaluate the reactivity and power transients following such an occurrence. Such information will also partially determine the incentive for improvements in safety circuits and equipment, accelerated safety rods in particular. A secondary objective is to learn more about the mechanism of the boil-out. Boil-out times have been theoretically predicted in the past (1,2) with very little experimental data to back them up.

SUMMARY

A scanning capacitance method is presented for measurement of the water distribution within a process tube under transient boiling conditions. Preliminary results of exploratory runs are included. The runs simulate inlet pigtail failures on process tubes operating at 725 and 1000 KW. Curves of water distribution over the tube with time and total tube water content are included. Recommendations are made that the tests be continued to provide valid data for assessing the reactor hazards involved in cases of cooling water supply failure.

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DISCUSSION

A reactor process tube may lose its cooling water flow through a number of mechanisms. The cause may be supply failure, piping failure, tube rupture, or blockage of the annulus or outlet. Probably the most rapid and serious failure for a single process tube is a total breakage or rupture of the piping, nozzle, or pigtail at the immediate inlet of the process tube. This case was selected as the first situation to study experimentally.

The dynamics of a process tube boil-out would be very difficult to simulate in any manner other than a full scale, full power mockup. The Heat Transfer Laboratory Facilities duplicate 'in reactor' conditions reasonably well, supplying both the power and flow in a full sized test section. The principal task to be done then was to develop a method of measuring the water distribution vs time in the test section of process tube when a pigtail rupture was simulated in the water system. In the following sections the method, equipment, procedure, and results will be discussed.

METHOD

There are, undoubtedly, several ways to measure the presence of water within a tube. It was desired in this case to measure the water distribution over a long tube vs time. An electrical capacitive method was selected which permitted high speed recording with a minimum of interference to the water flow. The process tube and the active, heat generating, center rod (similar to an uranium charge in shape) are effectively a concentric cylindrical capacitor. The tube is the outer plate, the heater the inner plate, and the water the dielectric. Water has a high dielectric constant (of the order of 80) while steam acts as a gas with a constant of one. The dielectric property of the cooling water will then undergo a marked decrease as a boilout occurs. The magnitude and change of the capacitance of a section of process tube is then a measure of the quantity of water contained in it; the capacitance dropping as steam is formed.

PROCESS TUBE

Since the distribution of water was desired, a process tube was cut into sections. This permitted the capacity, hence water volume of each section to be measured. The tube was a B, D, F type consisting of 22 one foot sections with eight and ten inch flanged sections as end pieces.

A four to six mil coating of Herisite⁽³⁾ resin was baked on the sections to provide electrical insulation from each other and the heater rod. A one inch band around the outside of each section was cleaned of resin to permit electrical connections to be made.

The sections of tube were butted against each other and covered with a 1 3/4 inch ID eight ply steam hose. The hose covered all but the one inch electrical connection band on each section. The hose served to seal the tube and hold it together, being clamped onto the tube sections by steel banding tape. The assembled test section was 23.5 feet long. Figures one and two show the assembled tube.

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FIGURE 1

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FIGURE 2

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CIRCUIT

The sensing device which measures the change in capacitance is a series capacitive-inductive circuit. The circuit is shown in Figure 3. The motor driven switch serves to place, separately, each one of the sections into the circuit. By application of an alternating voltage to the circuit, any change in the capacitance of the section that is connected into the circuit may be measured by observing the corresponding change in the voltage drop across the inductor of the circuit. The frequency of the alternating voltage was 10 KC. To record the data, the voltage across the inductor is applied to the vertical sweep of an oscilloscope. As the switch progressively samples the sections, a pattern of vertical lines or pips is displayed on the scope. Each vertical line is representative of the magnitude of the capacitance in a particular section of the tube. The capacitance of a full tube is approximately 36,000 mmfd and that of an empty tube is about 250 mmfd. A moving film oscilloscope-recording camera was used to photograph the patterns as the boilout progressed. The film speed was 400 in./min. The two 500 mfd capacitors in the circuit serve to keep the system isolated from ground, and the standard capacitor provides a means of calibration.

The rate of sampling of the capacitance was either one full traverse every 0.1 sec. or, if adjacent pairs of sections were placed in parallel, the rate of sampling could be increased to one traverse every 0.05 sec. A 600 rpm synchronous motor was used to drive a 60 contact switch. The 22 one foot sections of process tube were connected into the switch. Every other contact on the switch was blank so that the pips could be separated. The standard capacitor was connected at the beginning and the middle of sweep of the switch and the remaining contacts were left blank to allow for a gap between complete groups of samples. Connections could be easily rearranged to place adjacent pairs of sections in parallel so that the whole tube could be sampled in two foot sections twice every revolution of the switch rather than once every revolution.

