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TITLE

RESULTS OF TRANSIENT AND STEADY STATE EXPERIMENTS INVESTIGATING HAZARDS OF FLOW REDUCTIONS IN A K PROCESS TUBE

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RESULTS OF TRANSIENT AND STEADY STATE EXPERIMENTS INVESTIGATING HAZARDS OF FLOW REDUCTIONS IN A K PROCESS TUBE

by

G. M. Hesson and W. L. Thorne

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PURPOSE

The purpose of this report is to present the results of transient and steady state heat transfer experiments investigating the degree of protection offered by the Panellit pressure gage system to hazards arising from coolant flow reductions to a K process tube.

INTRODUCTION

The high temperatures within a process tube resulting from an accidental reduction in the flow of coolant are of utmost importance in regard to reactor safety. Events which might cause a flow reduction are varied, and while the probability of such events occurring is generally small, the consequences of not detecting a severe flow reduction can be serious. Excessive temperatures in the fuel elements can result if the flow reduction is sufficient to lead to boiling burnout¹, either immediately or through an intermediate period of unstable flow.²

In the years past, heat transfer experimentation has been directed toward defining process tube flows, temperatures, and pressures under steady-state conditions. This necessarily confined the experimentation to the stable flow regions. The Panellit protection systems, therefore, were set to insure, insofar as possible, a Panellit trip within the stable flow region. However, the behavior of the process tube variables after a sudden flow reduction or in the unstable flow region are transient in nature; that is, they vary with time. The exact values and time sequence of these process variables can only be determined by transient experimentation. Transient heat transfer experimentation on a large scale is quite difficult and has only recently been attempted. Knowledge of the time sequence of these variables is needed, however, to determine when a Panellit trip would be secured and the degree of temperature increases between the time of the trip and the time of effective reactor power decrease.

A realistic appraisal, then, of the limitations and capabilities of the Panellit gage protection system to guard against the hazards of flow reductions requires 1) knowledge of the steady-state behavior of the process tube variables extended sufficiently to define the severity of flow reduction the tube can sustain without resulting in burnout and 2) a knowledge of the sequence of events in a process tube in cases of flow reductions sufficiently severe that burnout could result.

This report is concerned with 1) steady-state experiments defining the region of safe non-burnout flows, and 2) transient experiments determining the behavior of the process tube variables for flow reductions outside the safe region for tubes of K reactor geometry. Experiments for other reactors will be presented elsewhere. The program was carried out by the Thermal Hydraulics Operation of the Hanford Laboratories Operation.

1. Boiling burnout is defined as the point where the heat transfer mechanism changes from nucleate to film boiling. The corresponding large increase in the resistance to heat flow may raise the temperature of the heated material above its melting point.
2. Unstable flow is defined as the flow at which the pressure available at the tube inlet to cause the given flow rate is less than the pressure required to cause the same flow rate through the tube and rear fittings.

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SUMMARY

An experimental assembly utilizing electrical heating of a metal rod was used to simulate nuclear heating of a 32 slug train of standard solid slugs in K geometry. This system was used to: 1) determine the steady-state relationship between the process variables (flow, temperatures, and pressures) for flows ranging from normal down to flows, in some cases, insufficient to prevent damage to the assembly, 2) determine the transient response of the process variables following the insertion of a sudden plug upstream of the Panellit tap sufficient to reduce the flow to as little as 20 per cent of the initial flow, and 3) determine the transient response of the process variables in those cases where unstable flow could be started by a gradual reduction of flow.

Steady-state determinations were made with an inlet temperature of about 25°C, 25 psig rear header pressure and at tube powers of 500, 1000 and 1250 KW. Test results are presented in Table II (page 11) and in Figures 3 and 4.

The transient tests were made at the same conditions as were the steady-state tests and at a controlled front header pressure of 350 psig. A synopsis of these runs is presented in Tables III and IV. Test results are given in Figures 6 through 31.

