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PRESSURE REQUIRED TO OVERCOME BOILING
AT LOW TUBE POWERS - BDF REACTORS

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HW-66274

PRESSURE REQUIRED TO OVERCOME BOILING
AT LOW TUBE POWERS - BDF REACTORS

INTRODUCTION

During certain stages in charge-discharge operations for Hanford reactors, the front and/or rear nozzle caps are removed from the process tube assembly. The coolant flow past the fuel elements might be altered or even stopped entirely for short periods of time. During these periods of flow interruption, there exists the possibility of boiling the water which is in the tube with attendant steam ejection and possible fuel element damage due to high temperatures. Even if damage did not occur while the caps were removed, the re-application of the original low water pressure (by replacing the nozzle cap) might not be sufficient to overcome a boiling condition in the tube. Thus, fuel element damage might occur in the "vapor-locked" tube even after front cap replacement.

Such nozzle cap removal procedures have been used extensively in the past without apparent adverse effects. However, the continued attainment of higher reactor equilibrium operating power levels has resulted in ever-increasing residual heat removal rates during reactor shutdown conditions. Thus, the time intervals between flow stoppage and initiation of boiling in the process channels are smaller now than for the previous experience. This fact, combined with occasional desires to vary the operating procedures, made it desirable to obtain data concerning the sequence of events and of possible boiling during a short term flow stoppage at low tube powers.

PURPOSE

The purpose of this report is to present laboratory data concerning thermal and hydraulic changes which occur in a low power process channel during a flow interruption. The experiments were conducted in the Heat Transfer Laboratory of Thermal Hydraulics Operation.

SUMMARY AND CONCLUSIONS

Electrical resistance heating of a metal bar in a laboratory apparatus was used to simulate the residual heating in a single process channel during reactor shutdown conditions. Steady state flow rates and temperatures were established in the mock-up at low front header pressures typical of those used during charge-discharge operations. The rear header was maintained at atmospheric pressure. The front header pressure was then suddenly removed and simultaneously the front pigtail was opened to the atmosphere. At various times after boiling was detected in the process channel, the original front header pressure was re-applied and the pigtail closed. It was then determined whether adequate fuel cooling was re-established. During each run the temperature of the simulated fuel was monitored as were the pressures at various points along the process tube. The experiments were conducted at tube powers of 15, 25, and 40 KW with front header pressures ranging from 40 to 140 inches of water.

From the experiments, the following data and conclusions were obtained:

- (1) Observed pressure buildup caused by boiling in the process channel during flow stoppage was so small (about 0.9 psig maximum) that fuel element ejection would be highly unlikely.
- (2) The experimentally observed time lapse between flow stoppage and initiation of boiling is presented in Figure 2. These values check fairly well with those which were calculated and presented in HW-63139.
- (3) Data in Figure 3 show whether or not adequate "fuel" cooling was re-established when a particular front header pressure was re-initiated at various times after boiling began. The data show that boiling can be tolerated for only very short periods of time if recovery is to be attained at the higher heating rates.
- (4) It would seem prudent to not allow cap removal and flow interruption for periods which are long enough to result in boiling in the process tube, except perhaps at very low residual heating rates.

The data thus obtained are thought to be slightly conservative for two reasons:

- (1) All of the heating was generated in the "fuel" rod. Thus, the metal surface temperatures during re-establishment of cooling would be greater on the experimental apparatus than for an actual reactor assembly where part of the heat is being transferred from the graphite stack. This should lead to conservatively high header pressure requirements.
- (2) On the experimental apparatus, it took a few seconds to actually re-establish the front header pressure after closing the front pigtail opening. The time values are reported on the basis of the time the front pigtail opening was closed so that conservatively short time requirements are stipulated on the data plots.

BACKGROUND OF THE PROBLEM

The problem of determining the course of events in a process channel during such cap removal procedures has many aspects. One aspect is "will flow through the tube be reduced to the point where boiling will occur." Laboratory experiments were conducted to determine flow rates and flow splits (front to rear) for various conditions of front and/or rear nozzle cap removal. The results, which are presented in HW-62798*, show that when the front nozzle cap is removed, the flow through the tube essentially ceases if the rear nozzle cap is off or if the rear nozzle cap is on and the rear header pressure is atmospheric. Thus, boiling will commence in the stagnant water in the tube at a time after cap removal which depends on the heat transfer rate to the water and the initial water temperature distribution.

* References are listed at the end of this report.

The next logical question concerns the time lapse between a complete flow stoppage and commencement of boiling in the process tube. This was explored analytically and the results were presented in HW-63139. Using the necessary bases and assumptions, calculated values were presented as curves to show the time lapse between flow stoppage and boiling as a function of heating rate and the initial flow rate or outlet temperature at the time of flow stoppage. These results showed that a time lapse as small as 30 seconds would be realistic for process channels with high residual heating rates (40 KW).

Another question concerned the possibility that the steam or water ejection rate during boiling would be great enough to cause a fuel element to be discharged from the process channel through the open nozzle. An approximate analytical solution to this question was carried out and presented in HW-63139. The results indicated that the maximum fluid ejection rates would be just less than that which would cause fuel ejection. However, the uncertainties connected with boiling and two-phase flow necessitated so many assumptions that the results were of questionable accuracy, especially when they predicted a near borderline condition.

