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TRANSIENT THERMAL-HYDRAULIC EXPERIMENTS --

N-REACTOR INLET CONNECTOR BREAK

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TRANSIENT THERMAL-HYDRAULIC EXPERIMENTS --
N-REACTOR INLET CONNECTOR BREAK

By

D. S. Rowe
J. K. Anderson
W. L. Thorne

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TRANSIENT THERMAL-HYDRAULIC EXPERIMENTS --

N-REACTOR INLET CONNECTOR BREAK

PURPOSE

The purpose of this report is to present the experimental results of laboratory thermal-hydraulic tests which were performed to determine the effect of an N-Reactor inlet* connector break.

INTRODUCTION

The possibility of a process tube connector break in N-Reactor requires that such an accident be included in the reactor safety analysis. It must be shown either by analytical or experimental means that the reactor can withstand this break without damage to the rest of the plant or without experiencing excessive fuel temperatures.

Since a lack of two-phase flow information hindered an analytical analysis of this problem, an experimental approach was taken to investigate the connector break. The experimental setup provided for simulation of a connector break at the inlet riser. This break would cause a flow reversal through the long inlet connector. Since this connector contains a "butterfly" type flow-adjusting valve, the study included an investigation of the effects of an inadvertent closing of this valve due to the reversed flow.

SUMMARY AND CONCLUSIONS

An N-Reactor inlet connector piping break was investigated in a laboratory study to determine the effect of this break on the affected process tube's thermal-hydraulic performance. A full-scale mock-up of the piping between the inlet and outlet risers was used which included actual reactor valves and fittings. An electrically heated half-length section which was equivalent to the downstream half of the reactor fuel column was used to model the heat-generating portion. The simulation of the connector break at the inlet riser was made possible by actuation of high-speed valves.

Six runs were made for these tests. Two runs were at 350 psi with initial flow rates of 47,000 lb/hr and test section powers of zero and 1,250 kw. Four runs were made at 1,400 psi with initial flow rates of 85,000 lb/hr and test section powers of zero and 2,500 kw. During two of these runs at 1,400 psi, the butterfly valve was closed to its stop during the flow reversal with scram delays of 1.5 and 5.0 seconds between the time of the "connector break" and the start of power reduction.

*The terms "inlet" and "outlet" refer to the steady-state flow orientation.

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In general, the following results were observed:

1. The flow reversed in less than a second with the initial flow oscillations damped out within two seconds.
2. Pressure fluctuations during the flow reversal and valve switching were moderate and were damped out within two seconds.
3. Violent oscillations of the pressure drop in the inlet venturi were measured during the flow reversal.
4. No significant test section temperature rises occurred when the butterfly valve remained open.
5. A maximum test section temperature of about 1200°F (initially about 830°F) was measured when the butterfly valve was closed to its stop during reverse flow with a scram delay of 5.0 seconds. For the same initial condition with 1.5 second scram delay, no large temperature increases were observed.

When differences between the test ⁰apparatus and the reactor are considered, it is found that for similar initial conditions the inlet connector break accident would result in higher fuel temperatures in the reactor. This can be attributed primarily to the differences in fuel column length. If these differences are considered, the test results can be extended to the reactor and the following conclusions can be made:

1. Pressure fluctuations during the flow reversal would damp out in one or two seconds without large pressure surges.
2. The inlet connector venturi pressure drop would experience some violent pressure fluctuations following the break and should provide a good indication of a break, provided that the safety circuit response to these fluctuations is fast enough.
3. The flow reversal is established in less than a second following the break.
4. A limiting connector break accident has been postulated -- a connector break upstream of the butterfly valve in a central zone inlet connector with butterfly valve closing to its stop during reverse flow.
5. Two criteria have been found for an allowable scram delay to prevent excessive fuel temperatures in the limiting accident. First, the scram should occur before the first arrival of a two-phase mixture at the closed butterfly

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valve after the flow reversal. Second, the scram should occur before the butterfly closes, if a two-phase mixture is already passing through it after the flow reversal. These two criteria would be satisfied with the normal 1.5 second scram time for N Reactor.

6. With a 1.5 second scram delay, a 5000-kw tube should survive the limiting accident. Should a burnout* condition occur, fuel temperatures would not rise more than about 375°F based on a conservative estimate.
7. For breaks downstream of the butterfly valve, the flow rates are much higher than for the limiting case; therefore, longer scram delays could be tolerated.
8. Additional consideration should be given to the limiting case to determine the effects of inlet connector length, butterfly valve closing time, tube power, system pressure, scram delay, and steady-state tube outlet enthalpy. These are all parameters which can have a significant effect on the accident.

