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RESULTS OF EXPERIMENTAL TESTS SIMULATING
SLOW PLUGGING OF A BDF PROCESS TUBE☐

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RESULTS OF EXPERIMENTAL TESTS SIMULATING
SLOW PLUGGING OF A BDF 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 an experimental program investigating the transient response of a BDF process tube to slow plugging of the coolant stream. The program was directed toward determining the degree of protection offered by the Panellit pressure gage system to the hazards arising from flow reductions following such plugs.

INTRODUCTION

This report is the second of a series^{1,2,3} reporting transient heat transfer experiments directed toward determining the degree of protection offered by the Panellit pressure gage system to hazards resulting from accidental flow reductions.

The first report of this series was concerned with the results of experiments which tended to define the amount of flow reduction caused by a sudden plugging which a BDF process tube could endure without resulting in excessive fuel element temperatures. The results showed that following the onset of a sudden plugging occurrence in a BDF coolant stream, the Panellit pressure would change considerably while the temperature increase would not be excessively rapid. Based on these results concerning sudden plugging it was pointed out that operation at higher power levels than have been hitherto permitted could be feasible.

Also of concern in any scheme of higher power levels is the degree of protection offered by the Panellit protection procedures against the hazard arising in event of flow reduction due to a slow, gradual plugging in the process tube assembly. Such events are important in that although the initial flow reductions may be gradual and harmless, should the plugging continue to the point where unstable flow⁴ occurs, a reactor shutdown must soon be initiated if a hazardous situation is to be avoided. This study then reports the sequence of pressures, flow, and temperatures within a BDF process tube following unstable flow due to a gradual plugging of the flow stream. The experiments were performed in the 189-D Laboratory of the Thermal Hydraulics Operation of the Hanford Laboratories Operation.

NOTE

The discussion in this document assumes that slow plugging occurrences both upstream and downstream of the Panellit tap are possible. Slow plugs downstream of the

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, 10/14/57.
3. HW-52424 C "Results of Experimental Tests Simulating a Power Excursion to a BDF Process Tube", G. M. Hesson, W. L. Thorne.
4. 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. In general, this leads to a self induced flow reduction resulting in temperatures which may be harmful to the integrity of the fuel element.

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Panellit tap can and do occur from incidents such as ruptured slugs. It is highly questionable, however, if a slow plugging upstream of the Panellit tap would occur. The only place in the system liable to such a plugging is the screen upstream of the venturis or orifices. The screens and cross wires presently used, however, have such large openings that any particle large enough to be stopped by the screens is so large it would result in a relatively large sudden plug.

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 gradual throttling of the coolant water was applied until incipient unstable flow was reached. A step increase in tube power was then made to establish unstable flow. Initial tube powers were from 300 to 1250 KW. Incipient unstable flow was arbitrarily defined to exist when the outlet water temperature was at approximately 175°C. Step power increases to initiate unstable flow ranged from 5 to 30 per cent.

Following the step power increase the tube flow experienced a self-induced flow 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 which might be damaging to the test equipment would be reached. The tube power was then reduced in accord with a simulated 1000 inhour scram.

Nineteen runs were made in which unstable flow developed and which did not result in damage to the apparatus. A synopsis of these runs is presented in Table I. The test results are given in Figures 4 through 22.

CONCLUSIONS

The results of the experiments show that after unstable flow is initiated following slow plugging of a process tube, the pressure rise is substantial and the temperature increases and flow decreases are not excessively rapid. It is concluded that it is conservative to require a Panellit trip of the reactor before unstable flow conditions result after a flow reduction caused by a plugging incident, except for cases of plugs upstream of the Panellit tap at tube powers under approximately 400 KW.

The pressure rise after the start of unstable flow due to steam formation is such that a safe reactor shutdown 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 and pressure increases following the start of unstable flow arising from a gradual plug are not extremely rapid.
2. A BDF process tube undergoing a slow plugging upstream of the Panellit gage will initially experience first a decrease in pressures and subsequently an increase in pressure when steam formation starts in the process tube and fittings. The pressures, however, will be very nearly those defined by the steady state boiling curve. Further progress of the slow plugging then leads

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to unstable flow. The unstable flow is accompanied by large increases in pressures which make extremely probable a high Panellit trip for those cases where a low trip was not effected by the initial decrease in pressure.