There is one further facet of the problem for which an analytical solution was not attempted. That is, if boiling occurs in the fuel channel, what pressure would need to be re-applied in order to sweep the water and steam out of the process tube and re-establish conditions of adequate fuel cooling. Of course, this required pressure would vary with the time lapse since flow stoppage. Such information is necessary to help establish operating procedures and determine whether re-application of full riser pressure would be necessary if boiling does occur during the charge-discharge procedure.

Data were obtained and presented in this report to answer the latter question and to provide a check of the solution of the previous two questions. The data were obtained from the single tube prototype Heat Transfer Apparatus of the Thermal Hydraulics Operation.

DESCRIPTION OF APPARATUS AND TECHNIQUES

A diagram of the experimental apparatus is presented in Figure 1. The assembly is a reasonably good prototype of a BDF process assembly from the tube inlet to the rear header except that the downstream dummy section is offset from the heated section to permit the electrical connections to the heater rod. At the upstream end of the heated section, the hole and annulus flow channels connect via 1" pipes into a 2" pipe before connecting to the simulated front header.

The process tube containing the heated section was a standard BDF aluminum ribbed tube with a "Heresite" insulation coating about 0.005 inches thick on the inside. The "heater rod" was made up of sections of cupro-nickel, copper, and brass constructed such that a step-cosine heat output would result. The "heater rod" was 1.435 inch OD by 0.310 inch ID to simulate an O-II I&E fuel element charge. (The OD of the heater rod was reduced slightly from nominal O-II fuel dimensions to compensate for the 5 mil "Heresite" insulation inside

of the process tube.) Thermocouples were imbedded near the surface of the heater rod to give indications of the rod surface temperatures at various locations along the heater rod.

In these experiments, a drain was provided through an air operated valve between the front header and the tube inlet. Symbols on the valves of Figure 1 indicate "normally open" and "normally closed" positions. Steady state conditions were established with the valves in the normal position. Then, simultaneous actuation of the valves removed the front header pressure and opened the tube inlet piping to the atmosphere. The pressures and rod surface and coolant temperatures were monitored with high-speed recording instruments. First indications of boiling in the process tube were noted by very slight pressure fluctuations - generally on pressure tap P_3 . The valves were re-actuated and front header pressure was re-established at some selected time after the first indications of boiling. The run was then continued until either adequate "fuel" cooling and non-boiling was re-established (as determined by heater rod surface temperatures, coolant outlet temperature, and coolant flow rate) or the heater rod temperatures became excessive and the electrical power input had to be reduced to prevent "fuel" (heater rod) damage. During the entire run the power input was not changed unless the run was terminated by cutting the power to prevent heater rod damage.

The experimental equipment and procedure described above would simulate the events as follows: steady state conditions exist with adequate cooling at a low front header pressure; then the front nozzle cap is removed, thereby reducing the applied pressure to zero and venting the front of the tube to atmosphere; at some time later, boiling occurs in the tube; the front nozzle cap is then replaced and it is determined whether the original low front header pressure is sufficient to sweep the steam out of the tube and re-establish adequate cooling.

DISCUSSION OF RESULTS

Time Lapse to Boiling

Data points on Figure 2 show the experimentally determined time lapse between flow stoppage and beginning of boiling in the process tube at heating rates of 15, 25, and 40 KW and at various initial (steady state) outlet water temperatures. This initial outlet water temperature was influenced by the initial front header pressure, of course, since the initial header pressure determined the flow rate through the process assembly. The time lapse values for the data points represent the time interval between valve change (depicting cap removal) and the first indication of boiling in the process tube. This first indication of boiling was evidenced by very small pressure fluctuations (± 0.1 psi). The fluctuations increased in magnitude as the boiling progressed, finally reaching values of about ± 0.8 psi. However, the early smaller fluctuations were easily discerned on the traces from the high speed recording equipment. Hence, it is felt that the experimental time-lapse-to-boiling values are quite accurate.

Also shown on Figure 2 are some calculated time-lapse-to-boiling values as given in HW-63139. The calculated values are shown as shaded bands for the

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various heating rates. The left side (smaller time value) of the band would correspond to a cosine heat input while the right side of the band would correspond to a significantly flattened heat input pattern along the heated length.

The experimental values show fair agreement with the calculated values. Heat losses due to natural convection from the outside of the uninsulated process tube could account for up to 0.5 KW of heating and thus would tend to make for better agreement of the 15 KW and 25 KW cases with the calculated values.

However, for the 40 KW case, calculated values seem to be non-conservative compared to the experimental values. Thus, it appears that an extra safety factor would be required for this case in applying calculated values of time-lapse-to-boiling to actual reactor operations.

Maximum Pressure Build-up

To help answer the question of fuel element ejection during the period with the nozzle cap removed, the pressures along the process tube were continuously monitored on high speed recorders during the experimental runs. Then during chart read out, the maximum pressure build-up in the tube was noted for this time interval while the front of the tube was open to atmosphere.