CONCLUSIONS

1. Experimental data indicated that the Panellit system is capable of initiating a reactor shutdown in time to prevent fuel element melting even though the flow were suddenly reduced to a point below where boiling burnout would eventually occur. This was demonstrated for tube powers as high as 1250 KW, initial outlet water temperatures as high as 125°C and flow reductions to a value of 80 per cent of normal.
 2. A characteristic of the K reactor geometry is the lack of high pressures within the process tube after boiling is initiated following a decrease in flow. This behavior is significantly different from that experienced in a BDF type process tube. As a consequence, the Panellit low trip must be entirely reliable in case of a plugging event upstream of the Panellit tap in a K process tube.
 3. It was found possible to operate the experimental apparatus under steady state conditions at flow rates associated with physical burnout of the experimental heater rod without encountering unstable flow conditions. This then defines the burnout conditions for K tubes over a wide range of tube powers.
 4. In the event of a flow reduction in tubes at powers below approximately 1000 KW, the data make evident that unstable flow will never exist.
 5. In the event of a slow gradual plug upstream of the Panellit tap in a tube operating at low tube powers, such as might be associated with fringe tubes, the data show that unstable flow will not exist and the pressurization is insufficient to make a high Panellit trip probable. A low Panellit trip is imperative in such cases.³
-
3. This discussion in this document assumed that slow plugging occurrences both upstream and downstream of the Panellit tap are possible. Slow plugs downstream of the Panellit tap can and do occur from incidents such as ruptured slugs. It may be questionable, however, if slow plugging upstream of the Panellit tap would occur.

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6. The Panellit pressure can be calculated in the event of a slow gradual plug upstream of the Panellit tap for all stages of the flow reduction to burnout flow and the appropriate Panellit trips determined.
7. The theoretical minimum Panellit pressure can be calculated in the event of a sudden plug upstream of the Panellit tap. However, a discrepancy was found between the calculated and experimental minimum Panellit pressures ranging up to 35 psig at large flow reductions.
8. The experimental program encompassed plugs upstream of the Panellit tap only. In the event of a plug downstream of the Panellit tap, however, either sudden or gradual, the Panellit pressure rise can be calculated for each stage of the flow reduction up to the burnout flow, and the appropriate high Panellit trip pressures determined.
9. The experimental assembly is probably a conservative representation of a reactor process tube.
10. The above conclusions lead to the summary conclusion that the present Panellit procedure at K is unduly conservative; however, this is true only if it can be assumed that a flow reduction due to slow plugging upstream of the Panellit tap will not occur.

EXPERIMENTAL APPARATUS

The tests were performed in the 189-D Thermal Hydraulics Laboratory. A diagram of the equipment is presented in Figure 1. The equipment consists of a mockup of a reactor process tube containing an electrically heated rod simulating a uranium slug column, a nominal 1125 KW dc generator to provide the electrical power for the heater rod, a water recirculation system to provide the coolant water flow, and instrumentation to measure the process variables.

The coolant water system includes a valve to control the rear header pressure, a condenser to cool the heated water, and the piping leading to the test section. The piping leading to the test section consists essentially of several feet of two-inch and one-inch pipe containing three valves, a venturi and a flow meter. The venturi was of standard K design. The valve immediately upstream of the venturi was used to simulate upstream plugs. The valve immediately downstream of the venturi was used to adjust the venturi pressure.

The test section is a reasonably accurate mockup of a K process tube downstream of the front Van Stone flange. It is made up of a K process tube discharging to rear face components of standard design. The tube is divided into an active section containing the heater rod and an offset section containing a standard dummy slug loading. The offset is necessary to permit the electrical connections to be made to the heater rod. The active and dummy sections are connected with approximately 2 1/2 feet of one-inch IPS pipe which introduces only a small increment of additional pressure drop. The active test section is 23 1/2 feet long. The inside of the process tube is coated with a 0.005 inch layer of varnish (Heresite) to provide electrical insulation. The heater rod diameter is 1.430 inches, 0.010 inches less than that of standard slugs in order to compensate for the Heresite lining in the tube.

Two heater rod types with slightly different designs were used. They were made up of sections of copper, brass and copper-nickel alloys welded together. The sections are bored out axially to various internal diameters to reduce their cross-sectional

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area. The variations in electrical resistance effected by the variations in materials and cross-sectional areas results in a stepwise variation in heat generation along the length of the rod approximating the chopped cosine heat generation in a reactor process tube. The details of the construction of the rods and the forms of their heat generation are shown in Figures 2 and 3. Where feasible, rod materials are chosen to create an assembly with thermal properties similar to those of uranium so the transient temperature responses of the electrically heated rod will generally resemble those of uranium slugs. Since recourse was made to drilling central holes to regulate heat output, and since various rod materials were used, the thermal responses of the rod vary from point to point and are not in all respects the same as those expected from uranium. The thermal properties of the rod materials are given below in Table I.

