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TITLE

RESULTS OF EXPERIMENTAL TESTS SIMULATING
SUDDEN PLUGGING OF A BDF PROCESS TUBE

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RESULTS OF EXPERIMENTAL TESTS SIMULATING
SUDDEN PLUGGING OF A BDF PROCESS TUBE

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PURPOSE

The purpose of this report is to present the results of an experimental program investigating the transient response of a BDF process tube to sudden plugging. The program was directed toward determining the degree of protection offered by the Panellit pressure gage system to the hazards arising from such plugs.

INTRODUCTION

The high temperatures within a process tube resulting from an accidental reduction in the flow of coolant are of utmost importance in regards to reactor safety. Events which might cause a flow reduction are varied and, while the mathematical probabilities of such events occurring are generally small, the consequences of not detecting a severe flow reduction can be serious. Even if the flow reduction is detected and the reactor is scrammed, there is a limitation on the severity of the flow reduction which can be sustained before excessive temperatures result in a process tube. The limit is dependent to a large extent on the initial conditions and the time elapse between flow reduction and effective reactor shutdown. This report is one of a series^{1,2,3} reporting transient heat transfer experiments which, for a variety of initial flow conditions, tend to define the limits of flow reduction before excessive temperatures are reached within a process tube and fuel elements. As a consequence of the experiments, it is possible to determine the degree of protection offered by the Panellit pressure gage system to hazards resulting from flow reduction. Knowledge of this protection is most valuable in specifying the power level of a process tube.

The flow, temperatures, and pressures within a process tube after a sudden flow reduction are transient in nature; that is, they vary with time. It is possible to define the exact values and the time sequence of these process variables only by transient experimentation. However, transient heat transfer experimentation on a large scale is quite difficult and only recently has been attempted. For the years previous to these transient experiments the experimentation had been directed toward defining the flow variables under steady state conditions. The Panellit protection procedures used during this time were necessarily confined in their basis to the known steady state region. Since transient experimentation tends to define the exact values of the process variables and their time sequence after a flow reduction, the results of this study should lead to Panellit protection procedures which are more realistic and which need not necessarily require the initiation of a reactor shut down within the stable flow region. Such procedures should permit higher power levels than those determined by steady state experimentation.

The possible flow reductions in a process tube may be divided into two types. First, consideration is given to rapid flow reductions as would occur, for example, if a foreign material suddenly plugged the inlet screen in a process tube. Second,

1. HW-52424 A "Results of Experimental Tests Simulating Sudden Plugging of a BDF Process Tube", J. M. Batch, G. M. Hesson, W. L. Thorne, 9/23/57.
2. HW-52424 B "Results of Experimental Tests Simulating Slow Plugging of a BDF Process Tube", G. M. Hesson, W. L. Thorne.
3. HW-52424 C "Results of Experimental Tests Simulating a Power Excursion to a BDF Process Tube", G. M. Hesson, W. L. Thorne.

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consideration is given to slow flow reduction as would result if a fuel element ruptured or there was a slow accumulation of foreign material on the tube inlet screen. Excessive temperatures in the fuel elements can result by either mode of flow reduction if 1) the flow reduction is sufficient to immediately lead to boiling burnout⁴ or 2) the flow reduction is sufficient to lead to unstable flow⁵ which in turn will eventually lead to boiling burnout. This report deals only with the consequences of rapid flow reductions in a BDF process tube caused by sudden plugs. Other cases and experiments for other reactors will be reported elsewhere. The entire program was carried out by the Thermal Hydraulics Operation of the Hanford Laboratories Operation.

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 BDF geometry. To such a system operating under steady state conditions at 525 psig front header pressure and 25 psig rear header pressure, a sudden partial closing of a throttle valve was applied. Initial steady state conditions were at tube powers of 300 to 1250 KW and outlet water temperatures of 90 to 155°C. The flows immediately following actuation of the flow reduction ranged from 70 to less than 10 per cent of the initial flow. Following insertion of the throttle the tube flow experienced a self-induced further decrease owing to operation in the unstable flow region. The flow, tube inlet pressure, heater rod temperature, and other variables were monitored by high speed recording devices. The runs were continued at full power until it appeared that temperatures would be reached which might be damaging to the test equipment. The tube power was then reduced in accord with a 1000 inhour scram.

Nineteen runs were made with an upstream plug sufficient to cause unstable flow and which did not result in damage to the apparatus. A synopsis of these runs is presented in Table II. Test results are given in Figures 3 through 21.

