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TITLE

RESULTS OF LABORATORY HEAT TRANSFER EXPERIMENTS FOR C-REACTOR OVERBORE FUEL CHANNELS

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PURPOSE

The purpose of this report is to present experimental data concerning the heat transfer and fluid flow conditions within a C-overbore geometry process channel for the cases of steady state operation, flow plugging incidents, and inlet piping failure incidents.

INTRODUCTION

One of the operating limits for the Hanford reactors is an outlet water temperature limit based on thermal and hydraulic characteristics of the individual process channels. This temperature limit combined with the response of the Panellit gage (flow monitor) system protects against excessive fuel temperatures by shutting down the reactor whenever the flow of coolant in a process tube becomes insufficient to properly cool the fuel. Specifications of suitable Panellit flow trip settings corresponding to the allowable outlet water temperature are known as Process Tube Instability Limits.

The analytical procedure of determining instability limit values relies upon a mathematical model which has been chosen after some years of experimental experience with the thermal and hydraulic characteristics of fuel coolant channels.^{(1)*} However, the model is a considerable simplification of the conditions within a coolant channel. Whenever there is a significant change in the geometry of the coolant channel assembly, the thermal and hydraulic characteristics of the new assembly must be determined experimentally to make sure that the model still results in suitable conservative reactor operating limits. The C Reactor Overbore Program ⁽²⁾ presents such a change in coolant channel geometry.

The fuel channel assembly which was chosen for C-overbore production tests was significantly larger than previous assemblies and provided protrusions on the fuel pieces to support the fuel concentrically within the tube rather than providing ribs on the inside of the coolant tube on which to support the fuel pieces. These geometry differences made it desirable to determine experimentally the heat transfer and fluid flow conditions for the new assembly and to determine whether the mathematical model would result in adequate instability limits for this new assembly.

SUMMARY AND CONCLUSIONS

Experiments were conducted in the 189-D Heat Transfer Laboratory to determine the thermal-hydraulic characteristics of the fuel and process tube geometry for the C-reactor Overbore Program. Nuclear heat was simulated by d-c electrical resistance heating in a 1.991 inch OD by 0.339 inch ID test section. The test section was positioned in a 2.147 inch ID smooth bore zircalloy tube by use of ceramic spacers (self-supports) and therefore it simulated a 32 piece charge of C-VI-N I&E fuel pieces. Using this test section, three different types of experiments were performed.

*Numbers in parentheses refer to entries in the Bibliography, page 9.

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1. Steady State Experiments - The relationship between pressure drop and flow rate was determined as the flow was reduced by small increments under conditions of constant heat input. Tube powers in the range from 690 to 2200 KW were investigated. Each run was terminated at film boiling (boiling burnout) conditions as detected by a large temperature rise at some point on the test section surface. The experimental data are shown in Figures 1 and 2. These data are shown in Figure 3 as generalized hydraulic demand curves. From these data, the following information was indicated for a front header pressure of 400 psig, a Panellit pressure of 200 psig and an outlet temperature of 130 C: (1) Hydraulic instability would only occur at tube powers greater than about 1050 KW; (2) The current method of calculating instability limits for Hanford reactors should be modified slightly for the C overbore geometry assembly. This latter condition results from extra, unexplained pressure drop across the fuel column during the early stages of boiling in the assembly.

2. Experiments Concerning Partial Flow Reduction - Transient flow plugging experiments were conducted with initial equilibrium tube powers of 1000 and 1800 KW. These experiments serve to define the minimum tube inlet pressure immediately following a sudden flow plug upstream of the Panellit pressure tap and they also relate the time sequence of the pressure-flow relation following such a plugging incident. From these experiments, it was determined that the minimum tube inlet pressure (and the minimum Panellit pressure) can be predicted by the usual mathematical model while using an outlet water temperature of 130 C (or less) and a 50 psig (or more) rear header pressure. For an outlet temperature of 160 C, however, the model would have to be modified for rear header pressures less than about 100 psig.

The time sequence of events during such plugging incidents is shown on Figures 4 through 8. These data show that very severe flow reductions can be sustained without fuel element melting. For example, with an 1800 KW tube power and a 130 C outlet temperature, a 70 per cent reduction in flow rate followed by a 14 second delay before power reduction did not cause excessive test section temperatures.