TABLE I
THERMAL PROPERTIES OF ROD MATERIALS

	Uranium	Brass	Copper-Nickel		Copper
			70-30	85-15	
Thermal Conductivity, B/hr-°F-ft	17	69	20	30	223
Density lb/cu ft	1154	529	558	558	558
Heat Capacity, B/lb-°F	0.028	0.09	0.09	0.09	0.092
Thermal Diffusivity sq ft/hr	0.525	1.45	0.40	0.60	4.20

The rod surface temperature was monitored with a thermocouple located 5.3 feet from the downstream end of the heated section. This location had been determined in previous tests to be approximately the point of maximum temperature. The thermocouple installation is such that it measures the rod temperature slightly below the surface, and therefore, indicates temperatures somewhat higher but proportional to the true surface temperature. Six zinc and six silver solder fusible plugs were imbedded in the surface of the rod to give additional indications of overheating. These plugs were examined after the conclusion of the transient experiments and were found intact. Additional but indirect indications of heater rod surface temperatures are available from behavior of the Heresite coating on the inside of the process tube. From experience, it has been determined that Heresite loses its electrical insulating characteristics when tube "surface" temperatures much in excess of 400°C are reached. This breakdown causes short circuits generally resulting in local melting of the process tube, loss of pressure, and termination of the experiment. Lack of short circuits during all the transient tests reported herein is additional evidence that temperatures within the process tube did not reach levels which could properly be associated with gross damage to the reactor.

EXPERIMENTAL METHOD

Steady-State Experiments

The steady-state characteristics of the process variables were determined for a given constant tube power by throttling the flow to the tube with a valve upstream of the Panellit tap. After steady-state conditions were reached for each flow adjustment, measurements were made of the flow, tube inlet pressure and other variables.

The tests were continued to the minimum flows possible. In the cases of the lowest and highest tube power investigated (500 and 1250 KW) the runs were terminated by a physical failure of the heater rod due to high rod temperatures. The other two runs were terminated at flows deduced to be near the point of rod failure.

Sudden Plugging Experiments

Process tube flow stream plugging was simulated in the following manner: Initial conditions were established and the system allowed to reach steady state. Even though a variety of initial flows were used the valves on either side of the venturi were so adjusted that the venturi throat, i.e. Panellit tap, pressure was approximately 180 psig. The tube flow was then suddenly reduced by rapidly partially closing the valve upstream of the venturi. The degree of closure was fixed by a pre-set stop on the valve. Flow, front header pressure, Panellit tap pressure, tube inlet pressure, tube outlet pressure, rear header pressure, tube outlet temperature, heater rod surface temperature and power input were monitored by individual high speed recording instruments. Each run was continued at full power for a period of three to six seconds, after which a power decrease was initiated. The power to the heater rod during the power decrease was controlled by a cam to simulate neutron flux decay arising from the insertion of approximately 1000 inhours of poison.

Slow Plugging Experiments

A slow plugging of the process tube flow stream was accomplished in the following manner: Initial conditions at incipient unstable flow were established and the system allowed to reach steady state. Since the unstable flow point is difficult to establish exactly, conditions which gave an outlet water temperature of approximately 150°C were arbitrarily chosen as the initial point. The venturi throat, i.e. Panellit tap, pressure was adjusted to approximately 180 psig at normal flow conditions at the start of each run. When steady state was reached unstable flow was initiated by a step increase in power. The use of a power increase rather than a flow decrease to start unstable flow was done for two reasons; 1) the power increase offers a positive and reproducible means of initiating unstable flow and 2) the power increase resembles the power increase experienced by a reactor process tube as the water is replaced by steam. Flow, front header pressure, Panellit tap pressure, tube inlet pressure, tube outlet pressure, rear header pressure, tube outlet temperature, heater rod surface temperature and power input were monitored by high speed recording instruments. Each run was continued at full power until it appeared that the heater rod temperature would exceed 400°C, after which a power decrease was initiated. The power to the heater rod during the power decrease was controlled by a cam to simulate neutron flux decay arising from the insertion of approximately 1000 inhours of poison.

THEORY

Steady State

The theory of the steady-state behavior of a reactor process tube coolant flow has been well developed (1)⁴. The relationships between the process variables can be quantitatively predicted for conditions up to boiling within the tube (2).

4. Number in parenthesis refer to entries in the bibliography.

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A brief summary of the theoretical behavior is as follows: For a condition of constant tube power, a flow reduction from normal flows results in a decrease in the pressure required to maintain flow through the tube; i.e., tube inlet pressure. Obviously the flow reduction is accompanied with an increase in outlet water temperature. Further flow reductions result in further tube inlet pressure decreases along the non-boiling required pressure curve until boiling starts at the end of the tube assembly. The two-phase flow resistance accompanying boiling results in the requirement of a higher tube inlet pressure and further flow reductions cause an increase in the required tube inlet pressure. This continues until the flow is reduced to a point where, even with extremely high steam qualities, the flow is so small that still further flow reductions result in decreasing required tube inlet pressures. During the period of boiling in the tube the water temperatures are determined by the saturation temperatures. The heat transfer characteristics are good and the slug surface temperature remains only a few degrees above the water temperature until the boiling becomes so vigorous that the transition from nucleate boiling to film boiling occurs. The poor heat transfer accompanying film boiling results in radical increases in slug surface temperatures, to the point where slug melting may occur.