The results showed that maximum pressure surges would be 0.9 psig or less. These were in the form of short term "bumps" lasting about one half of a second. The larger surges were always recorded at the P_3 location (see Figure 1) with lesser surges being recorded at the other locations. Although the 0.9 psig maximum was recorded for a 40 KW run, the maximum "bumps" for the 15 KW runs were 0.7 to 0.8 psig. Hence there was little effect of heating rate. These "bumps" may be compared to the early stages of boiling in a coffee percolator wherein a steam bubble is formed and then immediately condenses as it contacts cooler liquid away from the hot metal surface. This hypothesis is based on the chart readings which showed the pressure surges to build up above the normal pressure and then immediately drop below the normal or average pressure.

The maximum pressure "bumps" generally occurred at a time lapse from flow stoppage equal to about $1 \frac{1}{4}$ times the time-lapse-to-boiling. Then as the boiling progressed, the "bumps" or fluctuations smoothed out to steady pressures of 0.4 psig or less depending on the heating rate and the time interval for which the front of the assembly was left open to atmosphere.

Thus, at no time during the experimental runs were pressure build-ups noted which were greater than 0.9 psig. Since it requires a pressure drop of about 3 psi or more across a fuel element to cause it to move in the process tube (HW-54093), it is apparent that the observed pressure build-ups would be insufficient to cause fuel element movement even if the entire 0.9 psi were assumed to occur across one fuel piece.

Pressures Required for Recovery of Adequate Cooling

Data are shown on Figure 3 to relate front header pressure, time of flow interruption, and heating rates for all experimental runs. The symbols distinguish between those runs in which adequate "fuel" cooling was re-established and those runs which were terminated because adequate cooling was not re-established and heater rod temperatures were becoming excessive. Also plotted on Figure 3 are the experimental values of time lapse to boiling.

Figure 3 presents considerable information--so much so in fact that the figure might seem difficult to read. The following example is given to help clarify the figure: assume a process tube with a power output of 40 KW has a front header pressure of 90 inches of water and the rear header is at atmospheric pressure; suddenly the front nozzle cap is removed, which quite effectively stops the flow through the tube. By following a horizontal line (with ordinate value of 90 inches of water) across Figure 3, one may draw the following conclusions:

- (1) Boiling will begin in the tube at 28 seconds after flow stoppage (as indicated by the line which was drawn through data points, $\odot$).
- (2) If the 90 inch front header pressure is re-applied at about 31 seconds (or any time less than 31 seconds) after the flow stoppage, then adequate fuel cooling will be re-established in the process tube assembly.
- (3) A total time of about 120 seconds will have elapsed since flow stoppage when the adequate cooling is re-established (as indicated by numbers written by $\square$ symbols).
- (4) Adequate fuel cooling cannot be re-established by using the 90 inch front header pressure if more than 31 seconds have elapsed since flow stoppage.
- (5) If the 90 inch front header pressure is re-applied later than 31 seconds after stoppage, the "fuel" will be close to the damage stage (450 to 550°C) at about 140 seconds after flow stoppage, as indicated by the numbers written by $\times$ symbols for this 40 KW case.

Similarly, for the 25 KW and 90 inch pressure case, boiling would begin at about 65 seconds, recovery of cooling could be made if the original 90 inch pressure is re-applied at any time before 77 seconds, and recovery should be completed about 180 seconds after flow stoppage. But if pressure re-application were delayed until about 95 seconds after flow stoppage, then adequate fuel cooling would not be re-established and fuel damage would occur at about 700 to 800 seconds after flow stoppage.

From these data it is apparent that the time of flow interruption (or if you choose, the time interval between boiling and re-establishment of front header

pressure) is an important factor in determining whether the recovery from a boiling condition will be achieved. Boiling can be tolerated for relatively long periods and still attain recovery with a heating rate of 15 KW. With the 40 KW heating rate, however, the tolerable time interval between boiling and re-establishment of header pressure is very small if recovery of adequate cooling conditions is to be attained. It is also quite evident that the allowable time interval and the chance of recovery increases greatly as the front header pressure is increased from 40 or 60 inches of water to 150 inches of water.

As stated previously, there are many uncertainties connected with such transient boiling and two-phase flow problems. Although an exhaustive study of these data might yield some empirical correlation, it is not deemed worthwhile to pursue this approach at the present time.

The data presented in this report are considered to be slightly conservative. The conservatism arises from the following conditions:

1. All of the heat was "generated" in and transferred from the "fuel" (heater rod) to the coolant. Thus, the metal surface temperature during re-establishment of cooling would be greater on the experimental apparatus than for the reactor fuel pieces. This should lead to conservatively high header pressure requirements.
2. On the experimental apparatus, it took a few seconds to actually establish the header pressure value after closing the front pigtail opening. The time values, given on Figure 4, are reported on the basis of the time the pigtail opening was closed. Hence, conservatively short flow interruption times are stipulated on the data plots.

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Figure 1
Equipment Arrangement

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Figure 2
Time Lapse to Beginning of Boiling

Figure 3

Experimental Recovery Pressure - Time Relations

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