3. Recently secured steady state data⁵ show that a process tube can sustain plugs resulting in relatively severe flow reductions without experiencing unstable flow. This characteristic is enhanced at lower tube powers, and below approximately 400 KW a BDF tube could probably undergo a flow reduction to boiling burnout without going unstable. In such cases, in event of an upstream plug, no reliance may be placed upon a Panellit high trip.
4. Those aspects of the experimental assembly which do not exactly simulate reactor tubes are such that the application of the results obtained in the experimental tests to reactor use is conservative.
5. The experimental program encompassed slow plugging upstream of the Panellit tap only. Calculations can be made from the data, however, to show that in event of a plugging downstream of the Panellit tap, a high Panellit trip would be effected as early as or earlier than a corresponding upstream plug.

EXPERIMENTAL EQUIPMENT

The tests were performed in the 189-D Thermal Hydraulics Laboratory. A diagram of the equipment is presented in Figure 2. (A detailed description of the equipment is given in the first document of this series, HW-52424 A). The equipment consists of a mockup of a process tube containing an electrically heated rod simulating nuclear heating of 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 test section proper is a reasonably accurate mockup of a BDF process tube downstream of the front Van Stone flange. The tube is divided into an active section containing the heater rod and an offset section containing a dummy slug loading. The offset is necessary to permit the electrical connections to be made to the heater rod. The inside of the process tube is coated with a 0.005 inch layer of varnish (Heresite) to provide electrical insulation.

The heater rod is made up of sections of copper, brass and copper-nickel alloys welded together. The rod is designed to give a stepwise variation in heat generation in a reactor process tube. The details of the construction of the rod and the form of its heat generation are shown in Figure 3. Where feasible, the 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.

The rod surface temperature was monitored 5.5 feet from the end of the heated section, the point determined in previous tests to be at approximately the point of maximum temperature. The thermocouple installation is such that temperatures somewhat higher, but proportional to the true surface temperature, are read. Six zinc and six silver solder fusible plugs (melting points approximately 400 and 630°C, respectively) were imbedded in the surface of the rod to give further

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5. HW-52284 "Extended Generalized Boiling Curves BDF Geometry", D. E. Fitzsimmons, W. L. Thorne.

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indications of overheating. These plugs were examined after the conclusion of the experiments and found intact. An additional but indirect indication of the absence of excessive rod surface temperatures is available from the fact that the Heresite coating on the inside of the process tube maintained its integrity. From experience, it has been determined that the Heresite breaks down when tube "surface" temperatures are much in excess of 400°C.

EXPERIMENTAL METHOD

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 175 to 180°C were arbitrarily chosen as the initial point. A BDF system operating at 180°C has been determined to be very near to unstable flow. The venturi throat, i.e. Panellit tap, pressure was adjusted to approximately 250 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

A discussion of what takes place in a process tube during a slow gradual upstream plugging occurrence must be split into two parts covering 1) that period within the stable flow region and 2) that period in the unstable flow region. The behavior in the stable flow region can be quantitatively predicted with a reasonable degree of accuracy. The behavior in the unstable flow region can be predicted only qualitatively.

In the stable flow region, a slow gradual plugging would result in a gradual decrease in flow and an increase in temperature. The tube pressures would decrease at first, and then would increase after two phase flow conditions were reached in the rear Parker fitting. However, in the stable flow region, the flow, pressures, and temperatures would always be at near equilibrium as defined by the steady state boiling curve; and, if the plugging occurrence should cease, the tube behavior would stabilize at the equilibrium point at the time of the cessation of the plugging. This behavior is depicted schematically in Figure 1. A slow plugging upstream of the Panellit tap would result in the flows and Panellit pressures following curve ABCD.

If the plugging incident continues, the increasing tube pressures eventually raise the tube inlet pressure above the pressure supplied, and unstable flow starts. This can be best explained by reference to Figure 1. Point D represents the point of incipient unstable flow. A further reduction in flow would result in the

Figure 1. Illustration of Supply and Demand Curves
And Unstable Flow

pressure required to sustain flow (represented by the boiling curve) becoming greater than the supplied pressure (represented by the supply curve). The pressure would then increase and the flow decrease along line DE. If the unstable flow were allowed to continue it would reach Point E which is a stable operating point. This is a point, however, at such a low flow that it would be accompanied by melting of slugs.