This steady-state behavior can be demonstrated experimentally down to reduced flows limited by either 1) physical burnout of the test equipment, or 2) start of unstable flow, which occurs when the increasing tube inlet pressures raises above the pressure supplied to the tube inlet.

It may be pointed out that a K reactor process tube has relatively large rear fittings and a relatively large annulus. Consequently, it does not experience large increases in required tube inlet pressure as would, for example, a BDF tube. This gives rise to two important differences between K and BDF reactor steady-state behavior, namely: 1) the start of unstable flow requires much more extreme conditions in K reactors; i.e., lower flows and higher tube powers, and 2) the lower pressures in K tubes promotes a higher degree of boiling and the onset of film boiling at less extreme conditions.

Sudden Plug

A quantitative prediction of a tube behavior following a sudden flow reduction cannot be made. However, in the report concerning sudden plugs in a BDF process tube (3) a qualitative description of the sequence of events was developed, involving four successive steps. These four steps also apply to K reactor process tubes. The magnitude of the changes in the process variables, both absolutely and with respect to one another, will be different. The difference arises from the lack of pressurization in the K tube as compared with a BDF tube. The four steps are described below:

Step 1) describes the tube behavior immediately after the flow reduction. The behavior is dependent upon the water temperature and will take either of the following two courses:

A) If the water temperature is equal to or below the saturation temperature in the tube at pressures existing following the flow reduction, the tube inlet pressure will drop to that corresponding to passage of liquid water at the reduced flow. The pressure will remain constant at this value until the water temperature increases to the saturation temperature somewhere in the system. The temperature rise is relatively rapid. The time spent at this constant pressure point is decreased by higher initial water temperatures, higher tube powers, and greater degrees of plugging.

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B) If the water temperature is above the saturation temperature in the tube at pressures which would exist corresponding to passage of liquid water through the tube, the tube inlet pressure will drop to a value which is determined by the saturation pressure. The pressure will be higher than that corresponding to passage of liquid water at the reduced flow.

Step 2) describes that period of the transient tube behavior when steam formation is occurring downstream of the active section of the tube. K reactor process tubes have relatively little restriction to flow in the rear fittings and dummy section and boiling progresses up through these regions quite rapidly. This period is therefore brief and does not much affect the course of the transient.

Step 3) describes that period of the transient tube behavior when nucleate boiling is occurring in the active section of the tube. A large share of the heat going into the water is used to form steam rather than raise the sensible heat of the water, and the rate of water temperature rise is not rapid. Furthermore, since the tube pressures and water temperatures are related by saturation conditions and since the K reactor process tubes do not experience large two-phase pressure drops, neither the rate nor magnitude of pressure and temperature increases are large. The rate of progress of the transient is increased by higher tube powers and greater flow reduction. The flow decrease and pressure increase are related by the tube supply curve. Since the tube boiling curve represents an equilibrium condition, the relationship between the supply curve and the boiling curve affects the rate of progress of the transient.

Step 4) describes that period of the transient tube behavior following the onset of film boiling in the active section of the tube. Here the poor heat transfer accompanying film boiling results in still slower rates of temperature and pressure rise. Of prime importance, the poor heat transfer causes a greatly accelerated rate of slug surface temperature rise. The lack of pressurization in K reactor process tubes promotes an early onset of film boiling. The start of film boiling is earlier and the rate of surface temperature rise is increased by higher tube powers and greater flow reductions.

In summary, the important characteristics of the behavior of a K reactor tube which has experienced a sudden flow reduction of a magnitude which would result in burnout arise from the lack of pressurization of the K tubes with high water temperatures.

Slow Plugs

In the report concerned with slow plugging events in a BDF process tube (4) it was pointed out that a discussion of what takes place in a process tube during such an occurrence must be split into two parts covering 1) that period within the stable flow region, and 2) that period within the unstable flow region.

In the stable flow region the concepts developed for the steady-state behavior apply in their entirety. That is, in the event of a slow gradual plugging incident, the relationships between the process variables will at all times be very near to their steady-state values. The steady-state data then describes the course of the behavior of a slow plugging occurrence in the stable flow region.