The recording camera, a Dumont type 321, has a built in argon glow lamp. This lamp was connected to a pressure trip so that a time synchronization signal could be recorded with the capacitance data. The time signal is impressed as a series of dots derived from the 60 cps power line frequency.

CALIBRATION

A series of experiments were performed in an attempt to calibrate the system for capacitance vs water volume. These were small scale laboratory systems using water that was static, rather than flowing, until it was boiled out.

Water may be removed from a process tube through several mechanisms. If the water is below its boiling point and the control heater is well above the boiling point, a radial boiling will occur. An increasing blanket of steam will form around the water forcing the water against the outer tube. When the water is at or above its boiling point a bulk form of boiling can occur wherein the water and steam are intermixed. In the case where neither the water nor the heater surface are at the boiling point, the water can be swept or blown out of the tube by the expansion of the steam elsewhere in the tube.

The calibration for the radial boiling and the longitudinal blowout cases may be calculated if any temperature effects on the dielectric properties of water and steam are neglected. These are shown as curves one and two in Figure 4. The

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FIGURE 3
CAPACITIVE SENSING CIRCUIT

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FIGURE 4

CALIBRATION OF BOILOUT EQUIPMENT

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CALIBRATION (CONT'D)

initial very rapid drop in the radial boiling case is due to the assumption that the water is completely separated from the inner (heater) tube. This most probably would not be the case in an operating process tube case as the water and adjacent slug surface are at very nearly the same temperature. It is more reasonable to assume that some form of mixed boiling will occur which will more or less follow the longitudinal blowout curve until the water is boiled down to the point that it is in droplets dispersed in a steam atmosphere. At this point the wall to wall or electrode to electrode continuity of the water is broken and a rapid drop in capacitance similar to the radial case would be expected as in curve 3.

The small scale laboratory calibration runs were made with a foot long section of process tube with a heater contained within a slug can sized center tube. The runs were made with the entire assembly at room temperature. The heater (~ 500 watts) was turned on and the capacity and mass recorded as a function of time. A gradual increase in capacity was noted until boiling occurred, at which time the capacity and mass decreased to their minimum, boiled out values over an interval of about half a minute. Using the capacity at the onset of boiling as C_0 , the average result is plotted as Curve 4 in Figure 4. This curve is higher than would be expected from the calculations. This is due to the fact that water is not a perfect dielectric and its dissipation factor is a fairly strong function of temperature (4). The dielectric constant of water decreases somewhat as the temperature increases however the effect is far overbalanced by the increase in dissipation factor. Exact calculations cannot be made of the experimental system as there is a lack of data in the temperature ranges encountered. There is the additional factor that the dielectric properties of the Herisite coating are totally unknown. The rise in capacitance as the assembly is first heated is adequately explained by the same variation in dissipation factor of water.

Another experiment was performed where the cold tube assembly was gradually filled with water. This was performed with the tube vertical, inclined, and horizontal to test for rib effects and the effect of pooling of water in the lower portion of a horizontal tube. In all these cases the capacitance vs mass curve was very close to the linear Curve 2.

The full length full power tests will occur much more rapidly than the tests leading to Curve 4. The water will initially be much closer to the boiling temperature and will be essentially isothermal across the process tube annulus so that the thermal transient effects during the boilout will be smaller. It is reasonable to expect that the true calibration for the boiling regions will be somewhat between Curves 3 and 4. The calibration for the longitudinal blowout regions (colder upstream water) will follow Curve 2. The straight linear calibration, Curve 2, was finally used for all regions because of its ease of use, the uncertainty of the boiling calibration, and the reasonably close approximation of Curve 2 to an unknown curve between 3 and 4.

PHYSICAL MOCKUP

The Heat Transfer Laboratory mockup is based upon three large DC generators which power a specifically designed resistive heating element to simulate the heat generation of a full column active uranium charge. The heating element is contained within the test process tube section. The power is delivered in approximately a

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PHYSICAL MOCKUP (CONT'D)

cosine distribution over the test section by an appropriate variation in resistance over the length of the heater element.