3. Experiments Concerning an Inlet Piping Rupture - Experiments were conducted to investigate the fuel element temperatures which could result after a complete failure of the inlet connector to a single process tube. Following such a failure, the fuel would be cooled only by the reverse flow of hot water from the rear header. Inlet connector failure was simulated at equilibrium tube powers of 1000, 1400, and 1800 KW. Three seconds after failure, the power input to the test section was reduced in accordance with a 1400 ih reactor scram. Test section surface temperatures were recorded during the ensuing transient heat transfer conditions.

The experimental data are plotted in Figure 9. After adjustment for the effect of fuel element heat capacity, the data are replotted in Figure 10 to show the rear header pressure which is required to prevent fuel jacket melting during a piping failure incident as a function of the equilibrium tube power. A 60 psig rear header pressure would prevent fuel jacket melting for initial tube powers of about 1400 KW or less.

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The effect of removing the nozzle mounted flow meter (pinna meter) and the restrictive flexible connector from the flow path during the reverse flow after inlet piping failure was investigated briefly. It was found that this change would reduce the rear header pressure requirements by as much as 10 psi for the 1000 KW case.

Experimental Equipment

The experiments were conducted with a prototypical mock-up of a single process channel with nuclear heat being simulated by d.c. electrical resistance heating in a metal test section. Various metal alloys were utilized in constructing the test section such that the stepped cosine power distribution resulted in a peak power to average power ratio of 1.41. The test section was 1.991 inch OD by 0.339 inch ID by 23.6 feet long to simulate a 32 piece charge of C-VI-N I&E fuel pieces. Small holes were drilled to connect the internal and external flow channels at 9 inch intervals along the test section length to simulate the interjunction flow characteristics of reactor fuel charges.

The test section was placed in a 2.147 inch ID smooth bore zircalloy process tube. Ceramic ribs (0.185 inch wide by 0.625 inch long by 0.070 inch high) were fastened to the surface of the test section at 192 locations to simulate the self supports of the C-VI-N fuel and to act as electrical insulators between the test section and the process tube. This was the first time that a full length test section which simulated self-supported type fuel pieces had been used in the Heat Transfer Laboratory.

The inlet and outlet fittings which were used were spares of those designed especially for the C-overbore program. The inlet assembly is shown on drawing SK-1-4774 and utilizes the Pinna flow meter at the nozzle end of the inlet flexible connector. The outlet assembly is shown on drawing SK-1-4781. It provides two locations for temperature sensing elements to be inserted into the coolant outlet stream.

DISCUSSION

Steady State Experiments

Data were obtained to relate the flow rate to the pressure drop across various segments of a prototypical C-overbore fuel channel assembly. These data are presented on Figures 1 and 2. For each tube power, a flow rate high enough to prevent boiling was first established. Then the flow rate was reduced in small increments while flow, pressures, and temperatures were recorded after each increment. In each run, the flow rate was reduced until film boiling was initiated at some point on the simulated fuel as determined by large increases in the test section surface temperature. When this condition was reached, the test was terminated and non-boiling conditions were again established. The terminal (film boiling) points were at significantly reduced flow rates and were at conditions of net steam generation. The conditions at the terminal points are shown in the following table.

TABLE I

Tube Power, KW	Flow Rate gpm	Tube Inlet Pressure psig	Pressure at End Of Heated Section psig	Steam Quality at End wt. per cent
690	12.1	217	129	13.3
960	16.1	297	170	13.7
1380	22.9	419	229	10.9
1790	28.1	541	300	11.0
2200	33.5	635	355	10.9

Thus, reactor operation to the left of the terminal points on Figure 1 or 2 would result in bulk boiling with very high fuel element temperatures.

Comparison of the data in Table I with similar data for K reactor and for BDF reactor with enlarged outlet fittings shows that the C overbore fuel reaches a condition of film boiling at higher flow rates and at lower steam qualities than the other fuel geometries.^(3,4,5) The reason for this is not known unless the self-supported fuel results in flow patterns such that heat transfer rates are reduced downstream of each self-support. This may especially be true at low flow rates and with vapor formation.

The data are presented in Figure 3 as generalized hydraulic demand curves. (The generalizing technique is presented in HW-42469-C⁽⁶⁾). The generalized curves are useful to identify flow reductions which might lead to fuel element melting. This is done by constructing a supply curve just tangent to the hydraulic demand curve, as shown on Figure 3. This point of tangency represents a condition of incipient hydraulic instability. By constructing various supply curves it is found that an unstable flow condition could not occur for tube powers less than about 1050 KW.