DESCRIPTION OF EQUIPMENT

The tests were performed in the High-Pressure Apparatus of the 189-D Thermal-Hydraulics Laboratory. This is a recirculating loop with a direct current power supply capable of 3100 kw for these tests. A complete description of the laboratory and its facilities is given in References (1) and (2). Figure 1 is a schematic diagram of the test apparatus used for these tests.

Except for the heated portion of the test assembly, a nearly exact model of the actual reactor piping was used. The inlet and outlet connectors were full size, contained the same number and type of bends, and were of typical length as those used in the reactor. The lengths of the inlet and outlet connectors used for the tests were about 38 and 52 feet, respectively. Actual reactor venturi, butterfly valve, diversion valve, and fittings were used.

The dummy sections simulated that part of the process tube which extends through the reactor shielding and reflector and contain the dummy charge. Each of the dummy sections provided space for two short (15-1/2 inch) and four long (27-1/2 inch) dummy charges. Actual process tube nozzles and slightly modified caps were used on the dummy sections.

*"Burnout" in this report does not refer to physical burnout, but the deterioration of heat-transfer condition often termed, "departure from nucleate boiling (DNB)."

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Because the direct current power supply was limited, a full-length heated section could not be used. Instead, a model of the downstream half of the fuel column was made using a step cosine power distribution to simulate the actual power distribution in the reactor (Figure 2). Flow channel and fuel dimensions were approximately those of the reactor (Figures 3 and 4). The distribution of flow to each of the three flow channels was provided by short connections from the dummy sections to the ends of the heated section. They were not valved; therefore, a free distribution of flow to the test section existed.

Laboratory simulation of the piping break was made possible by actuation of three high-speed valves.* These valves simultaneously removed the test section from the recirculating loop and opened the inlet riser to a pool condenser discharging to the sewer. The water supply in the 1000-gallon storage tank, which was floating on the outlet piping, was immediately available for the blowdown following the valve action. A pressure control valve between the high-pressure air receiver and water storage tank maintained the initial outlet riser pressure in the water tank throughout the test. The flow path before and after the test is shown on the system schematic (Figure 1). It should be noted that the recirculating loop was completely isolated from the test apparatus once the valves were actuated.

Power reductions, following the valve actuation, were controlled by an X-Y curve follower, which followed a pre-determined voltage decay. For all power runs, a power reduction rate equal to a 1500 in-hour scram of the reactor was used. The programmed power decay (proportional to the square of the voltage) is shown in Figure 5, along with the relative power obtained from one of the test runs. The voltage oscillations which occurred were unavoidable for the rate of power change required for these tests. These voltage oscillations also caused some test section thermocouple temperature oscillations as will be seen later.

TEST PROCEDURE

All tests were run with approximately the same procedure. For a typical run, the events were as follows:

1. The high-pressure air receiver was pressurized.
2. The loop operating pressure was set and water was circulated through the 1000-gallon storage tank while heating it to the desired temperature. (This piping is not shown on Figure 1.)

*Valve response is less than 50 milliseconds. Electrical signal response to valves is about 0.2 second based on the data for these tests.

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3. Once the storage tank and recirculating loop were at the desired temperature, the storage tank was isolated and the test section conditions were set.
4. The storage tank pressure was set to equal the loop outlet riser pressure and the storage tank blocking valve opened.
5. The test was started by starting the recorders followed by actuation of the high-speed valves and a power reduction (if any) at the desired time.

Six runs were made at various initial temperature, flow, pressure, and power conditions. These are summarized in Table I.

After run 3, the air compressor failed during the next air receiver pressurization. Repairs of the compressor were to be time consuming; therefore, the storage tank water was heated and the steam vapor pressure was used to maintain the pressure during the blowdown. This provided a good pressure supply for the succeeding runs. The effects of using saturated water in the storage tank will be discussed later.