The cooling water is supplied to the test section by a closed loop hydraulic system (5). The system is outlined in figure five with all unused or unnecessary valves and piping omitted. The pump supplies water at the appropriate pressure through air operated valve V_1 to the test section. A dummy rear section is required to simulate the process tube downstream of the active charge. The test section can only represent the uranium charge section as access is necessary to each end of the heater element so that the electrical power may be applied. The water discharges from the rear dummy section through a regular nozzle and pigtail assembly to a length of rear header. This rear header has sufficient volume to provide a back flow into the process tube upon water supply failure. A bypass line from the discharge side of the pump through valve V_3 provides pressurization of the rear header to simulate the effect of other tubes emptying into a normal header and riser system. The water used is steam condensate so that the scale is not formed on the heating element. A condenser and pressure tank complete the closed loop to conserve the water. The condenser acts as a heat exchanger to cool the water before it is readmitted to the test section.

An inlet pigtail rupture is simulated by the simultaneous closing of valve V_1 and opening of valve V_2 . The inlet to the test section is then vented to atmospheric pressure through a surge tank. The piping between valves V_1 , V_2 , and the test section is a rough approximation of the empty process tube upstream from the normal active uranium charge.

The loop was monitored at several points for pressure, temperature, and flow. The pressures at the venturi, test section inlet, center, and outlet, rear nozzle, and rear header were fed into two Sanborn Triplexer units and a dual channel oscillograph recorder. This enabled the six signals to be recorded in their proper time relationship on the one recorder. A considerable sacrifice is made in the resolution of the traces as a particular pressure transducer was recorded about one third of the time at a rate of twice per second. The inlet and outlet temperatures of the test section were presented on strip chart recorders. The reverse flow out of the surge tank was sensed by a turbine type flow meter and presented as a flow rate on a strip chart recorder. An electrical synchronizing signal was recorded on each chart to provide time correlation.

Standard reactor fittings were used wherever possible to facilitate the simulation of actual flow conditions. The venturi, rear dummy section, rear nozzle, rear pigtail, and rear header were all standard reactor components.

The boilout test was run in conjunction with a test of water return characteristics by the Heat Transfer Group. The pressure triplexing system was designed for the latter experiment and did not provide fine enough resolution. Any further tests should be run with higher chart speeds and triplexing rates or with a greater number of recorder channels. The time signals used on the pressure and temperature charts were derived from a different source than the camera timing light, and correction factors were required. Further tests should include a single master timing coordinated with the action of the air operated valves.

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FIGURE 5
BOILOUT HYDRAULIC LOOP

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HEATER ROD

The heater rod was a resistive unit in which the power is proportional to I^2R , where I is the current and R is resistance. A cosine power distribution was simulated by stepped variations in the specific resistance of the rod. This was accomplished by using several different alloys and boring different sized holes in the center of the sections.

The rod has about 30 percent higher specific heat capacity than uranium, however, this is partially corrected for by the loss in mass of the rod due to the center boring. The rod was turned down slightly from standard slug diameter so as to correct for the thickness of the Herisite coating inside of the process tube and to maintain a proper water annulus size.

The process tube power was determined by measuring the voltage across and current through the heater rod. The current required to obtain 725 KW, which was used in four of the runs, was 18,000 amperes.

PROCEDURE

The experiment was performed by bringing the generators and hydraulic loop up to operating power conditions. Pressures, flows, temperatures, and power were adjusted till a reasonable simulation of an in pile process tube condition existed. Typical experimental conditions prior to boilout were:

Flow	32 gpm
Venturi pressure	217 psig
Tube inlet pressure	306 psig
Tube center pressure	185 psig
Tube outlet pressure	76 psig
Rear nozzle pressure	64 psig
Rear header pressure	17 psig
Inlet temperature	14° C
Outlet temperature	111° C

A few seconds before the boilout was to begin the data camera was started so that a steady state pattern of the tube section capacitances was recorded prior to the transient. The boilout was triggered by the two air operated valves. Two Panellit gauges in parallel were tripped when the venturi pressure dropped to 190 pounds. One Panellit started the timing light in the camera and stopped a timer which measured the time since the valving action. The second Panellit started a power decay cam. This cam introduced a 2.8 second time delay after the Panellit trip then reduced the generator power to simulate the decay of fission heat after a reactor scram. The time delay represented the lag of the safety rods in entering a reactor.