The behavior of process tube variables in the unstable flow region in a K reactor tube is of interest only at tube powers above about 1000 KW and then only after severe flow reductions. For purposes of this report it is sufficient to say that at high tube powers boiling starts at relatively high flows. In these cases the two-phase pressure drops are relatively large and the required tube inlet pressure is increased

to a value higher than the pressure supplied. The flow then suffers a further self-induced reduction due to this disparity between supplied and required pressure. The flow decrease is accompanied by an increase in supplied pressure. If it were allowed to continue the flow and pressure would reach a new steady-state condition at very low flows, provided burnout conditions were not reached during the course of the transition.

EXPERIMENTAL RESULTS

Steady State

Steady-state determinations were made at tube powers of 500, 750, 1000 and 1250 KW. The data is summarized in Figure 4 which is a plot of the tube inlet pressure against the flow. These are familiar boiling curves.

These data show the extension of the boiling curves to sufficiently low flow rates to permit an estimation of the burnout region. Two of the runs, at the highest and lowest tube powers investigated, were terminated by failure of the heater rod due to overheating. The other two runs were terminated at flows deduced to be near to burnout. Figure 4 includes a line estimating the demarcation between the burnout and non-burnout regions of the experimental apparatus.

It may be pointed out that the experimentally determined burnout points were at perfectly stable operating points at the 950 psig front header pressure used in these tests. Of importance is the fact that operation at these points was maintained for approximately ten minutes before failure of the heater rod occurred.

Sudden Plugs

Sudden plugging runs were made at tube powers of from 500 to 1250 KW, initial water temperatures of 100 to 125°C and plugs to effect flow reductions from 20 to 85 per cent. A synopsis of the runs is presented in Table III which gives the test conditions, initial conditions and flow reductions for each run. The experimental data are presented in Figures 6 through 28. Each figure is split into two parts, a Part A showing water outlet temperature, heater rod surface temperature and flow rate, and a Part B showing the tube inlet pressure and venturi throat pressure. All are plotted against time from the start of the flow reduction. The heater rod temperature was measured 5.3 feet from the downstream end of the active section. The water temperature was measured at the end of the active section.

These data show, in general, conformance to the behavior predicted by qualitative theory. In particular, the data all show an initial pressure drop upon insertion of the plug followed by a pressure rise as steam formation starts. The pressure rise is, however, neither rapid nor large. Interrelated with the lack of large pressure increases is the lack of large water temperature increases. The data also show an early start of film boiling as evidenced by a sharp increase in the rod surface temperature.

Slow Plugs

Three slow plug runs were made at tube powers of 750 and 1000 KW. The data are shown in Figures 29 through 31, and are presented in the same manner as were the data for the sudden plug runs. A synopsis of the runs is given in Table IV.

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The very paucity of the data illustrate the primary characteristics of the slow plug characteristics. That is, it is only under a limited range of high tube powers that a slow plugging condition will lead to unstable flow.

REACTOR APPLICATION

The physical differences and the differences in the relationships of process variables arising from the physical differences between a BDF and a K process tube have been pointed out earlier in this report. The differences in the relationships of the process variables, in turn, give rise to two significant differences in the concepts relative to the protection of the reactor against the hazards resulting from accidental flow reductions. These are: 1) an experimental burnout point can be determined and the steady-state behavior of the process variables experimentally determined up to this point and 2) the range of conditions for which a Panellit high trip is feasible to guard against plugs upstream of the Panellit tap is severely limited. Within the framework of these two concepts the steady-state and burnout data define the region of flow reductions which might lead to melting of the slugs; and, furthermore, permit the determination of the appropriate Panellit trips to shut down the reactor in the event of such flow reduction.

The steady-state data have been reported previously (5). The data is included in this report also, in a more fully developed form.

To illustrate the use of the steady-state data to determine potentially dangerous flow reductions and to determine the appropriate protective Panellit trips, the steady-state boiling curves are re-plotted in Figure 5. The steady-state flow and tube inlet pressure are normalized (6) to a pressure of 180 psig at an outlet temperature of 125°C and the data are plotted as Panellit pressure versus the square of the flow relative to that at an outlet temperature of 125°C. The experimentally determined burnout points are used to estimate a line of demarcation between burnout and non-burnout regions. This line is also shown in Figure 5, giving estimated burnout points at flows at B', B'', B''' and B'''' for the various tube powers.

Sudden plugs upstream of the Panellit tap just large enough to lead to burnout will result in an initial flow and pressure drops to points A', A'', A''' and A'''' for the various tube powers. The flow will then undergo a further self-induced reduction coincident with a pressure increase along lines AO until burnout is reached at points B. The pressures at points A are the minimum Panellit pressures reached following the plug. Since use of a high Panellit trip to protect against sudden severe plugs upstream of the Panellit tap was not demonstrated, the pressures at points A represent the Panellit pressure before which a Panellit low trip must be secured.