RESULTS

Pressures

For all runs, it was generally found that the initial pressure disturbances from the flow reversal and valve switching were damped out in about one or two seconds (Figures 6 through 10). The magnitude of oscillation was moderate with maximums of about ± 120 and ± 350 psi for nominal system pressures of 350 psi and 1400 psi, respectively. These maximums occurred primarily in the outlet riser. At other points, where pressures were measured, the maximums were about one-half the above values. The period of oscillation during these tests was not consistent but was predominantly from 0.05 to 0.15 second during the first second or two.

The inlet riser pressure for run 5 (Figure 9) is not the actual pressure recorded during the test because the actual recording was shifted off scale. The pressure shown is an estimate of the pressure based upon the inlet riser pressure of run 6, and the pressure drop across the butterfly valve for run 5. This estimate should be fairly good as the initial conditions for runs 5 and 6 were not much different.

Test Section Temperatures

During the first three runs, an attempt was made to measure the heated section temperatures on high-speed Offner strip-chart recorders. The signals to the recorder were very noisy, sensitive to power changes, and sensitive to electrical ground shifts in the test section power supply. This made them essentially useless.

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During run 3, the temperatures were also monitored on slower speed strip-chart recorders which provided a much better recording. (These recorders had a time response of one second for full scale.) No time marks were used during this run; therefore, a time reference was not available. It was found that no significant temperature rises occurred. The slower speed recorders, operating at their highest speed (about 1/2-inch of chart per second), were used for all succeeding runs.

Since no power was used for runs 1 and 2, the temperatures were not of much concern. Also, since no significant temperature changes were noticed, and no time reference was available for run 3, only the test section temperature data for runs 4, 5, and 6 will be presented (Figures 11 through 13).

No scram action was anticipated for run 4 unless test section temperatures rose significantly. As can be seen in Figure 11, small temperature changes occurred resulting from the flow reversal while still maintaining full power. The flow reversal was fast enough to prevent significant temperature rises. A scram was arbitrarily started at about 27 seconds. The oscillating temperatures, indicated by thermocouples 2, 9, and 10, during the scram, were not real. These thermocouples were found to be sensitive to the voltage oscillations during the scram for all runs.

Run 5 was the same as run 4, except the butterfly valve was allowed to close to its stop* during reverse flow. As in run 4, a scram was not started until rod temperatures began to rise. In this case, the temperatures did not start to rise significantly until about 2.5 seconds and then rose rapidly indicating a "burnout" condition. The scram was started at five seconds. Following the scram, some temperatures continued to rise to 1200°F at about 10 seconds. Cooling of the rod to near steady temperature was completed at about 28 seconds following a complete power reduction at 10.8 seconds. It is interesting to note that the hottest thermocouples were in the upper region of the test section as well as in the higher heat-generating sections.

Evidence of film boiling in the vicinity of the hotter thermocouples can be seen in the nature of their temperature decay. This can be seen, for example, from the decay of thermocouple 9 which decayed at a slow rate followed by a rapid cooling at about 20 seconds. This temperature decay is typical of cooling a hot surface first by film boiling and then by a transition to nucleate boiling. Although temperatures increased enough during run 5 to be considered burnout (or DNB), physical burnout of the test section did not occur.

*The low flow stop setting provides for a flow in the closed position (20 gpm at 45 psi pressure drop at 70°F).

Run 6 was the same as run 5, except an automatic scram was started at 1.5 seconds. In this case, no appreciable temperature rises occurred, as seen in Figure 13.

Water Temperatures

Water temperatures for the first two runs at zero power did not change significantly; therefore, only the data from the later runs are presented (Figures 14 and 15).

It should be noted that for all runs the outlet riser temperature dropped from its steady-state value at the start of the transient and remained nearly constant for some time before rising again. This drop in temperature (generally about 50°F) is caused by cooler water entering from the long supply line between the storage tank and test apparatus. Sufficient time existed from the time heating the tank water stopped until the test started to allow this cooling. This did not significantly effect the results because by the time the cooler water entered the test section (greater than five seconds), the most significant part of the transient had been completed.

Blowdown Flows

The flow rate to the test section was measured by a venturi at the water storage tank discharge. No provision was made for measuring actual discharge flow from the test section since flow-measuring devices could choke the flow and would not provide a very accurate measurement with a two-phase mixture. The flows measured during the test are given in Figures 16 through 19.