Unstable flow arising from a slow gradual plugging differs from that arising from a sudden plug only in its starting point. The sudden plug case reaches unstable flow by a large flow reduction from a condition of normal flows and moderate temperatures. The slow gradual case reaches unstable flow by a very small flow reduction from a condition of abnormally low flows and high temperatures. This is illustrated in Figure 1. A slow upstream plug reaches unstable flow by a small flow reduction from Point D. A sudden upstream plug just sufficient to result in unstable flow results in an instantaneous transition from the normal operating Point A to Point F. The flow and pressure then start to change along line FDE. The behavior of a slow plug is the same as that of a sudden plug which has progressed through the early stages of its sequence, i.e., from F to D.

In cases where the slow plugging has progressed to unstable flow, the sequence of events may be expected to go initially through a period when nucleate boiling is taking place in the active section of the tube followed by a period when film boiling is taking place in the active section.

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When nucleate boiling is taking place in the tube, a large share of the heat going into the water is used to form steam rather than to raise the sensible heat of the water and the rate of temperature increase is relatively slow. But, 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 characteristics, the rate of pressure rise and flow decrease are relatively rapid.

The tube boiling curve represents the equilibrium condition, the tube supply curve during unstable flow represents the operating condition, and the difference between the two represents a driving force. In the early stages of unstable flow arising from a slow plugging, the distance between the two curves is very small and the progress of the transient is very slow. In the later stages of the transient, the boiling curve and supply curve diverge and the progress of the transient speeds up. The rate of progress is also increased with increased tube powers. This is shown in Figure 1. The region near Point D is the region of the early stages. The distance between the supply curve and the boiling curve is small but becomes larger as the flow is further reduced.

The behavior of the tube after film boiling starts differs from that when nucleate boiling is occurring because of the poor heat transfer characteristics of film boiling. This results in relatively slower rates of water temperature and pressure increases and flow decrease. Of prime importance, the poor heat transfer of film boiling causes a greatly increased rate of slug surface temperature rise. At tube powers of interest, the slug surface temperature would 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.

The important characteristics of unstable flow in a BDF tube are strongly influenced by the choking effect due to critical flow in the rear Parker fittings. The end effect of this is that an increase in water temperatures causes an increase in the pressure upstream of the fitting. This results in rapidly increasing pressures in the tube, suppression of the start and degree of film boiling, and delaying the onset of film boiling with its attendant rapid slug surface temperature rise. This choking effect is most pronounced in its effects at higher flows. Slow plugging occurrences result in the start of unstable flow at relatively high flows, as plugging occurrences go. Consequently, the pressurization is large and film boiling is greatly delayed.

EXPERIMENTAL RESULTS

Slow plugging runs were made at tube powers of 300 to 1250 KW, and power increases to start instability of 5 to 30 per cent. A synopsis of the runs is presented in Table I which gives the test conditions, initial conditions, and power increases for each run. The experimental data is presented in Figures 4 through 22. Each figure is split into two parts, a Part A showing outlet water temperature, heater rod surface temperature and flow rate, and a Part B showing the tube inlet and the venturi throat pressures. All are plotted against time from the start of unstable flow. The heater rod temperature was measured 5.5 feet from the downstream end of the active section. The outlet water was measured at the end of the active section.

The data presented in Figures 4 through 22 show, in general, conformance to that predicted by the qualitative theory. Several examples are presented below: 1) Figures 10, 13, and 15 show the effect of the proximity of the boiling curve to the supply curve. These three figures represent identical runs except unstable

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flow starting with the boiling curve closer to the supply curve. These figures show that the closer the boiling curve to the supply curve, the slower is the initial stages of the transient.

- 2) Figures 8, 13, 18, and 21 show that the effect of higher power levels is to cause a faster progress of the transient behavior.
- 3) Figure 5 shows the start of film boiling late in the course of the transient. At approximately 12 seconds after the start of unstable flow the rod surface starts a rapid increase.

Not included in these figures are two runs made at a 300 KW tube power which did not go unstable.