Slow gradual plugs upstream of the Panellit tap result in Panellit pressure following the normalized curves of Figure 5. Since this identifies the Panellit pressure completely for flow reductions to burnout, appropriate Panellit trip pressures can be determined. It may be noted that the increase in Panellit pressure at low flows is insufficient to make a high Panellit trip feasible at the lower tube powers.

Plugs downstream of the Panellit tap, either sudden or gradual result in flow decreases and Panellit pressure increases along line NO. Since points B identify burnout flows the appropriate Panellit high trips can be determined.

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In this analysis and in Figure 5, the burnout flow reductions, points A and B are defined in terms of relative flows. They can be calculated in terms of absolute flows. These absolute flows together with other information concerning burnout conditions are presented in Table II below.

TABLE IIBURNOUT CONDITIONS IN A K REACTOR PROCESS TUBE

Tube Power KE	Burnout Flow, ^(a) GPM	Sudden Plug Burnout Flow, ^(b) GPM	Water Outlet Temp at Last Experimental Point ^(c) , °F	Steam Quality at Last Experimental Point, ^(d) Wt. %
500	4.4	5.8	332	33.7
750	9.0	15.5	363	31.4
1000	13.6	29.5	380	14.3
1250	15.8	38.2	398	24.3

Notes

- a) Points B on Figure 5
- b) Points A on Figure 5
- c) The last experimental point for 500 and 1250 KW was at burnout flow. The last experimental point for 750 and 1000 KW was greater than but near burnout flow. The temperatures were measured at the end of the heated section.
- d) Steam quality calculated at the end of the heated section, assuming zero slip.

The fact that the feasibility of a high Panellit trip in event of a sudden plug upstream of the Panellit tap was not demonstrated in this program has been emphasized several times in this report. This behavior is in direct contradiction to that of a BDF tube. For the BDF tube it was found that for a wide range of conditions encompassing moderate to severe upstream plugs a high Panellit trip was probable, for a range of conditions encompassing severe to very severe plugs a low Panellit trip was probable, and that these ranges overlapped by a wide margin. Undoubtedly, the same mechanisms apply to K tubes but over a very narrow range of conditions. For example, at 1250 KW and a sudden plug upstream of the Panellit tap just sufficient to lead to burnout, a high trip is feasible. This is probably true for plugs somewhat greater than this. However, the range of tube powers and flow reductions for which a high trip is probable is so limited, its use is not practical nor was it defined in these experiments.

The steady-state data do not answer two questions concerning the protection offered against sudden plugs, namely: 1) if there is a delay between the time of the actuation of the trip and the time of effective power reduction, does the slug surface temperature rise excessively and 2) does the minimum Panellit pressure incurred in event of the plug occurring upstream of the Panellit tap reach as low a value as the calculated value.

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The sudden plugging experiments give evidence bearing on these questions. The plots of rod surface temperatures, Figures 6 through 28 show that with a two-second delay between trip time and time of power reduction the rod surface temperature does not exceed 250°C , up to conditions of an 80 per cent flow reduction applied to a tube operating at 1250 KW and an outlet water temperature of 125°C .

Evidence concerning the agreement between the experimental and calculated minimum pressures occurring following a sudden plug upstream of the Panellit tap is presented in Table III. This table includes a column giving the flow immediately following the insertion of the plug as a percentage of the flow just leading to burnout. It also includes two columns giving the calculated minimum Panellit pressure and the experimental minimum Panellit pressure.

Only fair agreement is shown. The largest deviations tend to occur following large flow reductions, which are accompanied with large initial Panellit pressure drops. In the range of flow reductions to give flows 80 to 100 per cent of those just leading to burnout, the agreement is somewhat better, in the order of ± 10 psig. In general, the discrepancies tend toward the experimental minimum pressures being greater than those calculated. A possible reason for this may be due to steam formation resulting from the low pressures in the tube following the flow reduction. This is the type of behavior outlined in Step 1B of the expected behavior of a tube following a sudden flow reduction (see page 8).

It may be noted, parenthetically, that in the event of a sudden plug upstream of the Panellit tap that the data in Figures 6 through 28 show that the Panellit pressure increase following the initial decrease is not particularly rapid. This means that the Panellit response time is less critical than it is in the BDF reactors.