An estimate of the expected maximum error in the flow data is given in the Appendix and shows that at low flows large errors could exist. While the magnitude of the flow for the runs which had low flows may be in question, the shape of the curves should be reasonably accurate. Some error in the flow for runs 4 and 6, in addition to the expected maximum error, could exist because liquid flashing in the venturi probably occurred. It is not known how this would affect the measured flow since saturated liquid is not normally discharged from the storage tank. It is also believed that the large oscillating flows measured at the beginning of runs 4 and 6 could be caused by liquid flashing in the storage tank outlet venturi.

The flow signal for run 5 failed; therefore, no flow was measured. An attempt was made to determine its magnitude, however, by using steady-state pressure drop versus flow data which are available⁽³⁾ for this part of the apparatus. An oscillating flow was calculated to be 20,000 ± 64,000 lb/hr with a 1.5 second period, 10 seconds after the transient started. Poor agreement between the flow calculated by this method and measured flow oscillations at the beginning of runs 3, 4, and 6 was found; therefore, it is believed that the flow calculation for run 5

could be questionable because of the large flow oscillations. It would also be subject to larger errors than the flows measured by the tank outlet venturi. Oscillations probably did occur, however, because the water temperature at the downstream end of the inlet dummy section showed increases which would not have occurred without flow reversals caused by oscillations. The oscillating system pressures for run 5 also indicate an oscillatory flow.

For the first four runs, the pressure data gave no evidence of choking between the inlet and outlet risers. The point of a possible choke, at the discharge of the connector into the inlet riser, had only a small pressure drop compared to what would have existed if a choke has occurred. For runs 3, 4, 5, and 6, limited pressure data upstream and downstream of valve "D" indicated that choking could have occurred in or near the valve. If no restriction had existed in the discharge piping for the runs where no choking was observed upstream of the discharge piping, higher flows would have been measured.

Only for runs 5 and 6 was there any indication of a choked flow. For both of these runs, a sharp drop in inlet riser pressure and flow occurred between 2 and 3 seconds, indicating that a choke probably occurred in the butterfly valve which was closed to its stop (Figures 9 and 10). Also, the transit time from the heated section to the butterfly valve is about 2.5 seconds which would bring the first two-phase mixture to the valve at this time and cause a possible choke.

After about three seconds, the pressure drop across the butterfly valve and venturi did not change much for run 6 (Figure 10). Also, after three seconds, the flow increased which indicates that the flow was being governed by the pressure drop across the valve. This is not a characteristic of a choked flow. Single-phase flow was probably being established since the water temperature and pressure data indicate near saturated fluid conditions at the valve during this time. The possibility of a metastable discharge through the valve also seems possible.

After about 2.5 seconds, the inlet riser pressure of run 5 dropped to a lower value than in run 6 and remained low without much variation. With this large pressure drop across the butterfly valve and the low flow, which was estimated for run 5, it appears that a choked condition probably occurred during this run. The increase in inlet riser pressure at 30 seconds for run 5 (Figure 9) could be compared to the increase at eight seconds in run 6 (Figure 10). This is about the time subcooled water arrived at the valve based on water temperature data and would represent the time when a non-choked discharge would begin to establish.

Venturi Pressure Drop

The inlet connector venturi pressure drops were found to give some violent fluctuations as compared to their steady-state values. For the nominal 350-psi runs (1 and 3), and 1400-psi runs (2, 4, 5, and 6), these fluctuation maximums were on the order of ± 100 psi and ± 300 psi,

respectively (Figures 20 through 22). The period of oscillation during the first second was about 0.08 second. Pressure fluctuations of this magnitude would give a good indication of a connector rupture provided a rapid response to the pressure change exists in the reactor detection and safety circuit system.

Power Decay

The power decay used for the scram was the same for all runs and corresponds to the power decay of a 1500 in-hour scram. As mentioned previously, the test section voltage was the controlled variable.

Difficulties with the test section voltage and current measurement on the high-speed recorders prevented complete power decay data from being obtained. The only data which were found to be valid were the voltage decays of runs 4 and 5 (Figures 23 and 24). Both of the voltage decays were essentially the same for these two runs and it would be reasonable to expect the same for runs 3 and 6.

Comparison of the programmed and measured power decay in Figure 5 shows two differences. First, oscillations in the voltage were obtained during the rapid power change. The reason for this oscillation is not completely understood but is believed to be caused by the inability of the control system to adequately follow such rapid power changes. The second difference between the measured and programmed power decay is that the measured power was higher by nearly a constant amount (about 4 percent of the initial power). The reason for this discrepancy could not be found.