When the hydraulic demand curves of Figure 3 are compared with the mathematical model which is used to establish outlet water temperature limits (or Panellit trip set points), it is found that the model would not predict conservative limits for the C-overbore geometry. This is because of unusually high pressure drop across the heated section for flow rates which correspond to abscissa values of about 0.4 to 0.8 on Figure 3. (For example, when the mathematical model indicates that sudden plugging to an $(F/F^*)^2$ value of 0.61 would cause unstable flow for the 1790 KW tube power, the data show that plugging to an $(F/F^*)^2$ value of 0.72 could cause flow instability.) The reason for the extraordinary pressure drop across the 'fuel charge' is not known. These are the first experimental data for hydraulic demand of self-supported fuel, so it is easy to suspect that the self supports may be the cause of the high pressure drop during the early stages of local or surface boiling conditions. Further experiments are planned to investigate this

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hypothesis. Meanwhile, the methods of establishing outlet water temperature limits must be modified for the C-overbore geometry.

Upstream Plugging Experiments

One other phase of investigating the applicability of the mathematical model in providing adequate Panellit trip settings was to run simulated flow plugging experiments. To do this, normal flow rate and outlet temperature conditions were first established in the prototype assembly. Then a flow restriction (a partially closed plug valve) was suddenly inserted in the flow path upstream of the Panellit pressure tap. The relation between pressure and flow rate was followed by means of high speed recording equipment. When film boiling conditions were detected by a large surface temperature rise of the test section, the power input was reduced according to a 1400 ih reactor scram. The main points of interest in such tests are: (1) does the minimum observed inlet pressure fall on the isothermal demand curve (the mathematical model); and (2) what is the sequence of the pressure-flow rate relation during the time between minimum observed inlet pressure and the condition when a power decay is required to prevent high temperature damage to the fuel?

Data from flow plugging experiments are shown in Figures 4 through 8 for various initial tube power and outlet temperature conditions. These data show that the minimum inlet pressure does fall on the isothermal demand curve for 130 C outlet temperatures and 50 psig rear header pressure. However, for 160 C outlet temperatures, a rear header pressure of almost 100 psig was required to obtain agreement between minimum observed pressure and the isothermal demand curves, as is shown on Figure 6. Similar data at 130 C outlet temperature and 25 psig rear header pressure also showed some deviation from the isothermal demand curve. A rear header pressure of 40 to 50 psig was necessary to achieve complete agreement with the model at 130 C outlet temperature. (Previous experiments have shown that the mathematical relation between tube inlet pressure and Panellit pressure is valid during flow plugging incidents. Hence, the data of Figures 4 through 8 can be generalized to any desired Panellit pressure.)

The data on these figures also show the time sequence of events after plugging incidents of various severity. It will be noticed that the flow rate at the time when power decay was initiated for the severe plugs was considerably lower than the flow rate at which film boiling was detected under steady state operating conditions (Figures 1, 2, and 3). Even so, no excessive test section temperatures were detected in any of these experiments. This would indicate that flow trip limits based on steady state film boiling conditions would provide adequate protection against excessive fuel temperatures during upstream plugging incidents.⁽⁷⁾ This would especially be true with the presently restricted Panellit span of 60 psig.

Inlet Piping Failure Experiments

Experiments were conducted to investigate the fuel element temperatures which could result from coolant flow loss following a complete failure of the inlet connector to a process tube of C-overbore geometry. Such a failure would stop the forward flow of coolant to the fuel elements and initiate a reactor

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scram. The only means of heat removal from the affected channel during the post-scram period would be by reverse flow of hot water from the rear header. The objective of the experiments was to determine what rear header pressures would be required to prevent fuel jacket melting during such a post-scram period.

Failure of the inlet connector was simulated at equilibrium tube powers of 1000, 1400, and 1800 KW by suddenly stopping the coolant supply to the inlet of the process tube and simultaneously opening the tube inlet to the atmosphere at the header end of the inlet connector. Three seconds after the simulated failure, the power input to the test section was reduced in accordance with a 1400 ih scram. The reverse flow rate, rear header pressure and temperature, and the temperatures from thermocouples on the heater rod were recorded during the transient conditions.