REACTOR APPLICATION

In the previous report concerning sudden plugs, there was developed the concept of moderate upstream plugs for which the probability of a Panellit low trip was not great, but the subsequent pressurization was large and the probability of Panellit high trip was great. This case is the same as the case of the slow upstream plugging. That is, the behavior of a tube which has undergone a slow gradual plugging to unstable flow is identical to that of a tube which has experienced sudden plug just sufficient to lead to unstable flow, which has not incurred a low Panellit trip, and which has progressed through the early stages of its transient sequences. The slow gradual plug has as great a possibility of a high Panellit trip as does its sudden plug counterpart.

A sudden plugging upstream of the Panellit tap results in an initial pressure drop down to pressures corresponding to passage of liquid water. A slow upstream plugging occurrence results in gradually decreasing pressures until two phase flow starts in the rear fittings, followed by a pressure increase. The minimum pressure reached during a slow plugging occurrence is at a higher pressure than the minimum reached by a sudden plug. See Figure 1 for an illustration of this. The slow gradual plug has, therefore, a lesser probability of a low Panellit trip than does its sudden plug counterpart.

To recapitulate, a slow gradual upstream plug leading to unstable flow has as its counterpart a sudden upstream plug just sufficiently large to reach unstable flow. The slow plug has a lesser probability of effecting a low Panellit trip but an equal probability of effecting a high Panellit trip as does its sudden plug counterpart.

As an example of the feasibility of using a high Panellit trip to protect against slow gradual upstream plugs, the experimental data show:

1. If there was a 100 psi range between the high and low Panellit trips,
2. If the Panellit pressures were approximately 250 psig at normal flow conditions,
3. If the high trip was 100 psi above the Panellit pressure immediately prior to the start of unstable flow,

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4. If there was a 2 1/2 second delay between the time of the Panellit trip and the time of effective power reduction, it is highly probable that a Panellit trip would take place in time to prevent the uranium surface from exceeding 350°C for tube powers from 500 to 1250 KW.

The experimental program and the discussion above pertain to plugs upstream of the Panellit taps only. For cases of slow plugs downstream of the Panellit tap, the Panellit pressure is a true measure of 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 sequence. Such calculations show that over a wide range of conditions a Panellit high trip would be secured as early as or earlier than would have been secured for the corresponding upstream plug.

Of concern in the application of these data to reactors are questions concerning whether the experimental apparatus and its behavior constitute an accurate simulation of a reactor tube. In the first document of this series the conclusion was reached that the apparatus is a reasonable representation of a reactor tube and the data are probably conservative. This conclusion also holds for the data presented here. However, one question unique to the slow plugging experiments remains. In these tests a step power boost rather than a continued slow flow reduction was used to initiate unstable flow. The power boost resembles the increase in tube power associated with the complete replacement of water in the tube with steam. In a BDF tube this power increase amounts to 15 per cent.⁶ The power boosts used in the tests ranged from 5 to 30 per cent. In a reactor tube, however, the expulsion of the water is spread out over a period of time and the actual power increase would range from near zero at the start of unstable flow up towards 15 per cent at the end. The experimental tests, therefore, imposed a more severe power boost than a reactor would experience. This results in a faster transient, particularly in the early stages.

Limitation of results in this report.

The results are limited:

BDF, DR geometry process tubes

Solid fuel elements

Constant front header pressure of 525 psig (Higher tube powers make these conclusions conservative)

Initial rear header pressure of 25 psig (Since critical flow exists during the course of these situations, the data and conclusions are probably applicable to all rear header pressures of operational interest.)

The results will probably represent H reactors very closely as well, but not C or K reactors.