Butterfly Valve Closing Time

When starting runs 5 and 6, the signal to close the high-speed valves and butterfly valve was given simultaneously. A butterfly valve response test, after the completion of the transient tests, showed that the valve started to close at 0.87 second and was closed to its stop at 1.34 seconds. These tests were performed without flow and would represent a longer time than would exist for the tests where the valves had a flow assist in closing. In the reactor, a somewhat different condition exists since closing of the valve requires the hydrodynamic forces of the reverse flow to overcome the frictional resistance of the valve. The response time for the reactor valves could, therefore, be longer. This is especially true for central zone tubes which would most often have a nearly full open butterfly valve. More will be said later about the effect of the valve closing time.

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DISCUSSION

Experimental and Reactor System Comparison

Since the laboratory apparatus could not exactly simulate the reactor piping, riser-to-riser, let us consider the primary differences between these two systems, and how the differences would effect the test results when applied to the reactor.

The most obvious difference is that a half-length simulated fuel column was used for the tests. For steady-state operation, this simulation would not cause much difficulty since the test section inlet conditions can be adjusted to get outlet fluid conditions equivalent to the reactor. In a reverse flow transient, however, fluid returning to the test section will realize an enthalpy increase which is only one-half that of the reactor. Under the reactor conditions, therefore, we would have higher enthalpy fluid which would eventually reduce the blowdown flow rate and also increase the probability of burnout. As will be seen, this has the greatest effect when trying to extend the test results to the reactor.

The difference in inlet water temperature, also resulting from the half-length fuel column, is another important consideration for the first few seconds. With the lower inlet water temperature in the reactor, the two-phase pressure drop would be less for discharge through a break downstream of the butterfly valve. This would result in larger flow rates for the reactor. For a discharge through the butterfly valve closed to its stop, flashing in the connector could be ruled out for the first few seconds -- until saturated water arrived at the valve. The flow rates at this time would be a little larger because of the increased density of the cooler water. Once a two-phase mixture arrived, a choked flow would occur.

Another difference between the test apparatus and the reactor is the point of connector break. For these tests, the nearest approximation to the reactor would be a connector break at the inlet riser or between the inlet riser and butterfly valve. The effect of a break at other points closer to the process tube would be a flow increase caused by reduced frictional resistance. A break at an elbow, however, could reduce the flow because of flow pattern disturbances. The effect of this should not be very great, however, when compared to the large flow rates which would exist under these conditions.

Another difference between the test apparatus and the reactor is the mass of fluid involved in the flow reversal. The mass of water contained between the inlet and outlet risers in the reactor is not much different than for the corresponding part of the test apparatus. In the test apparatus, however, a considerable amount of water between the test section and the storage tank must be put into motion. If we assume the reverse flow is the same as the initial flow, this additional water would cause the flow reversal time to be about 40 percent longer than in the reactor. The effect of a shorter reversal time in the reactor would be to reduce enthalpy increases during the reversal and also decrease the probability of burnout.

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During the time after water heating in the storage tank stopped, until the test started, the water in the supply from the tank to the test apparatus cooled, as seen by the outlet riser temperatures in Figures 14 and 15. This cooler water entering the test section would only affect the transient after it reached the heated section. The time for this is on the order of five seconds for the runs with the high flows. For runs 5 and 6, the time is considerably longer. The effect of the cooler water would be to reduce temperatures in the test section and eventually permit higher flow rates. By this time, however, the interesting part of the transient is past.

Limiting Condition

Before describing a limiting condition for the inlet connector break accident, let us consider the fluid enthalpy distribution in the heated section following the flow reversal. In the sketch below is shown an initial enthalpy distribution and enthalpy distributions at several times after the flow reversal in the reactor.

As seen in the sketch, an enthalpy wave passes back through the fuel column and will eventually achieve a reverse flow enthalpy distribution. The shape of these distributions will depend upon the flow and heat input along the fuel column. The effect of using the half column for the tests can also be seen from the sketch. The region applicable to the test section is at the right half of the sketch. It is apparent that once the enthalpy peak passes the inlet of the test section, conditions as severe as in the reactor will not longer exist. This time was on the order of 0.8 second for these tests and would represent a maximum scram delay for the reactor if fuel temperature rises as mild as in run 6 are to be realized. Since the normal scram delay is longer than this, other effects must be considered.