Data from the experiments are shown in Figure 9. These data relate the maximum observed test section (simulated fuel) temperature to the rear header pressure and the steady state tube power prior to the piping failure. The data of Figure 9 show two curves for each initial tube power. The difference between the two curves results from using different power input curves in the programmed power reduction following the simulated scram. The lower curve of each case is for the condition that the heat input rate be equal to the theoretical nuclear heat generation rate in a reactor lattice (both in fuel and graphite) as given by Figure 1 of HW-33870.⁽⁸⁾ For the upper curve of each case, the heat input rate was set equal to the theoretical nuclear heat generation (fuel plus graphite) plus five per cent (5%) of the initial tube power. The additional five per cent is an allowance for sensible heat release from the graphite to the coolant. This technique of simulating graphite sensible heat release is discussed more fully in reference (9). It is believed that the additional 5 per cent is conservatively high, especially for cases involving high fluid discharge temperatures, and that the actual situation lies somewhere between the upper and lower curves of Figure 9.

Application of the data of Figure 9 to reactor conditions requires some consideration of the effect of fuel element heat capacity as compared to the heat capacity of the experimental test section. The ratio of heat capacity of the test section to that of bare uranium C-VI-N fuel pieces is 1.85; for the aluminum jacketed C-VI-N fuel pieces, this ratio is 1.57. The effect of this difference in heat storage capacity was investigated and discussed in reference (10). It was found that the limited heat transfer which does occur during such a piping failure is sufficient to somewhat reduce the effect of the heat capacity differences. It is estimated that actual C-VI-N fuel elements would experience surface temperature rises about 1.4 times that which was observed for the test section which was used in the present experiments. Then by adjusting the temperature rise represented on Figure 9 by the factor 1.4, one finds that a test section surface temperature of 960 F would correspond to a fuel element surface temperature of 1220 F (approximate aluminum melting temperature). Thus, a very minimum condition of acceptable cooling would be represented by a rear header pressure corresponding to 960 F test

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section temperatures. The rear header pressure which is required to achieve minimal adequate cooling of overbore fuel elements is plotted versus equilibrium tube power in Figure 10. From this figure, for example, a 60 psig rear header pressure would prevent fuel jacket melting for initial tube powers of about 1400 KW or less.

A brief investigation was made to determine the effect of the coolant flow path geometry after inlet piping failure. For this test, the pinna flow meter was removed and the C-overbore flexible connector, which has a small ID at the header end, was replaced with a CG-558 inlet connector. The flow path after piping failure was then out the nozzle and through the CG-558 connector into a 4 inch discharge pipe. The data from this test at an equilibrium tube power of 1000 KW are also shown on Figure 9. One finds that the rear header pressure requirements are about 10 psi lower than the standard overbore geometry data at a test section surface temperature of 960 F. One could argue the merits of removing just one of the flow restrictions (pinna meter or small ID pigtail) at a time. However, the pinna meter presents the smallest flow area of the two fittings so its affect should contribute the majority of the difference between the data for this latter assembly and that data for the standard overbore assembly with failure at the header end of the pigtail.

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Figure 1 - Steady State Hydraulic Demand Curves.

Basis: Outlet Fittings - SK-1-4781
Simulated 32 - C-VI-N I&E's
Inlet Water Temp. = 27 to 30 C
Rear Header Pressure = 50 psig
Shaded symbols indicate film boiling conditions.

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Figure 2 - Steady State Pressure Drop Across Active Section.

Basis: Simulated 32 - C-VI-N I&E's
Inlet Water Temp. = 27 to 30 C
Rear Header Pressure = 50 psig
Shaded symbols indicate film boiling conditions.

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Figure 3 - Generalized Steady State Hydraulic Demand.

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Figure 9 - Results of Inlet Piping Failure Experiments.

Fasis: C-overbore mockup with front pigtail open to atmosphere at header end. Temperature of water from rear header = 130 F.

Simulated 32 piece C-VI-N fuel charge. Rod surface temperature = 300 F before transient began. See discussion regarding upper and lower curves for each tube power and regarding special assembly for Curve E.

Note: Temperature rise of reactor fuel will be about 1.4 times that of experimental test section. See discussion, page 7.

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Figure 10 - Pressure Required to Prevent Fuel Jacket Melting.

Basis: Cross plot from Figure 9 at a test section temperature of 960 F.
This should be approximately equivalent to a uranium fuel surface temperature of 1220 F.

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