6. Confidential-Undocumented "Instantaneous Tube Power Increases on Loss of Water", W. E. Neimuth, February 21, 1957.

G. M. Hesson

G. M. Hesson, Engineer
Thermal Hydraulics Operation

W. L. Thorne

W. L. Thorne, Engineer
Thermal Hydraulics Operation

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DECLASSIFIEDTABLE ISUMMARY OF TEST PROGRAM

<u>Run No.</u>	<u>F_i Gpm</u>	<u>Q_i KW</u>	<u>Q_f KW</u>	<u>ΔQ %</u>	<u>T_{oi} °C</u>	<u>Figure No.</u>
7	16.4	735	955	30	178	4
8	17.3	750	965	29	178	5
9	11.4	480	645	34	187	6
10	11.6	520	580	12	178	7
11	11.0	470	530	12	182	8
12	18.0	740	940	27	174	9
13	18.4	760	955	26	173	10
14	18.0	770	955	24	175	11
15	18.2	770	950	23	174	12
16	18.5	760	860	13	173	13
17	18.0	770	810	5	173	14
18	18.1	760	815	7	178	15
19	25.0	1040	1260	21	175	16
20	23.4	1045	1220	17	177	17
21	23.3	1030	1170	14	175	18
22	22.5	1035	1115	8	178	19
23	28.6	1175	1410	20	179	20
24	28.3	1265	1390	11	176	21
25	28.7	1175	1370	17	175	22

Front header pressure = 525 psig

Rear header pressure = 25 psig

Inlet water temperature = 15 °C

SUMMARY OF NOMENCLATURE

F = Flow, Gpm

F_i = Initial flow at start of runP_{fh} = Front header pressure, PsigP_{pan} = Panellit pressure, PsigP_{rh} = Rear header pressure, PsigP_{ti} = Tube inlet pressure, Psig

Q = Test section tube power, KW

Q_i = Initial tube power at start of run, KWQ_f = Final or increased tube power, KWT_o = Tube outlet water temperature, °CT_{oi} = Initial tube outlet water temperature at start of run, °CT_s = Surface temperature of heater rod, °C

ΔQ = Per cent increase in tube power

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FIGURE 2

FULL SCALE MOCK UP
PRESSURE & TEMPERATURE
LOCATION

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FOR I&E STUDIES

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-Z584

FIGURE 3

HEATER ROD ASSEMBLY
AND HEAT GENERATION CHARACTERISTICS

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Figure 4A

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

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

Figure 4 B

REF ID: A66884

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TIME - SECONDS

Figure 5 A

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

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Figure 5 B

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

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Figure 6 A

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

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Figure 6 B

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

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Figure 7 A

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

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

Figure 7 B

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Figure 8 A

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

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

Figure 8 B

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

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Figure 9 B

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

DECLASSIFIED

DECLASSIFIED

HM-52424 B

Figure 10 A

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

DECLASSIFIED

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

DECLASSIFIED

TEST DATA

F_i 18.0
Q_i 770
Q_f 955
P_{FH} 525
P_{RH} 20

LEGEND

P_{T1} ———
P_{PAN} - - -
P_{FH} ·····
P_{RH} - · - ·

Figure 11 B

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

DECLASSIFIED

Figure 12 A

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

DECLASSIFIED

Figure 12 B

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

DECLASSIFIED

TIME - SECONDS

Figure 13 A

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

DECLASSIFIED

DECLASSIFIED

Figure 13 B

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

DECLASSIFIED

DECLASSIFIED

Figure 14 A

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

DECLASSIFIED

DECLASSIFIED

Figure 14 B

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

DECLASSIFIED

Figure 15 A

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

DECLASSIFIED

DECLASSIFIED

Figure 15 B
PRESSURE RESPONSES IN A BDF PROCESS TUBE
FOLLOWING A SLOW FLOW REDUCTION

DECLASSIFIED

FLOW - GPM

DECLASSIFIED

TIME - SECONDS

Figure 16 A

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

DECLASSIFIED

Figure 16 B

PRESSURE
FOLLOWS FLOW REDUCTION

DECLASSIFIED

Figure 17 A

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

DECLASSIFIED

DECLASSIFIED

Figure 17 B

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

DECLASSIFIED

DECLASSIFIED

Figure 18 A

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

DECLASSIFIED

Figure 18 B

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

DECLASSIFIED

Figure 19 A

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

DECLASSIFIED

DECLASSIFIED

Figure 19 B

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

DECLASSIFIED

Figure 20 A

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

DECLASSIFIED

Figure 20 B
PRESSURE RESPONSES IN A BDF PROCESS TUBE
FOLLOWING A SLOW FLOW REDUCTION

DECLASSIFIED

DECLASSIFIED

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

DECLASSIFIED

DECLASSIFIED

Figure 21 B

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

DECLASSIFIED

FLOW - GPM

DECLASSIFIED

Figure 22 A

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

DECLASSIFIED

DECLASSIFIED

Figure 22 B

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

DECLASSIFIED