The operation of the inlet connector butterfly valve will have significant effect on a connector break upstream of this valve; therefore, let us consider its use and operation. This valve is a two-position valve which is either open or closed to its respective stops. The closed stop setting is governed by the desired venturi pressure drop (or flow) when the nozzle caps are removed during charge-discharge operations -- for these tests, 20 gpm and 45 psi at 70°F. The closed stop setting of the valve on each reactor process tube would be nearly the same.

Some consideration has also been given to use of the butterfly valves as flow limiters by adjusting their open stop. This would position the butterfly, which is mounted eccentrically on its shaft, for possible closure during reverse flow -- for forward flow, the valve would be held open. It is possible that all tubes could have a valve which is partially closed. Since all tubes have valves with about the same closed stop setting and all tubes could have partially closed valves during normal flow, the high power tubes would be most affected by the valve closure with reverse flow.

A break upstream of a butterfly valve under the above conditions would be the worst that the reactor would experience. This has been selected as the limiting connector break accident in the reactor; i.e., a break upstream of the butterfly valve in a central zone inlet connector with the butterfly valve closing to its stop during reverse flow.

The primary factor governing the severity of the limiting break is the scram delay. The effect of this is illustrated very well by the test section temperatures of runs 5 and 6 (Figures 12 and 13). It does not seem possible that a five-second scram delay could be tolerated in the reactor without even higher temperatures than in run 5. It does seem reasonable, however, that the normal reactor scram delay of about 1.5 seconds could be tolerated without excessive temperatures. For the downstream half of the fuel column, this has been demonstrated by test run 6 (Figure 13) where small temperature rises occurred. Since no data exist for the upstream half of the fuel column, only estimates of maximum temperatures can be made for that part of the fuel column.

For an estimate of the effect of a burnout, should it occur, let us assume that a burnout condition started at 1.5 seconds in the upstream half of the fuel column. Also, assume that the temperatures will rise an amount similar to those of run 5 after the scram at five seconds. If we correct for the differences in heat capacity* between the fuel and test section, the reactor fuel temperatures would not be expected to rise more than about 375°F based on run 5 temperatures.

This estimate should be conservative since the flow rates for about the first three seconds would be higher in the reactor than those which existed in run 5** following the scram. This would inhibit and delay the start of a possible burnout condition. It would also seem reasonable that with the rapid power decay of the scram, a burnout condition should be stopped in a short time if the blowdown flow has not been choked prior to the scram.

Effects of Other Parameters

So far, we have described a limiting case in the reactor which was close to the test conditions of runs 5 and 6. Let us now consider several other important parameters which affect the limiting accident and point out their effect in a qualitative way.

1. Inlet Connector Length***

The connector length has an effect on the accident since the transit time of the first two-phase mixture from the heated section to the butterfly valve will mark the time when a sharp flow reduction will occur (choking). If power has not been sufficiently reduced at this time, a burnout condition is probable. This was the case in run 5 where the flow probably choked at about 2.5 seconds (transit time to valve) with a very rapid temperature increase. The scram at five seconds was far too late to prevent the large temperature increases. A criterion for the allowable scram delay for the limiting case should, therefore, require that the scram be started before the first two-phase mixture arrives at the butterfly if it closes to its stop.

*The heat capacity of the test section in the highest heat-generating region is about 1.5 times that of the reactor fuel.

**As mentioned previously, the flow was probably choked at the butterfly valve after about 2.5 seconds in run 5.

***Reactor inlet connectors range from about 39 to 66 feet in length, as compared to 38 feet for these tests.

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2. Butterfly Valve Closing Time

This is an important consideration with effects similar to those of the connector length. The butterfly valve was forced closed using its air actuator in these tests; whereas, in the reactor, the closing is caused by the hydrodynamic forces of the reverse flow. A variation in the closing time could, therefore, exist, depending upon the initial valve position. For a high power tube operating with nearly a saturated exit condition, the reverse flow with the butterfly valve open for a few seconds delay would cause a two-phase mixture to arrive at the valve in a short time (one or two seconds) following the break. If the valve closed after this time, but before the scram, a choked flow at high power would exist. This would cause large enthalpy increases and a probable burnout if power could not be reduced fast enough. Also, since a two-phase mixture would exist between the butterfly valve and fuel section, the flow would remain choked until subcooled fluid arrived at the valve. This could be on the order of 10 seconds. In contrast to this, had the scram occurred earlier, subcooled fluid would arrive at the valve shortly after the initial choked condition occurred and establish a higher flow. Here, we see that it is desirable to have a scram before the valve closes if a two-phase mixture is already passing through the valve.