Prior to each boilout experiment, the electronic capacitance recording equipment was calibrated by varying the standard capacitor (figure 3) over the capacitance range being used. The camera was operated during this interval to provide a capacitance calibration directly on the recording film. A complete log was maintained so that each exposure run could be fully identified.

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RESULTS

Five experimental boilout runs were made; four were at a tube power of 725 KW and one at 1000 KW. These runs were intended as exploratory work to determine the practicality of the methods used. The data presented here is purely preliminary and must not be utilized for firm predictions. The prime value is in the partial confirmation of previous calculations.

Runs one and two were made at 725 KW using pairs of adjacent one foot sections of process tube electrically connected to provide readout in two foot increments at a rate of one complete tube traverse every 0.05 second. Runs three and four were made at 725 KW using single one foot sections in the readout at a rate of one complete tube traverse every 0.1 second. Run five was made at 1000 KW using one foot sections at the 0.1 second scan rate.

The filmed data were reduced after the runs were over by developing the film and tabulating the data as read from an enlarging type viewer equipped with a ruled screen. All data reductions were performed by the same observer to keep observation errors constant, although undetermined. The filmed data capacitance calibration was obtained from the calibrated portion of the film mentioned in the section on procedure. The percent water calibration was assumed to be linear with capacitance from the peak value as 100 percent to the minimum value as 0 percent. The data were reduced in this manner to plotted curves of percent water content vs time for each measurement section of process tube in each experimental run. The value of any section of the tube at any time could then be read directly from the curves. The accuracy, exclusive of calibration assumptions is estimated at about 10 percent.

725-KW TUBE

The data for the first four runs at 725 KW are presented in Figures 6 through 9 as plots of water content vs position in the active region at quarter second increments of time after the initial valving or simulated pigtail rupture. The curves are a visual fit of the data which were checked by planimeter integrations over each measurement section. The fits are within two percent total water volume of the data points. Those sections that are dashed had to be assumed as the data was lost due to burning and shorting of those sections to the heater rod. The times are accurate to within 0.2 seconds.

The four runs are averaged on the basis of two foot sections and presented as a composite in the curves of figure 10. It will be noted that the rather considerable humps in the downstream half of the tube in the individual runs tend to differ among the runs. This may be due to timing errors, but is more likely as a result a rather turbulent form of boiling which does not reproduce in exactly the same manner each time.

The composite curves were integrated at quarter second intervals to obtain the total water content of the active tube region vs time. This is plotted in Figure 11. The vertical bars indicate the degree of error that could have been introduced by the calibration assumptions. This data indicates that the previous calculations by W. F. Ekern (1) were somewhat conservative as they were intended and that the subsequent reactivity and transient power calculations by J. H. Brown (2) are limiting cases as desired.

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FIGURE 6

RUN NO. 1

725 KW

WATER DISTRIBUTION IN PROCESS TUBE AS A FUNCTION
OF TIME IN SECONDS AFTER PIGTAIL RUPTURE

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FIGURE 7
RUN NO. 2
725 KW

WATER DISTRIBUTION IN PROCESS TUBE AS A FUNCTION
OF TIME IN SECONDS AFTER PIGTAIL RUPTURE

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FIGURE 8

RUN NO. 3

725 KW

WATER DISTRIBUTION IN PROCESS TUBE AS A FUNCTION
OF TIME IN SECONDS AFTER PIGTAIL RUPTURE

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FIGURE 9

RUN NO. 4

725 KW

WATER DISTRIBUTION IN PROCESS TUBE AS A FUNCTION
OF TIME IN SECONDS AFTER PIGTAIL RUPTURE

FIGURE 10
COMPOSITE
725 KW
WATER DISTRIBUTION IN PROCESS TUBES AS A FUNCTION
OF TIME IN SECONDS AFTER PIGTAIL RUPTURE

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FIGURES 11

COMPOSITE

725 KW

TOTAL ACTIVE TUBES WATER CONTENT

VS TIME AFTER PIGTAIL RUPTURE

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FIGURE 12

RUN NO. 5

1000 KW

WATER DISTRIBUTION IN PROCESS TUBE AS A FUNCTION OF TIME IN SECONDS

AFTER PIGTAIL RUPTURE (ABSOLUTE VALUE OF TIME IN DOUBT)

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FIGURE 13

RUN NO. 5

1000 KW

TOTAL ACTIVE TUBE WATER CONTENT VS TIME AFTER PICTAIL RUPTURE
(ABSOLUTE VALUE OF TIME IN DOUBT)

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