Of concern in the application of these data to reactor use are questions concerning whether the experimental apparatus and its behavior constitute an accurate simulation of a reactor tube and its behavior. In other reports (3,4) concerning tests of the BDF geometry this question was examined and the conclusion made that the experimental apparatus was a reasonable and probably conservative representation of a reactor tube. These same conclusions apply to the present tests concerning the K reactor, with two exceptions. These are: 1) the active heated section is 23.5 feet long, compared with an active heated section in the reactor of 28.5 feet and 2) the mechanism of the burnout. These will be discussed below.

The shorter active section of the experimental apparatus results in:

- 1) a higher specific power
- 2) a lower pressure drop across the tube and a lower tube inlet pressure in the non-boiling region.
- 3) In the boiling region the pressure drop across the tube and the tube inlet pressure for the experimental apparatus are about equivalent to those of the reactor. This is difficult to determine but the argument is this; the shorter tube results in a lower pressure drop, however, the lower pressures incurred in the shorter tube result in a higher steam volume quality giving an increased pressure drop. There then exists two compensating factors, and the tube inlet pressures for the experimental apparatus and a reactor tube should be comparable.

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The normalizing technique absorbs the lower pressure drop and the normalized experimental curves should be equivalent to those of a reactor tube in the liquid region. The higher specific powers of the experimental apparatus aggravate the local boiling effects and the minimum point of the experimental boiling and normalized curves may be higher than those of a K reactor tube. If conclusion 3) above is valid, the pressures of the normalized curves in the boiling region will be about the same or somewhat above those of a K reactor tube. Since the burnout region was defined on the normalized curves the definition is a reasonable and possibly conservative one.

The experimental burnout was a physical failure of the rod. The failure was not the result of melting of the rod but was a cracking across the top half of the rod at a thermocouple well due to thermal stress. At 500 KW the run was terminated with the cracking of the rod. At 1250 KW the smaller cross-sectional area which remained after the cracking resulted in a higher electrical resistance thereby causing higher temperatures and a melting of the lower half of the rod. In neither case was there evidence of melting of the rod in the region of the crack, although in both cases the silver solder of the thermocouple well did melt. In neither case was there failure of the Heresite lining of the process tube.

It is difficult to relate this experimental burnout to what might happen in a reactor. The cracking experienced is unique to the long rod of various materials and cross sections. The lack of failure of the Heresite lining of the tube indicates that neither excessively high temperatures were reached nor were there high temperatures of long duration. However, the thermal gradient across the rod causing the failure was undoubtedly due to film boiling with stratification of the steam at the top of the rod. The experimental failure, therefore, is a reasonable and probably conservative representation of burnout in a reactor.

Limitation of results in this report

The results are limited to:

- K geometry process tubes

- Solid fuel elements

- Constant front header pressure of 350 psig (Higher front header pressures make these results conservative.)

- Rear header pressure of 25 psig (A range of rear header pressures of operational interest probably will affect these conclusions only slightly).

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TABLE III

SUMMARY OF SUDDEN PLUG TEST PROGRAM

Run No.	Q KW	F _i GPM	F _p GPM	F.R. %	F _p /F _b %	Toi °C	Minimum Panellit Pressure Psig		Figure
							Experimental	Calculated	
114	500	26.5	4.5	83	79	98	47	30	6
117	750	30.5	12.0	61	82	98	61	48	7
121	1000	44.7	16.6	63	58	104	63	48	8
124	1125	39.9	32.7	18	98	124	131	137	9
125	1125	40.0	25.2	37	75	124	100	91	10
129	1250	51.3	33.5	27	88	125	100	86	11
134	1000	35.4	19.6	16	69	126	95	72	12
135	1000	35.5	15.2	57	53	126	76	53	13
138	750	25.7	10.5	59	72	122	75	52	14
140	500	16.5	5.2	68	91	125	60	58	15
141	500	16.6	3.3	80	58	124	55	89	16
142	1250	48.8	30.0	39	79	127	104	84	17
143	1250	48.8	24.0	51	63	125	89	62	18
144	1250	48.8	20.8	57	55	126	97	52	19
145	1250	48.7	9.5	81	25	125	70	36	20
146	1000	37.5	22.2	41	78	122	98	79	21
147	1000	37.7	20.5	46	72	120	95	71	22
148	1000	37.5	14.0	63	49	123	74	47	23
149	1000	37.5	6.6	82	23	122	60	73	24
150	750	25.8	8.7	66	60	127	75	42	25
151	750	26.0	8.2	68	56	125	63	40	26
152	750	26.4	8.5	68	58	123	60	40	27
153	750	27.2	3.7	86	25	123	55	28	28