3. Tube Power

Higher tube power would affect the accident in two ways. First, the higher power would cause larger enthalpy increases in the fuel column. Second, the resulting higher enthalpy at higher power has a compound effect to increase the probability of burnout.

4. Outlet Riser Enthalpy

Higher outlet riser enthalpy would have a detrimental effect by causing a higher fuel section enthalpy during reverse flow which would give a greater probability of burnout. As the greater enthalpy is realized in the discharge, the reduced flows would make things worse.

5. Pressure

Lower system pressure could adversely affect this accident. Less driving force would be available, therefore, lower flow as seen for runs 1 and 3. At low pressures, the two-phase pressure-drop characteristic for the fuel section could also cause flow instabilities leading to a burnout condition. It is apparent that the accident is less probable at low pressure, but if the power and flow rates give high outlet enthalpy at low pressure, a break could mean trouble.

While it is rather easily seen how the above parameters would affect the accident, it is difficult to obtain the magnitude of these effects for a general accident of this type. It would be desirable, however, to further investigate these effects.

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REFERENCES

- (1) J. M. Batch, K. G. Toyoda, and H. E. Hanthorn. The Thermal Hydraulics Laboratory at Hanford. HW-65722 REV. November, 1961.
- (2) K. G. Toyoda. Description of Transient System High Pressure Heat Transfer Apparatus - 189-D. HW-71389. October 23, 1961.
- (3) J. K. Anderson, J. M. Batch, W. L. Thorne, and D. E. Fitzsimmons. Thermal Hydraulic Characteristics of an N-Reactor Fuel Column. HW-80692. June 25, 1964. (Confidential)

DRAWING REFERENCES

SK-1-6764, Transient Piping Arrangement.

SK-1-5994, Steady State Piping.

H-1-14116, Heater Rod No. 328.

SK-1-4170, Hydraulic Heads and Process Tube.

APPENDIX

ERROR ANALYSIS

During the transient, most of the data were recorded on a Visicorder (light-beam oscillograph) whose record is subject to some error. In order to determine what errors could exist, the effect of various parts of the recording system was considered. The items considered were:

1. Transducer (if used).
2. Amplifier.
3. Galvanometer (negligible error).
4. Chart readability.

For the data presented in this report, the results of the recorded accuracy estimate are shown in the table below. They represent the maximum error and are probably quite conservative. No statistical data are available to provide confidence levels for these estimates.

Recorded Signal	Maximum Error			
	Transducer	Amplifier	Chart Reading	Total
Pressures, psi	±7.5	±20	±2.5	±30.0
Inlet connector venturi pressure drop	±5.0	± 6.7	±1.7	±13.4
Storage tank venturi pressure drop	±0.50	± 0.07	±0.08	± 0.65
Water Temperature, °F	±2 (a)	± 1.1	±1.3	± 4.4
Rod Temperature, °F	±2 (a)	±20 (b)	--	±22

(a) Estimate based upon general agreement with resistance temperature detectors for non-power runs.

(b) Strip charts are rated at ±1 percent full scale (2000°F).

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The pressure-drop error for the tank venturi in the above table was related to the flow error for a given flow rate. This is shown in the following table for several flow rates assuming a density of 49 lb/cu ft.

<u>Flow</u> <u>(lb/hr)</u>	<u>Maximum Error</u> <u>(percent)</u>
50,000	±65
80,000	±26
120,000	±11
150,000	± 7
200,000	± 4

A comparison of the initial pressures recorded on the strip chart with the initial measured (and estimated) system pressures showed considerable disagreement (up to about 100 psi). This was outside of the expected maximum error. A check of the pressure signals, whose calibration was checked at the beginning of each run, showed that a shift in the output of each pressure transducer output by various amounts had occurred between runs. This shift was nearly the same at both the zero and the calibrate pressure check points and was large enough to account for the observed discrepancies. This shift was present because the calibration procedure did not permit a zero reset; therefore, the signal shifted by a constant amount. A constant pressure correction which was taken to be the difference between the initial recorded pressure and actual system pressure was, therefore, assumed to apply at all times for the run.