CONCLUSIONS

The results of this experimental program substantiate and extend the conclusion presented in the preliminary reports (1, 2, 3)*; that is, 1) the results of these transient heat transfer experiments closely simulate an actual reactor response to a sudden flow reduction and 2) the interpretation of these results can allow higher tube power limits than any previous means of determining allowable tube power levels. It is concluded that it is conservative to always require a Panellit trip of the reactor before unstable flow conditions result after a flow reduction caused by a sudden plug. The pressure drop immediately following the plug and the

-
4. 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, in some cases, raise the temperature of the heated material above its melting point.
 5. 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.

* Numbers in parenthesis refer to entries in the bibliography.

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pressure rise following the start of steam formation are sufficient that a safe Panellit trip would be secured even though the Panellit system requirements were such that the trip may not occur until after unstable flow has started.

Supporting and secondary conclusions are presented below:

1. The temperature increases and the pressure changes following the insertion of a sudden plug in the coolant stream of a BDF tube are not excessively rapid.
2. On initiation of a sudden plug upstream of the Panellit tap, the tube inlet and Panellit pressures first decrease and subsequently rise when steam formation starts in the process tube and fittings.
 - a) For the case of a moderate plug, the initial pressure decrease is not large. This lessens the chance for a low Panellit trip but the subsequent pressure rise is large, both absolute and relative to the heater rod temperature, and a chance for a high Panellit trip is large. An example of this may be seen in Figure 11.
 - b) For the case of a severe plug, the initial pressure decrease is substantial and the chance for a low trip is large. However, the subsequent pressure increase is not large, particularly relative to the heater rod temperature, and the chance for a high trip is lessened. An example of this may be seen in Figure 16.
 - c) For nearly all cases of practical interest the initial pressure decrease and the subsequent pressure increase are sufficient such that there is a good chance for both a high and a low trip. This is unique to the BDF type process tube and is, in effect, double protection.
3. Recently secured steady-state data (7) show that a process tube at low powers can sustain plugs resulting in relatively severe flow reductions without experiencing unstable flow leading to burnout conditions. Even if the reactor were not shut down after such plugging occurrences, operating conditions would be at high outlet water temperatures and perhaps steam formation in the tube, but would not result in immediate nor serious damage to a reactor. When such tubes experienced a sudden plug upstream of the Panellit tap, stable flow conditions would be re-established before a high trip was reached.
4. The large increase of pressures in a process tube following relatively severe flow reductions is due primarily to a phenomenon termed critical flow which occurs in the rear Parker fitting. Since this experimental program used BDF geometry fittings, the data and conclusions are applicable for the most part only to BDF geometry reactors.
5. Those aspects of the experimental assembly which do not exactly simulate reactor tubes are such that application of the results obtained in the experimental tests to reactor use is probably conservative.
6. The degrees of plugging used in these tests probably represent the more extreme cases of what might be expected to occur in a reactor.

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7. The experimental program encompassed insertions of plugs upstream of the Panellit tap only. Calculations can be made from the data, however, to show that in event of a plug downstream of the Panellit tap, a high Panellit trip would be effected as early or earlier than a corresponding upstream plug.
8. It is not possible to define an exact allowable outlet water temperature for reactor operation from these experiments. It must be realized that a tube cannot sustain a complete and permanent flow stoppage under any reasonable power level. Therefore, the maximum power level of a tube should be determined with a knowledge of the flow reduction necessary to cause damage and with a consideration of the probability of ever experiencing an event leading to such a flow reduction. Of importance is that a large number of allowable power level schemes may be developed using the results presented in Figures 3 through 21 together with a knowledge of Panellit trip settings and normal values of Panellit pressures. The maximum value of the limits depends mainly on the boldness of the assumptions relating to the credibility of the severest flow reduction necessary to cause reactor damage.

EXPERIMENTAL EQUIPMENT

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 consists of 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 CG-558 BDF 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 BDF process tube downstream of the front Van Stone flange. It is made up of a BDF process tube discharging to rear face components of standard design. The tube is divided into an active section containing the heater rod and an off-set 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.

The heater rod is made up of sections of copper, brass and copper-nickel alloys welded together. Some of the sections are bored out internally to reduce their cross-sectional 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

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rod and the form of its heat generation are shown in Figure 2. 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 as given below in Table I.