Front header pressure = 350 psig

Rear header pressure = 25 psig

Inlet water temperature $\approx$ 25°CNomenclature

F	Flow, gallons per minute
F _i	Initial flow to process tube, gallons per minute
F _p	Throttled flow resulting from an upstream plug, gallons per minute
F _b	Throttled flow resulting from an upstream plug just large enough to lead to burnout, gallons per minute. Are points A on Figure 5.
F.R.	Flow reduction, per cent
P _{FH}	Front header pressure, lbs per sq in, gage
P _{PAN}	Panellit pressure, lbs per sq in, gage
P _{RH}	Rear header pressure, lbs per sq in, gage
P _{ti}	Tube inlet pressure, lbs per sq in, gage
Q	Test section power, kilowatts
To	Outlet water temperature, °C
Toi	Initial outlet water temperature, °C
Ts	Rod surface temperature, °C

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TABLE IV

SUMMARY OF SLOW PLUG TEST PROGRAM

<u>Run No.</u>	<u>F1 GPM</u>	<u>Q1 KW</u>	<u>Qf KW</u>	<u>ΔQ %</u>	<u>Toi °C</u>	<u>Figure No.</u>
71	34.5	1060	1270	19.8	153	29
87	25.7	750	1000	33.3	142	30
92	32.8	1020	1200	15	150	31

Front header pressure = 350 psig
Rear header pressure = 25 psig
Inlet water temperature $\approx 25^{\circ}\text{C}$

Nomenclature

F Flow, GPM
F1 Initial flow at start of run, GPM
Pfh Front header pressure, psig
Ppan Panellit pressure, psig
Prh Rear header pressure, psig
Pti Tube inlet pressure, psig
Q Test section tube power, KW
Q1 Initial tube power at start of run, KW
Qf Final or increased tube power, KW
To Outlet water temperature, °C
Toi Outlet water temperature at start of run, °C
Ts Rod surface temperature, °C
 ΔQ Per cent increase in tube power.

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FULL SCALE MOCK UP
PRESSURE & TEMPERATURE
LOCATION

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REAR NOZZLE DETAIL

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SECTION	ID"	MATERIAL
A	1/4	99Cu-1Pb
B	1/4	85Cu-15Ni
C	0.80	85Cu-15Ni
D	1/4	70Cu-30Ni
E	15/32	
F	1/2	
G	17/32	
H	1/2	
I	15/32	
J	1/4	70Cu-30Ni
K	0.80	85Cu-15Ni
L	1/4	85Cu-15Ni
M	1/4	YELLOW BRASS
N	1/4	99Cu-1Pb

ROD DESIGN CONDITIONS:

1. TEMP. ~ 400 °C
2. VOLTS ~ 52
3. AMPS ~ 24,600
4. POWER ~ 1280 KW
5. DESIGN NO. 9
MODIFICATION 1
SK-1-2584

FIGURE 2

HEATER ROD ASSEMBLY
AND HEAT GENERATION CHARACTERISTICS

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FIGURE 3
HEATER ROD ASSEMBLY AND
HEAT GENERATION CHARACTERISTICS

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FIGURE 4. EXPERIMENTAL BOILING CURVES

FLOW, GPM

TUBE INLET PRESSURE, PSIG

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FIGURE 5.

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Figure 6A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 6 B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 7A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 7B
 PRESSURE RESPONSES IN A K PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 8A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 8B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 9A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 9B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 10A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 10B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 11A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure //B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 12A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 12B
PRESSURE RESPONSES IN A ∇ PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 13A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 13B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 14A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 14B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TEST DATA		LEGEND	
Q	500 KW	F	— · —
F_i	16.5	T_o	— — —
F_f	5.2	T_s	· · ·
P_{FH}	350	SCRAM	↓
P_{RH}	25		

Figure 15A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 15 B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TIME - SECONDS

Figure 16A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION.

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Figure 16B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 17A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 17B
 PRESSURE RESPONSES IN A K PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

TEST DATA		LEGEND	
Q	1350	F	— — —
F _i	48.8	T _o	— — —
F _f	18.0	T _s	- - - -
P _{FH}	350	SCRAM	↓
P _{RH}	25		

Figure 18A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 18B
 PRESSURE-TIME CURVES IN A K PROCESS
 FROM THERMAL - SCRAM TIME INITIATION

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Figure 19A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 20A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 20B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 2 / 4
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 2/B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 22 A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 22 B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 23A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 23 B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TIME - SECONDS

Figure 24A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 24B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TIME - SECONDS

Figure 25 A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 25B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 26A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 26B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 27A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 27B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 28 A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 28B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 29A
FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TIME - SECONDS

Figure 30 A

FLOW AND TEMPERATURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 30 B
PRESSURE RESPONSES IN A K PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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