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Appendix (continued)TABLE I -- INITIAL TEST CONDITIONS

Parameter	Run					
	1	2	3	4	5	6
Outlet riser pressure, psig	350 (a)	1,400 (a)	350 (a)	1,420	1,400	1,400 (a)
Inlet riser pressure, psig	383 (b)	1,506 (b)	386 (b)	1,548 (b)	1,528 (b)	1,528 (b)
Flow rate, lb/hr	47,000	85,000	47,000	86,000	85,000	85,000
Test section power, kw	0	0	1,250	2,507	2,503	2,509
Inlet riser temperature, °F	414	405	338	465	466	467
Outlet riser temperature, °F	412	404	420	545	546	547
Storage tank temperature, °F	406	404	392	571	574	578
Connector venturi pressure drop, psi	4.65	15.63	4.52	17.04	16.53	16.8
Preset scram delay, sec	--	--	1.0	(c)	(d)	1.5
Butterfly valve action	Open	Open	Open	Open	(e)	(e)

(a) Control pressure -- no actual pressure measurement made.

(b) Estimated from initial piping pressure drops and steady-state pressure drops from previous tests.⁽²⁾

(c) No automatic scram -- manual scram at 27 seconds.

(d) No automatic scram -- manual scram after test section temperatures began to rise, at five seconds; electric breakers dropped at 10.8 seconds.

(e) The butterfly valve was open for the normal flow orientation and then allowed to close to its stop during reverse flow.

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Appendix (continued)

TABLE II -- HEATER ROD MATERIAL PROPERTIES

Material	Density (gm/cu cm)	Specific Heat Capacity (cal/gm °C)	Thermal Conductivity (cal/sec cm °C) (at ~ 100°C)
Inconel	8.51	.109	.036
Hastelloy "B"	9.25	.0907	.0265
Chromax	7.95	.110	.031
Cu-Ni (60-40)	8.9	.098	.065
Cu-Ni (70-30)	8.94	.09	.069
Cu-Ni (80-20)	8.94	.09	.087

TABLE III -- ESTIMATED STEADY-STATE TRANSIT TIMES
FOR VARIOUS PARTS OF THE TEST APPARATUS

$$\tau = K \frac{\rho}{m}$$

Component	K $\left(\frac{\text{cu ft/sec}}{\text{hr}} \right)$
From storage tank to outlet riser	39,200
Outlet connector	4,350
Dummy sections	790
Connections from dummy to active zone	880
Active zone	1,180
Inlet connector to butterfly valve (or inlet riser)	3,090

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Figure 1. Schematic of Transient Test Apparatus

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FIGURE 2. Comparison of power distribution in electrically heated model with cosine distribution in reactor fuel column.

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FIGURE 3: Schematic diagram -- electrically heated model of downstream half of N-Reactor fuel column.

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Figure 4. Active Section Dimensions and Thermocouple Locations.

Figure 5. Comparison of the Actual and Programmed Relative Power Decay.

Time from Start of Test, seconds

Figure 6. System Pressures for Runs 1 and 3.

Time from Start of Test, seconds
Figure 7. System Pressures for Run 2.

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Time from Start of Test, seconds
Figure 8. System Pressures for Run 4.

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Time from Start of Test, seconds
Figure 9. System Pressures for Run 5.

Figure 10. System Pressures for Run 6.

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Figure 11. Active Section Temperatures for Run 4.

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Time from Start of Test, seconds

Figure 12a. Active Section Temperatures for Run 5.

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Figure 12b. Active Section Temperatures for Run 5.

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Time from Start of Test, seconds

Figure 13. Active Section Temperatures for Run 6.

Time from Start of Test, seconds

Figure 14. System Water Temperatures for Runs 3 and 4.

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Figure 15. System Water Temperatures for Runs 5 and 6.

Figure 16. Blowdown Flow Rates for Runs 1 and 3.

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Time from Start of Test, seconds

Figure 17. Blowdown Flow Rates for Run 2.

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Time from Start of Test, seconds

Figure 18. Blowdown Flow Rates for Run 4.

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Figure 19. Blowdown Flow Rates for Run 6.

Figure 20. Inlet Connector Venturi Pressure Drop for Runs 1 and 2.

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Figure 21. Inlet Connector Venturi Pressure Drop for Runs 3 and 4.

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Figure 22. Inlet Connector Venturi Pressure Drop for Runs 5 and 6.

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Figure 23. Test Section Voltage for Run 4.

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