TABLE I
THERMAL PROPERTIES OF ROD MATERIALS

	<u>Uranium</u>	<u>Brass</u>	<u>Copper-Nickel</u>		<u>Copper</u>
			<u>70-30</u>	<u>85-15</u>	
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 5.5 feet from the 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 experiments and were found intact. Additional but indirect indication 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 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

Process tube flow stream plugging was simulated in the following manner: Initial conditions were established and the system allowed to reach steady state. While a variety of initial flows were used, as a matter of operating convenience the valves on either side of the venturi were so adjusted that the venturi throat, i.e. Panellit tap, pressure was approximately 250 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

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continued at full power until it appeared that the temperature of the heater rod surface 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

A quantitative prediction of a tube behavior following a flow reduction cannot be made; but qualitatively the sequence of events would occur in four successive steps, as follows:

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 someplace 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.

- 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.

Saturation conditions in a BDF tube are first reached in the rear Parker fitting, the point of greatest restriction to flow, and results in a phenomenon termed critical flow (8). The end effect of this critical flow is that an increase in water temperature causes an increase in the pressure upstream of the fitting. This tends to suppress boiling in the tube. Eventually, as the transient progresses, boiling starts upstream of the Parker fitting and progresses up through the rear piping and the dummy section.

The rates of temperature and pressure rise and flow decrease through this period are relatively rapid, and are increased by higher tube powers and greater initial flow reductions. 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 affect the rate of progress 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. Step 3) differs from Step 2) primarily in that 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

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temperature increase is less rapid. Since the pressure is an exponential function of the water temperature at saturation conditions and since the flow is related to the pressure by the supply curve characteristics, the rate of pressure rise and flow decrease continue to be rapid. As under Step 2) conditions the rate of progress of the transient is increased by higher tube powers and greater flow reductions and is affected by the relationship between the supply and boiling curves.

Step 4) describes that period of transient tube behavior following the onset of film boiling in the active section of the tube. Here the poor heat transfer resulting from film boiling results in still slower rates of water temperature and pressure rise and flow decrease. Of prime importance, the poor heat transfer resulting from film boiling causes a greatly increased rate of slug surface temperature rise. At tube powers of interest, the slug temperatures would most surely rise to the melting point. The onset of film boiling is earlier and the rate of surface temperature rise is increased by higher tube powers and greater flow reductions.

In summary, important characteristics of unstable flow in BDF tubes are strongly influenced by critical flow in the rear Parker fittings. This results in rapidly increasing pressures in the tube, suppression of the start and degree of boiling, and delaying the onset of film boiling with its attendant rapid slug surface temperature rise.

EXPERIMENTAL RESULTS

Sudden plugging runs were made at tube powers of from 300 to 1250 KW, initial outlet water temperatures of 90 to 155°C and plugs to effect flow reductions of from 30 to greater than 90 per cent. A synopsis of the runs is presented in Table II which gives the test conditions, initial conditions, and flow reductions for each run. The experimental data is presented in Figures 3 through 21. 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 5.5 feet from the downstream end of the active section. The outlet water temperature was measured at the end of the active section.

The data presented in Figures 3 through 21 show, in general, conformance to that predicted by the qualitative theory. Several examples are presented below:

1. Comparison of Figures 8 and 9 illustrates behavior described in Step 1a) on page 7. The effect of a lower initial outlet water temperature for a given plug is to delay the start of the pressure rise. Once the pressure has started to rise, the rates of rise are comparable.
2. Figure 21 illustrates behavior described in Step 1b) on page 7. This run started with an outlet temperature of 155°C, well above the saturation temperature at the liquid flow pressures after the insertion of the plug. The tube inlet pressure drop after insertion of the plug was to 221 psig which may be compared with the 75 psig which would have been attained if the flow remained all liquid.
3. Figure 11 is an excellent illustration of the effect of the relationship of the supply and tube boiling curves. Through the central period of the run presented in this figure, the supply and boiling curves were quite close resulting in a marked slowing of the progress of the transient behavior.

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4. Figures 17, 18, and 19 form one of several illustrations that show that the effect of increasing severity of plugs is to increase the rate of progress of the transient behavior and to cause film boiling to start earlier in the sequence of events.

5. Figures 6 and 19 show that the effect of higher power levels is to cause a faster progress of the transient behavior, and to cause film boiling to start earlier in the sequence of events.

Reactor Application

The results of the experiments shown in Figures 3 to 21 tend to define the maximum amount of flow reduction by sudden plugging which a BDF process tube can endure without resulting in excessive slug temperatures. This flow reduction is defined for outlet water temperatures up to 155°C and tube powers up to 1250 KW. These temperatures and tube powers are by no means limits for reactor operation. The results here, rather, give an accurate indication of what would happen in a reactor process tube should a certain flow reduction occur to a tube at a certain initial tube power. The actual operating limits must be dependent on "ground rules" accepted for operation.

The "ground rules" for reactor operation must be based on the probability of the most credible plugging event occurring and the consequences of the occurrence. For example, under the present "ground rules" it must be thought that the probability of a complete flow stoppage to a BDF process tube is so small that the chance is worth taking, even in the face of the consequences. This must be so because a complete and permanent flow stoppage to a central zone tube would surely result in damage.

A set of limits for the BDF reactors based on sudden plugging of the process tube are not offered here. However, an example of the application of the results is shown:

1. If it agreed that plugging events leading to flow reductions of no more than 60 per cent can be tolerated, and
2. if there were a 100 psi range between the high and low Panellit trips, and
3. if the Panellit pressures were approximately 250 psi at normal operating conditions, and
4. if there was a 2 1/2 second delay between the time of Panellit trip and time of effective power reduction, then an outlet water temperature of 155°C would be permissible and it could be assured that the Panellit trips would prevent the uranium surface temperature from exceeding 400°C for any flow reduction caused by a sudden plugging.

It may be pointed out again that the transient behavior of a BDF tube following flow reductions resulting in unstable flow is strongly influenced by the critical flow phenomenon occurring in the rear Parker fitting. This phenomenon causes a significant increase in pressure in the tube, which not only results in a large increase in the Panellit pressure but also suppresses the degree of boiling and

delays the start of film boiling in the tube. The delay in the start of film boiling with its attendant high slug surface temperatures coupled with the large Panellit pressure increases makes possible the use of a Panellit high trip in event of a sudden upstream plugging incident which does not effect a low trip.

The experimental program encompassed and the discussion above pertains to plugs upstream of the Panellit taps only. For cases of plugs downstream of the Panellit tap, use can be made of the fact that for such plugs, the Panellit pressure is a true measure of the flow. The experimental data accumulated using upstream plugs can be used to predict Panellit pressures for cases of downstream plugs by calculating the Panellit pressure which would exist at the flow existing at each stage of the transient behavior following the flow reduction. Such calculations show that over a wide range of conditions a Panellit high trip would be secured for the case of a downstream plug as early as or earlier than a Panellit trip would have been secured for an upstream plug of the same degree.

Of concern in the application to reactors of the data secured in this investigation are questions concerning whether the experimental apparatus and its behavior constitute an accurate simulation of a reactor tube and its behavior. Probably the most important questions are 1) does the valve used to effect plugs in the experimental apparatus simulate actual reactor plugs, 2) do the degrees of plugging simulated cover the range of plugging incidents which may be expected of a reactor tube, and 3) does the transient heat response of the heater tube conform to that of a slug column. These are discussed below:

- 1) The pressure flow relations found in the experimental program did not quite behave as expected, raising the suspicion that the simulation of plugs in the apparatus might not conform to those of a reactor. An additional experimental study was undertaken to investigate this possibility. The conclusion reached in this study (4) was that the simulated plugs constituted a conservative approximation to most reactor plugging incidents.
- 2) To investigate what might be expected of a reactor plugging incident, deliberate plugs were placed on screens in the 189-D Hydraulics Laboratory process tube mockup. This is an exact mockup of a reactor process tube. The results (5) indicate that the simulated plugs reported here represent the more extreme cases which might occur in a reactor. For example, one of the larger pieces of plastic found on some of the H reactor screens following the post CG-558 startup (9) reduced the flow to approximately 24 gpm. When several pieces of this plastic material were placed on the screen, the flow was reduced to only approximately 11 gpm. These may be compared with the flow reductions to less than 5 gpm simulated in these tests.
- 3) The heater rod was made of sections of copper-nickel alloy which were bored out internally. As such it might be expected to have different transient heat responses than would a solid uranium slug. However, a comparison on a theoretical basis of the heater rod and a fuel element (6) indicates that the overall effect of the differences is to cause only minor differences in their transient response.

Limitation of results in this report

The results presented are limited to:

BDF, DR geometry process tubes
Solid fuel elements
Constant front header pressure of 525 psig
Initial rear header pressure of 25 psig
Flow reductions caused by sudden plugging of the process tube or fittings.

While the results will probably represent H reactors very closely it is also true that the results for C and K reactors will be significantly different.

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5. HW-51883 - "Experimental Plugging of Tube Inlet Screens", E. D. Waters, to be issued.
6. HW- - "A Comparison of Transient Thermal Conditions in an Electrically Heated Resistance Rod with Reactor Fuel Elements", R. W. Moulton and J. Muraoka, to be issued.
7. HW-52284 - "Extended Generalized Boiling Curves BDF Geometry", D. E. Fitzsimmons and W. L. Thorne, 8/28/57.
8. HW-52303 - "Critical Flow Conditions for BDF and DR Outlet Fittings", J. M. Batch and E. D. Waters, 9/23/57.
9. Letter - "Partial Plugging of Venturi Tubes and Orifices at H Reactor", E. E. Leitz to R. W. Reid, 7/30/57.

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TABLE II

SUMMARY OF TEST PROGRAM AND NOMENCLATURE

<u>Run No.</u>	<u>Q KW</u>	<u>F_i GPM</u>	<u>F_f GPM</u>	<u>F.R. %</u>	<u>T_{oi} °C</u>	<u>Figure No.</u>
IXE-3	300	26.1	< 2.5	> 90	103	3
-4	300	24.2	< 3	> 90	95	4
-6	500	24.2	6.3	74	95	5
-7	500	18.6	12.4	33	117	6
-8	500	25.3	4.5	82	90	7
-9	500	25.3	6.4	75	90	8
-10	500	20.0	7.0	65	110	9
-11	500	20.0	4.0	80	110	10
-12	750	32.5	18.0	45	100	11
-13	750	32.5	11.1	66	103	12
-14	750	32.5	8.3	74	103	13
-15	750	25.8	16.0	38	130	14
-16	750	25.7	10.6	59	128	15
-17	750	26.2	3.8	85	126	16
-18	1000	34.8	24.0	31	126	17
-19	1000	34.2	8.1	76	126	18
-20	1000	34.3	13.2	62	125	19
-21	1250	33.0	18.9	43	156	20
-25	1250	33.1	13.9	58	155	21

Front Header Pressure $\approx$ 525 psigRear Header Pressure $\approx$ 25 psigInlet Water Temperature $\approx$ 15°CNOMENCLATURE

F Flow, gallons per minute
 F_i Initial flow to process tube, gallons per minute
 F_f Throttled flow resulting from an upstream plug, gallons per minute
 F.R. Flow reduction, per cent
 P_{fh} Front header pressure, lbs per sq inch gage
 P_{pan} Panellit pressure, lbs per sq inch gage
 P_{rh} Rear header pressure, lbs per sq inch gage
 P_{ti} Tube inlet pressure, lbs per sq inch gage
 Q Test section tube power, kilowatts
 T_o Outlet water temperature, °C
 T_{oi} Initial outlet water temperature, °C
 T_s Rod surface temperature, °C

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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. 3
MODIFICATION 1
SK-1-2584

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FIGURE 2

HEATER ROD ASSEMBLY
AND HEAT GENERATION CHARACTERISTICS

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Figure 3A
FLOW AND TEMPERATURE RESPONSES IN A EDF PROCESS
FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 3B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 4A

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

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Figure 4B

PRESSURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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FLOW - G

Figure 5A
FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 5B
 PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 6A
FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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

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Figure 7A
FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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

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Figure 8A

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

PRESSURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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

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Figure 10A
FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

TOP SECRET

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

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FLOW - GPM

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

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Figure 11B

PRESSURE RESPONSES IN A EDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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FLOW - GPM

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Figure 12A

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

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Figure 12B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 13A
FLOW AND TEMPERATURE RESPONSES IN A EDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 13B

PRESSURE RESPONSES IN A EDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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TIME - SECONDS

Figure 14A
FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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REF ID: A62970

Figure 14B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 15A

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

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TEST DATA

LEGEND

Q - 750 KW

F_i - 25.7 GPM

F_f - 10.6 GPM

P₁ -

P₂ -

P₃ -

P₄ -

PRH - 23.5 PSIG

SCRAM

TIME - SECONDS

Figure 15B

PRESSURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 16A
 FLOW AND TEMPERATURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 16B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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FLOW - GPM

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Figure 17A

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

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Figure 17B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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40 30 20 10 0

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

Figure 18B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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FLOW - GPM

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Figure 19A

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

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Figure 19B

PRESSURE RESPONSES IN A BDF PROCESS
TUBE FOLLOWING A SUDDEN FLOW REDUCTION

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Figure 20A

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

Figure 20B

PRESSURE RESPONSES IN A BDF PROCESS
 TUBE FOLLOWING A SUDDEN FLOW REDUCTION

Figure 21A

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

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